ATLAS Search for Non-Pointing and Delayed Photons

Devin Mahon

DPF2021

July 13, 2021

Nevis Laboratories
Columbia University

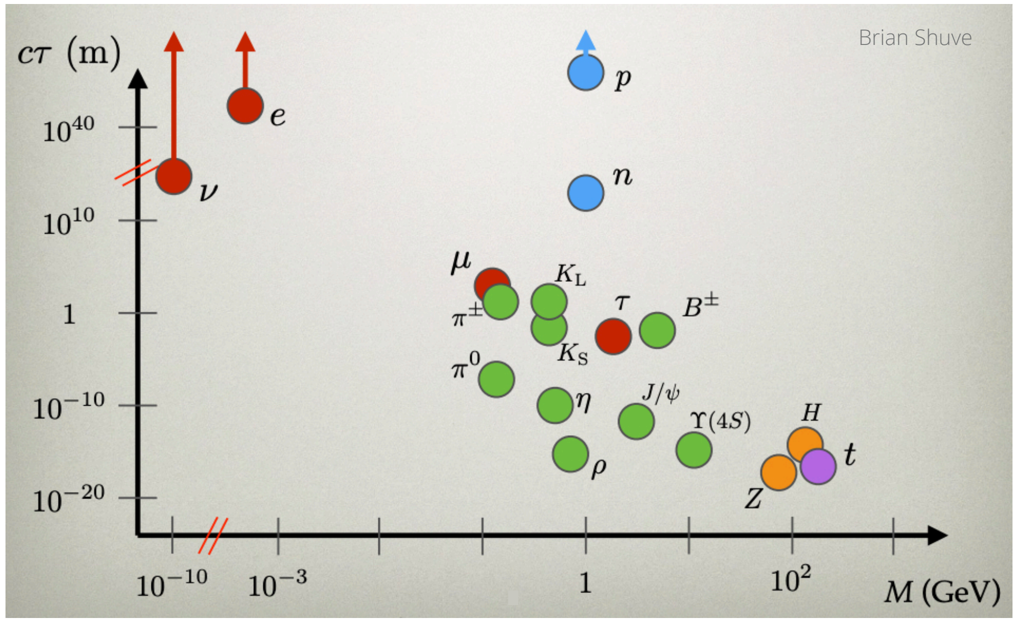
ATLAS Experiment

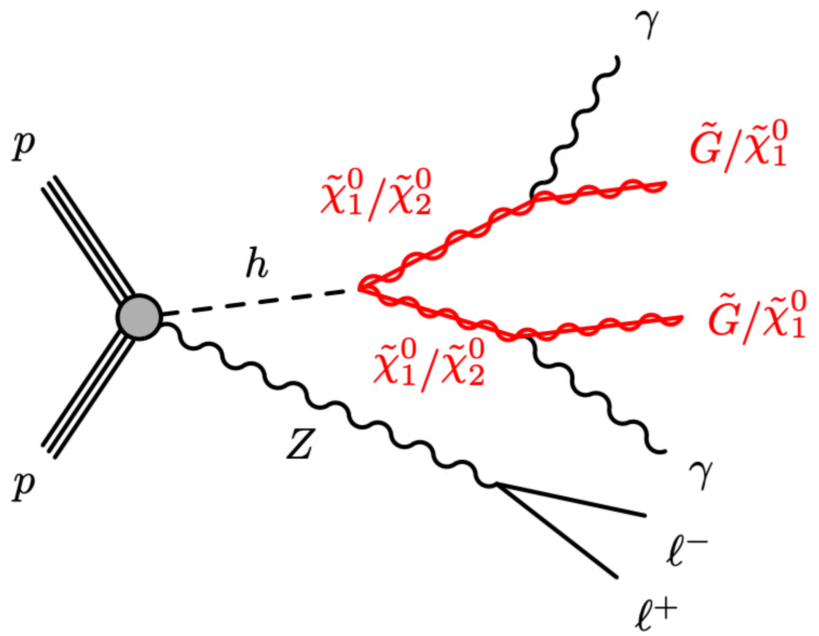
Outline

- Physics Motivation
- ATLAS Liquid Argon (LAr) Calorimeter
- Timing & Pointing Measurements
- Analysis Strategy
- Expected Sensitivity
- Summary

Physics Motivation

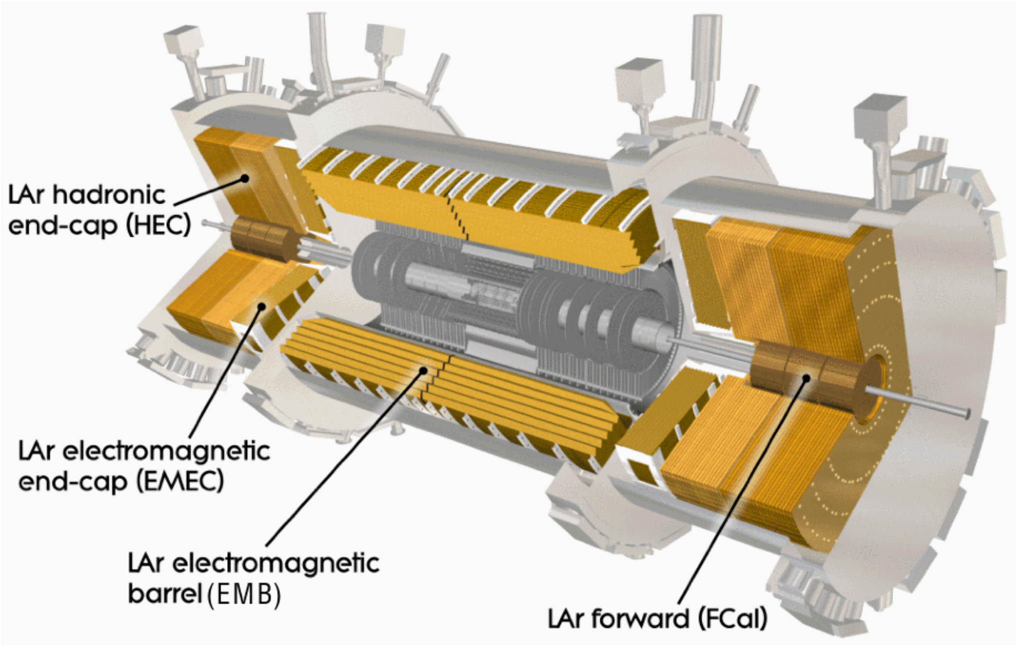
- No definitive evidence for beyond the Standard Model (BSM) physics from collider searches
  - Mostly focused on prompt, high p_T, high MET signatures
  - What if they're looking in the wrong places?
- Long-lived particles (LLPs)
  - Many SM particles are long-lived
    - Hierarchy between scales, small mass splittings, small couplings
  - For similar reasons, BSM particles may also be long-lived
- Signal model: $H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \gamma \tilde{G}$
  - Current exclusion limits still allow $BR_{H \rightarrow inv.} \lesssim 11\%$
  - Gauge-mediated SUSY breaking (GMSB) models allow for long-lived, heavy $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$



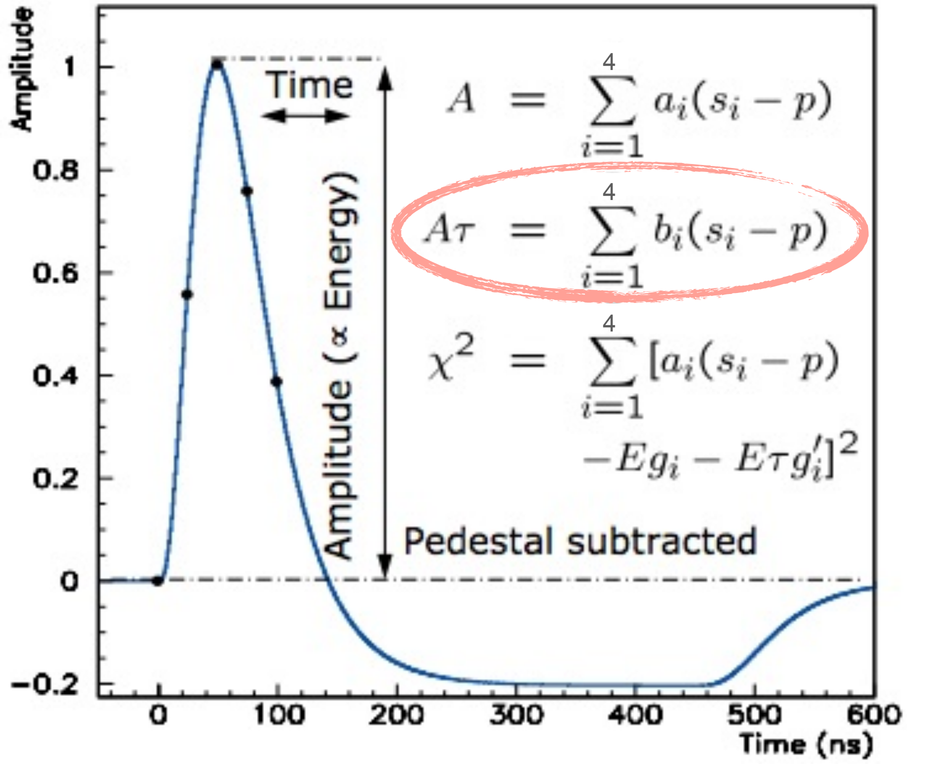


LAr Calorimeter Overview

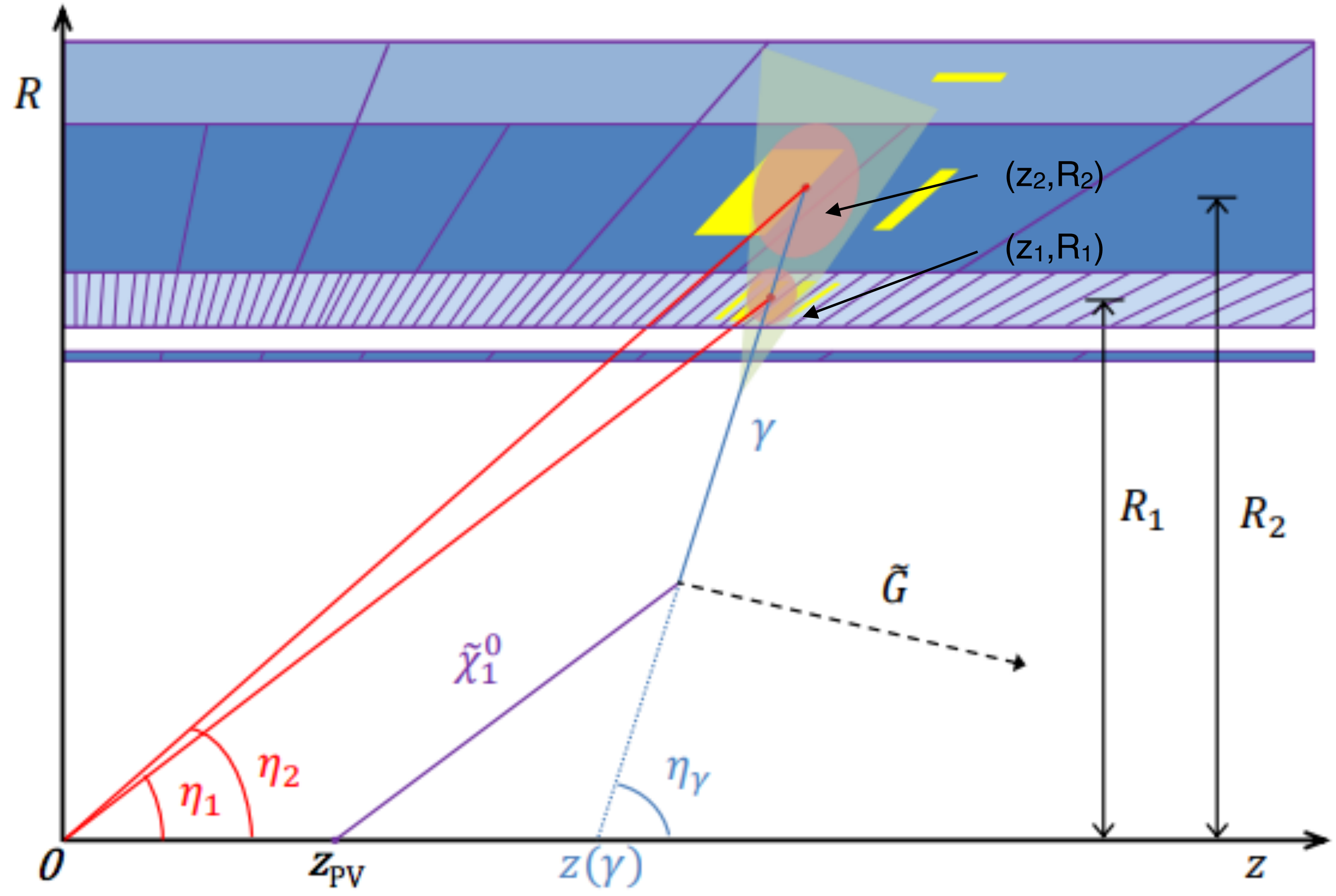
- LAr calorimeter design:
  - Cells segmented both transversely (η, φ) and longitudinally (R)
  - Incoming EM particle hits lead absorber
  - Shower produced into LAr
  - Current collected by electrodes
- Energy and time computation
  - Pulse sampled every 25 ns
  - Optimal filtering coefficients used to compute energy and time from 4 samples



The ATLAS Collaboration et al 2008 JINST 3 S08003

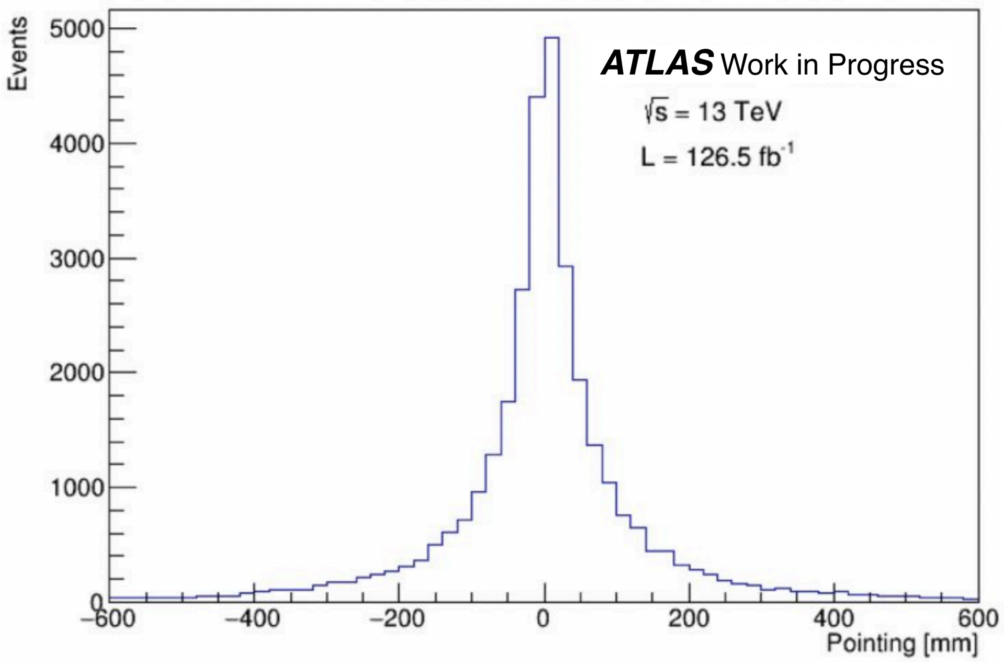


LAr Calorimeter Pointing



Using beamspot-corrected R values:

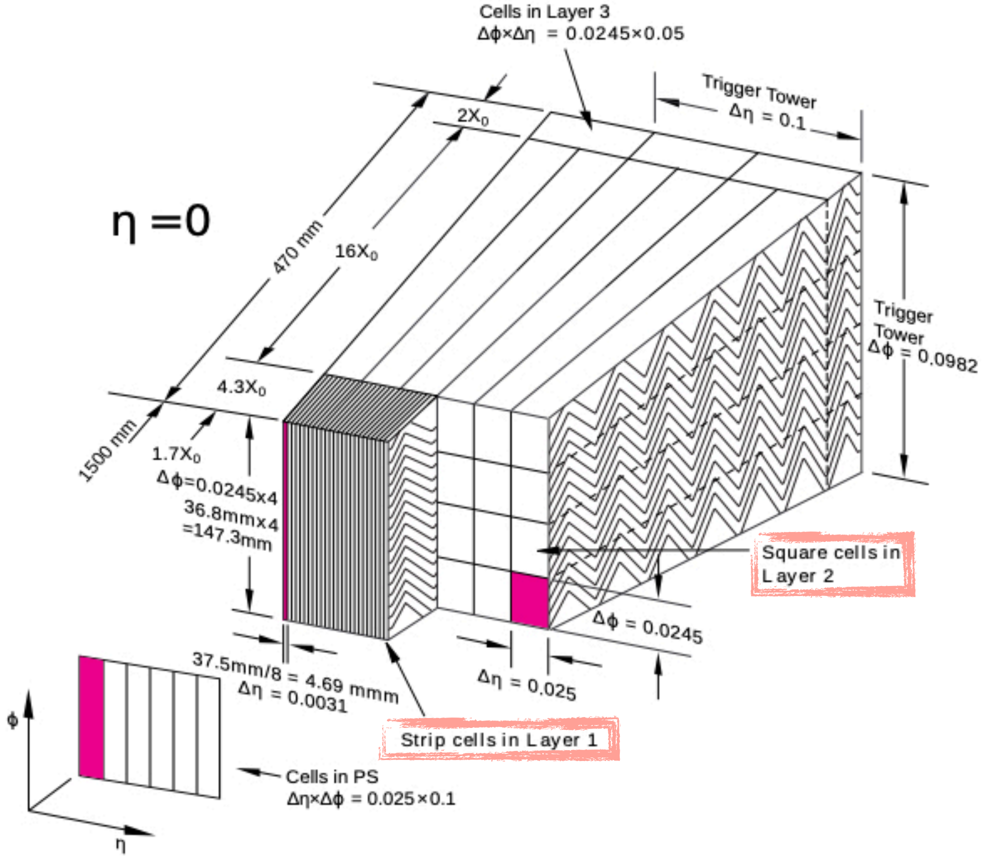
$$z_{point} = \frac{z_1 R_2 - z_2 R_1}{R_2 - R_1}$$



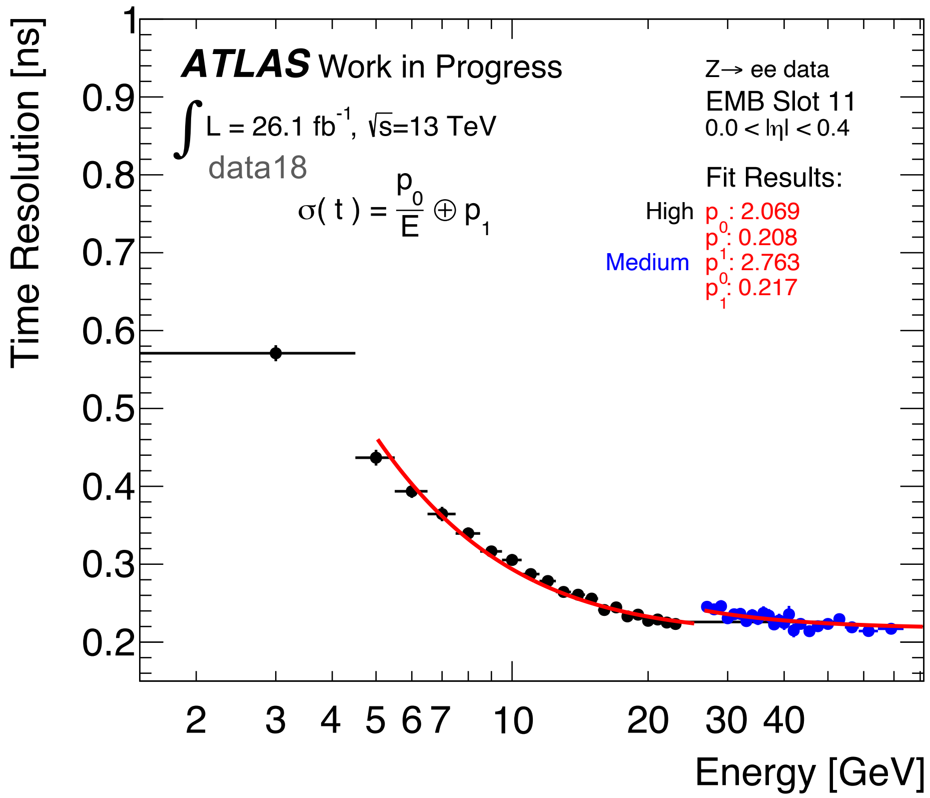
- Tracker-independent pointing back to beam line
  - Exploits longitudinal segmentation of LAr calorimeter
  - Based on cluster barycenters in first and second layers
- LLP decays:
  - Displaced decay vertices with photons recoiling off MET give non-zero pointing values

LAr Calorimeter Timing

- Timing measurement
  - Based on time measured in 2nd layer cell with largest energy deposit
  - Calibrated offline using $W \rightarrow e\nu$ data to remove known timing variations
- Timing performance
  - Characterized as a function of E_{cell}: energy in 2nd layer cell with largest energy deposit
  - Beam spread contribution ~190 ps
  - Most precise timing measurement in ATLAS in Run 2
- Monte Carlo (MC) is smeared to match calibrated resolutions in data

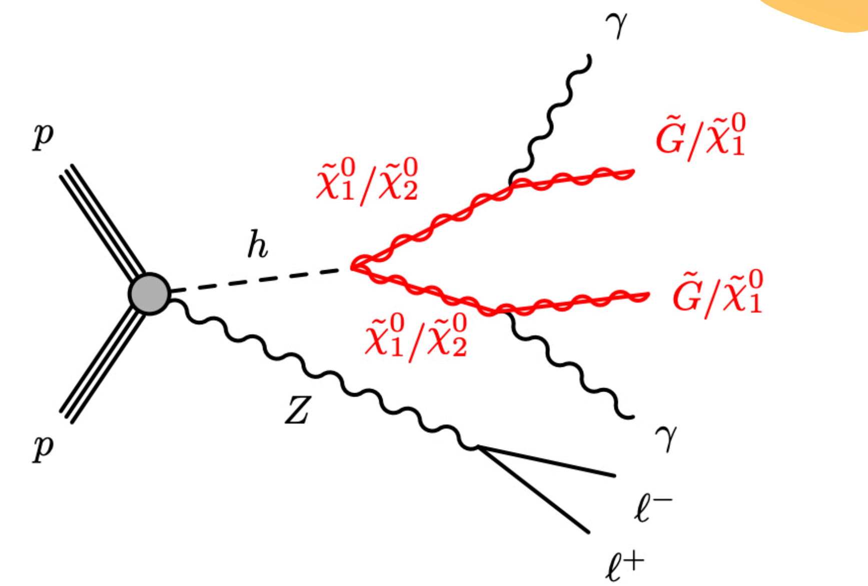


The ATLAS Collaboration et al 2008 JINST 3 S08003

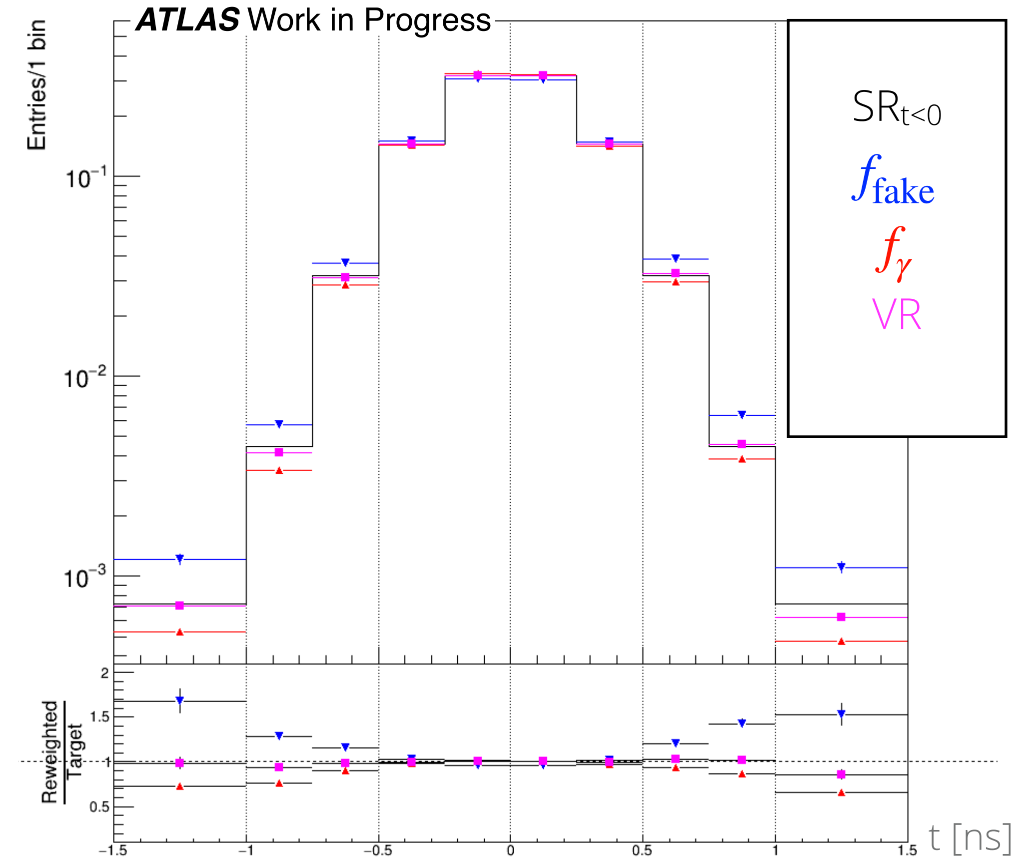


Analysis Strategy

- Final state: e/μ + 1 or 2 barrel photons + MET
  - Photons are fairly soft, so trigger on lepton from VH/ttH processes
  - CR/VR/SR distinguished only by MET
- Signal lies in tails of timing and pointing distributions
  - Signal parameters: τ_{NLSP}, m_{LSP}, m_{NLSP} (up to 60 GeV $\sim m_{\mathrm{H}}/2$)
  - We seek to measure $BR(H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$
- Data-driven background estimation using templates
  - MC does not model pointing and timing properly, particularly in non-Gaussian tails
  - Rely entirely on data to model background
- Timing is the most sensitive variable
  - Smaller non-Gaussian tails and less background dependence
- Bin events in pointing, perform template fits simultaneously in each pointing bin i over timing bins j:
  - f^{γ}: photon-enriched template from Z→lly and CR photons
  - f^{fake}: fake-photon-enriched template from CR photons with looser ID requirement
  - Fit is a linear combination with mixing fraction α_i
  - Both templates are reweighted by E_{cell} to the SR

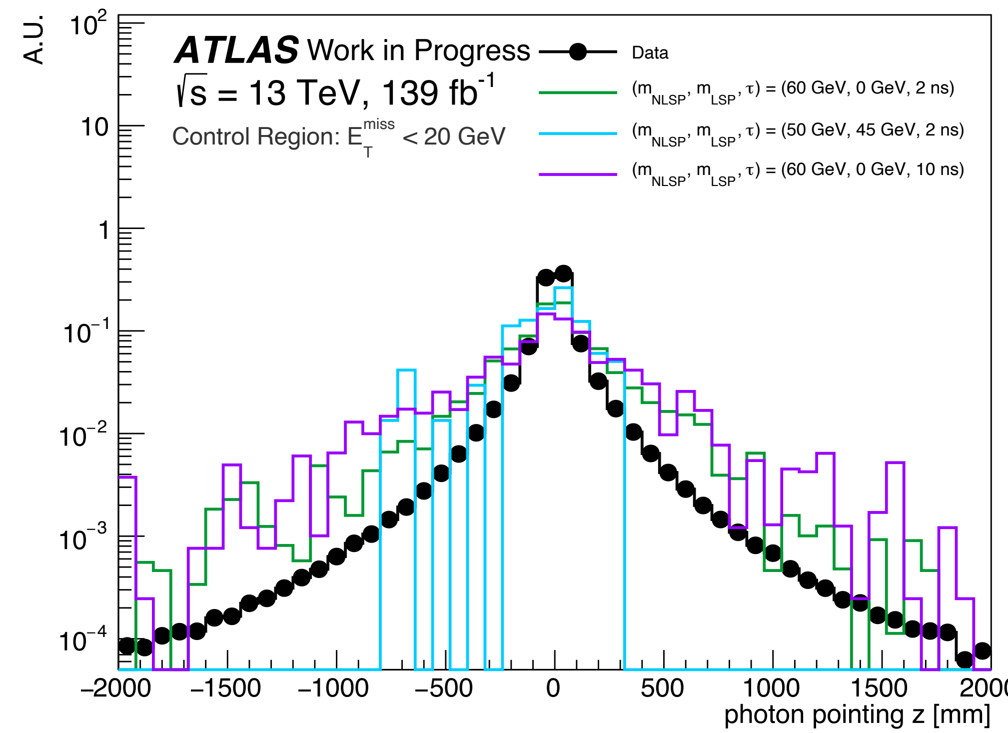


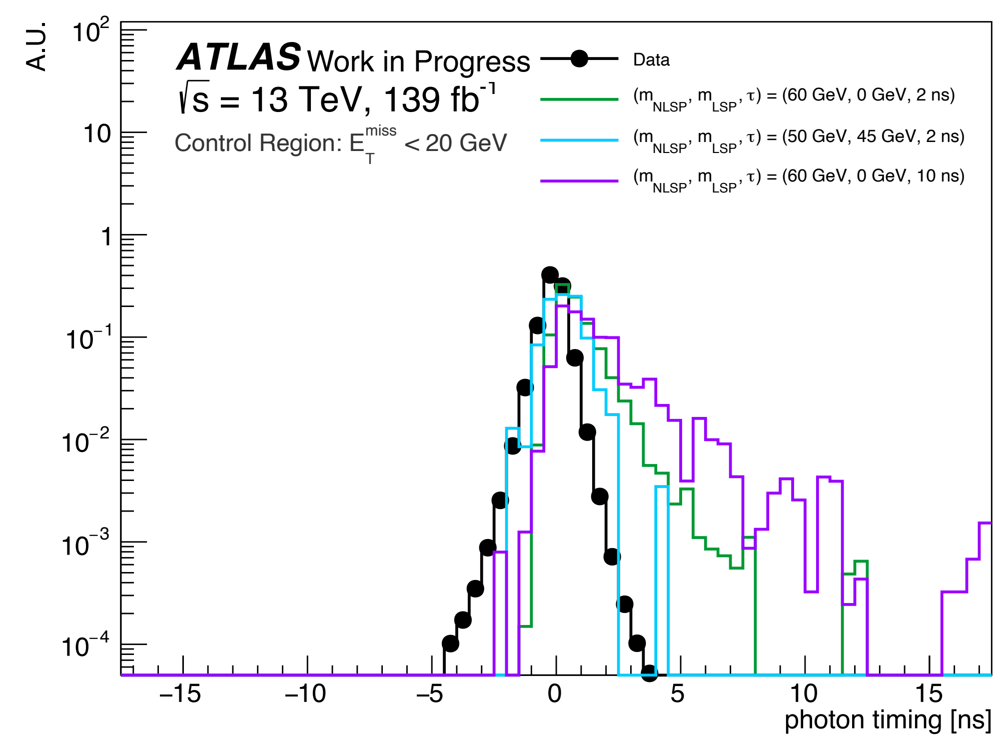
$$N_{ij}^{\mathrm{pred}} = N_i^{\mathrm{bkg}} \left(\alpha_i f_{ij}^{\gamma} + (1-\alpha_i) f_{ij}^{\mathrm{fake}} \right) + \mathrm{BR}(H \to \chi_1^0 \chi_1^0) N_i^{\mathrm{sig}} f_{ij}^{\mathrm{sig}}$$



Analysis Strategy

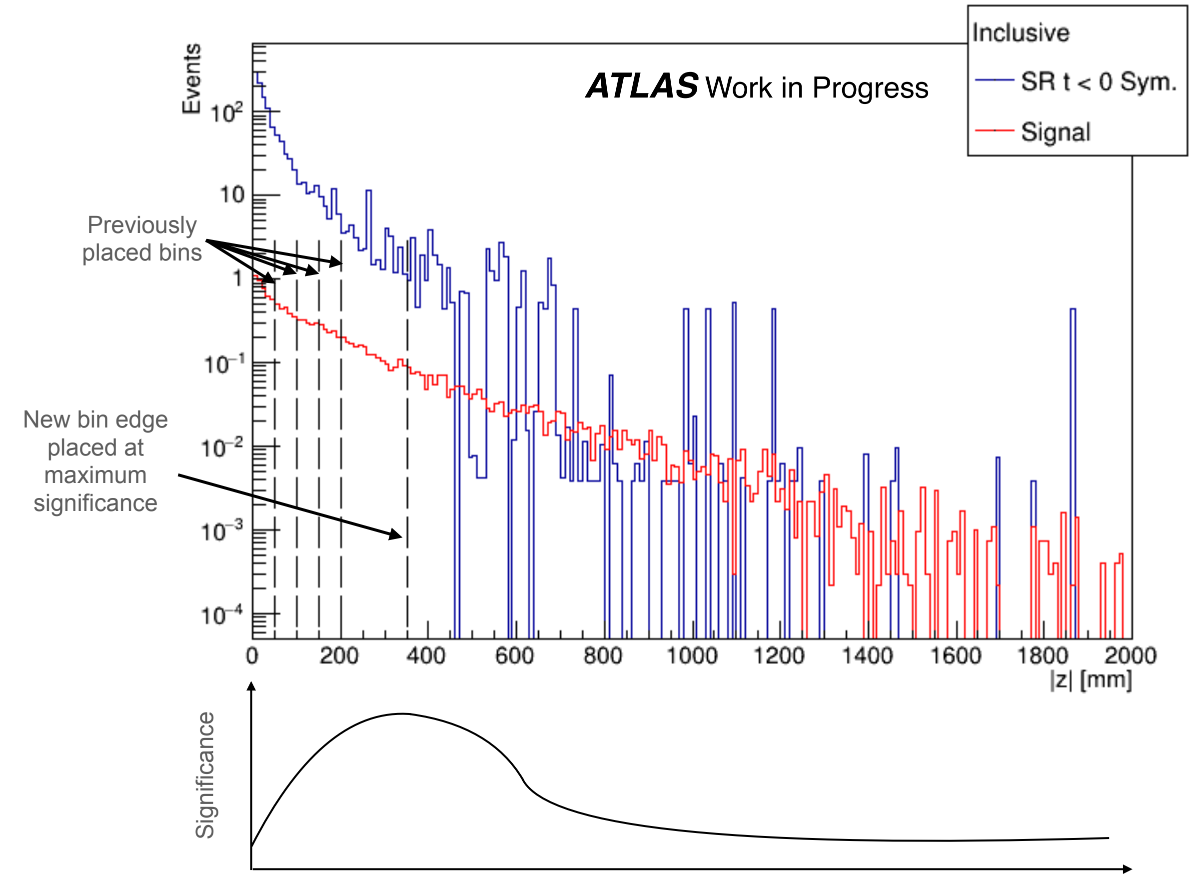
- Final state: e/μ + 1 or 2 barrel photons + MET
  - Photons are fairly soft, so trigger on lepton from VH/ttH processes
  - CR/VR/SR distinguished only by MET
- Signal lies in tails of timing and pointing distributions
  - Signal parameters: τ_{NLSP}, m_{LSP}, m_{NLSP} (up to 60 GeV $\sim m_{\mathrm{H}}/2$)
  - We seek to measure $BR(H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$
- Data-driven background estimation using templates
  - MC does not model pointing and timing properly, particularly in non-Gaussian tails
  - Rely entirely on data to model background
- Timing is the most sensitive variable
  - Smaller non-Gaussian tails and less background dependence
- Bin events in pointing, perform template fits simultaneously in each pointing bin i over timing bins j:
  - f^{γ}: photon-enriched template from Z→llγ and CR photons
  - f^{fake}: fake-photon-enriched template from CR photons with looser ID requirement
  - Fit is a linear combination with mixing fraction α_i
  - Both templates are reweighted by E_{cell} to the SR





Analysis Optimization

- Maximize sensitivity with respect to:
  - E_{cell}
  - Region definitions: MET cuts defining CR, VR, SR
  - Number of timing and pointing bins
  - Placement of timing and pointing bin edges
- Method:
  - Construct background from templates
  - Average signals
  - Brute force scan of parameter space
- Conclusions:
  - Two separate optimizations for $\Delta m \leq 10$ GeV, $\Delta m > 10$ GeV ($\Delta m = m_{NLSP} - m_{LSP}$)
  - Sensitivities to BRs up to ~2-5 times lower for some signal points relative to a nominal configuration based on previous analyses

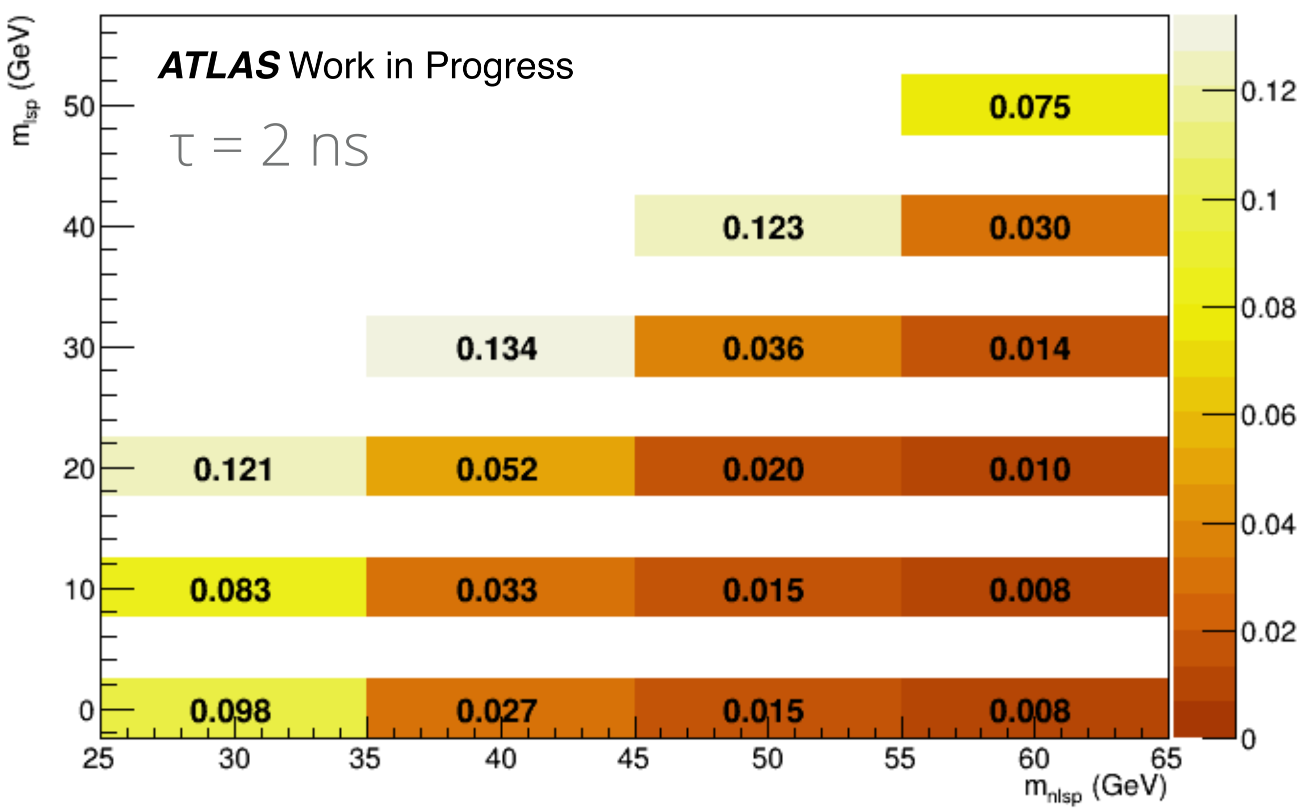


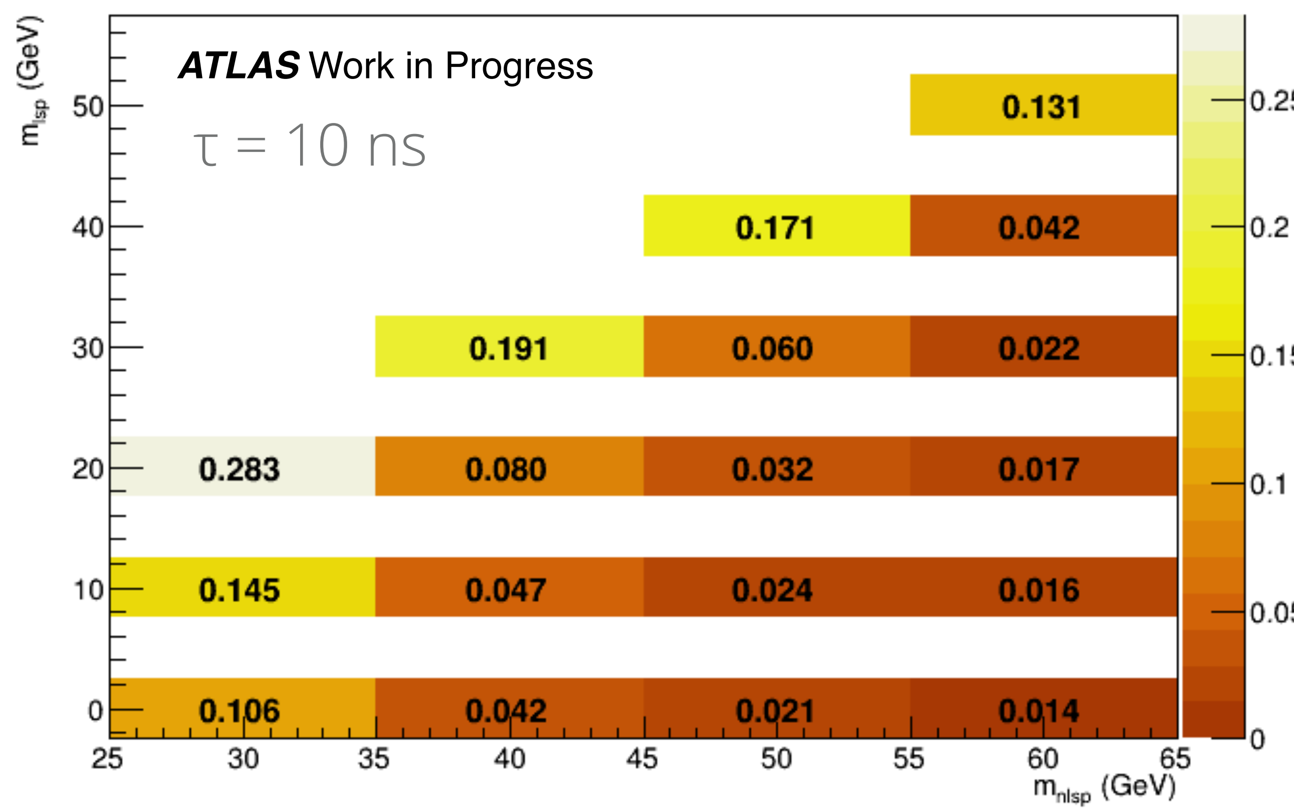
Parameter	Optimized Cuts/Bins $\Delta m \lesssim 10$ GeV	Optimized Cuts/Bins $\Delta m > 10$ GeV
E_{cell} Cut [GeV]	7	10
CR $E_{\text{T}}^{\text{miss}}$ [GeV]	<30	<30
VR $E_{\text{T}}^{\text{miss}}$ [GeV]	30–50	30–50
SR $E_{\text{T}}^{\text{miss}}$ [GeV]	>80	>50
$\|z\|$ bins [mm]	[0,50,100,200,300,2000]	
γ channel : t bins [ns]	[0,0.2,0.4,0.6,0.8,1.0,1.5,12.0]	
$\gamma\gamma$ channel: t bins [ns]	[0,0.2,0.4,0.6,0.8,1.0,12.0]	

Expected Sensitivity

- Uncertainties:
  - Signal yield: standard luminosity, trigger, instrumental systematics
  - Signal and background shape: template and MC statistics, template non-closure uncertainty
- Expected sensitivities calculated from $SR_{t<0}$ region
  - Reweighing procedure will allow for scanning sensitivity in the NLSP lifetime space
- Model-independent discovery region established using only last pointing and timing bin:
  - Expected sensitivity to 6.7 events in combined ≥1 photon category

Expected 95% CL $BR(H \to \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ Sensitivity



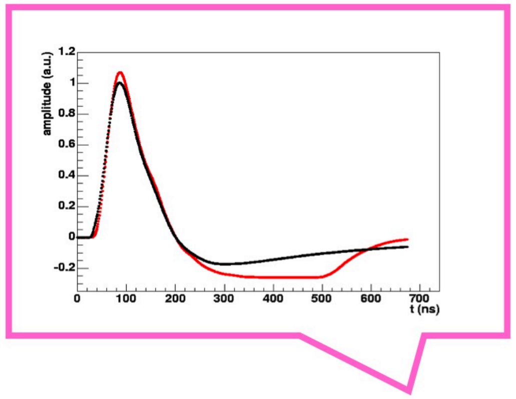


Summary

- Novel SUSY search for displaced photons from exotic decays of 125 GeV Higgs
- Exploits excellent timing performance and longitudinal segmentation of the ATLAS LAr calorimeter
- Data-driven background estimation using templates
- Analysis optimization dramatically improves sensitivity by up to 5 times, while maintaining sensitivity to any soft, displaced photons
- Sensitivity to $BR(H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ ~ few percent for much of the m_{NLSP}, m_{LSP} space
- Unblinding of $SR_{t>0}$ region to come!

Backup

LAr Energy Reconstruction



$$E_{\text{cell}} = F_{\mu\text{A}\to\text{MeV}} \cdot F_{DAC\to\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

Cell energy | Sampling fraction | Calibration board | ADC to DAC (Ramps) | Pulse Samples | Optimal Filtering Coefficients | Pedestals

The above formula describes the LAr electronic calibration chain (from the signal ADC samples to the raw energy in the cell. Note that this version of the formula uses the general M_{ramps}-order polynomial fit of the ramps. We use a linear fit as the electronics are very linear, and we only want to apply a linear gain in the DSP in order to be able to undo it offline, and apply a more refined calibration. In this case, the formula is simply:

$$E_{\text{cell}} = F_{\mu\text{A}\to\text{MeV}} \cdot F_{DAC\to\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \cdot R \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]$$

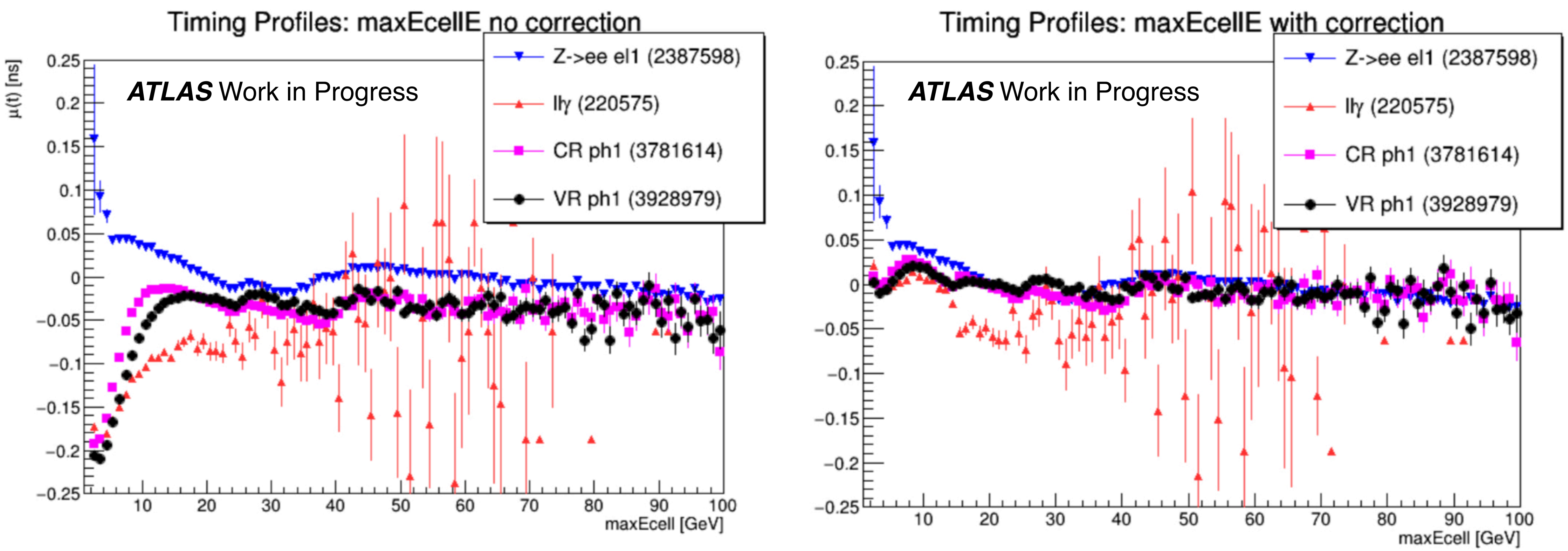
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArCaloPublicResultsDetStatus

Timing Calibration: Procedure

- Series of passes to empirically remove averaged/fitted variations
  - Pass 0: time-of-flight (TOF) from PV to cell and average time per run (by FEC)
  - Pass 1: average time per FEB
  - Pass 2: average time per channel
  - Pass 3: energy-dependence (by slot)
  - Pass 4: middle-layer cross-talk (by slot, based on $\delta\eta$, $\delta\varphi$)
  - Pass 5: inter-layer cross-talk (by slot, based on f1, f3)
  - Pass 6: average time per channel (pass 2 repeated)
    - Added because patterns re-emerged after applying other passes (passes are actually subtly correlated with each other)

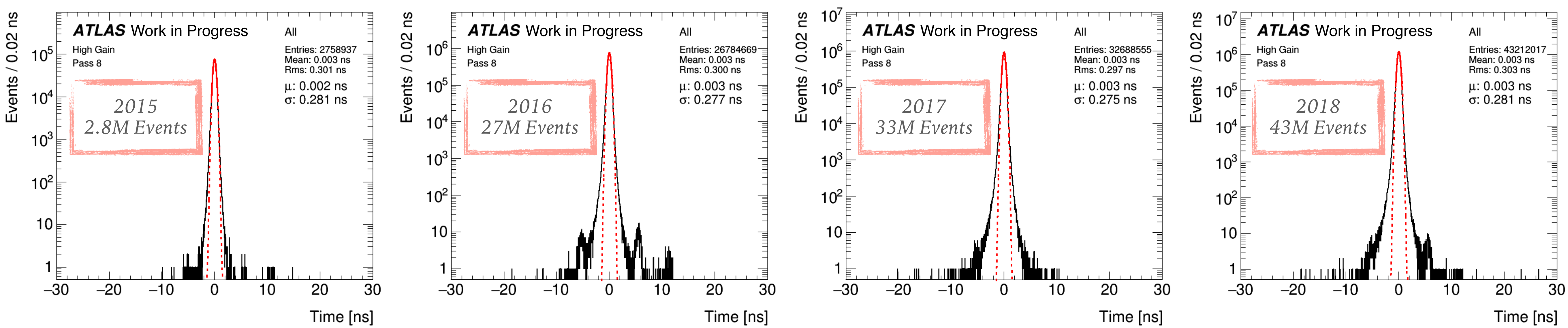
New Photon Timing Correction

- Electron vs. photon timing
  - Generally, they behave similarly for timing purposes
  - But at lower energies ($E_{cell} \lesssim 10$ GeV), a shift in timing mean for photons was observed
- New, additional photon correction has been derived
  - Cluster-energy dependent correction at low energies, constant shift at higher energies
  - Greatly reduces timing shift systematic

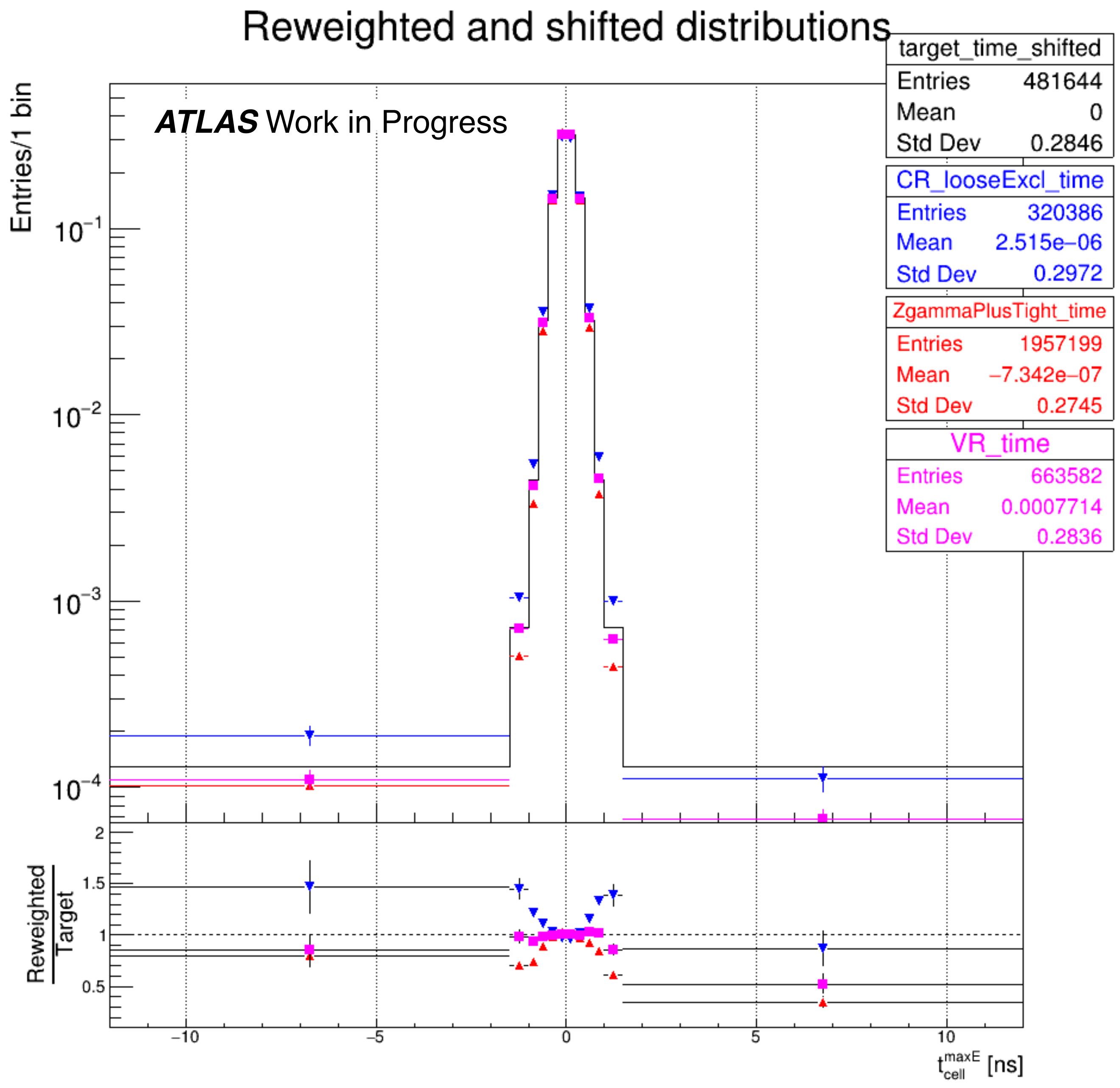


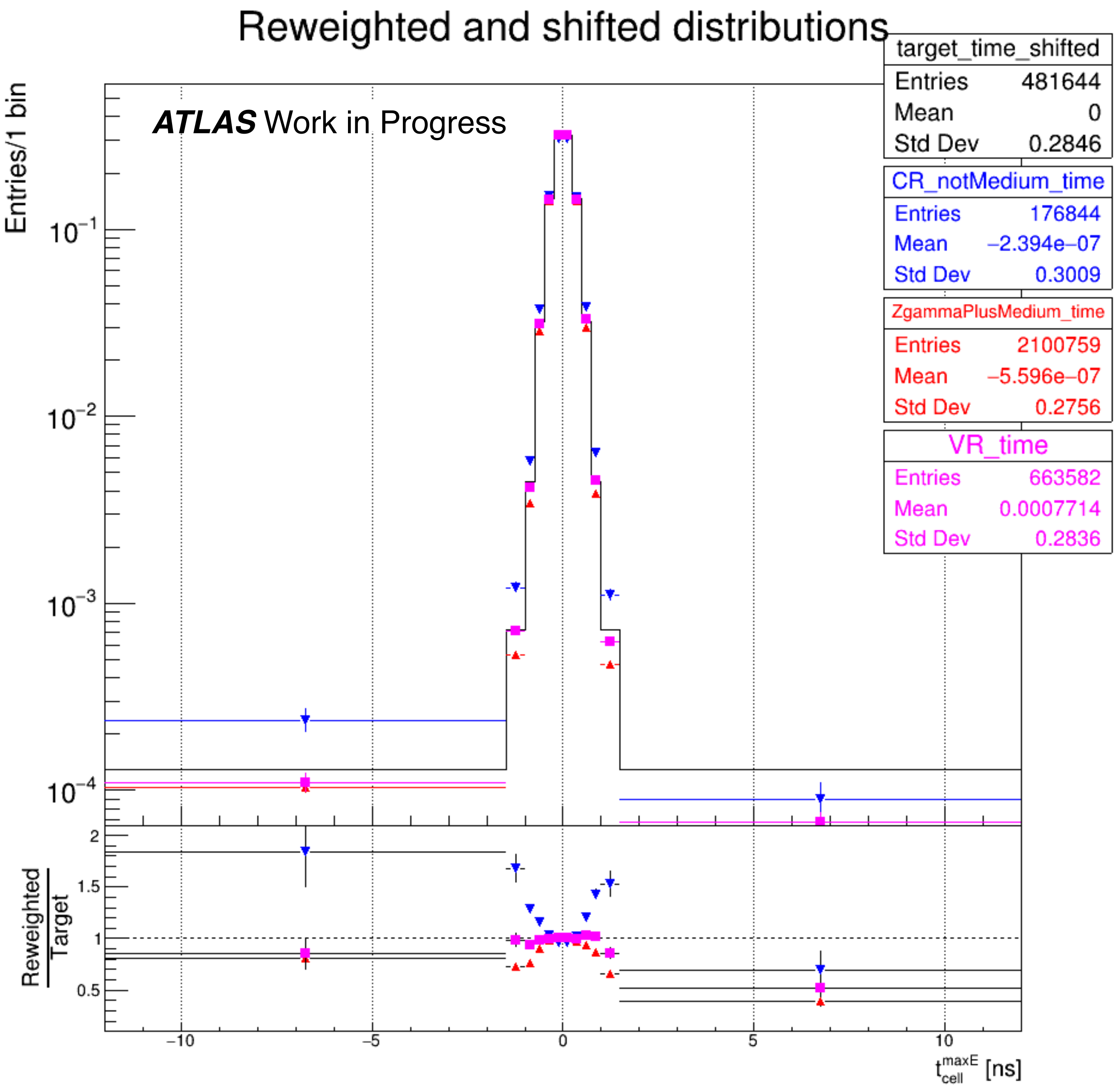
LAr Timing Calibration: Satellite Collisions

- After main-main, satellite-satellite collisions at ±5 ns (at the IP) are the dominant observable collision mode
  - Due to bunch structure, crossing angle, trigger efficiency
  - Suppressed by ~10^6 compared to the main peak
- Similar collisions can occur at multiples of ±5 ns but are suppressed even further
  - Importance of these peaks likely depends on many factors in the LHC beam conditions
- We observe satellite-satellite collisions but in slightly different locations and frequencies throughout Run 2 (see Zee data below by year)



Templates: Extended Range





Event Selection

	Lepton (e/μ)	Photon
Multiplicity	>=1	>=1
ID	Medium	Loose
Calo. Isolation	e: $p_{\mathrm{T},\Delta R=0.2}/p_{\mathrm{T}} < 20\%$ μ: PFlowLoose_FixedRad (see Ref. [86])	$p_{\mathrm{T},\Delta R=0.2}/p_{\mathrm{T}} < 6.5\%$
Track Isolation	e: $p_{\mathrm{T},\Delta R_{\mathrm{max}}=0.2}/p_{\mathrm{T}} < 15\%$ $\lvert z_0 \sin\theta\rvert < 0.5$ mm $\lvert d_0\rvert/\sigma_{d_0} < 5$ μ: PFlowLoose_FixedRad (see Ref. [86]) $\lvert z_0 \sin\theta\rvert < 0.5$ mm $\lvert d_0\rvert/\sigma_{d_0} < 5$	$p_{\mathrm{T},\Delta R=0.2}/p_{\mathrm{T}} < 5\%$
Leading (Subleading) p_{T} [GeV]	> 27 (> 10)	> 10
$\lvert\eta\rvert$	e: < 1.37 or [1.52, 2.47] μ: < 2.7	< 1.37 or [1.52, 2.37]

[86] R. Hyneman et al., Tech. Rep. ATL-COM-PHYS-2019-432, CERN, Geneva, Apr, 2019. https://cds.cern.ch/record/2672803.

Optimization Results

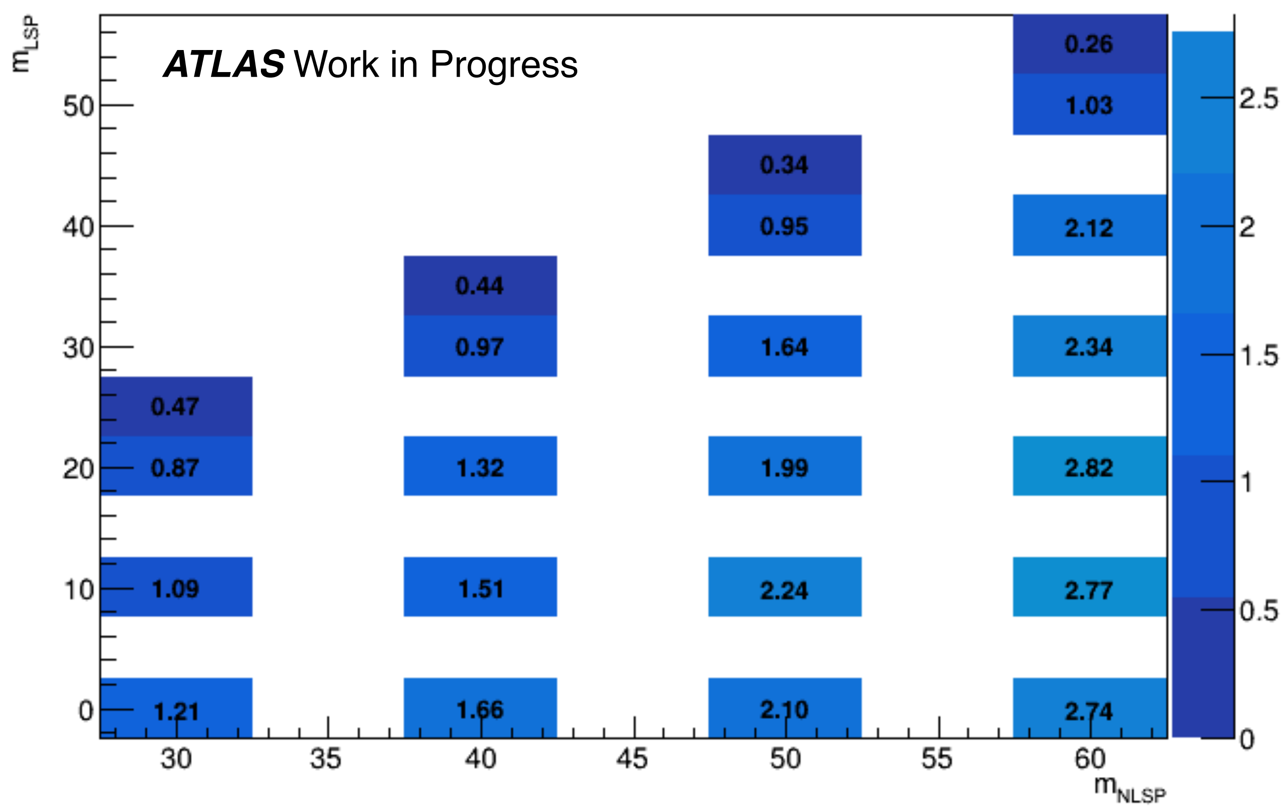
Original Cuts/Bins
(based on informed guesses)

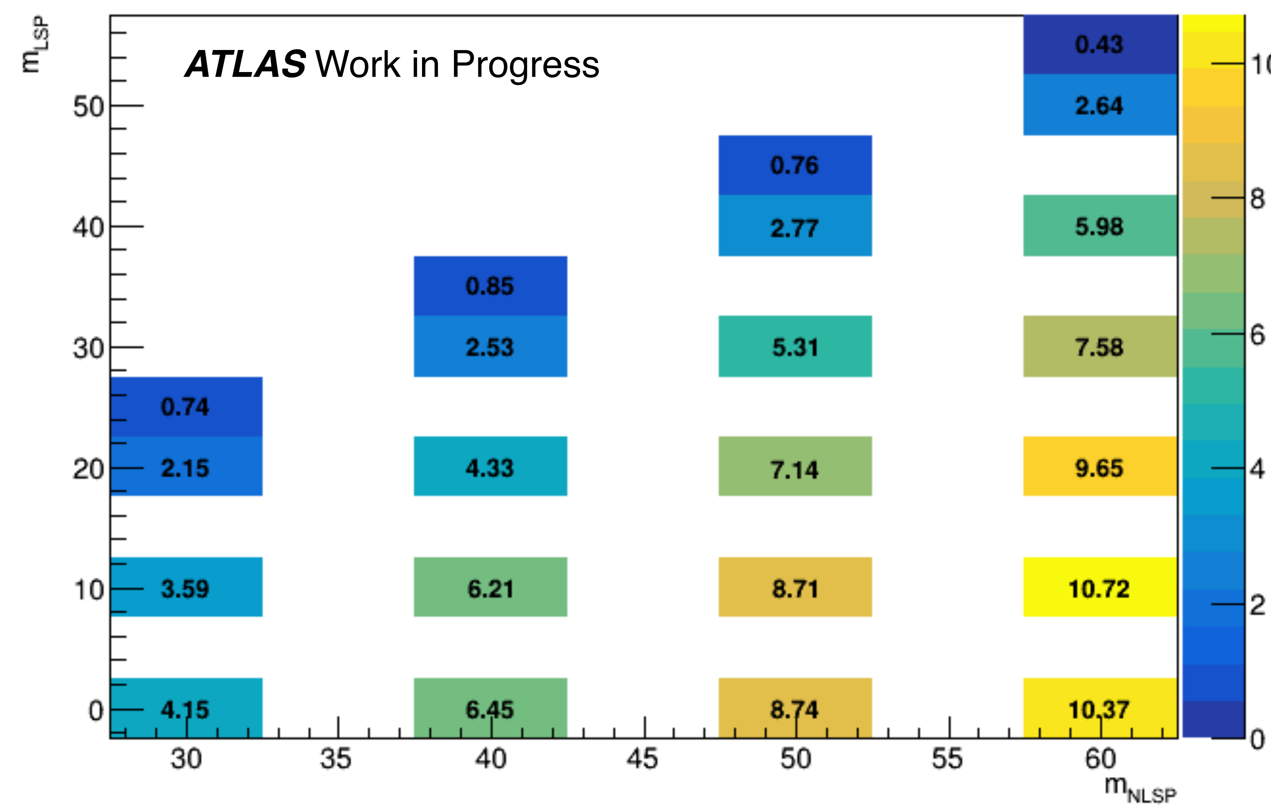
	Previous Cuts/Bins
Energy Cut [GeV]	2
VR Low MET [GeV]	30
VR High MET [GeV]	50
z bins	[0, 50, 100, 150, 200, 250, 500, 2000]
t bins	[0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.5, 4.5, 6.5, 12.0]

Final Optimized Cuts/Bins

		Proposed Optimized Cuts/Bins	
		Δm ≤ 10 GeV	**Δm > 10 GeV**
	Energy Cut [GeV]	7	10
	VR Low MET [GeV]	30	30
	VR High MET [GeV]	80	50
	z bins	[0, 50, 100, 200, 300, 2000]	
g	**t bins**	[0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 12.0]	
gg	**t bins**	[0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 12.0]	

Significances at $BR(H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ = 30% with α = 0.5 for τ = 2 ns Samples





Same color scale for both plots

Discovery Region Expected Sensitivity

		1ph, 1.5<t<12ns	2ph, 1<t<12ns	Combined 1ph+2ph
$SR_{t<0}$ Data →	N_data	5	1	6
Bkg Estimate	N_bkg	4.90924	0.28223	5.1915
Bkg Estimate	N_bkg error	2.20423	0.11812	2.2074
$SR_{t<0}$ Observed Significance	p-value	0.49	0.155	0.395
$SR_{t<0}$ Observed Significance	significance	0.025	1.02	0.266
Expected Sensitivity (N) →	95% CL limit	6.387	3	6.712

- $SR_{t<0}$ validation:
  - Small observed significance in absence of signal
- Sensitivity to 6.4 events in 1 photon channel and 3 events in 2 photon channel
  - 2 photon channel: CL limit < 3, ATLAS recommendation is to quote 3
- Combined ≥1 photon sensitivity estimate: 6.7 events
  - 1 photon channel has one extra bin edge at 1.5 ns compared to 2 photon channel, otherwise their configurations are identical
  - Total expected events from [1.5, 12] ns can be predicted conservatively by simply adding 1 & 2 photon events together

Flat Systematic Uncertainties

Systematic Source		γ		$\gamma\gamma$	
Description	Name	Up [%]	Down [%]	Up [%]	Down [%]
e/γ Energy Resolution	EG_RESOLUTION_ALL	-0.0757	0.0163	-0.1531	0.3326
e/γ Energy Scale	EG_SCALE_ALL	-0.2416	-0.1073	0.8533	-0.6288
μ Isolation	MUON_EFF_ISO_STAT	0.1262	-0.5830	0.1242	-0.6159
	MUON_EFF_ISO_SYS	0.2034	-0.1827	0.2096	-0.1819
μ Reco.	MUON_EFF_RECO_STAT	0.0307	-0.0307	0.0354	-0.0354
	MUON_EFF_RECO_STAT_LOWPT	0.0014	-0.0018	0.0020	-0.0027
	MUON_EFF_RECO_SYS	0.1351	-0.1345	0.1387	-0.1377
	MUON_EFF_RECO_SYS_LOWPT	0.0019	-0.0019	0.0031	-0.0031
μ Track to Vertex Assoc.	MUON_EFF_TTVA_STAT	0.0213	-0.0214	0.0222	-0.0222
	MUON_EFF_TTVA_SYS	0.0267	-0.0246	0.0258	-0.0242
μ ID Track Smearing	MUON_ID	-0.0584	-0.0067	-0.0028	0.0673
μ MS Track Smearing	MUON_MS	0.0823	-0.0047	0.0145	-0.0338
μ Sagitta (p_{T})	MUON_SAGITTA_RESBIAS	0.0003	0.0003	0.0000	0.0000
	MUON_SAGITTA_RHO	0.0003	0.0003	0.0000	0.0272
μ Energy Scale	MUON_SCALE	-0.0237	0.0372	-0.0093	0.0269
e Efficiencies	EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR	0.3410	-0.3404	0.3040	-0.3037
	EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR	0.0235	-0.0235	0.0174	-0.0174
	EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR	0.0699	-0.0699	0.0634	-0.0634
	EL_EFF_TriggerEff_TOTAL_1NPCOR_PLUS_UNCOR	0.0001	-0.0001	0.0000	-0.0000
	EL_EFF_Trigger_TOTAL_1NPCOR_PLUS_UNCOR	0.0823	-0.0823	0.0770	-0.0770
$E_{\mathrm{T}}^{\mathrm{miss}}$ Soft Track	MET_SoftTrk_ResoPara	-0.7479	-0.7479	-0.0899	-0.0899
	MET_SoftTrk_ResoPerp	-0.3325	-0.3325	0.3150	0.3150
	MET_SoftTrk_Scale	-0.3572	0.0760	0.0451	0.1317

Table 9.1: Flat systematic uncertainty breakdown for the $m_{\mathrm{NLSP}} = 60$ GeV, $m_{\mathrm{LSP}} = 0.5$ GeV, $\tau = 2$ ns signal point. Columns show up- and down-variations by photon channel. Rows corresponds to a variations from the indicated source alone, expressed as percentages of the signal yield in the SR.

Using Prompt Electron Timing

Assume the measured time t for prompt events can be written as follows:

$$\begin{aligned} t &= t_{true} + t_{corr} + t_{uncorr} \\ &= 0 + t_{corr} + t_{uncorr} \\ &= \mathcal{N}(\sigma_{beam}) + \mathcal{N}(\sigma_{uncorr}) \end{aligned}$$

If we subtract the electron time from the photon time, the time resolution of the resulting difference is:

$$\sigma_{t_\gamma - t_e} = \sqrt{\sigma_\gamma^2 + \sigma_e^2 - 2\sigma_{e\gamma}}$$

If we require that the resolution improves by using the electron time, i.e. $\sigma_{t_\gamma - t_e} < \sigma_\gamma$, then we must have:

$$\sigma_{e\gamma} > \frac{1}{2}\sigma_e^2 \tag{2}$$

(Note: this means the correlation must obey $\rho_{e\gamma} > \frac{\sigma_e}{2\sigma_\gamma}$)

Combining equations 1 and 2, we get:

$$\boxed{\sigma_e < \sqrt{2}\sigma_{beam}}$$

Note: for $\sigma_{beam} = 190$ ps, σ_e must be $\lesssim 267$ ps.

If the resolution σ_e can be understood as the quadrature sum of an $E_{\text{max cell}}$-dependent noise term and a constant term (p_0 and p_1, respectively), then we can write the following requirement:

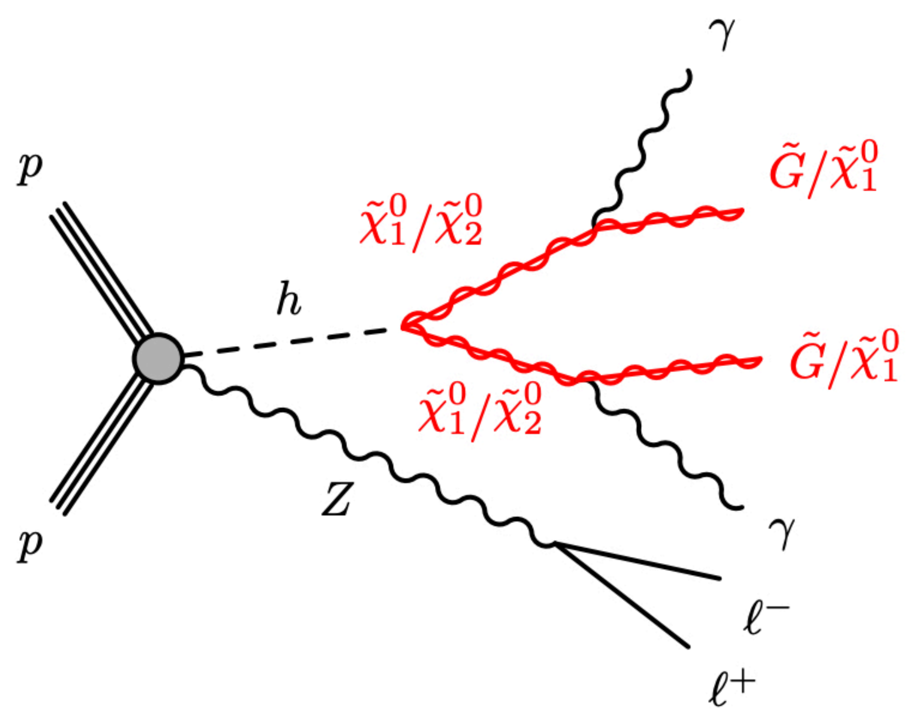
$$\sqrt{\left(\frac{p_0}{E_{\text{max cell,e}}}\right)^2 + p_1^2} < \sqrt{2}\sigma_{beam}$$

$$\boxed{E_{\text{max cell,e}} > \frac{p_0}{\sqrt{2\sigma_{beam}^2 - p_1^2}}}$$

From Z $\rightarrow$ ee studies $\sigma_{beam} = 190$ ps, and for electrons in the barrel, $p_0 \sim 2700$ GeV $\cdot$ ps and $p_1 \sim 230$ ps.

Therefore, in order for an electron to improve the timing resolution of photons in the same event:

$$\boxed{E_{\text{max cell,e}} \gtrsim 19 \text{ GeV}}$$



MC: Lifetime Reweighting

- Lifetime reweighting
  - Signals with different lifetimes can be constructed by simply reweighting by $w(t_1)w(t_2)$
  - $w(t) = \frac{p'(t)}{p(t)} = \frac{T}{T'} \exp\left(-t\left(\frac{1}{T'} - \frac{1}{T}\right)\right)$
    - t_1: proper decay time of neutralino 1
    - t_2: proper decay time of neutralino 2
    - T: lifetime of current sample
    - T': desired lifetime of new sample
- Closure tests of reweighting existing samples successful
  - 2→10, 10→2, 2→5, & 10→5 ns
- Official production of new 0.5, 5, and 20 ns samples done (JIRA)

Selections	60,0.5,2->5ns		60,0,10->5ns	
Selections	#events	error	#events	error
Total	71695.5	1309.56	75190.3	409.757
>=1trigger+>=1lep	33772.3	1099.02	34208.2	268.247
Trigger+>=1lep+>=1ph	11862.5	108.915	11266.5	106.144
Trigger+>=1lep+>=1ph+SR	6182.98	78.6319	6005.92	77.4979