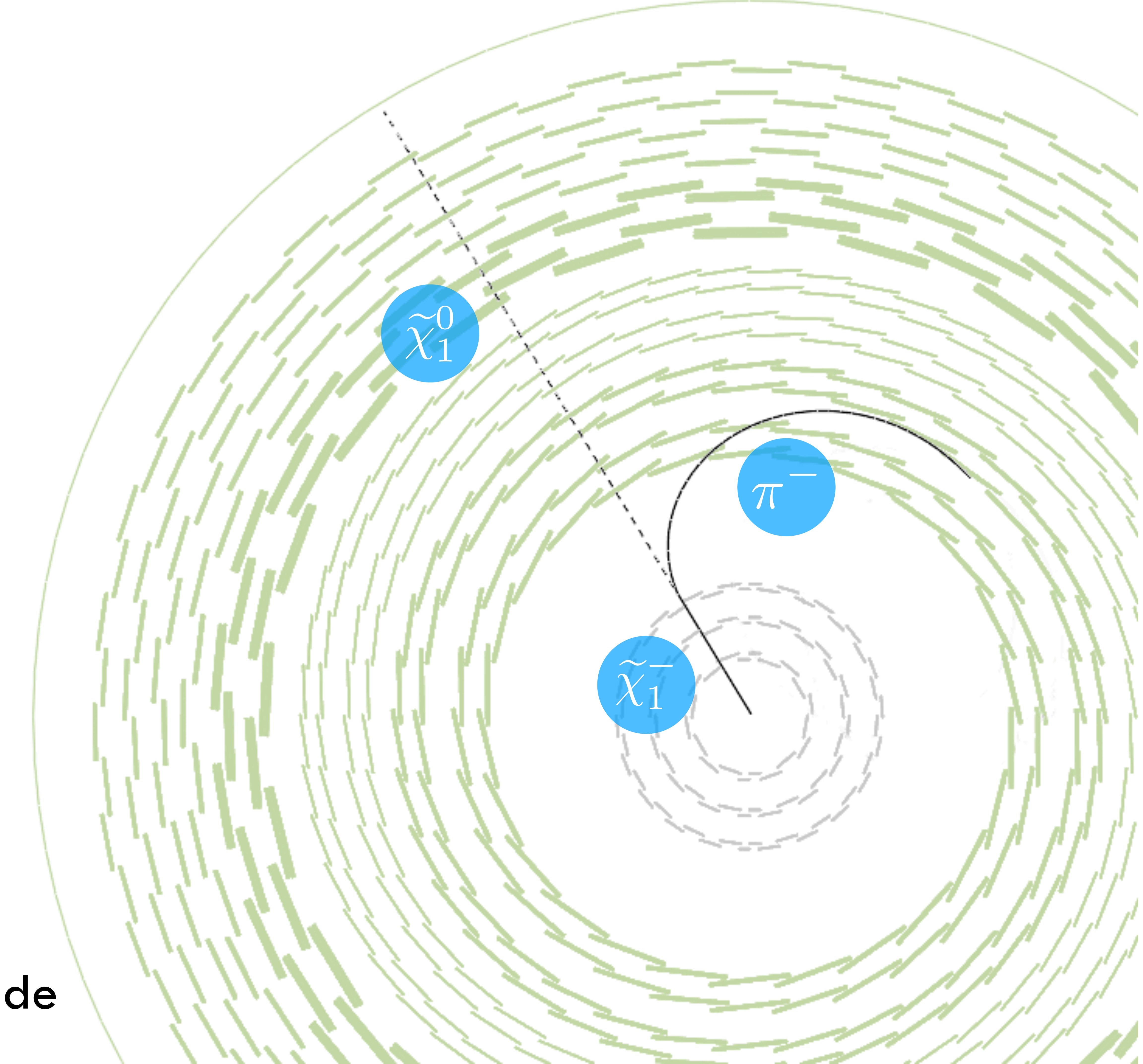
Search for long-lived SUSY with disappearing tracks

Searching for long-lived particles at the LHC and beyond: Thirteenth workshop of the LLP Community
July 19 2023



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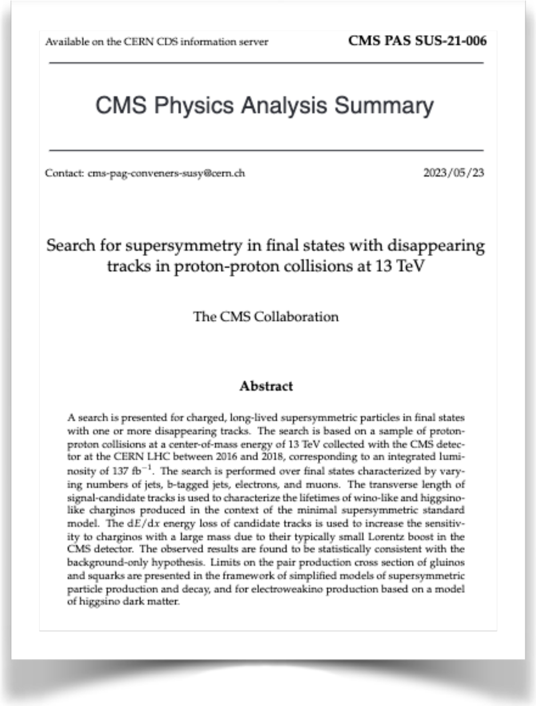
Search for long-lived SUSY with disappearing tracks

- new analysis first publicly presented at LHCP 2023
- published Physics Analysis Summary: CMS-PAS-SUS-21-006 [**link**]



Available on the CERN CDS information server | CMS PAS SUS-21-006

CMS Physics Analysis Summary

Contact: cms-pag-conveners-susy@cern.ch | 2023/05/23

Search for supersymmetry in final states with disappearing tracks in proton-proton collisions at 13 TeV

The CMS Collaboration

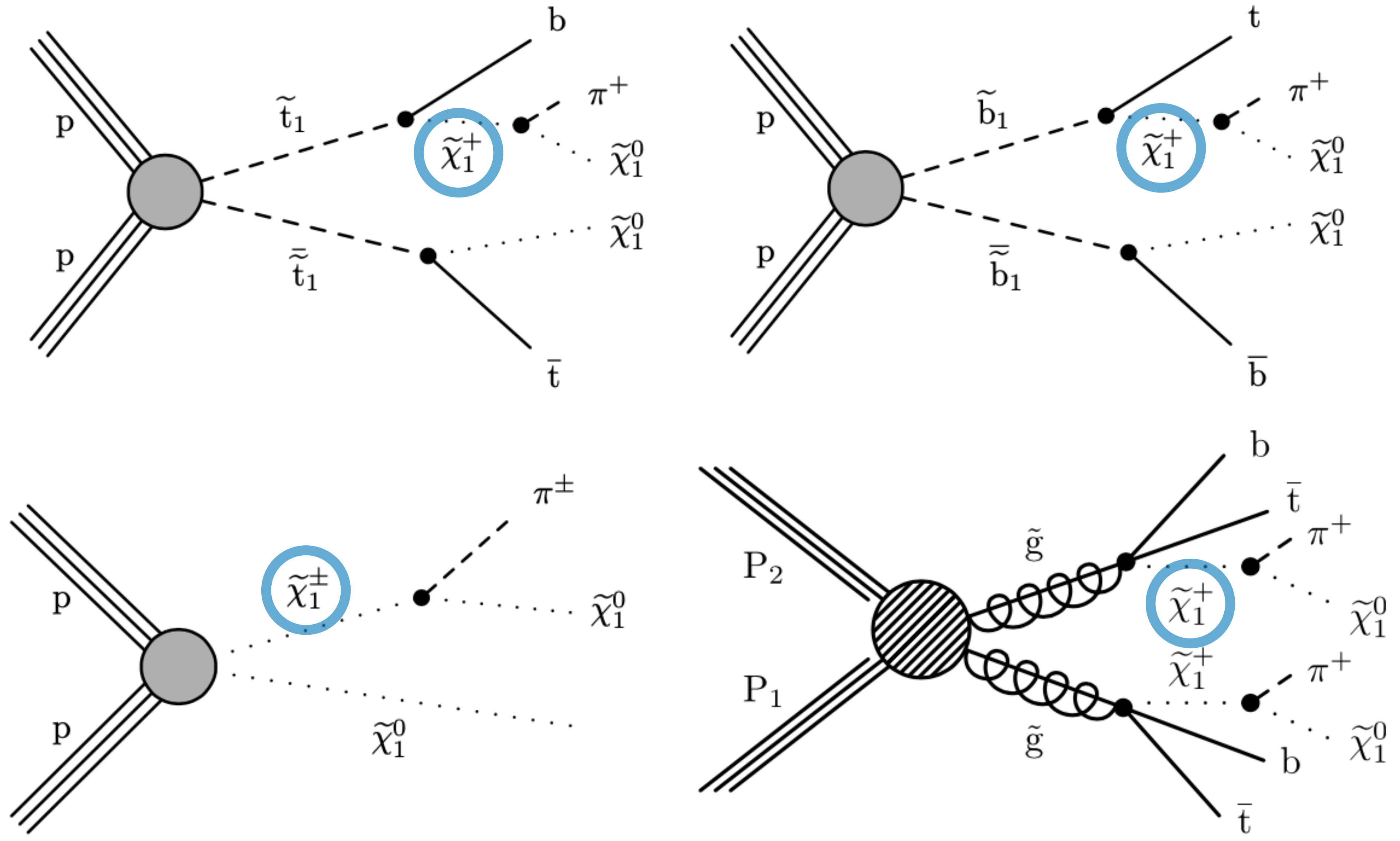
Abstract

A search is presented for charged, long-lived supersymmetric particles in final states with one or more disappearing tracks. The search is based on a sample of proton-proton collisions at a center-of-mass energy of 13 TeV collected with the CMS detector at the CERN LHC between 2016 and 2018, corresponding to an integrated luminosity of 137 fb^{-1}. The search is performed over final states characterized by varying numbers of jets, b-tagged jets, electrons, and muons. The transverse length of signal-candidate tracks is used to characterize the lifetimes of wino-like and higgsino-like charginos produced in the context of the minimal supersymmetric standard model. The dE/dx energy loss of candidate tracks is used to increase the sensitivity to charginos with a large mass due to their typically small Lorentz boost in the CMS detector. The observed results are found to be statistically consistent with the background-only hypothesis. Limits on the pair production cross section of gluinos and squarks are presented in the framework of simplified models of supersymmetric particle production and decay, and for electroweakino production based on a model of higgsino dark matter.

- chargino mixing: $\tilde{W}^{\pm}, \tilde{H}^{\pm} \rightarrow \tilde{\chi}^{\pm}_{1,2,3,4}$
- models with little mixing have <u>compressed mass spectra</u>
  - e.g., for pure Higgsino/pure wino LSP models
    - $\Delta m(\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_1) \sim$ 300 MeV
    - $c\tau(\tilde{\chi}^{\pm}_1)$ up to 10 cm
  - chargino produced at the pp vertex
  - typical decay:

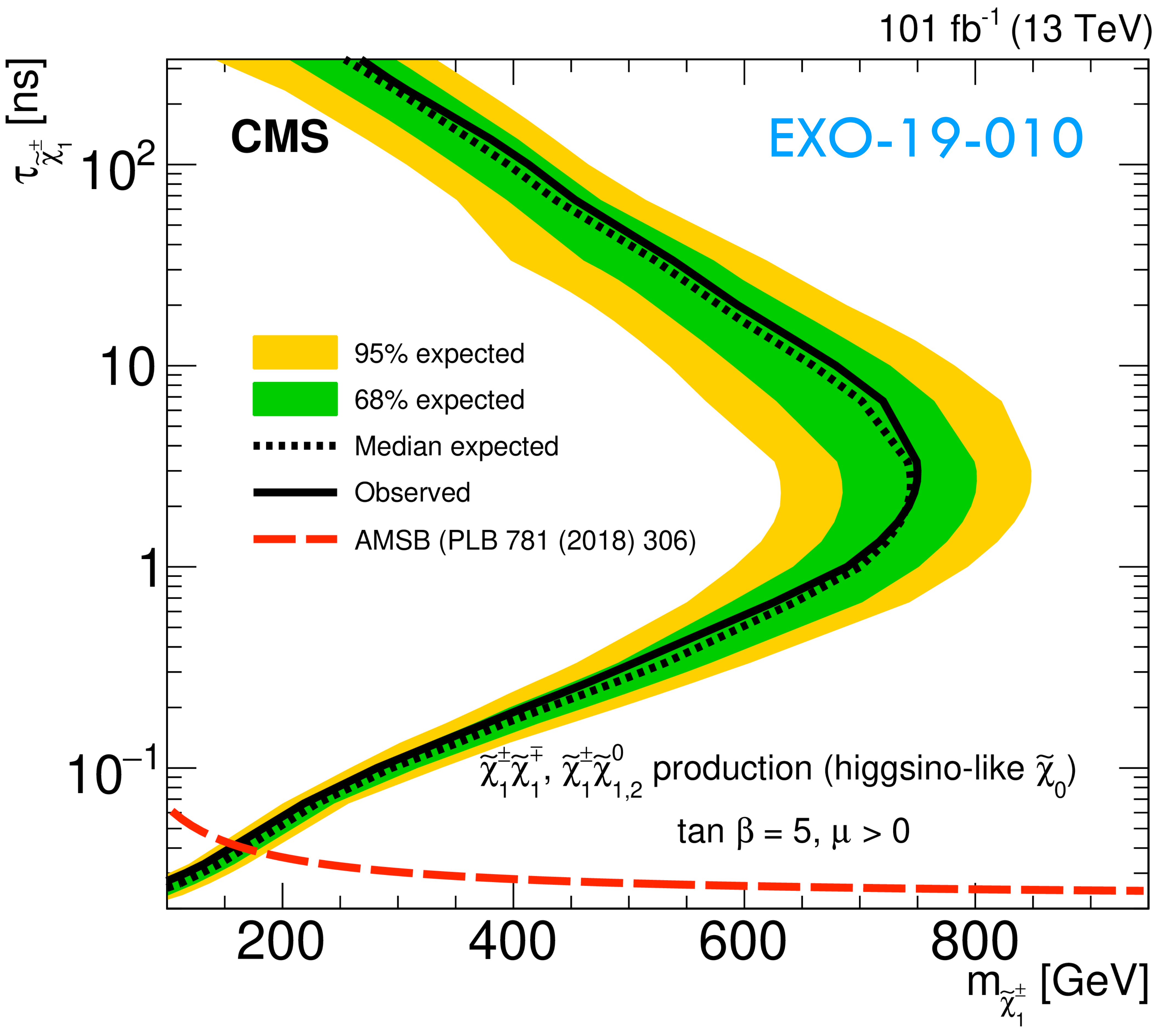
  - pion is very soft in lab frame, $\tilde{\chi}^{\pm}_1$ leaves track and "disappears"

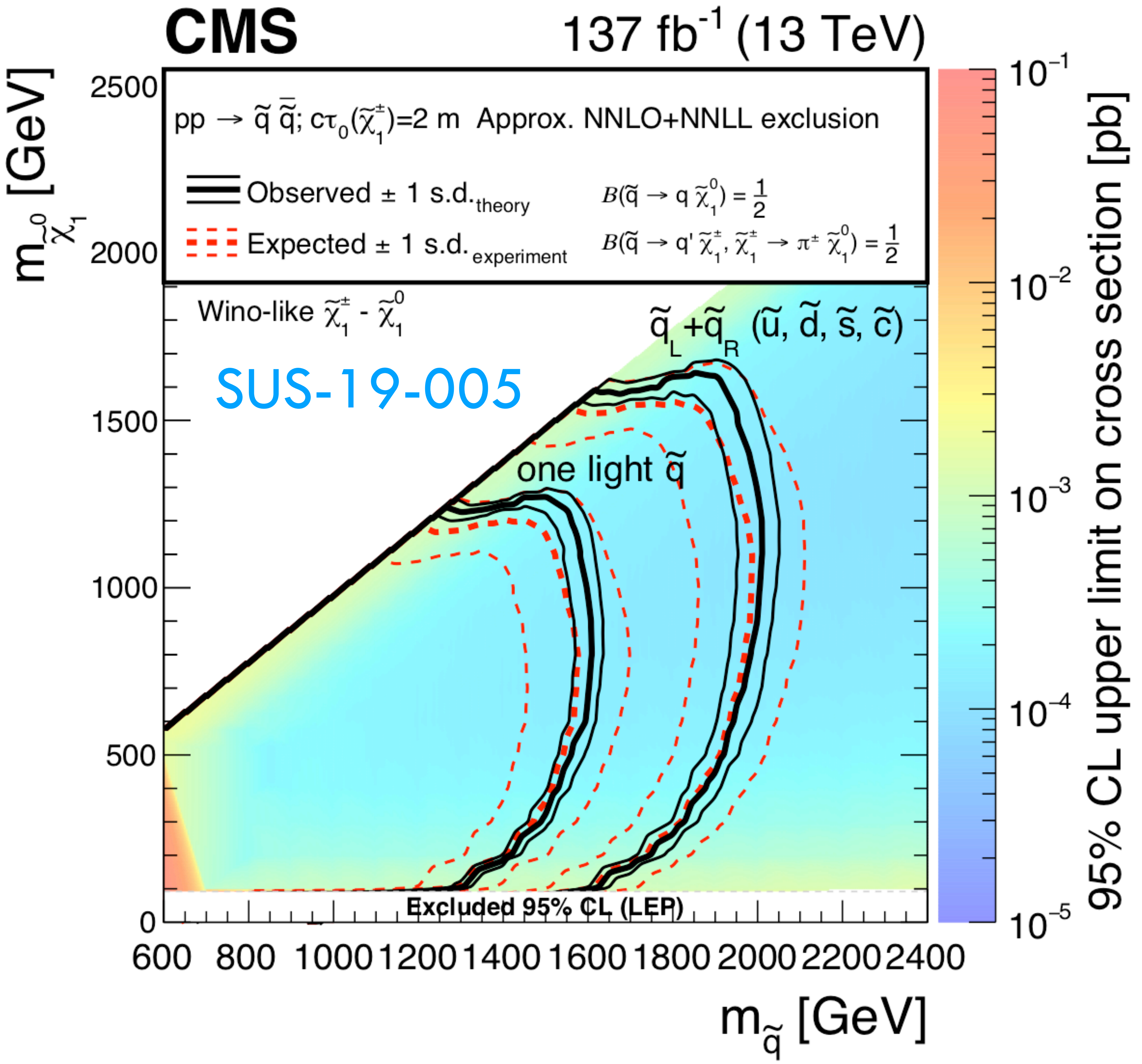
- many possible production, decay modes:
  $\tilde{g}\tilde{g}, \tilde{t}\bar{\tilde{t}}, \tilde{b}\bar{\tilde{b}}, \tilde{q}\bar{\tilde{q}}, \tilde{\chi}\tilde{\chi}$
  $\tilde{g} \rightarrow b\bar{t}\tilde{\chi}^+, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}^+, \tilde{t} \rightarrow b\tilde{\chi}^+, \tilde{b} \rightarrow t\tilde{\chi}^-$
- simplified models:



CMS disappearing tracks

- results are complementary to previous CMS results, such as EXO-19-010 (arxiv:2004.05153) and SUS-19-005 (arxiv:1909.03460)





Analysis overview

Track selection/categorization

Track preselection
- $p_{T,short}$>25 GeV, |η|<2.0
- $p_{T,long}$>40 GeV, |η|<2.0, missing outer hits≥2

→ **Categories:**
- **short** - only pixel hits → Track BDT (short)
- **long** - pixel and strips hits → Track BDT (long)

NEW

→ **Signal cand. tracks:**
- **BDT_{short} > 0.1 (0.15**)**
  E_{dep} < 15 GeV
- **BDT_{long} > 0.12 (0.08**)**
  E_{dep} < 0.2 * p^{track}

(DTk)

Event selection

Channels	Triggers	Baseline selection
≥1 DT, 0 lepton	MET/MHT cross triggers	hard p_{T}^{miss}>150 GeV, ≥1 jets, 0 leptons
≥1 DT, ≥1 electron (NEW)	single-electron trigger, p_T>27 GeV	≥1 jet, 1 tight iso el, m_T>100, m_{Lt}>140 GeV
≥1 DT, ≥1 muon (NEW)	single-muon trigger, p_T>24 GeV	≥1 jet, 1 tight iso mu, m_T>100, m_{Lt}>140 GeV

Background estimation

Fake track background

	low hard p_{T}^{miss}	analysis baseline
BDT sideband	A	C
BDT signal region	B	D

high-low ratio from low-MHT, 0-lepton region

Real-particle background

	DY region	analysis baseline
E_{dep} (μ-match) sideband	A	C
E_{dep} (μ-veto) SR	B	D

high-low ratio from DY electron+DT (μ+DT) region

hard p_T^{miss} = $|-\sum_{\text{over PF jets with } p_T>30\text{ GeV}, |\eta|<5.0} \vec{p}_{T,i}|$

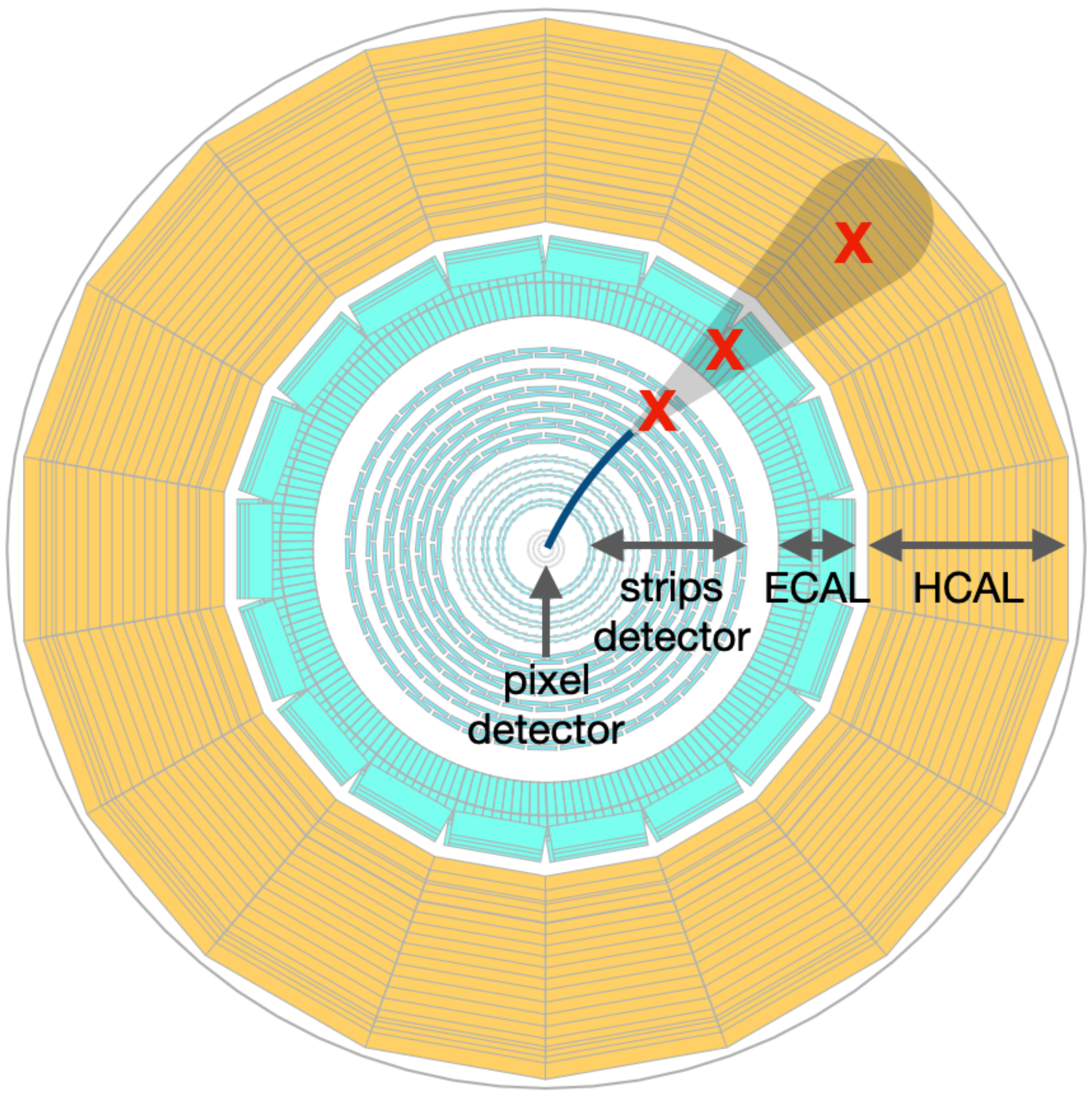
NEW Signal regions binned in: hard p_{T}^{miss} | N_{jet}, $N_{b\text{-}jet}$ | dE/dx low/high

*cut inverted for validation control region

**Phase-1 conditions

*cut inverted for fake track control region

Track pre-selection



- <u>short tracks</u>: pixel-only tracks
- <u>long tracks</u>: pixel+strips

track kinematics:

- p_T > 25 (>40) GeV for short (long) tracks
- |η|<2.0 - fiducial tracker volume

track properties:

- high quality track, no missing inner hits
- long tracks: ≥ 2 missing outer hits
- short tracks: ≥ 3 valid pixel hits, 0 strips hits
- η-φ mask (post-selection, derived with loose BDT cut)

reduce fake tracks:

- d_{xy}(PV), d_z(PV) < 0.1 cm

isolation:

- relative track isolation < 0.2
- veto if ΔR(track, PF candidate)< 0.01 or ΔR(track, jet)< 0.4

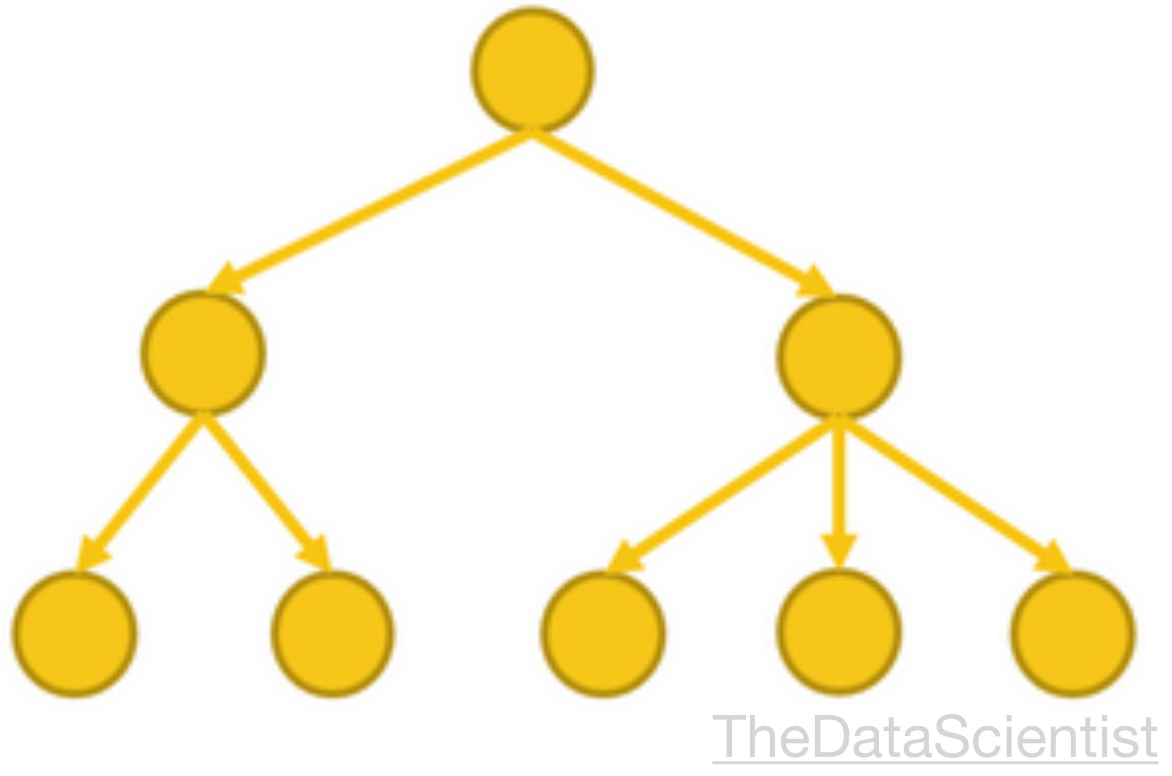
calometric deposited energy:

- E_{dep} < 15 GeV (short tracks)
- E_{dep}/p < 20% (long tracks)

$$E_{\mathrm{dep}} = \sum_{i \in \mathrm{ECAL,\ HCAL}}^{\Delta R < 0.5} E_i$$

Disappearing track selection using MVA classifier

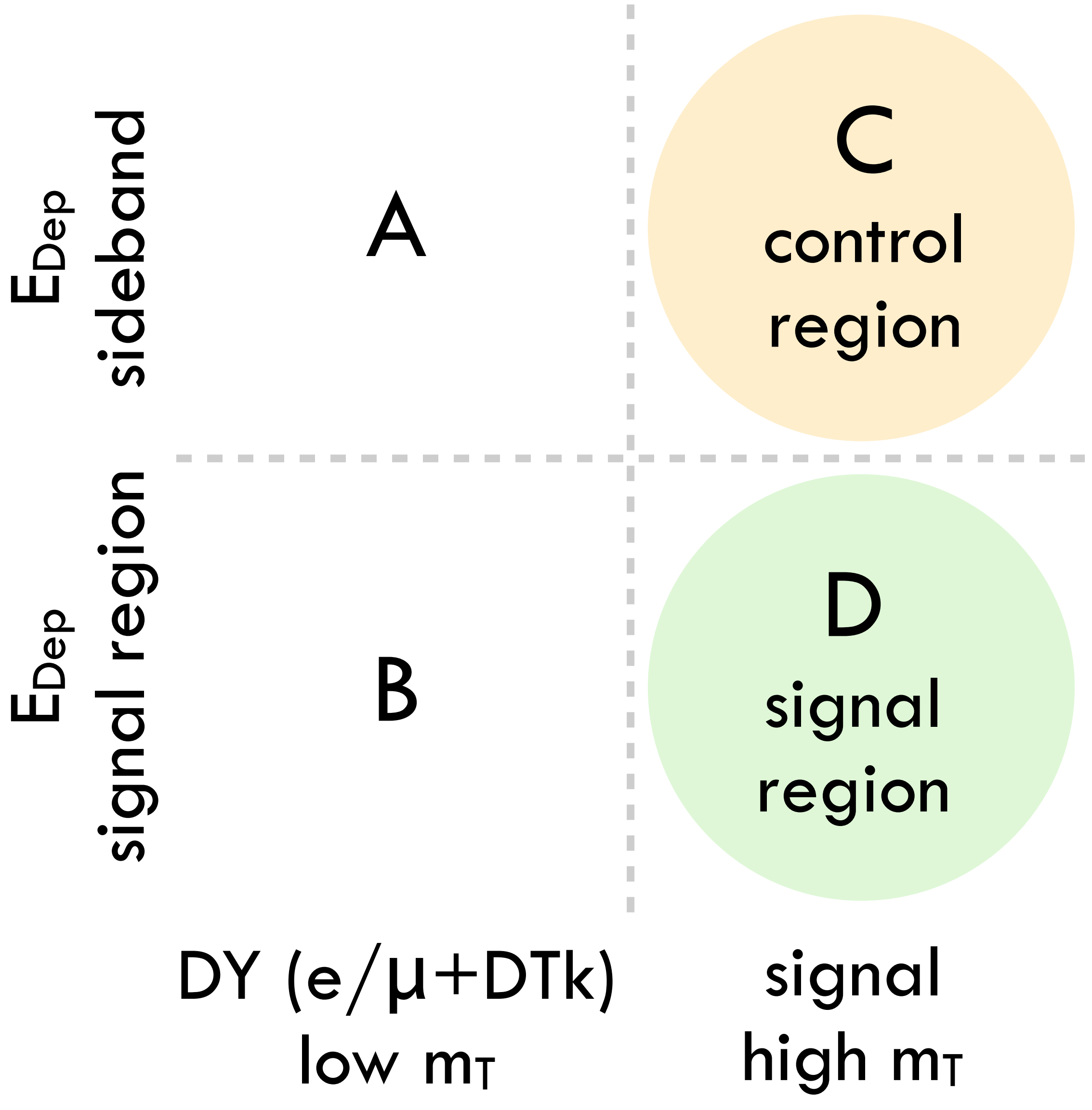
- trained boosted decision trees with TMVA
  - background training samples: SM Monte Carlo tracks (unweighted)
  - signal training sample: pooled T5btbtLL MC tracks (unweighted)
- BDT input variables, sorted by importance:
  - short tracks:
    1. d_{xy} (track, PV)
    2. d_z (track, PV)
    3. relative track isolation
    4. χ^2/ndof
    5. $\Delta p_T/p_T^2$
    6. pixel hits
  - long tracks:
    1. d_{xy} (track, PV)
    2. strips hits
    3. d_z (track, PV)
    4. $\Delta p_T/p_T^2$
    5. pixel hits
    6. relative track isolation
    7. χ^2/ndof
    8. missing outer hits



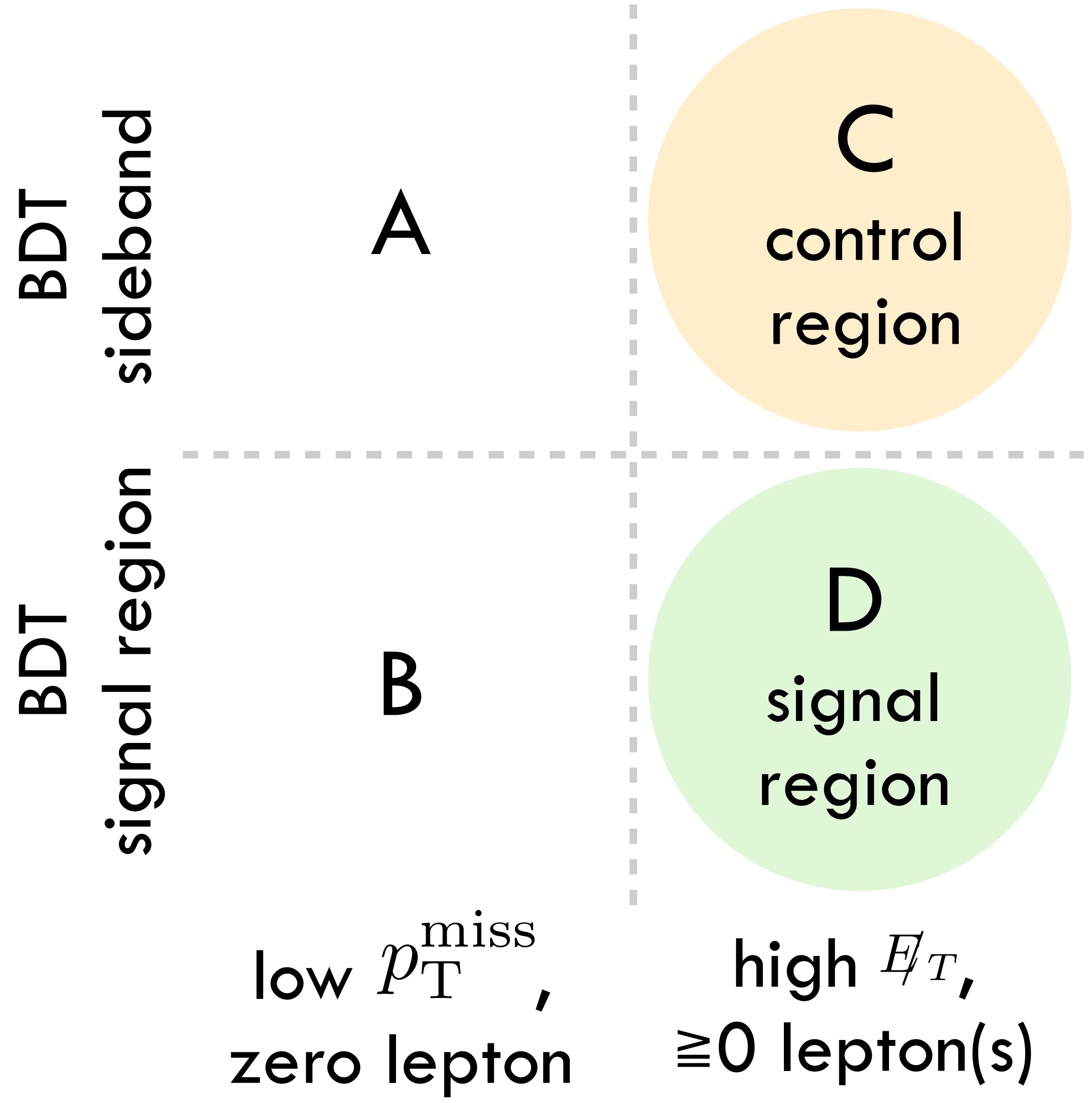
- moderate gain in signal eff. with reduced background rate w.r.t. other CMS searches

Data-driven background estimation

- <u>real-particle</u> background from particles that fail the reconstruction
  - showering background due to e.g. electrons due to Bremsstrahlung
  - muon background measured separately
- combinatoric background from <u>fake tracks</u> due to random alignment of detector hits (by chance or due to detector noise)
  - real-particle bg.:



  - combinatoric bg.:



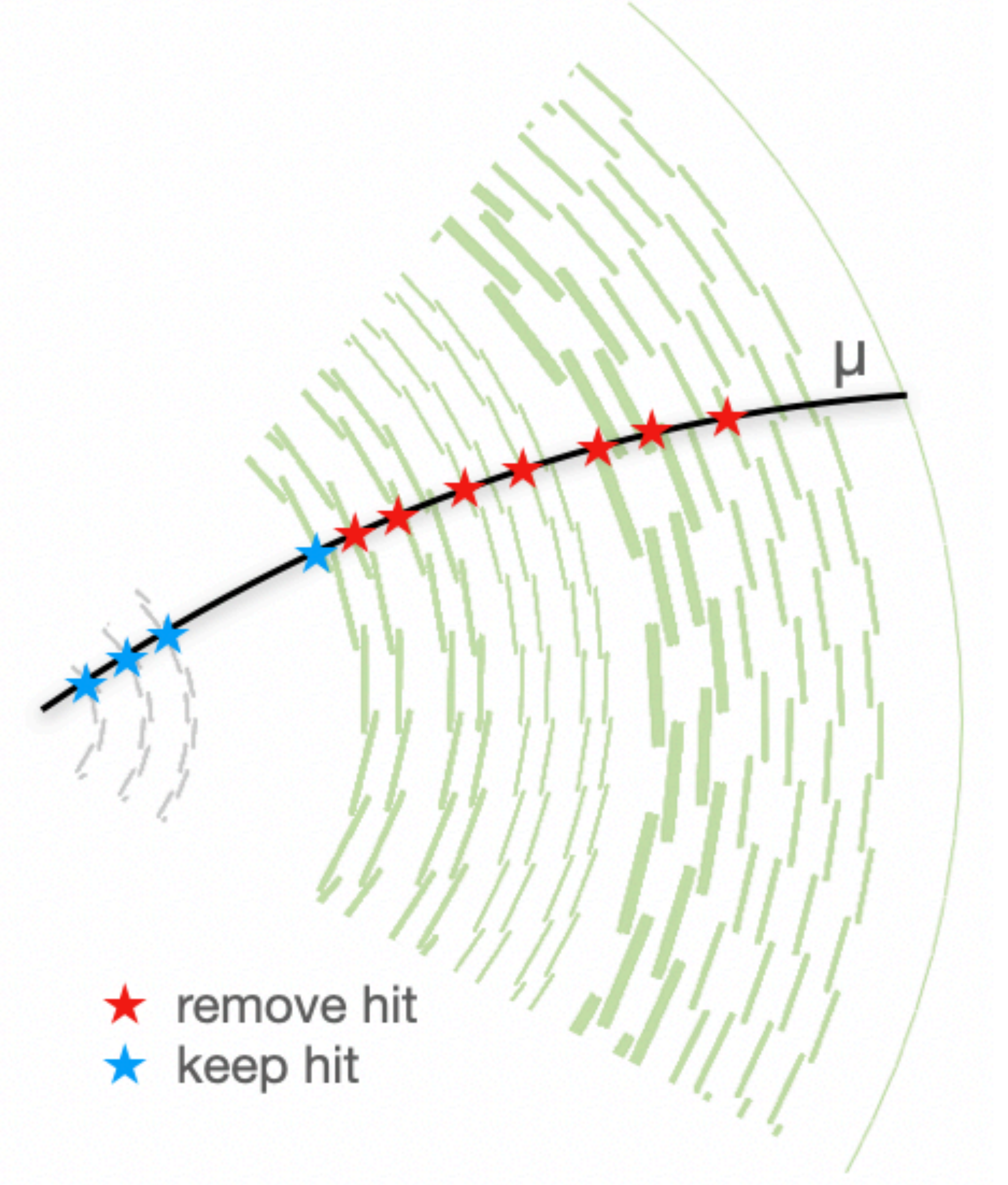
- predicted number of SR events:
  D = C · B / A
- measure transfer factor
  - for real-particle bg. in DY-enriched e/μ + DTk region
    $m_{l,DTk}$ = [65, 110] GeV, m_T < 100 GeV
  - for combinatoric bg. in zero-lepton QCD region:
    hard p_T^{miss} = [30, 60] GeV
- define sidebands
  - for real-particle bg.: use sideband region with large (background-like) E_{Dep}
  - for combinatoric bg.: use sideband region

Systematic uncertainties

Source	rel. uncertainty (%)
DTk selection efficiency	10-17
Integrated luminosity	1.6
Jet energy scale and resolution	0-24
b-jet tagging	0-4
Renormalization and factorization scales	0-2
Initial-state radiation	0-3
Pileup modeling	0-2
Trigger efficiency	0-4
dE/dx calibration	3-8
Showering long tracks	20-28
Showering short tracks	24-104
Muon long tracks	25-38
Fake long tracks	5-52
Fake short tracks	6-28

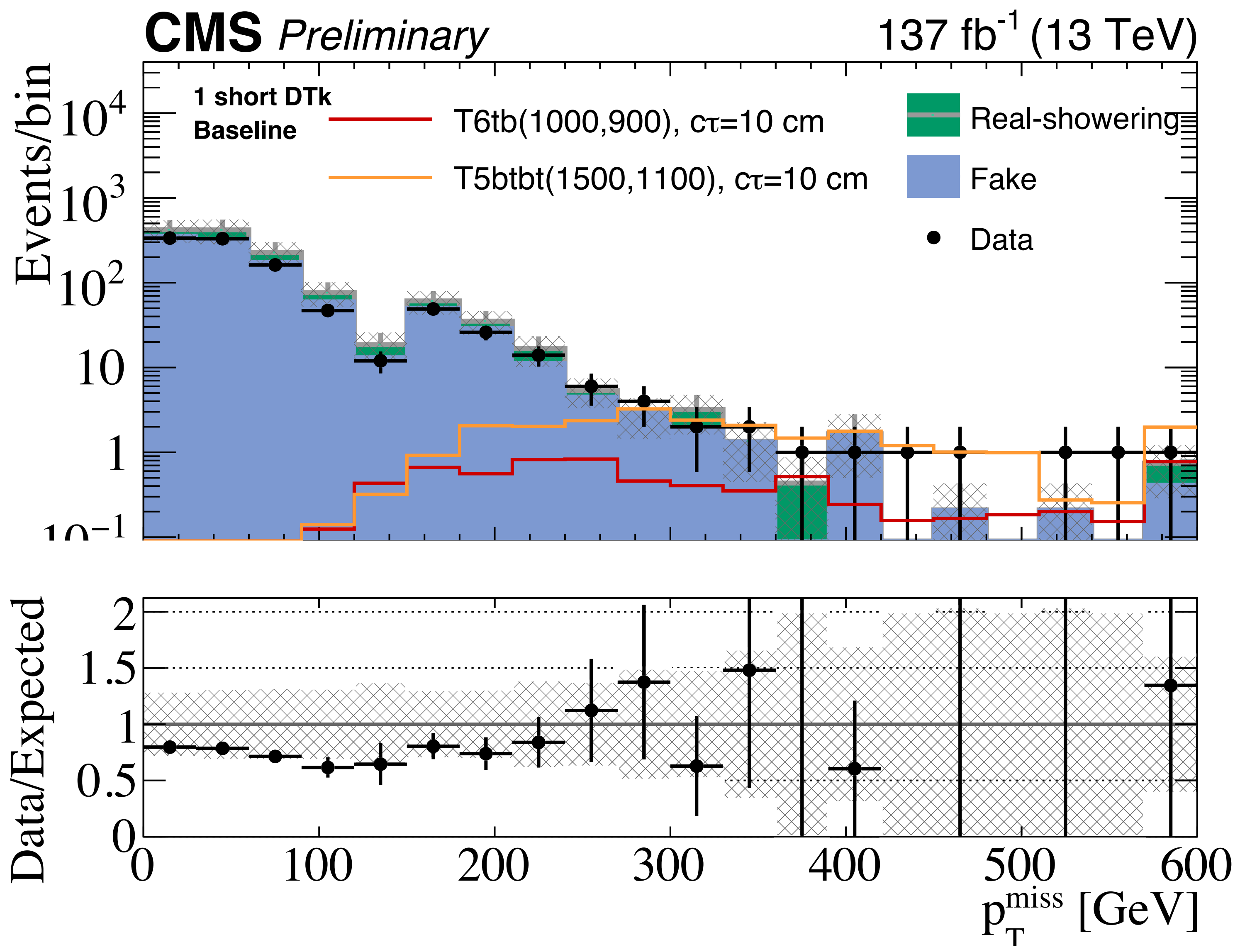
- derive **DTK scale factors** by using a novel method to artifically shorten muon tracks and re-running the track reconstruction
- use shortened muons as a proxy for the chargino:
  1. select isolated muons with $p_T > 25$ (40) GeV for short (long) tracks
  2. identify best muon track with ≥ 10 layers with measurement
  3. artificially shorten tracks by removing hit clusters
  4. re-run complete reconstruction step for each N remaining layers
  5. evaluate track tag on shortened tracks

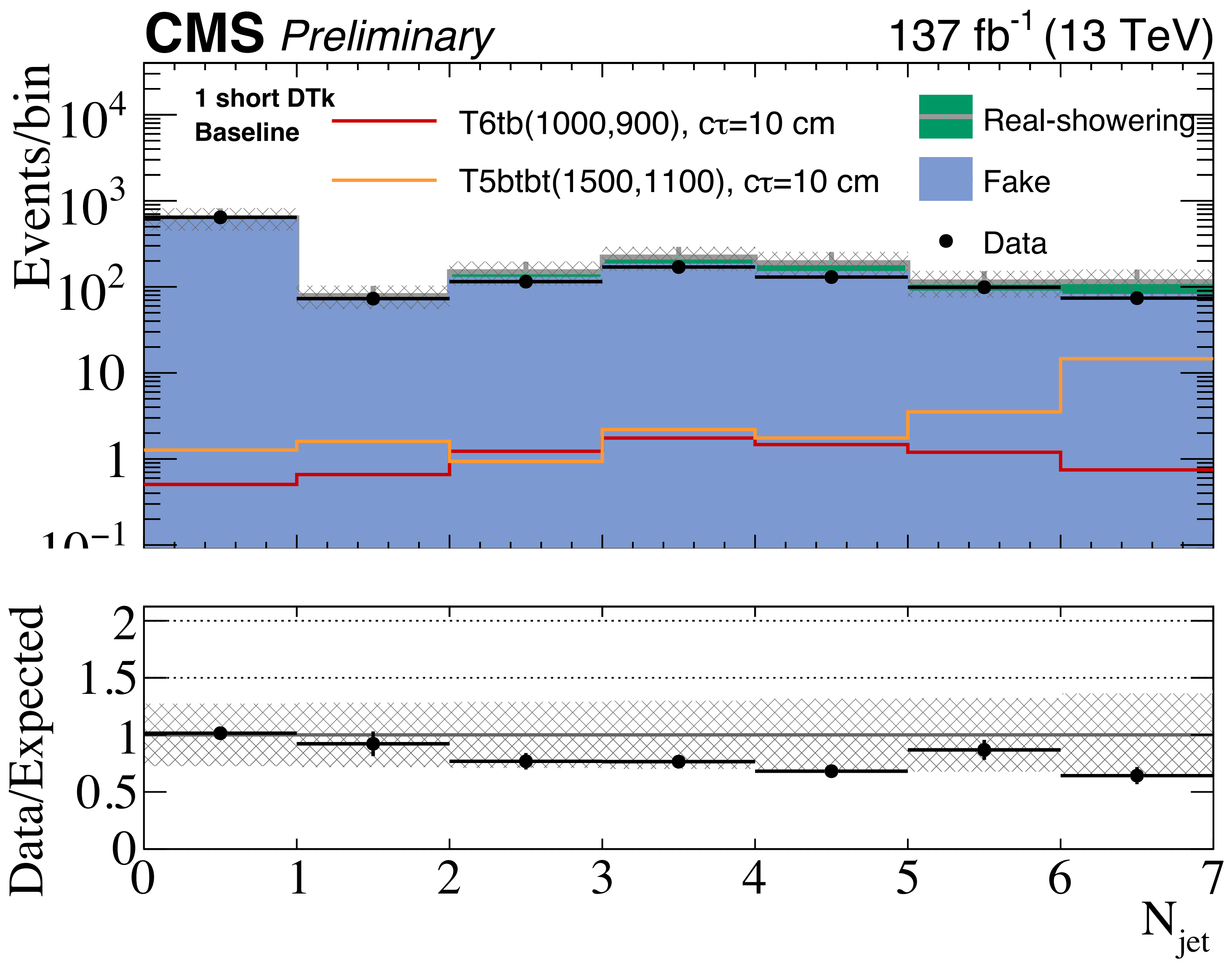
developed by A. Tews [**link**]

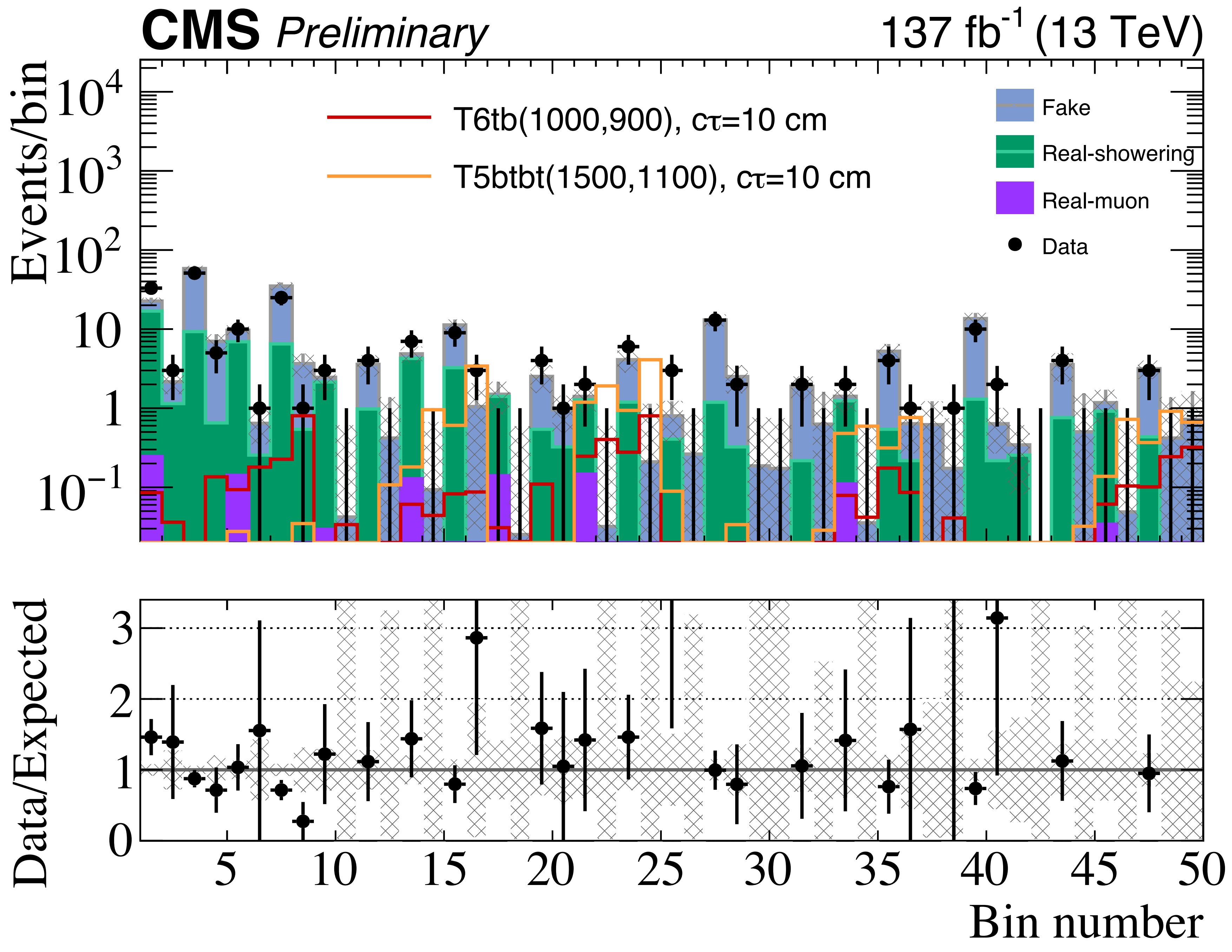


Results

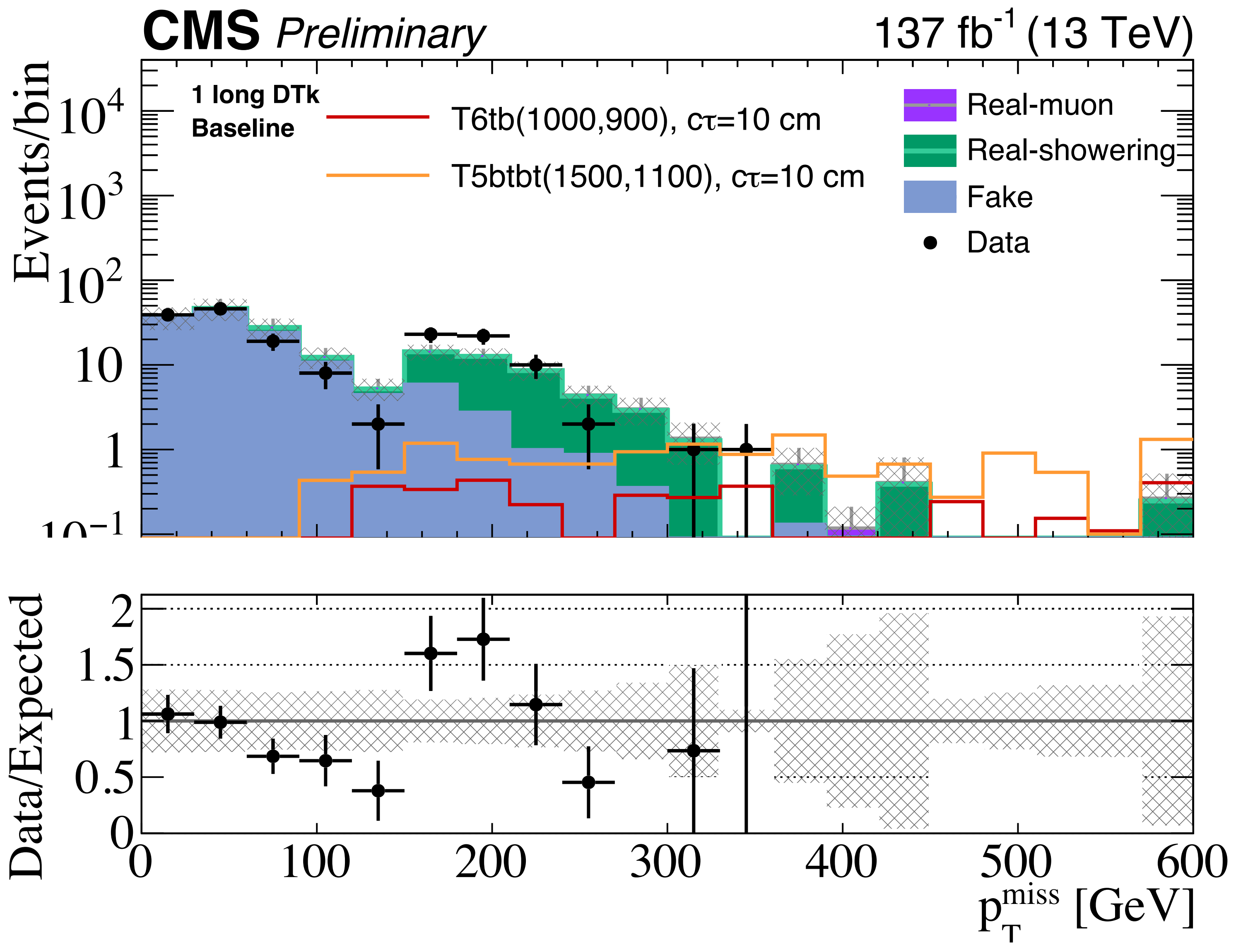
short tracks

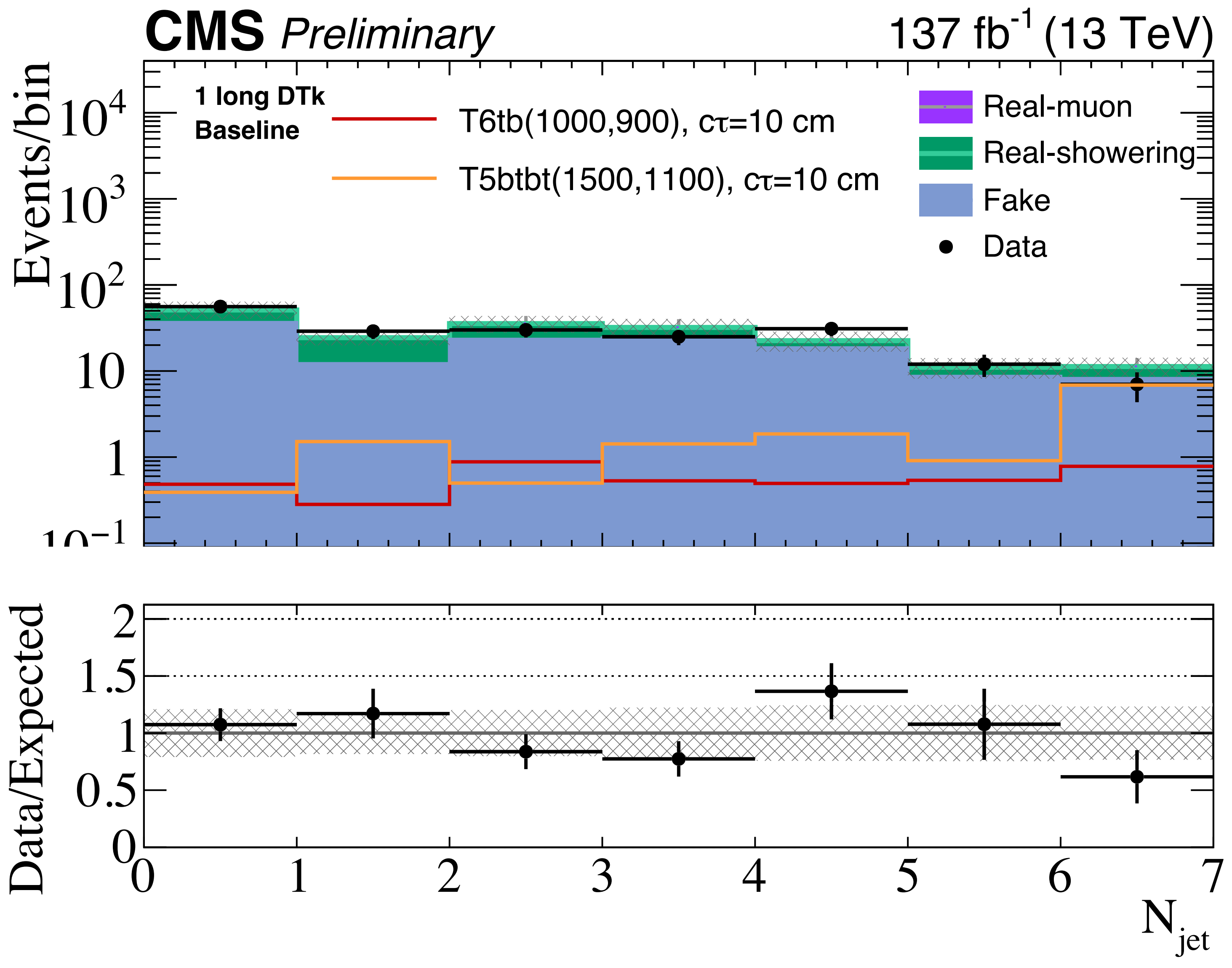






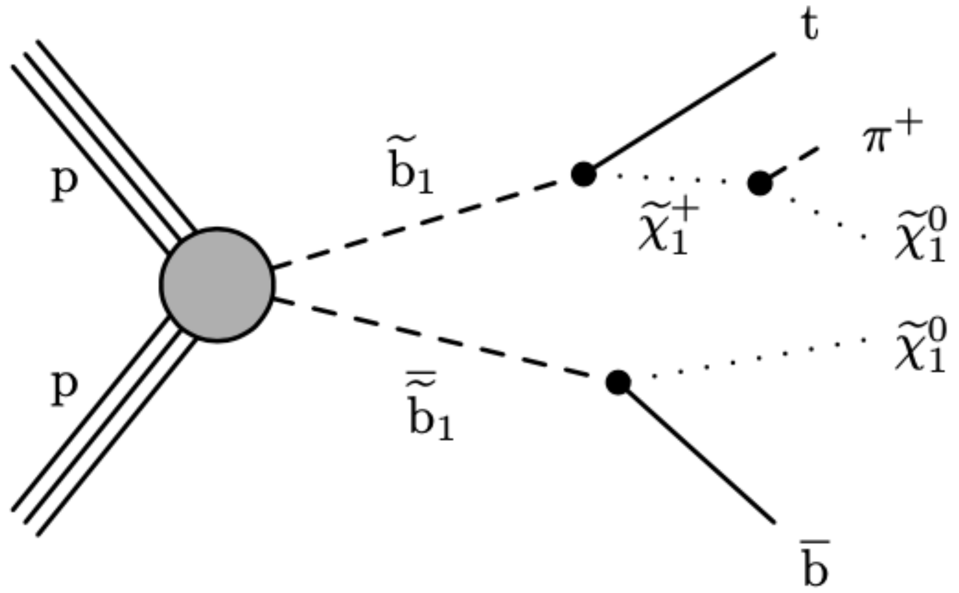
long tracks



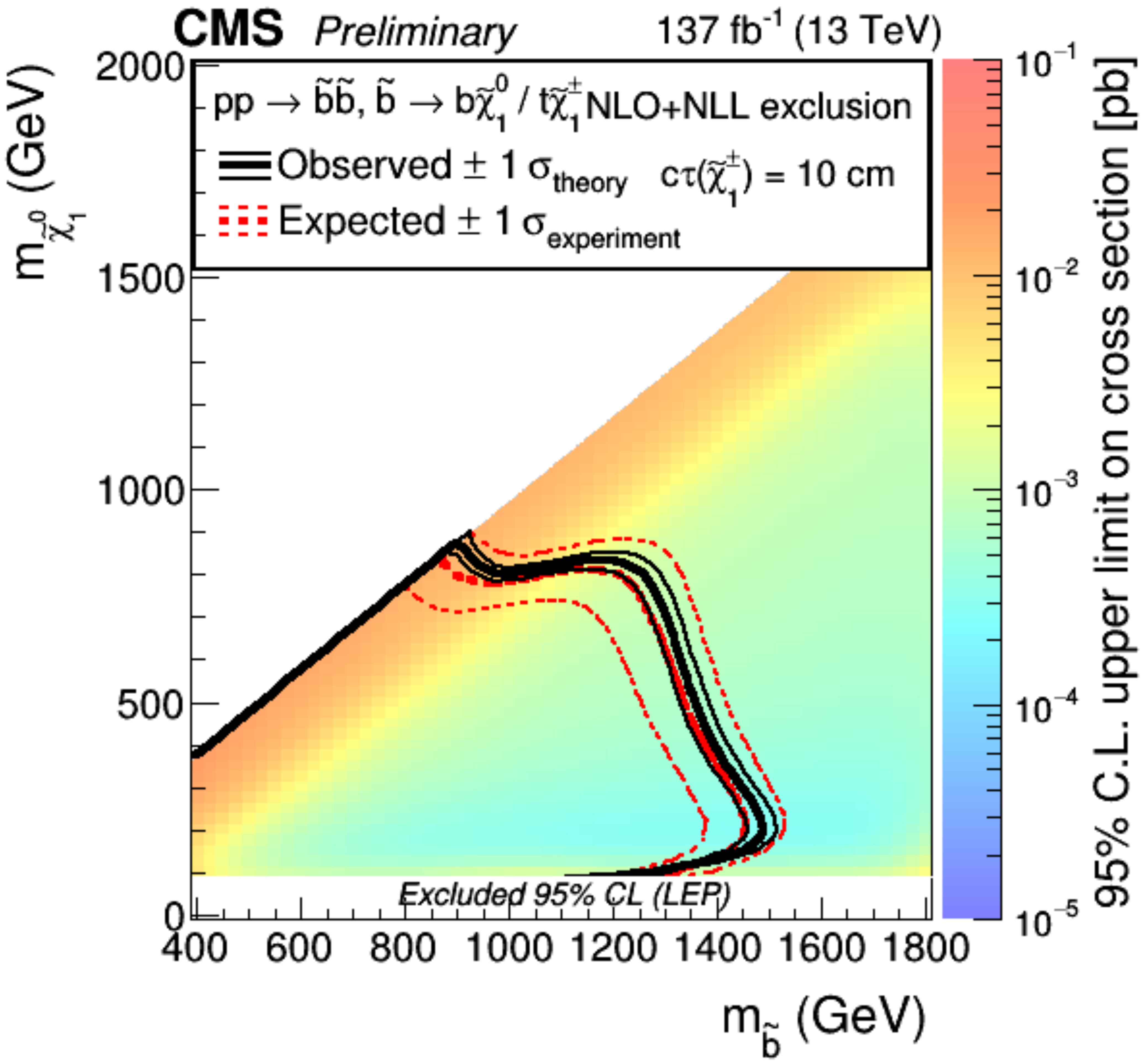


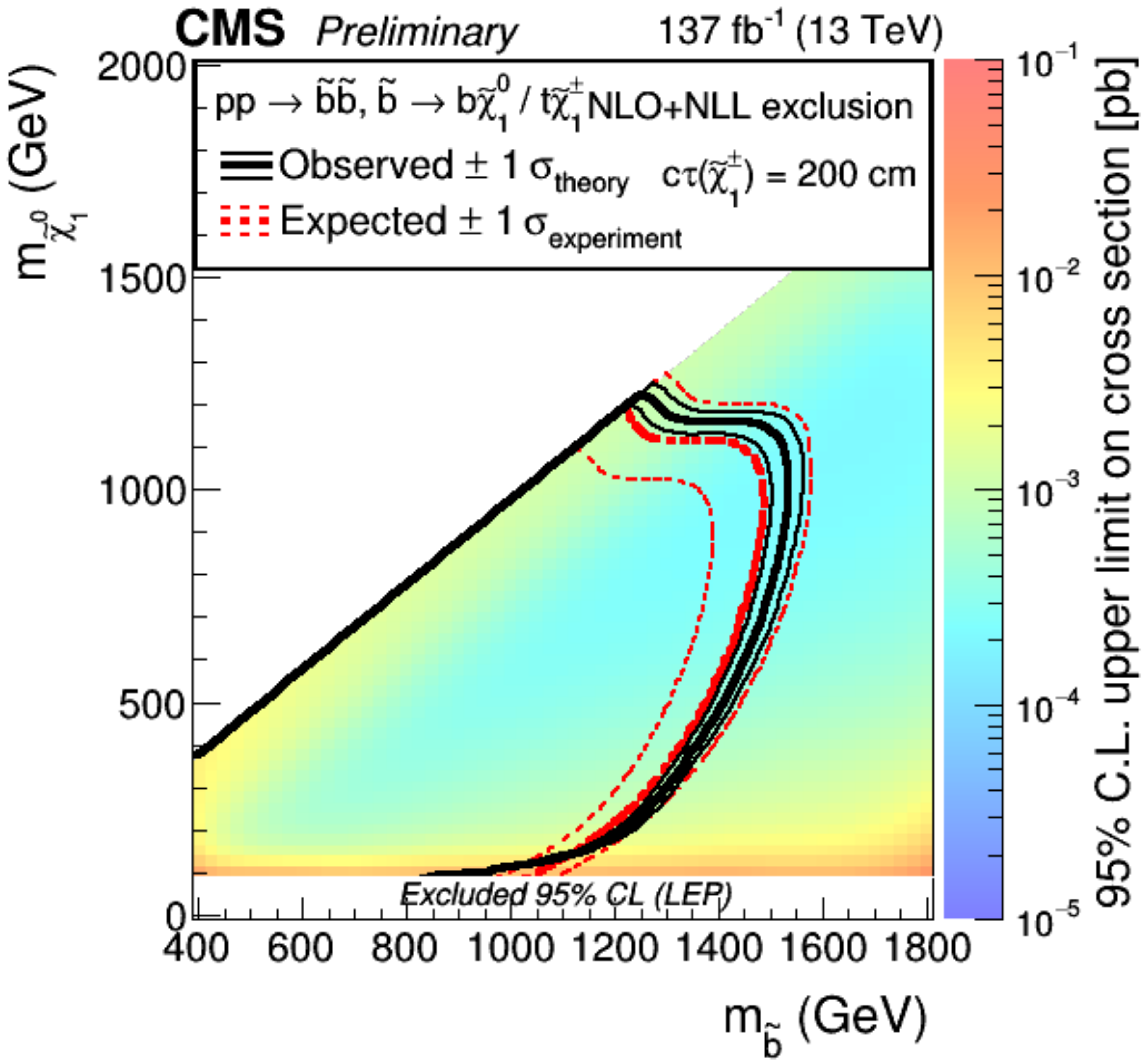
- no statistically significant excess observed in a single SR
- overprediciton for short tracks due to contamination in showering transfer factor measurement region for short tracks
  - covered by uncertainties, thus mitigated in likelihood fit

Interpretation: $pp \to \tilde{b}\tilde{b}, \tilde{b} \to t\tilde{\chi}_1^{\pm}$



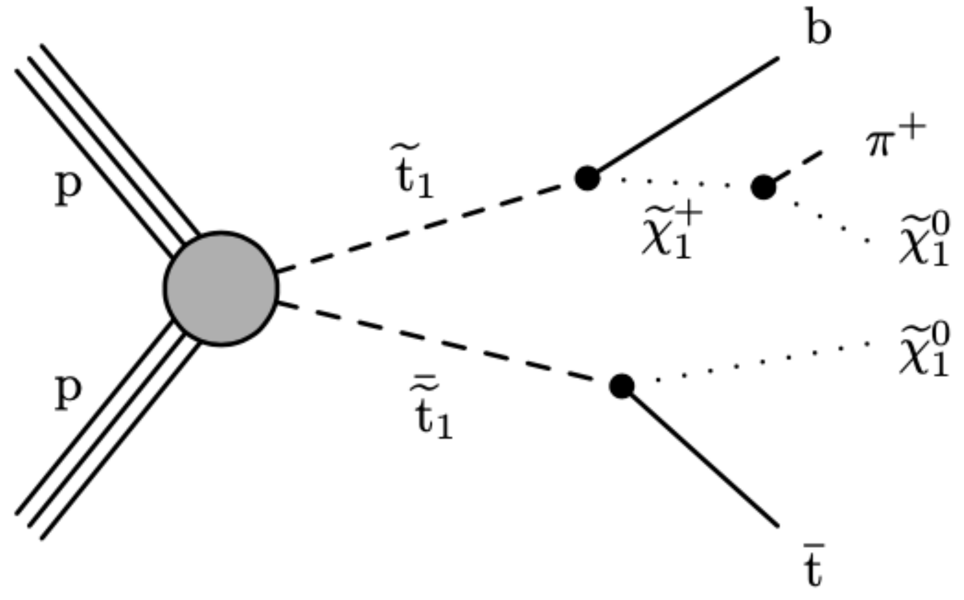
limit reaches up to $m_{\tilde{b}} \lessapprox$ 1.5 TeV / $m_{\tilde{\chi}_1^0} \lessapprox$ 1.1 TeV ($c\tau$ = 200 cm):

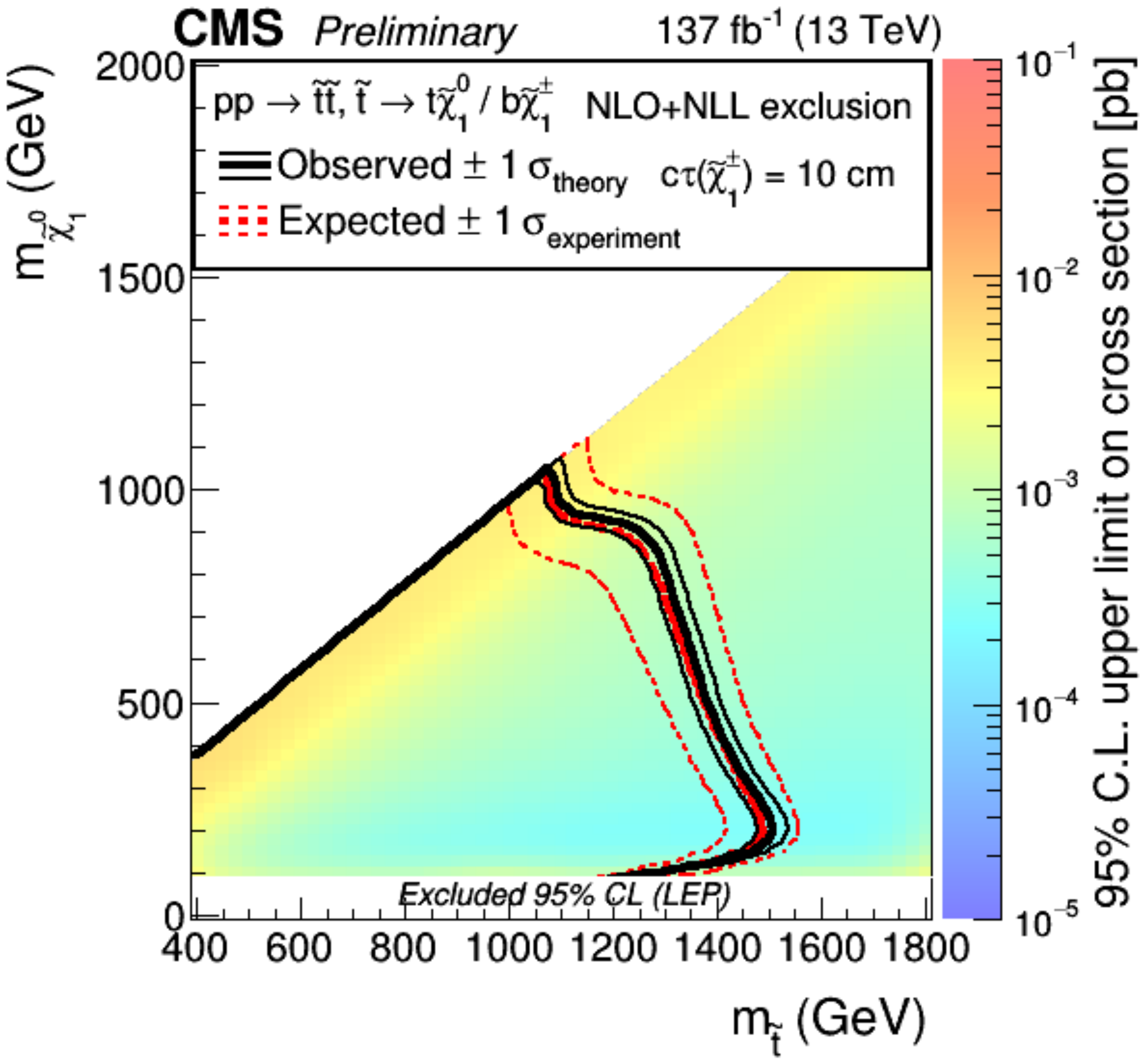


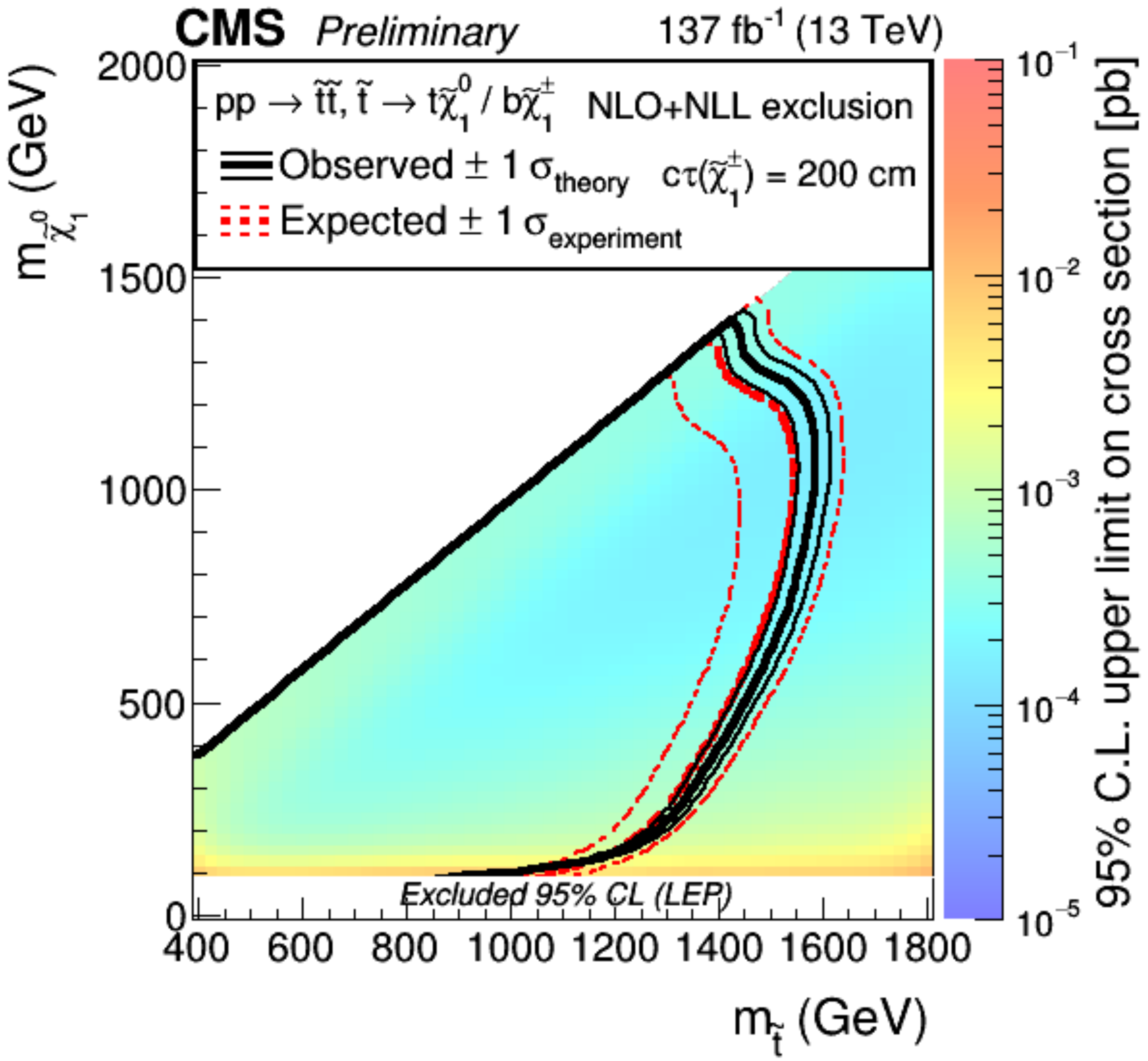


Interpretation: $pp \to \tilde{t}\tilde{t}, \tilde{t} \to b\tilde{\chi}_1^{\pm}$

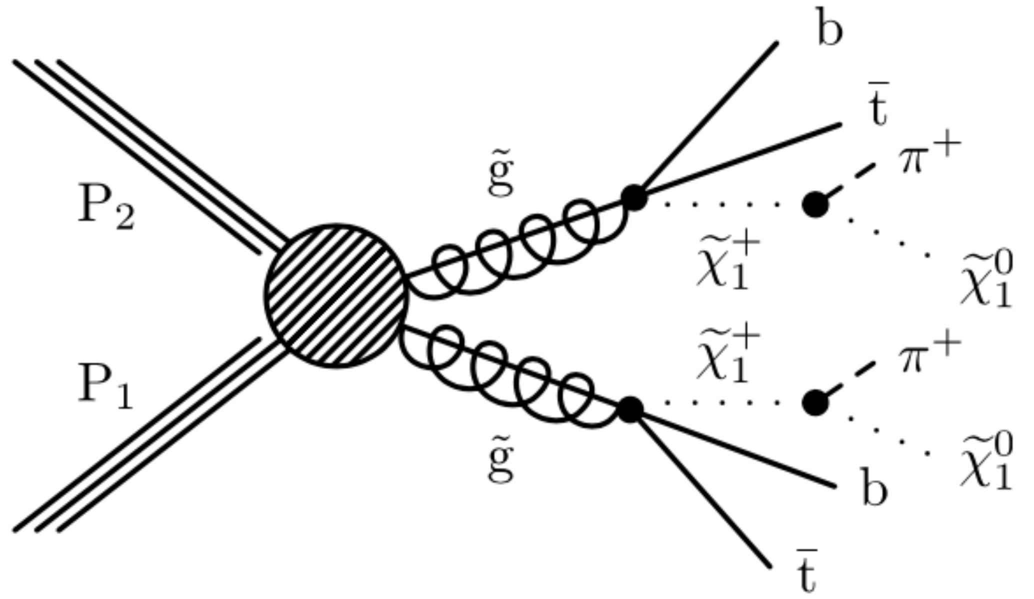
limit reaches up to $m_{\tilde{t}} \lessapprox$ 1.6 TeV / $m_{\tilde{\chi}_1^0} \lessapprox$ 1.4 TeV ($c\tau$ = 200 cm):



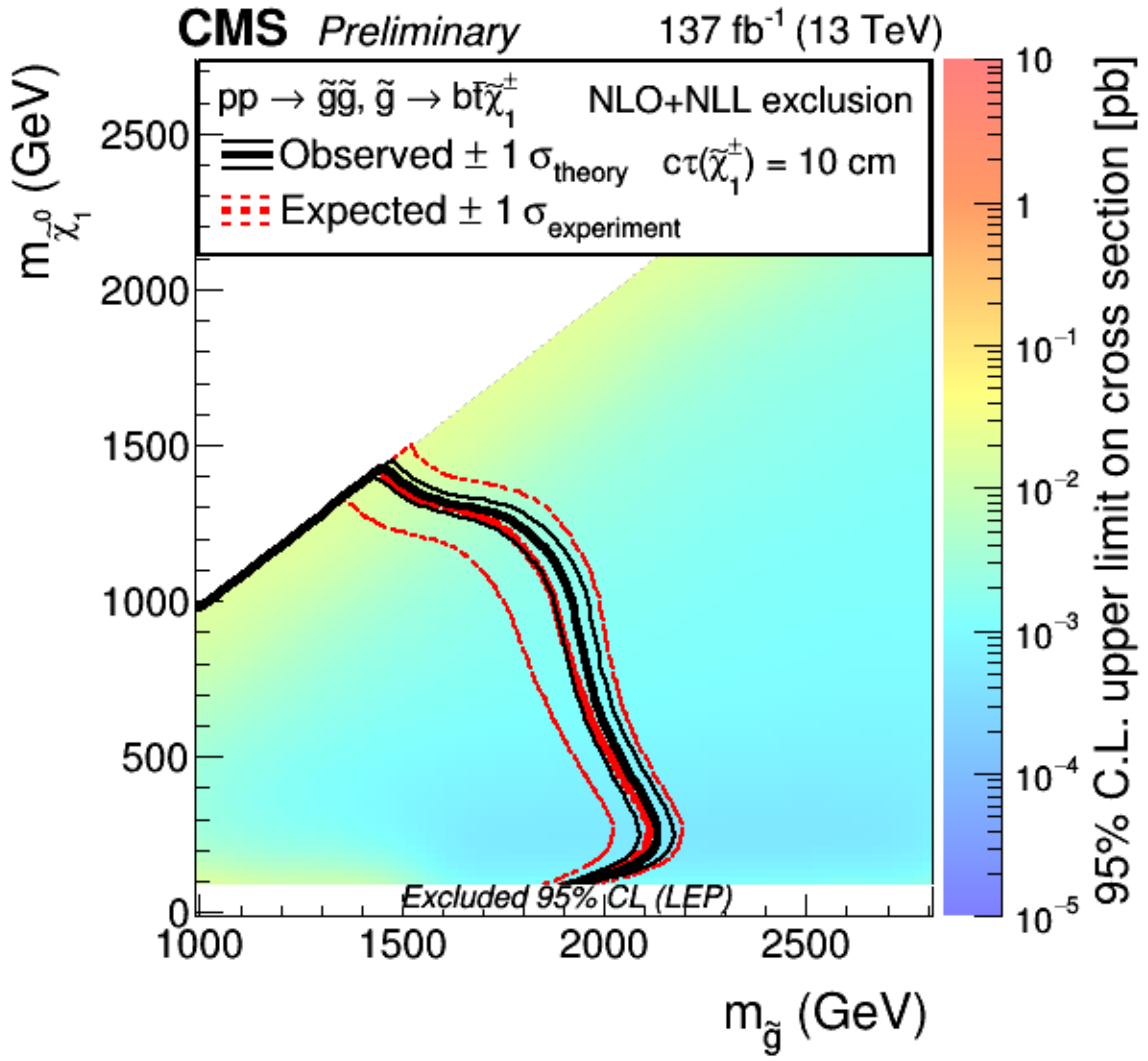


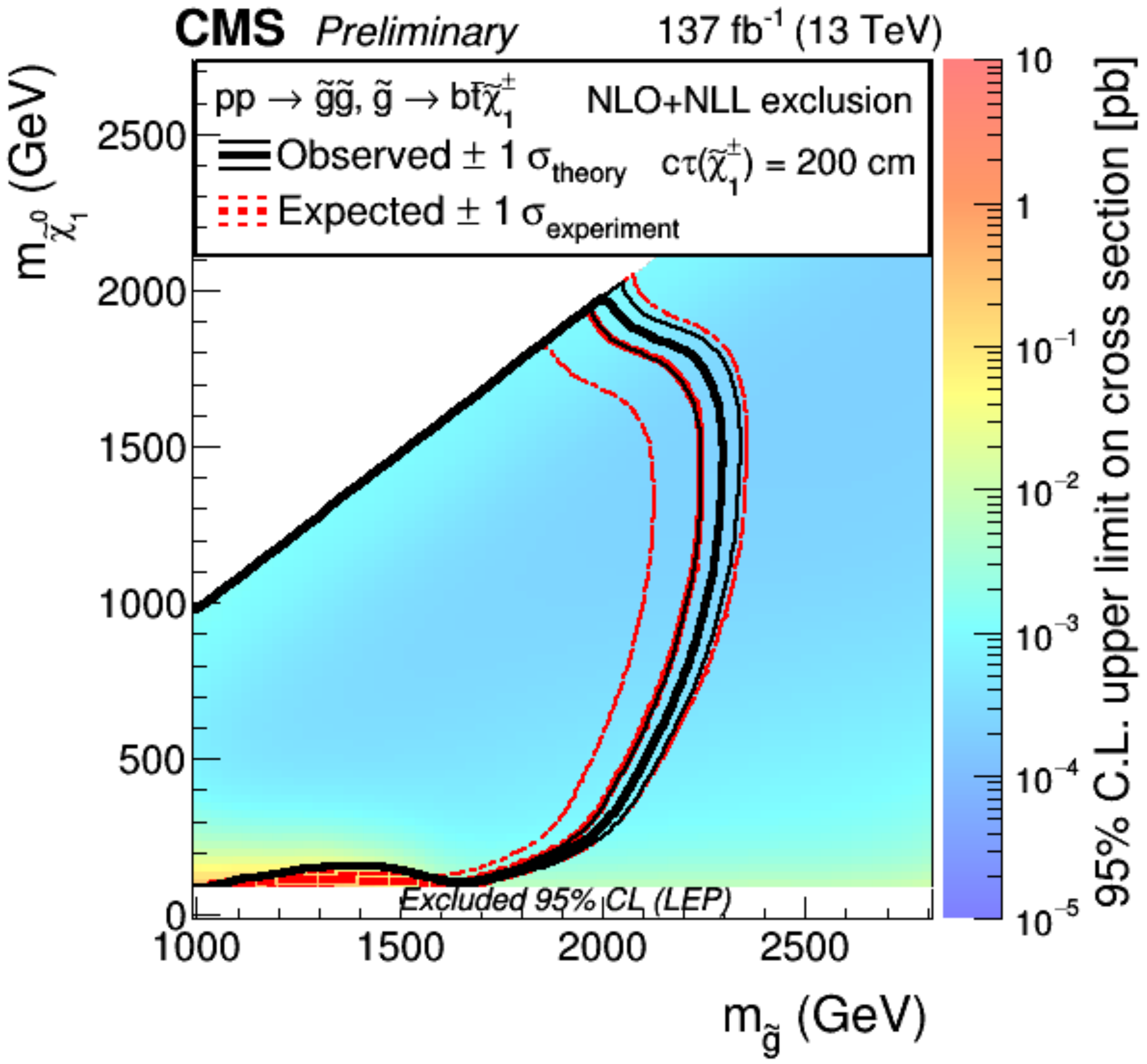


Interpretation: $pp \to \tilde{g}\tilde{g}, \tilde{g} \to bt\tilde{\chi}_1^{\pm}$

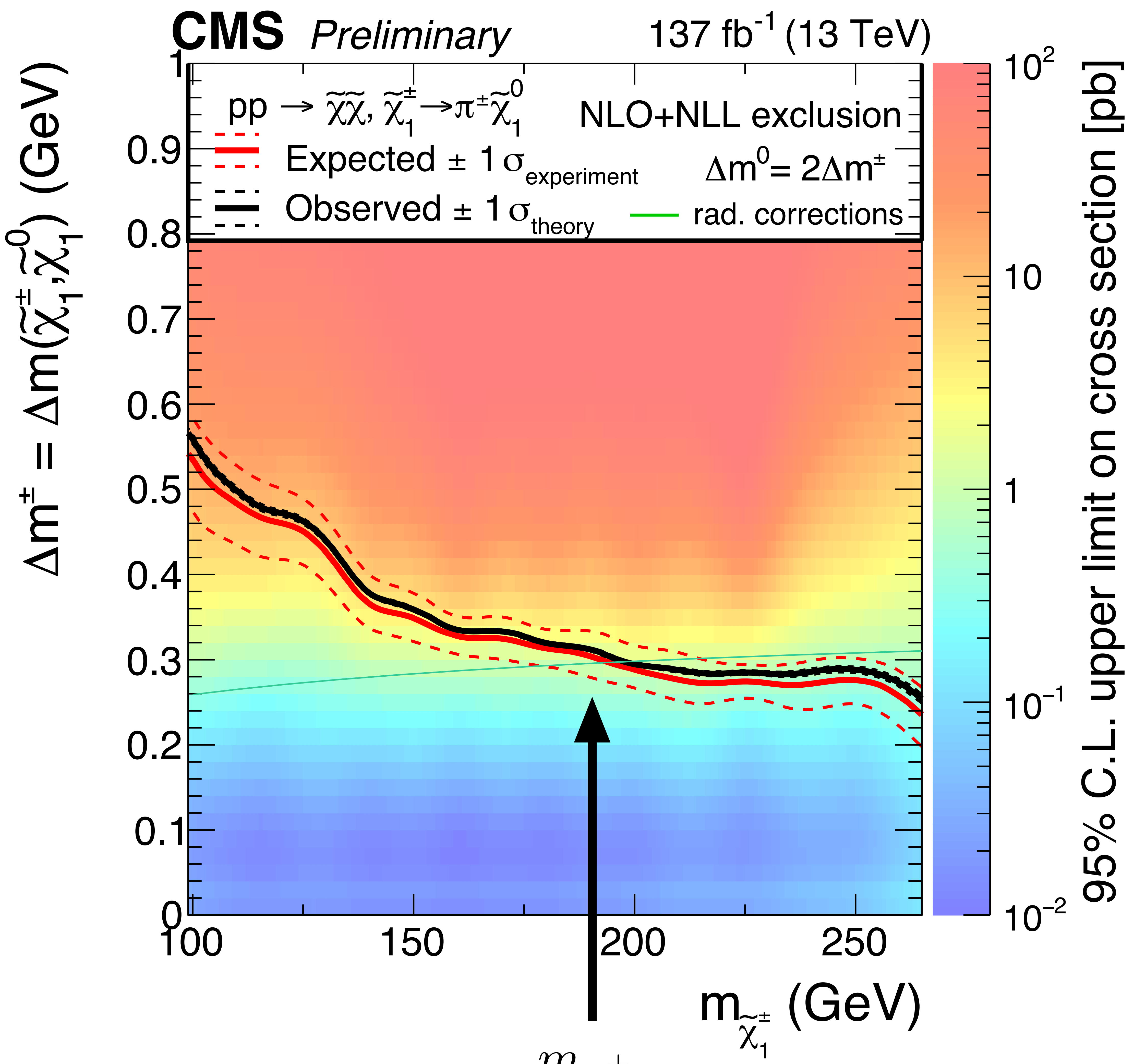


limit reaches up to $m_{\tilde{g}} \lessapprox$ 2.3 TeV / $m_{\tilde{\chi}_1^0} \lessapprox$ 2.0 TeV ($c\tau$ = 200 cm):





Interpretation: higgsino model



can exclude up to $m_{\tilde{\chi}_1^{\pm}} \lessapprox 180$ GeV

Model name	Description	Decays
T2btLL	Top squark-associated $\tilde{\chi}_1^{\pm}$ production	$\tilde{t} \to t\tilde{\chi}_1^0, \tilde{t} \to b\tilde{\chi}_1^{\pm}$
T2tbLL	Bottom squark-associated $\tilde{\chi}_1^{\pm}$ production	$\tilde{b} \to b\tilde{\chi}_1^0, \tilde{b} \to t\tilde{\chi}_1^{\pm}$
T5btbtLL	Gluino-associated $\tilde{\chi}_1^{\pm}$ production	$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0, t\bar{t}\tilde{\chi}_1^0, t\bar{b}\tilde{\chi}_1^-, \bar{t}b\tilde{\chi}_1^+$
TChiWZ		$\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\pi^{\pm}$
TChiWW	Models with a nearly pure higgsino LSP	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\pi^{\pm}, \tilde{\chi}_1^{\mp} \to \tilde{\chi}_1^0\pi^{\mp}$
TChiZ		$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0\pi^*, \tilde{\chi}_1^0$

- higgsino model: MSSM DM candidate with direct EWKino production
  - see Nagata, Shirai arXiv:1410.4549v2; Fukuda, Shirai et al. arXiv:1910.08065
- $\Delta m^{\pm} = \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
- cross sections σ: fully-degenerate higgsino production
- green: minimum $\Delta m^{\pm}$ allowed by radiative corrections assuming pure Higgsino model points

ADL & reinterpretation

- ADL: Analysis Description Language
  - declarative domain specific language for describing physics algorithms
  - decoupled from analysis software frameworks
  - esp. useful for analysis design, use and preservation
- we are working to provide the full information in ADL format soon
  - available for public use
  - provide ADLs for actual CMS data tiers (AOD/TreeMaker) and Delphes
  - allows analysis to be fully preserved
- reinterpretation
  - intending to provide DTk tagging efficiencies vs. transverse decay length
  - checking dependence on p_T and different signal models
  - other suggestions?

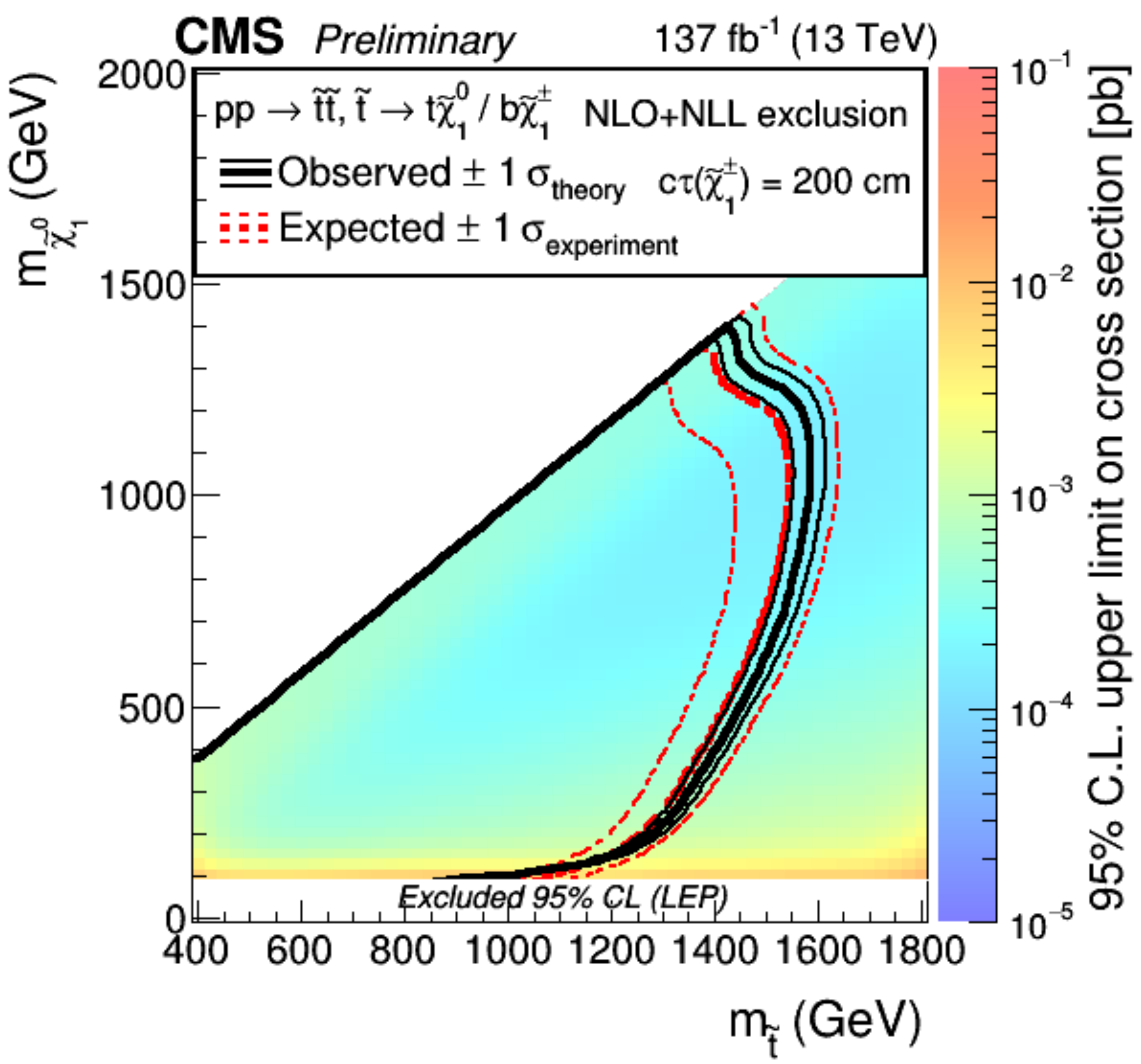
cern.ch/adl

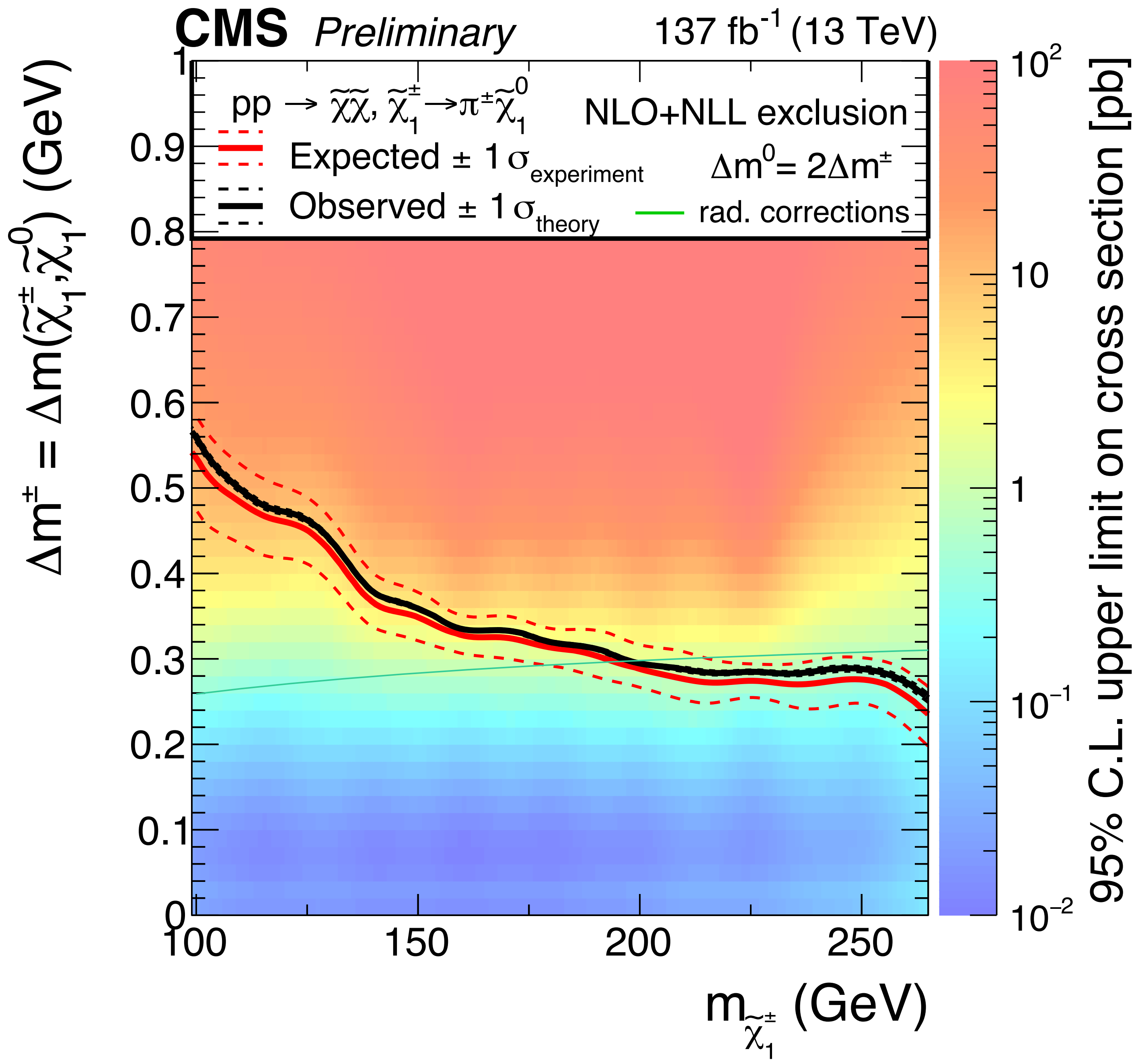
```
# OBJECTS

# Leptons
object electrons
  take electron
  select pt > 40
  select abs(eta) < 2.4
  select passIso == 1
  select tightID == 1

object muons
  take muon
  select pt > 40
  select abs(eta) < 2.4
  select passIso == 1
  select mediumID == 1

...
```

ADL documented in arxiv:1605.02684, arxiv:2203.09886, arxiv:2101.09031

Search for long-lived SUSY with disappearing tracks

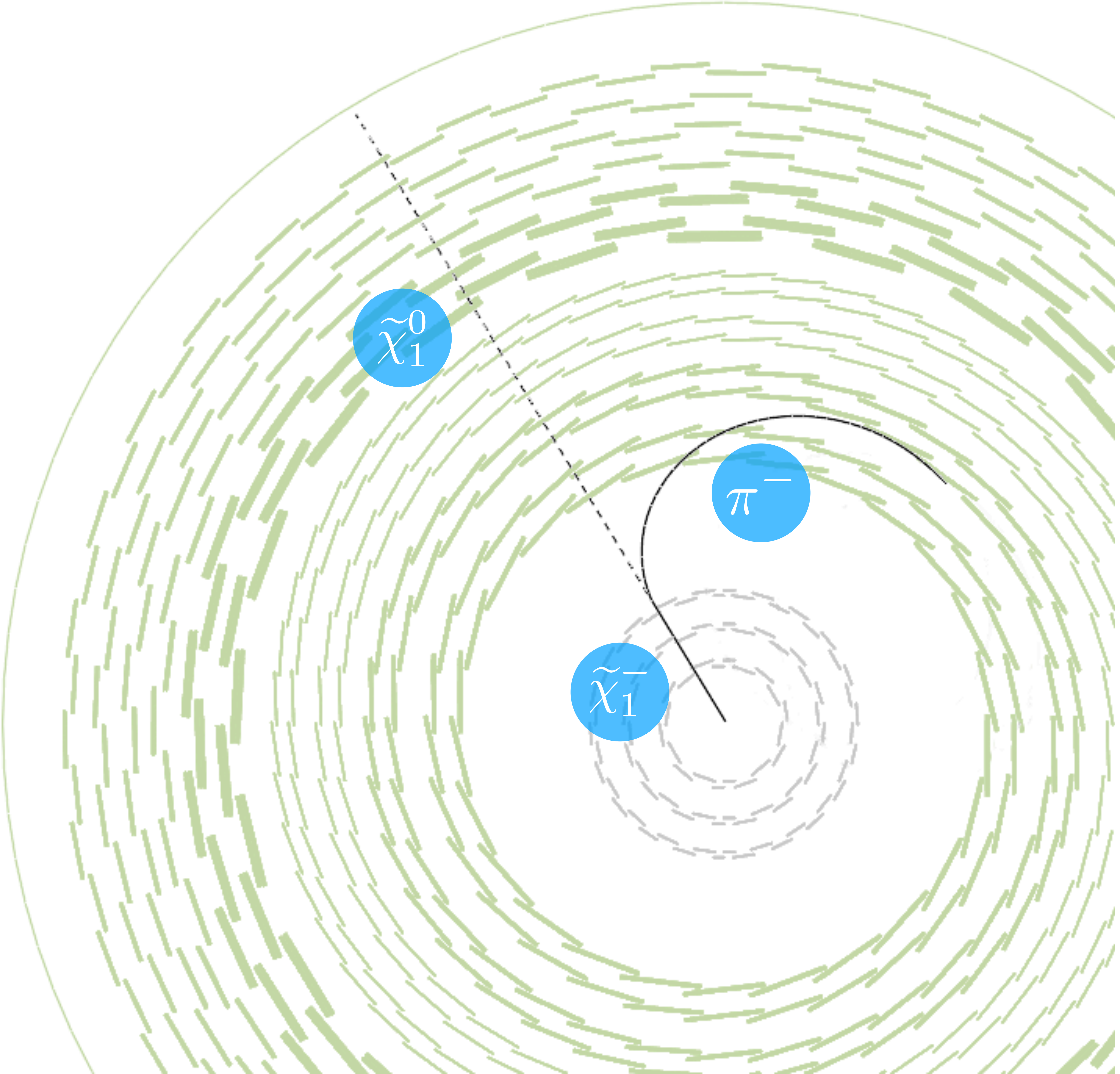
- search for long-lived SUSY with disappearing tracks
  - targeting pure wino / higgsino dark matter
- first analysis with
  - e/μ + disappearing track(s) in final states
  - BDT in disappearing track tag
  - usage of dE/dx in disappearing track SR binning
- no clear indication of a positive signal
- we will provide the full information in ADL format soon for full preservation of analysis
- for reinterpretation purposes, we intend to provide disappearing track tagging efficiencies vs. transverse decay length





Thank you for your attention!

Backup



Event selection

- require
  - at least one DTk
  - $N_{jet} \geq 1$ (ak4PFjets with $p_T > 30$ GeV, $|\eta| < 2.4$)
  - hard $p_T^{miss} = |-\sum_{i=1}^{\text{PF jets}, \; p_T > 30 \text{ GeV}, |\eta| < 5.0} \vec{p}_{T,i}|$
  - standard event cleaning, MET filters
- search bins defined by
  - hard p_T^{miss}, n_{jet}
  - $n_{b\text{-}tag}$ (deepCSV medium WP)
  - track length: short and long tracks
  - dE/dx „harmonic2“ esimator:

$$I_h = \left(\frac{1}{N}\sum(\Delta E/\Delta x)_i^{-2}\right)^{-1/2}$$

Hadronic channel ($N_{DTk} = 1, N_\mu = 0, N_e = 0$)						
hard p_T^{miss} range	$N_{b\text{-jet}}$	N_{jet}	N_{short}	N_{long}	dE/dx	SR
150–300 GeV	0	[1,3)	0	1	L	1
					H	2
			1	0	L	3
					H	4
		≥3	0	1	L	5
					H	6
			1	0	L	7
					H	8
	≥1	[1,3)	0	1	L	9
					H	10
			1	0	L	11
					H	12
		≥3	0	1	L	13
					H	14
			1	0	L	15
					H	16
>300 GeV	Any	[1,3)	0	1	L	17
					H	18
			1	0	L	19
					H	20
		≥3	0	1	L	21
					H	22
			1	0	L	23
					H	24

Muon channel ($N_{DTk} = 1, N_\mu \geq 1, N_e = 0$)						
hard p_T^{miss} range	$N_{b\text{-jet}}$	N_{jet}	N_{short}	N_{long}	dE/dx	SR
30–100 GeV	0	≥1	0	1	L	25
					H	26
			1	0	L	27
					H	28
	≥1		0	1	L	29
					H	30
			1	0	L	31
					H	32
>300 GeV	Any		0	1	L	33
					H	34
			1	0	L	35
					H	36
Electron channel ($N_{DTk} = 1, N_e \geq 1$)						
30–300 GeV	0	≥1	0	1	L	37
					H	38
			1	0	L	39
					H	40
	≥1		0	1	L	41
					H	42
			1	0	L	43
					H	44
>300 GeV	Any		0	1	L	45
					H	46
			1	0	L	47
					H	48
$N_{DTk} \geq 2$ channel						
>30 GeV	Any	≥1	Any			49

bin dE/dx in:

- low (L) dE/dx<4.0 MeV/cm
- high (H) dE/dx≥4.0 MeV/cm

Track selection in signal and control regions

- list of cuts defining tracks in signal and various control regions:

Phase/category	Phase 0/short	Phase 0/long	Phase 1/short	Phase 1/long
BDT for SR samples	>0.1	>0.12	>0.15	>0.08
E_{dep} for SR samples [GeV]	$<15\,\text{GeV}$	$<0.2p$	$<15\,\text{GeV}$	$<0.2p$
E_{dep} for CR^{real} samples [GeV]	$[30, 300]\,\text{GeV}$	$[0.3, 1.2]p$	$[30, 300]\,\text{GeV}$	$[0.3, 1.2]p$
BDT for CR^{real} samples	>0.1	>0.05	>0.05	>0.08
BDT for CR^{fake} samples	$[-0.1, -0.05]$	$[-0.1, 0.0]$	$[-0.1, 0.05]$	$[-0.1, 0.0]$

Phase 1 pixel detector upgrade