Delayed and Displaced Photons

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on behalf of the vertexed non-prompt photons analysis team
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LLP13 Workshop

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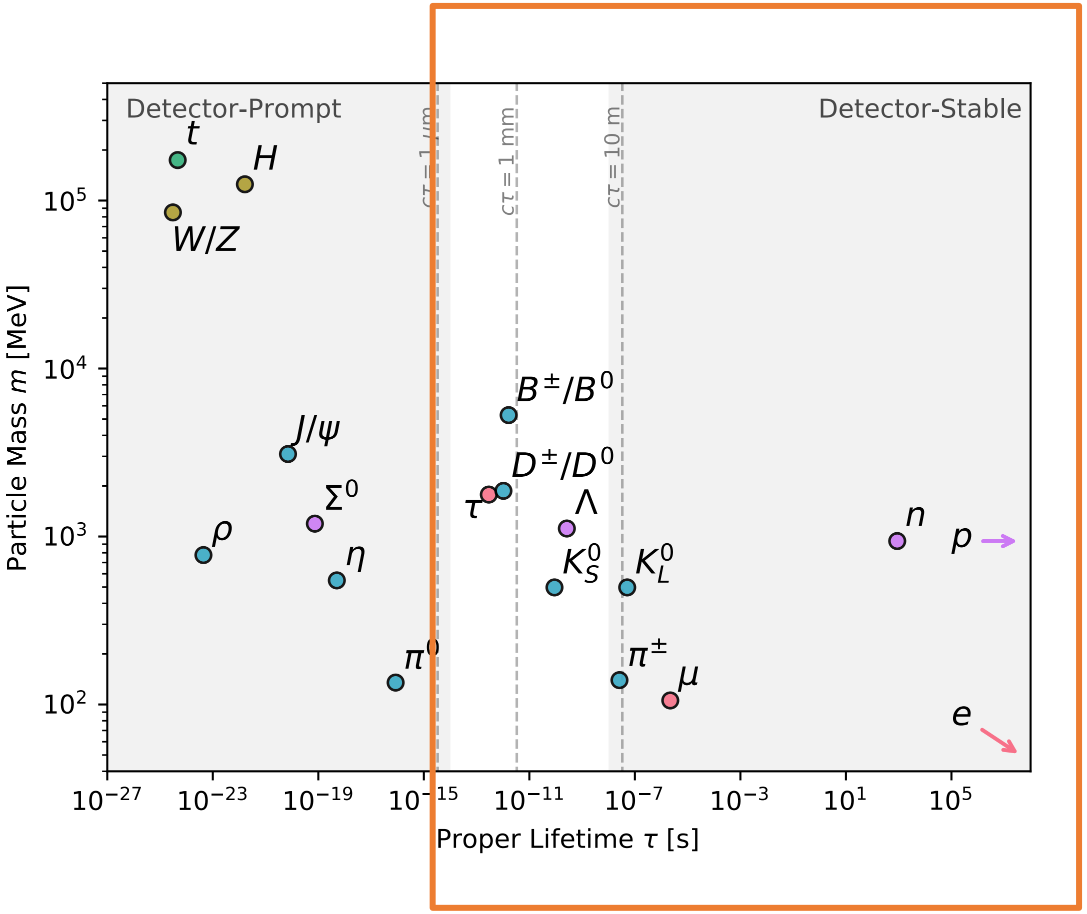
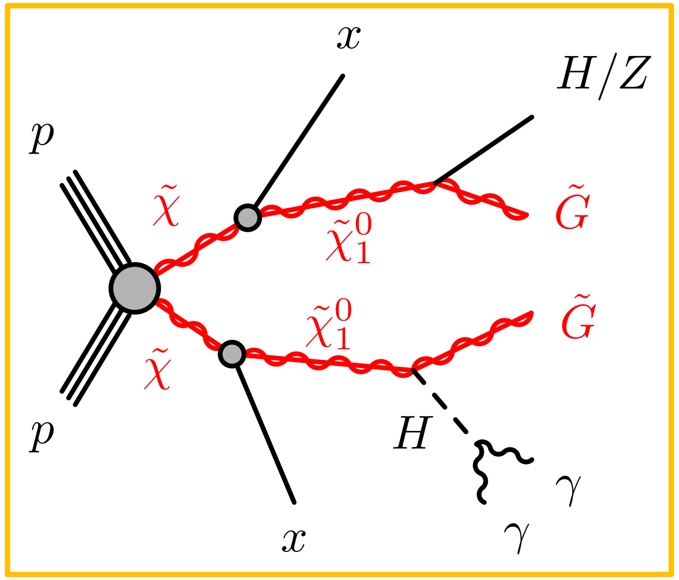
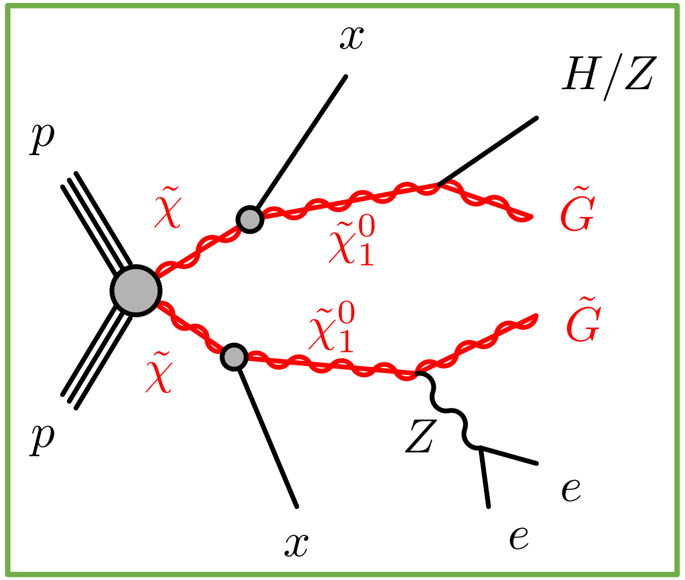
Long-lived particles

- Long-lived particles (LLPs) are abundant in the SM and well-motivated in other BSM models.
- LLPs give rise to experimentally unique signatures and unusual backgrounds.
  - Projective geometry of detectors ⇒ necessitates special reconstruction methods.
  - Require dedicated triggers, excellent knowledge of detector & its performance, …
- E.g., Exploit calorimeter detector-design and performance to search for LLP decays into electrons/photons.
  - Projective geometry can be used to measure “non-pointing”-ness.
  - Time-of-flight to the calorimeter can be used to measure delayed objects



GMSB Model and LLP signatures

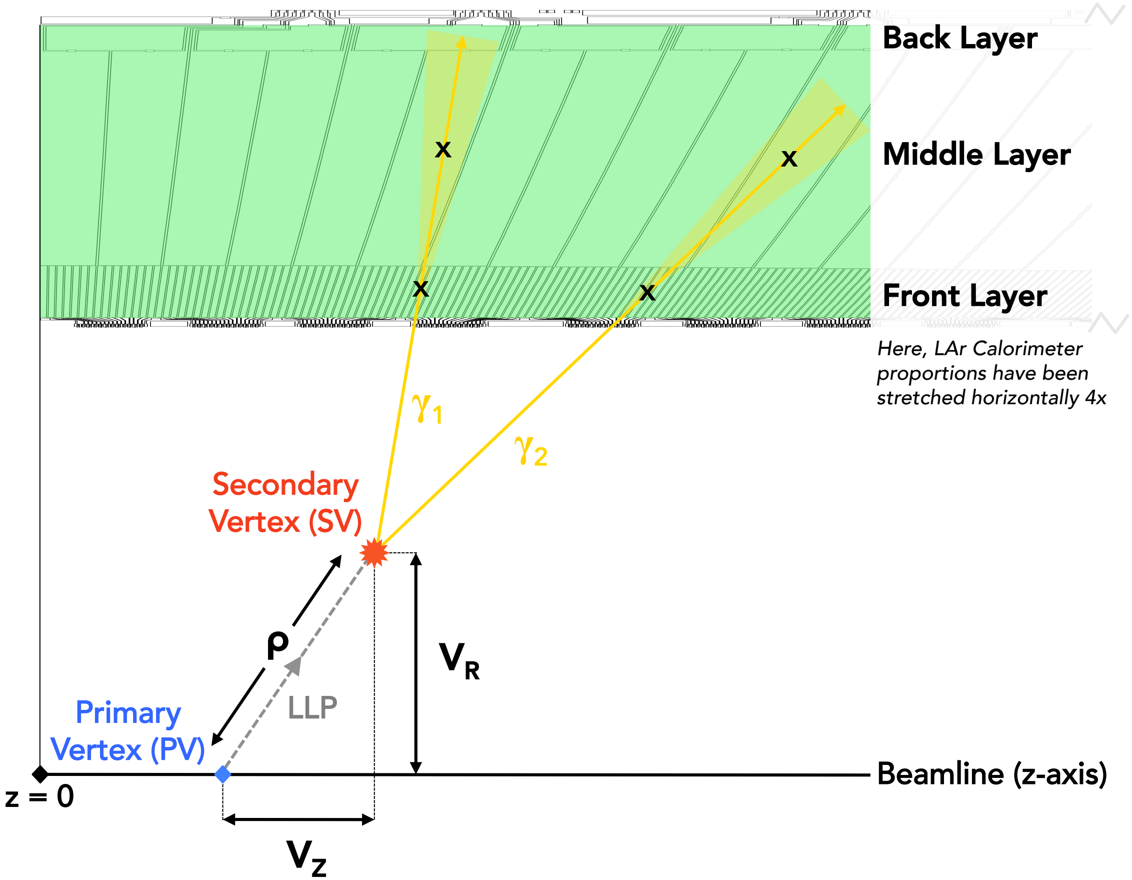




- $\tilde{\chi}^{\pm}/\tilde{\chi}_2^0$, denoted by, $\tilde{\chi}$, decays to the long-lived neutralino, $\tilde{\chi}_1^0$.
- Mass and lifetime of $\tilde{\chi}_1^0$ are free parameters in the GMSB model under study.
    - Vary the mass between 135–925 GeV.
    - Vary the lifetime between 0.25–1000 ns.
- Additionally, the decay of each $\tilde{\chi}_1^0$ to either H/Z boson is a free parameter.
    - ***Note:*** Force the decay of one of the H/Z boson to decay 100% to γγ (e^+e^-).
- Based on the decay of the two $\tilde{\chi}_1^0$, four possible decay modes are available.

Displaced Calorimeter Vertices and Delayed Objects

- If the SUSY breaking scale is ~10^2–10^3 TeV, the sparticle is long-lived such that it decays away from the primary collision vertex ⇒ *displaced vertex*.
- Finite flight path of the sparticle ⇒ H/Z boson decay products arrive at the calorimeter with a non-zero time of arrival ⇒ *delayed objects*.



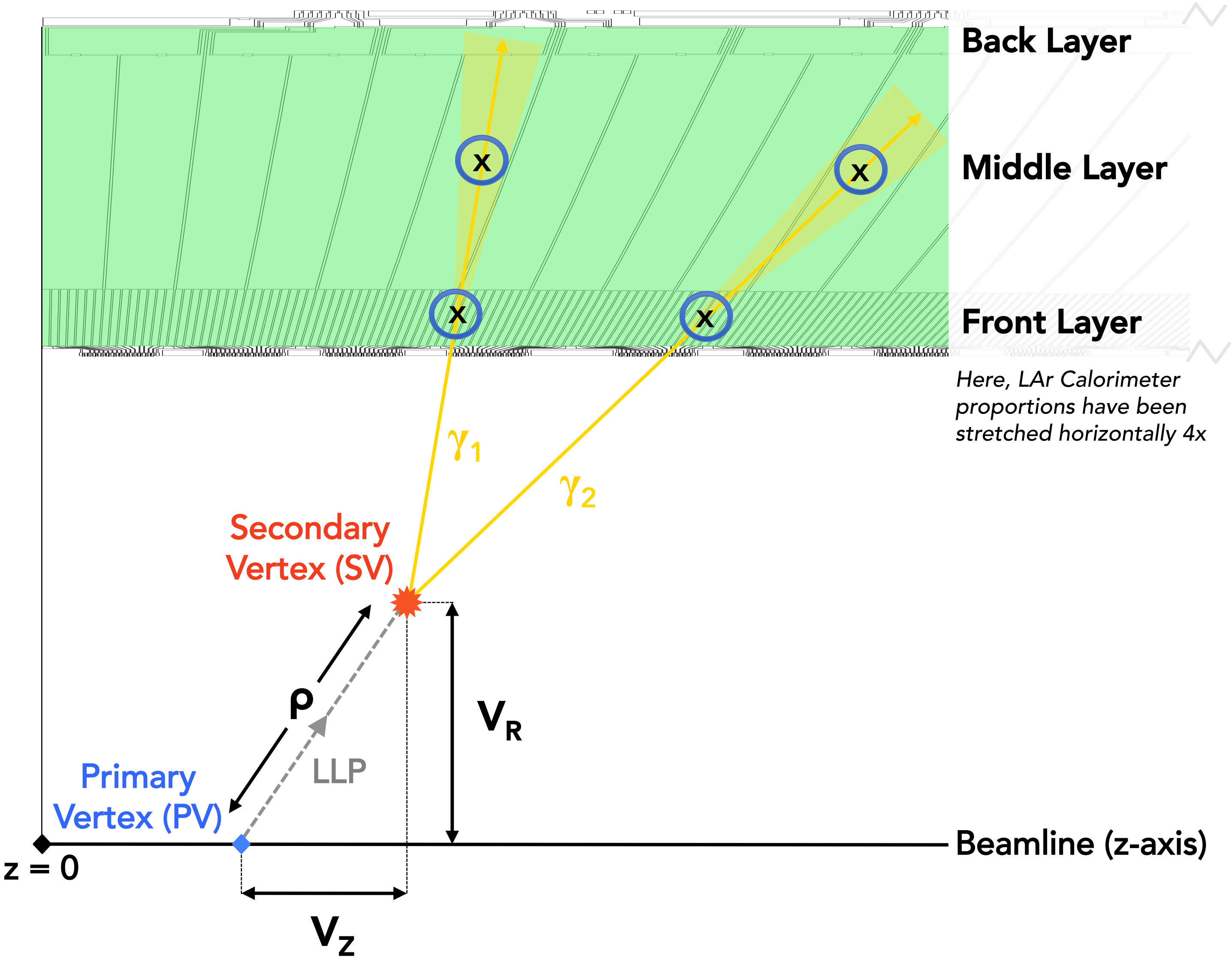
Here, LAr Calorimeter proportions have been stretched horizontally 4x

Trackless Calo-Vertexing

Exploit the fine segmentation of the calorimeter and EM shower information to determine photon *pointing*.

Find the intersection of the two photon-pointing lines to localize the *secondary vertex*.

Calculate the displacement ρ, and its components V_R and V_z.



Here, LAr Calorimeter proportions have been stretched horizontally 4x

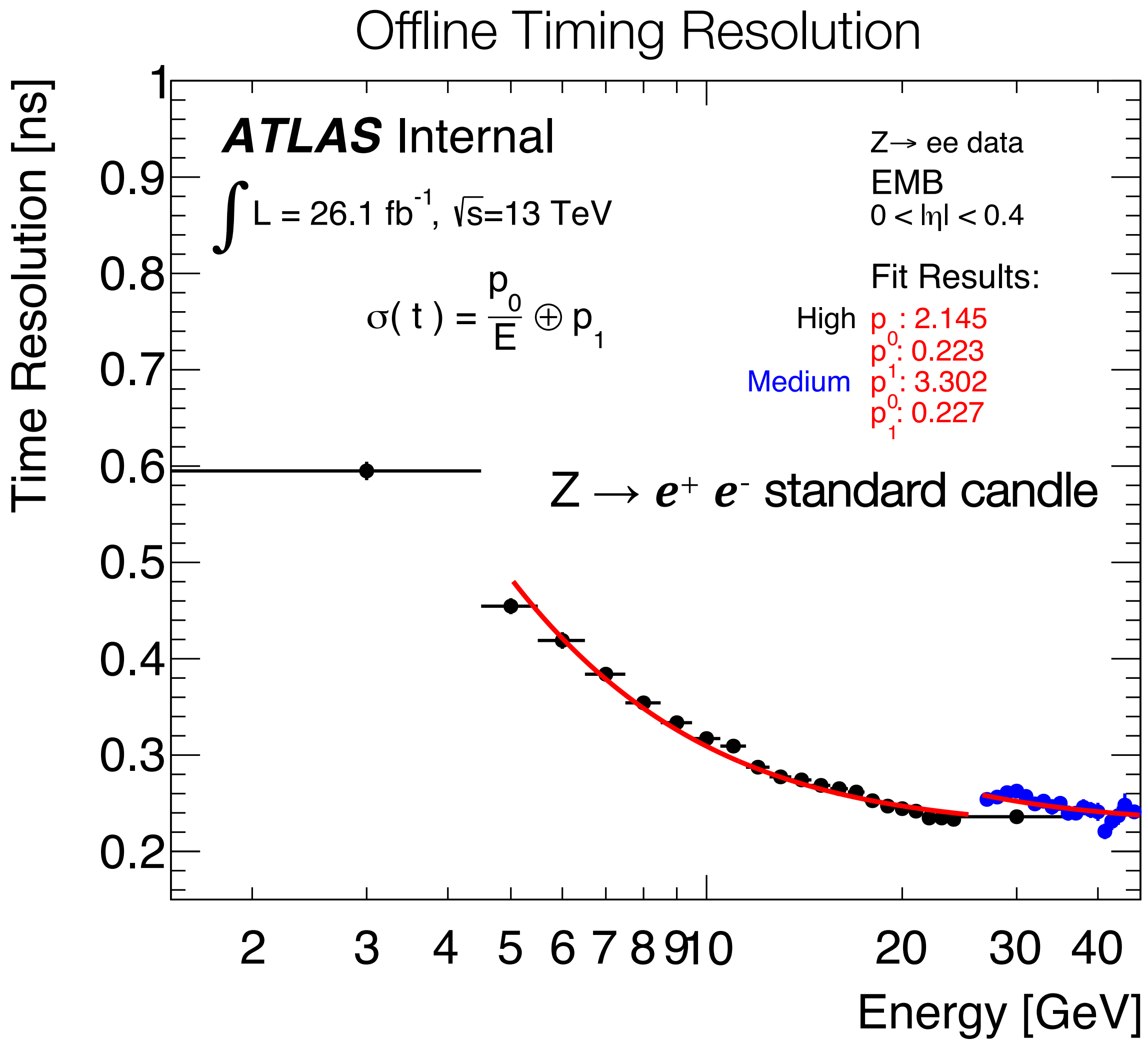
LAr Clock: A 250 ps precision timekeeper!

- Timing resolution as a function of the cell energy can be expressed as:

$$\frac{\sigma(t)}{E} = \frac{p_0}{E} \oplus p_1$$

p_0 = noise term, p_1 = constant term

- Achieve a ~1 ns resolution during data-taking.
- Improve the resolution offline by performing a series of offline calibrations to achieve a ~190–240 ps timing resolution.



Selecting Photon Candidates

- For the analysis, the displaced electrons and photons are reconstructed as photon candidates.
    - Object selections are applied to all signals, regardless of the final state $H \to \gamma\gamma/Z \to e^+e^-$.

Parameter	Selection Value
Photon multiplicity	≥ 2
Photon η	$\geq 1\ \gamma$ with $\lvert\eta\rvert < 1.37$
E_{cell}^{max} [GeV]	> 5
Leading (subleading) p_T [GeV]	> 40 (> 30)
Identification	`Medium`
Isolation	`FixedCutLoose`
Calorimeter Signal Gain	MEDIUM or HIGH

Selecting Events

Parameter	Selection Value
Photon multiplicity	≥ 2
Trigger	
2015–2016	`HLT_g35_loose_g25_loose`
2017–2018	`HLT_g35_medium_g25_medium`
Timing [ns]	$\in$ (-12, 12)
$\Delta\eta_{\gamma\gamma}$	> 0.1
$m_{\gamma\gamma}$ [GeV]	> 60
V_R [mm]	$\in (0, 1500)$
$\|V_Z\|$ [mm]	< 3740
Sign of t_γ	$t_{\gamma1} \times t_{\gamma2} > 0$

Two photons in an event with $p_T > 35$ GeV and 25 GeV, and Loose (Medium) identification

Avoid events from adjacent bunches

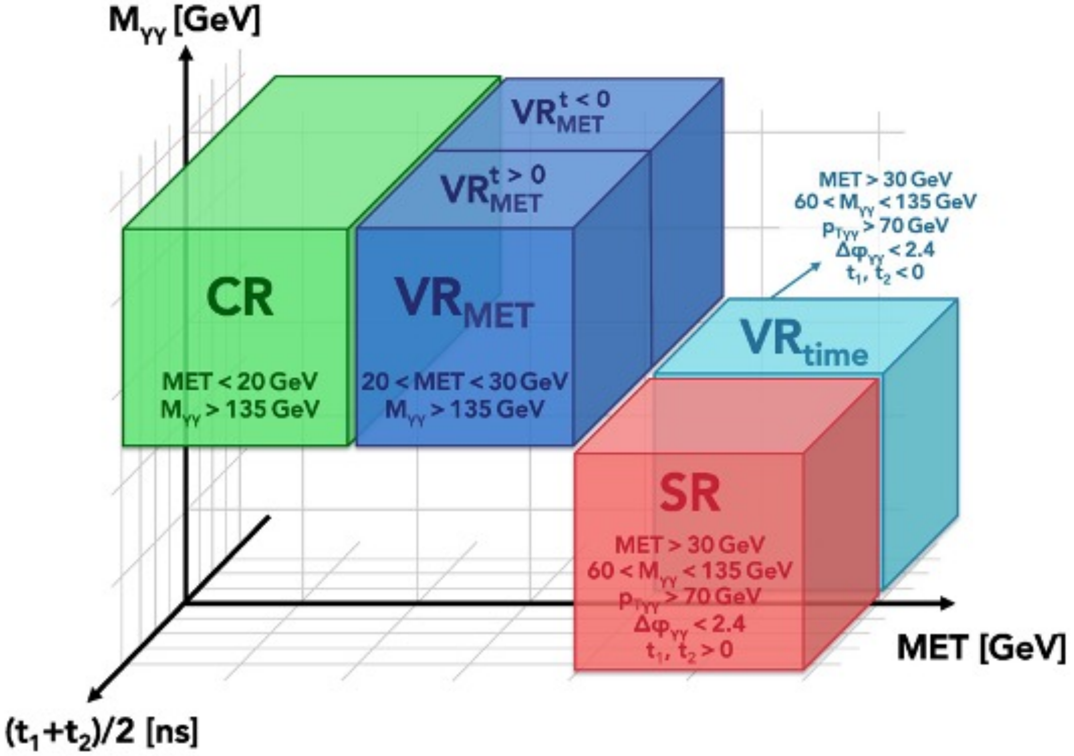
Kinematic selections to mitigate trigger turn-on effects & improve vertex resolution

Ensure $\tilde{\chi}_1^0$ decays before calorimeter

Require same-sign of photon time

Defining the Analysis Regions

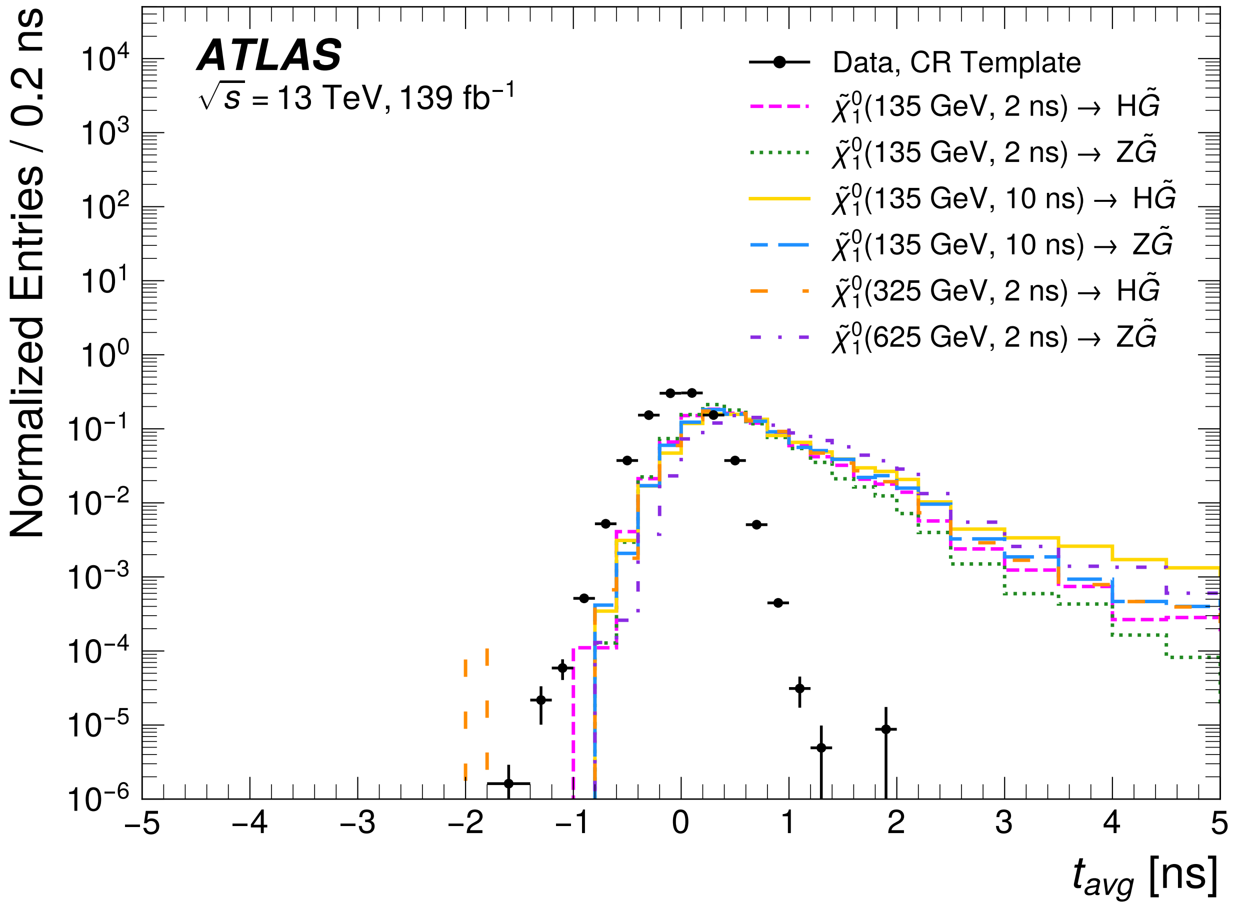
- Control Region (CR):
  - Derive the background model.
  - Low $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$, high $m_{\gamma\gamma}$ ⇒ low signal contamination.
  - $t_{\gamma 1} \times t_{\gamma 2} > 0$ to enhance statistics.
- Validation Regions ($\mathrm{VR}_{\mathrm{MET}}$):
  - Validate extrapolation across $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}$.
  - Validate extrapolation across positive & negative t_{γ}.
- Validation Region ($\mathrm{VR}_{\mathrm{time}}$):
  - Validate extrapolation across $\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}, m_{\gamma\gamma}, p_T^{\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$.
- Signal Region (SR):
  - Search for possible SUSY signal(s).

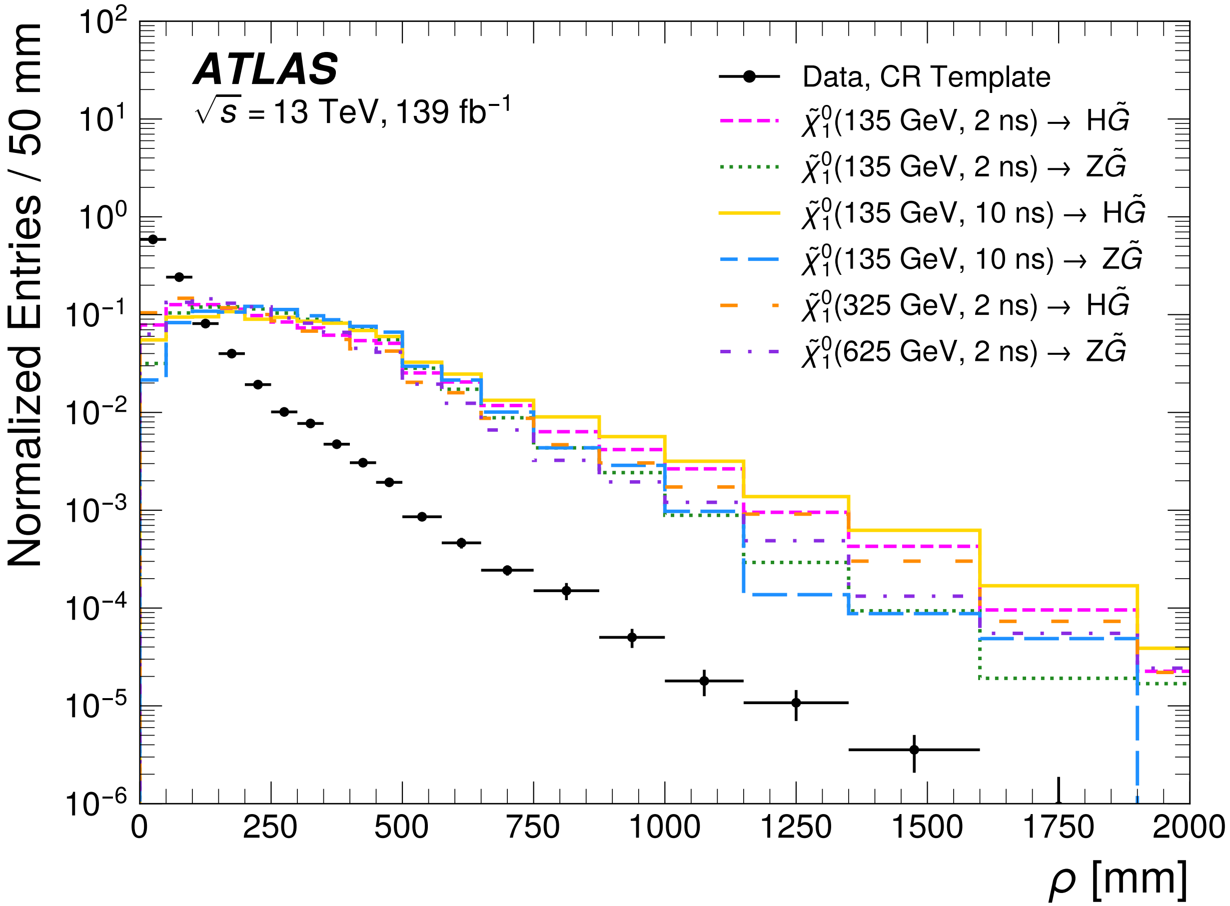


Analysis Sensitive Variables

$$t_{\mathrm{avg}} = \frac{1}{2}\left(|t_{\gamma 1}| + |t_{\gamma 2}|\right)$$

$$\rho = \sqrt{V_R^2 + V_Z^2}$$





Background Estimation: An Overview

- Background estimation procedure is *fully data-driven*.
  - Tails of the timing distribution are not well-modeled in simulation.
- Sources of background:
  - Mismeasurement of genuine and fake photons.
  - Genuine and fake photons from *satellite collisions*.
- Derive background model from the timing distribution shape in the CR.
- Perform simultaneous fit of t_{avg} in categories of displacement ρ. Optimized choice of bins are:

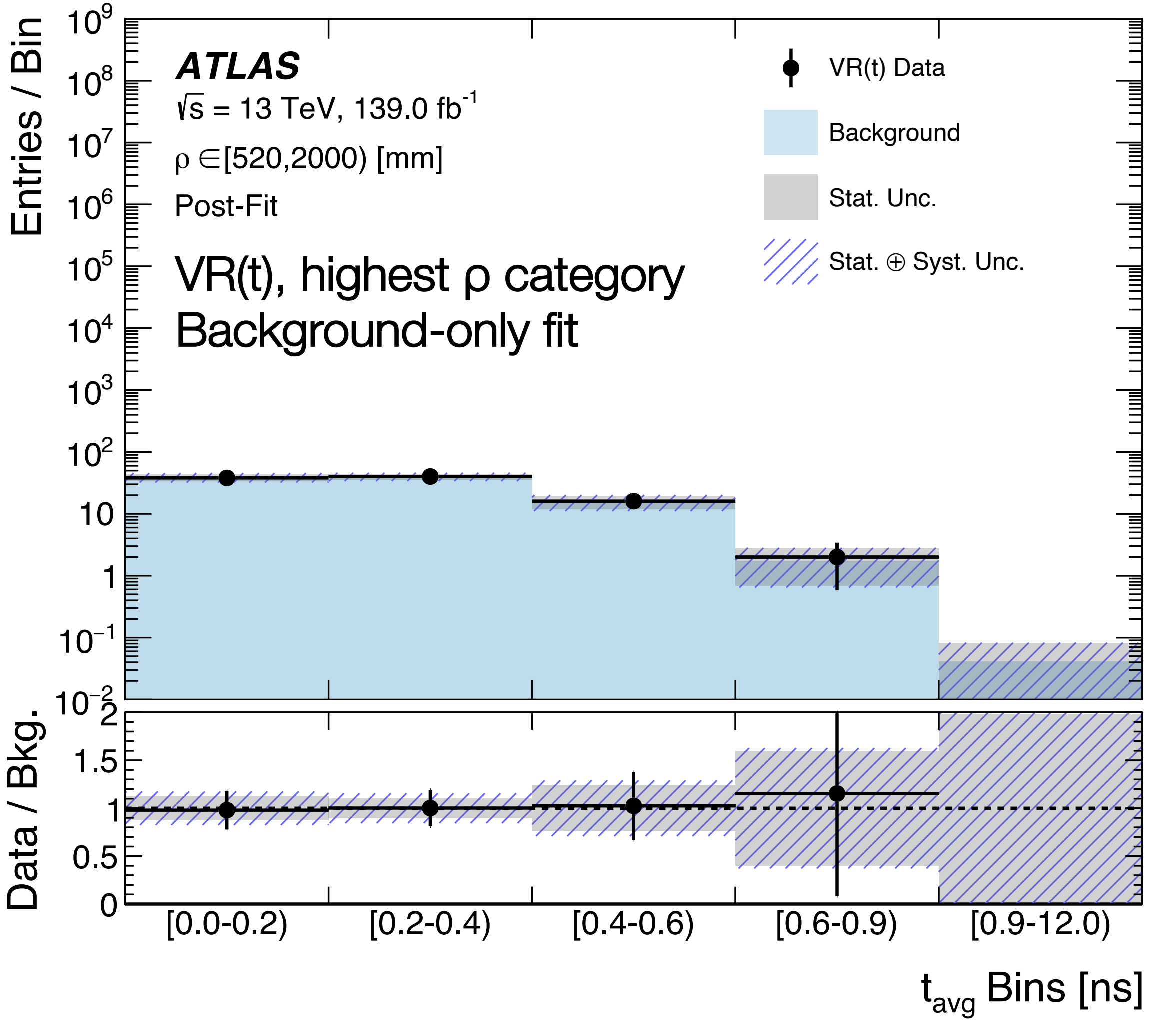
t_{avg} bins: [0.0, 0.2, 0.4, 0.6, 0.9, 12.0] ns.
ρ bins: [0, 80, 160, 300, 520, 2000] mm.

Profile Likelihood Fit Procedure

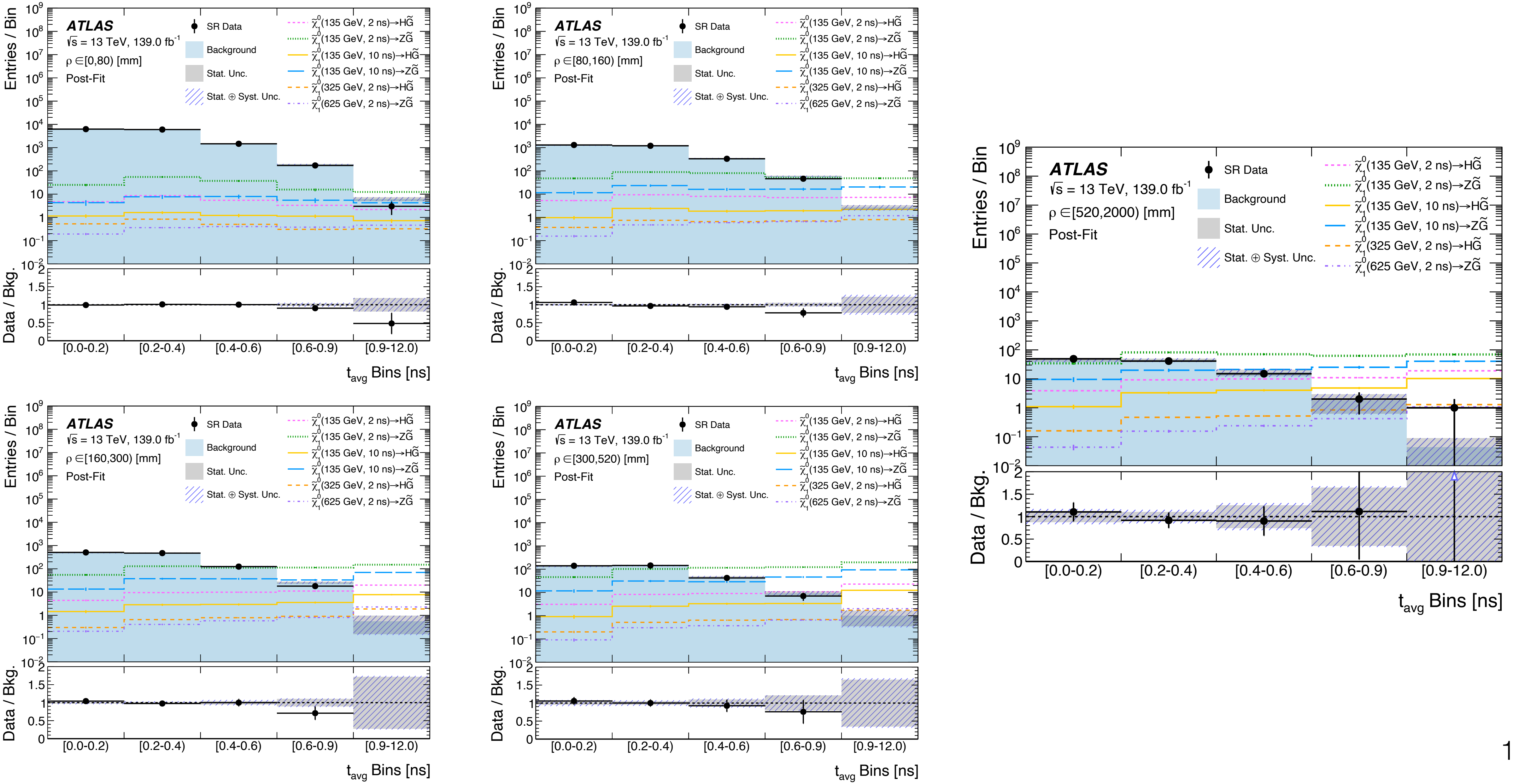
- Perform a simultaneous fit of the t_{avg} distribution in categories of ρ.
- Parameter-of-interest is the signal strength:

$$\mu = \frac{\sigma_{\mathrm{obs}}}{\sigma_{\mathrm{exp}}} = \frac{N_{\mathrm{obs}}}{N_{\mathrm{exp}}}$$

- Signal strength is correlated across ρ categories.
- Each ρ category has an independent background normalization factor.



Fits to Signal Region

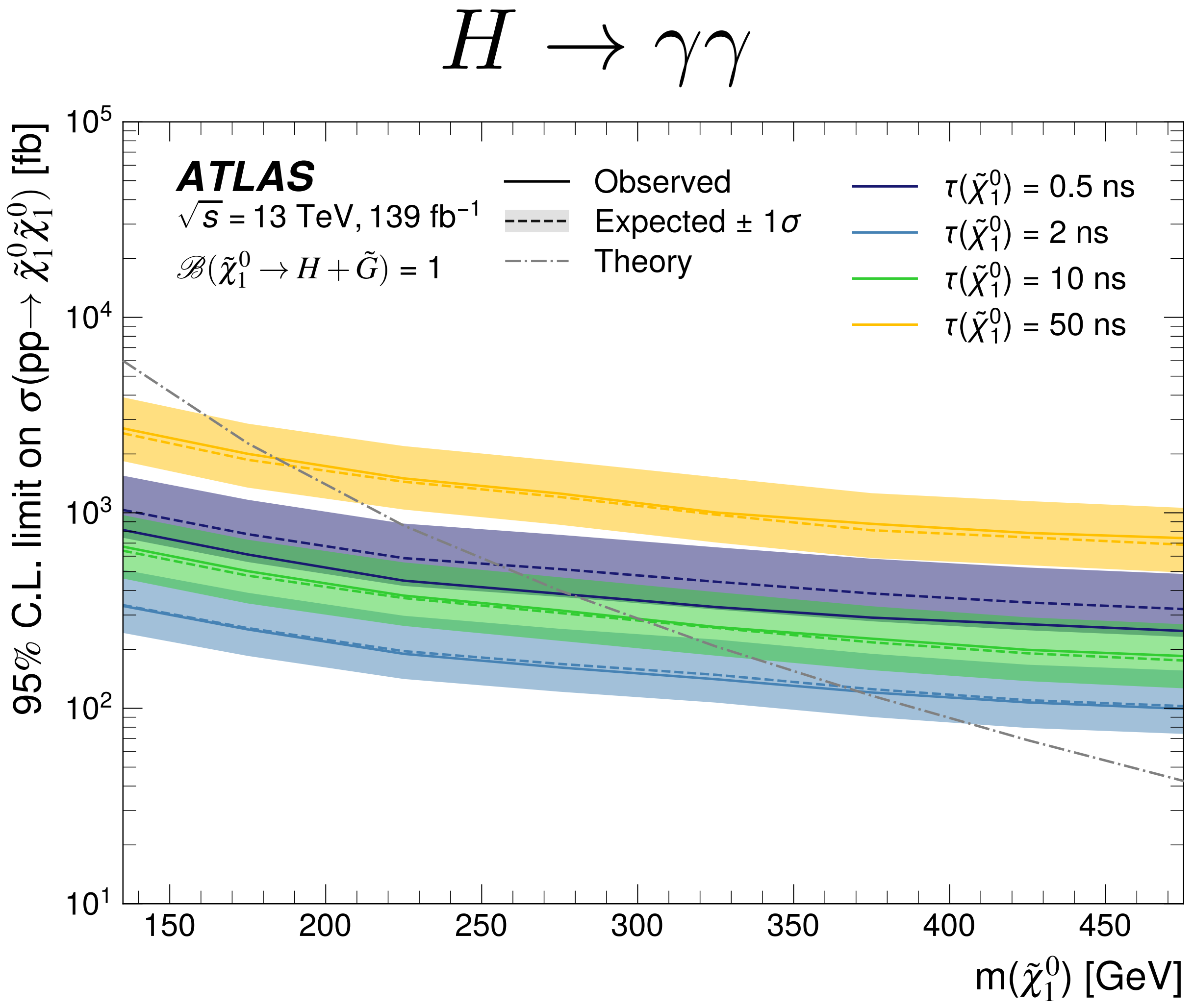


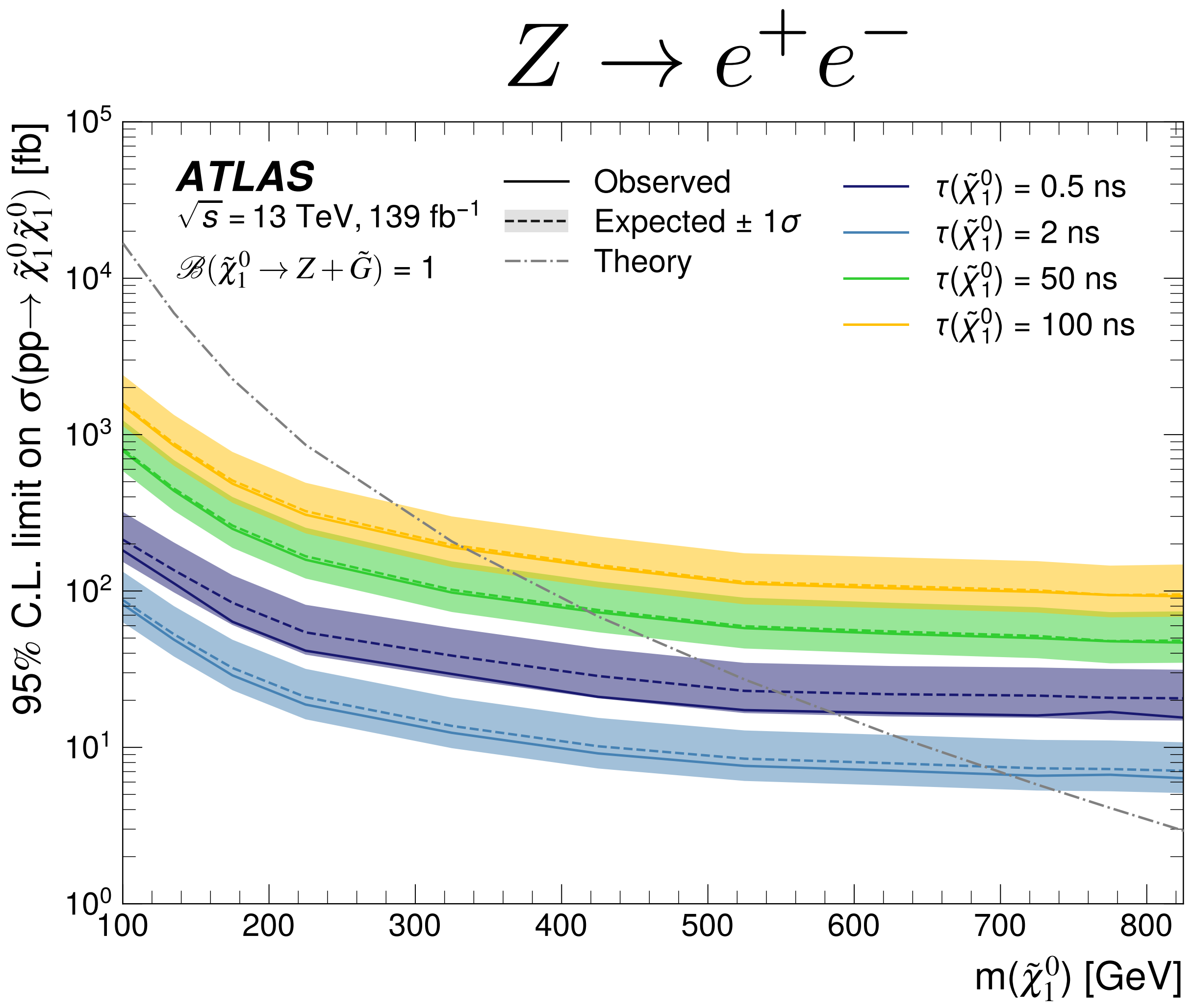
Excluding the Model with Confidence!

- In absence of signal, set exclusion limits on several model parameters.
- Exclusion upper limit calculated using the $\mathrm{CL_s}$ method.
- Set 95% C.L. upper limits on the $\tilde{\chi}_1^0$ production cross section $\sigma(\tilde{\chi}_1^0\tilde{\chi}_1^0)$ as a function of the $\tilde{\chi}_1^0$ mass, lifetime, and decay modes $H \to \gamma\gamma/Z \to e^+e^-$.

- Additionally, model-agnostic results provided for the high-timing bin ($t_{\mathrm{avg}} > 0.9$ ns) and no vertex categorization.
- Provide a simple cut-and-count analysis of the expected number of background events in the high-timing region.

Excluded $\tilde{\chi}_1^0$ masses

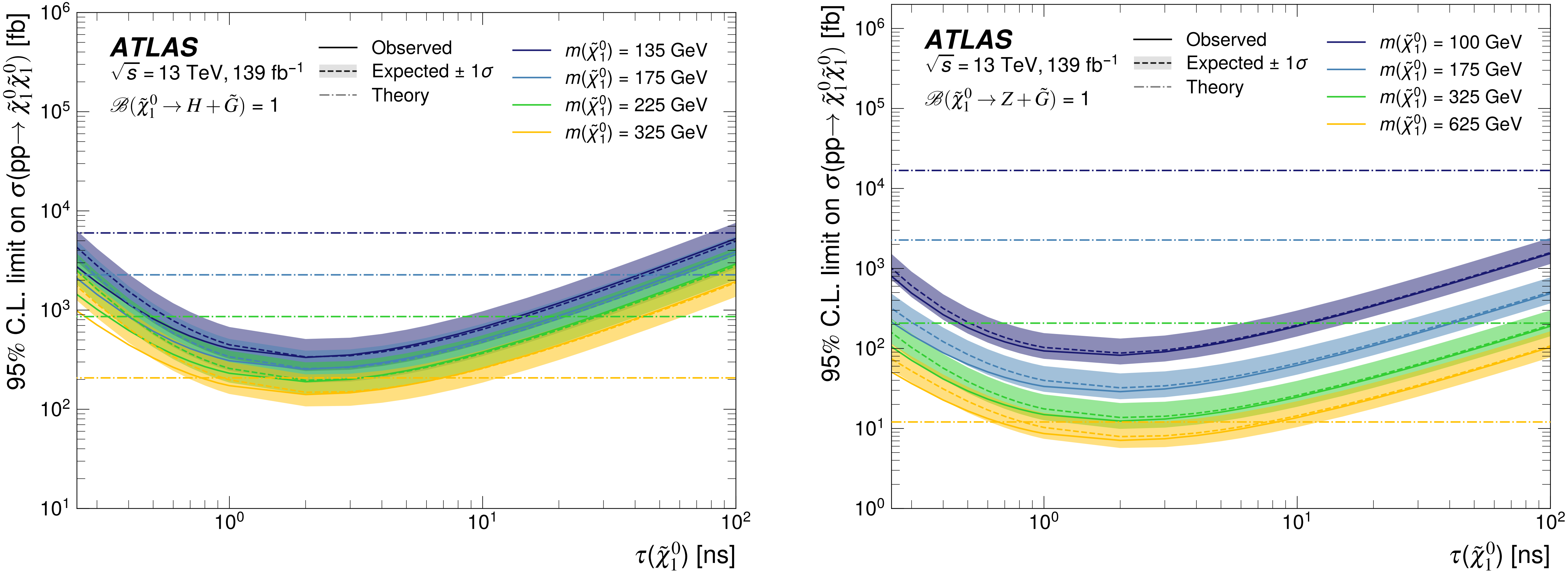




Excluded $\tilde{\chi}_1^0$ lifetimes

$H \rightarrow \gamma\gamma$

$Z \rightarrow e^+e^-$



Different model(s), same signature

RECAST

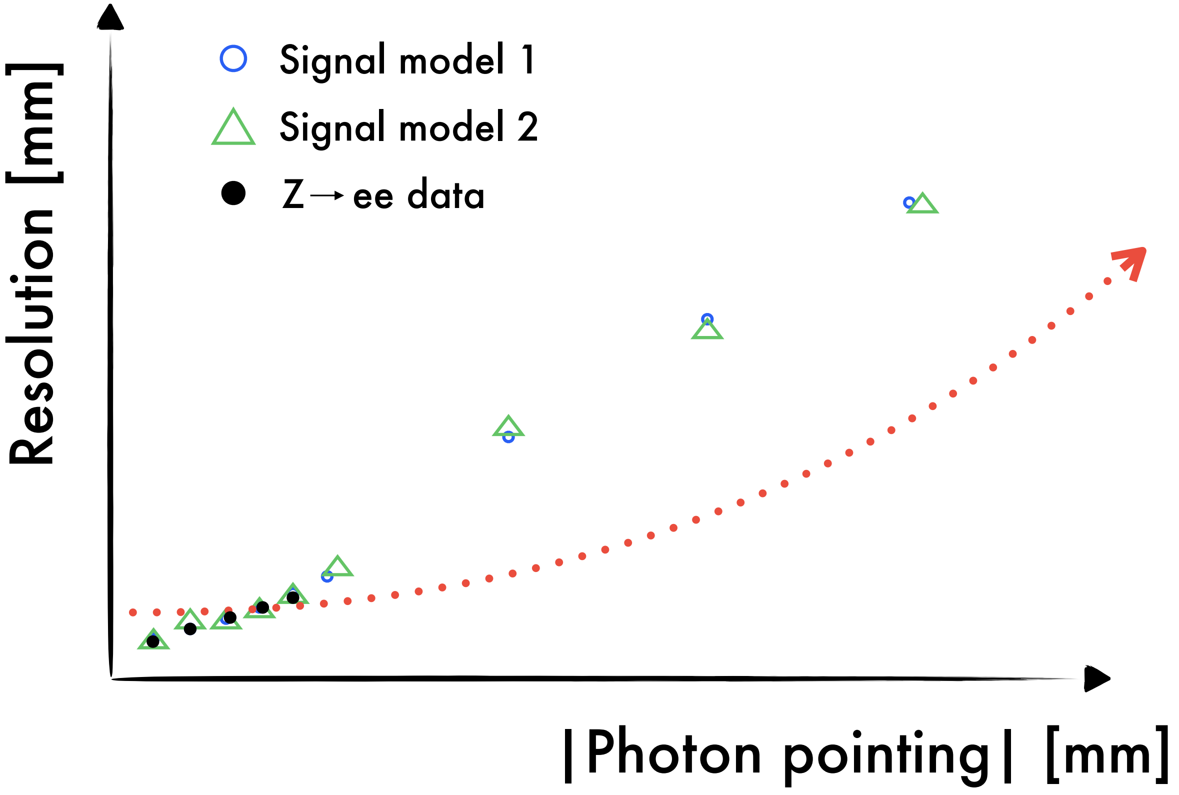
- Easy-to-use, containerized docker package to re-perform the analysis or to recast the analysis onto a different signal model.
- Provides a frozen copy of the entire analysis framework. Workflow designed to produce NTuples, perform fits, and calculate exclusion limits as a function of the $\tilde{\chi}_1^0$ mass and lifetime parameters.

HEPData

- Published data-tables for all the plots published in the paper.
- Also published tables for the signal acceptance, efficiency, and event cutflow for several of our signal final states.

Calo-vertexing performance

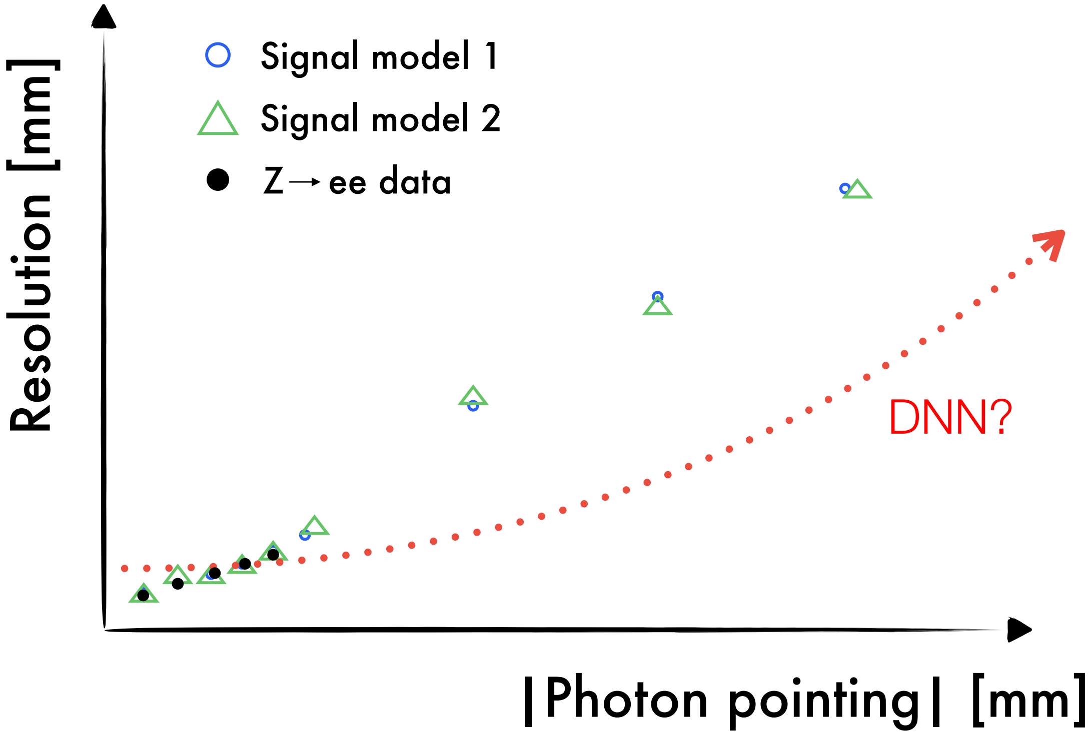
- Use the calo-vertexing to localize, in 2D, the LLP decay vertex.
- Calo-vertexing method is built on the idea of photon pointing.
- Prompt events produced within the beamspread used to measure pointing resolution as a function of displacement in the z-direction.
- Can we improve on the photon pointing resolution?



Improving the calo-vertexing performance…

Can we use Deep Neural Networks to more accurately estimate displaced vertices?

- Could develop a feed-forward neural network with a combination of low- and high-level input variables.
  - E.g., 3D position of the cell with the maximum deposited energy, cell peaking, …
- May improve the pointing resolution → could improve performance of calo-vertexing method.
- Possibility to use a DNN to provide a three-dimensional localization of the LLP decay vertex.
- Better vertex-localization → reduce backgrounds in signal-rich (high-displacement) regions-of-interest.



Summary

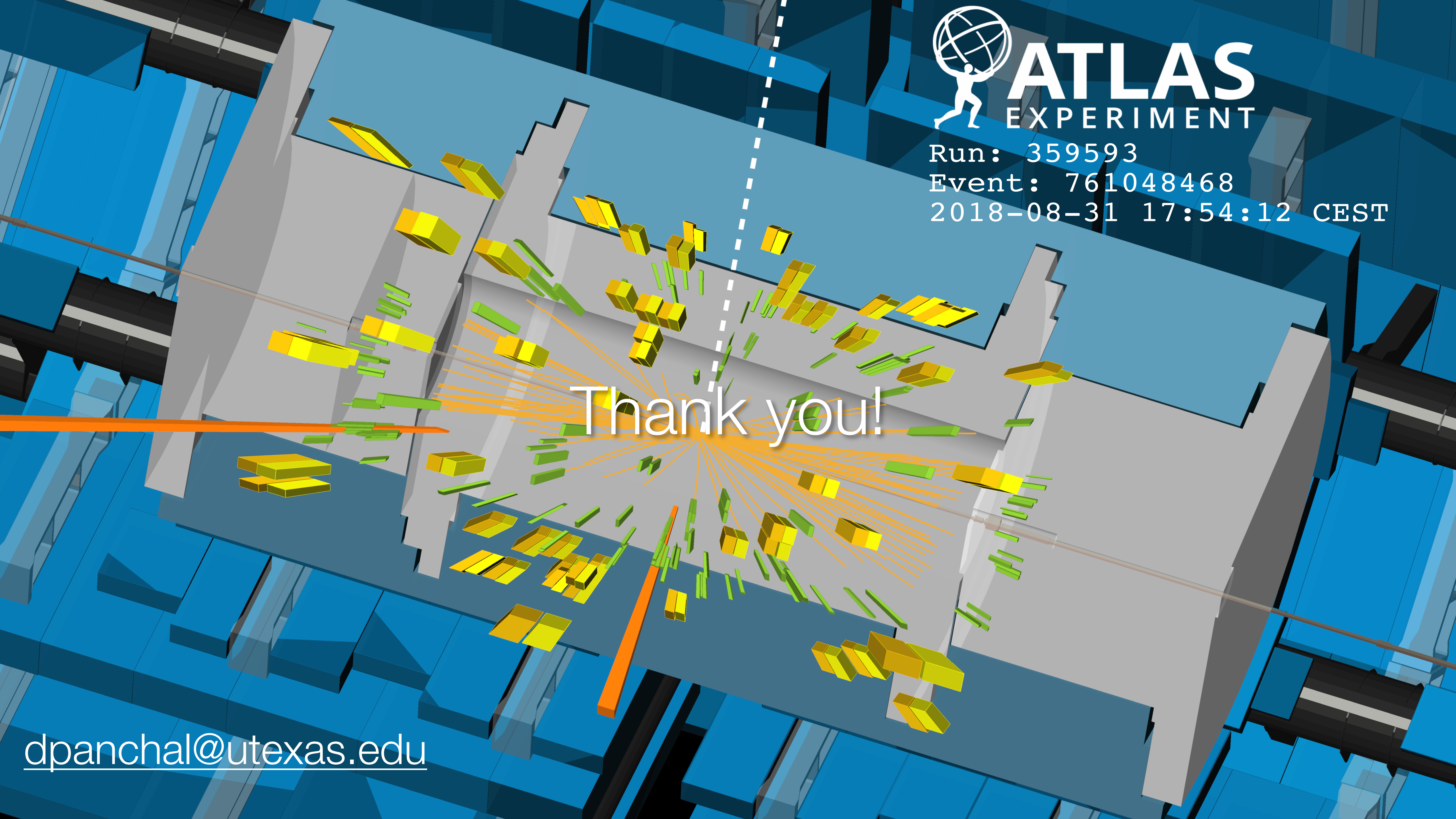
Presented a search for long-lived particles in a SUSY GMSB model:
Novel, unexplored signature of displaced vertices with delayed photons.

- Search optimized the LAr calorimeter at the ATLAS experiment as a vertexing and a timing detector.
- No evidence of LLPs in BSM model (yet); set strong exclusion bounds on the SUSY model explored in this search.
- For a branching fraction of 100% of $\tilde{\chi}_1^0$ to H or Z bosons, highest excluded $\tilde{\chi}_1^0$ masses are 369 GeV for Higgs and 704 GeV for Z bosons.
- Provide a model-independent interpretation for any BSM theories involving displaced and delayed photons.

The Landscape Tomorrow

- Calo-vertexing developed for this analysis could be used in several LLP analyses searching for displaced photons or electrons.
  - Vertexing method using calorimeter-only information could also complement tracking-based vertexing methods such as Large Radius Tracking.
- Although powerful, the calo-vertexing technique could be improved for future analyses.
  - Machine-learning-based approach to improve vertex resolution, vertexing in 3D, ...
- Besides vertexing, timing information from the LAr calorimeter is a powerful tool to search for delayed objects.
  - Timing information from the calorimeter can provide a complimentary method to study displaced jets, (micro-) displaced electrons, …

Detoured and Delayed: Let's dive into the world of displaced objects!



Thank you!

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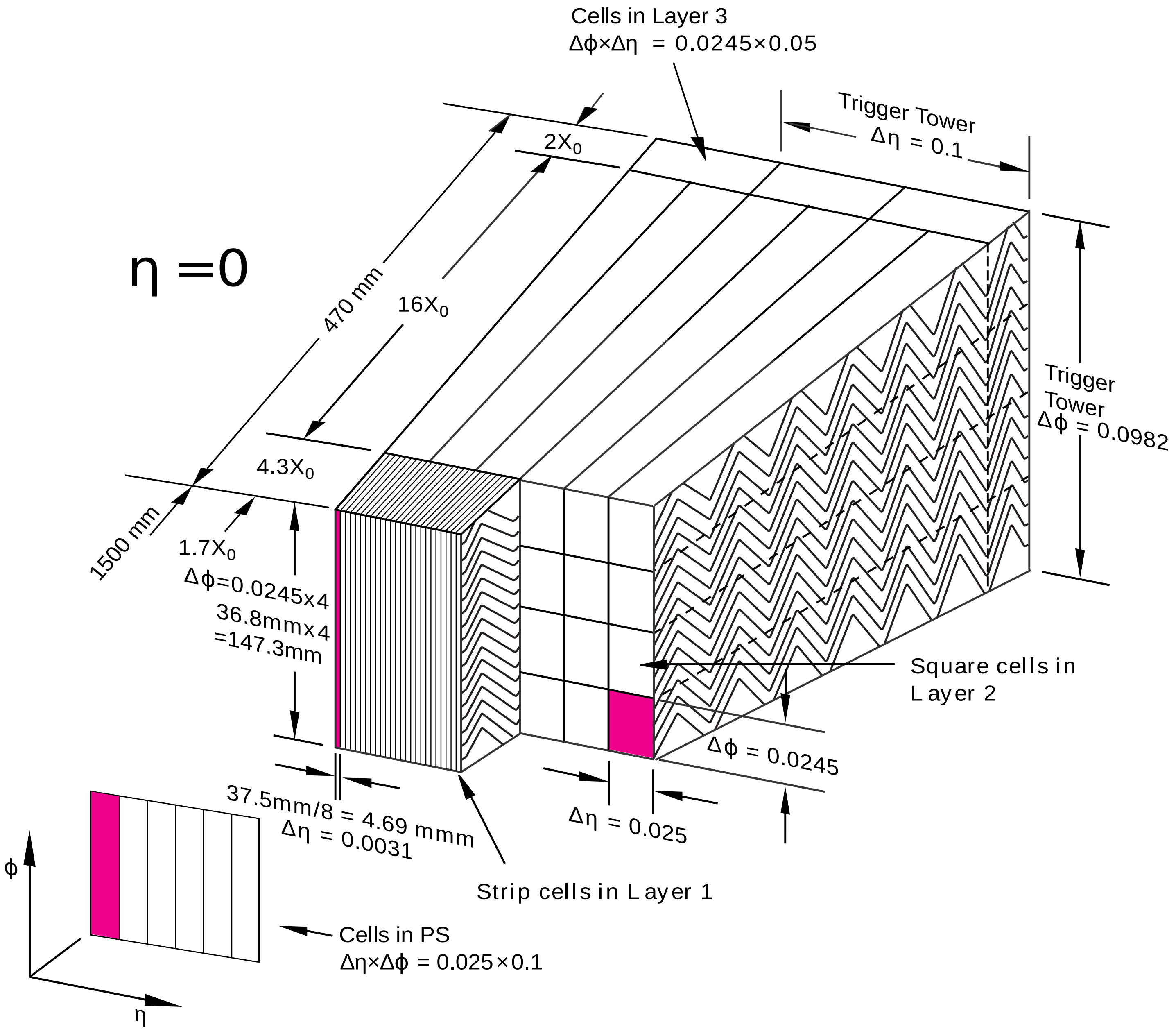
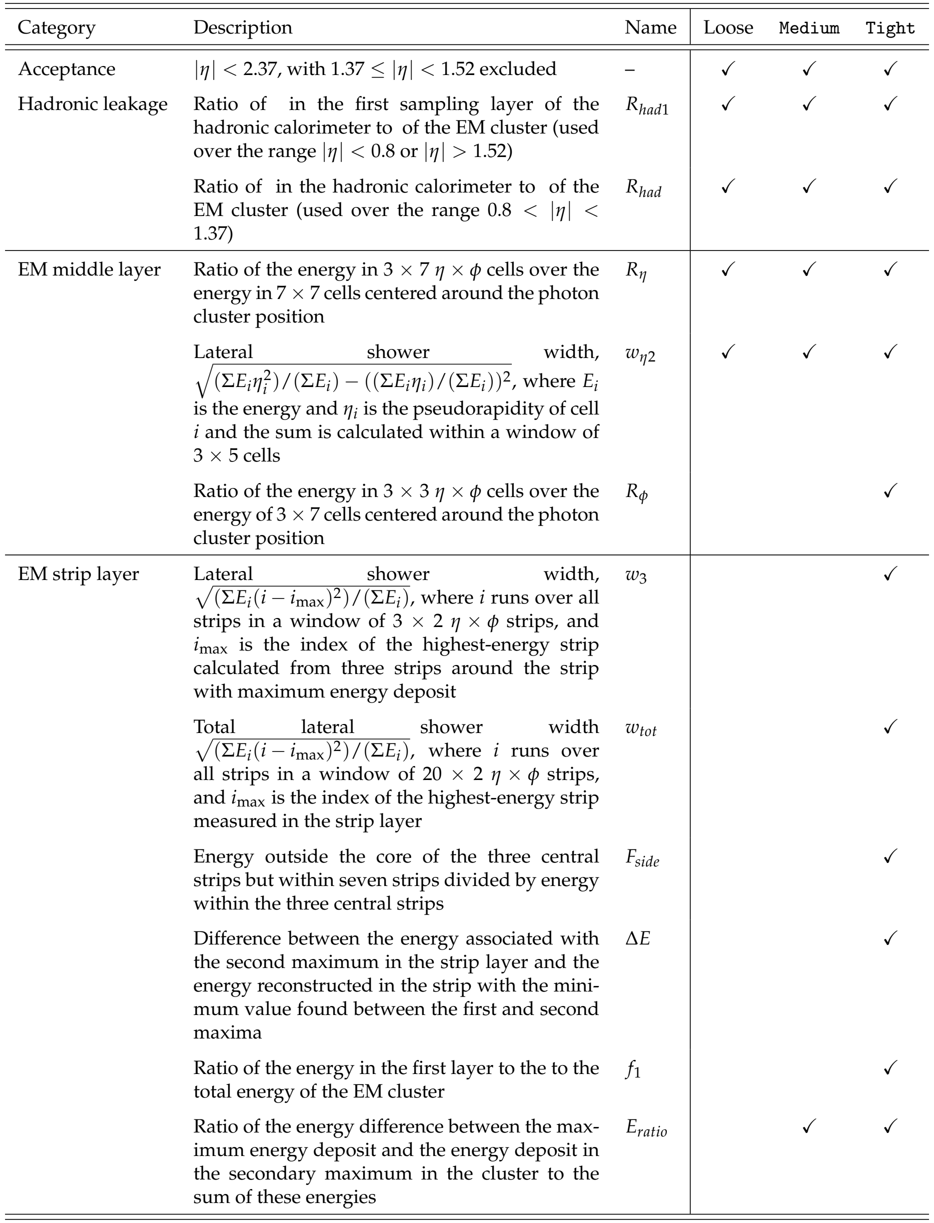
Backup Slides

Electromagnetic Barrel (EMB) Layers



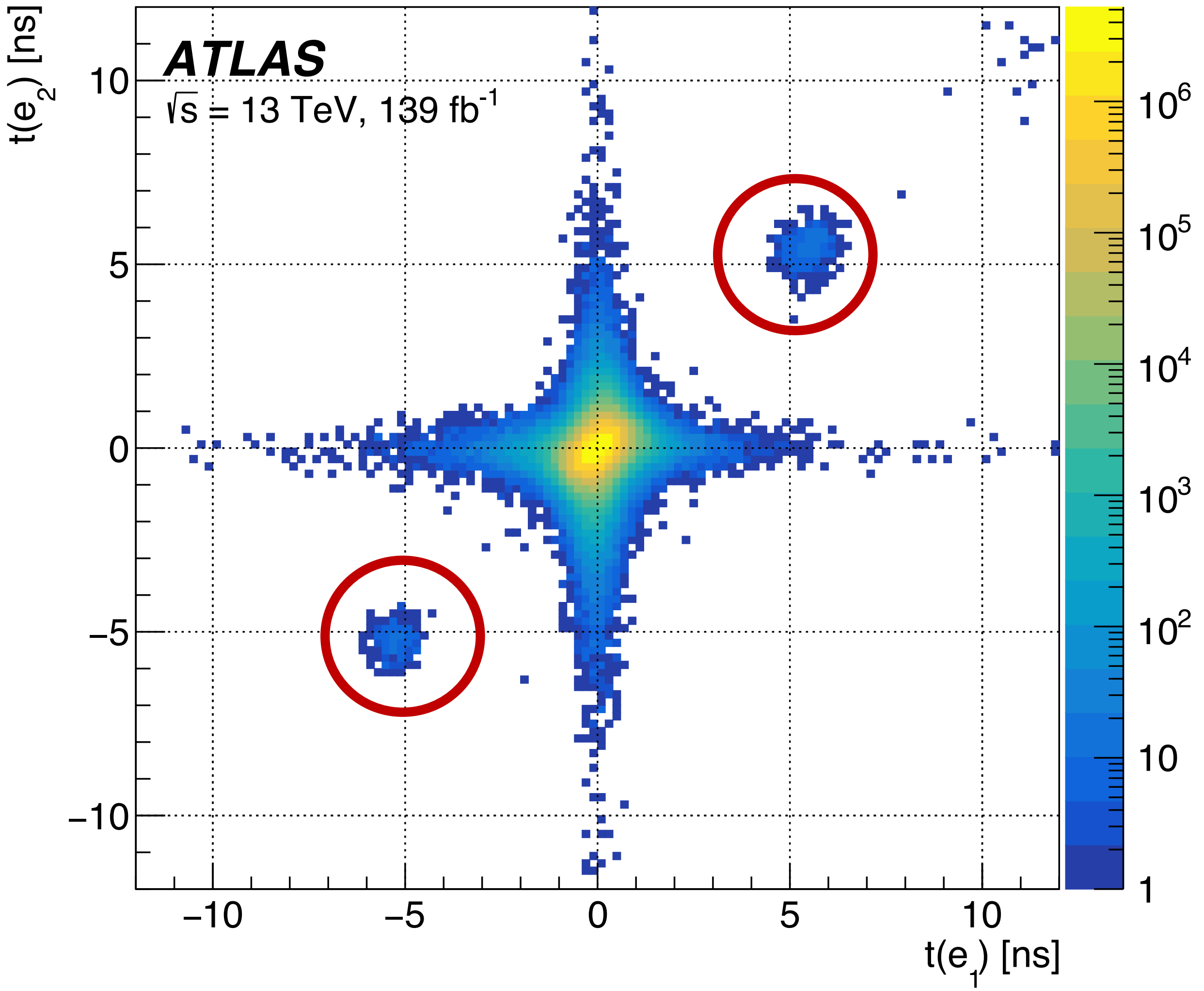
Calo. Variables used in photon identification



Category	Description	Name	Loose	`Medium`	`Tight`
Acceptance	$\|\eta\| < 2.37$, with $1.37 \leq \|\eta\| < 1.52$ excluded	–	✓	✓	✓
Hadronic leakage	Ratio of in the first sampling layer of the hadronic calorimeter to of the EM cluster (used over the range $\|\eta\| < 0.8$ or $\|\eta\| > 1.52$)	R_{had1}	✓	✓	✓
	Ratio of in the hadronic calorimeter to of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}	✓	✓	✓
EM middle layer	Ratio of the energy in 3×7 $\eta \times \phi$ cells over the energy in 7×7 cells centered around the photon cluster position	R_η	✓	✓	✓
	Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2)/(\Sigma E_i) - ((\Sigma E_i \eta_i)/(\Sigma E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$	✓	✓	✓
	Ratio of the energy in 3×3 $\eta \times \phi$ cells over the energy of 3×7 cells centered around the photon cluster position	R_ϕ			✓
EM strip layer	Lateral shower width, $\sqrt{(\Sigma E_i (i - i_{\max})^2)/(\Sigma E_i)}$, where i runs over all strips in a window of 3×2 $\eta \times \phi$ strips, and $i_{\max}$ is the index of the highest-energy strip calculated from three strips around the strip with maximum energy deposit	w_3			✓
	Total lateral shower width $\sqrt{(\Sigma E_i (i - i_{\max})^2)/(\Sigma E_i)}$, where i runs over all strips in a window of 20×2 $\eta \times \phi$ strips, and $i_{\max}$ is the index of the highest-energy strip measured in the strip layer	w_{tot}			✓
	Energy outside the core of the three central strips but within seven strips divided by energy within the three central strips	F_{side}			✓
	Difference between the energy associated with the second maximum in the strip layer and the energy reconstructed in the strip with the minimum value found between the first and second maxima	ΔE			✓
	Ratio of the energy in the first layer to the to the total energy of the EM cluster	f_1			✓
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in the secondary maximum in the cluster to the sum of these energies	E_{ratio}		✓	✓

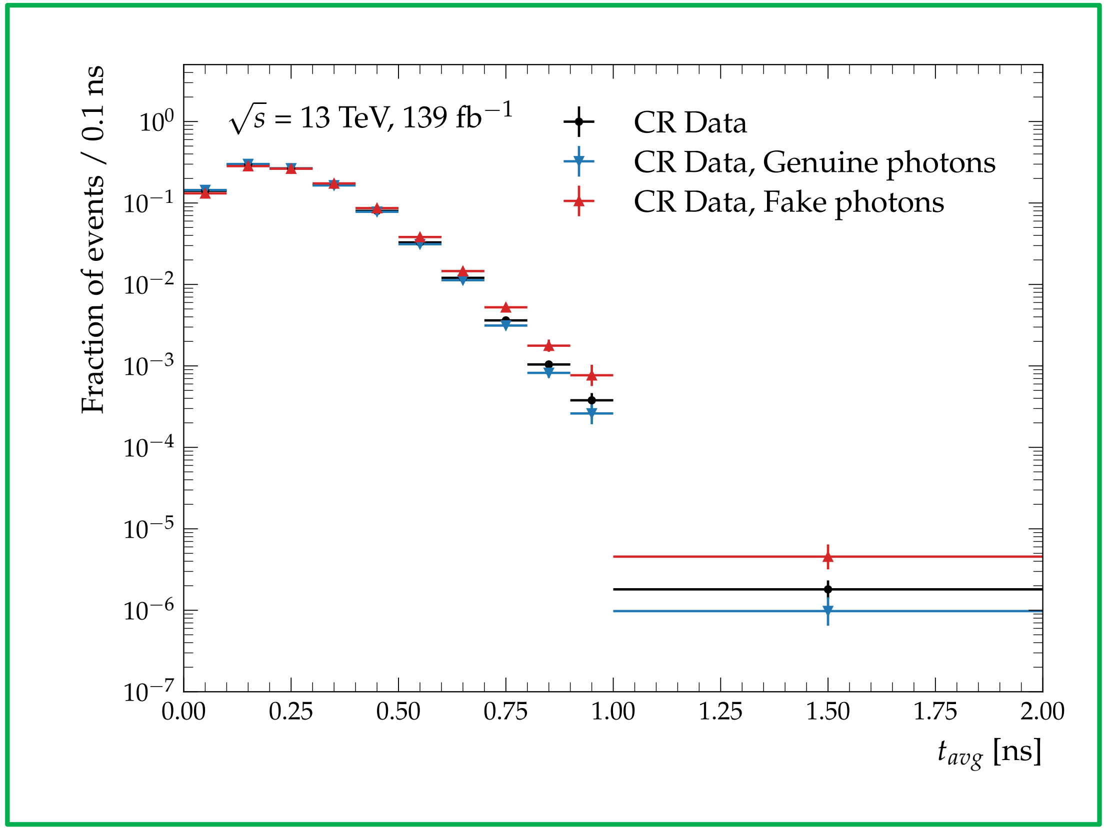
Satellite Collisions

- LHC radio frequency cavities sort protons into bunches. Satellite bunches arise from spillover into adjacent bunches.
- Population satellite bunches is ~10^3 times smaller than the main bunch.
- At collision times of ±5 ns, the satellite-satellite bunches collide at the center of the detector.
- Effect of satellite collisions clearly visible in timing distributions of electrons/photons.
  - Well documented in previous studies: [8 TeV study](), [13 TeV timing calibration]().

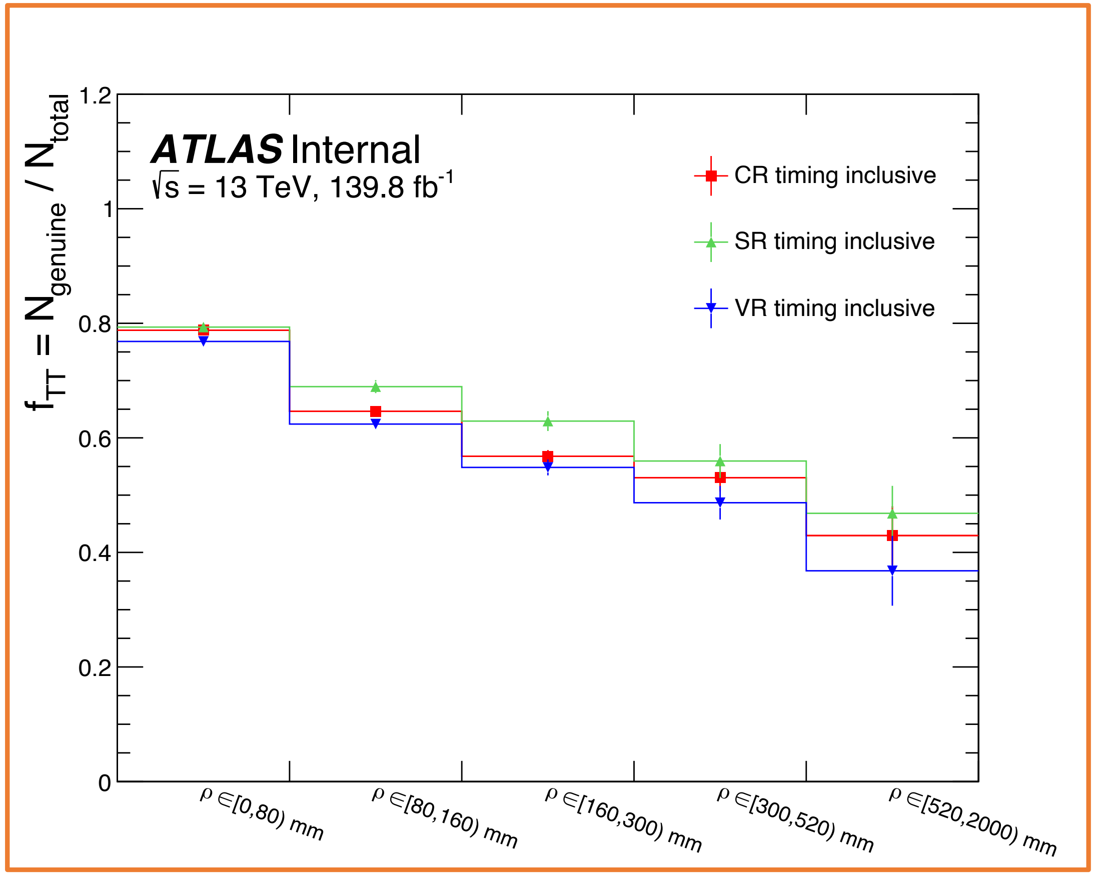


Photon Purity Scaling

- Timing distributions of genuine photons are narrower than those of fake photons.
- To capture the shape difference, define templates by varying photon ID requirement.

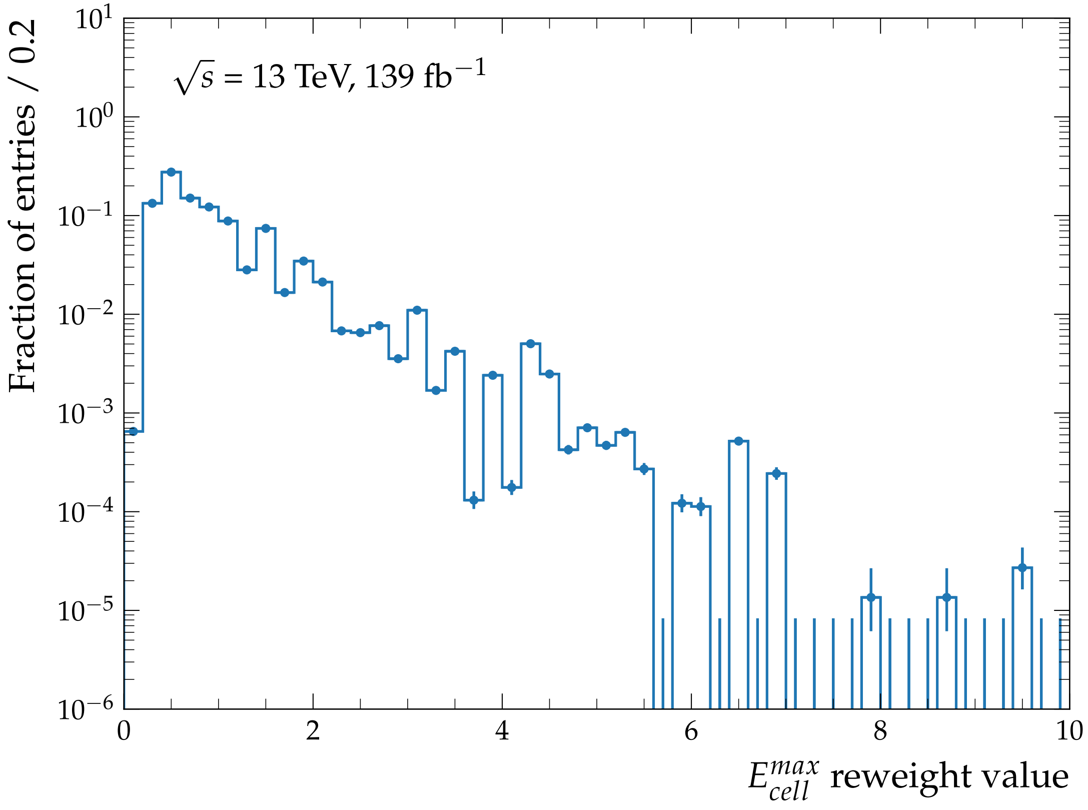


- Purity fraction, $f_{TT} = N_{genuine}/N_{total}$ varies by analysis region and by ρ category.
- Perform a rescaling per ρ category to match the purity fraction observed in the SR.

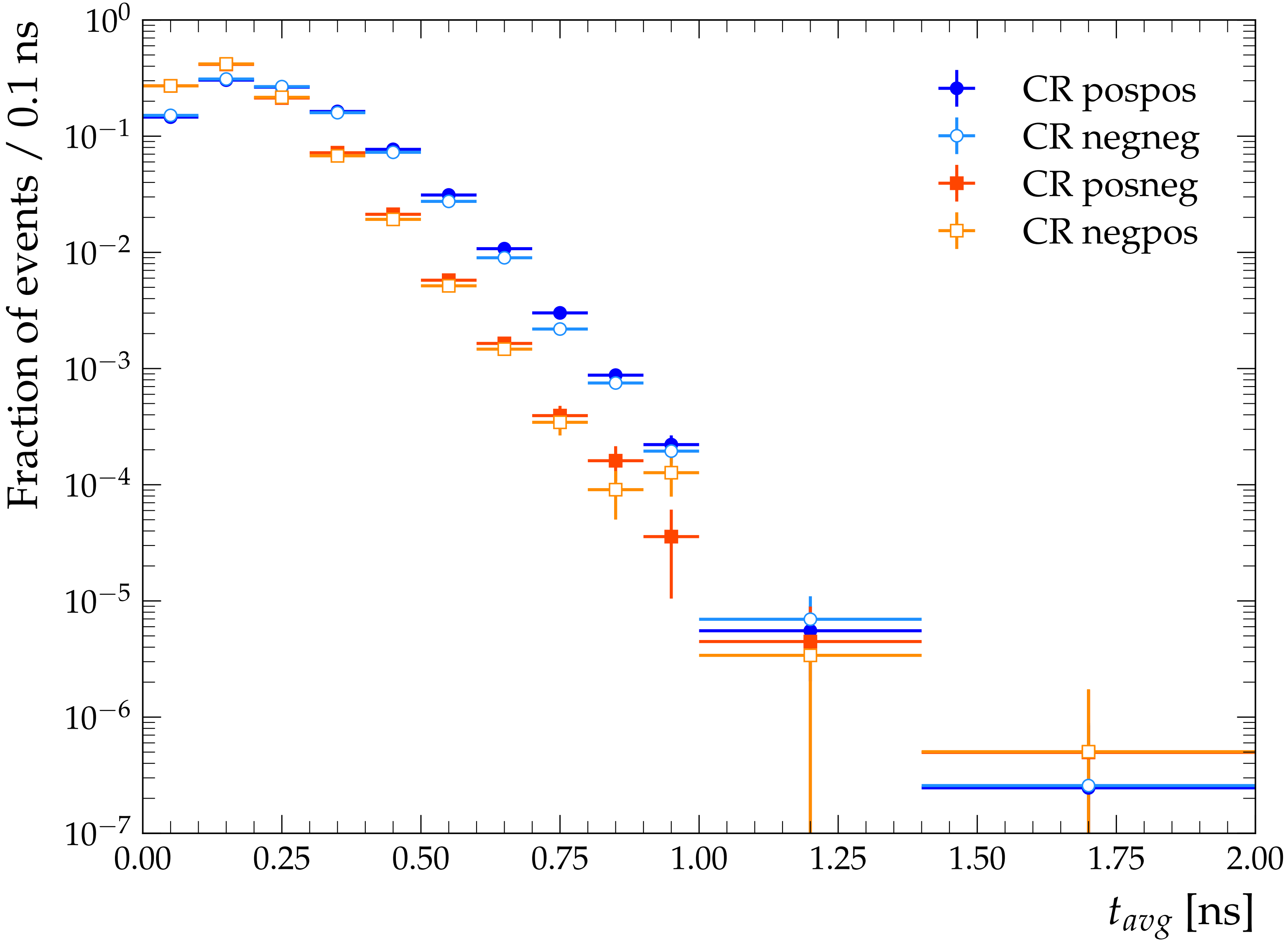


E_{cell}^{max} reweighting

- Timing resolution is inversely related to the deposited cell energy.
- Photon object timing is calculated from the time associated with the E_{cell}^{max}.
- Perform a E_{cell}^{max} reweighting to account for the difference in the E_{cell}^{max} spectra of the CR and the SR photons.
- Reweighting is performed separately for the real- and fake-enhanced templates, and for each ρ category.



Timing Distributions Across Quadrants

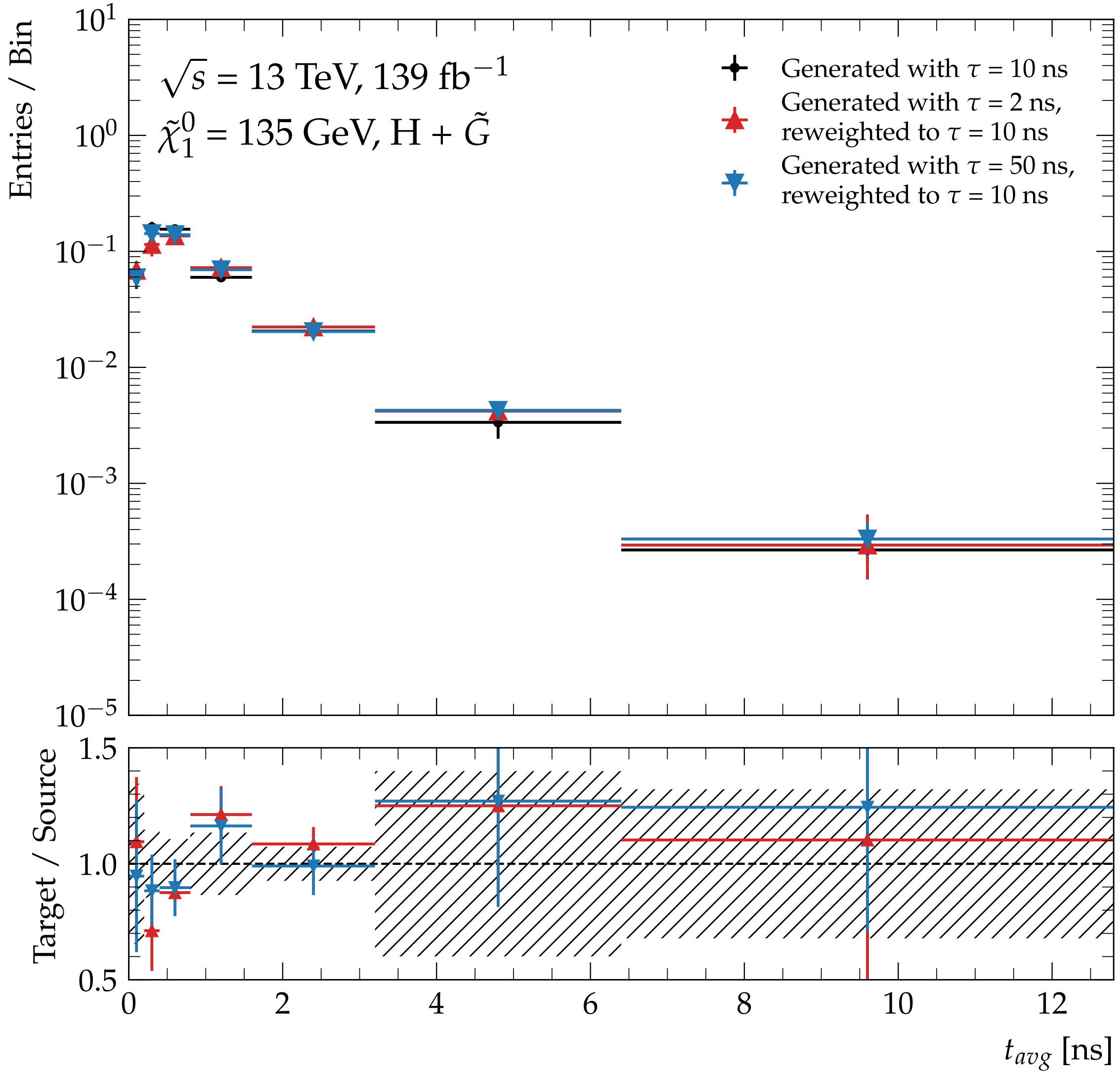


Lifetime Reweighting Procedure

- Reweight exponential decay of the source $\tilde{\chi}_1^0$ lifetime to target of choice:

$$w_{source \rightarrow target} = \frac{\tau_{source}}{\tau_{target}} \exp\left[-t_{event}\left(\frac{1}{\tau_{target}} - \frac{1}{\tau_{source}}\right)\right]$$

- Use generated points at 2, 10, 20, and 50 ns to extrapolate to [0.25, 1000] ns.
- Validate the procedure by reweighting between generated lifetimes.
- Discrepancy between reweighted distributions within statistical error.



Statistical Analysis

- Perform statistical analysis by constructing the likelihood function:

$$\mathcal{L}(\mu, \theta) = \prod_{i,j,k=1}^{N_{\text{bins}}} \underbrace{\mathcal{P}(n^i_{obs} | n^i_{exp})}_{\text{Poisson p.d.f.}} \quad \underbrace{\mathcal{G}(\tilde{\theta}^j_s | \theta^j_s, \sigma^j_s)\ \mathcal{G}(\tilde{\theta}^k_b | \theta^k_b, \sigma^k_b)}_{\text{Gaussian p.d.f.s for signal \& background uncertainties}}$$

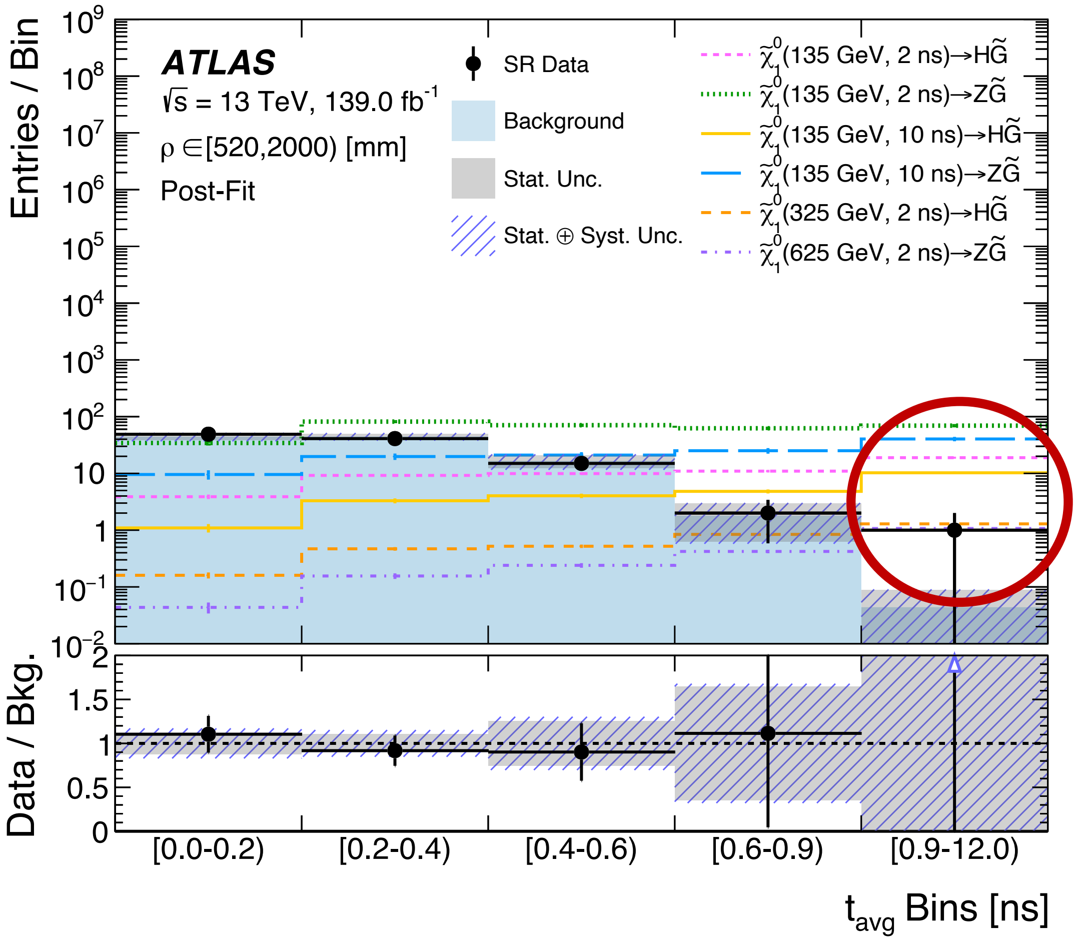
- Profile likelihood ratio is the ratio between the global and conditional maximum likelihood:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta}(\mu))}$$

- Profile likelihood ratio is the test statistic used to calculate p-value and confidence limits.

Signal Region Fit Characteristics

- Background-only fits to the Signal Region t_{avg} distributions show no significant deviation…
- Except for the one event in the highest ρ category and the highest t_{avg} bin.
- Event was recorded in Run 359593, on August 31, 2018.
- Single-bin-event was studied further to understand the event characteristics.



Single-bin-event Characteristics

Sensitive Analysis Variables		
t_{avg}	3.13 ns	
Vertexing ρ	559.7 mm	
Event-level Variables		
E_T^{miss}	79.5 GeV	
$\langle\mu\rangle$	43.9	
PV_z	-29.8 mm	
V_R	554.2 mm	
V_Z	78.7 mm	
Photon-object Variables		
	Leading Photon	Subleading Photon
Photon ID	`Medium`	`Tight`
p_T	65.3	32.4 GeV
E(γ)	187.1	32.7 GeV
E_{cell}^{max} gain	`Medium`	`High`
E_{cell}^{max}	53.4 GeV	6.3 GeV
$\eta(\gamma)$	-1.71	0.12
t_γ	5.82 ns	0.45 ns
z_γ	2578.1 mm	-11.6 mm
Diphoton Variables		
$m_{\gamma\gamma}$	108.6 GeV	
$p_T^{\gamma\gamma}$	84.4 GeV	
$\Delta\eta_{\gamma\gamma}$	1.8	
$\Delta\phi_{\gamma\gamma}$	1.13	