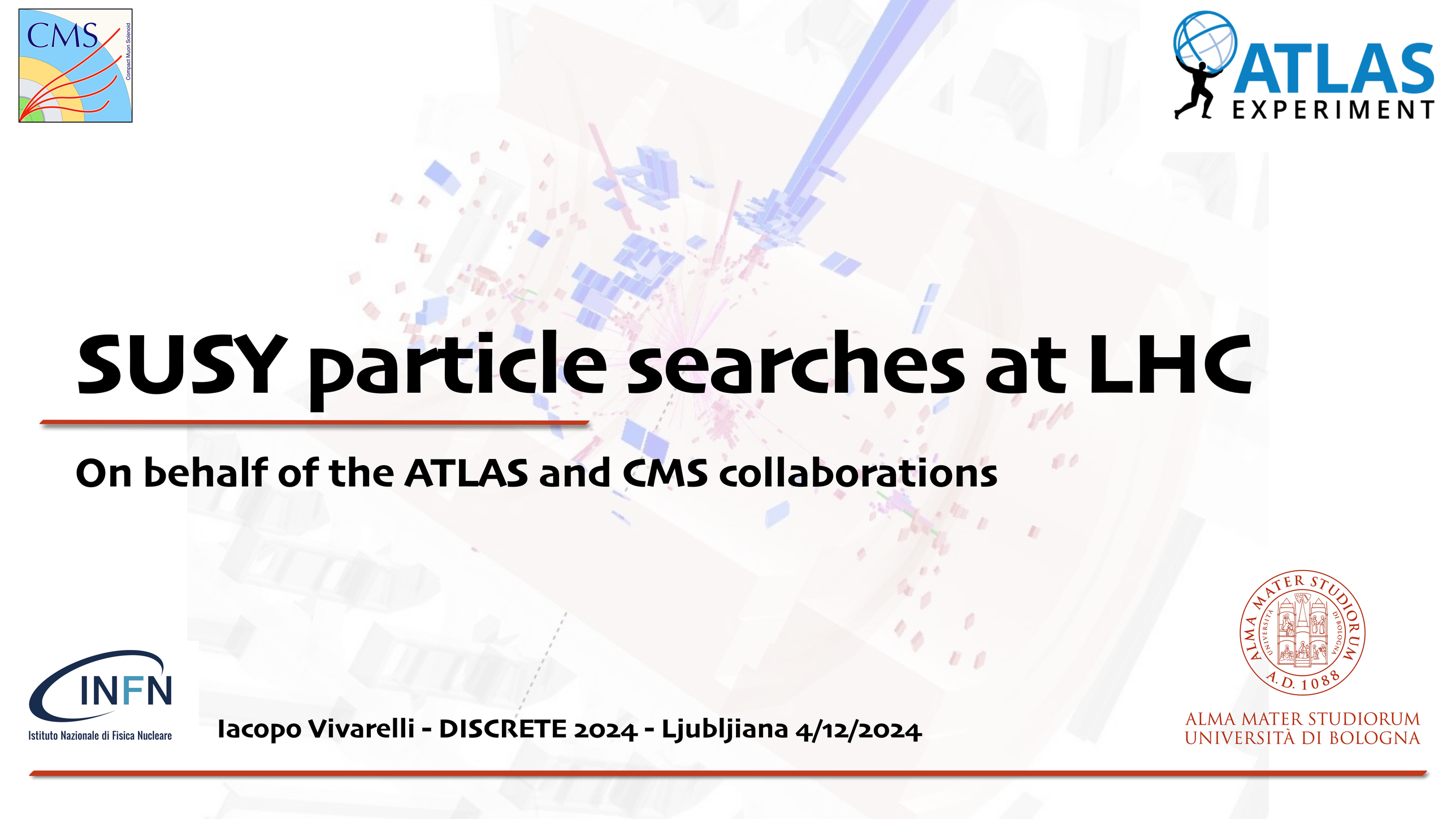

SUSY particle searches at LHC

On behalf of the ATLAS and CMS collaborations

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

Istituto Nazionale di Fisica Nucleare

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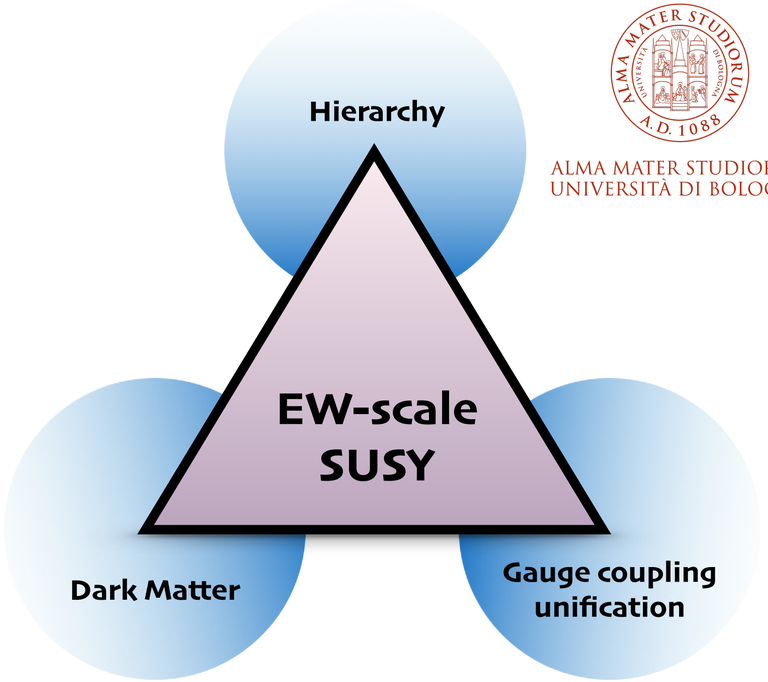
Desperately seeking SUSY…



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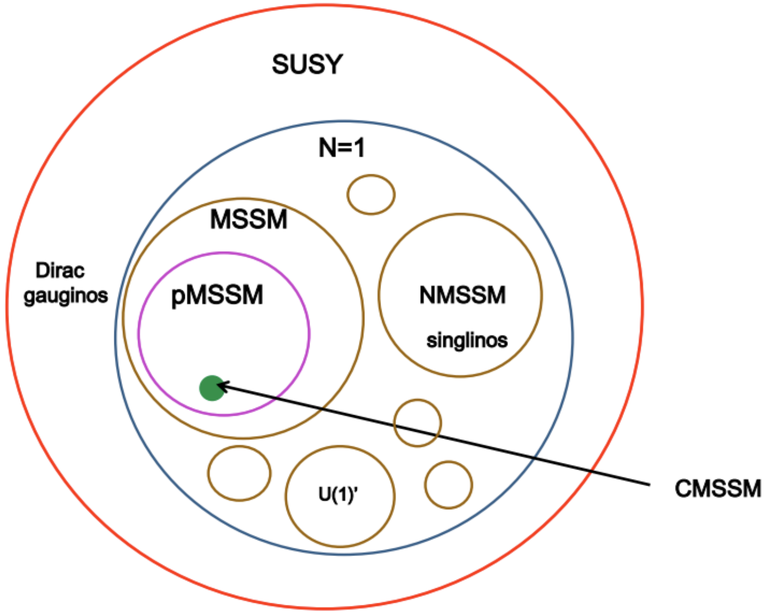
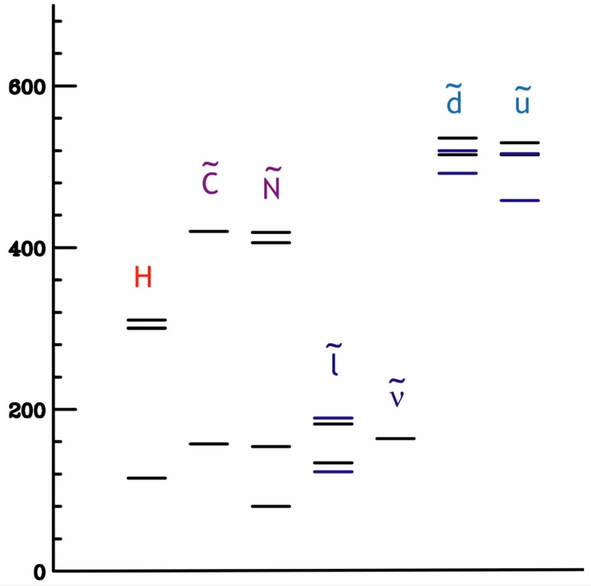
As a minimum we are dealing with 124 parameters (MSSM)
…which can maybe be reduced to 19/20 (pMSSM)

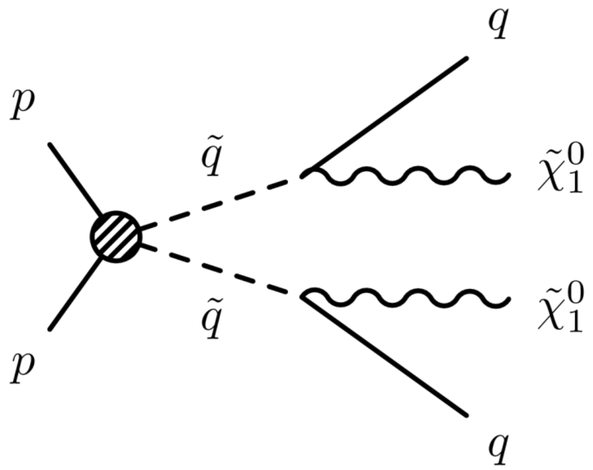
SUSY conserving sector	SUSY breaking sector
3 coupling constants for SU(3)xSU(2)sU(1)	5 3x3 hermitian mass matrices (one per EW multiplet)
4 Yukawa couplings per generation	3 complex 3x3 matrices (Higgs trilinear couplings to sfermions)
	3 mass terms for the Higgs sector + 2 additional off-diagonal terms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

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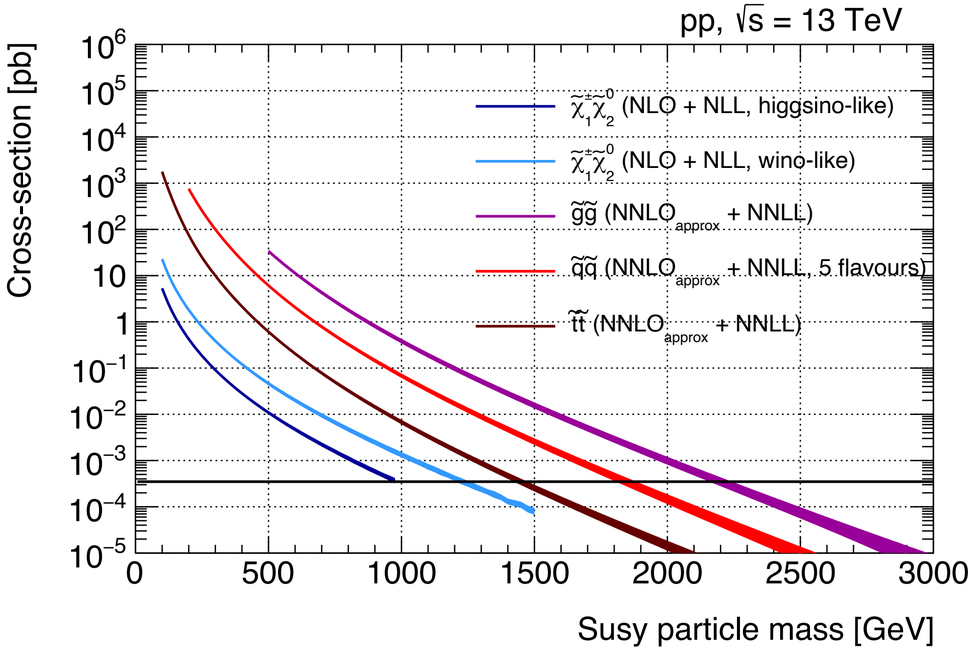
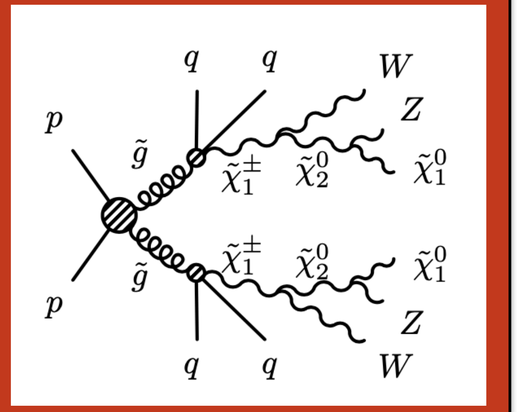
- They depend on **particle masses** and (for EW), on **few model parameters**.
- Thumb rule for experiment sensitivity: **50 produced events determine sensitivity**.
- Expected sensitivities: beyond 2 TeV for $\tilde{g}\tilde{g}$, ~ 1-1.5 TeV for $\tilde{t}\tilde{t}$, ~ 1 TeV for eweakinos.



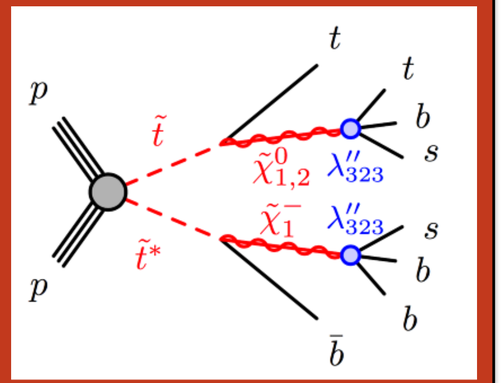
Example decay

R-parity conserving gluino decay.
Signature: $p_{\mathrm{T}}^{\mathrm{miss}}$ + stuff

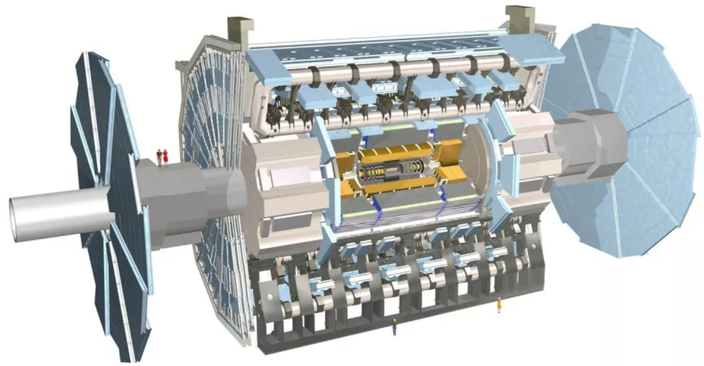


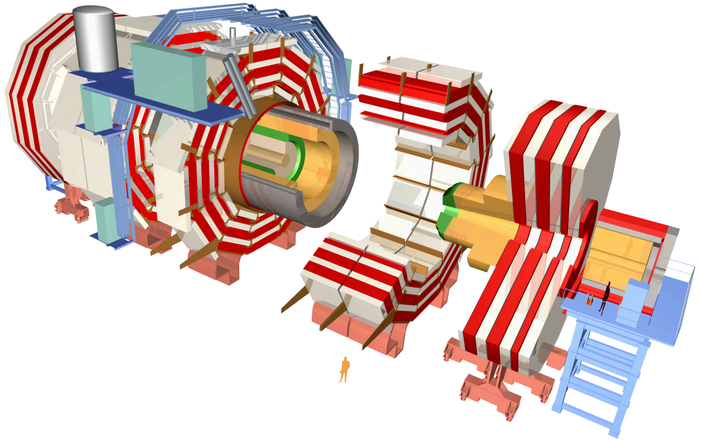
Example decay

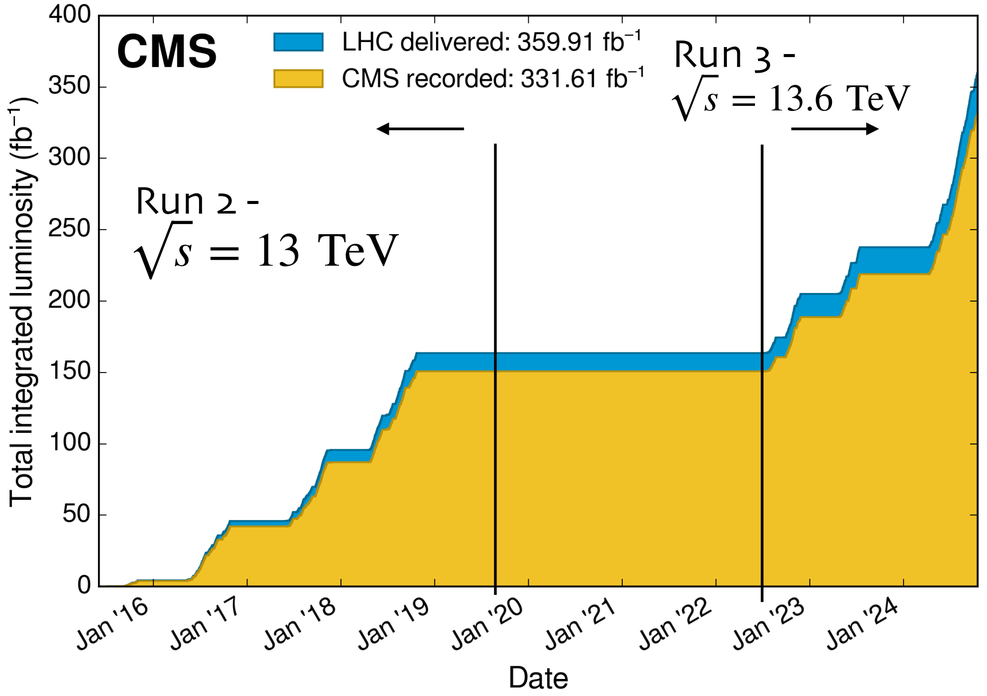
R-parity violating stop decay. **Signature:** no (or small) $p_{\mathrm{T}}^{\mathrm{miss}}$, many jets

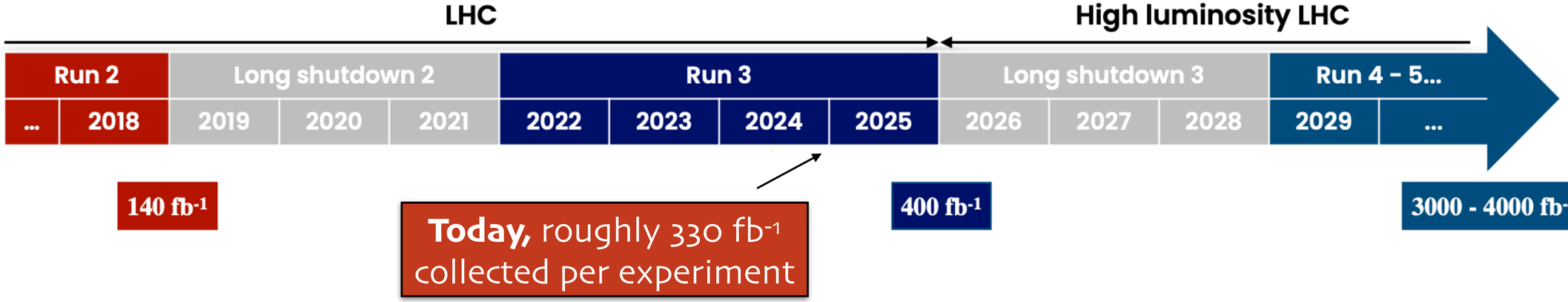


ATLAS & CMS






CMS
LHC delivered: 359.91 fb⁻¹
CMS recorded: 331.61 fb⁻¹
Run 3 -
$\sqrt{s} = 13.6$ TeV
Run 2 -
$\sqrt{s} = 13$ TeV
Total integrated luminosity (fb⁻¹)
0
50
100
150
200
250
300
350
400
Jan '16
Jan '17
Jan '18
Jan '19
Jan '20
Jan '21
Jan '22
Jan '23
Jan '24
Date


LHC
High luminosity LHC
Run 2
Long shutdown 2
Run 3
Long shutdown 3
Run 4 - 5...
...
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
...
140 fb-1
400 fb-1
3000 - 4000 fb-1
Today, roughly 330 fb-1 collected per experiment

Naturalness

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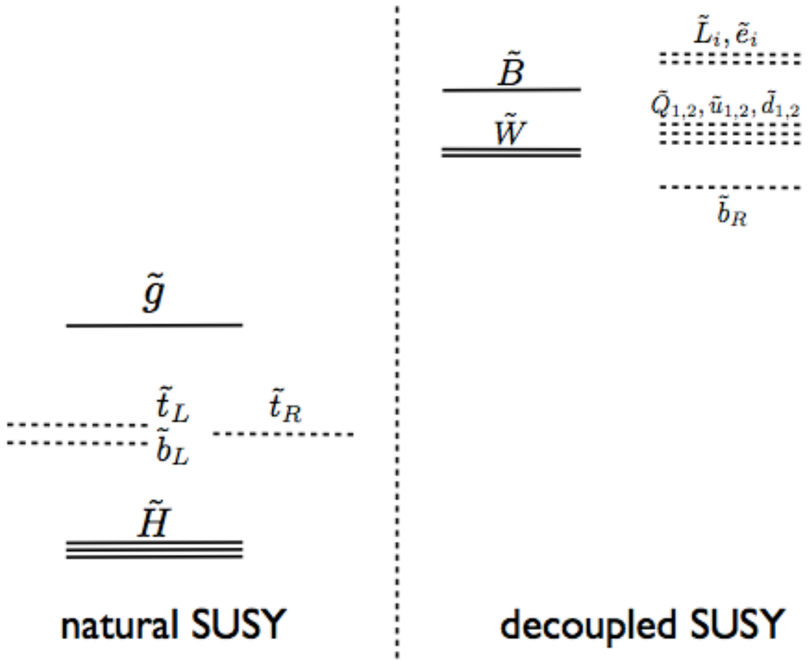
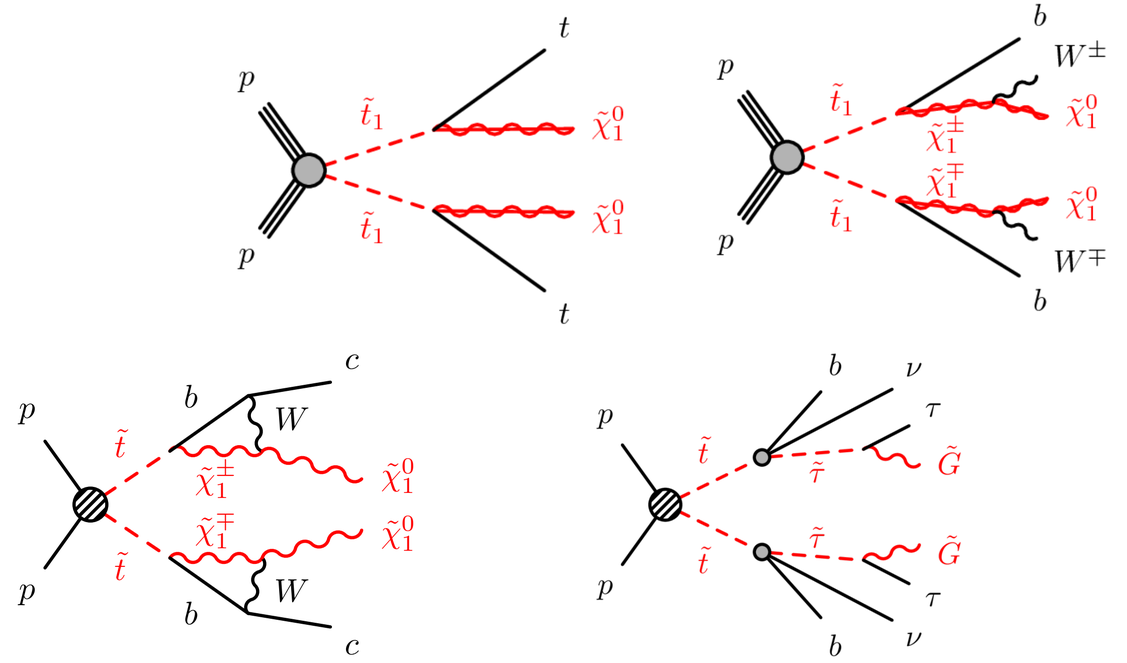
- The naturalness of the Higgs boson mass requires:
  - A **Higgsino mass** of maximum **few hundred GeV**.
  - A **top partner** mass at the TeV scale.
  - A **gluino mass** of maximum few TeV.

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





Strong production - gluinos and squarks

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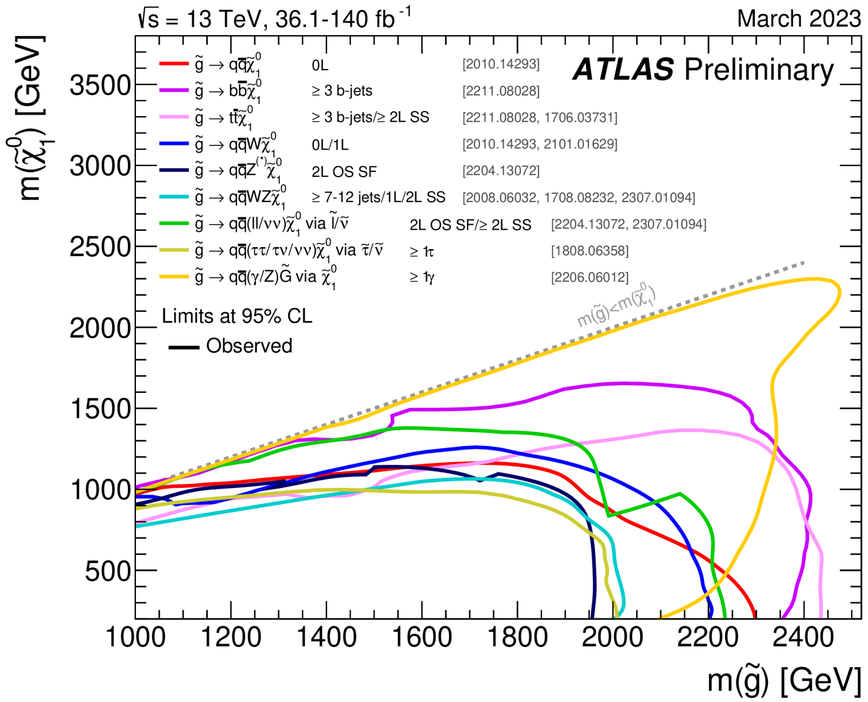
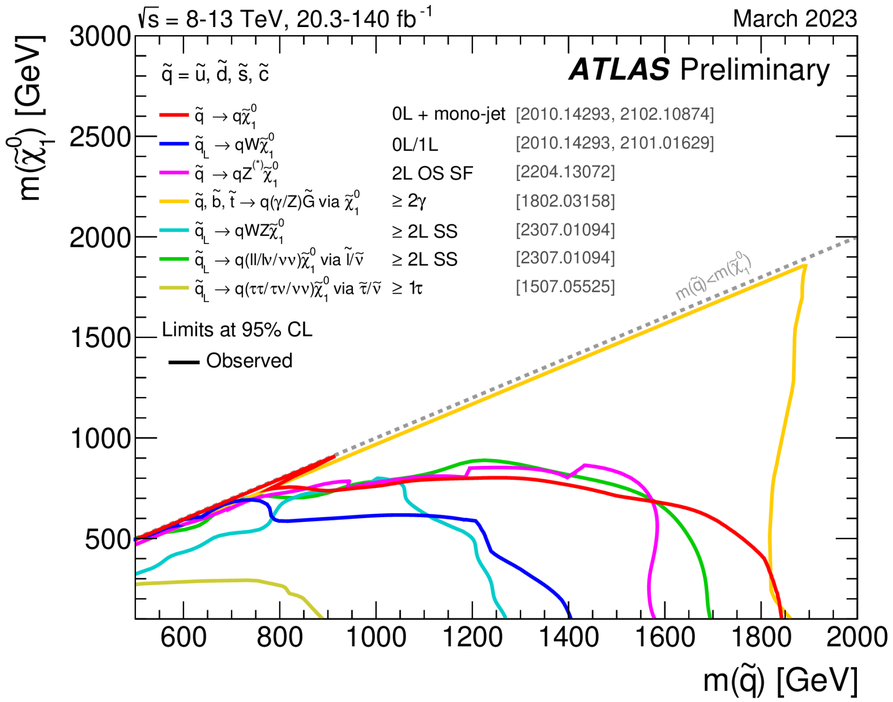
Taken from here





- 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

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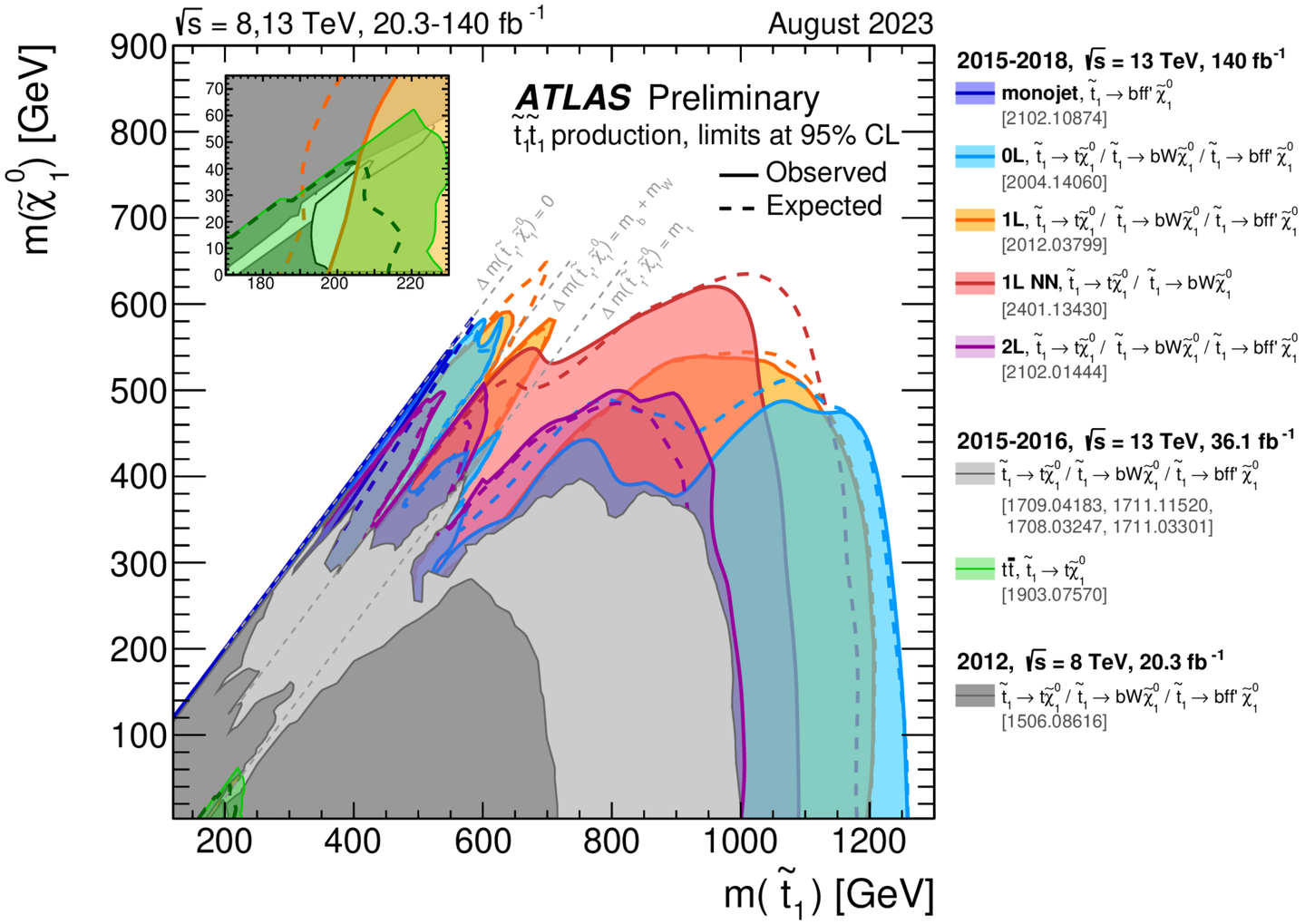
Taken from here



- 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

SUSY-23-001

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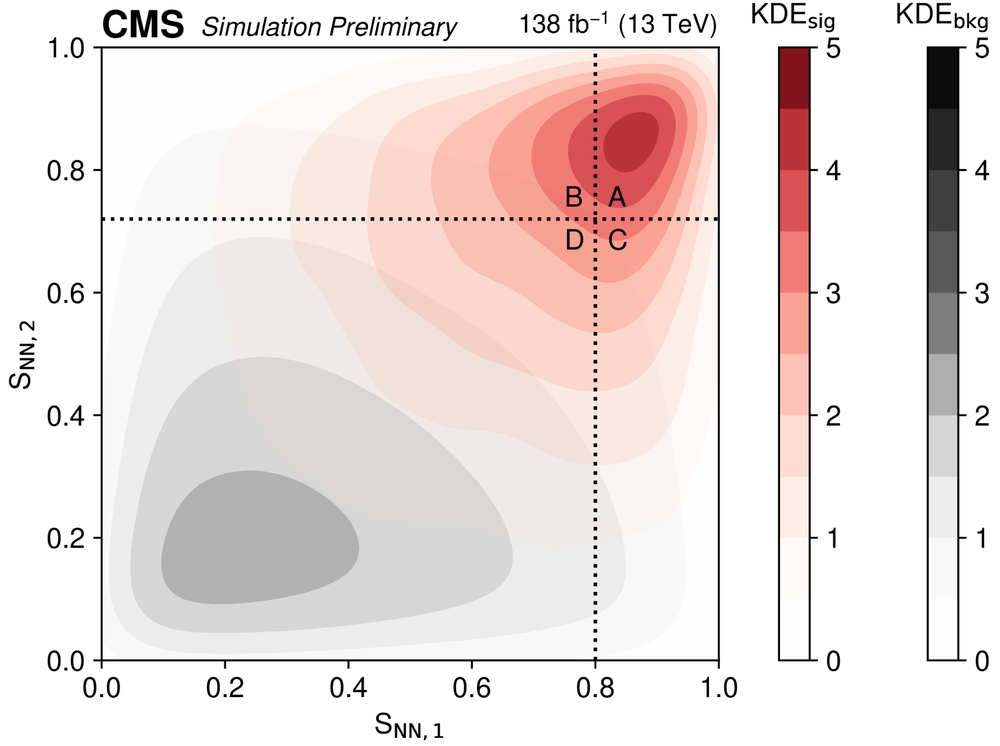
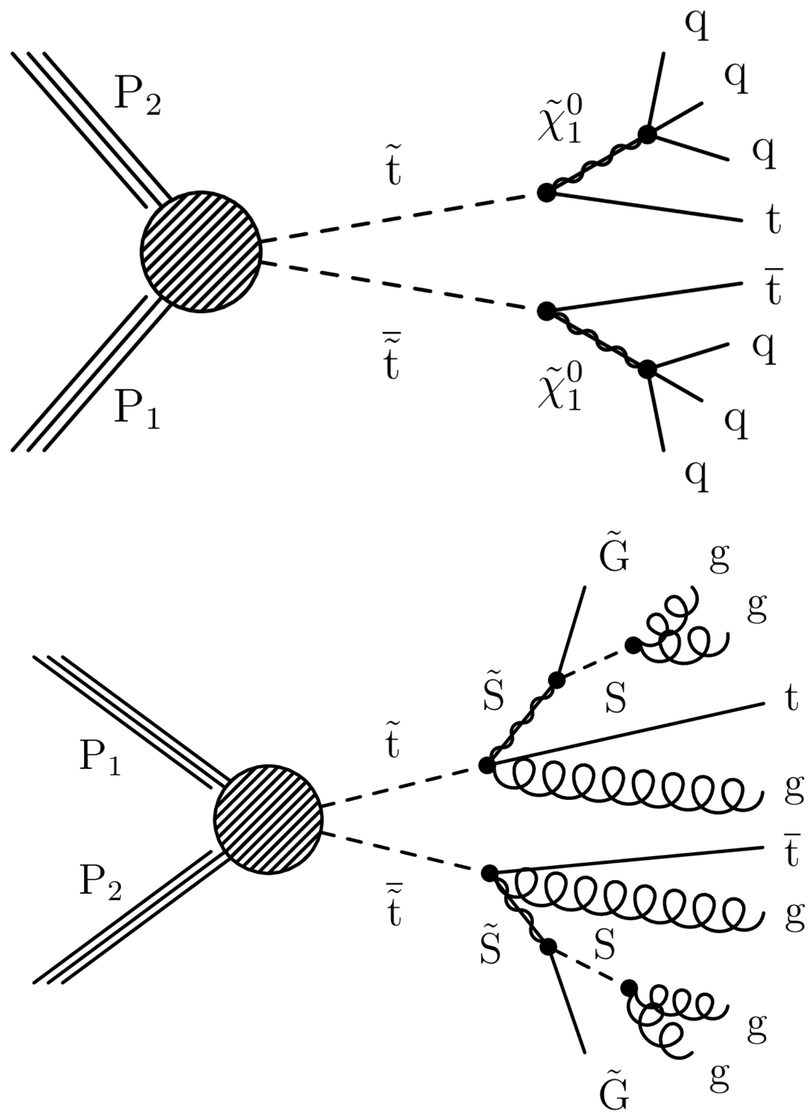
- **0, 1, or 2 leptons** in addition to **at least 6 jets**.
- Dominant $t\bar{t}$ background estimated with data by defining **two decorrelated NN estimators** (Distance correlation loss term - ABCD).





RPV/stealth stop decays

SUSY-23-001

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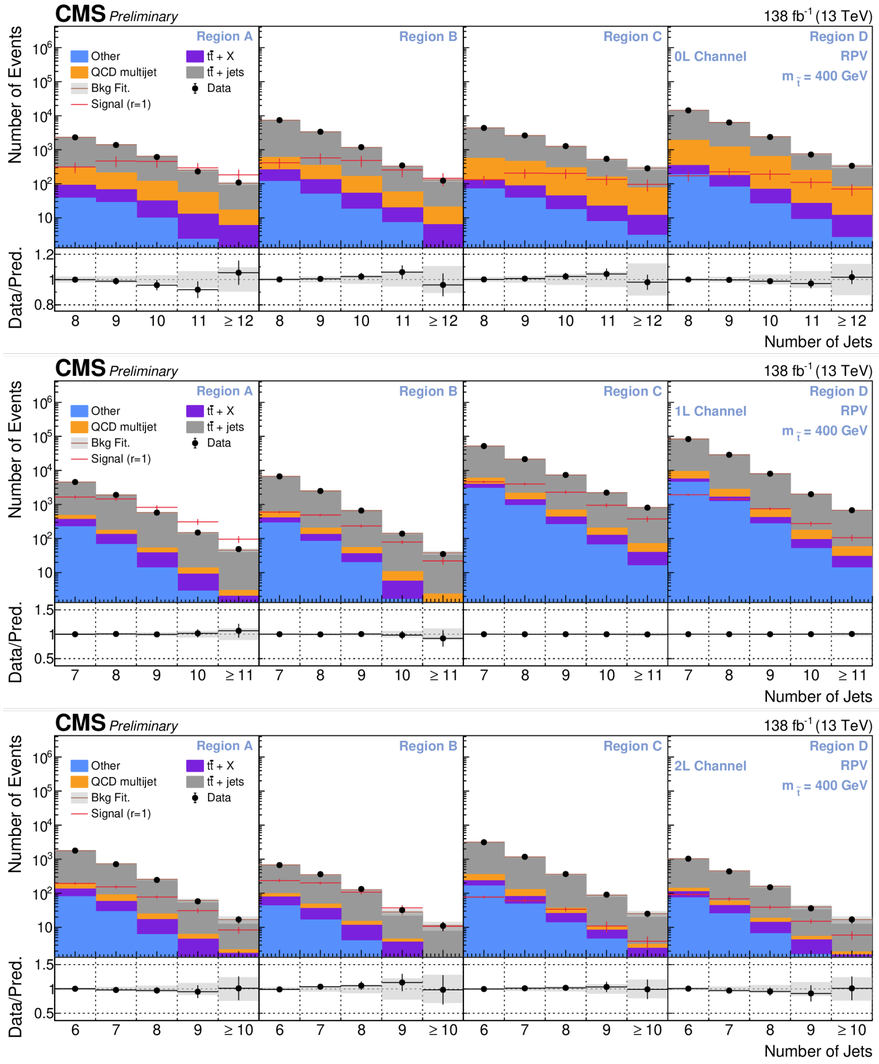
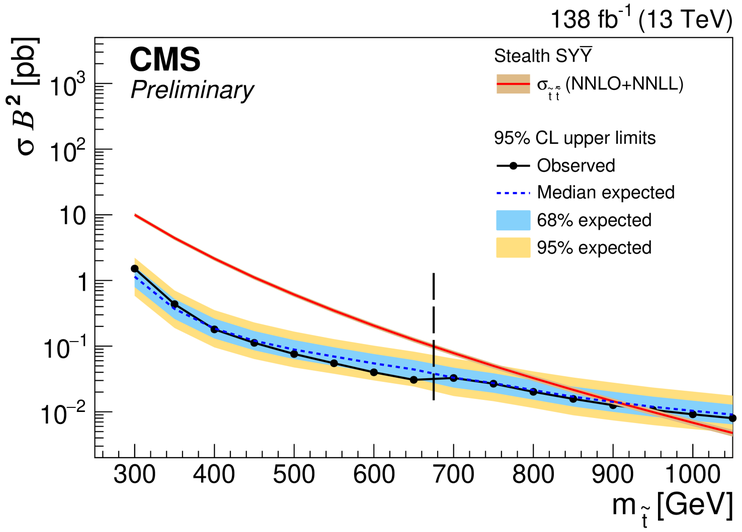
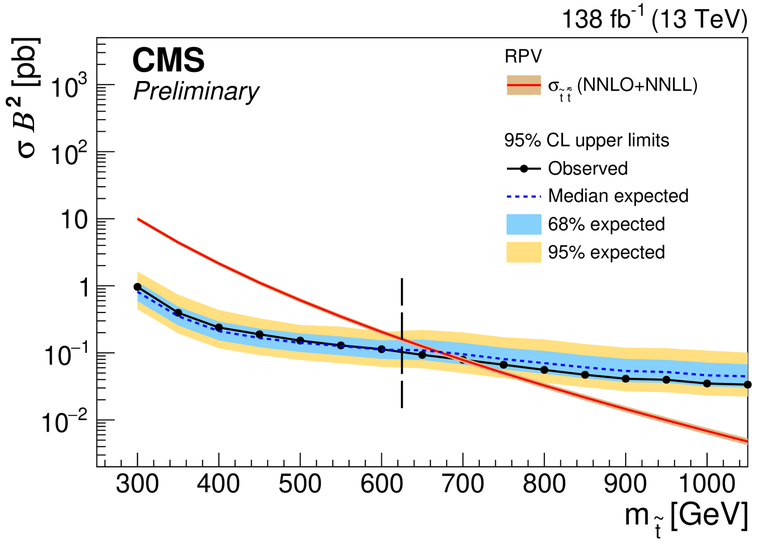
- Non excess above background prediction
- Stops exclusion up to ~ 700 GeV in RPV scenarios, 900 GeV in stealth stop scenarios



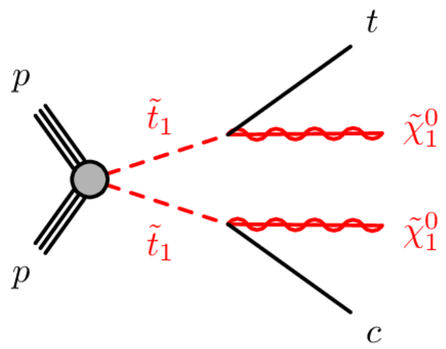




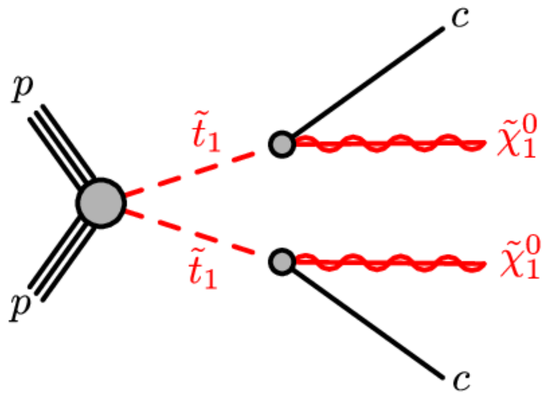
Stop to charm

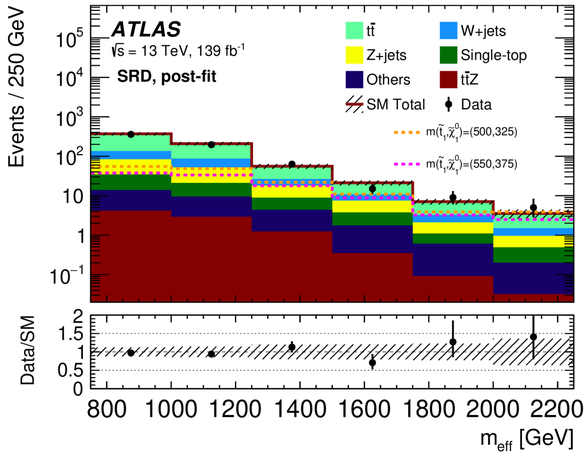
- **Flavour-violating** $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ can become relevant **depending on the parameter space**.
- Targeted using c**—tagging** in conjunction with exploiting **ISR jets** (for compressed regimes)

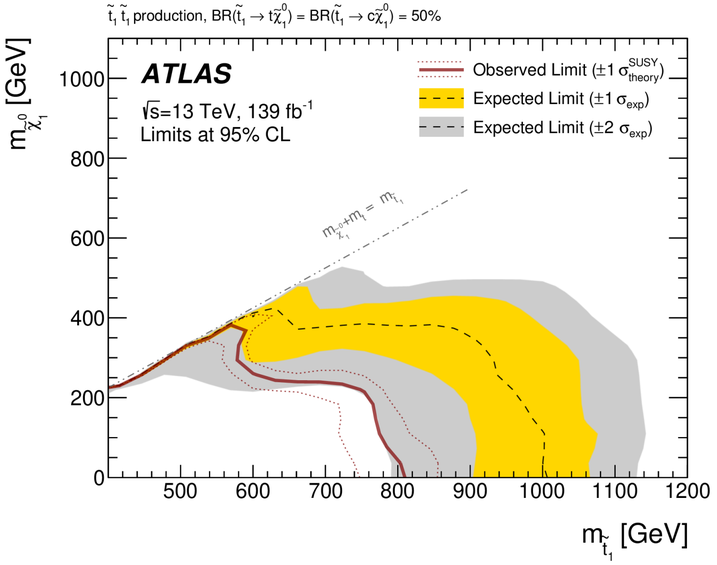
SUSY-2019-23

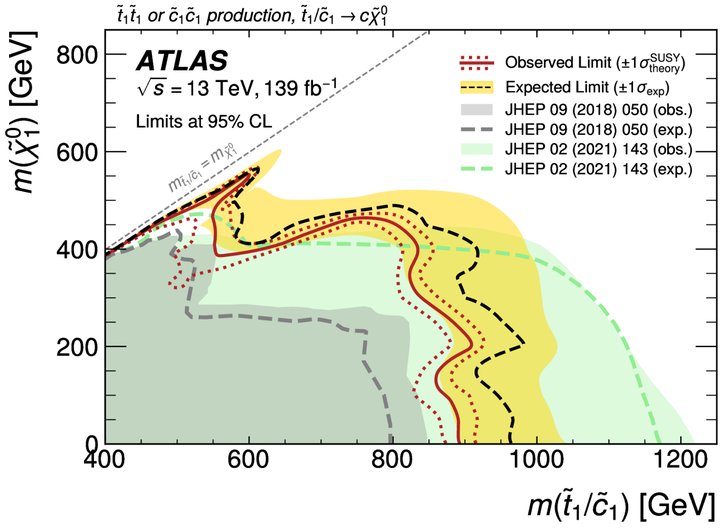


SUSY-2018-25



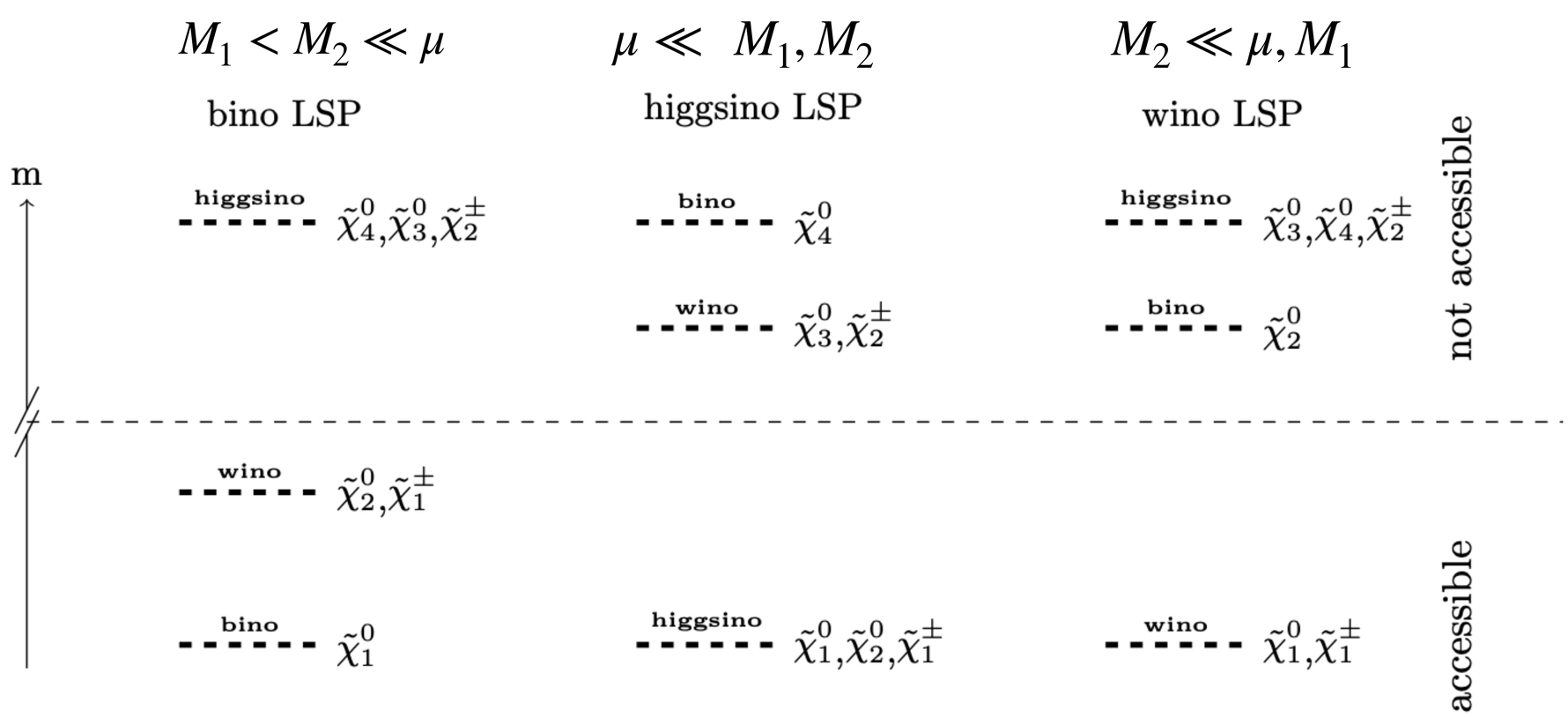






The electroweak sector

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



…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

SUSY-2020-05

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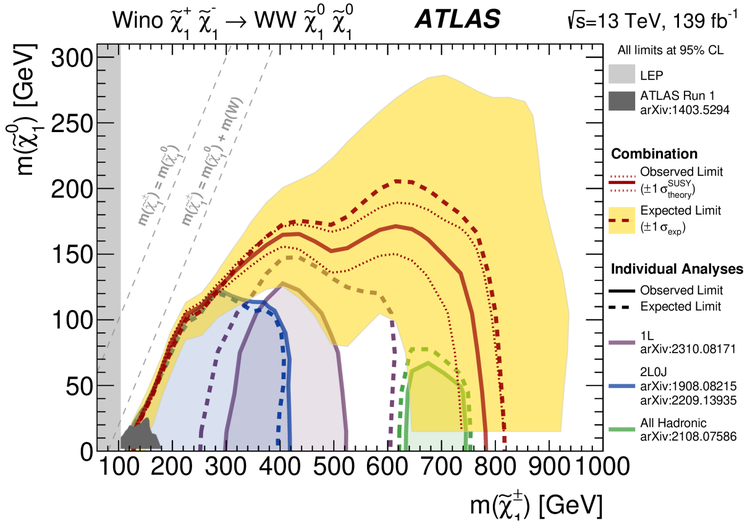
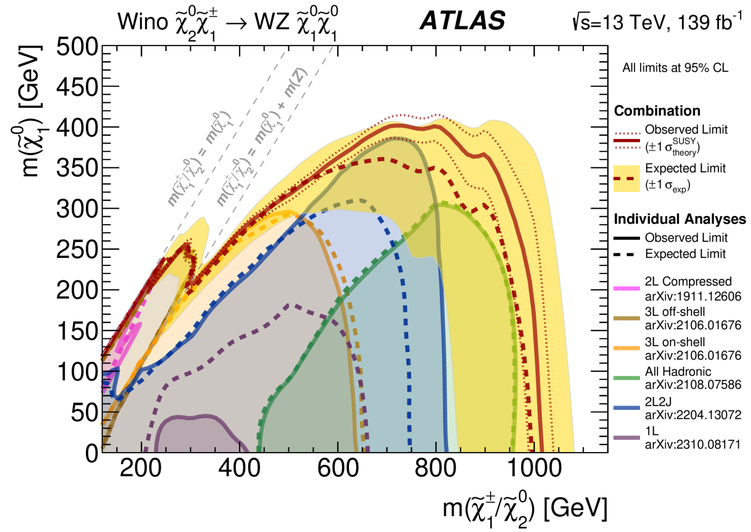
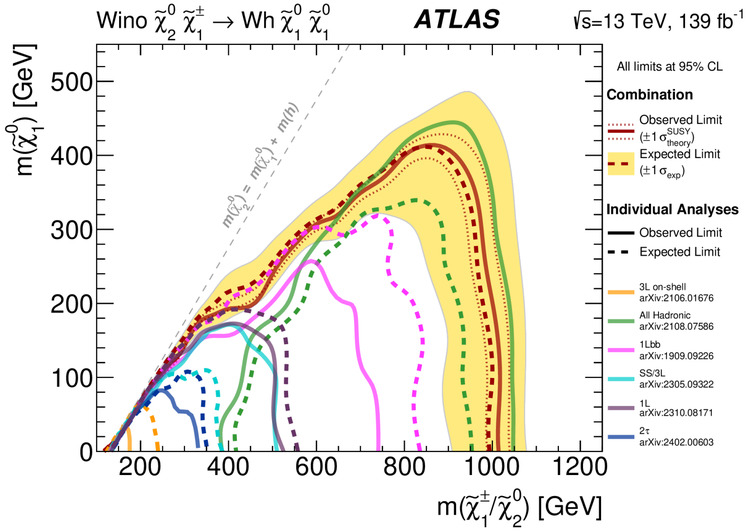
- **Bino-LSP scenarios** - the "historical" electroweak SUSY.
- Limits start to **knock at the TeV scale** (thanks to all-hadronic analyses - a nice development of Run 2)
- Focus shifted to less common scenarios.







Compressed electroweakino spectra

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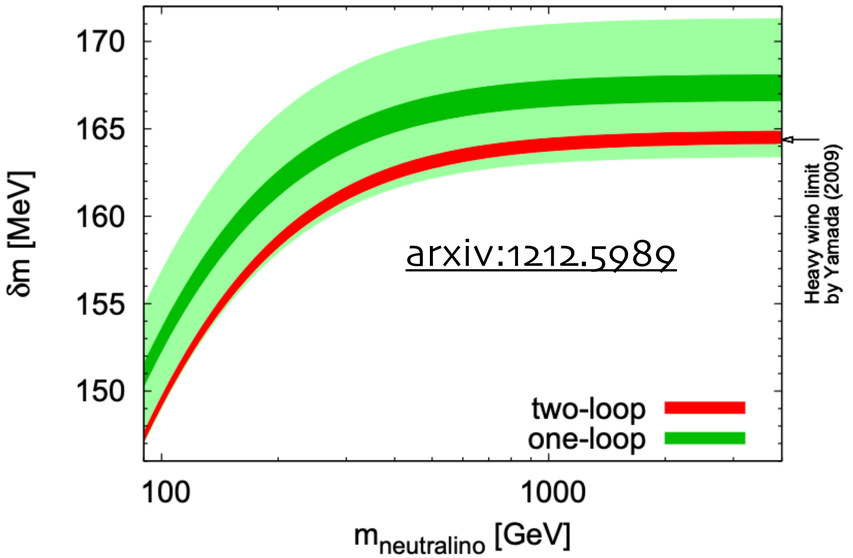
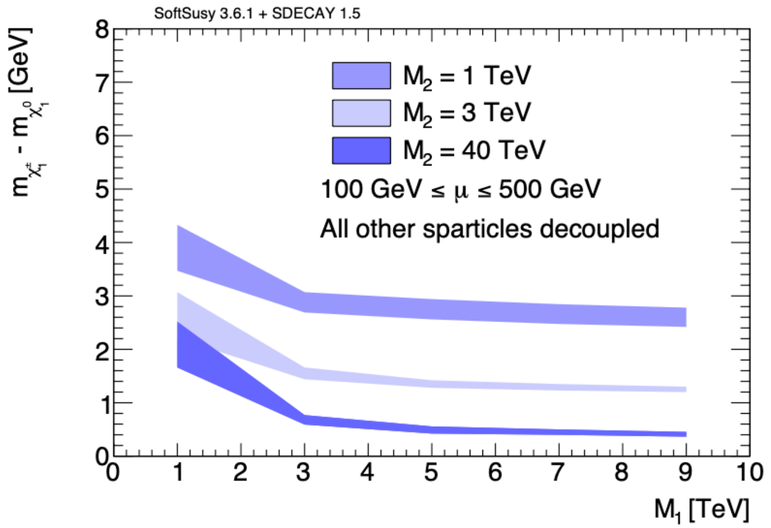
- Wino-LSP: $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim 150$ MeV implies long-lived charginos.
- Higgsino-LSP: $\Delta M(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \sim 300$ MeV may imply slightly long-lived $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ (but requires very large M_1/M_2. More natural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





Disappearing track

SUS-21-006

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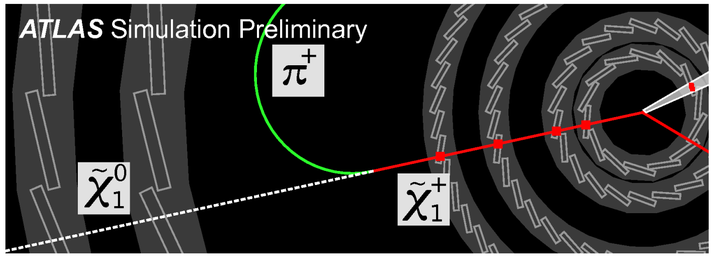
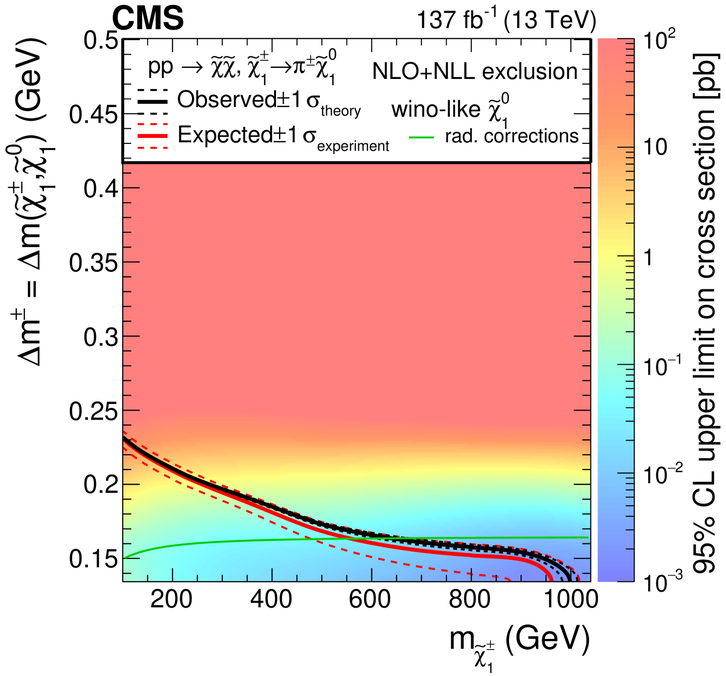
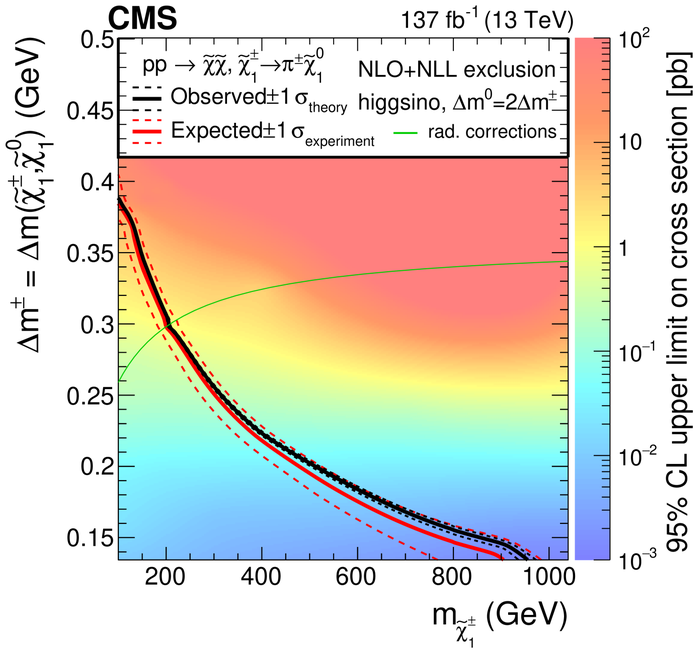
Silver bullet against **wino-like scenarios**, with sensitivity to (very compressed) higgsino scenarios.



- 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.

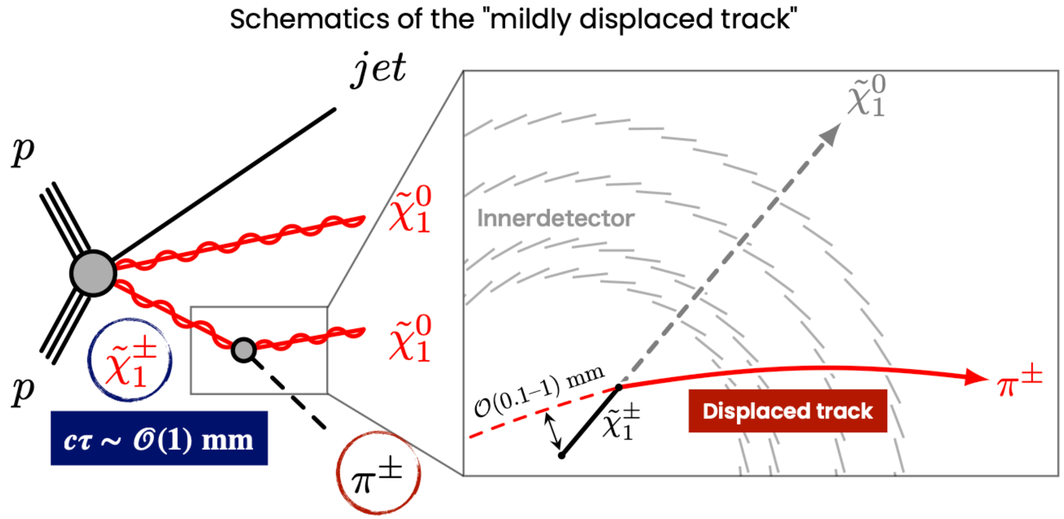


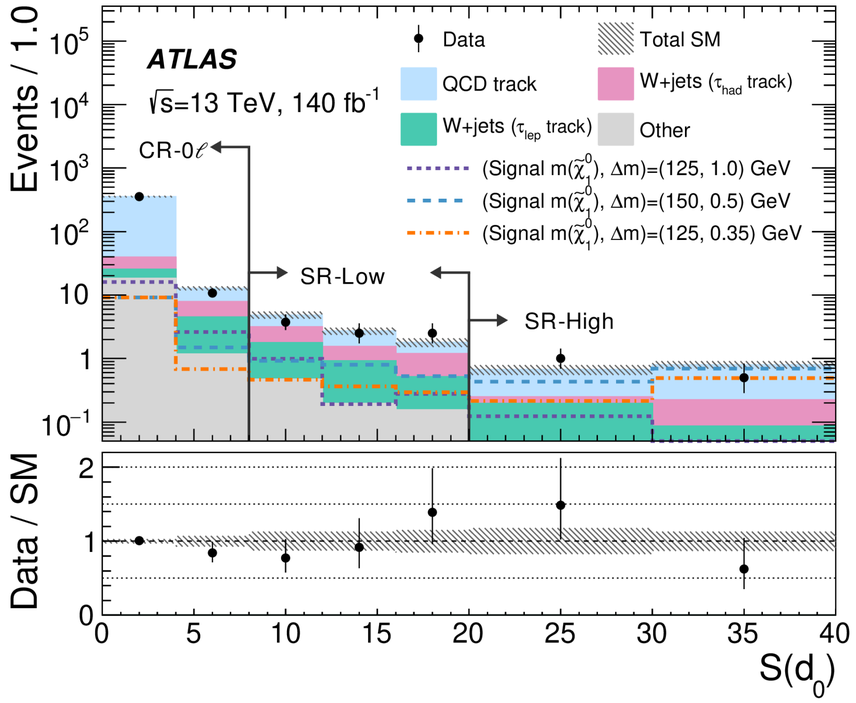


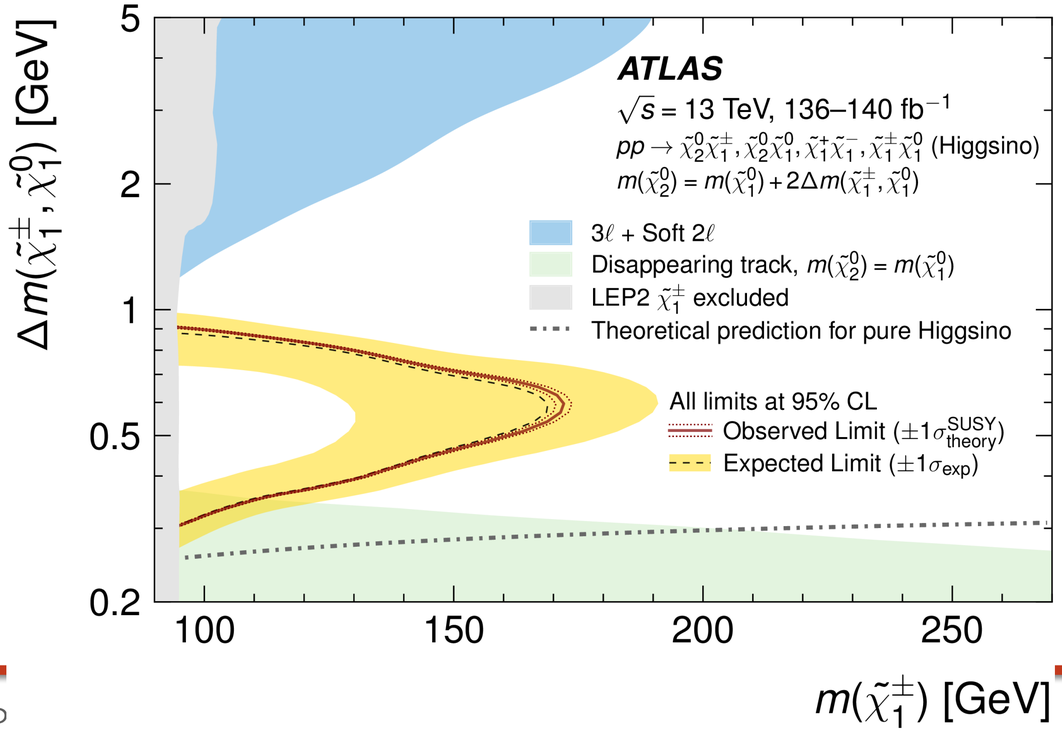
Mildly displaced tracks

SUSY-2020-04

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







Using Vector Boson Fusion

SUSY-2023-26

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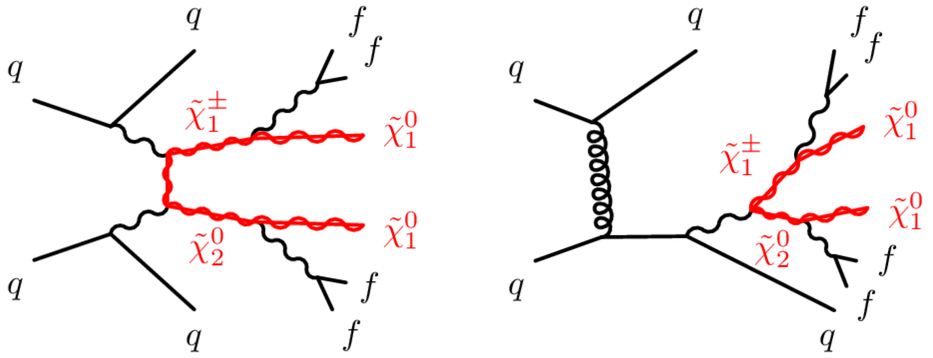
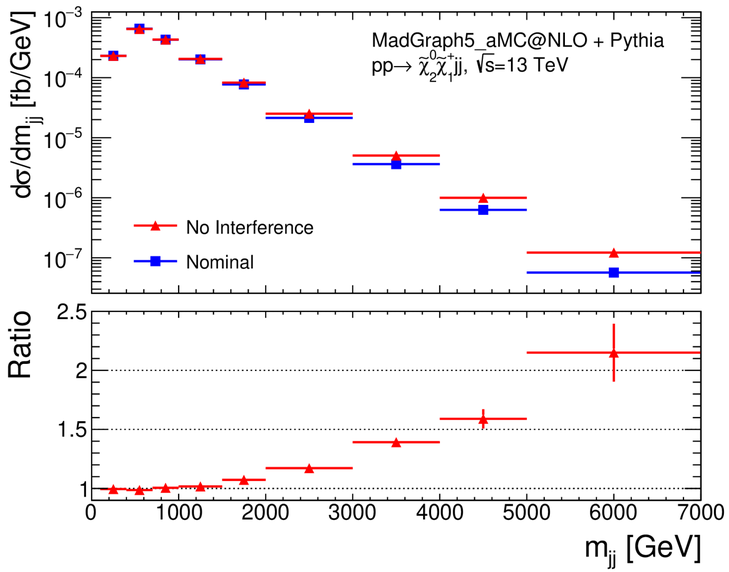
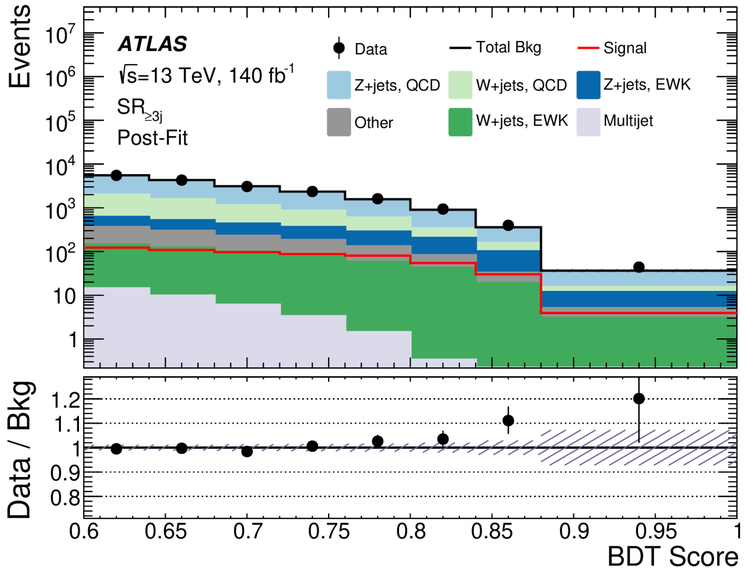
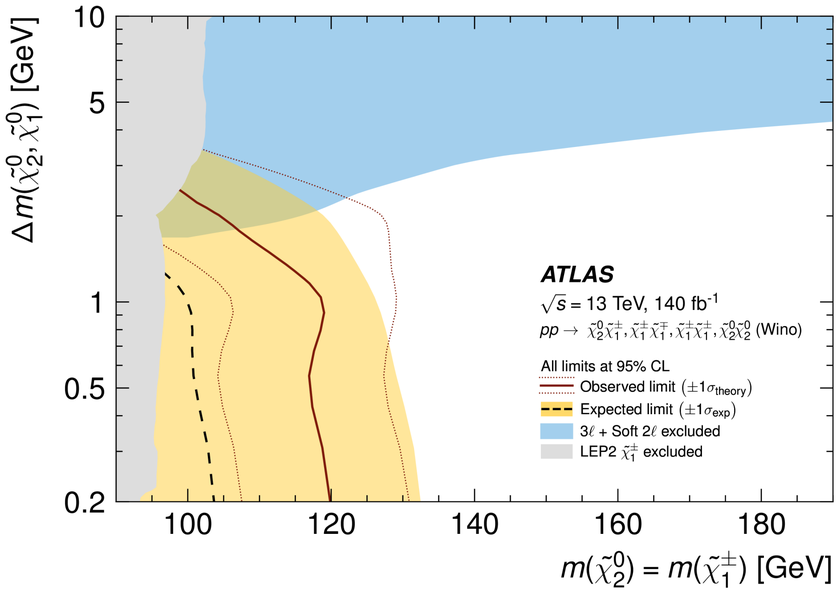
Definition of **VBF cross sections** in SUSY **far from trivial**:

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

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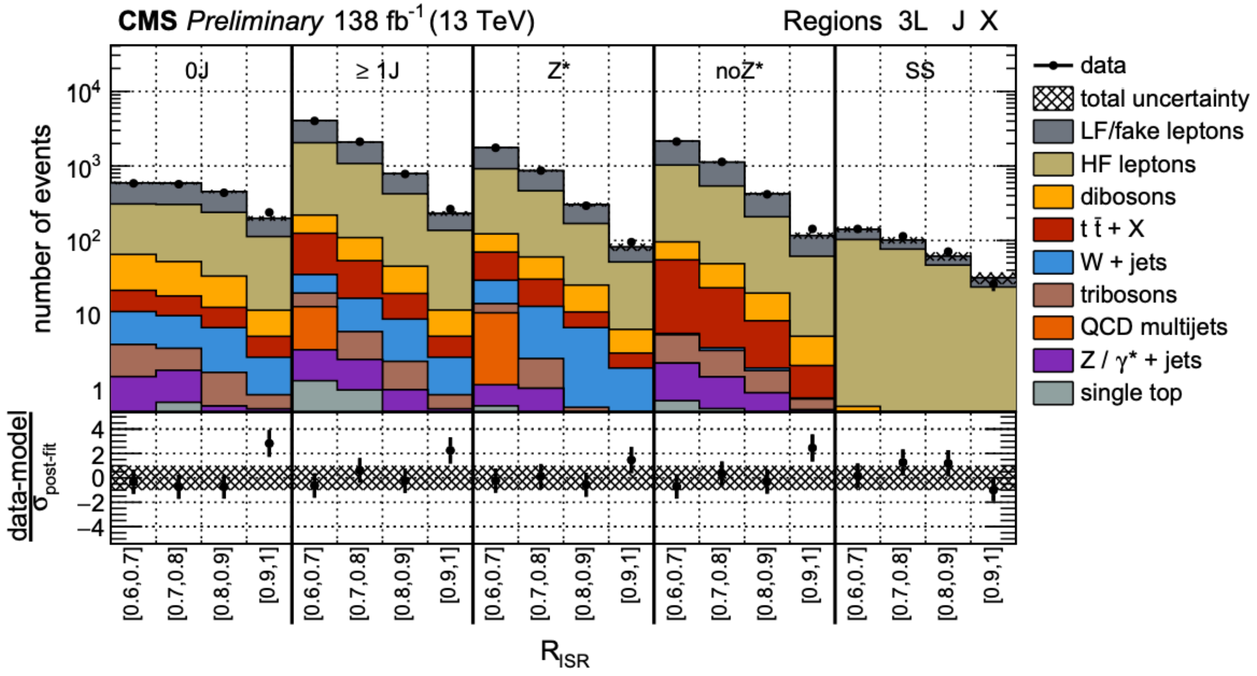
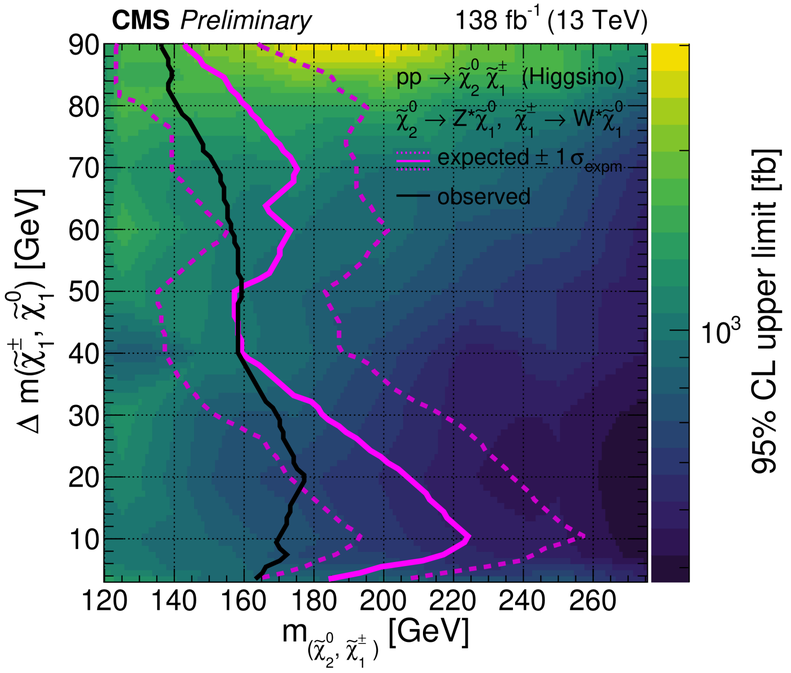
- Approach based on RJR variables ($R_{ISR} = \frac{\mathbf{p}_i \cdot \hat{\mathbf{p}}_{ISR}}{\mathbf{p}_{ISR}} \sim \frac{m_i}{m_P}$ for a pair-produced particle P recoiling against an ISR jet and decaying into invisible particles i)
- Events categorised based on number of leptons, $b-$tags, jet multiplicity





Comparison ATLAS-CMS

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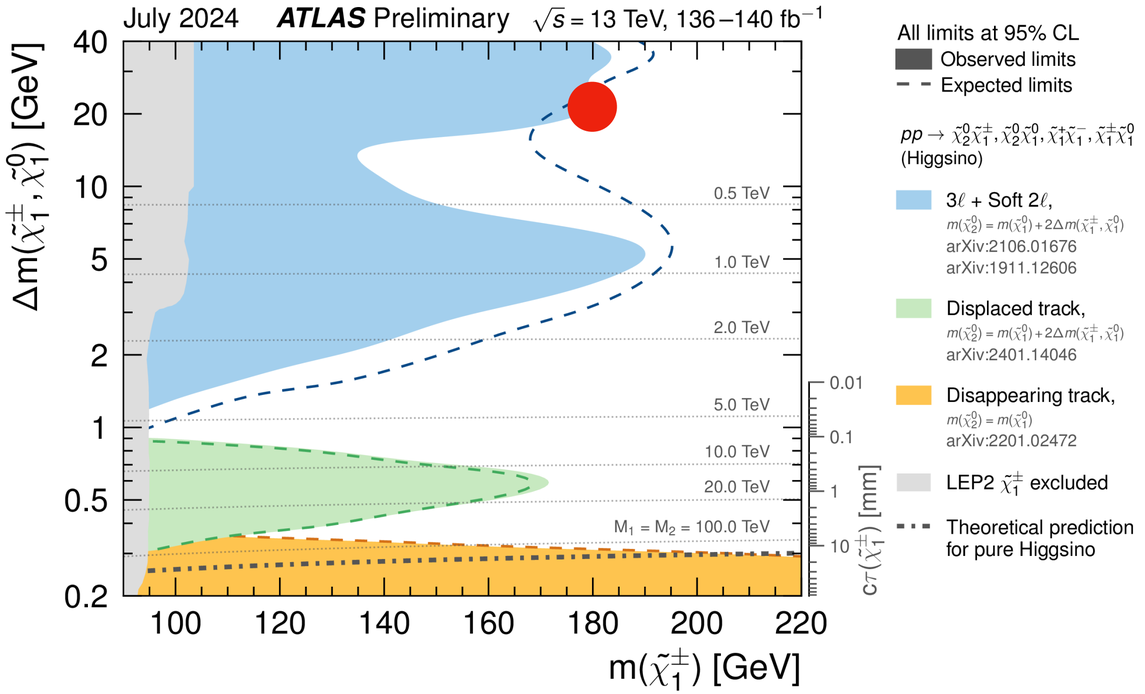
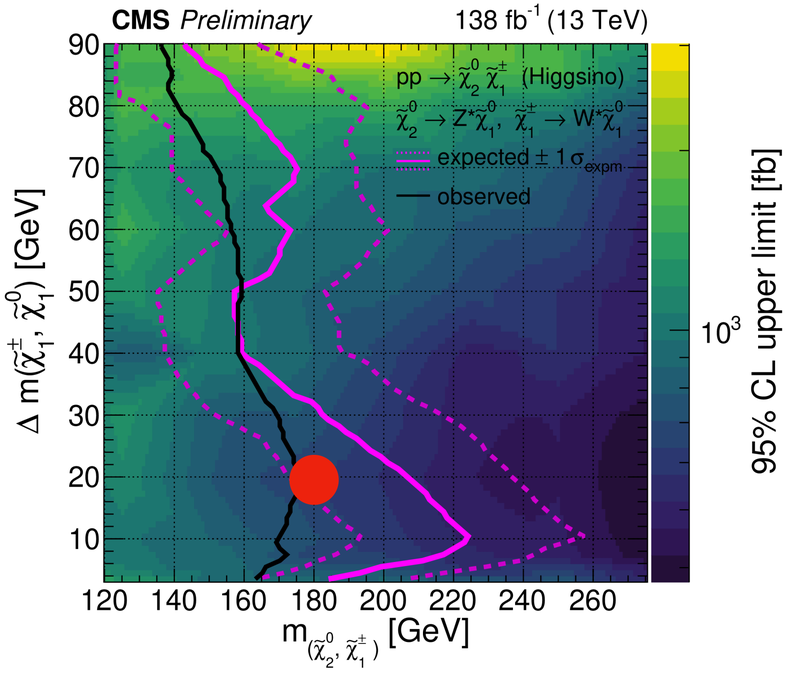
- **Similar excesses** in ATLAS and CMS (each at the level of ~ 2σ). **SUSY in plain sight or just a statistical fluctuation**?
- Certainly **something to be scrutinised carefully** with the Run 3 data.
  - **Bulk of sensitivity coming from soft-lepton analyses (2L and 3L channels).**





A Run 3 search - displaced leptons

SUSY-2022-11

EXO-23-014

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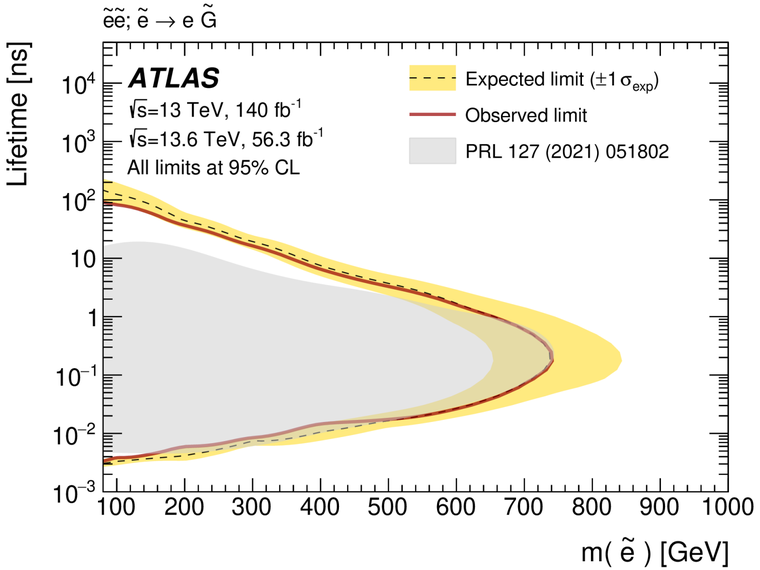
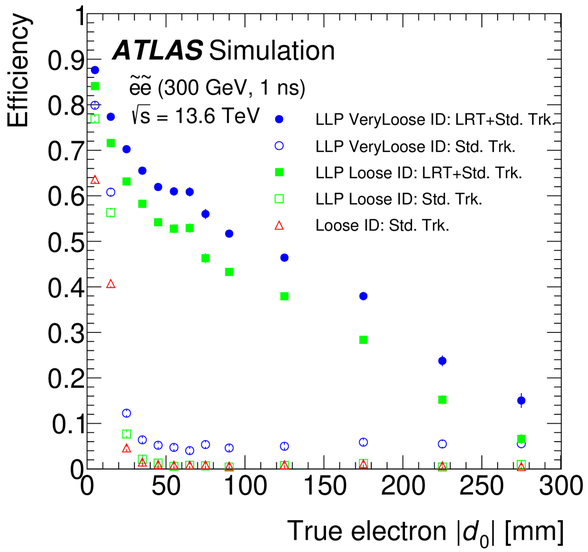
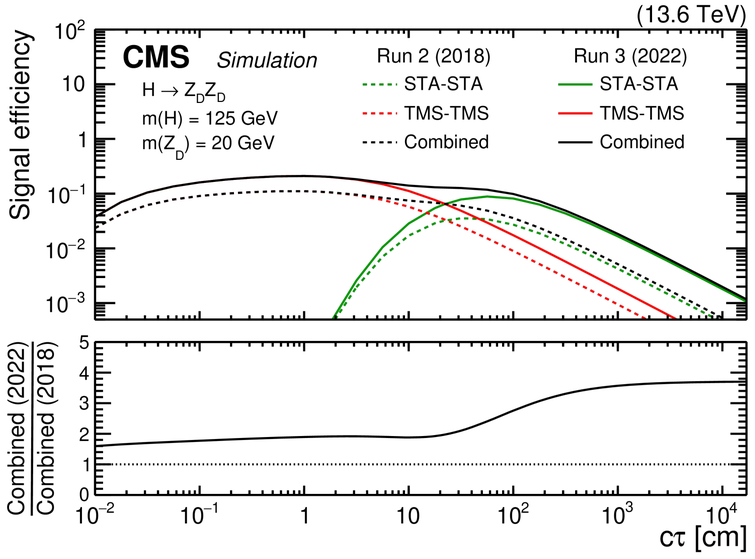
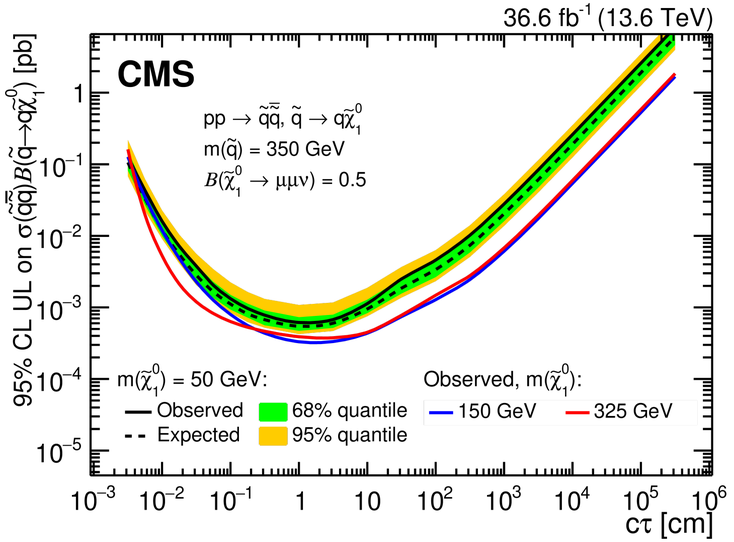
- The Run 3 search programme is in **full swing**. The **first Run 3 SUSY searches** are available
  - Non-pointing leptons arising from long-lived sleptons or charginos.
  - Long-lived particle decay yielding a dimeno vertex in CMS
- A showcase of improvements for Run 3:
  - **Large Radius Tracking**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



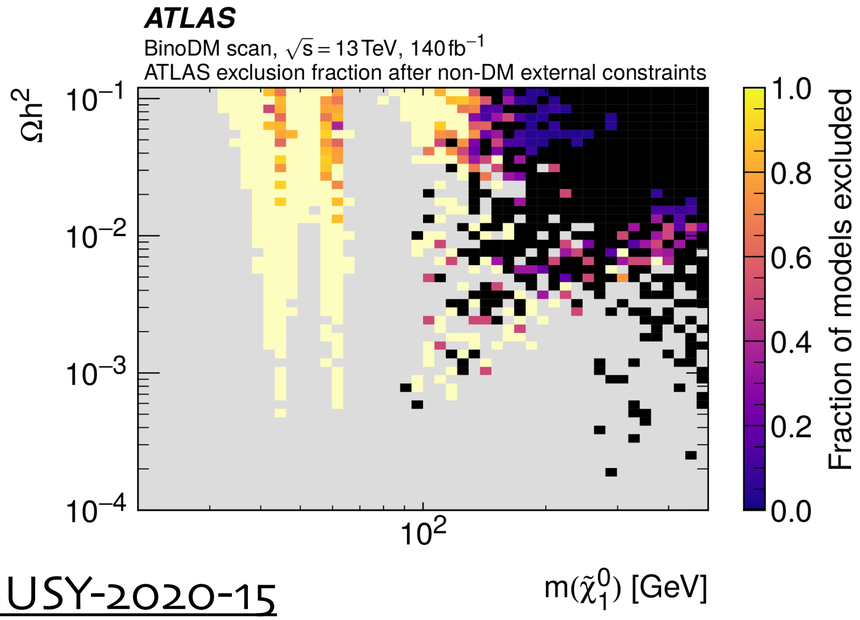




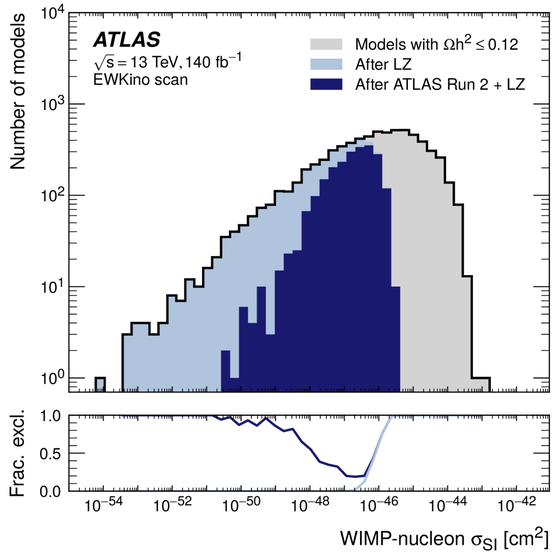


From simplified to UV-complete models

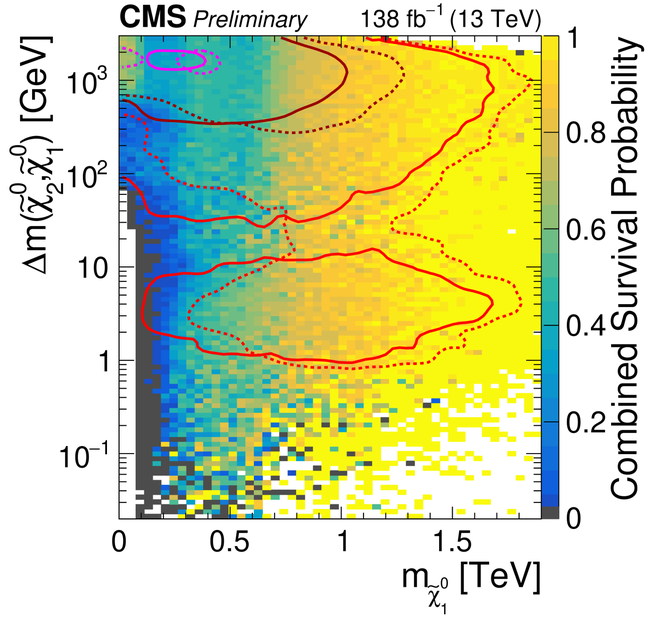
- The **simplified models** do not allow to make **solid statements on model parameter exclusions**.
- pMSSM scans in full swing (using different approaches):
  - One example: EW 5-parameters for ATLAS.
  - Another example: 19-parameters for CMS.
- A testament to the reinterpretation capabilities of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

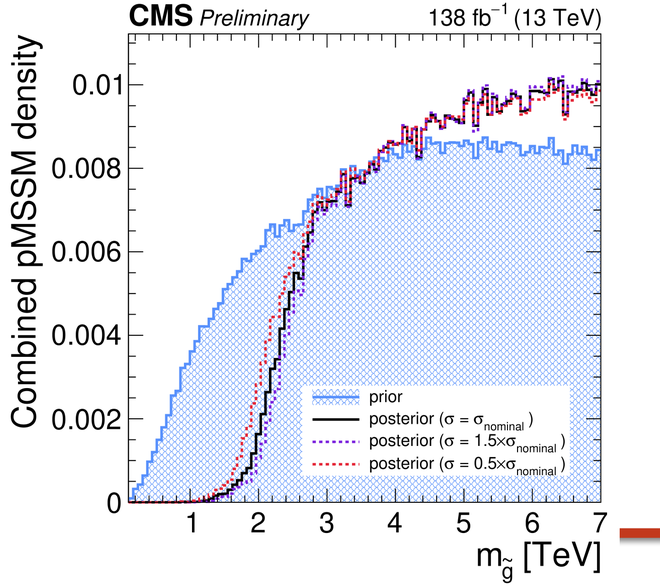


SUSY-2020-15



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

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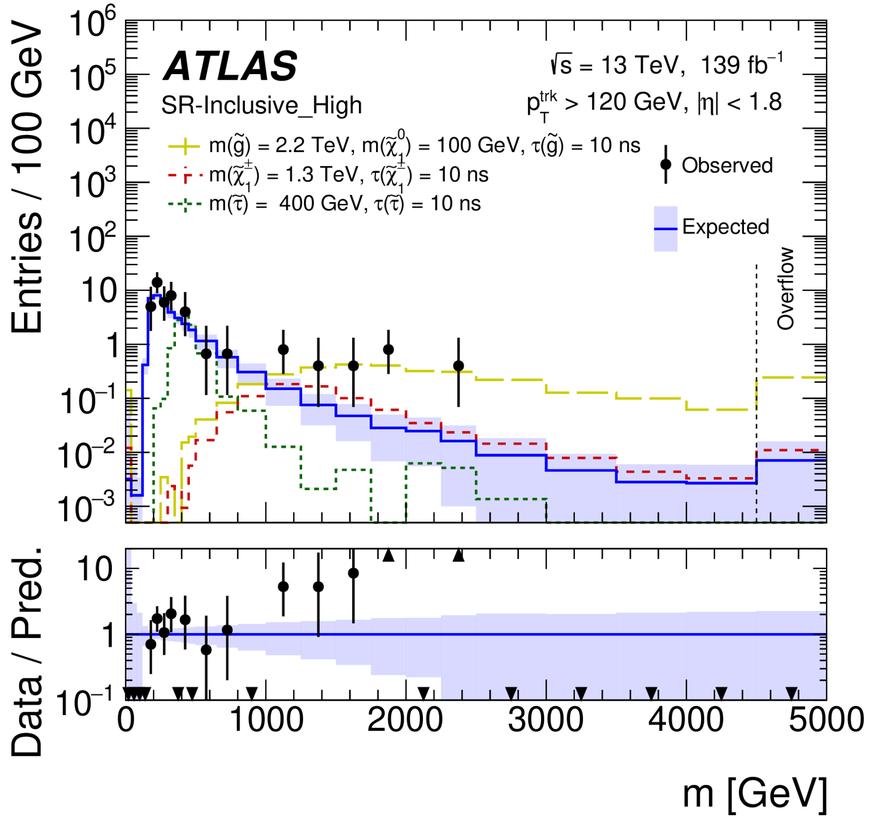
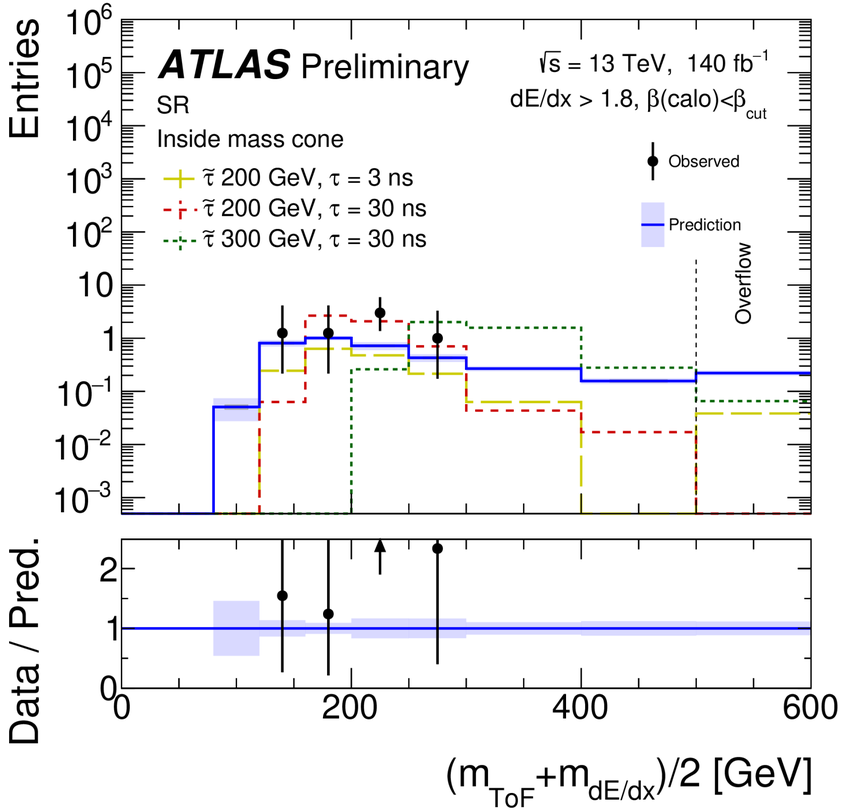
From SUSY-2018-42



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