SUSY in ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

28 August 2024

Corfu 2024 : Workshop on the Standard Model and Beyond

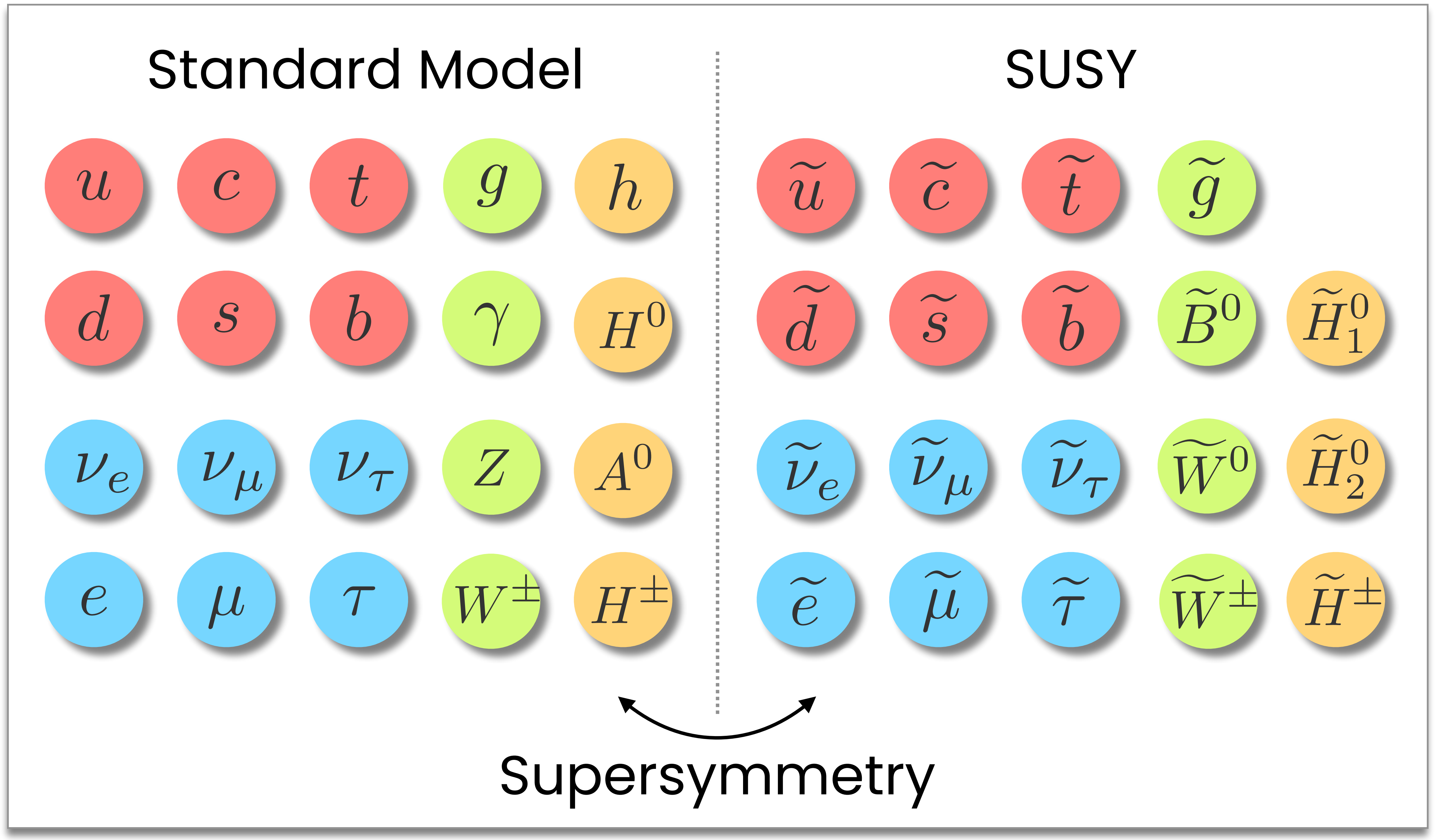
Supersymmetry

Supersymmetry : SUSY

- Symmetry between bosons and fermions
- Introduce superpartners for each SM particle

Minimal SUSY Standard Model : MSSM

- Minimal extension of the SM ➡ one superpartner for each SM particle and two Higgs doublets



Motivation of SUSY

① Explains observed Higgs mass near the electroweak scale ➡ **Hierarchy problem**

② Unifies coupling constants at high-energy scales ➡ **Grand unification**

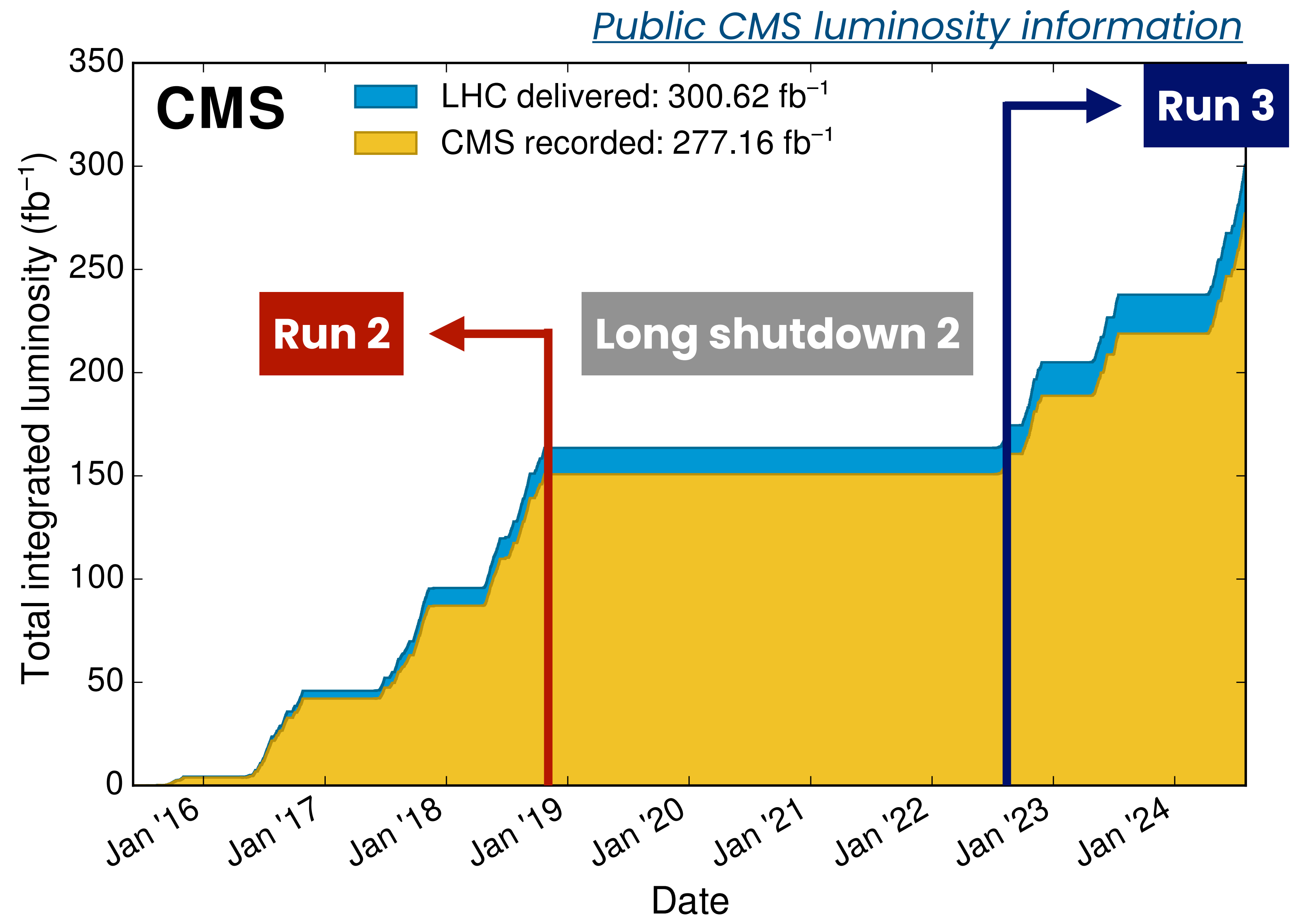
③ Lightest SUSY Particle (LSP) becomes a good dark matter candidate ➡ **Dark matter**

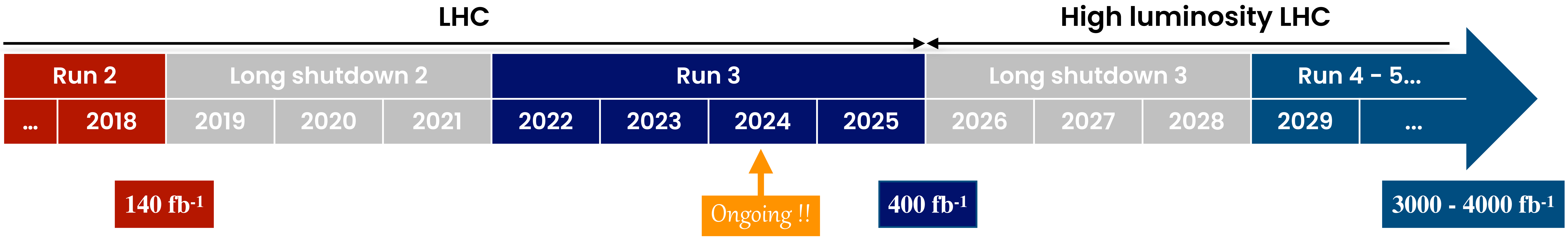
Large Hadron Collider

Large Hadron Collider : LHC

- Proton-proton collider with a circumference of 27 km
- **LHC Run 2 period (2015 – 2018)** operated with a center-of-mass energy of **13 TeV**
- **LHC Run 3 period (2022 – 2025)** has started in 2022, increasing the center-of-mass energy to **13.6 TeV**

Cumulative delivered and recorded luminosity

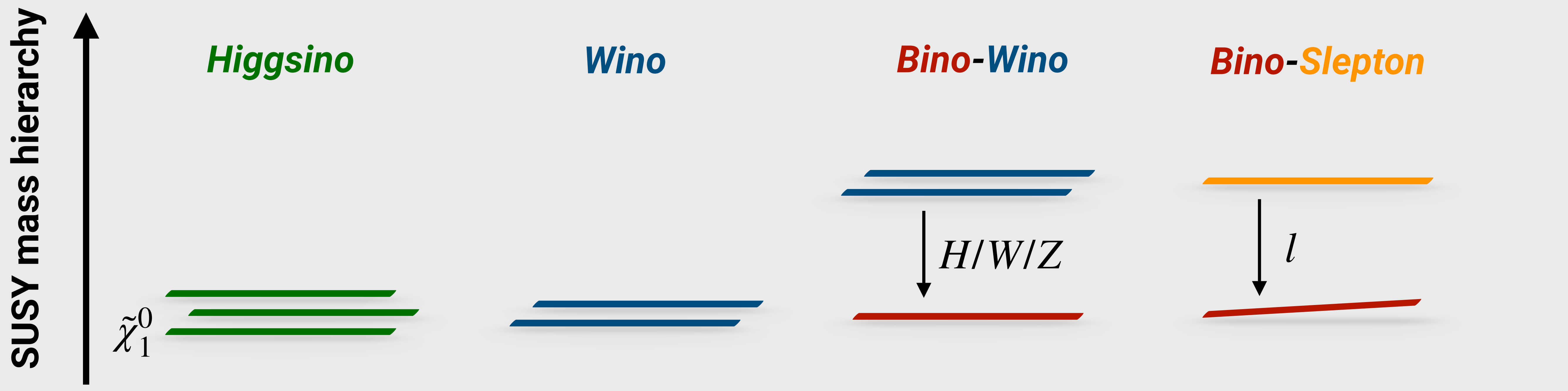


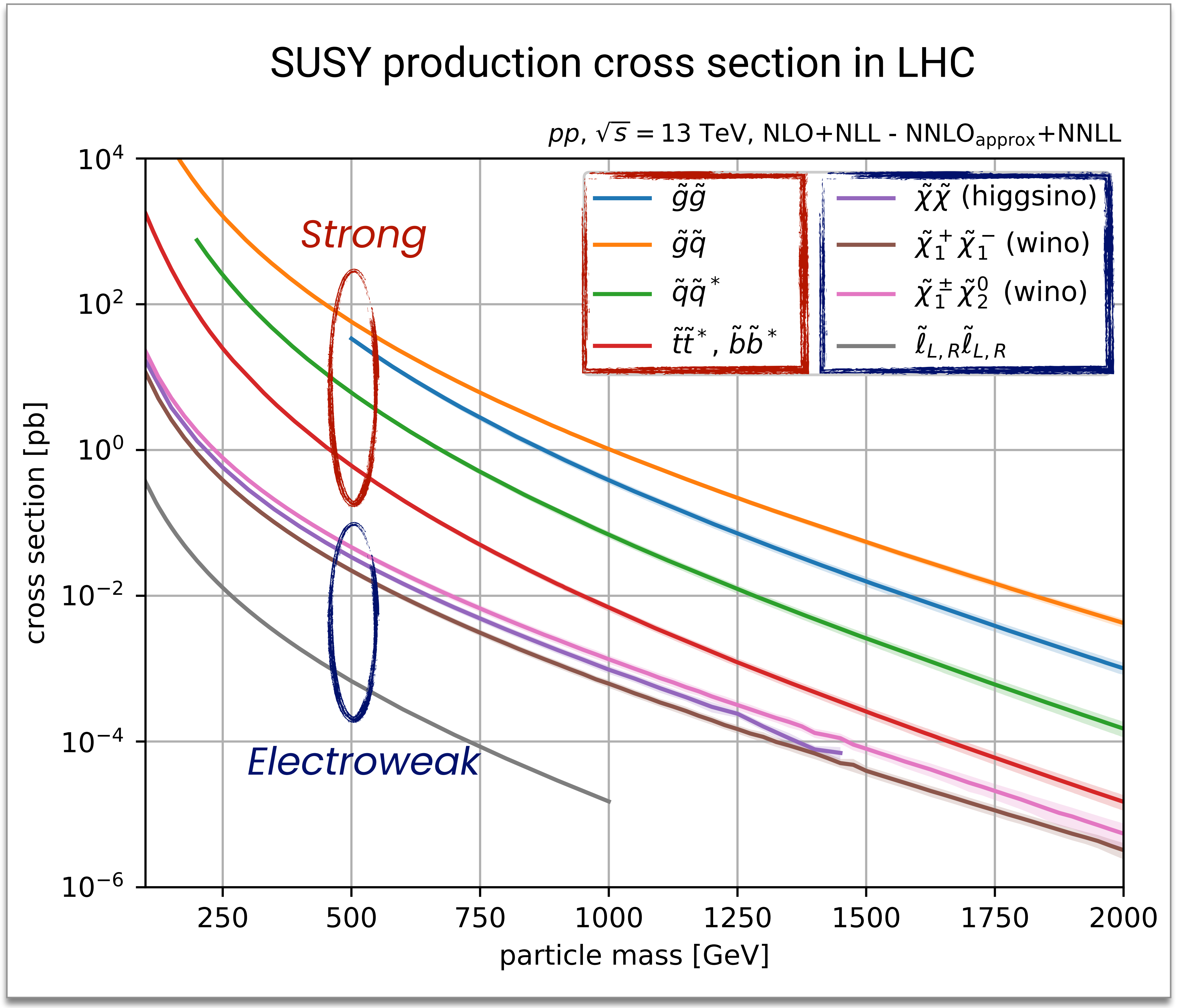


SUSY Searches in LHC

- **Strong production** & **Electroweak production** in LHC
  - *Large cross section*
  - *Energetic jet activities*
  - *Small cross section*
  - *Small mass splitting ➡ soft objects*

- **Different search strategies depending on mass spectra**
  - Various mass hierarchies predicted from
    - *Naturalness, dark matter, SUSY breaking model etc.*

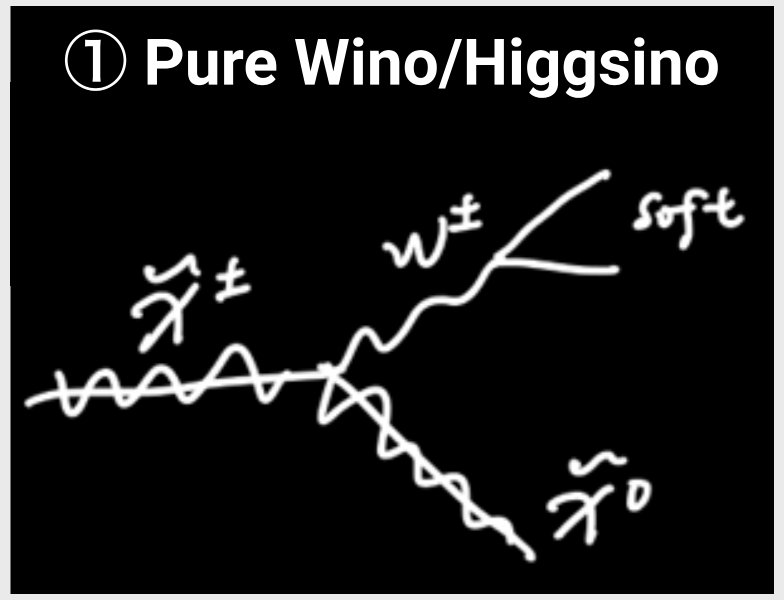


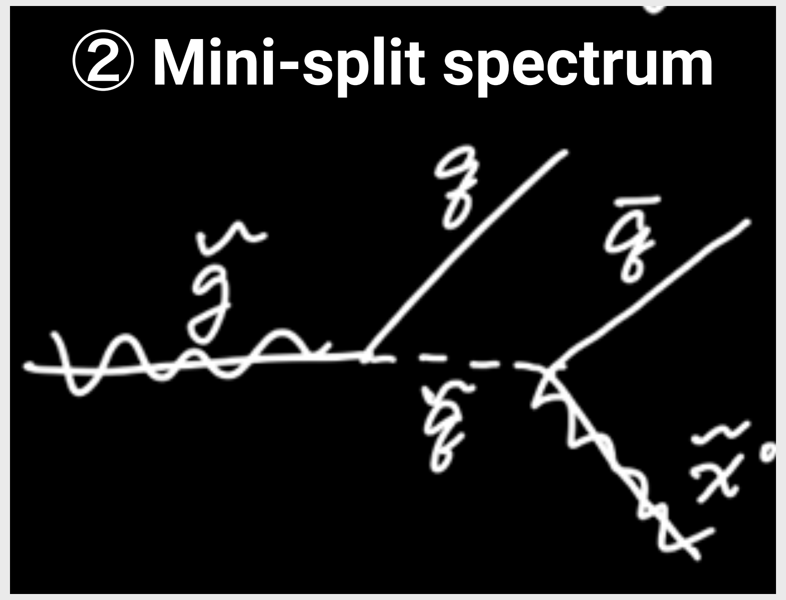


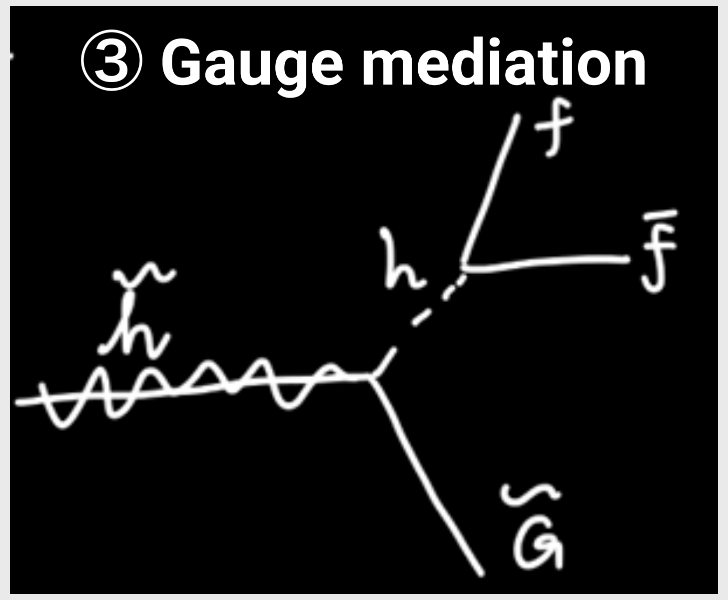
Broad program of searches targetting different production modes & final states

Long Lived Particles

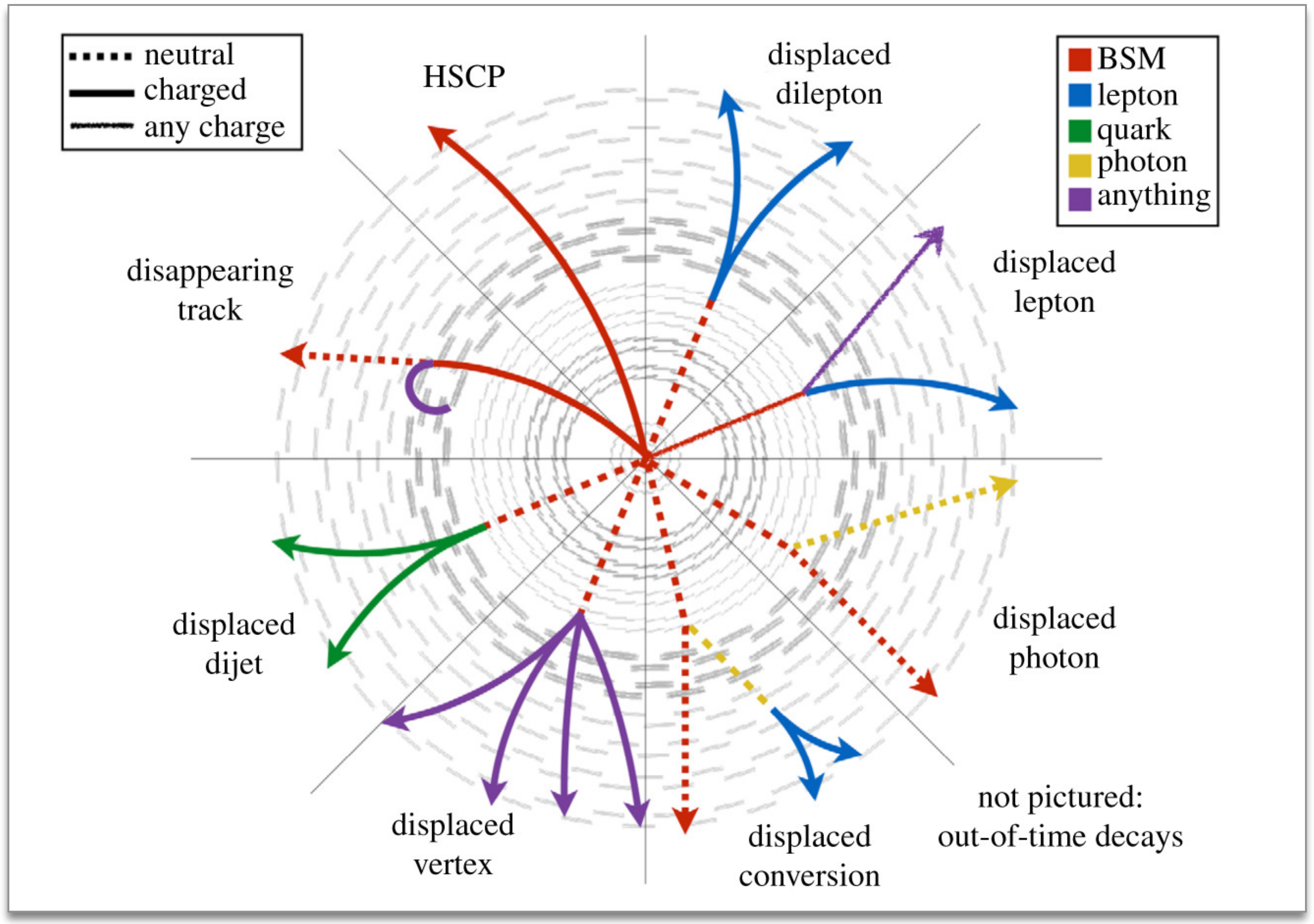
- Many BSM theories predict new particles with long lifetime due to
  - ① Limited decay phase space
  - ② Highly virtual intermediate states
  - ③ Small couplings







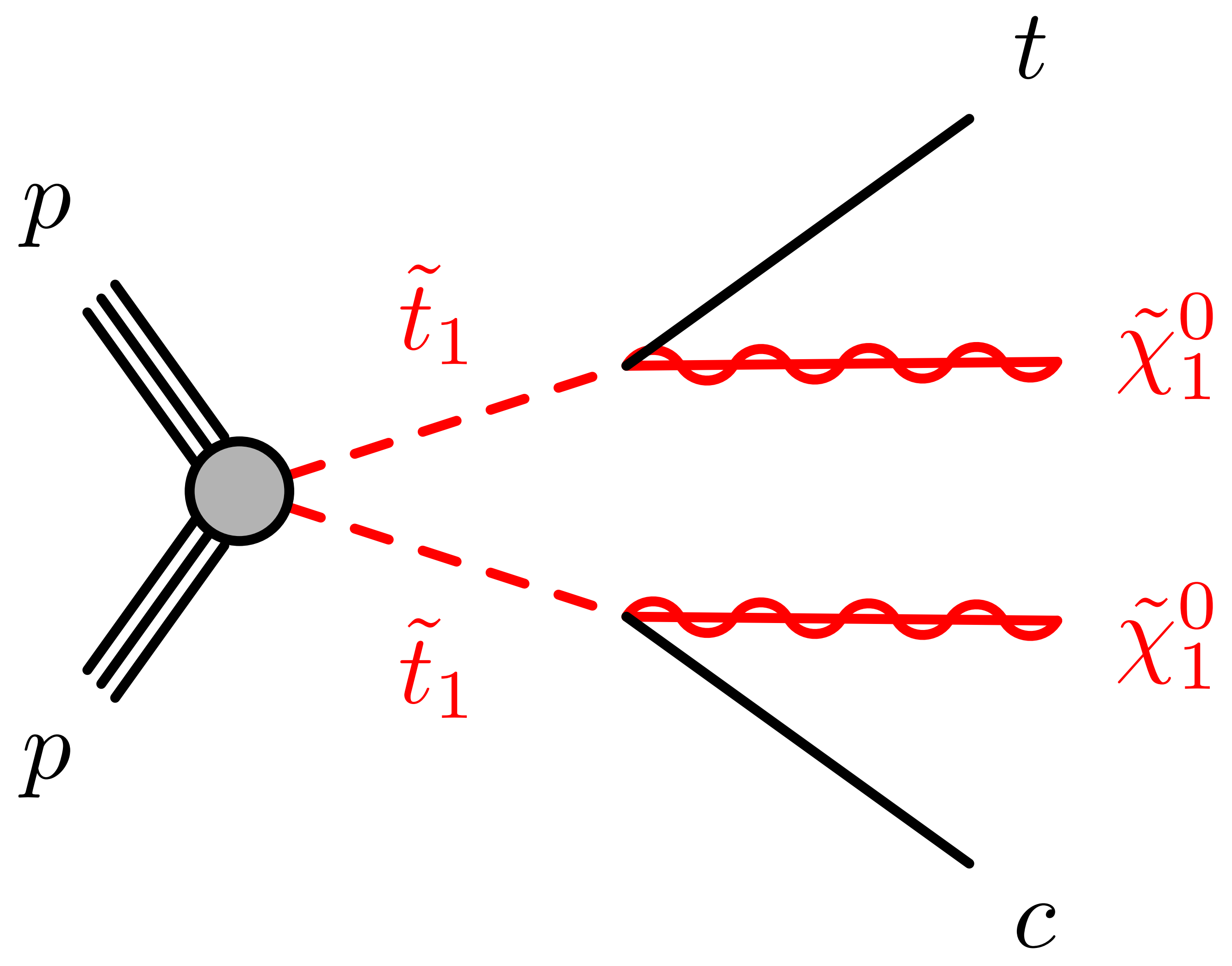
- Long-lived particles produce unconventional signatures, which are extremely challenging
  - *MC simulations not accurate*
  - *Dedicated triggers are required*
  - *Require special reconstruction methods*
  - *Unusual backgrounds*



STRONG PRODUCTION

Stop to Top/Charm + Missing Transverse Momentum

- Naturalness arguments favour light stops ($\tilde{t}_L, \tilde{t}_R \Rightarrow \underline{\tilde{t}_1, \tilde{t}_2}$)
  mass eigenstate
- Non-minimal flavour violation extension of the MSSM considered
  - **$\tilde{t}_1$ can decay into a top or charm quark ($\tilde{t}_1 \to c\,\tilde{\chi}_1^0$ / $t\,\tilde{\chi}_1^0$)**
  - Consider decays with on-shell top quarks ($\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \geq 175$ GeV)



- Common event selection : **top-tagged large-R jets, b- or charm-tagged jets, large E_T^{miss}**
- **First exploration of signature with top- and charm-jets**
  - Analysis-specific charm-tagging algorithm ($DL1r_c$) developed based on b-tagging algorithm (DL1r)

b-tagging working point

b-jet efficiency	*c-jet misidentification*	*light-jet misidentification*
77%	*20%*	*0.9%*

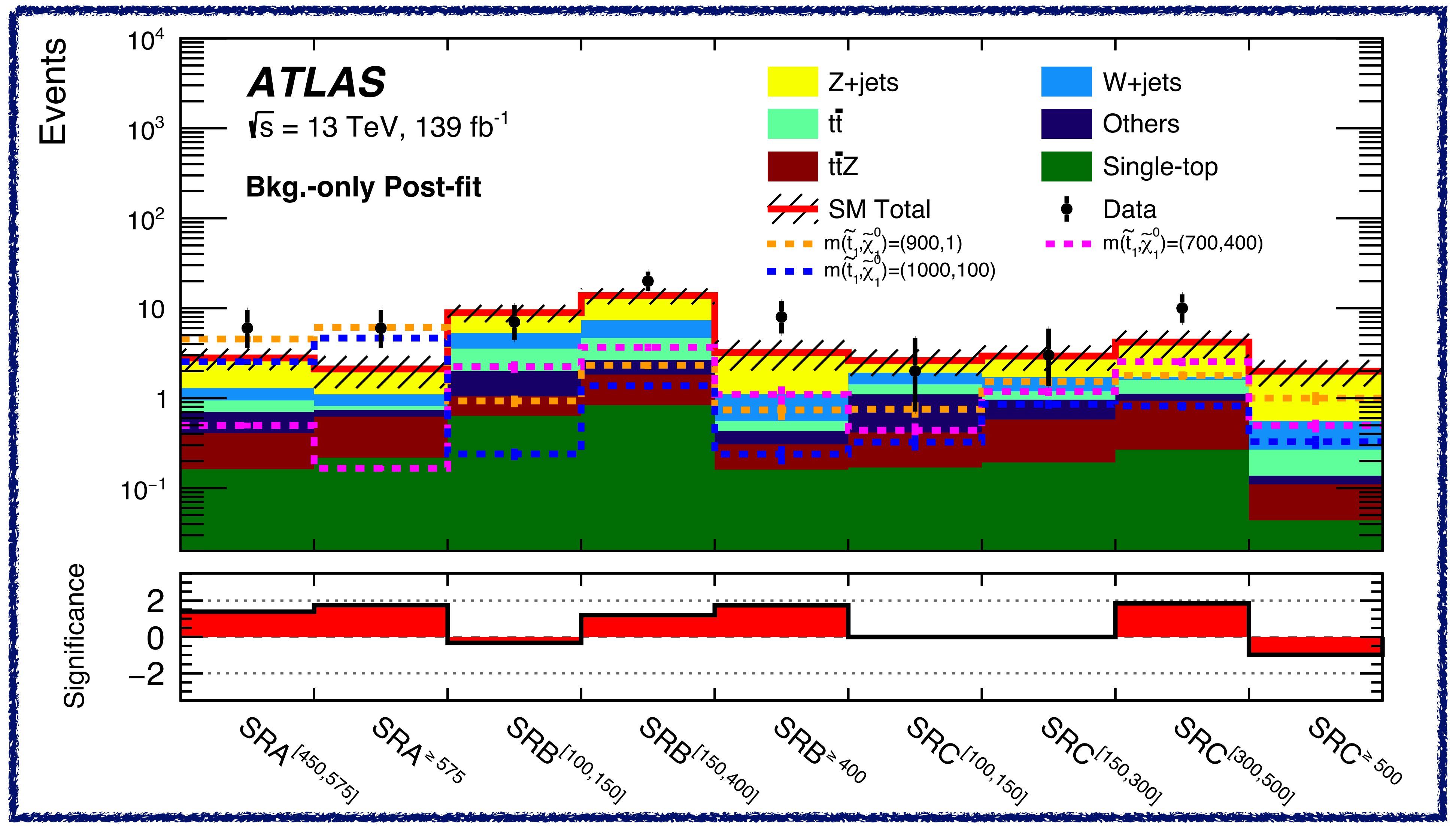
c-tagging working point

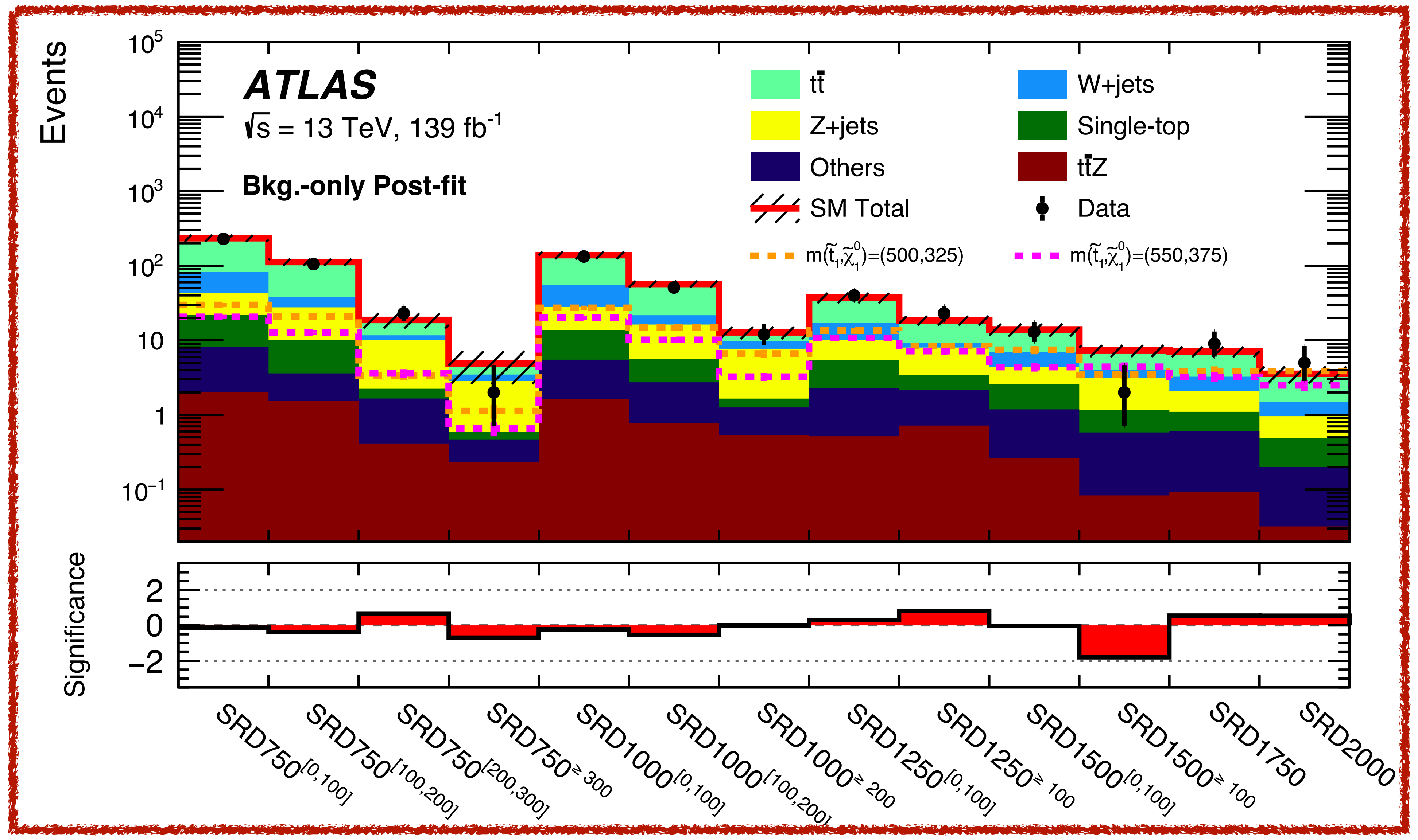
c-jet efficiency	*b-jet rejection*	*light-jet rejection*
20%	*29*	*57*

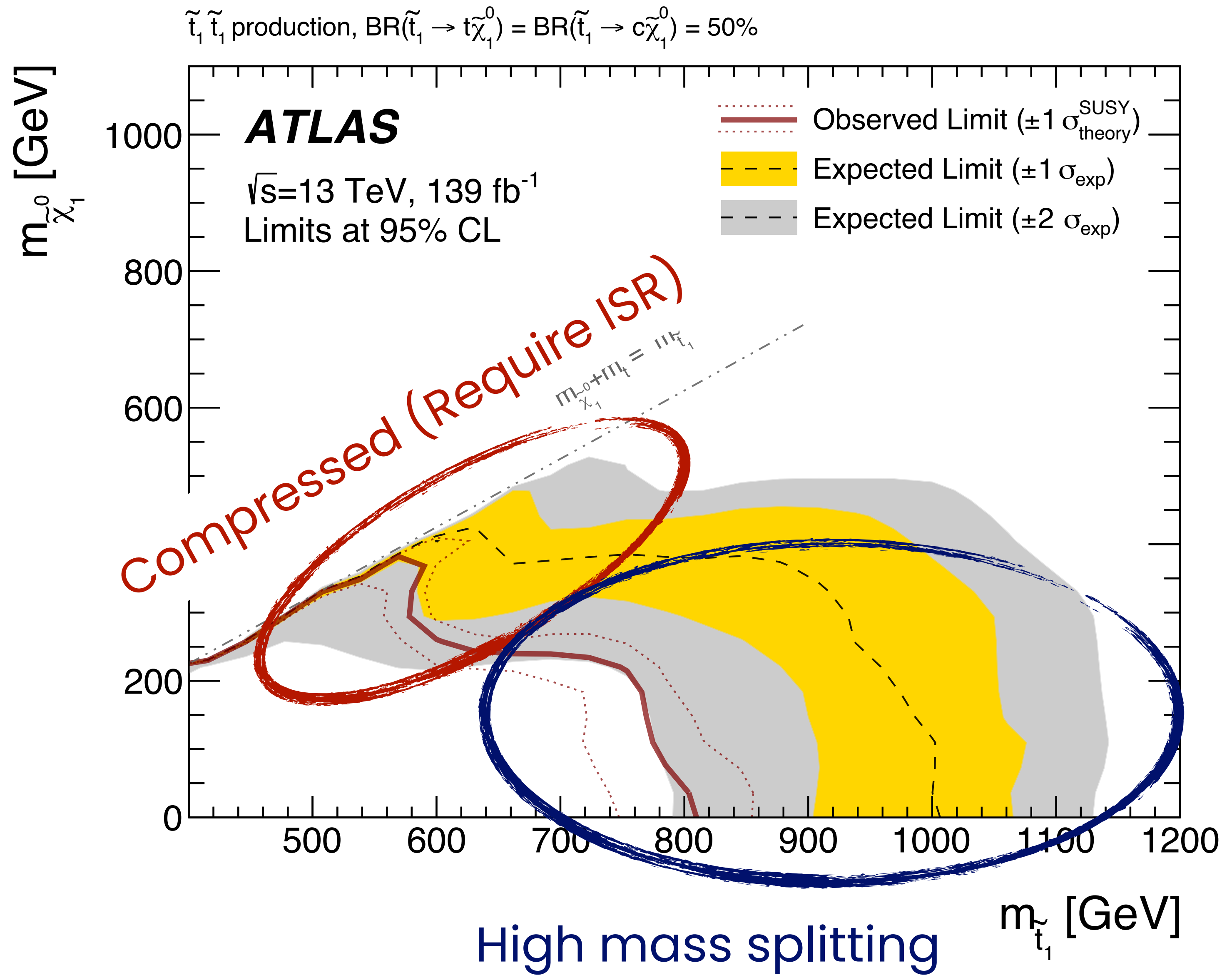
Stop to Top/Charm + Missing Transverse Momentum

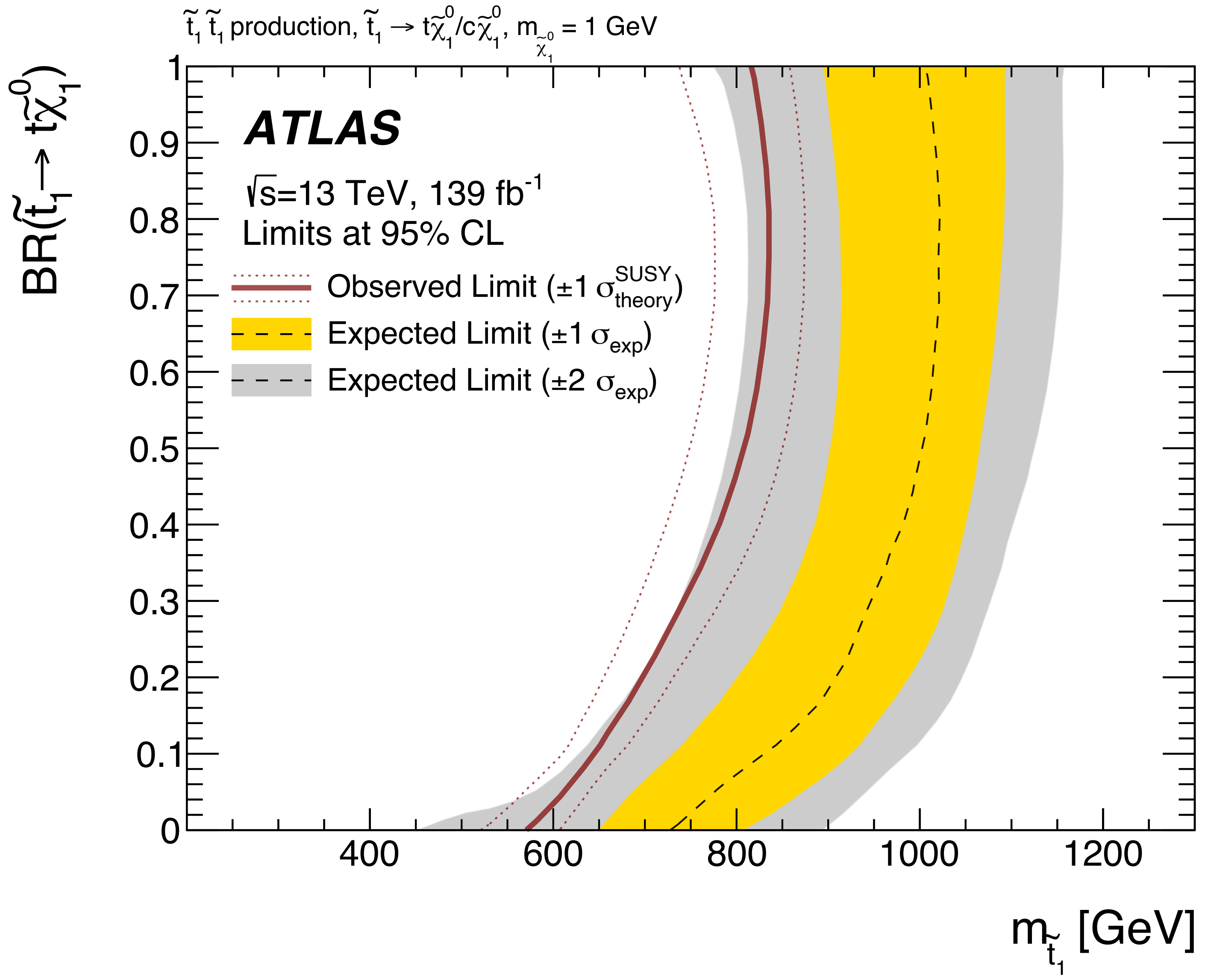
[JHEP 07 (2024) 250]

- SRs targetting **high mass splitting** (**compressed**) regime, observe excesses/deficits but all within 2σ
- Stop mass excluded up to
  - **800 GeV in high mass splitting regime**
  - **600 GeV in compressed regime**







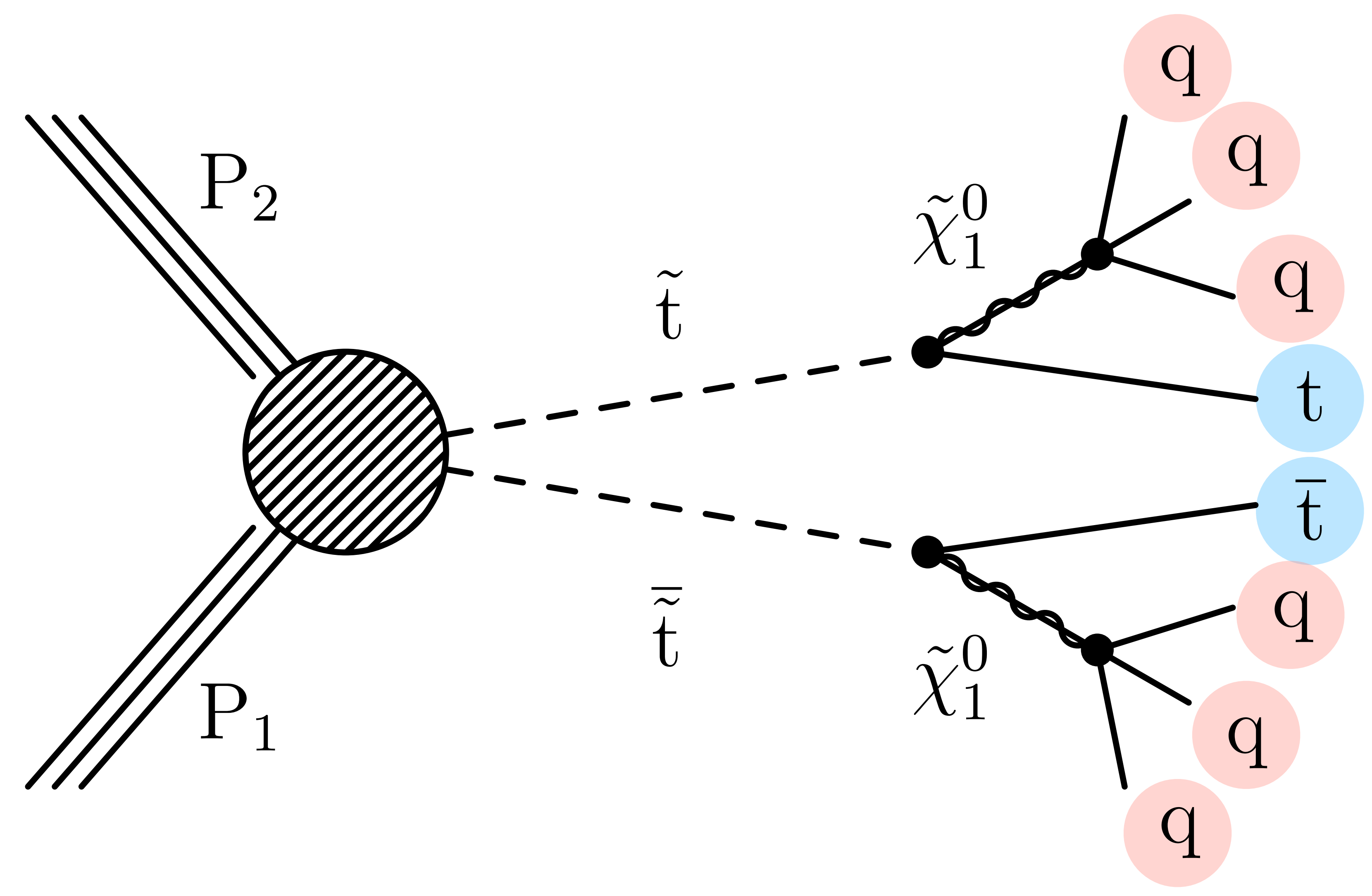


Stop Search with many Light Flavor Jets and Leptons

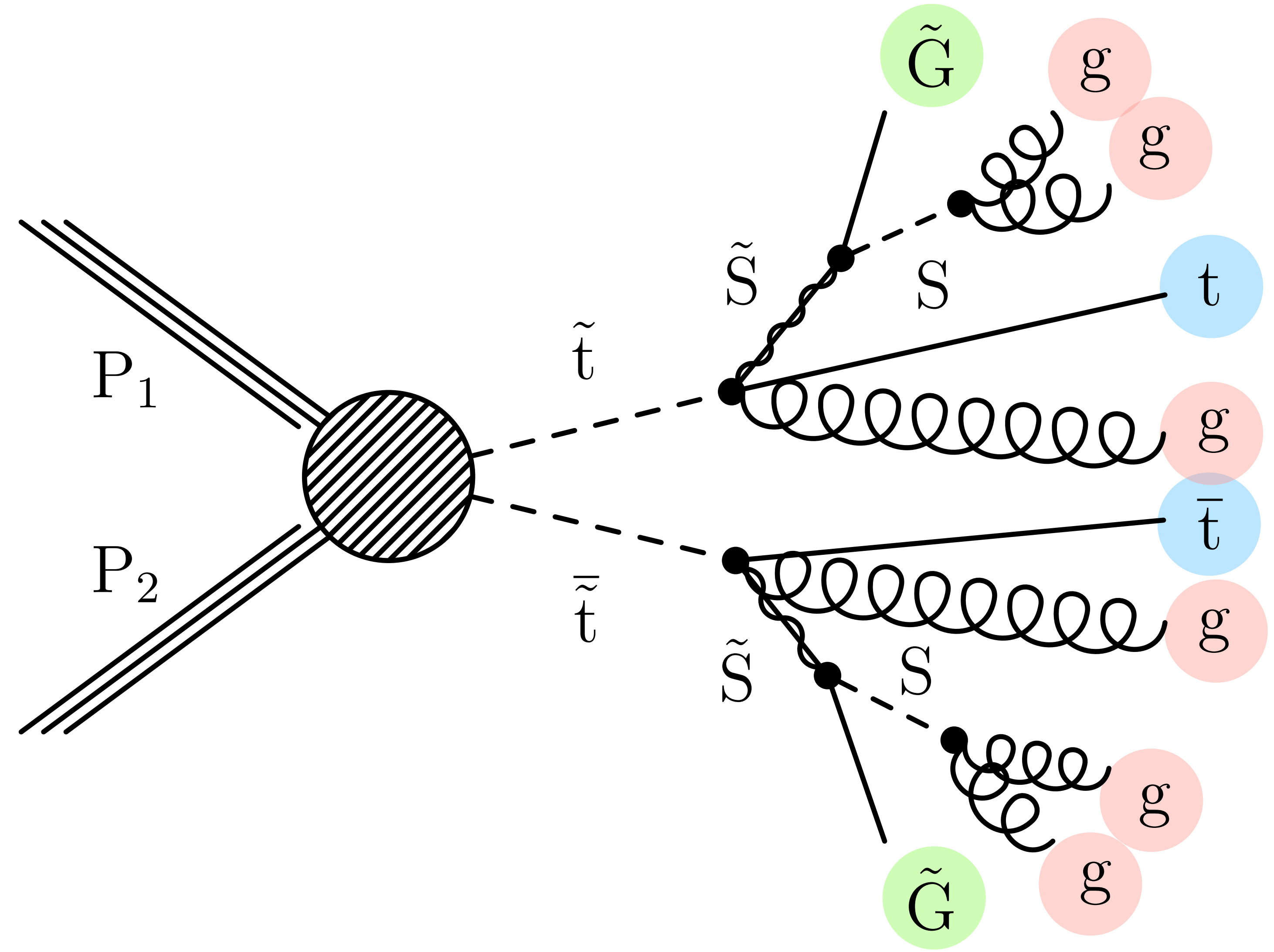
CMS-PAS-SUS-23-001

- Search for stop production in R-parity violating (RPV) and Stealth SUSY (SYY) models
  - **SYY : Hidden sector with mass degenerate scalar particle (S) and its superpartner ($\tilde{S}$)**
  - **RPV : Lightest SUSY particle allowed to decay to SM particles (e.g. $\tilde{\chi}_1^0 \rightarrow uds$)**
  - ➡ These scenarios lead to final states ***without*** large missing transverse momentum

R-parity violating scenario



Stealth SUSY scenario



Light flavor jet

top quark (➡ lepton)

Gravitino (but very soft)

Stop Search with many Light Flavor Jets and Leptons

CMS-PAS-SUS-23-001

- Final state : 2 top quarks + multiiple jets ➡ **Main background : $t\bar{t}$ + jets**
  - Top quark pair production with jets from initial- and final-state radiation (ISR and FSR)
  - Estimated by a data-driven method (ABCDisCoTEC method)

Distance Correlation : statistical measure of nonlinear dependence

ABCDisCoTEC method

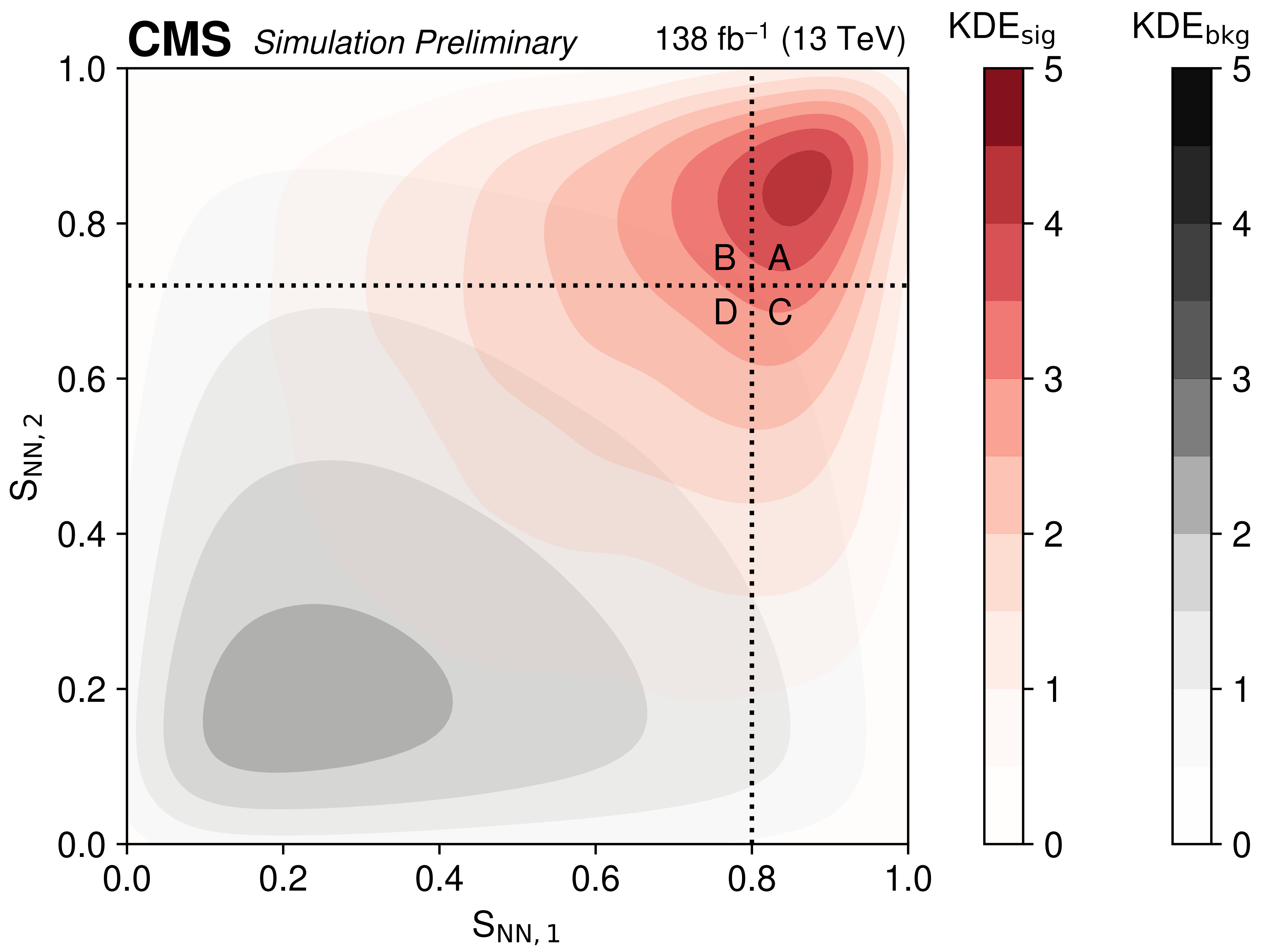
- ABCD method requires two independent variables
- Train two NNs with classifier loss term and

① Distance correlation loss term (DisCo)

② Non-closure loss term

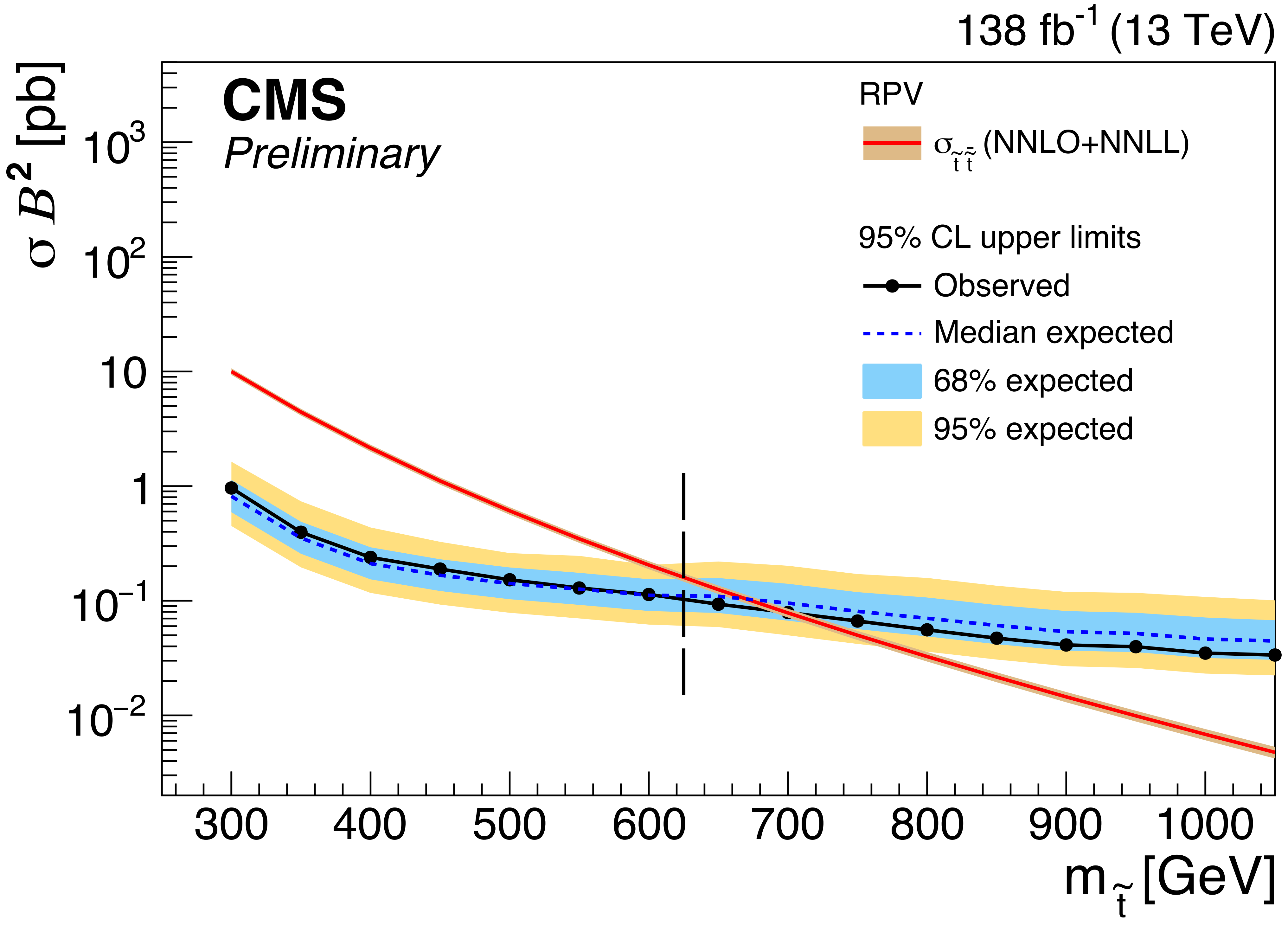
➡ **NN scores forced to be independent**

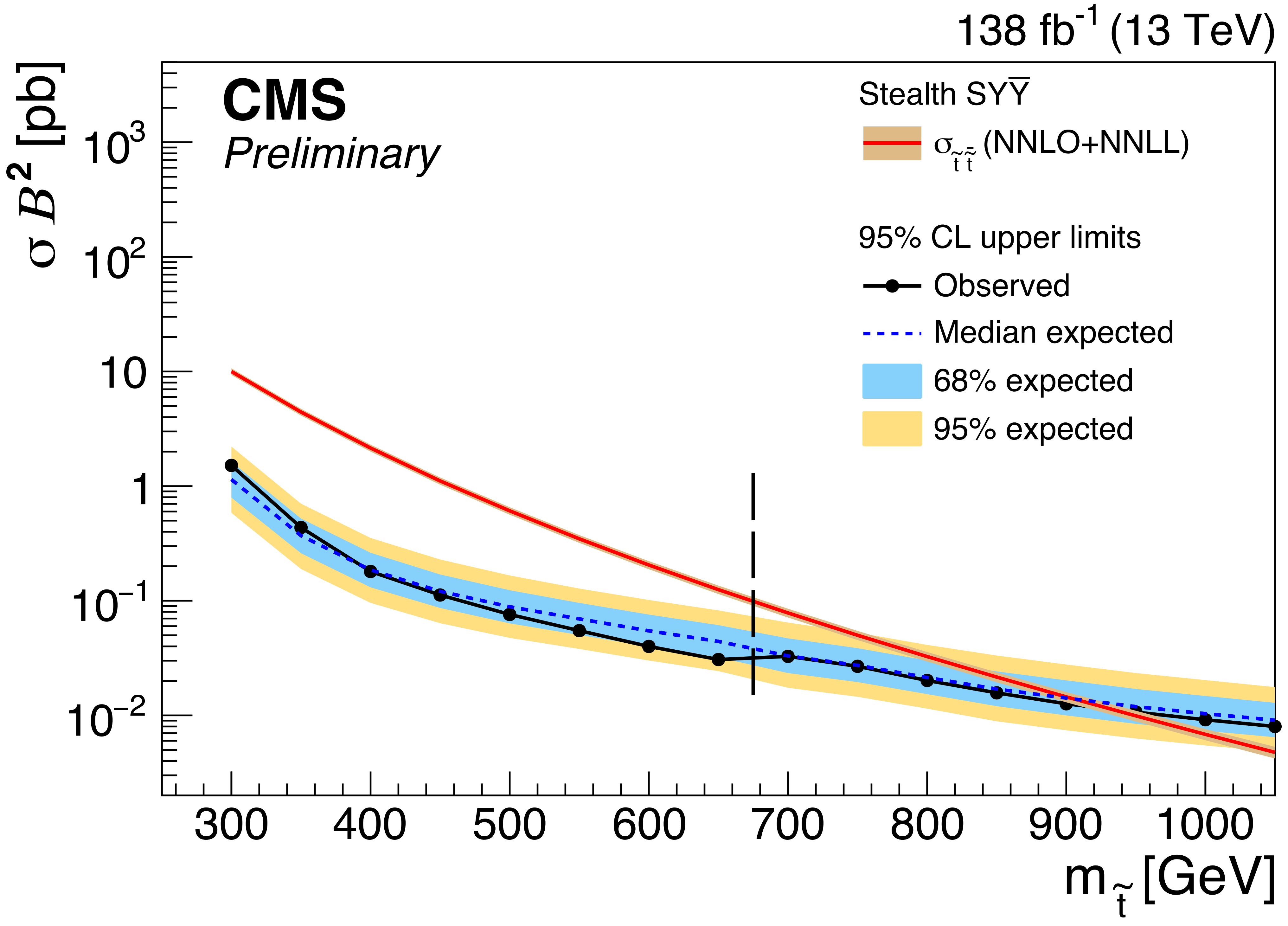
Distribution of output scores from two NNs ($S_{NN,1}$ & $S_{NN,2}$)



Stop Search with many Light Flavor Jets and Leptons

- Lower boundary of output scores ($S_{NN,1}$ & $S_{NN,2}$) optimized for low- and high-mass
- Good agreement between observed data and prediction by ABCDisCoTEC method
  - **Stop mass in RPV (SSY) model excluded up to 700 (930) GeV**





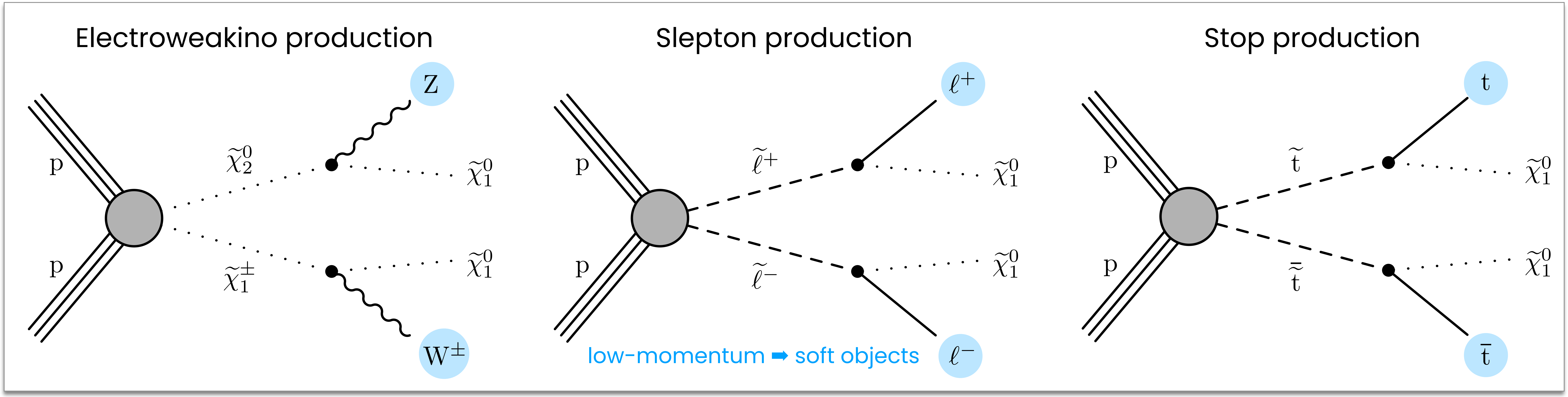
Vertical dashed line : Transition from low-mass optimization to high-mass optimization ABCD boundaries

ELECTROWEAK PRODUCTION

General Search for Compressed SUSY

CMS-PAS-SUS-23-003

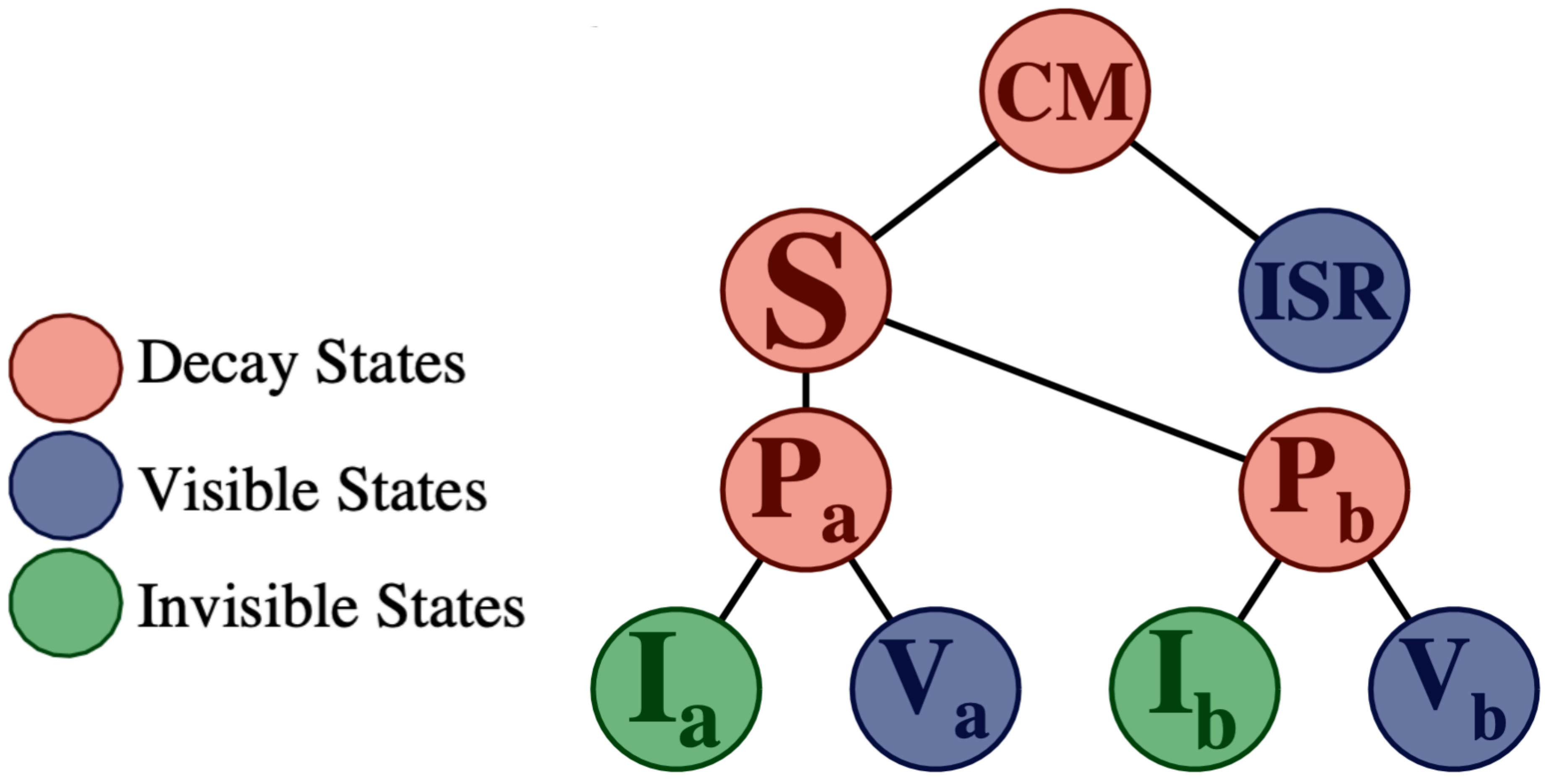
- *Compressed* mass spectra motivated by Bino coannihilation, nearly pure higgsino etc.
  - Small mass splitting leads to visible objects with low-momentum
- Strategy to search for a wide range of potential sparticle signatures
  - **Require ISR jet to boost SUSY system and require large E_T^{miss}**
  - **Categorize events by number of leptons, jets, b tags and kinematic variables**



General Search for Compressed SUSY

CMS-PAS-SUS-23-003

- Event kinematic variable reconstructed with **Recursive Jigsaw Reconstruction (RJR) algorithm**
  ① Impose a decay tree on the events
  ② Recursively iterate through rest frames
  ③ Specify four-vectors of each frame

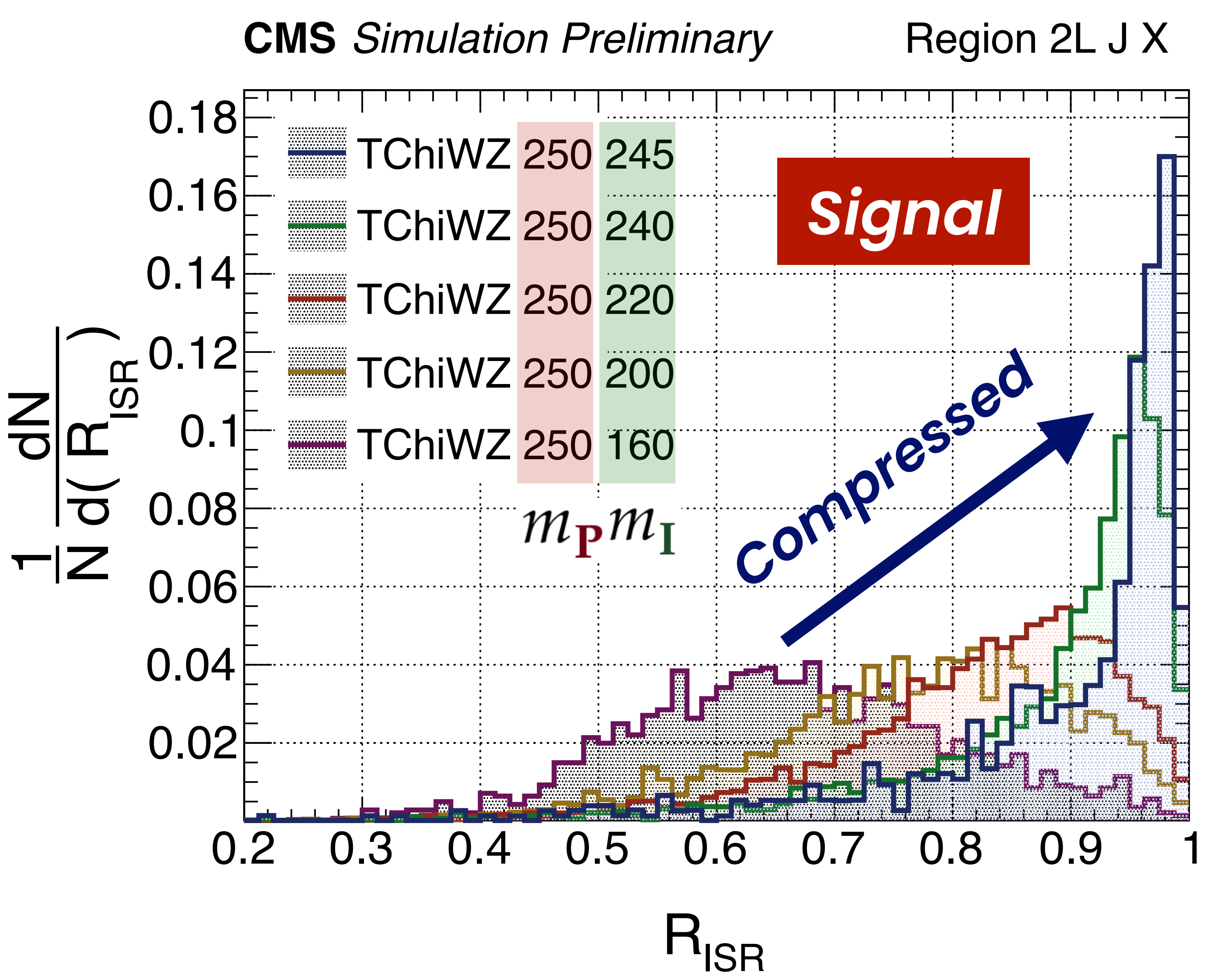


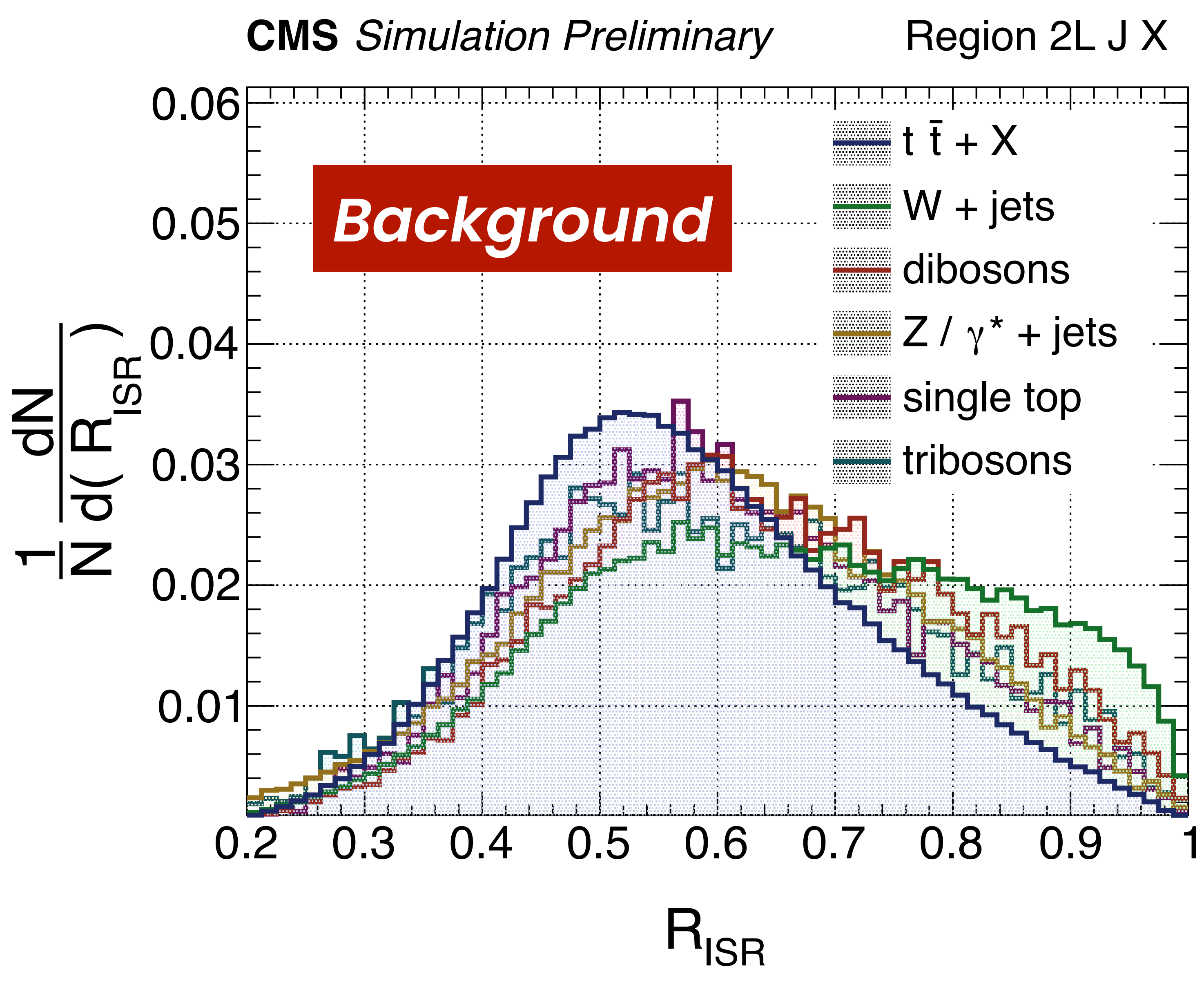
Example of RJR variable

$$R_{\mathrm{ISR}} = \frac{\left|\vec{p}_{\mathrm{I}}^{\,\mathrm{CM}} \cdot \hat{p}_{\mathrm{ISR}}^{\,\mathrm{CM}}\right|}{\left|\vec{p}_{\mathrm{ISR}}^{\,\mathrm{CM}}\right|} \sim \frac{m_{\mathrm{I}}}{m_{\mathrm{P}}}$$

If $m_{\mathrm{I}} \sim m_{\mathrm{P}}$, invisible particles receive out-sized momentum of the ISR kick

➡ **R_{ISR} sensitive to mass splitting**



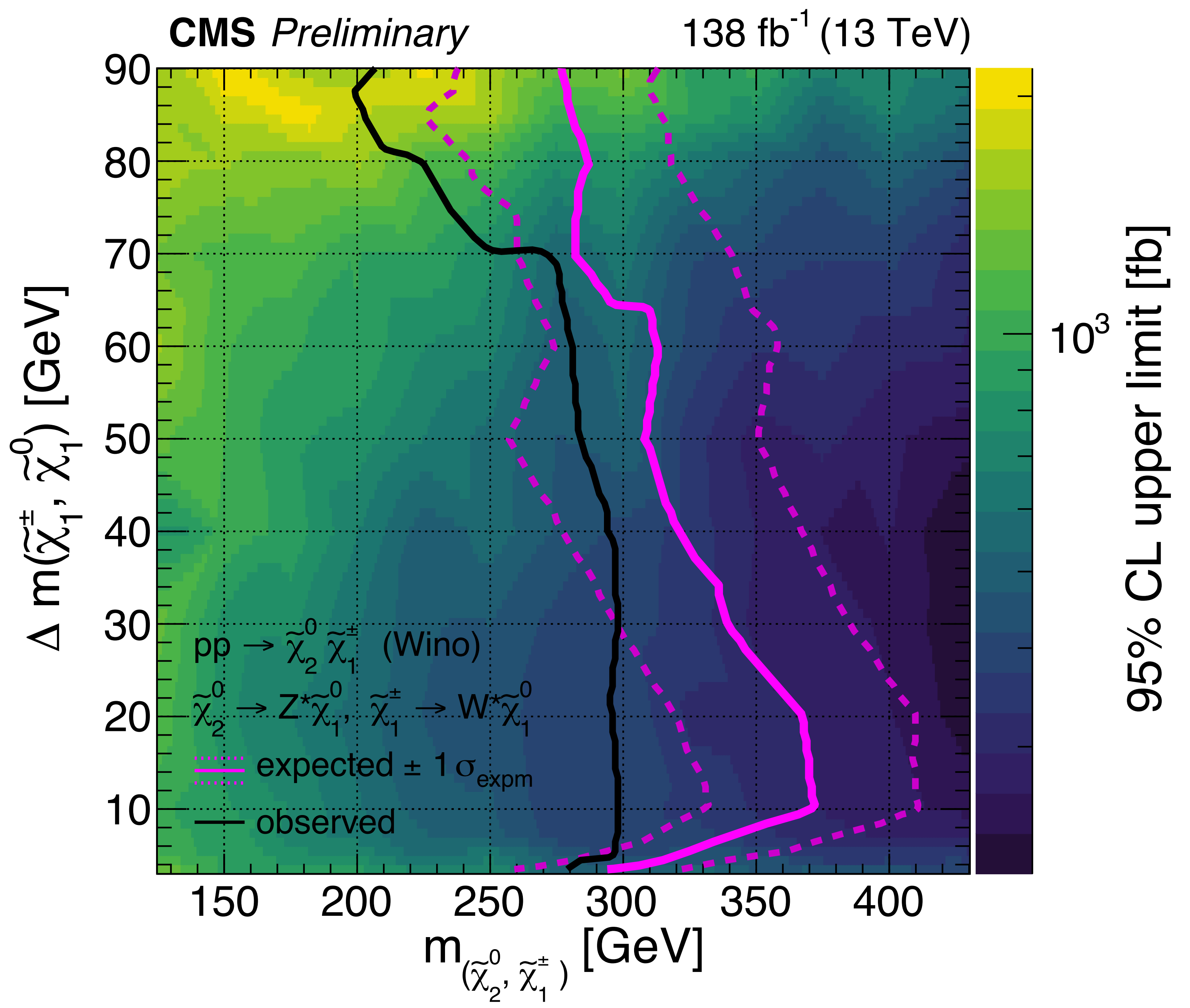


General Search for Compressed SUSY

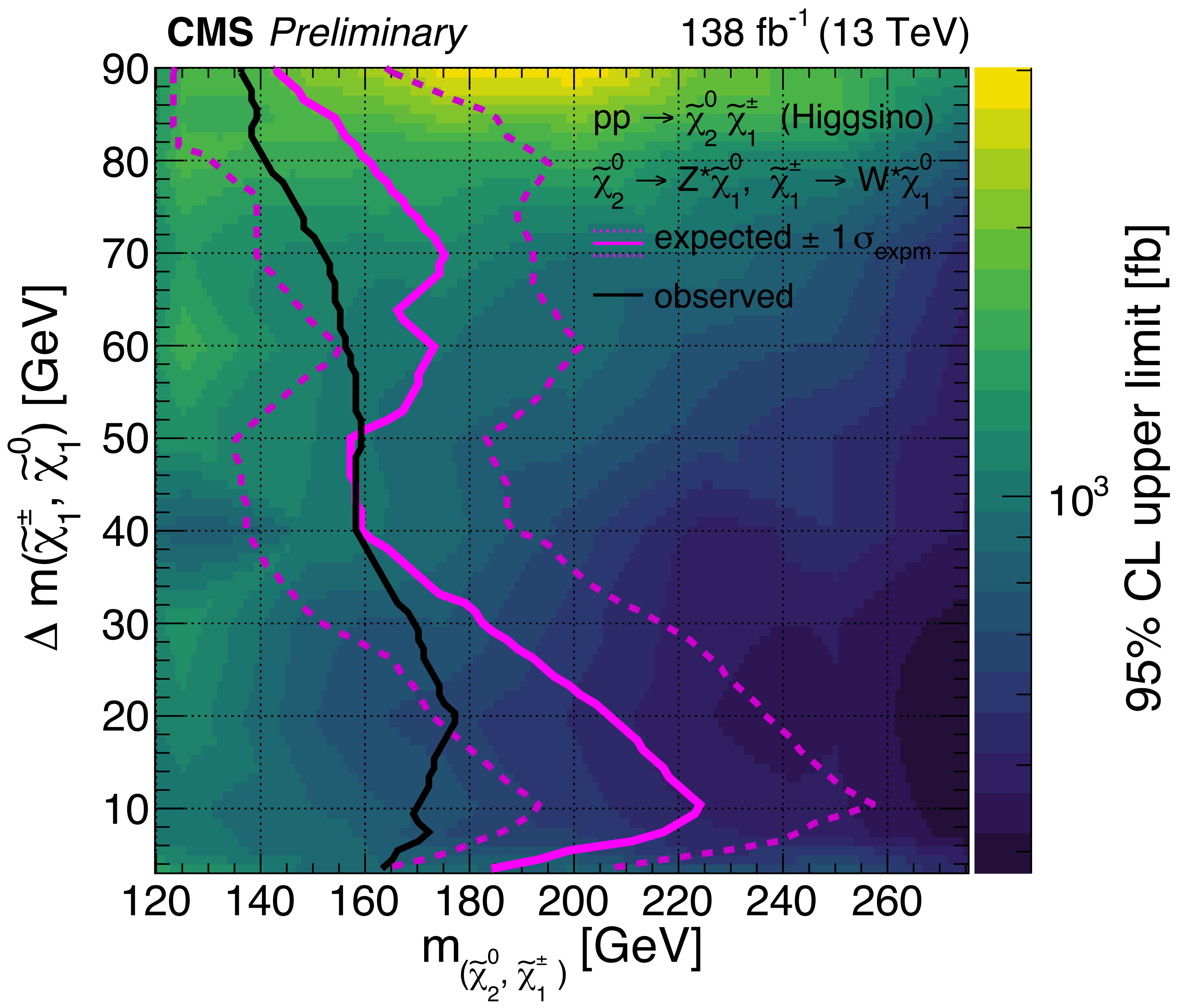
CMS-PAS-SUS-23-003

- Sensitivity extended to higher masses especially in compressed mass regime
  - Wino (Higgsino) limits extending to 300 GeV (180 GeV)
  - Slepton limits extending to 275 GeV

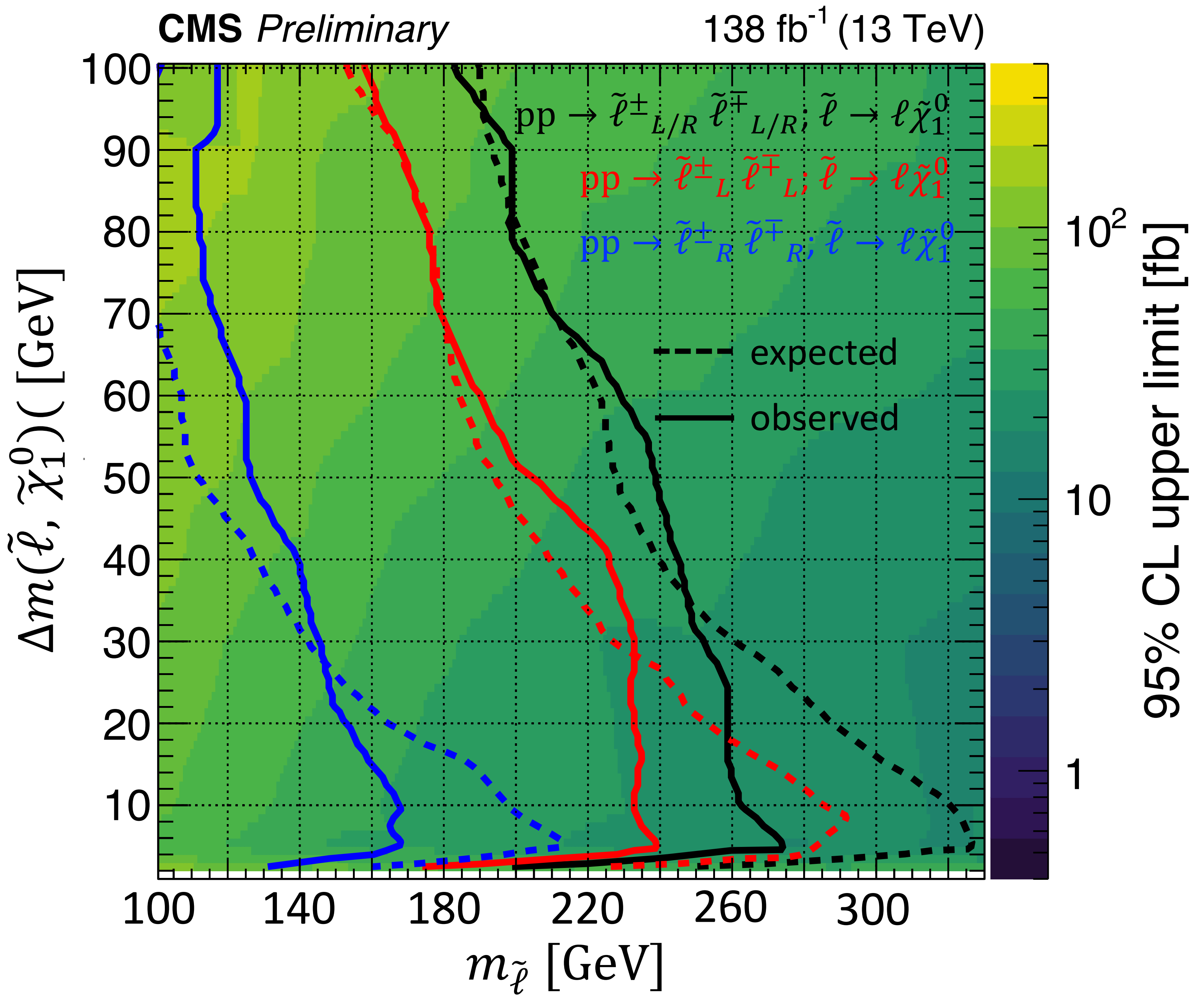
Wino



Higgsino



Slepton

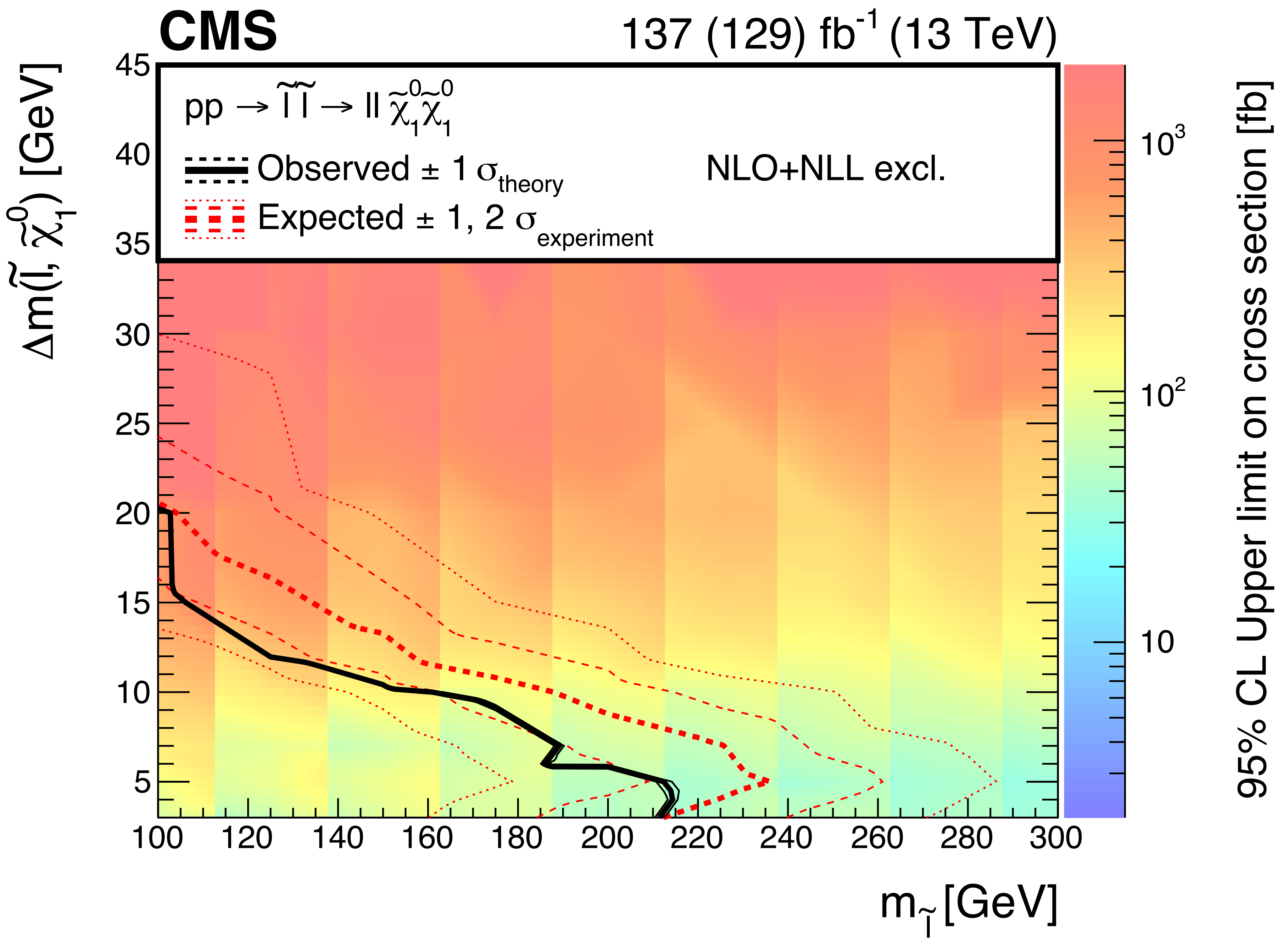


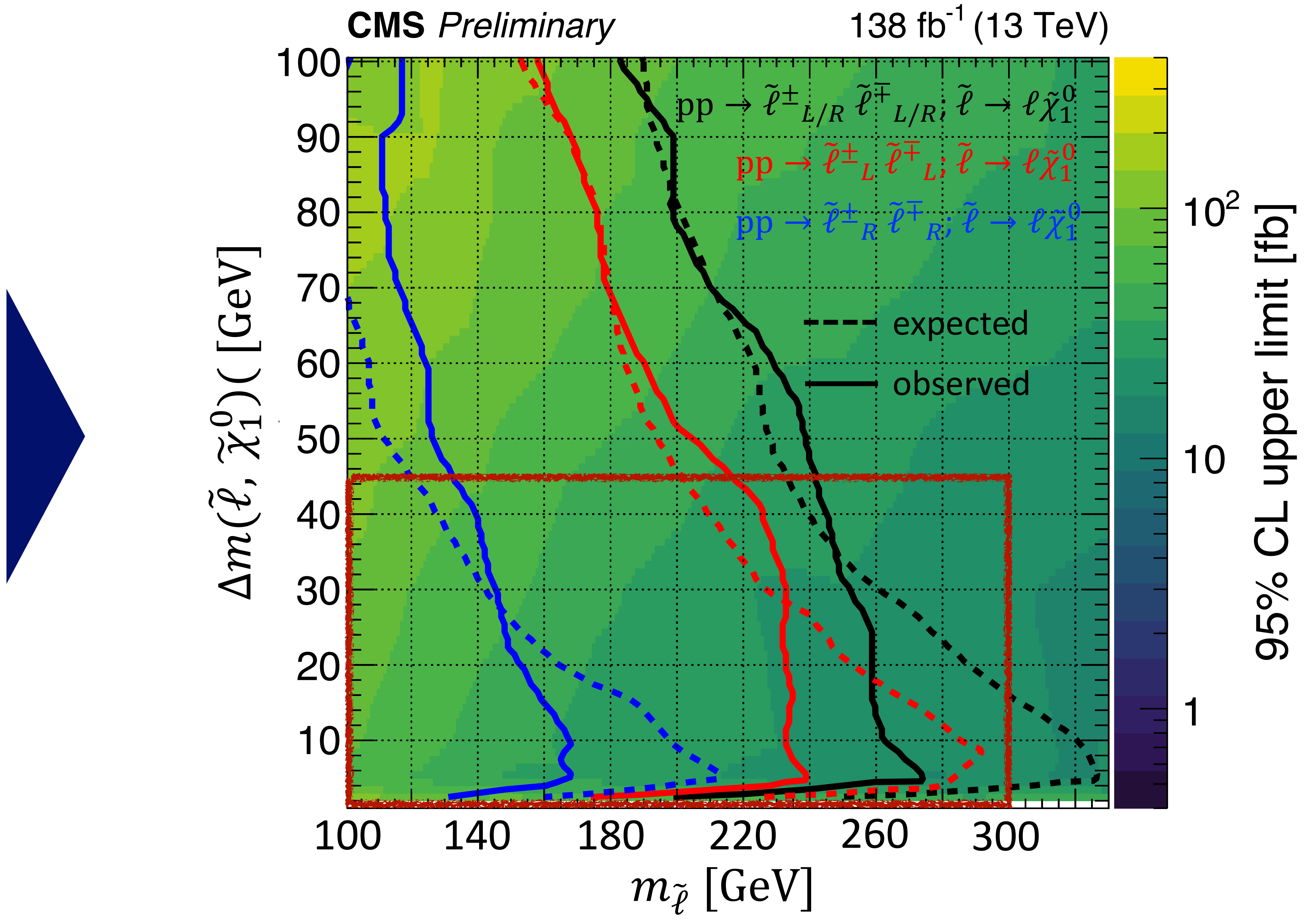
General Search for Compressed SUSY

CMS-PAS-SUS-23-003

- Sensitivity extended to higher masses especially in compressed mass regime
  - Wino (Higgsino) limits extending to 300 GeV (180 GeV)
  - Slepton limits extending to 275 GeV ⬅ **Limits extended to wide range of $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0)$**

Phys. Rev. D 109 (2024) 112001





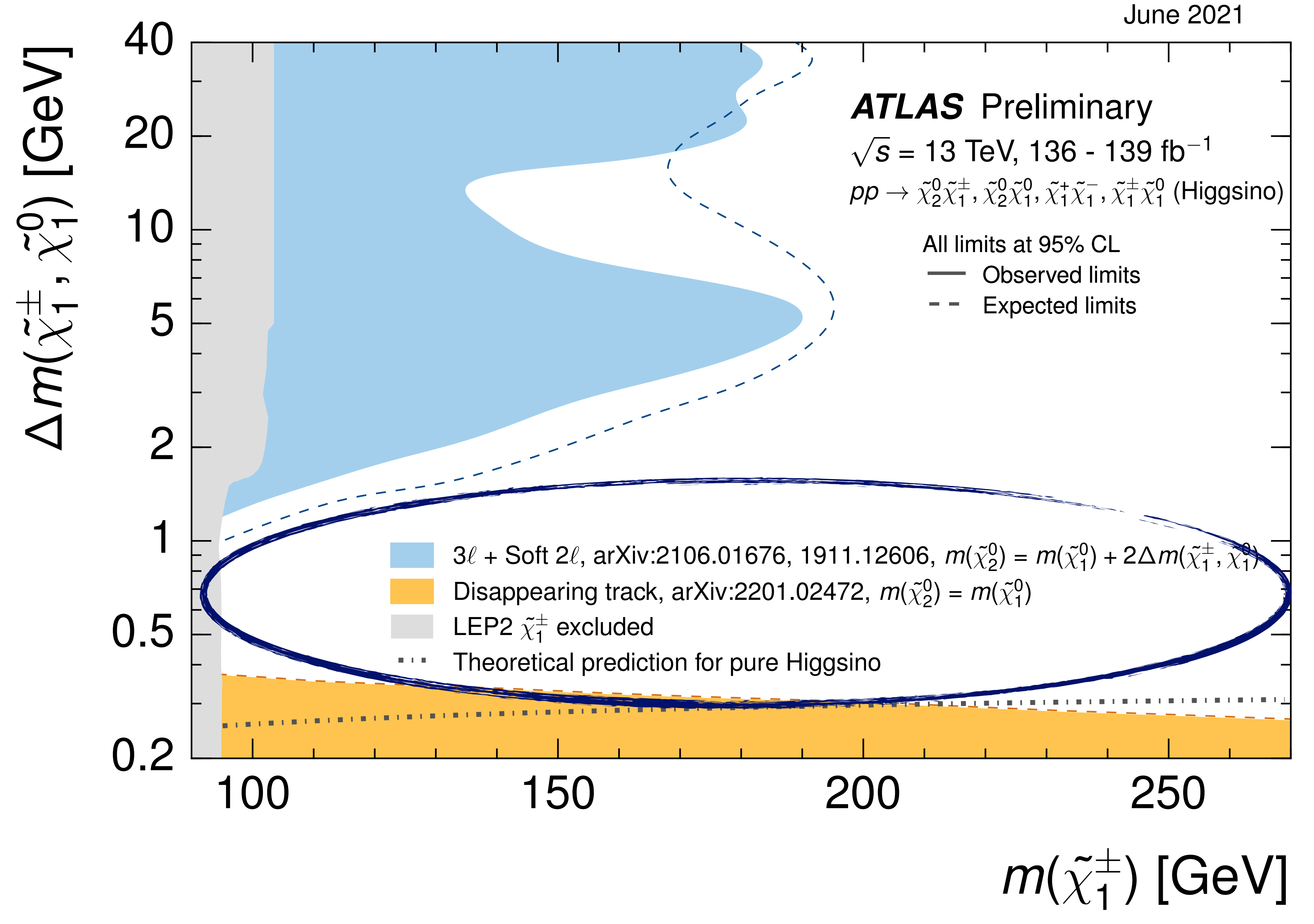
Compressed Higgsinos wIth Mildly-Displaced Tracks

Phys. Rev. Lett. 132 (2024) 221801

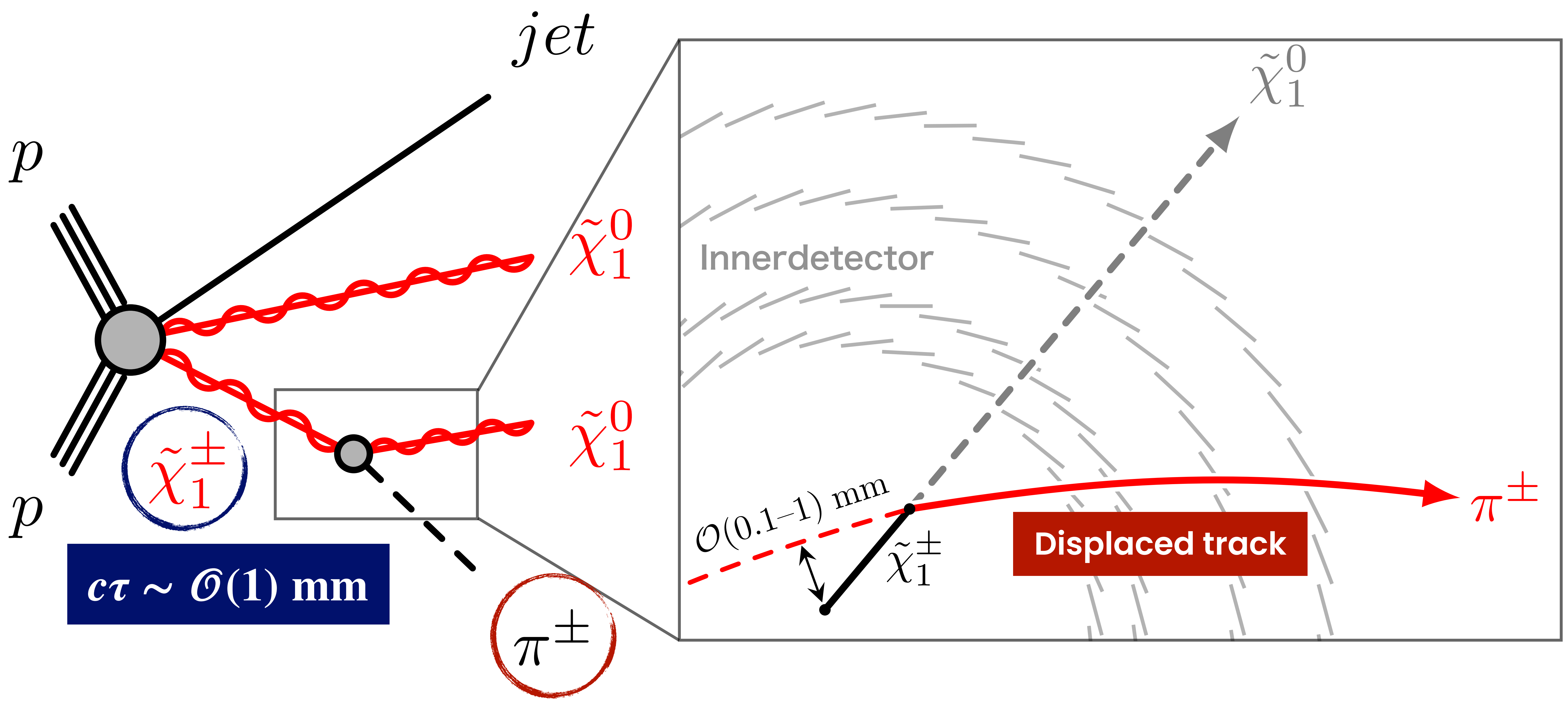
In the compressed Higgsino regime, $\tilde{\chi}_1^{\pm}$ acquire a lifetime of order $c\tau \sim \mathcal{O}(1)$ mm

- $\tilde{\chi}_1^{\pm}$ decay produce tracks with increased impact parameters (d_0)
- Identify $\tilde{\chi}_1^{\pm}$ decay tracks by requiring a **"mildly displaced track"** : $S(d_0) = |d_0|/\sigma(d_0)$
  - Idea from the "cornering higgsino" paper [H. Fukuda et al., Phys. Rev. Lett. 124, 101801 (2020)]

Higgsino exclusion limits



Schematics of the "mildly displaced track"

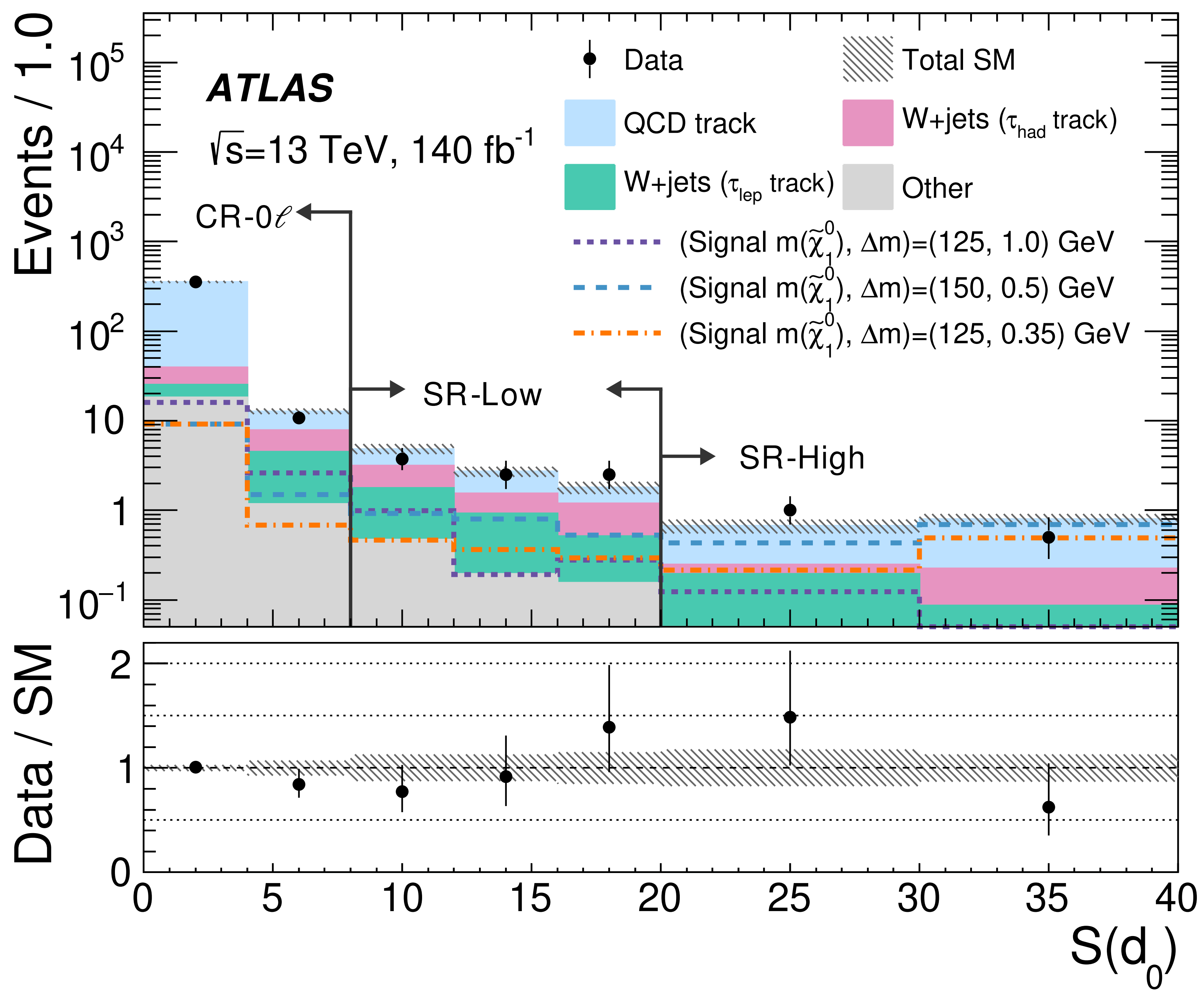


No significant data excess in all SRs

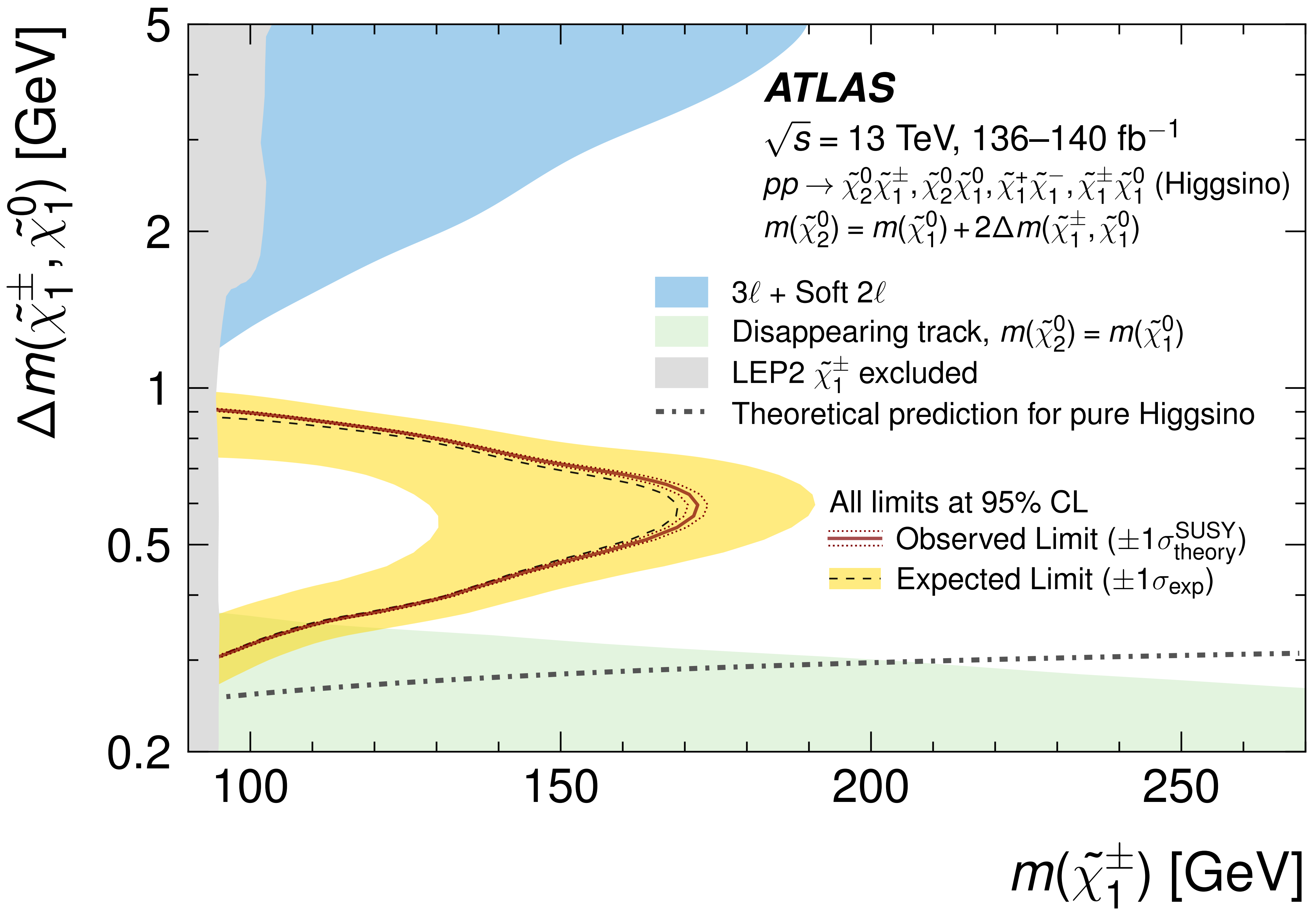
➡ Covered the higgsino gap ($0.3\ \mathrm{GeV} < \Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) < 0.9\ \mathrm{GeV}$), with a maximum reach of 170 GeV in the chargino mass

	SR-Low	SR-High
Observed data	35	15
SM prediction	37 ± 4	14.8 ± 2.0
QCD track	14.0 ± 1.7	10.0 ± 1.6
$W(\to \tau_\ell \nu)$+jets	9.6 ± 1.6	2.0 ± 0.6
$W(\to \tau_h \nu)$+jets	10.6 ± 2.0	1.9 ± 0.8
Others	3.2 ± 0.7	0.8 ± 0.4

Track $S(d_0)$ distribution



Exclusion limits (overlayed with previous analyses)



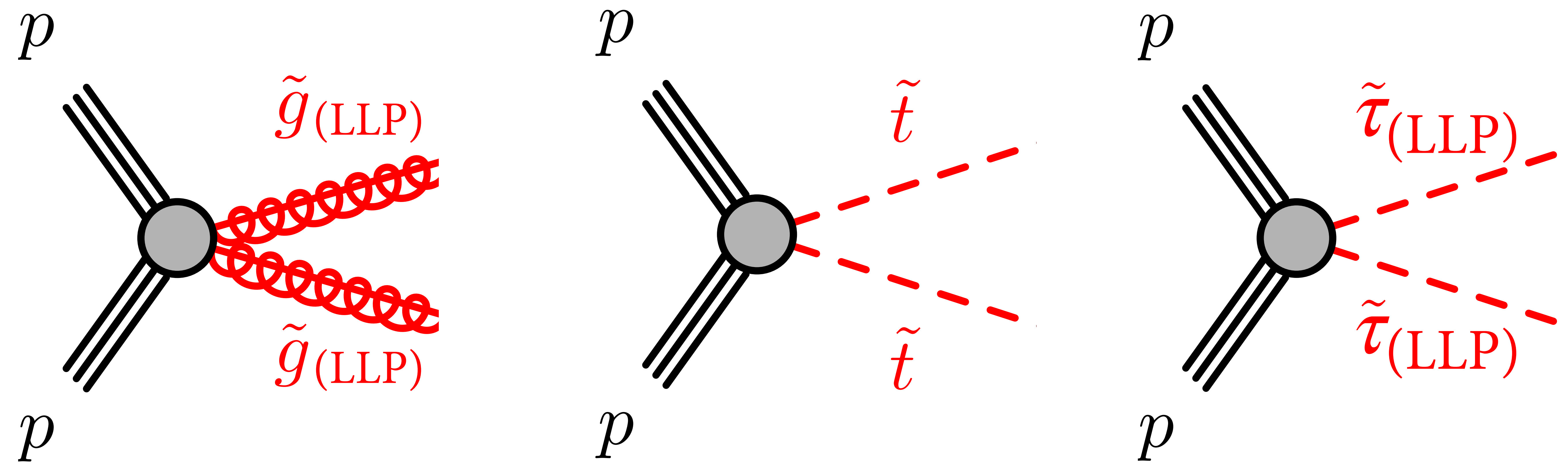
LONG-LIVED PARTICLE SEARCH

LLPs with Large Ionization Energy Loss

CMS-PAS-EXO-18-002

- Heavy stable charged particles have a small relative velocity $(\beta \equiv v/c)$
  - **Can be detected by higher rate of ionization energy loss (dE/dx)**
  - Target : **long-lived gluino, stop, stau particles** & fourth generation lepton (τ')

Long-lived SUSY particles



- Two methods developed to cross-check any potential excess in the data
  ① A simple, very inclusive search ➡ **Ionization method**
  ② More exclusive channel ➡ **Mass method**

LLPs with Large Ionization Energy Loss

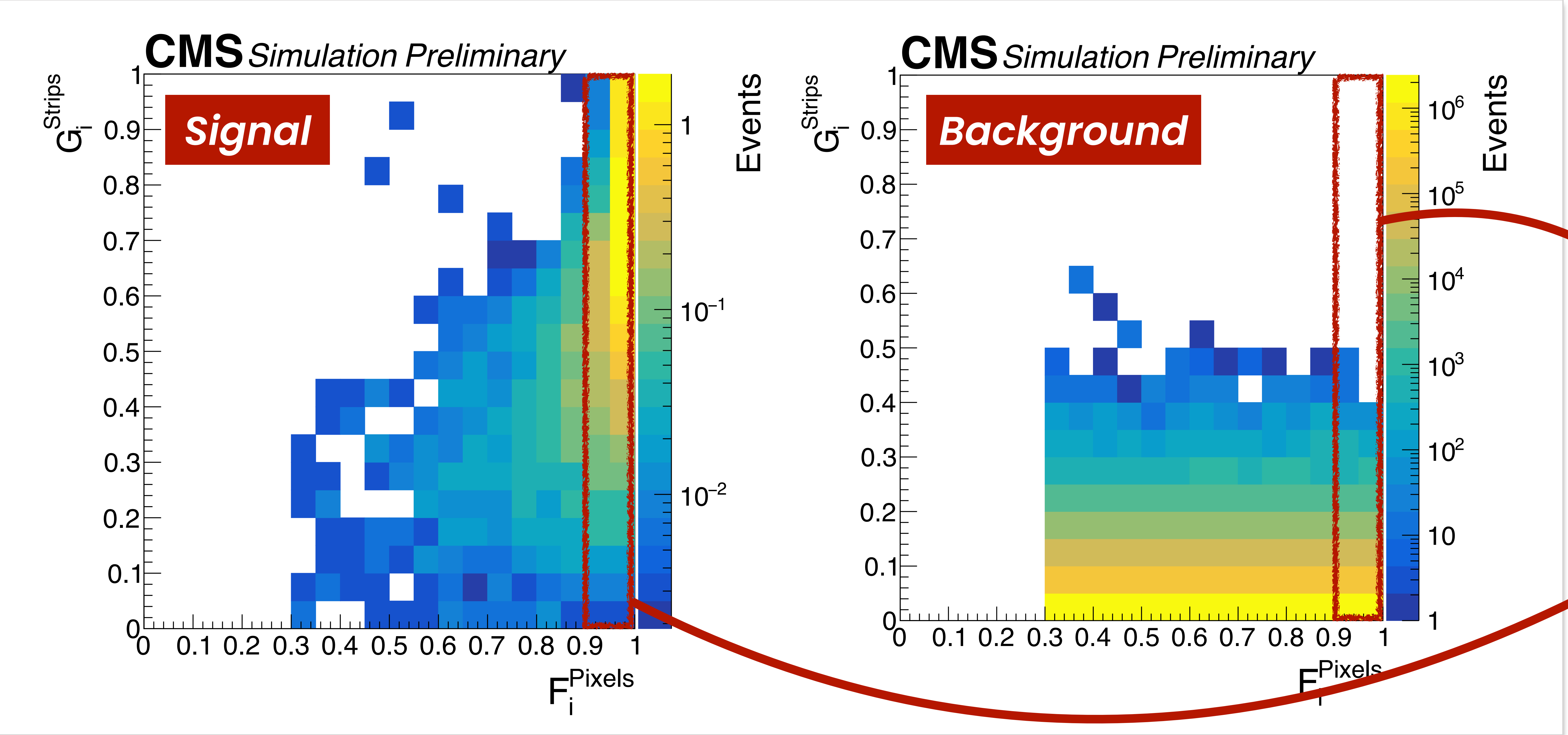
CMS-PAS-EXO-18-002

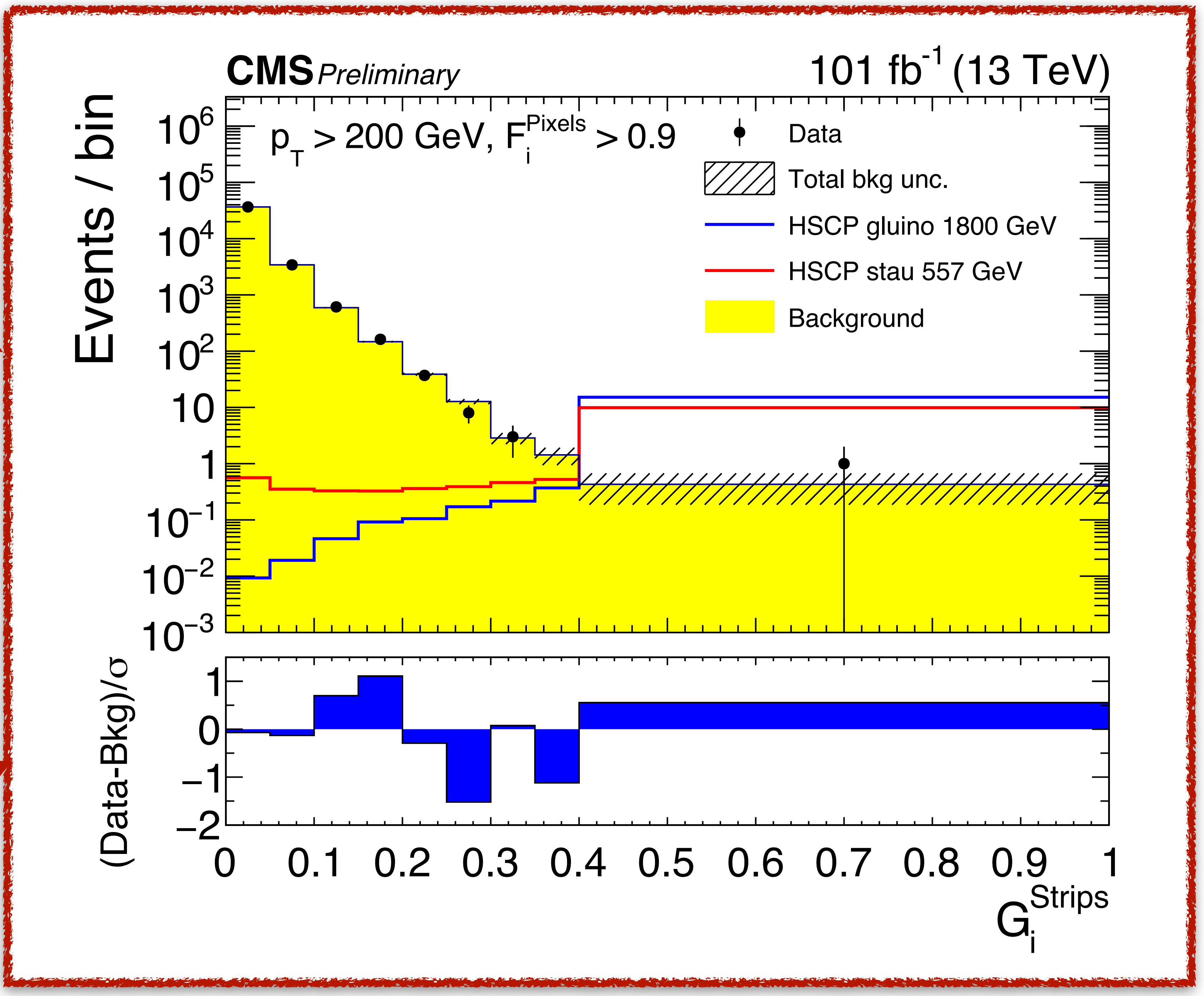
Inclusive Ionization method

- Use two uncorrelated dE/dx discriminant measured in pixel & strip detectors

➡ **Probability that a track is not a MIP (F_i^{Pixels} & G_i^{Strips})**

	F_i^{Pixels}	G_i^{Strips}
Signal	→ 1	→ 1
Background	0 - 1	→0





LLPs with Large Ionization Energy Loss

CMS-PAS-EXO-18-002

Exclusive mass method

- Mass of candidate particle can be calculated by approximating Bethe-Bloch formula

$$I_h = K\frac{m^2}{p^2} + C \Rightarrow m = p\sqrt{\frac{I_h - C}{K}}$$

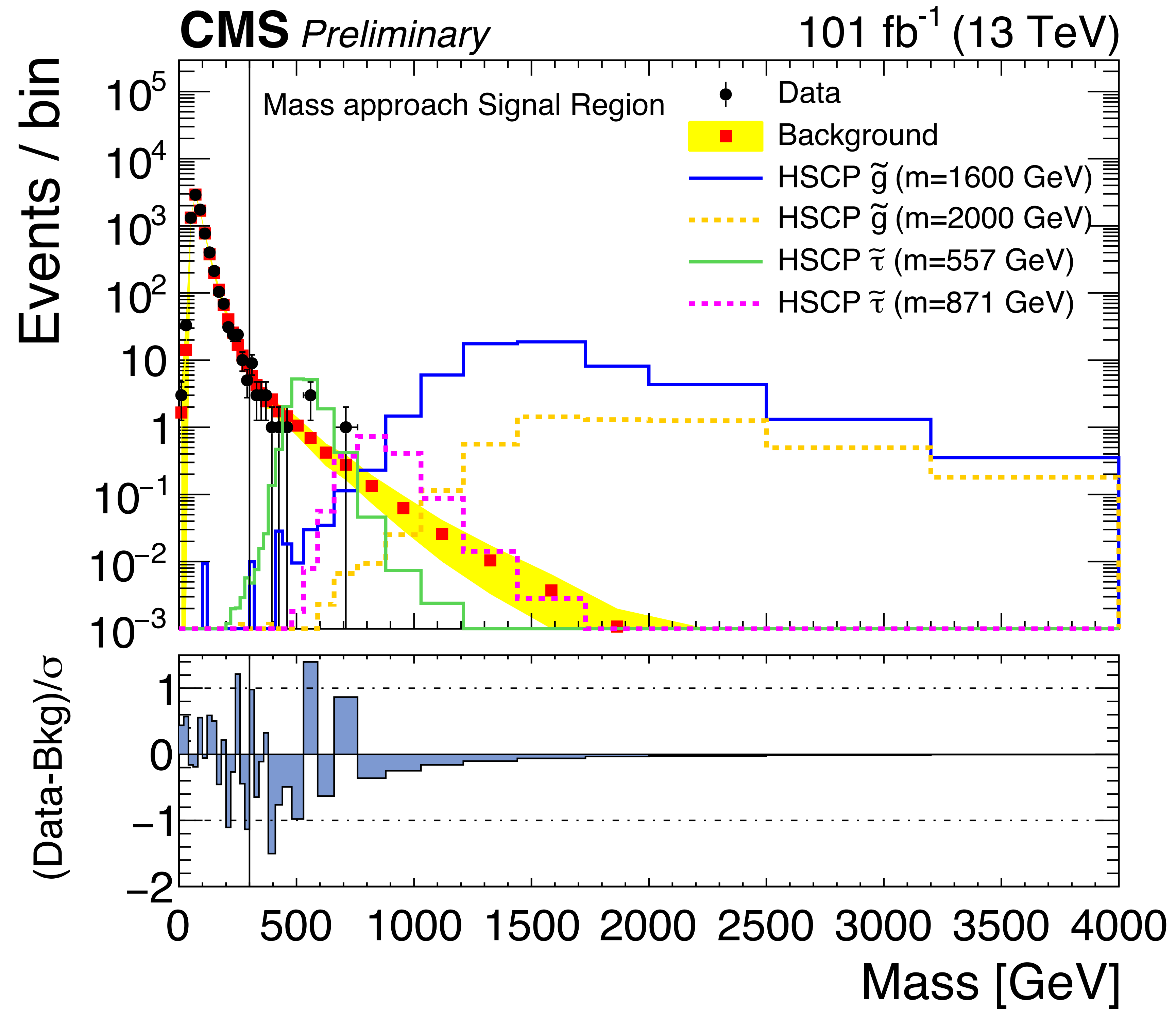
dE/dx estimate

Empirical parameters

Probable value of dE/dx estimated by squared harmonic mean

$$I_h = \left(\frac{1}{N}\sum_j^N \left(\frac{dE}{dx_j}\right)^{-2}\right)^{-1/2}$$

Values of K and C are determined using protons, kaons and pions in data and MC for each year

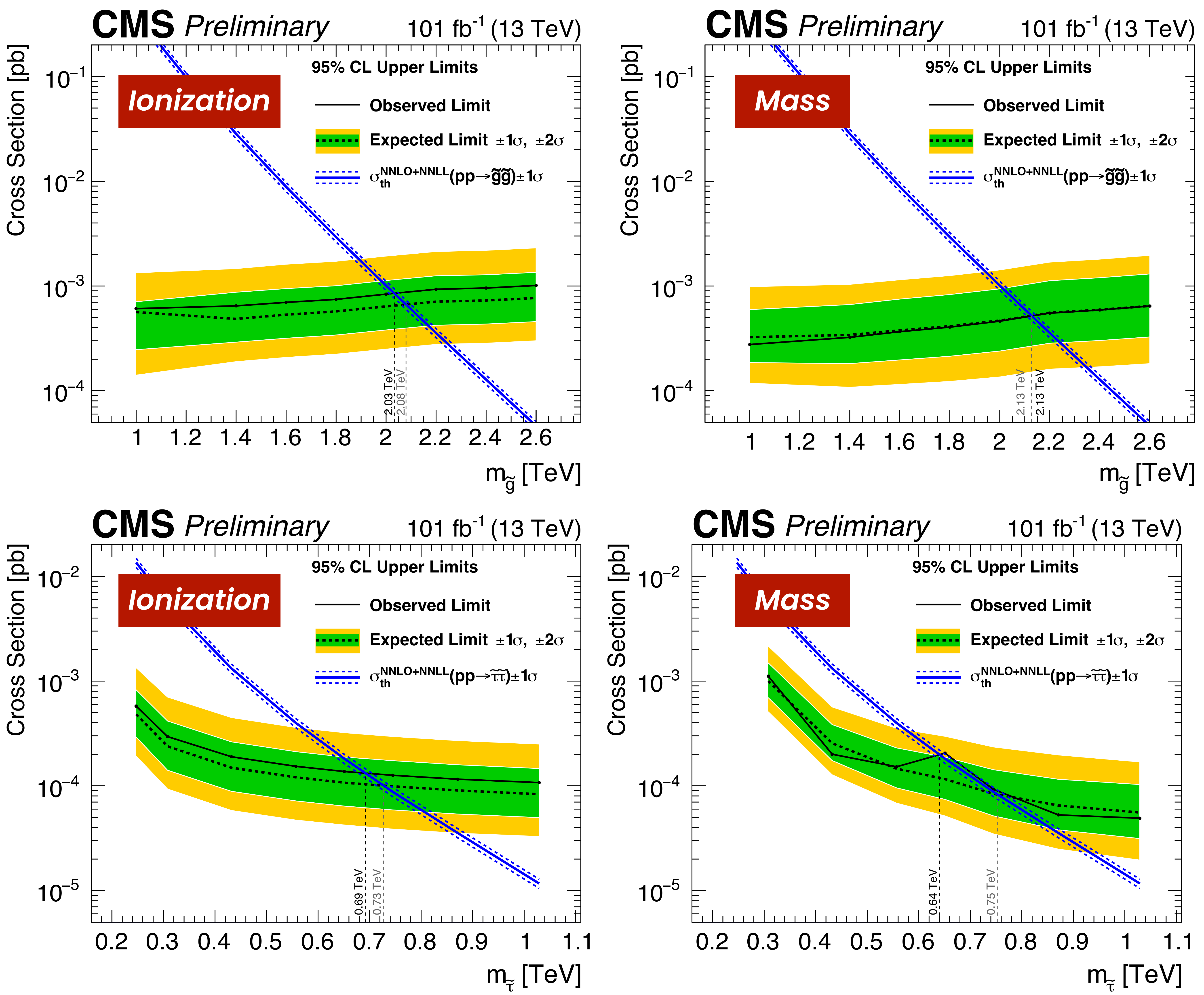


LLPs with Large Ionization Energy Loss

CMS-PAS-EXO-18-002

- No significant excess in both approaches
  - Gluinos excluded up to 2.03 TeV (2.13 TeV) for ionization (mass) method

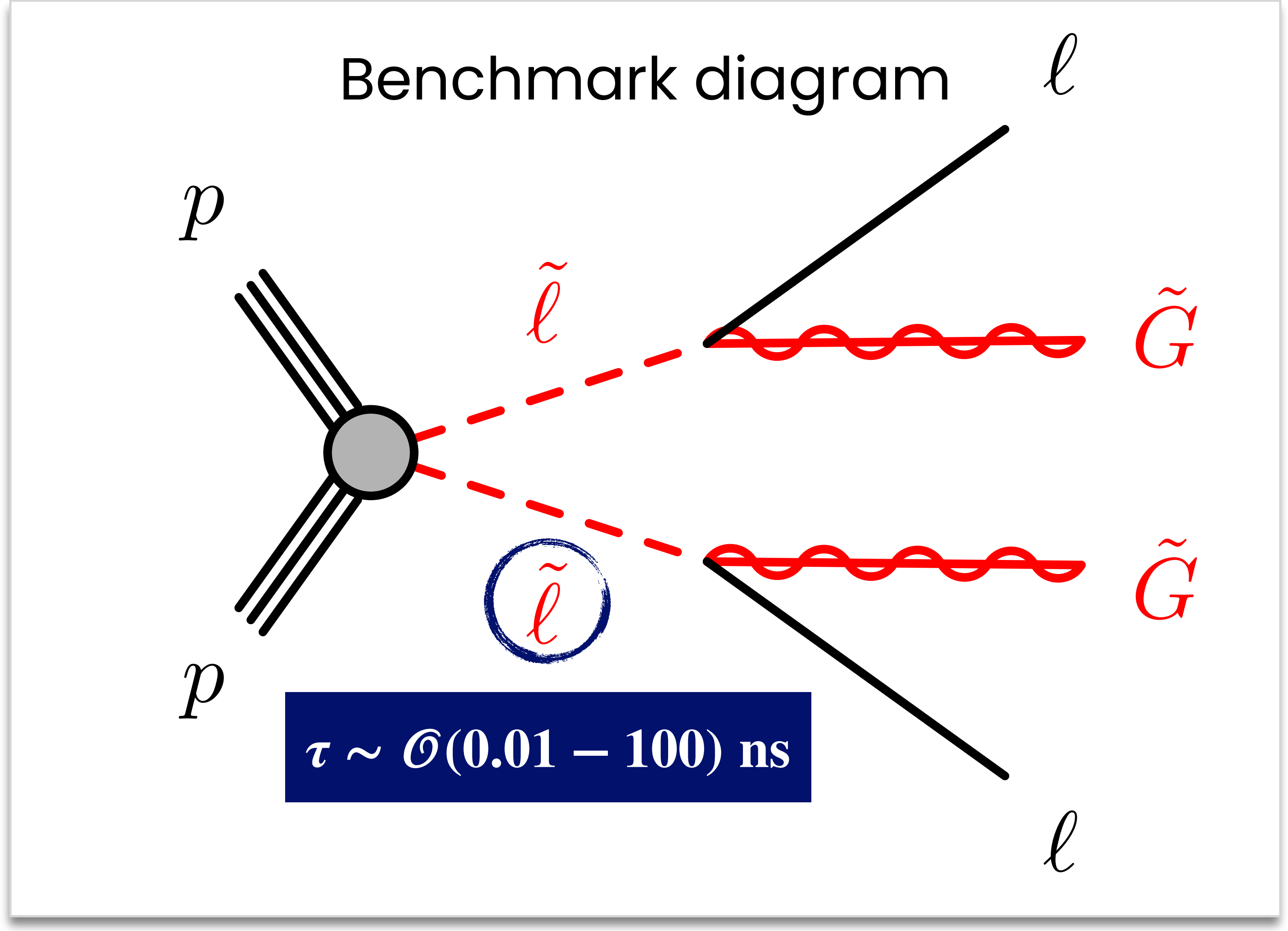
- The mass method provides stronger limits for signals with large mass (> 600 GeV) due to small background



Displaced Leptons

ATLAS-CONF-2024-011

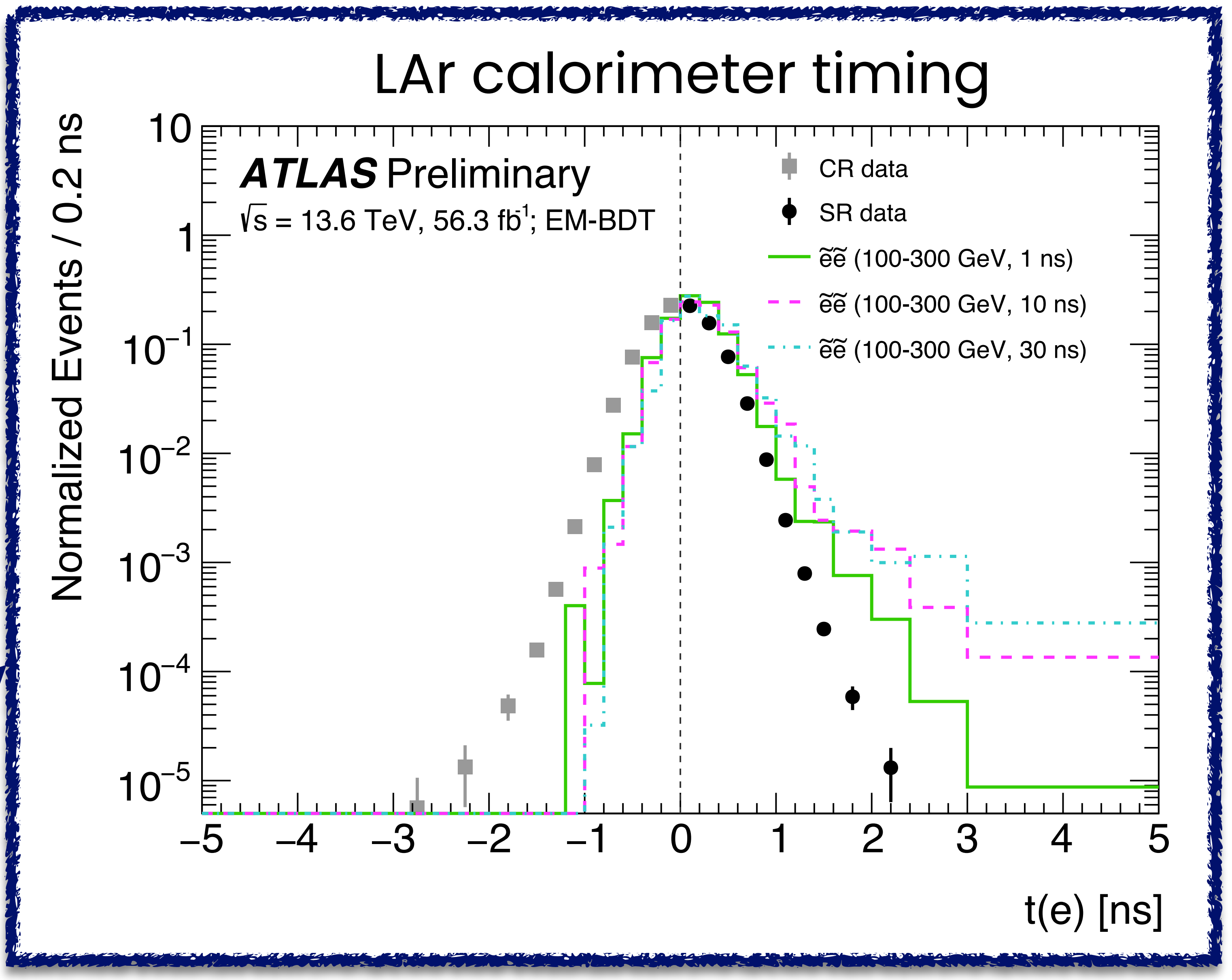
- Gauge-Mediated SUSY Breaking model as benchmark
  - Long lifetime due to small gravitational coupling
- Performed search with **full Run 2** + **early Run 3** data
  140 fb^{-1} 56.3 fb^{-1}



- Two approaches : ABCD analysis & EM-BDT analysis

① **ABCD analysis (Run 2 + Run 3)**
  - Focus on dilepton events (ee, μμ, eμ)

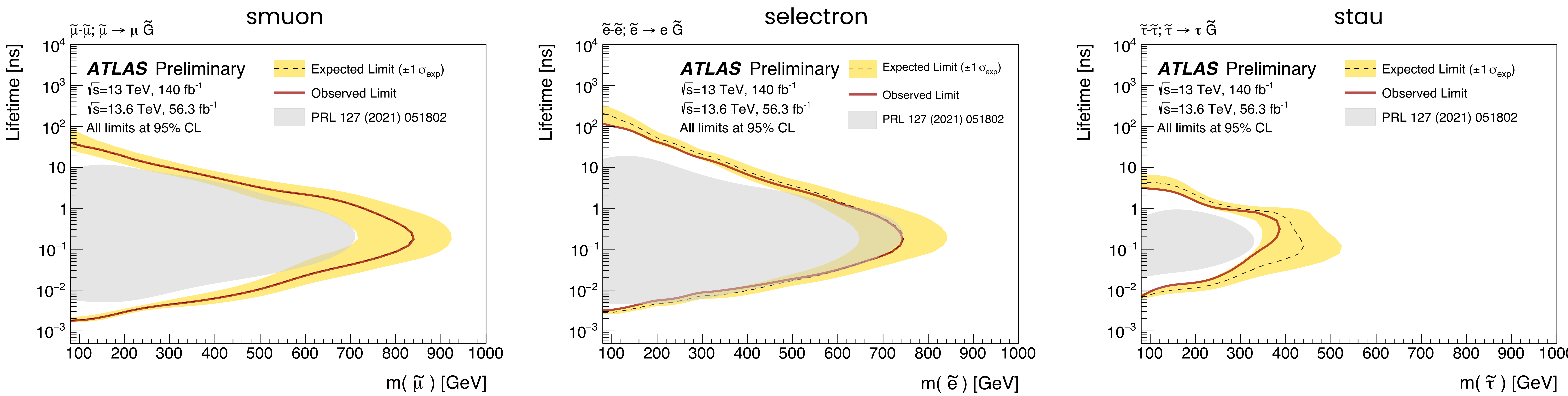
② **EM-BDT analysis (Run 3)**
  - Focus on displaced e/γ final states (1e, eγ, γγ)
    - Electrons with no tracks will be reconstructed as photons
  - Identify displaced (delayed) e/γ using ML techniques
    - **Use Liquid Argon (LAr) calorimeter timing as input**



Displaced Leptons

ATLAS-CONF-2024-011

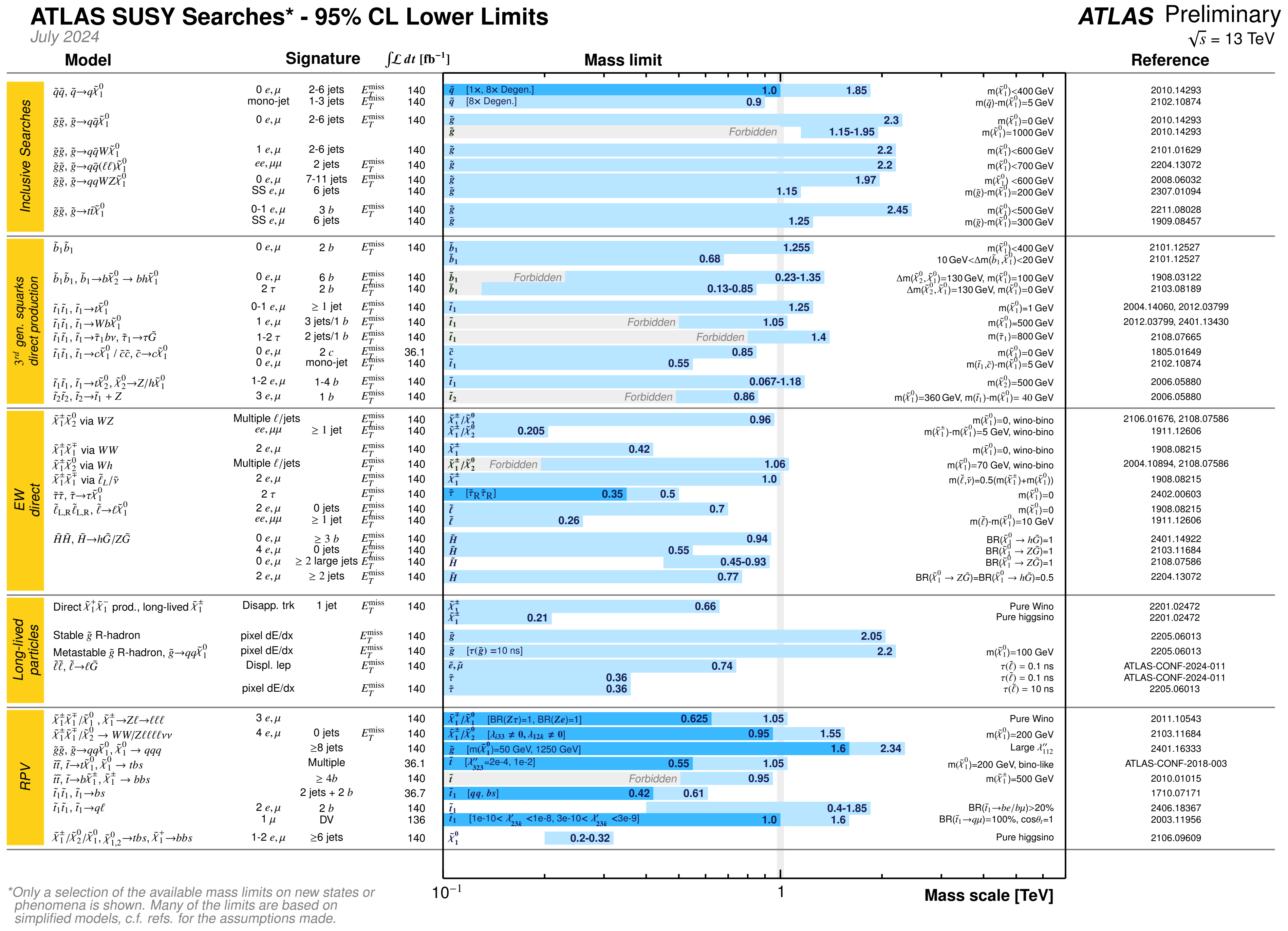
- No significant data excess in all SRs
- Improvement in sensitivity due to
  - smuon : **New LRT-based trigger** + better trigger acceptance in forward region
  - selectron : **New LRT-based trigger** + **EM-BDT analysis**
  - stau : Benefits from all improvements above



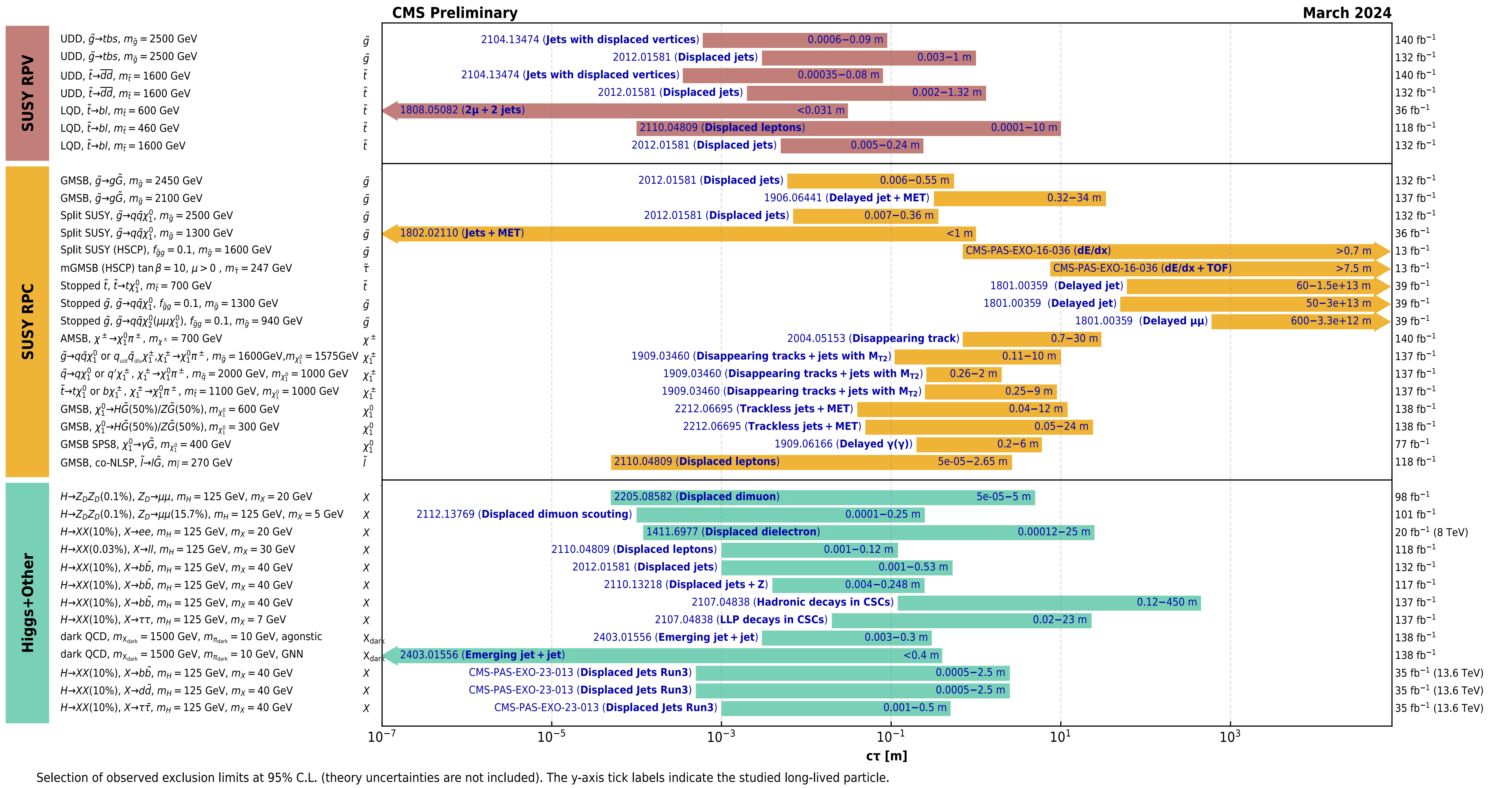
Summary

- Many new results published with full Run 2 data (Including many results not covered today)
  - Large sensitivity improvement not only by statistics, but also by new analysis methods
  - SUSY results with early Run 3 data are also starting to come out
  - Run 3 ongoing with exciting developments that will enhance the discovery potential

ATLAS SUSY public results



CMS SUSY public results



BACKUP

- 4 SRs defined to target different mass splittings $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ ↑

- SRA : Bulk region
- SRB, SRC : Intermediate region

➡ Insure orthogonality using
① Number of top-tagged large-R jets
② **Stransverse mass (m_{T2})**

- SRD : Compressed region ➡ Require ISR jet to boost neutralinos

Variable	SRA	SRB	SRC
$N_{\text{tops}}^{\text{DNN}}$ $(R = 1.0)$	≥ 1	$= 0$	≥ 1
$m_{T2}(j^b_{R=1.0}, c)$ [GeV]	≥ 450 *	≥ 150	$[200, 450]$

Orthogonal selections

Variable	SRD	CRttD	CRWD
E_T^{miss} [GeV]	≥ 250		
$p_T(j_1)$ [GeV]	≥ 100		

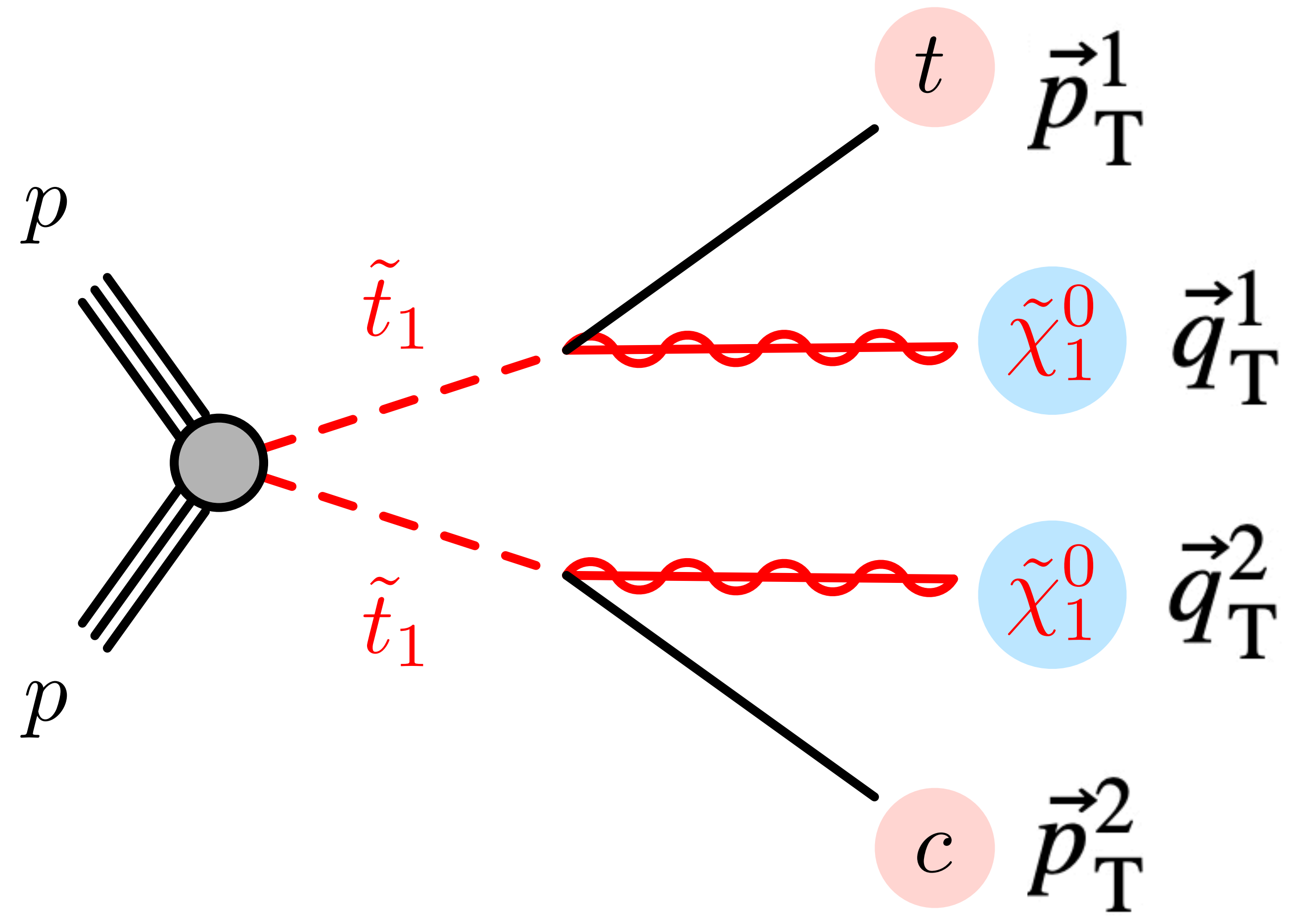
Initial-state radiation jet (ISR) selection

JHEP 07 (2024) 250

Stransverse mass

- Generalization of the transverse mass when there are two semi-invisibly decaying particles

$$m_{T2}(\vec{p}_T^{\,1}, \vec{p}_T^{\,2}, \vec{p}_T^{\,miss}) = \min_{\vec{q}_T^{\,1}+\vec{q}_T^{\,2}=\vec{p}_T^{\,miss}} \{\max[m_T(\vec{p}_T^{\,1}, \vec{q}_T^{\,1}), m_T(\vec{p}_T^{\,2}, \vec{q}_T^{\,2})]\}$$



① Decompose the missing transverse momentum ($\vec{p}_T^{\,miss}$) into two vectors and assign to each top- or charm-tagged jet

② Calculate transverse mass for each top- or charm-tagged jet

③ Select trial vector which minimizes larger transverse mass

➡ ttbar background dramatically drop-off at the top quark mass

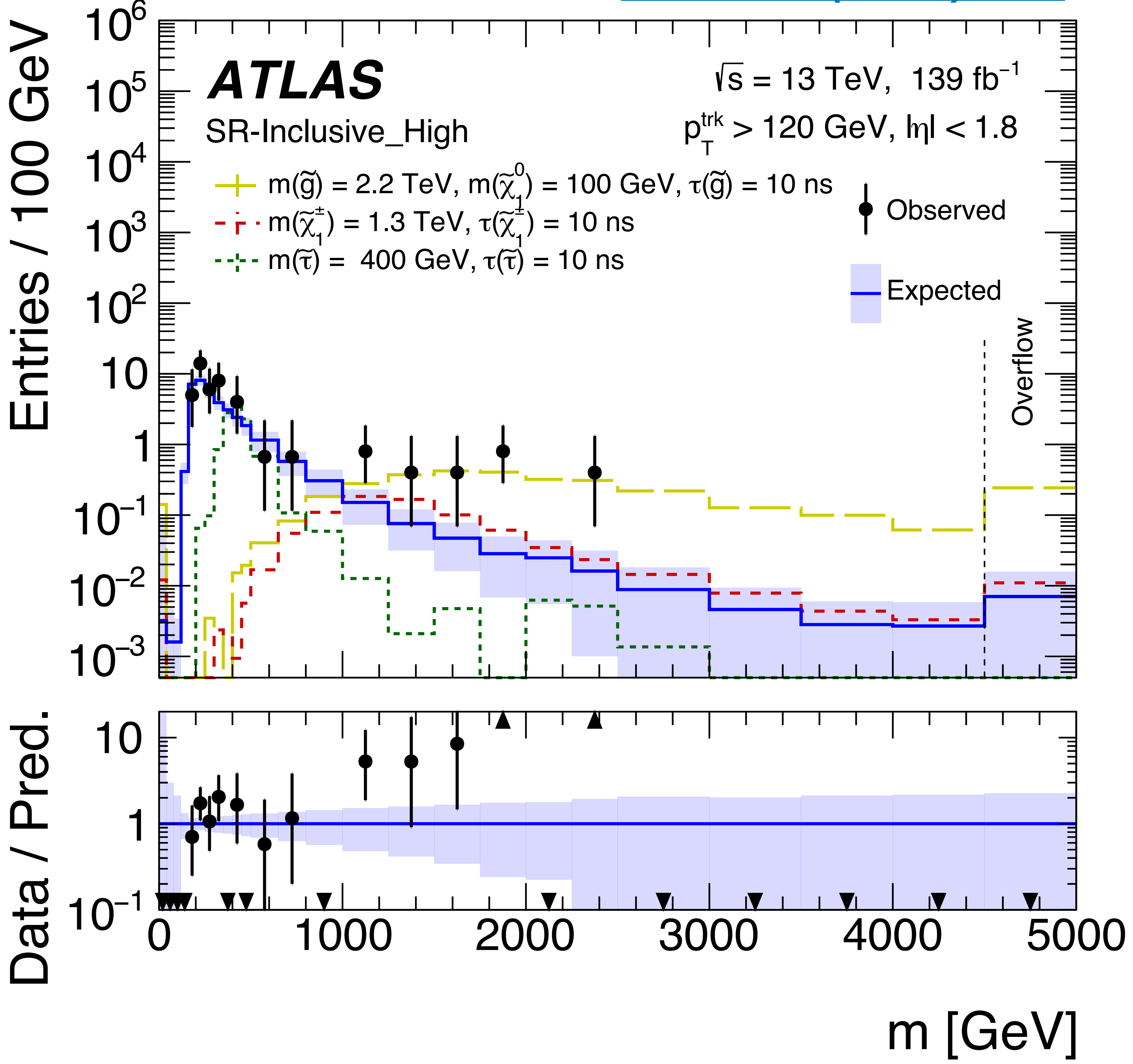
LLPs with Large Ionization Energy Loss

ATLAS EXPERIMENT

- Results using only pixel dE/dx information ➡ **Observed 3.6 σ (local) excess**
- New analysis using both pixel dE/dx & calorimeter time-of-flight (ToF) information

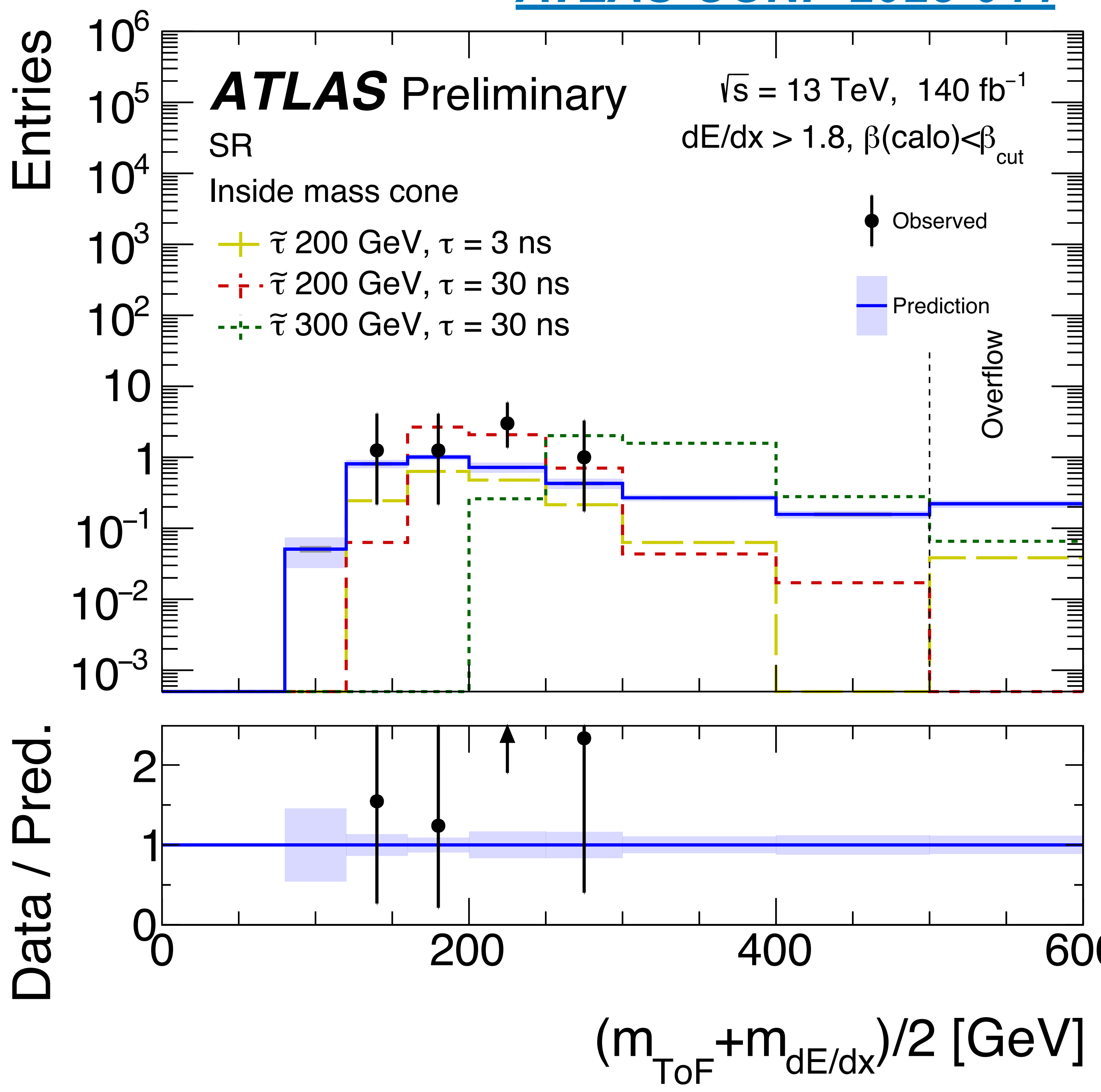
pixel dE/dx

[JHEP 06 (2023) 158]



pixel dE/dx + calo ToF

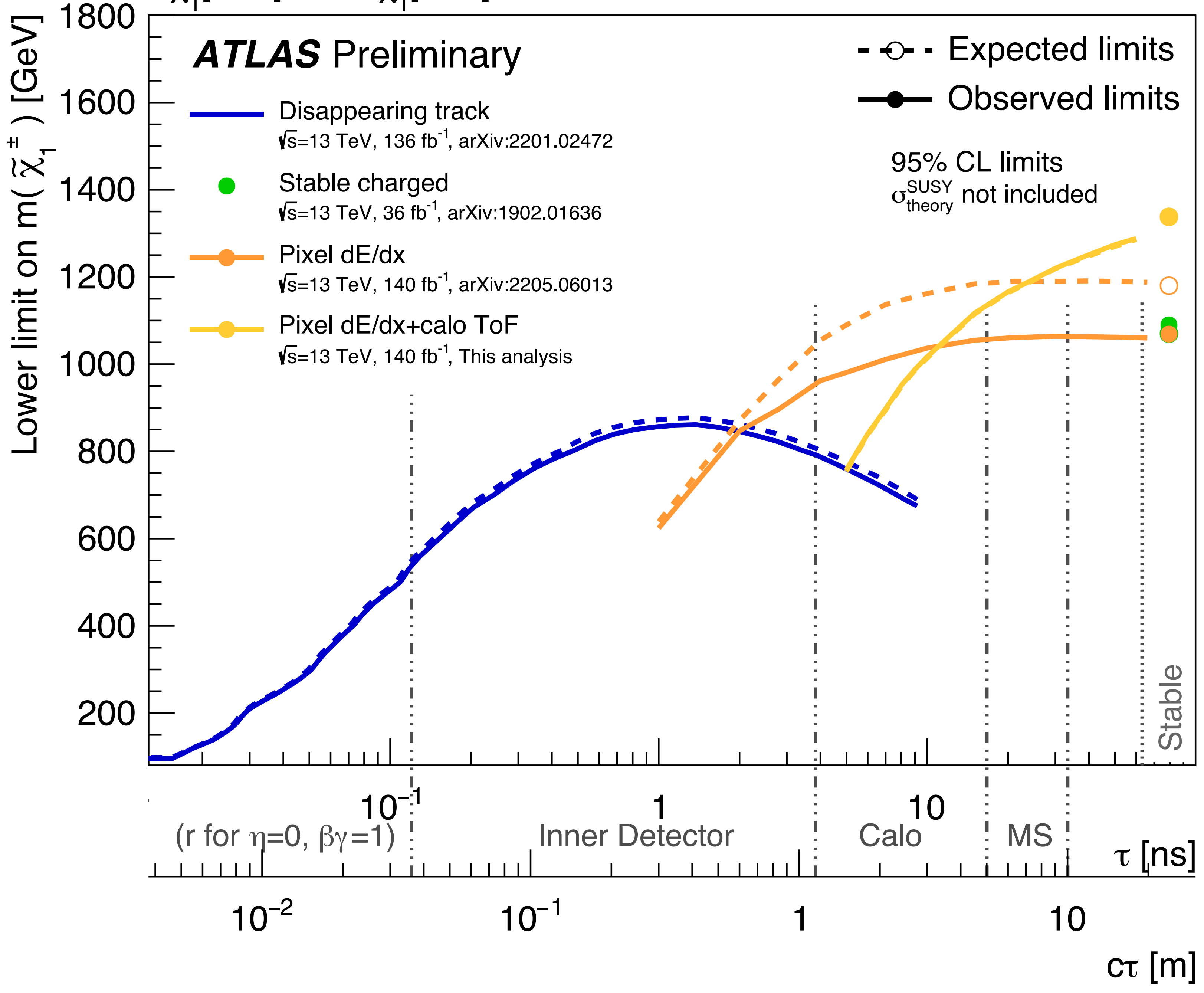
[ATLAS-CONF-2023-044]



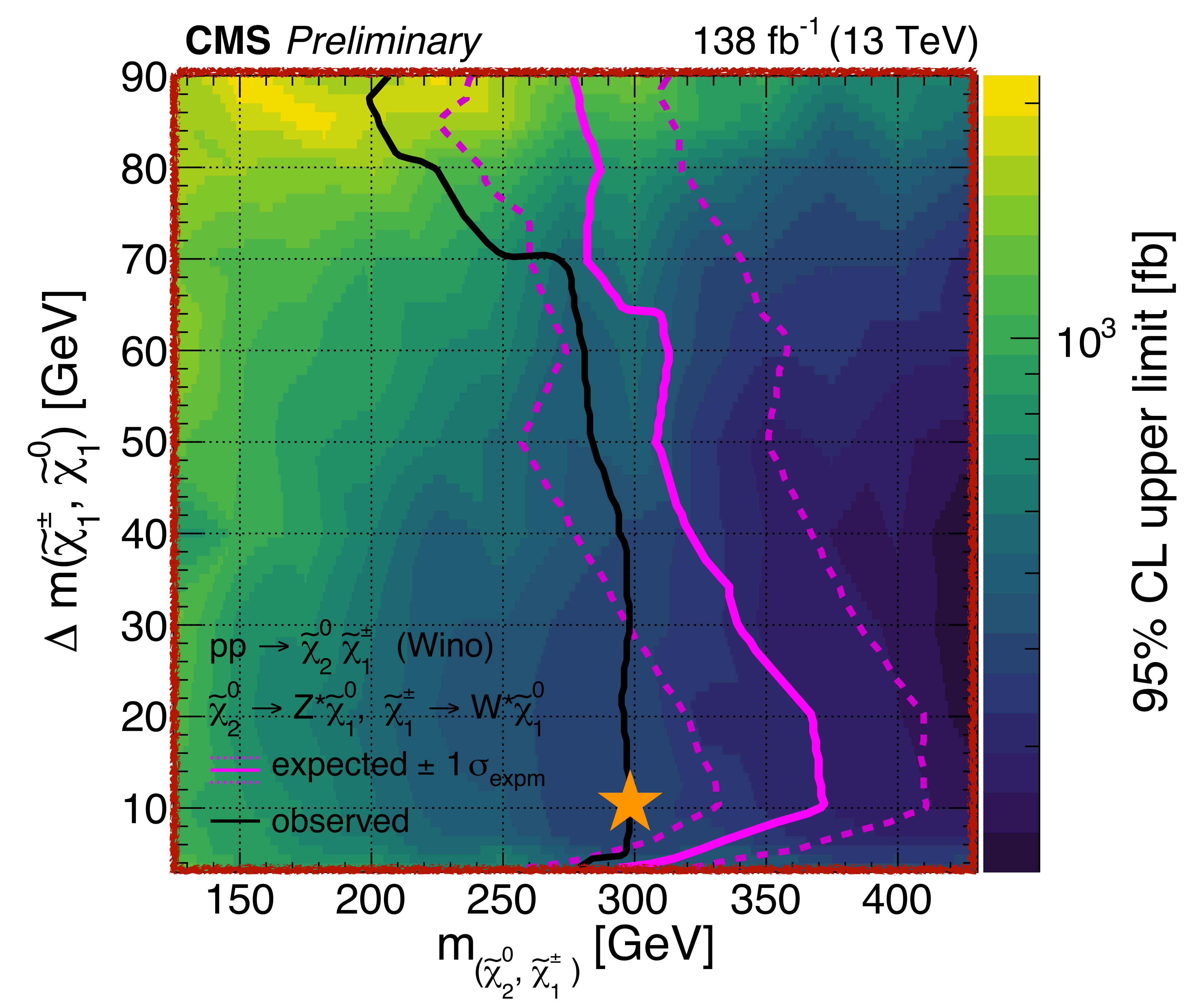
chargino interpretation

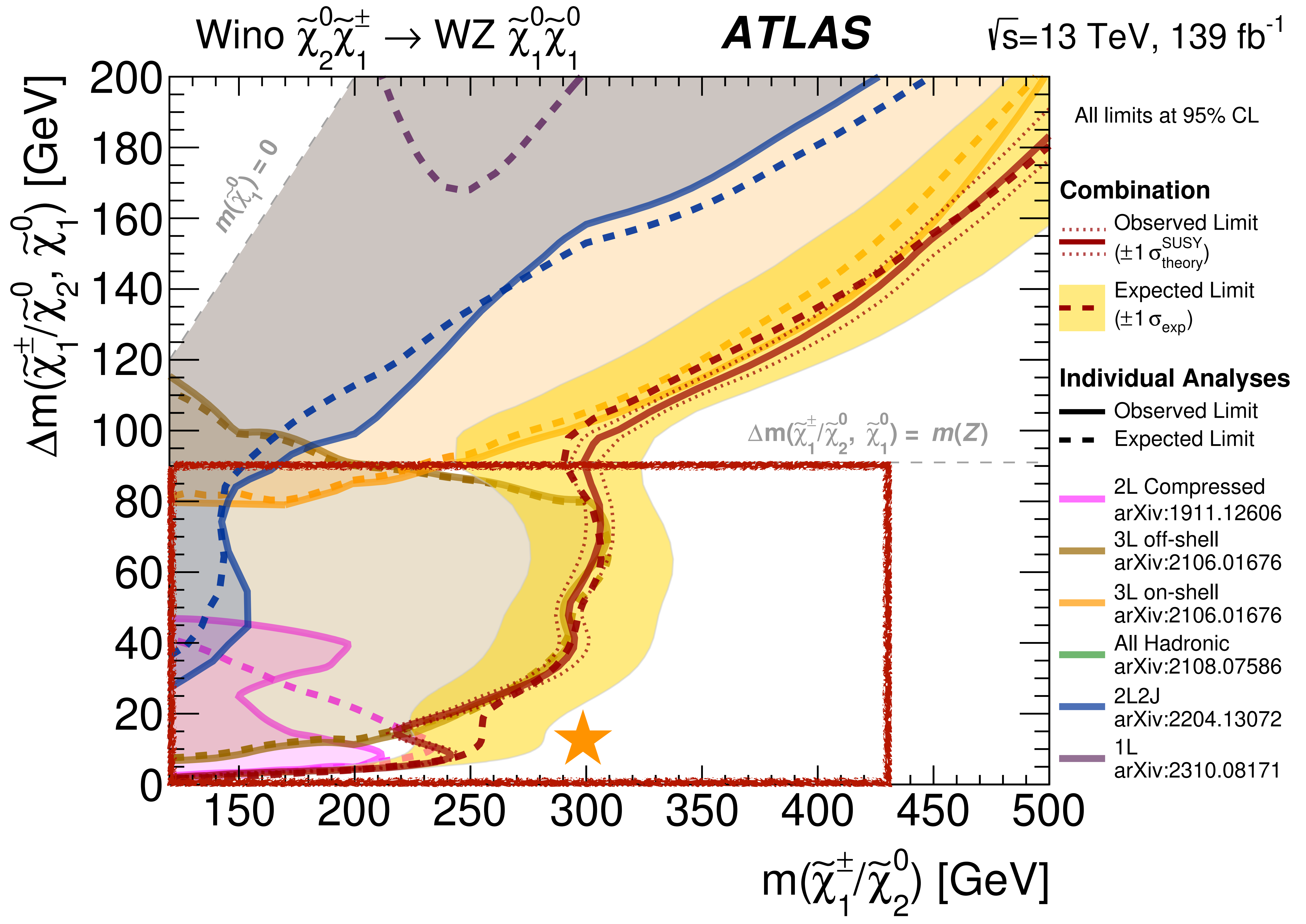
$\tilde{\chi}_1^\pm[\sim\tilde{W}^\pm] \to \pi^\pm \tilde{\chi}_1^0[\sim\tilde{W}^0]$

[ATL-PHYS-PUB-2024-009]

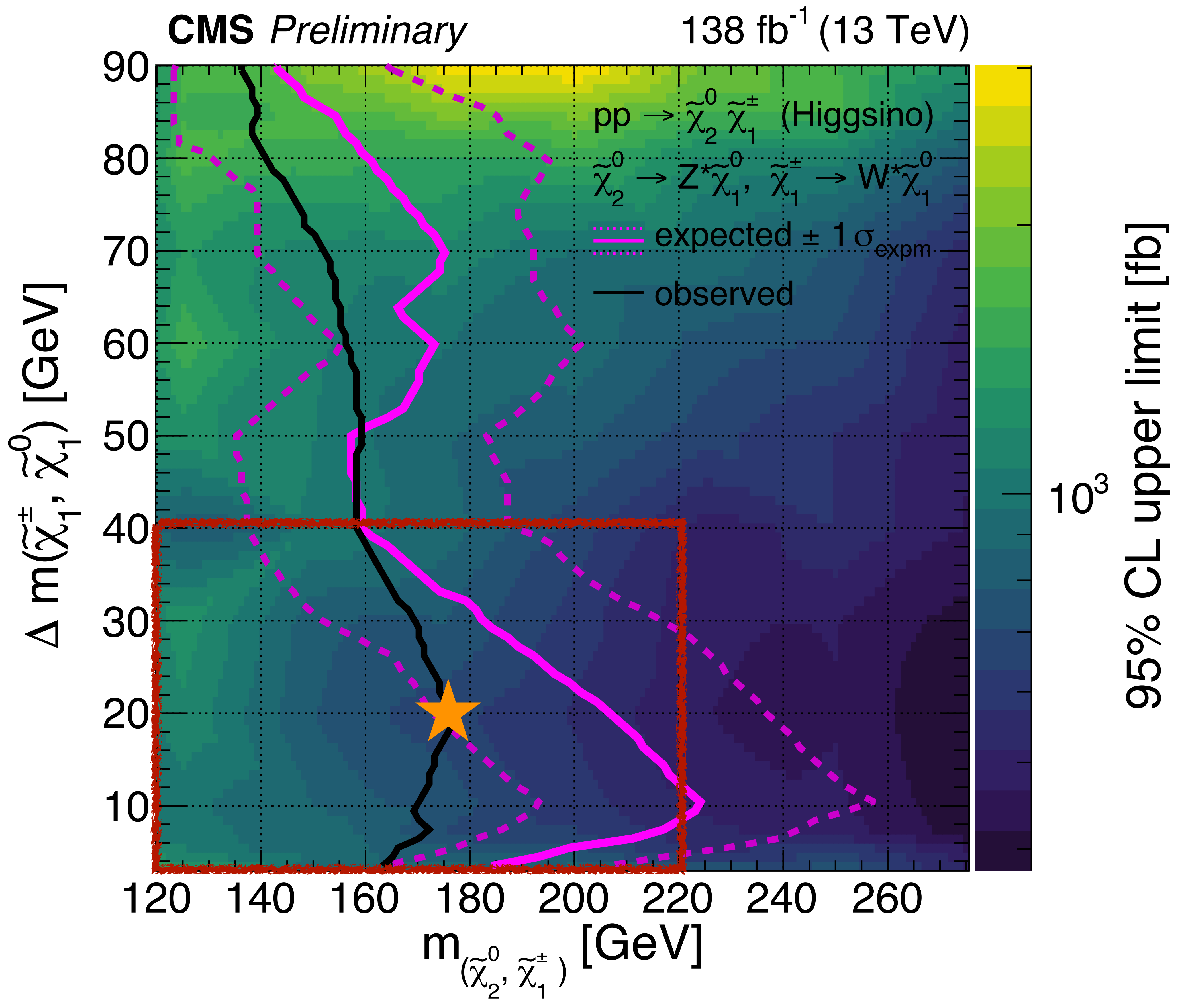


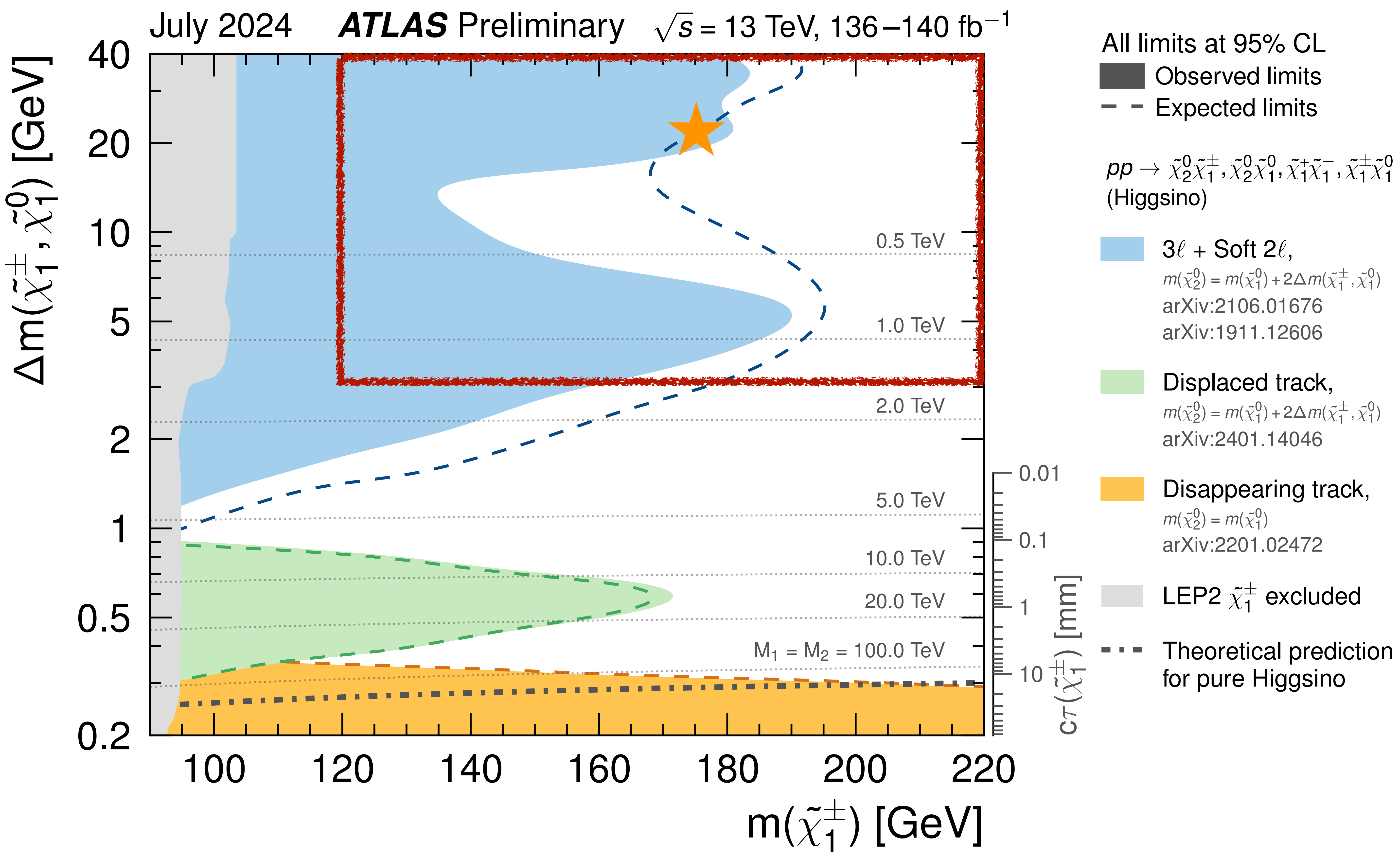
Compressed SUSY Results : Wino



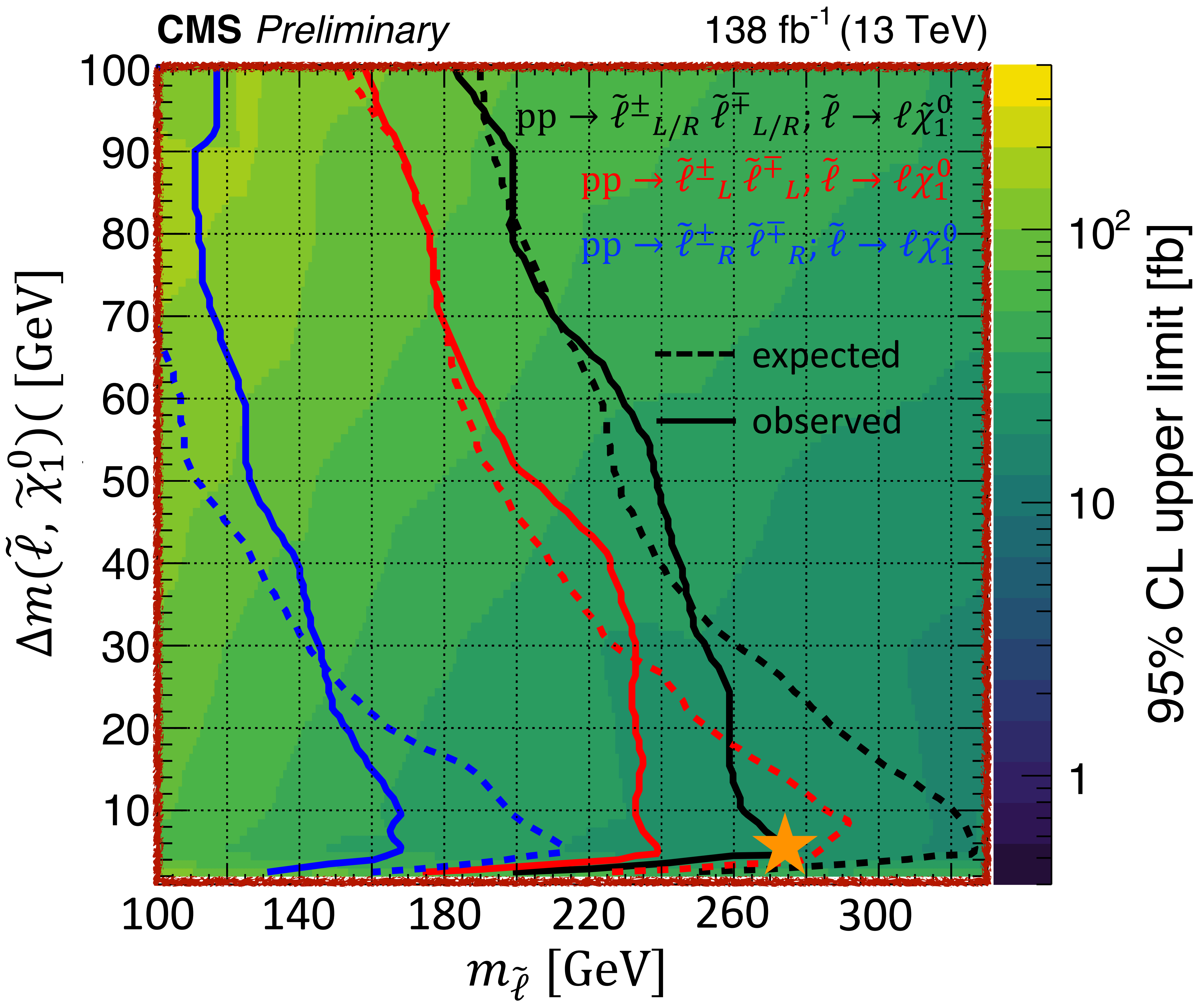


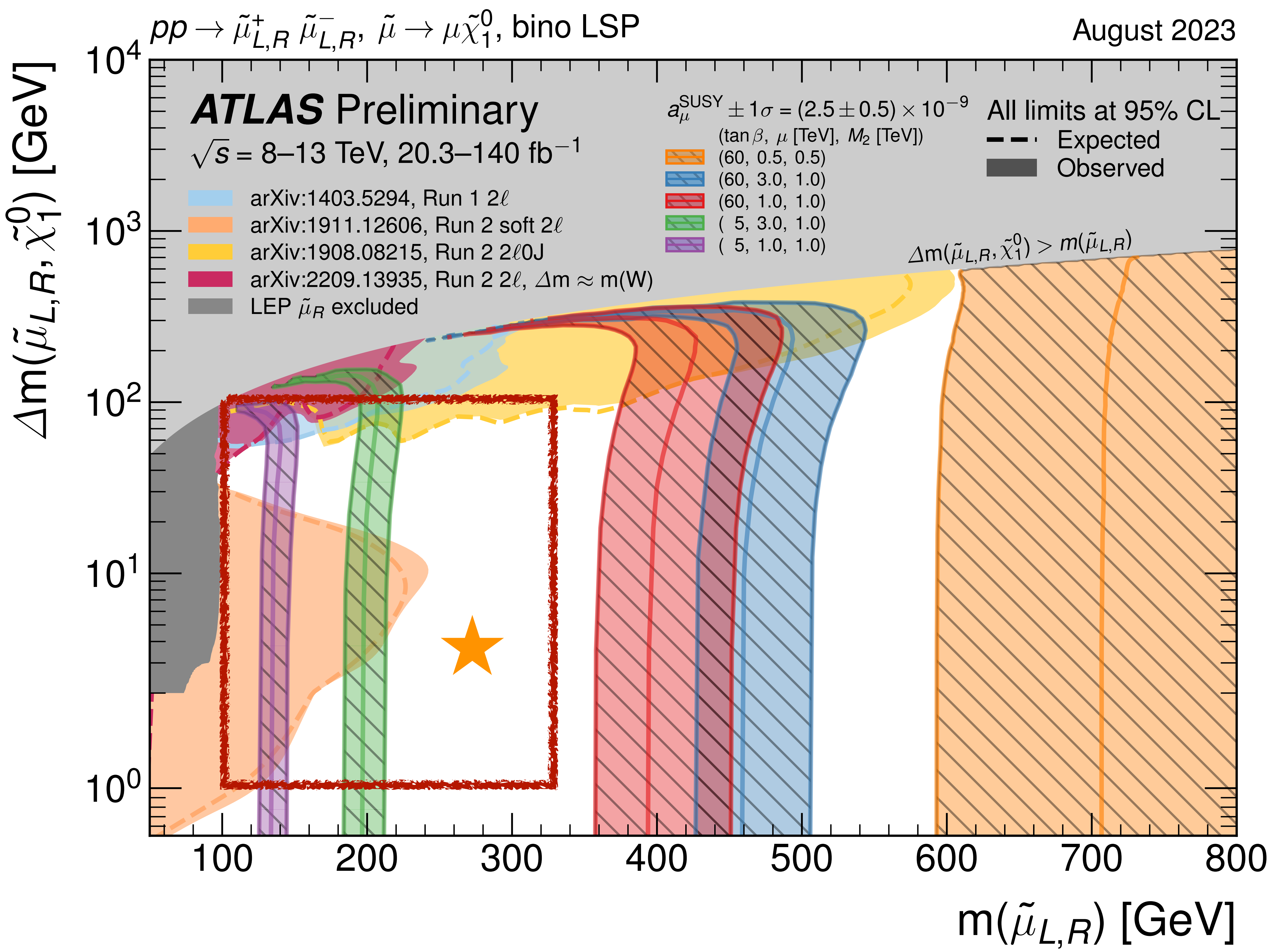
Compressed SUSY Results : Higgsino





Compressed SUSY Results : Slepton





Higgsino Searches by Collider Experiments

Compressed higgsino states explored by existing searches (Soft 2L + Disappearing track)

- **Soft 2-lepton** : Leptons too soft to be reconstructed
- **Disappearing track** : $\tilde{\chi}_1^{\pm}$ lifetime is too short to pass enough inner detector layers

➡ **New analysis method required to cover the compressed mass region ("Higgsino gap")**