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Full Run 2 Results
for Disappearing Tracks at CMS

Pheno 2020

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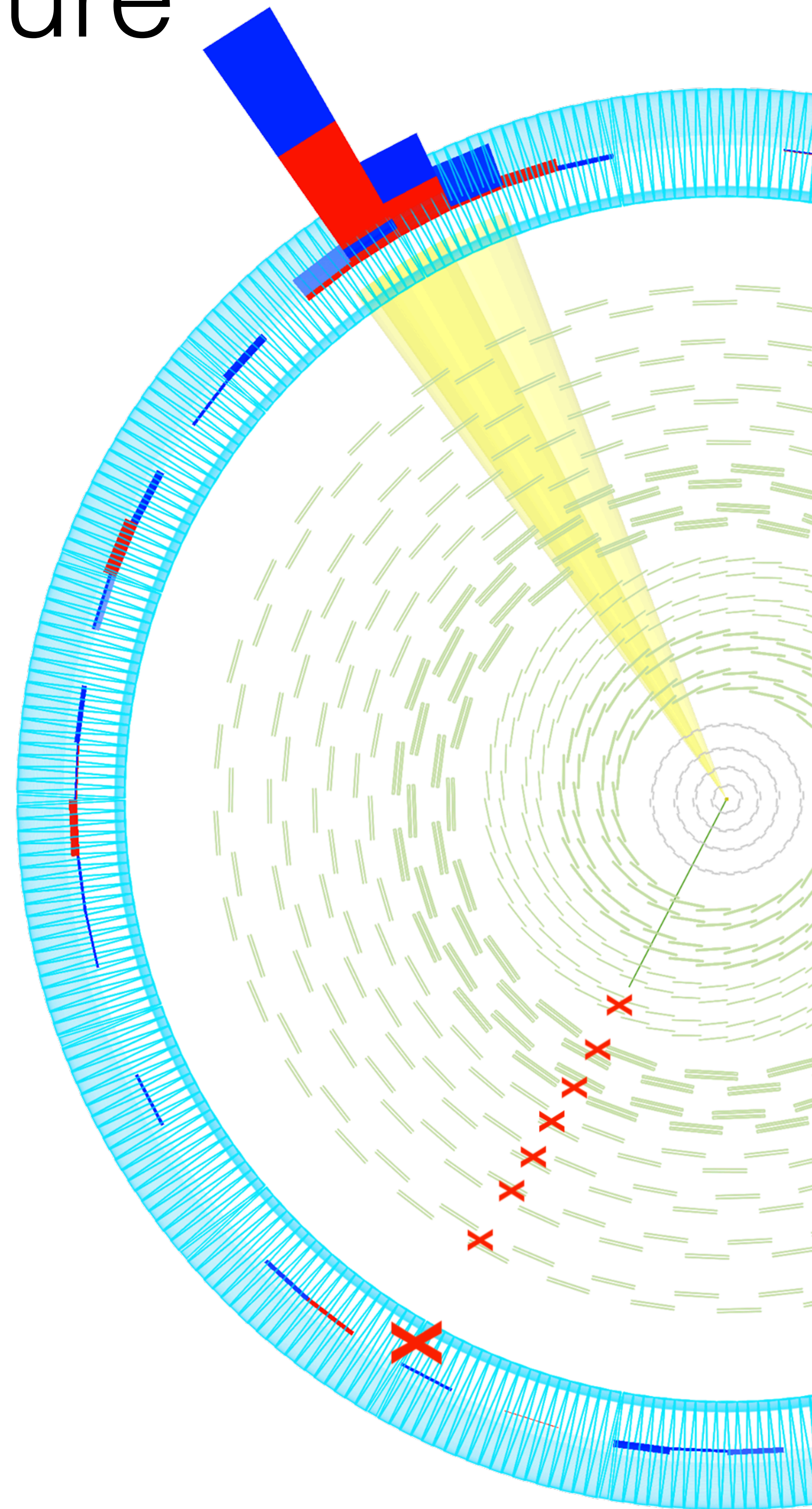
for the CMS Collaboration

Newly submitted to PLB: arXiv:2004.05153 (CMS public page)
Featured: cms.cern/news/disappearing-act-cms

A Striking Signature



- A long-lived charged particle decaying within the CMS tracker
- If the decay products are undetected, the track "disappears"
  - Neutral, weakly interacting
  - Too low momentum to be reconstructed
- Observation would be a striking sign of BSM physics
  - **Arises in many models**
  - Multiple handles to study — decay length, mass, dE/dx, potential recovery of decay products

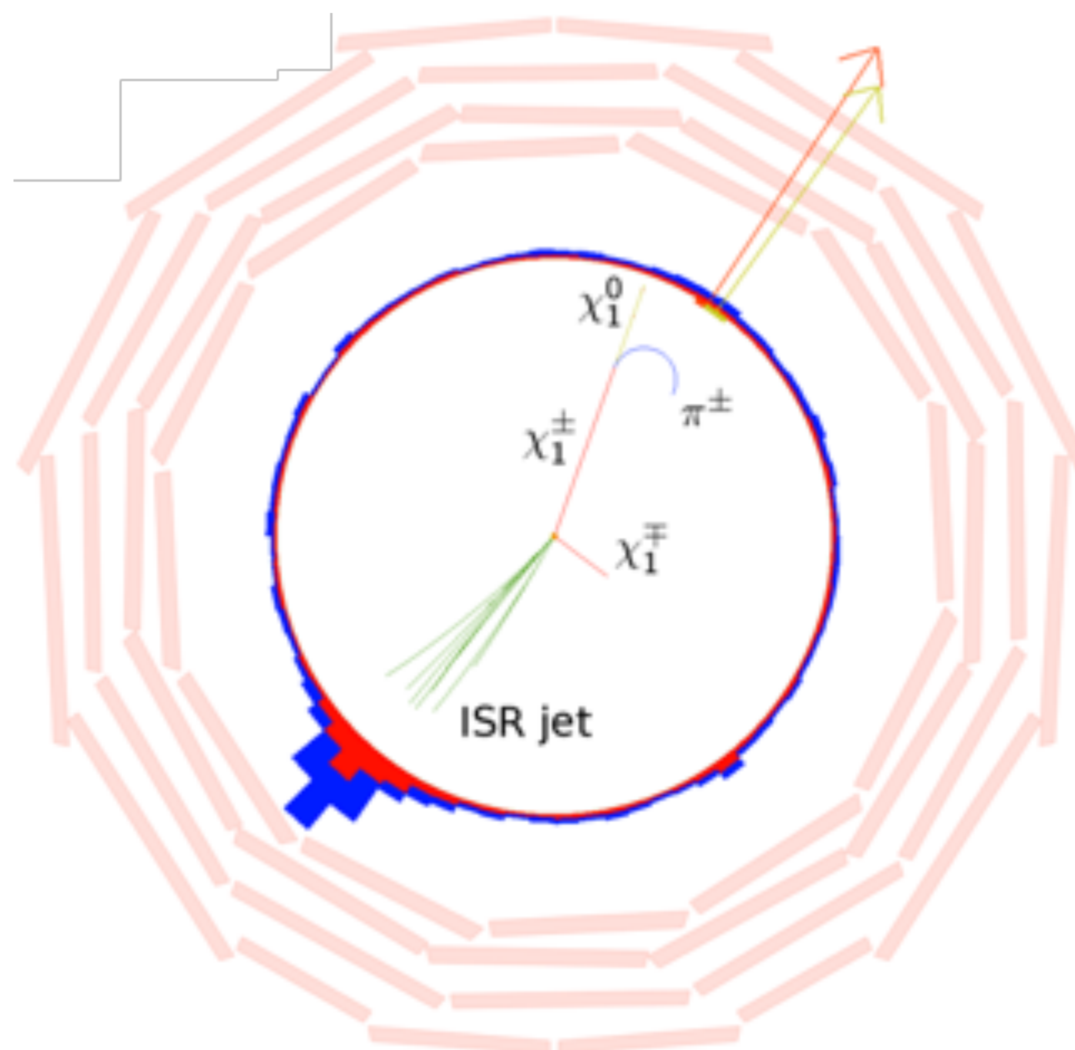
Canonical Benchmark — AMSB

- Consider anomaly-mediated supersymmetry breaking (AMSB)
- Small mass splitting between chargino ($\tilde{\chi}^{\pm}$) and neutralino ($\tilde{\chi}^{0}$)
  - Direct electroweak production:

$$pp \to \tilde{\chi}^{\pm}\tilde{\chi}^{\mp},\ \tilde{\chi}^{\pm}\tilde{\chi}^{0}$$

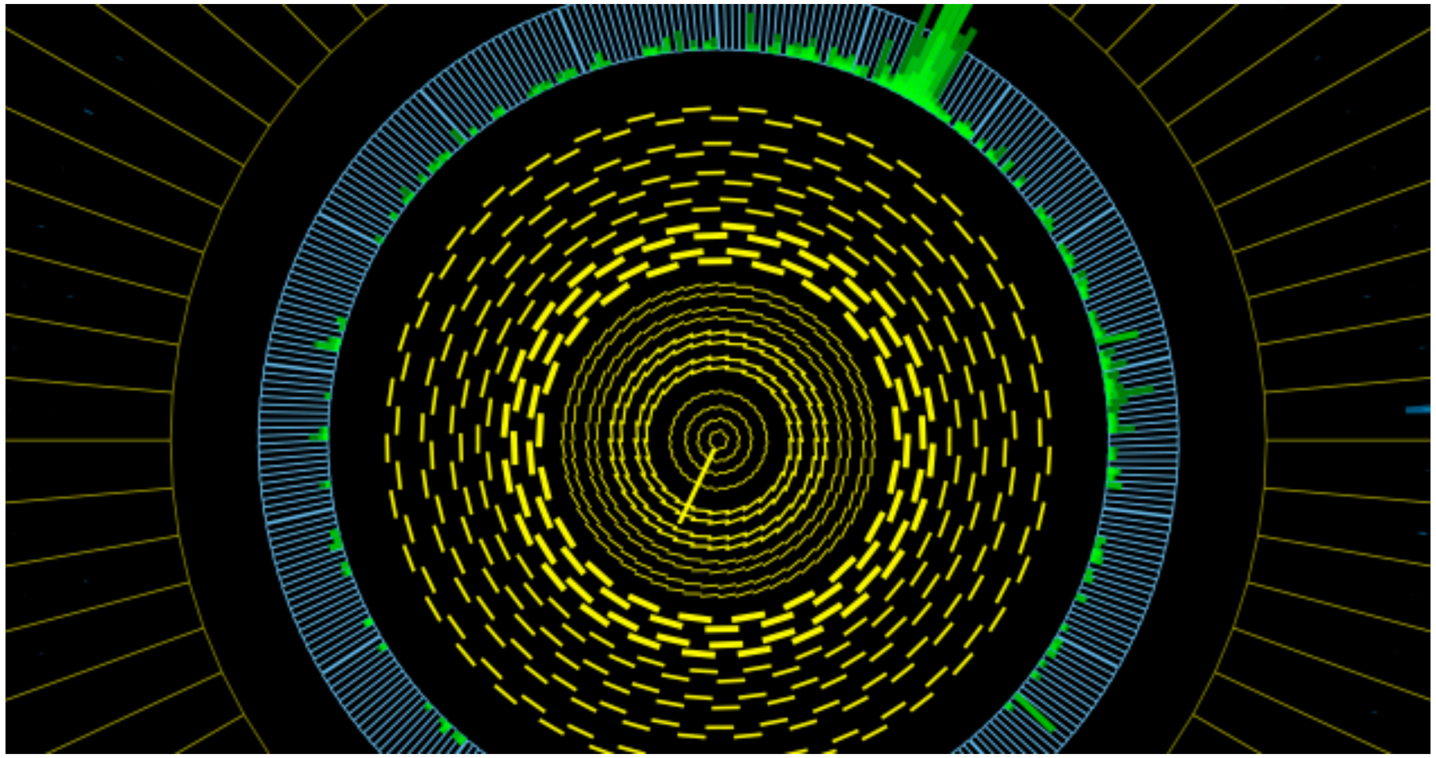
  - $\tilde{\chi}^{\pm} \to \pi^{\pm}\chi^{0}$ with lifetime O(1) ns
  - $\tilde{\chi}^{0}$ interacts only weakly, and $\pi^{\pm}$ is too soft to be reconstructed

Simulation



AMSB is one benchmark of many that would frequently produce disappearing tracks

Rare Backgrounds

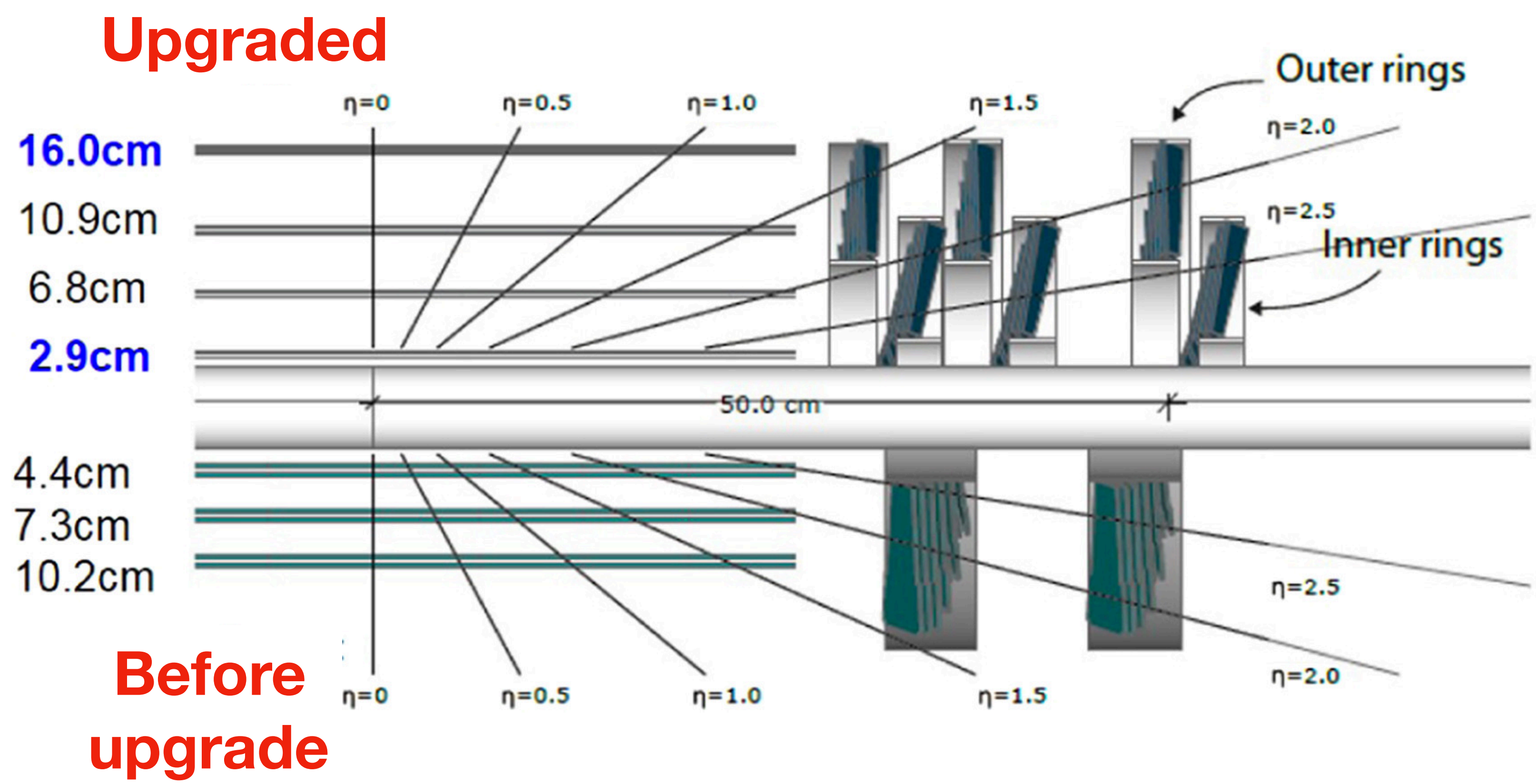


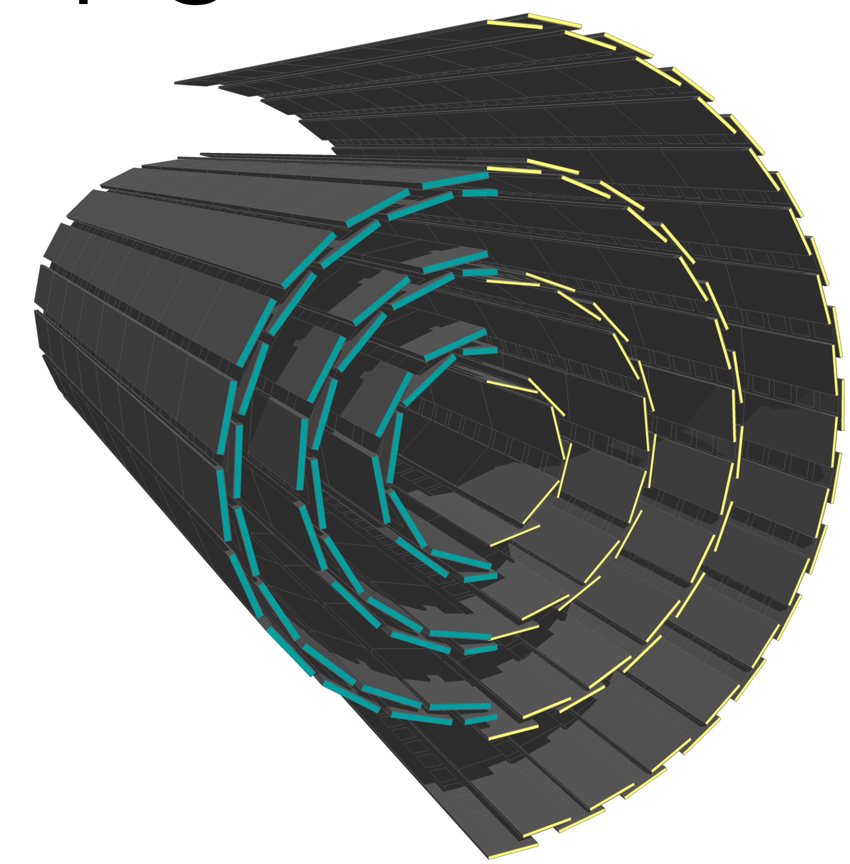
- SM particles don't disappear, however there are rare backgrounds:
  - Charged hadrons can interact with detector material, e.g.

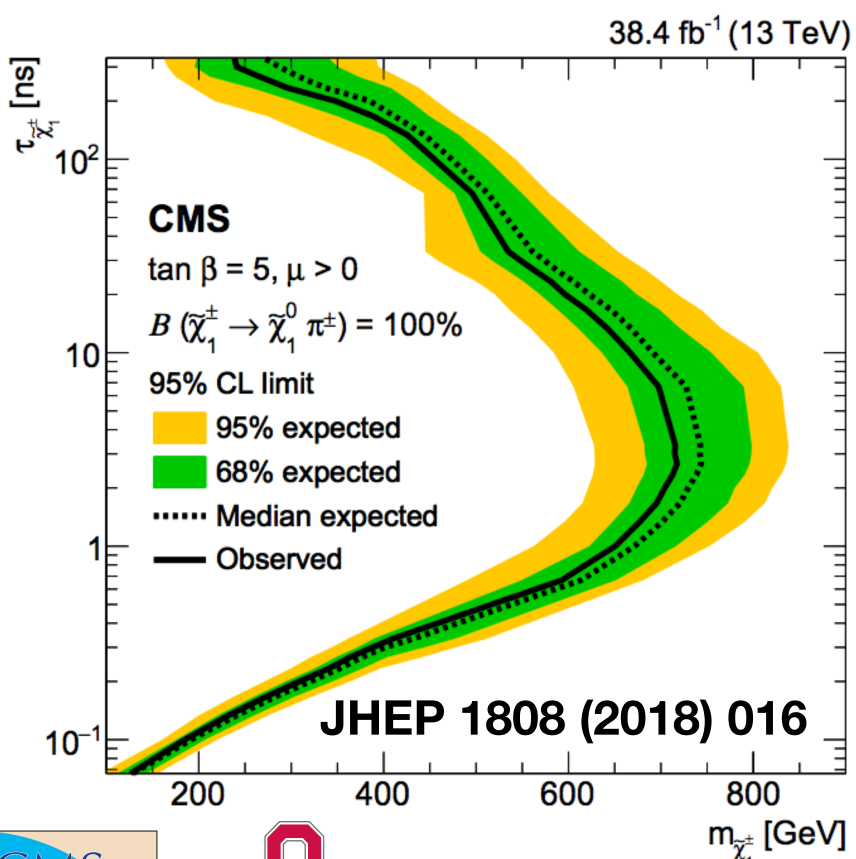
$$\pi^+ + n \to \pi^0 + p$$

  - Leptons can be mis-reconstructed
  - Spurious ("fake") tracks — pattern recognition errors
- Approach to controlling these:
  - Explore and mitigate all possible ways to lose tracker hits
  - Estimate the remaining probability to fall into search region

Phase 1 CMS Pixel Upgrade







- CMS previously searched for disappearing tracks (@ 8 and 13 TeV) using a 3-layer pixel tracker
  - Limited sensitivity to short tracks (compared to ATLAS' JHEP 1806 (2018) 022)
- Since 2017 CMS now has a 4-layer pixel tracker
- New analysis bins results in the number of layers with measurements:
  - n_{layers} = 4, 5, ≥6
  - **New sensitivity to shorter particle lifetimes**

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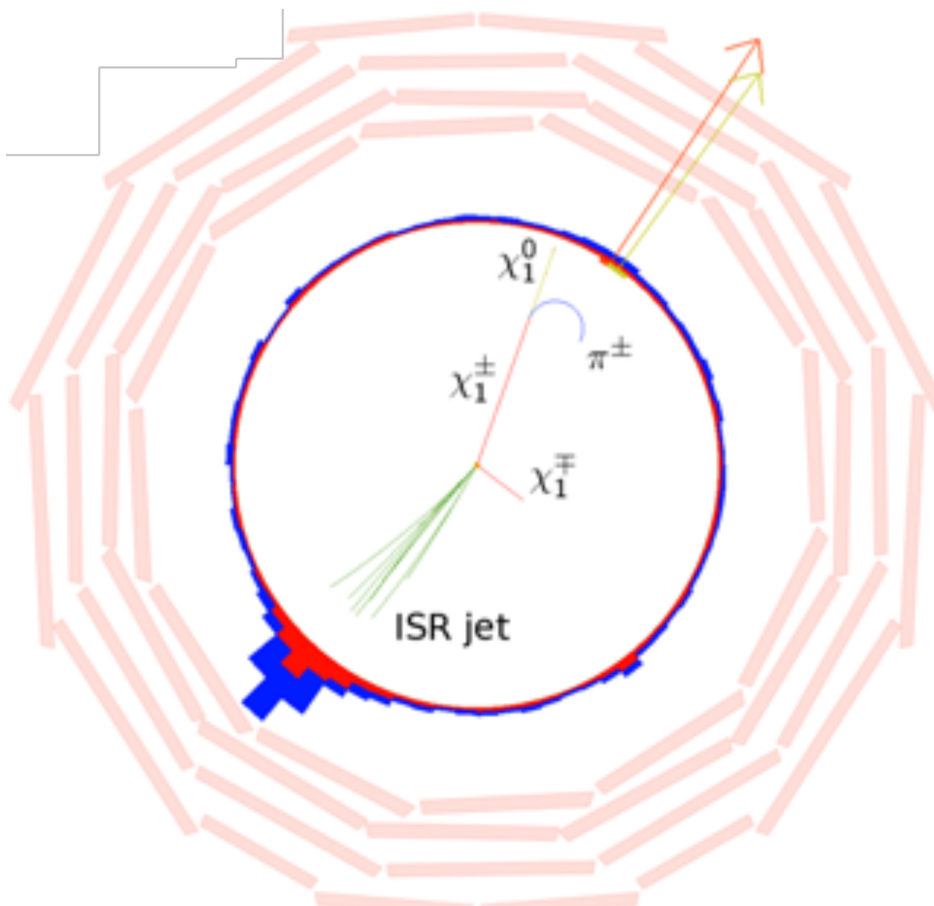
Event Selection



- No tracking information at L1 trigger
  - Trigger on MET from ISR jets at L1
  - At HLT, OR of several MET requirements
    - MET > 105-300 GeV
    - Lowest threshold: MET > 105 GeV and pt > 50 GeV isolated track
- At the offline reconstruction level, require event is consistent with ISR jet
  - MET > 120 GeV
  - ≥1 jet with pt > 110 GeV

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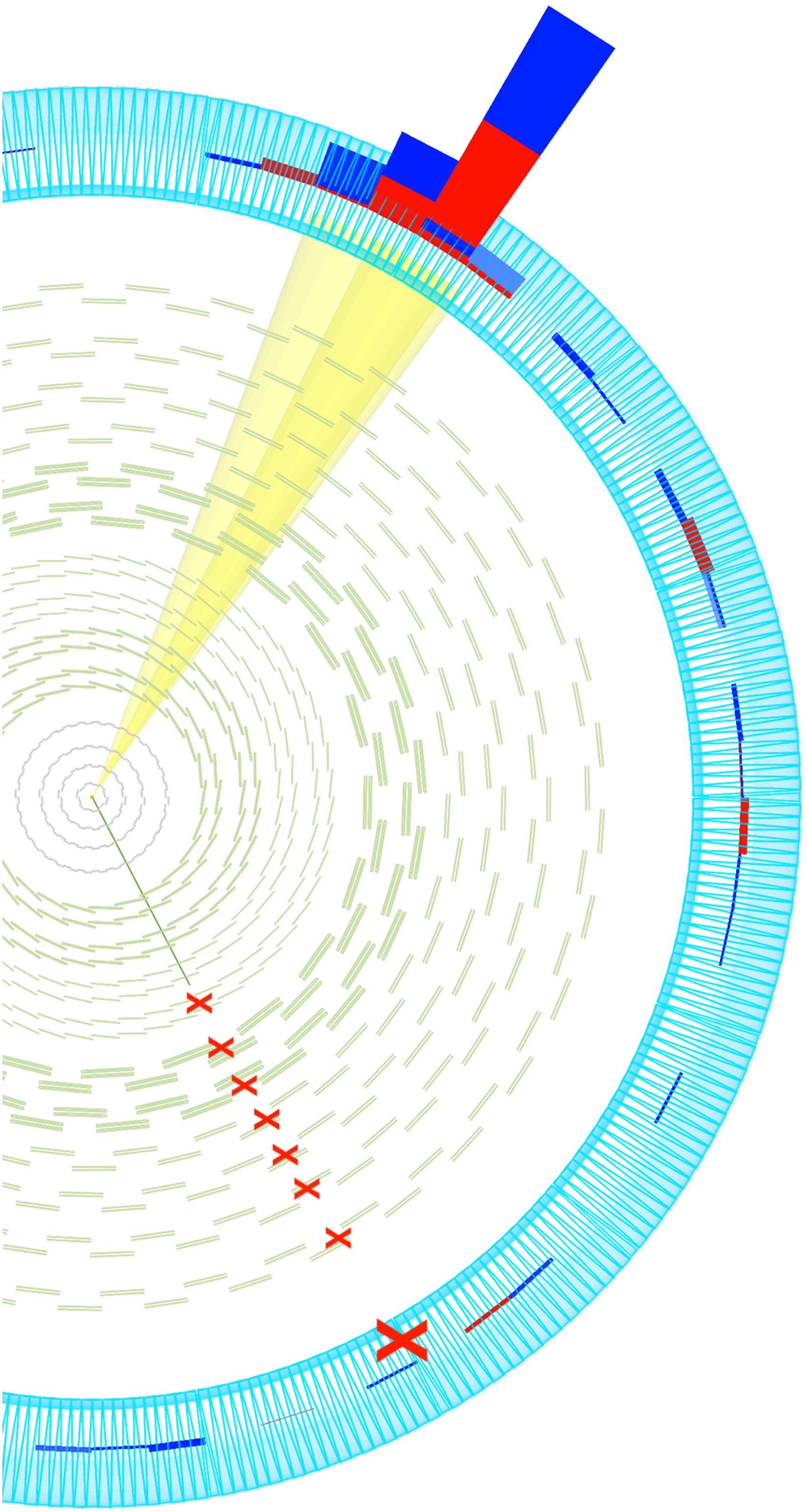
Track Selection



- pt > 55 GeV, isolated from other tracks/jets
- Require high track quality:
  - ≥4 pixel hits
  - No missing inner/middle hits
- Veto all tracks identified as leptons ($e/\mu/\tau_h$)
- Reject tracks in regions of lower lepton reconstruction efficiency
- “Disappearing” is defined as:
  - ≥3 missing outer hits — rejects most SM tracks
  - <10 GeV energy deposited within $\Delta R < 0.5$
    - Rejects most electrons and charged hadrons
    - E.g. electrons with significant brem. energy causing a track reconstruction failure

Backgrounds

- Possible for leptons to enter search region
  - Dead/noisy channels, track fitting errors, nuclear interactions with the tracker material, etc
  - Estimate probability for several conditions:

$$N^{\ell}_{\mathrm{est}} = \frac{N^{\ell}_{\mathtt{ctrl}}}{\epsilon^{\ell}_{\mathtt{trigger}}} P_{\mathrm{veto}} P_{\mathrm{off}} P_{\mathrm{trig}} P_{\mathrm{HEM}}$$

- "Spurious" tracks: not real charged trajectories, but pattern recognition errors
  - Tend to have missing hits and little associated calorimeter energy
  - Estimate probability of such tracks in Z(μμ) (plus track) events and extrapolate to search region

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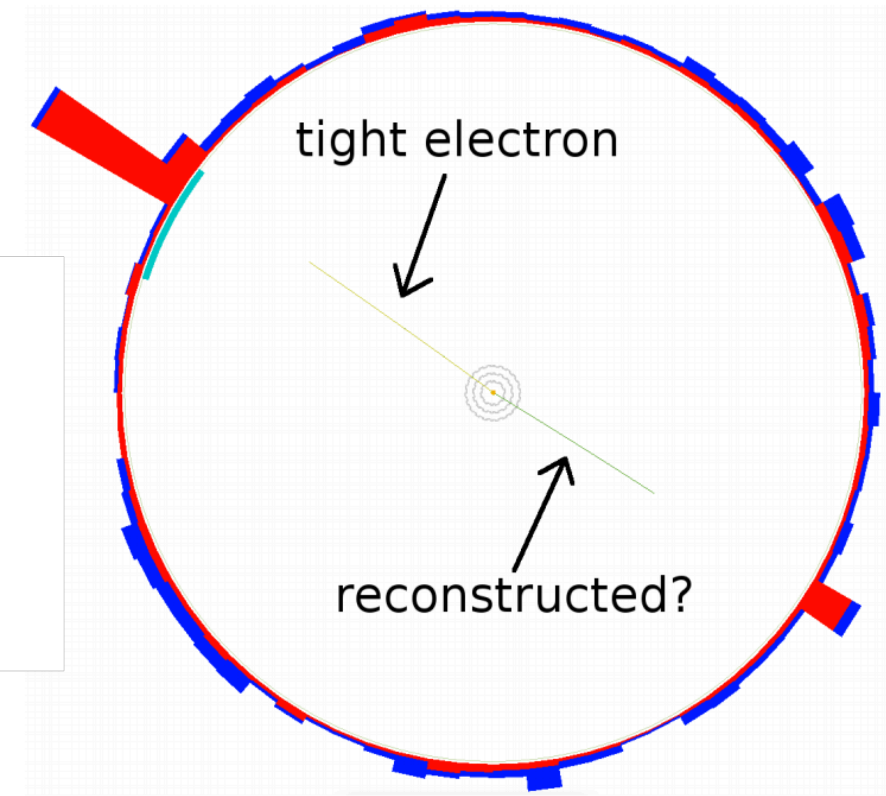
Lepton P(veto)

- Measured using a tag-and-probe method for each flavor
- Calculate the probability for probes to disappear
- Also select a same-sign sample to subtract non-Z background events from T&P sample



$$P_{\mathrm{veto}} = \frac{N^{\mathrm{veto}}_{\mathrm{T\&P}} - N^{\mathrm{veto}}_{\mathrm{SS\,T\&P}}}{N_{\mathrm{T\&P}} - N_{\mathrm{SS\,T\&P}}}$$

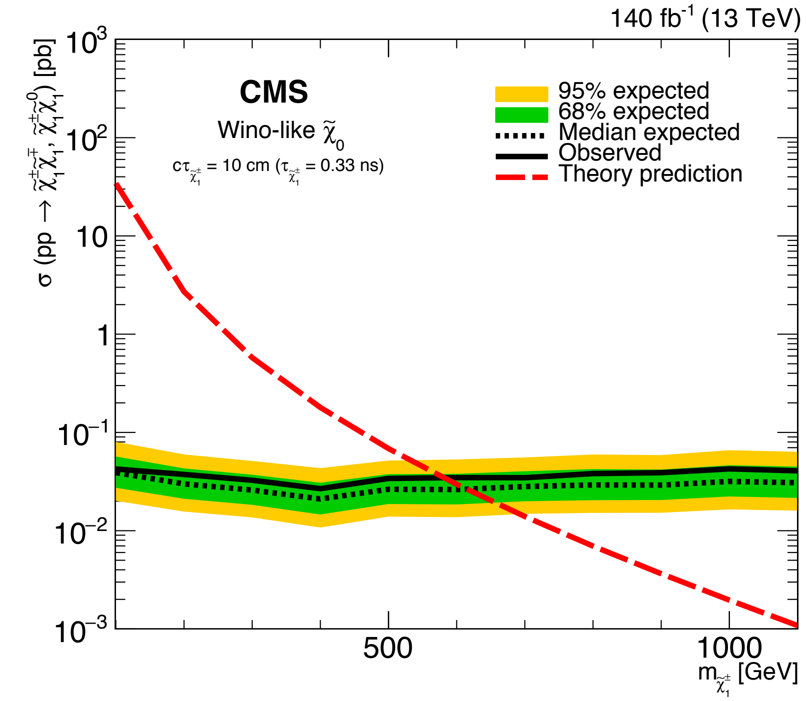
Data-taking period	n_{lay}	P_{veto}		
		Electrons	Muons	τ_{h}
2017	4	$(8.2 \pm 5.2) \times 10^{-4}$	$(0.0^{+3.9}_{-0.0}) \times 10^{-3}$	$(6.9^{+8.3}_{-5.1}) \times 10^{-2}$
	5	$(2.2 \pm 0.9) \times 10^{-4}$	$(3.2 \pm 1.3) \times 10^{-2}$	$(6.5^{+2.9}_{-2.7}) \times 10^{-2}$
	$\geq$6	$(2.7 \pm 0.5) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-6}$	$(1.0 \pm 0.4) \times 10^{-3}$
2018 A	4	$(1.3 \pm 0.7) \times 10^{-3}$	$(1.0 \pm 1.0) \times 10^{-1}$	$(7.1^{+5.5}_{-3.8}) \times 10^{-2}$
	5	$(0.9^{+1.5}_{-0.9}) \times 10^{-4}$	$(7.4 \pm 4.2) \times 10^{-2}$	$(4.4^{+5.5}_{-4.4}) \times 10^{-2}$
	$\geq$6	$(1.6 \pm 0.6) \times 10^{-5}$	$(1.9 \pm 0.8) \times 10^{-6}$	$(0.0^{+7.3}_{-0.0}) \times 10^{-4}$
2018 B	4	$(0.0^{+1.1}_{-0.0}) \times 10^{-4}$	$(4.0^{+15.0}_{-4.0}) \times 10^{-2}$	$(5.6^{+6.5}_{-5.0}) \times 10^{-2}$
	5	$(1.4 \pm 1.1) \times 10^{-4}$	$(5.8 \pm 3.8) \times 10^{-2}$	$(5.1^{+4.5}_{-3.7}) \times 10^{-2}$
	$\geq$6	$(3.3 \pm 0.7) \times 10^{-5}$	$(1.5 \pm 0.6) \times 10^{-6}$	$(2.3 \pm 1.0) \times 10^{-3}$

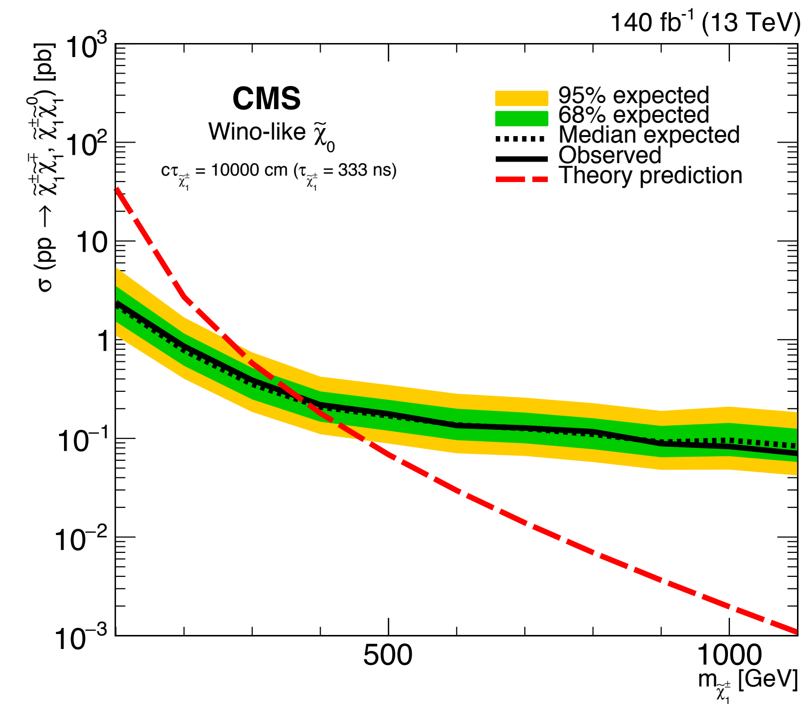
Search Results

- Searched 101/fb 13 TeV data recorded in 2017-8

Data-taking period	n_{lay}	Expected backgrounds: Leptons	Expected backgrounds: Spurious tracks	Expected backgrounds: Total	Observation
2017	4	$1.4 \pm 0.9 \pm 0.2$	$10.9 \pm 0.7 \pm 4.7$	$12.2 \pm 1.1 \pm 4.7$	17
	5	$1.1 \pm 0.4 \pm 0.1$	$1.0 \pm 0.2 \pm 0.6$	$2.1 \pm 0.4 \pm 0.6$	4
	≥ 6	$6.7 \pm 1.1 \pm 0.7$	$0.04 \pm 0.04^{+0.08}_{-0.04}$	$6.7 \pm 1.1 \pm 0.7$	6
2018 A	4	$1.1^{+1.0}_{-0.6} \pm 0.1$	$6.2 \pm 0.5 \pm 3.5$	$7.3^{+1.1}_{-0.8} \pm 3.5$	5
	5	$0.2^{+0.6}_{-0.2} \pm 0.0$	$0.5 \pm 0.1 \pm 0.3$	$0.6^{+0.6}_{-0.2} \pm 0.3$	0
	≥ 6	$1.8^{+0.6}_{-0.5} \pm 0.2$	$0.04 \pm 0.04^{+0.06}_{-0.04}$	$1.8^{+0.6}_{-0.5} \pm 0.2$	2
2018 B	4	$0.0^{+0.8}_{-0.0} \pm 0.0$	$10.3 \pm 0.6 \pm 5.4$	$10.3^{+1.0}_{-0.6} \pm 5.4$	11
	5	$0.4^{+0.7}_{-0.3} \pm 0.1$	$0.6 \pm 0.2 \pm 0.3$	$1.0^{+0.7}_{-0.3} \pm 0.3$	2
	≥ 6	$5.7^{+1.2}_{-1.1} \pm 0.6$	$0.00^{+0.04}_{-0.00} \pm 0.00$	$5.7^{+1.2}_{-1.1} \pm 0.6$	1

- Observation of 48 events is consistent with a total background estimate of 47.8 +2.7 -2.3 (stat) ± 8.1 (syst) events
- Results are combined with those from 2015-6 to provide upper limits for the full 140/fb of the Run 2 data set





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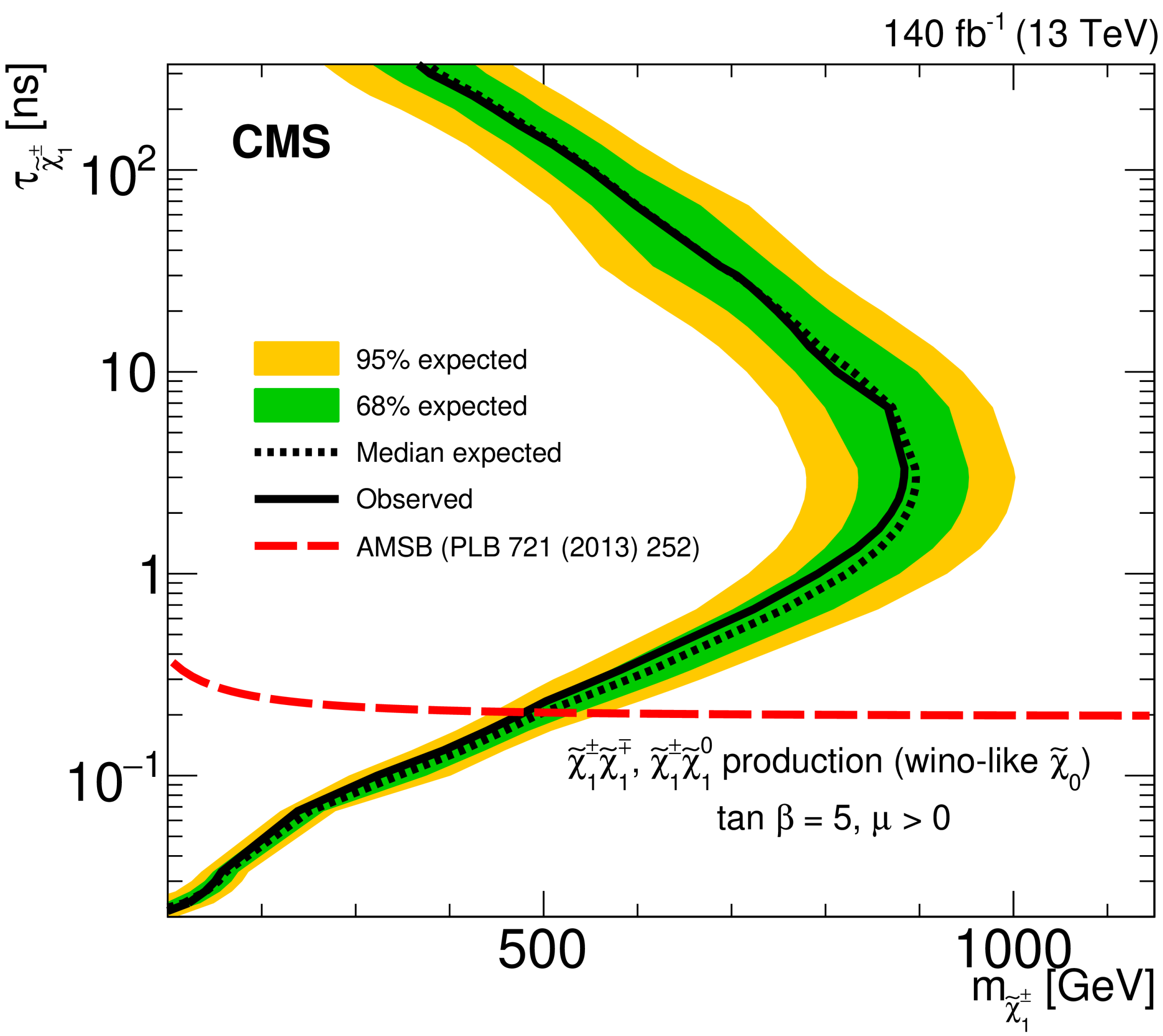
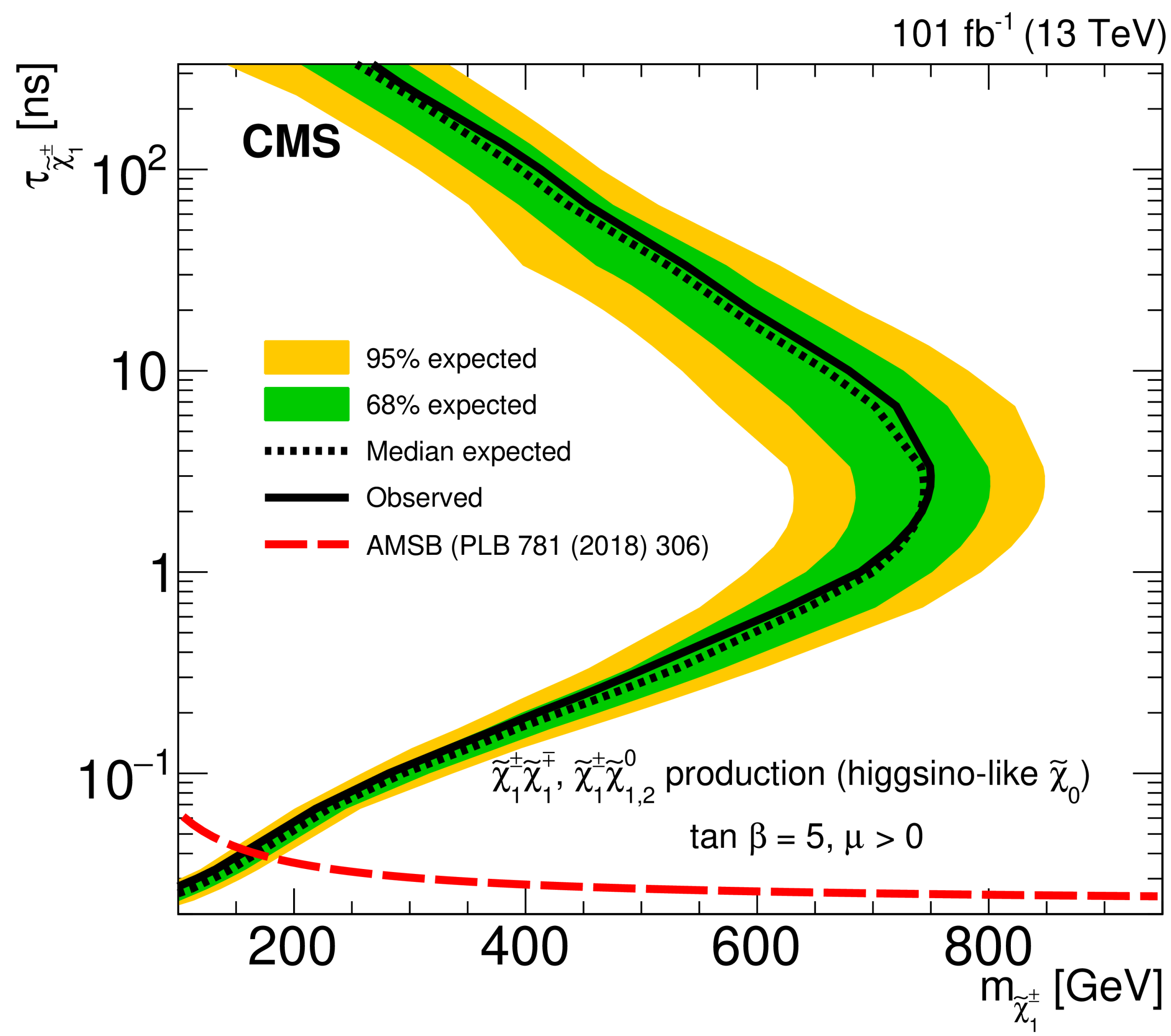
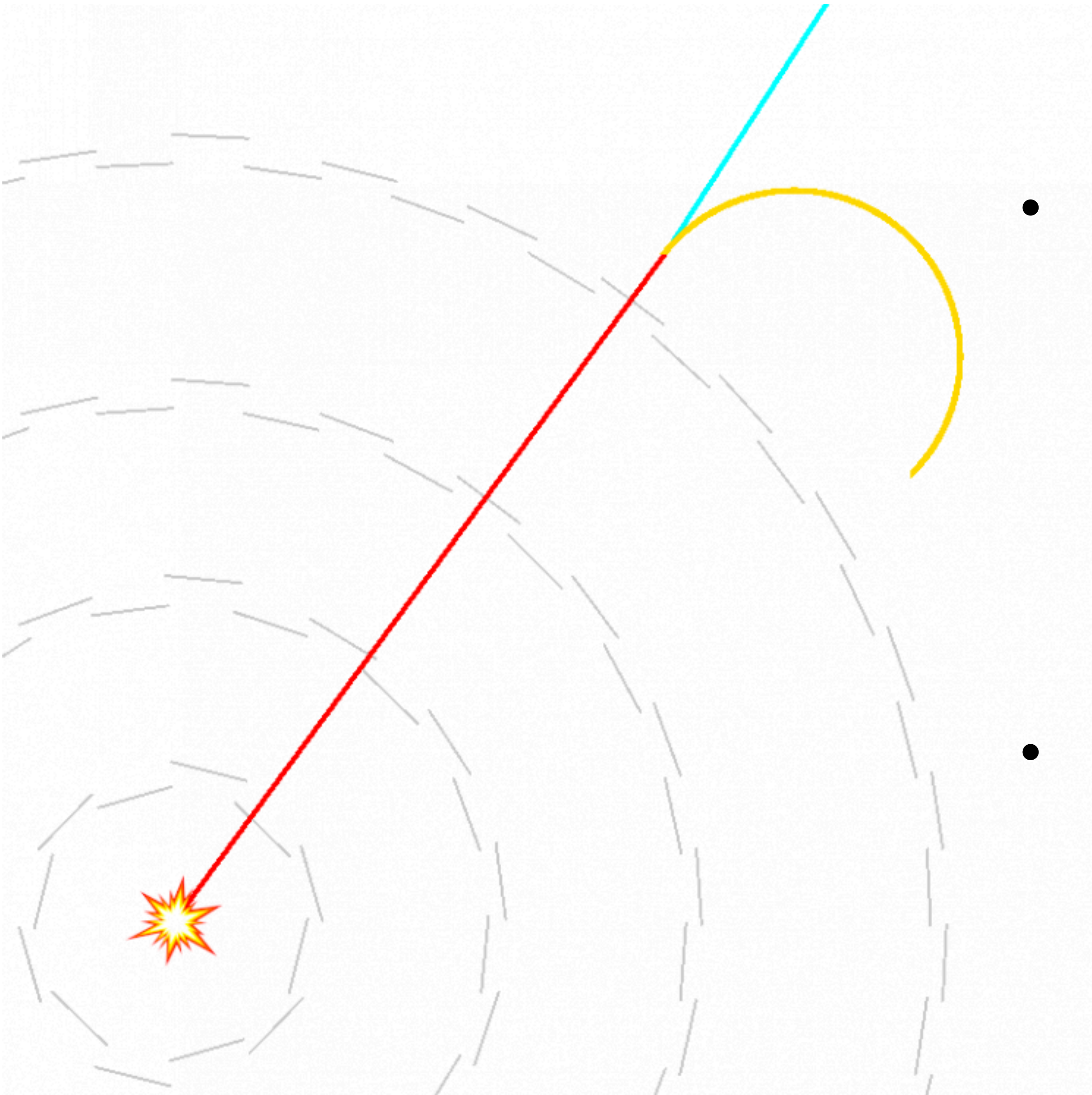
Exclusions





- In the context of AMSB, these results exclude charginos below:
  - Wino-like neutralino case — 884 (474) GeV for a lifetime of 3 (0.2) ns
  - Higgsino-like neutralino case — 750 (175) GeV for a lifetime of 3 (0.05) ns
    - **New interpretation for 2017-8 data**

Summary



- CMS has updated its disappearing track search
  - Full Run 2 data set
  - Making use of the Phase 1 pixel upgrade to extend sensitivity to lower particle lifetimes
  - Adding a new higgsino-like neutralino interpretation
- No excess observed over estimated backgrounds
  - Currently obtains the world-best limits at 95% CL over a wide range of particle masses and lifetimes

Newly submitted to PLB: arXiv:2004.05153 (CMS public page)
Featured: cms.cern/news/disappearing-act-cms

Backup

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Background Systematics

- Spurious tracks:
  - Test assumption that track occurrence probability is independent of physics content by comparing Z->μμ to Z->ee estimates
  - Uncertainties in transfer factor (ζ) fit parameters
- Leptons:
  - Test assumption that unreconstructed leptons deposit no calorimeter energy by allowing them to instead deposit 10 GeV
  - Limited statistics in NLayers=4,5 muons/taus — compare to electrons, which have sufficient events

Averages across data-taking period, NLayers categories

Background	Source	Uncertainty $n_{\text{lay}} = 4$	$n_{\text{lay}} = 5$	$n_{\text{lay}} \geq 6$
Spurious tracks	Control sample	±19%	±29%	±116%
	ζ	±47%	±47%	±47%
Electrons	Visible calorimeter energy	±14%	±14%	±13%
Muons	P_{off}	+7%	+7%	—
	P_{trig}	+8%	+2%	—
τ_{h}	Visible calorimeter energy	±19%	±19%	±19%
	P_{off}	+7%	+7%	—
	P_{trig}	+8%	+2%	—

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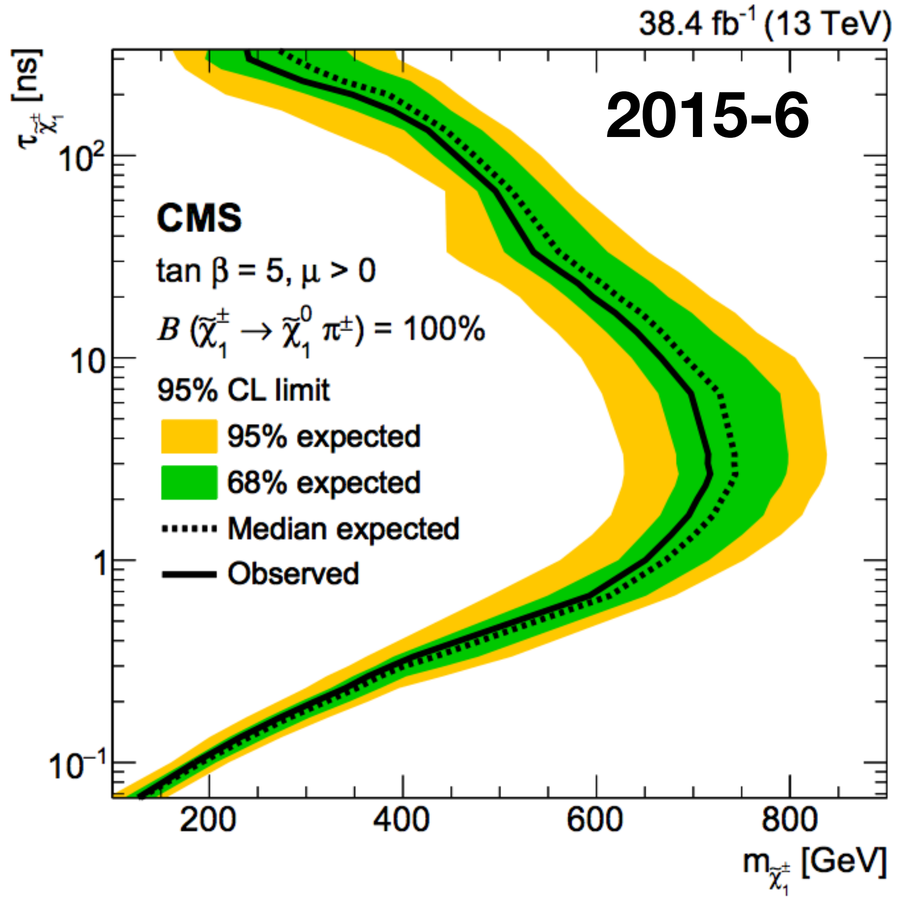
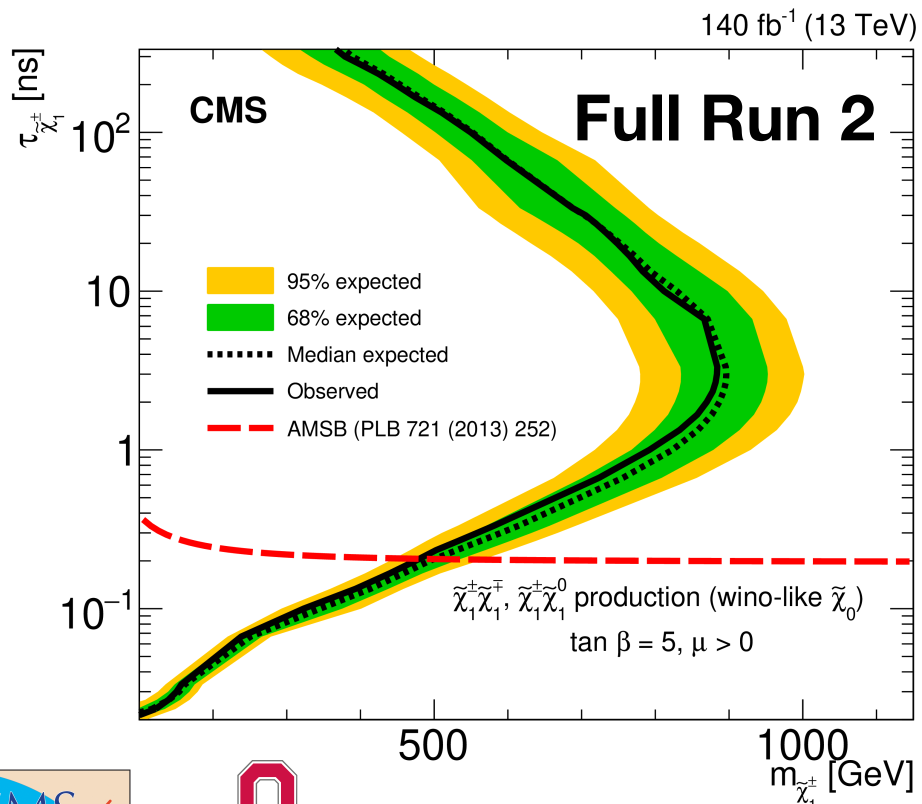
Signal Systematics

Averages across data-taking conditions

Source	Uncertainty		
	$n_{\text{lay}} = 4$	$n_{\text{lay}} = 5$	$n_{\text{lay}} \geq 6$
Pileup	3.0%	3.3%	2.8%
ISR	13%	13%	13%
Trigger efficiency	1.1%	0.8%	0.4%
Jet energy scale	0.6%	0.7%	1.6%
Jet energy resolution	0.5%	0.5%	1.3%
$p_{\text{T}}^{\text{miss}}$	0.3%	0.3%	0.4%
$E_{\text{calo}}^{\Delta R<0.5}$	0.7%	0.7%	0.7%
Missing inner hits	2.3%	1.0%	0.3%
Missing middle hits	3.9%	5.1%	4.4%
Missing outer hits	—	—	0.2%
Reconstructed lepton veto efficiency	0.1%	0.1%	—
Track reconstruction efficiency	2.3%	2.3%	2.3%
Total	14%	15%	14%

Previous Results in 2015-6 Data





- Previously published results from proton collision data from 2015-6
  - JHEP 06 (2018) 022

Run period	Estimated number of background events: Leptons	Spurious tracks	Total	Observed events
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$	0.1 ± 0.1	1
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$	$2.4 \pm 0.5 \pm 0.4$	2
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$	$4.0 \pm 0.7 \pm 0.9$	4
Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$	$6.5 \pm 0.9 \pm 1.0$	7