SUSY particle searches at LHC

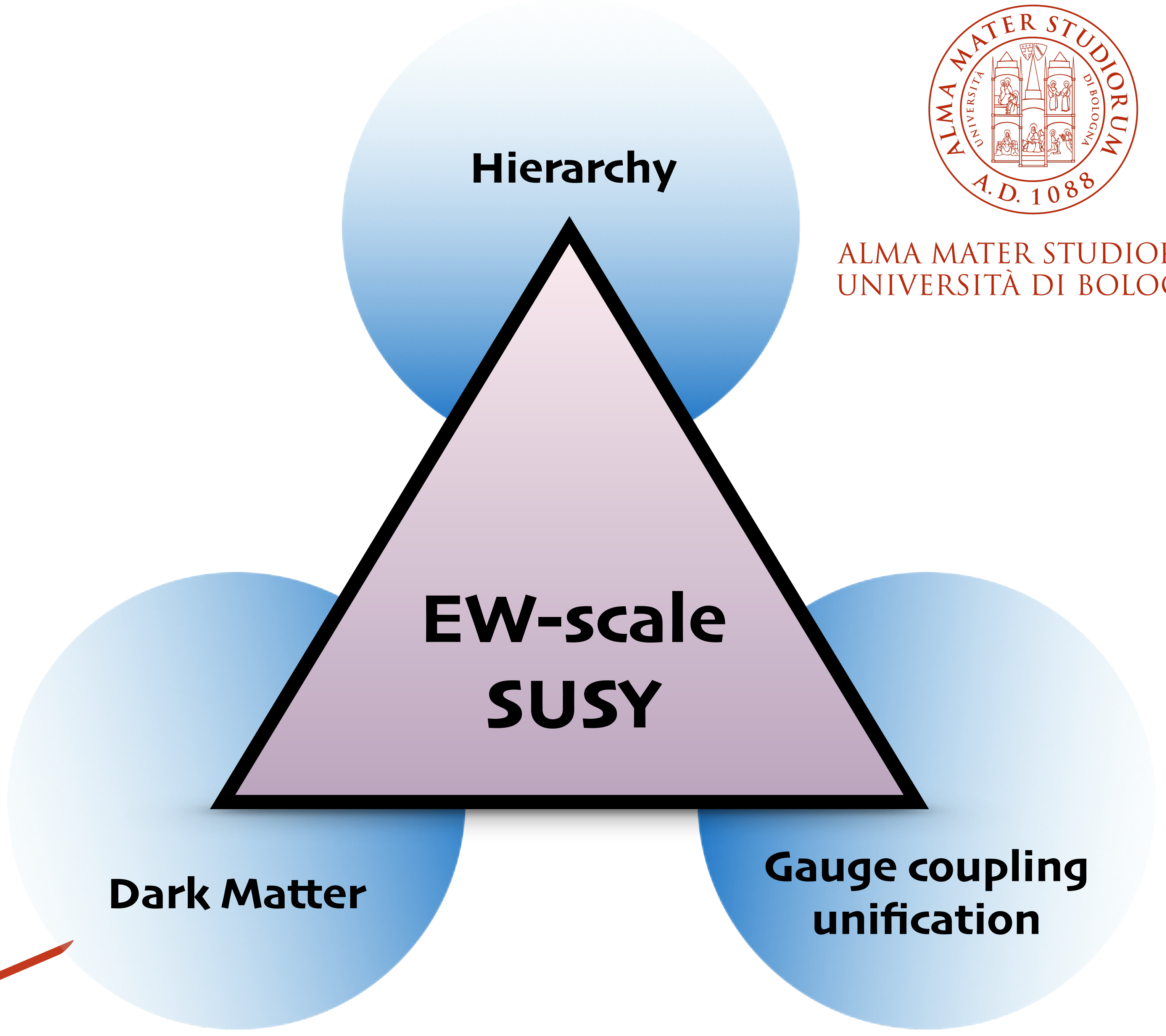
On behalf of the ATLAS and CMS collaborations

Iacopo Vivarelli - DISCRETE 2024 - Ljubljiana 4/12/2024

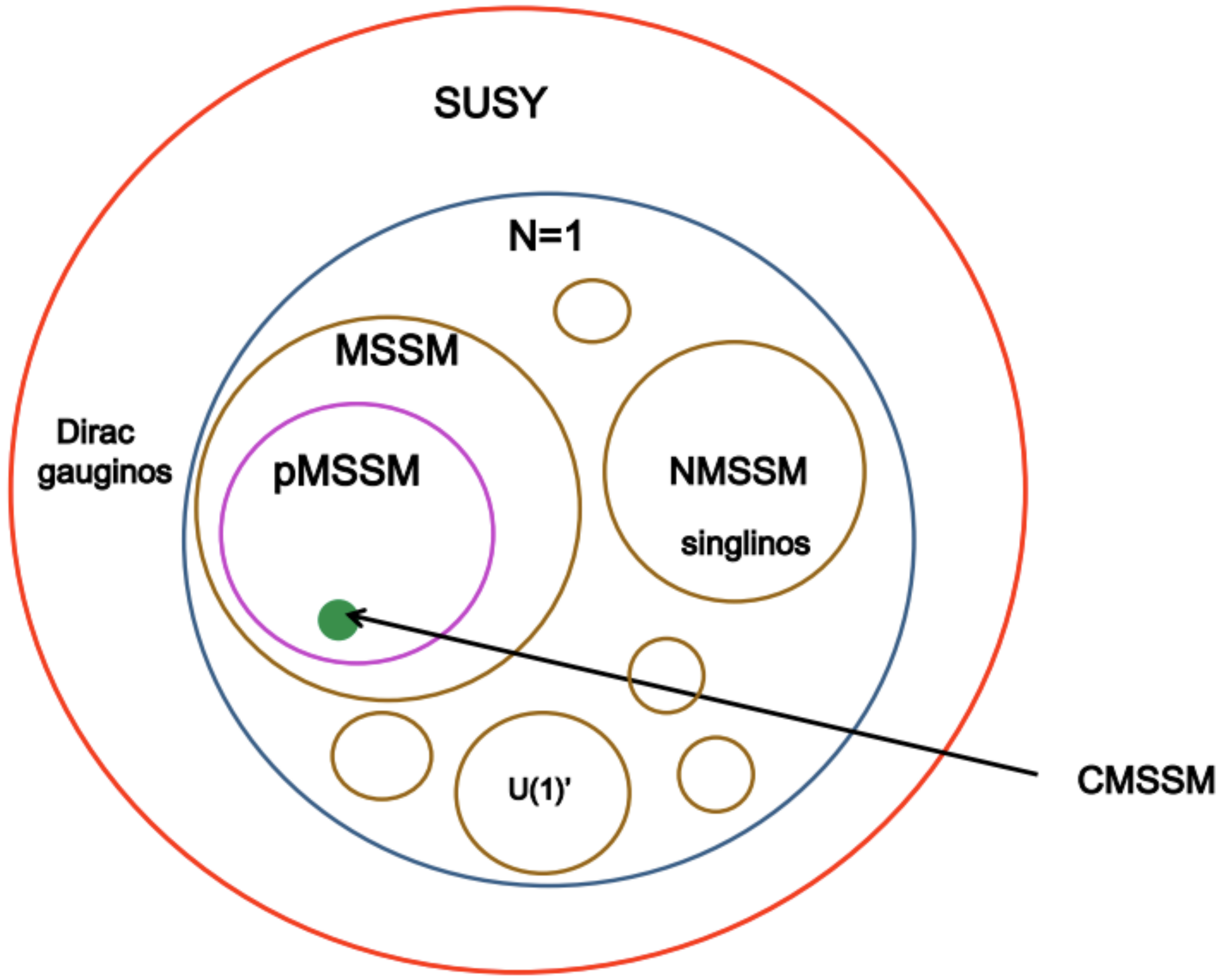
Desperately seeking SUSY…

As a minimum we are dealing with 124 parameters (MSSM) …which can maybe be reduced to 19/20 (pMSSM)

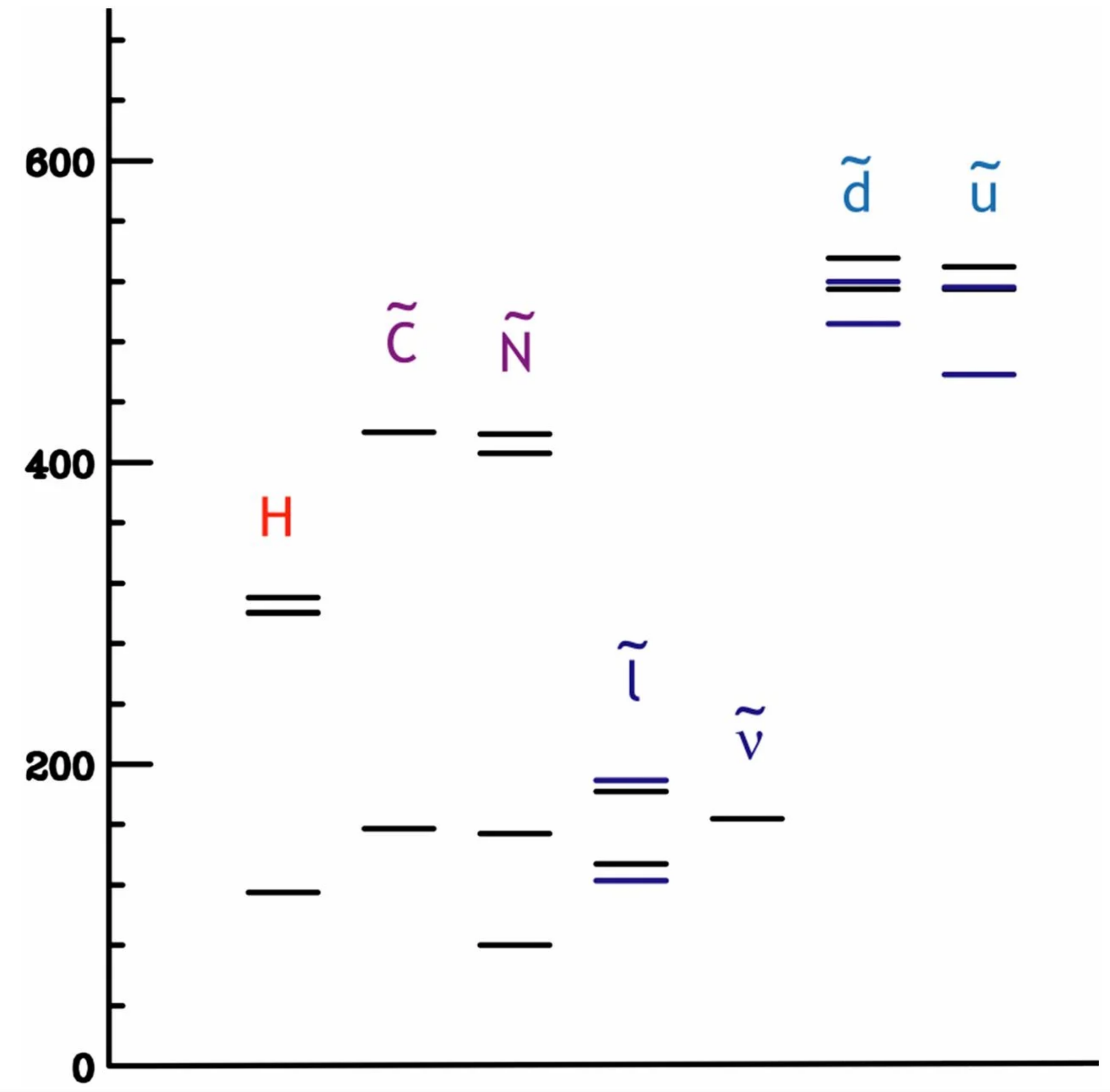
SUSY conserving sector	SUSY breaking sector
3 coupling constants for SU(3)xSU(2)sU(1)	5 3x3 hermitian mass matrices (one per EW multiplet)
4 Yukawa couplings per generation	3 complex 3x3 matrices (Higgs trilinear couplings to sfermions)
	3 mass terms for the Higgs sector + 2 additional off-diagonal terms
	Higgs VEV expectation angle β

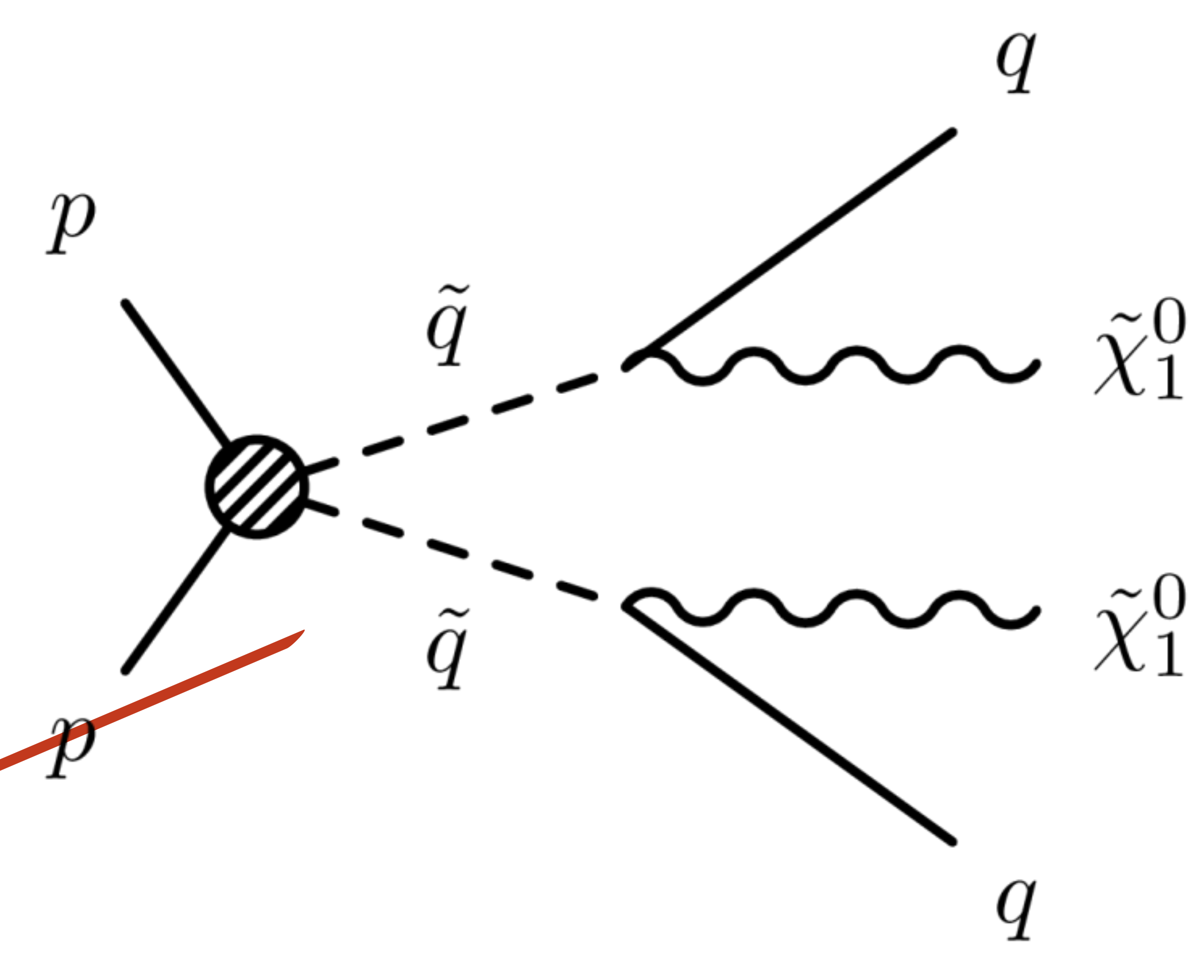


- Given where we are with the data taking, the questions are:
  - Has the LHC found SUSY? **No**
  - Then **what SUSY** has the LHC excluded?
  - How are we covering a **parameter space with high dimensionality**?



Complete Vs Simplified models





Real SUSY models

- Many **concurrent production** processes.
- Many **different decay** modes for SUSY particles.
- **Many diagrams** to target.

- Direct connection to physics.
- Limits apply directly to parameters.
- But… analysis strategy very model dependent.

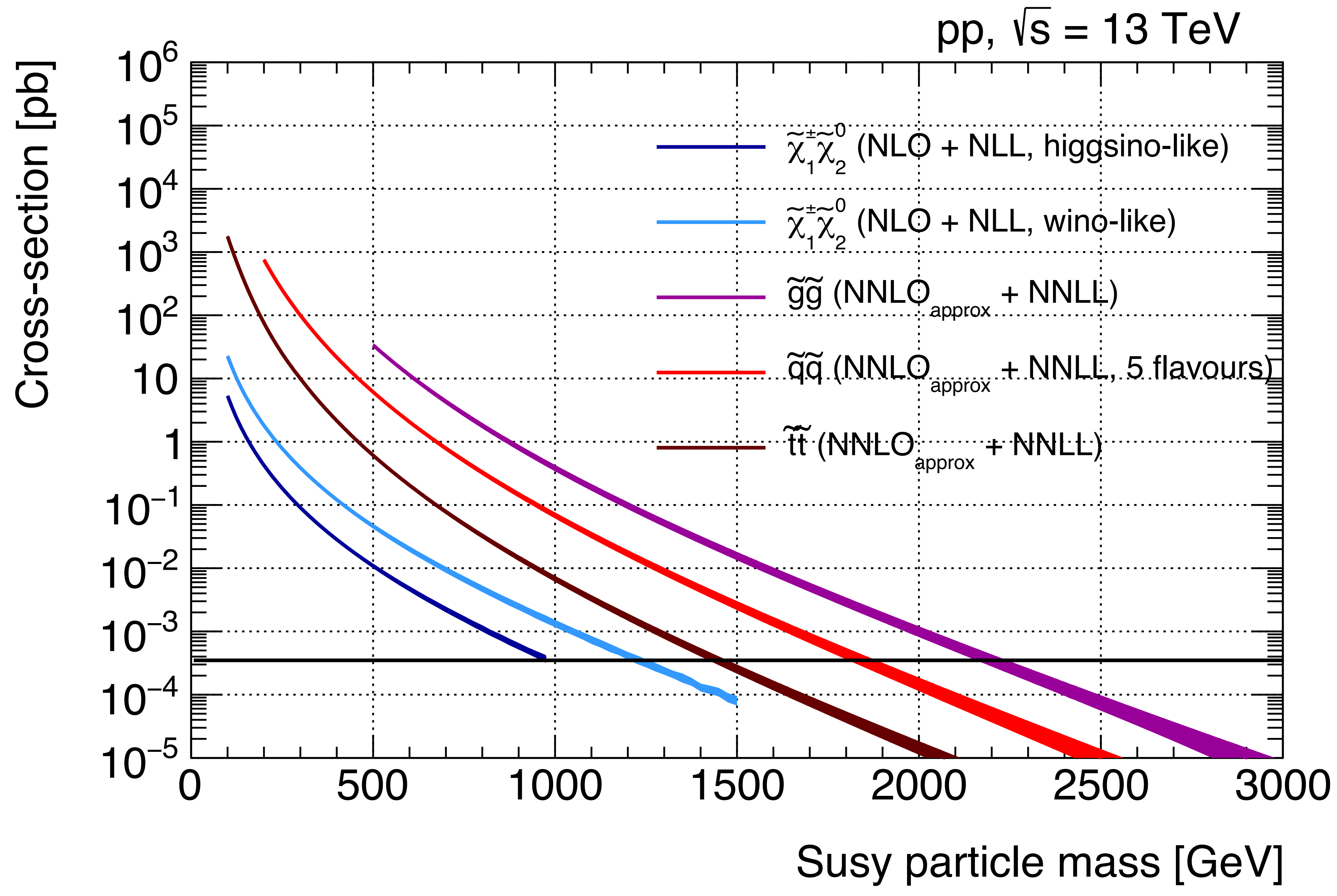
Simplified model

- Very **few production processes** (often only one).
- Very **few decay modes** (often only one).
- **One (or few) diagrams** to target.

- Analysis target a specific topology.
- But… limits on mass parameters should be taken with a pinch of salt.

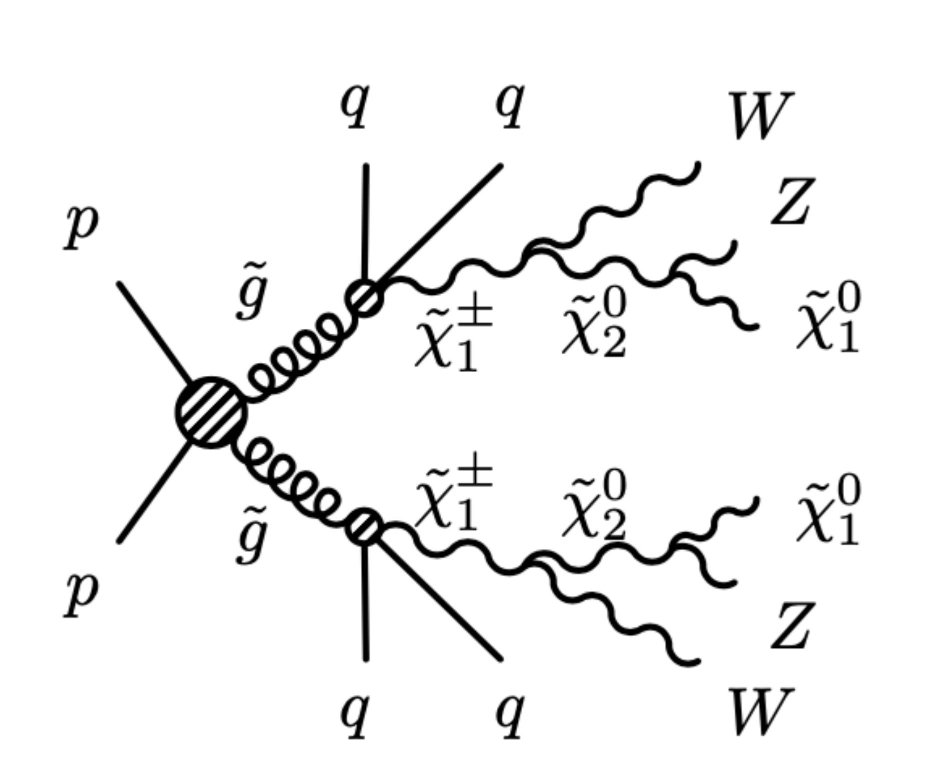
Cross sections

- They depend on **particle masses** and (for EW), on **few model parameters**.
- Thumb rule for experiment sensitivity: **50 produced events determine sensitivity**.
- Expected sensitivities: beyond 2 TeV for $\tilde{g}\tilde{g}$, ~ 1-1.5 TeV for $\tilde{t}\tilde{t}$, ~ 1 TeV for eweakinos.



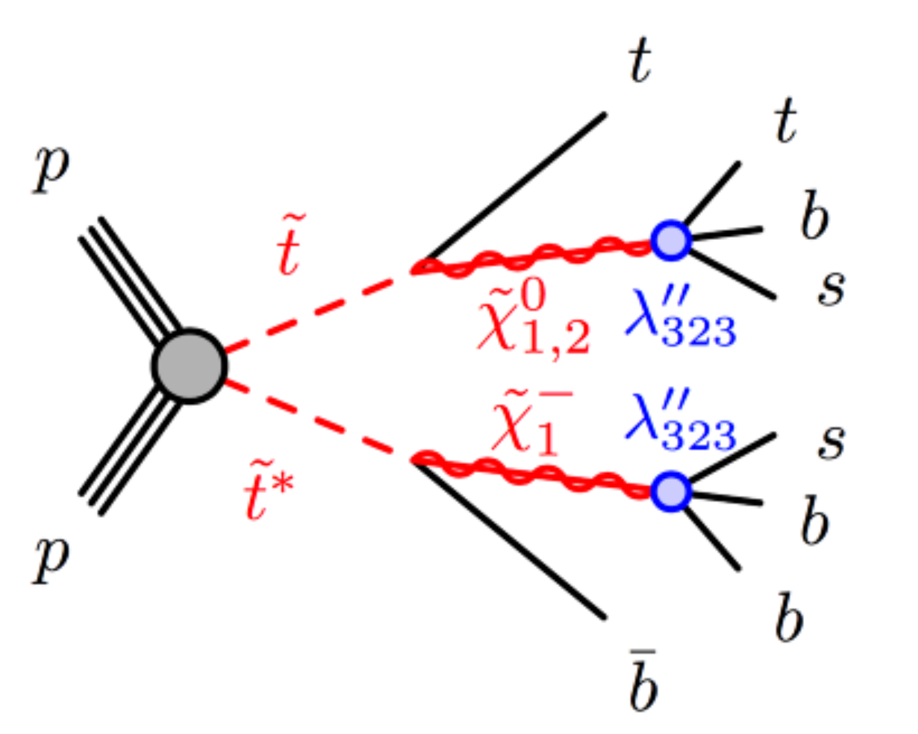
Example decay

R-parity conserving gluino decay.
Signature: p_T^{miss} + stuff

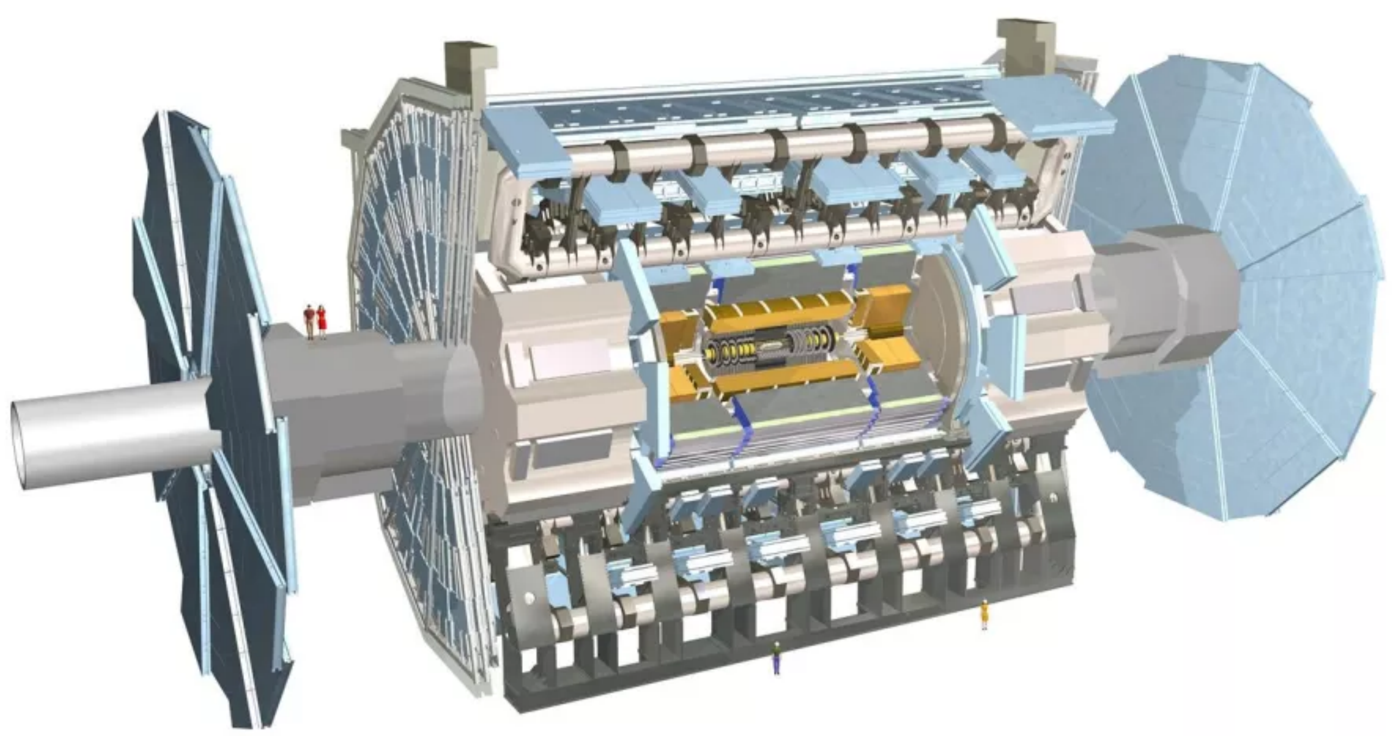


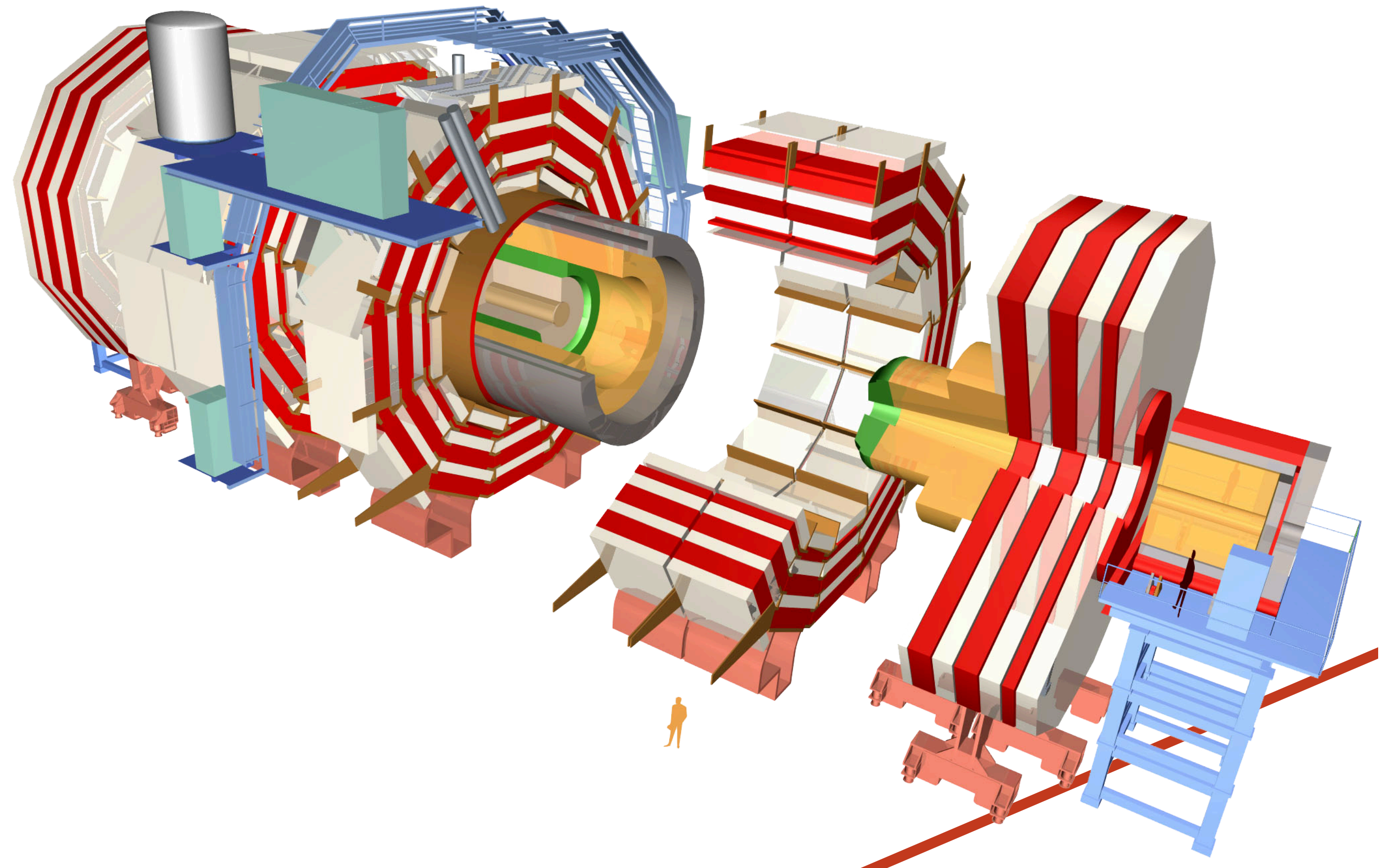
Example decay

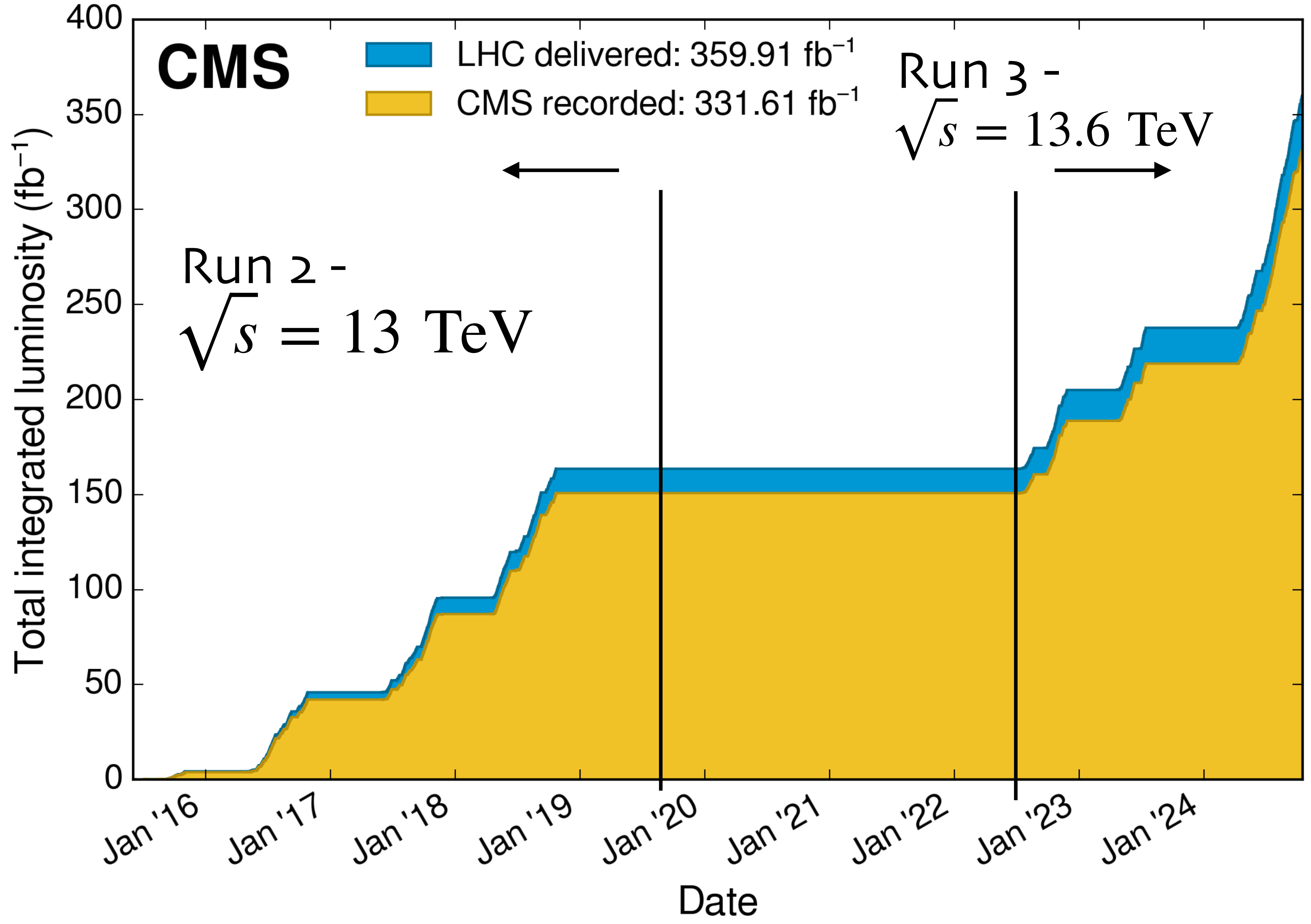
R-parity violating stop decay. **Signature:** no (or small) p_T^{miss}, many jets

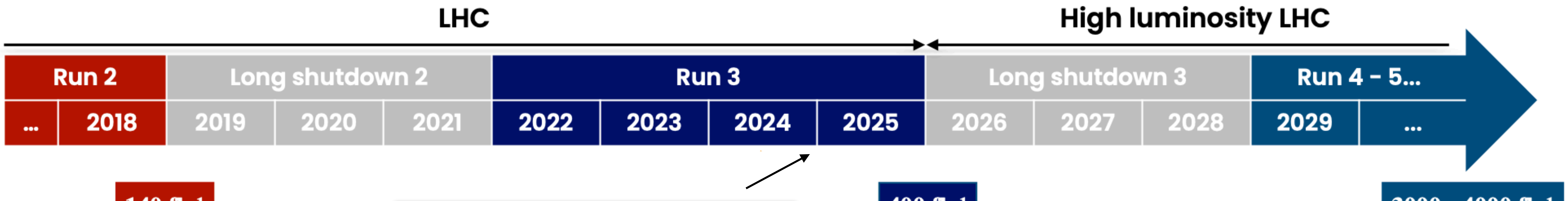


ATLAS & CMS







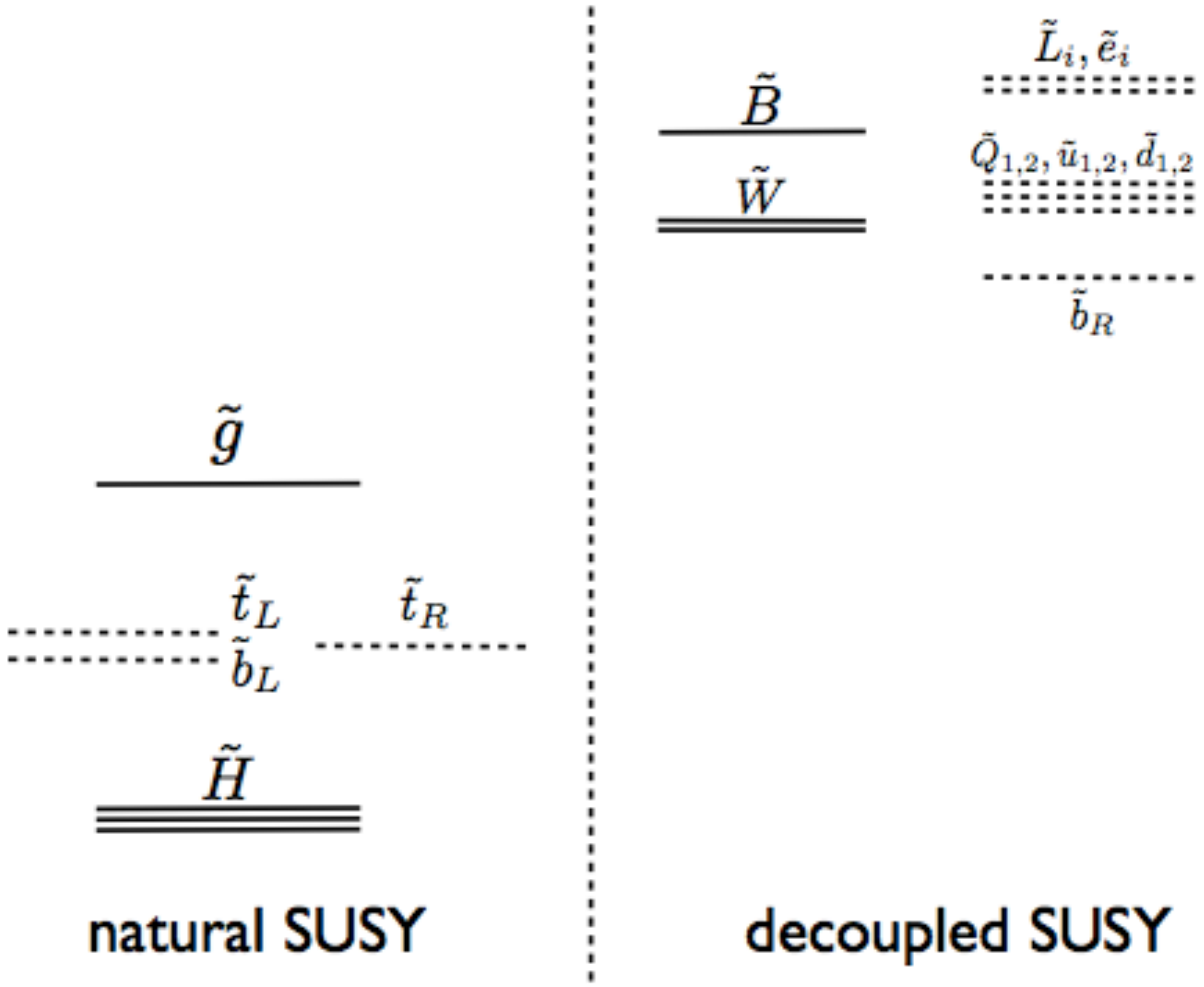


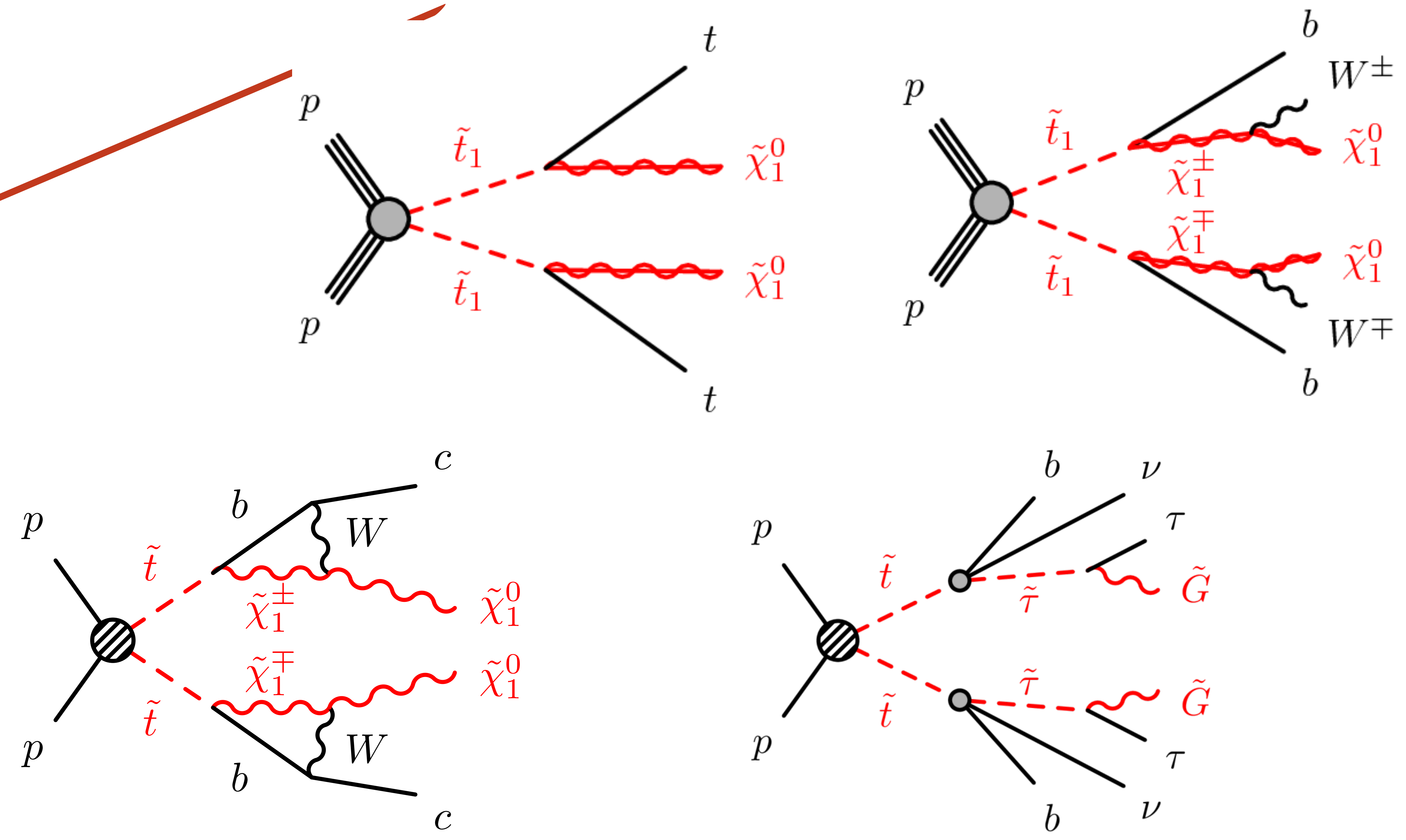
Today, roughly 330 fb^{-1} collected per experiment

Naturalness

- The naturalness of the Higgs boson mass requires:
  - A **Higgsino mass** of maximum **few hundred GeV**.
  - A **top partner** mass at the TeV scale.
  - A **gluino mass** of maximum few TeV.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$





Strong production - gluinos and squarks

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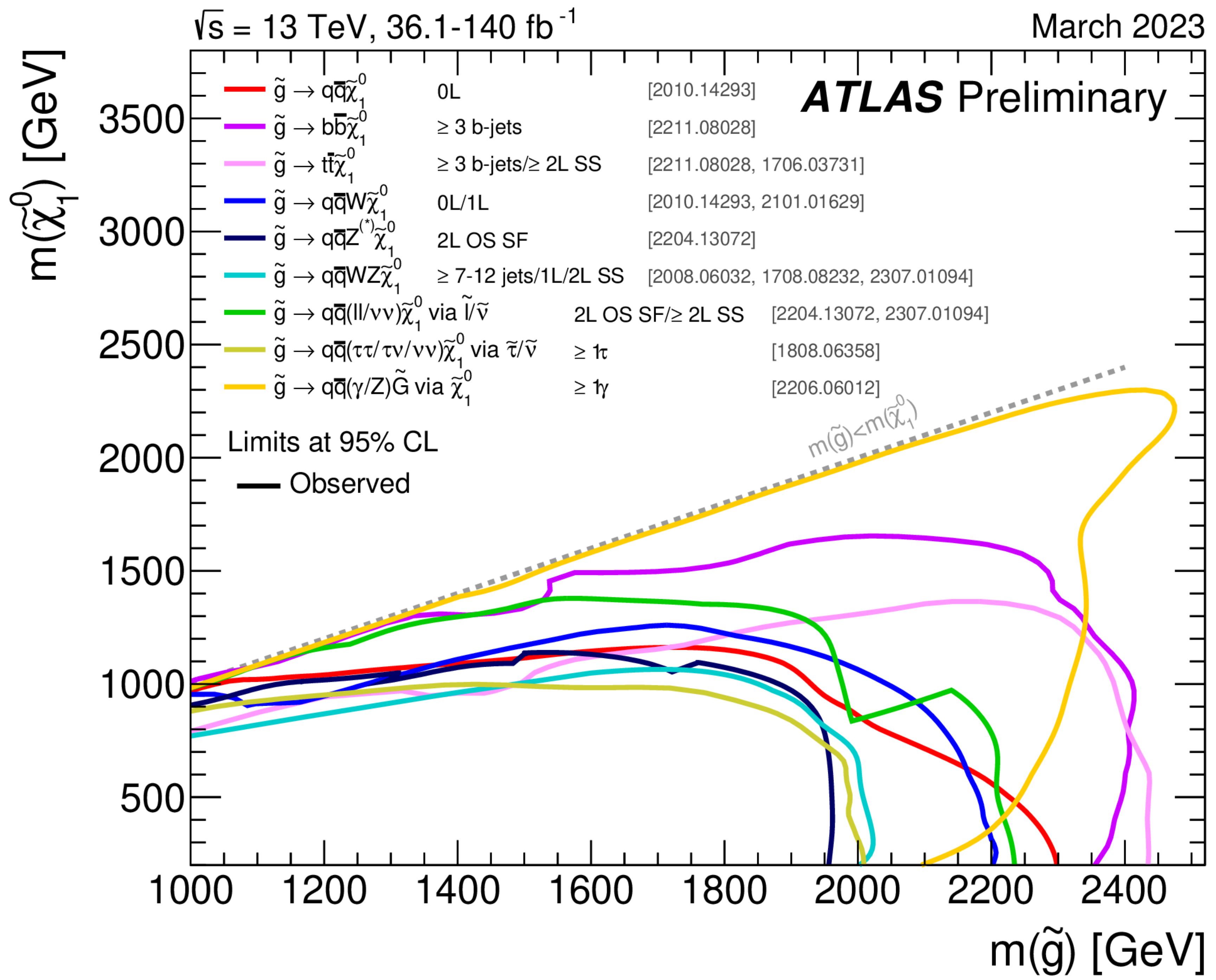
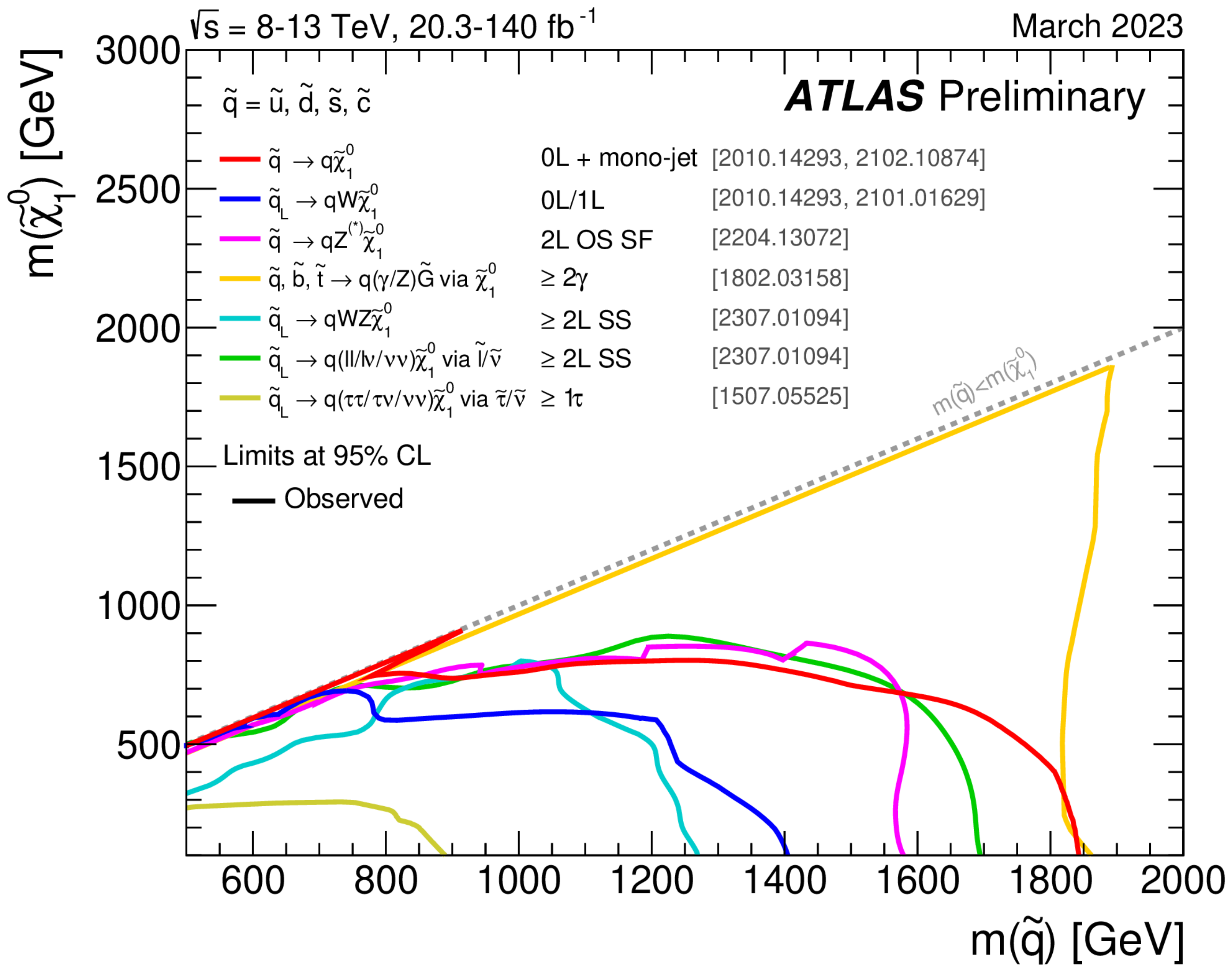
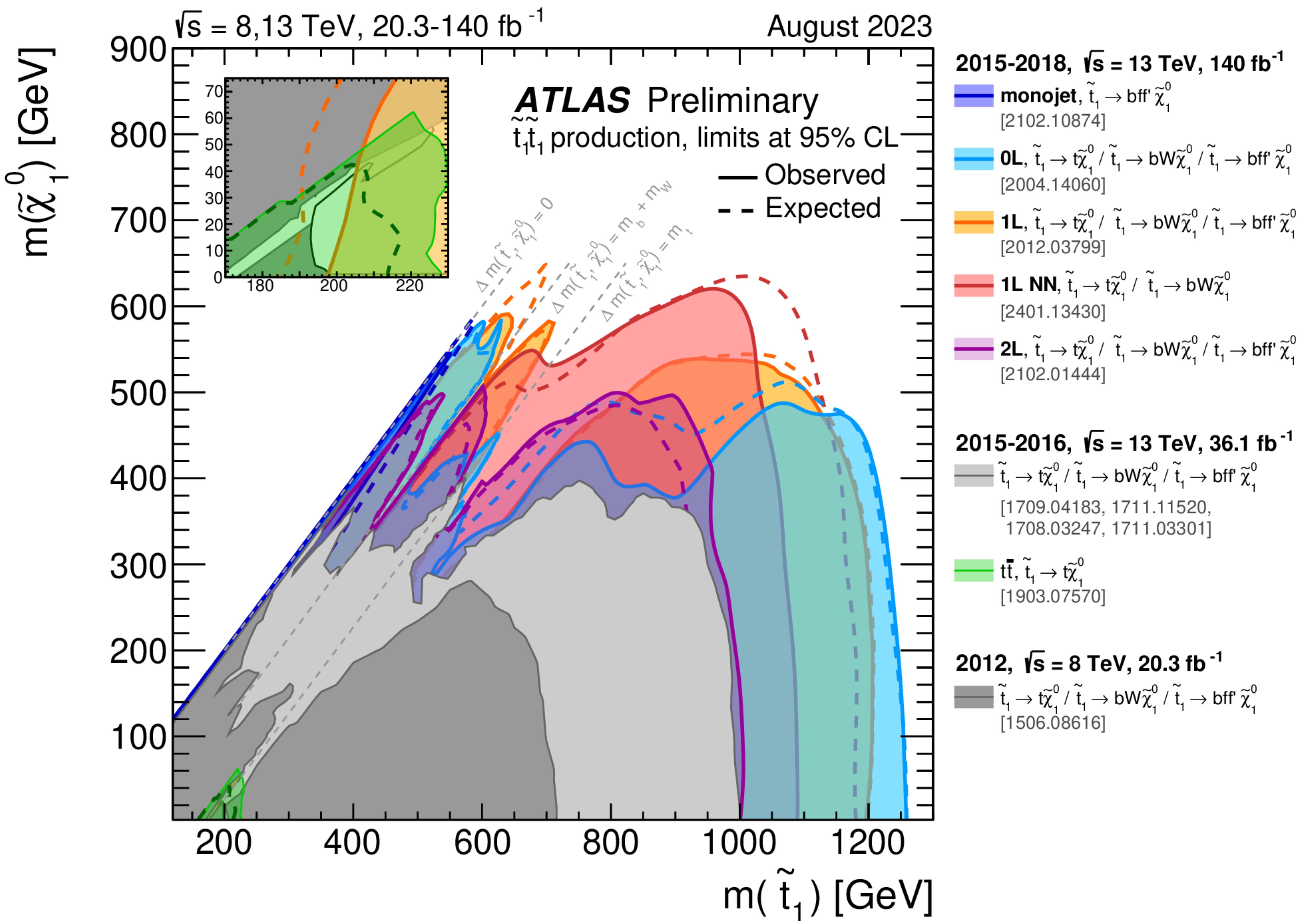




- These plots include **many different scenarios** - each with 100% branching ratio.
- Naive expectations met for **scenarios with large mass separations**. Compressed scenarios lead to **weaker limits**.

Stops

Taken from here



- Search in "standard" scenarios ($\tilde{t} \rightarrow t^{(*)}\tilde{\chi}_1^0$) in full swing.
  - **Simplified model** limits extend **beyond 1 TeV** for small neutrino mass.
- Recent focus on **more "exotic" scenarios**. Two examples:
  - RPV/stealth stop decays to many light jets.
  - Stop to c-quarks

RPV/stealth stop decays

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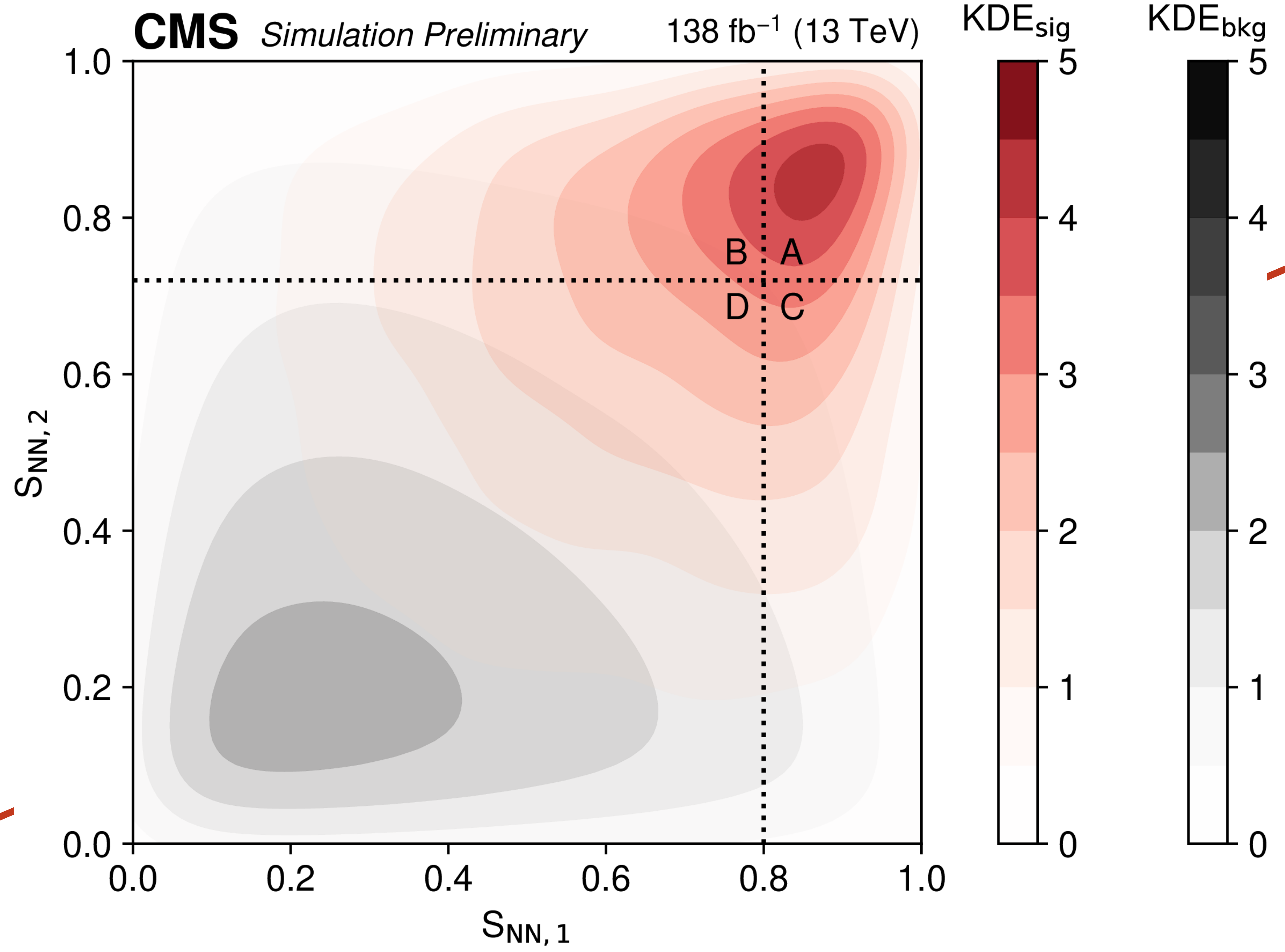
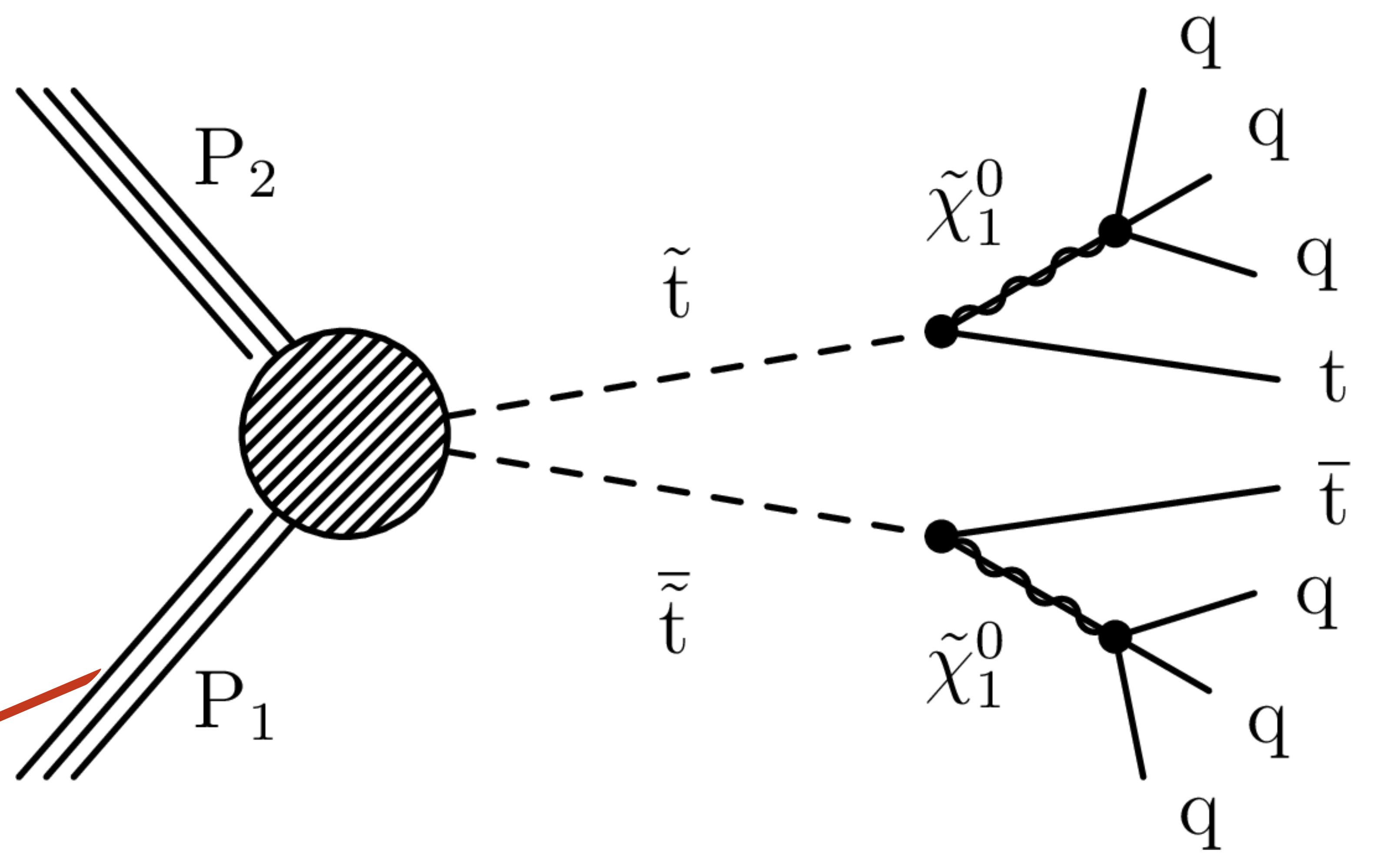
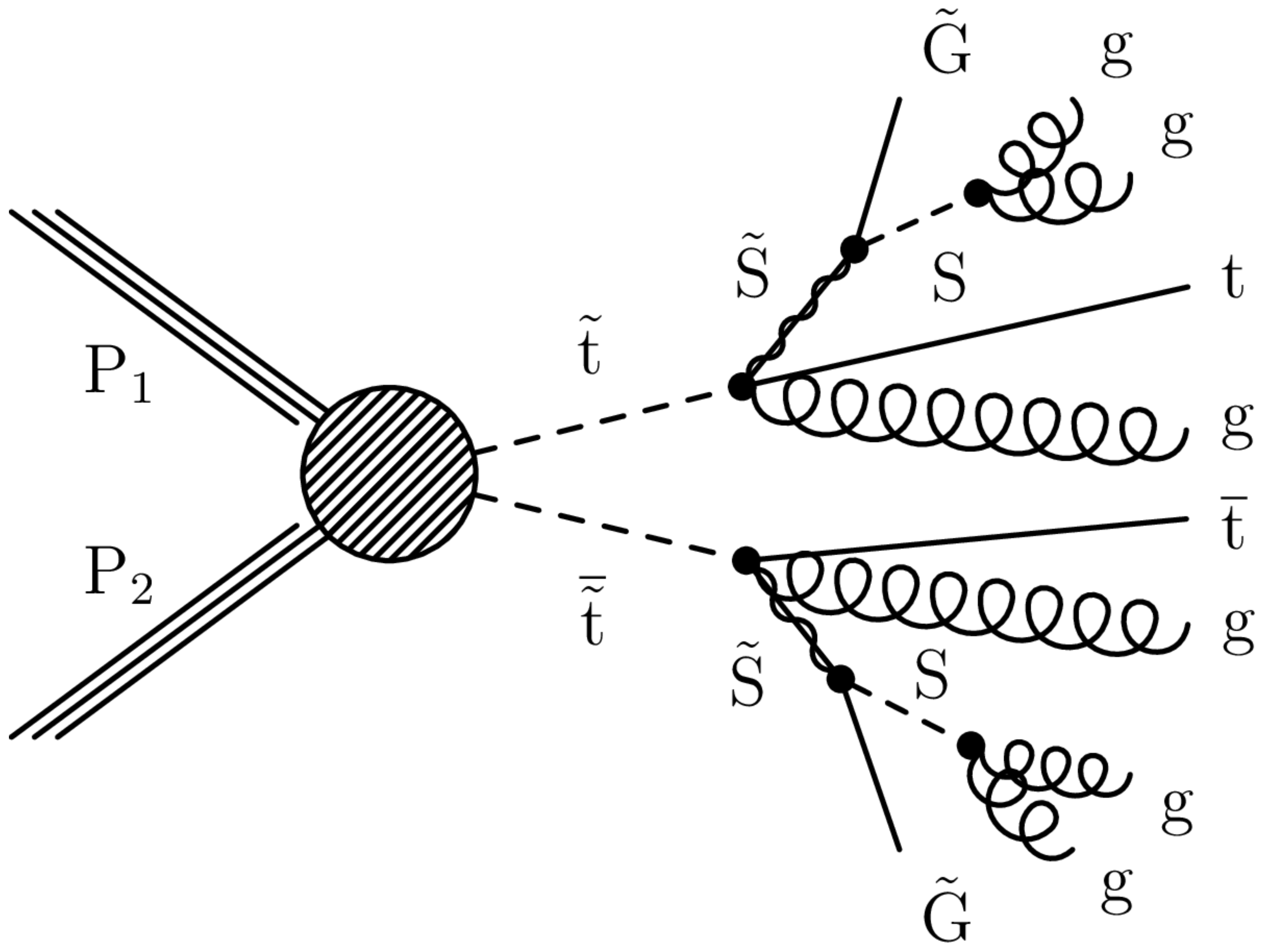
- **0, 1, or 2 leptons** in addition to **at least 6 jets**.
- Dominant $t\bar{t}$ background estimated with data by defining **two decorrelated NN estimators** (Distance correlation loss term - ABCD).







RPV/stealth stop decays

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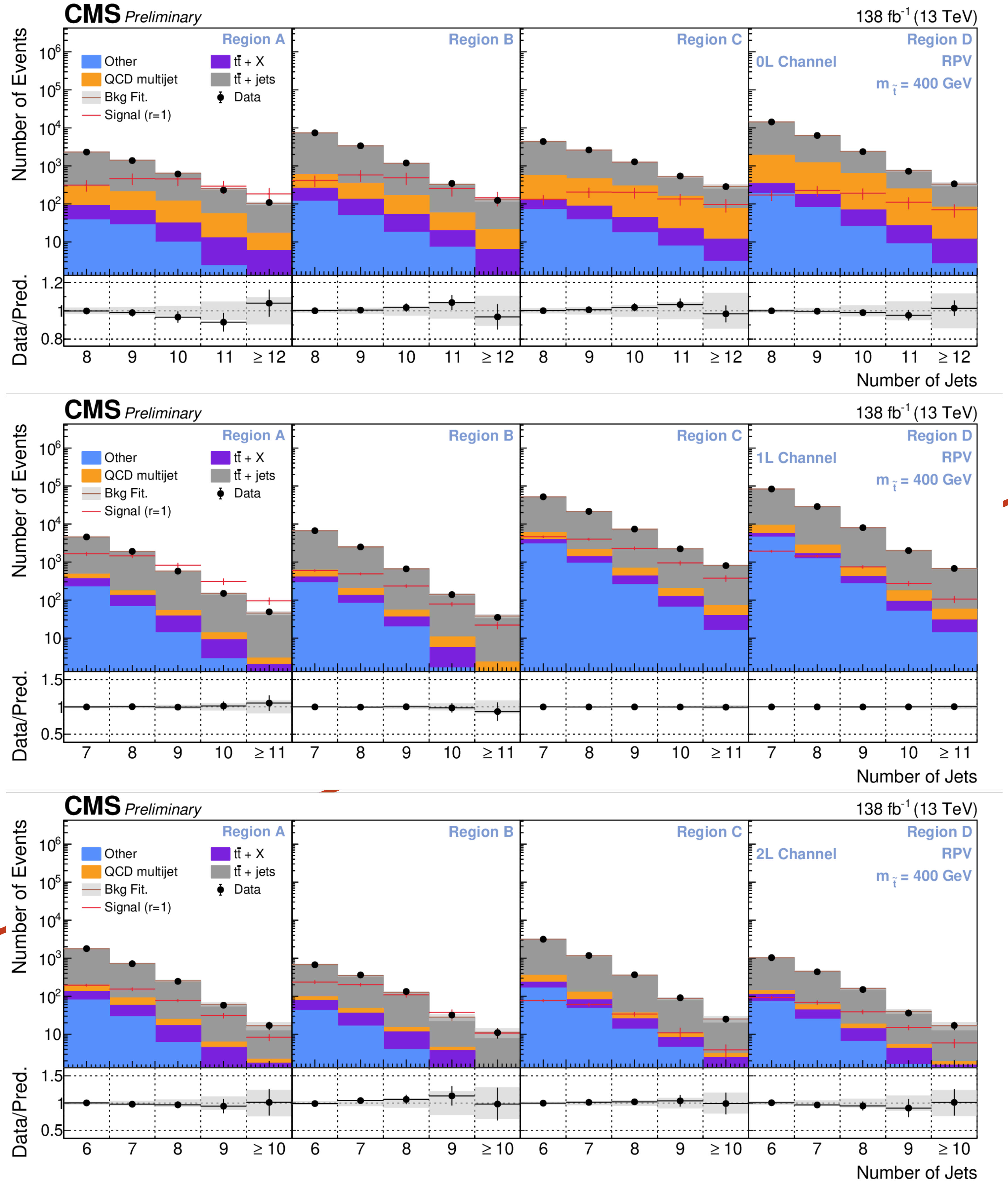
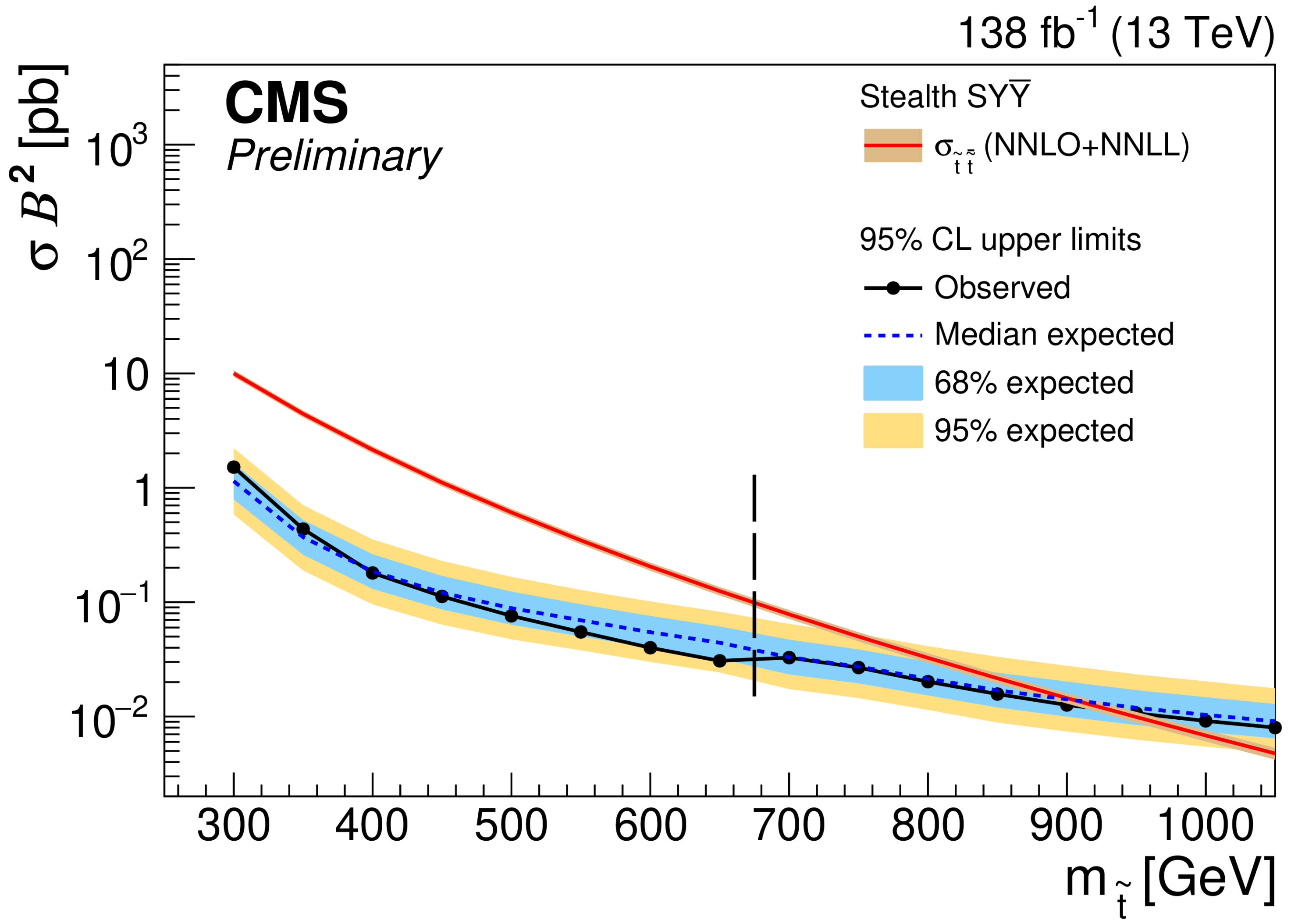
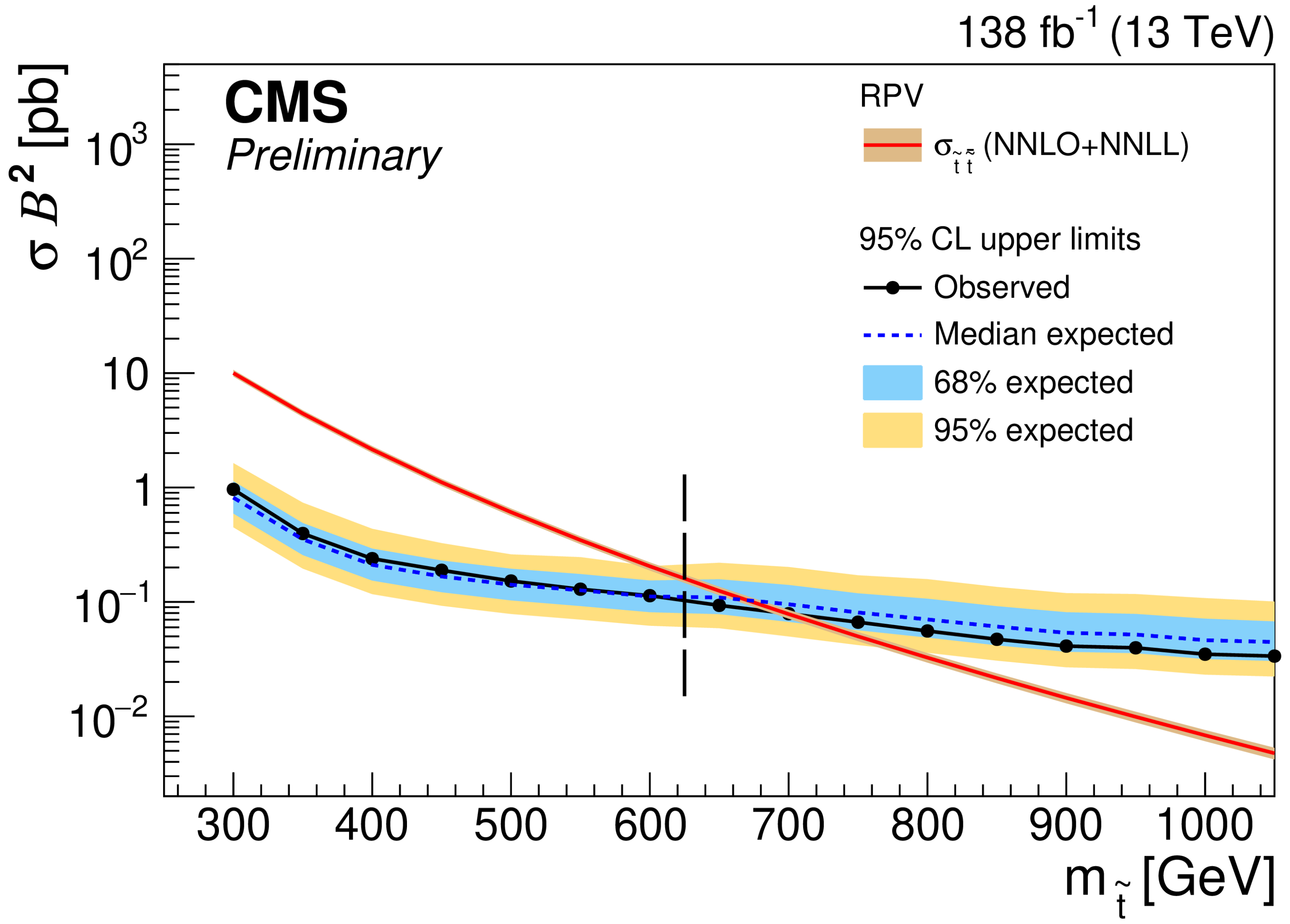
- Non excess above background prediction
- Stops exclusion up to ~ 700 GeV in RPV scenarios, 900 GeV in stealth stop scenarios





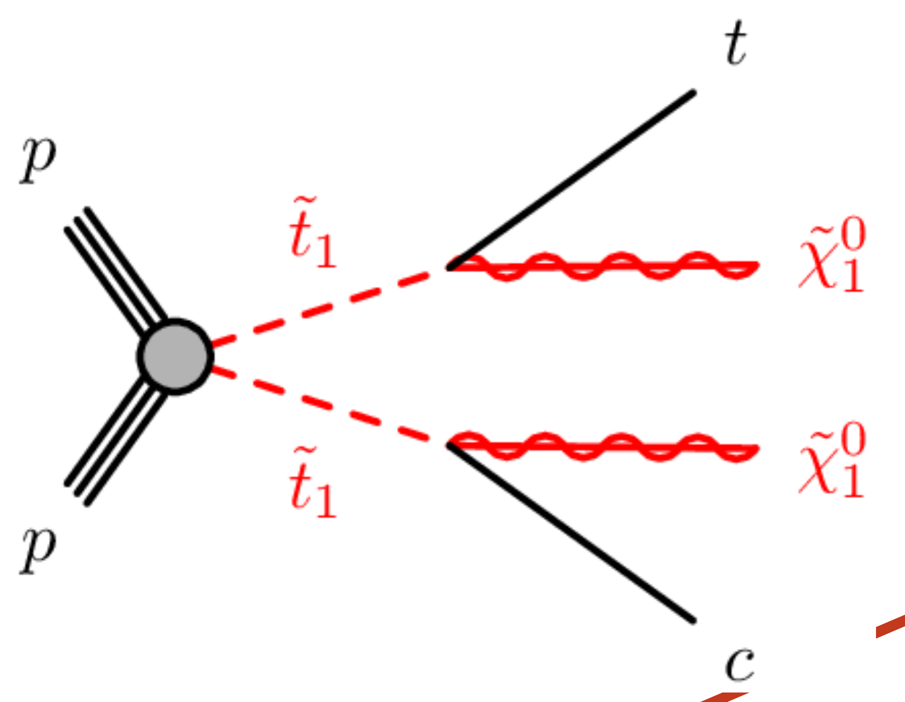


Stop to charm

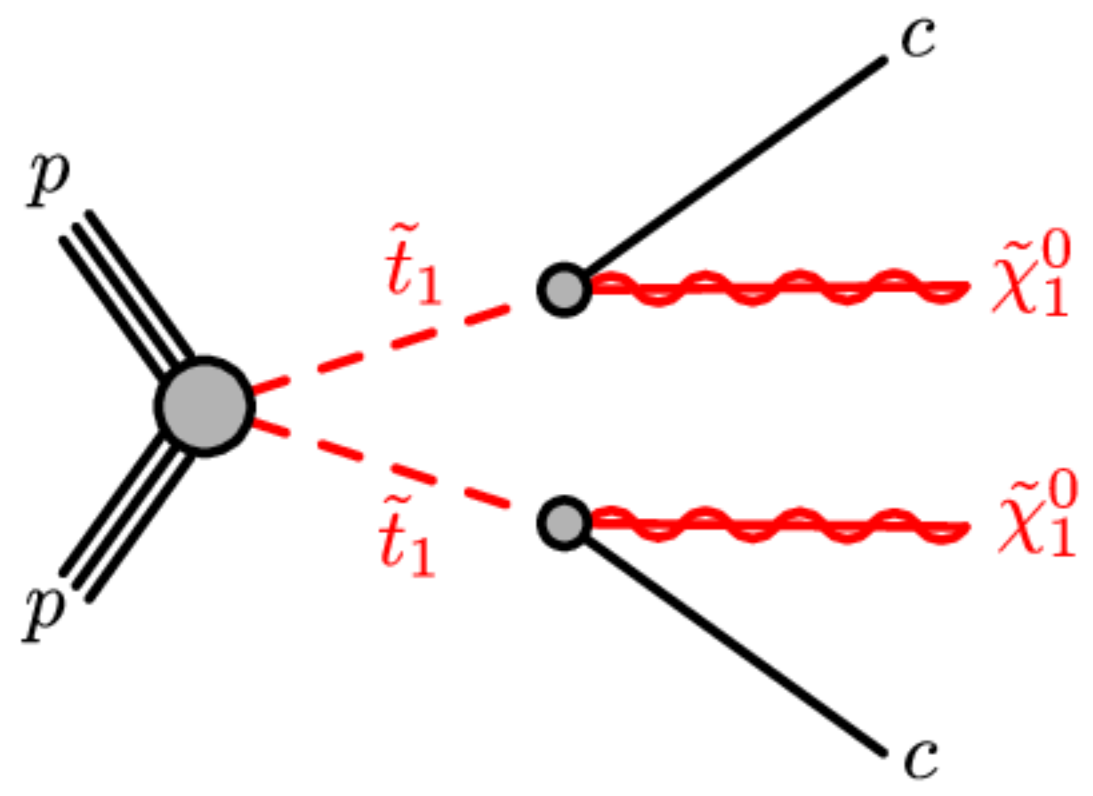
- **Flavour-violating $\tilde{t}_1 \to c\tilde{\chi}^0_1$** can become relevant **depending on the parameter space**.

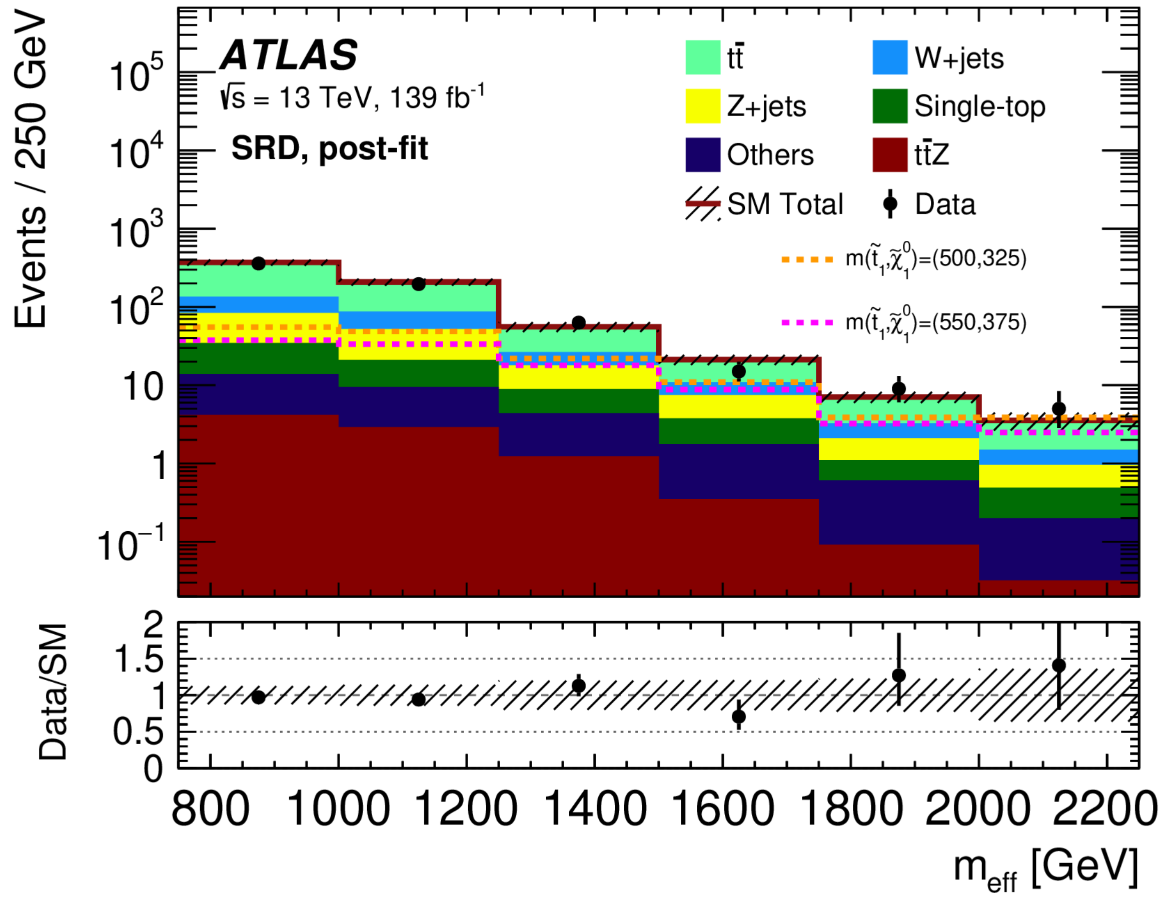
- Targeted using $c-$**tagging** in conjunction with exploiting **ISR jets** (for compressed regimes)

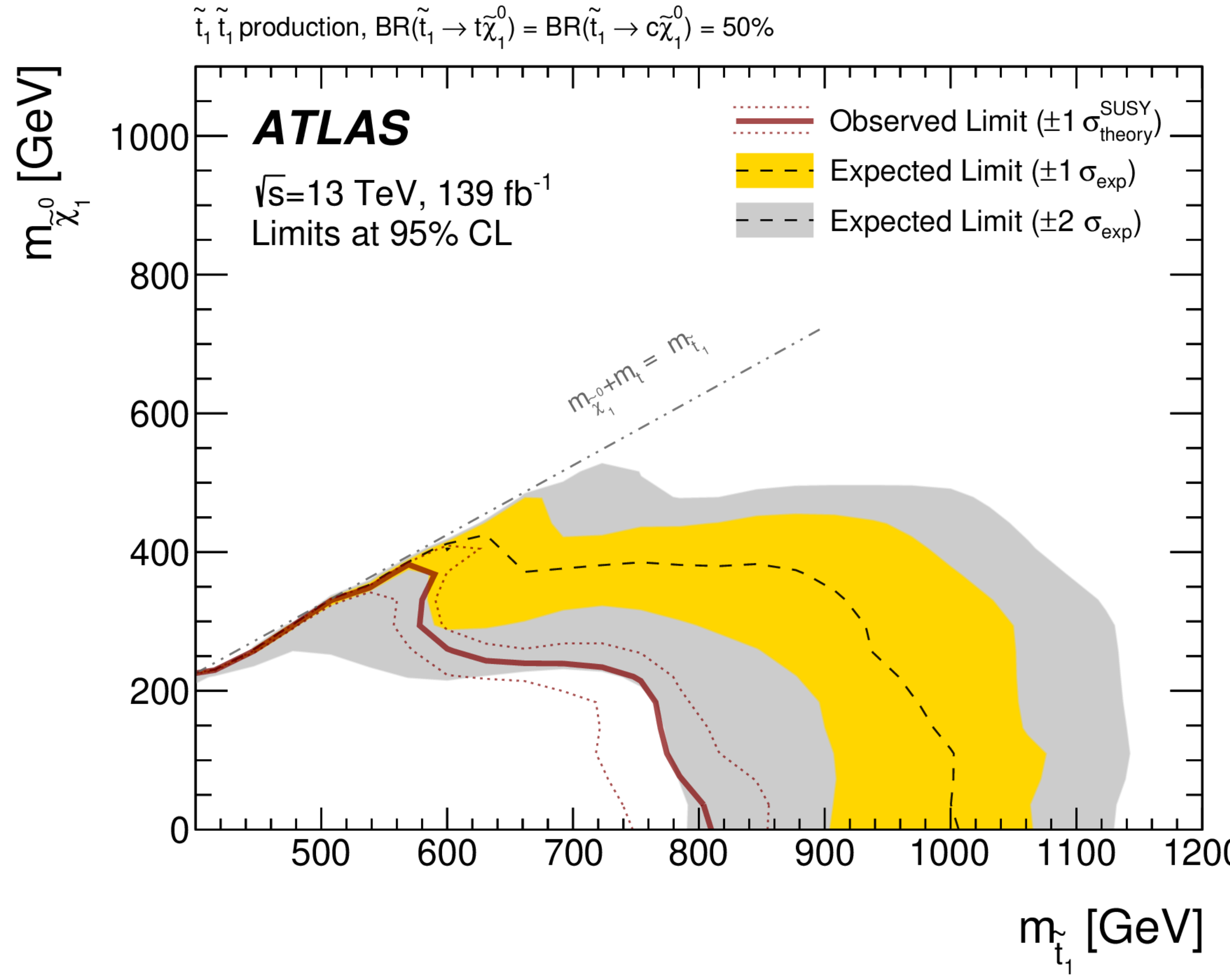
SUSY-2019-23

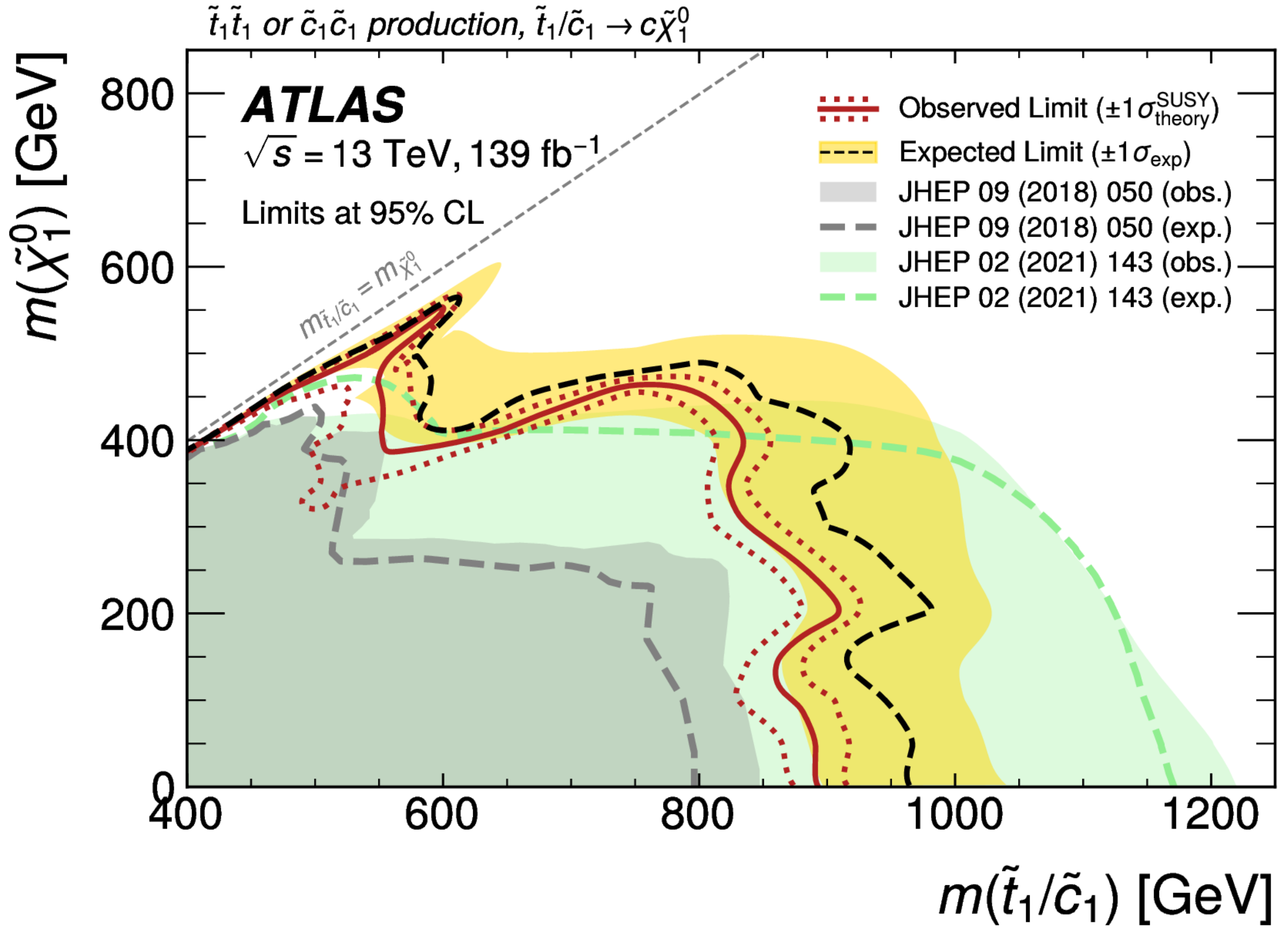


SUSY-2018-25



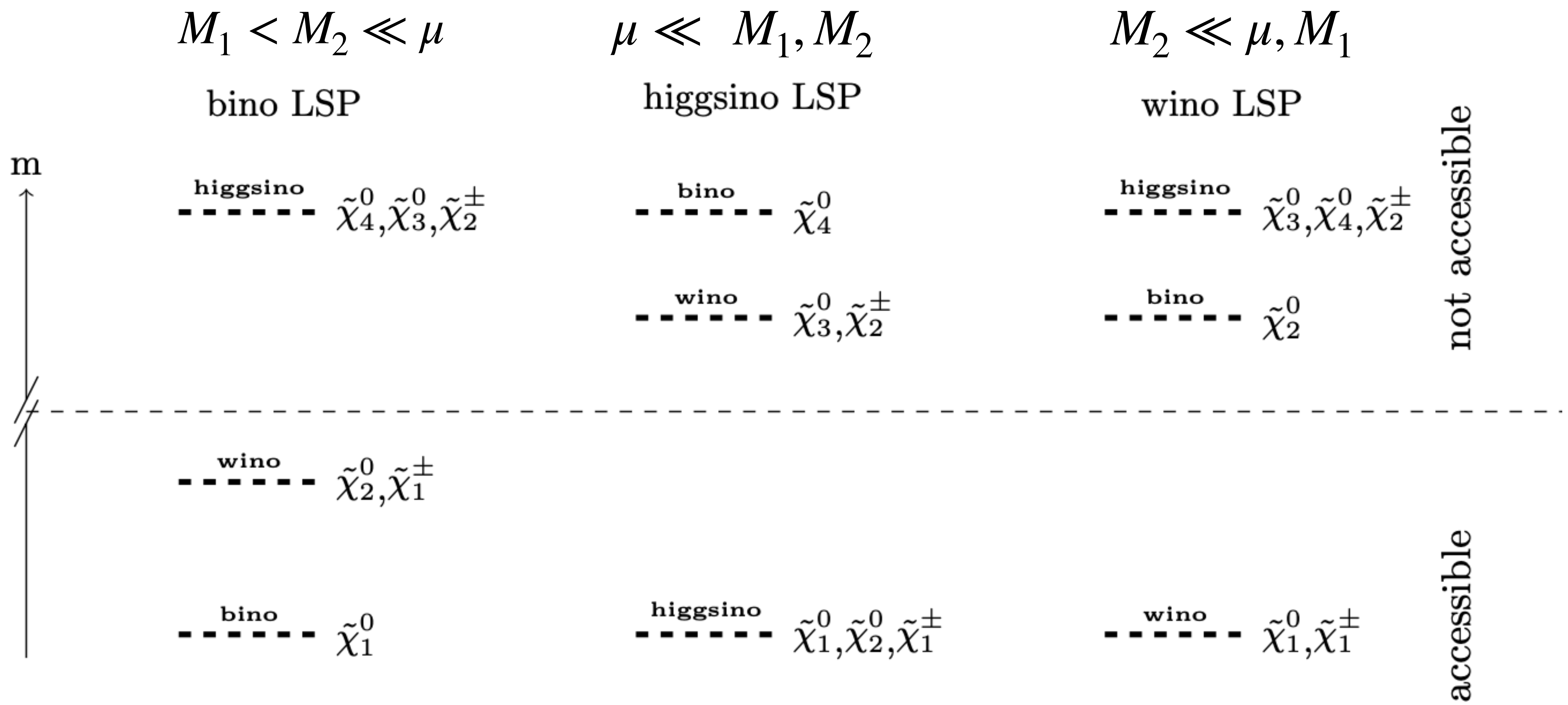






The electroweak sector

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$



…or gravitino LSP (in which case the phenomenology is determined by the NLSP)

mSUGRA/CMSSM, dark matter density typically too high

"Natural" scenarios, dark matter density typically too low

Dark matter density typically too low

GGM-like scenarios, dark matter difficult to get right.

Electroweak production

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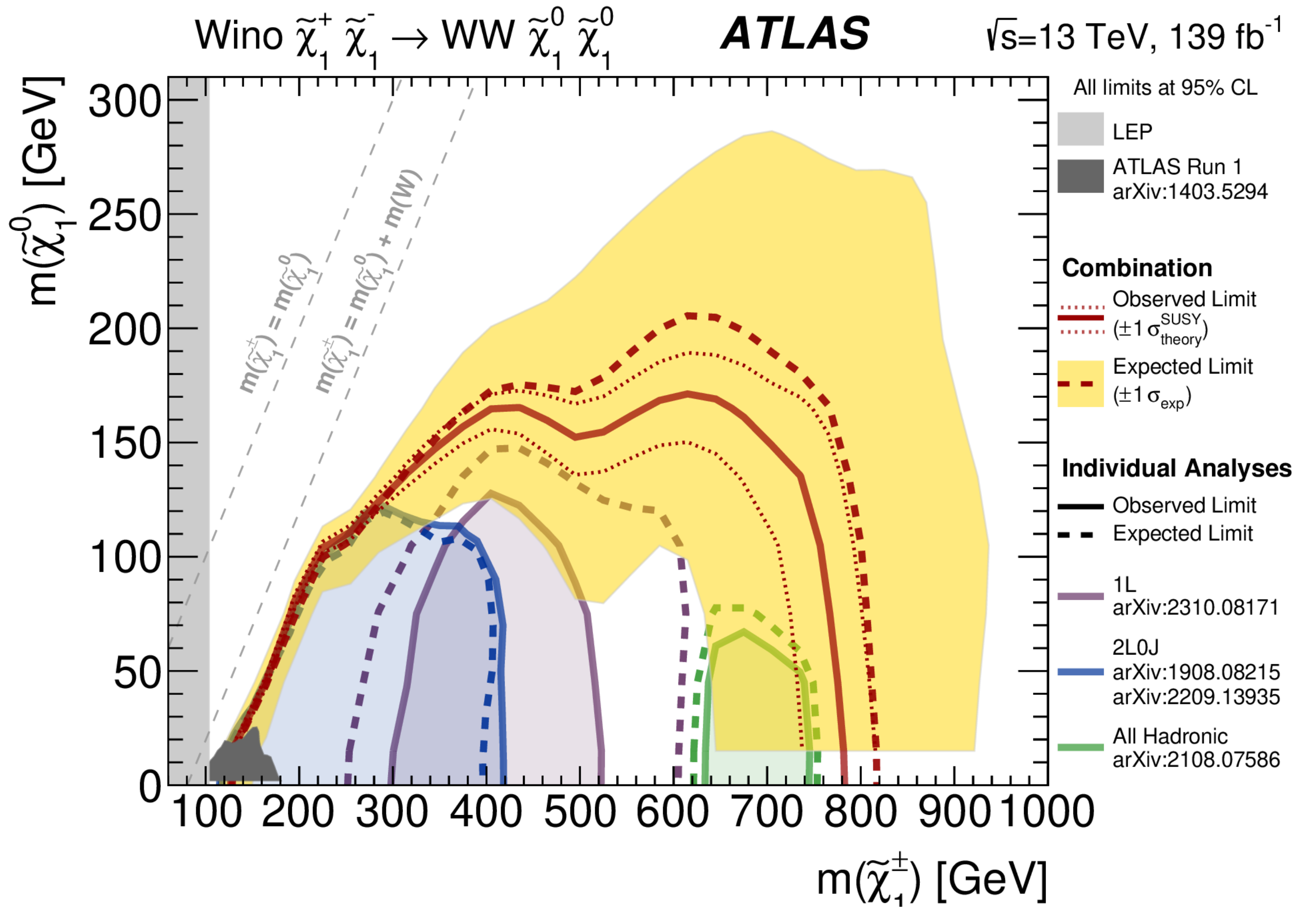
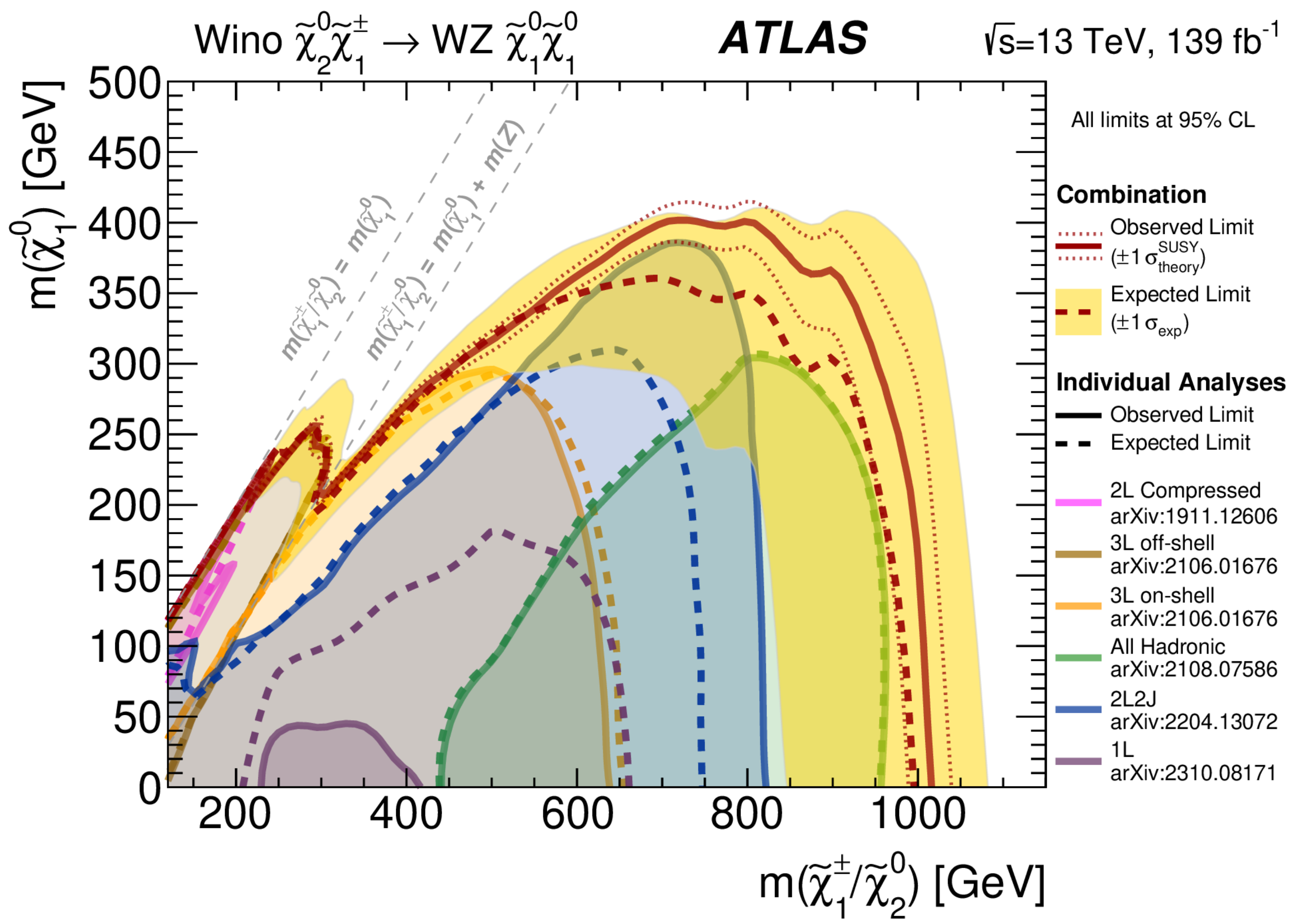
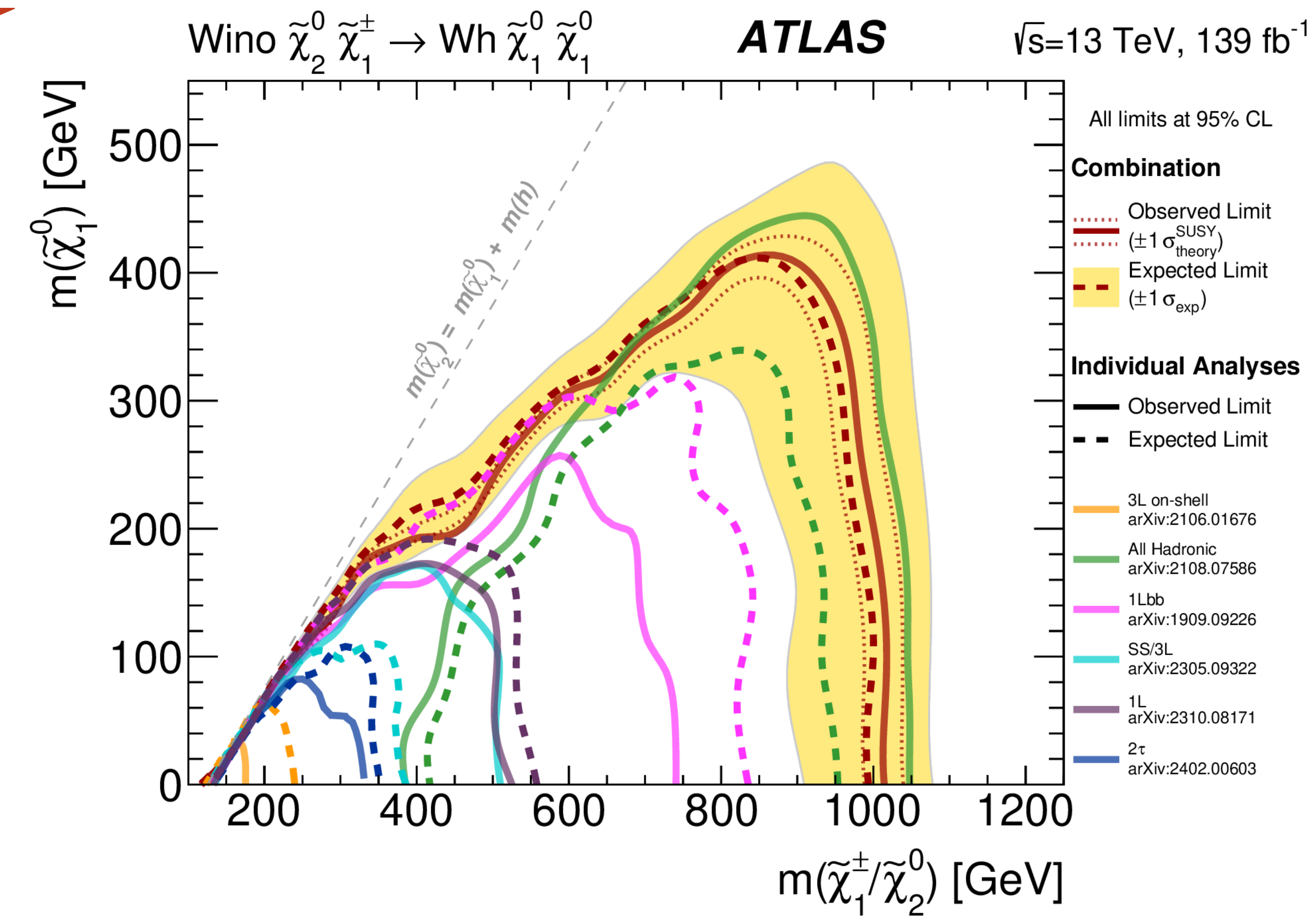
- **Bino-LSP scenarios** - the “historical” electroweak SUSY.
- Limits start to **knock at the TeV scale** (thanks to all-hadronic analyses - a nice development of Run 2)
- Focus shifted to less common scenarios.

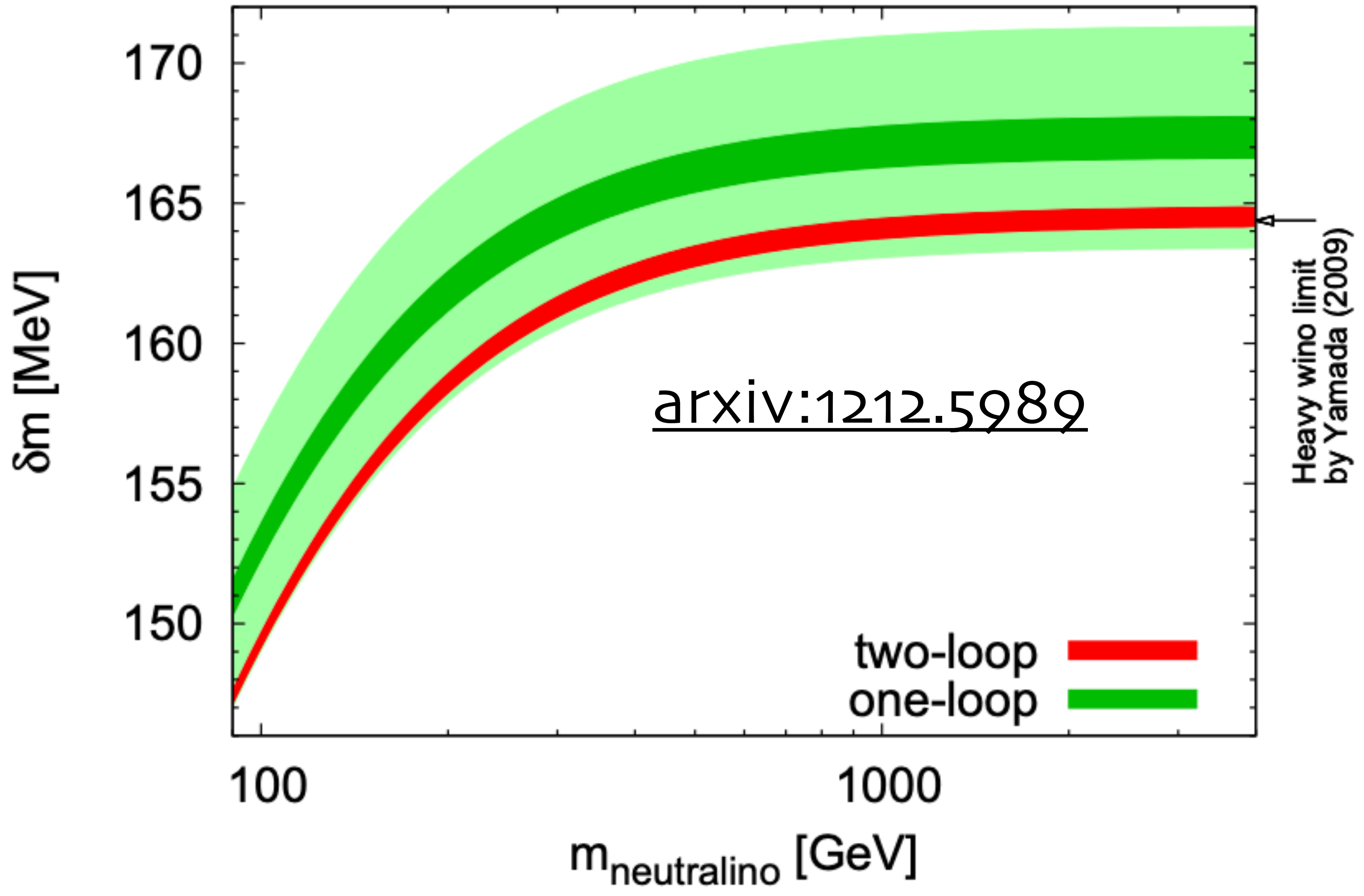


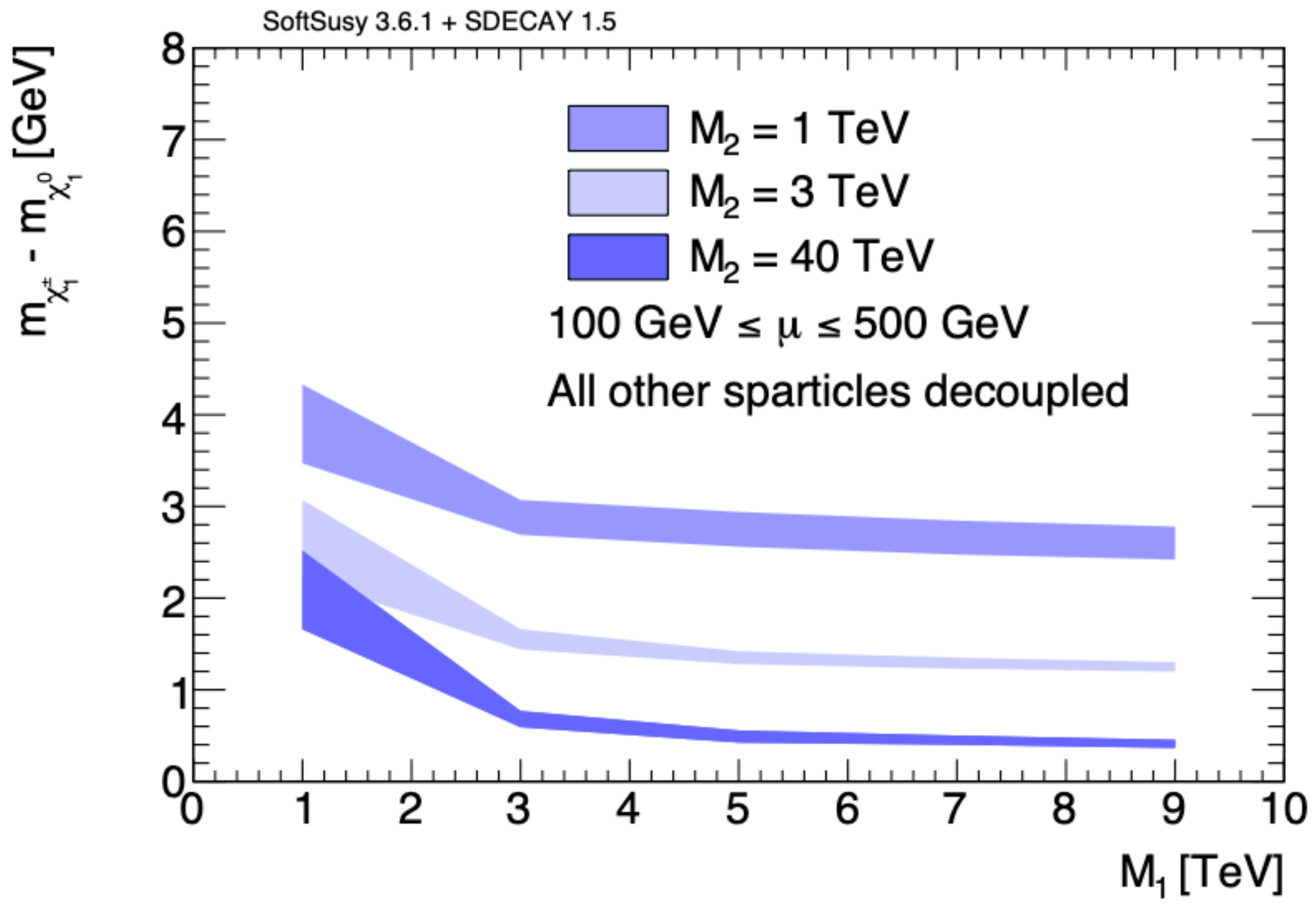




Compressed electroweakino spectra

- Wino-LSP: $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 150$ MeV implies long-lived charginos.
- Higgsino-LSP: $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 300$ MeV may imply slightly long-lived $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ (but requires very large M_1/M_2. More natural $\Delta M(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim o(10 \text{ GeV})$)
  - And higgsinos at the heart of the naturalness argument
- Run 2: the **golden age** of the **compressed scenarios**.

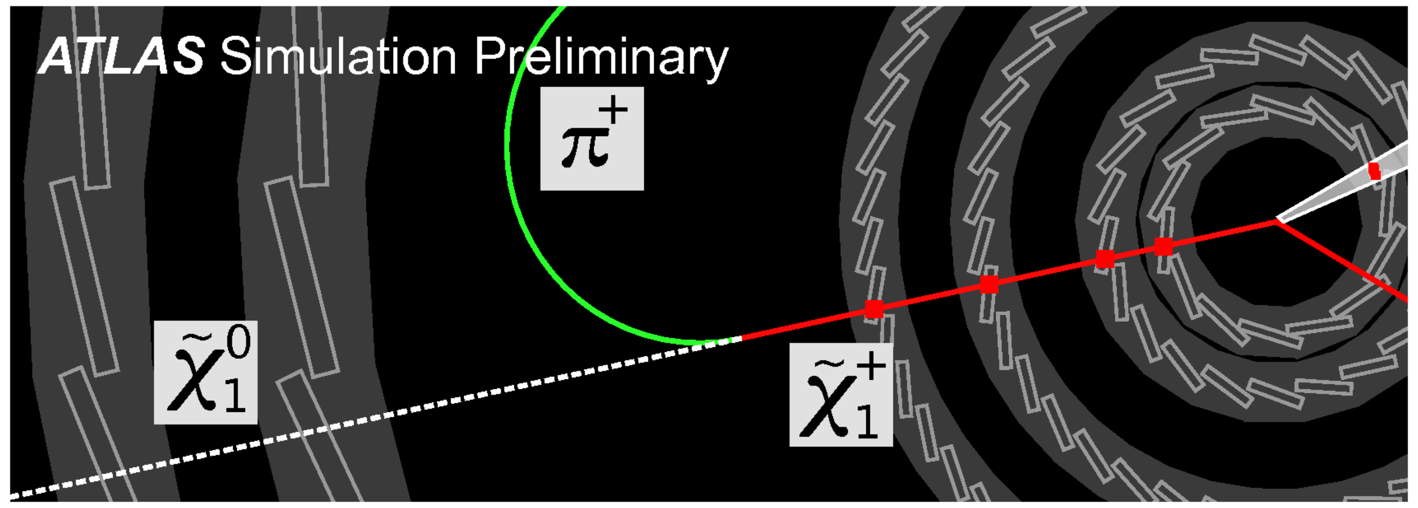




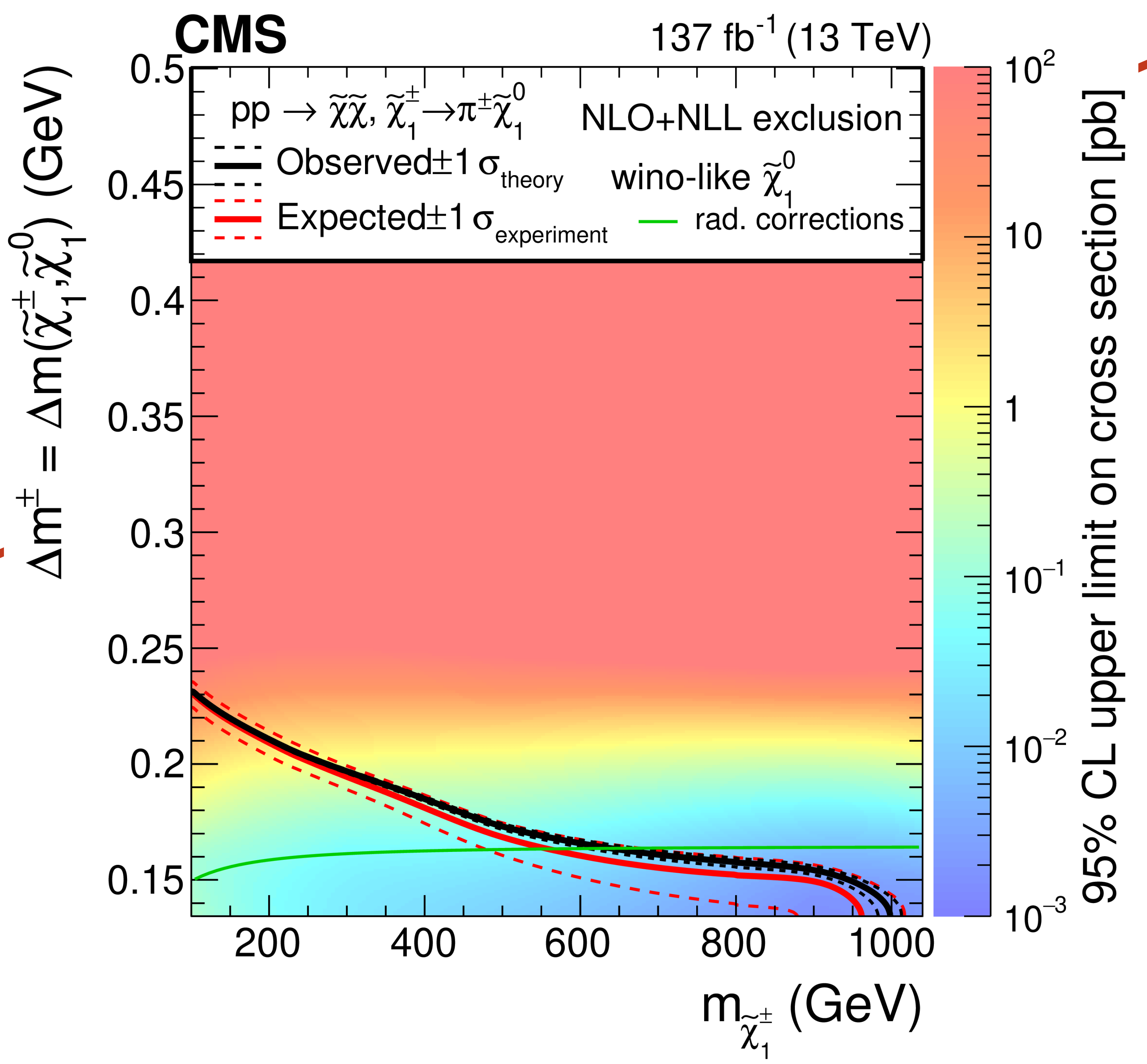
Disappearing track

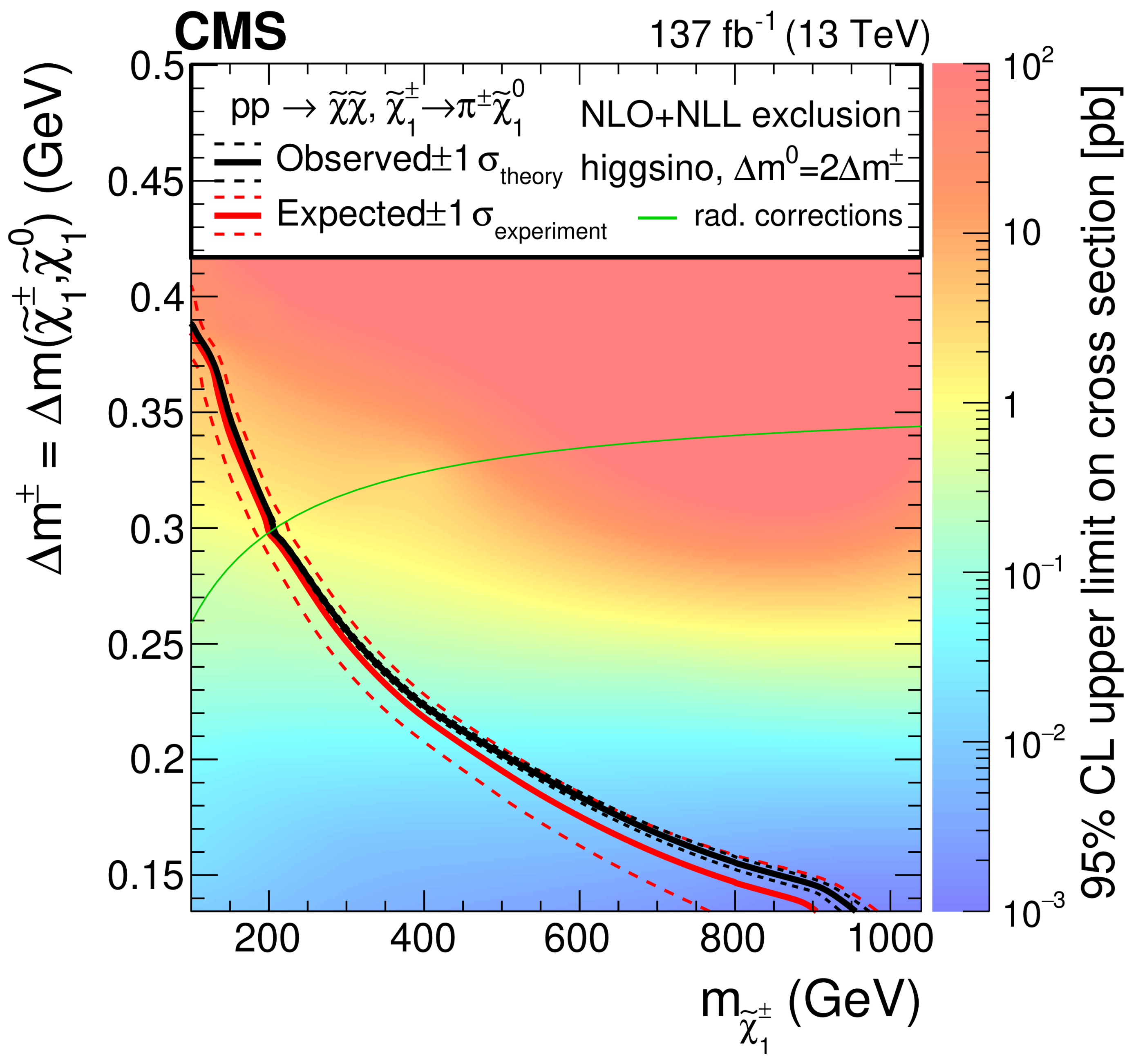
SUS-21-006

Silver bullet against **wino-like scenarios**, with sensitivity to (very compressed) higgsino scenarios.



- Looking for final states with a **disappearing track**, **different lepton and b-jet multiplicities**, utilising also specific ionisation losses (**dE/dx**).
- Many interpretations including **wino-like and higgsino-like** scenarios.



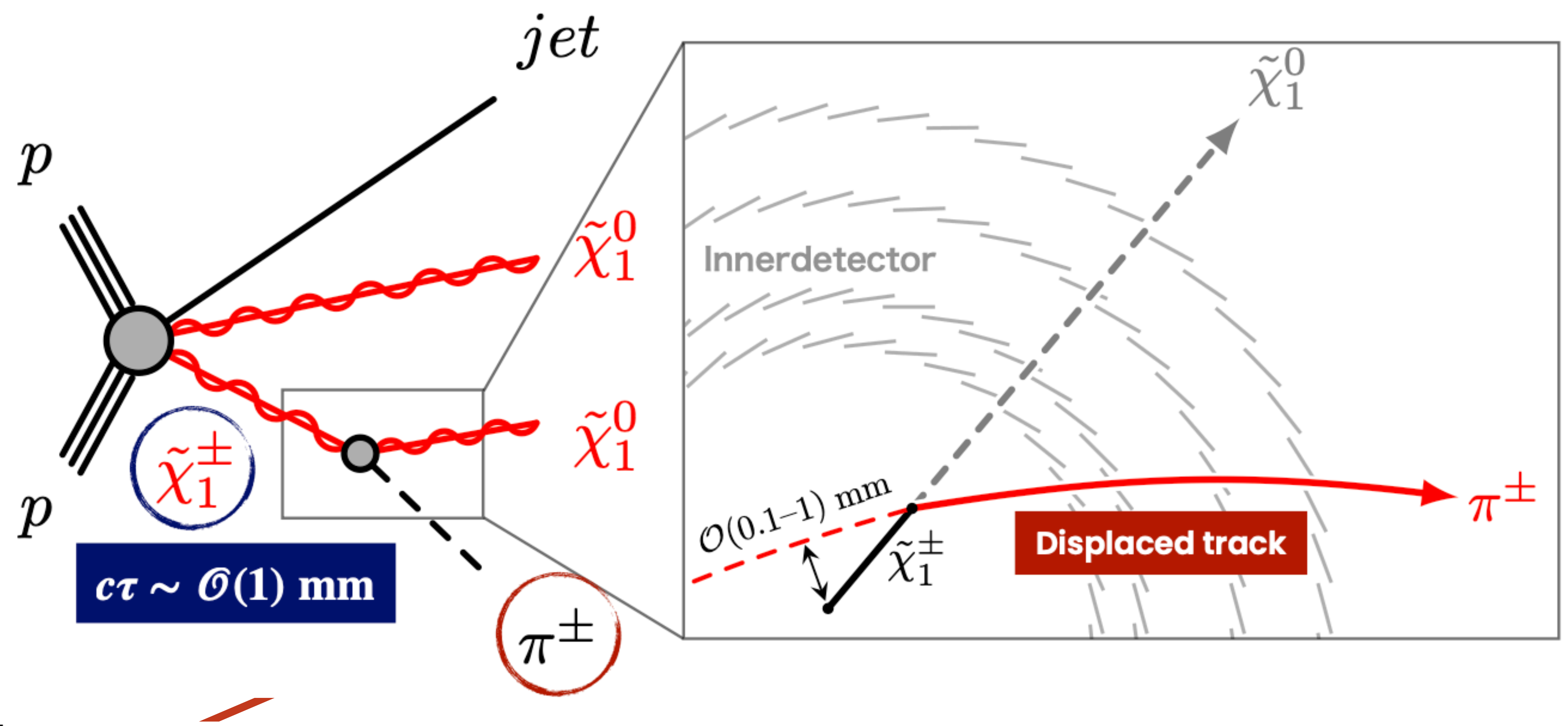


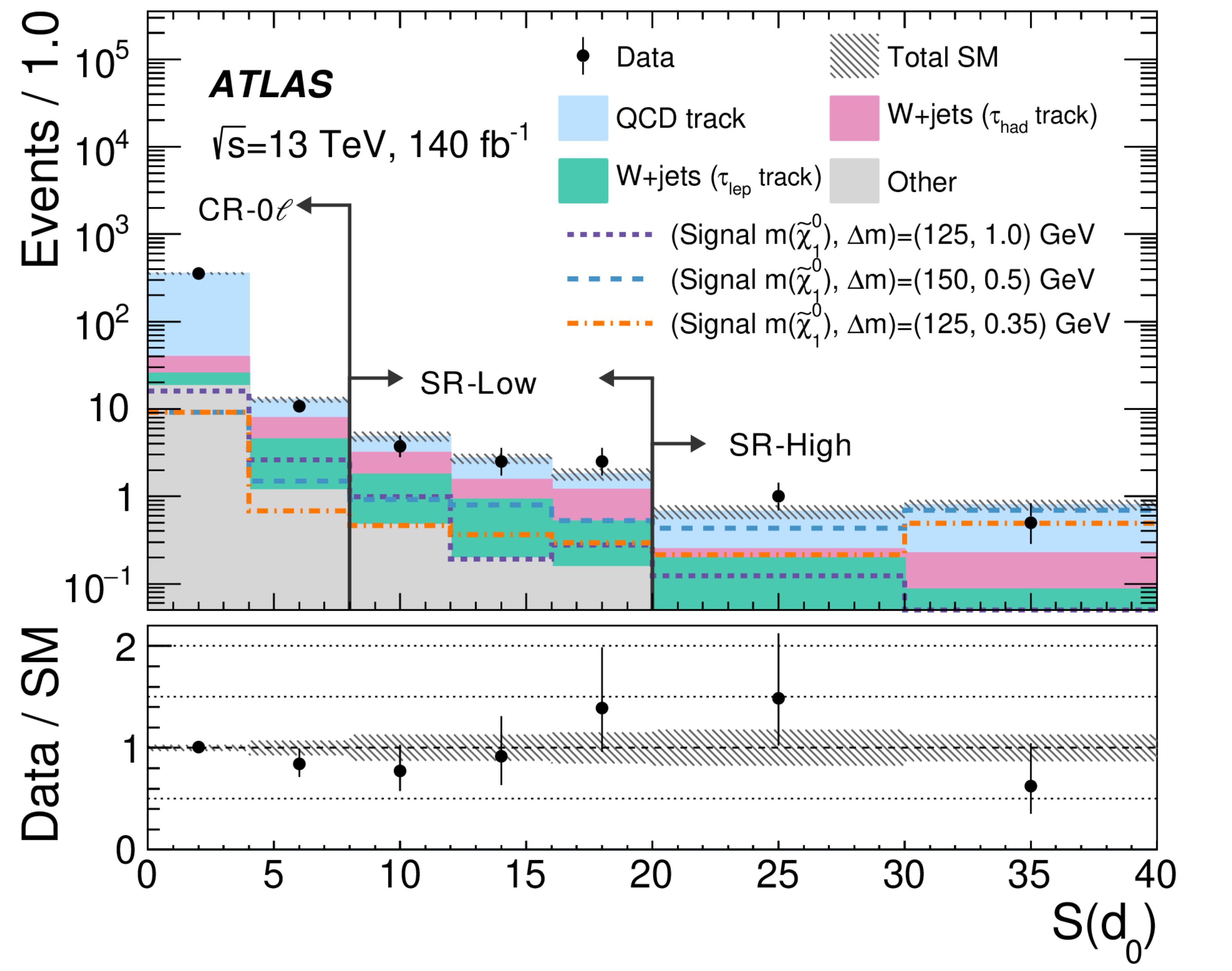
Mildly displaced tracks

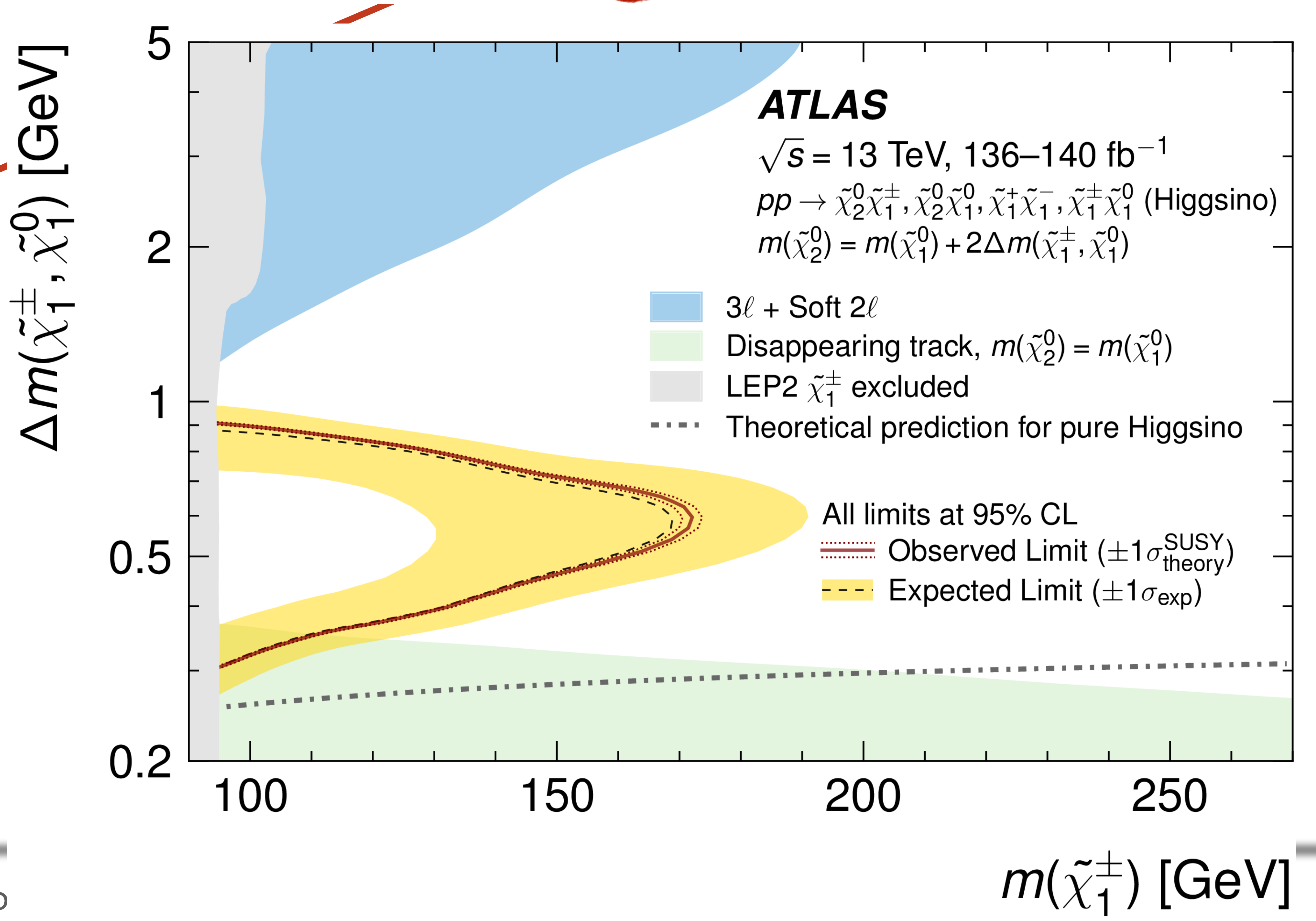
SUSY-2020-04

- Similar scenario (slightly shorter lifetimes).
- The electroweakino decay is identified through **an isolated track with high impact parameter.**

Schematics of the "mildly displaced track"







Using Vector Boson Fusion

SUSY-2023-26

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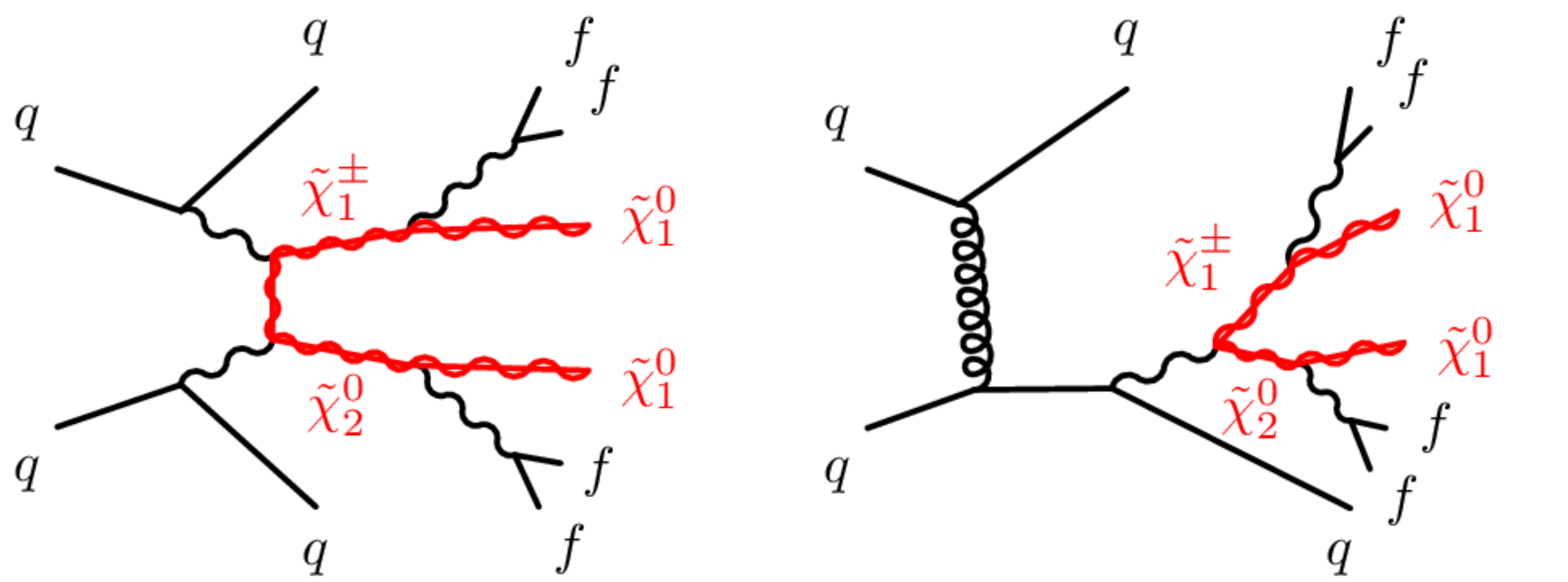
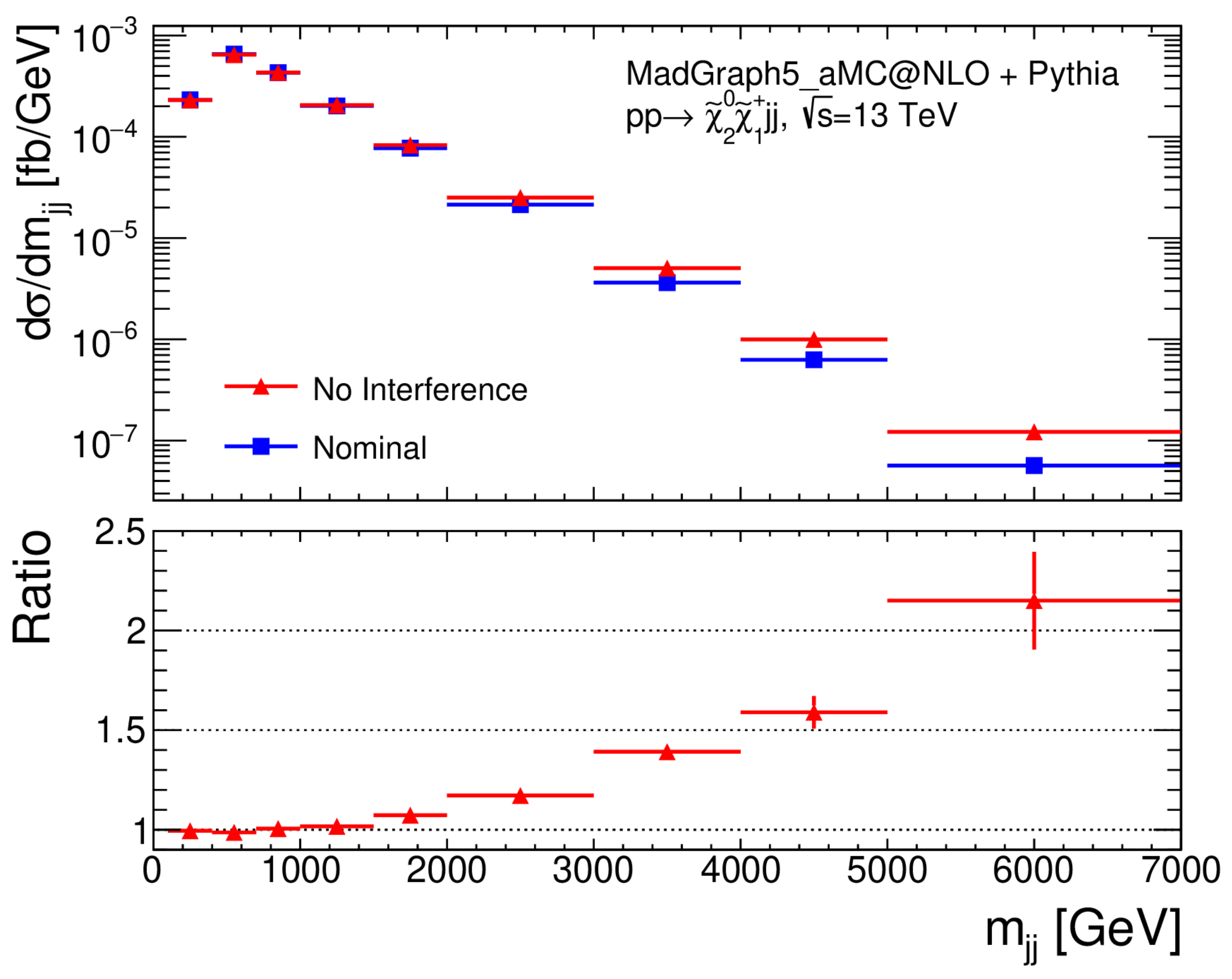
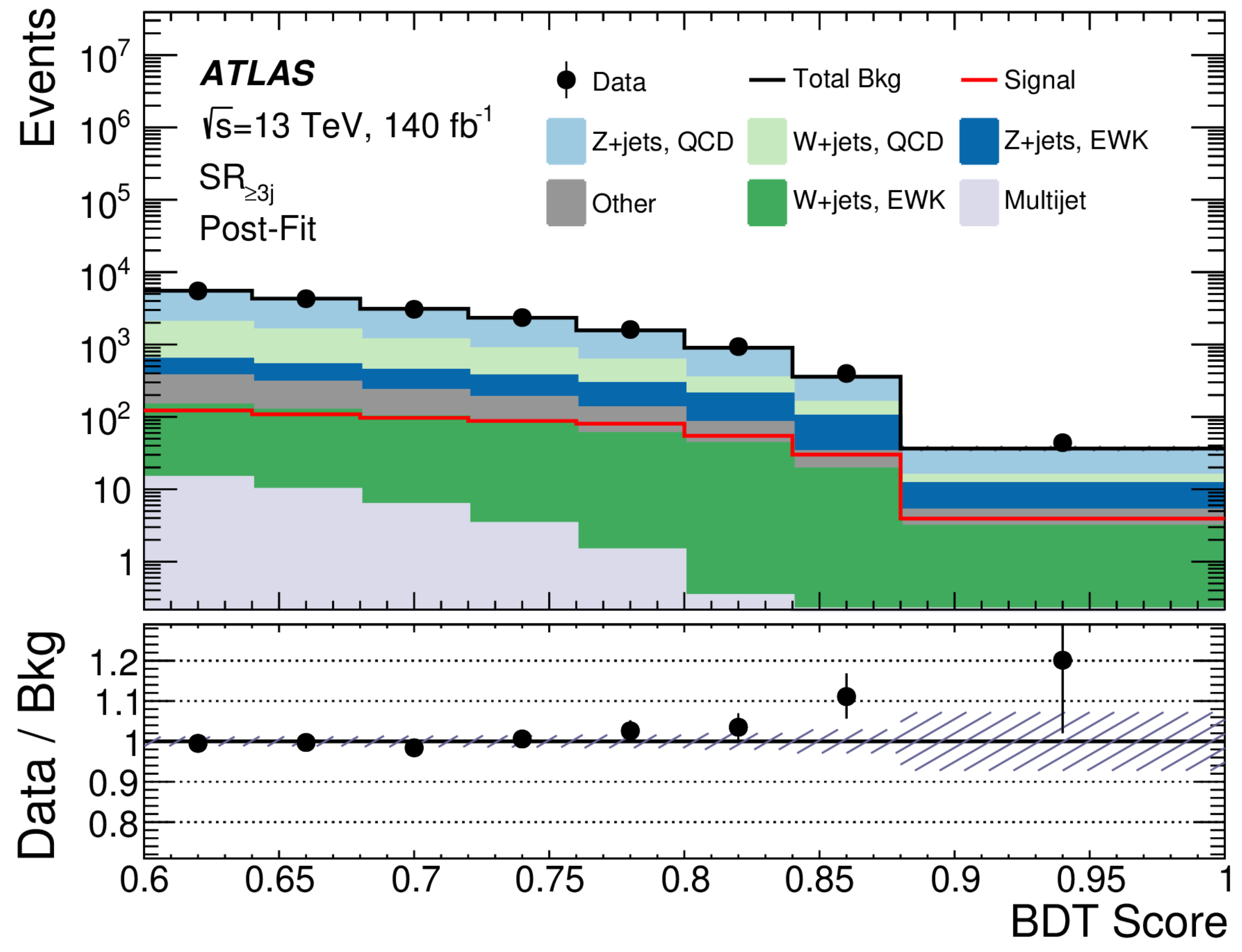
Definition of **VBF cross sections** in SUSY **far from trivial**:

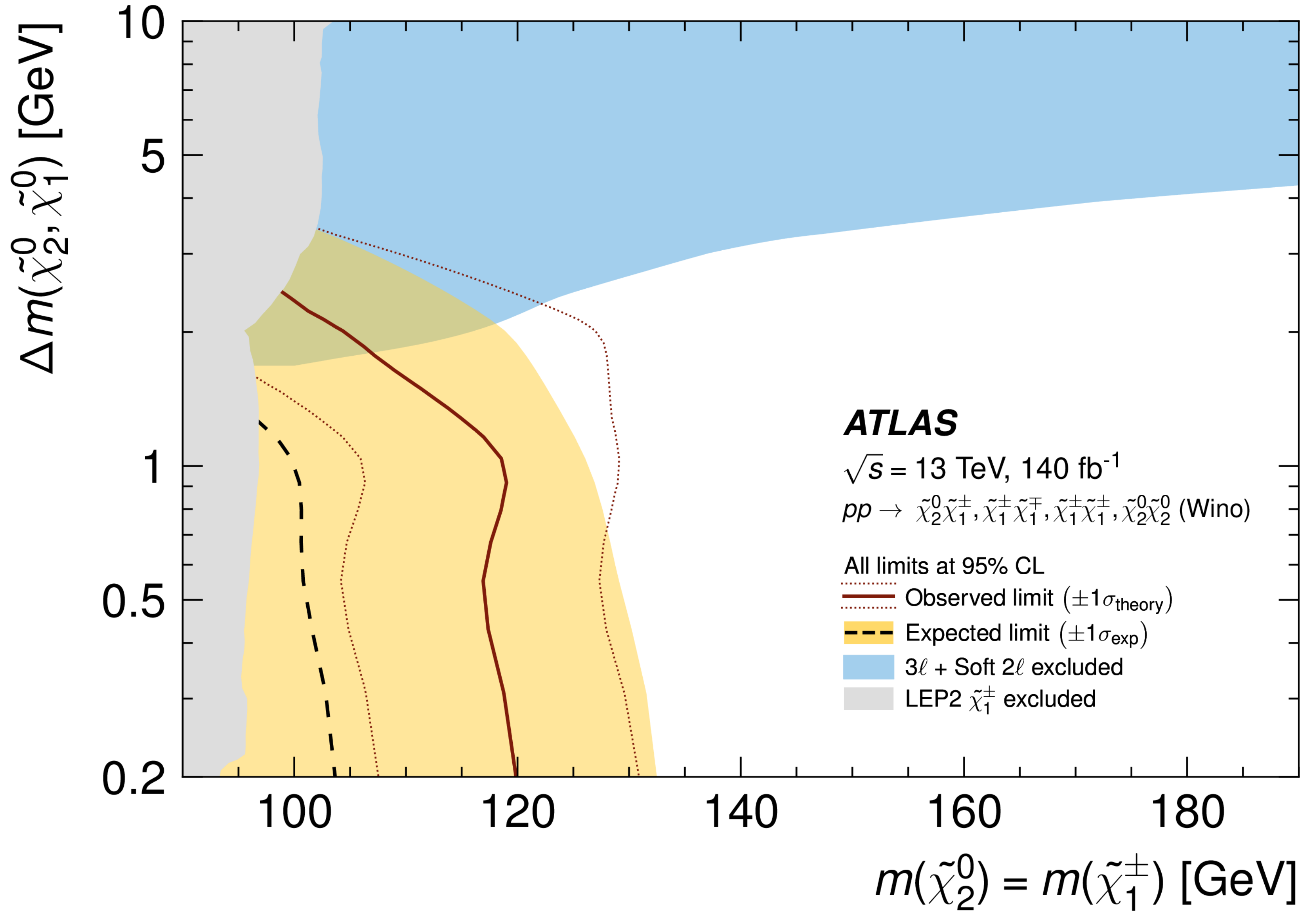
Interference between **s-channel and t-channel EW and mixed EW/QCD diagrams** very relevant for cross section determination.

Great care in making sure cross sections are sensible.





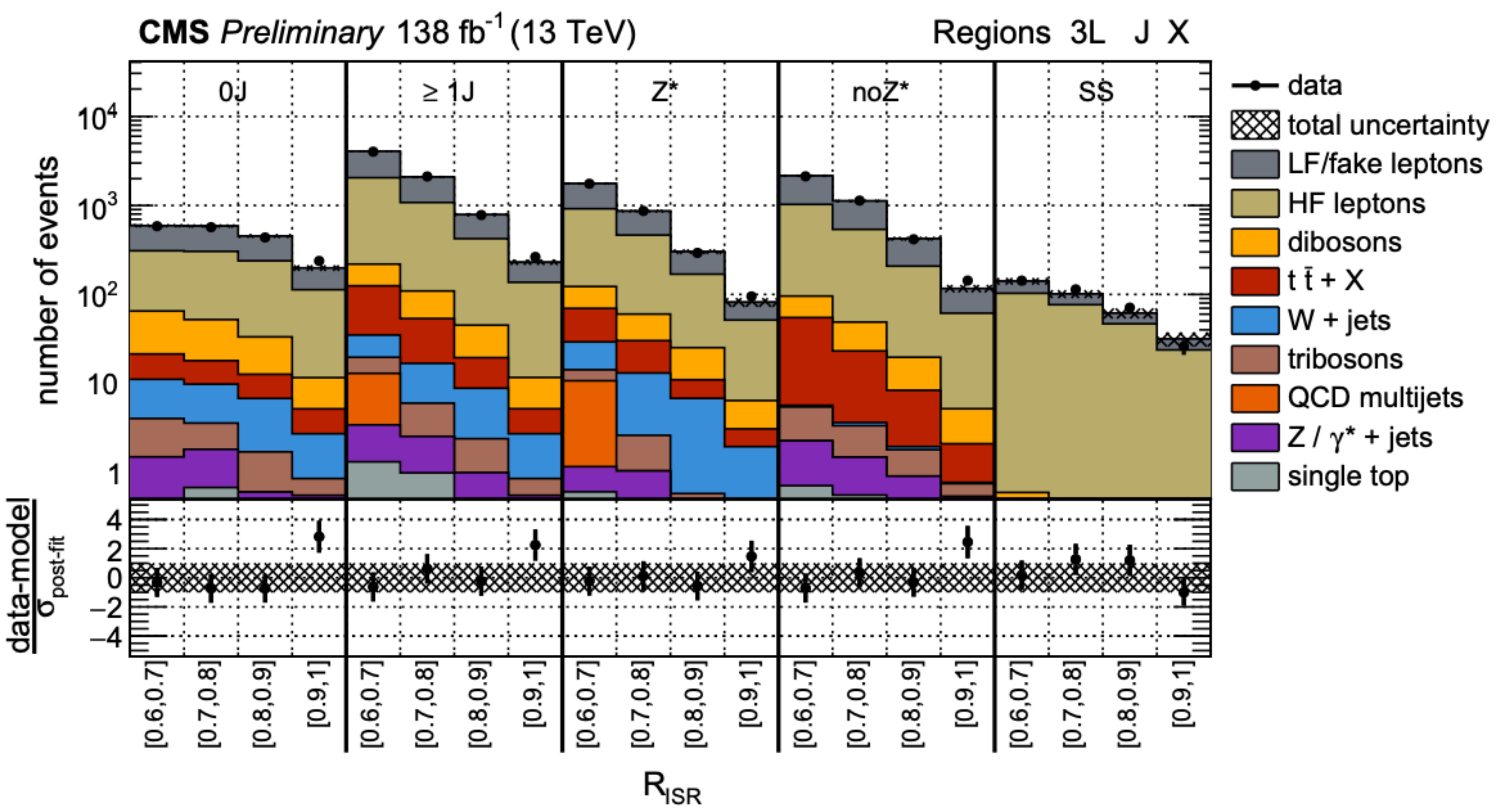


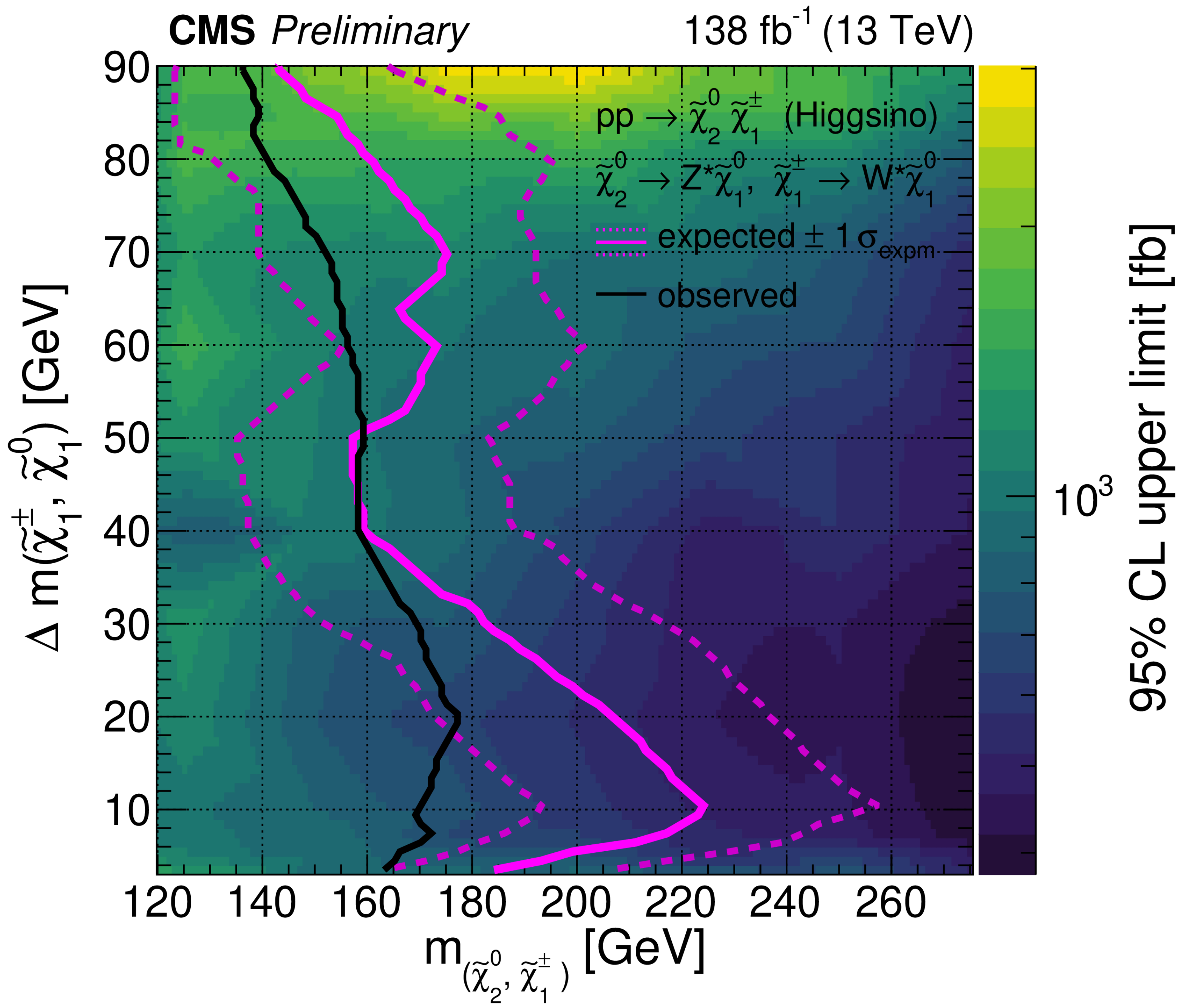


General Compressed Search

SUS-23-003

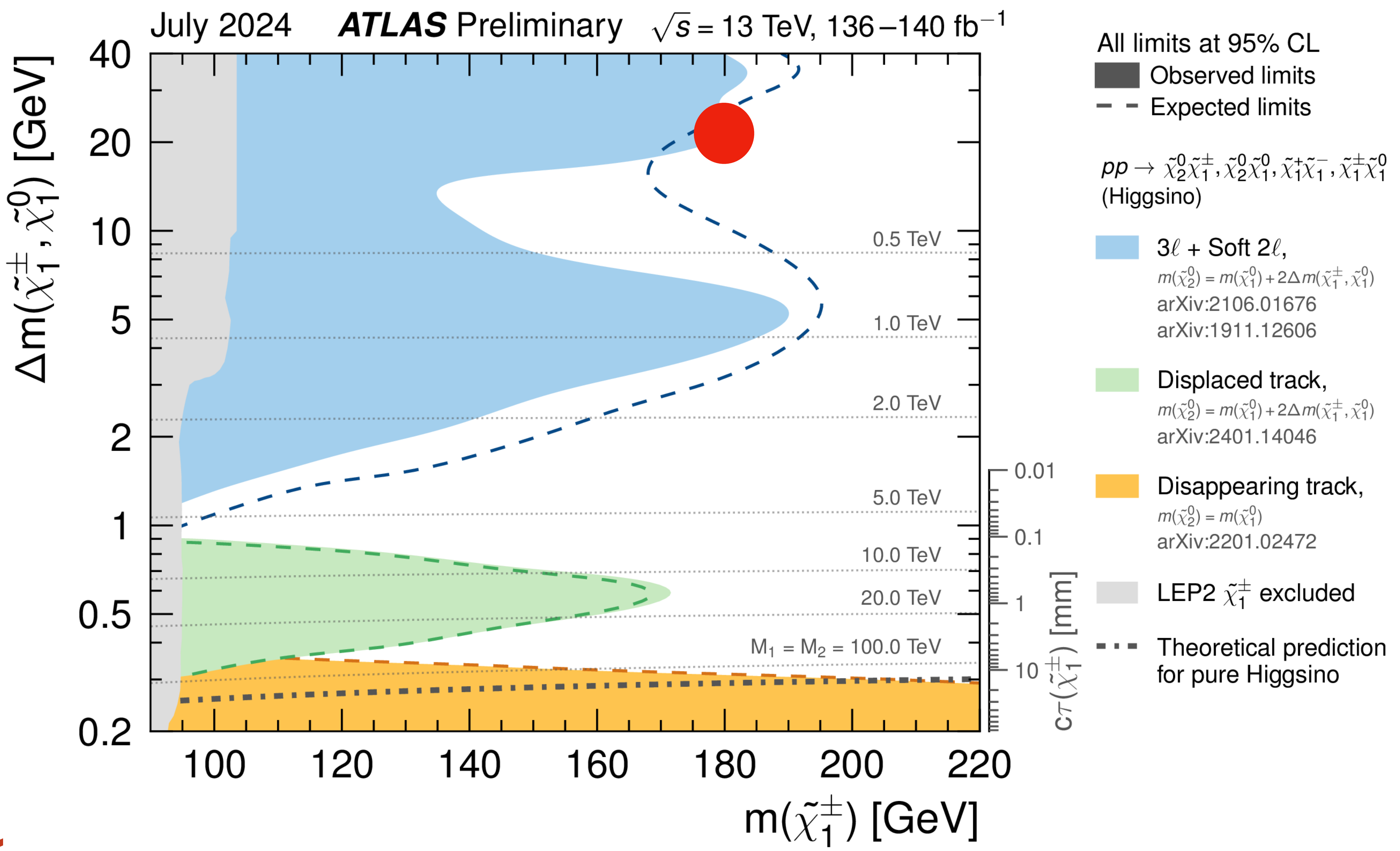
- Approach based on RJR variables ($R_{ISR} = \frac{\mathbf{p}_i \cdot \hat{\mathbf{p}}_{ISR}}{\mathbf{p}_{ISR}} \sim \frac{m_i}{m_P}$ for a pair-produced particle P recoiling against an ISR jet and decaying into invisible particles i)
- Events categorised based on number of leptons, $b-$tags, jet multiplicity

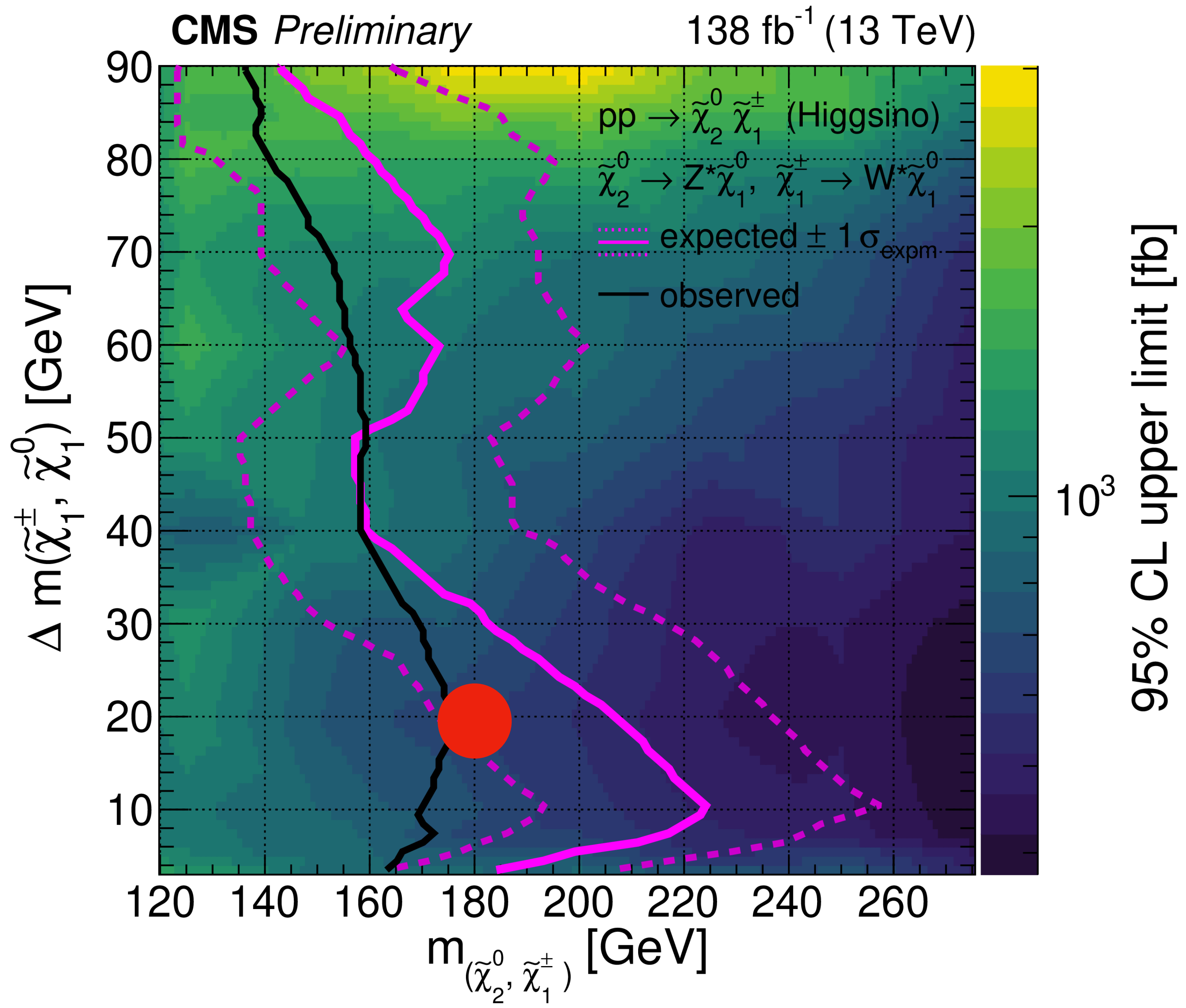




Comparison ATLAS-CMS

- **Similar excesses** in ATLAS and CMS (each at the level of ~ 2σ). **SUSY in plain sight or just a statistical fluctuation**?
- Certainly **something to be scrutinised carefully** with the Run 3 data.
  - **Bulk of sensitivity coming from soft-lepton analyses (2L and 3L channels).**





A Run 3 search - displaced leptons

SUSY-2022-11

EXO-23-014

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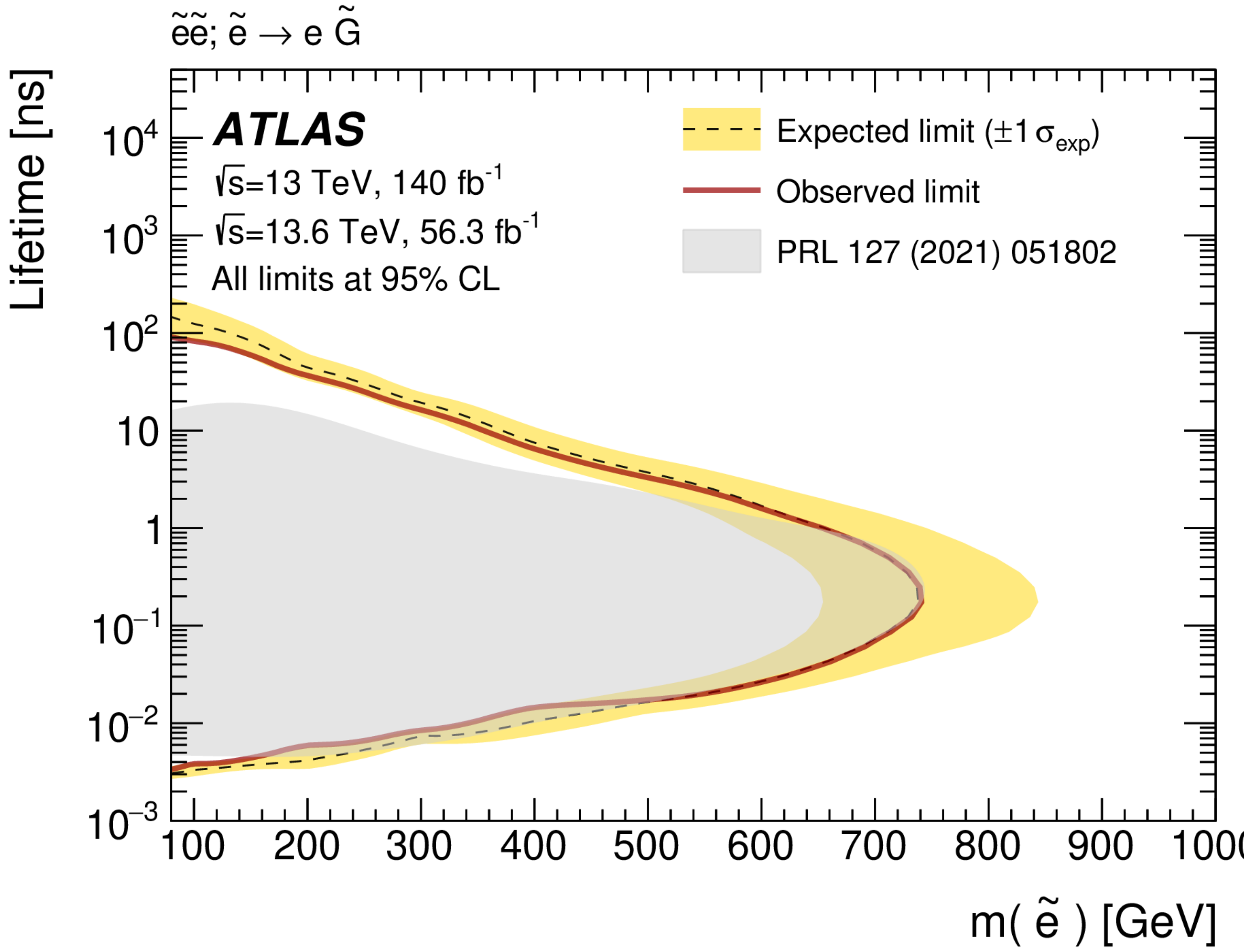
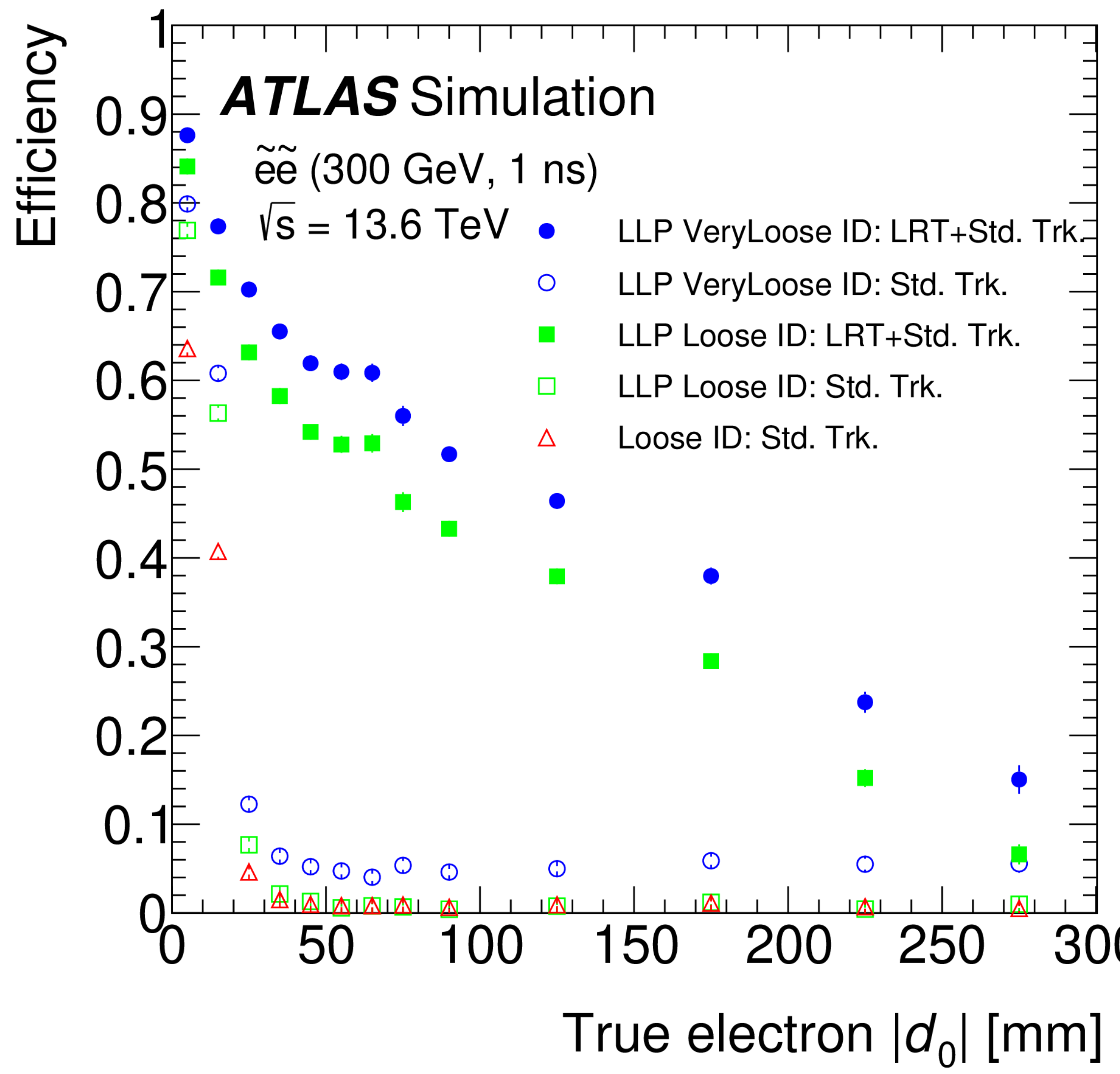
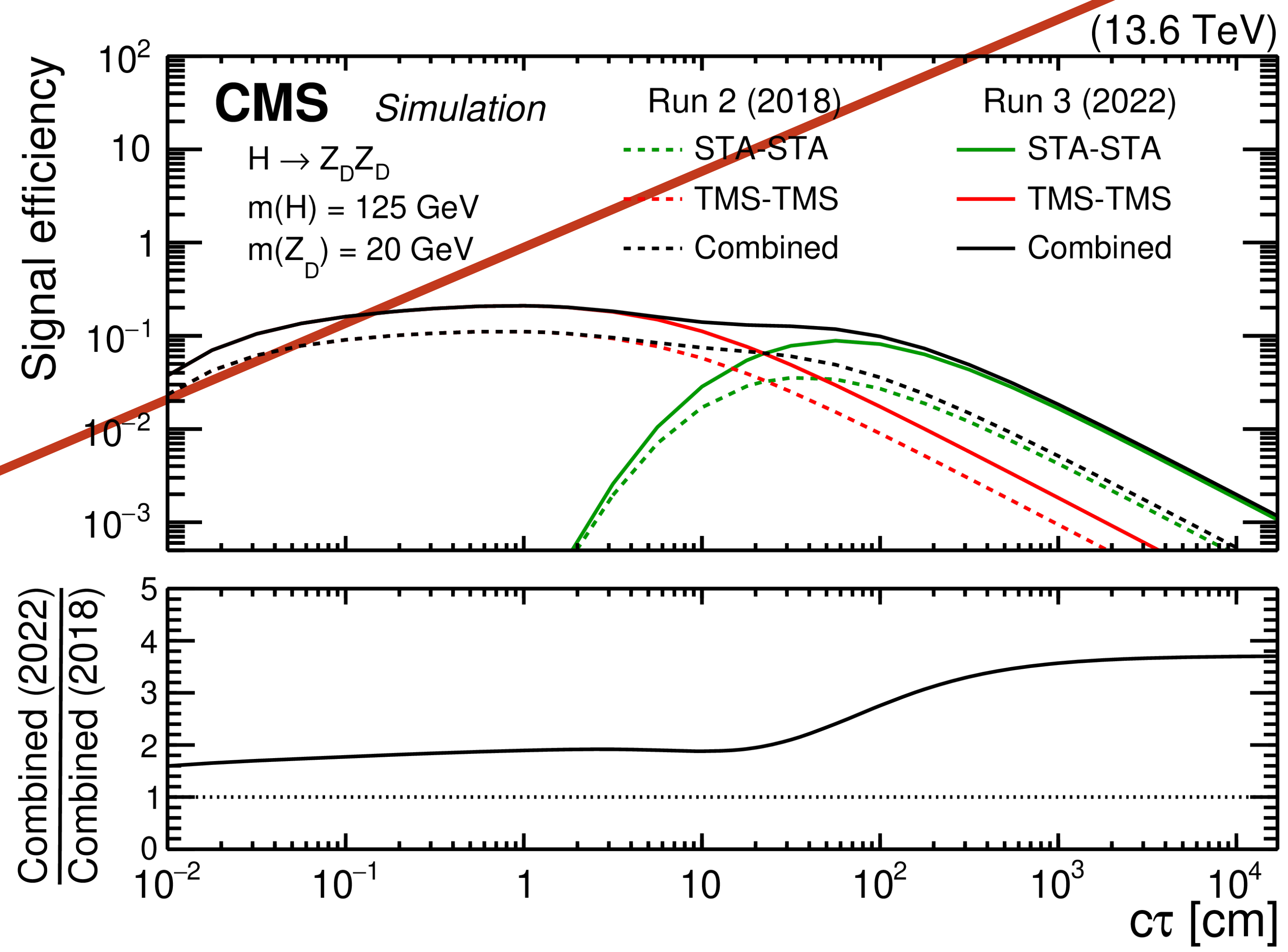
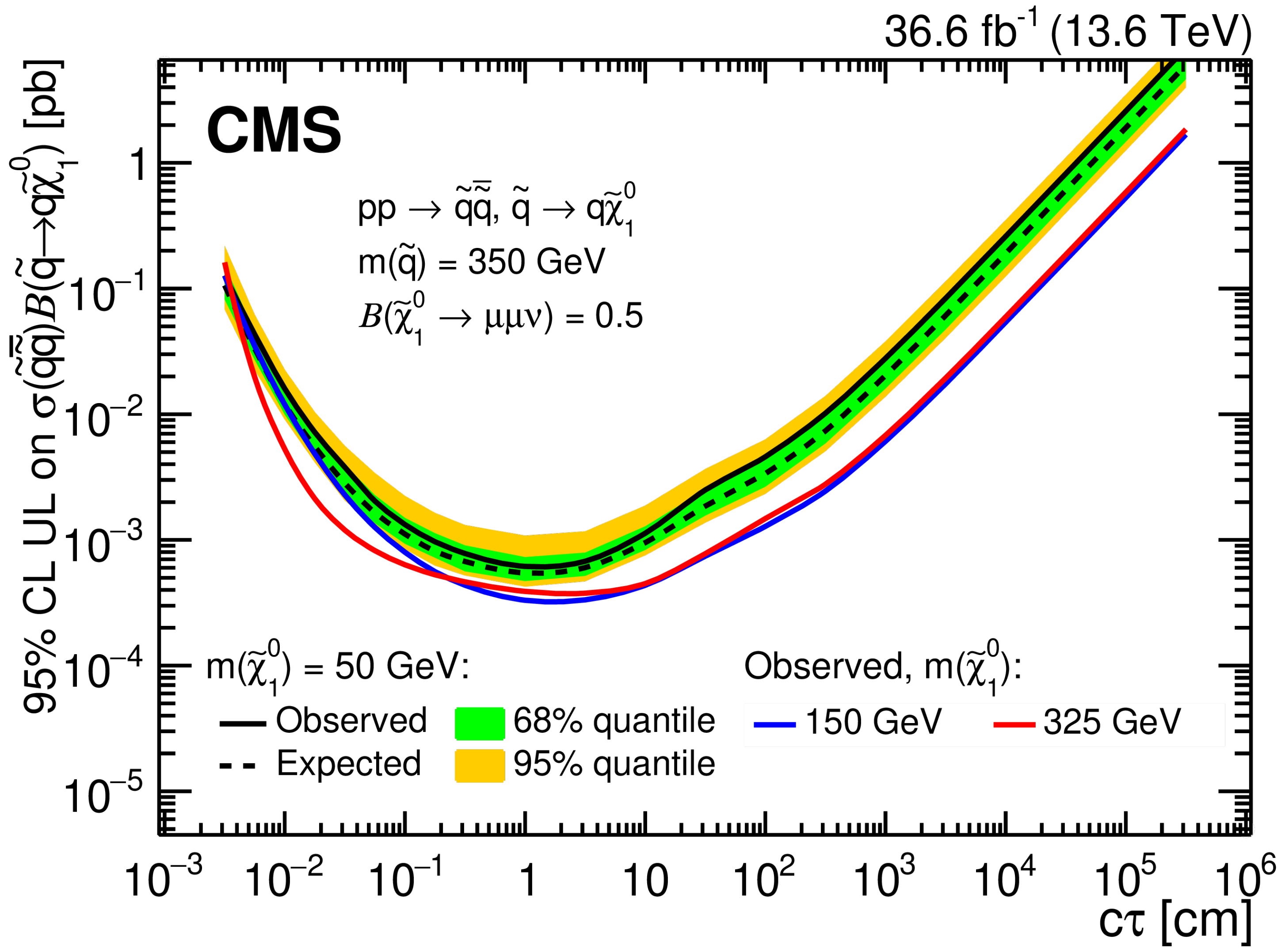
- The Run 3 search programme is in **full swing**. The **first Run 3 SUSY searches** are available
  - Non-pointing leptons arising from long-lived sleptons or charginos.
  - Long-lived particle decay yielding a dimeno vertex in CMS
- A showcase of improvements for Run 3:
  - **Large Radius Tracking** @ HLT in ATLAS at **trigger level and offline**.
  - Improved L1 tracking reducing p_T thresholds for muon triggers in CMS



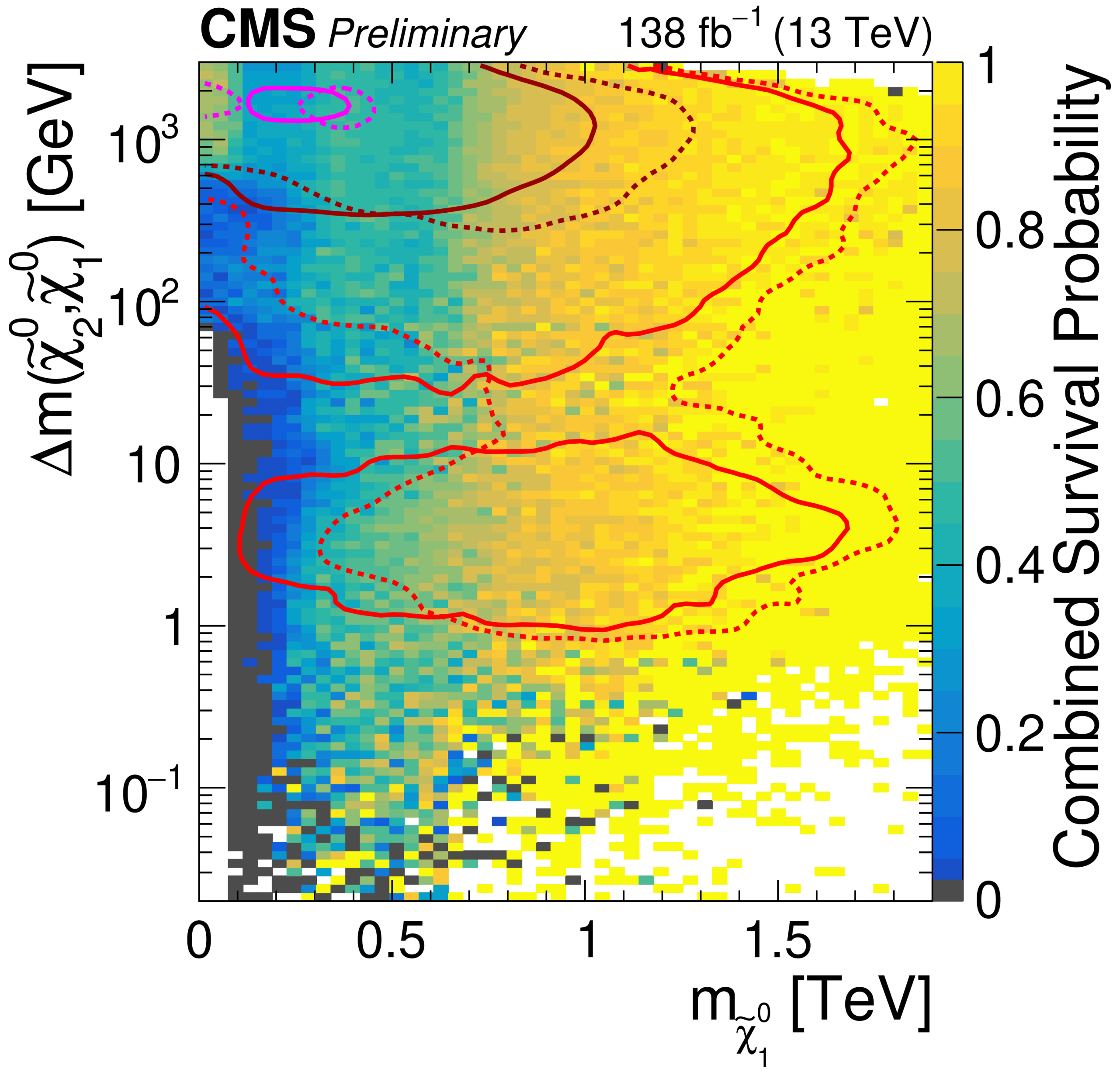


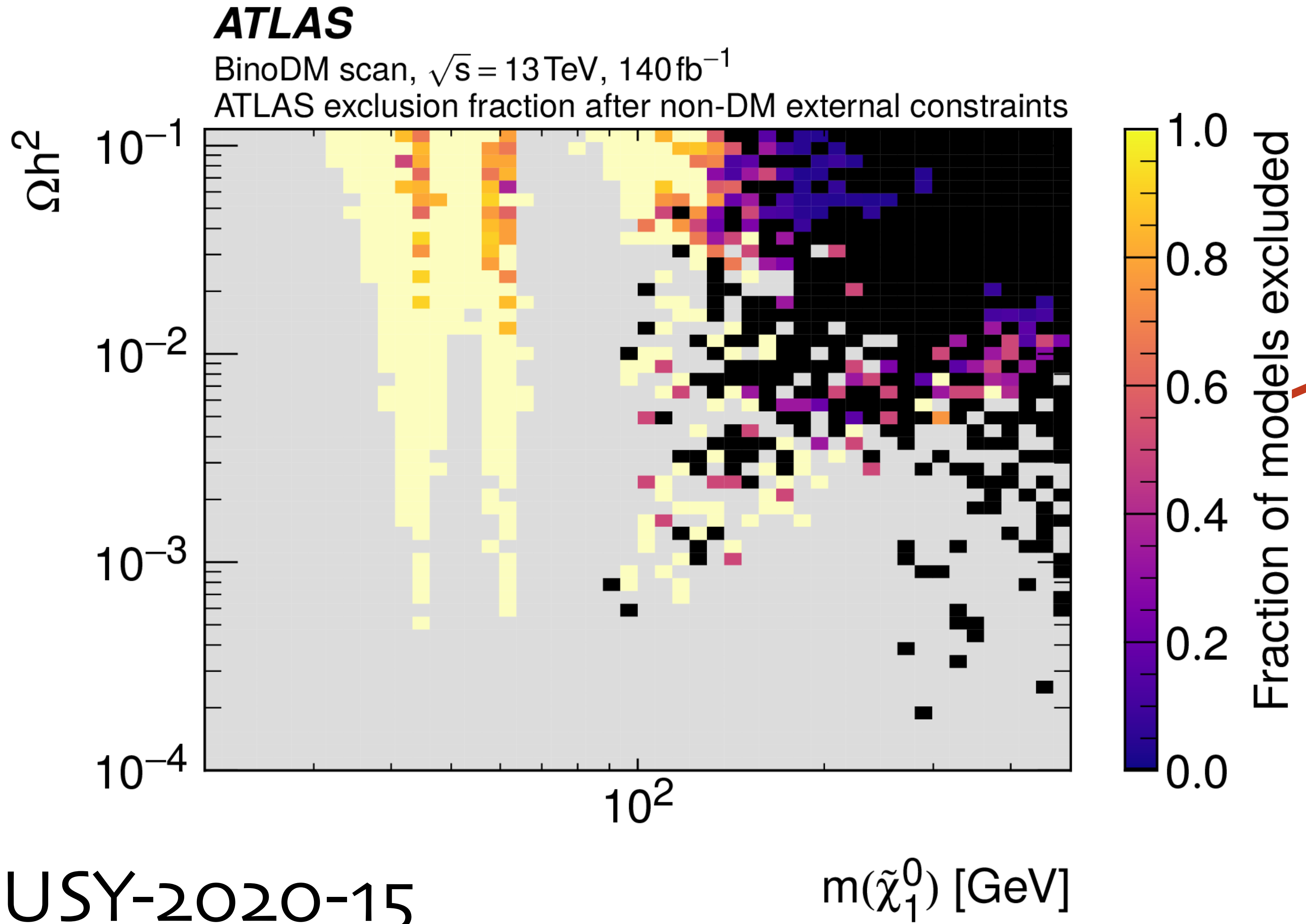


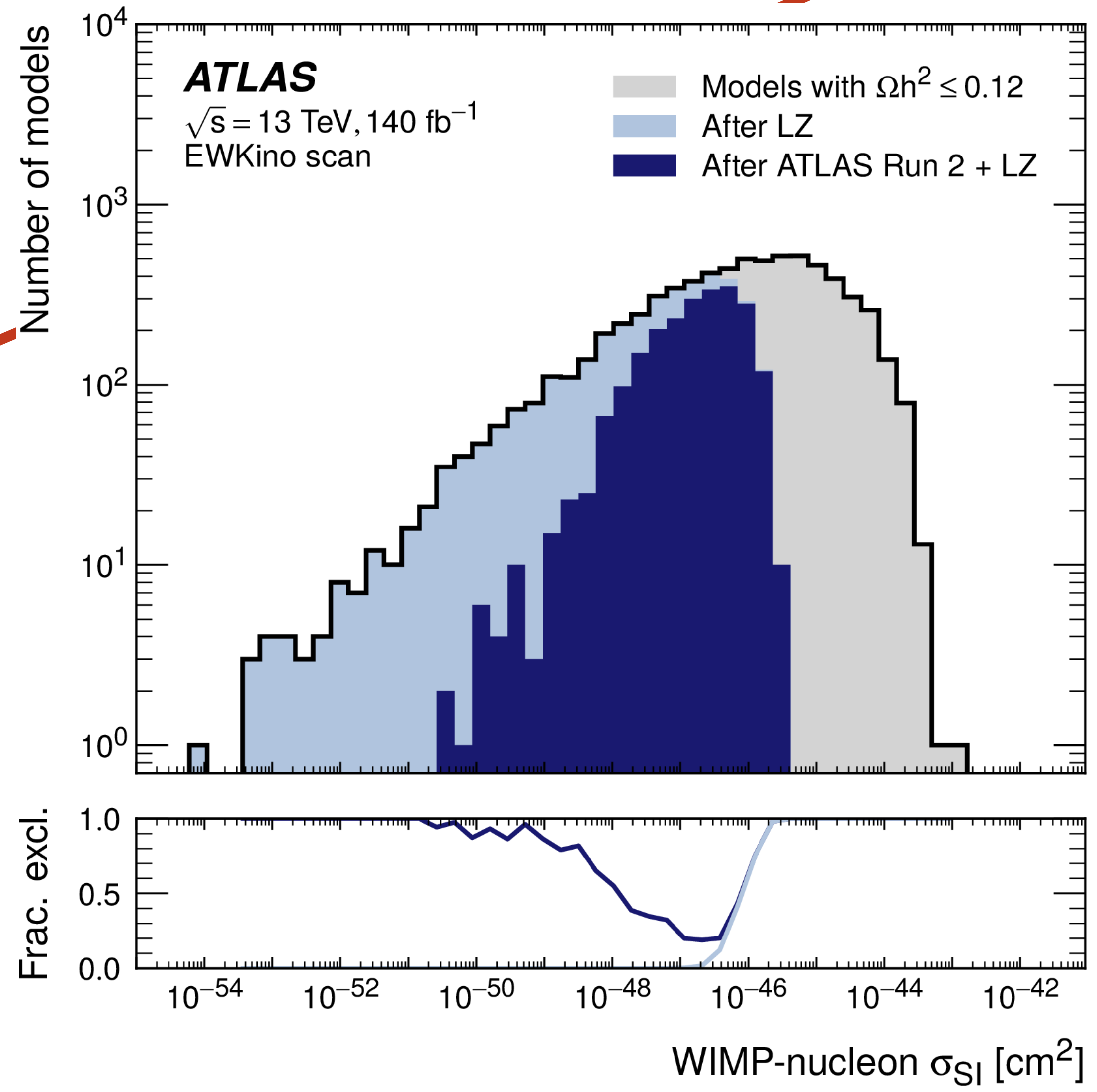


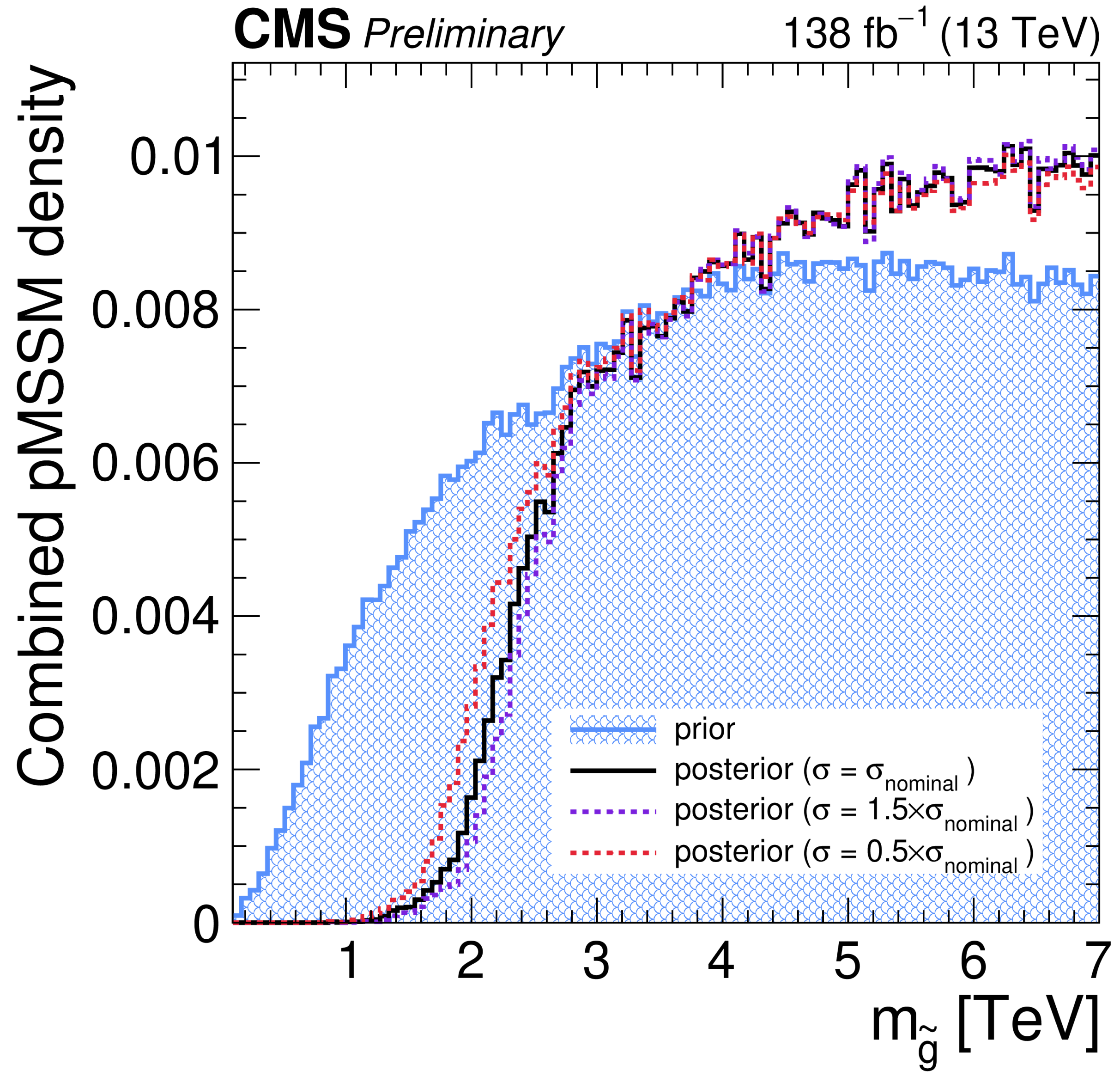
From simplified to UV-complete models

- The **simplified models** do not allow to make **solid statements on model parameter exclusions**.
- pMSSM scans in full swing (using different approaches):
  - One example: EW 5-parameters for ATLAS.
  - Another example: 19-parameters for CMS.
- A testament to the reinterpretation capabilities of the experiments.









SUSY-2020-15

SUS-2024-04

Summary

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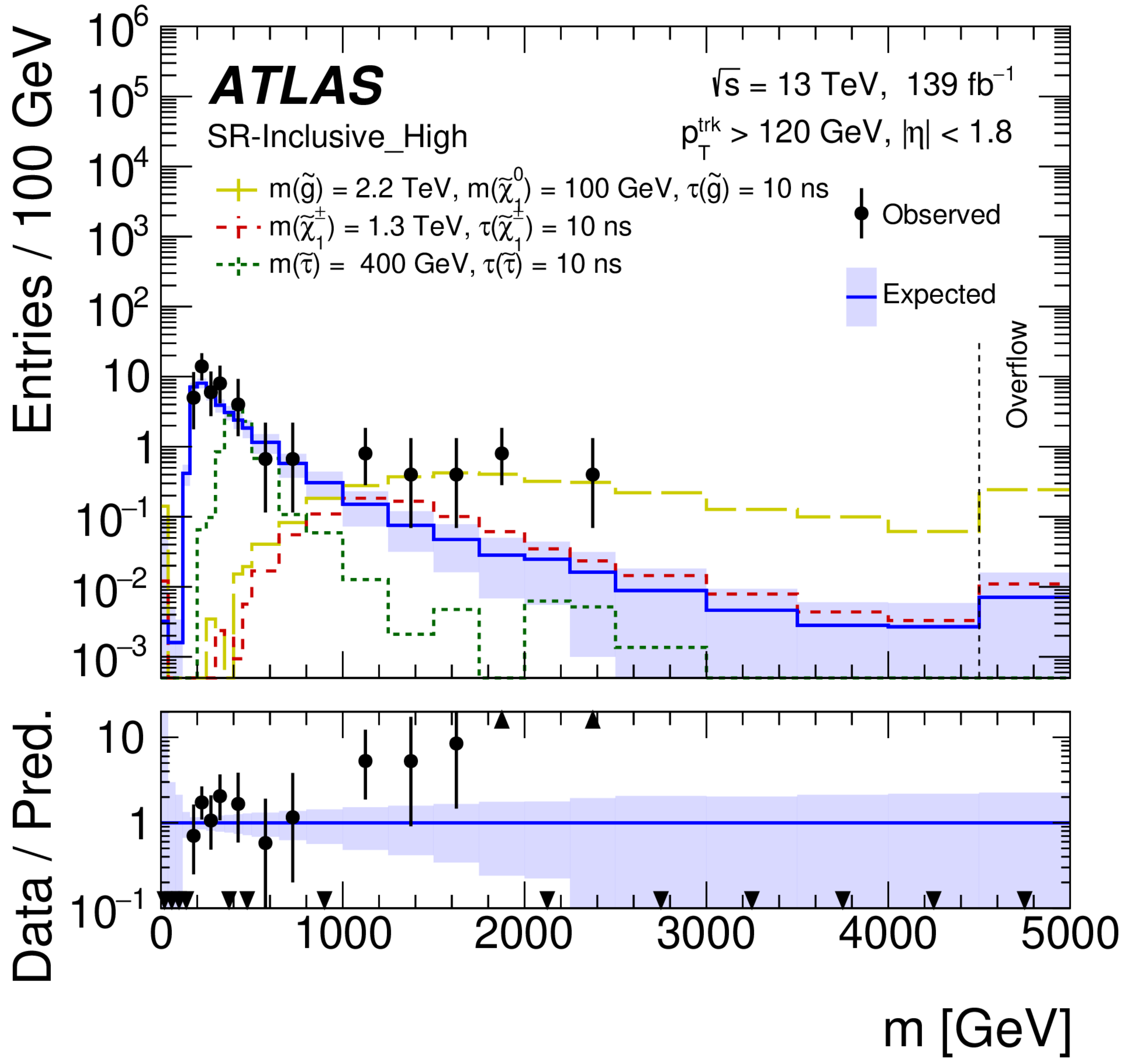
- Hardly to identify a sector of HEP with a **higher impact from LHC**.
- 14 years into the LHC and **no answer for naturalness and dark matter**. The relevance of the questions **pretty much unchanged**. Our perception is, though.
- Not many stones left unturned…..
- **No significant excess**. So, **what SUSY has the LHC excluded**?
  - Limits on gluinos and stops put **classical arguments of naturalness under stress.**
    - But **higgsino parameter space much less constrained**.
  - Bino-like dark matter under pressure.
    - But **Higgsino-Bino** and Wino-Bino-like DM **pretty much unscathed**.
  - Mild excess in compressed parameter region **to be followed up**.
- **Run 3 analyses in full swing**. Expect a lot more than just $\sqrt{L}$ (and a modest $\sqrt{s}$) scaling (upgrades + trigger improvements, large radius tracking, data scouting at trigger level, machine learning…..)

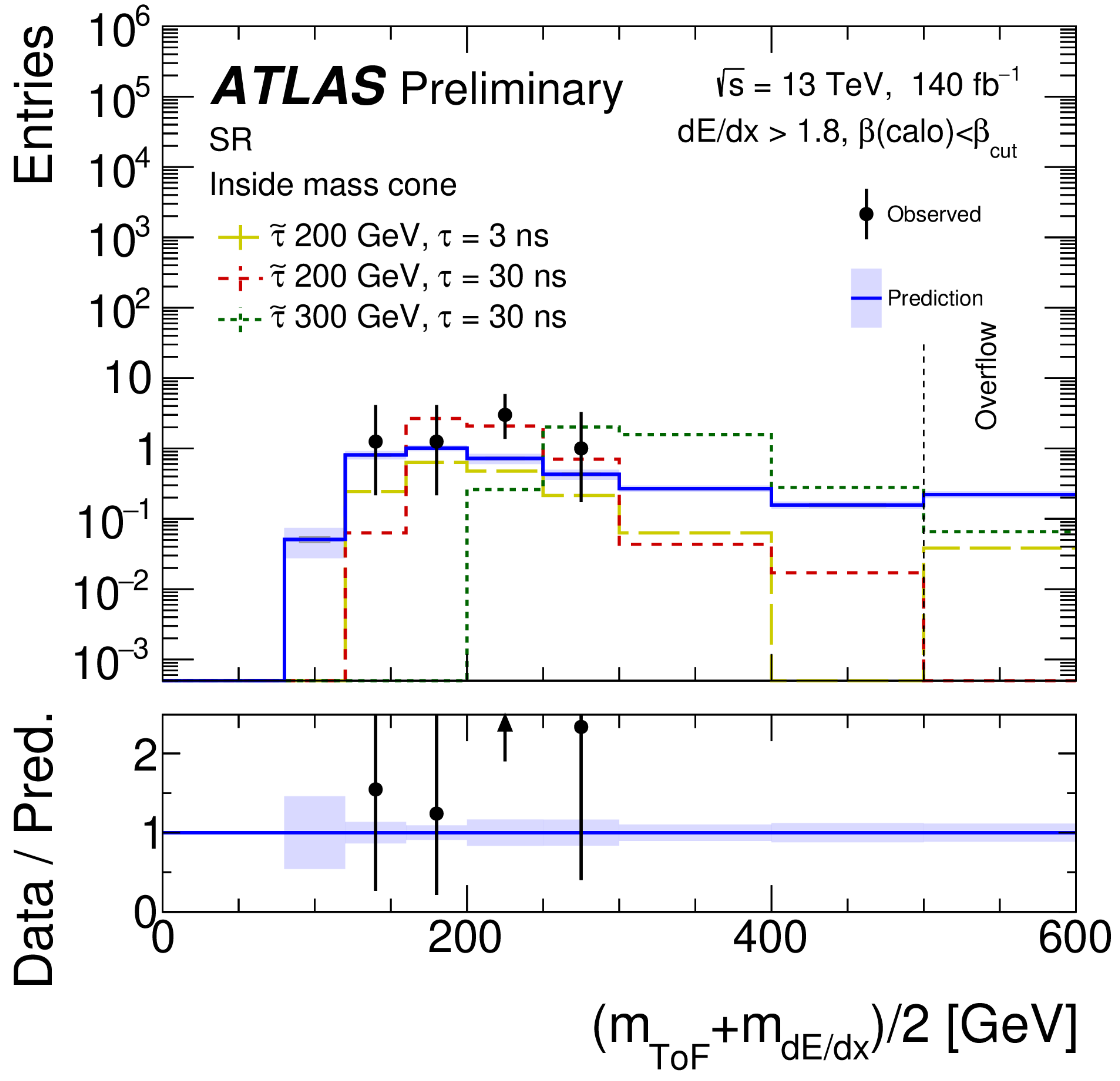
BACKUP

ATLAS dE/dx excess

From SUSY-2018-42



From ATLAS-CONF-2023-044



Requiring time of flight of the candidate tracks to the calorimeter removes the excess.

The excess cannot be due to heavy, q=1, long-lived particles.

If insisting on a signal interpretation, a fast, q>1 particle is still a possibility