Search for non-pointing and delayed photons in the $\gamma\gamma + E_T^{Miss}$ final state

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Reference Papers

Presented today & recently accepted for publication in PRD!

"Search for non-pointing and delayed photons in the diphoton and missing transverse momentum final state in 8 TeV pp collisions at the LHC using the ATLAS detector"

- http://arxiv.org/abs/1409.5542

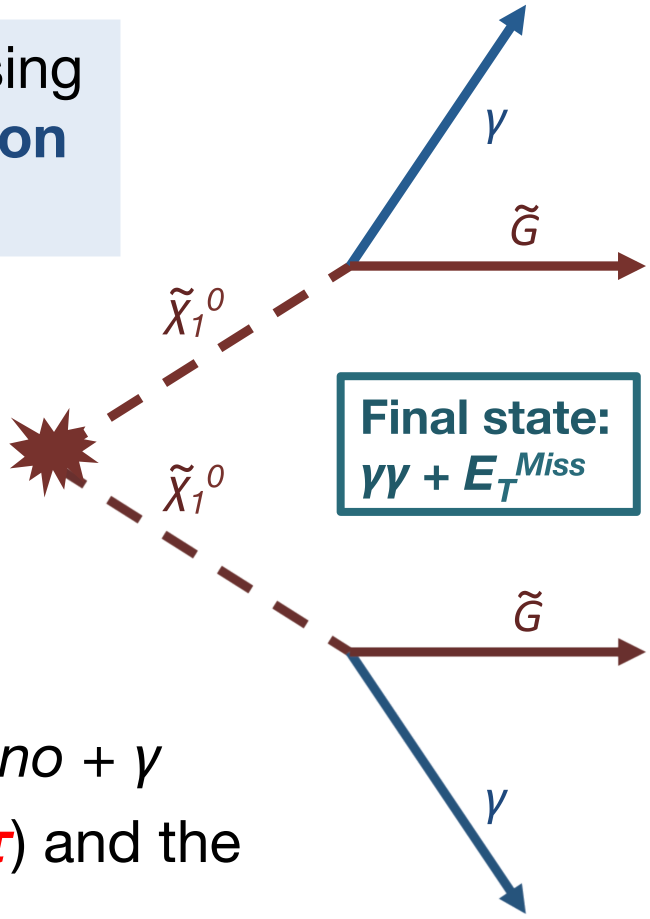
"Search for non-pointing photons in the diphoton and E_T^miss final state in sqrt(s) = 7 TeV proton-proton collisions using the ATLAS detector"

- http://arxiv.org/abs/1304.6310

"Search for new physics with long-lived particles decaying to photons and missing energy in pp collisions at sqrt(s) = 7 TeV" [CMS collaboration]

- http://arxiv.org/abs/1207.0627

Conduct a search for new phenomena using unique **pointing capabilities** and **precision timing** of the ATLAS EM calorimeter



Many models give rise to neutral long-lived particle pair production

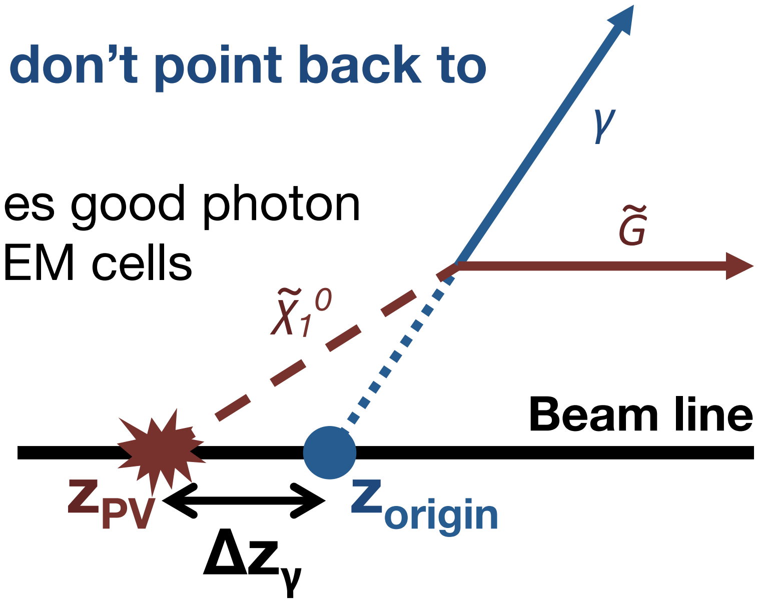
- Interpret results in the context of Gauge-Mediated Super-symmetry Breaking (**GMSB**) models
- *Neutralino* NLSP decays to LSP *gravitino* + γ
- **Free parameters:** neutralino lifetime (**τ**) and the effective scale of SUSY breaking (**Λ**)

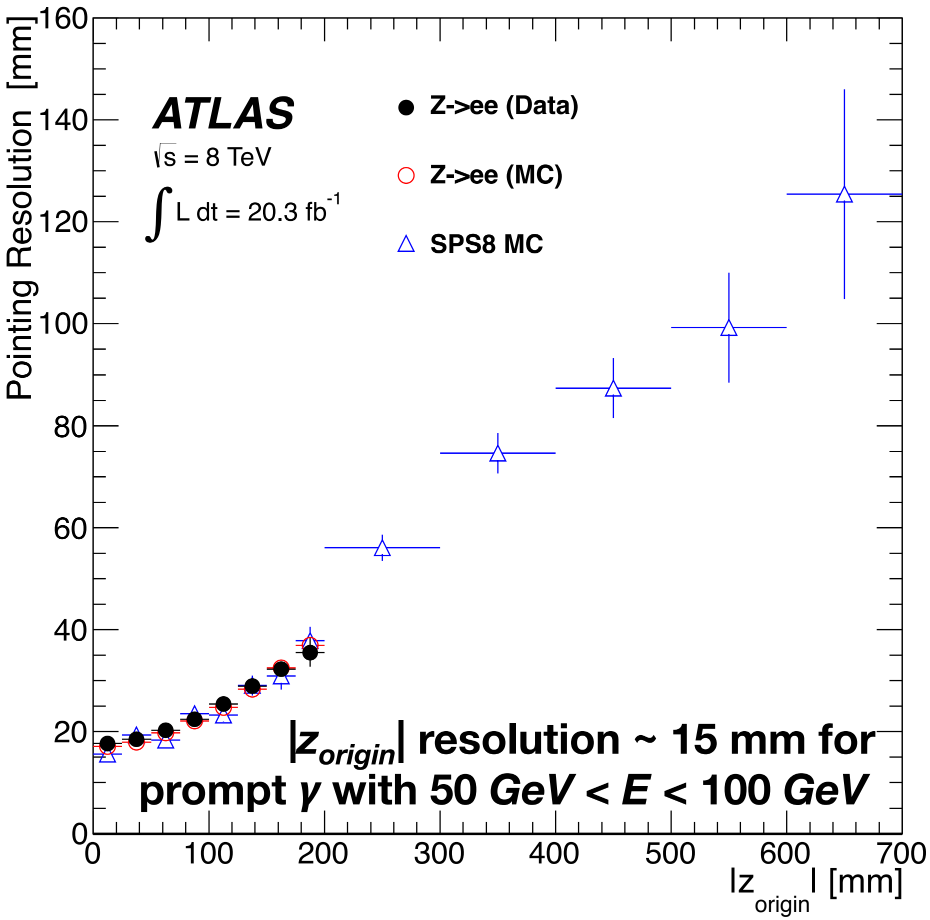
Search in the full 20.3 fb^{-1} dataset collected from the LHC at $\sqrt{s}$ = 8 *TeV* in 2012. Published $\sqrt{s}$ = 7 *TeV* analysis previously.

Photon Pointing (Δz_γ)

Signal photons can have flight paths that don't point back to the primary (highest Σp_T^2) vertex

- ***η* segmentation of EM calorimeter** provides good photon vertex reconstruction using first 2 layers of EM cells





Define the photon vertex pointing variable:

$$\Delta z_\gamma = z_{origin} - z_{PV}$$

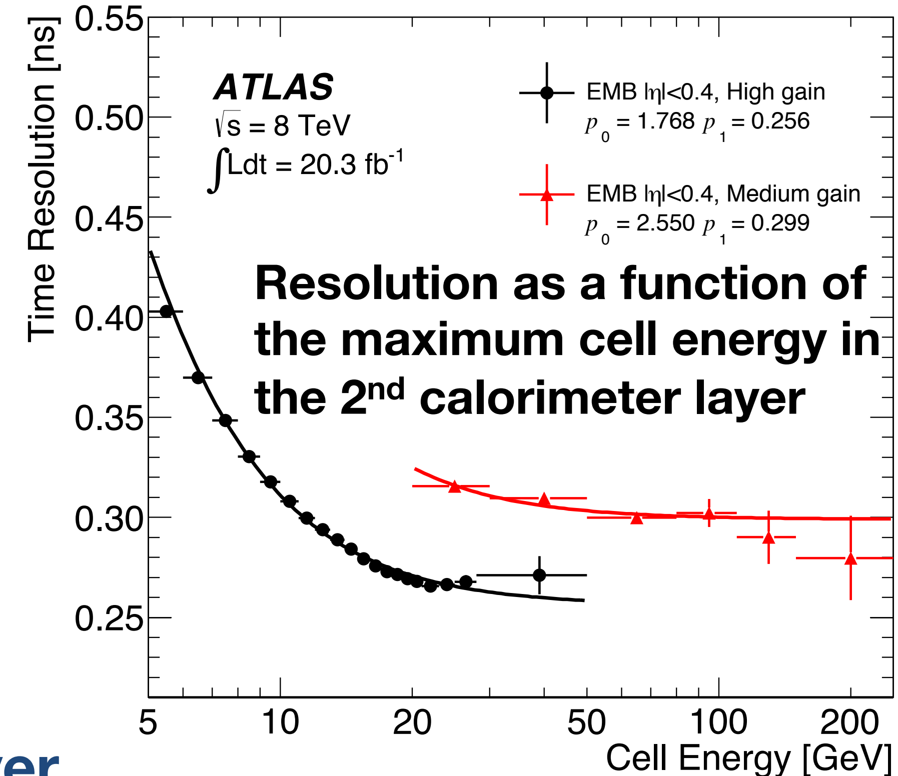
Difference between the primary vertex position (z_{PV}) and the *z* position that the EM calo. reconstructs (z_{origin}) for the *γ*

Vertex resolution measured using $Z \rightarrow e^+e^-$ events and compared with signal Monte Carlo

Photon Timing (t_γ)

Signal photons would reach EM calorimeter with a slight delay compared with prompt photons from a hard scatter

- Massive neutralino: ***β=v/c*** distributed to low values
- **Longer geometrical path** for non-pointing photons



Arrival time of EM shower measured with 2nd EM calo. layer

- Timing and energy reconstructed using optimal filtering algorithm
- **Validate calibration with *Z→e+e-*** (see figure)
- **Time resolution of 299 *ps* (256 *ps*) for medium (high) gain *γ*** (includes 220 *ps* contribution from time spread in *pp* collisions)

Event Selection for $\gamma\gamma + E_T^{Miss}$

Photon selection

- "Loose" **cut-based identification** uses shower shape in 2nd EM calorimeter layer and leakage into hadronic calorimeter
- **Transverse energy cut:** $E_T > 50\ GeV$
- **Pseudo-rapidity cut:** $|\eta| < 2.37$, excluding $1.37 < |\eta| < 1.52$
- **Isolation:** $E_T < 4.0\ GeV$ in $\Delta R = 0.4$ cone around γ
- **Timing:** $|t_\gamma| < 4\ ns$ to avoid satellite collision events

Event selection

- **Trigger:** 2 "loose" γ in $|\eta| < 2.5$ with $E_T^1 > 35\ GeV$, $E_T^2 > 25\ GeV$
- At least **2 photons in the event**
- At least **1 barrel photon** $|\eta| < 1.37$

τ	Signal acceptance times efficiency [%]		
[ns]	$\Lambda = 80$ TeV	$\Lambda = 160$ TeV	$\Lambda = 320$ TeV
0.5	8.4 ± 0.6	30 ± 1	46 ± 2
2	5.1 ± 0.3	21 ± 0.2	33.0 ± 0.3
6	1.7 ± 0.1	7.3 ± 0.1	12.5 ± 0.2
10	0.86 ± 0.03	3.71 ± 0.06	6.45 ± 0.09
40	0.089 ± 0.004	0.38 ± 0.01	0.70 ± 0.02
100	0.016 ± 0.001	0.070 ± 0.002	0.129 ± 0.004

Signal region: $E_T^{Miss} > 75\ GeV$

Control reg. 1: $20\ \text{GeV} < E_T^{Miss} < 50\ GeV$

Control reg. 2: $50\ \text{GeV} < E_T^{Miss} < 75\ GeV$

Prompt backgrounds: $E_T^{Miss} < 20\ GeV$

Signal acceptance increases with larger Λ (more energetic events) and **decreases with longer τ** (more decays outside calorimeter)

Signal and Background Modeling

Signal shape from Monte Carlo samples

- Generated samples with ***Λ*** in [70 *TeV*, 400 *TeV*]
- Reweight to different neutralino lifetimes (***τ***)
- Cross-sections calculated at **NLO**

Time resolution not modeled well in MC:

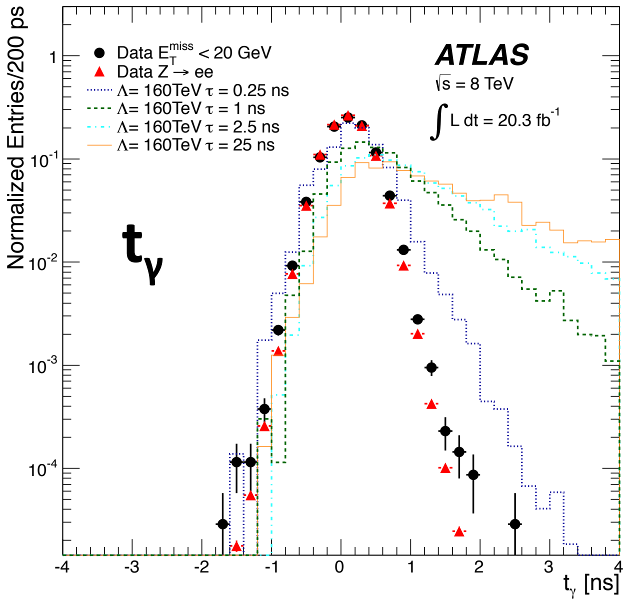
- **Smear timing**, match resolution of $Z \rightarrow e^+e^-$ data

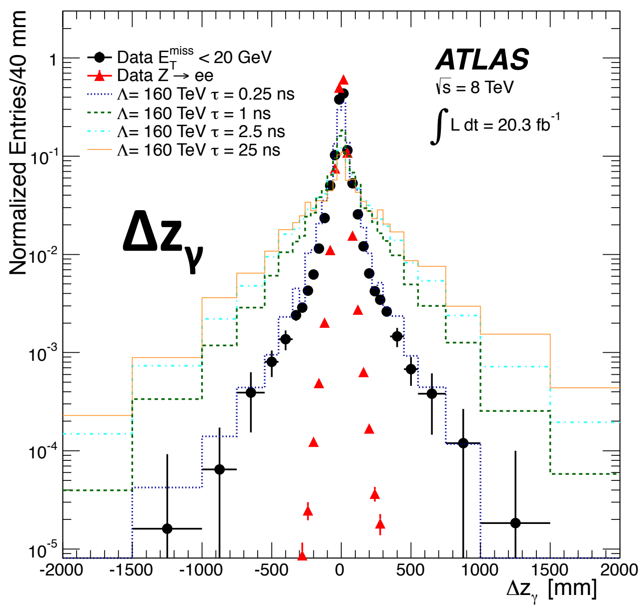
Backgrounds from data control regions

- **Prompt *γ* and electron fakes**: $Z \rightarrow e^+e^-$ events
- **Jets faking *γ***: $E_T^{Miss} < 20\ GeV$ region in data
- Data-driven methods account for influence of pileup and primary vertex misidentification

Background shapes very similar in tγ:

→ **Use $E_T^{Miss} < 20\ GeV$ region to model all backgrounds in fit**





Fit Method

Fit incorporates two discriminating variables: timing t_γ and pointing $|\Delta z_\gamma|$ parameters of the *barrel* photon with *largest* t_γ.

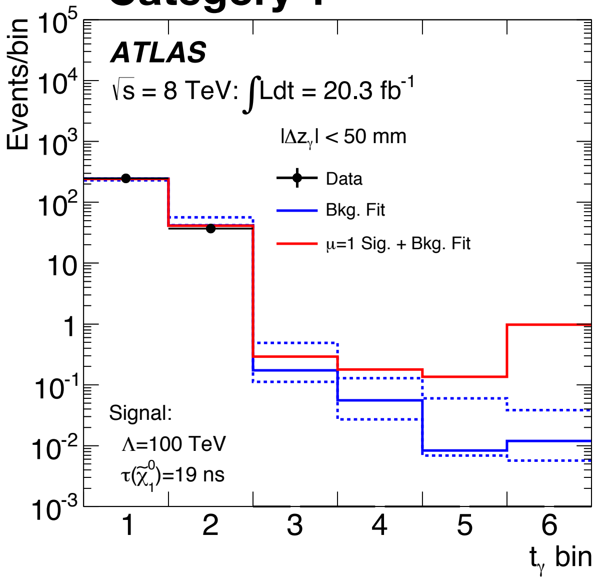
Divide data into 6 categories based on $|\Delta z_\gamma|$

- Varying ***S/B*** enhances the statistical significance

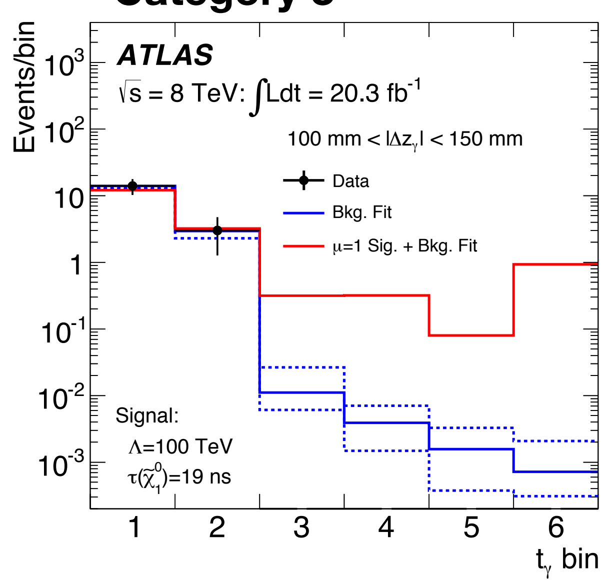
Simultaneously perform 1D fit to t_γ in each category

- **Signal normalization** correlated between categories
- **Background normalizations** uncorrelated, obtained from **data**
- Enables the use of a **single template** shape for all backgrounds

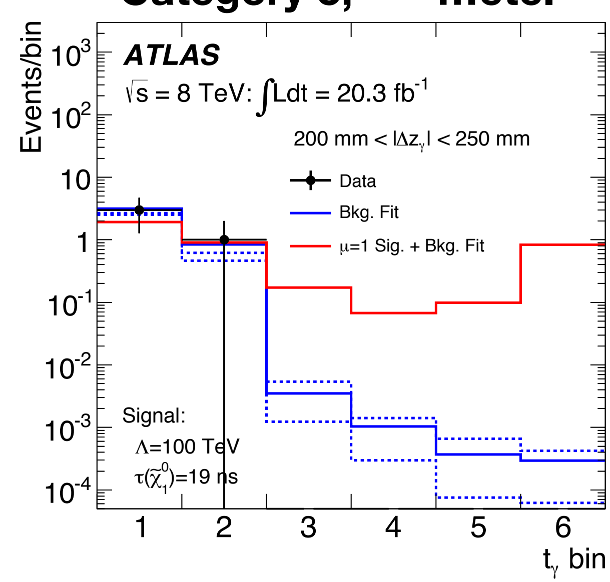
Category 1



Category 3



Category 5, …etc.



Systematic Uncertainties

Dominant signal normalization uncertainties listed in the table

Source of uncertainty	Value [%]
Integrated luminosity	$\pm$ 2.8
Trigger efficiency	$\pm$ 2
Photon E_T scale/resolution	$\pm$ 1
Photon identification and isolation	$\pm$ 1.5
Non-pointing photon identification	$\pm$ 4
E_T^{miss} reconstruction	$\pm$ 1.1
Signal MC statistics	$\pm$ (0.8–3.6)
Signal reweighting	$\pm$ (0.5–5)
Signal PDF and scale uncertainties	$\pm$ (9–14)

Signal t_γ shape uncertainties:

- **Time reconstruction** algorithm produces up to 10% bias for t_γ (measured in satellite collisions)
- **Pileup modeling** affects $|\Delta z_\gamma|$ and t_γ with higher PV mis-ID
- Combined shape impact **< 10%**

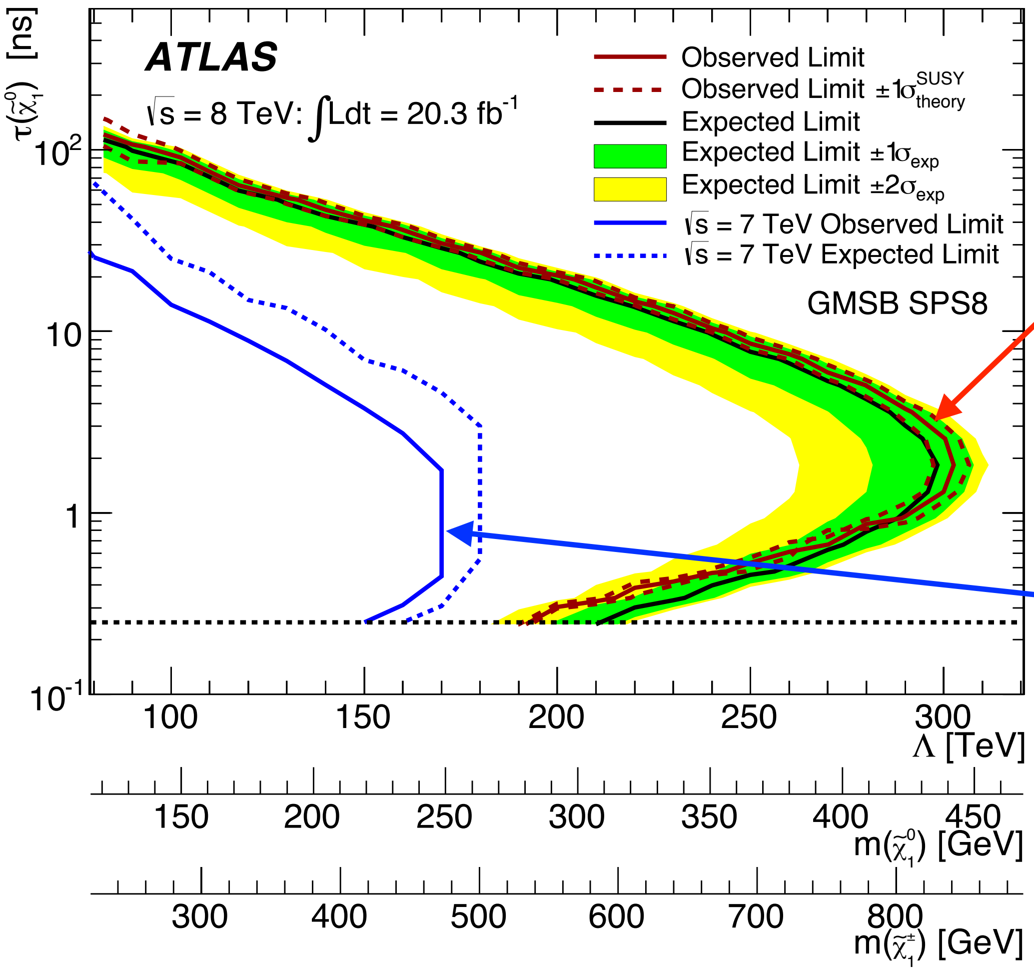
No need for background normalization systematics: fit to data gives normalization of background (controlled by **unconstrained parameters**)

Background t_γ shape uncertainties:

- **Background composition** is not measured, take the difference between $Z \rightarrow e^+e^-$ and jet-enriched low-E_T^{Miss} data as systematic uncertainty
- **Barrel-barrel and barrel-endcap events** have different $|\Delta z_\gamma|$ shapes Reweight to fraction in data (61±4% BB), vary by ±4% to get systematic

No sign of an excess in the data (*p_0 = 88%*)

- Signal and control regions well modeled by prompt backgrounds



Observed 95% *CL* exclusion in the (*Λ*,*τ*) signal plane extends to ***Λ* = 300 TeV** and ***τ* = 100 ns**

Ability to exclude signals with as few as 3 accepted events!

Significant improvement over ***√s = 7 TeV* exclusion!**

Possibilities in Run-II include Higgs: *$H \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma+E_T^{Miss}$*

ATLAS
√s = 8 TeV
∫L dt = 20.3 fb^{-1}
Data E_T^{miss} > 75 GeV
Data E_T^{miss} < 20 GeV
Entries/40 mm
Δ $z_γ$ [mm]

ATLAS
√s = 8 TeV
∫L dt = 20.3 fb^{-1}
Data E_T^{miss} < 20 GeV
Data Z → ee
Λ= 80TeV τ = 1 ns
Λ= 160TeV τ = 1 ns
Λ= 300TeV τ = 1 ns
Normalized Entries/200 ps
$t_γ$ [ns]

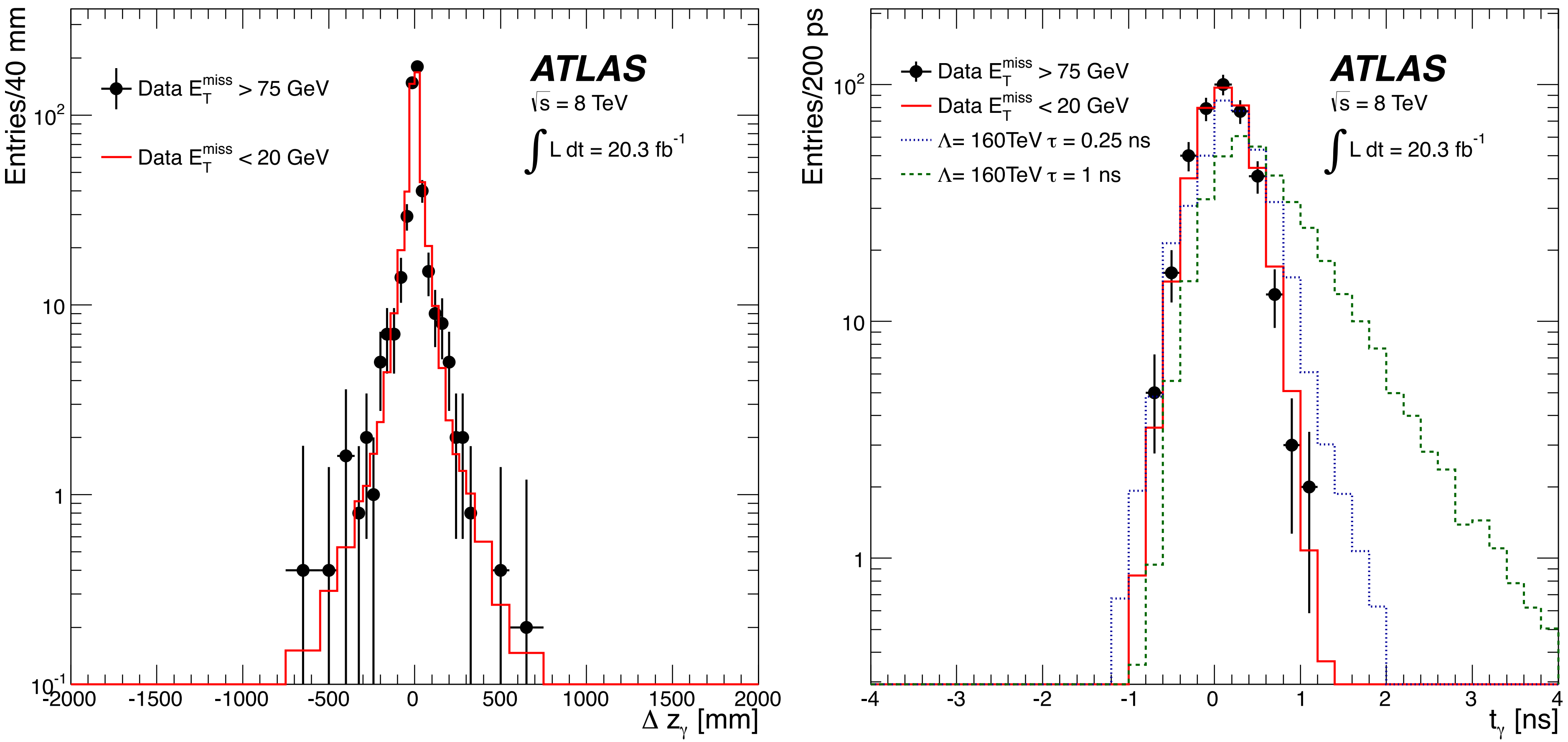
ATLAS
√s = 8 TeV: ∫Ldt = 20.3 fb^{-1}
|Δ$z_γ$| < 50 mm
Data
Bkg. Fit
μ=1 Sig. + Bkg. Fit
Signal:
Λ=100 TeV
τ($\tilde{χ}_1^0$)=19 ns
Events/bin
$t_γ$ bin

Appendix

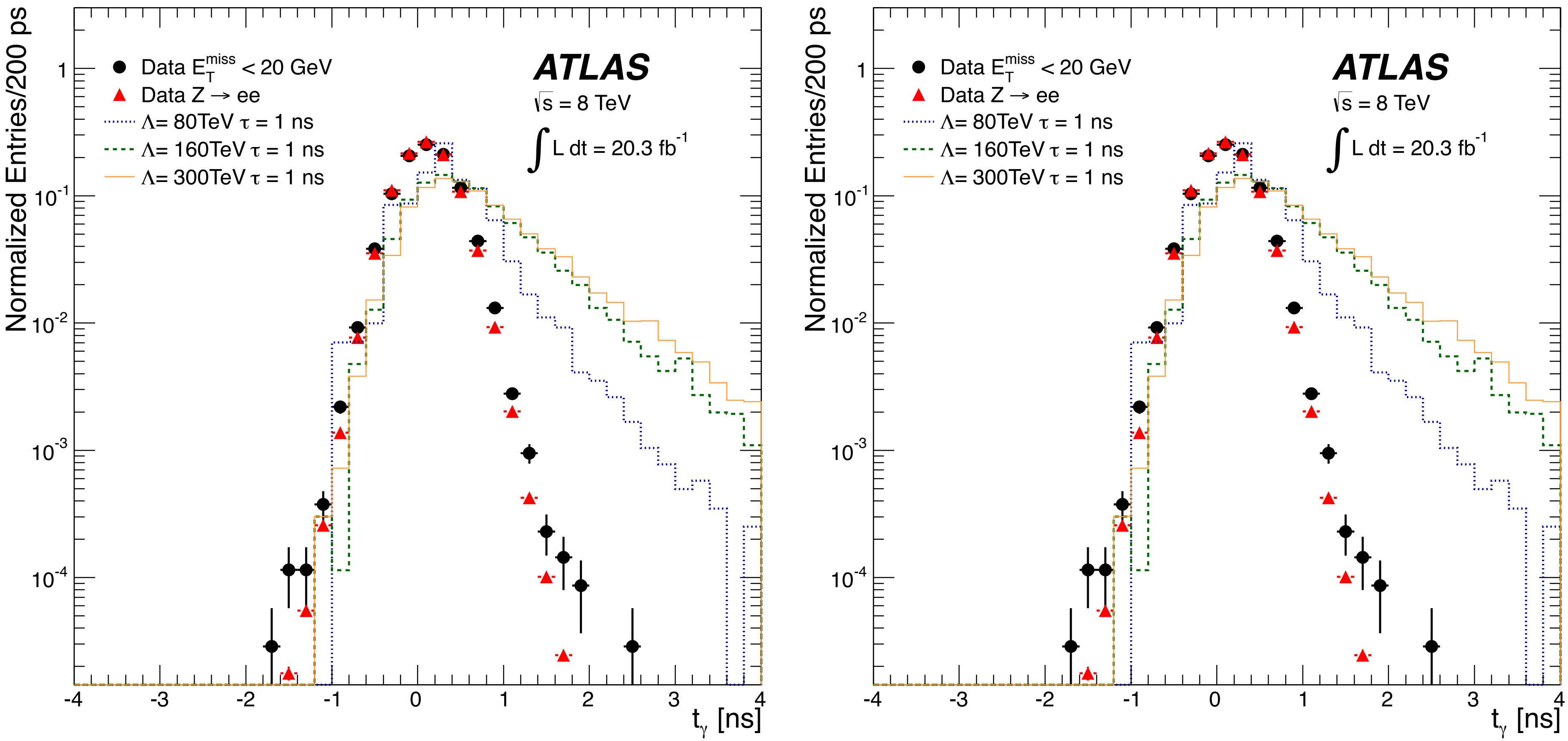
ATLAS
√s = 8 TeV: ∫Ldt = 20.3 fb^{-1}
Λ = 200 TeV
Obs. Limit
Exp. Limit
Exp. Limit ±1$σ_{exp}$
Exp. Limit ±2$σ_{exp}$
SPS8 Theory ±$σ_{theory}^{SUSY}$
95% CL limit on accepted signal events
τ($\tilde{χ}_1^0$) [ns]

Obs. Limit
Exp. Limit
Exp. Limit ±1$σ_{exp}$
Exp. Limit ±2$σ_{exp}$
SPS8 Theory ±$σ_{theory}^{SUSY}$
ATLAS
Λ = 200 TeV
√s = 8 TeV: ∫Ldt = 20.3 fb^{-1}
95% CL limit on σ [fb]
τ($\tilde{χ}_1^0$) [ns]

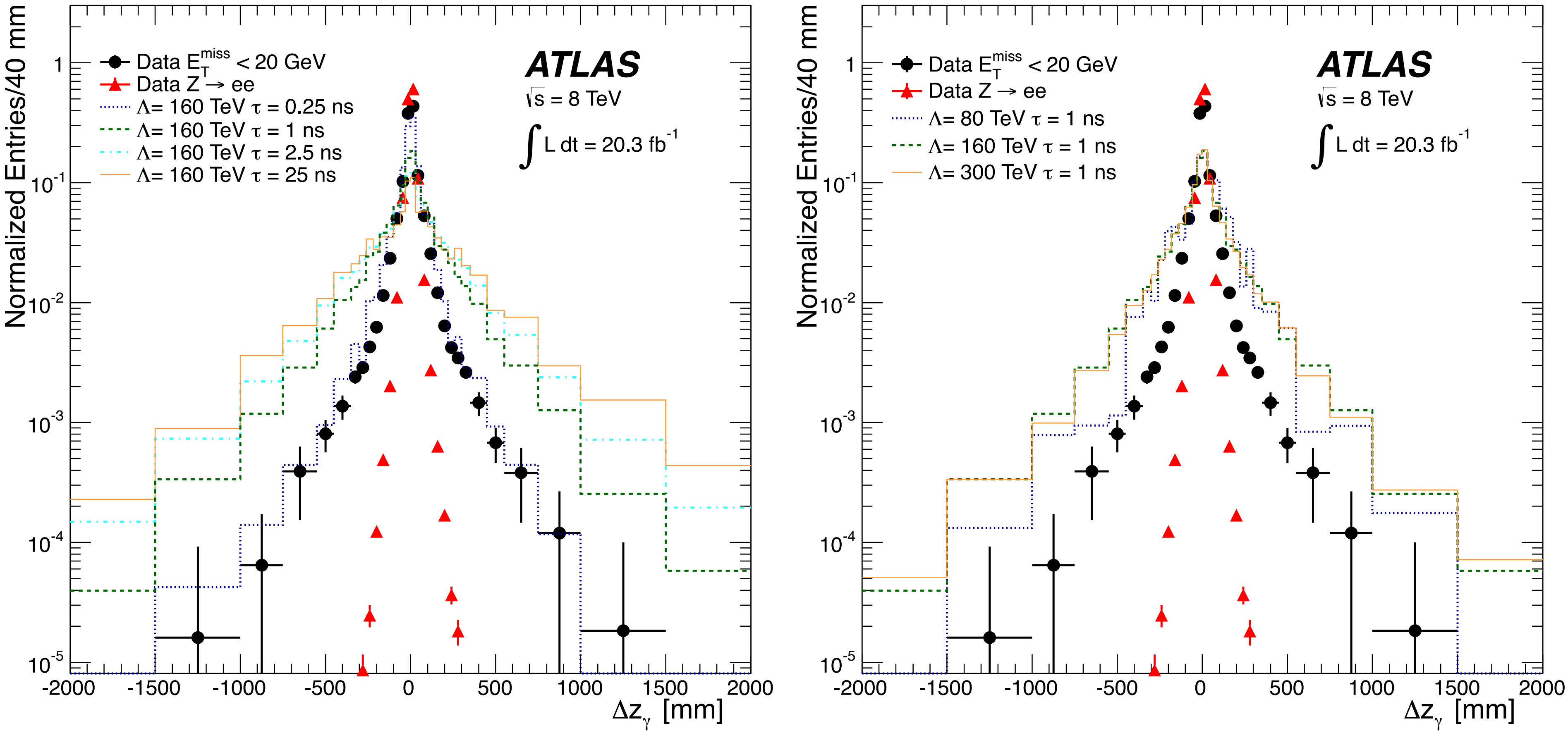
Distributions of $|\Delta z_\gamma|$ and t_γ in the Signal Region



Photon Timing (t_γ) Distributions



Photon Pointing ($|\Delta z_\gamma|$) Distributions



$|\Delta z_\gamma|$ Categories and t_γ Bins For Fitting

TABLE II. Values of the optimized ranges of the six $|\Delta z_\gamma|$ categories, for both low and high NLSP lifetime (τ) values.

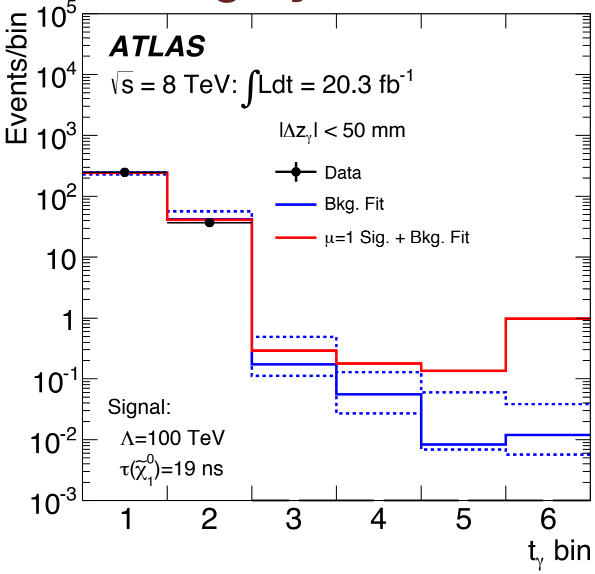
NLSP	Range of $|\Delta z_\gamma|$ values for each category [mm]					
Lifetime	Cat. 1	Cat. 2	Cat. 3	Cat. 4	Cat. 5	Cat. 6
$\tau < 4$ ns	0 – 40	40 – 80	80 – 120	120 – 160	160 – 200	200 – 2000
$\tau > 4$ ns	0 – 50	50 – 100	100 – 150	150 – 200	200 – 250	250 – 2000

TABLE III. Values of the optimized ranges of the six t_γ bins, for both low and high NLSP lifetime (τ) values.

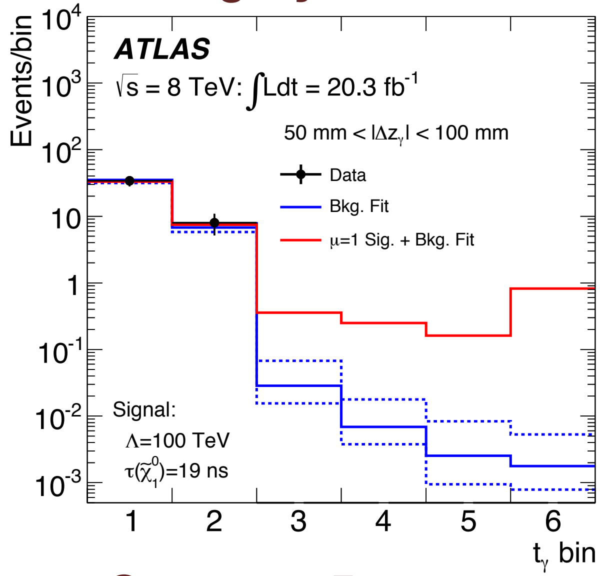
NLSP	Range of t_γ values for each bin [ns]					
Lifetime	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5	Bin 6
$\tau < 4$ ns	−4.0 – +0.5	0.5 – 1.1	1.1 – 1.3	1.3 – 1.5	1.5 – 1.8	1.8 – 4.0
$\tau > 4$ ns	−4.0 – +0.4	0.4 – 1.2	1.2 – 1.4	1.4 – 1.6	1.6 – 1.9	1.9 – 4.0

Signal-Plus-Background Fits by Analysis Category

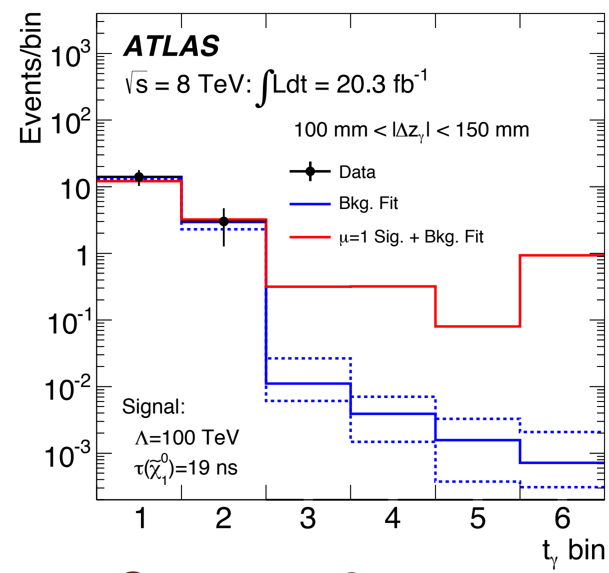
Category 1



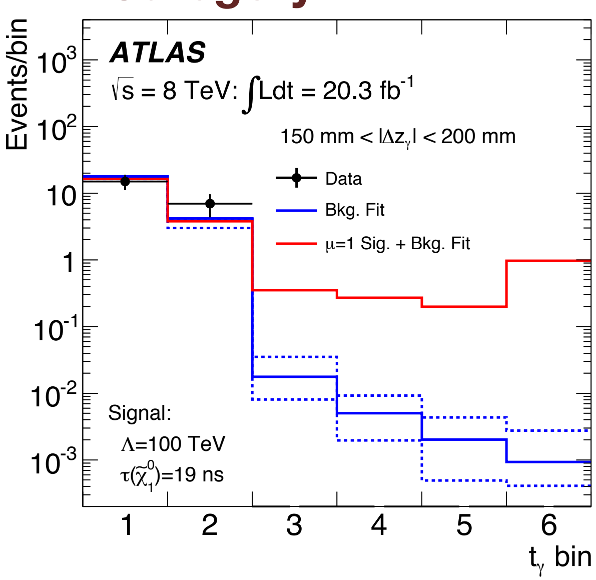
Category 3



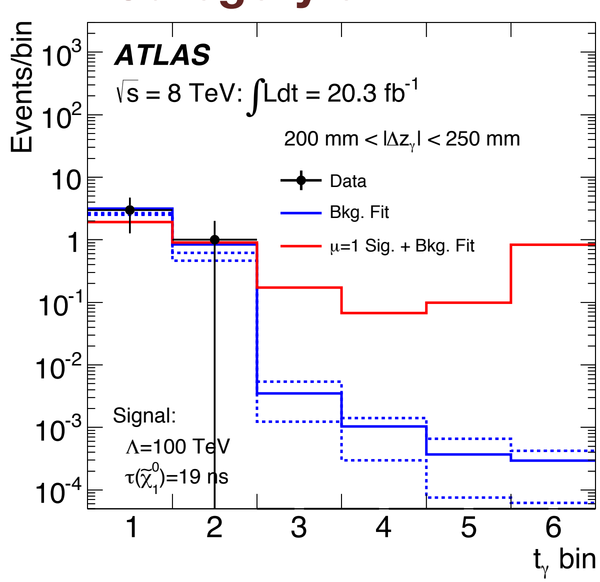
Category 5



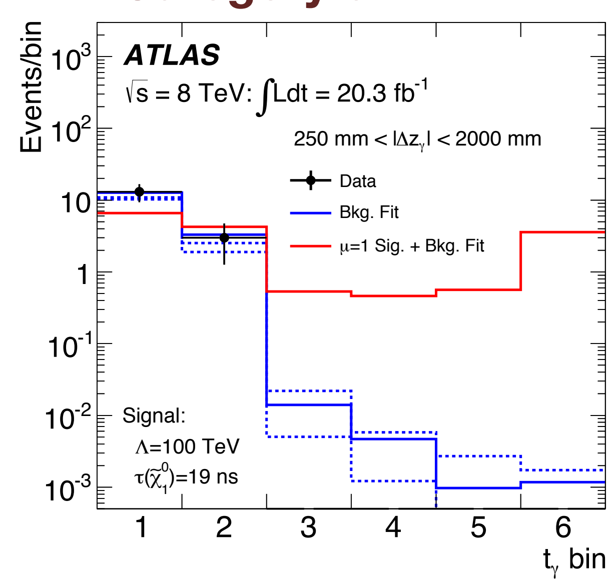
Category 4



Category 5



Category 6



95% CL Exclusion for Λ = 200 TeV