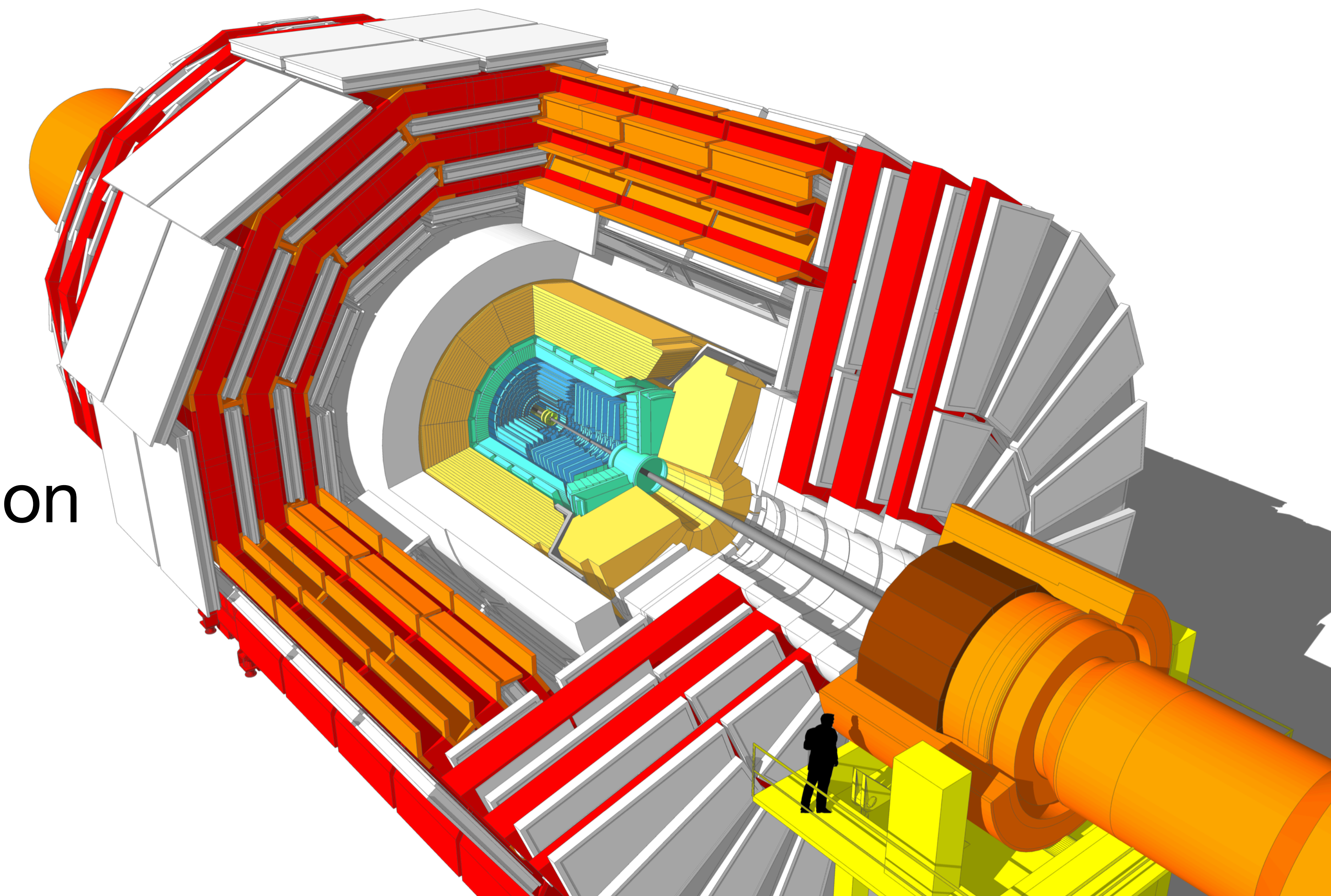
THE OHIO STATE UNIVERSITY

Searches for new physics with unconventional signatures at CMS



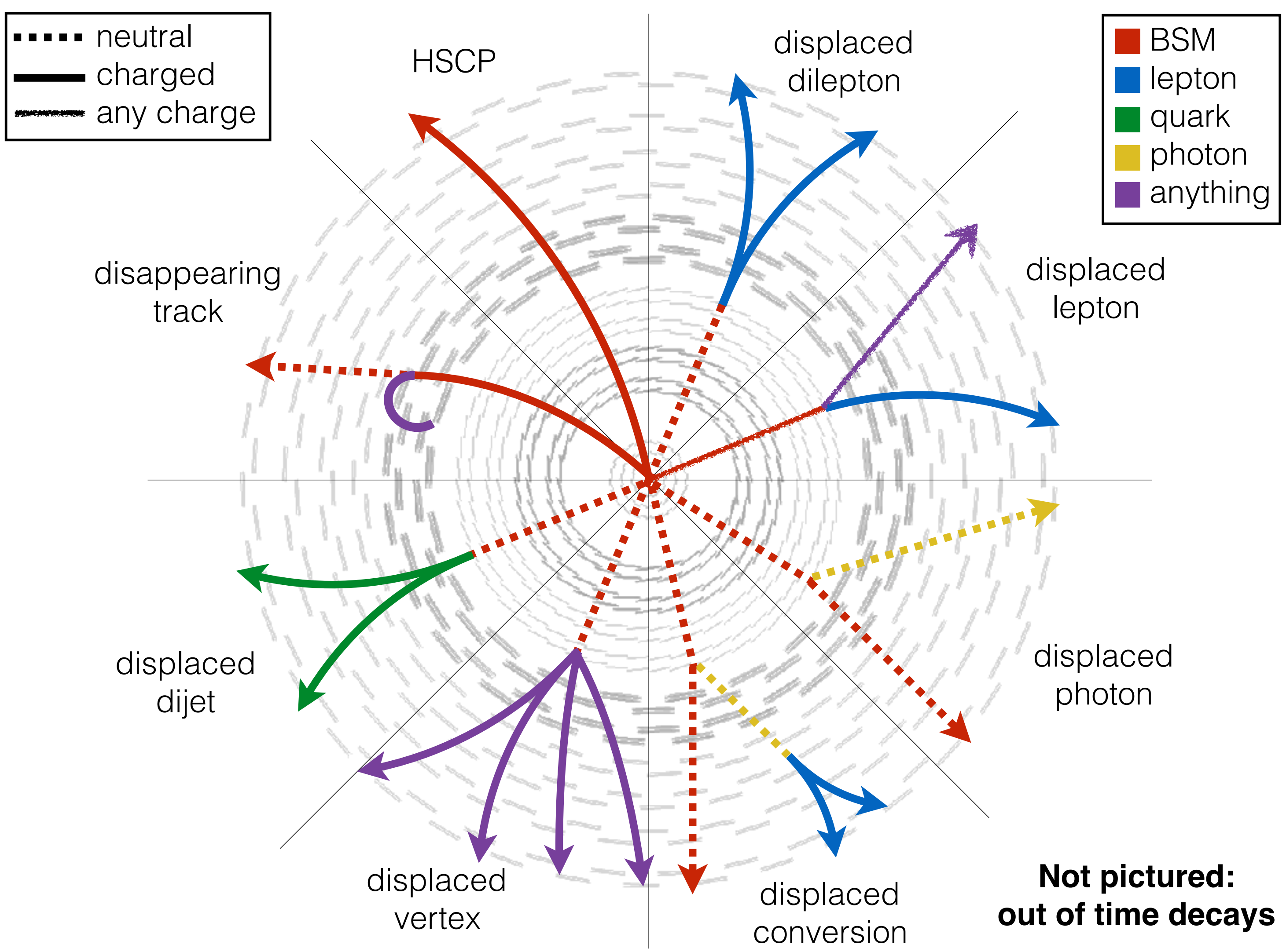
Brian Francis
for the CMS Collaboration

July 28th
ICHEP 2020

Unconventional: long-lived particles

- Wide variety of signatures depending on LLP
  - Lifetime, boost
  - Charge, interactions
  - Mass
  - Decay products
- Experimentally challenging:
  - Often triggering is difficult
  - Non-standard reconstruction techniques frequently needed
    - Large displacements
    - Atypical ionization
    - Out of time (time-of-flight)

Figure: J. Antonelli

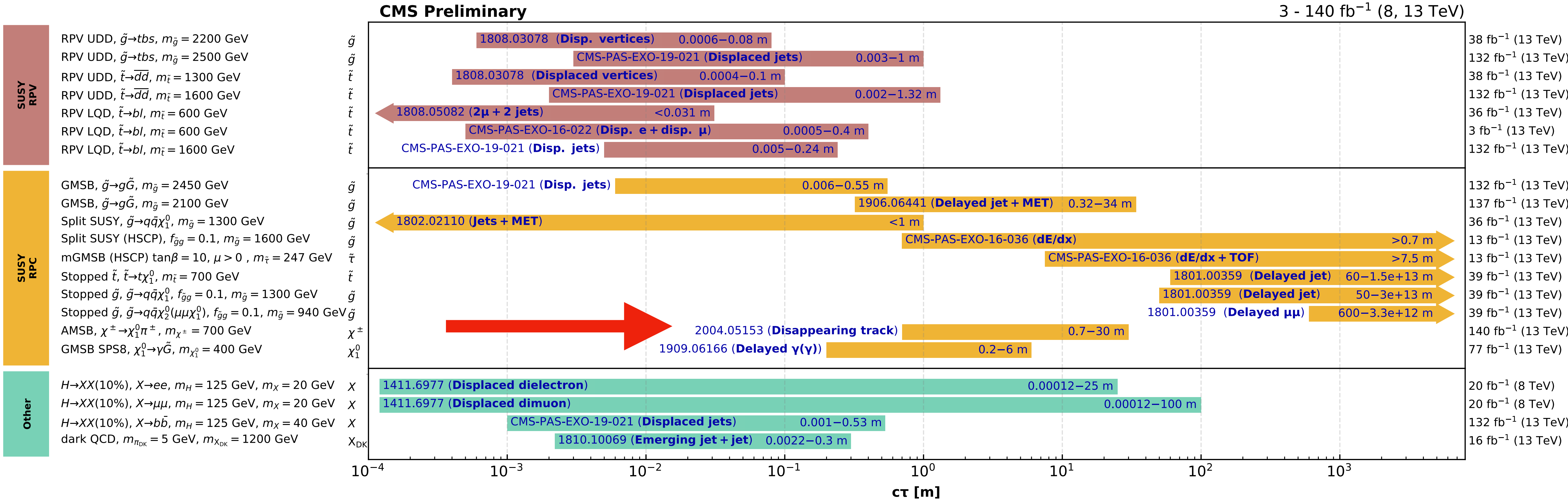


Not pictured: out of time decays

- Challenging backgrounds, often estimated from data
  - Detector noise or reconstruction failures, cosmic rays…

Searches for LLPs

Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

- Broad program of searches, but here focus on recent, particularly unconventional results at 13 TeV:
  - Strongly interacting massive particles (SIMPs) with trackless jets — 2016: 16/fb
    - Brand new result!
  - Disappearing tracks — 2017-8: 101/fb (plus 2015-6 results: 140/fb)

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Strongly Interacting Massive Particles with Trackless Jets

CMS-PAS-EXO-17-010

Brand new!

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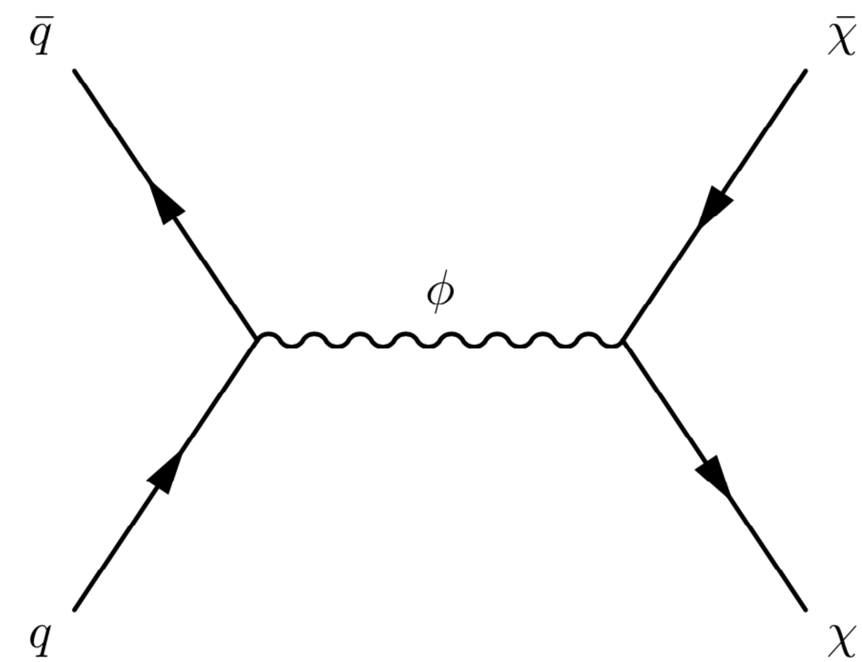
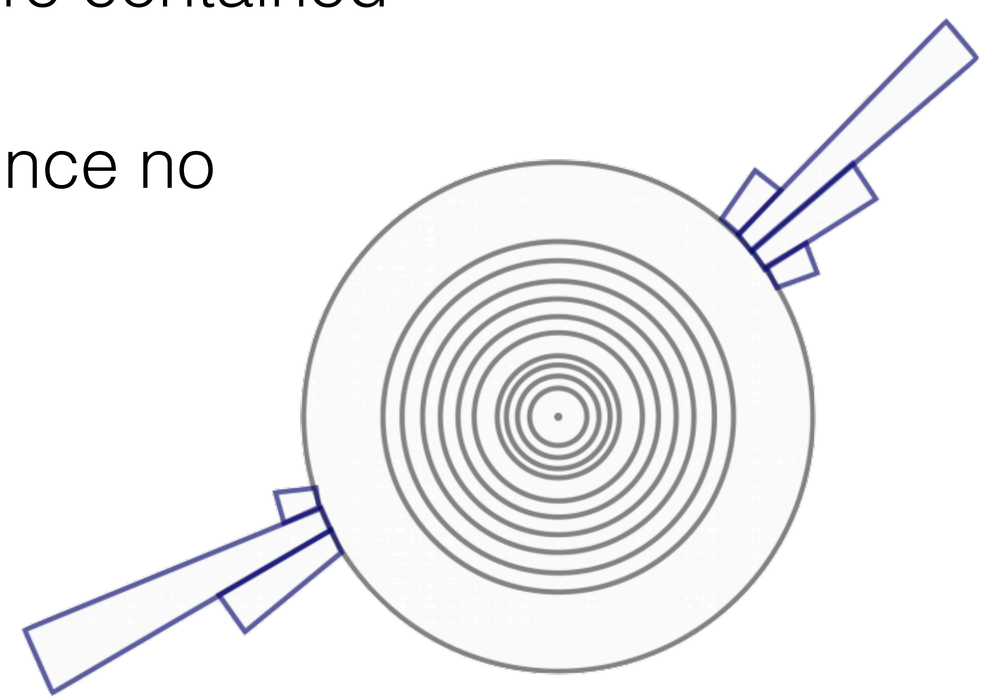
Search for SIMPs with Trackless Jets

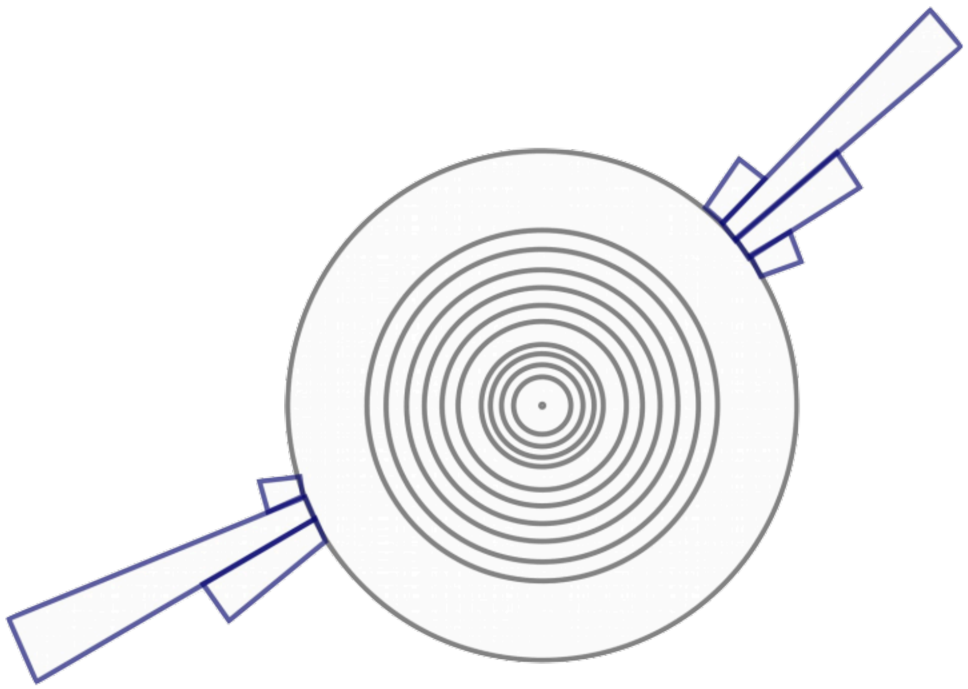


- **S**trongly — large interaction cross section
- **I**nteracting — new light mediator
- **M**assive — dark matter candidate
- **P**article — fermionic, asymmetric dark matter
- The signature is a pair of neutral jets
  - Narrow jets from high-pt, single particle source
  - Target interaction cross sections: showers are contained in the hadronic calorimeter
  - Very little **charged energy fraction (ChF)** since no hadronization of SIMP occurs



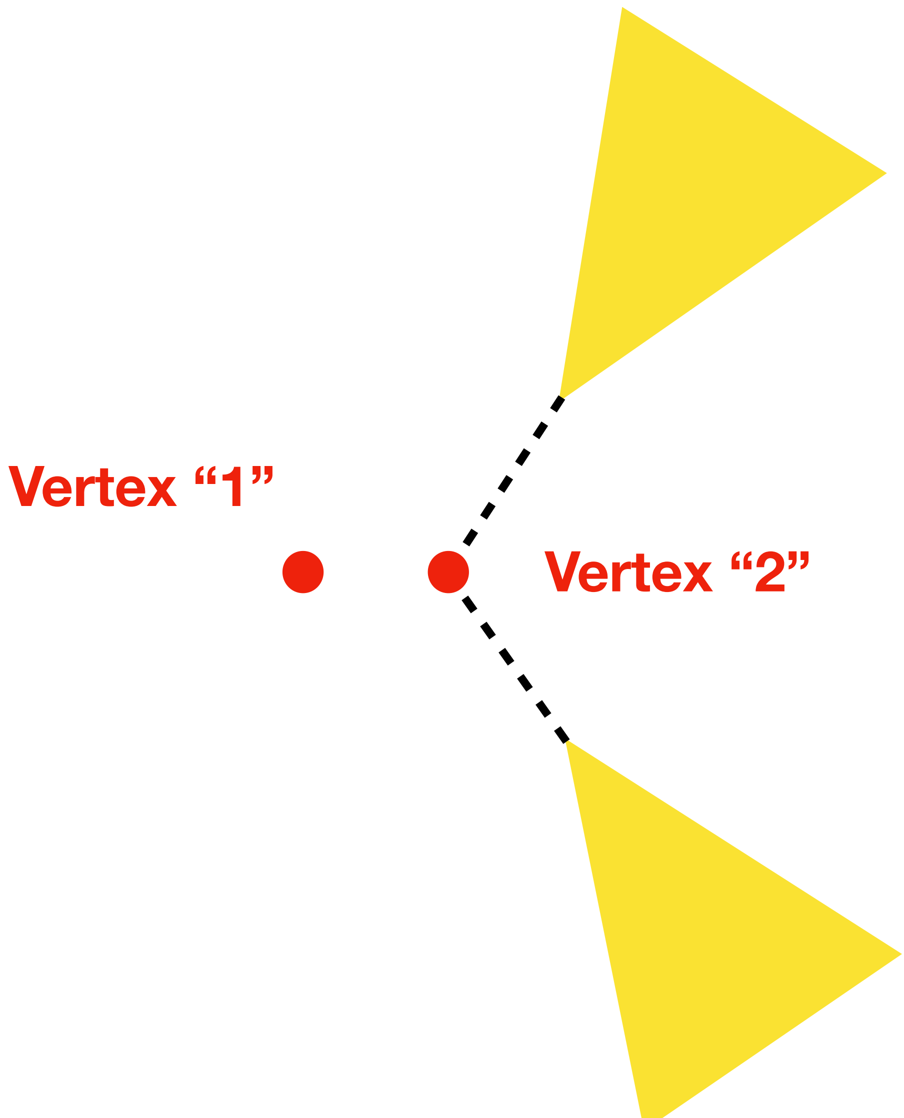
This new result is the first of its kind at colliders for this phase space!

Search Overview, Selection



- Trigger strategy — ≥1 jet having pt > 450 GeV
- Select events with two back-to-back jets with low ChF
  - pt > 550 GeV, $|\eta| < 2.0$
  - $\Delta\phi$(lead jet, sub-lead jet) > 2
  - Reject jets reconstructed as photons
  - Neutral EM energy fraction < 0.9
  - Reject events with >2 jets having pt > 30 GeV, $|\eta| < 5$
  - ≥2 reconstructed vertices
- Background: QCD multijet events
  - Typically have large ChF, several jets

Reconstruction



Incorrect vertex assignment artificially decreases ChF

- Typical primary vertex (PV): one with highest sum of assigned physics-object pt^2
  - All others deemed pileup, and associated tracks are removed in ChF calculations
- Possible to assign incorrectly
  - Artificially lowers ChF in QCD multijet events — **significant** source of background
  - Often in this case, the second vertex is the true primary
- Solution: reconstruct jets using **both** the first and second vertex
  - Signal has low ChF in both versions
  - Background has large ChF in one or the other

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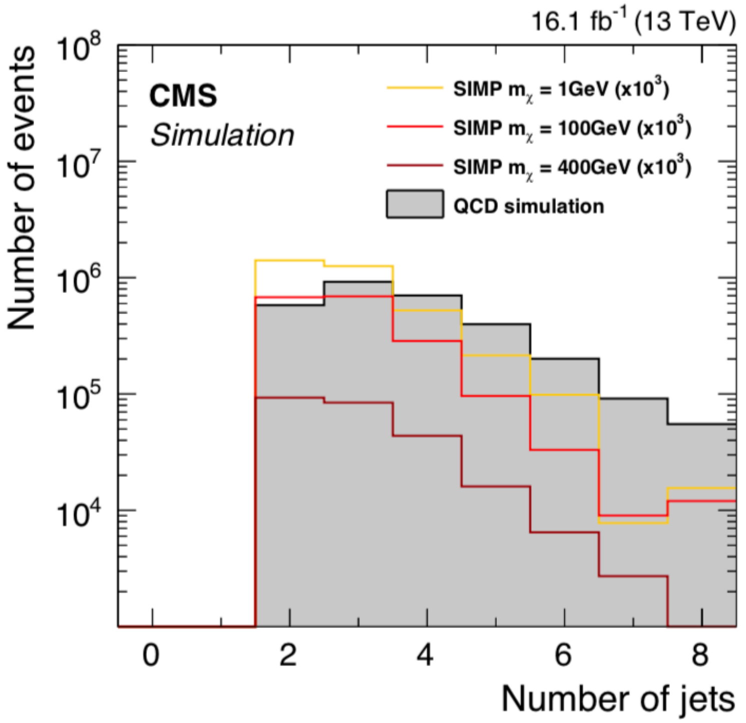
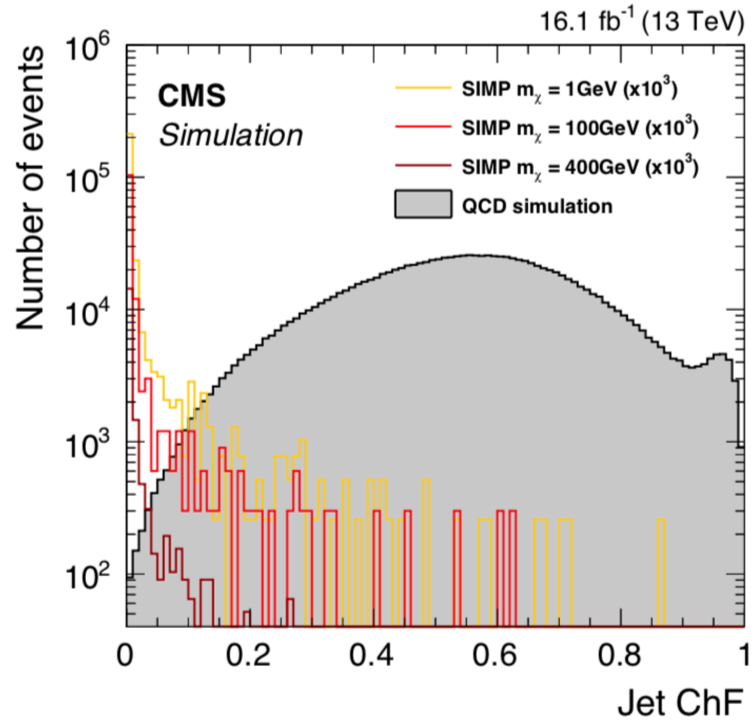
Background Estimation





- Control region:
  - ChF of one jet > 0.25
  - Using default (first) vertex
- Signal region:
  - ChF of both jets < 0.05
  - Using **both** first and second vertices

- Data-driven estimation of QCD:
  - In control region, measure the probability for the *other* jet to have ChF < 0.05
  - Binning probability in jet pt, η
  - Normalize events by these probabilities:
    - 1-leg: one low-ChF jet, normalize for the other
    - 2-leg: neither jet have low ChF, normalize both
  - Both methods agree well; 2-leg is used for the final estimate

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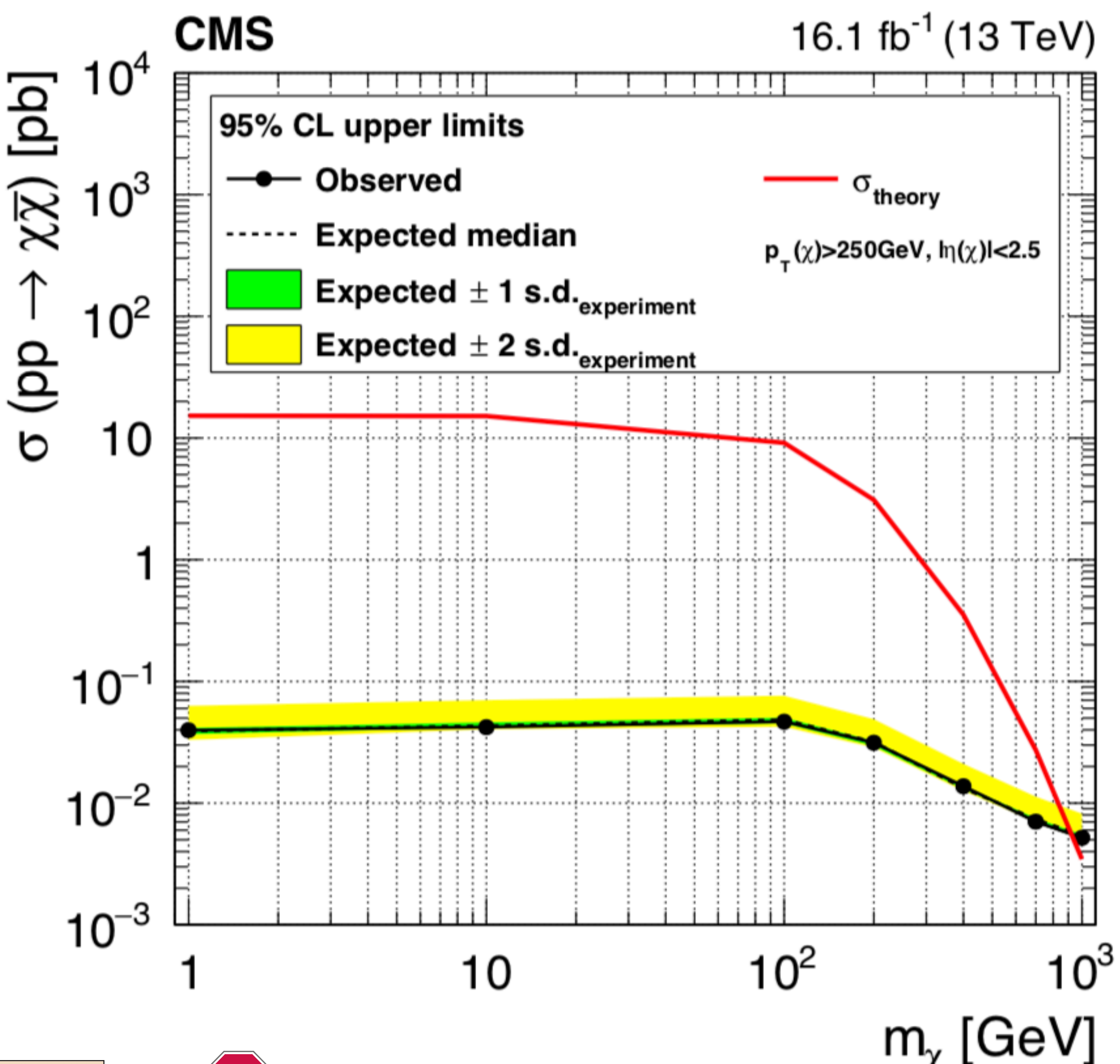
Results

ChF selection criterion	data prediction	observed	SIMP signal [m_χ] 1 GeV	SIMP signal [m_χ] 1000 GeV
< 0.2	898 ± 30 (stat.) $\pm$ 33 (syst.)	969	1300 ± 58	2.25 ± 0.07
< 0.15	209 ± 10 (stat.) $\pm$ 17 (syst.)	229	1269 ± 57	2.18 ± 0.07
< 0.1	26.6 ± 2.2 (stat.) $\pm$ 9.3 (syst.)	30	1197 ± 56	2.09 ± 0.07
< 0.07	5.1 ± 0.6 (stat.) $\pm$ 4.1 (syst.)	4	1153 ± 55	2.00 ± 0.07
< 0.05	1.28 ± 0.22 (stat.) $^{+3.40}_{-1.28}$ (syst.)	0	1101 ± 53	1.90 ± 0.06



- Model-independent limit using the ChF < 0.05 requirement
  - **$\sigma^{95\%}_{obs}$ = 0.18 fb** (0.18 fb expected)
- SIMP limits (left):
  - Exclude SIMP masses up to 900 GeV
- **First limits in this phase space at colliders**

Disappearing Tracks

Phys. Lett. B 806 (2020) 135502

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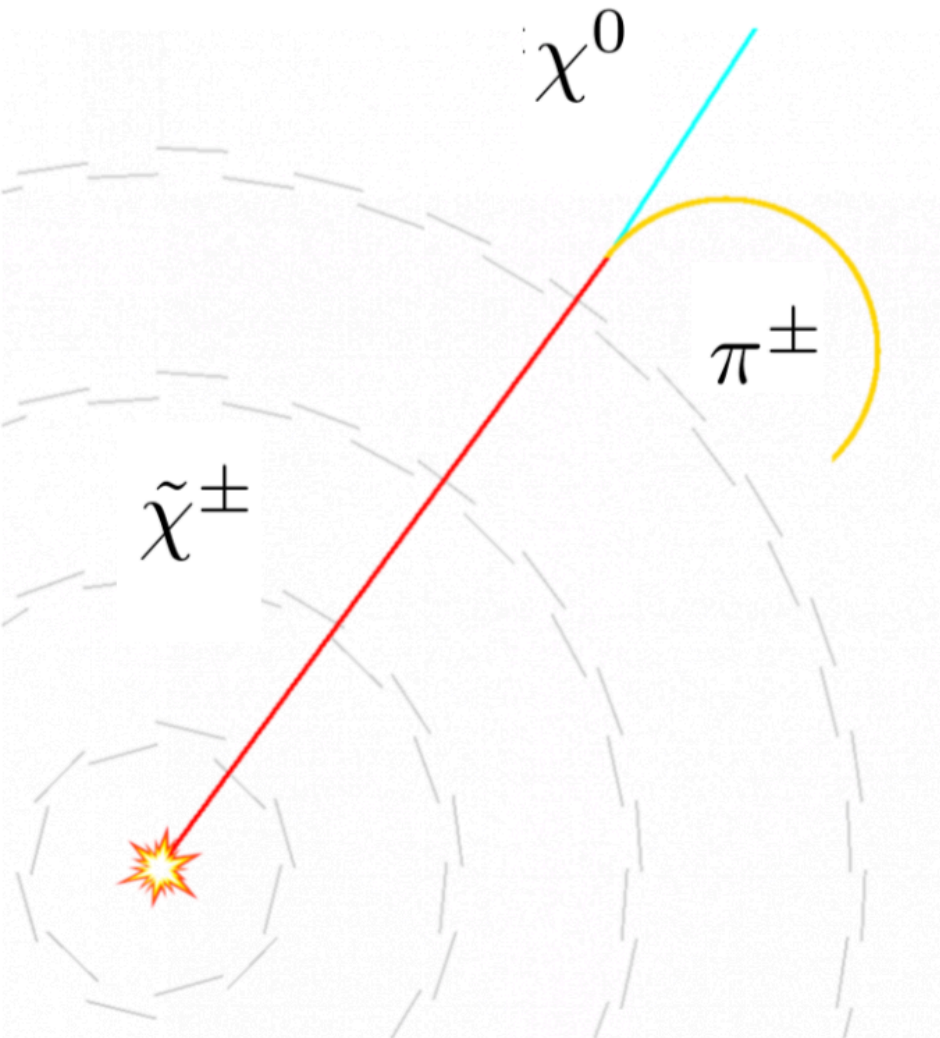
Search for Disappearing Tracks

- Signature-driven search for long-lived charged particles decaying within the silicon tracker
- Many models introduce this signature, for example anomaly-mediated supersymmetry breaking (AMSB)

$$\tilde{\chi}^{\pm} \rightarrow \pi^{\pm}\chi^{0}$$

- With a small mass splitting between chargino ($\tilde{\chi}^{\pm}$) and neutralino ($\tilde{\chi}^{0}$):
    - Chargino is long-lived, O(1) ns
    - Neutralino interacts only weakly, and pion is too soft to be reconstructed
- With an its decay products either unobserved or unreconstructed, the chargino track "**disappears**"
- Search uses 13 TeV from 2017-8 corresponding to 101/fb



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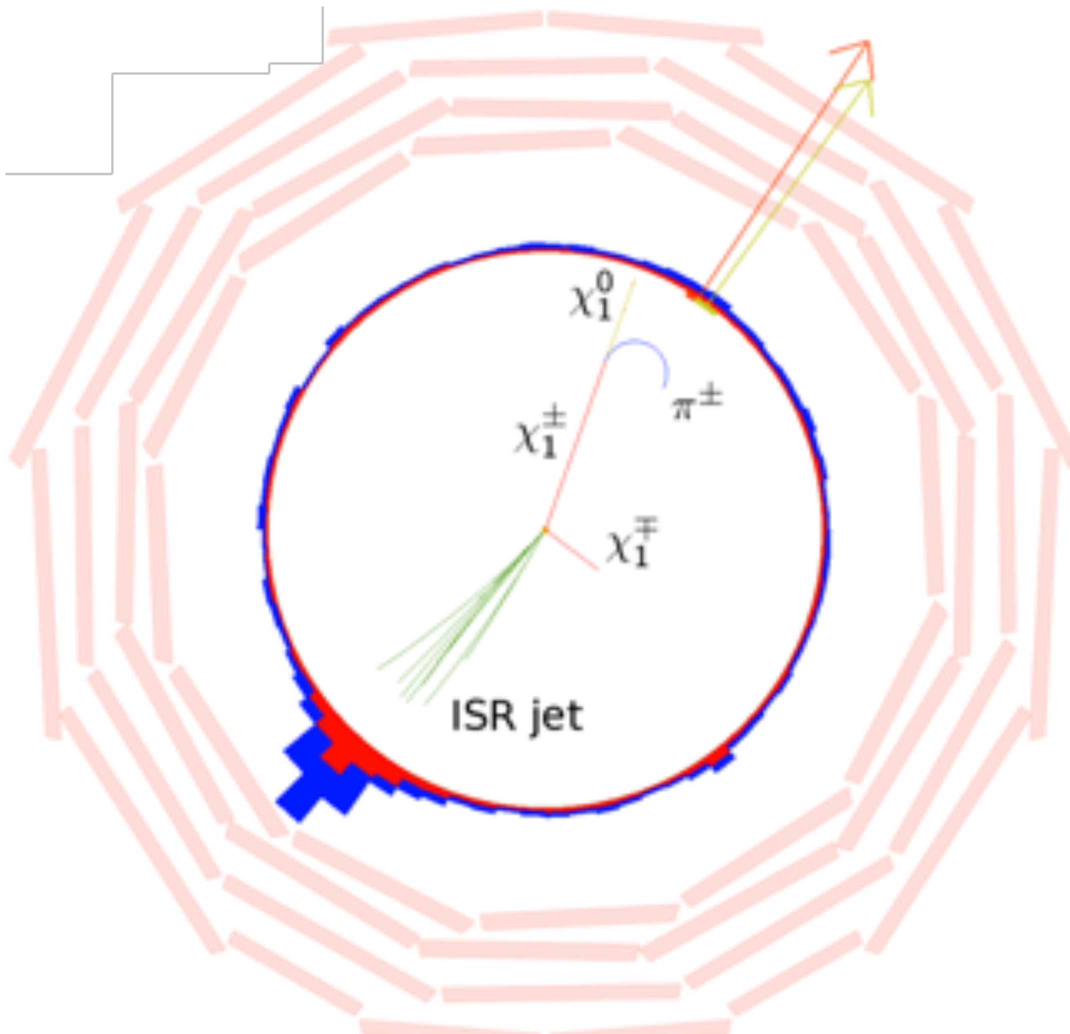
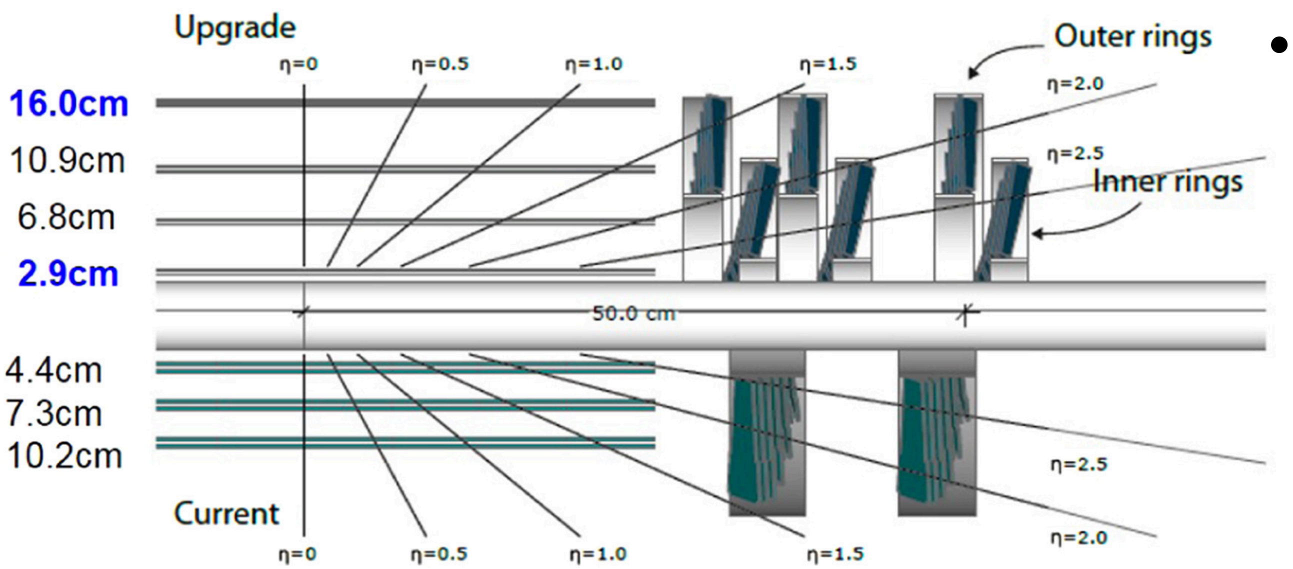
Search Overview

Simulation



- Trigger strategy — large MET from ISR jet at L1, isolated track at HLT
- Select events with an isolated track having:
  - Missing outer hits
  - Little associated calorimeter energy
  - No hits in the muon detectors
- Remaining backgrounds are rare:
  - Isolated, charged leptons not correctly reconstructed
  - Spurious tracks from pattern recognition errors

Event Selection



Four layer Phase 1 pixel upgrade (top)

- ISR jet (pt > 110 GeV), MET > 120 GeV
- ≥1 track:
  - pt > 55 GeV, |η| < 2.1
  - **≥4 pixel hits ***
  - Pass fiducial selections: reject gaps in detector coverage, regions of low lepton reco. efficiency
  - Isolated from jets and reconstructed leptons
  - Zero missing inner/middle silicon hits — minimize spurious tracks

- “Disappearing” criteria:
  - Sum of calorimeter deposits in ΔR<0.5 less than 10 GeV
  - ≥3 missing outer hits
- Separate into three signal categories
  - Number of tracker layers with hits: **=4, =5 ***, ≥6

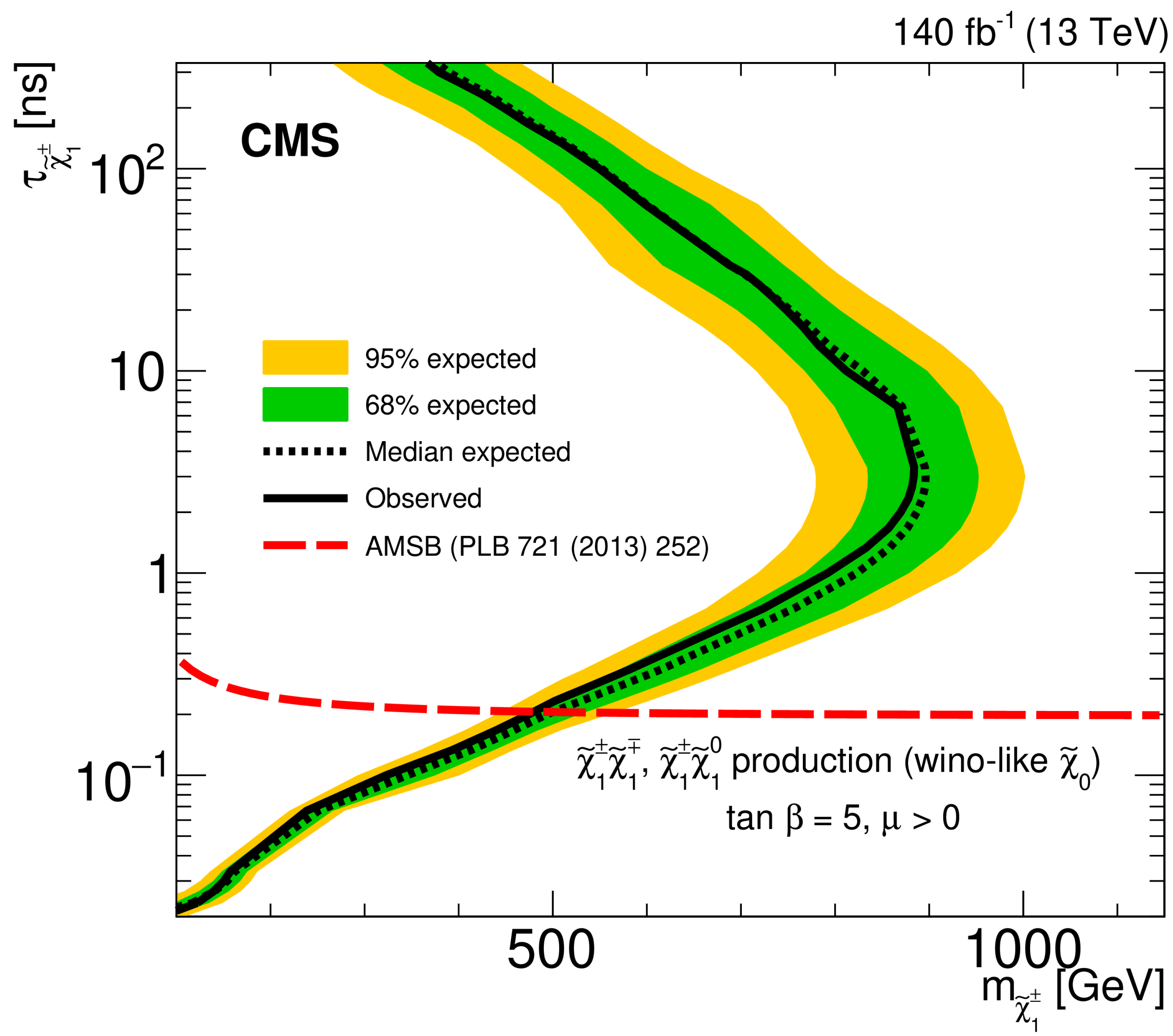
*** Newly possibly since Phase I upgrades!**

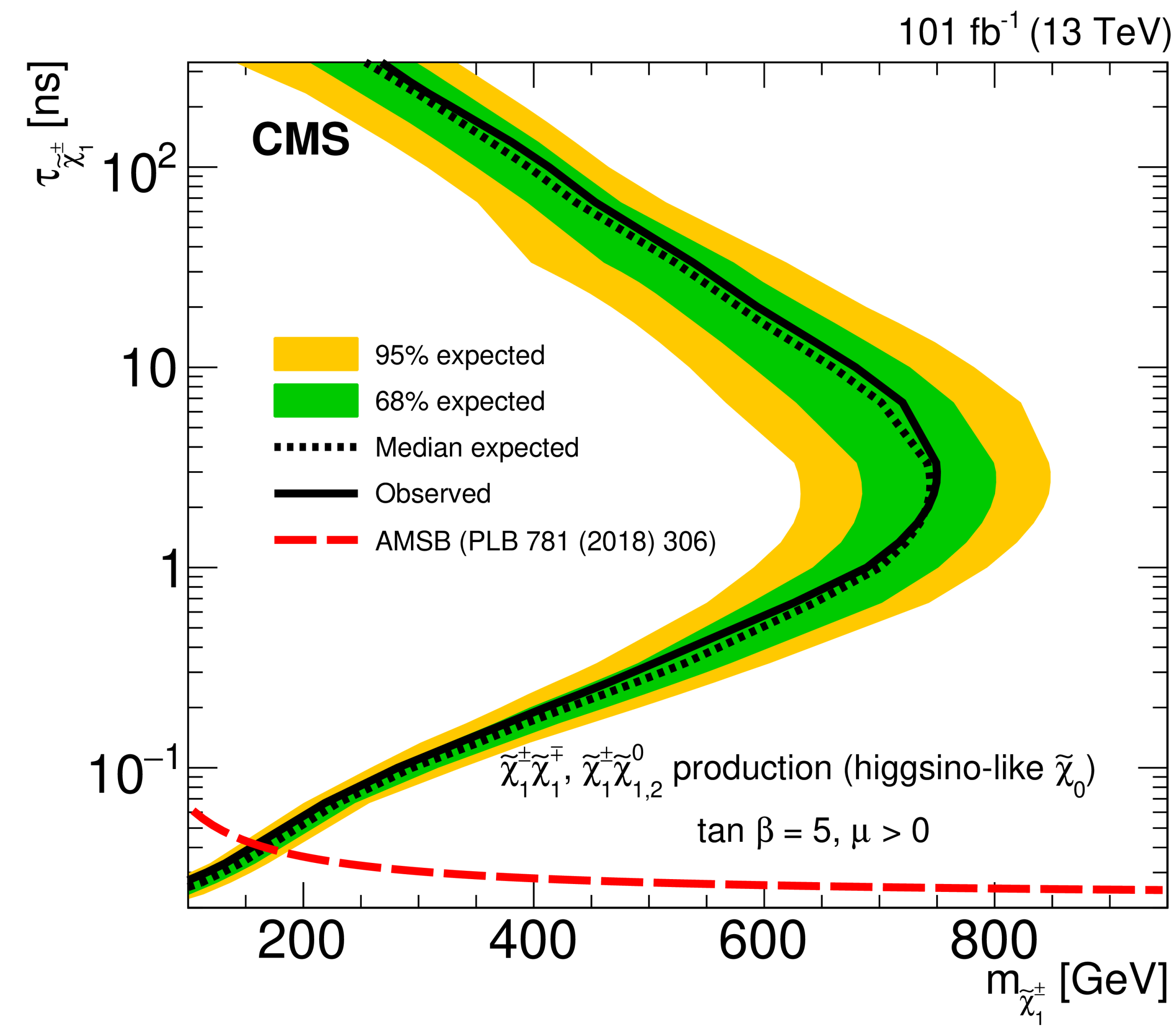
Background Estimation

- Entirely data-driven approach
- Leptons: calculate the probability for each flavor (e, μ, τ_h) to survive each step of the selection
  - Normalize single-lepton control regions to this probability
- Spurious tracks: estimate event-by-event probability for such a track in Z + track events, both Z->μμ and Z->ee
  - Select tracks in displaced sideband
- Total background expected is **$47.8^{+2.7}_{-2.3}$ (stat) ± 8.1 (syst) events** — observed **48 events**

Data-taking period	n_{lay}	Expected backgrounds			Observation
		Leptons	Spurious tracks	Total	
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

Results





- Combined with 2015-6 results for a purely wino-like neutralino in AMSB — **best limits to date!**
  - Left: exclude chargino masses up to 884 (474) GeV for a lifetime of 3 (0.2) ns
- **First limits** for purely higgsino-like neutralino in AMSB
  - Right: exclude chargino masses up to 750 (175) GeV for a lifetime of 3 (0.05) ns

Conclusions

- CMS is pursuing a broad program of searches for long-lived particles
  - Many signatures considered are quite unconventional, requiring novel triggering or reconstruction techniques, data-driven background estimations
- Recently published results for several such searches:
  - Search for Strongly Interacting Massive Particles with Trackless Jets
    - CMS-PAS-EXO-17-010
    - **First results in this phase space at colliders**
    - Model-independent cross section upper limit: $\sigma^{95\%}_{obs}$ = 0.18 fb
    - Exclude SIMP masses up to 900 GeV
  - Search for disappearing tracks
    - Phys. Lett. B 806 (2020) 135502
    - Wino-like neutralino AMSB: improve chargino mass reach by >150 GeV — **strongest limits to date**
    - Higgsino-like neutralino AMSB: **first limits** in AMSB using this signature
- Many more exciting results coming soon!

Full list of CMS Exotica results: PhysicsResultsEXO

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Additional Material

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SIMP Phase Space

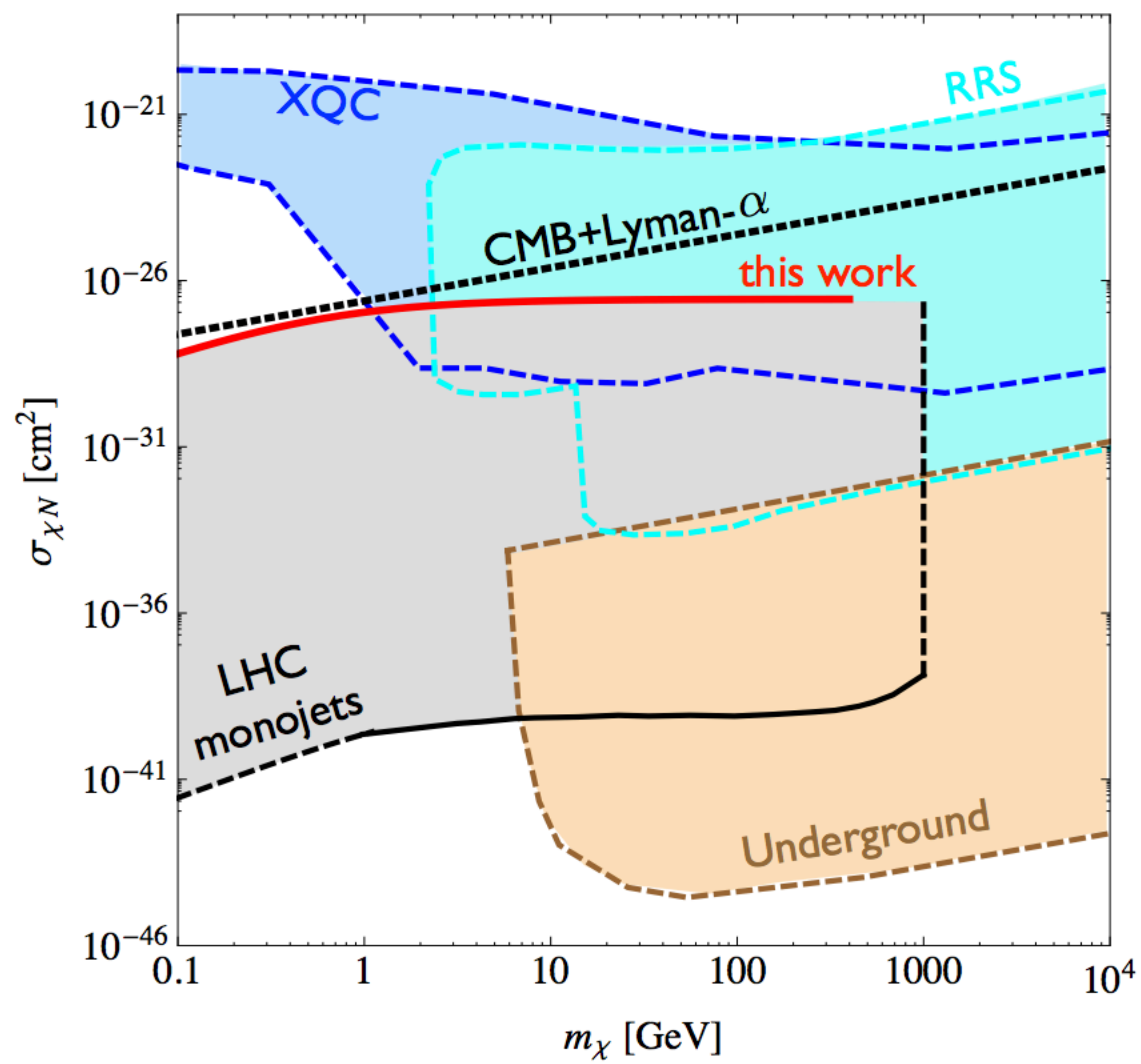
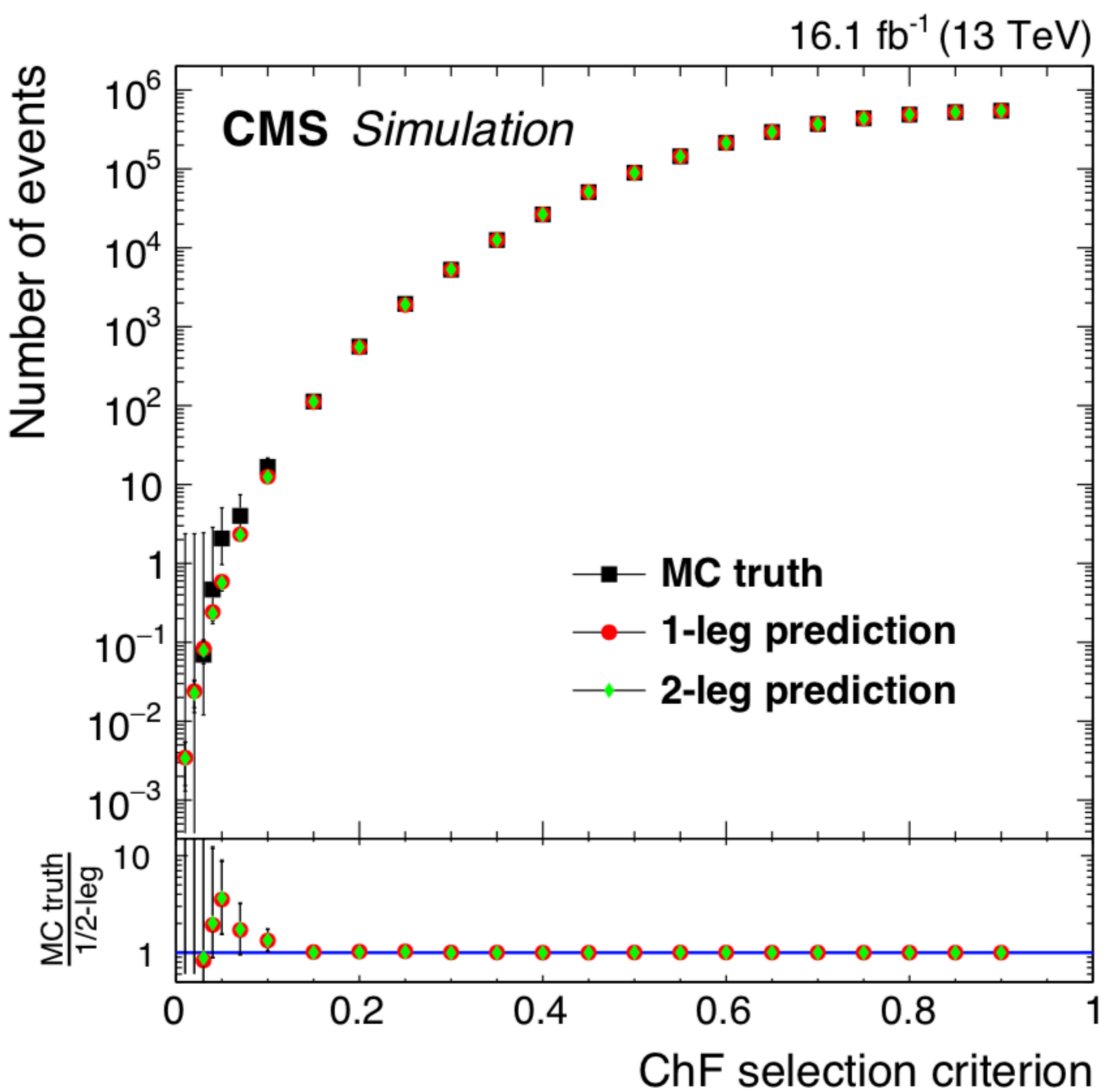
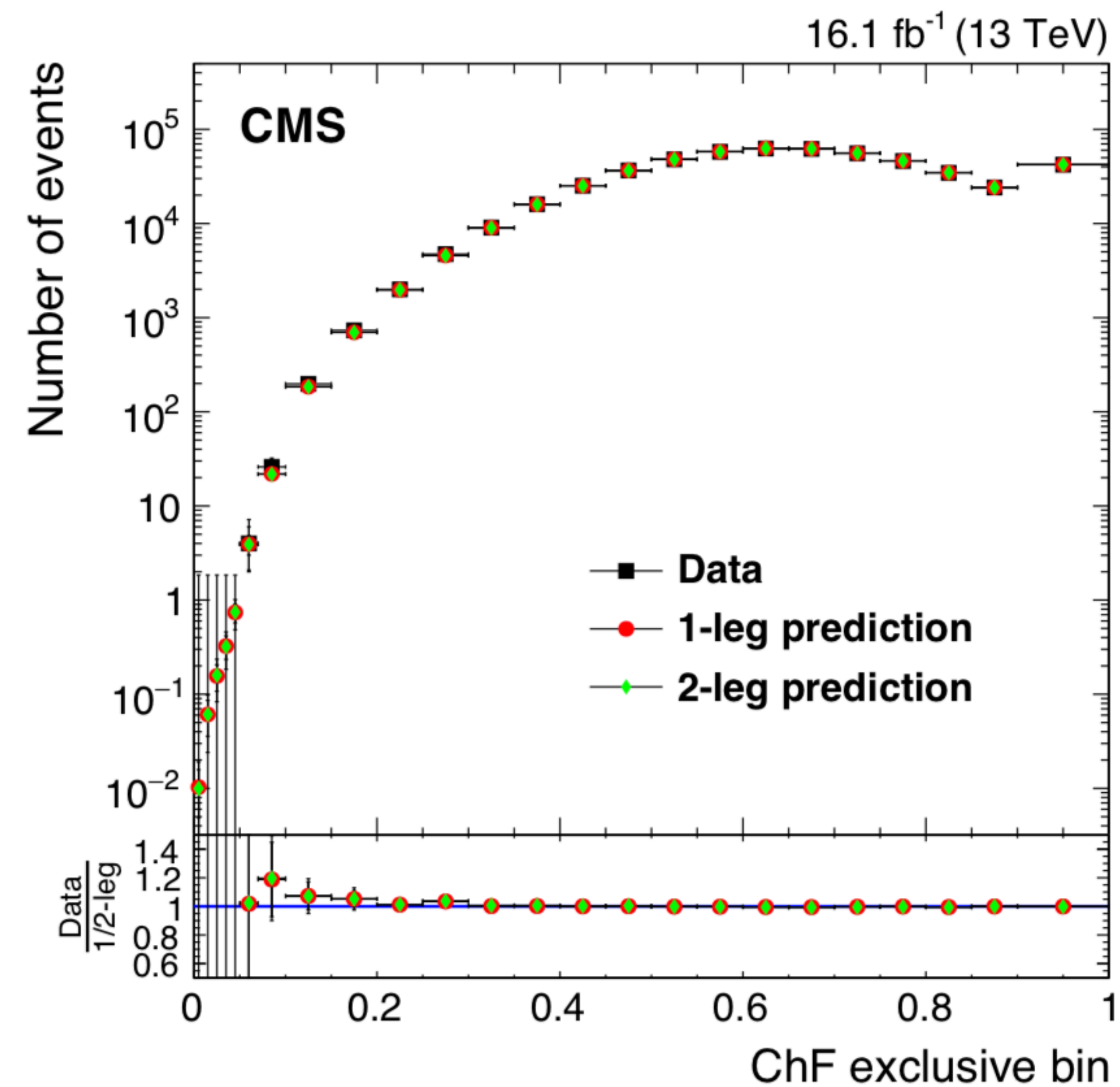


FIG. 4. Summary plot showing all the most important applicable constraints. Our results are shown in the upper solid red line ("this work"), which corresponds to the green line of Figure 3 (left). In black solid/dashed (lower lines), the monojet constraints are shown. The other constraints are: atmospheric XQC and RRS experiments (blue and cyan, respectively), underground experiments (brown dashed), and CMB+Lyman-α (black dashed).

https://arxiv.org/abs/1503.05505

SIMP Background Closure





source	uncertainty
jet energy corrections	2.2 - 5.4%
integrated luminosity	2.5%
trigger inefficiency	2%

Systematic uncertain on signal efficiencies

Disappearing Track Lepton Backgrounds

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	$(2.2 \pm 0.9) \times 10^{-4}$	$(3.2 \pm 1.3) \times 10^{-2}$	$(6.5^{+2.9}_{-2.7}) \times 10^{-2}$
	≥ 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	$(0.9^{+1.5}_{-0.9}) \times 10^{-4}$	$(7.4 \pm 4.2) \times 10^{-2}$	$(4.4^{+5.5}_{-4.4}) \times 10^{-2}$
	≥ 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	$(1.4 \pm 1.1) \times 10^{-4}$	$(5.8 \pm 3.8) \times 10^{-2}$	$(5.1^{+4.5}_{-3.7}) \times 10^{-2}$
	≥ 6	$(3.3 \pm 0.7) \times 10^{-5}$	$(1.5 \pm 0.6) \times 10^{-6}$	$(2.3 \pm 1.0) \times 10^{-3}$

- P(veto): probability for each flavor (e, μ, τ_h) to survive the veto against reconstructed leptons of that flavor
- Measured with Z events using tag-and-probe techniques

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Disappearing Track Systematics

Background	Source	Uncertainty $n_{\mathrm{lay}} = 4$	$n_{\mathrm{lay}} = 5$	$n_{\mathrm{lay}} \geq 6$
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%	—

Systematic uncertain on background estimates

Source	Uncertainty $n_{\mathrm{lay}} = 4$	$n_{\mathrm{lay}} = 5$	$n_{\mathrm{lay}} \geq 6$
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%
$p_{\mathrm{T}}^{\mathrm{miss}}$	0.3%	0.3%	0.4%
$E_{\mathrm{calo}}^{\Delta R<0.5}$	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%

Systematic uncertain on signal efficiencies

Disappearing Track Results