



Image from arXiv: 2303.13613  
multicharge particle search

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# Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector

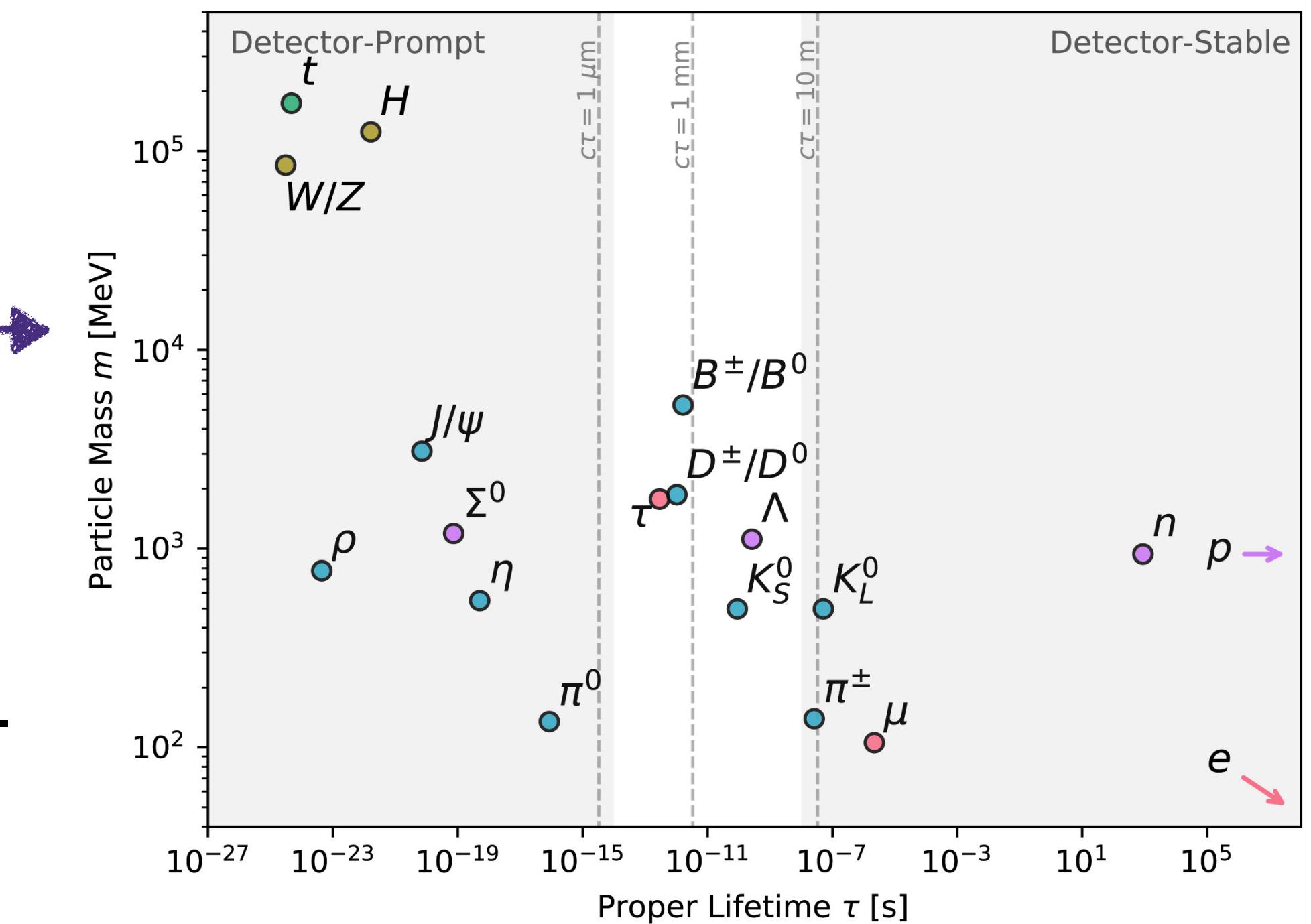
Margaret Lutz, Tel Aviv University  
on behalf of

The ATLAS Collaboration

Pheno 2023  
09 May 2023

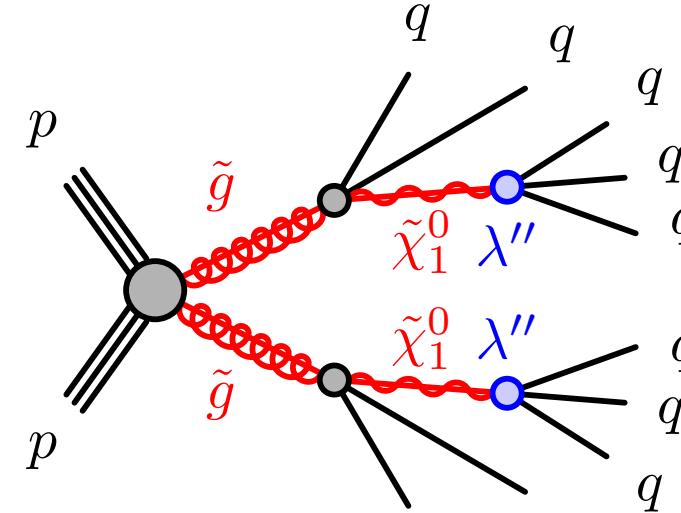
# Long-lived particles

- While the SM is the best description we have so far of the laws of nature, we need BSM physics to help answer many open questions
- Many BSM searches are underway at ATLAS and other experiments
  - However, no new physics has been found
    - Time to be creative, and make sure we are looking everywhere
- Most BSM searches are for prompt physics 
- In fact, there are many long-lived particles in the SM
- Naturally arise in many BSM models as well, important part of the phase space
  - Hidden sector models - SUSY - Heavy neutral leptons - dark photons - Axion like particles
- This can come about due to small couplings with the SM, small mass differences, highly virtual mediators...

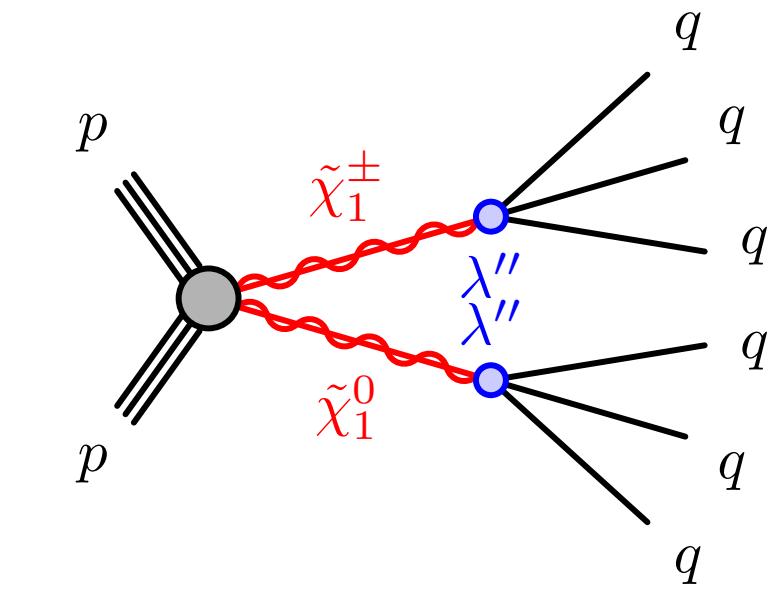
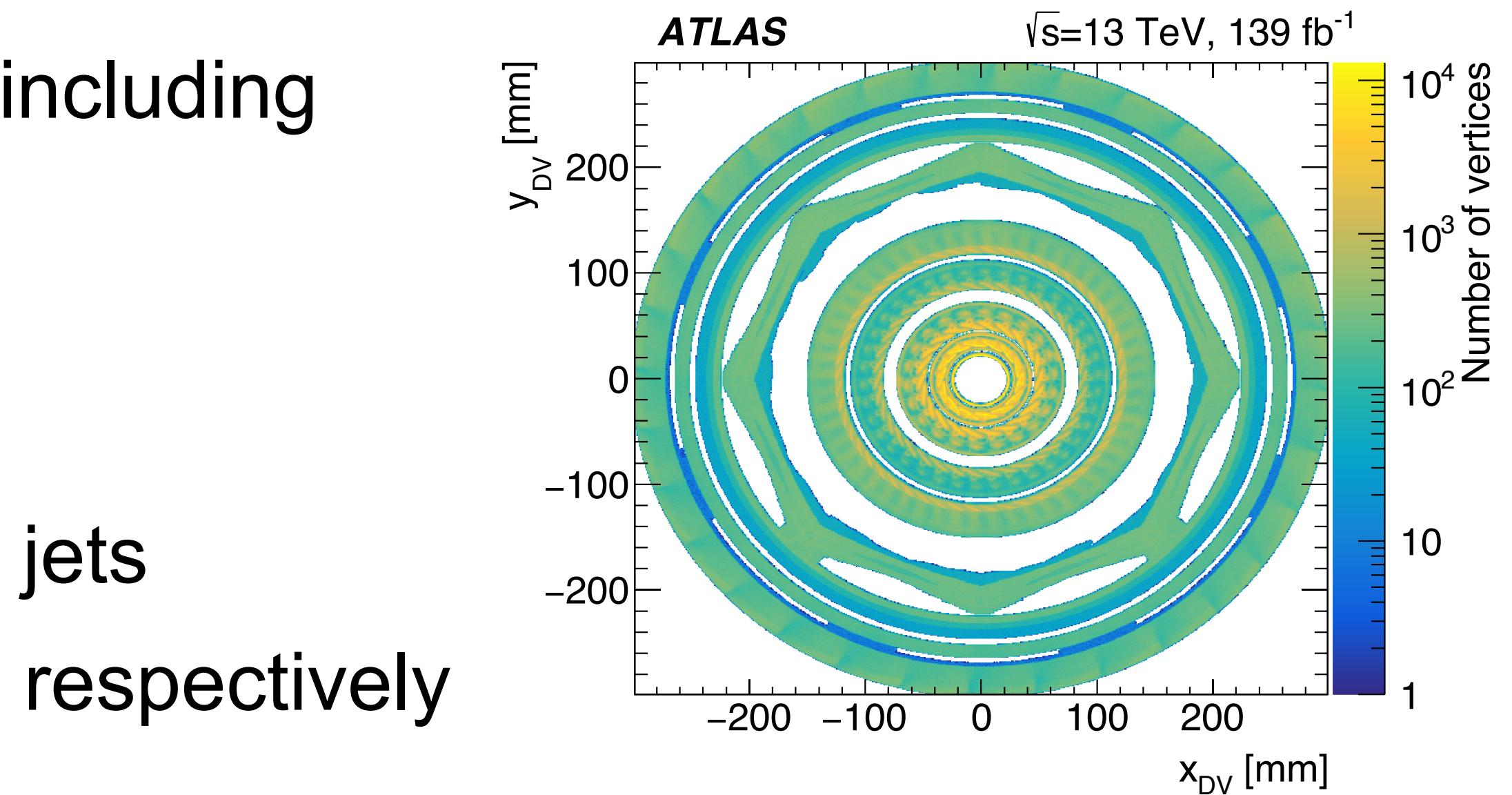
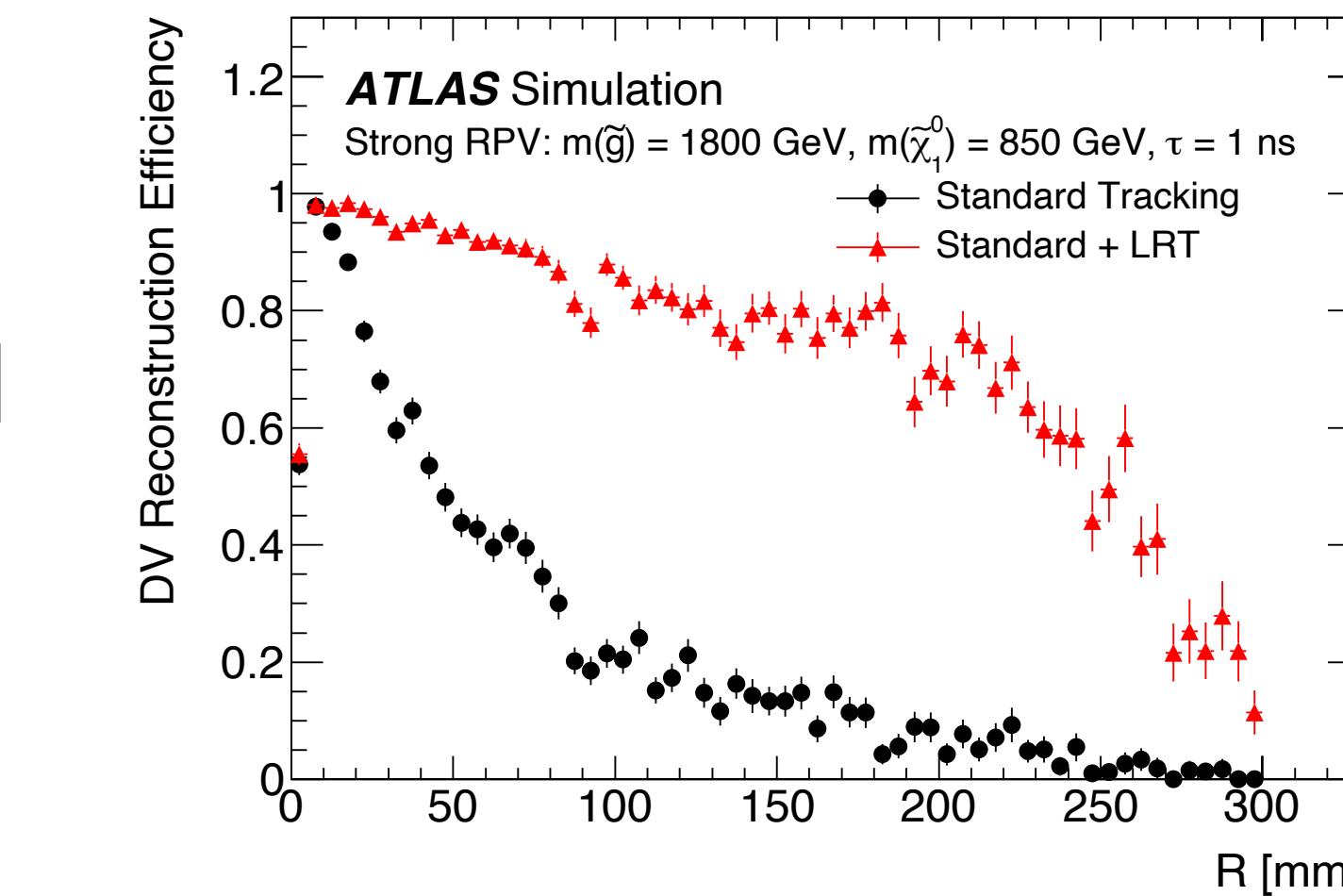


arXiv: 1810.12602

# Displaced hadronic vertices

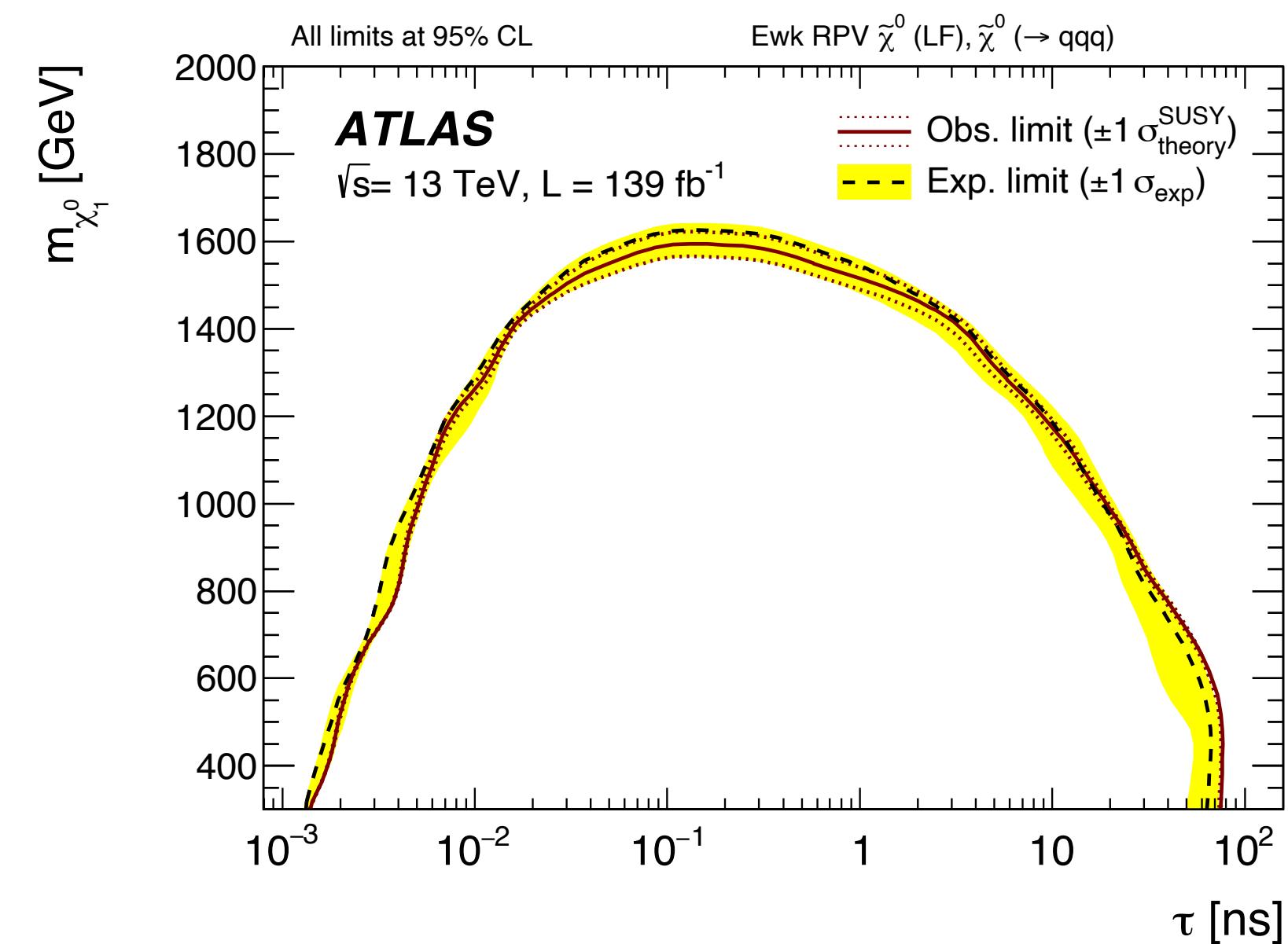
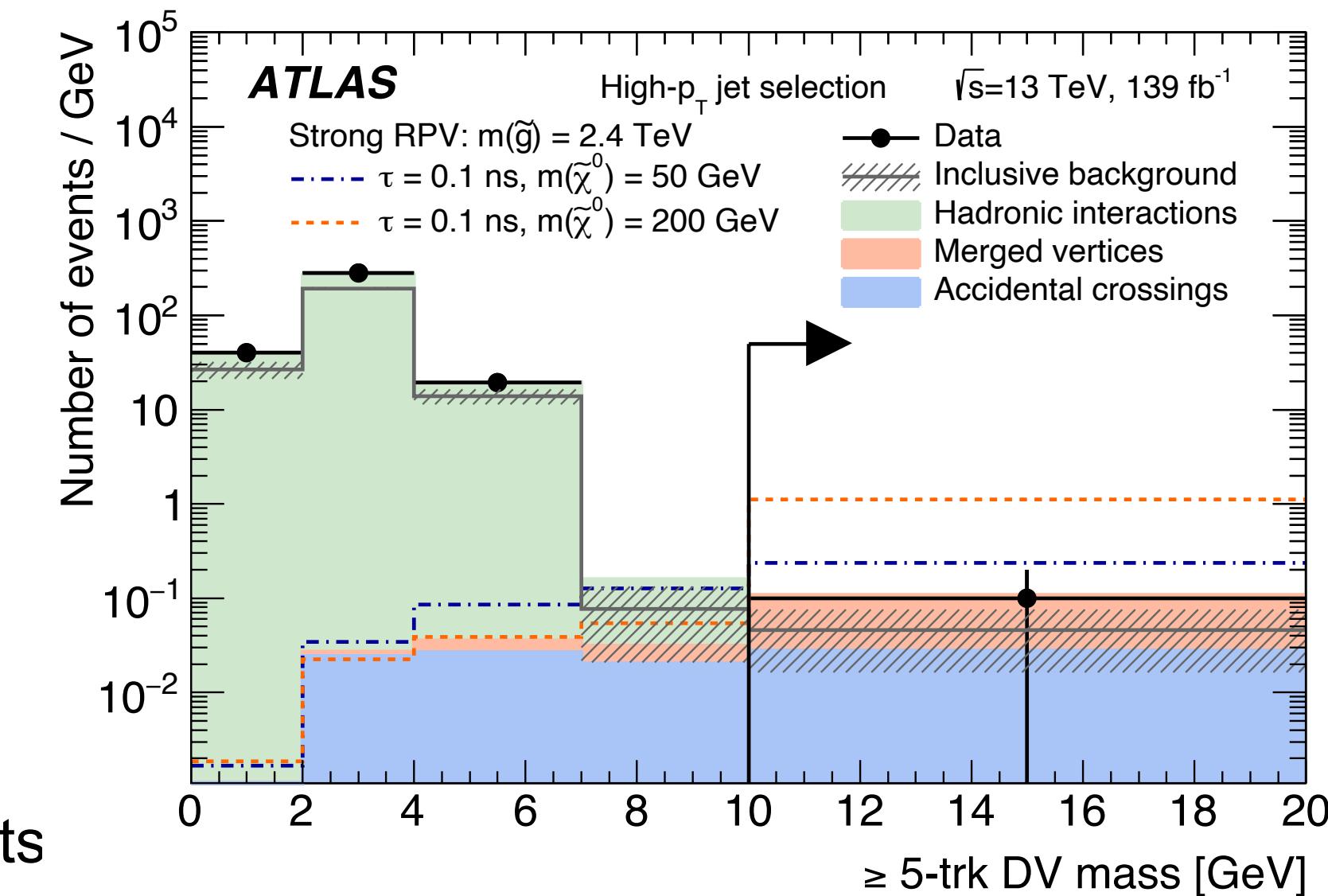
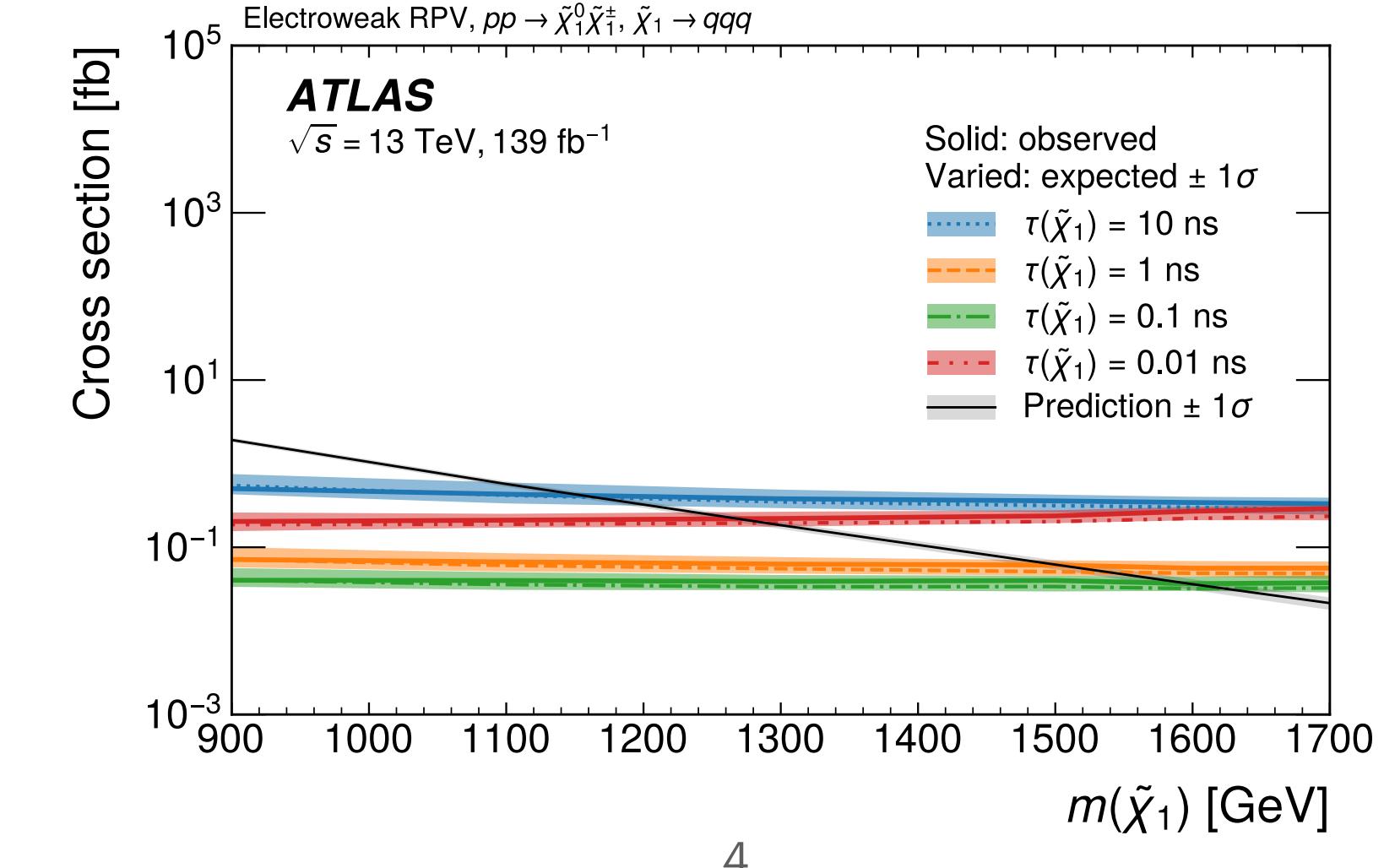


- R-parity violating SUSY, both electroweak and strong scenarios
- $\tilde{\chi}_1^0$  long-lived due to small coupling,  $\lambda''$
- Use multi-jet triggers, multiple high  $p_T$  jets
- Key objects: reconstructed displaced vertices including displaced tracks
- Key selections:
  - Material veto,  $m_{DV} > 10$  GeV, and  $n_{trk} \geq 5$
  - Two signal regions - high  $p_T$  jets and trackless jets
  - To target strong and electroweak scenarios, respectively

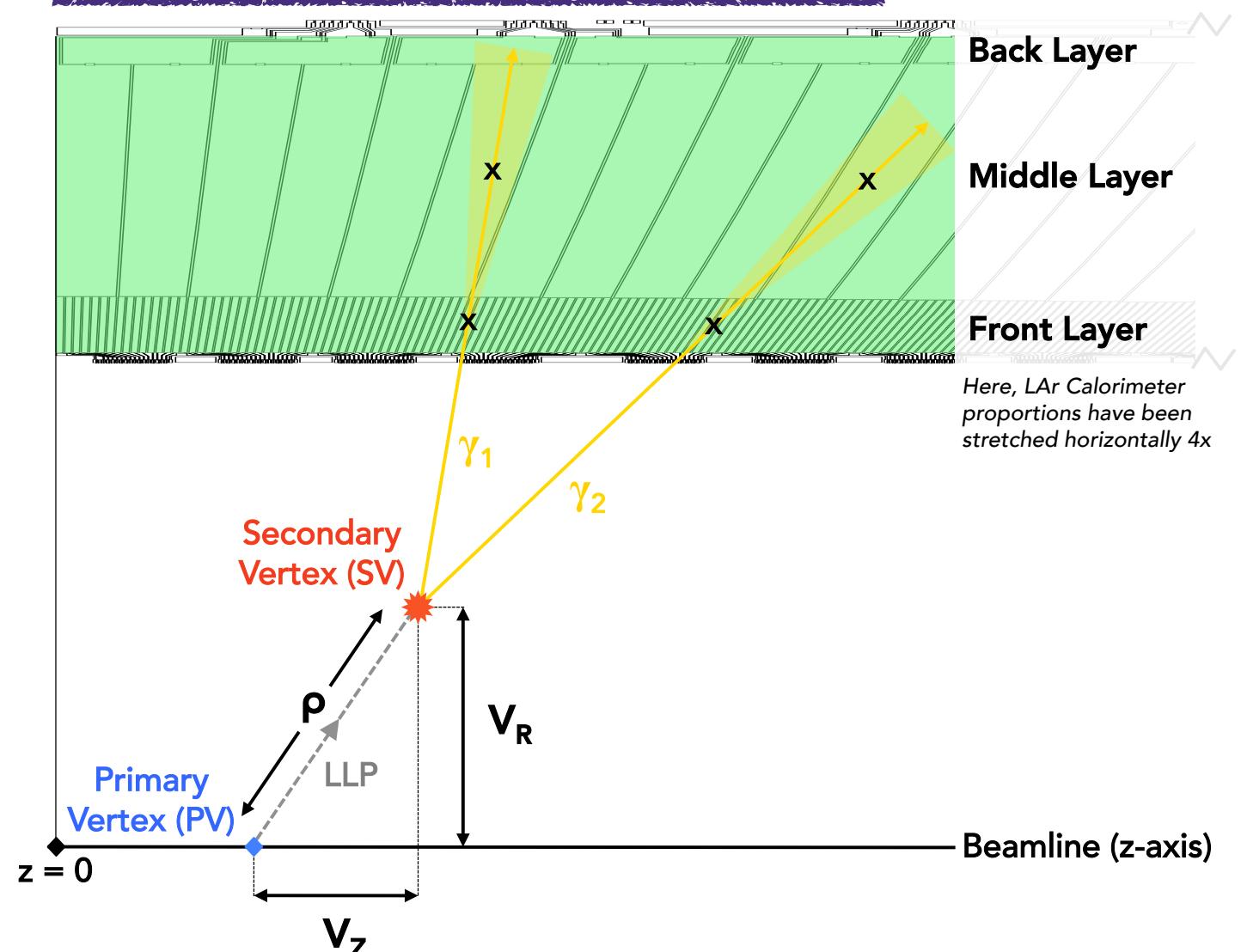


# Displaced hadronic vertices

- Main backgrounds hadronic interactions with detector material, accidental crossings, merged vertices
- Data driven background estimation
  - Probability of finding DVs measured as a function of jet properties - weight assigned to track-jets - estimate  $n_{\text{events}}$  with a DV in the SR
- One event found passing selections - consistent with background estimation
- Exclusion limits set on mass and lifetime for electroweakino and gluino pair production models,  $m(\tilde{\chi}_1^0)$  up to 1.58 TeV for  $\tau = 0.1$  ns

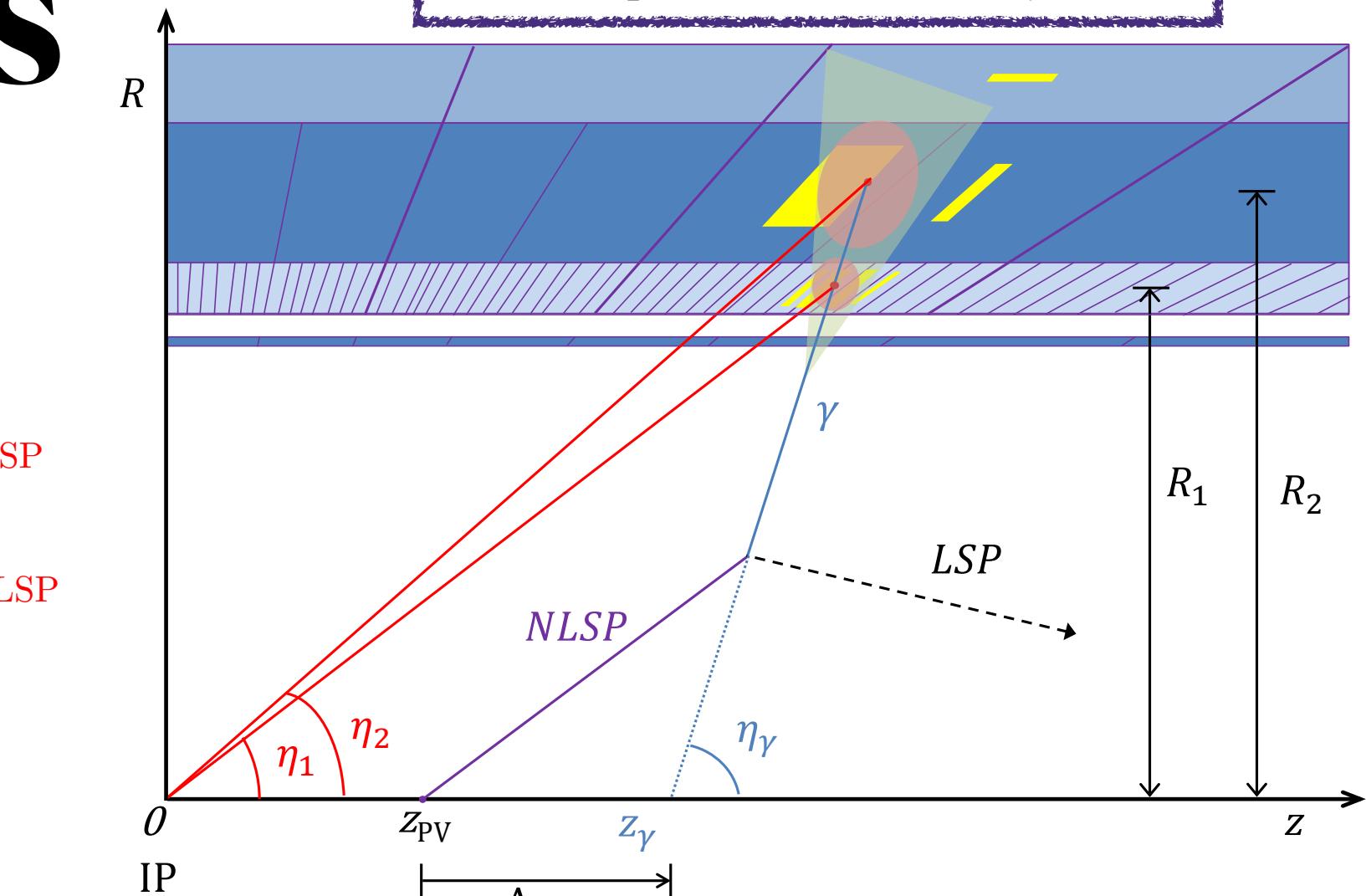
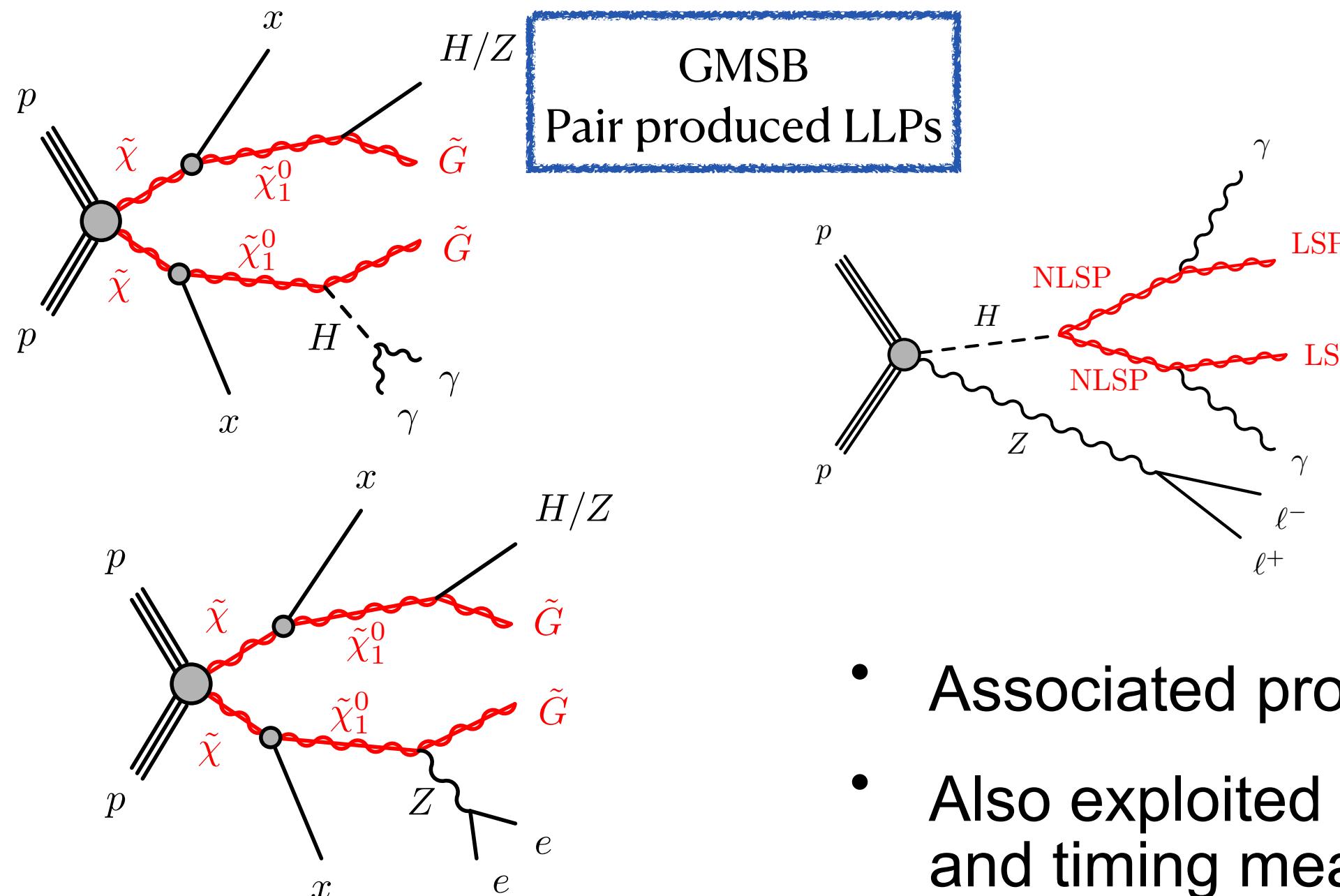


Same decay



# Displaced photons

Separate decays



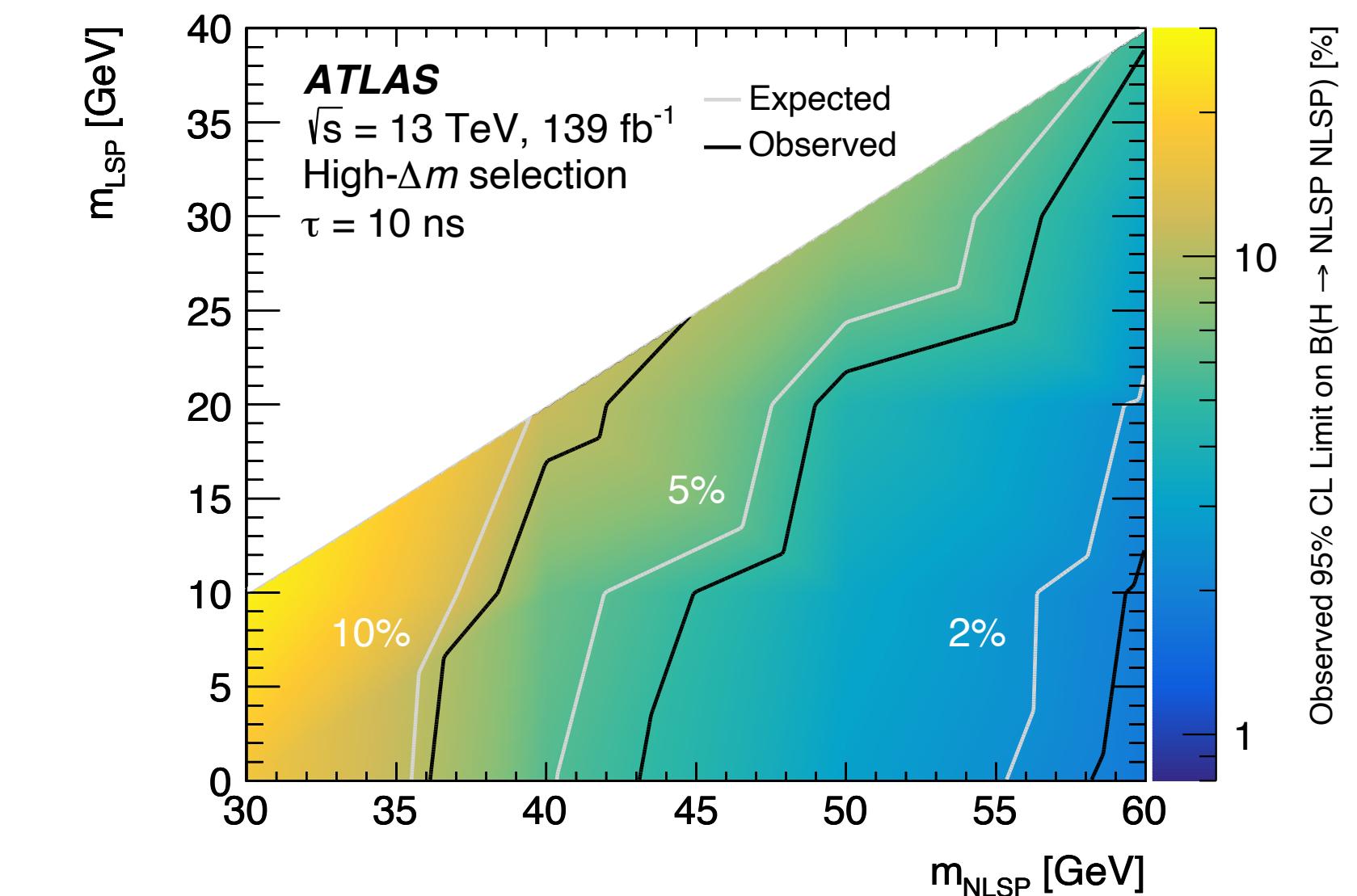
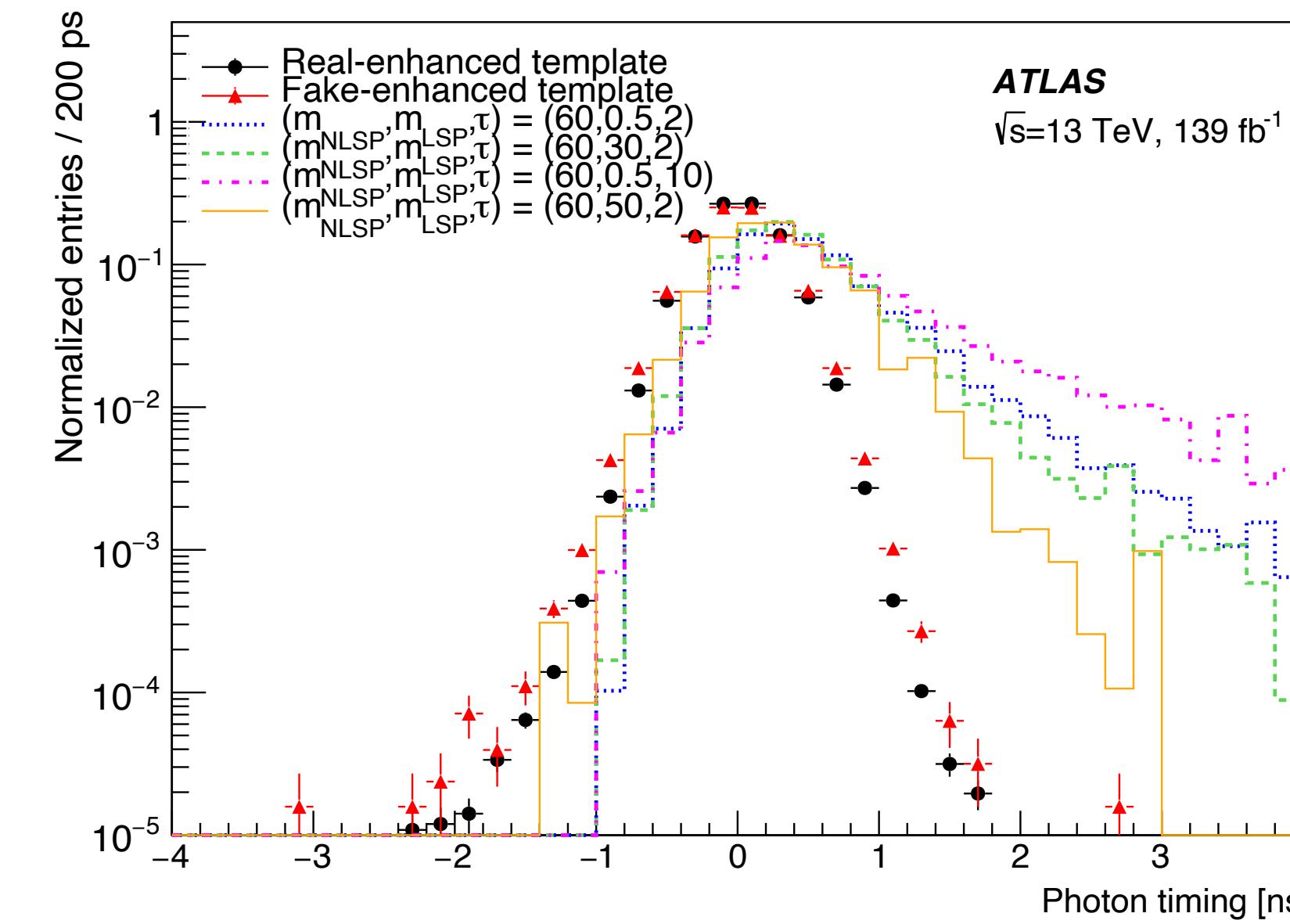
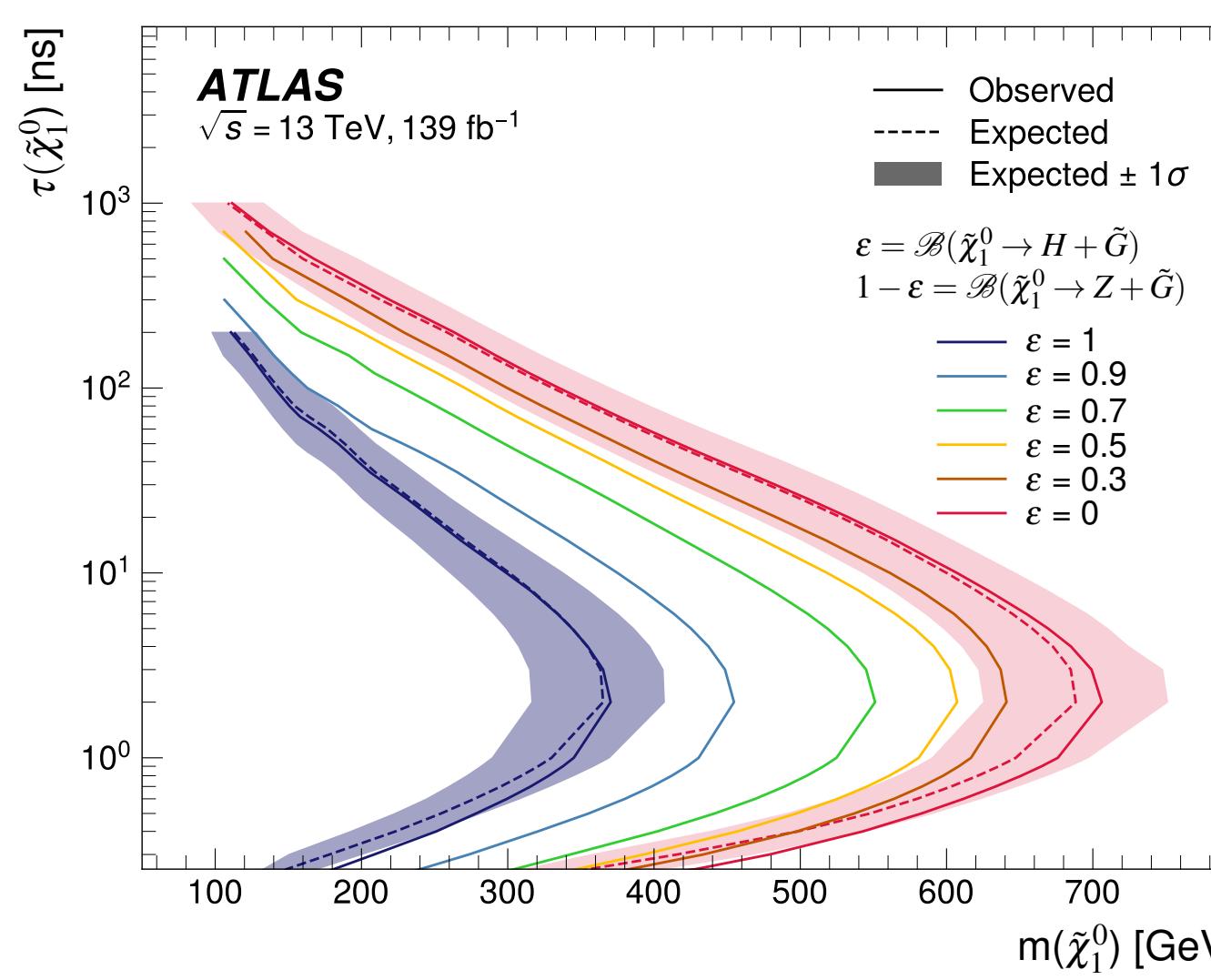
- Di-photon trigger
- Only EM calorimeter info -  $\gamma$  and  $e^-$  final states look equivalent
  - Photon signature sensitive to electrons
  - Trajectory based on shower shape  $\rightarrow$  find vertex origin
    - Resolution down to 10 mm!
  - Key variables: photon timing, trajectory
- SR - high  $E_T^{\text{miss}}$  and at least 2 trigger matched photons

- Associated production - single lepton trigger
- Also exploited EM calorimeter info for precise pointing and timing measurements
  - Identify delayed, non-pointing photons
  - Key variables: photon timing, trajectory
- Two signal regions,  $\approx 1$  and  $\geq 2$  photons
  - Low and high  $\Delta m = m_{\text{NLSP}} - m_{\text{LSP}}$  selections
  - Isolated photons,  $\geq 1$  lepton and high  $E_T^{\text{miss}}$

# Displaced photons

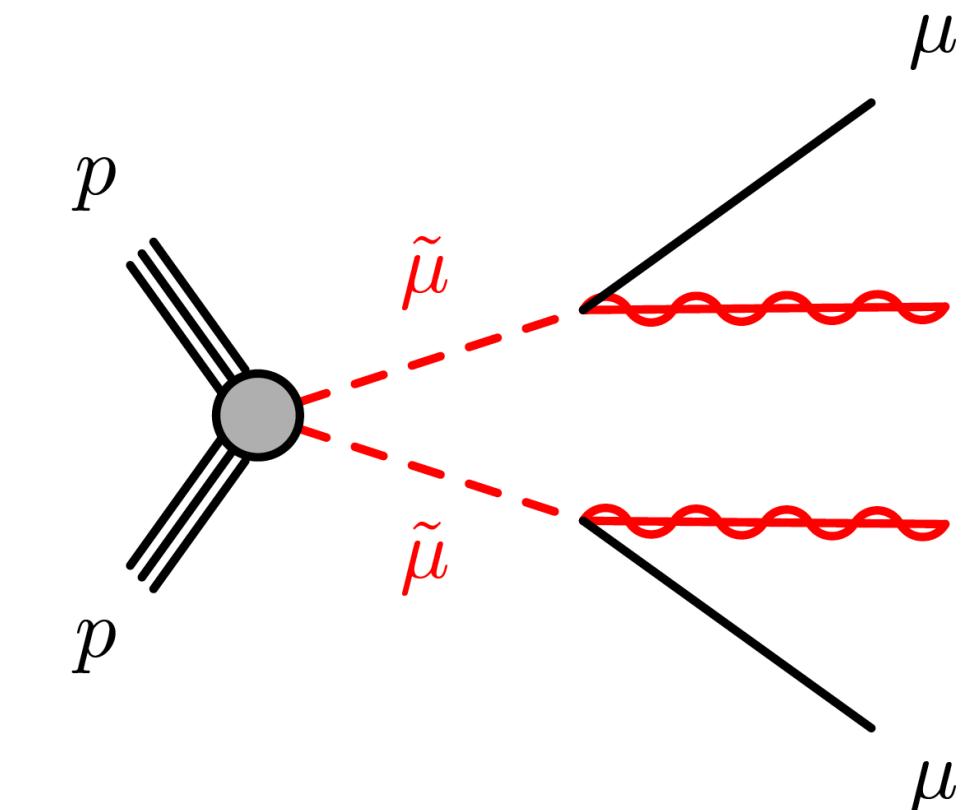
Same decay

- Main backgrounds - mis-reconstructed or fake photons
- Fully data-driven background estimate
  - Templates of photon timing shape from control regions
- Data in agreement with background prediction
  - Limits set on cross-section for di- $\tilde{\chi}_1^0$  production



**NEW!**

- GMSB - pair produced sleptons (NLSP) decay to lepton + gravitino
- Targets prompt - long lived gap in coverage
- Event selection
  - Di-muon trigger - no impact parameter cuts
  - Two oppositely charged muons passing requirements
  - Main SM background from b-hadron decays  $b\bar{b} \rightarrow \mu^-\mu^+$
  - Extended ABCD  $\rightarrow |d_0|$  of (+) $\mu$  vs (-) $\mu$ , split by invariant mass into 3 overlapping regions



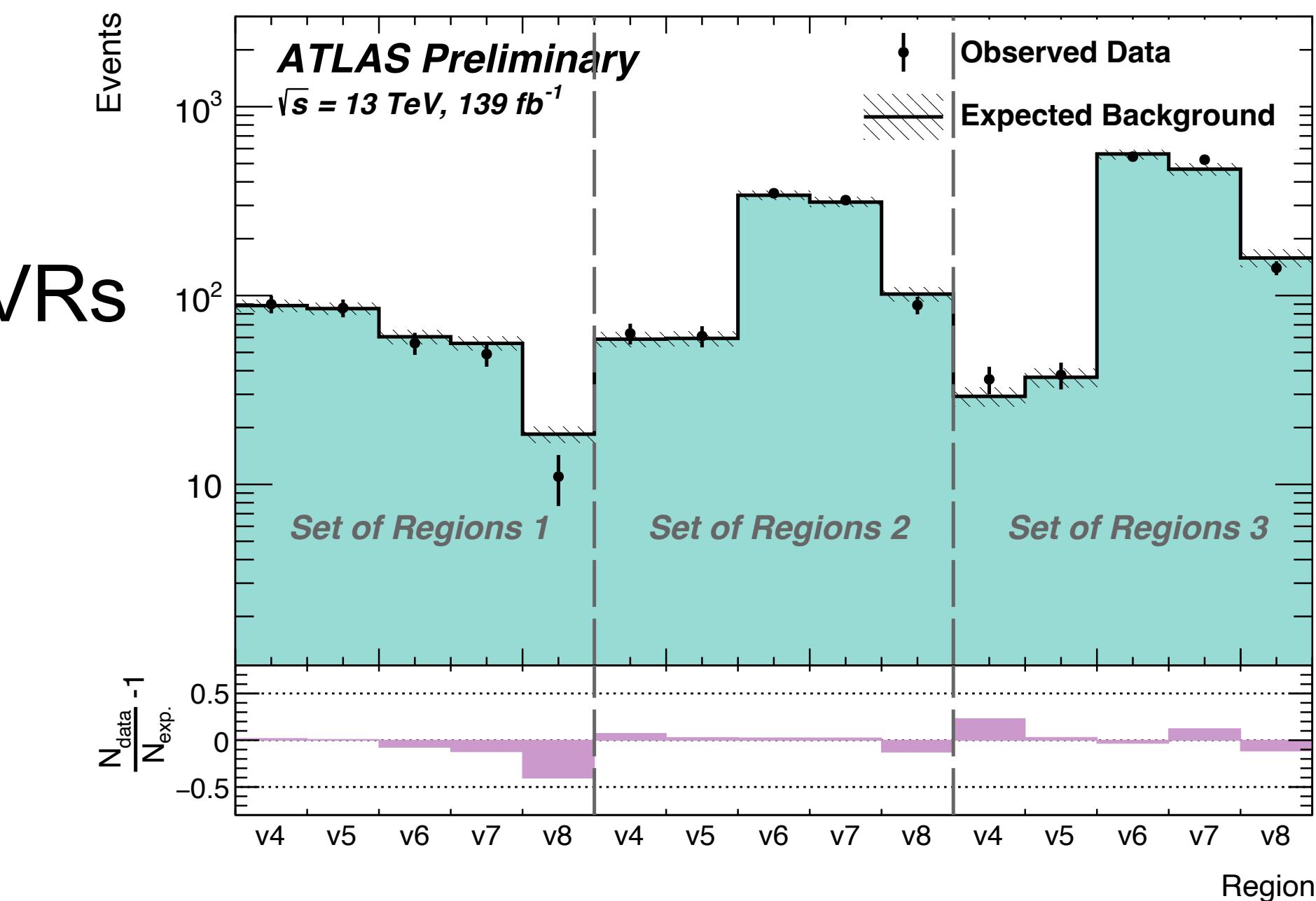
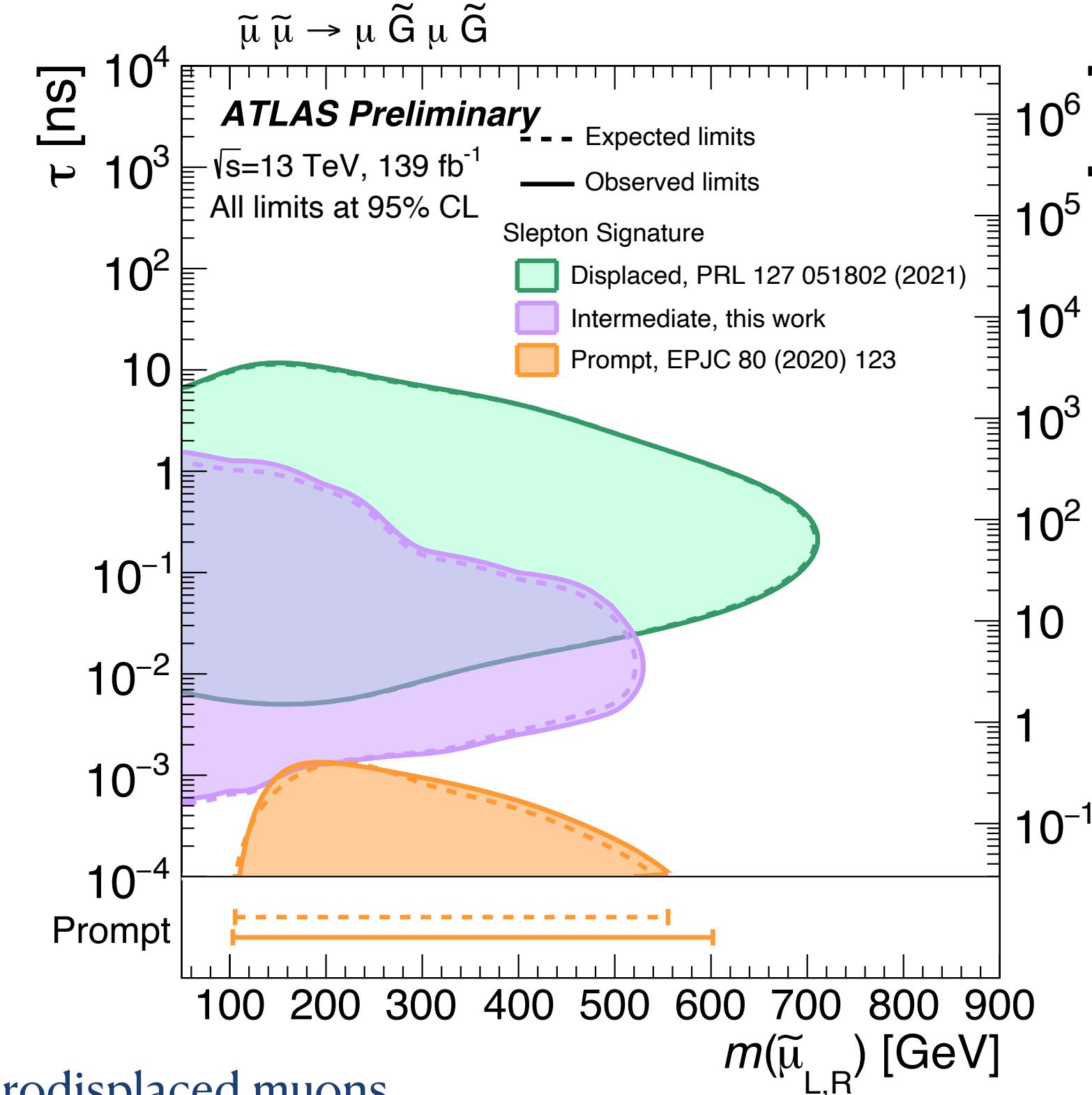
Muon Requirements
Trigger matched
$ l  < 2.5$
Quality cuts + isolation
$d_0 > 0.1 \text{ mm}$
No cut on $z_0$
$m_{\mu\mu} > 110 \text{ GeV}$

Set of Regions	Lower displacement region	Higher displacement region	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	$0.1 \leq  d_0  < 0.3$	$0.6 \leq  d_0  < 3 \text{ mm}$	200 GeV	-
2	$0.1 \leq  d_0  < 0.3$	$0.6 \leq  d_0  < 3 \text{ mm}$	140 GeV	-
3	$0.1 \leq  d_0  < 0.3$	$0.6 \leq  d_0  < 1.3 \text{ mm}$	125 GeV	$\Delta R_{\mu^+\mu^-} > 3 \text{ rad.}$

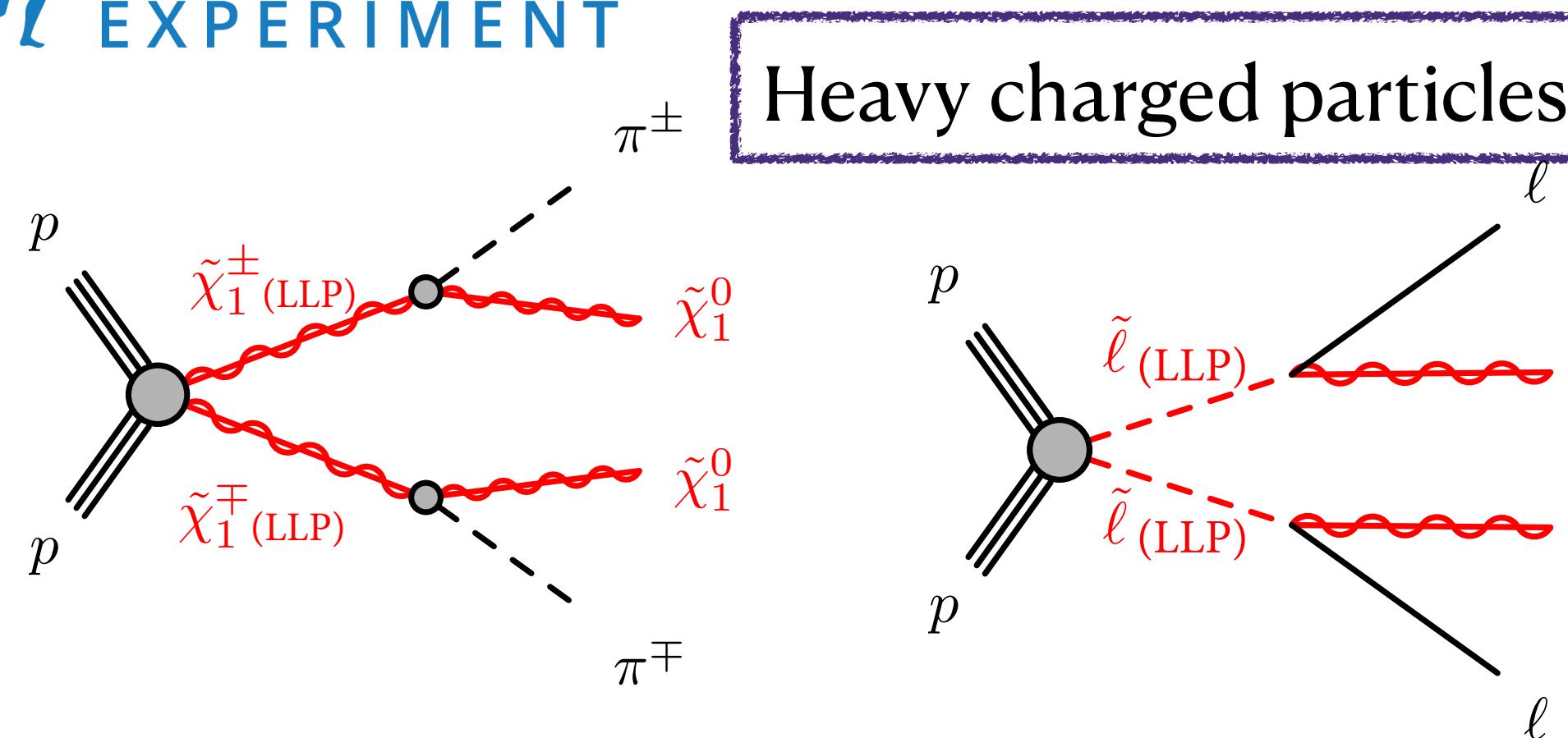
**NEW!**

# Microdisplaced muons

- The background estimate was validated in 5 different VRs for each set of regions
- No excess observed beyond predicted backgrounds
- Region 1 provides best sensitivity, used for fit



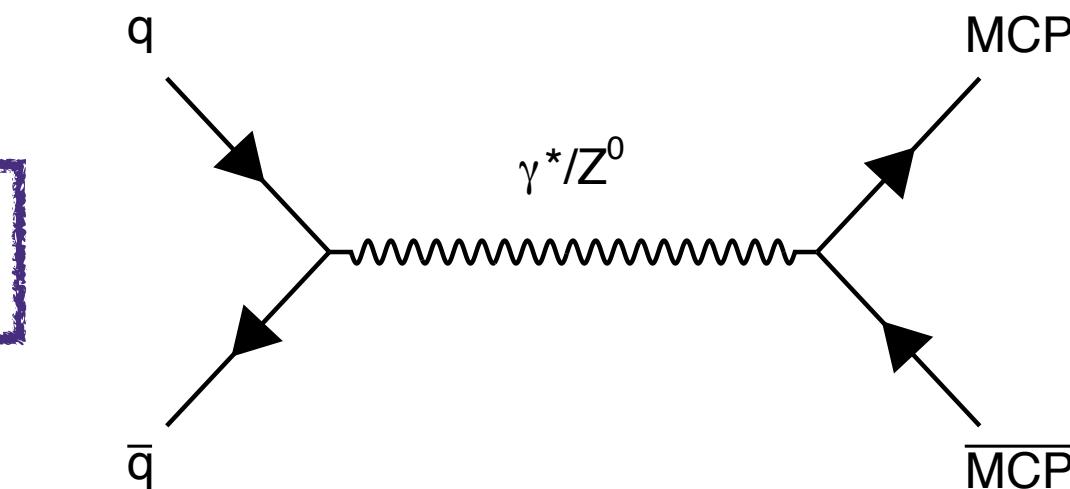
- smuon lifetime down to 1 ps and mass up to 520 GeV excluded at 95% confidence interval
- Model independent - no requirements on  $E_T^{\text{miss}}$ , vertices, jets



- Heavy, long-lived singly charged particles
- Long-lived charged SUSY particles - high ionization
- Use  $E_T^{\text{miss}}$  triggers and additional cut offline
- Isolated, central tracks with high  $p_T$  and large  $dE/dx$
- Key variables:
  - Truncated  $dE/dx$  in the pixel, mass calculated as  $p/\beta\gamma$

# High $dE/dx$

## Multicharge particles



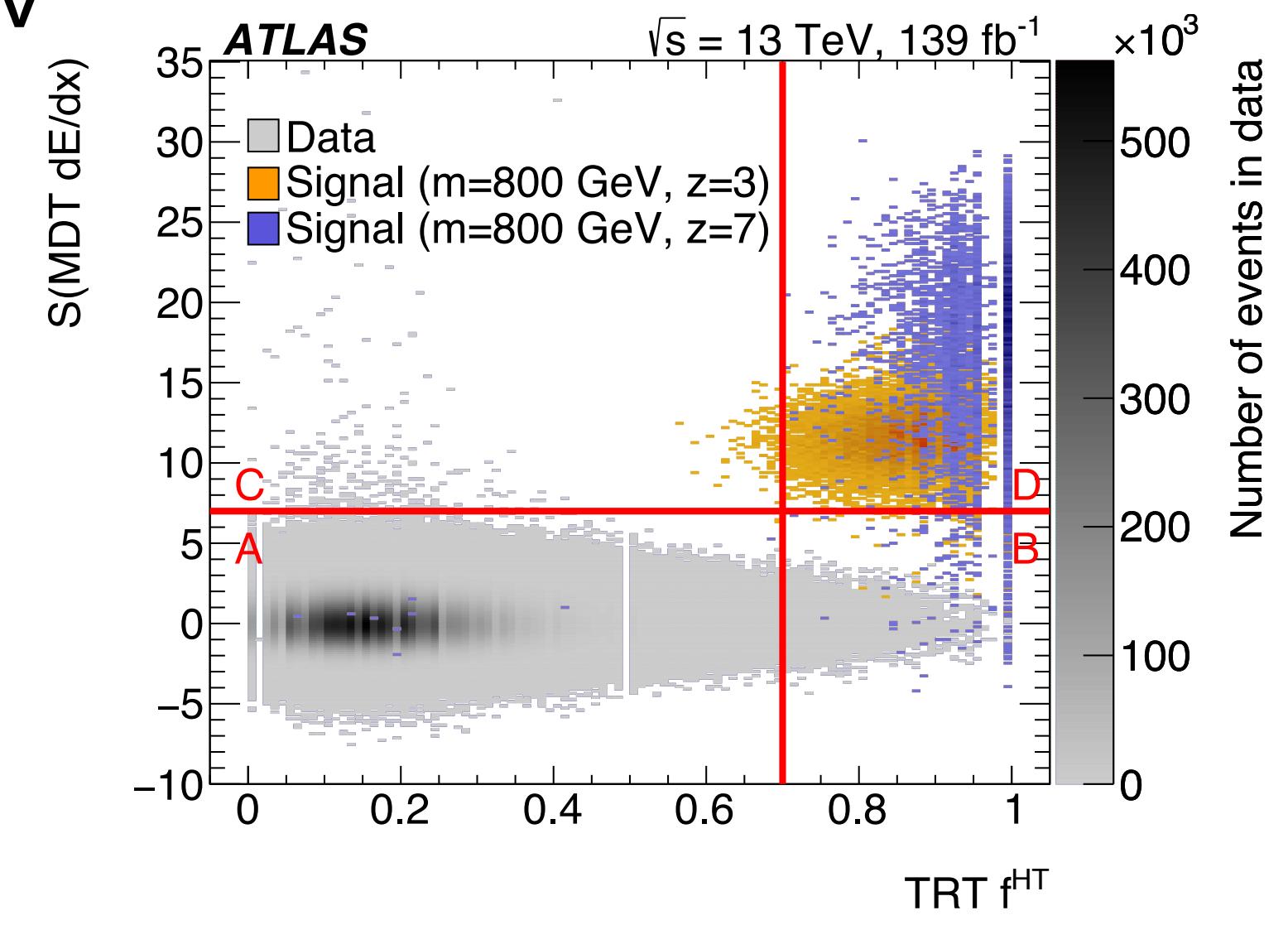
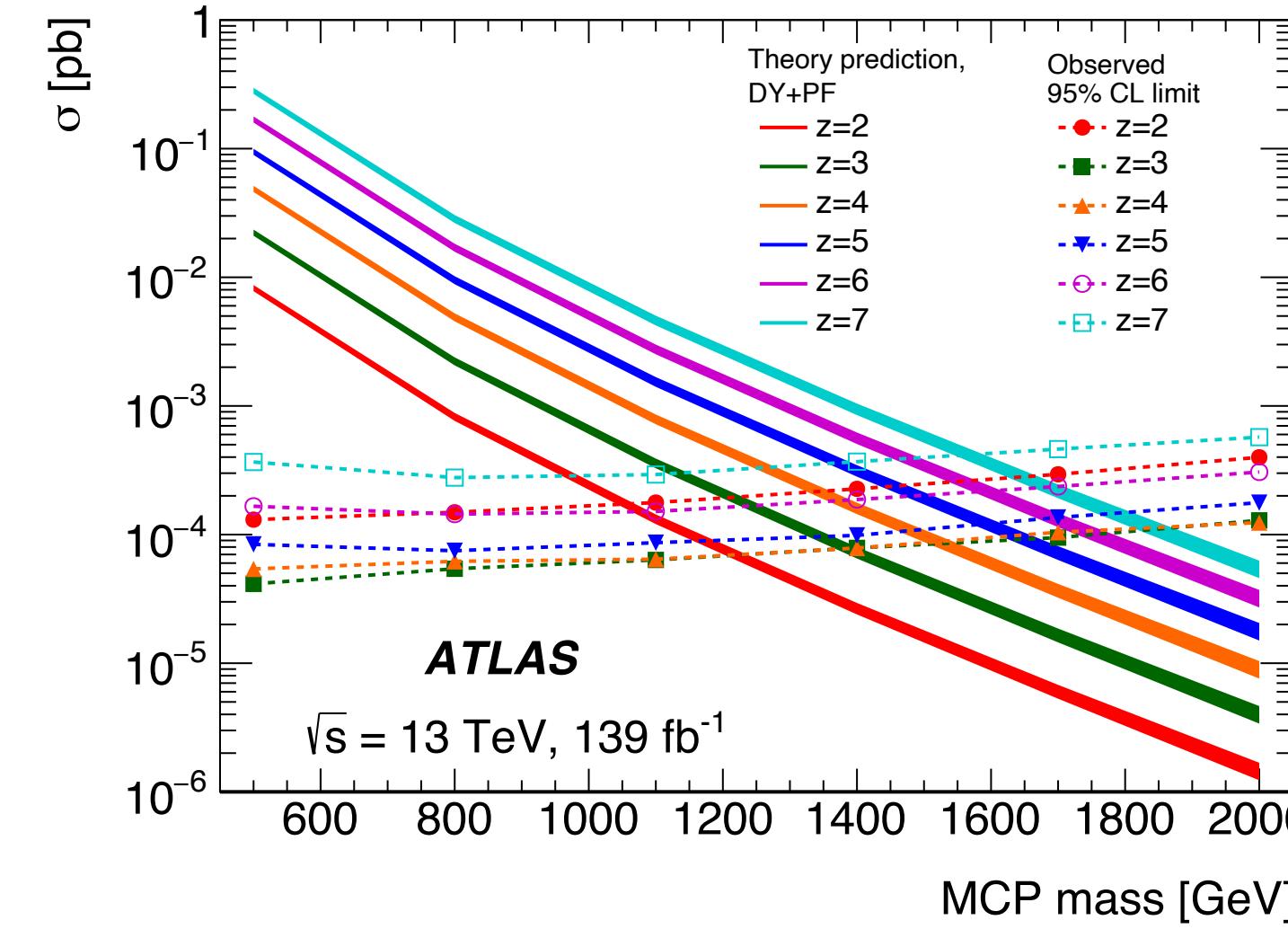
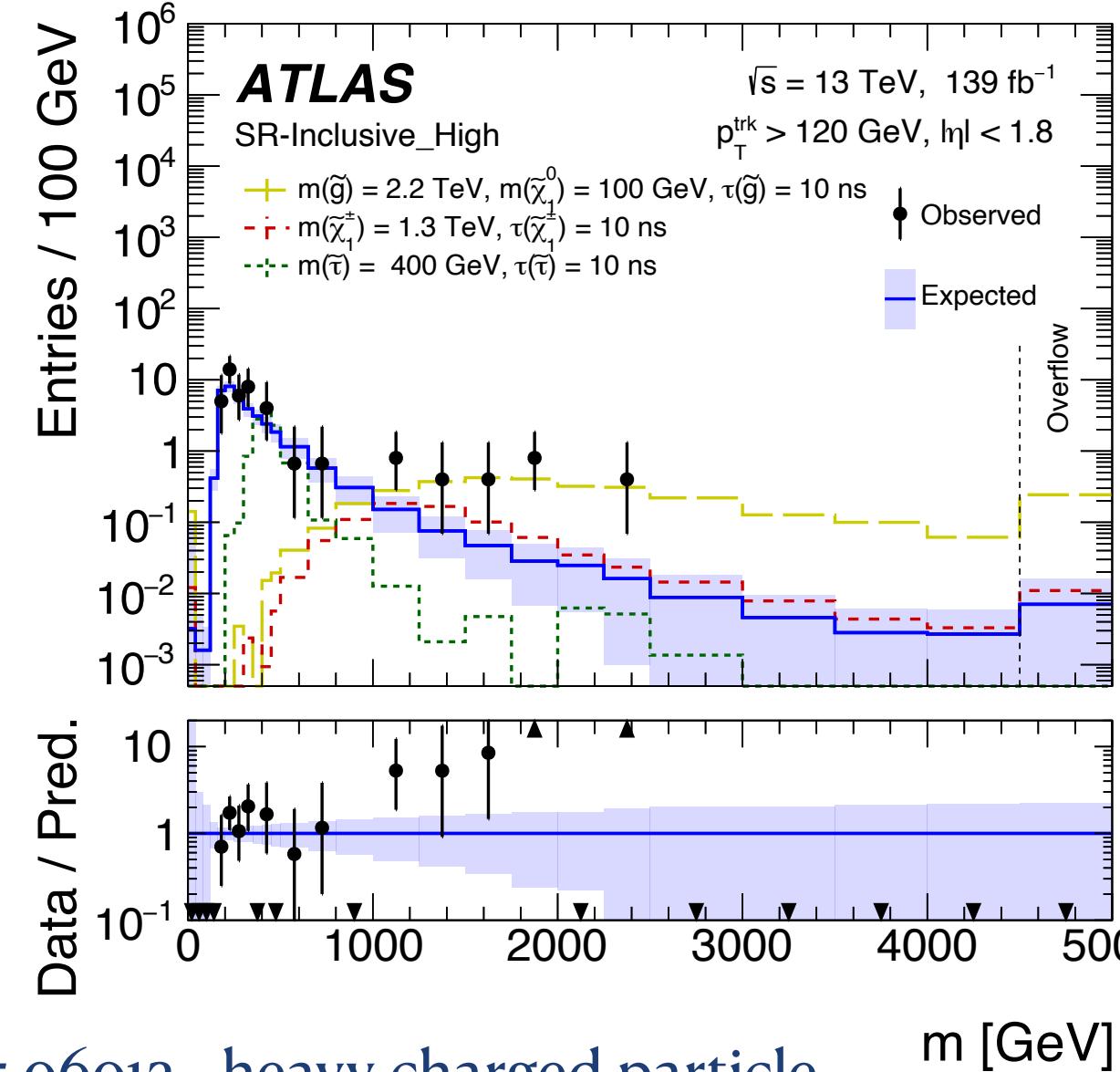
- Particles with charge  $|q| = z^*e$ ,  $2 \leq z \leq 7$
- Many theories predict multi-charge particles
  - AC-leptons, technibaryons, Goldstone bosons...
- Long lived  $\rightarrow$  muon like signature
- Single  $\mu$ ,  $E_T^{\text{miss}}$ , and late- $\mu$  triggers
  - High  $dE/dx \rightarrow$  slower particles  $\rightarrow$  do not always fire single muon triggers
- One track within TRT,  $p_T^\mu/z > 50 \text{ GeV}$
- Key variables
  - $S(\text{pix } dE/dx)$ ,  $S(\text{TRT } dE/dx)$ ,  $S(\text{MDT } dE/dx)$ ,  $\text{TRT } f^{\text{HT}}$

**Heavy charged particles**

# High $dE/dx$

**Multicharge particles**

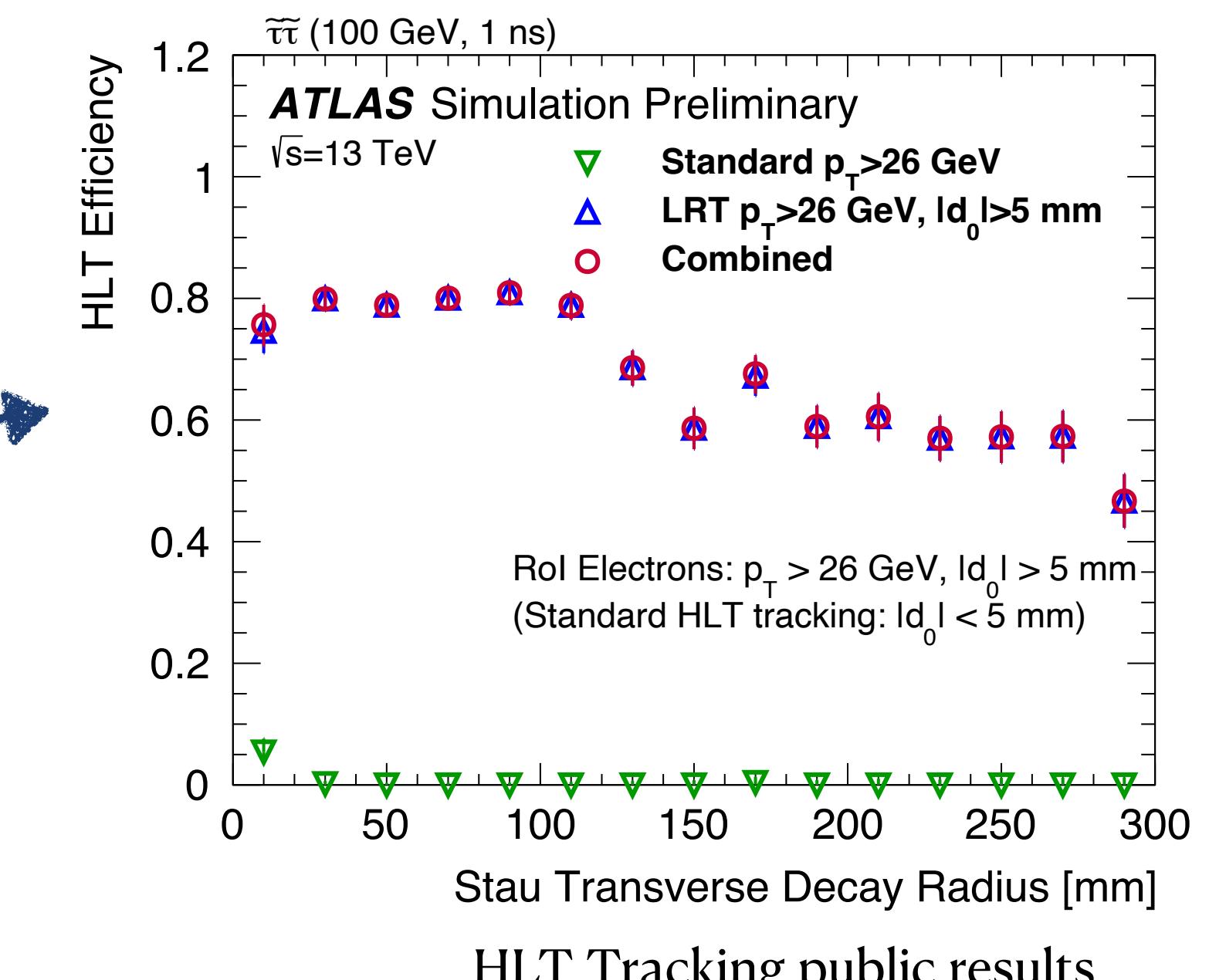
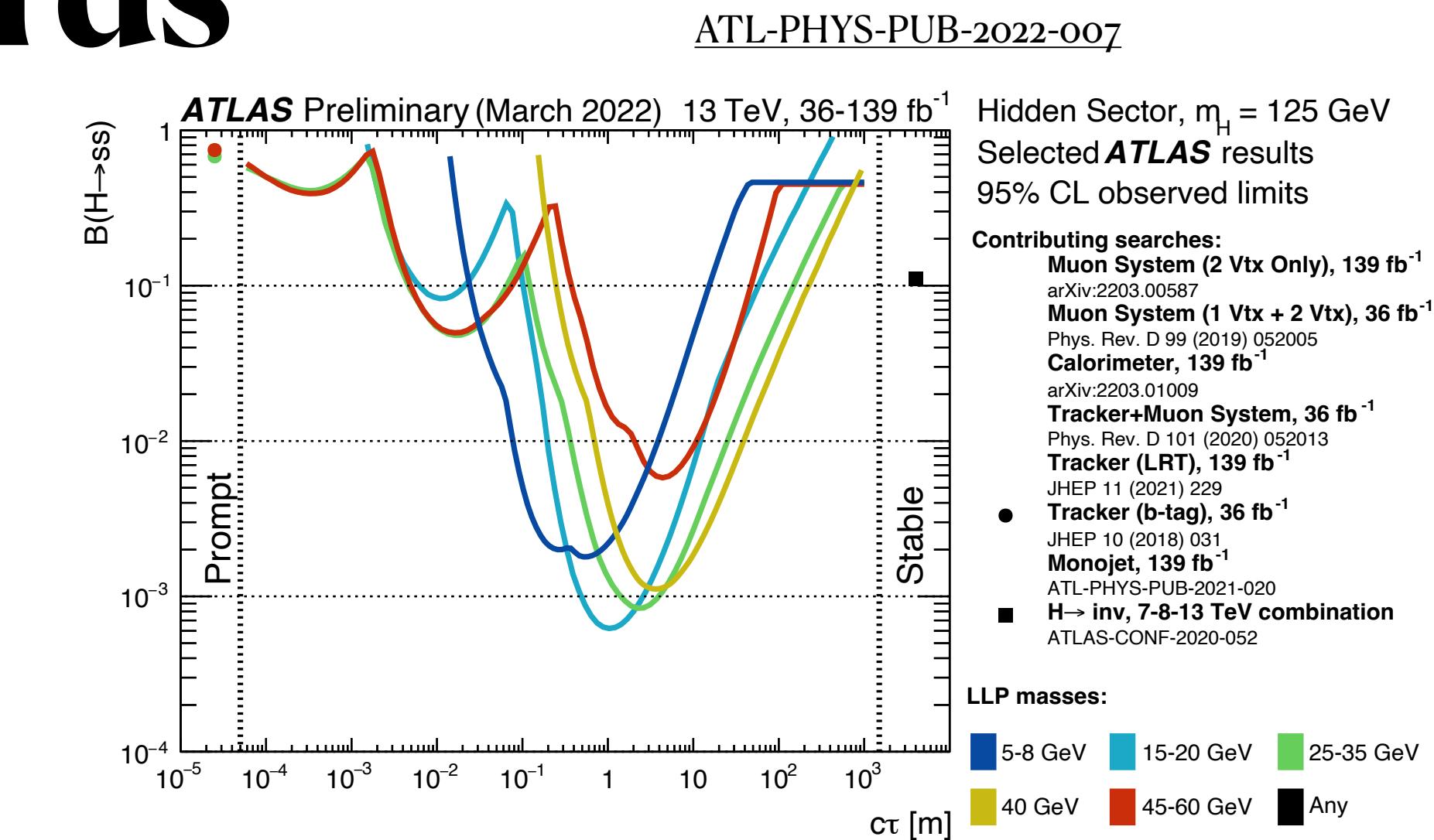
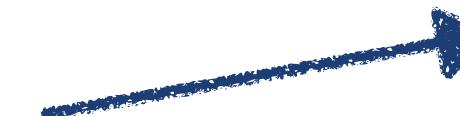
- Main background: high  $p_T$ , isolated tracks with high  $dE/dx$
- Slight excess observed, not consistent with slow particles
- Local (global) significance  $3.6\sigma$  ( $3.3\sigma$ )
- 7 events seen - all checked by multicharge particle search - none pass full signal selections





# Run 3 and onwards

- Very exciting LLP search program at ATLAS right now
- ATLAS began collecting run 3 data last summer
- Already 36  $\text{fb}^{-1}$  of 13.6 TeV data collected
- Second year of data taking will begin soon
- New and improved large-radius tracking algorithm implemented
- New long-lived particle targeting triggers included
- Looking forward to new results run 3 will bring



# In summary

Search	Final state	arXiv	Paper public
<b>Displaced hadronic vertices</b>	DV + jets	<a href="#">arXiv: 2301.13866</a>	1 Feb 2023
<b>Displaced photonic vertex</b>	Di- $\gamma$ or di-e- DV + MET	<a href="#">arXiv: 2304.12885</a>	25 April 2023
<b>Displaced photons</b>	1, $\geq 2$ displaced $\gamma$ + leptons + MET	<a href="#">arXiv: 2209.01029</a>	2 Sept 2022
<b>Displaced muons</b>	2 displaced muons	<a href="#">arXiv: 2305.02005</a>	3 May 2023
<b>Heavy charged particles</b>	Track with large dE/dx	<a href="#">arXiv: 2205.06013</a>	12 May 2022
<b>Multicharge particles</b>	Track with large dE/dx	<a href="#">arXiv: 2303.13613</a>	23 March 2023

- Thanks for listening!
- Any questions?

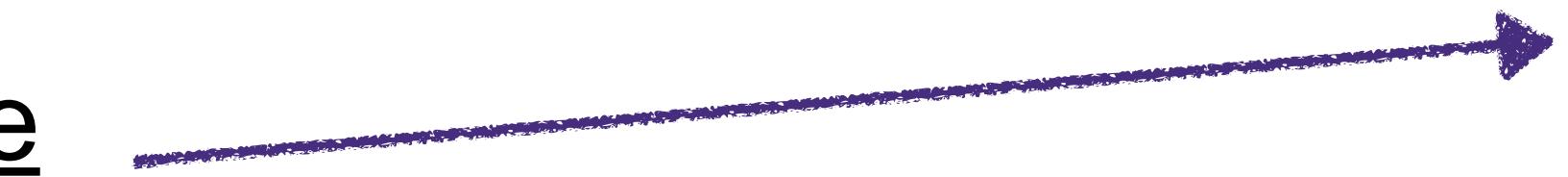
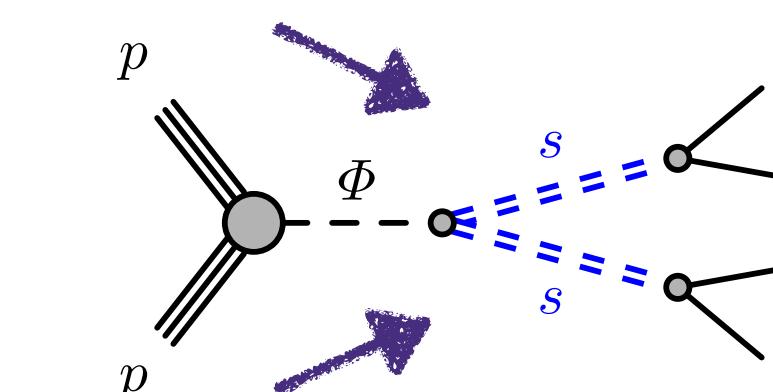
# Backup



# Other recent searches

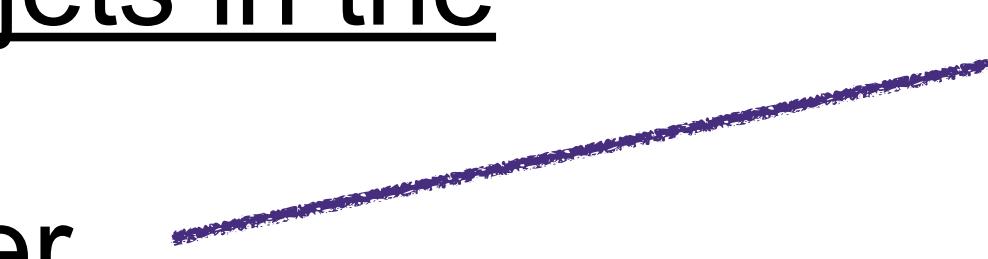
- Displaced hadronic vertices in the

Muon Spectrometer



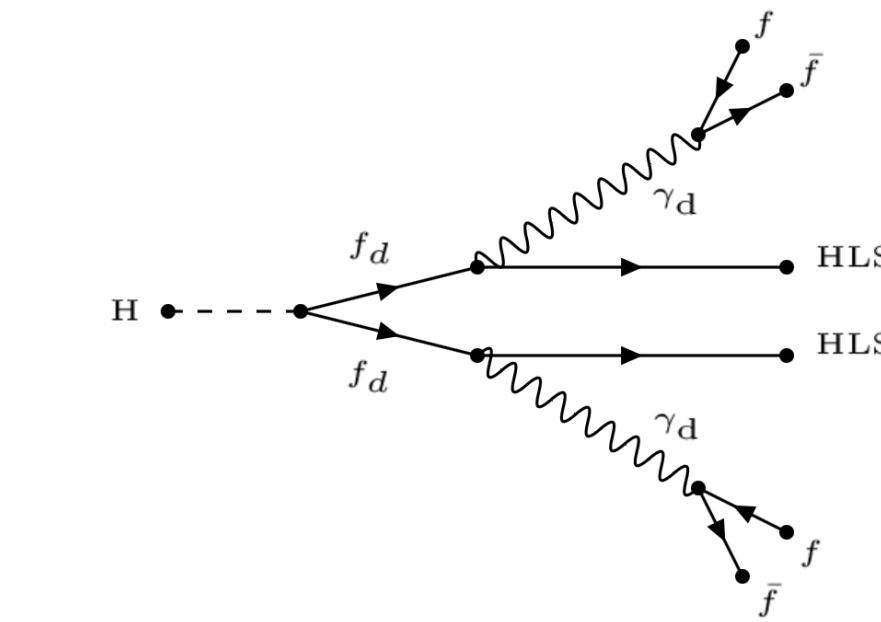
- Displaced hadronic jets in the

Hadronic Calorimeter

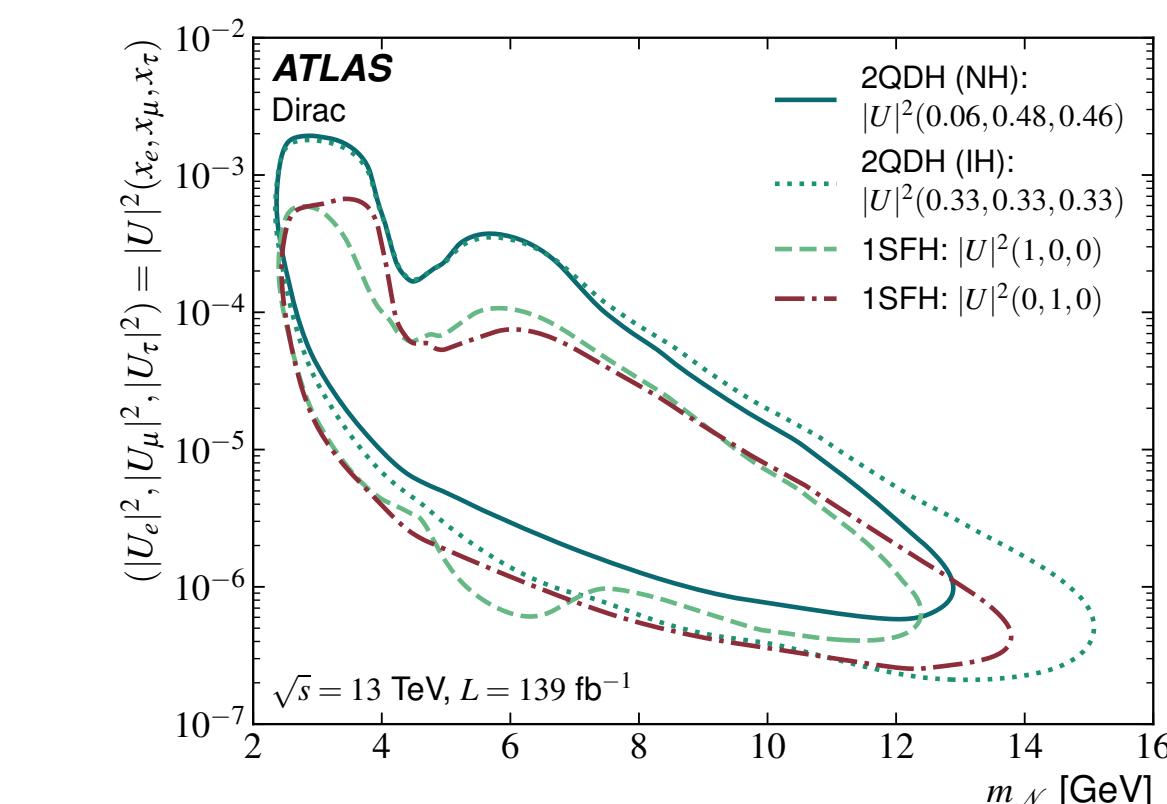
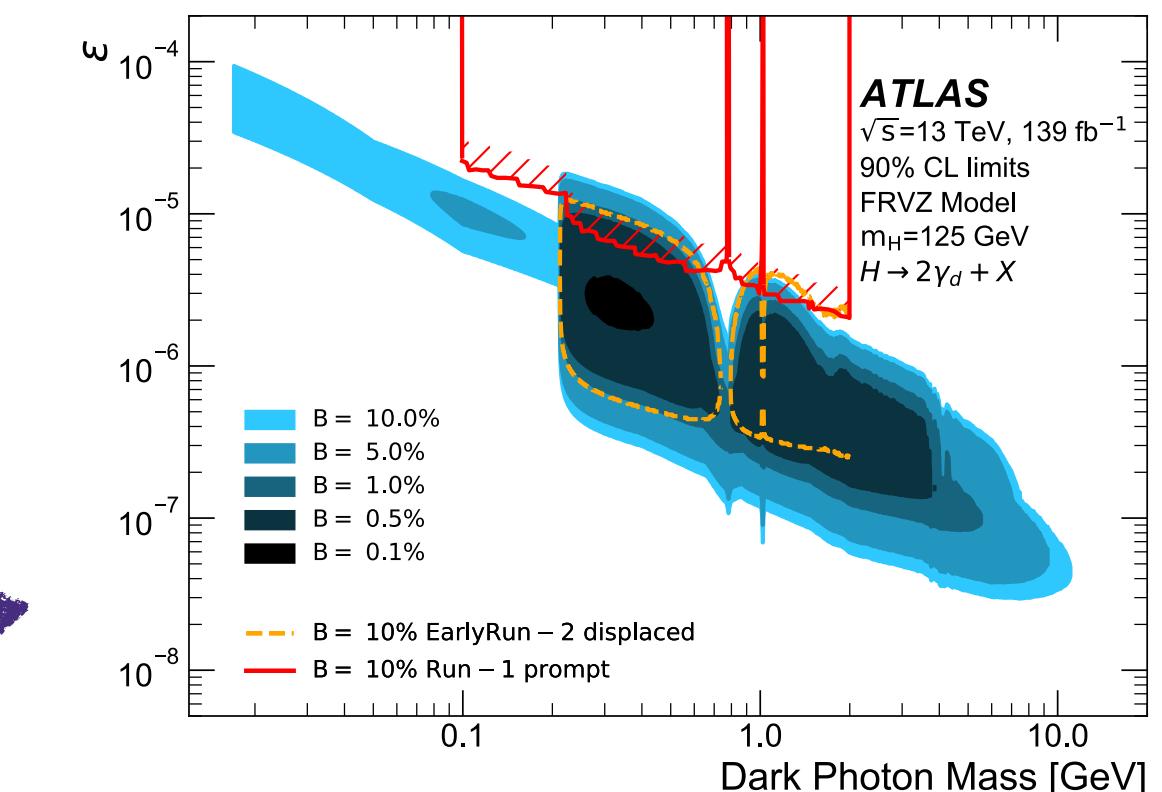
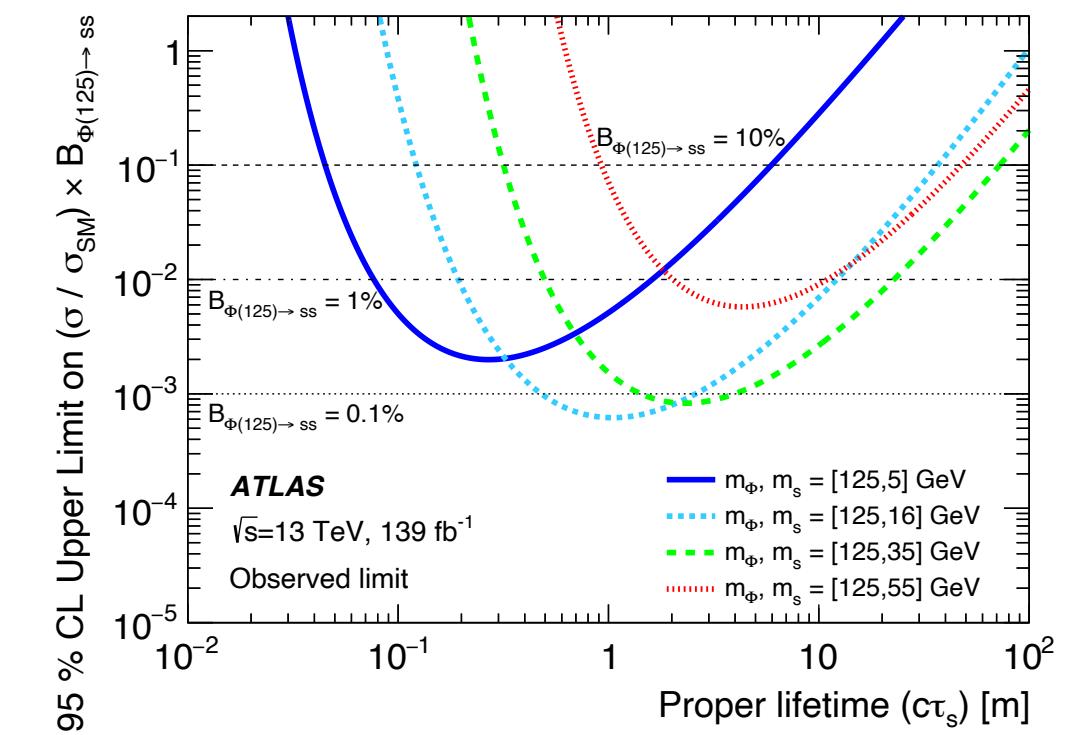
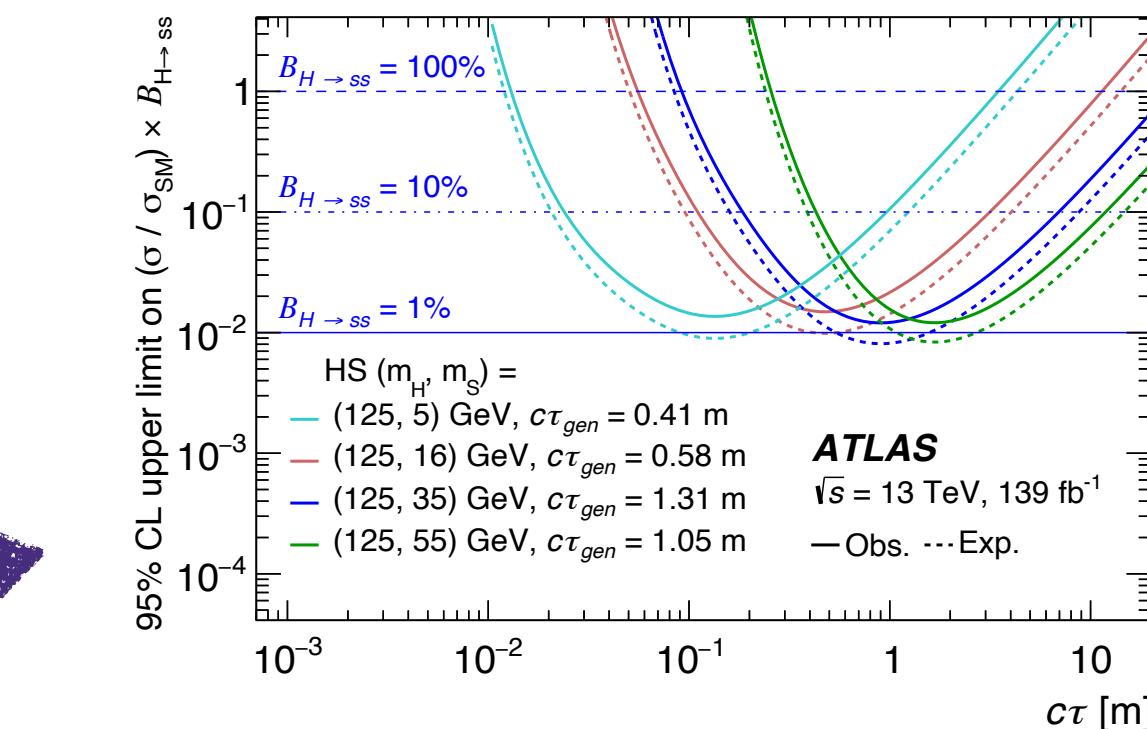
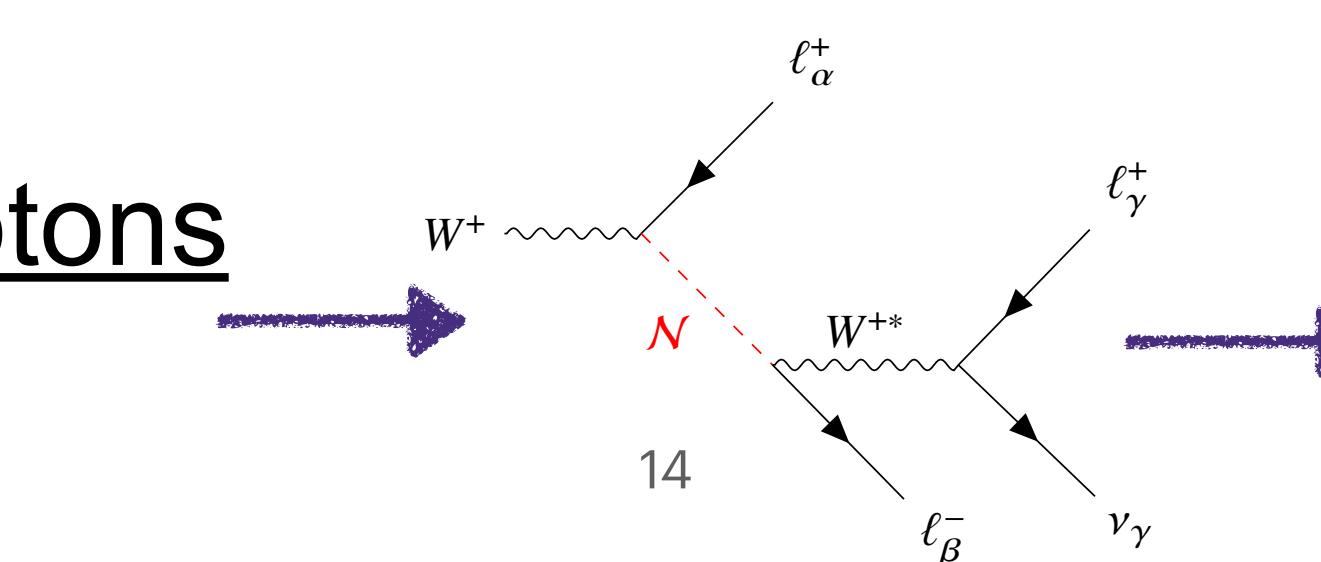


- Displaced lepton jets in ggF and

VH production modes

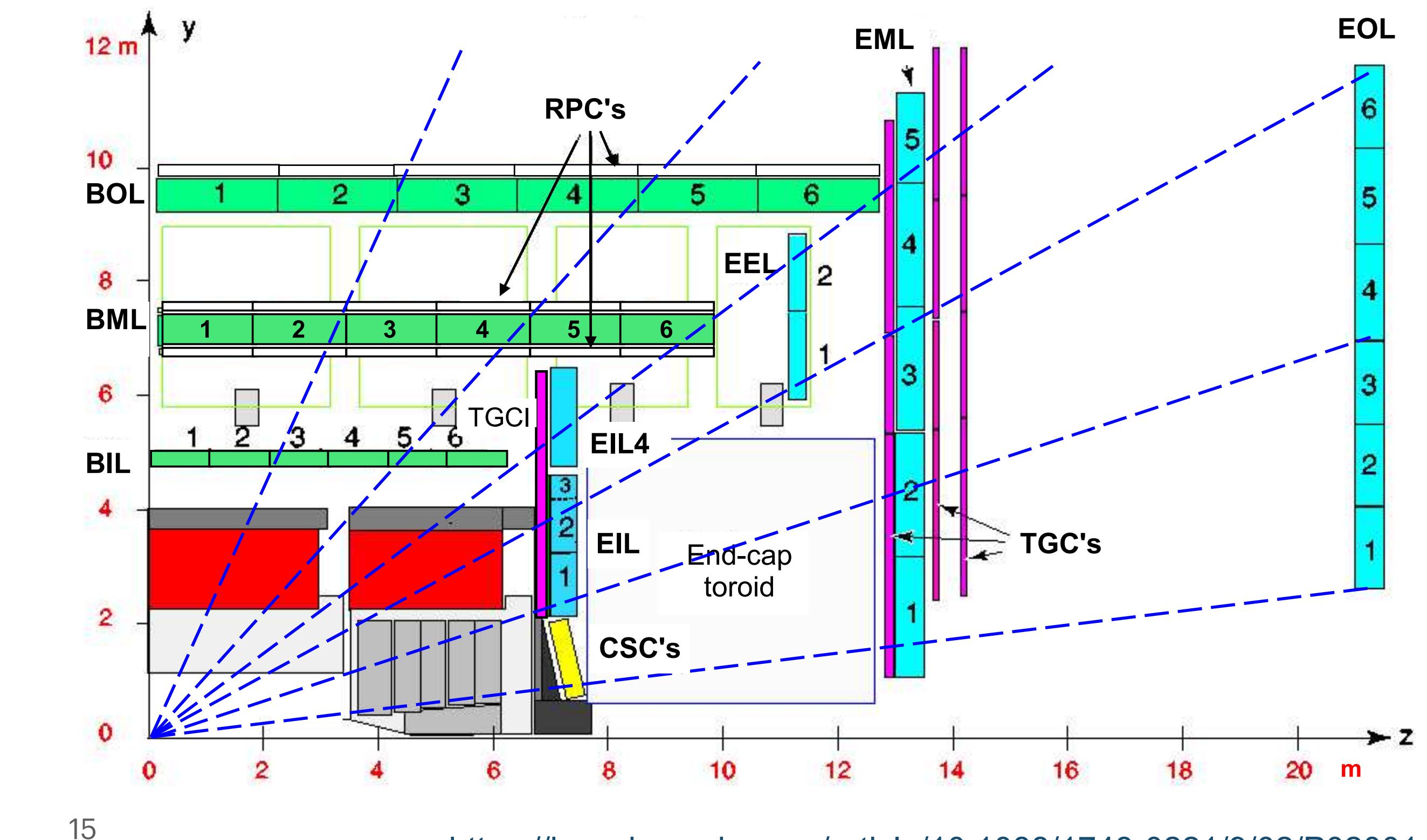


- Displaced Heavy Neutral Leptons



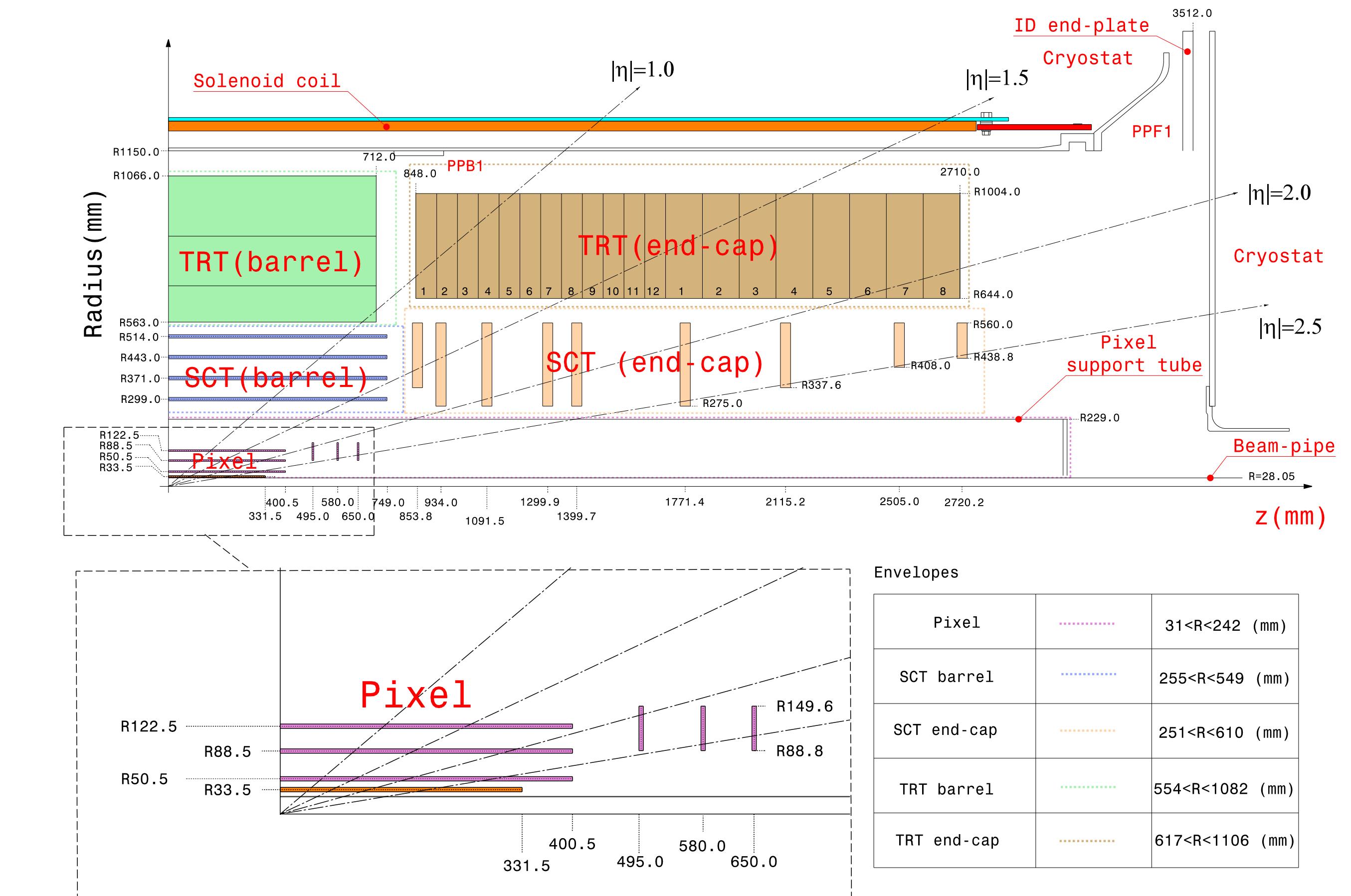
# The muon spectrometer (detail)

- Precision tracking ( $|\eta| < 2.7$ ) and triggering ( $|\eta| < 2.4$ )
- MDT
  - Precision tracking in the barrel and endcaps
  - 2 multilayers (MLs) of tubes per chamber
  - Limited  $\phi$  precision
- CSC
  - Precision tracking
  - Forward region
- RPC
  - Barrel, triggering and  $\phi$  measurement
- TGC
  - Endcap, triggering and  $\phi$  measurement



# The inner detector (detail)

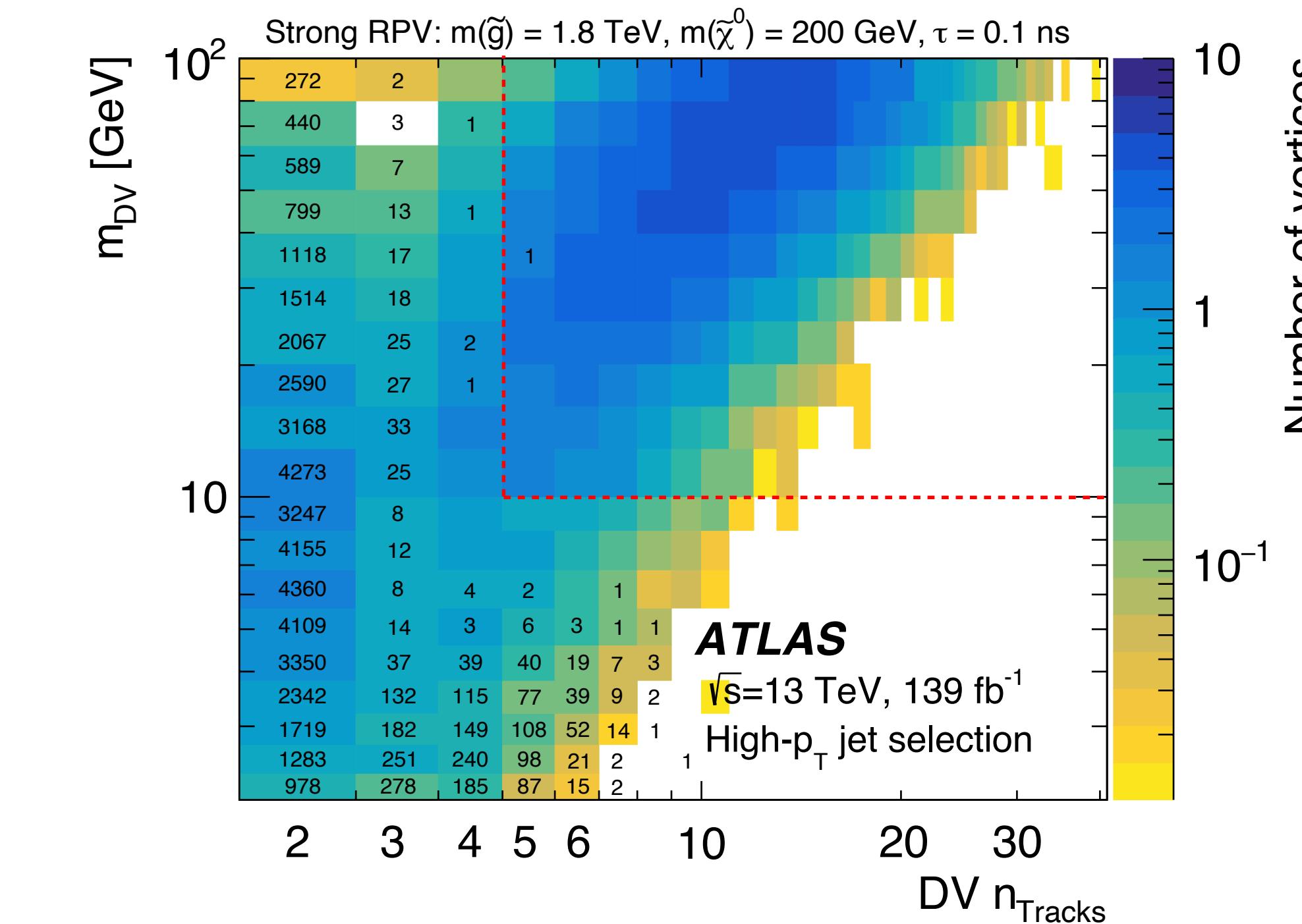
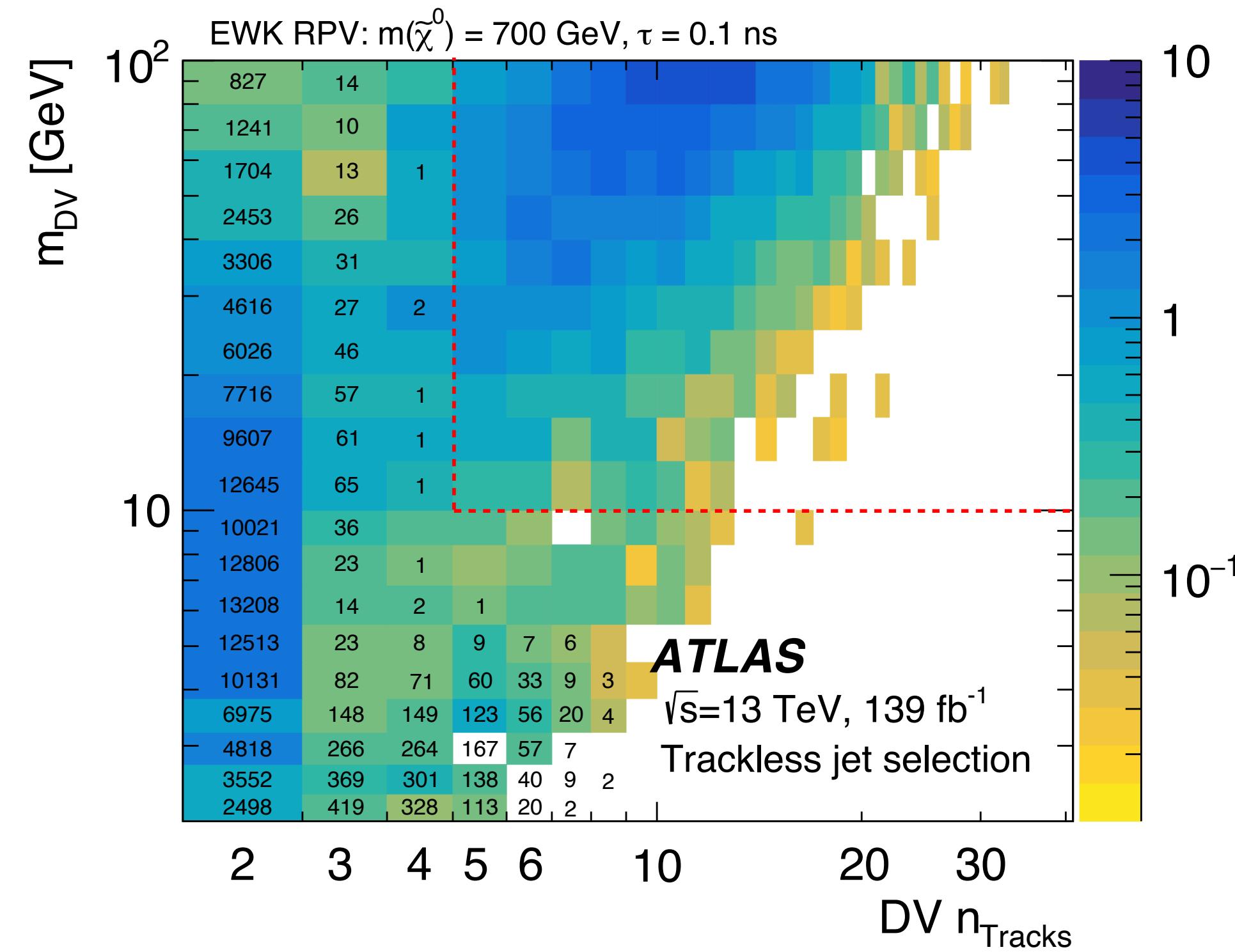
- Tracking of charged particles within  $R < \sim 1$  m,  $|z| < \sim 3$  m,  $|\eta| < 2.5$
- Pixel, SCT,  $|\eta| < 2.5$ 
  - Silicon detectors
  - Precision tracking
  - 3-D points (pixel) and space points (SCT)
- TRT,  $|\eta| < 2.0$ 
  - Straw tubes
  - 2-D points
  - Electron ID
  - Add points to tracks seeded in the Silicon



<https://iopscience.iop.org/article/10.1088/1748-0221/12/12/P12009>

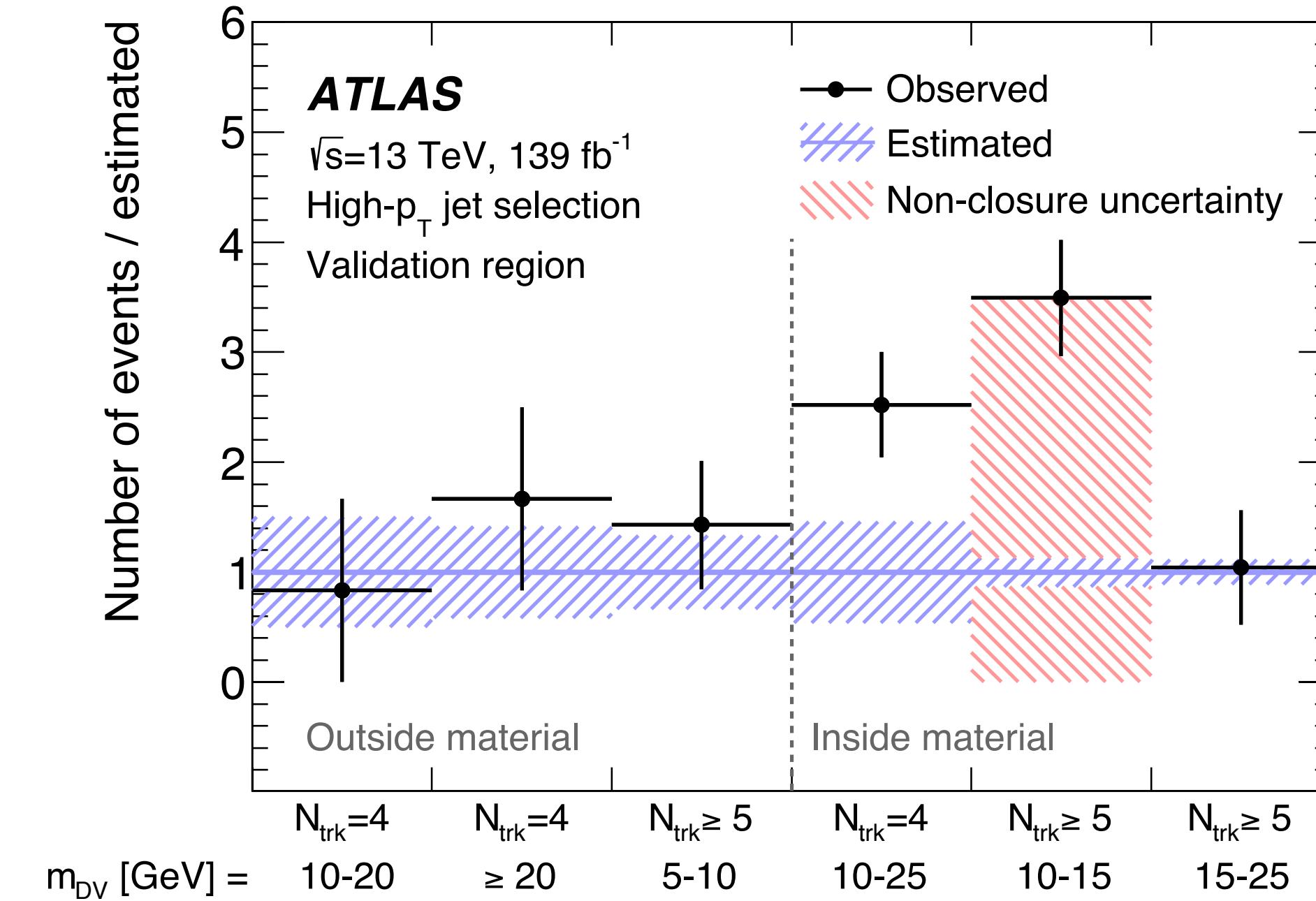
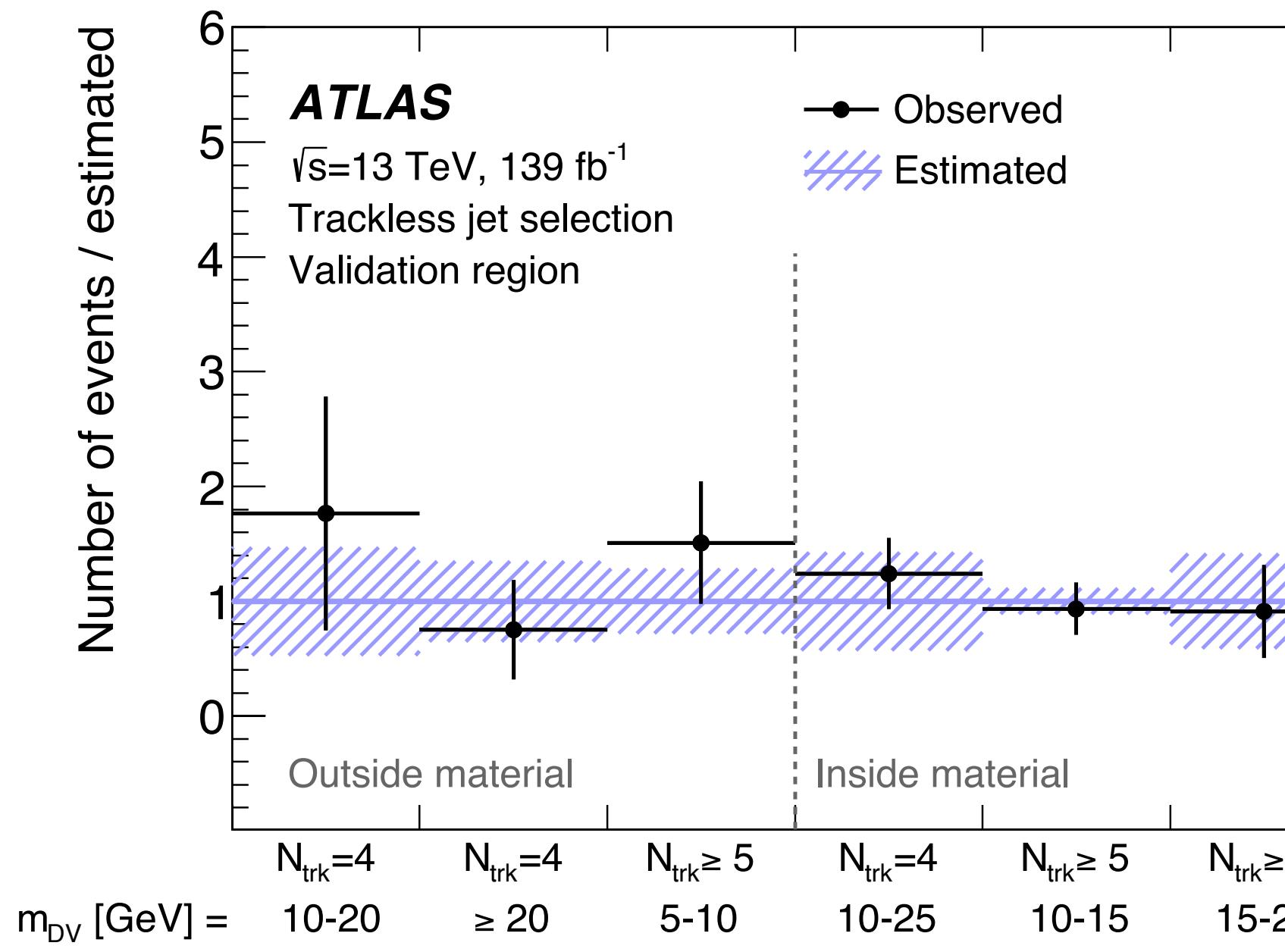
# Displaced hadronic vertices

- $m_{DV}$  vs DV ntracks for trackless jet (electroweak) and high-pT jet (strong) signal regions



# Displaced hadronic vertices

- Track-jets, are constructed with an anti- $kt$  algorithm with  $R = 0.4$  using all tracks with  $p_T > 1 \text{ GeV}$  and  $|d_0| < 2 \text{ mm}$ . In contrast to the jet reconstruction algorithm from calorimeter energy deposits, the track jet reconstruction is not sensitive to displaced LLP decays, due to the selection on the tracks  $|d_0|$ .



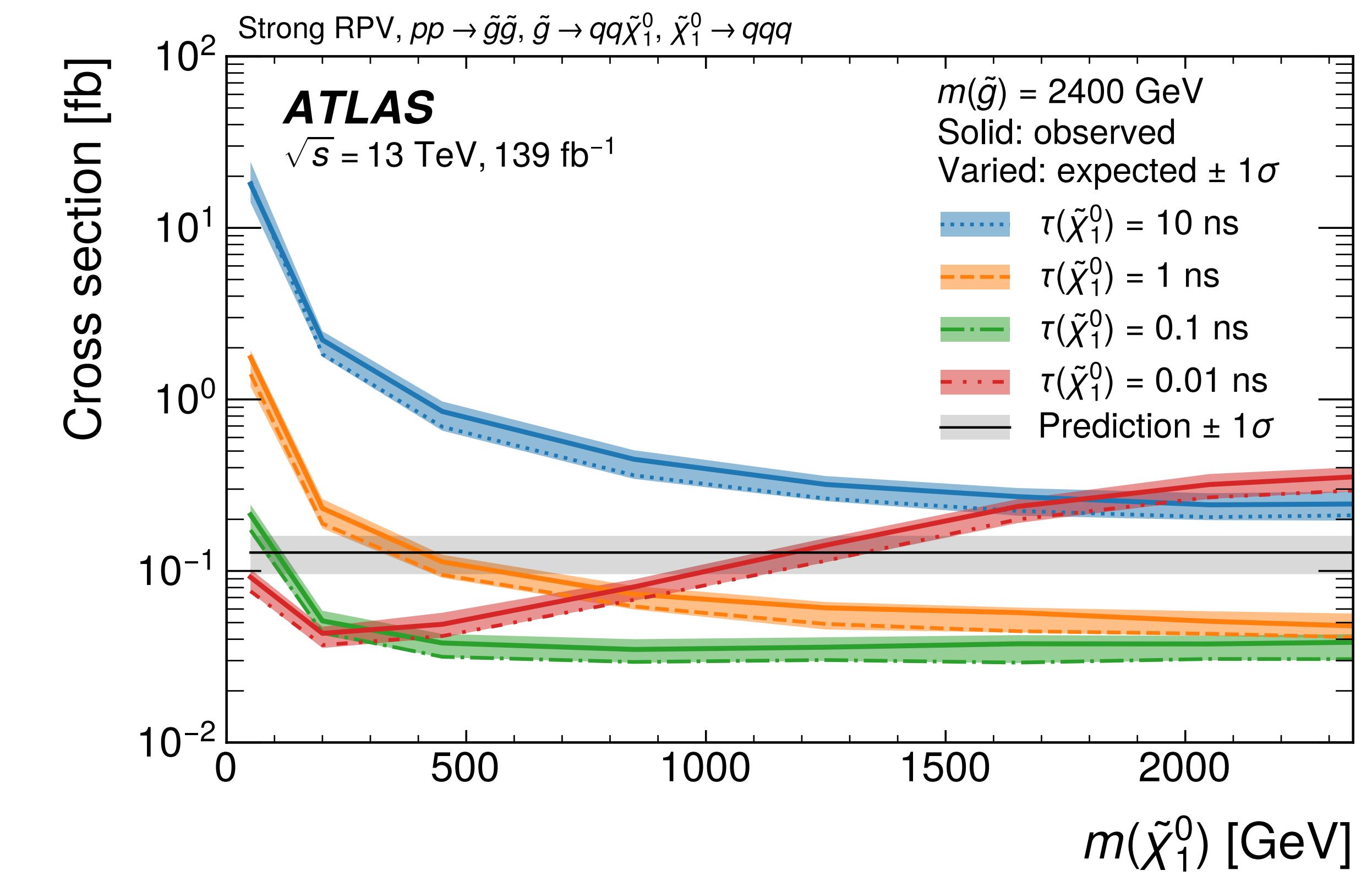
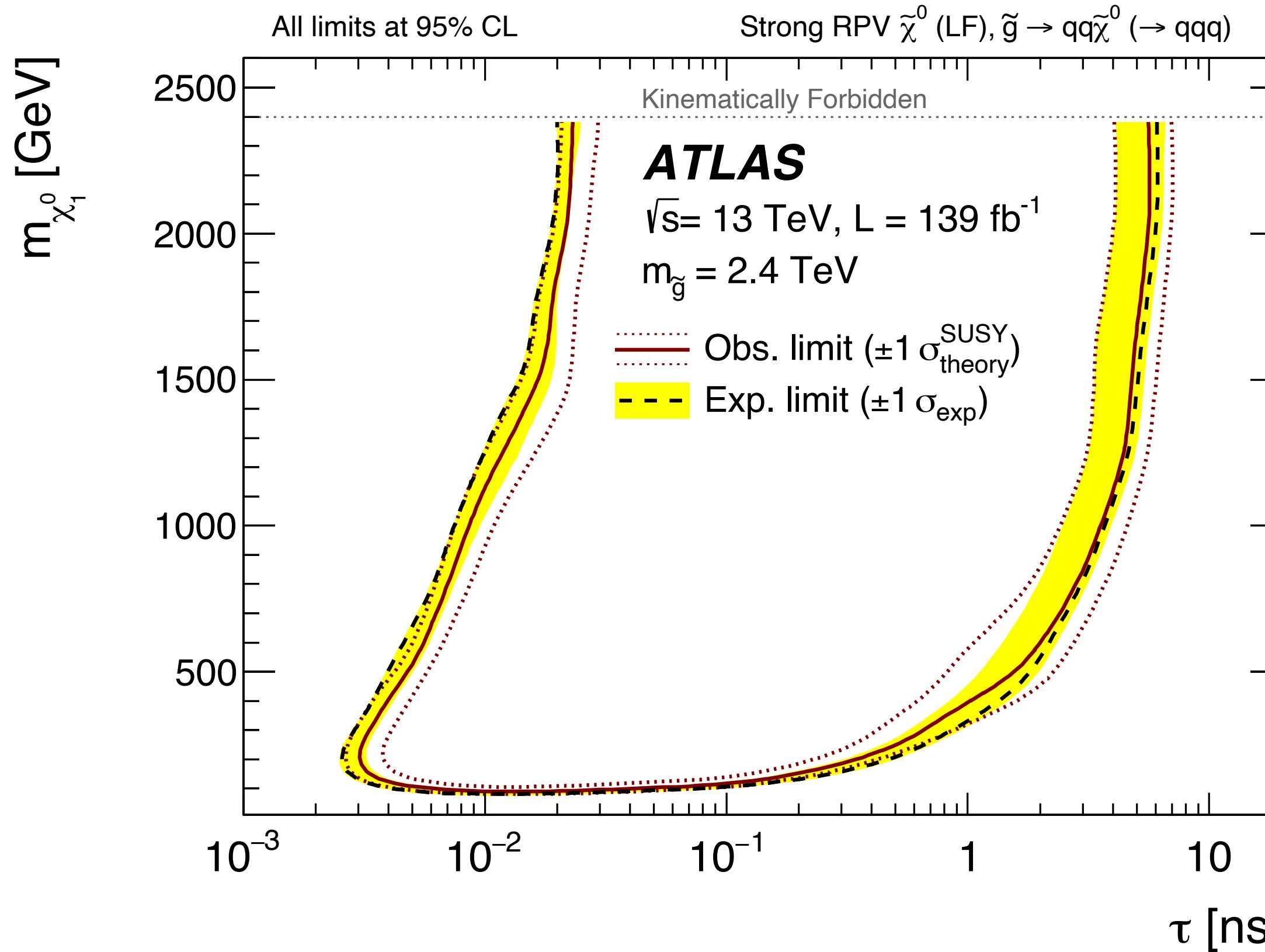
# Displaced hadronic vertices

Region	$0 < R_{\text{DV}} < 25 \text{ mm}$	$25 < R_{\text{DV}} < 145 \text{ mm}$	$R_{\text{DV}} > 145 \text{ mm}$	
Attached tracks	Track $p_{\text{T}}$ [GeV]	$> 2$	$> 3^{\dagger}$	$> 4$
	Track $d_0$ -significance	$> 10$	$> 15$	–
	$\Delta\phi_{\text{PV-DV}}$	$< \pi/2$		
Selected tracks	Upstream veto	No hits allowed with $R < R_{\text{DV}}$		
	Track $p_{\text{T}}$ [GeV]	$> 2$	$> 2^{\dagger}$	$> 2$
	Track $d_0$ -significance	$> 10$	–	$> 10$
Upstream veto		No hits allowed with $R < R_{\text{DV}}$		

$\dagger$  this requirement is tightened to  $p_{\text{T}} > 4 \text{ GeV}$  for tracks with  $\Delta\phi_{\text{PV-DV}} < 0.2$

Signal Region	High- $p_{\text{T}}$ jet SR	Trackless jet SR
Jet selection	$n_{\text{jet}}^{250} \geq 4$ or $n_{\text{jet}}^{195} \geq 5$ or $n_{\text{jet}}^{116} \geq 6$ or $n_{\text{jet}}^{90} \geq 7$	Fail High- $p_{\text{T}}$ jet selection, $n_{\text{jet}}^{137} \geq 4$ or $n_{\text{jet}}^{101} \geq 5$ or $n_{\text{jet}}^{83} \geq 6$ or $n_{\text{jet}}^{55} \geq 7$ , $n_{\text{Trackless jet}}^{70} \geq 1$ or $n_{\text{Trackless jet}}^{50} \geq 2$
DV preselection	$R_{\text{DV}} < 300 \text{ mm}$ , $ z_{\text{DV}}  < 300 \text{ mm}$ , $\min( \vec{R}_{\text{DV}} - \vec{R}_{\text{CV}} ) > 4 \text{ mm}$ , $\chi^2/n_{\text{DoF}} < 5$ , $n_{\text{Selected tracks}}^{\text{DV}} \geq 2$ , satisfy material map veto	
$n_{\text{Tracks}}^{\text{DV}}$ $m_{\text{DV}}^{19}$		$\geq 5$ $> 10 \text{ GeV}$

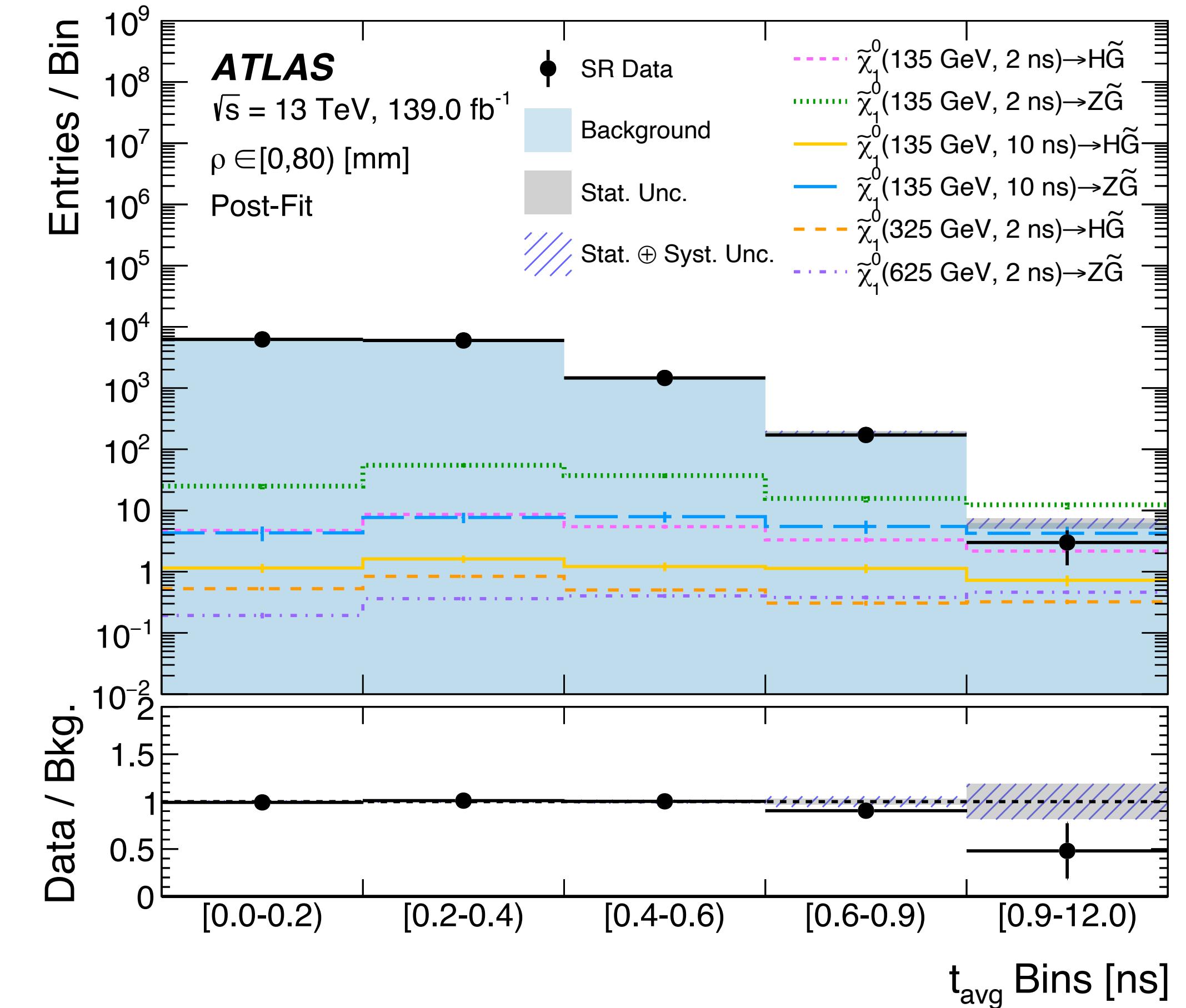
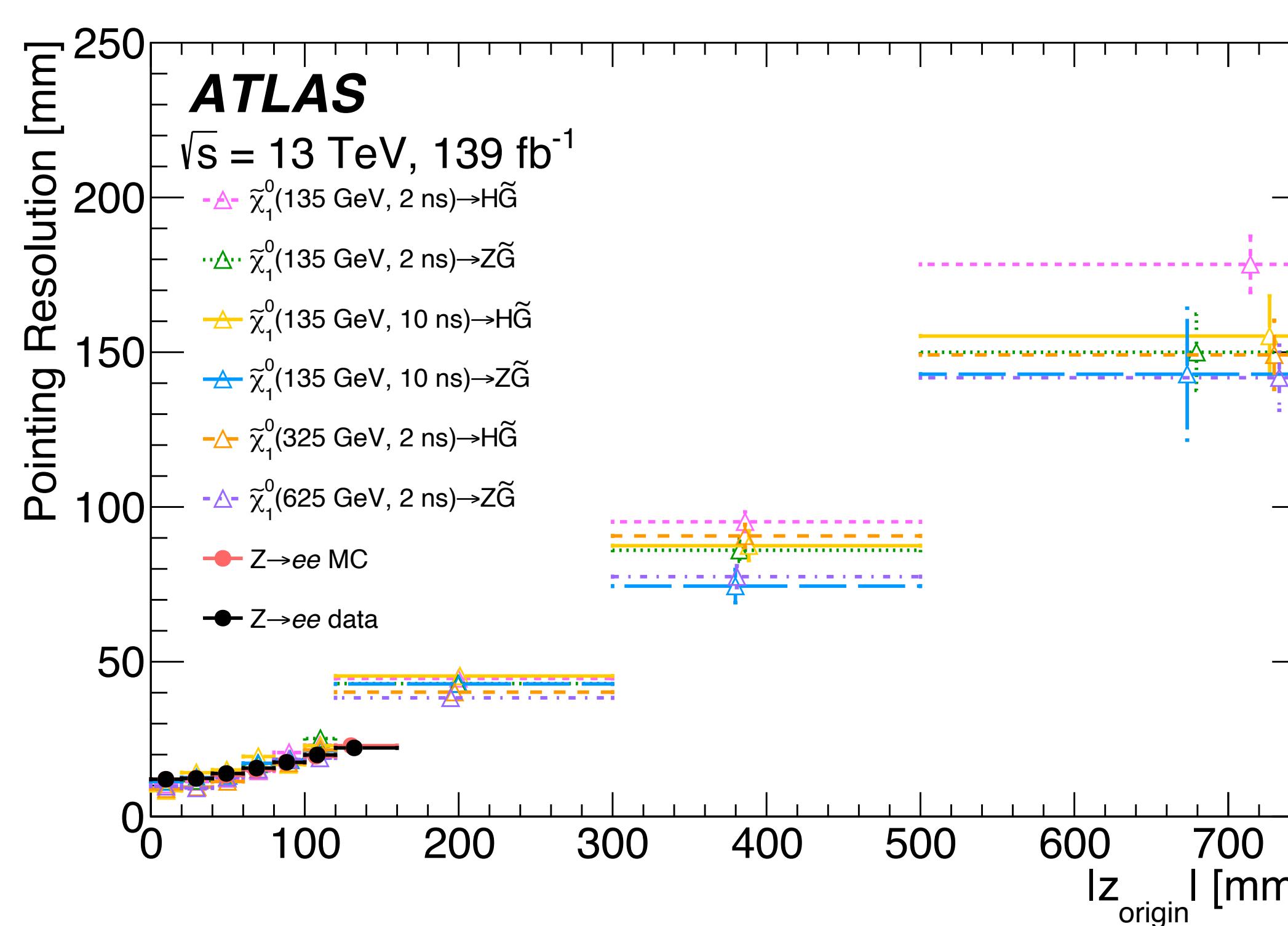
# Displaced hadronic vertices



# Displaced photons

Parameter	Preselection requirements			
Photon multiplicity				$> 1$
Photon $\eta$				$ \eta  < 1.37$ or $1.52 <  \eta  < 2.37$ ( $\geq 1$ with $ \eta  < 1.37$ )
$E_{\text{cell}}(\gamma)$ [GeV]				$E_{\text{cell}}(\gamma_1), E_{\text{cell}}(\gamma_2) > 5$
$p_T(\gamma)$ [GeV]				$p_T(\gamma_1) > 40, p_T(\gamma_2) > 30$
$\Delta\eta_{\gamma\gamma}$				$> 0.1$
$m_{\gamma\gamma}$ [GeV]				$> 60$
$V_R$ [mm]				$[0, 1500]$
$ V_z $ [mm]				$< 3740$
$t_\gamma$ [ns]				$t_{\gamma_1}, t_{\gamma_2} \in [-12, 12]$
Parameter	Analysis region requirements			
$E_T^{\text{miss}}$ [GeV]	$< 20$	20–30		$> 30$
$m_{\gamma\gamma}$ [GeV]		$> 135$		$[60, 135]$
Sign of $t_\gamma$		$t_{\gamma_1} \times t_{\gamma_2} > 0$	$t_{\gamma_1}, t_{\gamma_2} < 0$	$t_{\gamma_1}, t_{\gamma_2} > 0$
$p_T^{\gamma\gamma}$ [GeV]		-		$> 70$
$\Delta\phi(\gamma_1, \gamma_2)$		-		$< 2.4$
Vertexing and timing bins				
$\rho$ bin edges [mm]				$[0, 80, 160, 300, 520, 2000]$
$t_{\text{avg}}$ bin edges [ns]				$[0, 0.2, 0.4, 0.6, 0.9, 12]$

# Displaced photons

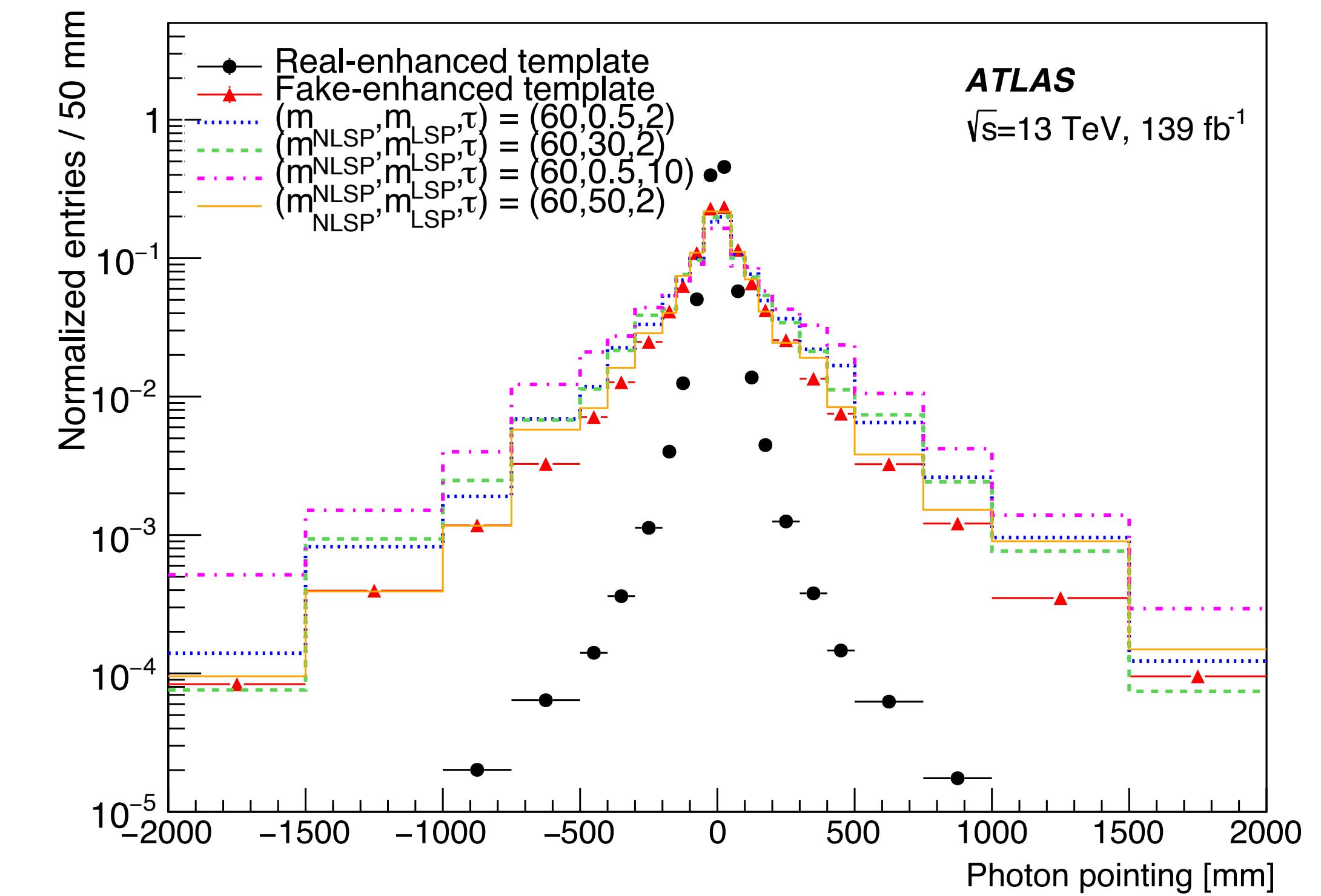
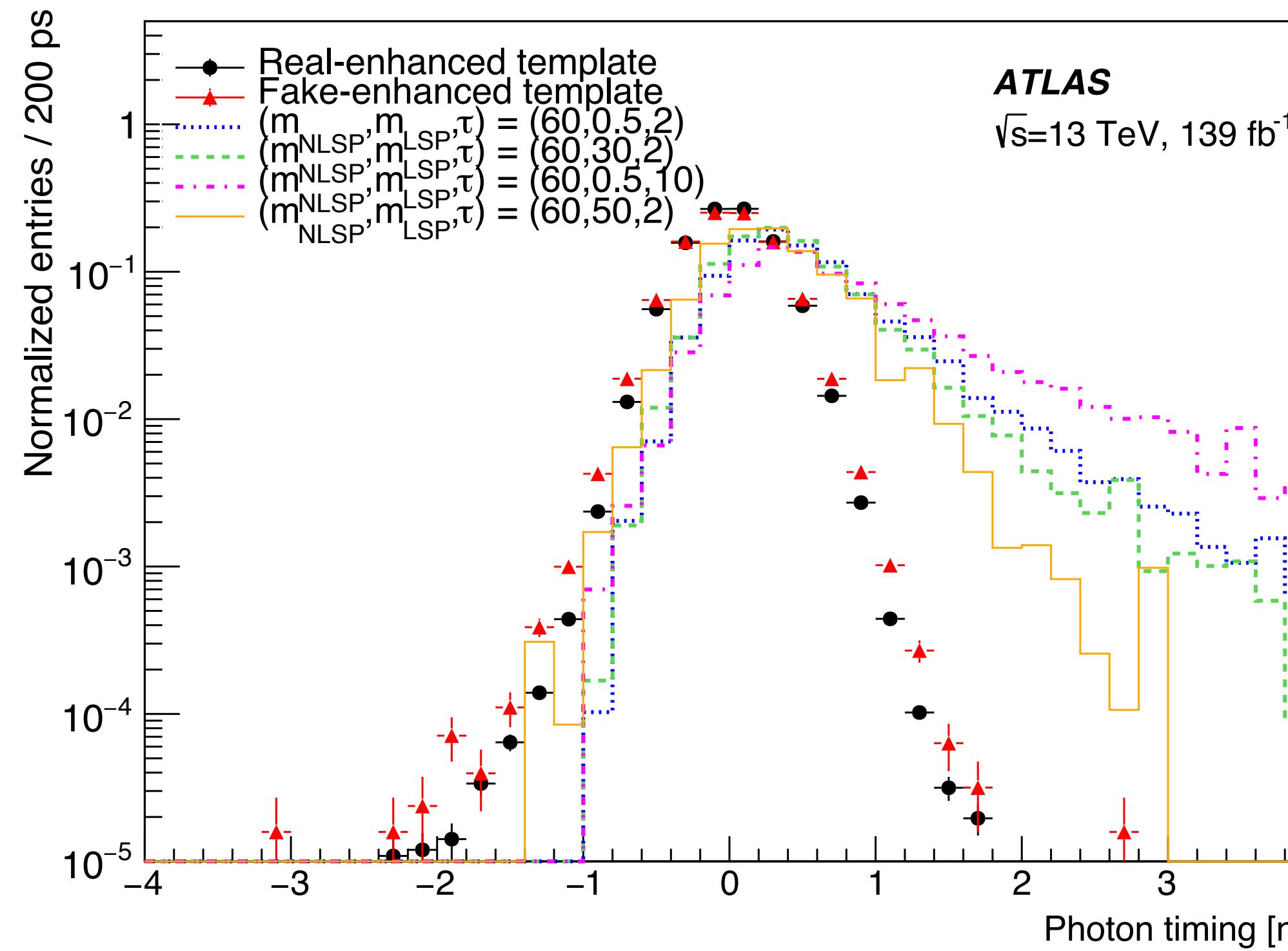


# Displaced photons

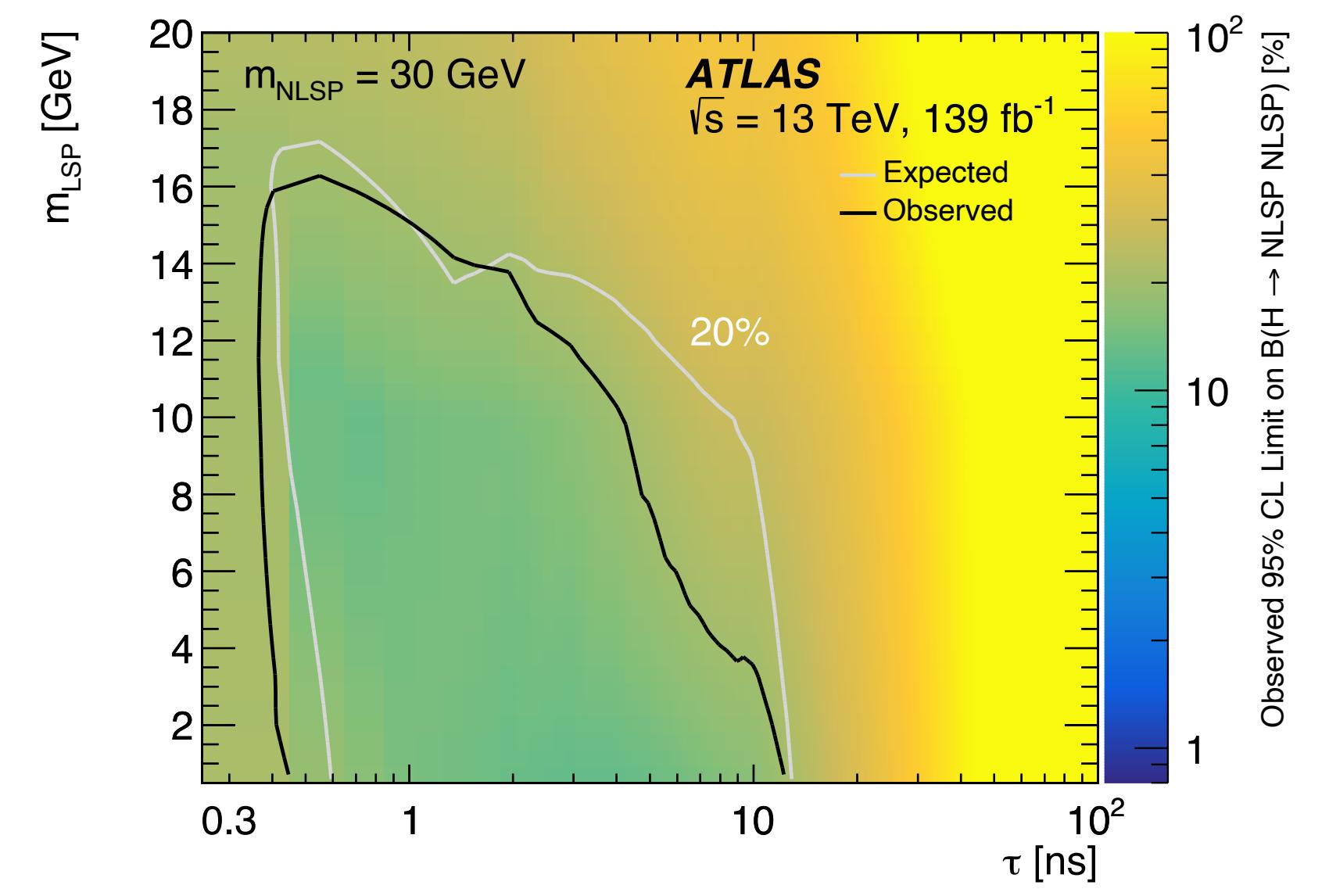
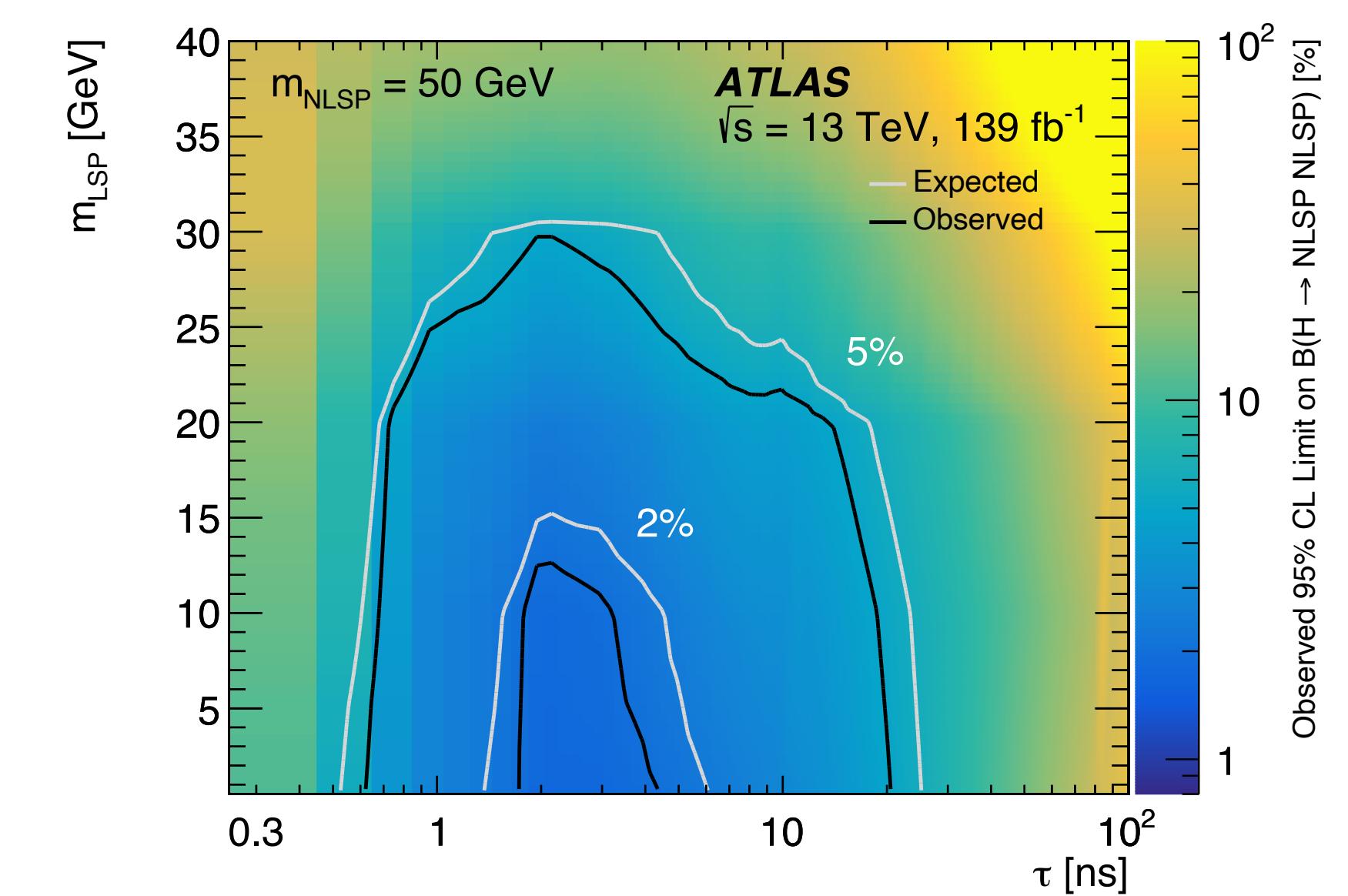
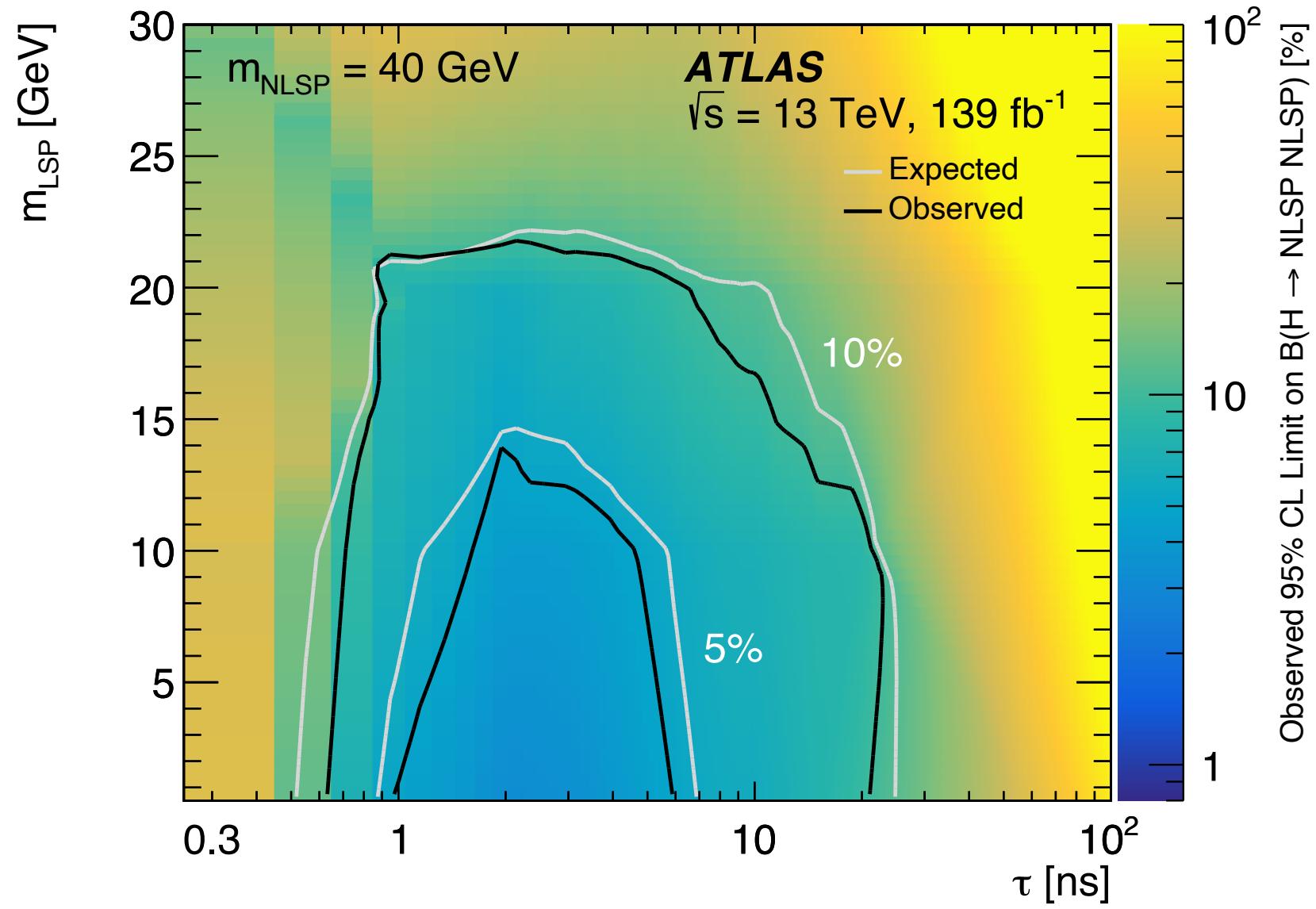
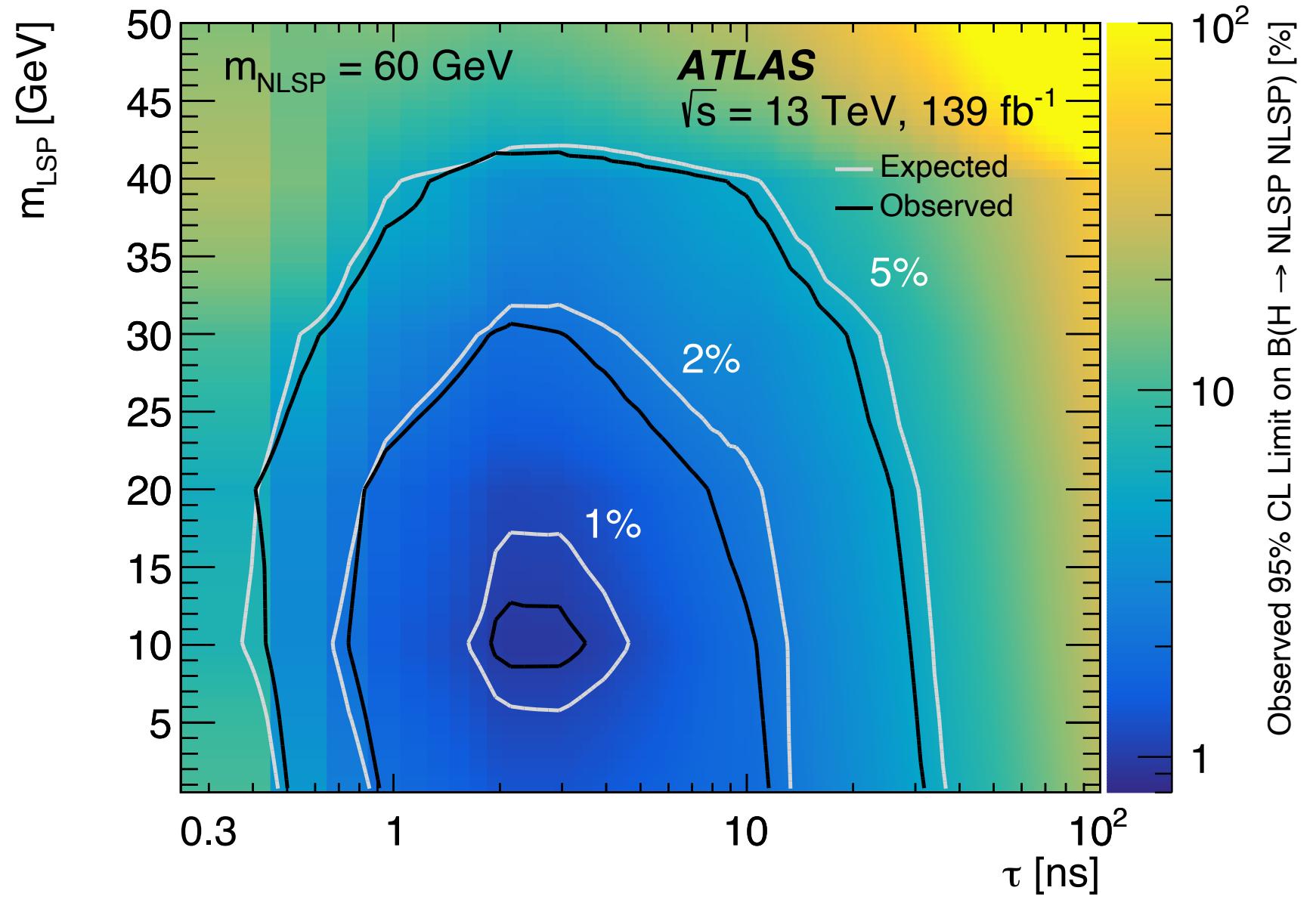
Selection	Number of events
Total	1.19E+08
Events passing trigger + $\geq 1$ lepton	1.12E+08
Events passing trigger + $\geq 1$ lepton + $\geq 1\gamma$	1.39E+07
$1\gamma$	1.37E+07
$\geq 2\gamma$	1.21E+05
CR region	9.56E+05
$1\gamma$ CR region	9.41E+05
$\geq 2\gamma$ CR region	1.49E+04
$1\gamma$ low- $\Delta m$ SR region	8.60E+04
$\geq 2\gamma$ low- $\Delta m$ SR region	1.24E+03
$1\gamma$ high- $\Delta m$ SR region	2.06E+05
$\geq 2\gamma$ high- $\Delta m$ SR region	2.82E+03

# Displaced photons

- Photon pointing and timing distributions

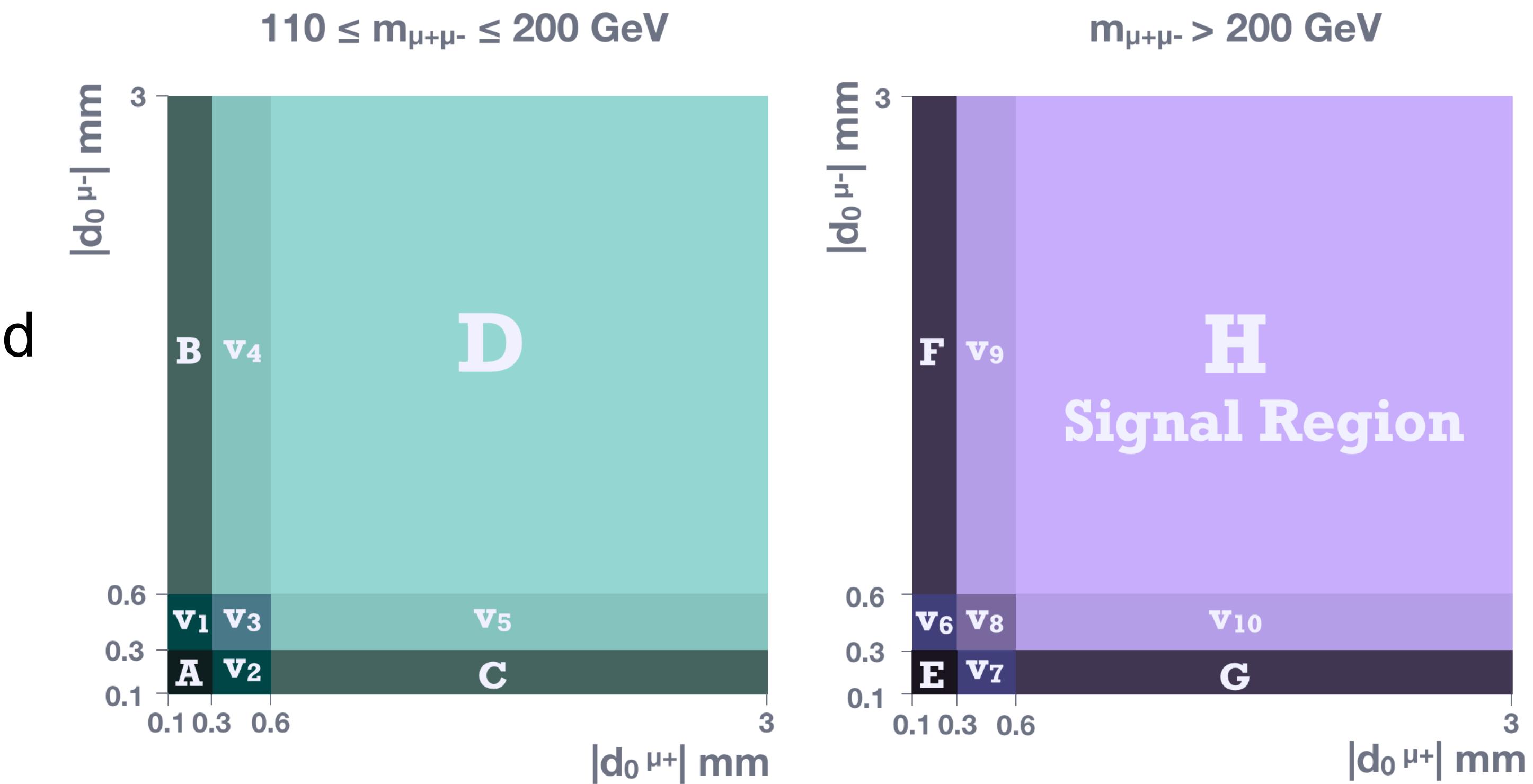


# Displaced photons



# Microdisplaced muons

- The different validation regions for the extended ABCD planes
- Expected and observed background in each of the overlapping sets of signal regions

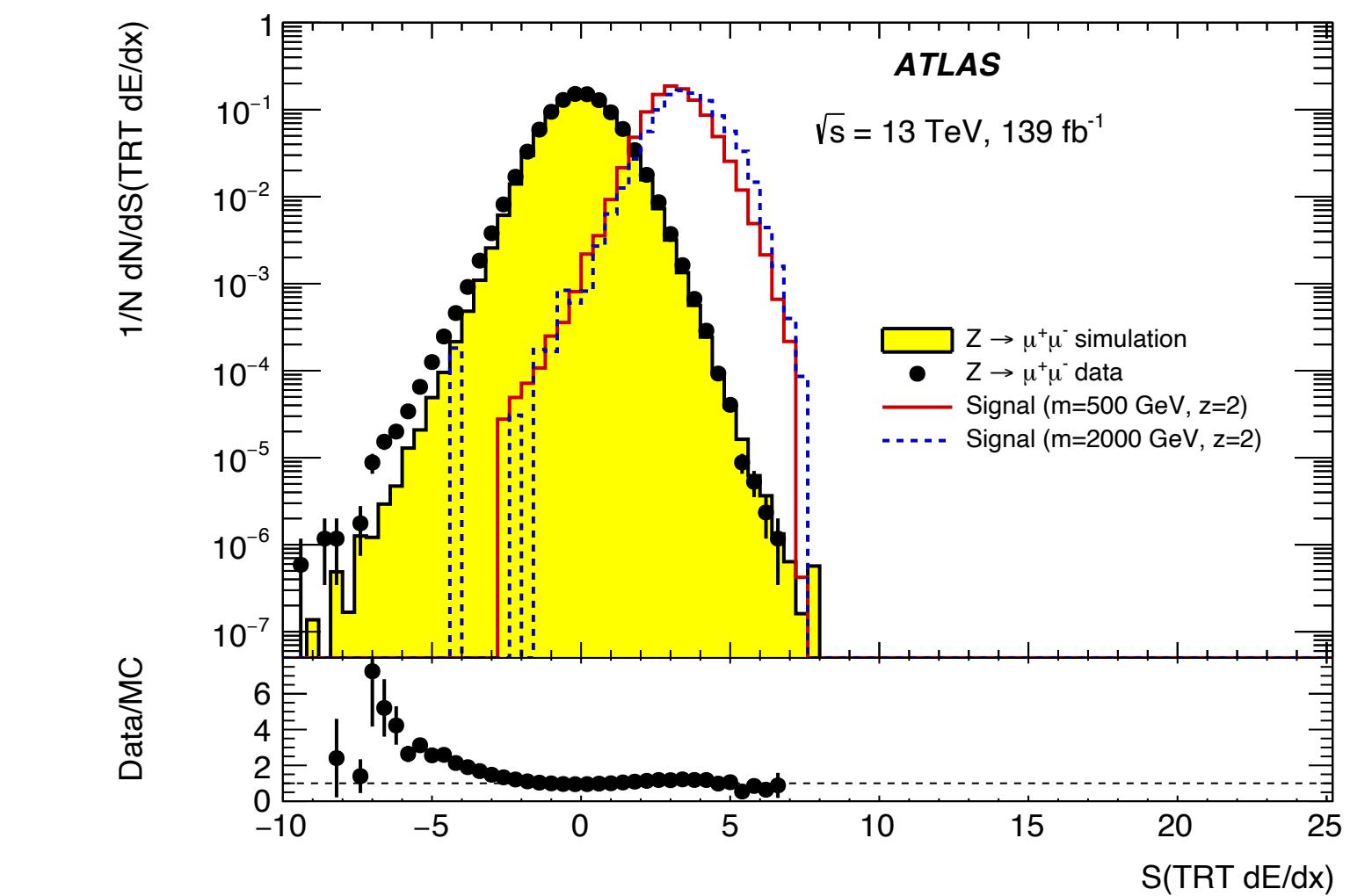
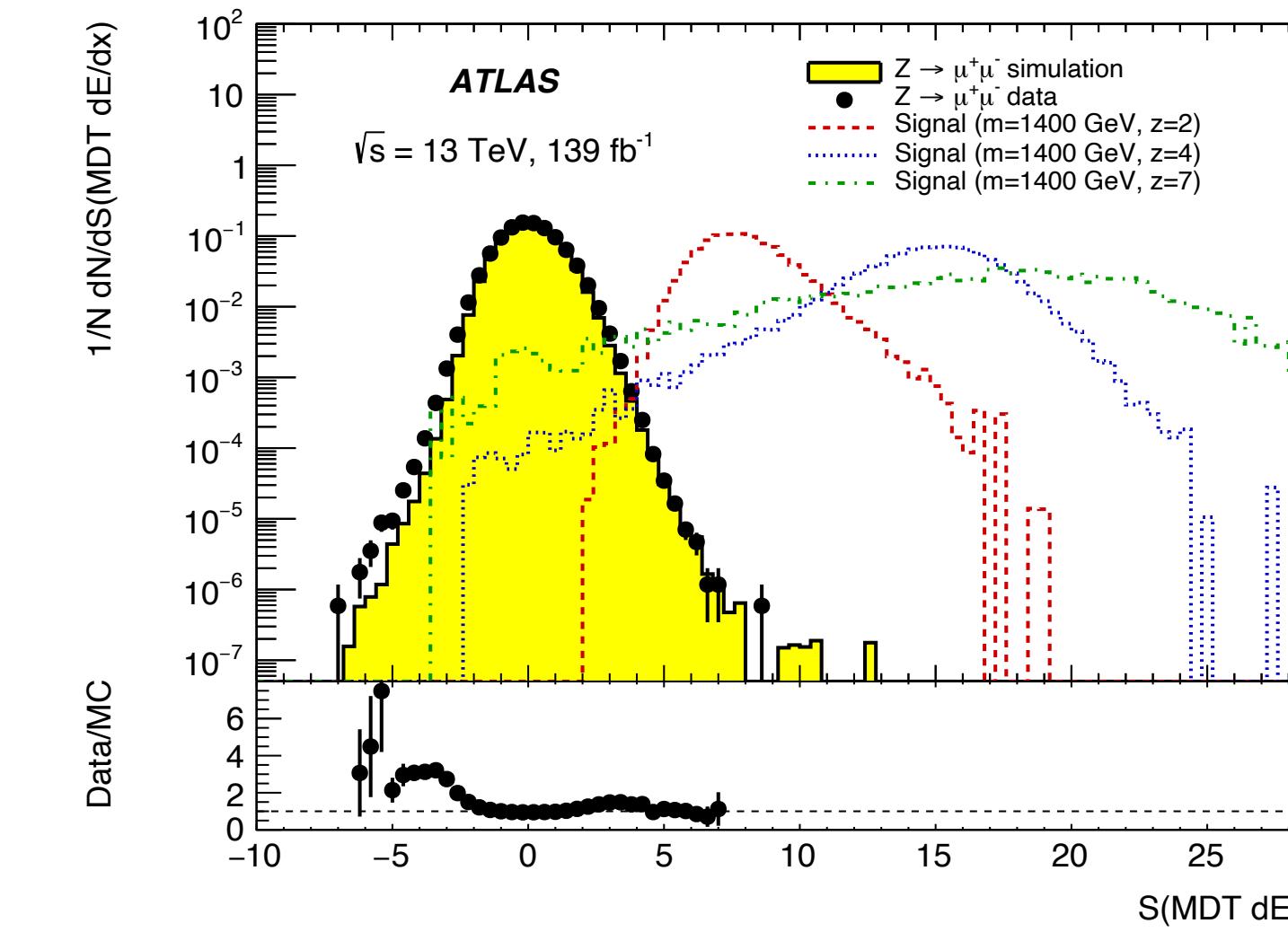
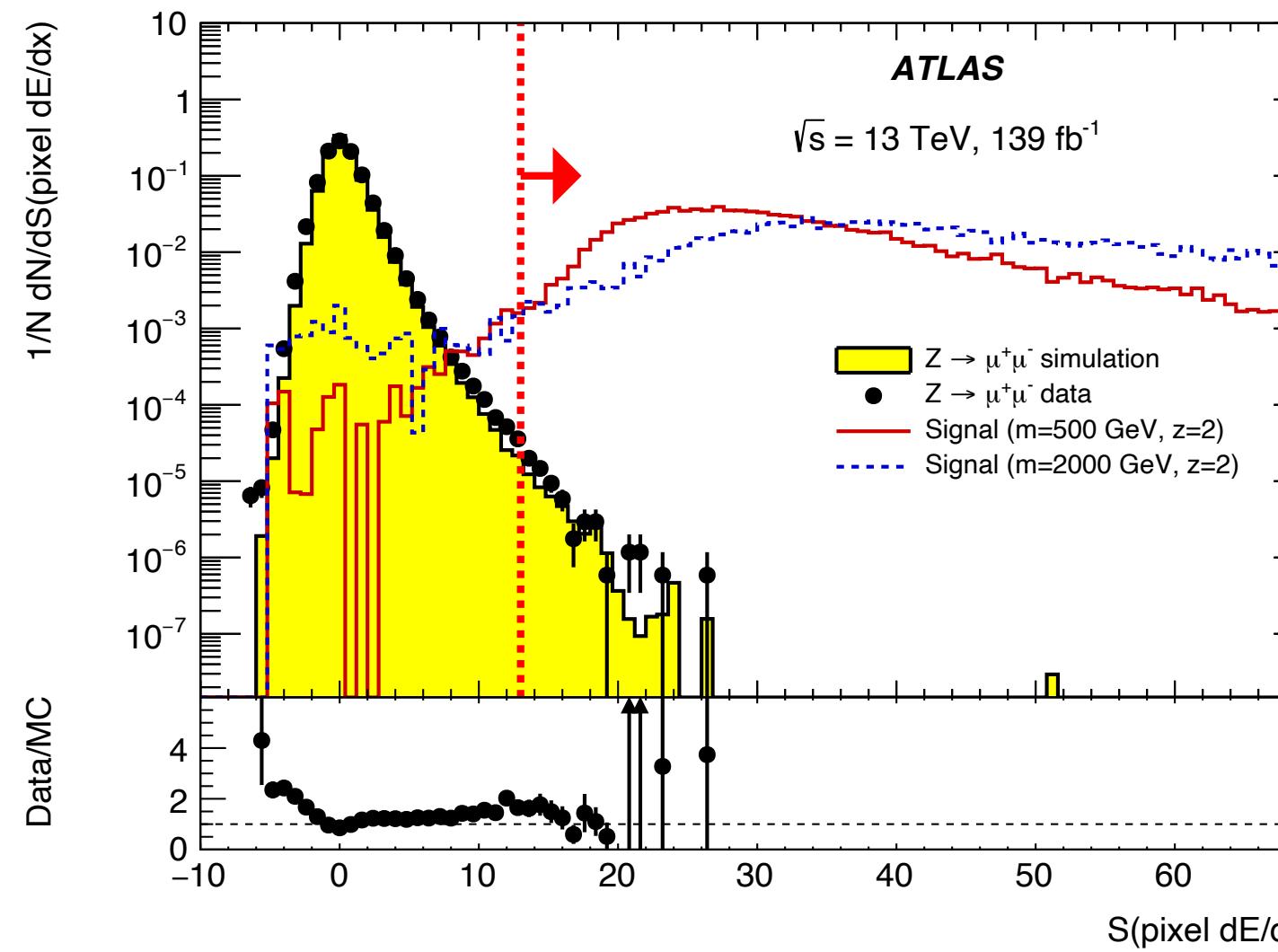
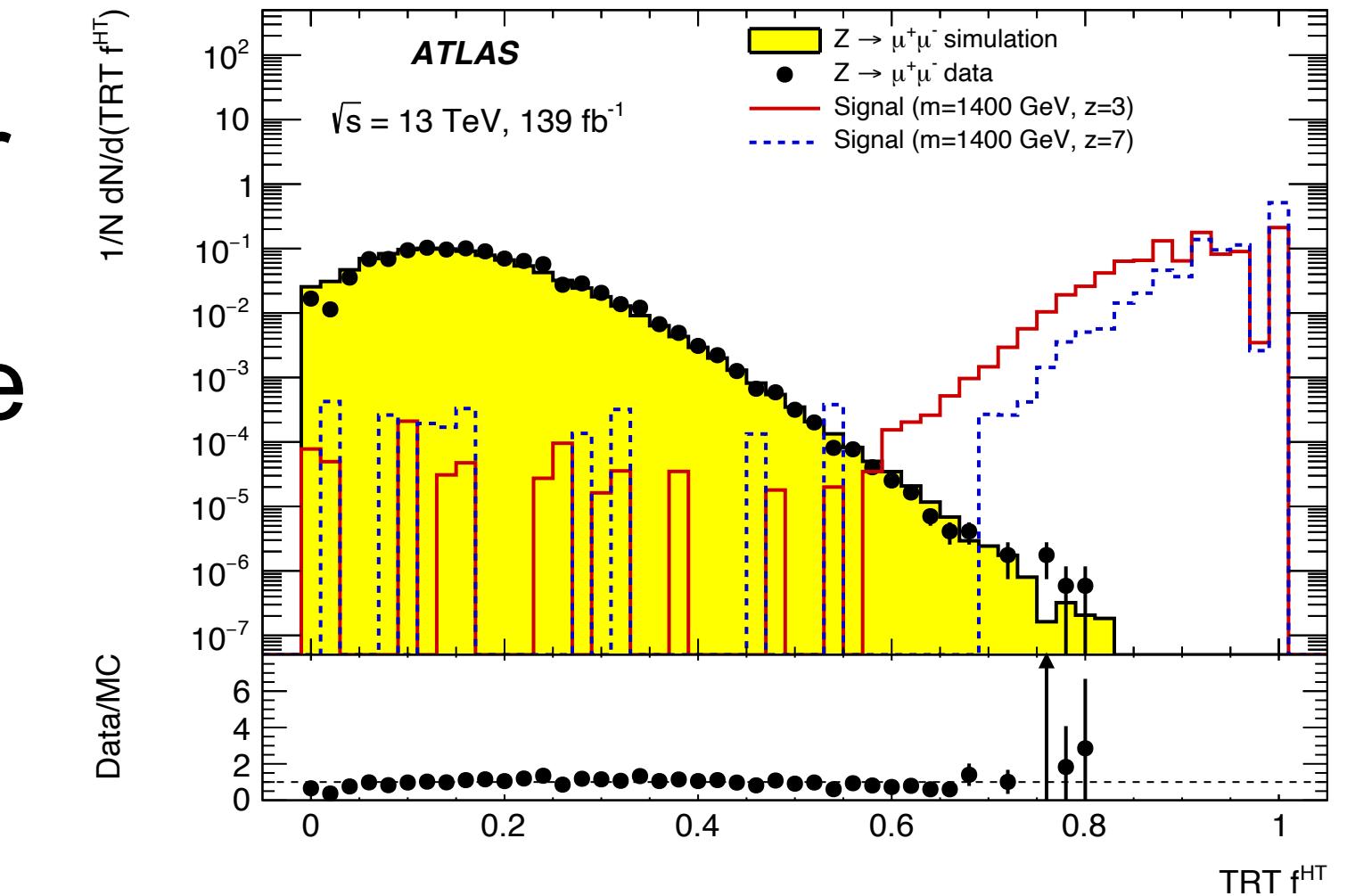


Set of Regions	Expected $N_H^{\text{bkg}}$	Observed $N_H^{\text{data}}$	$\langle A\epsilon\sigma \rangle_{\text{obs}}^{95} [\text{fb}]$	$S_{\text{obs}}^{95}$	$S_{\text{exp}}^{95}$	$CL_B$	$p(s = 0) (Z)$
1	$2.1 \pm 0.8$	1	0.02	3.3	$4.2^{+2.5}_{-1.4}$	0.27	0.50 (0.00)
2	$12.5 \pm 5.2$	7	0.04	5.2	$8.5^{+4.0}_{-2.7}$	0.08	0.50 (0.00)
3	$17.2 \pm 7.4$	14	0.06	8.9	$10.5^{+5.0}_{-3.1}$	0.26	0.50 (0.00)

# High $dE/dx$ - multi charge

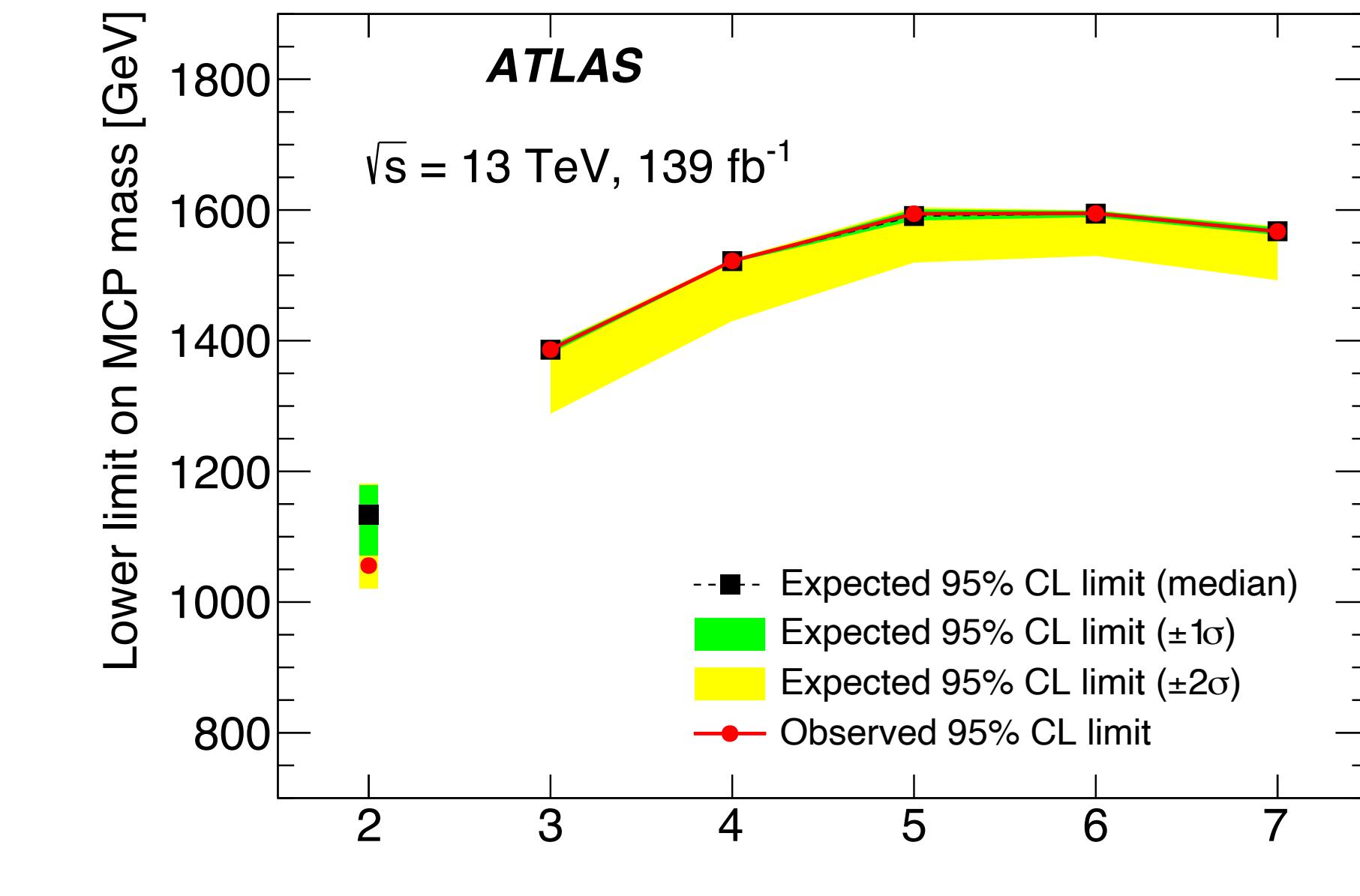
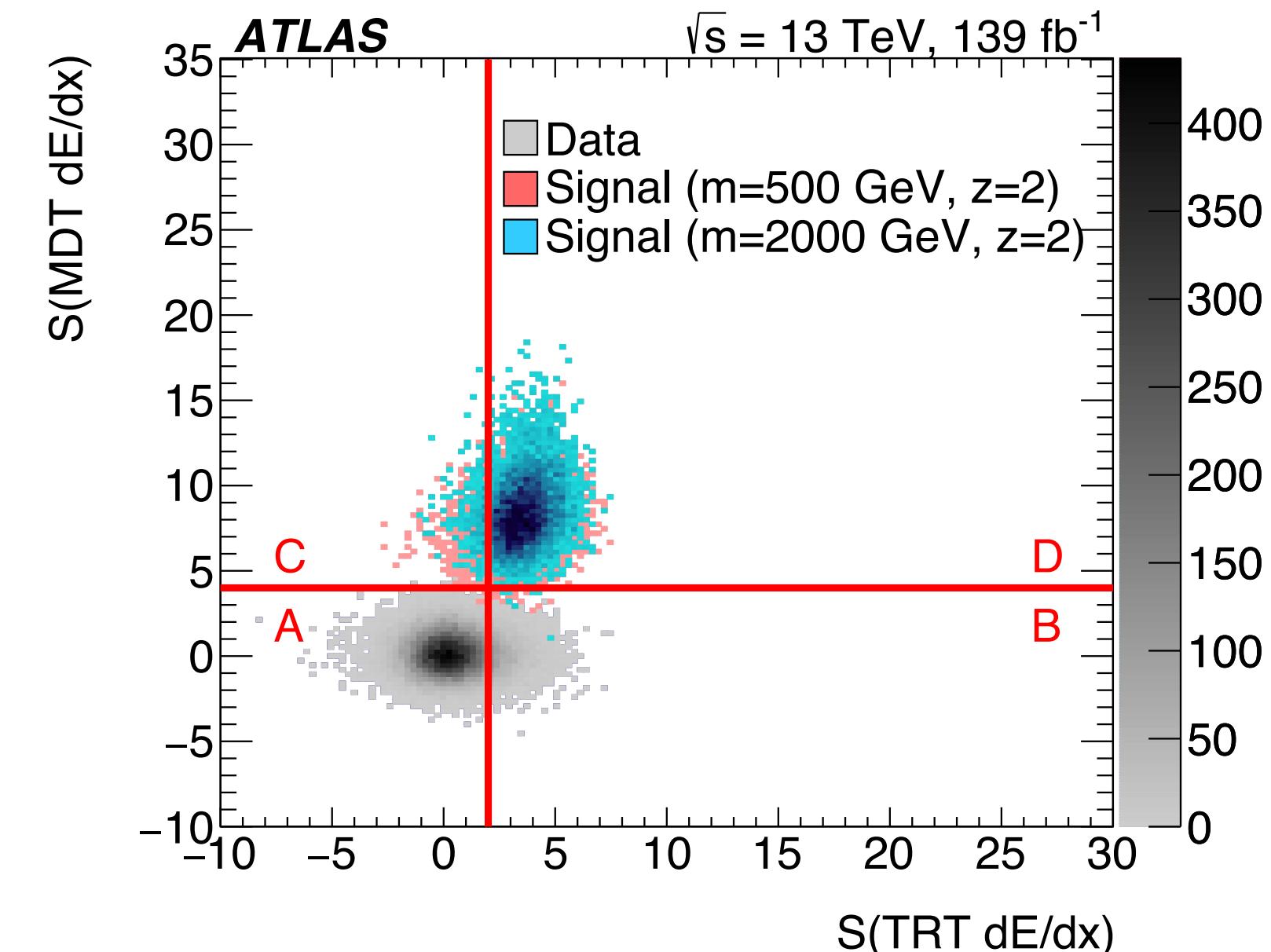
- The muon transverse momentum measured by the MS after the energy loss in the calorimeters is denoted by  $p_T^\mu/z$ , while transverse momentum of charged particles measured by the combination of the ID and MS is denoted by  $p_T/z$

$$\text{Significance: } S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_\mu}{\sigma(dE/dx)_\mu}$$



# High $dE/dx$ - multi charge

Search category	Preselection	Tight selection	Final selection
$z = 2$	Combined muon with: ‘medium’ identification criteria, $p_T^\mu/z > 50 \text{ GeV}$ , $p_T/z > 10 \text{ GeV}$ , $ \eta  < 2.0$ , no other particles with $p_T/z > 0.5 \text{ GeV}$ within $\Delta R = 0.01$	Preselected candidate with $S(\text{pixel } dE/dx) > 13$	Tightly selected candidate with: $S(\text{TRT } dE/dx) > 2$ , $S(\text{MDT } dE/dx) > 4$
$z > 2$		–	Preselected candidate with: $\text{TRT } f^{\text{HT}} > 0.7$ , $S(\text{MDT } dE/dx) > 7$



# High $dE/dx$ single charge particles

Summary of signal selections

[arXiv: 2205.06013](https://arxiv.org/abs/2205.06013)

Category	Item	Description
Event topology	Trigger $E_T^{\text{miss}}$ Primary vertex	Unprescaled lowest-threshold $E_T^{\text{miss}}$ trigger $E_T^{\text{miss}} > 170 \text{ GeV}$ The hard-scatter vertex must have at least two tracks
Events are required to have at least one track fulfilling <i>all</i> criteria listed below; tracks sorted in $p_T$ descending order		
Track kinematics	Momentum Pseudorapidity $W^\pm \rightarrow \ell^\pm \nu$ veto	$p_T > 120 \text{ GeV}$ $ \eta  < 1.8$ $m_T(\text{track}, \vec{p}_T^{\text{miss}}) > 130 \text{ GeV}$
Track quality	Impact parameters Rel. momentum resolution Cluster requirement (1) Cluster requirement (2)	Track matched to the hard-scatter vertex; $ d_0  < 2 \text{ mm}$ and $ \Delta z_0 \sin \theta  < 3 \text{ mm}$ $\sigma_p < \max\left(10\%, -1\% + 90\% \times \frac{ p }{\text{TeV}}\right)$ and $\sigma_p < 200\%$ At least two clusters used for the $\langle dE/dx \rangle_{\text{trunc}}$ calculation Must have a cluster in the IBL (if this is expected), or a cluster in the next-to-innermost pixel layer (if this is expected while a cluster is not expected in IBL)
Veto	Cluster requirement (3) Cluster requirement (4) Isolation Electron veto Hadron and $\tau$ -lepton veto Muon requirement	No shared pixel clusters and no split pixel clusters Number of SCT clusters $> 5$ $\left(\sum_{\text{trk}} p_T\right) < 5 \text{ GeV}$ (cone size $\Delta R = 0.3$ ) EM fraction $< 0.95$ $E_{\text{jet}}/p_{\text{track}} < 1$ SR-Mu: MS track matched to ID track; SR-Trk: otherwise
Pixel $dE/dx$	Inclusive	Low: $dE/dx \in [1.8, 2.4] \text{ MeV g}^{-1} \text{cm}^2$ High: $dE/dx > 2.4 \text{ MeV g}^{-1} \text{cm}^2$
	Binned	IBL0_Low: $dE/dx \in [1.8, 2.4] \text{ MeV g}^{-1} \text{cm}^2$ and $\text{OF}_{\text{IBL}} = 0$ IBL0_High: $dE/dx > 2.4 \text{ MeV g}^{-1} \text{cm}^2$ and $\text{OF}_{\text{IBL}} = 0$ IBL1: $dE/dx > 1.8 \text{ MeV g}^{-1} \text{cm}^2$ and $\text{OF}_{\text{IBL}} = 1$

# High $dE/dx$ single charge particles

Region	$p_T$ [GeV]	$ \eta $	$E_T^{\text{miss}}$ [GeV]	$dE/dx$ [MeV g $^{-1}$ cm $^2$ ]
SR			$> 170$	$> 1.8$
CR-kin	$> 120$	$< 1.8$	$> 170$	$< 1.8$
CR-dEdx			$< 170$	$> 0$
VR-LowPt			$> 170$	$> 1.8$
CR-LowPt-kin	[50, 110]	$< 1.8$	$> 170$	$< 1.8$
CR-LowPt-dEdx			$< 170$	$> 0$
VR-HiEta			$> 170$	$> 1.6$
CR-HiEta-kin	$> 50$	[1.8, 2.5]	$> 170$	$< 1.6$
CR-HiEta-dEdx			$< 170$	$> 0$

Different signal region bins - discovery or limit setting

Signal, control, validation regions

SR name	Discovery	Limit setting	Track category	IBL overflow	$dE/dx$ [MeV g $^{-1}$ cm $^2$ ]
SR-Inclusive_Low	✓		inclusive	yes or no	[1.8, 2.4]
SR-Inclusive_High	✓				$> 2.4$
SR-Trk-IBL0_Low		✓		no	[1.8, 2.4]
SR-Trk-IBL0_High		✓	track	no	$> 2.4$
SR-Trk-IBL1		✓		yes	$> 1.8$
SR-Mu-IBL0_Low		✓		no	[1.8, 2.4]
SR-Mu-IBL0_High		✓	muon tracks	no	$> 2.4$
SR-Mu-IBL1		✓		yes	$> 1.8$