# LLP Signatures with Missing Transverse Energy*

Roadmap of Dark Matter Models for Run 3 Workshop

* focusing on BSM, not neutrinos


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# Experimental considerations

## Missing energy ("MET") is challenging:

- Need to understand *every other object* in an event in order to compute it
- Most searches I'll describe use MET triggers and MET $\gtrsim$ 200 GeV, often with other quality requirements (e.g. reject events where MET aligned w/ jet)

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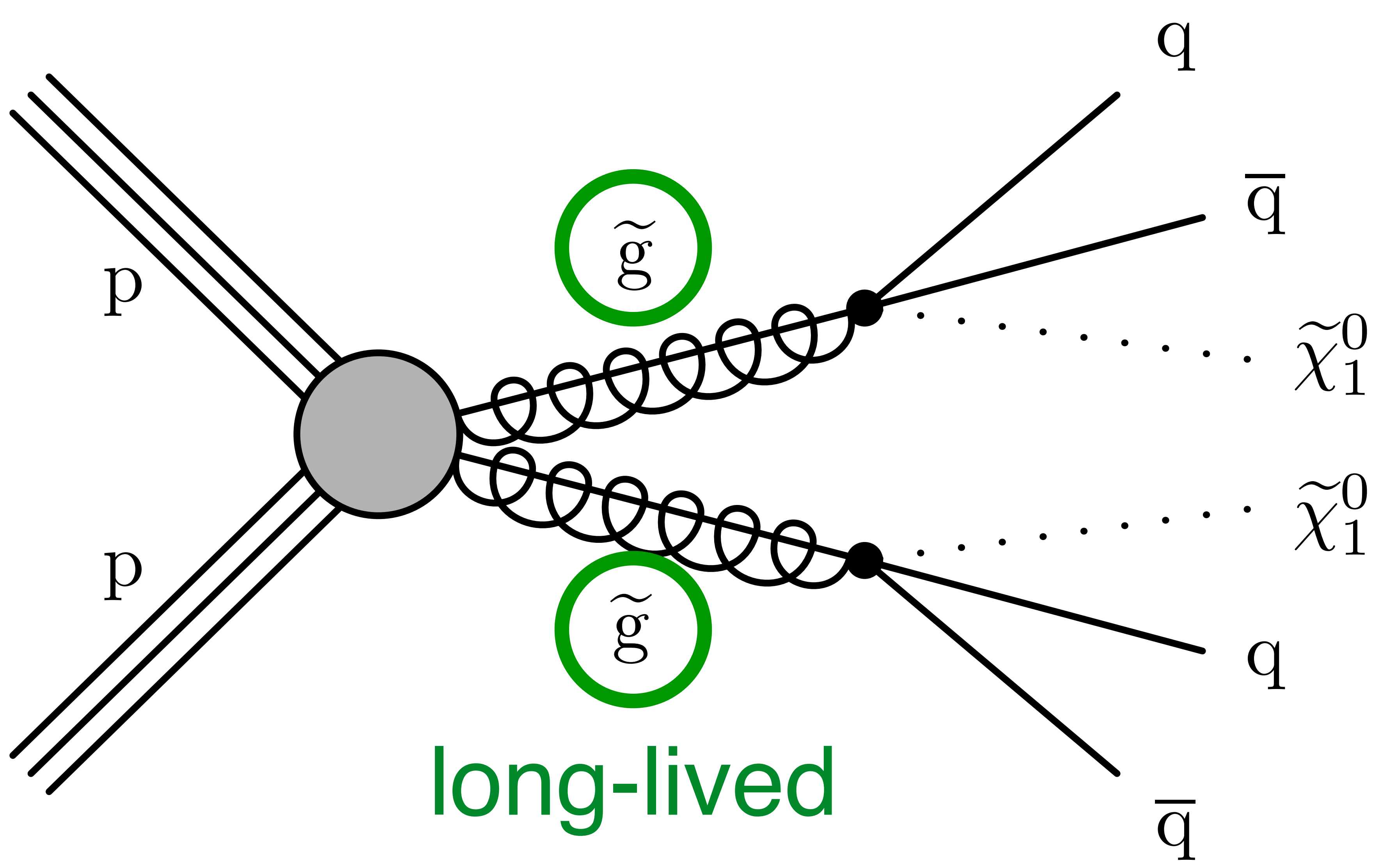
On the plus side: MET is a key signature of dark matter and SUSY! And LLPs naturally arise in many BSM theories—*if we don't look, we won't find them*

# CMS: Hadronic displaced vertices + MET

CMS EXO-22-020

Vertex LLP decay points w/ tracks; then suppress SM and material interaction bkgs.

Compressed split SUSY $\Longrightarrow$ *soft decay products*. May not reconstruct both LLPs!



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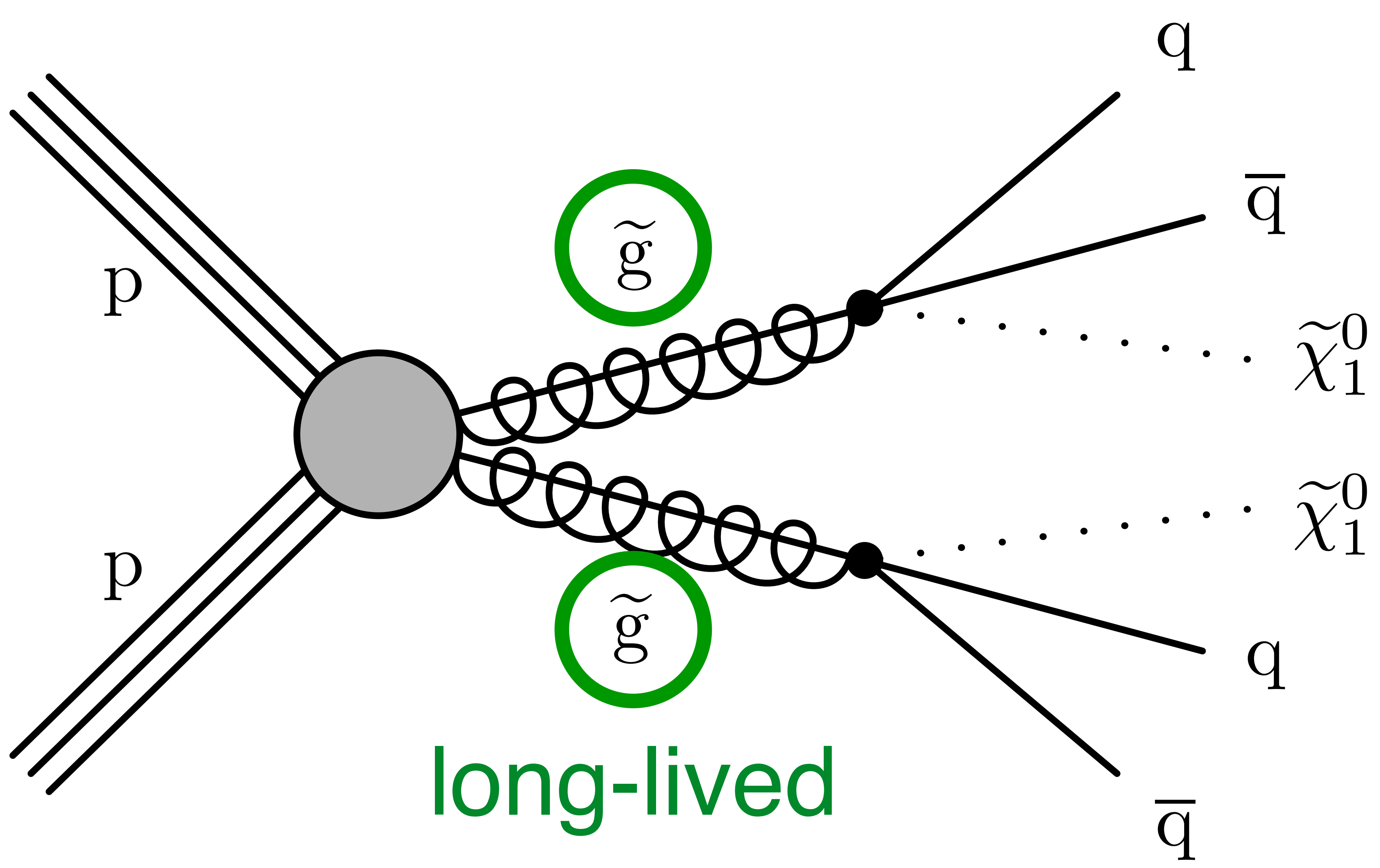
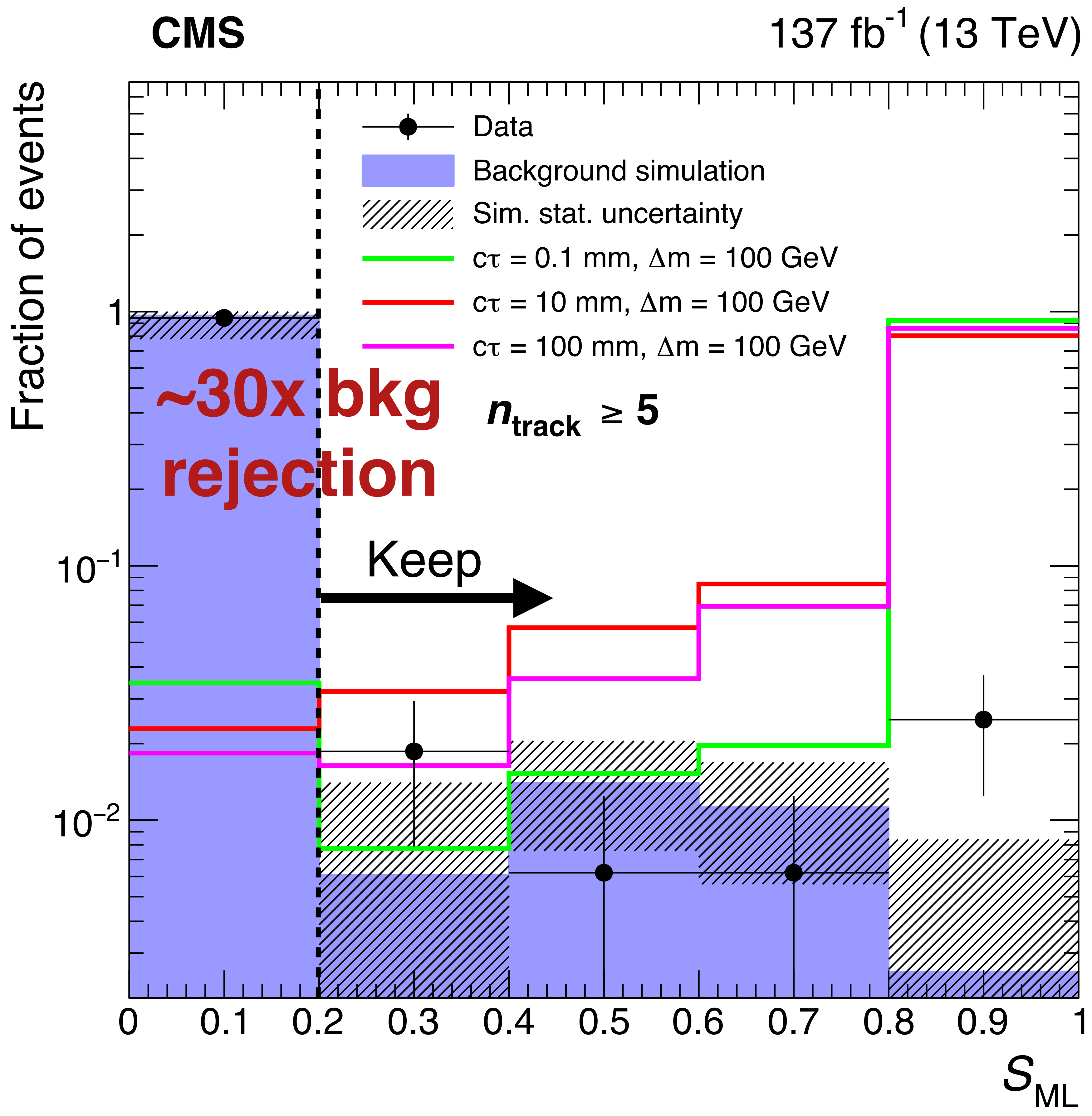



Use ≥1-vtx signal region with interaction network
to learn track relationships

ABCDisCo method (via IN score and $n_{tracks}$)
for data-driven bkg estimate



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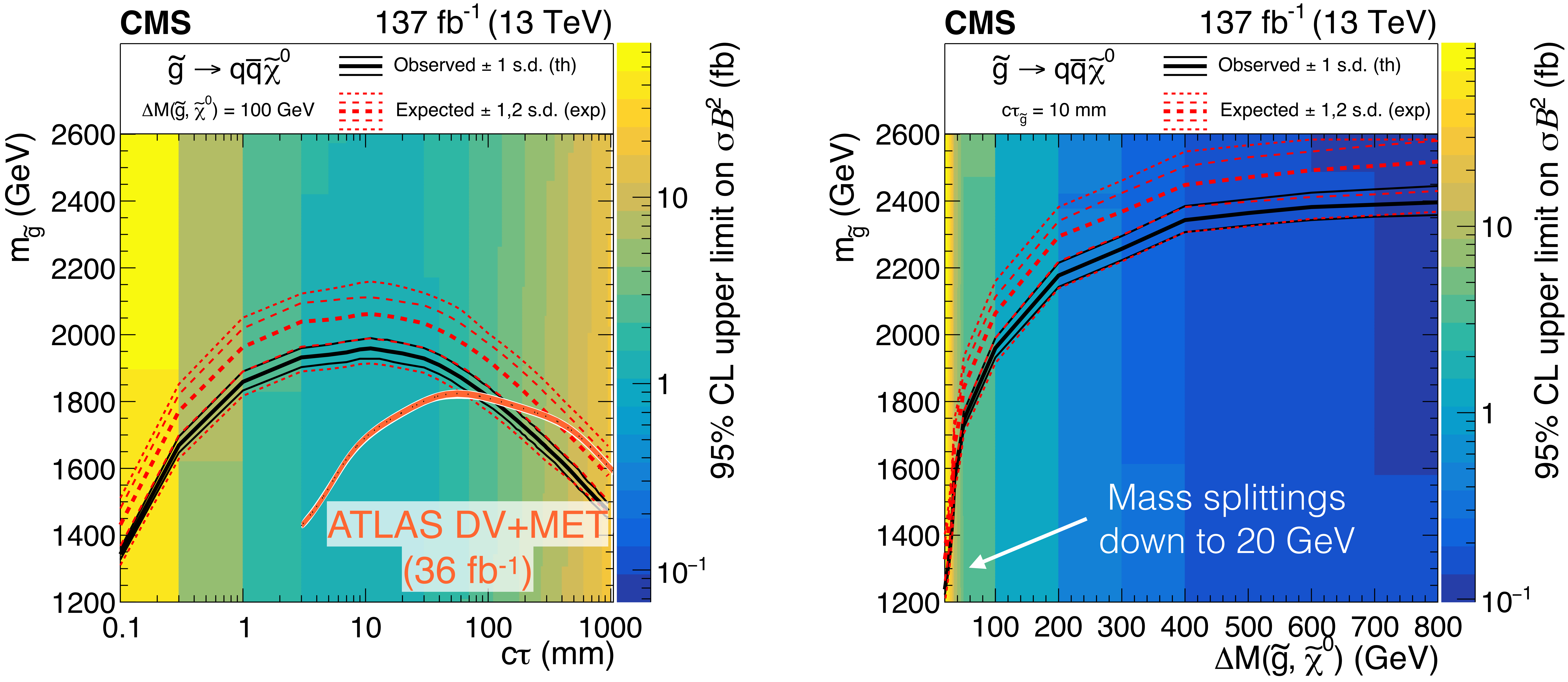
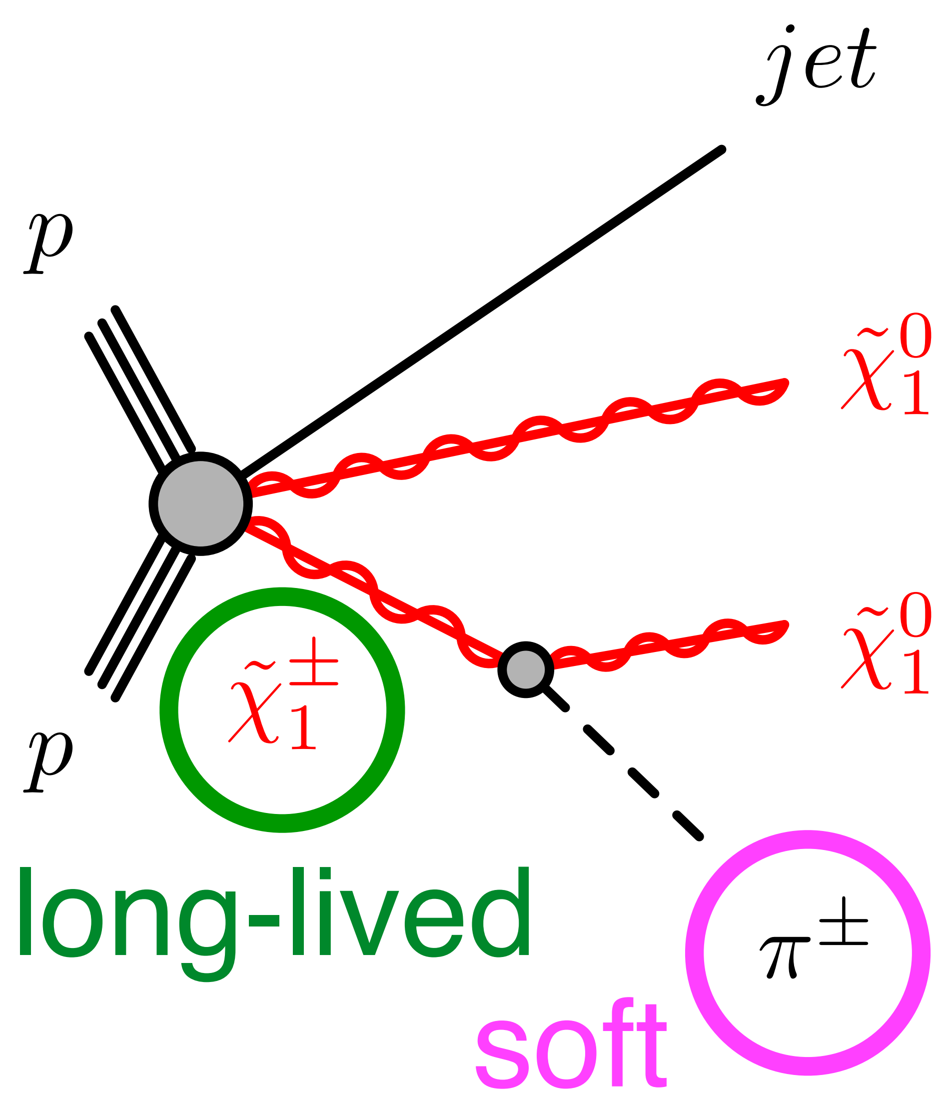


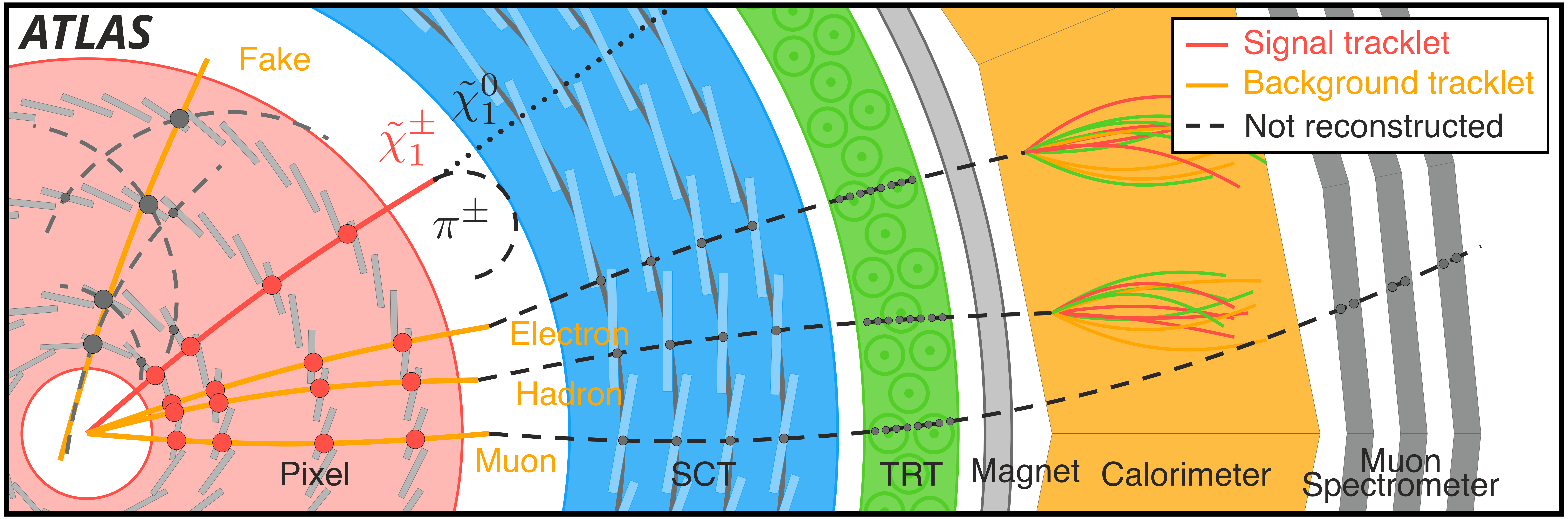

Powerful search techniques: probes production cross sections that are up to *100x smaller* than previous searches, for O(mm) lifetimes.

# Disappearing tracks + MET

ATLAS SUSY-2018-19
CMS EXO-19-010
CMS SUS-21-006

Light Higgsinos important for naturalness; in scenarios where the lightest EWKinos are pure $\tilde{H}$ or $\tilde{W}$, expect $\mathcal{O}$(100s MeV) splittings and $\mathcal{O}$(cm) lifetimes

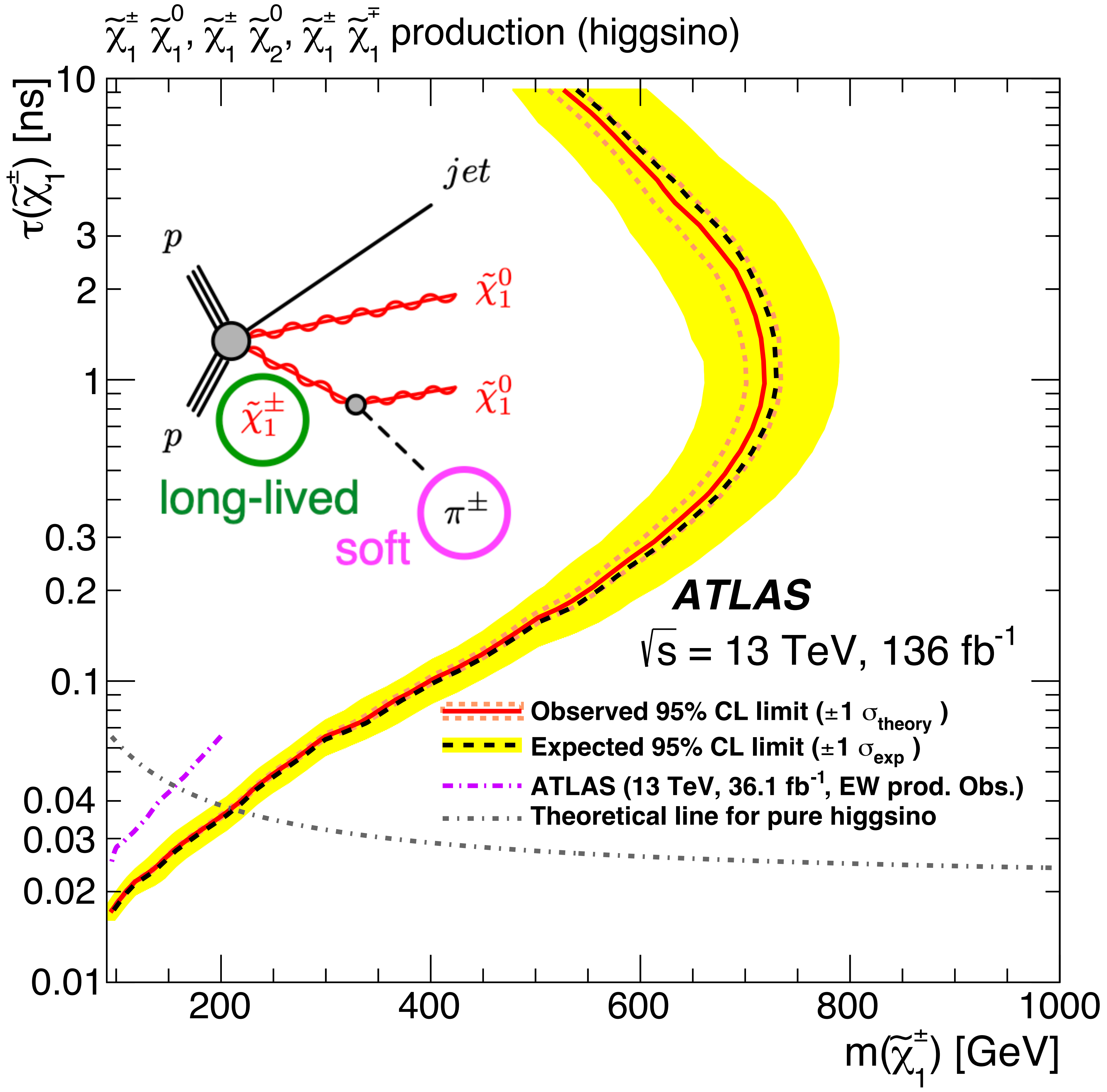



Look for charged particles that leave hits in the tracker before decaying!

Rely on well-isolated, high pT chargino track.

# Disappearing tracks + MET




One ATLAS and two CMS searches w/ full Run 2; all also include $\tilde{W}$ interpretations.

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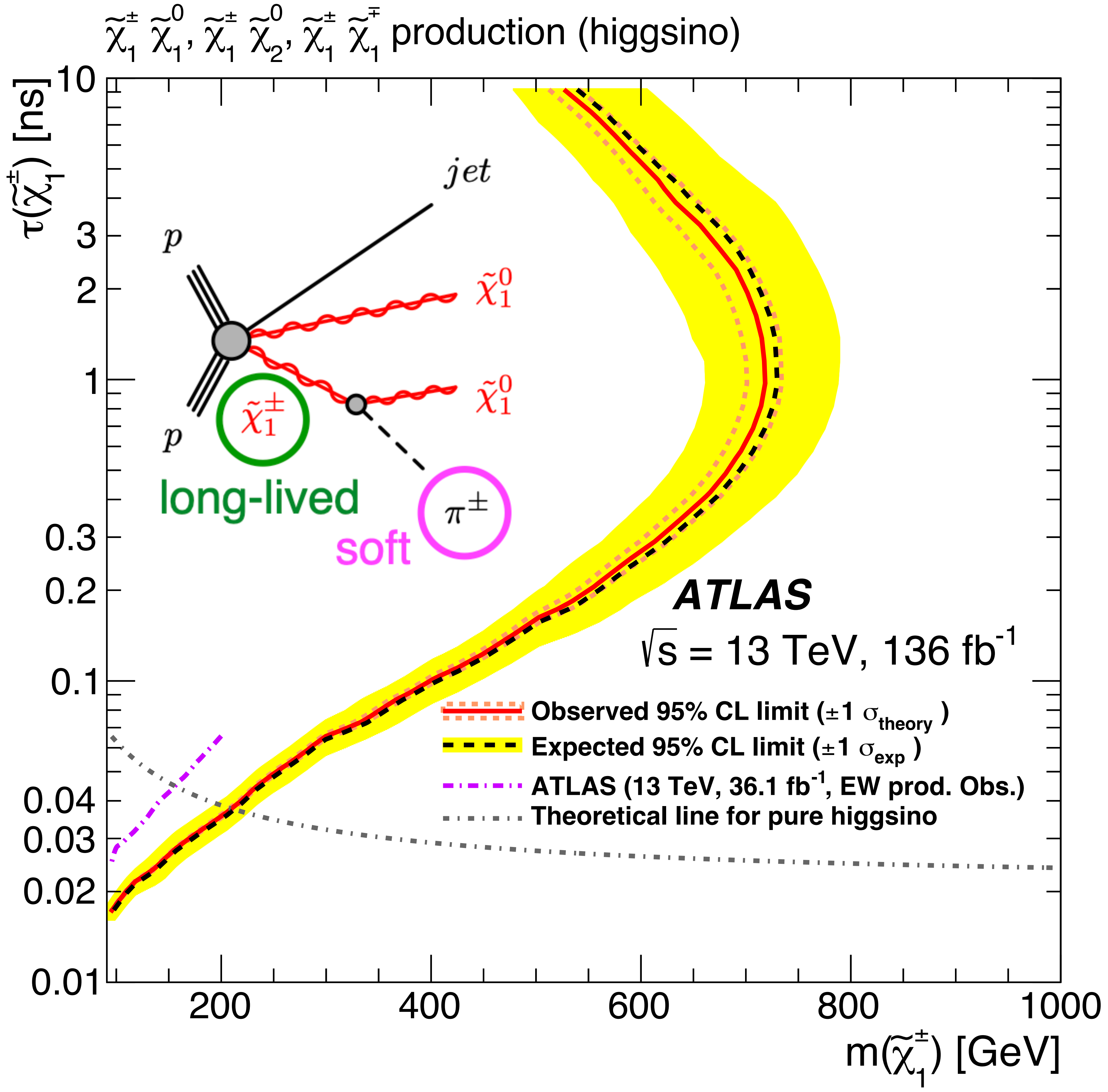
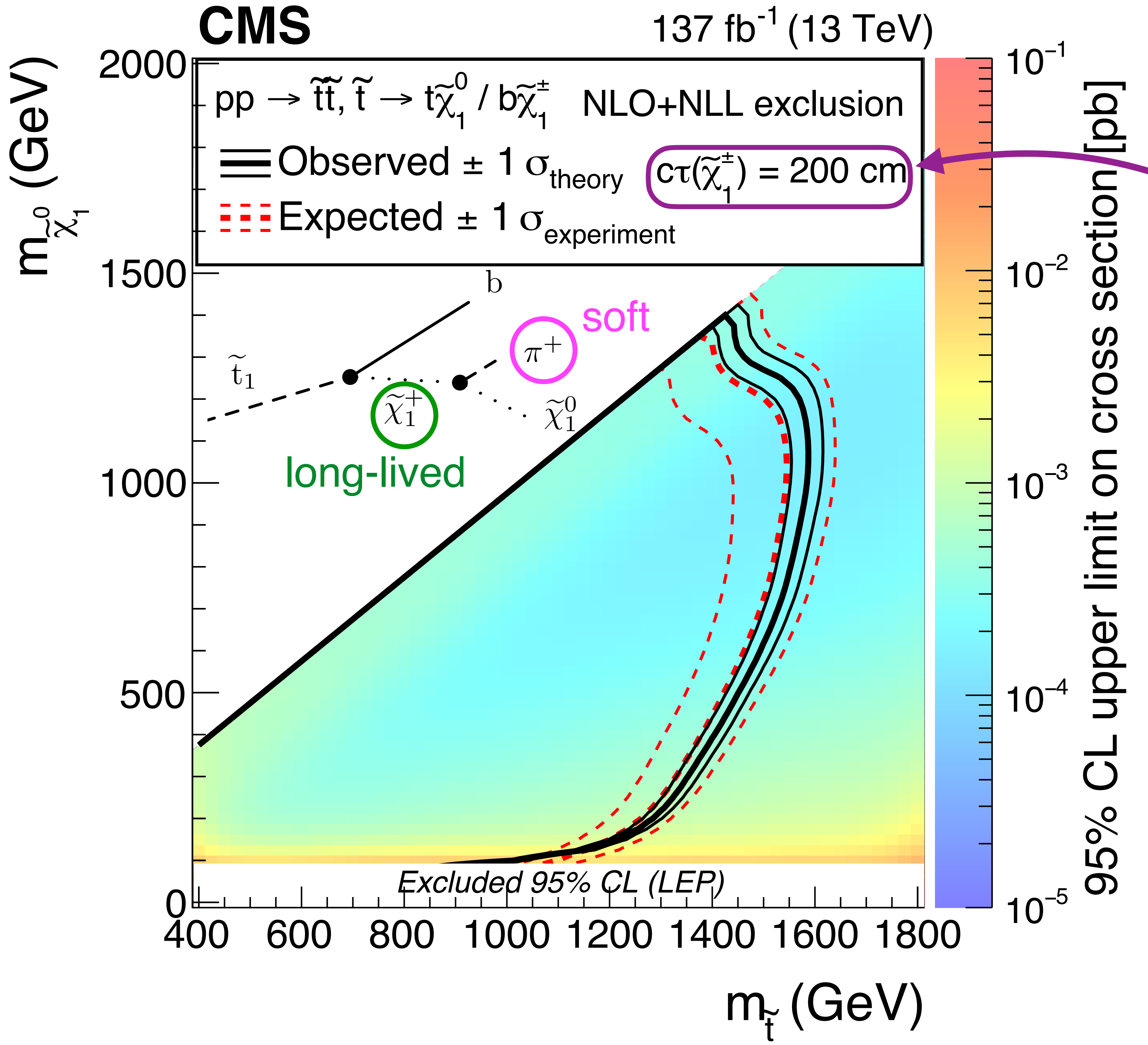


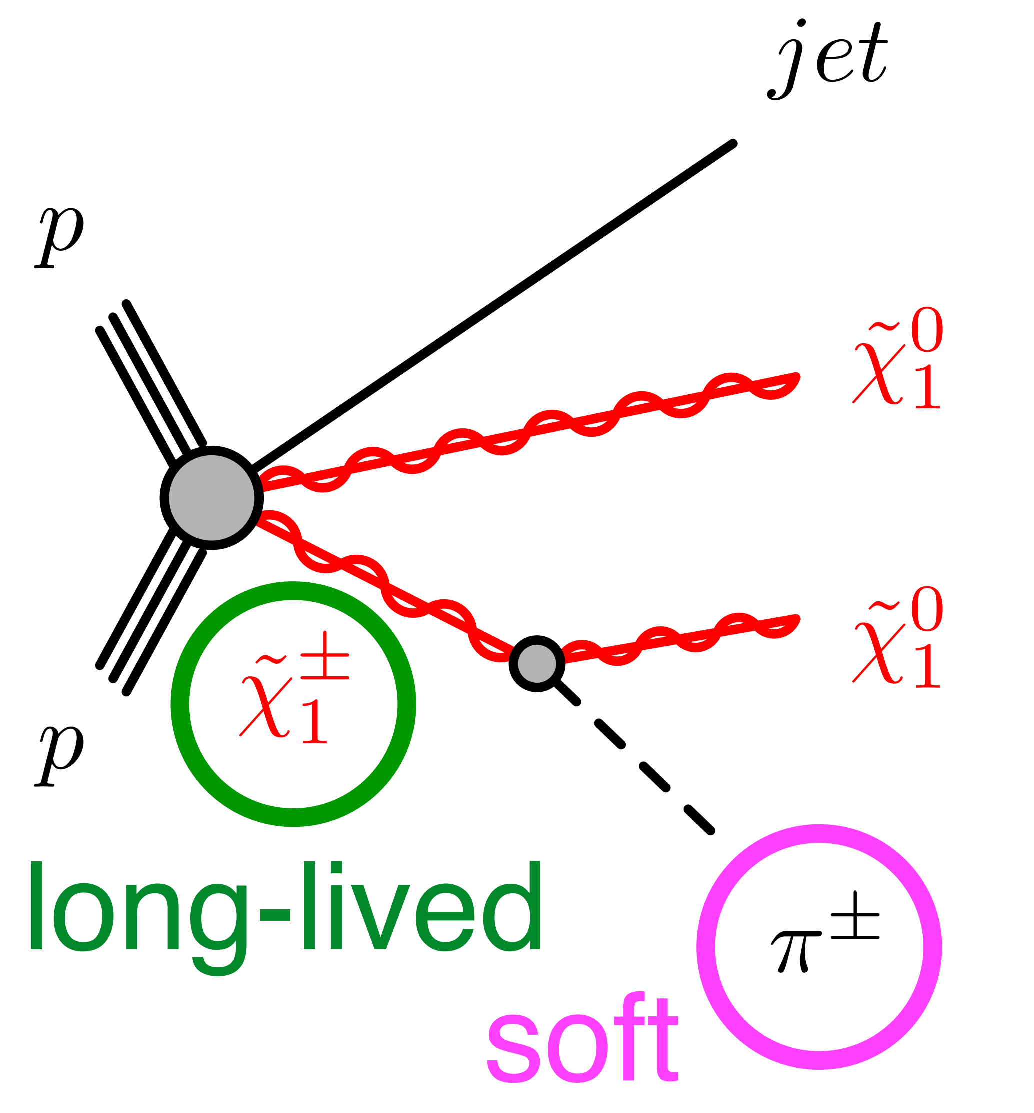

$\tilde{W}/\tilde{B}$ coannihilation scenarios

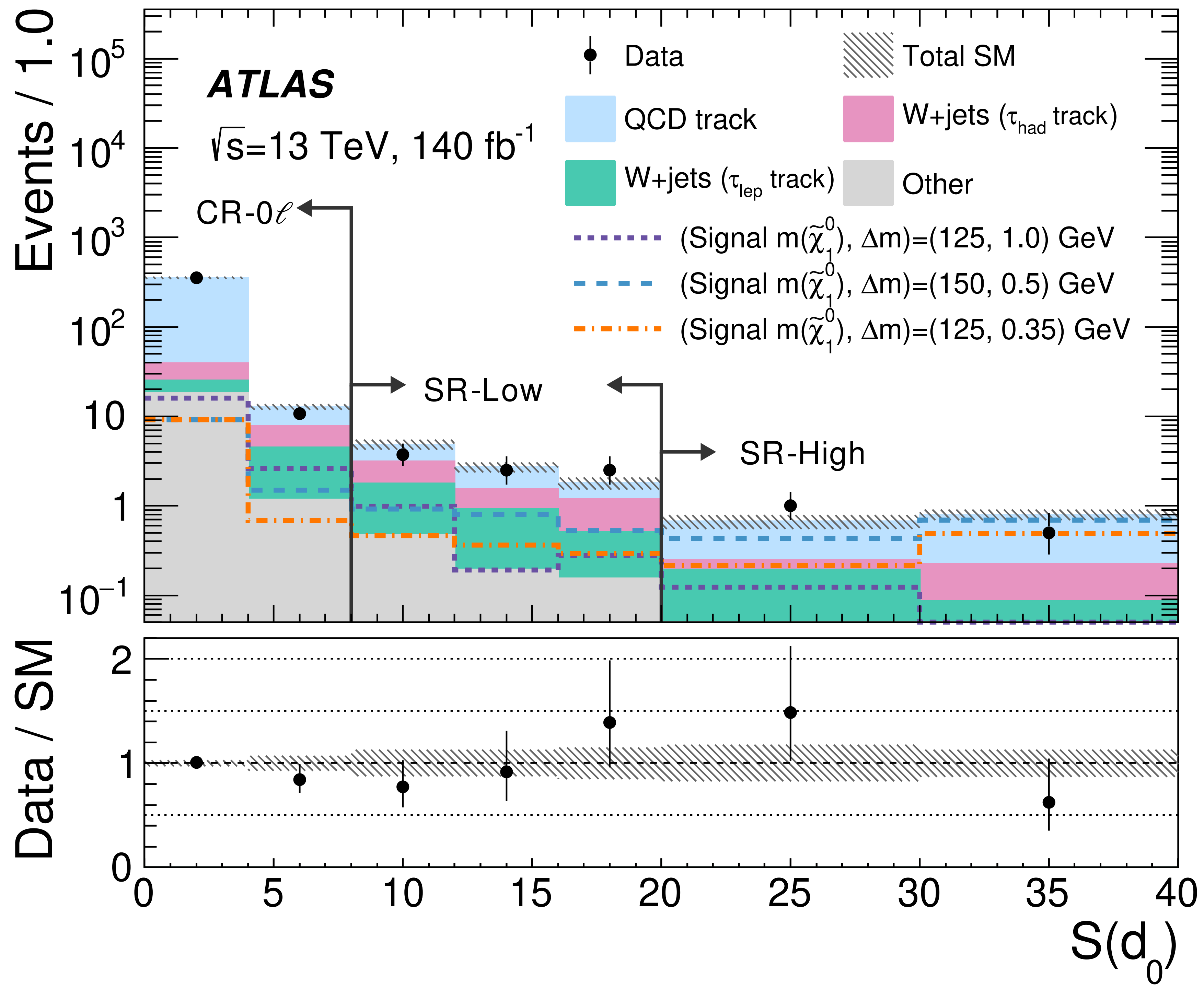
One ATLAS and two CMS searches w/ full Run 2; all also include $\tilde{W}$ interpretations.

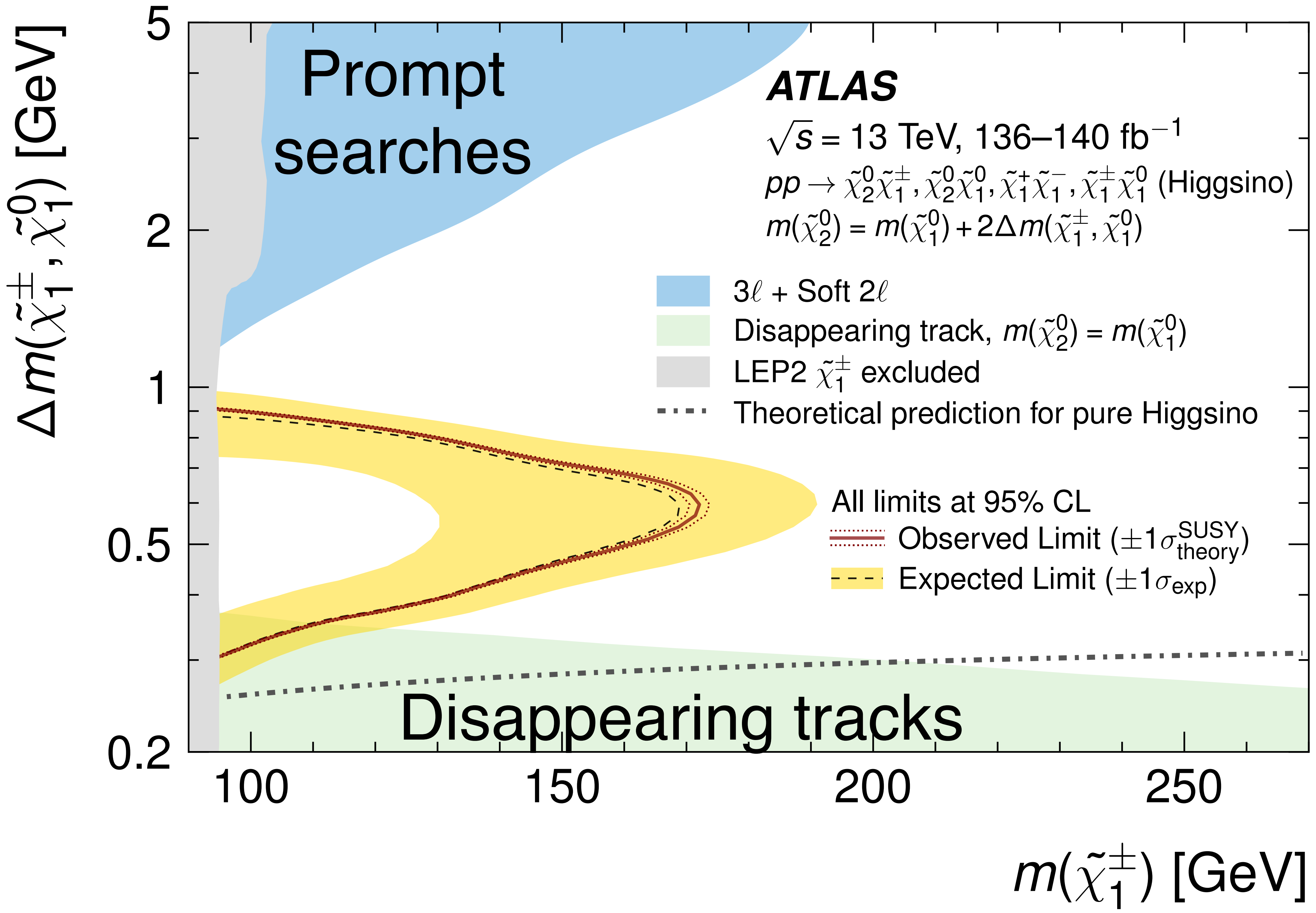
Most recent CMS search also includes additional production modes / signal models and use of dE/dx + a BDT to separate signal from background.

# ATLAS: Soft mildly-displaced tracks + huge MET

ATLAS SUSY-2020-04




*Same model, slightly larger mass splittings*: search relies on **MET > 600 GeV** to suppress W/Z+jets and QCD, with **track pT ∈ [2, 5] GeV** and **$|d_0| < 10$ mm**.

Probes the gap between disappearing track and prompt Higgsino searches!

# dE/dx (+ MET) searches

ATLAS SUSY-2018-42
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CMS EXO-18-002

Heavy charged particles travel slowly and ionize detector *much more* than a MIP.

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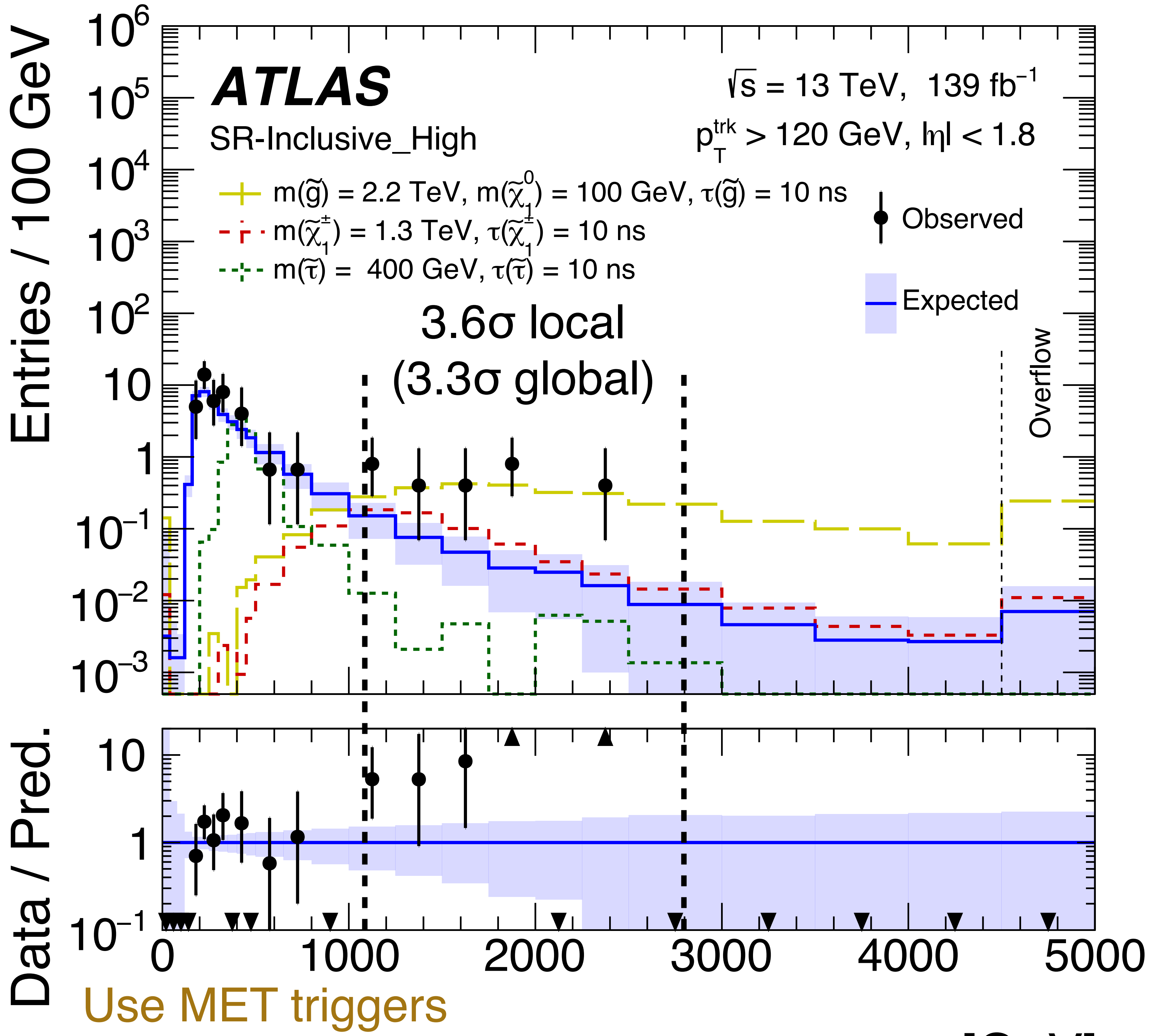


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>1/2 of excess reco'd as muons

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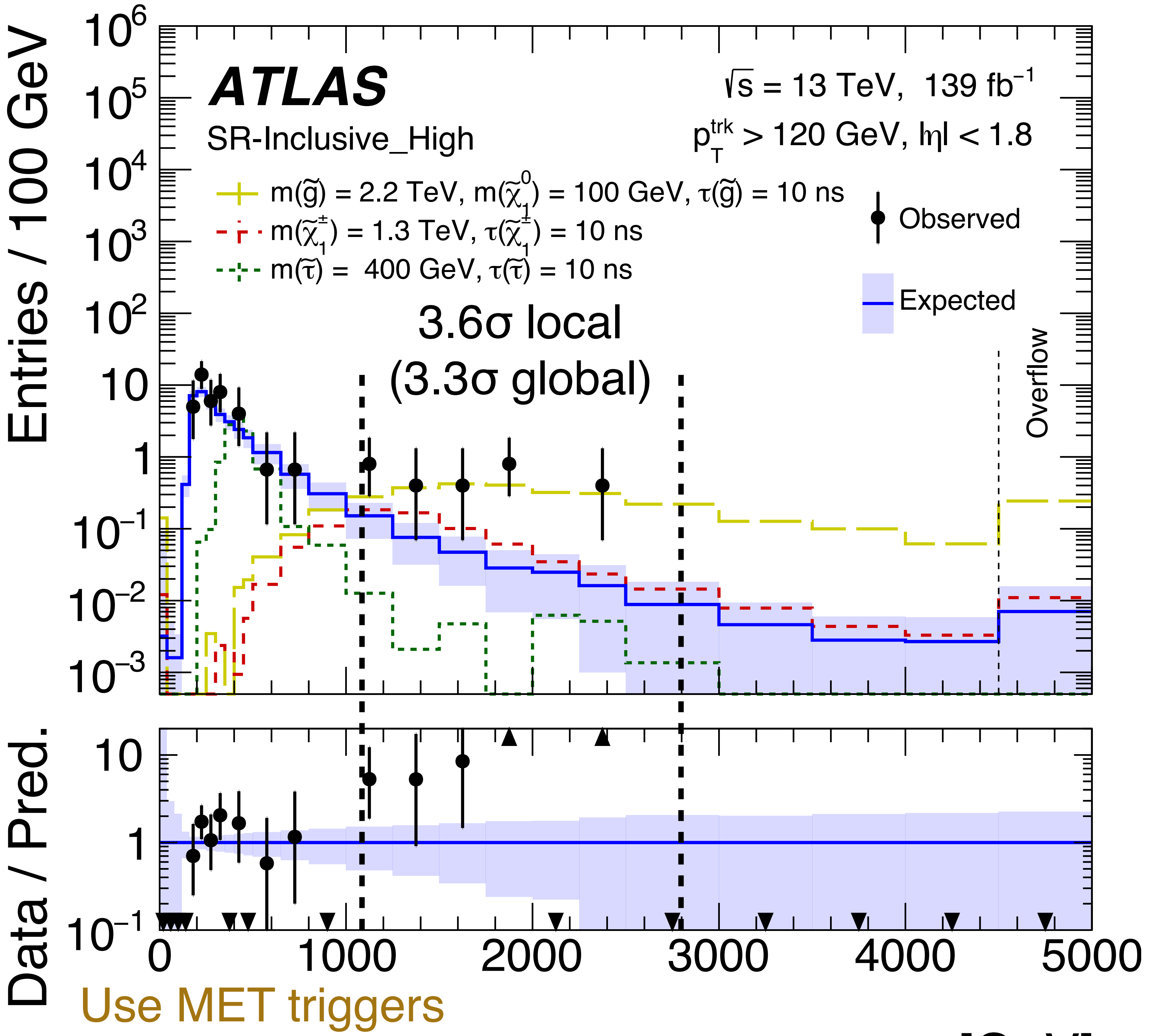


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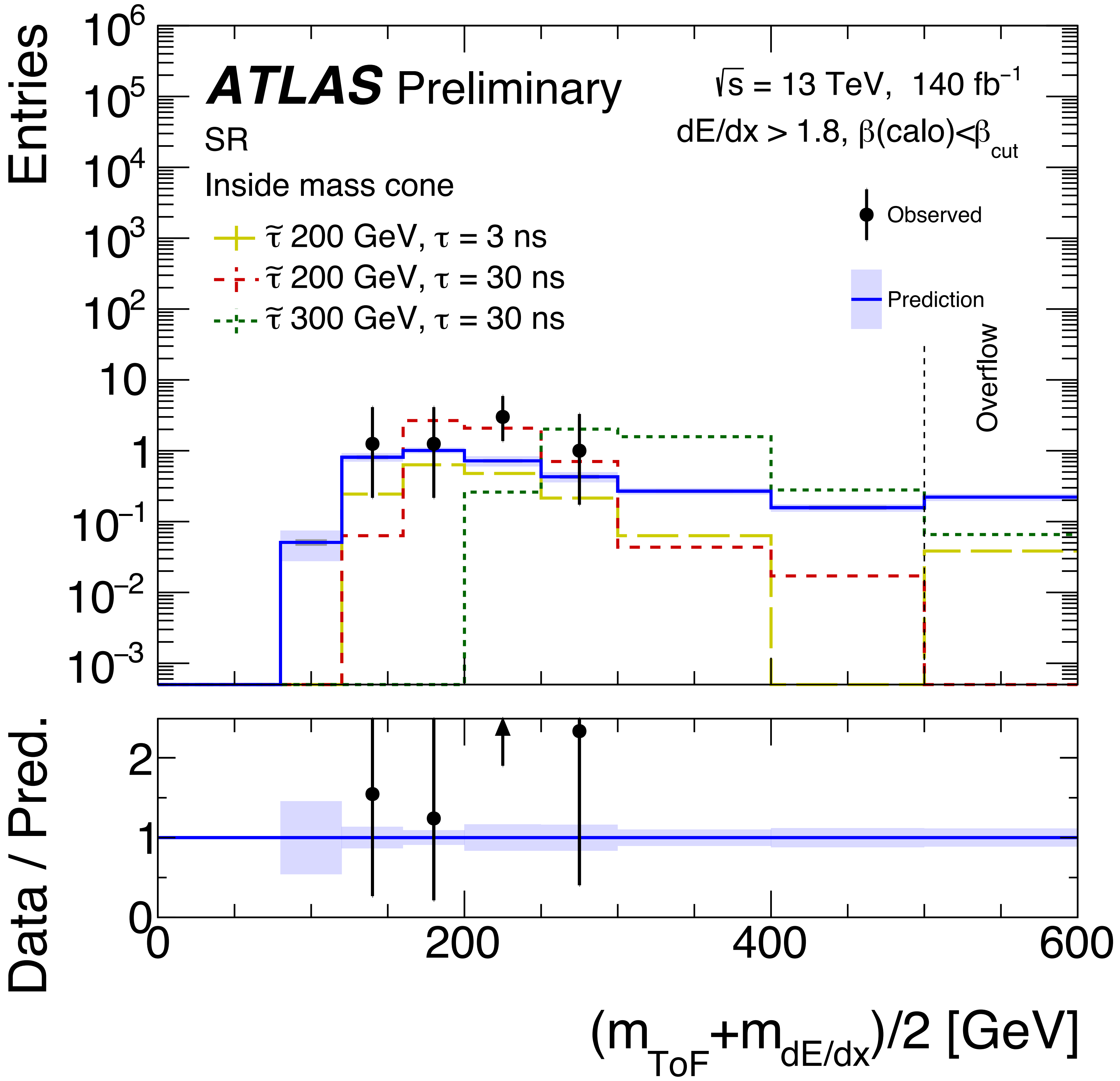


Additional ATLAS search; requires $\beta_{TOF} \lesssim 0.75\text{-}0.9$

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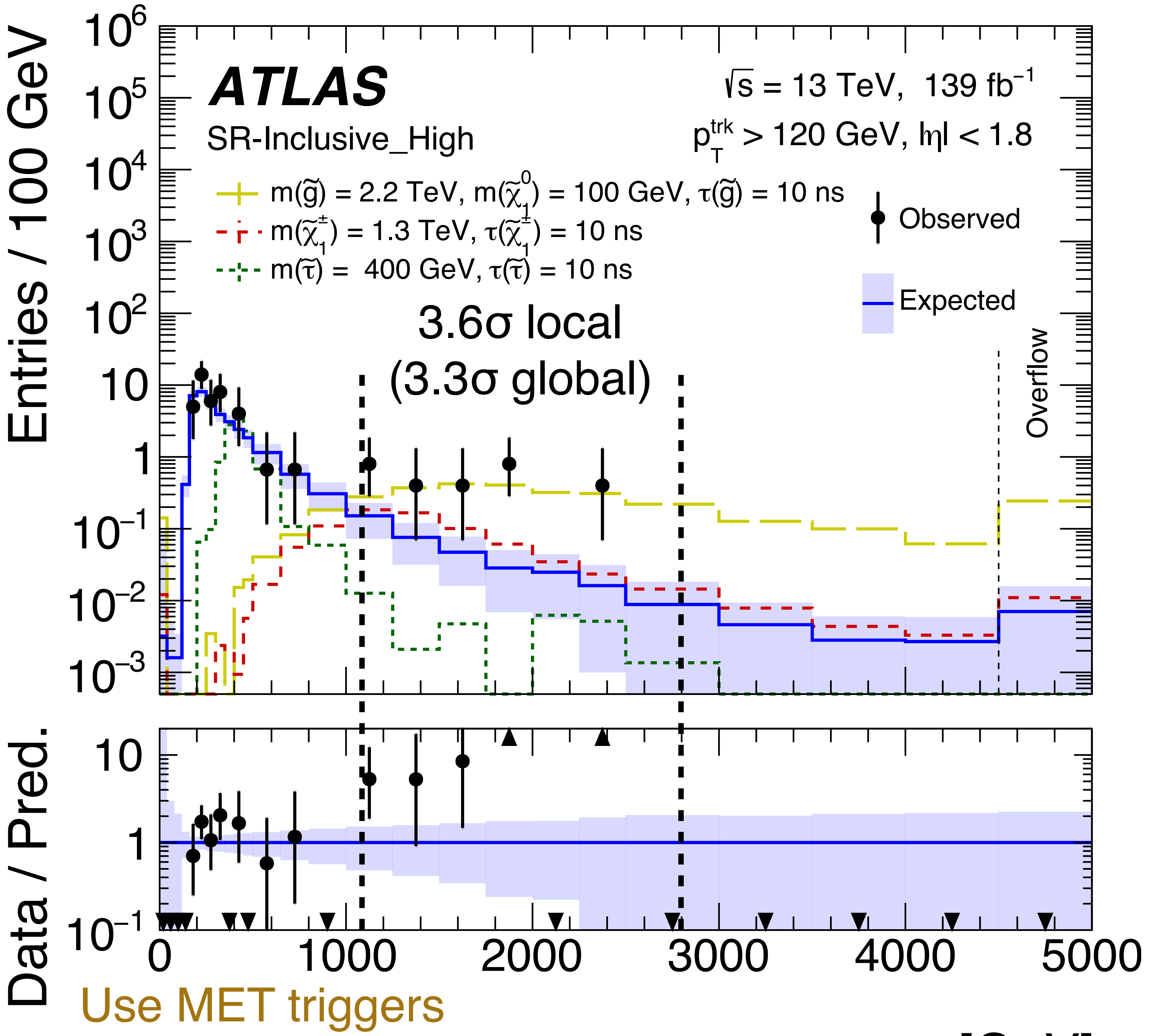


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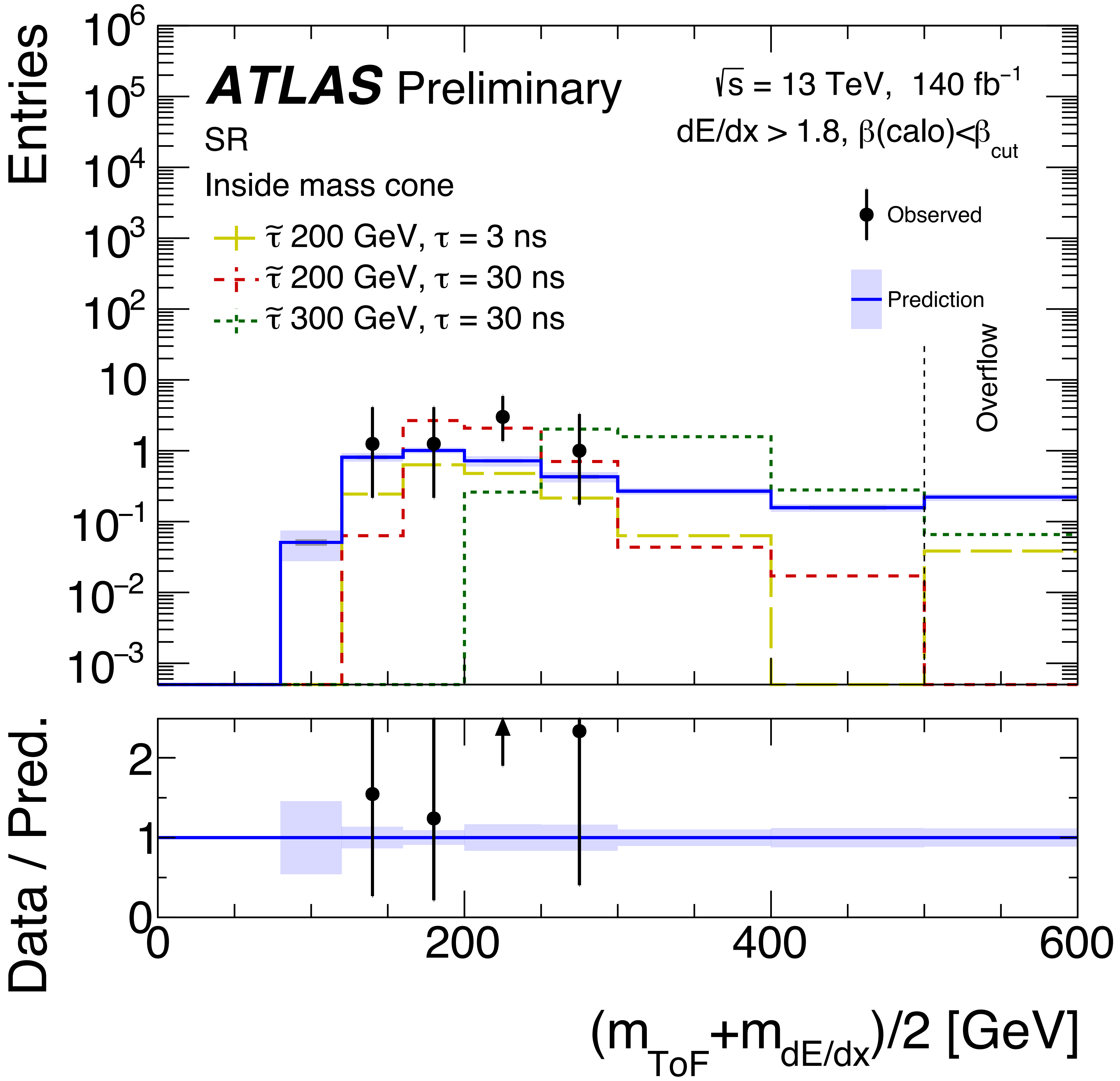


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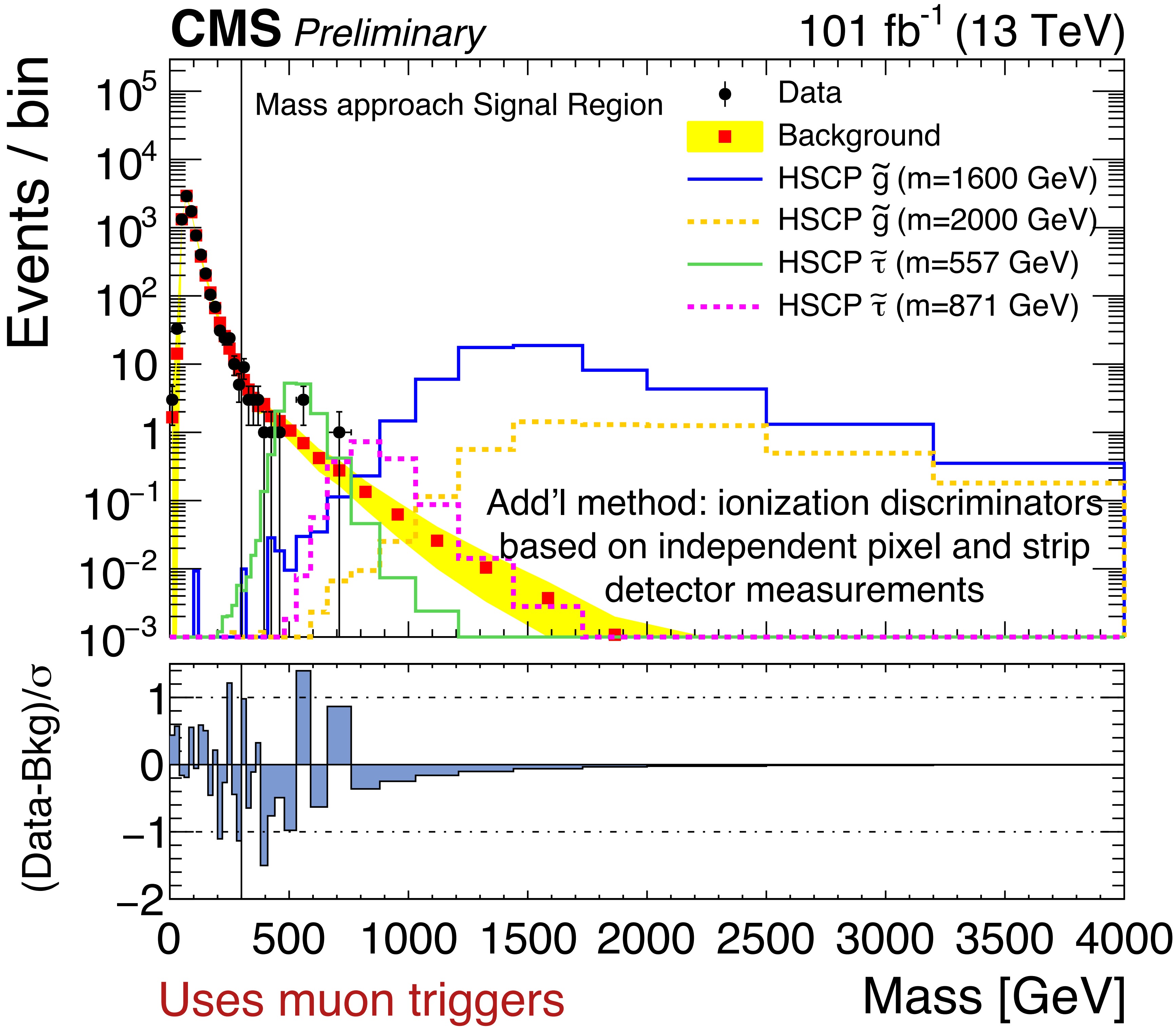


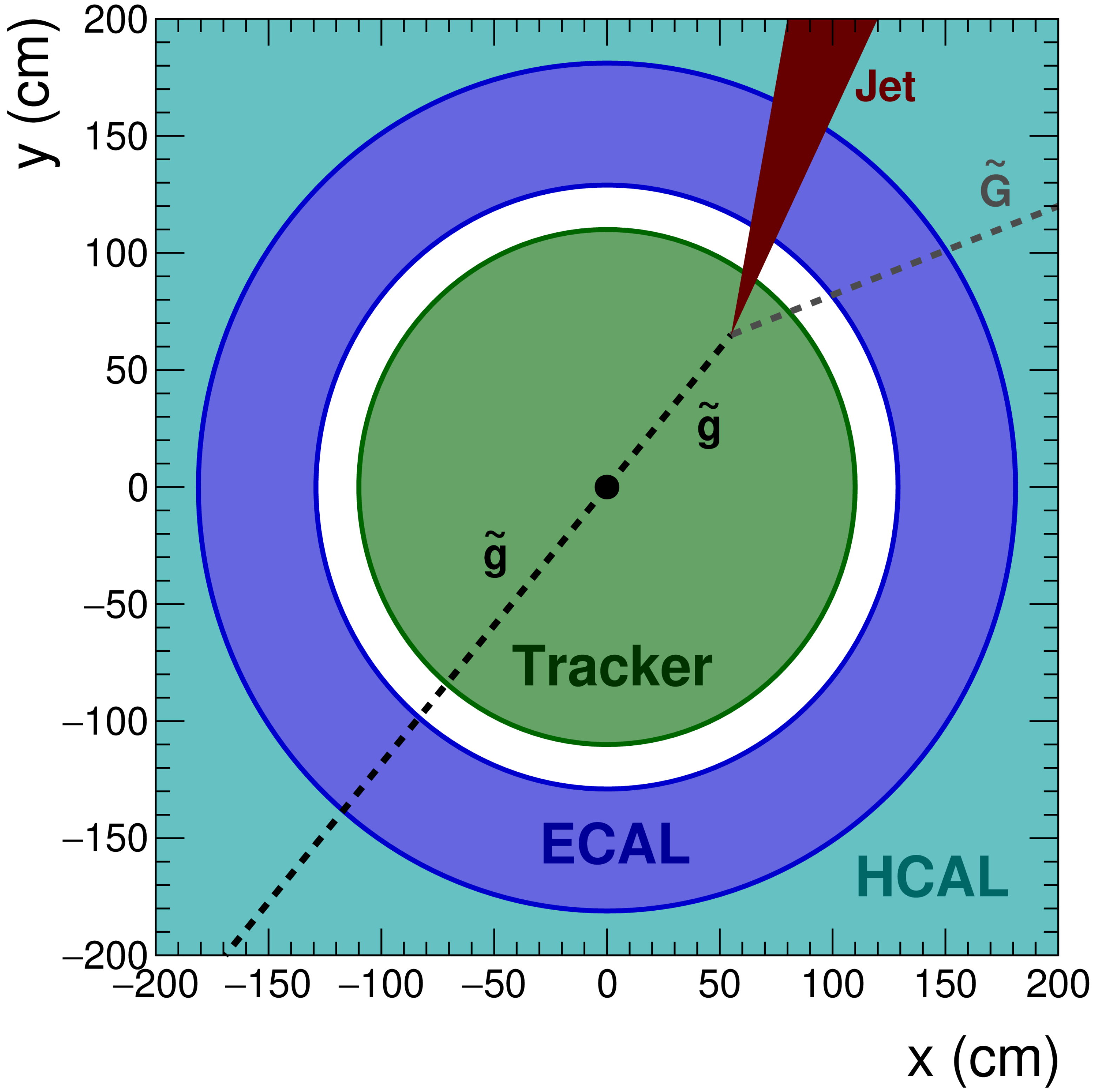

Uses muon triggers
CMS cannot confirm the excess
Many models considered, by both experiments!

# Delayed signatures + MET

ATLAS SUSY-2019-14
ATLAS SUSY-2020-28
CMS EXO-19-001
CMS EXO-19-005
CMS EXO-21-014

## Heavy LLPs travel slower than c $\Longrightarrow$ use ECAL timing to distinguish from SM!

Several searches with delayed γ or jets: $\mathcal{O}$(100s picoseconds) timing resolution, vs. few ns delay for TeV particle reaching ECAL



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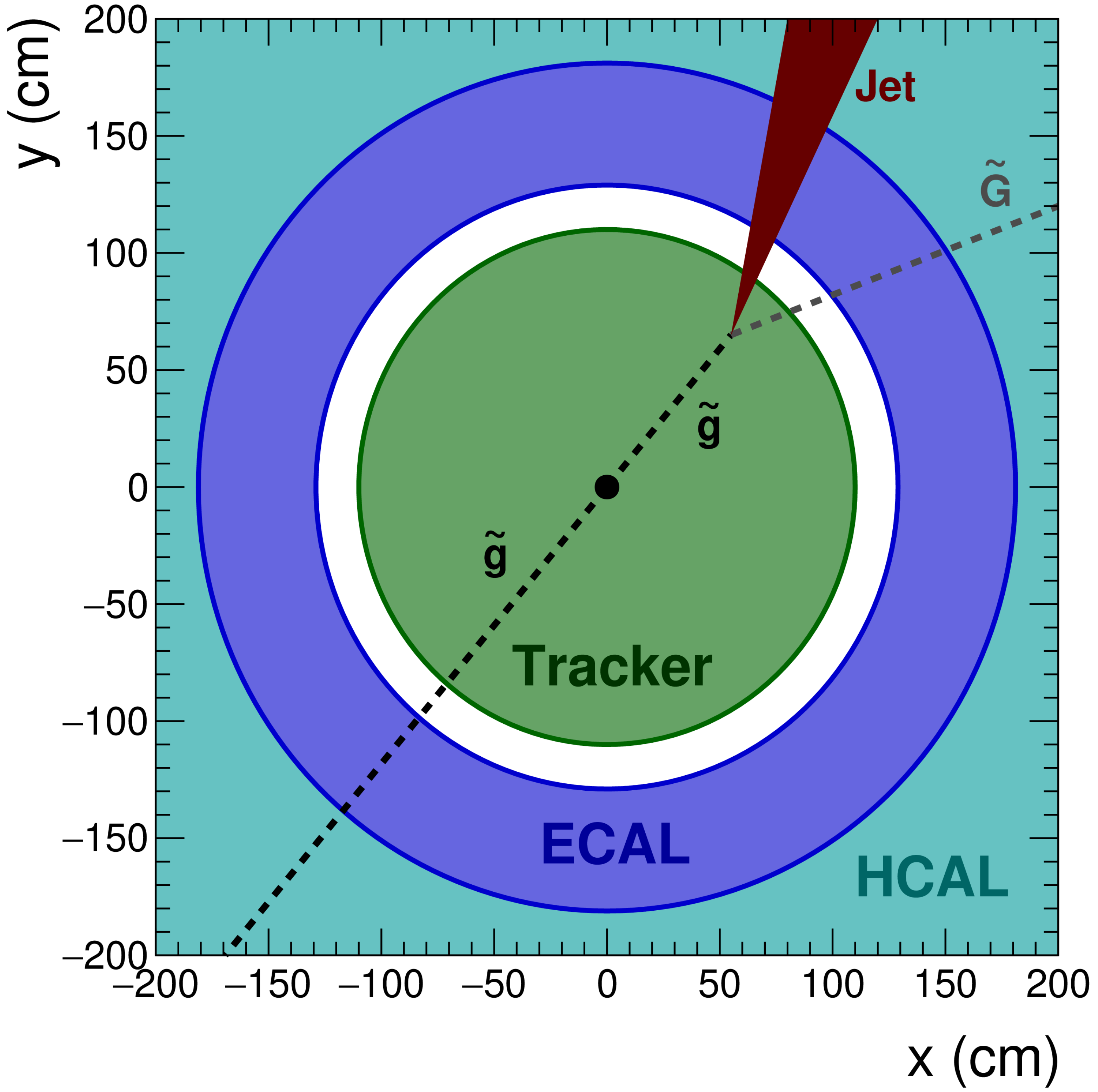


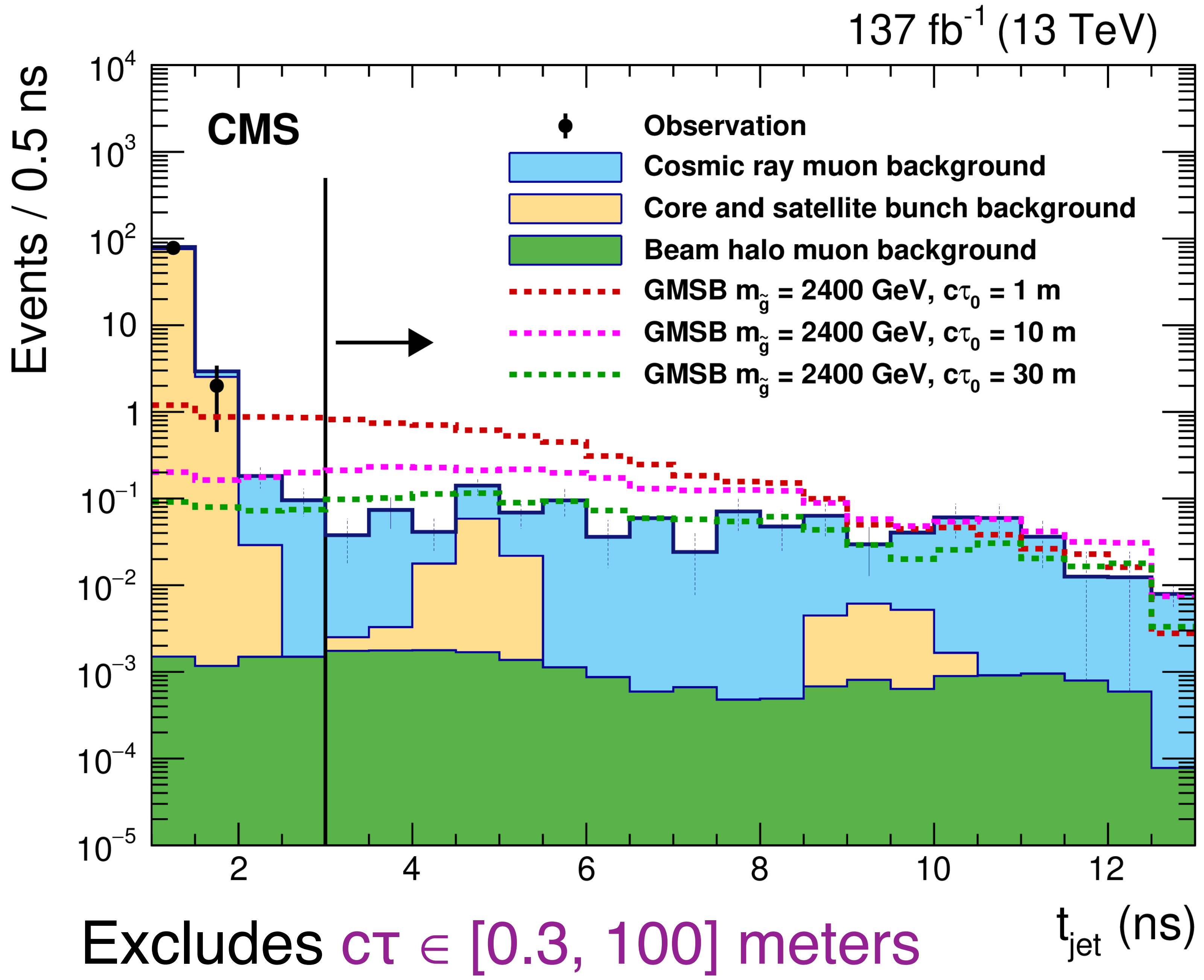

These signals will also have ~no tracks, which gives an extra handle for the jet signatures

- But do need to be careful: cosmics, beam halo, and various instrumental backgrounds must be handled

# CMS: Delayed / trackless jets + MET

CMS EXO-19-001
CMS EXO-21-014

High mass: directly require $t_{jet}$ > 3 ns and various timing quality criteria.

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for GMSB gluinos up to 1900 GeV

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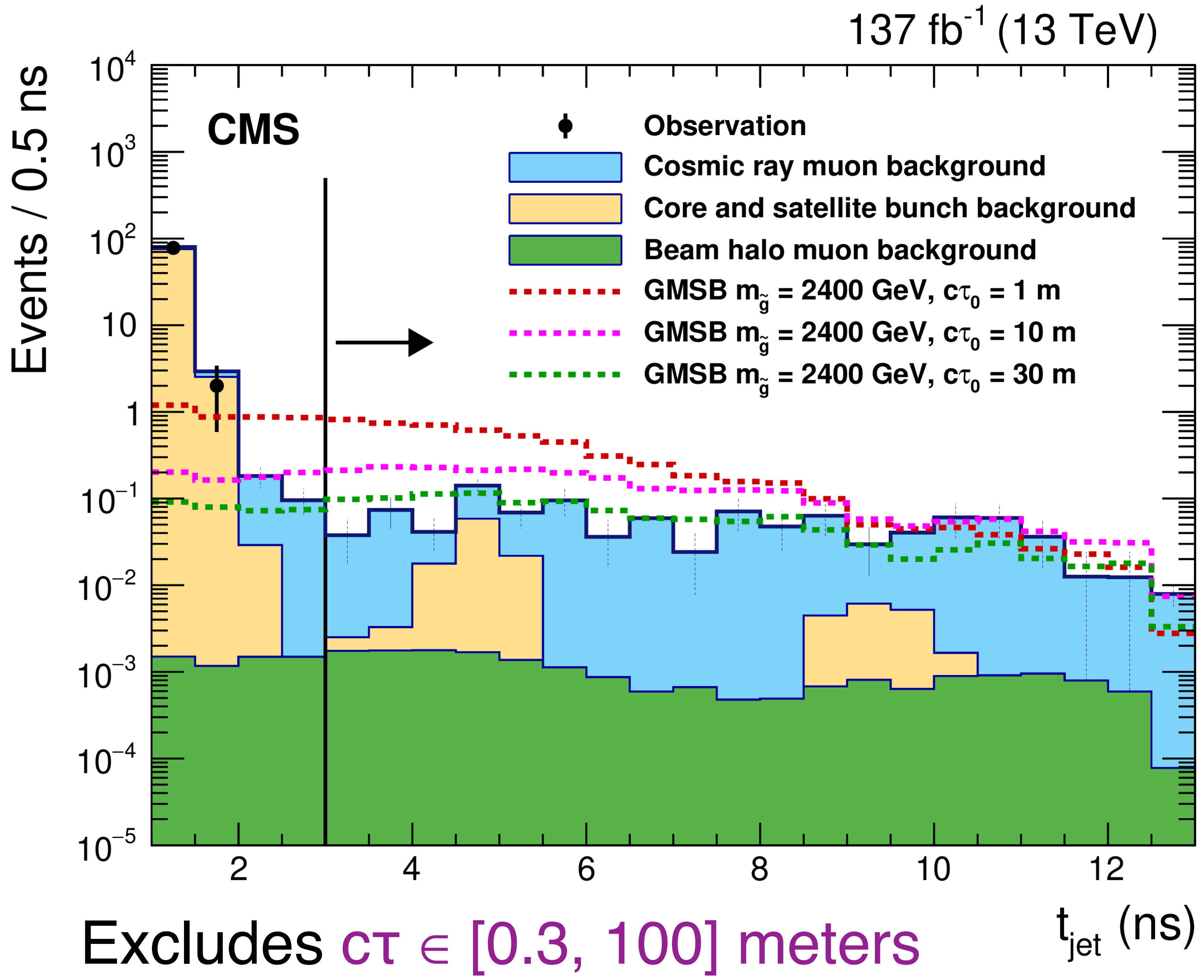
Low mass / cross sections: another search tags trackless/delayed ("TD") jets via DNN

- Based on timing, # of tracks and energy contributed to jets, and more
- Calibrate tagger efficiency w/ EM objects, timing w/ b-jets, and estimate bkg w/ 1-tagged events

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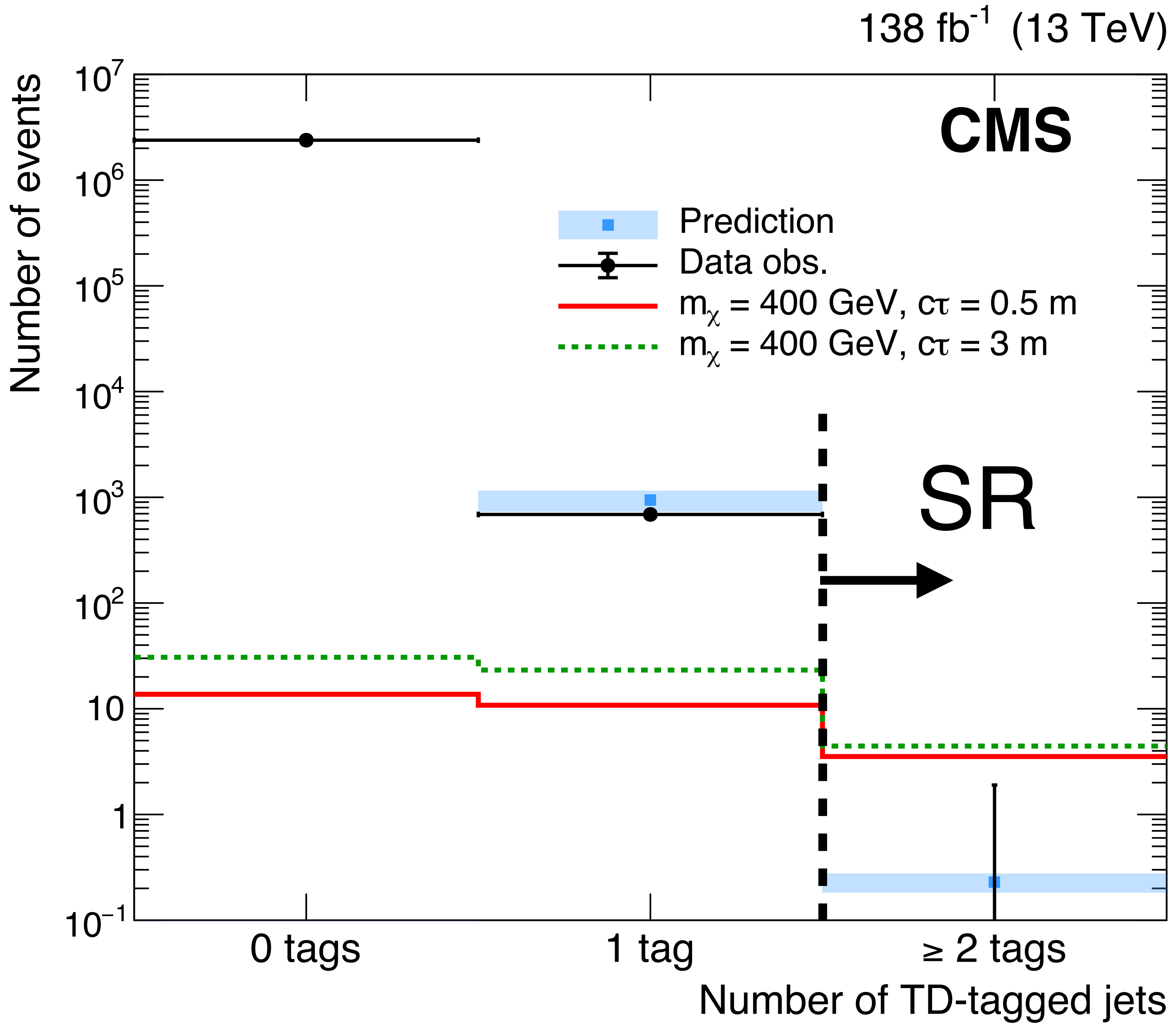


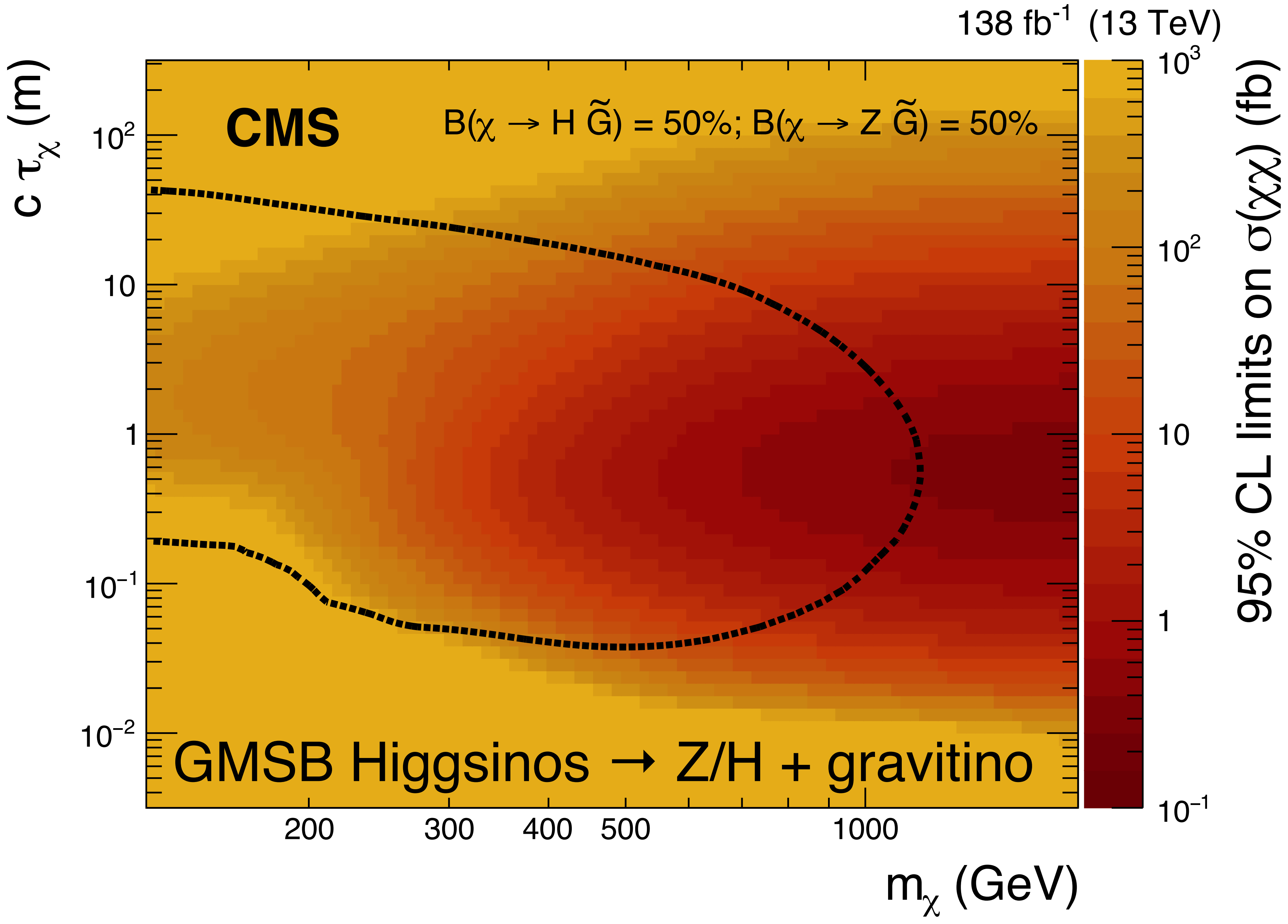

# Non-pointing / delayed photons + MET

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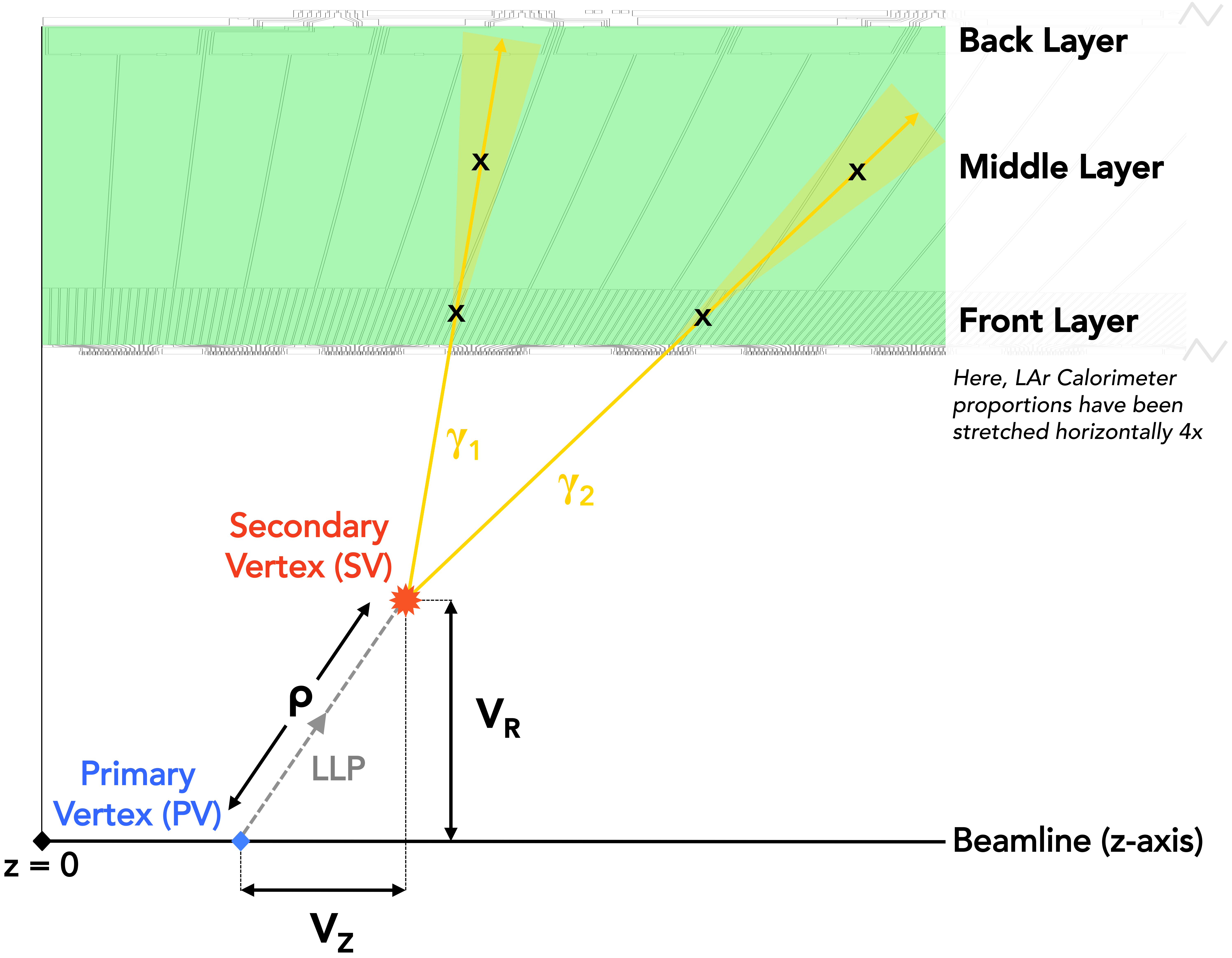


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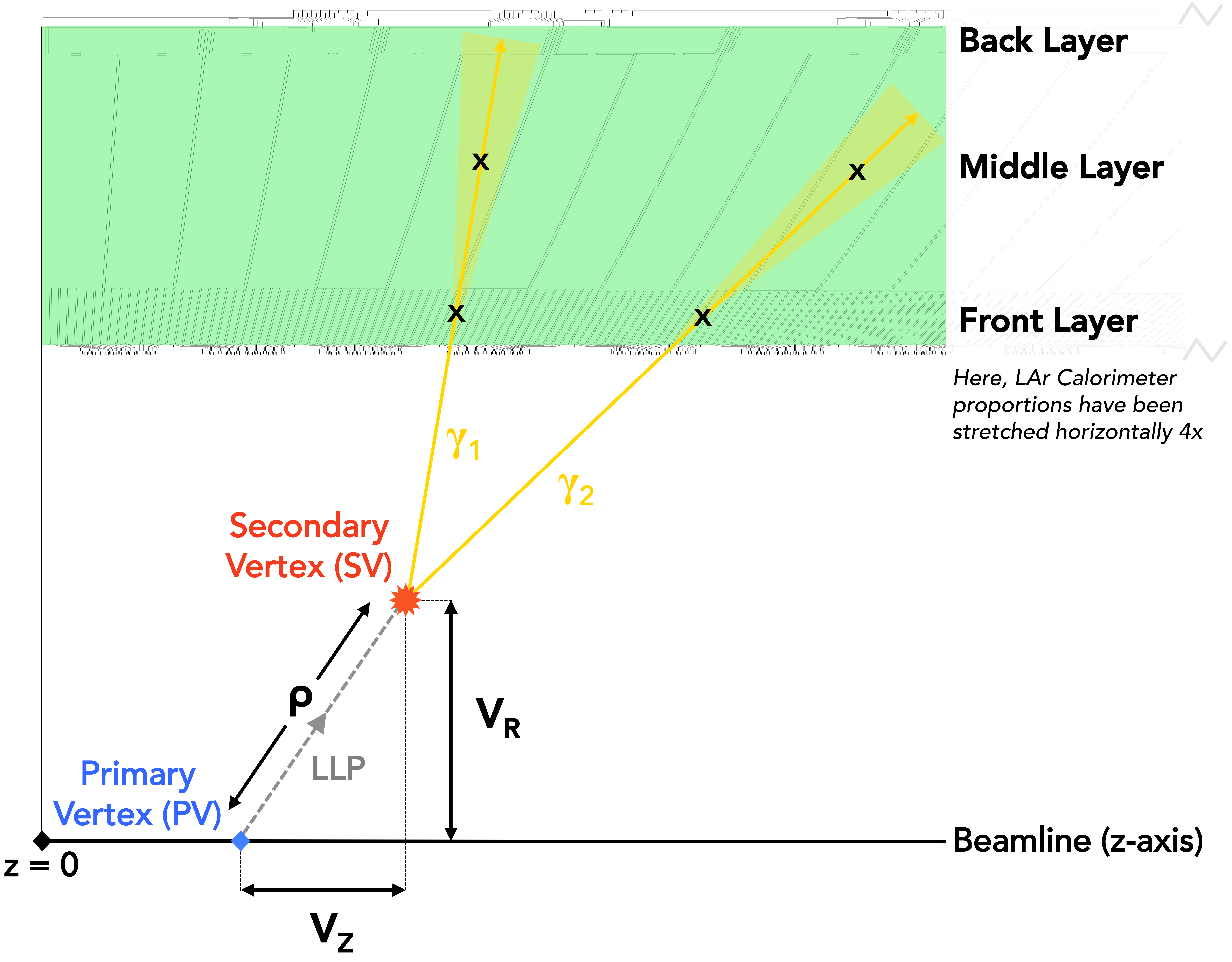


Characteristics of photons from LLP decays:

1) Arrive at ECAL with a delay (i.e. use timing info)

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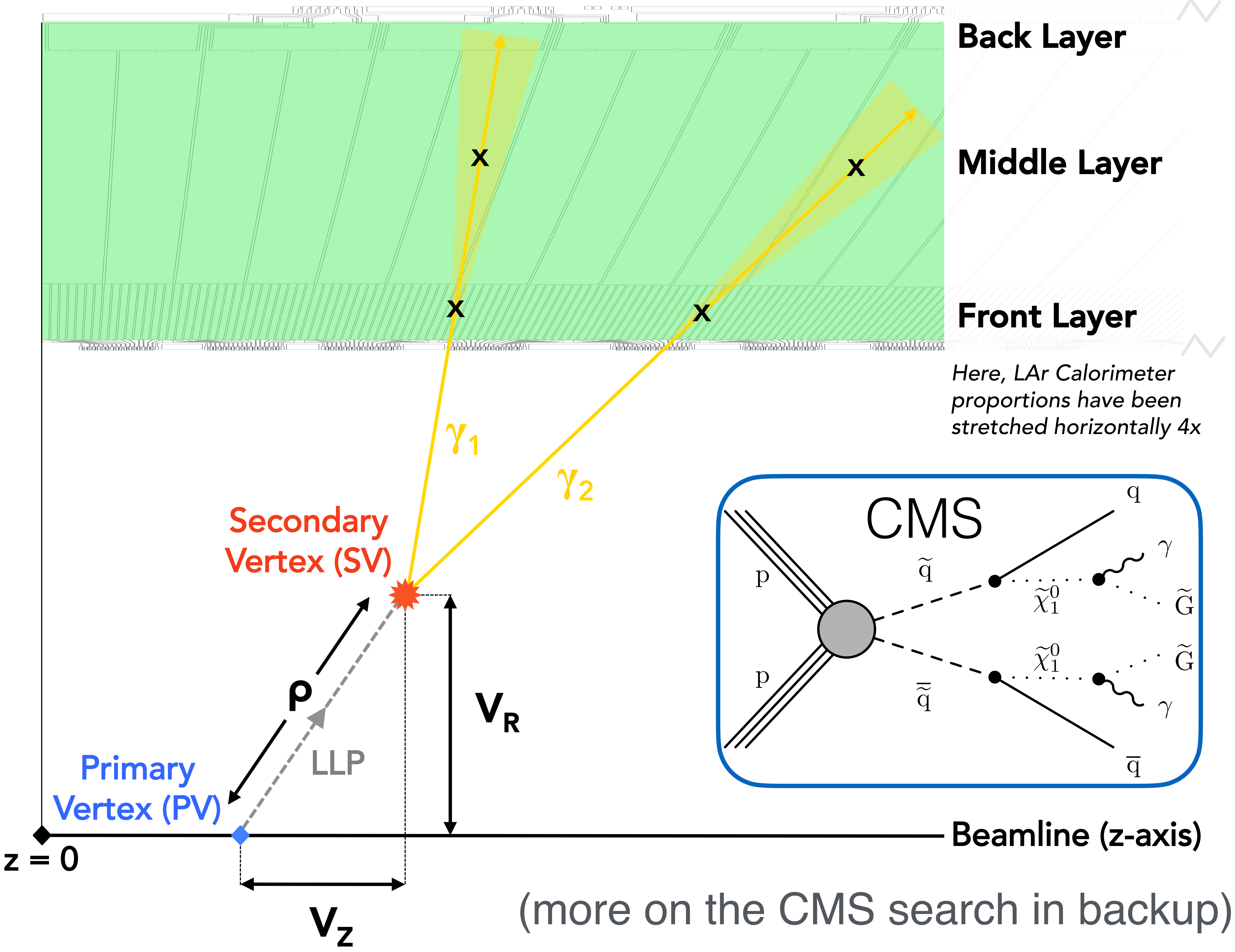


(more on the CMS search in backup)

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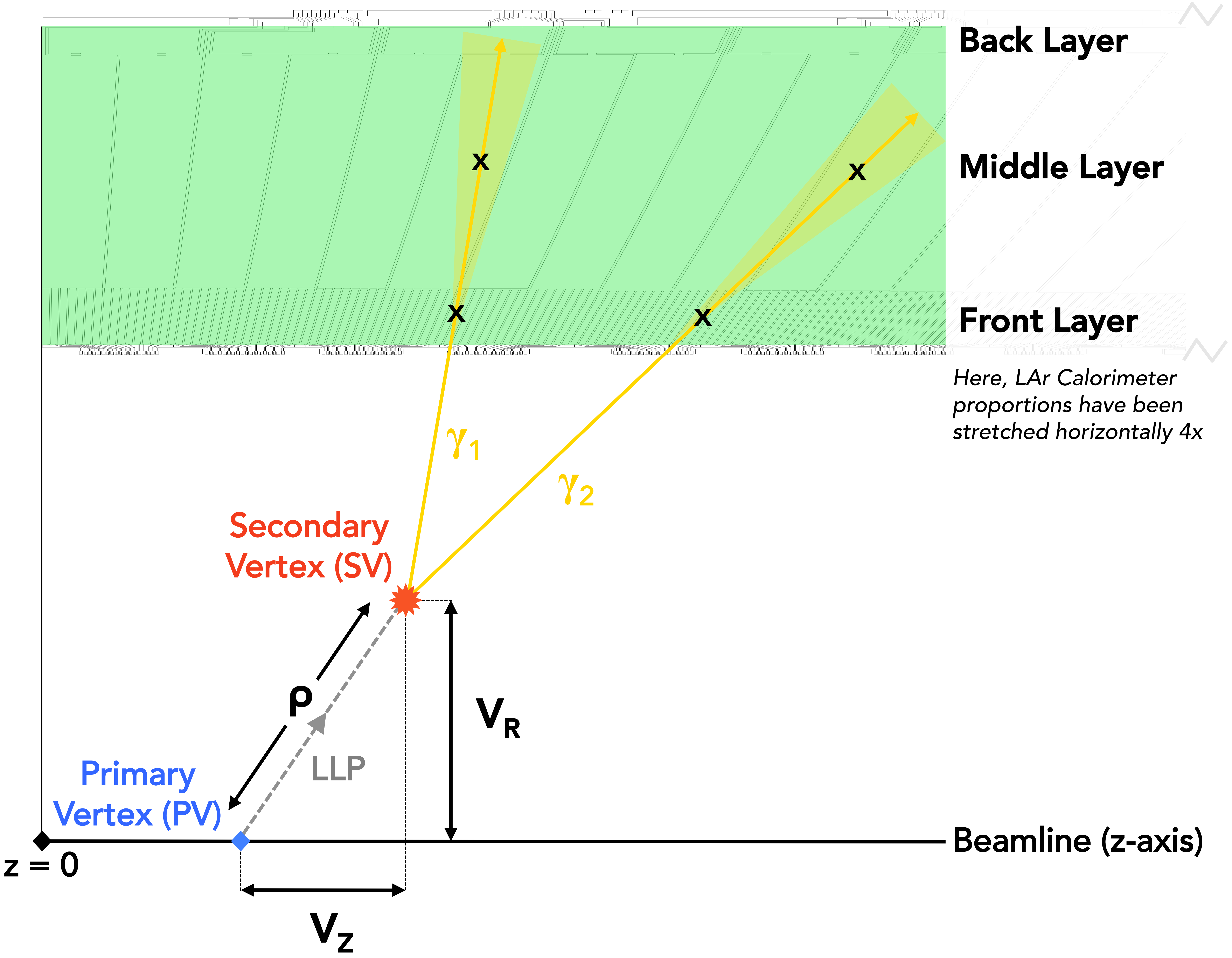


*Here, LAr Calorimeter proportions have been stretched horizontally 4x*

Characteristics of photons from LLP decays:

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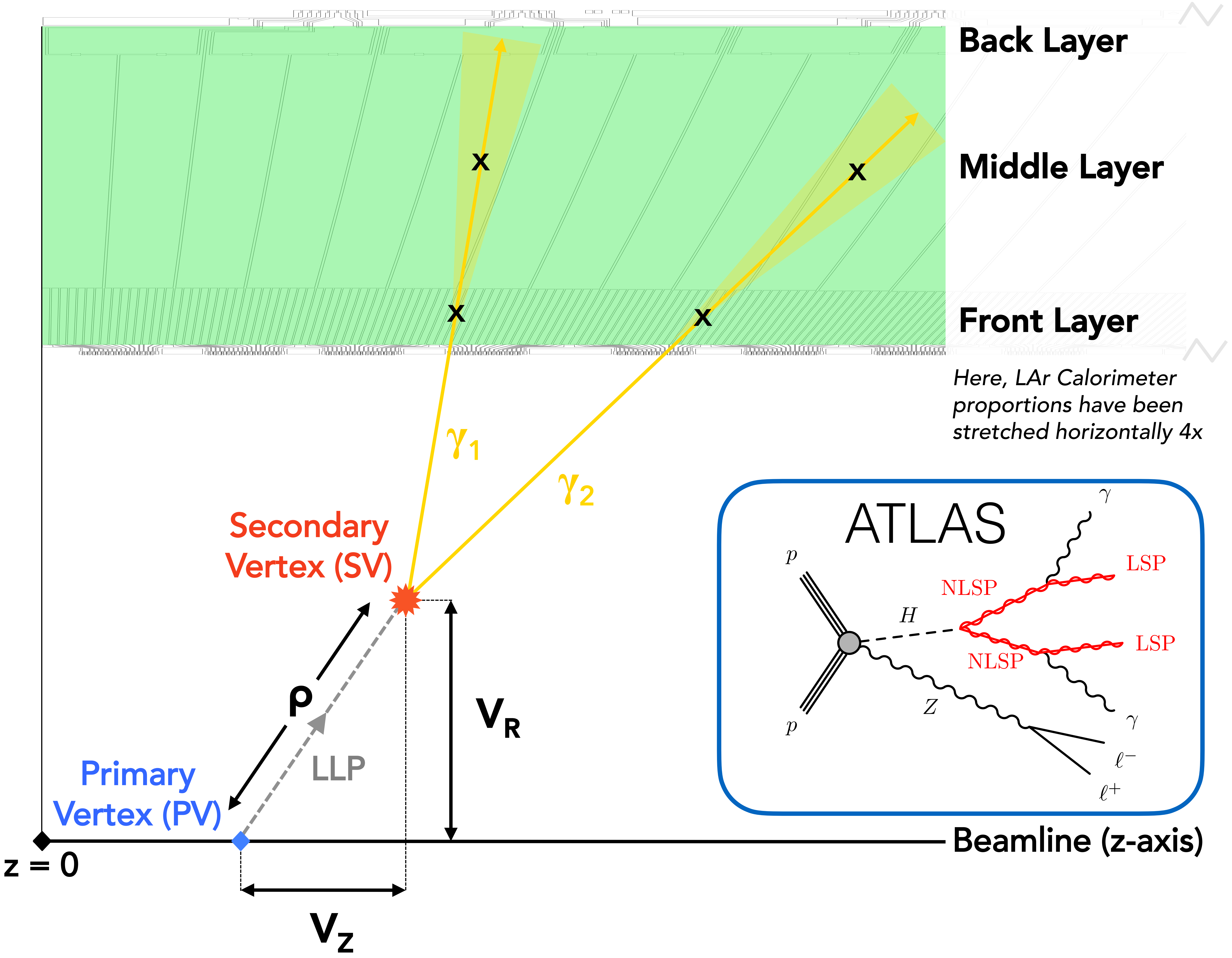


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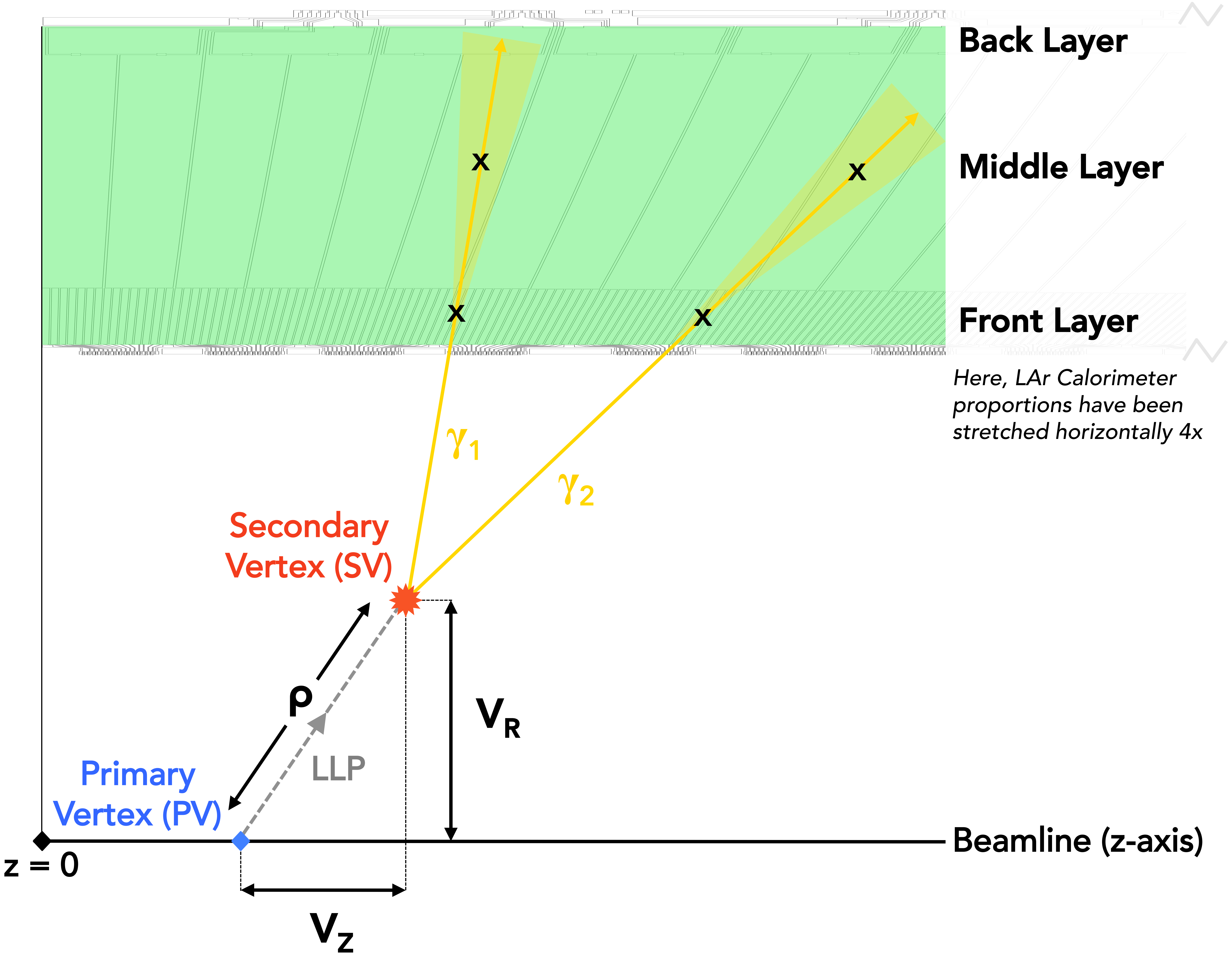


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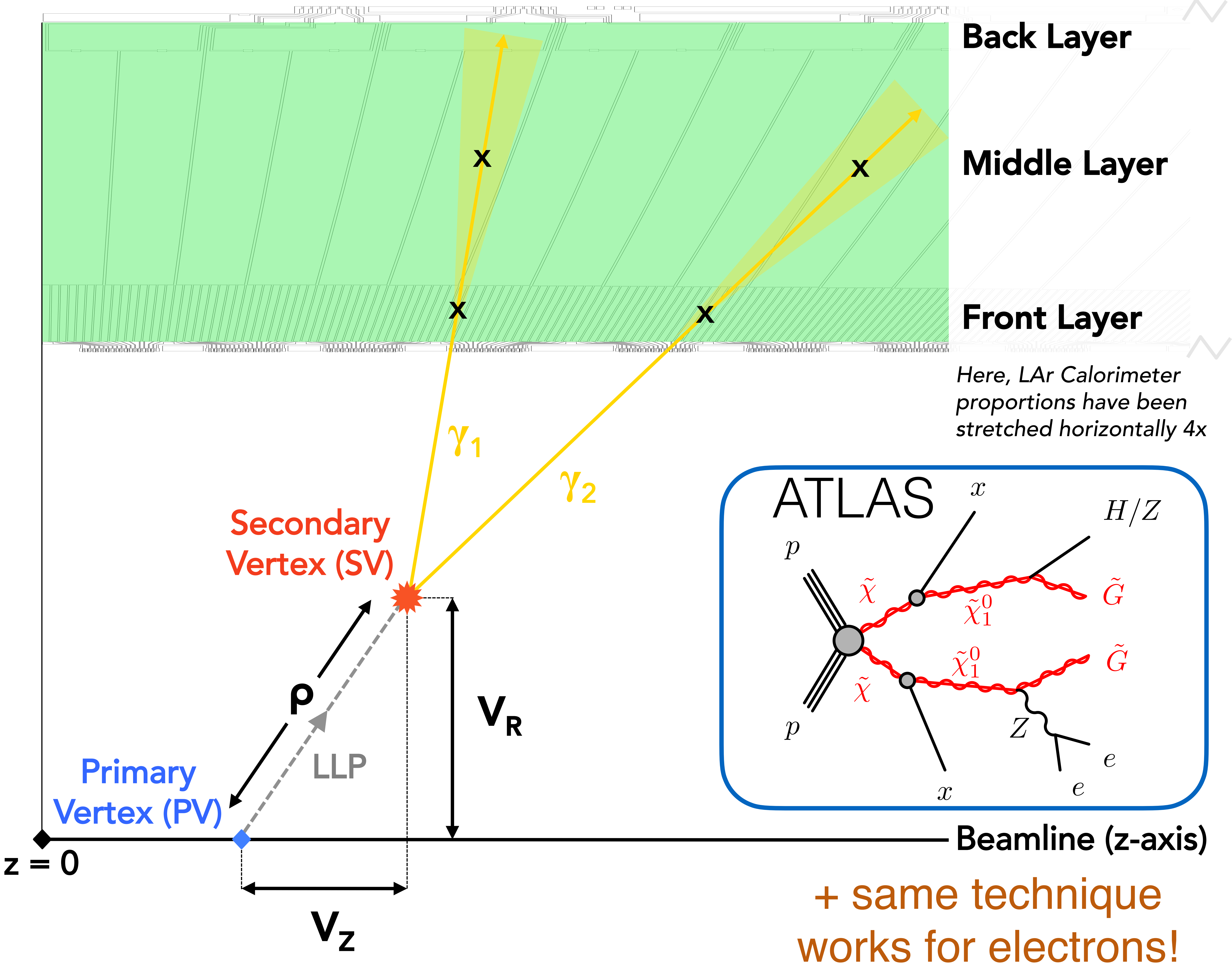


+ same technique works for electrons!

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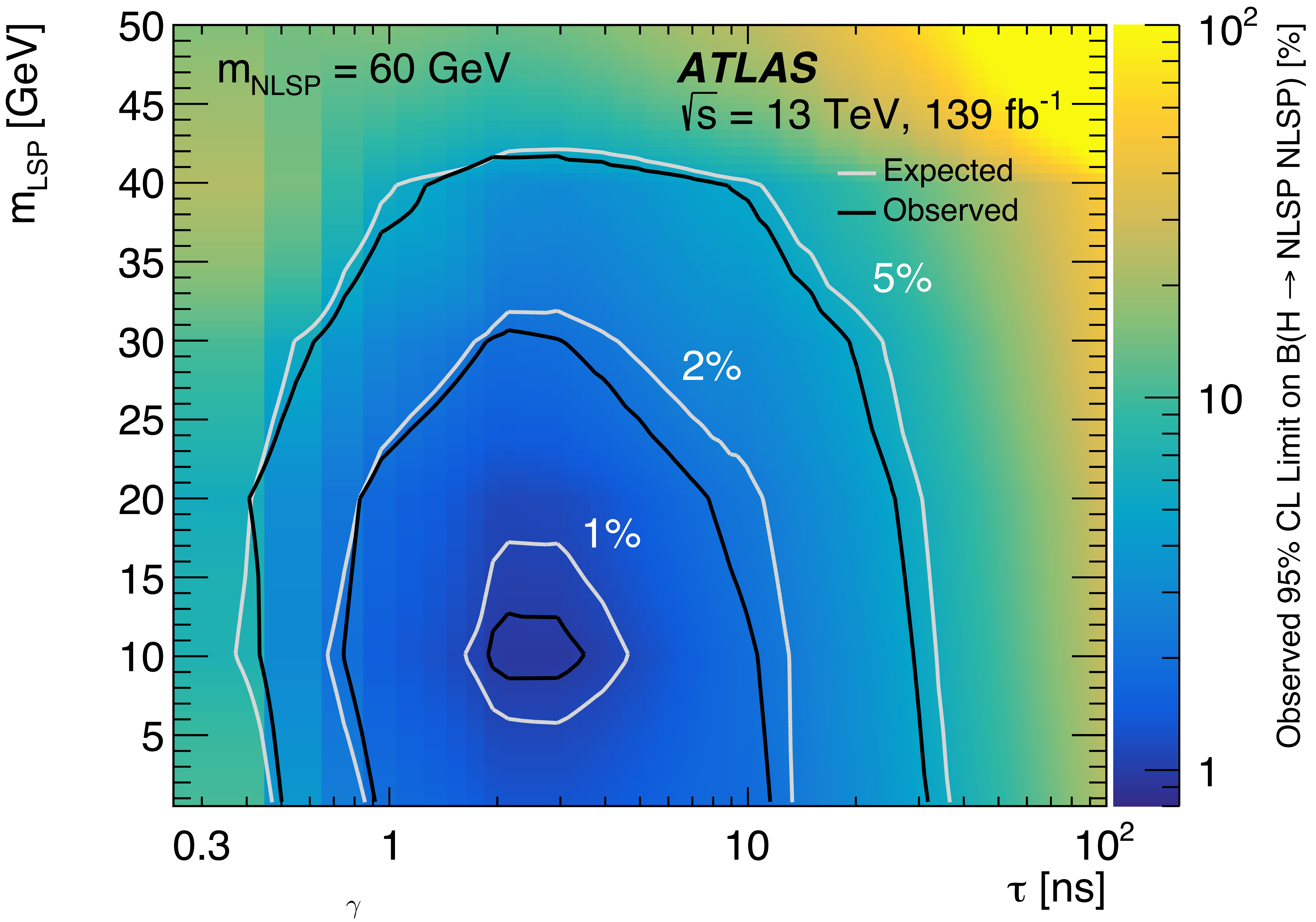
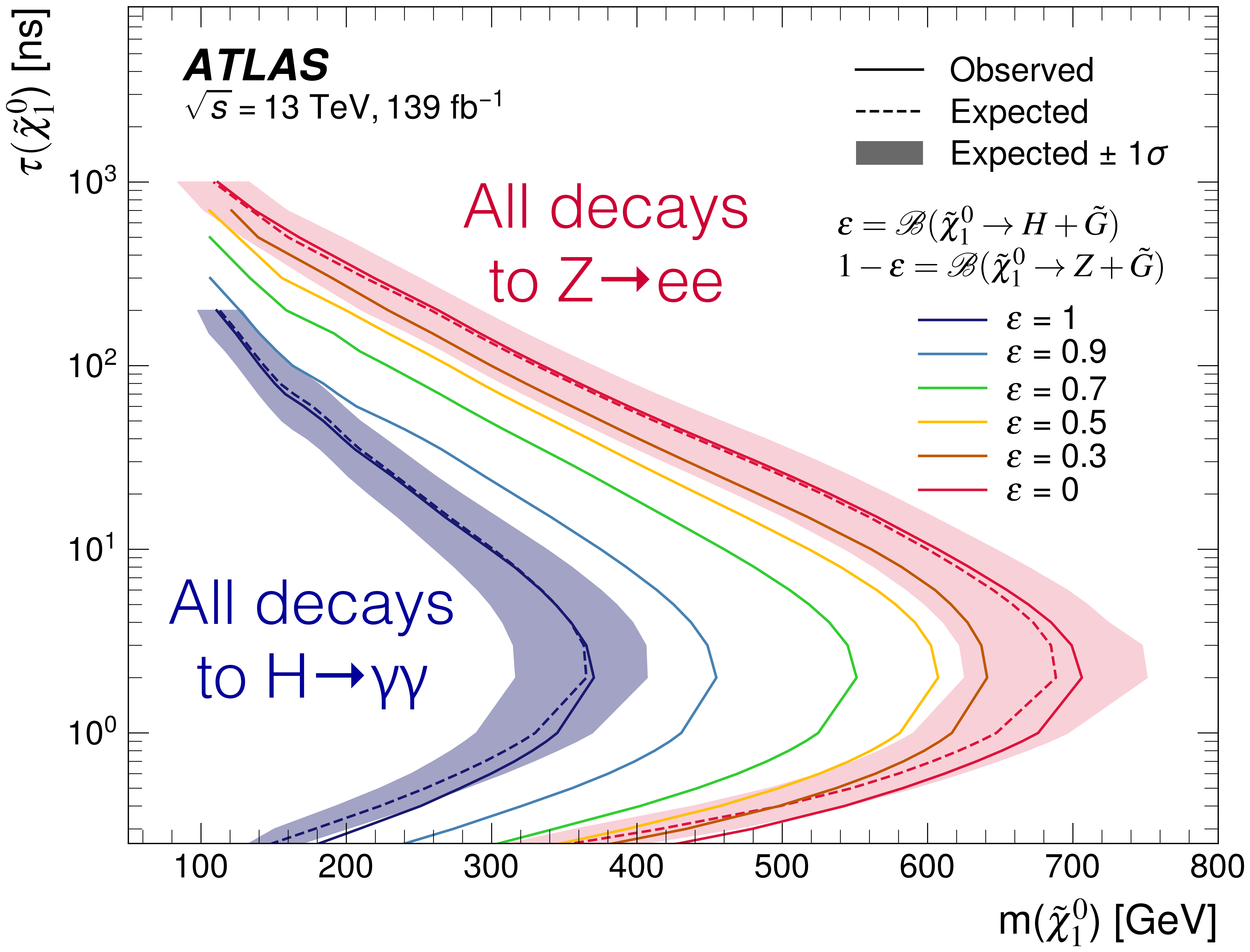
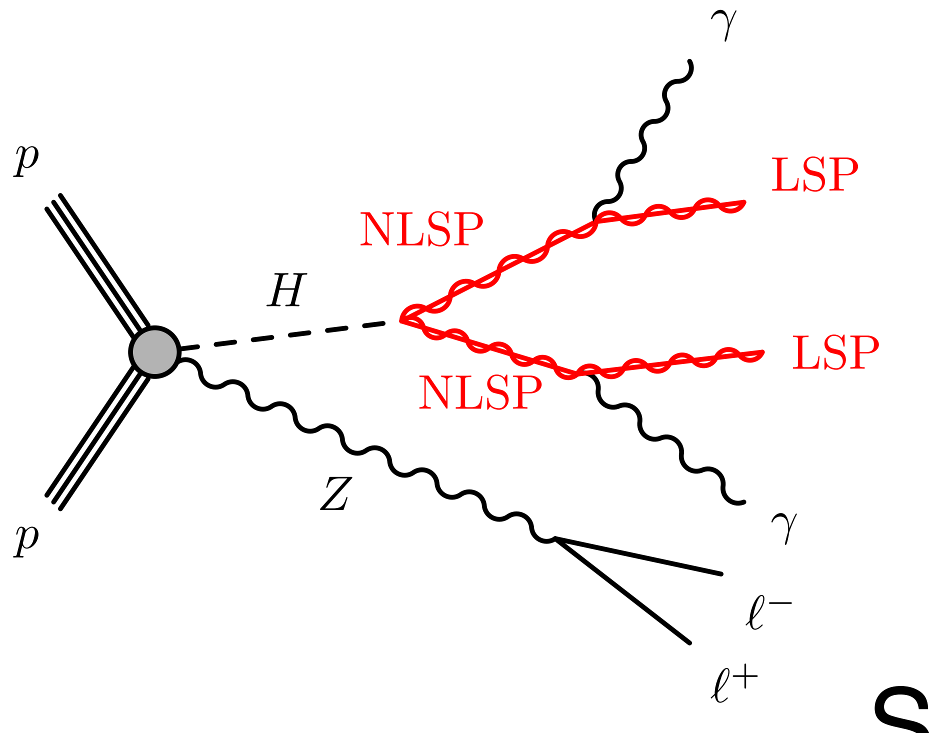
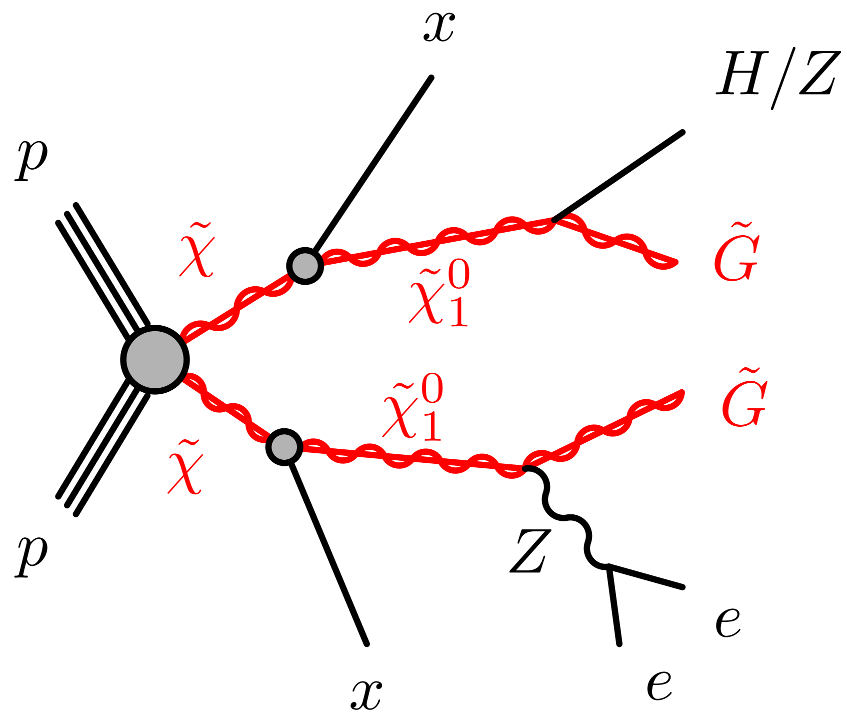



Trigger on leptons; use timing, pointing, 1γ / 2γ channels, and MET > 50 or 80 GeV

Diphoton trigger; use timing, pointing, vertex displacement, and MET > 30 GeV




Similar bkg estimation strategies, e.g. use templates of timing shape in bkg

# Summary

LLPs and MET each provide powerful handles in BSM searches.

Run 2 LLP + MET searches often focused on SUSY scenarios, but we have benchmarked our results with other DM models too

- See Thursday's dark photon session for a few more LLP + MET searches

With the hard work we put into designing + understanding our LLP reco algorithms, we should include channels w/ large MET whenever possible.

- Entirely possible to have BSM signals we could have already seen, if only we'd picked the right trigger!

# Backup

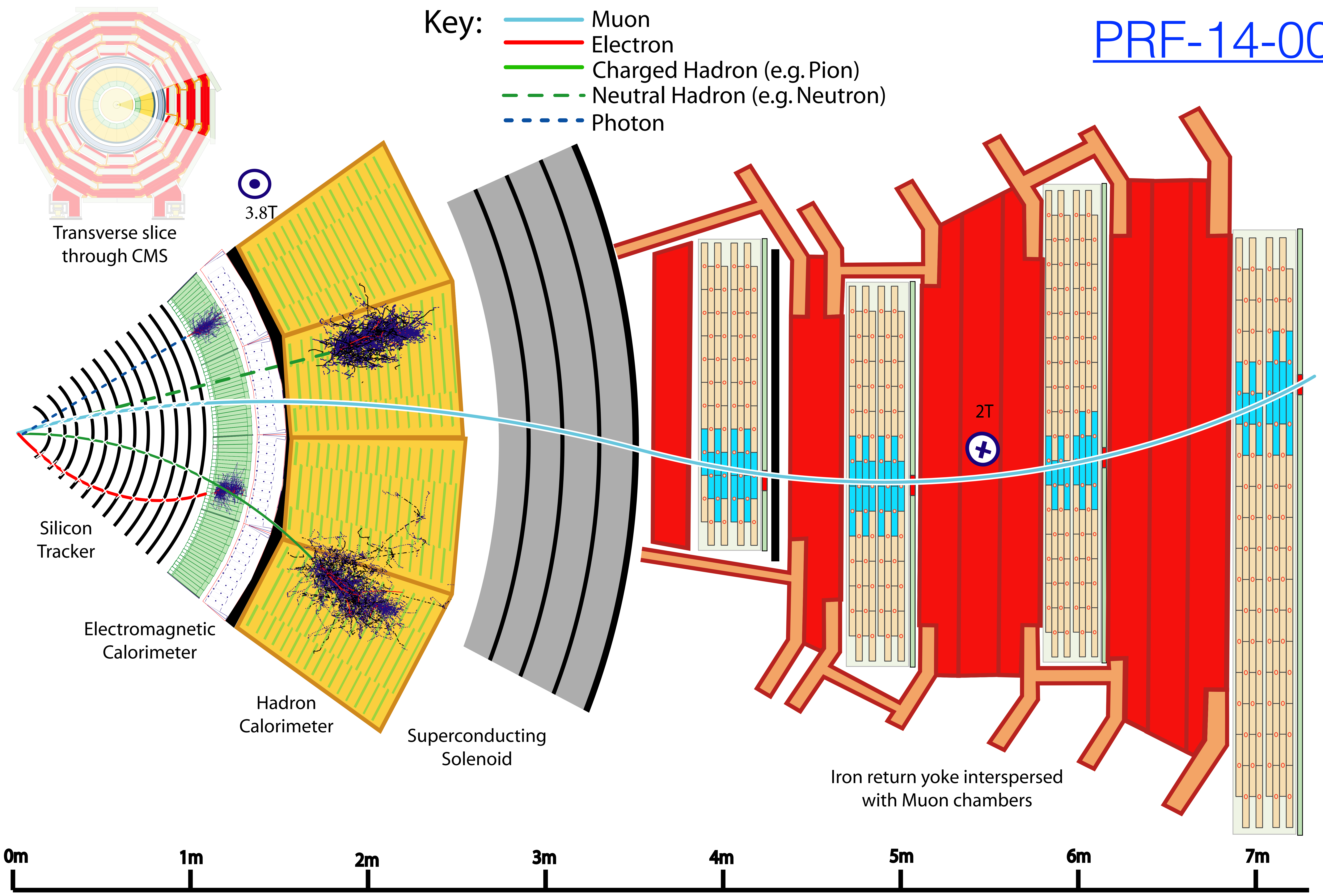
# Snapshot of Run 2 searches for LLPs + MET

- Displaced vertices
- Disappearing tracks
- Soft "mildly displaced" tracks
- dE/dx searches
- Delayed / out-of-time / trackless jets
- Non-pointing / delayed photons

+ others covered elsewhere in the workshop (e.g. dark photon session), or searches using standard objects w/ large impact parameter (e.g. displaced taus).

# CMS detector for a sense of scale

PRF-14-001



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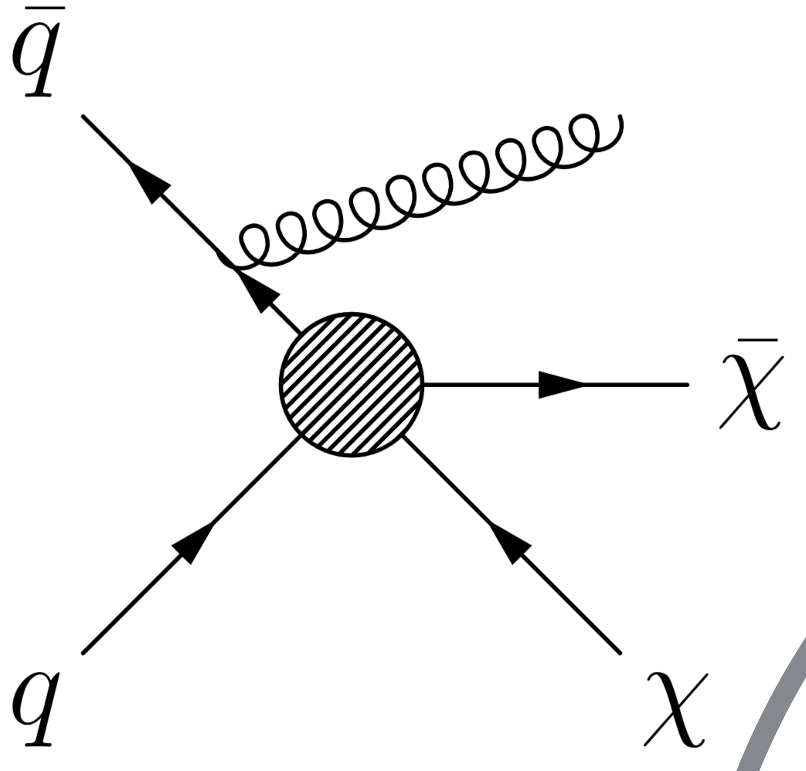
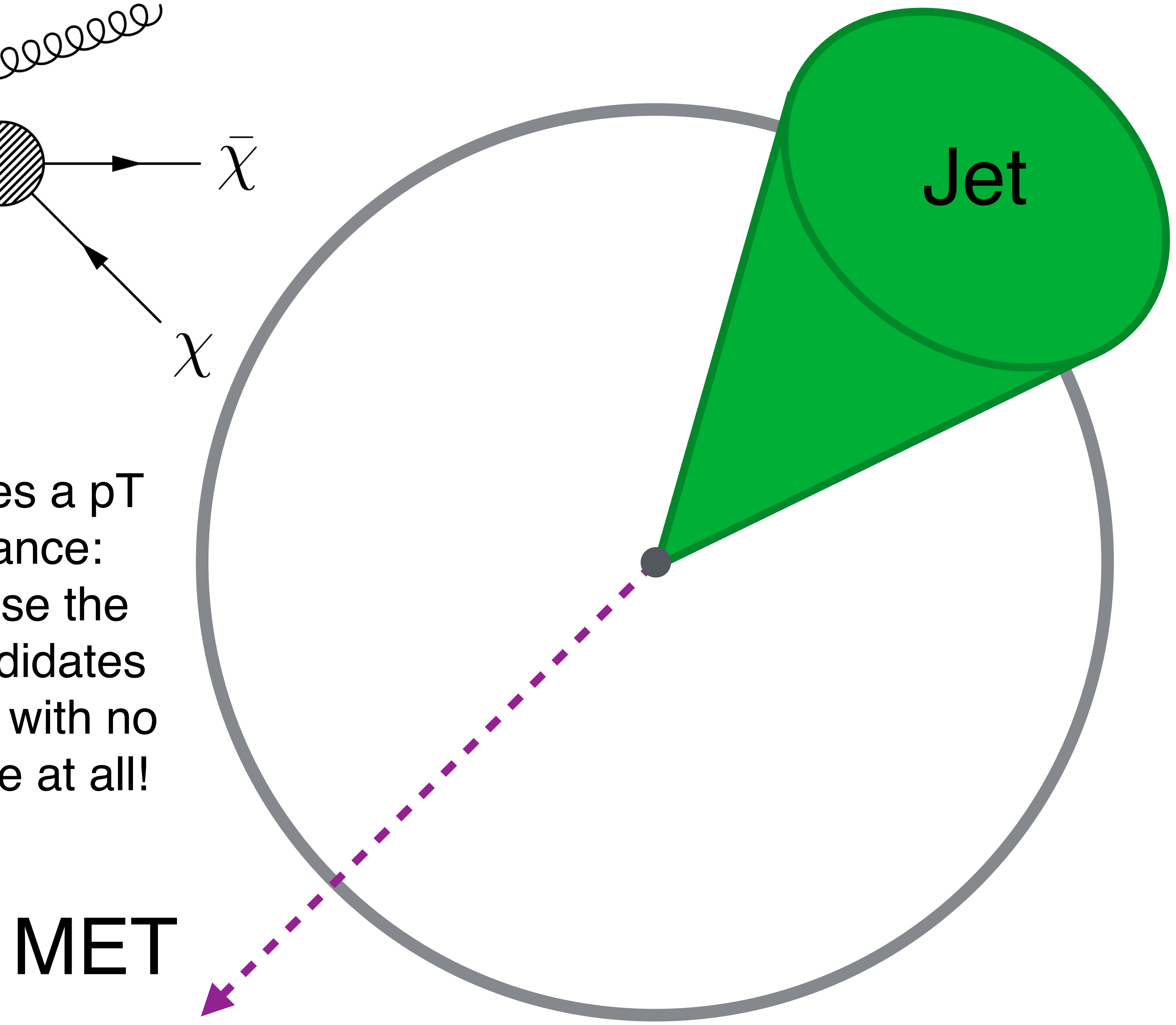



ISR gives a pT imbalance: otherwise the DM candidates leave us with no signature at all!



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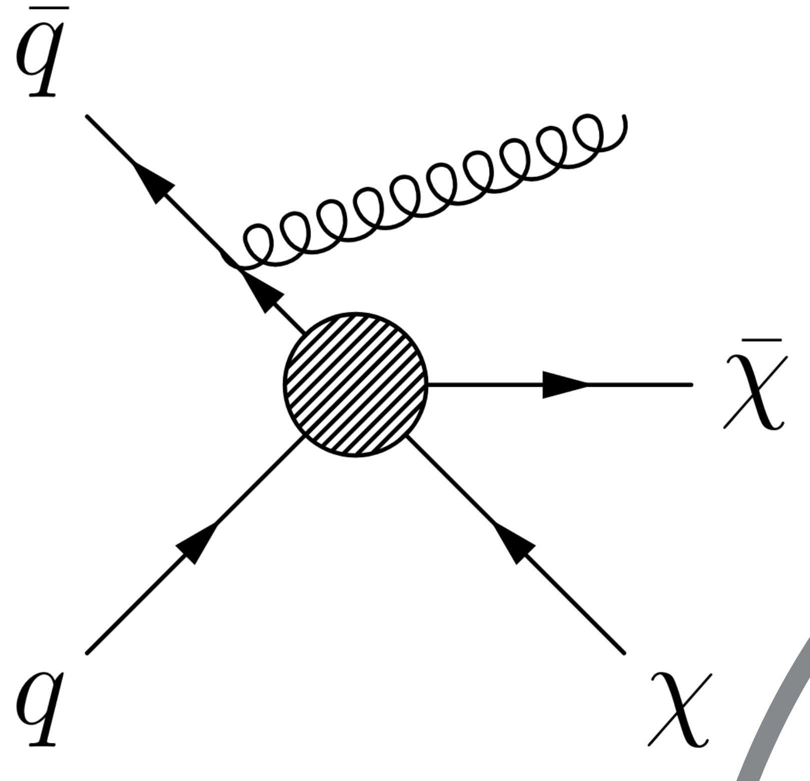


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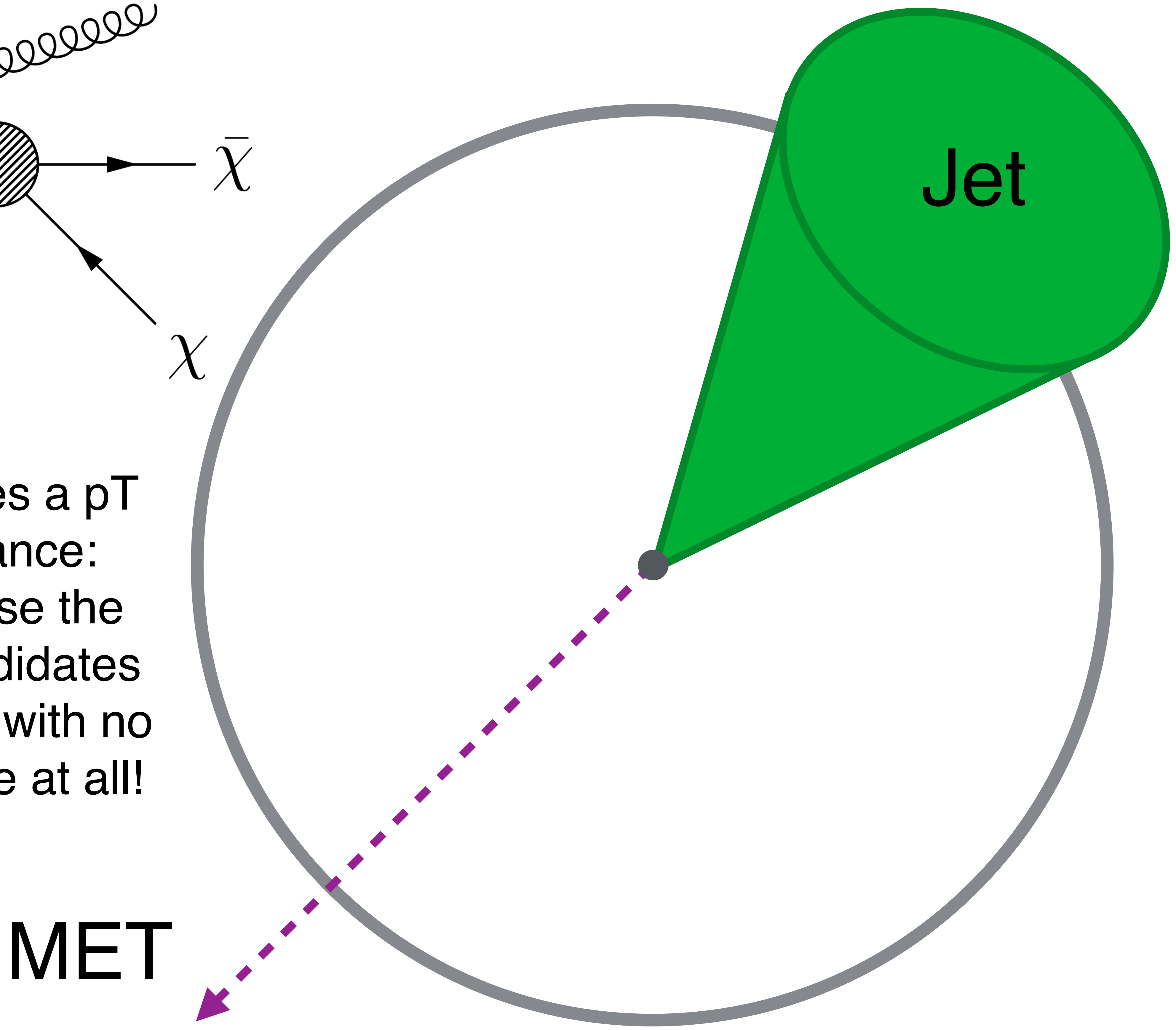
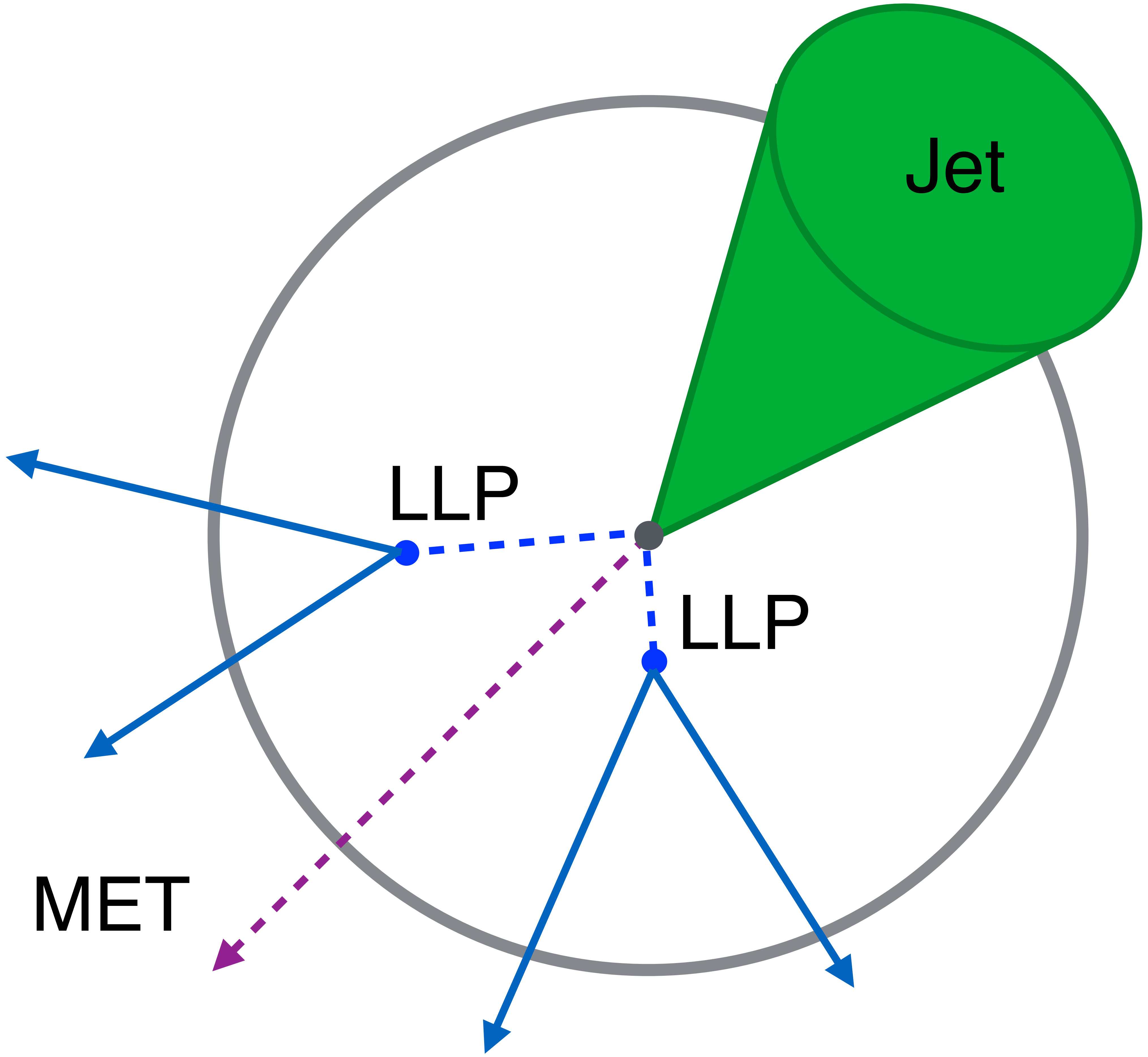


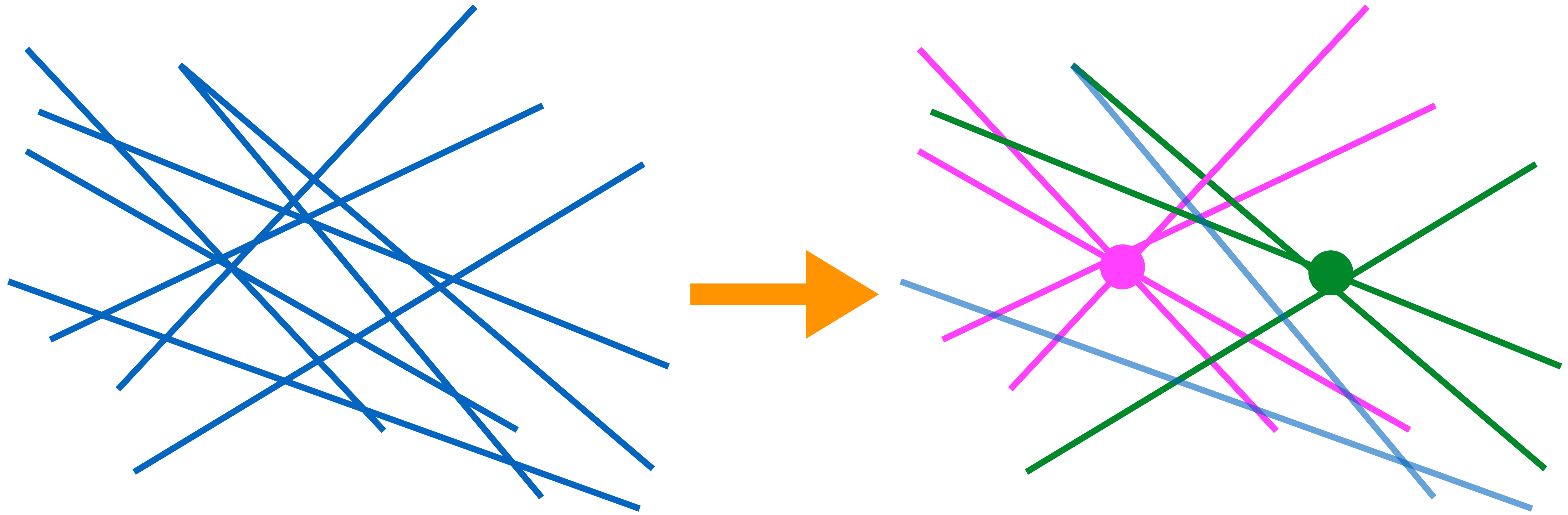

Reinterpreting traditional “prompt” searches is always possible, but by reconstructing the LLP signatures, we can suppress backgrounds and *significantly* improve sensitivity

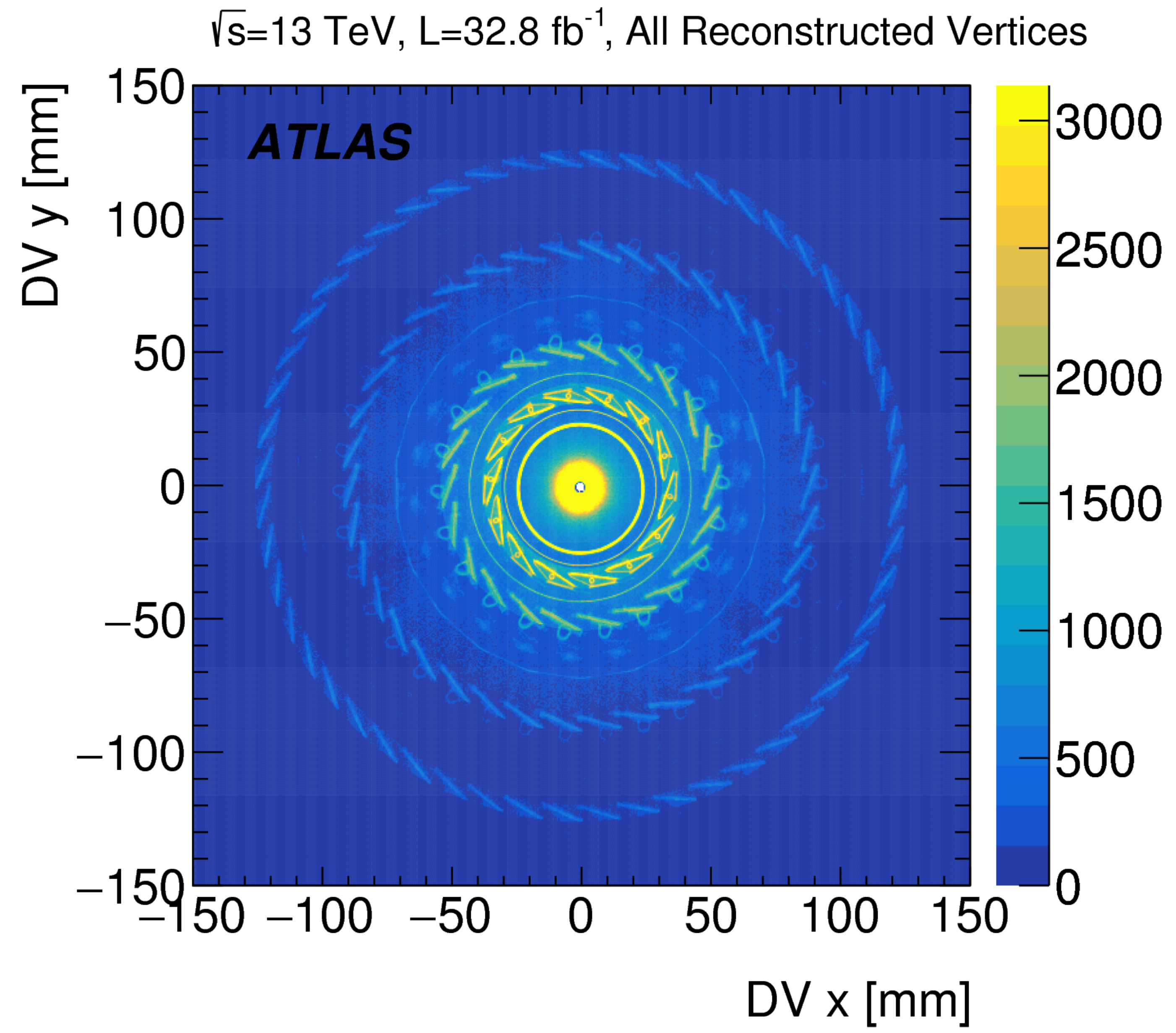
# Hadronic displaced vertices + MET

CMS EXO-22-020
ATLAS SUSY-2016-08

General idea: reconstruct LLP decay points using tracks

- Eliminate SM backgrounds via mass or boost-related requirements
- Require many tracks per vertex (≥5) to suppress random crossing bkgs
- Avoid material interaction backgrounds by either restricting vertices to be within beampipe, or using material map vetos





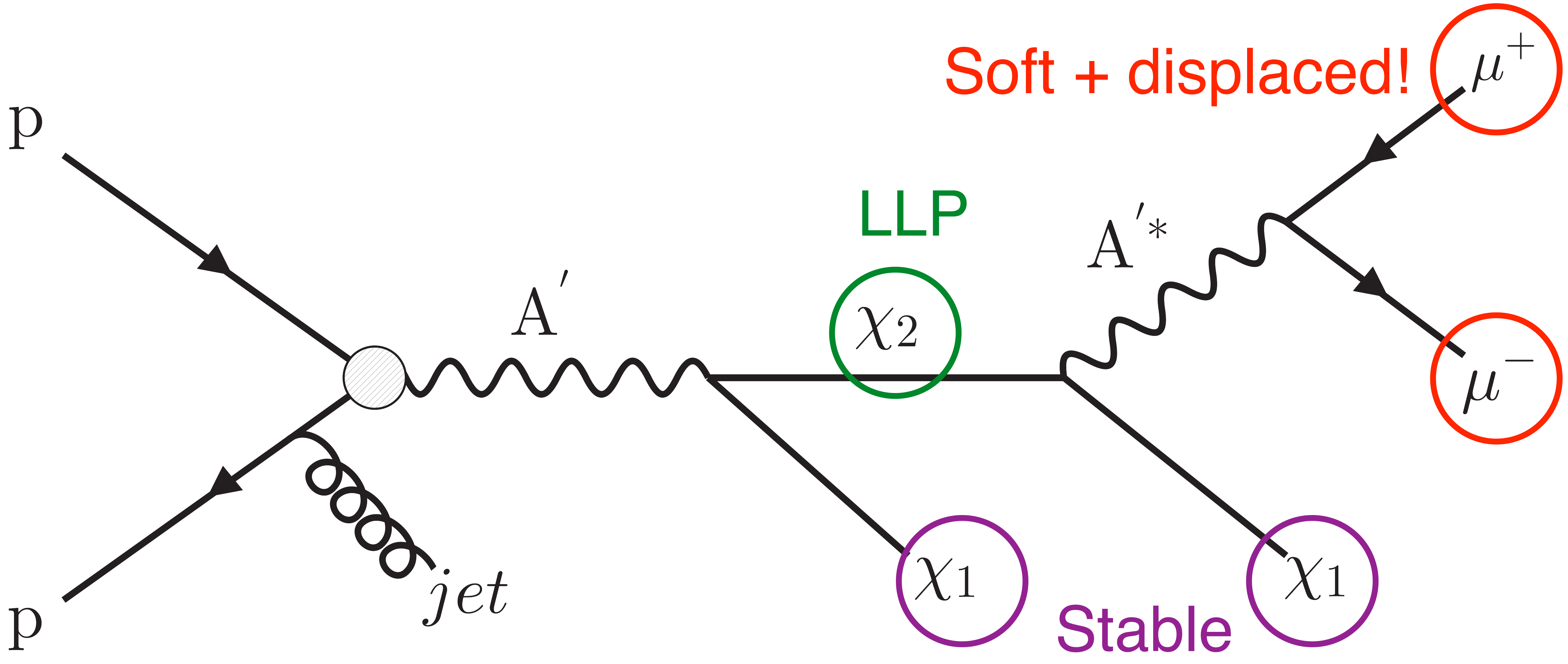
# CMS: Inelastic dark matter via displaced muons + MET

CMS EXO-20-010

Two dark matter states coupled via dark photon.

Heavier DM has long lifetime due to small mass splitting ⟹ pair of soft displaced leptons.

$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$ ; target 1 mm - 1 meter range.



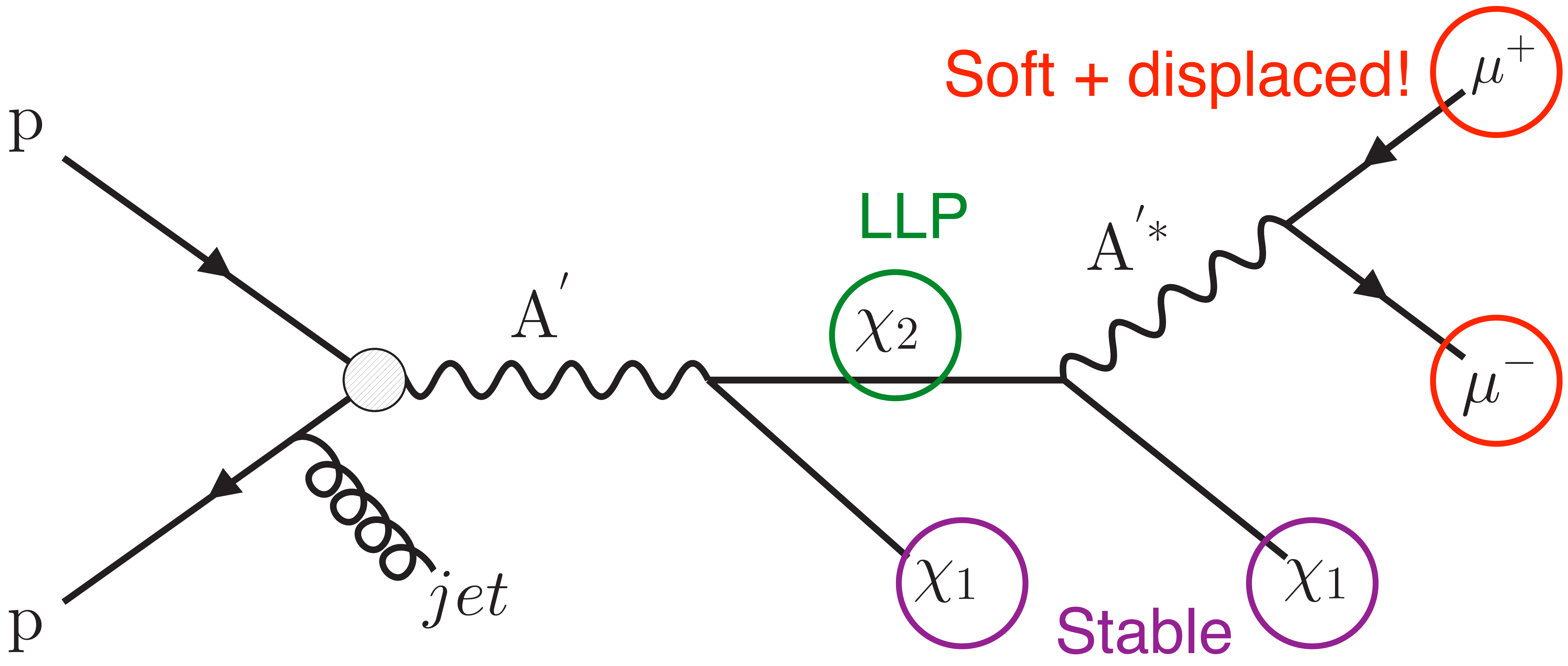
# CMS: Inelastic dark matter via displaced muons + MET

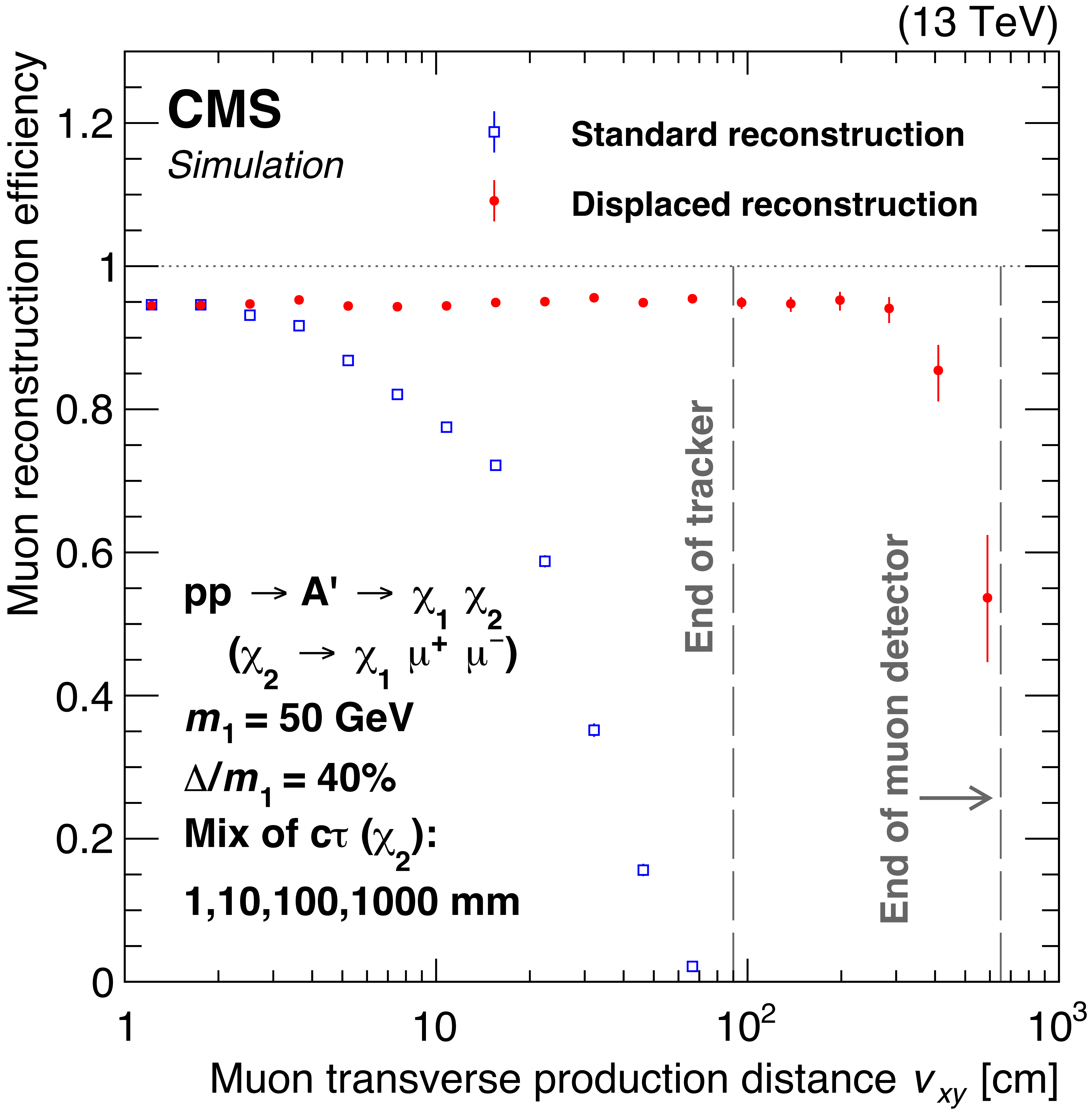
[CMS EXO-20-010]

Two dark matter states coupled via dark photon.

Heavier DM has long lifetime due to small mass splitting ⟹ pair of soft displaced leptons.

$c\tau \propto \frac{(m_{A'})^4}{(\Delta m_{DM})^5}$ ; target 1 mm - 1 meter range.



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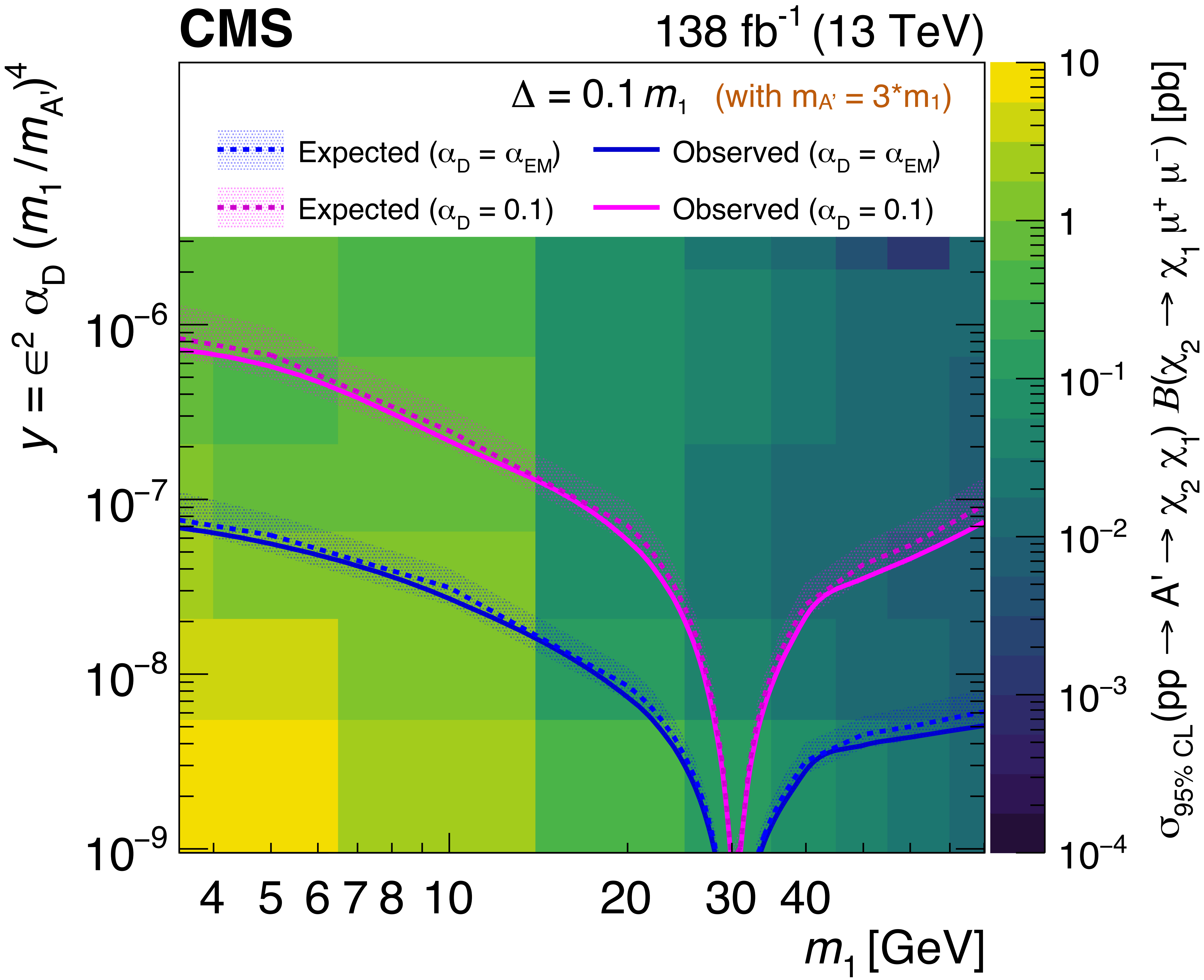
CMS EXO-20-010

Categorize by number of displaced muons that match in ΔR to a standard muon.

- Fewer matches ⟹ larger displacement
- Use kinematics, isolation, and muon $d_{xy}$ to both suppress and estimate background (mostly QCD)

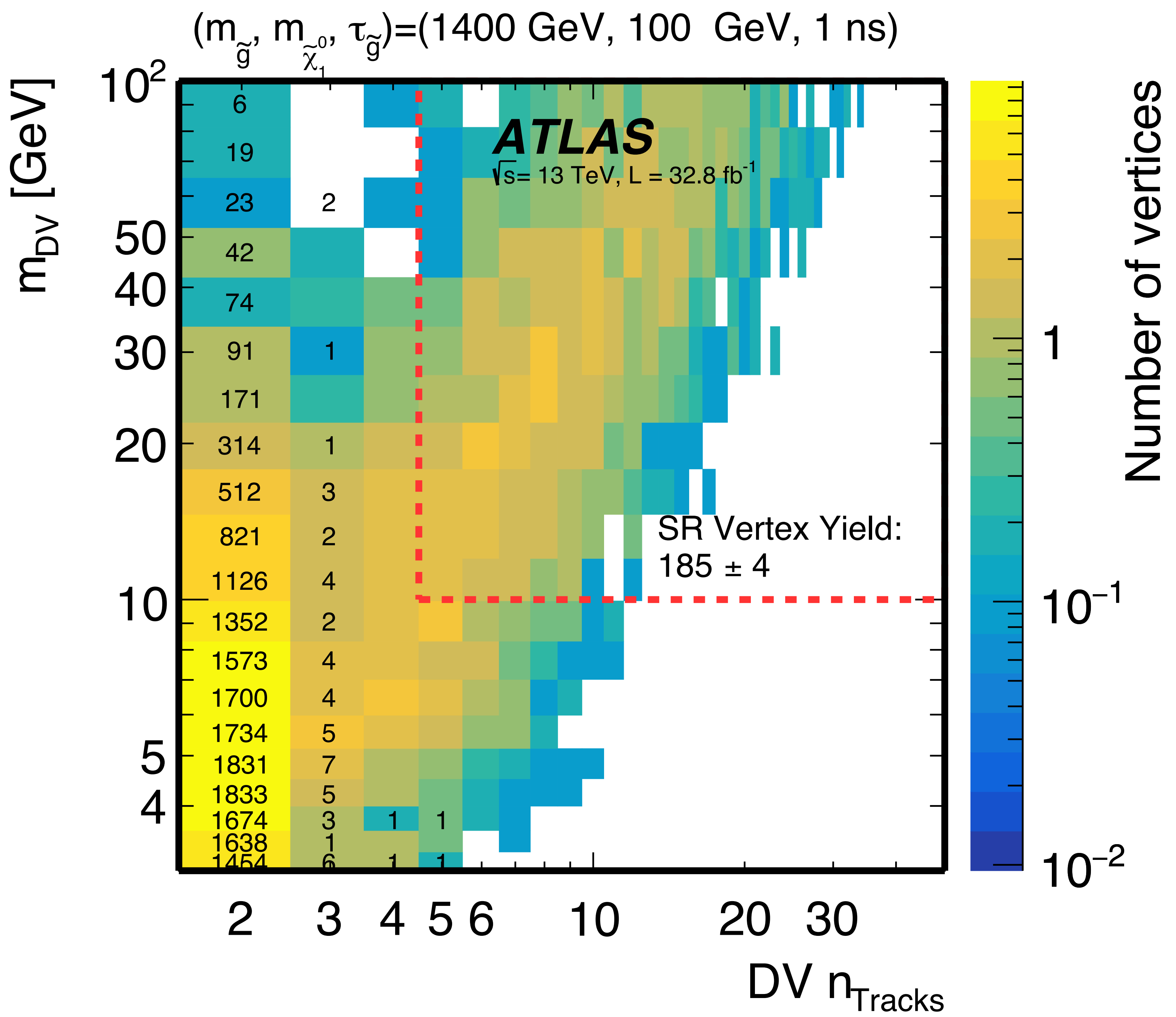
| | Events per SR category | | |
|---|---|---|---|
| | 0-match | 1-match | 2-match |
| Pred. | 1.2 ± 0.6 | 0.5 ± 0.2 | 0.5 ± 0.2 |
| Obs. | 2 | 0 | 0 |

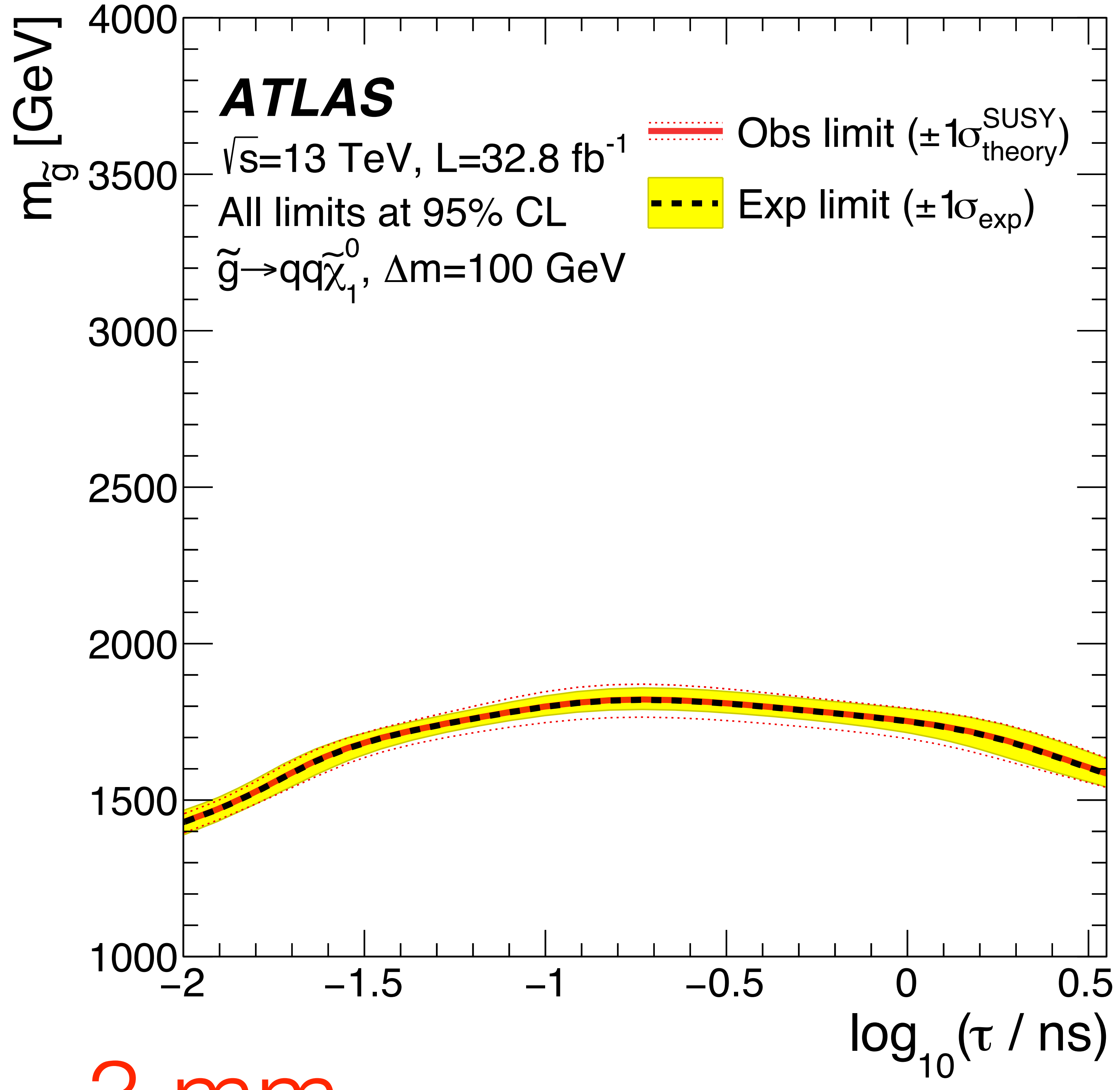


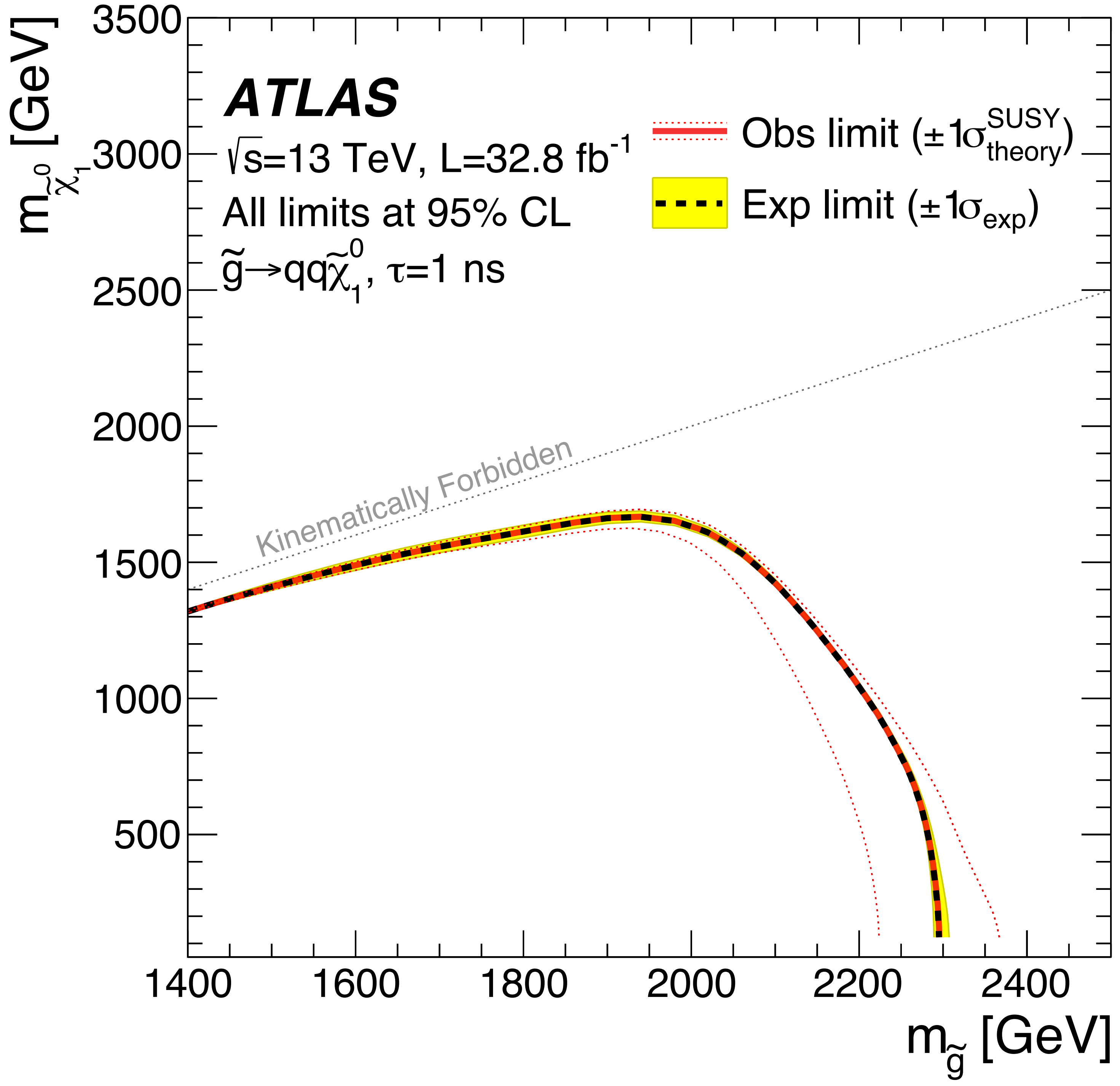

First such search at a hadron collider!

# ATLAS Displaced Vertices at high MET

[ATLAS SUSY-2016-08](#)




3 mm

30 mm

300 mm

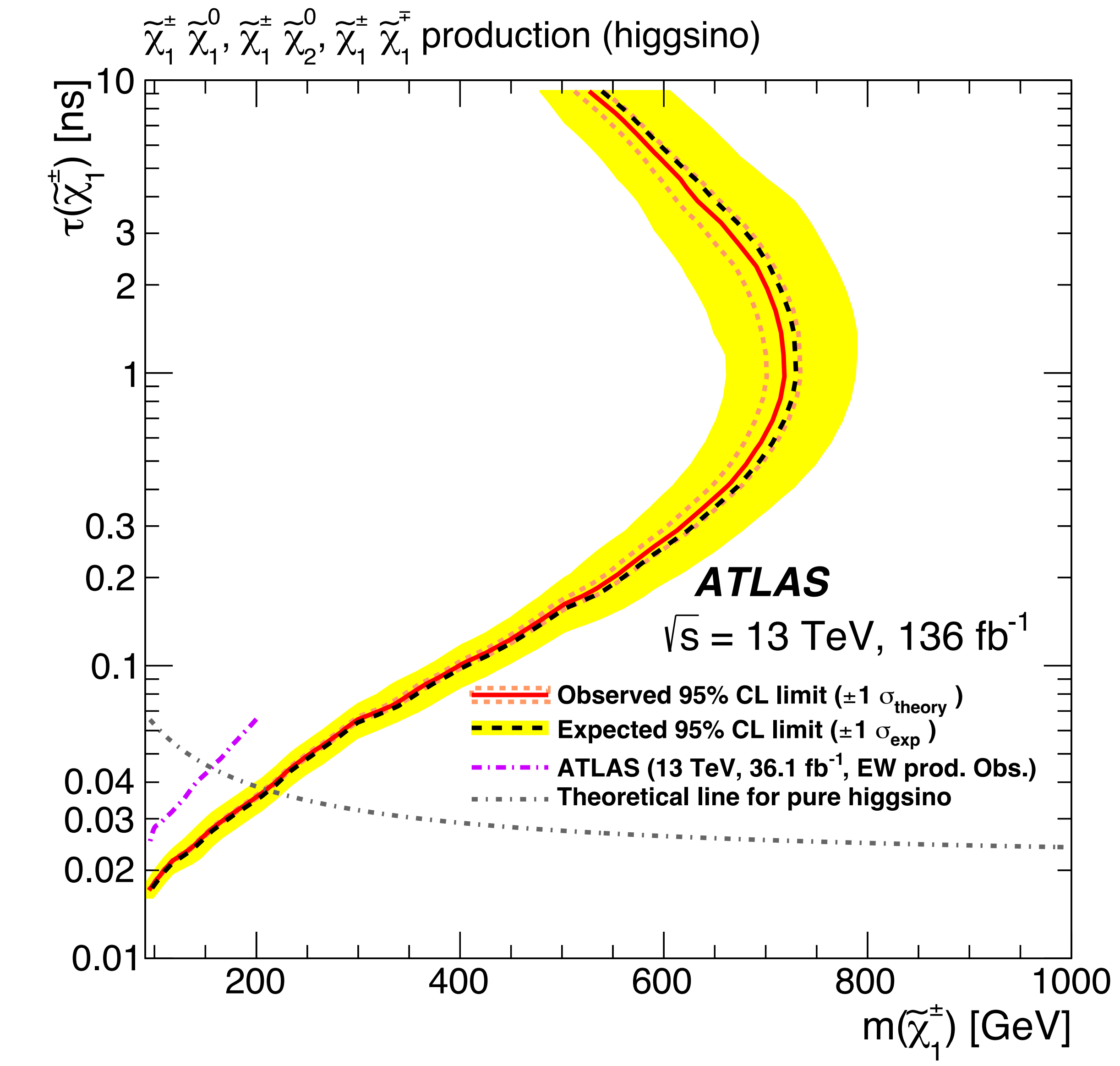
Uses:

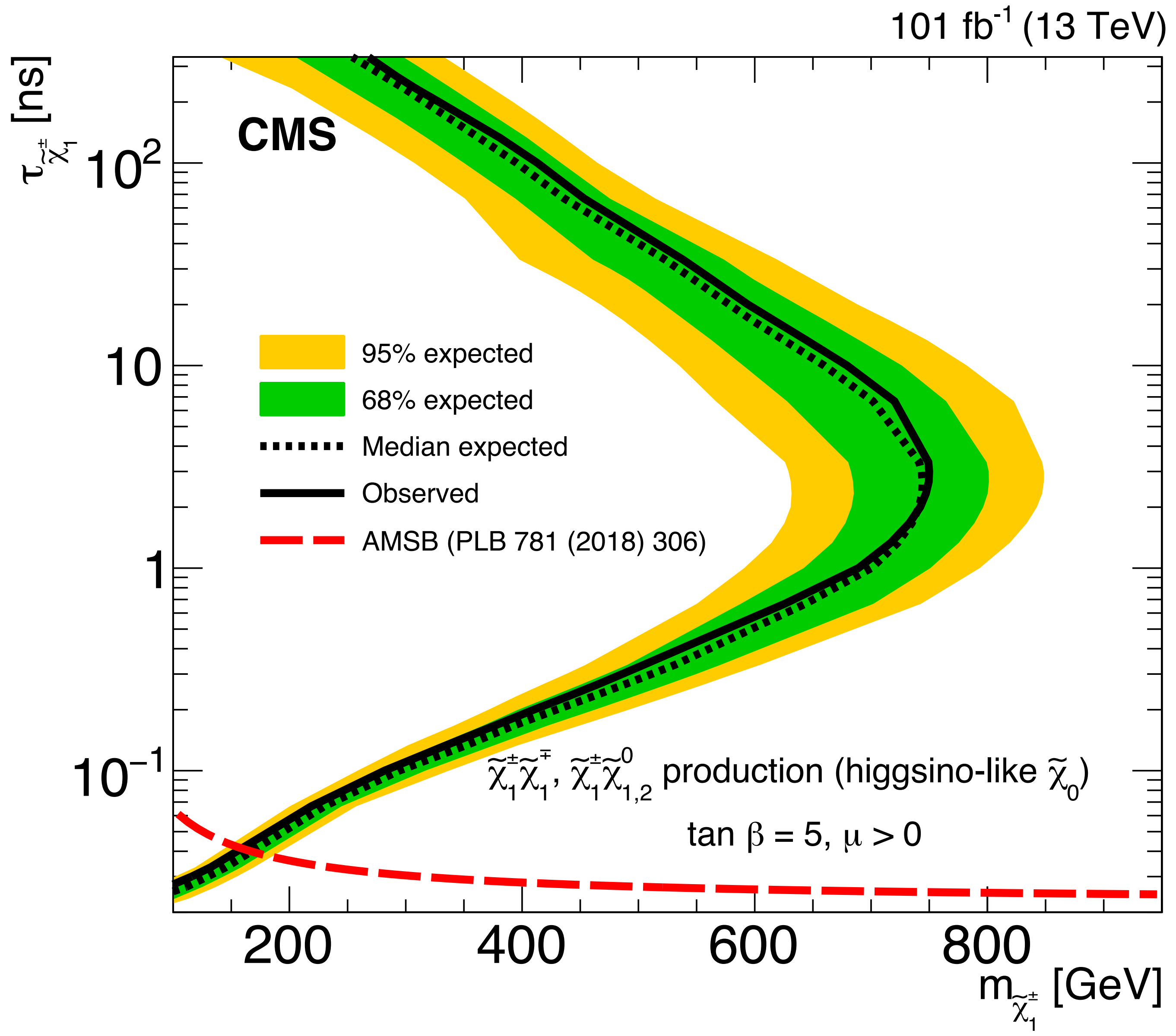
- Track d0 > 2 mm
- MET > 250 GeV
- SR with ≥1 DV
- ≥5-trk vertices w/ material map vetoes, $m_{DV}$ > 10 GeV

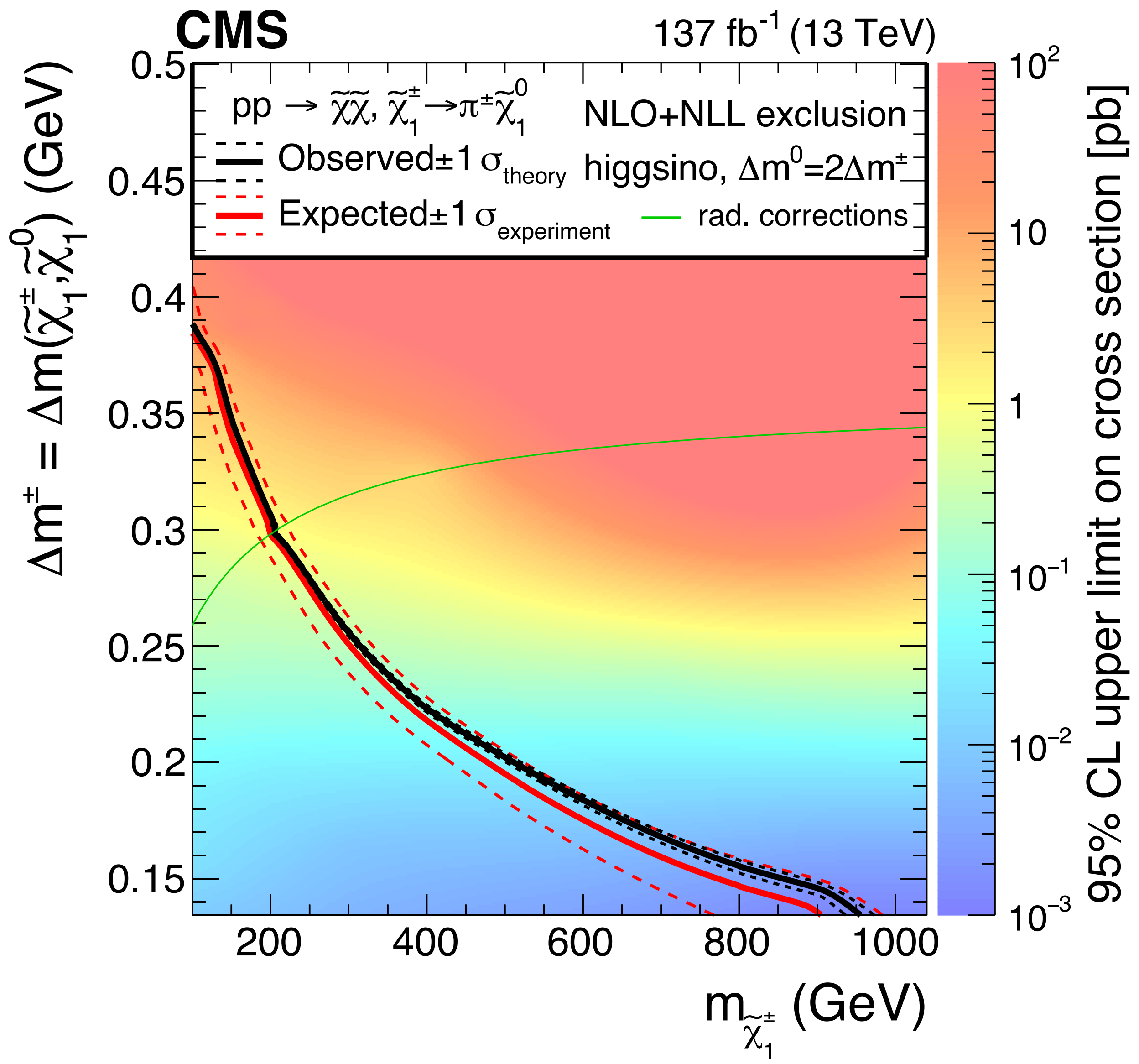
[Phys. Rev. D 97 (2018) 052012](#)

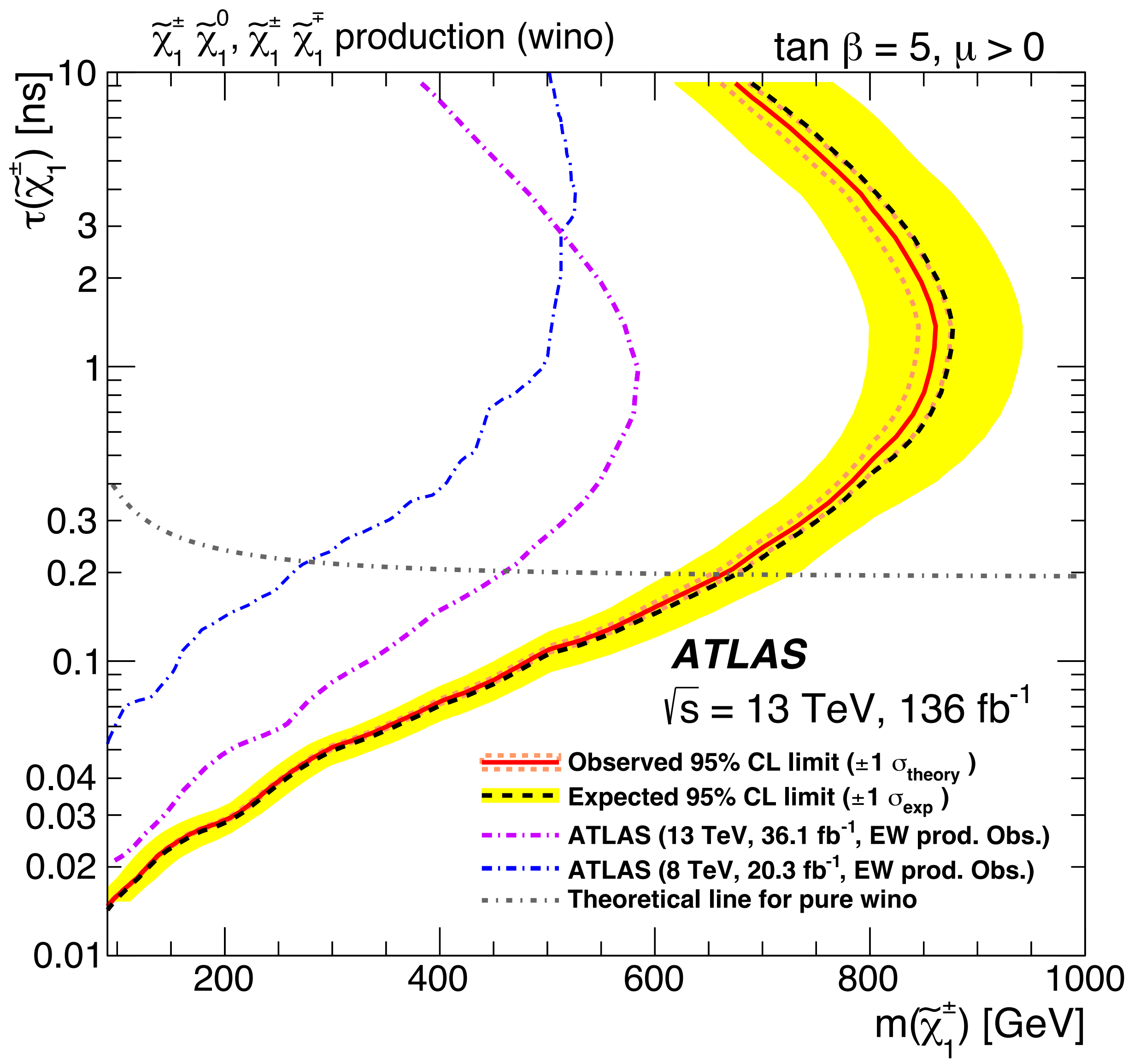
# Disappearing tracks + MET

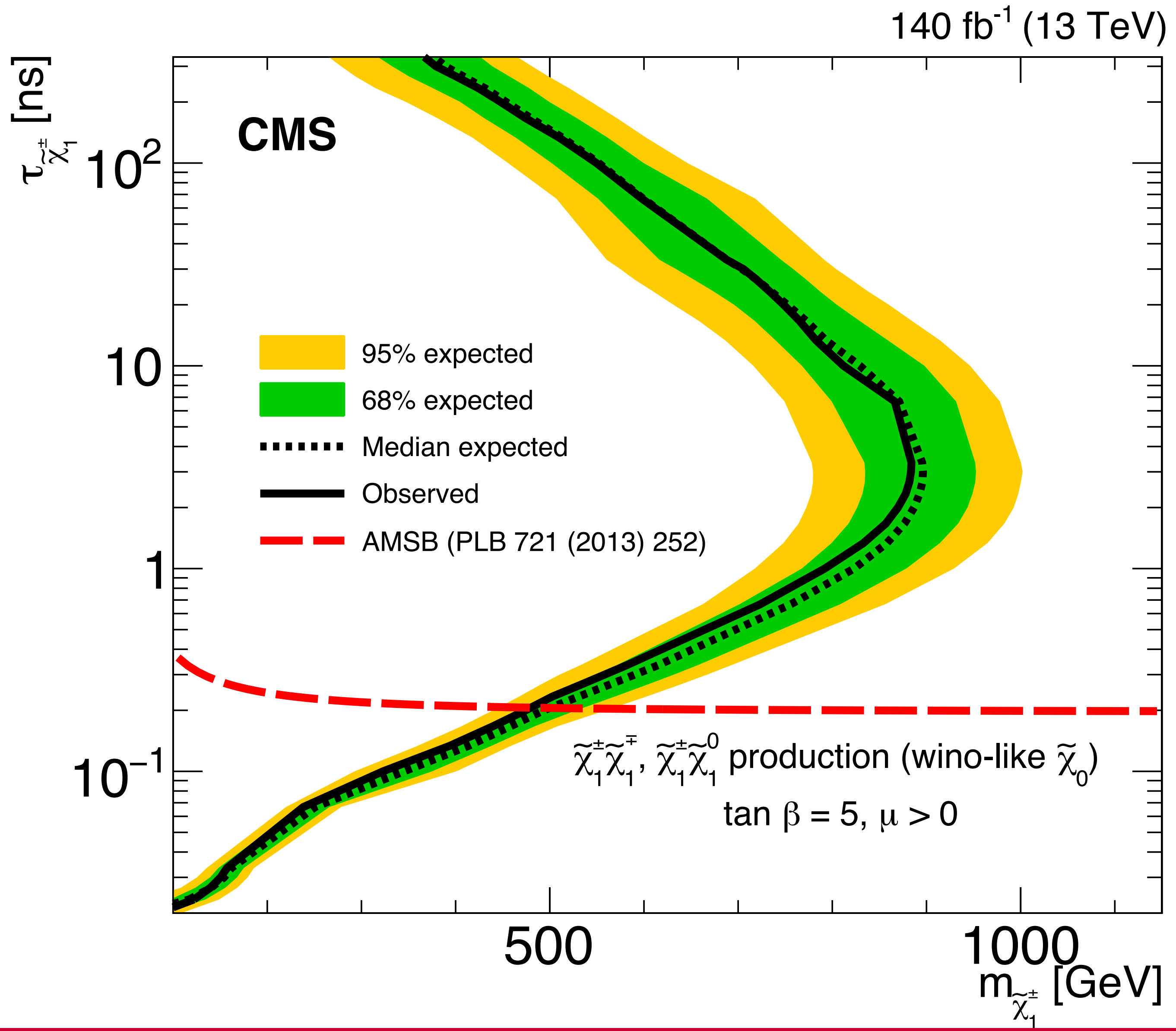
ATLAS SUSY-2018-19
CMS EXO-19-010
CMS SUS-21-006

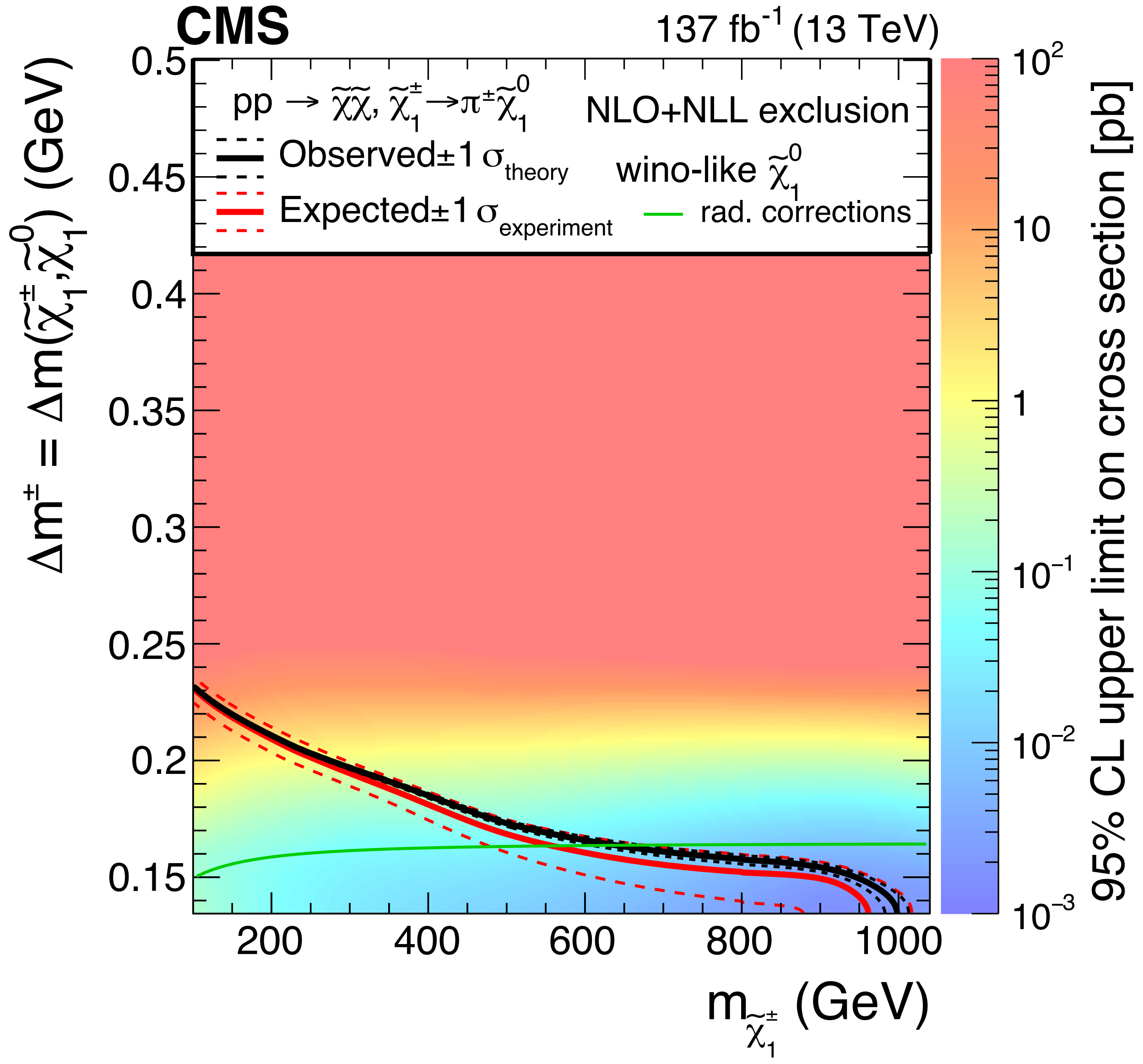


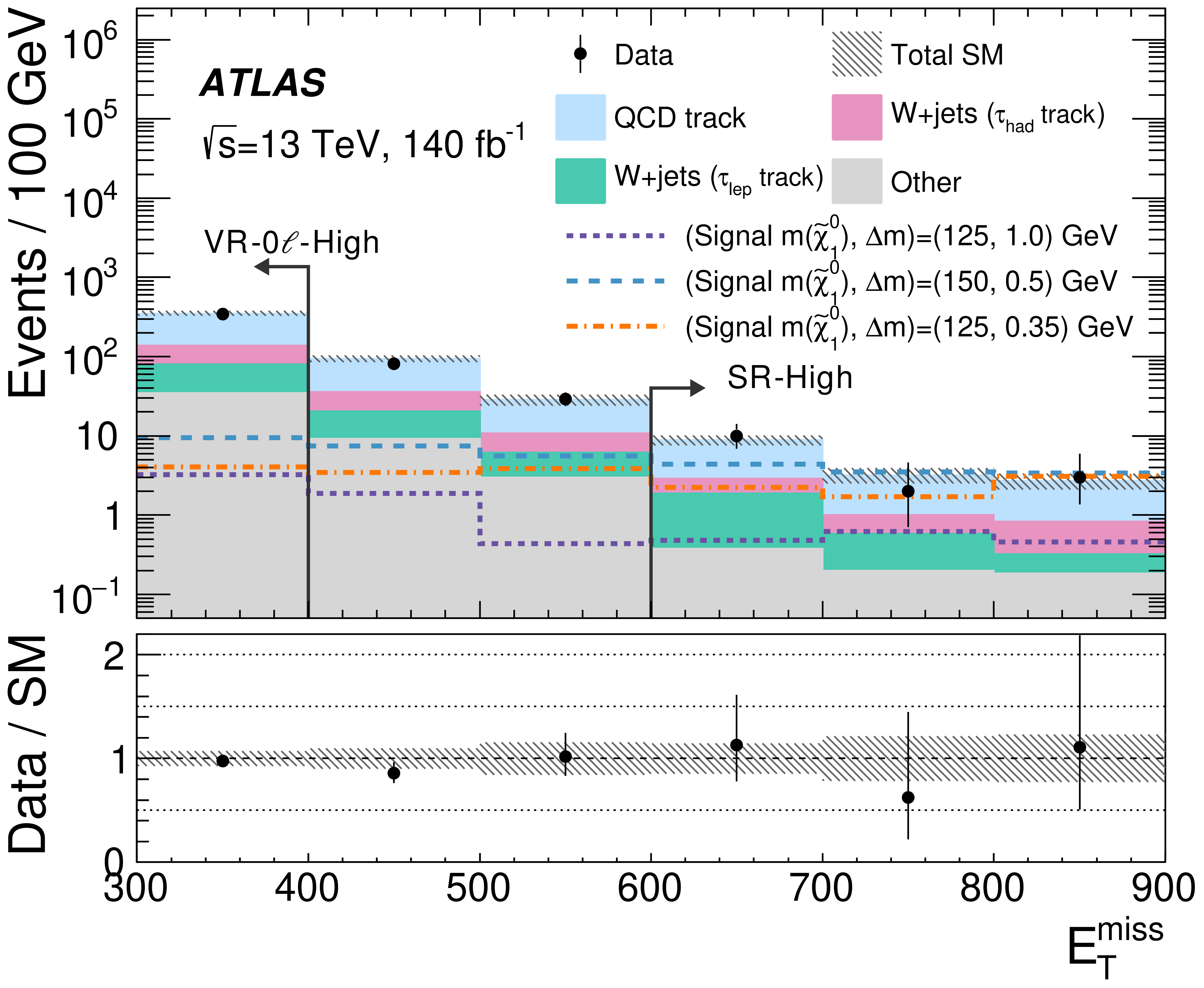



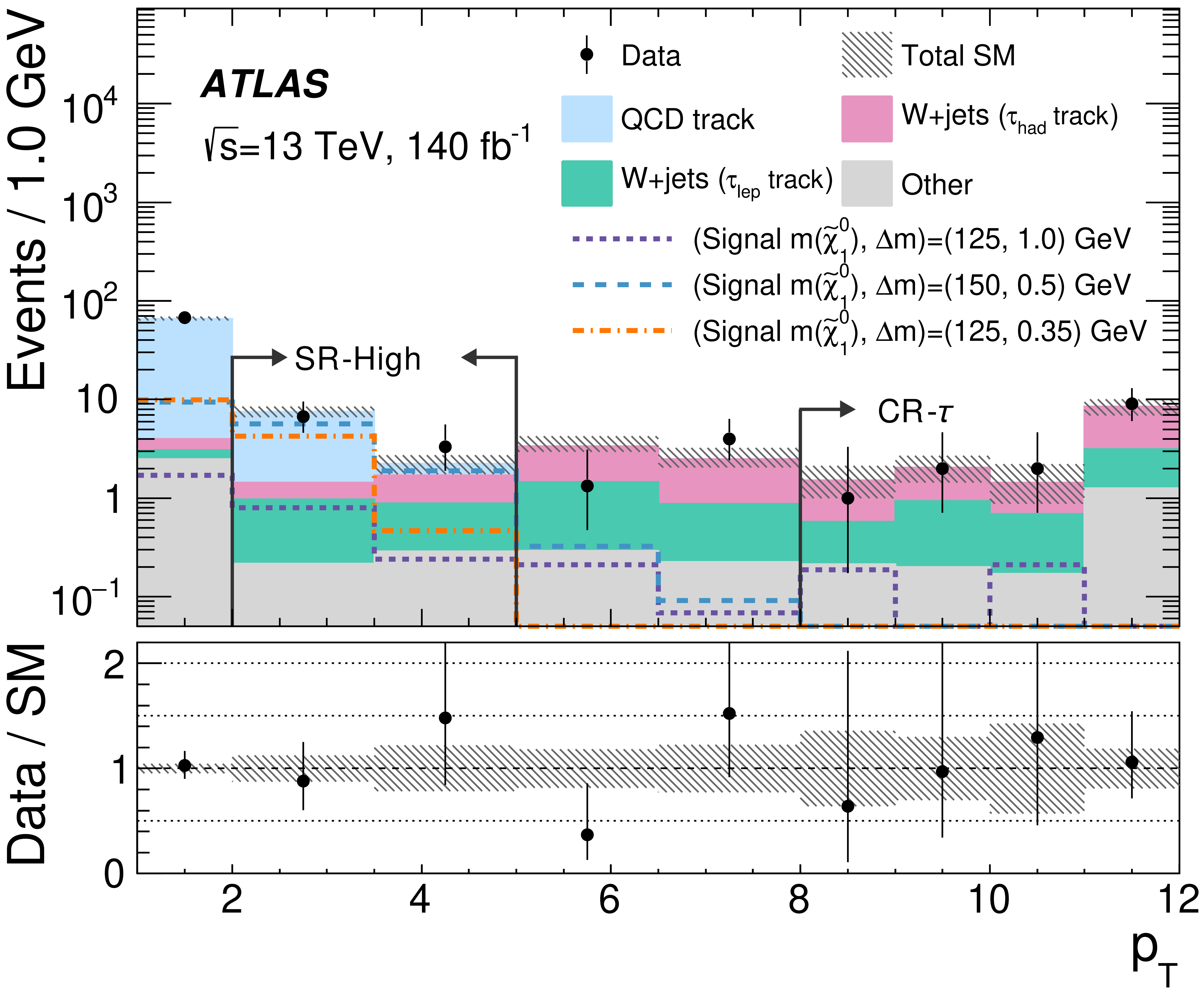



# ATLAS: Soft mildly-displaced tracks + huge MET

ATLAS SUSY-2020-04



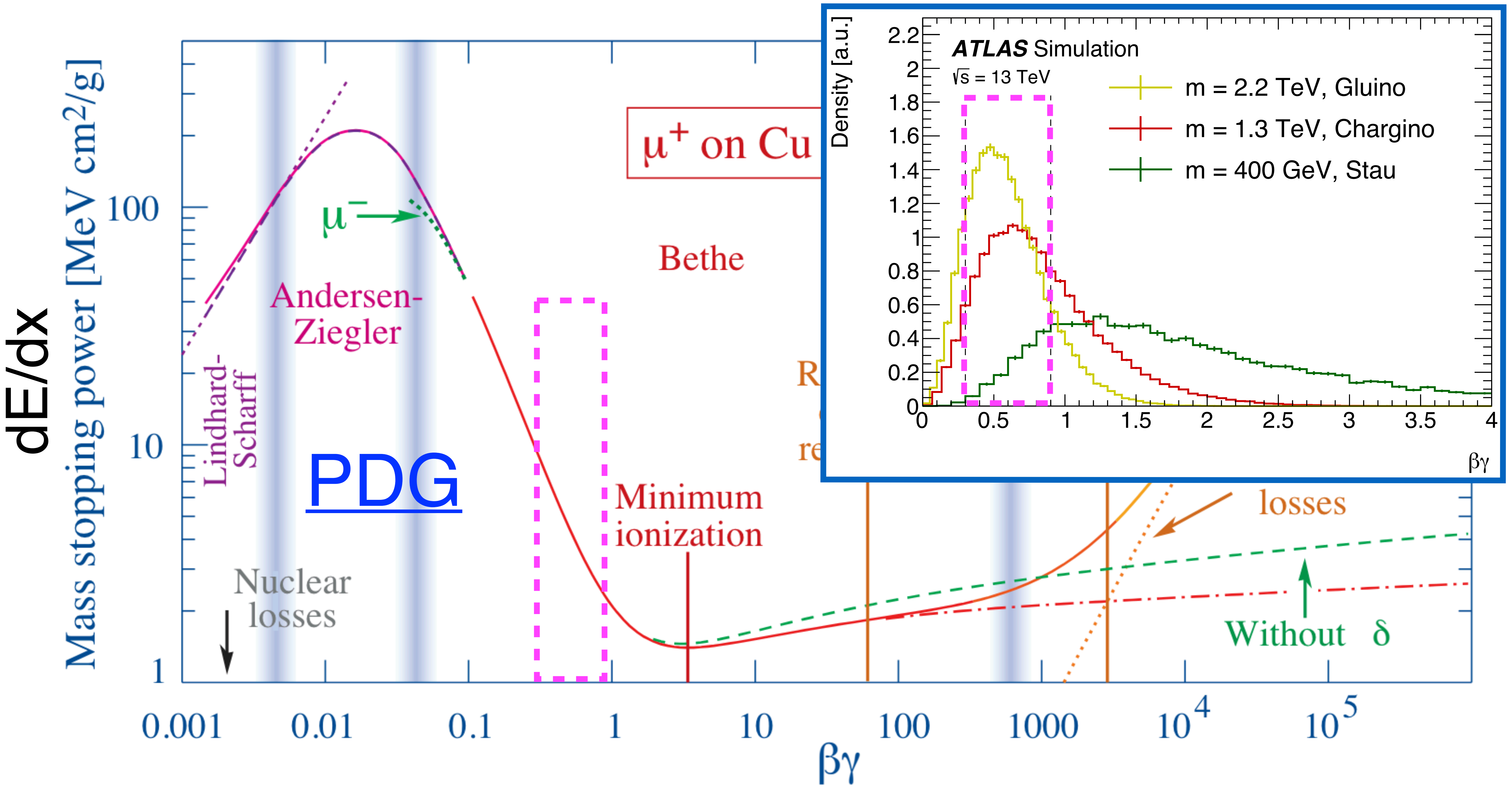



# dE/dx (+ MET) searches

ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
CMS EXO-18-002

Heavy *charged* LLPs will travel through and ionize the detector.

Bethe-Bloch tells us that these slowly moving charged particles will have much larger ionization than SM ones.



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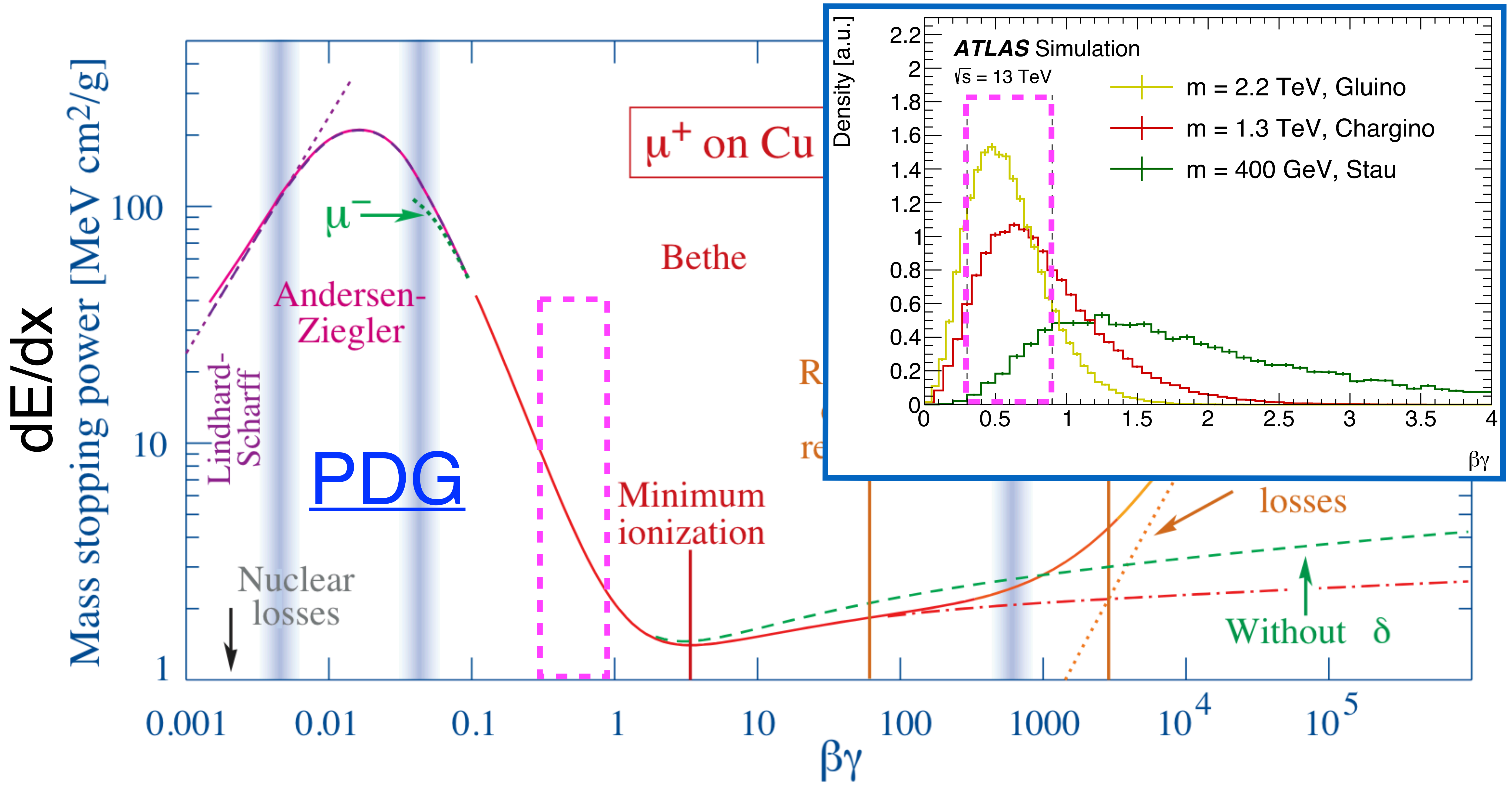


Look for high pT tracks with large dE/dx

- ATLAS: calo MET triggers (decays beyond calo, or decays to stable LSP)
- CMS: muon triggers (track looks similar!)
- R-hadrons, charginos, and sleptons in split / AMSB / GMSB SUSY models, and Z' → $\tau'^{(2e)}\tau'^{(2e)}$

# dE/dx (+ MET) searches

ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
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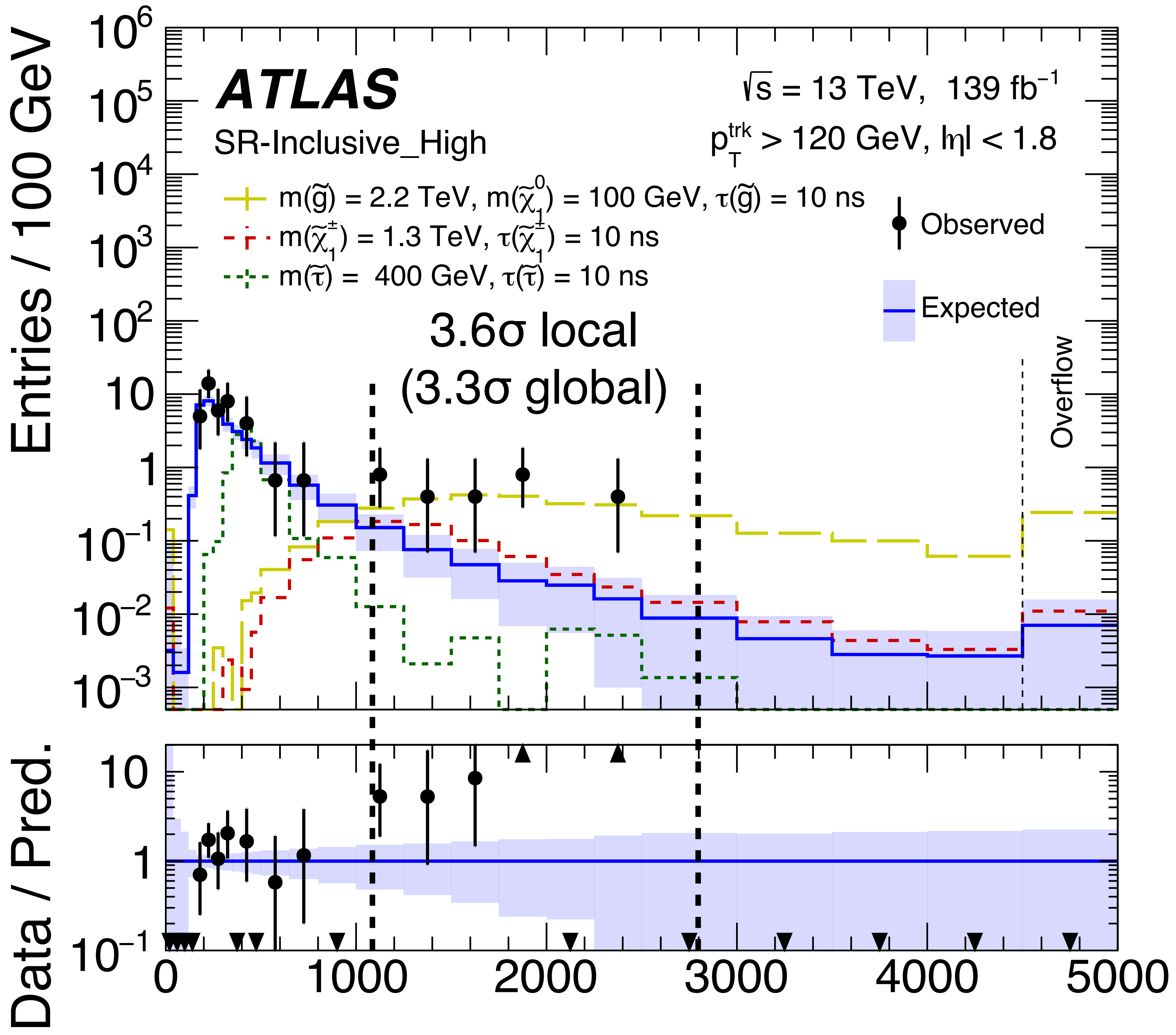
Measure dE/dx in the silicon tracker—need dedicated calibrations and careful understanding of detector effects such as radiation damage.

Use momentum and dE/dx to reconstruct mass:




>1/2 of excess reco'd as muons

β by dE/dx ∈ [0.5, 0.6] but β ≈ 1 via calo and MS ToF

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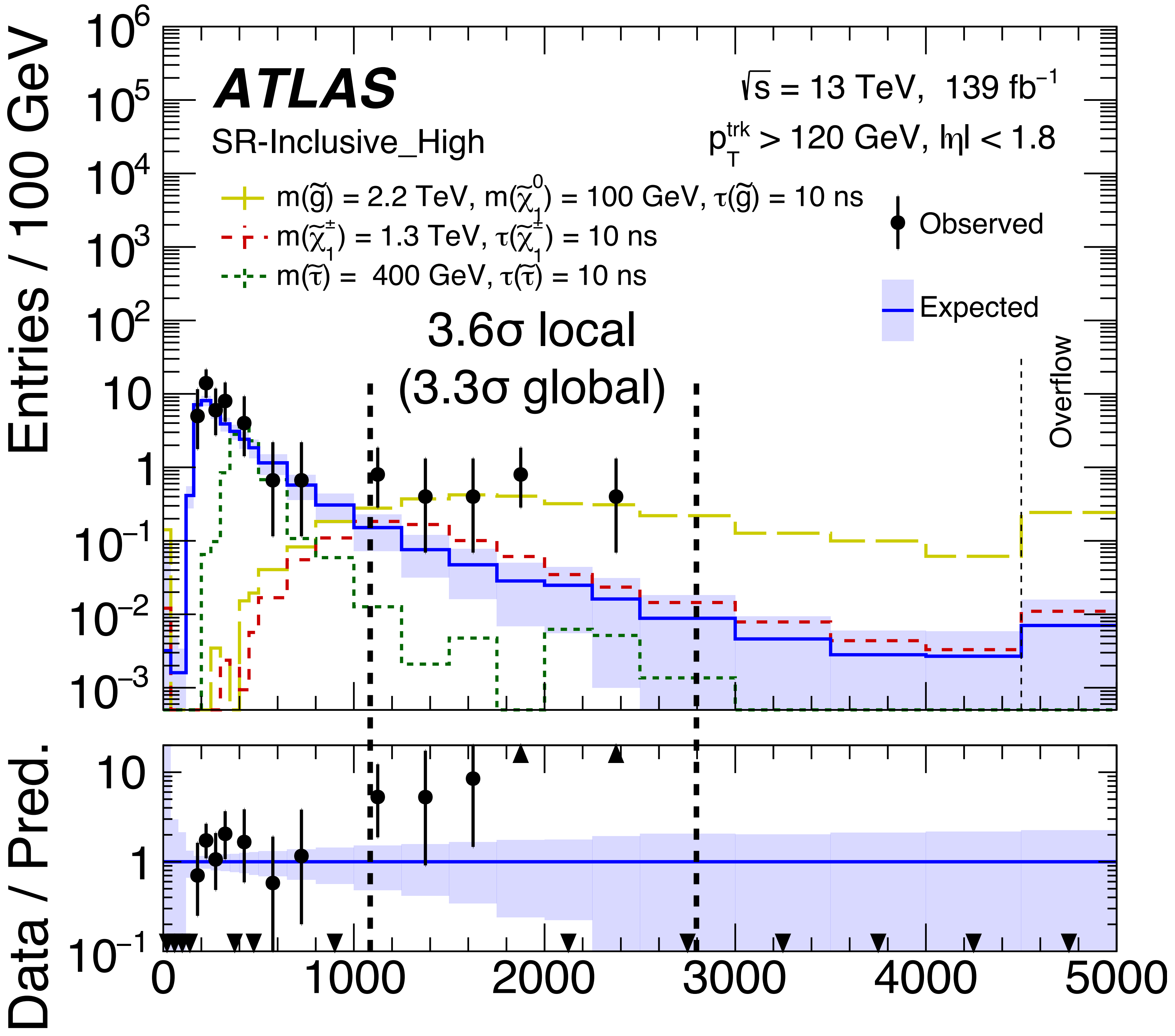


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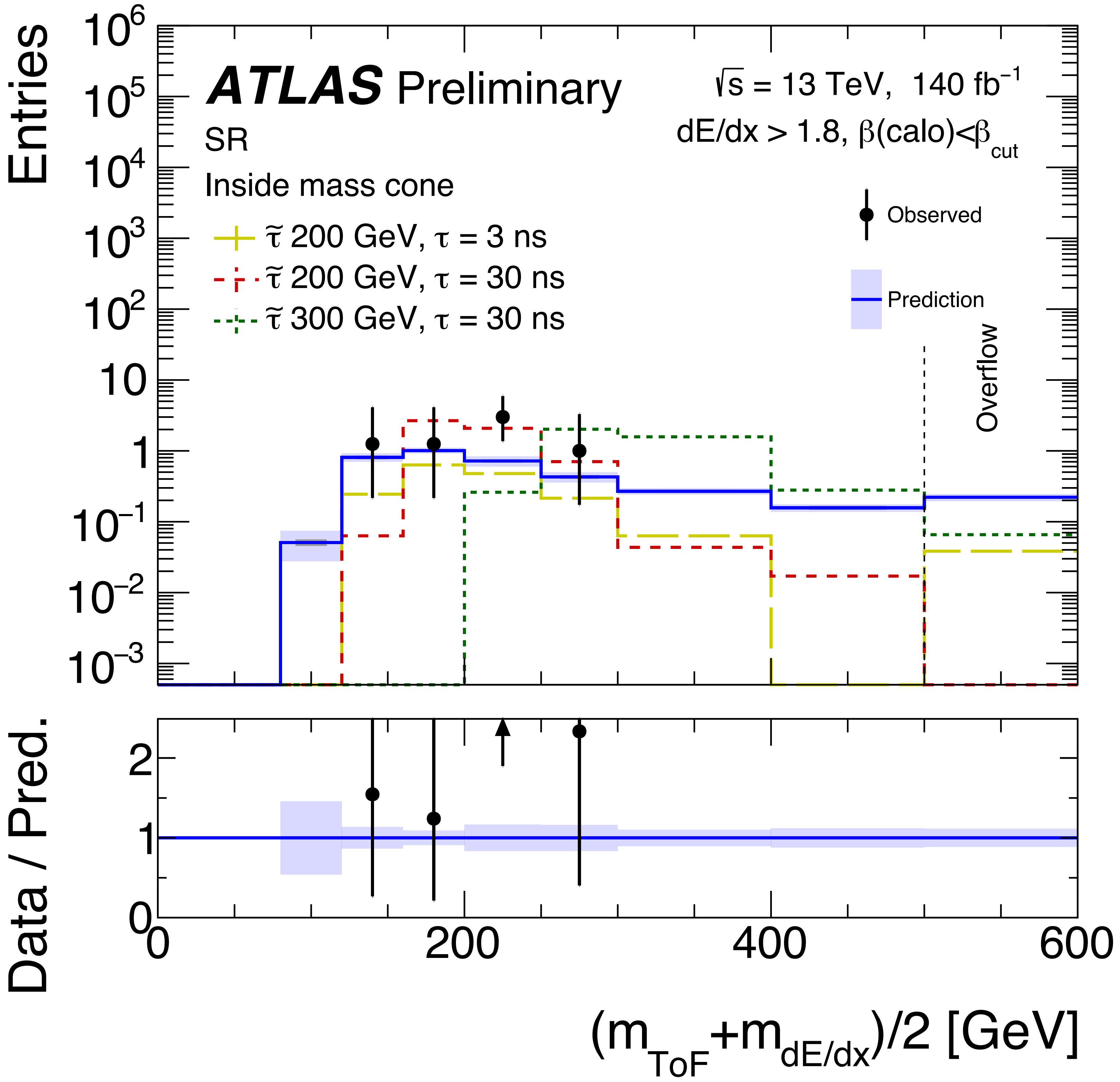


Additional ATLAS search; requires $\beta_{TOF} \lesssim 0.75$-$0.9$

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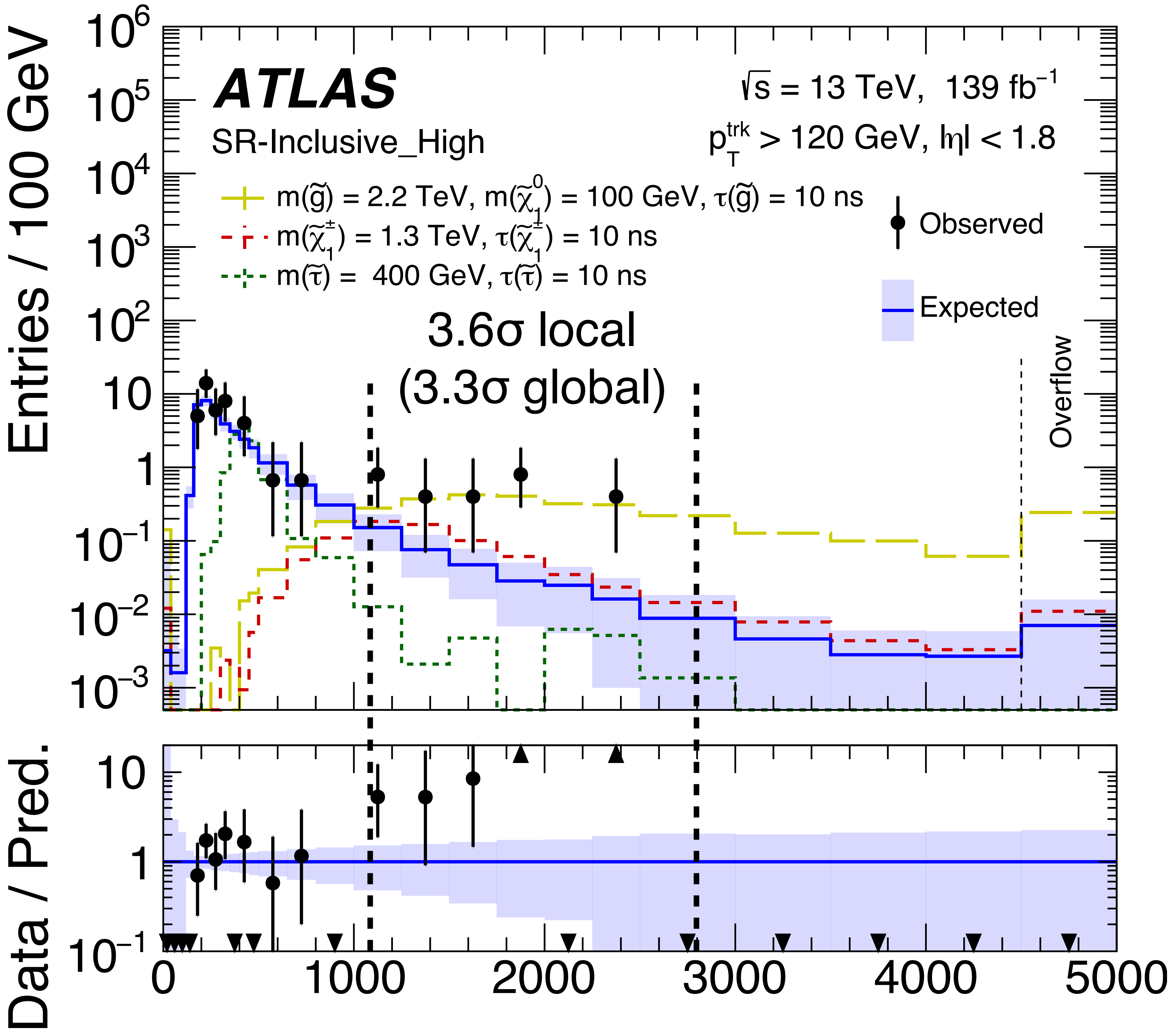


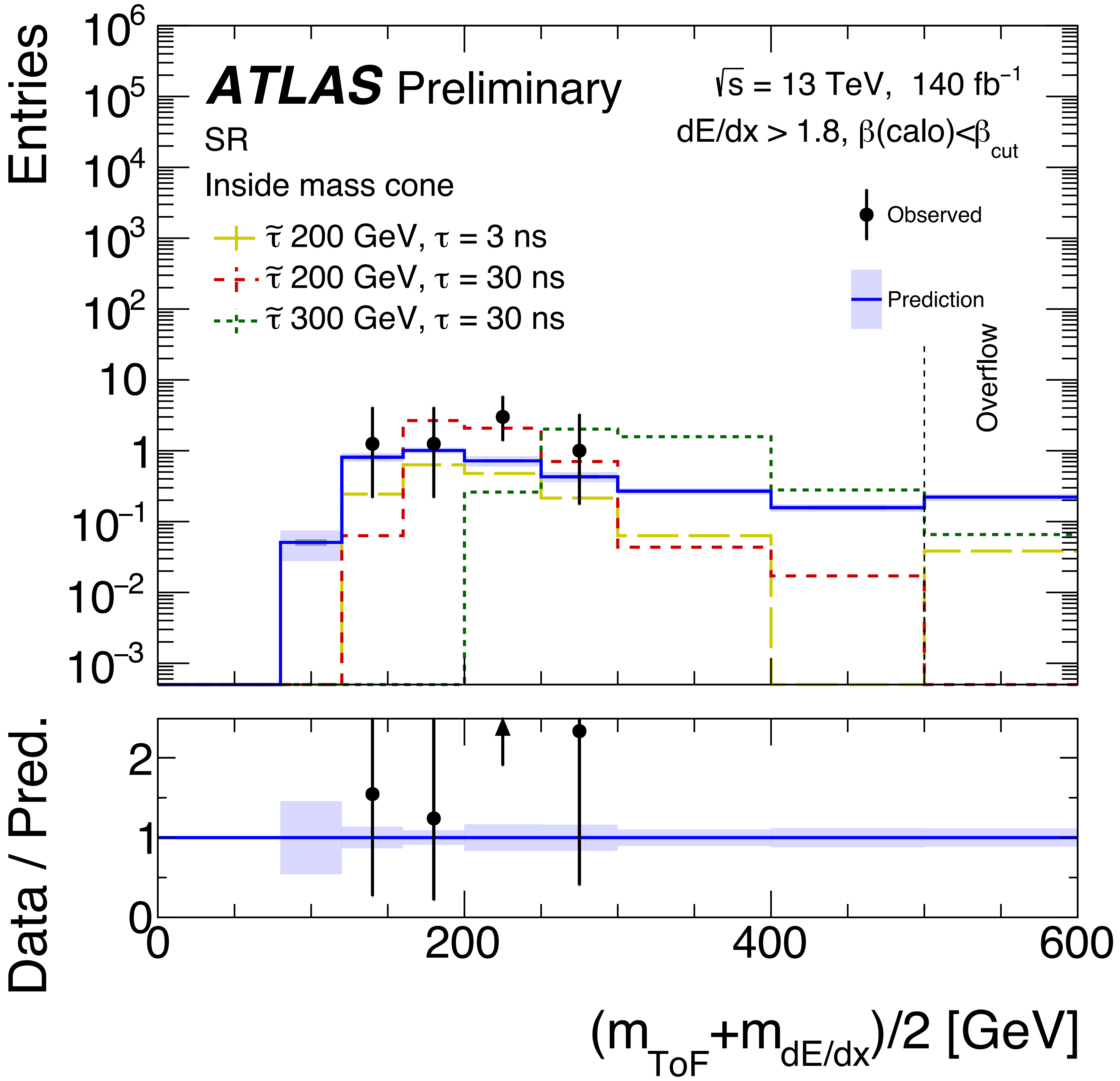


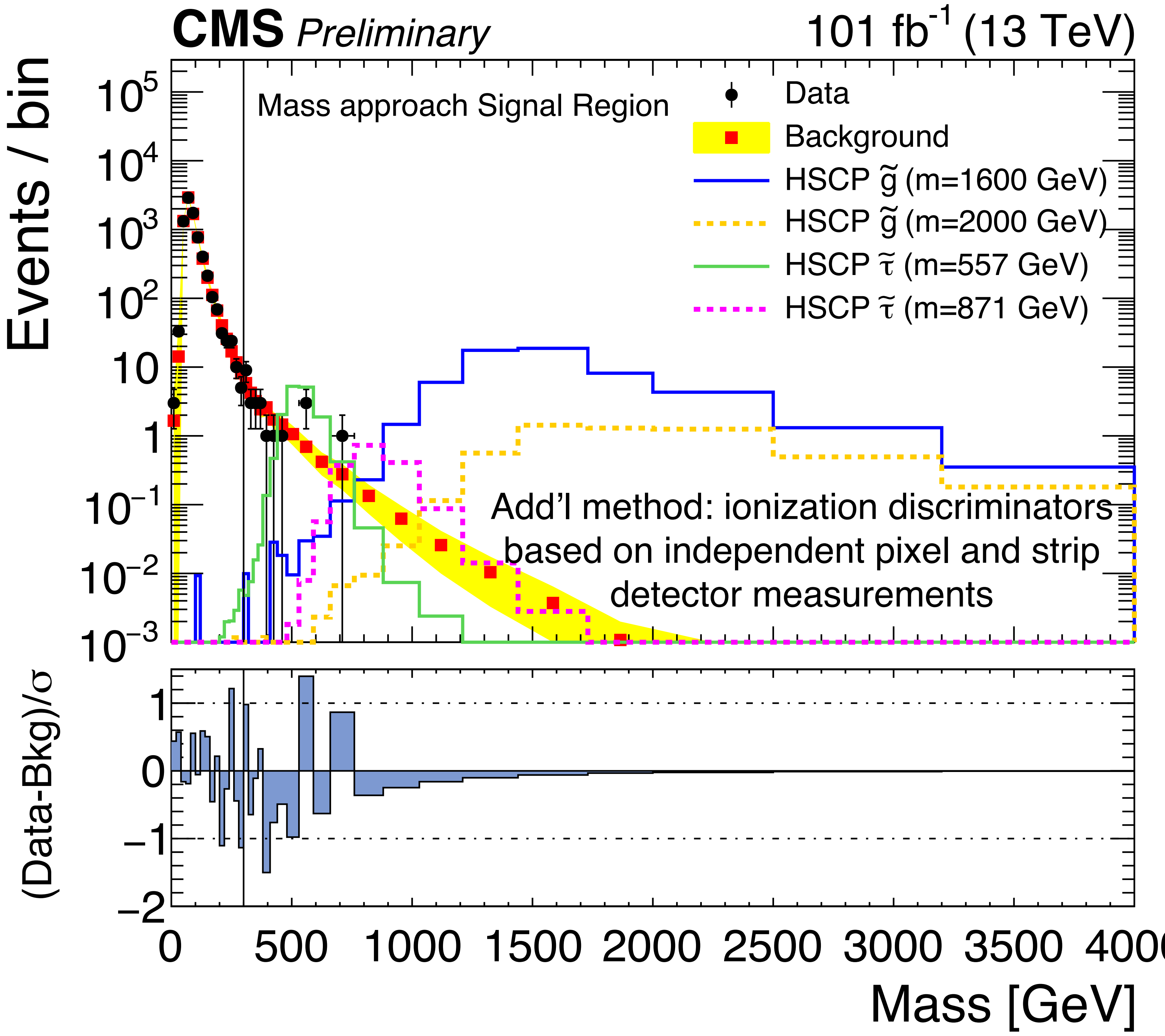


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CMS cannot confirm the excess

# ATLAS dE/dx selections

ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
CMS EXO-18-002

| Category | Item | Description |
|---|---|---|
| Event topology | Trigger | Unprescaled lowest-threshold $E_T^{miss}$ trigger |
| | $E_T^{miss}$ | $E_T^{miss} > 170$ GeV |
| | Primary vertex | The hard-scatter vertex must have at least two tracks |
| Events are required to have at least one track fulfilling *all* criteria listed below; tracks sorted in $p_T$ descending order | | |
| Track kinematics | Momentum | $p_T > 120$ GeV |
| | Pseudorapidity | $\lvert\eta\rvert < 1.8$ |
| | $W^{\pm} \rightarrow \ell^{\pm}\nu$ veto | $m_T(\text{track}, \vec{p}_T^{\,miss}) > 130$ GeV |
| Track quality | Impact parameters | Track matched to the hard-scatter vertex; $\lvert d_0\rvert < 2$ mm and $\lvert\Delta z_0 \sin\theta\rvert < 3$ mm |
| | Rel. momentum resolution | $\sigma_p < \max\left(10\%, -1\% + 90\% \times \frac{\lvert p\rvert}{\text{TeV}}\right)$ and $\sigma_p < 200\%$ |
| | Cluster requirement (1) | At least two clusters used for the $\langle dE/dx\rangle_{trunc}$ calculation |
| | Cluster requirement (2) | 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) |
| | Cluster requirement (3) | No shared pixel clusters and no split pixel clusters |
| | Cluster requirement (4) | Number of SCT clusters > 5 |
| Vetoes | Isolation | $\left(\sum_{trk} p_T\right) < 5$ GeV (cone size $\Delta R = 0.3$) |
| | Electron veto | EM fraction < 0.95 |
| | Hadron and $\tau$-lepton veto | $E_{jet}/p_{track} < 1$ |
| | Muon requirement | SR-Mu: MS track matched to ID track; SR-Trk: otherwise |
| Pixel $dE/dx$ | Inclusive | Low: $dE/dx \in [1.8, 2.4]$ MeV g$^{-1}$cm$^2$ |
| | | High: $dE/dx > 2.4$ MeV g$^{-1}$cm$^2$ |
| | Binned | IBL0_Low: $dE/dx \in [1.8, 2.4]$ MeV g$^{-1}$cm$^2$ and $\text{OF}_{IBL} = 0$ |
| | | IBL0_High: $dE/dx > 2.4$ MeV g$^{-1}$cm$^2$ and $\text{OF}_{IBL} = 0$ |
| | | IBL1: $dE/dx > 1.8$ MeV g$^{-1}$cm$^2$ and $\text{OF}_{IBL} = 1$ |

| 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 | | ✓ | track | no | [1.8, 2.4] |
| SR-Trk-IBL0_High | | ✓ | | no | > 2.4 |
| SR-Trk-IBL1 | | ✓ | | yes | > 1.8 |
| SR-Mu-IBL0_Low | | ✓ | muon tracks | no | [1.8, 2.4] |
| SR-Mu-IBL0_High | | ✓ | | no | > 2.4 |
| SR-Mu-IBL1 | | ✓ | | yes | > 1.8 |

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

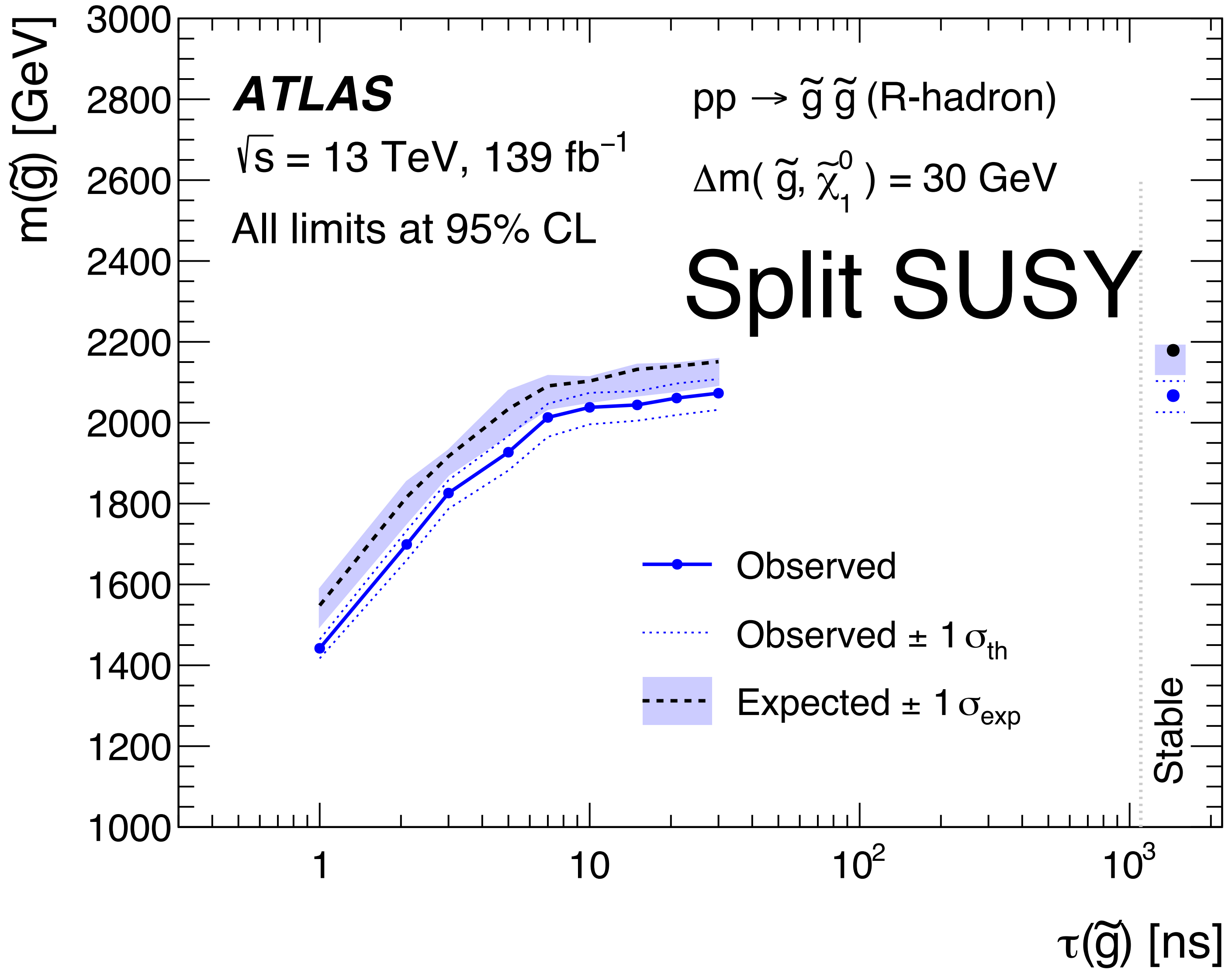
# CMS dE/dx selections

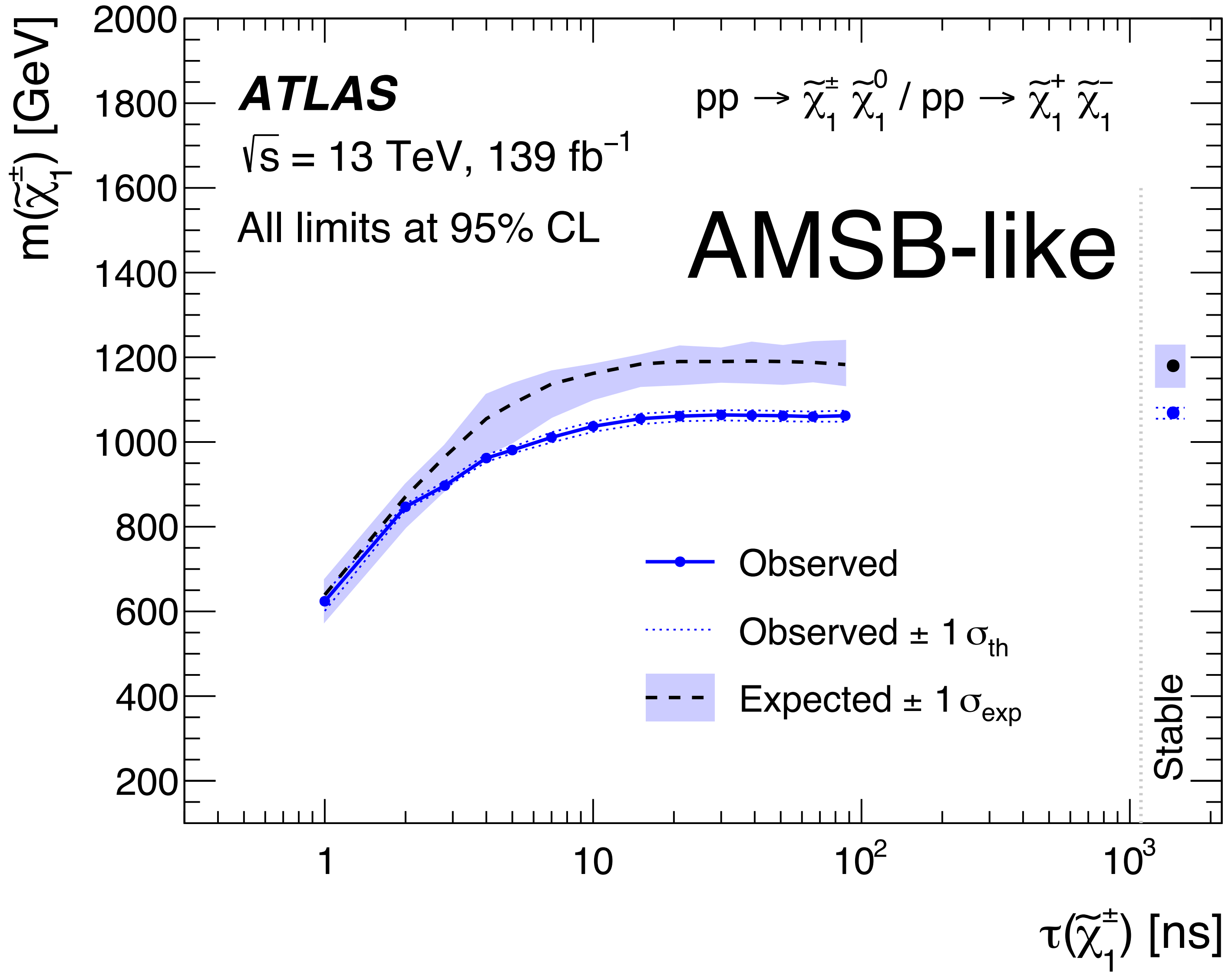
ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
CMS EXO-18-002

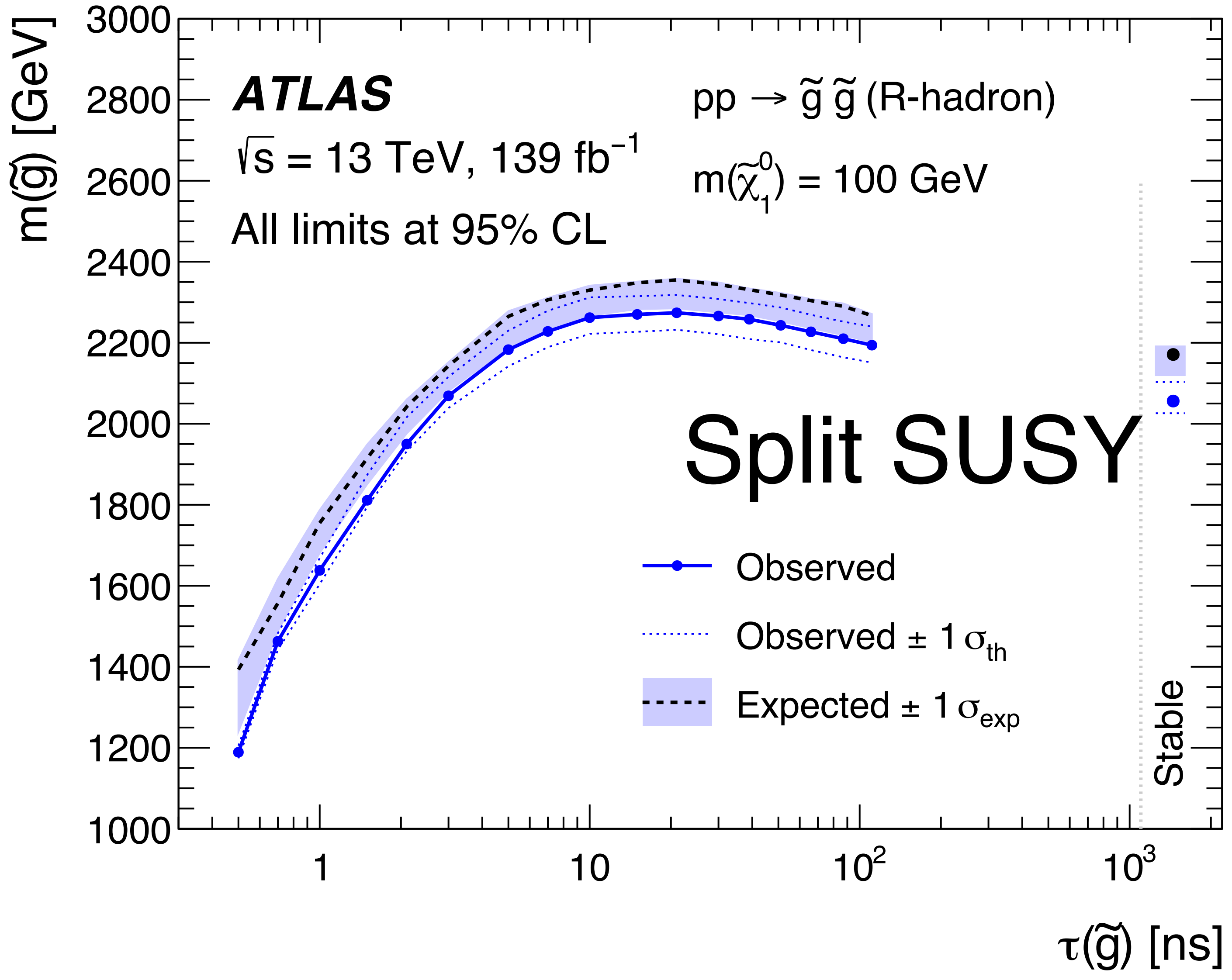
| Selection criteria | Data | $\tilde{g}$ (1.8 TeV) | Pair-prod. $\tilde{\tau}$ (557 GeV) |
|---|---|---|---|
| All events | 1 | 1 | 1 |
| Trigger | 0.15 | 0.11 | 0.86 |
| $p_T > 55$ GeV | 0.11 | 0.11 | 0.86 |
| $\lvert\eta\rvert < 1$ | 0.059 | 0.074 | 0.64 |
| # of valid pixel hits in L2-L4 $\geq 2$ | 0.056 | 0.071 | 0.62 |
| Fraction of valid hits $> 0.8$ | 0.052 | 0.069 | 0.62 |
| # of $dE/dx$ measurements $\geq 10$ | 0.052 | 0.069 | 0.62 |
| High purity track | 0.052 | 0.069 | 0.62 |
| Track $\chi^2/\mathrm{dof} < 5$ | 0.052 | 0.069 | 0.62 |
| $d_z < 0.1$ cm | 0.052 | 0.069 | 0.62 |
| $d_{xy} < 0.02$ cm | 0.048 | 0.069 | 0.62 |
| $I_{PF}^{rel} < 0.02$ | 0.014 | 0.065 | 0.61 |
| $I_{trk} < 15$ GeV | 0.014 | 0.065 | 0.61 |
| PF $E/p < 0.3$ | 0.014 | 0.064 | 0.61 |
| $\sigma_{p_T}/p_T^2 < 0.0008$ | 0.014 | 0.064 | 0.61 |
| $F_i^{Pixels} > 0.3$ | 0.011 | 0.064 | 0.60 |

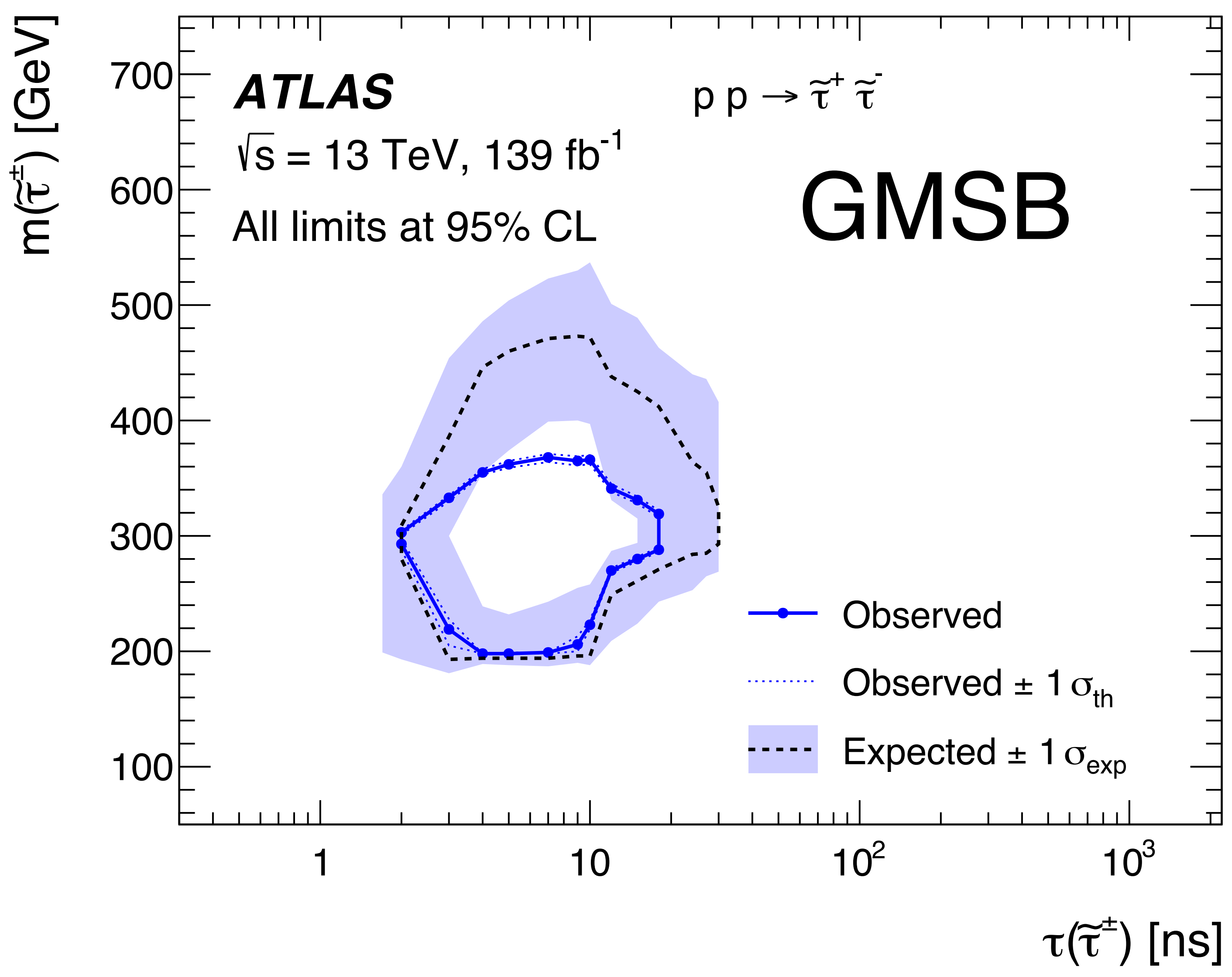
# ATLAS dE/dx limits

ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
CMS EXO-18-002



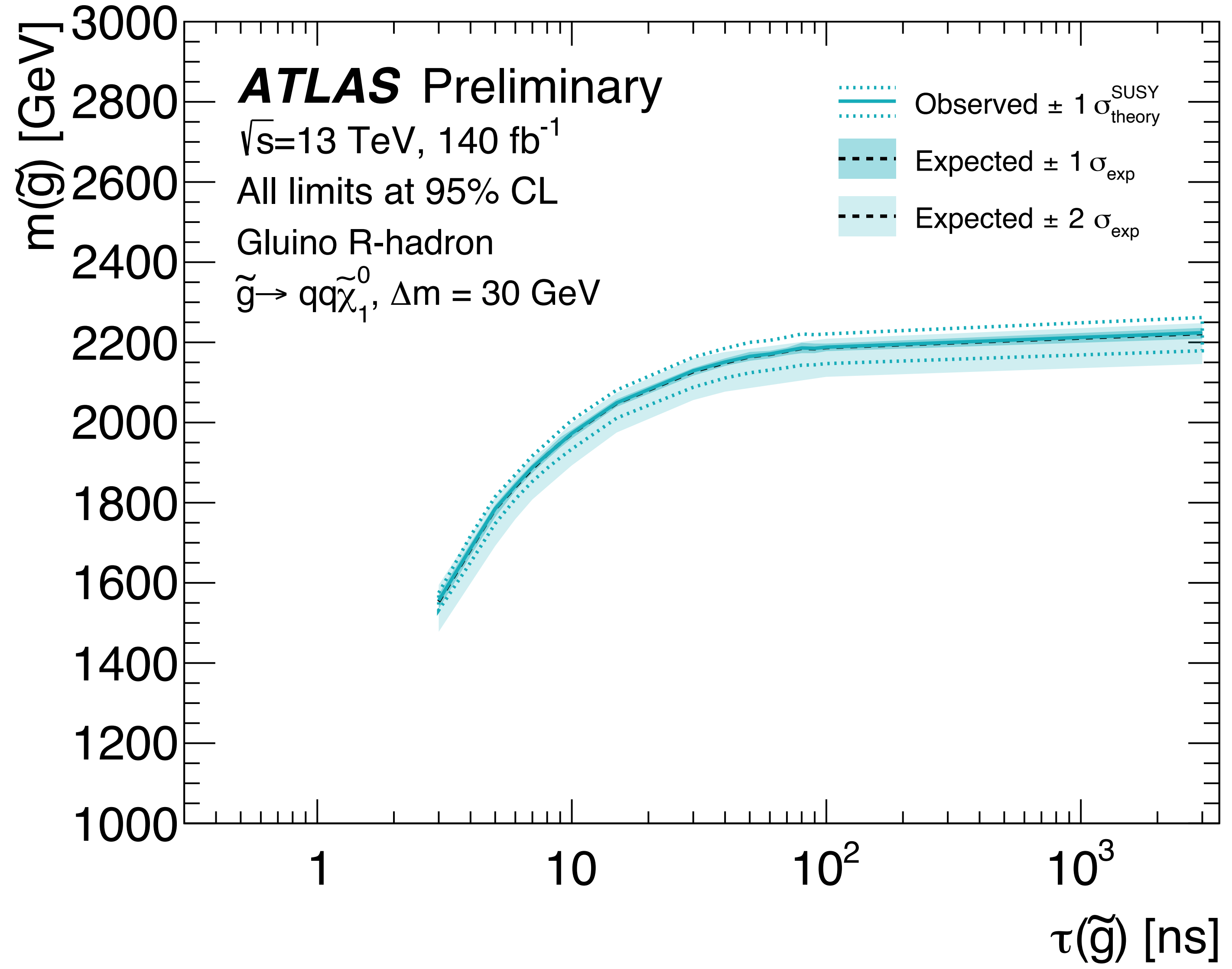



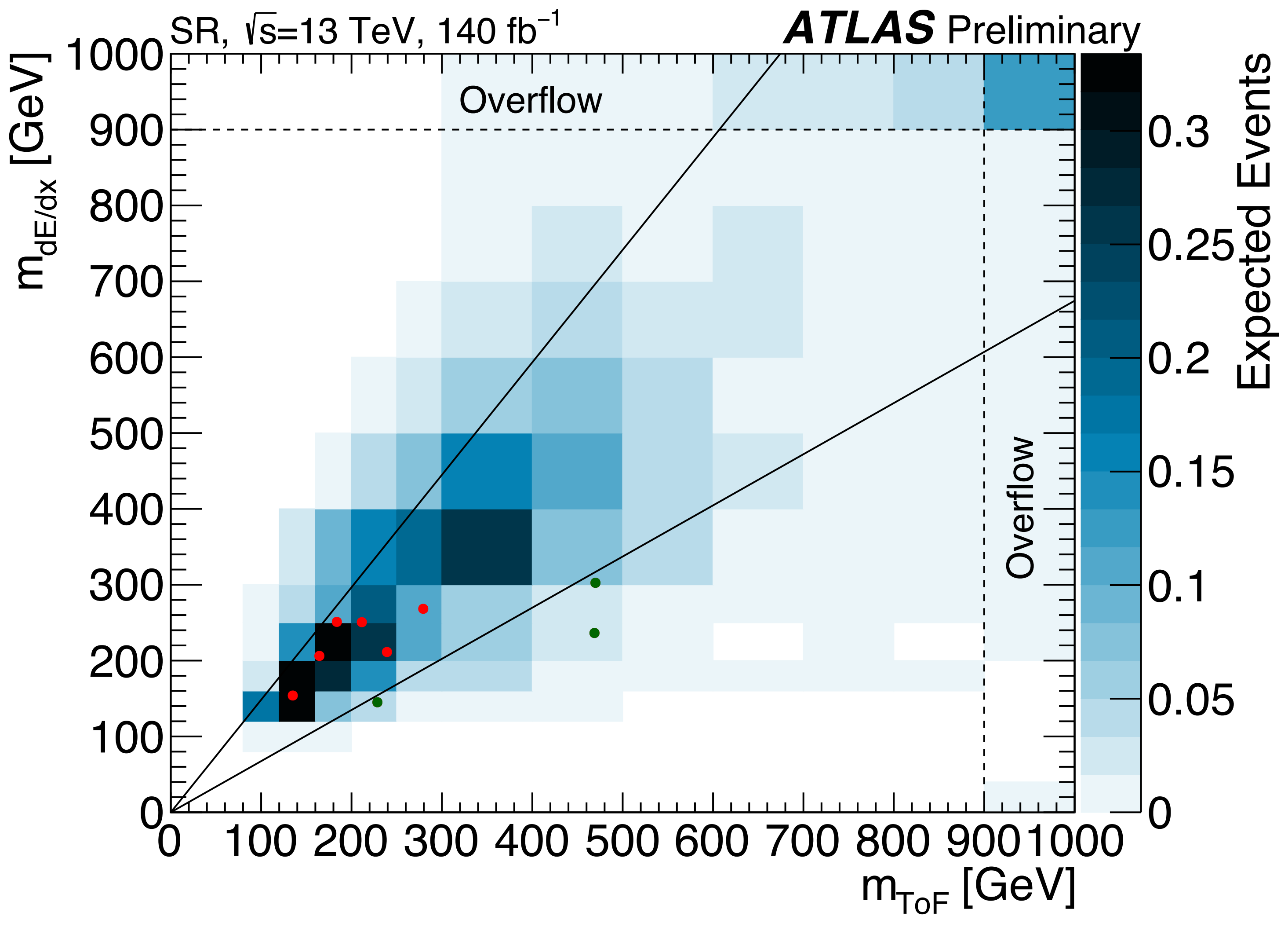



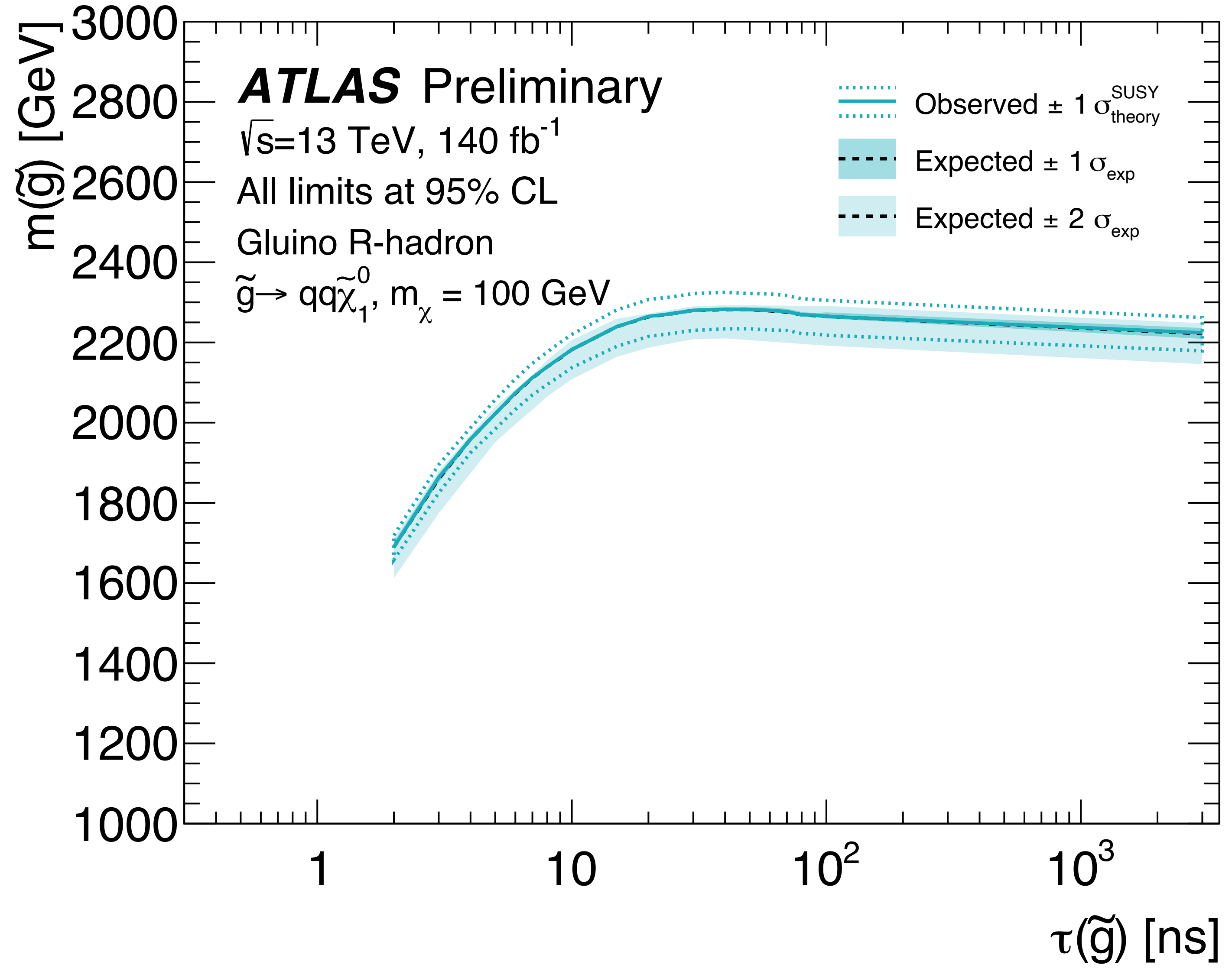



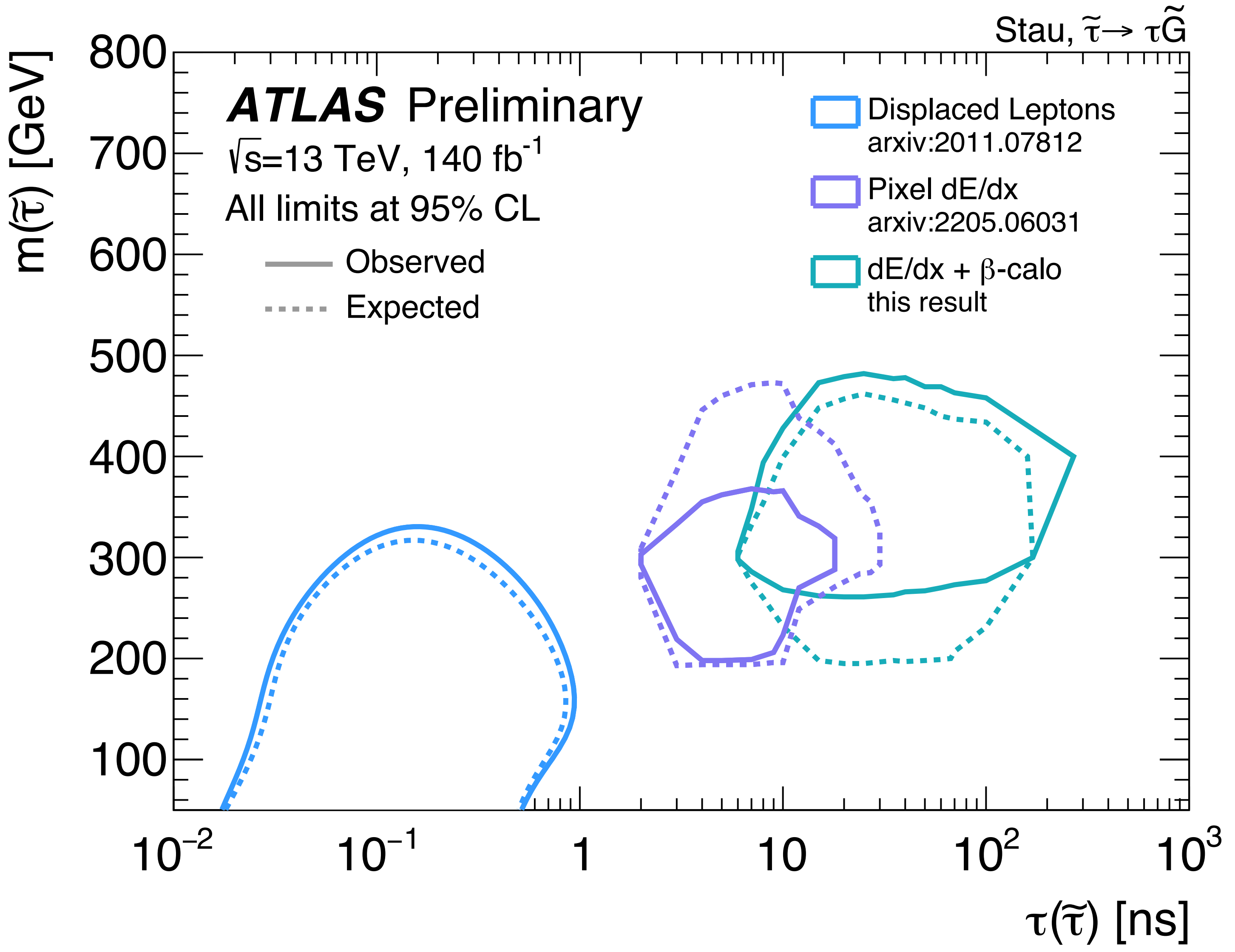
# ATLAS dE/dx with low β limits

ATLAS SUSY-2018-42
ATLAS-CONF-2023-044
CMS EXO-18-002



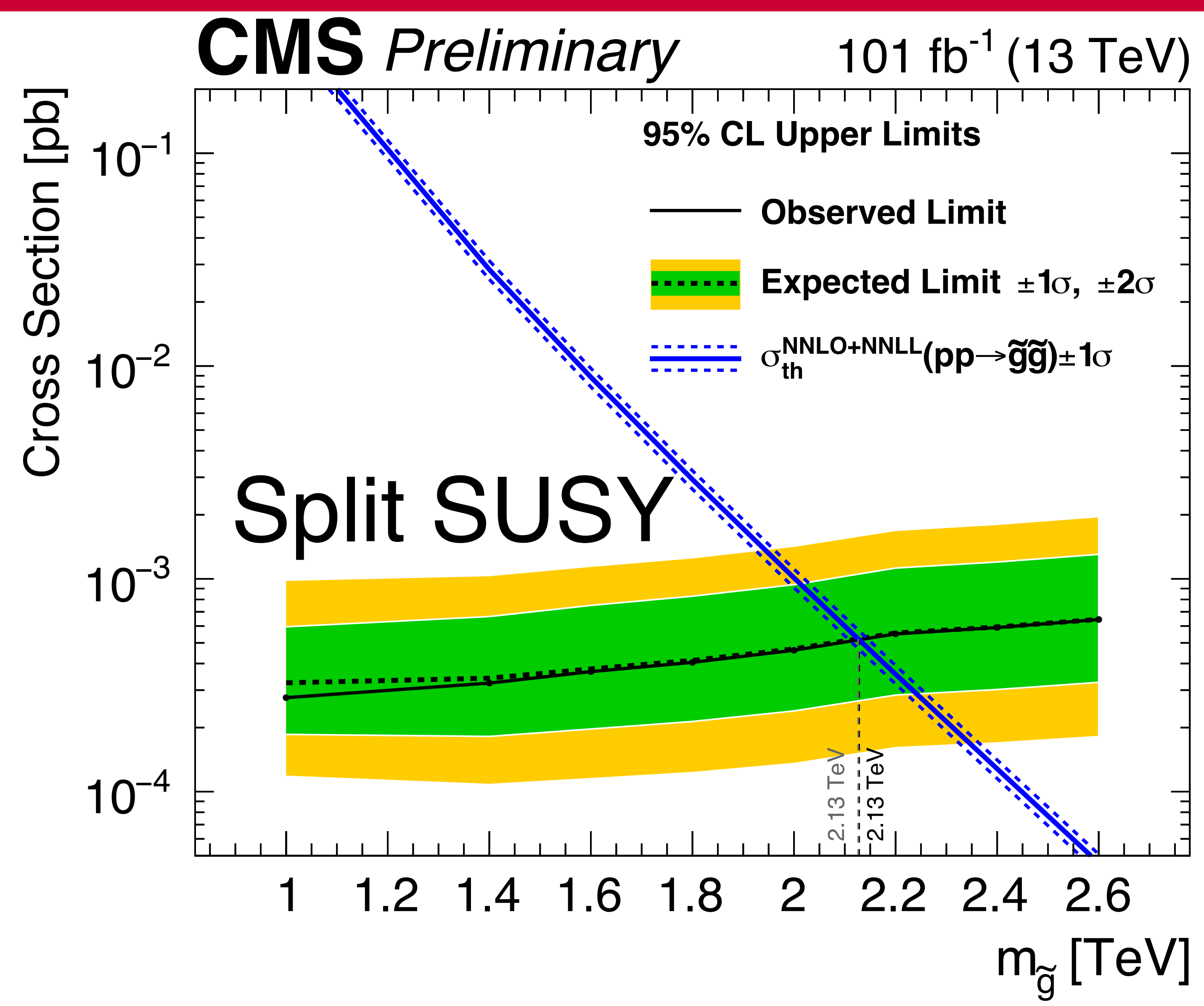



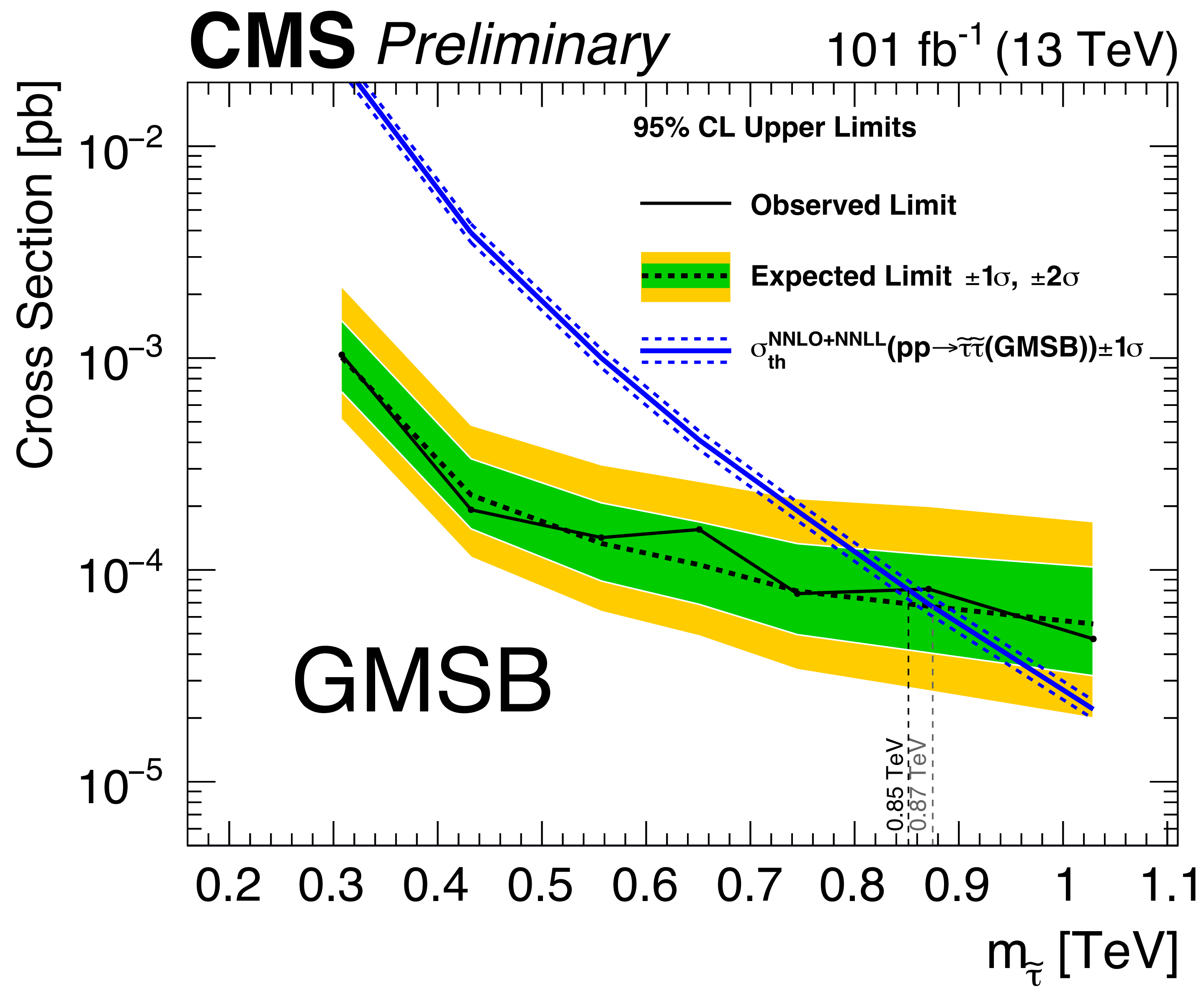



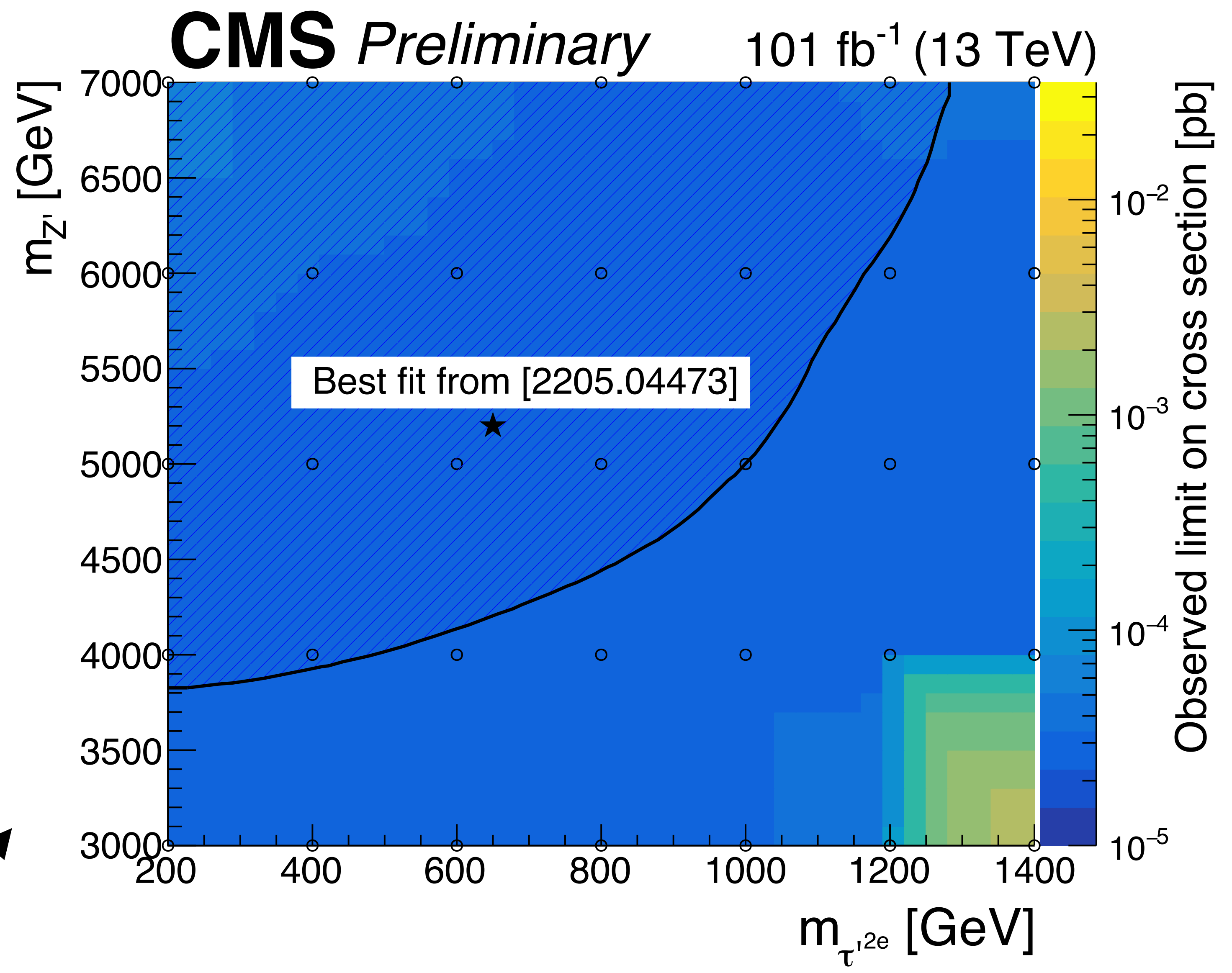
Assumes stable LLP for all of these

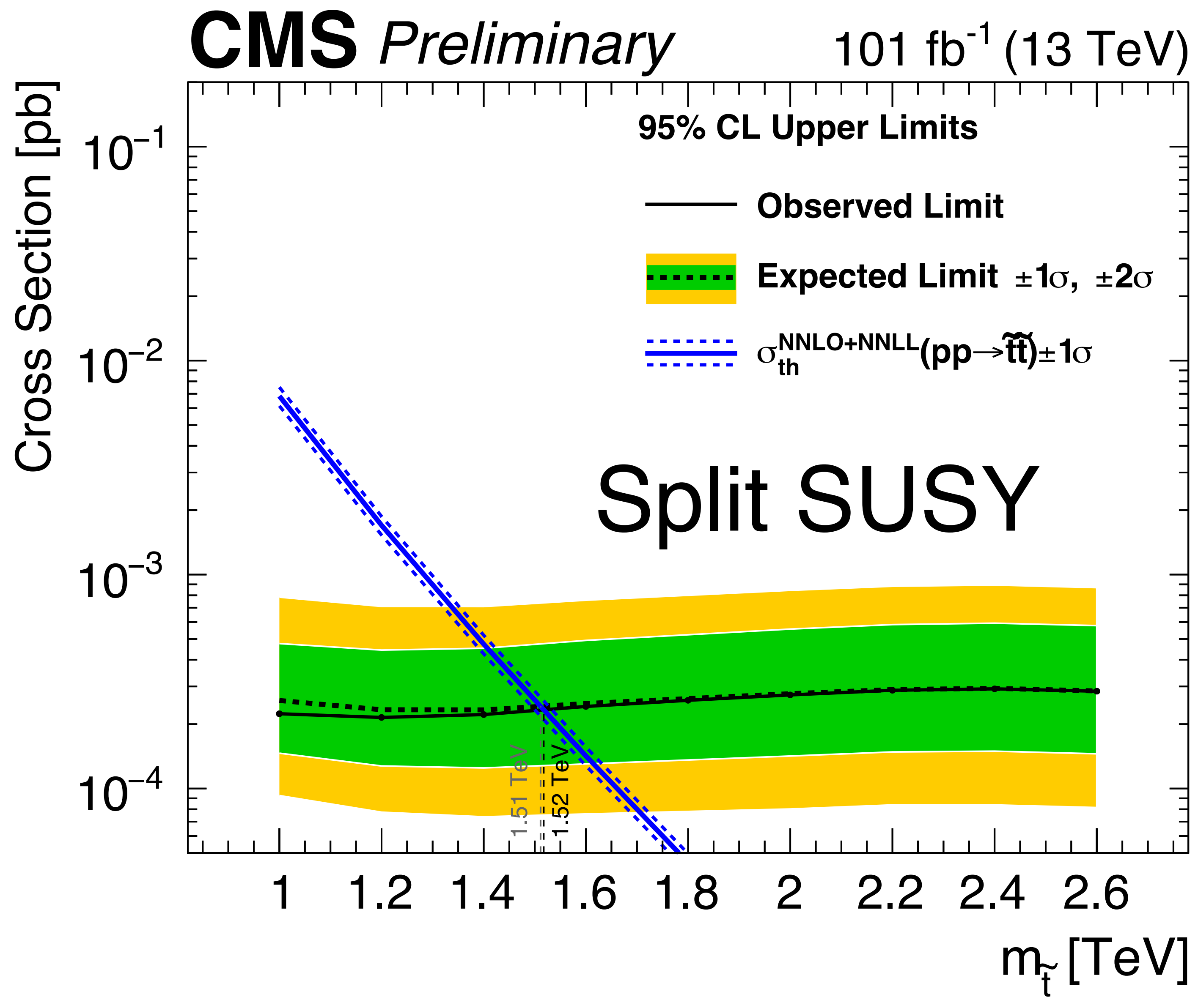
# CMS dE/dx limits

[ATLAS SUSY-2018-42](#)
[ATLAS-CONF-2023-044](#)
[CMS EXO-18-002](#)

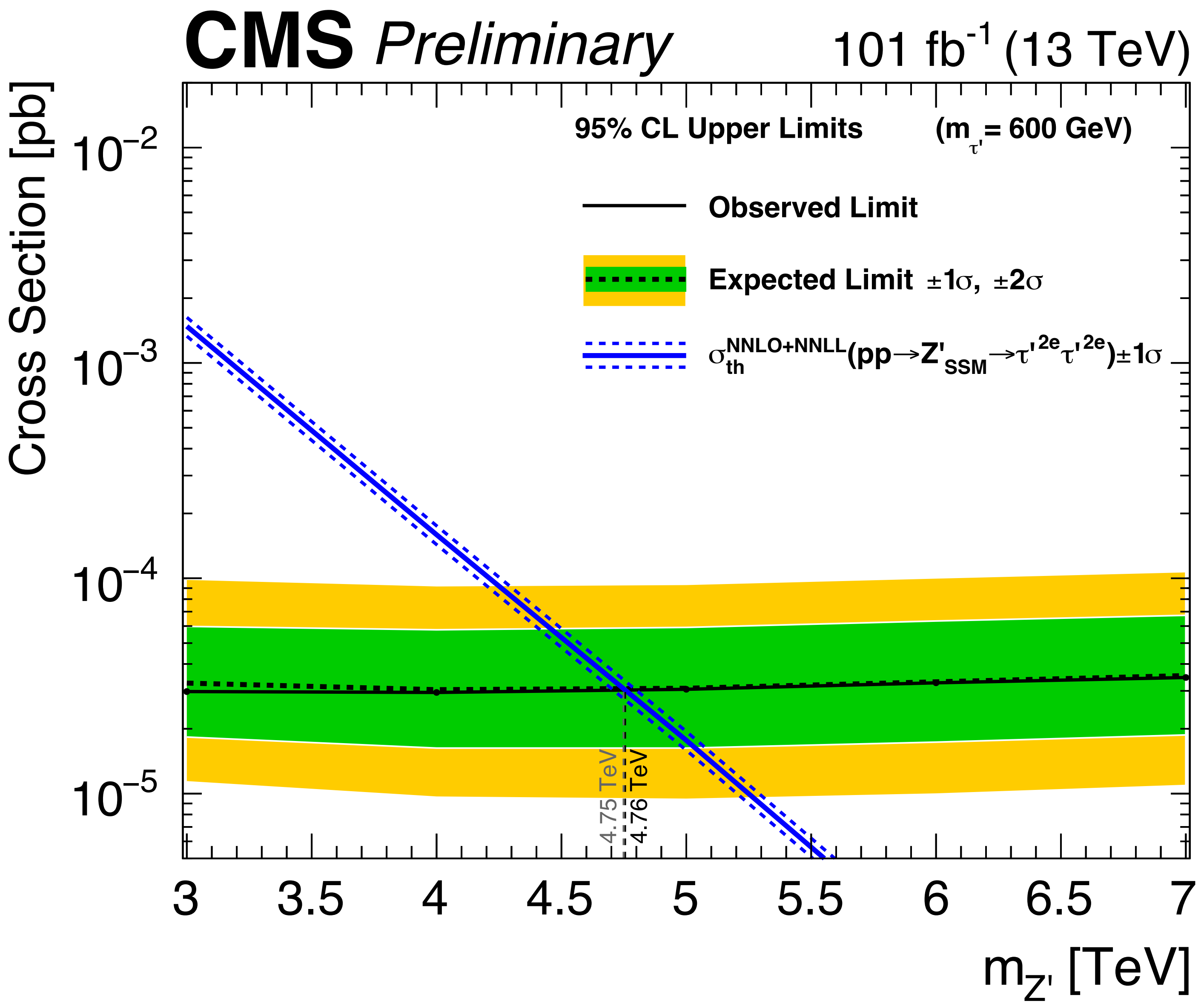


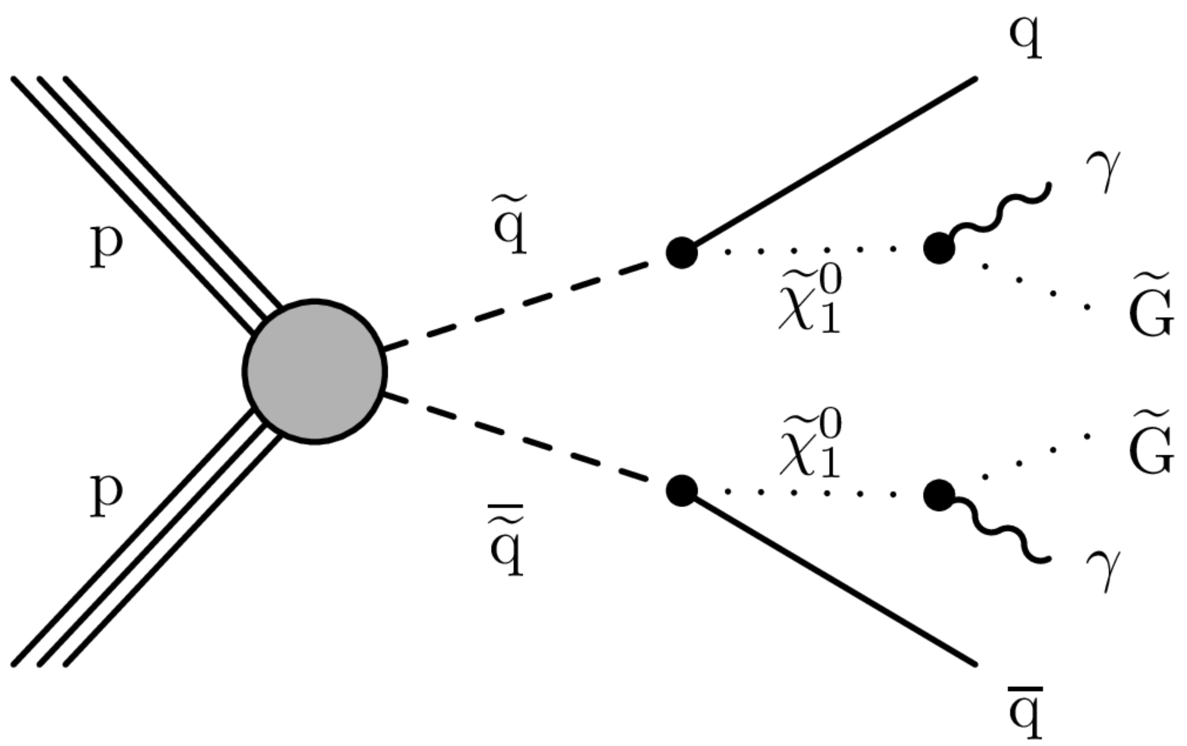




Model proposed to explain ATLAS excess, here w/ SSM Z' cross sections



# CMS delayed photons

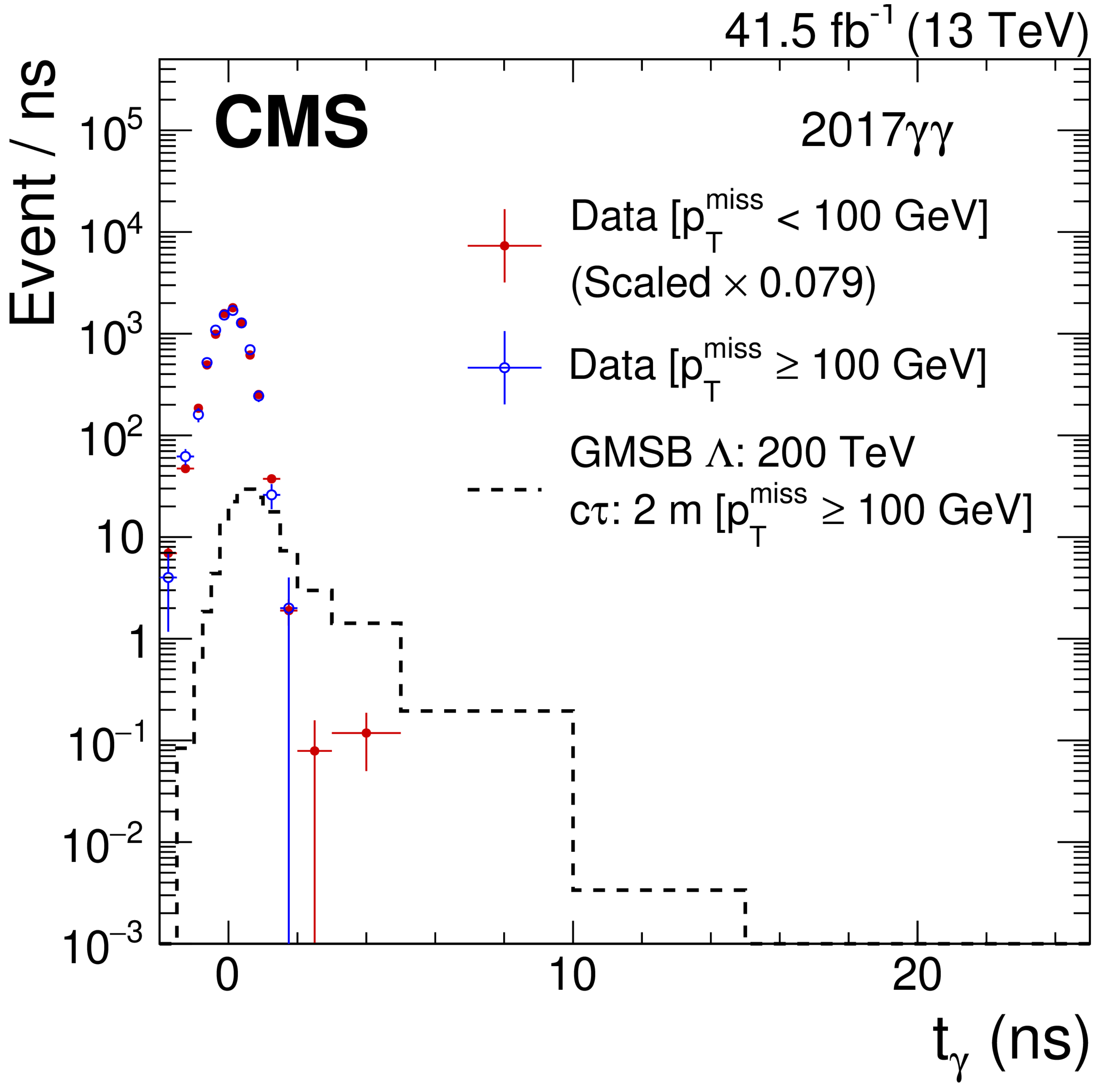
CMS EXO-19-005

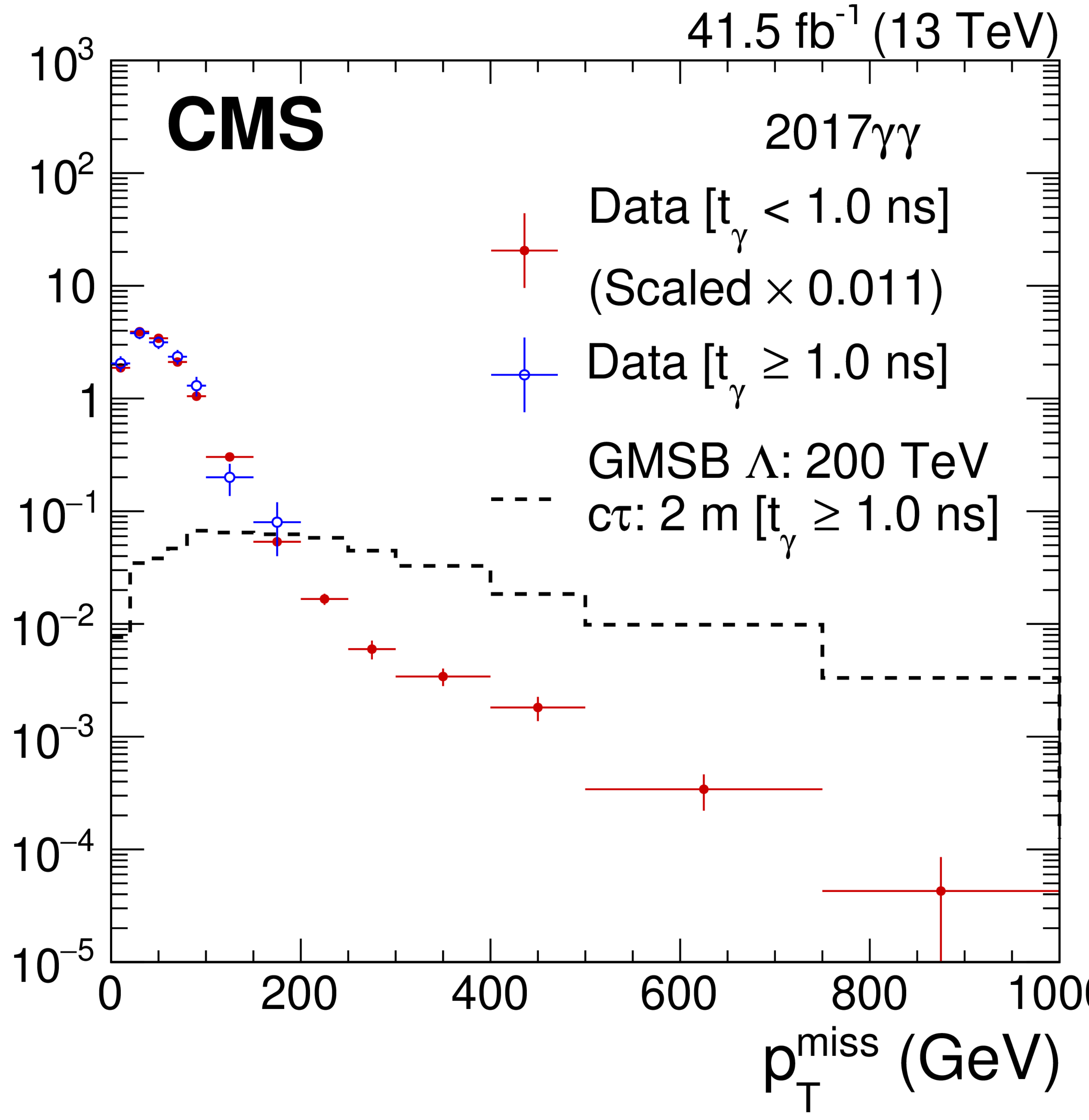


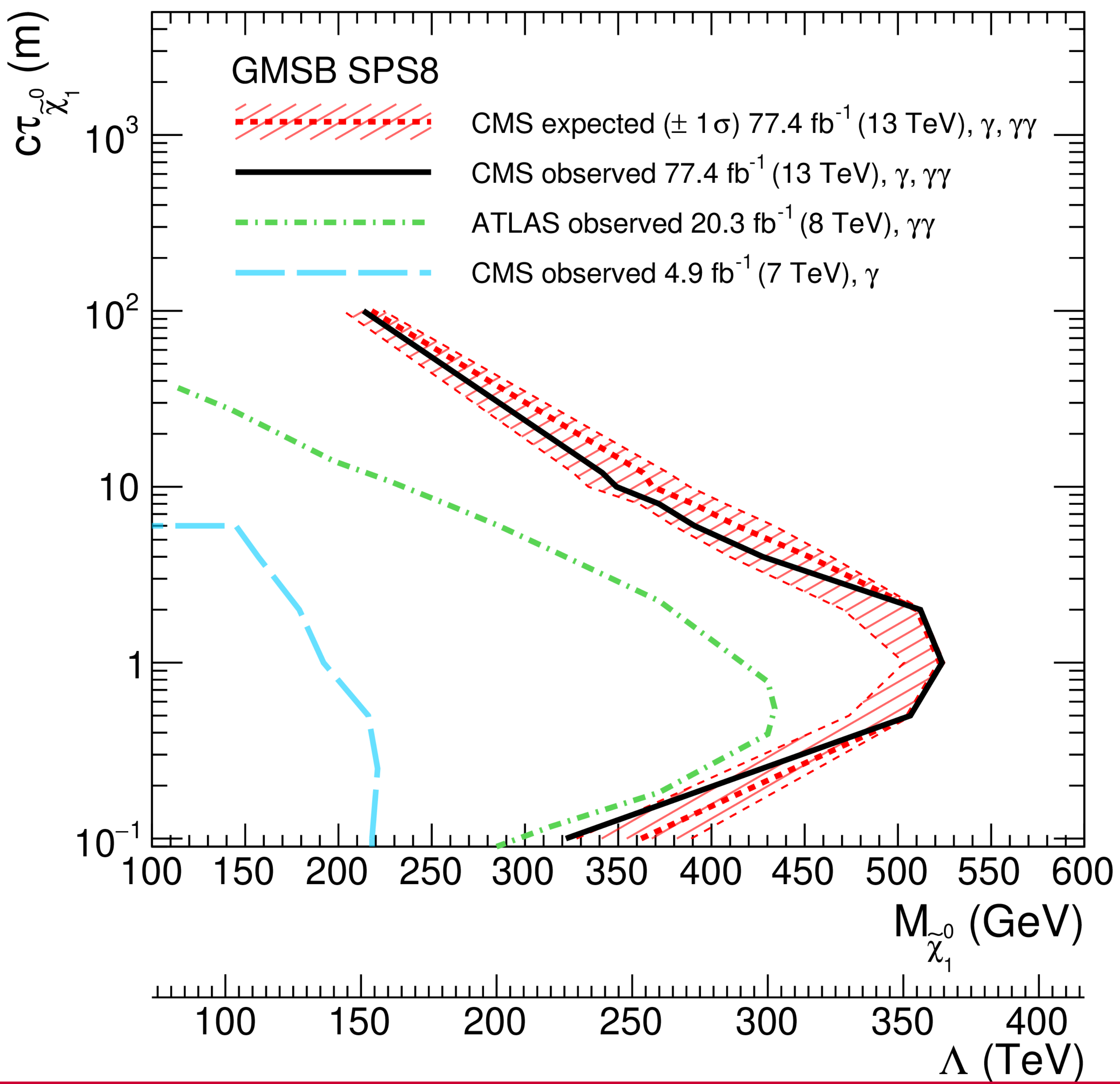

γ(γ)+MET+jets in GMSB SUSY models w/ cascade decays

Incident angle on ECAL ⟹ elliptical shower shapes. Use along with timing info, and include photons that arrived after 3 ns (not usually reconstructed).

Trigger w/ standard diphotons or elliptical shower shapes + some HT requirements.

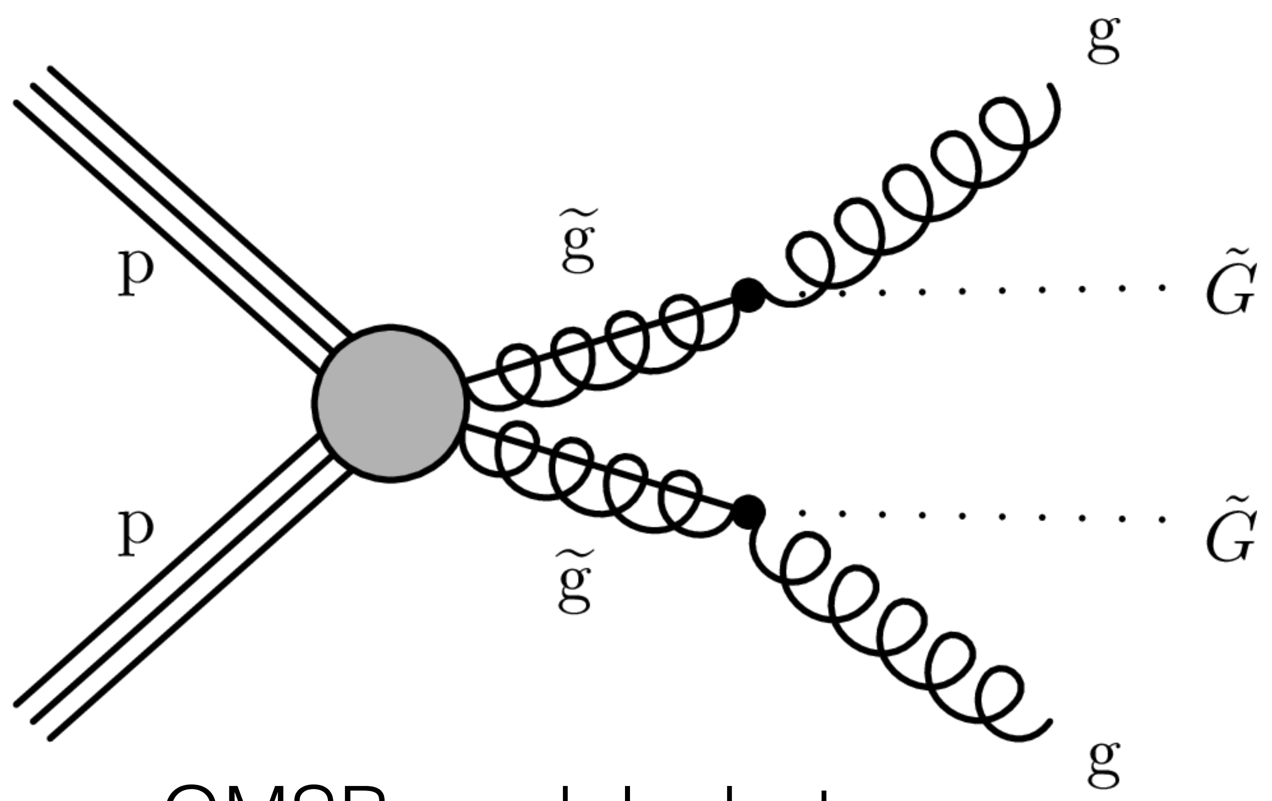


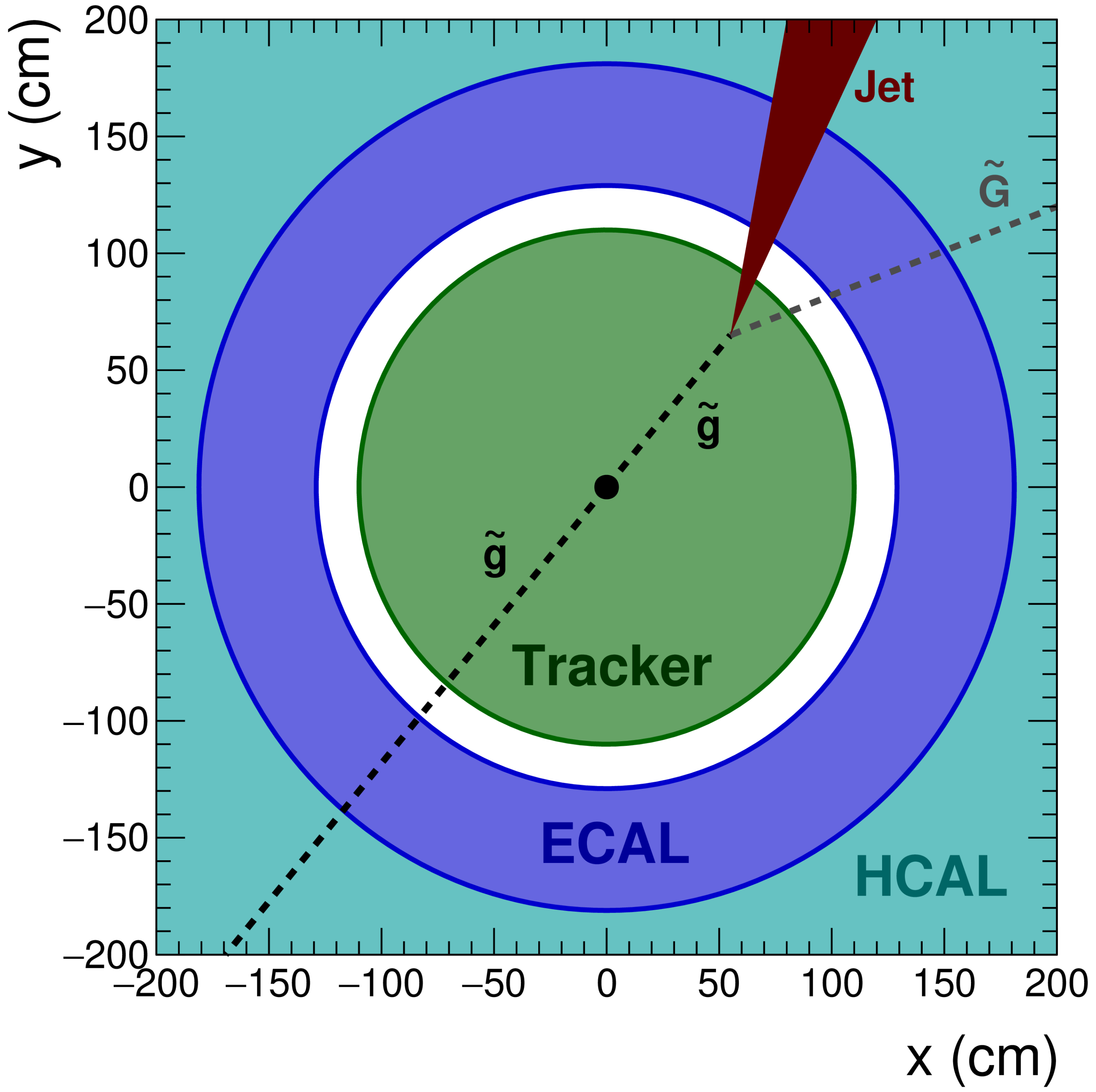



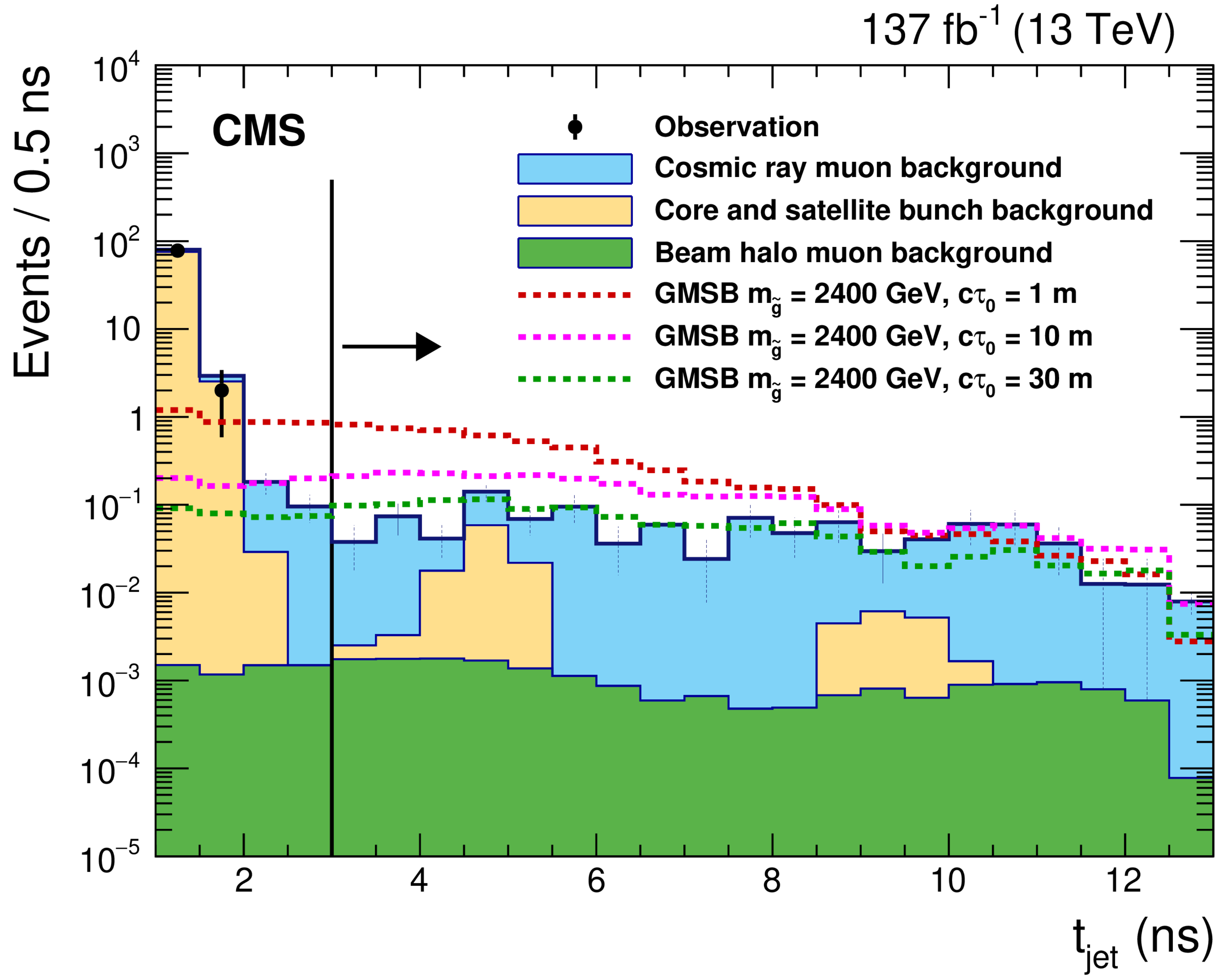
# CMS delayed jets

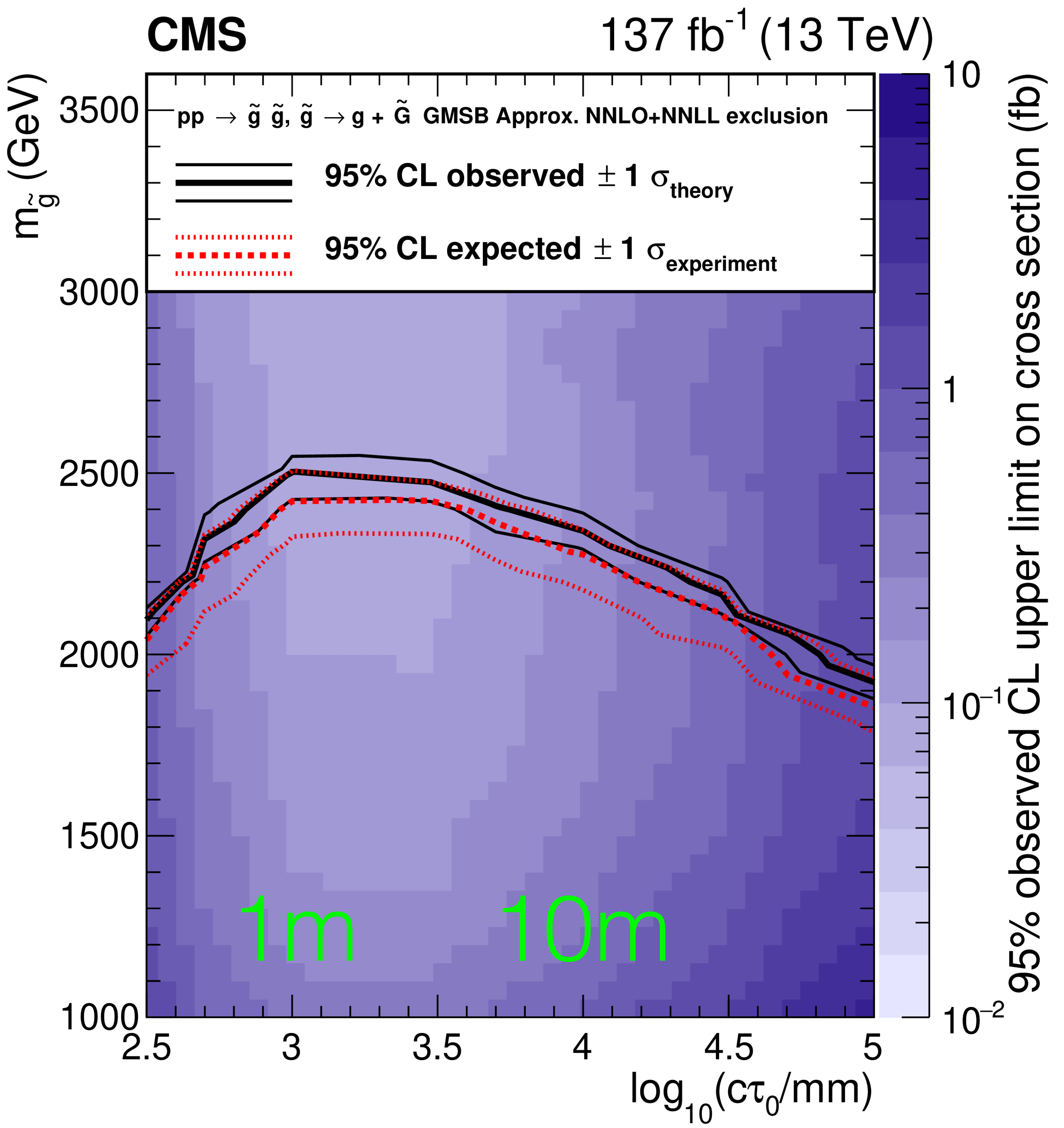
CMS EXO-19-001




GMSB models, but can reinterpret for other scenarios




ECAL timing (+ timing quality criteria) used to separate signal from background in scenarios with LLP decays in the calorimeter, along with MET > 300 GeV.

# Non-pointing / delayed photons + MET

ATLAS SUSY-2019-14
ATLAS SUSY-2020-28
CMS EXO-19-005

## H → LLPs search

| Parameter | Low-$\Delta m$ selection ($\Delta m = 10$ GeV) | | | | High-$\Delta m$ selection ($\Delta m > 10$ GeV) | | | |
|---|---|---|---|---|---|---|---|---|
| | CR | VR($E_T^{miss}$) | VR($t$) | SR | CR | VR($E_T^{miss}$) | VR($t$) | SR |
| $E_{cell}$ [GeV] | > 7 | | | | > 10 | | | |
| $E_T^{miss}$ [GeV] | < 30 | 30–50 | > 80 | > 80 | < 30 | 30–50 | > 50 | > 50 |
| $t_\gamma$ [ns] | > 0 | > 0 | < 0 | > 0 | > 0 | > 0 | < 0 | > 0 |
| $\lvert\Delta z_\gamma\rvert$ bins [mm] | [0, 50, 100, 200, 300, 2000] | | | | | | | |
| $\lvert t_\gamma\rvert$ bins [ns] | | | | | | | | |
| $1\gamma$ channel | [0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 12.0] | | | | | | | |
| $\geq 2\gamma$ channel | [0, 0.2, 0.4, 0.6, 0.8, 1.0, 12.0] | | | | | | | |

| Channel | Test region requirements | Expected | Observed | $\sigma_{vis}^{95}$ [fb] |
|---|---|---|---|---|
| $1\gamma$ | $1.5 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm | 3.8 ± 1.6 | 4 | 0.042 |
| $\geq 2\gamma$ | $1.0 < t_\gamma < 12$ ns, $\lvert\Delta z_\gamma\rvert > 300$ mm | 0.28 ± 0.04 | 0 | 0.022 |
| $\geq 1\gamma$ | | 4.1 ± 1.7 | 4 | 0.041 |

## Vertexed photons search

| Parameter | Preselection requirements |
|---|---|
| Photon multiplicity | > 1 |
| Photon $\eta$ | $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$ ($\geq 1$ with $\lvert\eta\rvert < 1.37$) |
| $E_{cell}(\gamma)$ [GeV] | $E_{cell}(\gamma_1),\ E_{cell}(\gamma_2) > 5$ |
| $p_T(\gamma)$ [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] |
| $\lvert V_z\rvert$ [mm] | < 3740 |
| $t_\gamma$ [ns] | $t_{\gamma_1}, t_{\gamma_2} \in$ [-12, 12] |

| Parameter | Analysis region requirements: CR | VR($E_T^{miss}$) | VR($t$) | SR |
|---|---|---|---|---|
| $E_T^{miss}$ [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] |
| $t_{avg}$ bin edges [ns] | [0, 0.2, 0.4, 0.6, 0.9, 12] |

| Selection | Data | Total Background | $p_0$ | Z ($\sigma$) | $N^{excl}$ Events |
|---|---|---|---|---|---|
| SR, $t_{avg} > 0.9$ ns | 4 | 10.2 ± 3.0 | 0.97 | -1.96 | 14.4 |