Stealth and RPV SUSY searches with CMS

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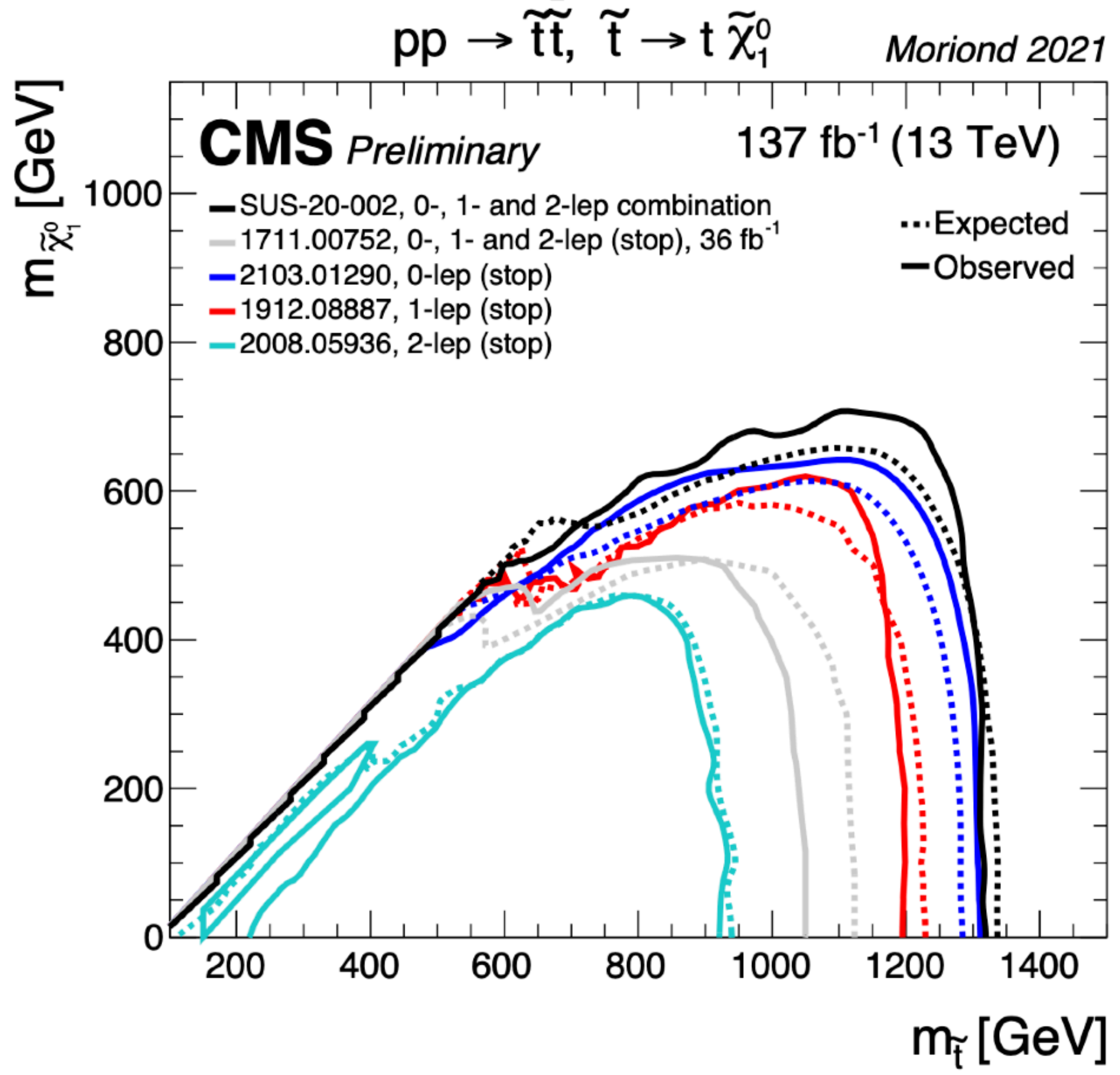
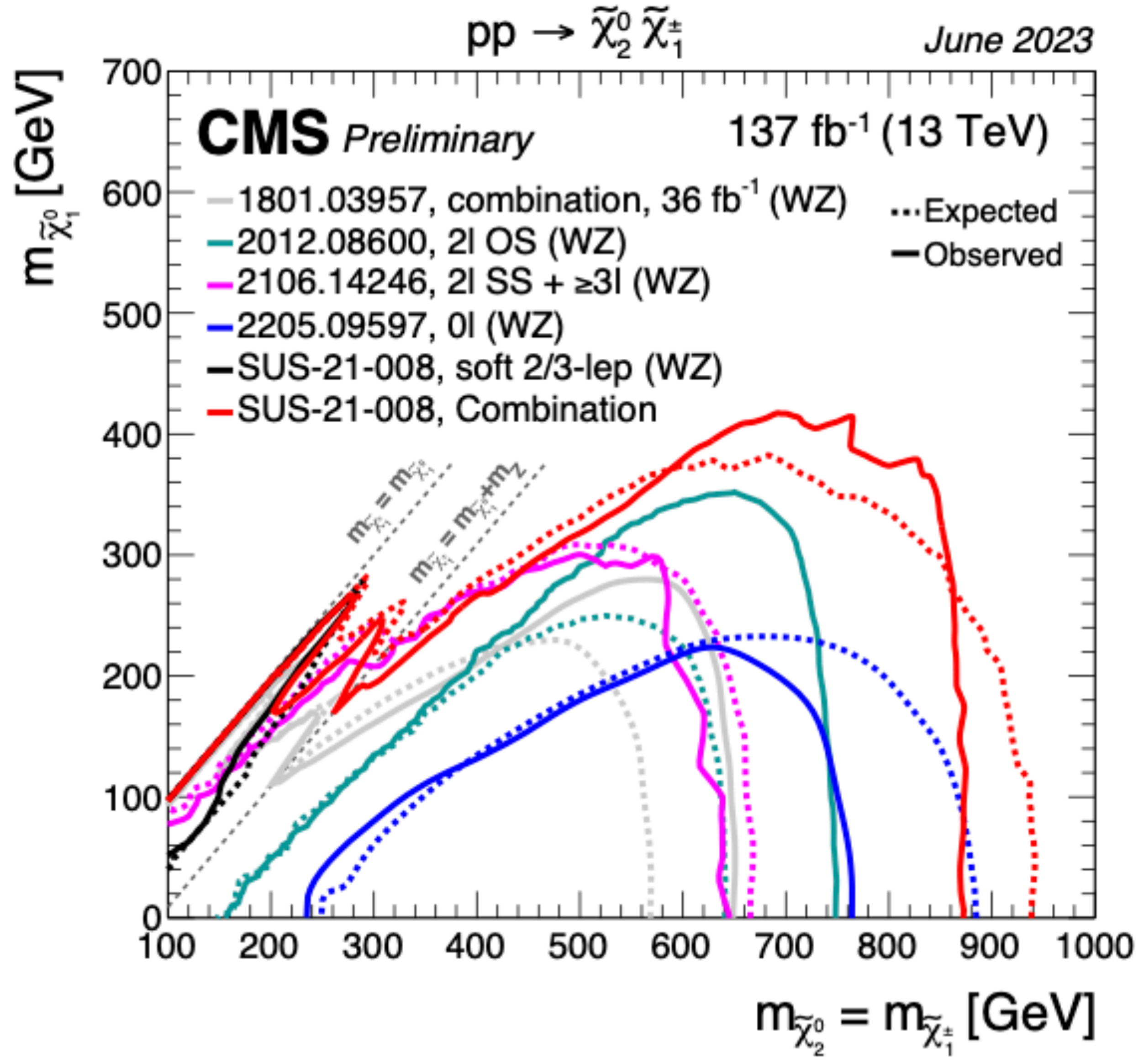
On behalf of the CMS Collaboration

LP2025, Madison
Aug 26, 2025

Introduction

- Many searches for “standard” SUSY have been completed, with no evidence for new sparticles found
- Only three options:
  - SUSY doesn’t exist in any form
  - SUSY particles are at a mass beyond the reach of the LHC
  - SUSY particles are hiding in tricky corners: focus of this talk
- I’ll discuss three recent analyses that search for signs of R-parity violating SUSY or stealth SUSY
  - SUS-23-015: WZ+jets in 3-lepton final state
  - SUS-23-001 & MLG-23-003: $t\bar{t}$+jets in 0/1/2-lepton final state
  - SUS-23-014: inclusive search with boosted objects & razor variables
- Note: only considering prompt final states here — see other talks for long-lived cases



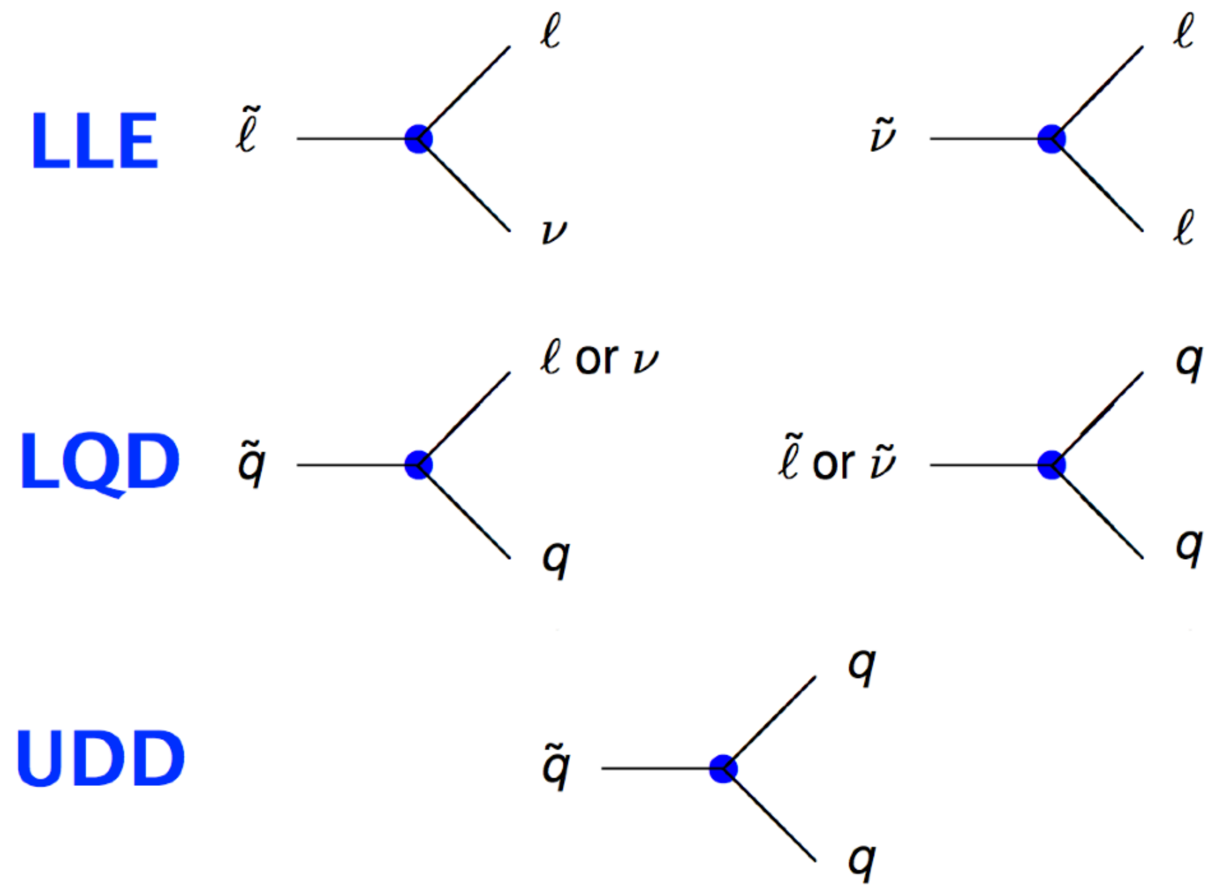


R-parity violating & Stealth SUSY

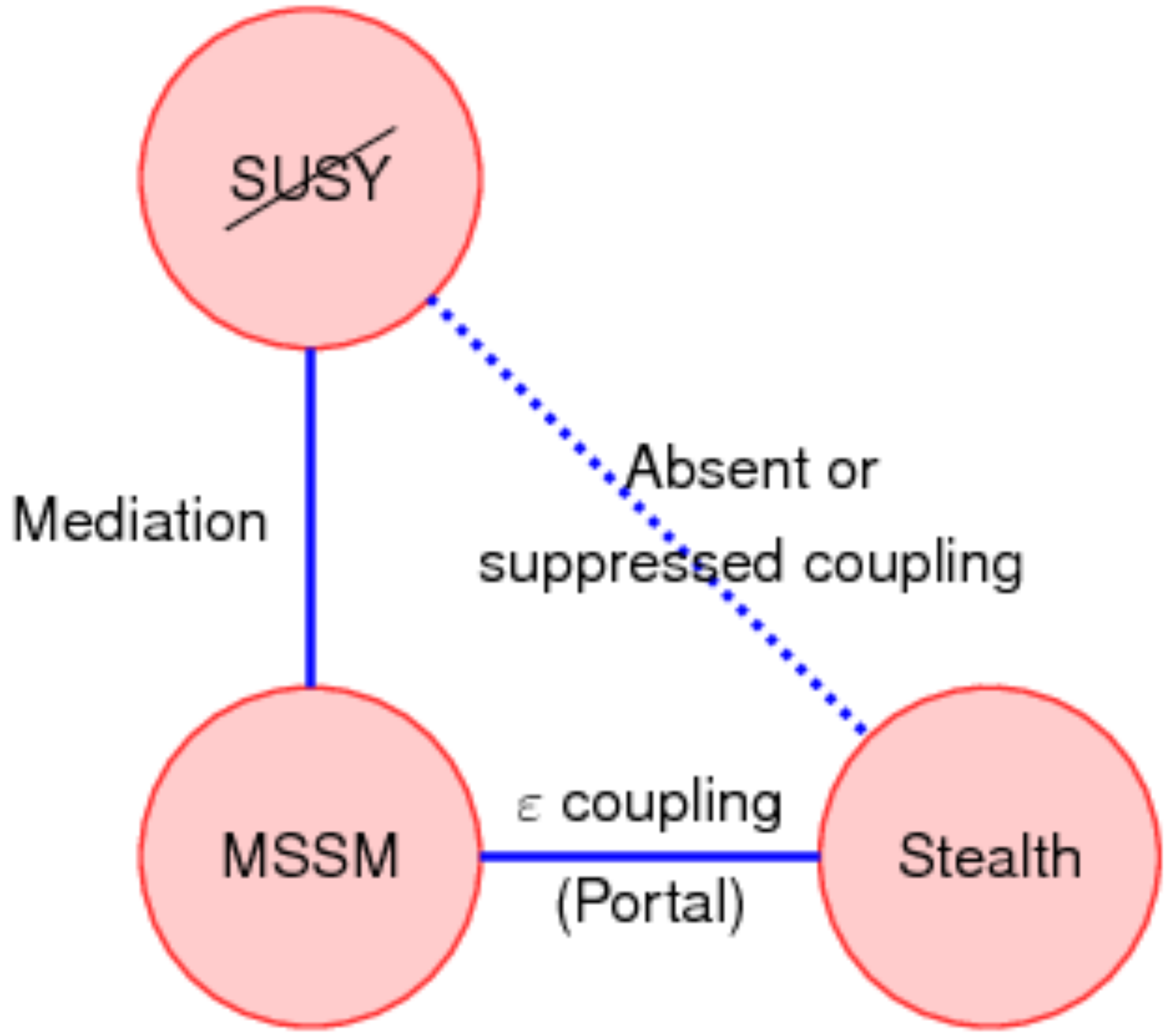
Dreiner et al (JHEP07(2023)215)
Fan et al (JHEP07(2016)016)

- **RPV**: allow the lepton- and baryon-number violating couplings in the MSSM, typically 1 at a time (to avoid proton decay)
  - Lightest SUSY particle is no longer stable

$$W_{RpV} = \epsilon_{ab}[\lambda_{ijk}L_i^a L_j^b \bar{E}_k + \lambda'_{ijk}L_i^a Q_j^b \bar{D}_k + \kappa_i L_i^a H_u^b] \qquad \not{L}$$
$$+\lambda''_{ijk}\epsilon_{xyz}\bar{U}_i^x \bar{D}_j^y \bar{D}_k^z \qquad \not{B}$$



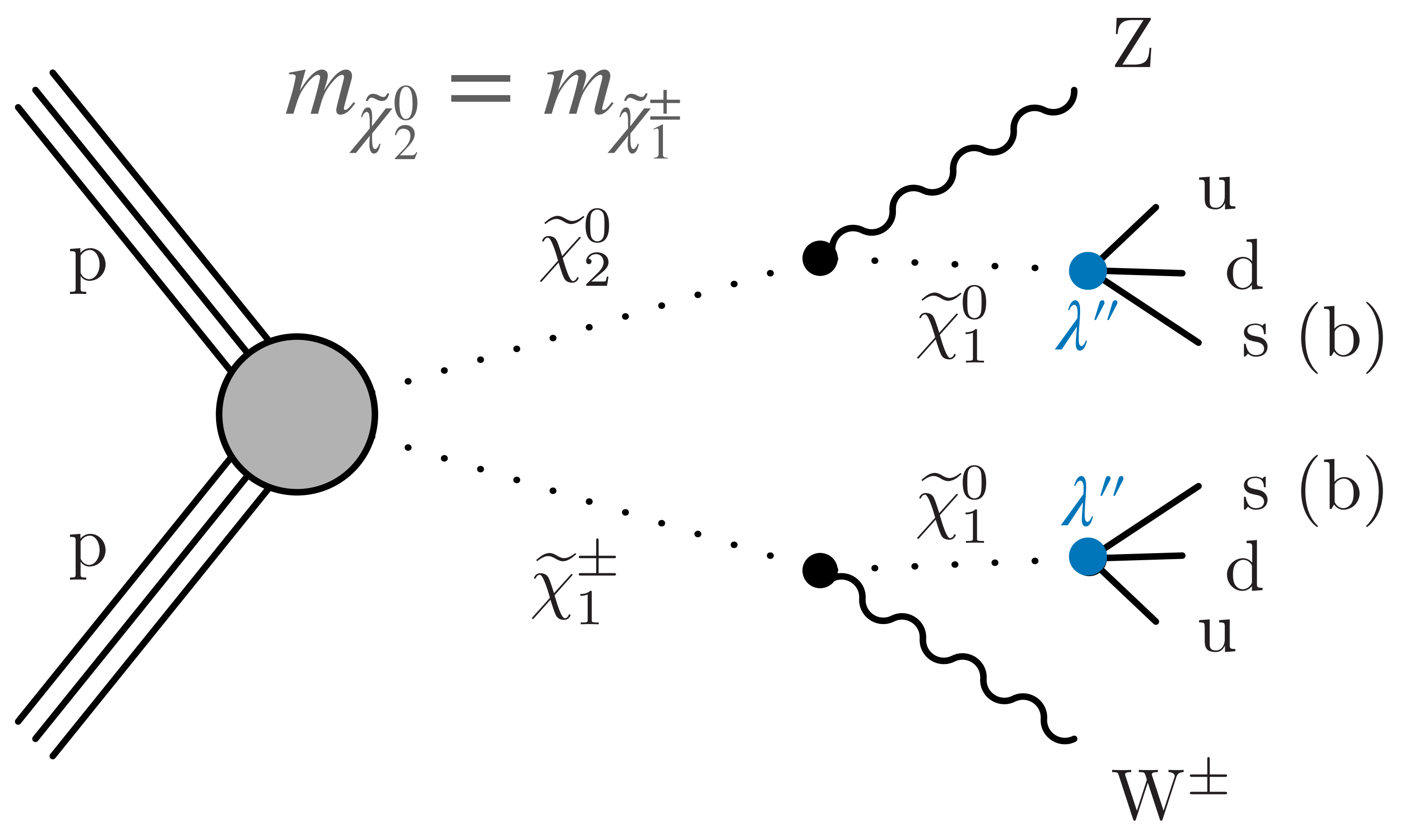
- **Stealth**: introduce a stealth hidden sector in which SUSY is conserved, connected to MSSM via a small coupling.
  - Minimal version introduces a singlet + singlino partner with small mass splitting



- **Typically: p_T^{miss} is exchanged for visible SM particles**
  - Many possibilities!
  - Can result in events with high object multiplicity

SUS-23-015
arxiv:2503.06726

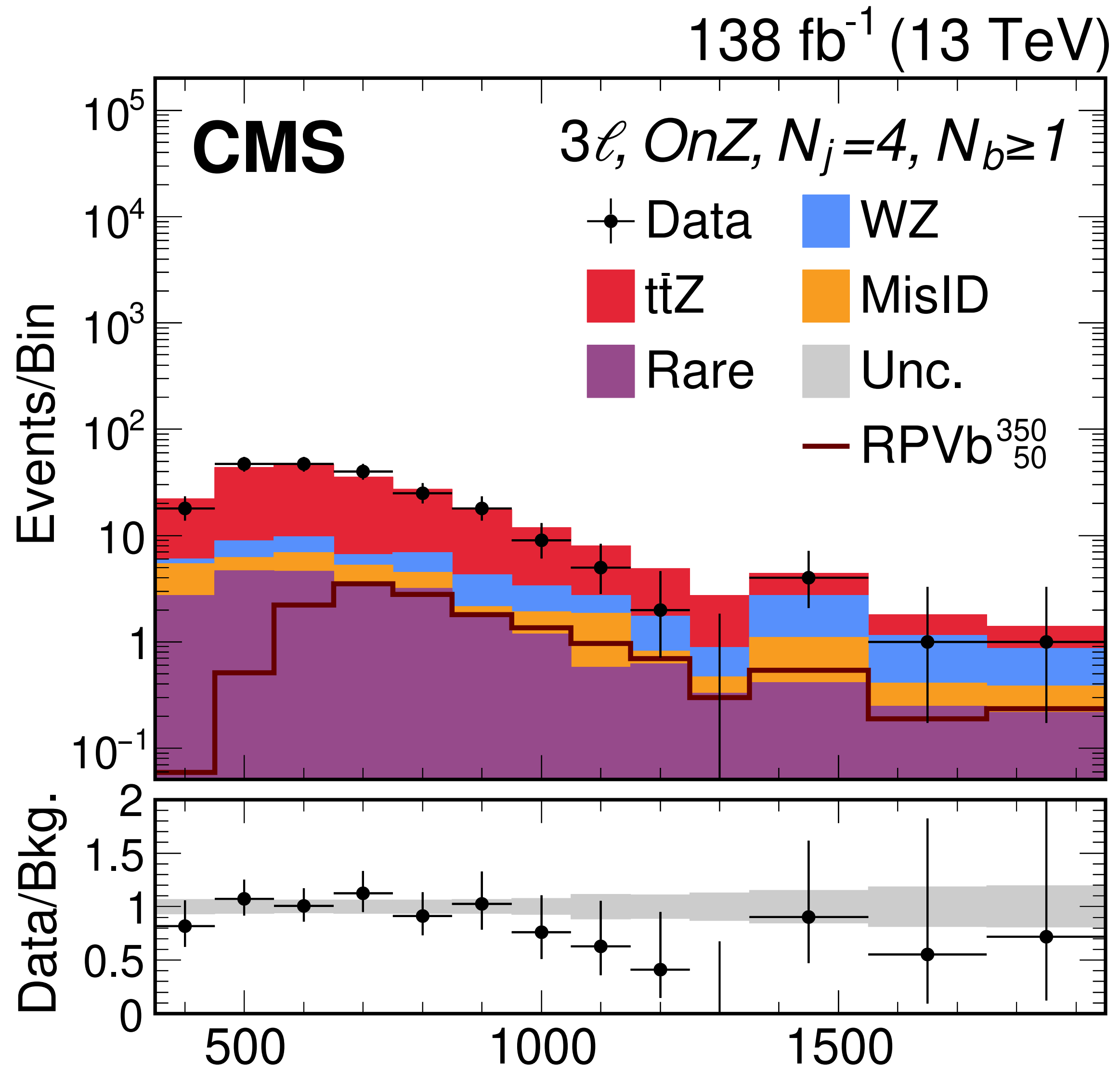
Search for new physics in jet scaling patterns of multilepton events



Experimental signature:
- W and Z boson
- Large jet multiplicity
- No large p_T^{miss}

Why interesting?
- Signature unexplored (weak production & strong decay)
- Challenging final state, need for innovation!

- Targets ewkino production with decays via RPV UDD coupling λ''_{112} or λ''_{113}
- This search considers the **fully leptonic decay** modes of the W & Z bosons, and considers categories at **2, 3, 4, ≥5 jets**, with **0 or ≥1 bjets**
  - Decay products may merge or fall out of acceptance
  - Additional signal sensitivity based on the S_T **variable**
- Backgrounds in signal region (SR) with 3-leptons are constrained using jet multiplicity distributions in control regions (CR) with 1, 2, and 4-leptons

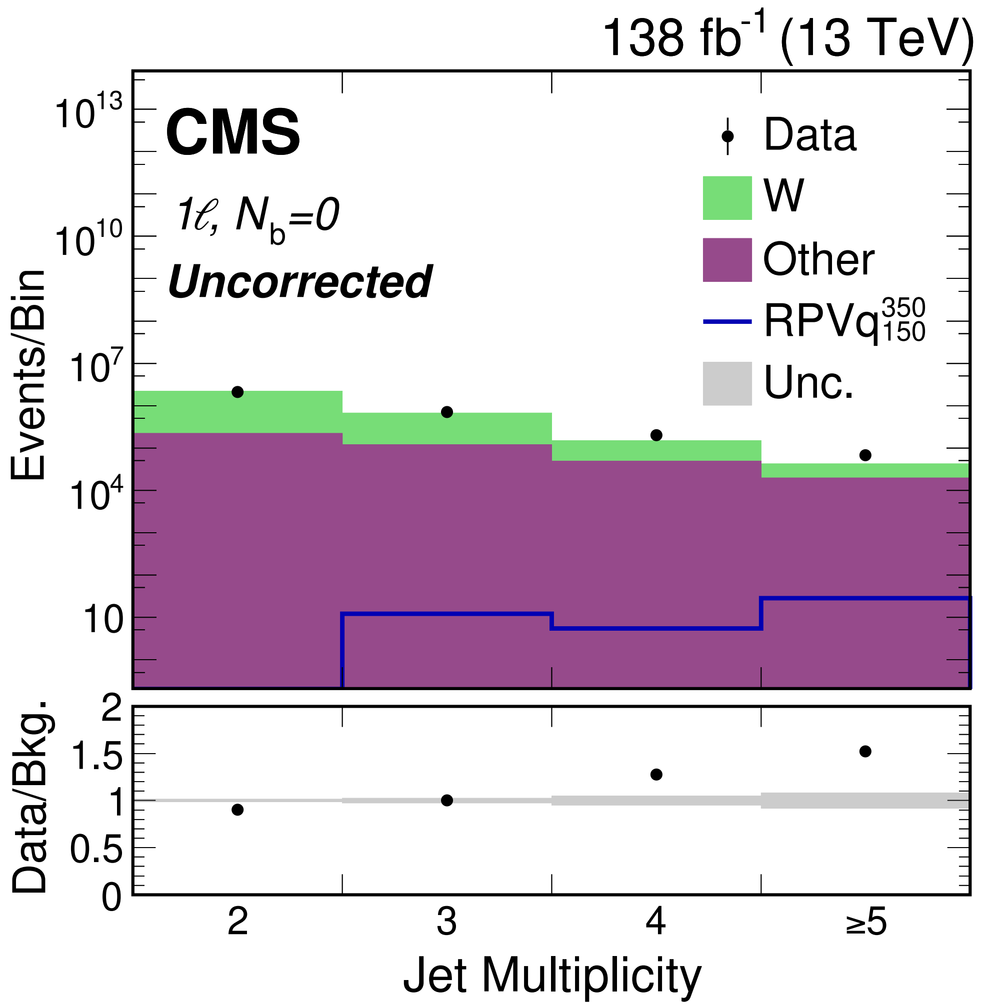


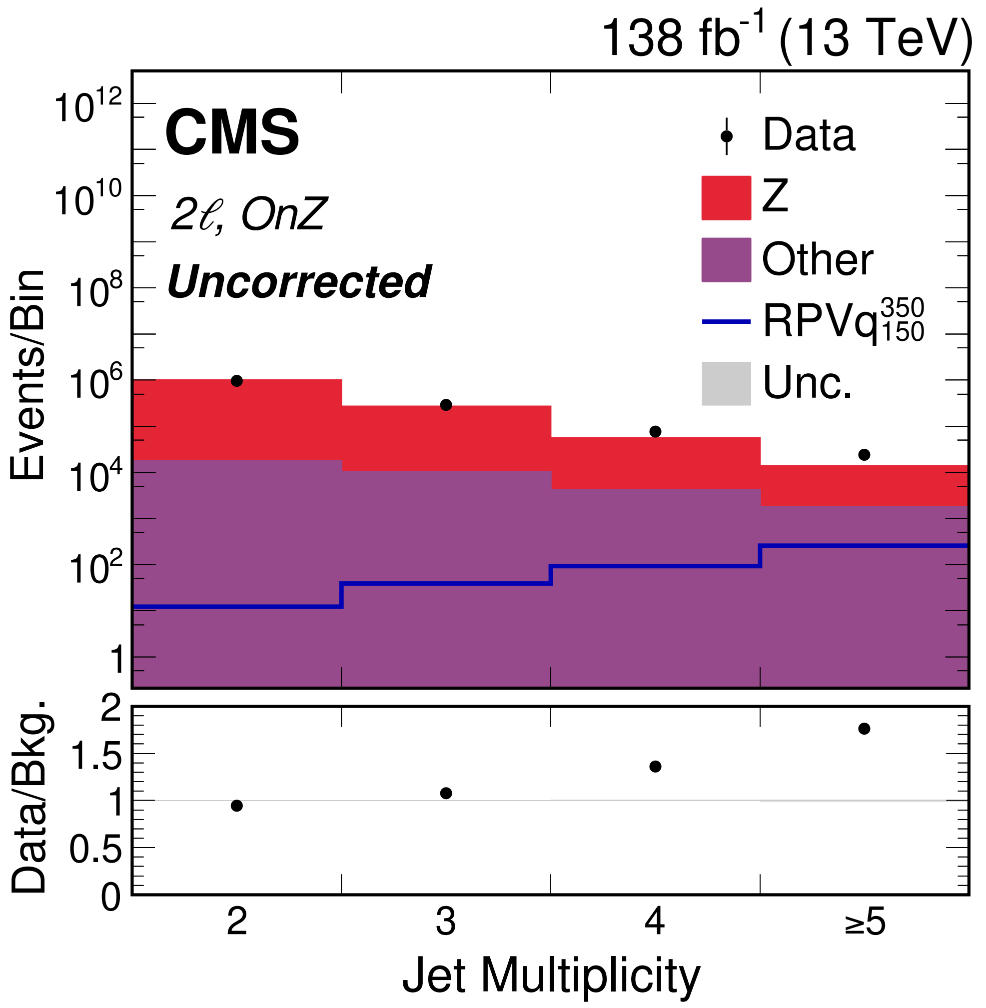
$$S_T = \sum_{i=j,\ell} p_{T,i} + p_T^{\text{miss}}$$

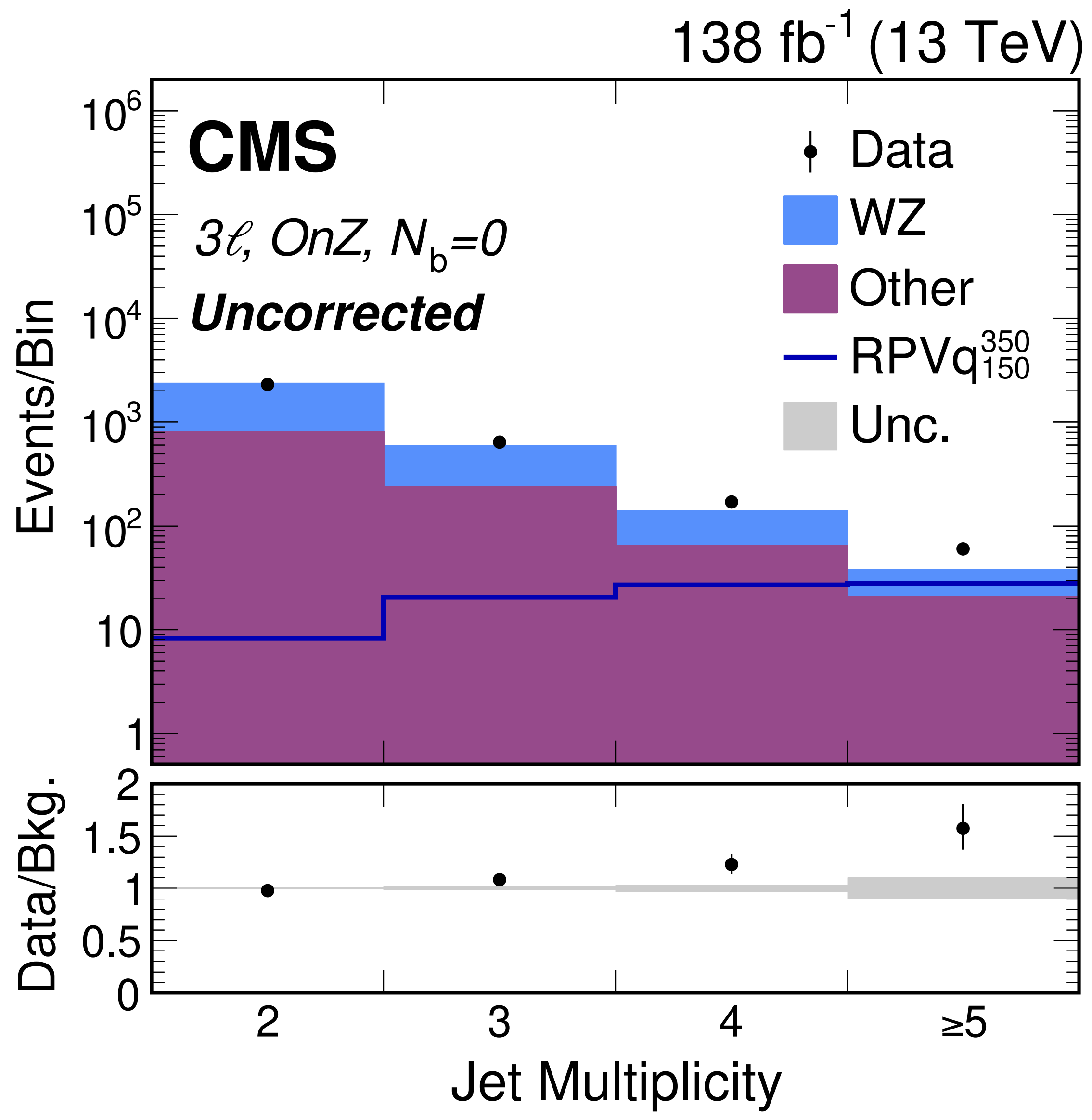
Jet multiplicity modeling

SUS-23-015
arxiv:2503.06726

- Major backgrounds in 3-lepton SR are WZ+jets (0b) and $t\bar{t}Z$ (≥1b)
- Modeling of N_j is difficult, and has large theory uncertainties
- **Use jet scaling patterns to correct N_j distribution with data**
  - Ratio of number of events in adjacent N_j bins becomes constant at high N_j ("staircase scaling") and is similar for similar processes
  - Use Z+jets events (2ℓ) with $p_T^{\ell\ell} > 100\,\mathrm{GeV}$ to correct the WZ process (validated with W+jets)
  - Use $t\bar{t}$+jets (1ℓ) events to correct $t\bar{t}Z$

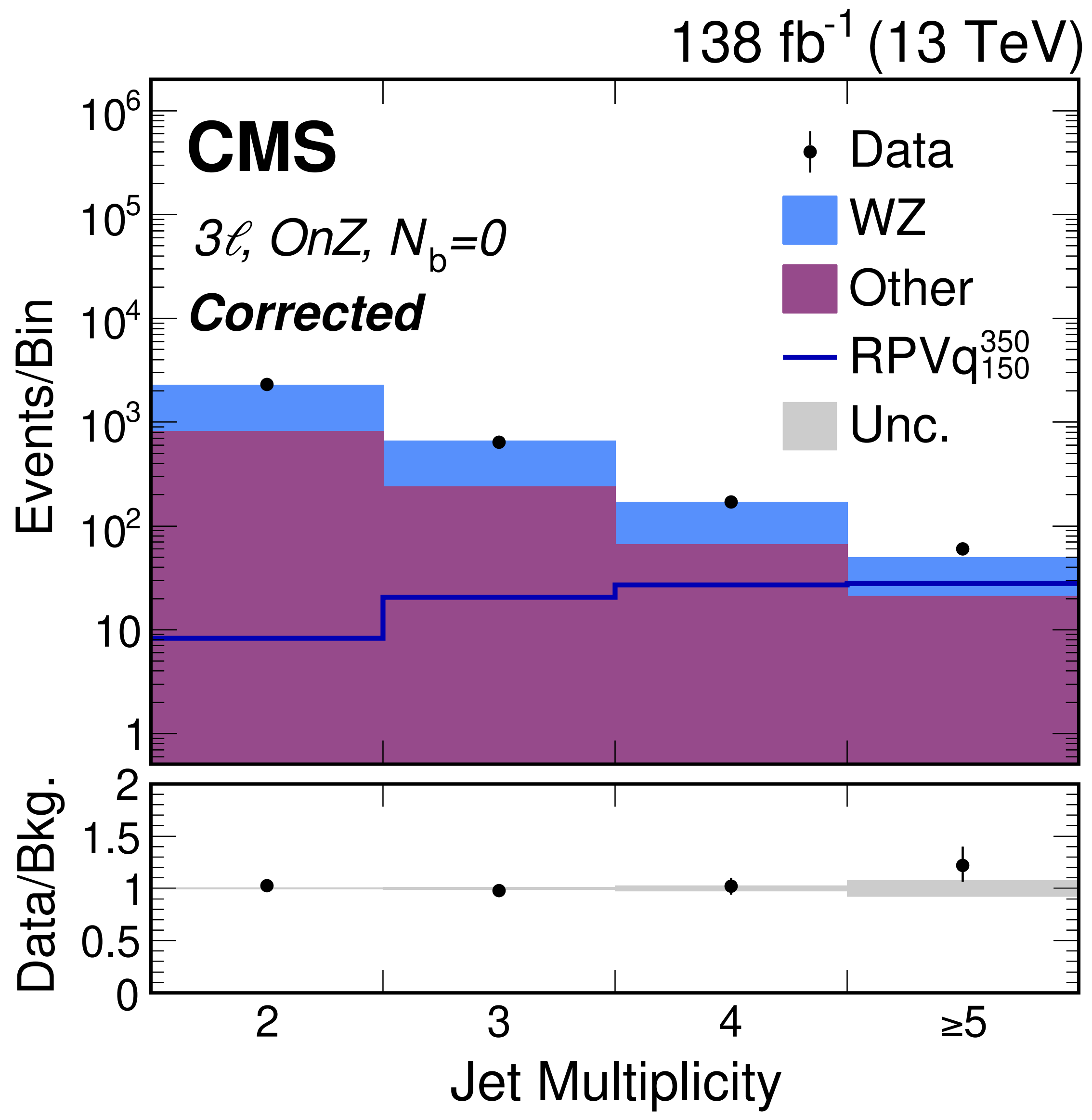






Signal region shows similar trend
How to disentangle from signal?

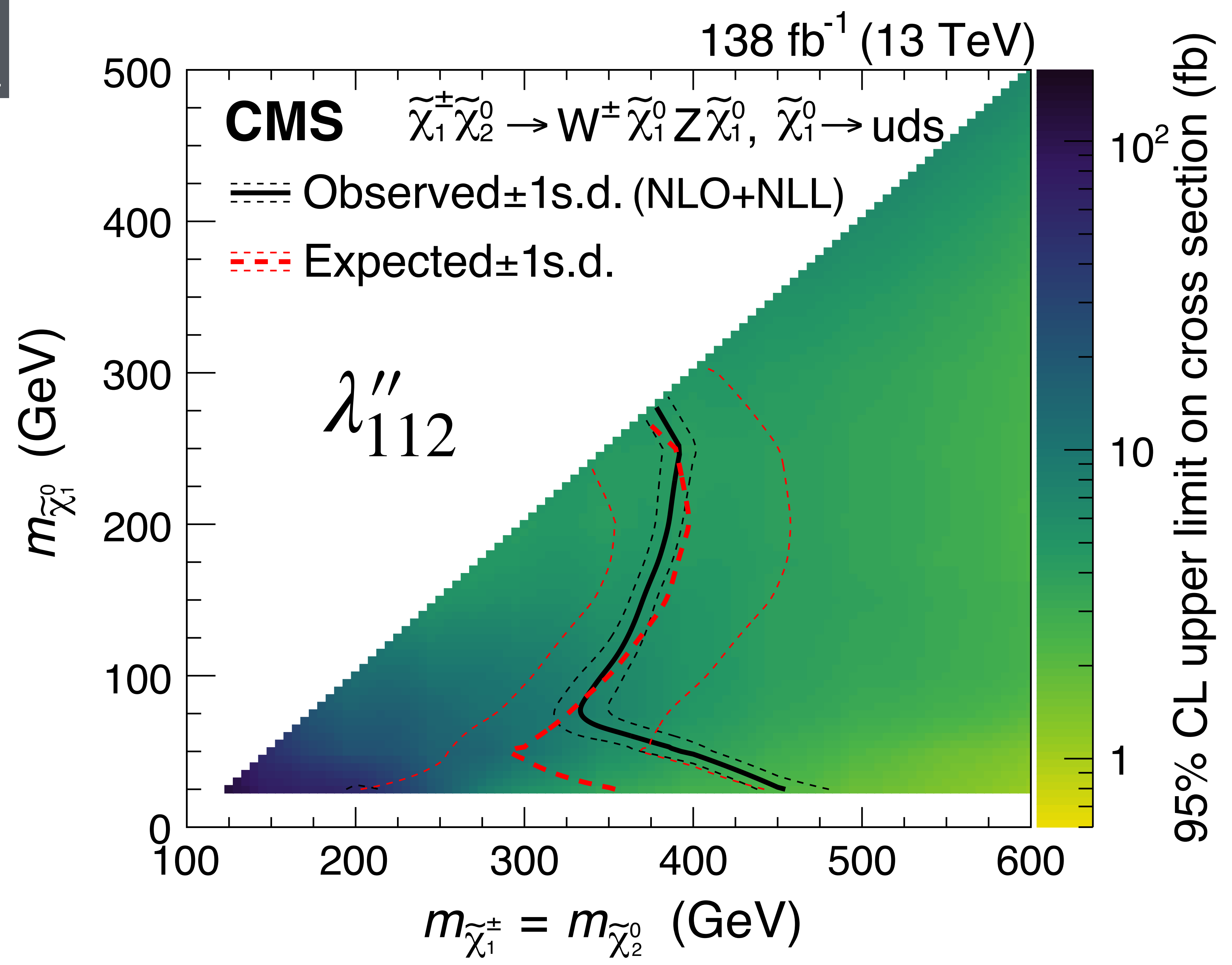
Apply correction factors from data CRs instead of relying on MC

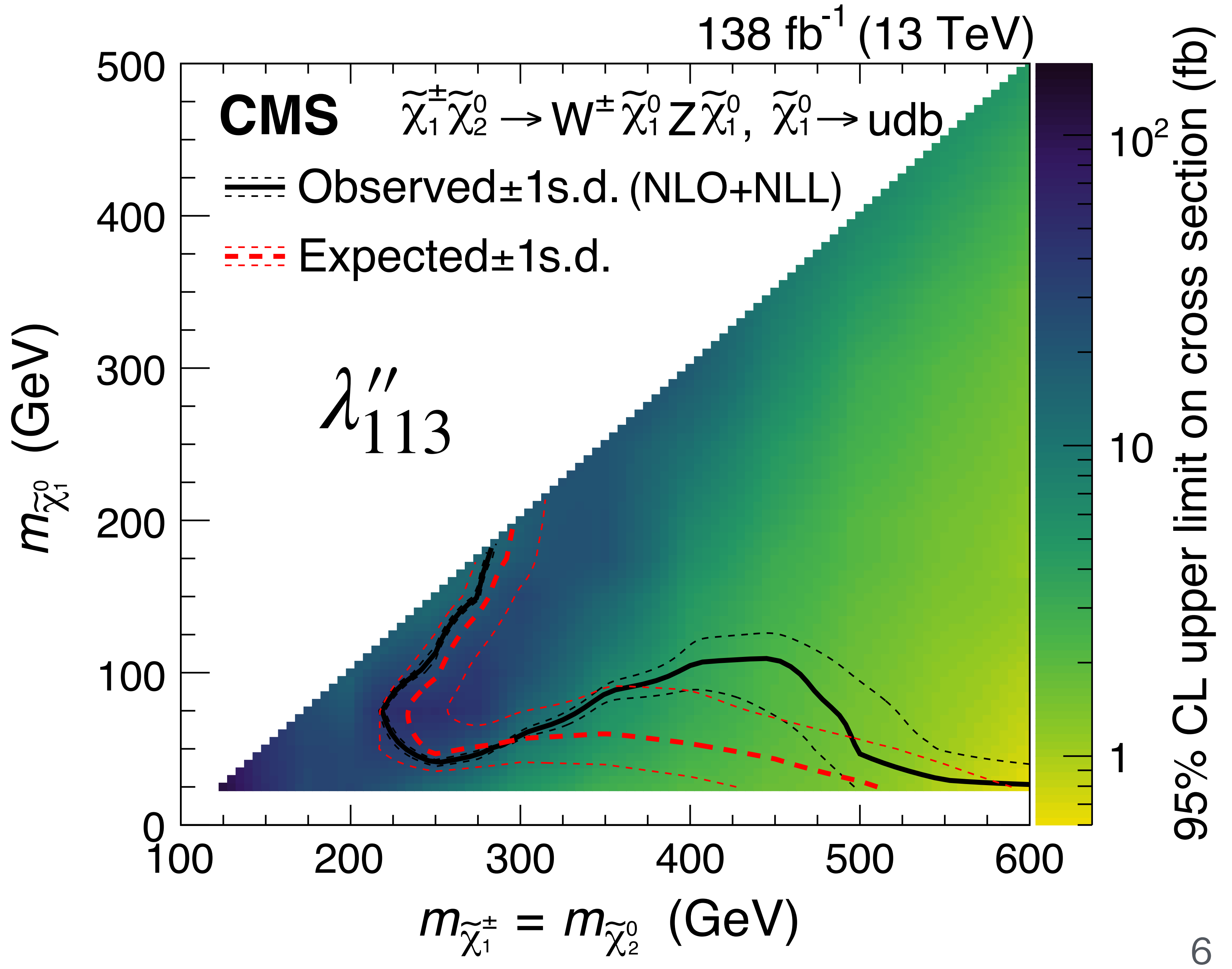


SUS-23-015: Results

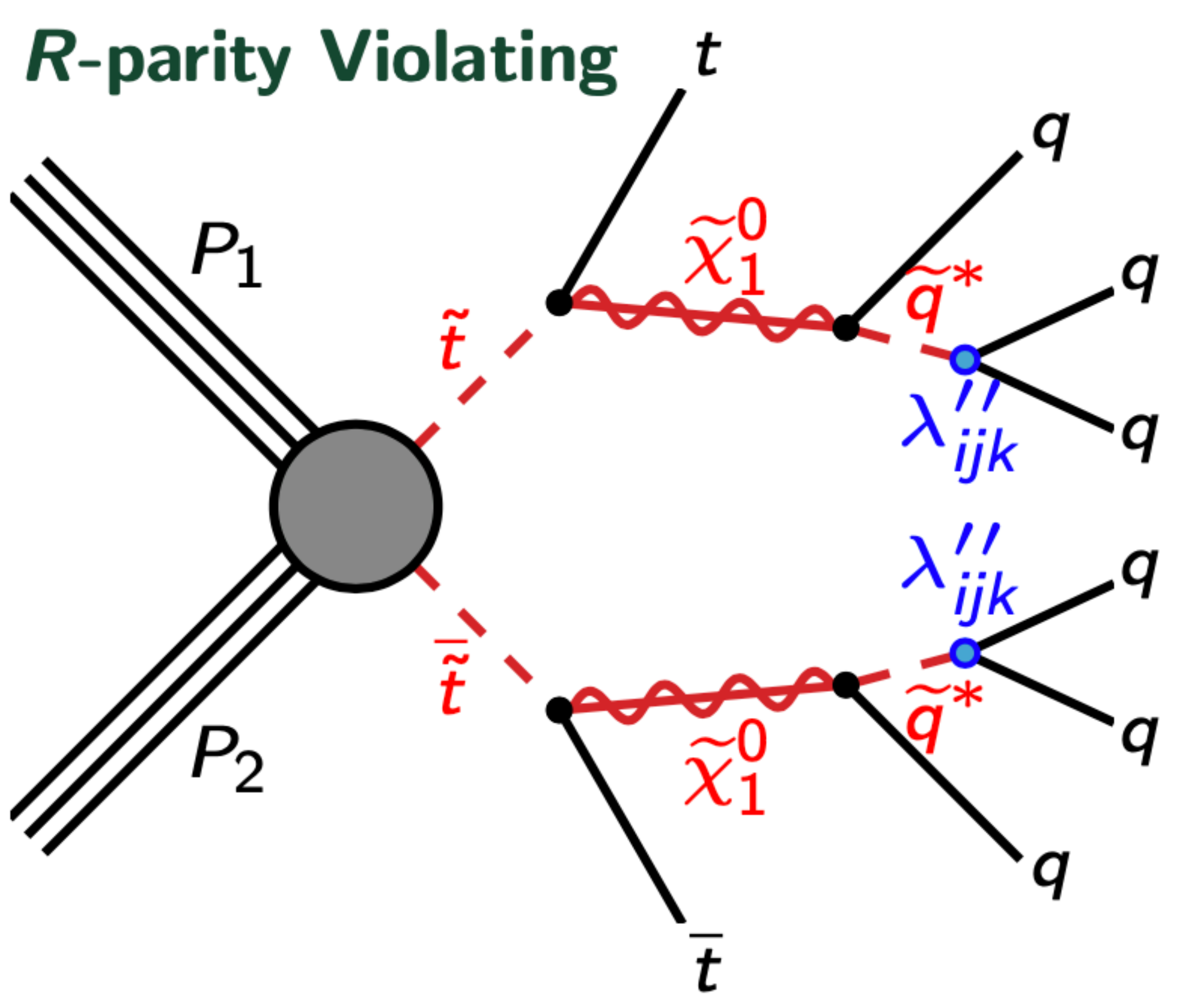
SUS-23-015
arxiv:2503.06726

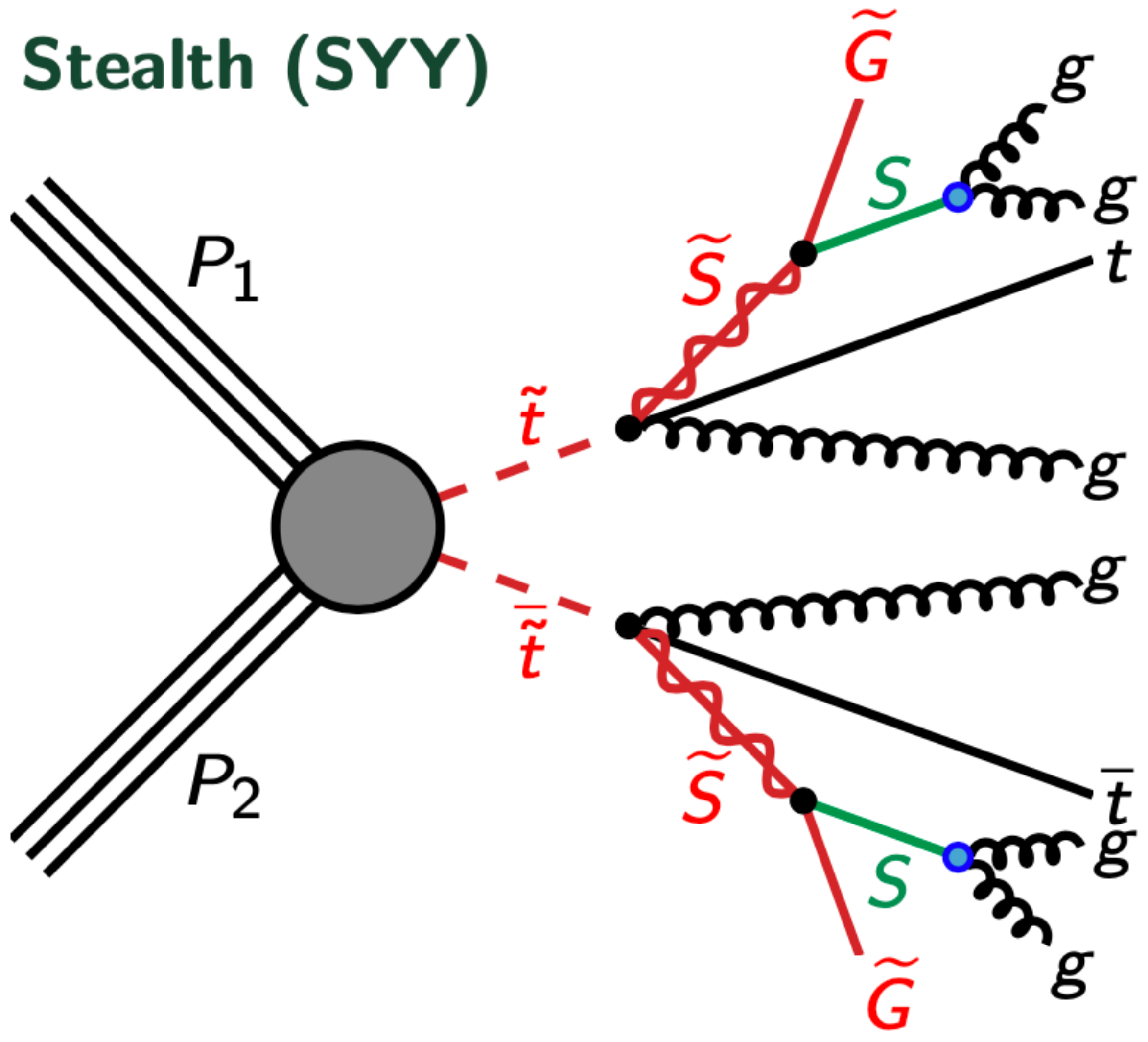
- Results are obtained from a simultaneous multibin fit to all signal and control regions
  - Including range of systematic uncertainties in the shape of the N_j, N_b, and S_T
- **Good agreement between data and prediction is observed**
- Limits on the signal cross section are set.
  Masses in the range 200-500 GeV are excluded, depending on the coupling and $\tilde{\chi}_1^0$ mass
  - Assumes wino-like $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ with bino-like $\tilde{\chi}_1^0$
  - Structure in expected limit from signal shape becoming similar to tt̄Z backgrounds for those mass combinations





Search for RPV and stealth top squark decays





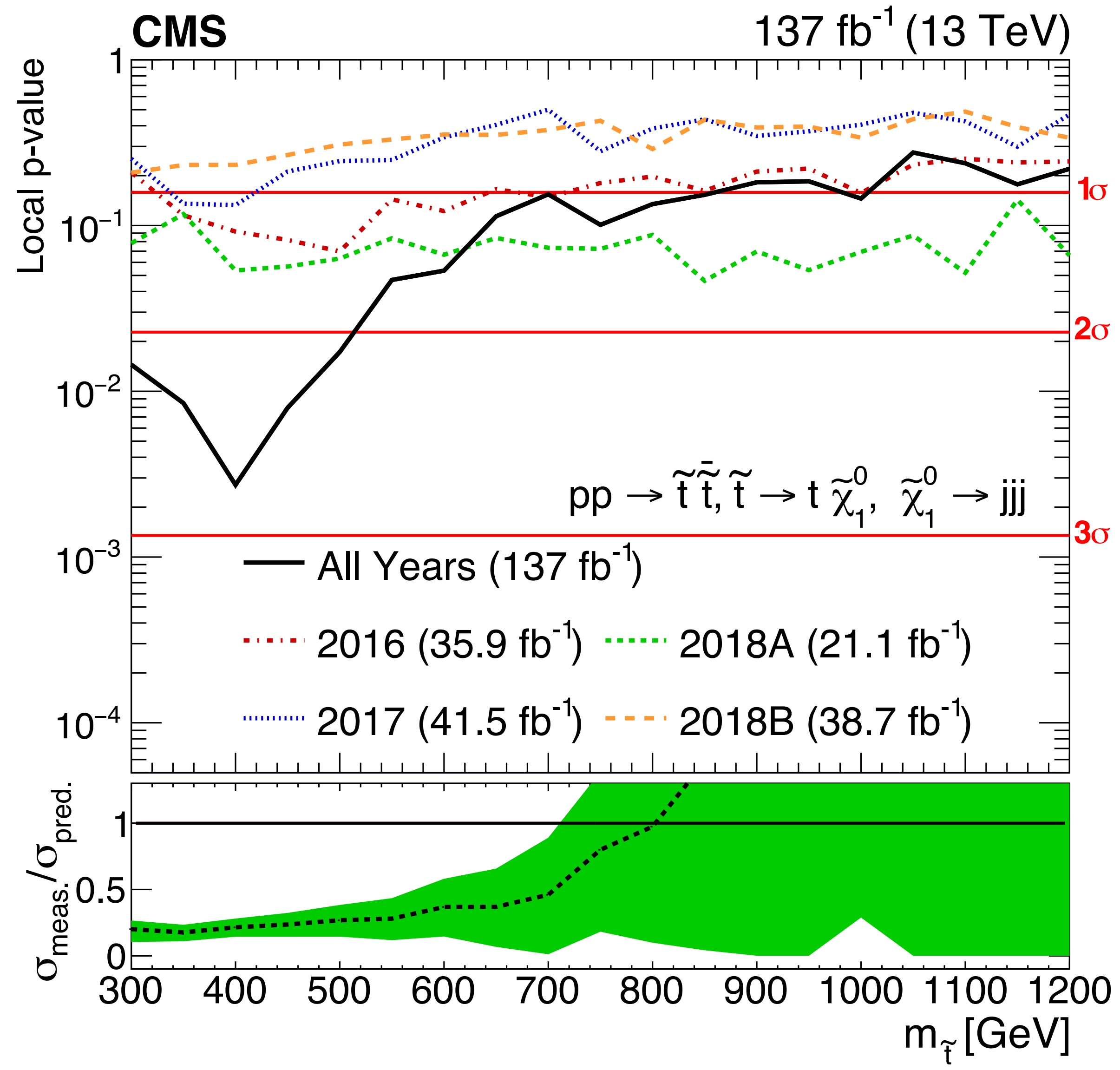
Experimental signature:

- Two top quarks
- Large jet multiplicity
- No large $p_{\mathrm{T}}^{\mathrm{miss}}$

Why interesting?

- Signature unexplored
- Challenging final state, need for innovation!

- **Main characteristic of the signal: many jets**
  - By itself not powerful enough to distinguish between signal & background
  - There are resonances present, but they are very hard to reconstruct
- Previous version of the analysis (SUS-19-004) performed a simultaneous fit to the N_j distribution in several bins of a neural network score. N_j shape was fit to a function based on jet scaling patterns.
- Interesting result observed (2.8σ). Unfortunately, significant pulls from systematic uncertainties (1.7σ) made result hard to interpret

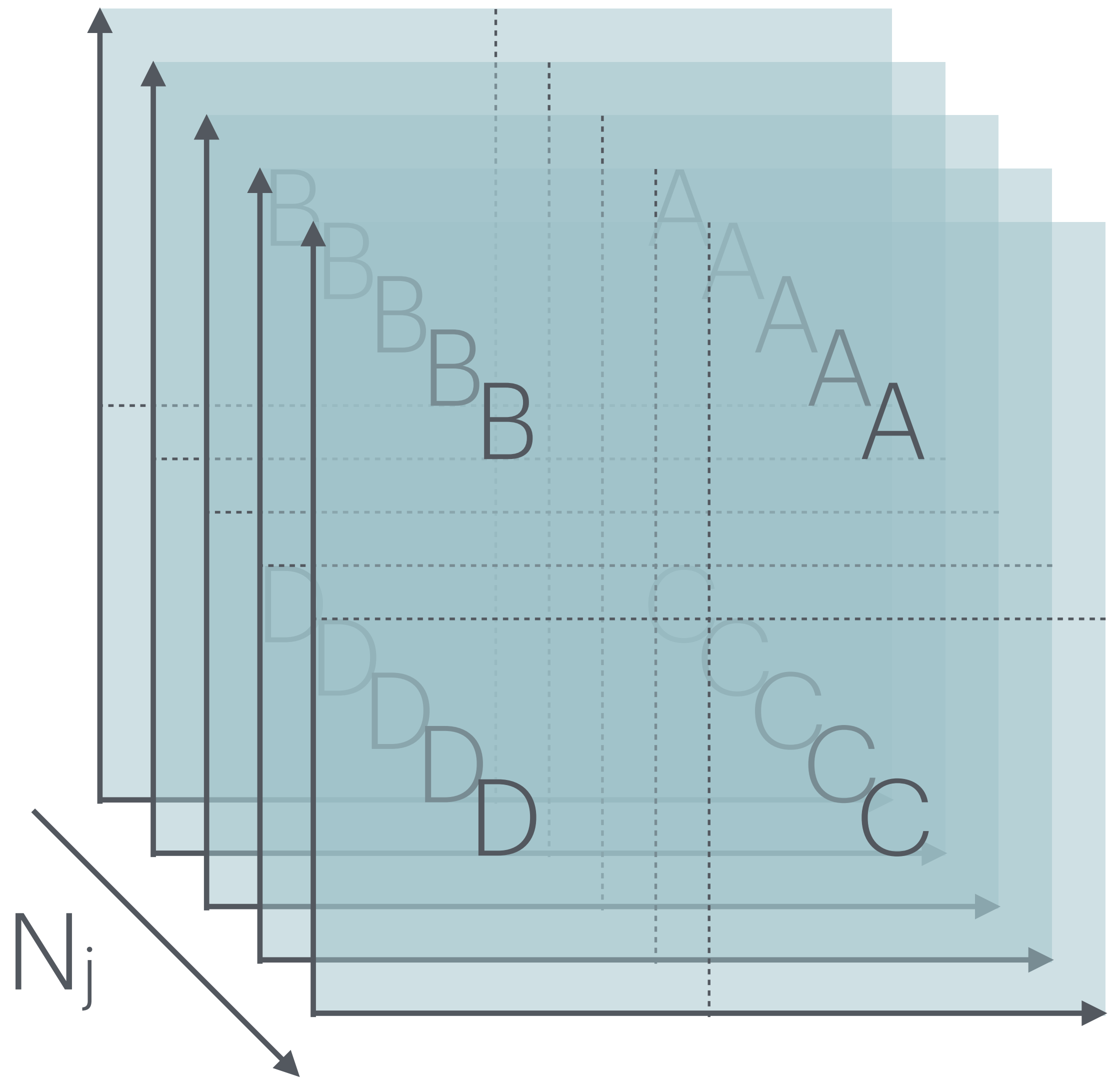


SUS-23-001 & MLG-23-003

New result makes two improvements:

- Added 0- and 2-lepton regions to the 1-lepton region
  - *Evaluate consistency of any possible excess among final states with two top quarks*
  - Main background is $t\bar{t}$+jets in all categories
- Fully revamped background estimation using novel ML-based ABCD method
  - *Reduce sensitivity to systematic uncertainties related to N_j modeling*
  - Treat each N_j category as independent: Apply ABCD method in each N_j category rather than fitting the N_j shape
  - Use built-in sidebands in the ABCD plane for validation in data and derivation of systematic uncertainty

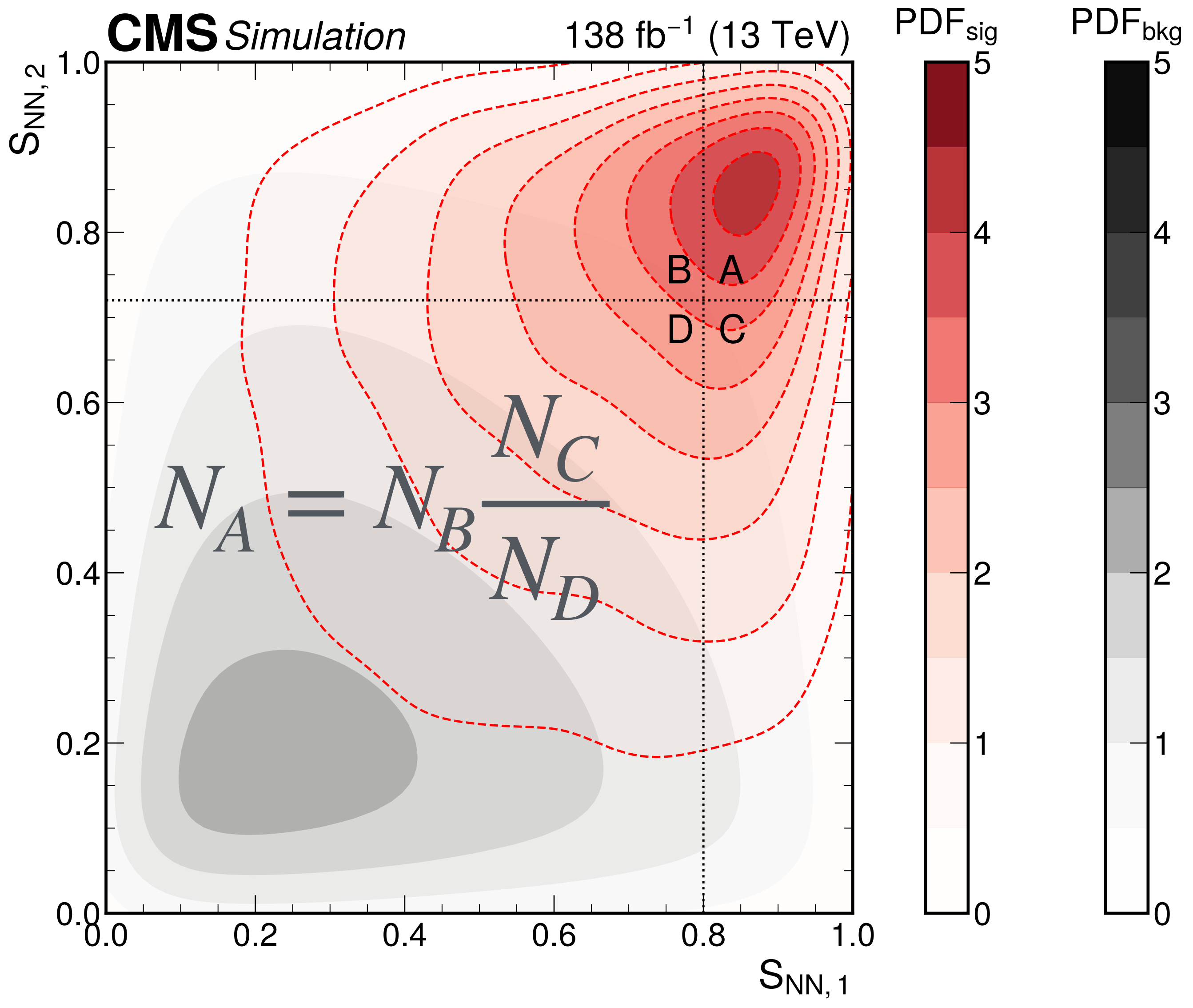
Selection criteria	0ℓ	1ℓ	2ℓ
$N^{\text{iso}}_{\text{leptons}}$	0	1	2, oppositely charged
$N^{\text{noniso}}_{\text{muon}}$	0	0	0
H_T (GeV)	>500	>500	>500
N_{jets} $(p_T > 30\,\text{GeV})$	≥8	≥7	≥6
N_{jets} $(p_T > 45\,\text{GeV})$	≥6	—	—
N_b $(p_T > 30\,\text{GeV})$	≥2	≥1	≥1
N_b $(p_T > 45\,\text{GeV})$	≥1	—	—
N_t	≥2	—	—
$M_{b\ell}$ (GeV)	—	>50, <250	—
$M_{\ell\ell}$ (GeV)	—	—	<81 or >101
ΔR_{bjets}	>1	—	—



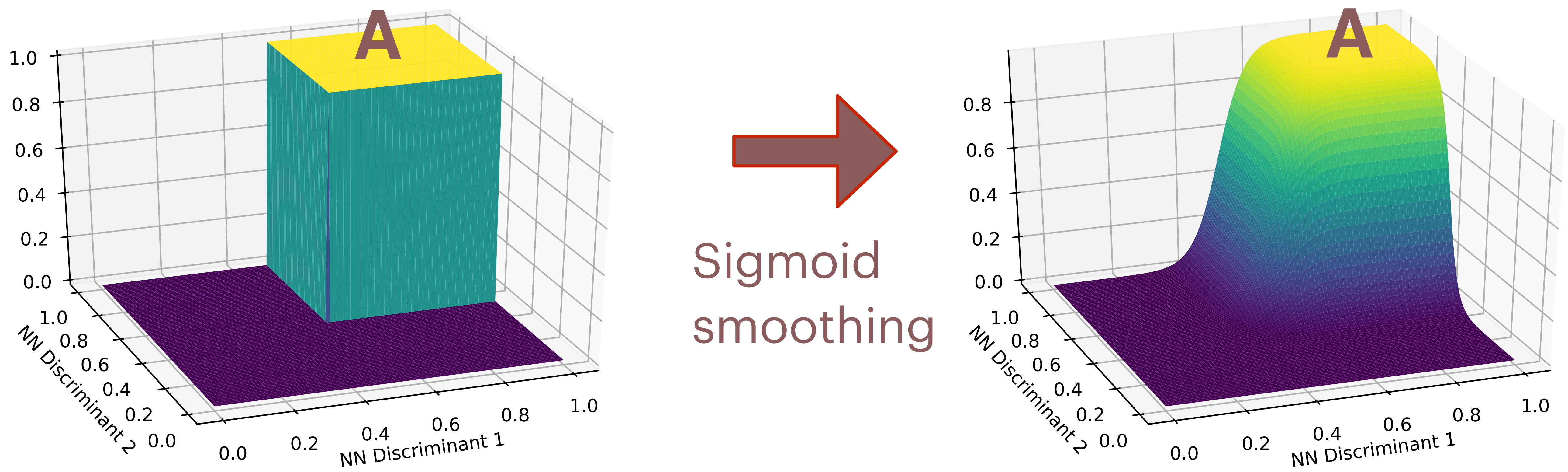
ABCDisCoTEC: robust background estimation with decorrelated variables

MLG-23-003
arxiv:2506.08826

- Use ML to prepare two synthetic variables that can be used for the ABCD method:
  - Good signal-background separation — hard to do with "expert" variables for this analysis
  - Excellent decorrelation as measured by a small nonclosure across the 2D plane
- Developed novel loss term that encodes the ABCD relationship while maintaining differentiability; used in addition to the "DisCo" loss term
- Method is completely general! Stay tuned for more applications



$$L_{\text{non-closure}} = \left(\frac{N_A N_D - N_B N_C}{N_A N_D + N_B N_C} \right)^2$$



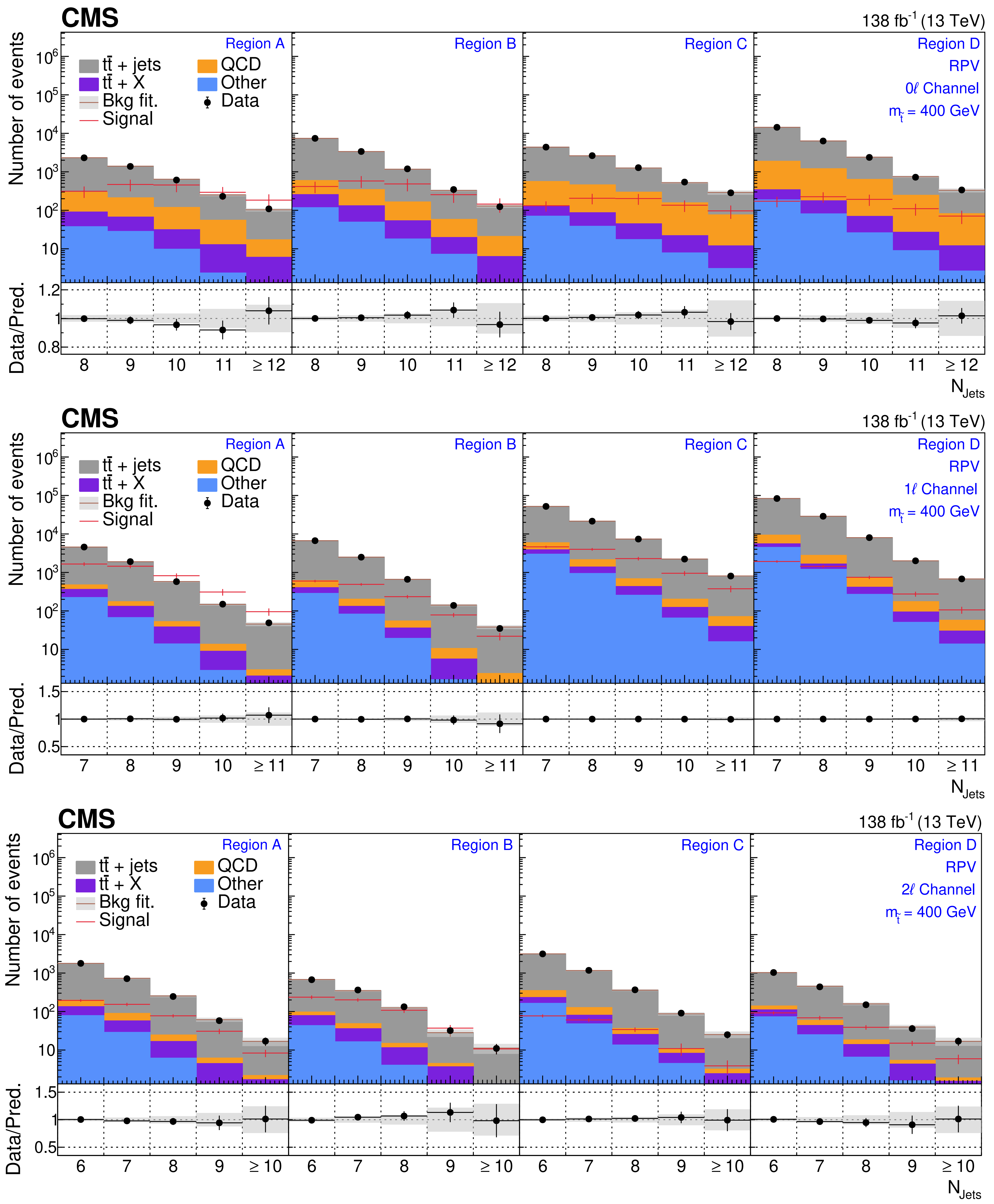
SUS-23-001: Results

SUS-23-001
arxiv:2506.08825

- For each lepton channel (0, 1, 2 leptons) and N_j region, we perform a simultaneous fit to the A, B, C, D regions
  - The main $t\bar{t}$+jets background is constrained using the ABCD relationship

$$N_A = N_B N_C / N_D$$

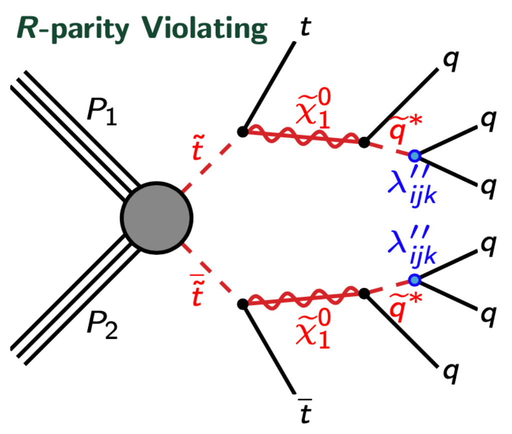
  - QCD multijet background is determined using a data control region, and smaller backgrounds are estimated from simulation
- Plots show the background-only fit results: good agreement between data and prediction is observed
- **We do not confirm the discrepancy observed previously**

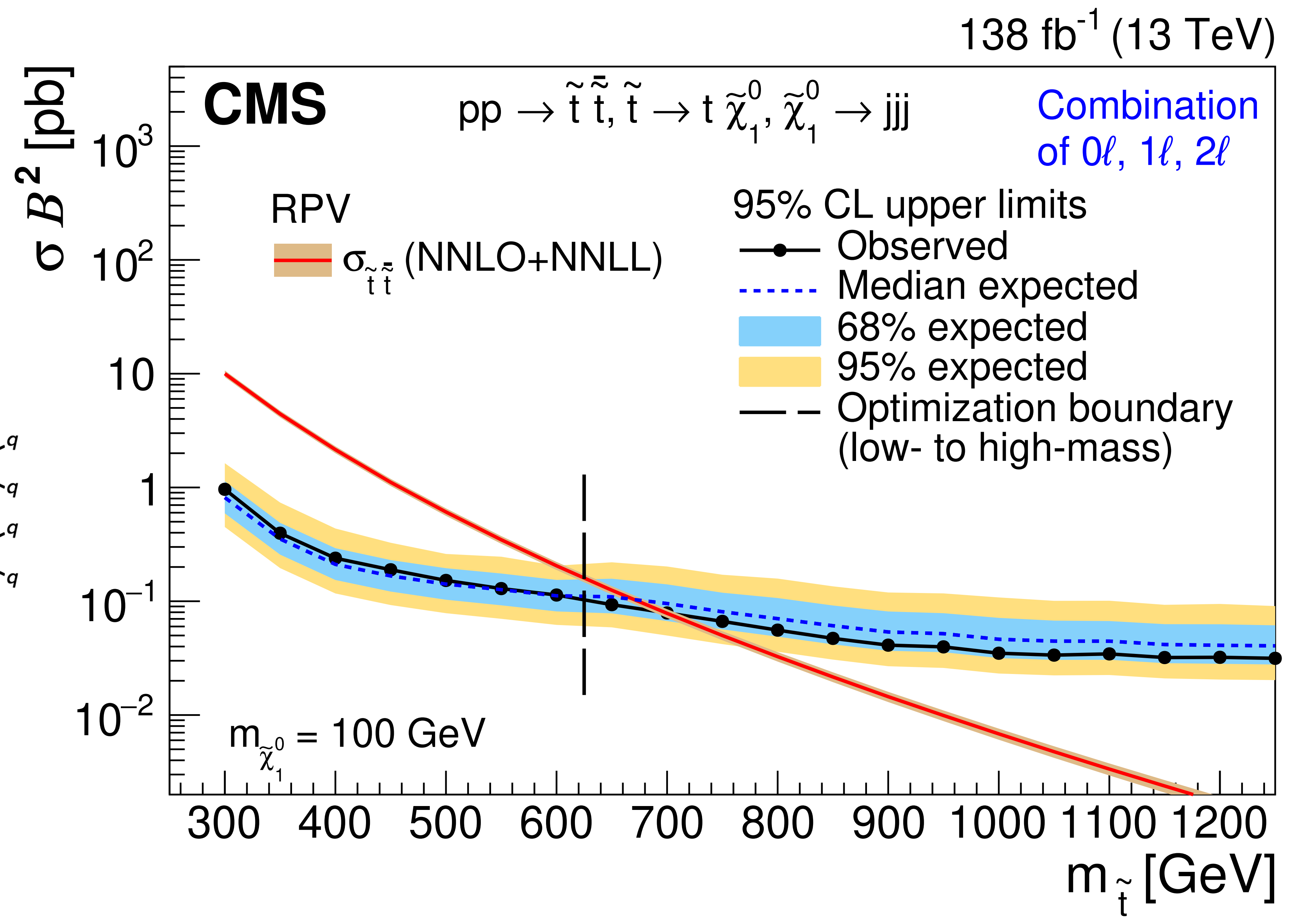


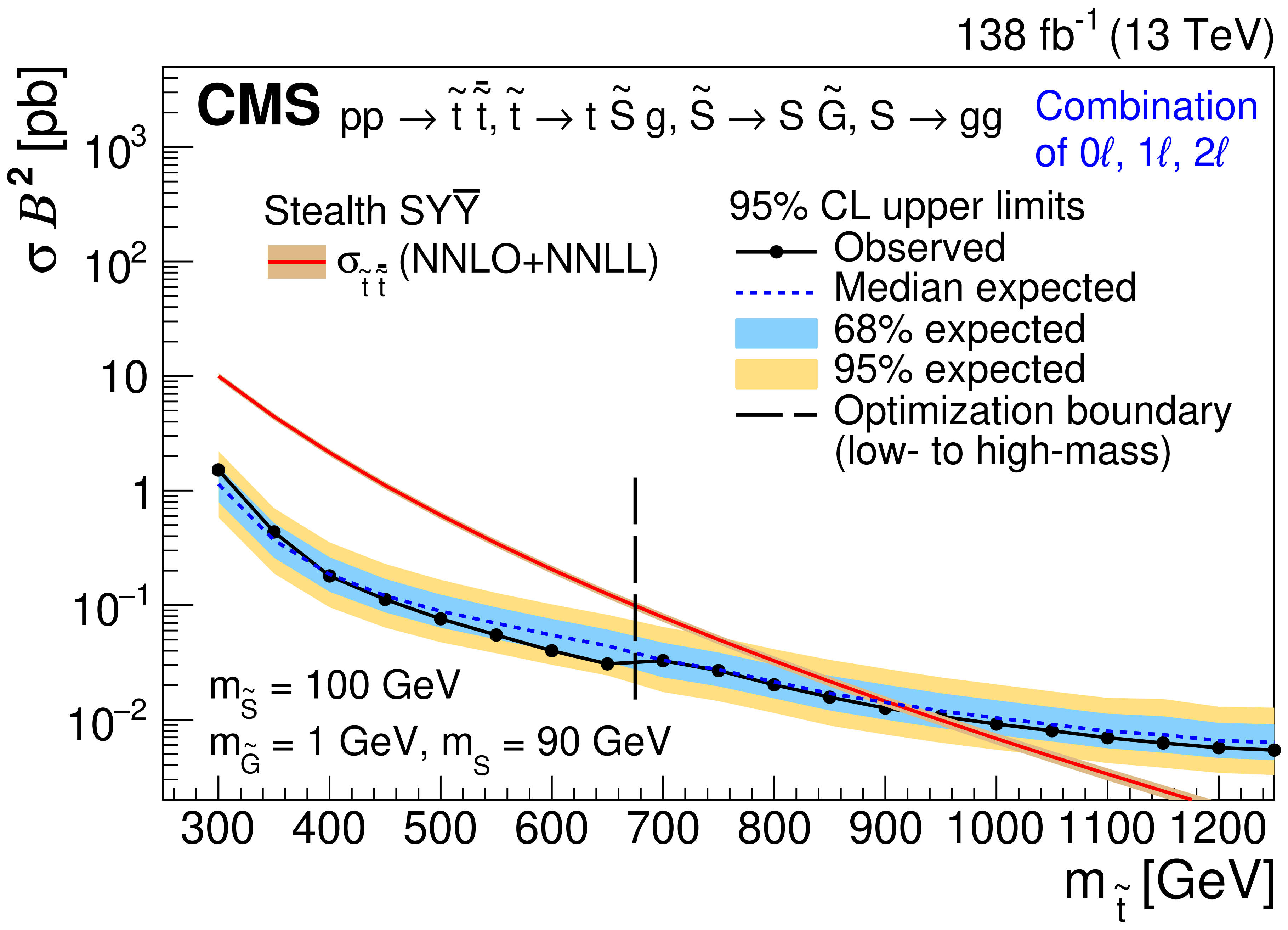
SUS-23-001: Results

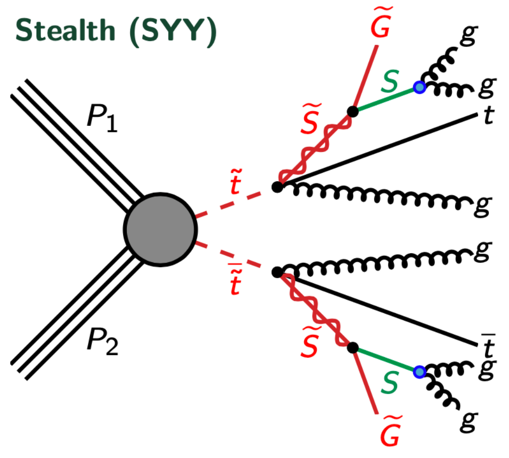
SUS-23-001
arxiv:2506.08825

- Novel background estimation method is more robust and has **reduced impact from systematic uncertainties** overall
- Significantly **increased sensitivity** at low top squark masses where the previously analysis observed an excess in the 1l channel
- Exclude top squarks with mass up to 700 GeV for RPV model and up to 900 GeV for stealth model

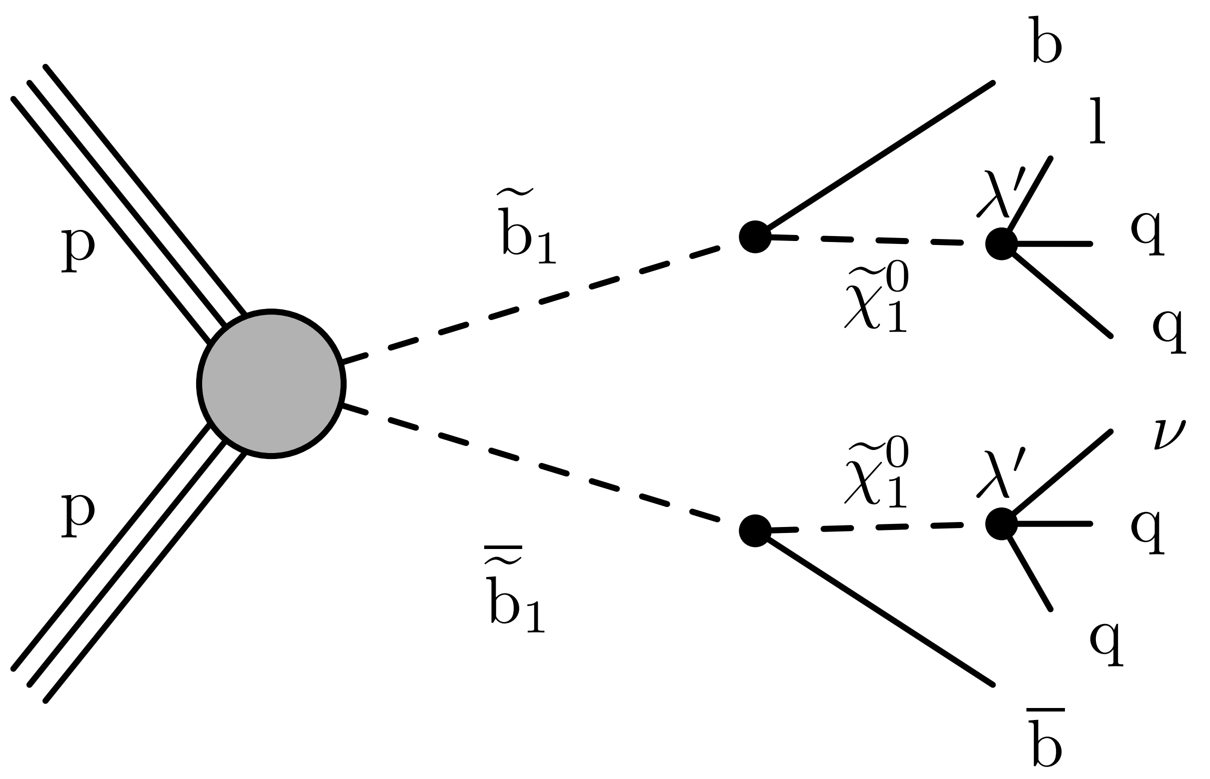


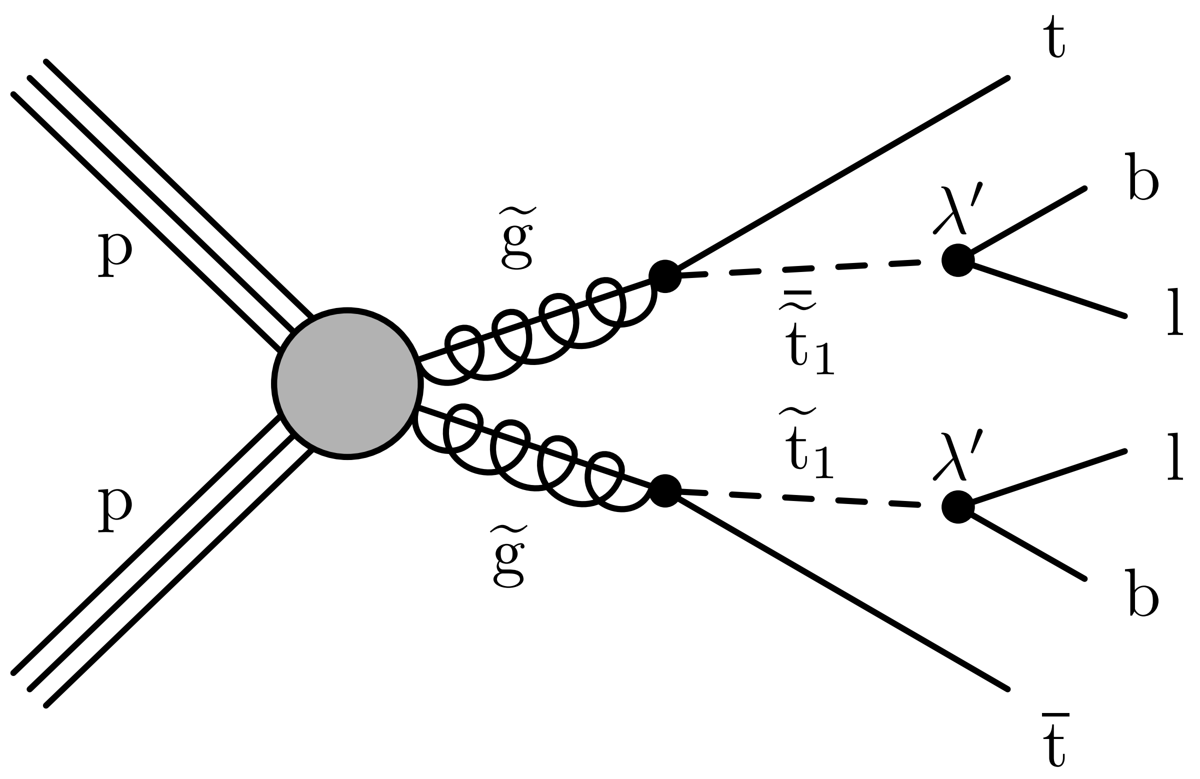






Search for SUSY in final states with boosted objects and razor variables





Experimental signature:
- Boosted leptonic jets
- Large jet multiplicity
- No large p_T^{miss}

Why interesting?
- Signature unexplored
- First SUSY search with leptonic jets

- Comprehensive search with **boosted objects**: hadronic W/Z/H boson, hadronic top, or leptonic jets
- Search is sensitive to a wide range of models, I'll focus on RPV
- Analysis categories for **0l, 1l, and 1 non-isolated lepton**. With further classification based on **jet and b-jet multiplicity**.
- Signal is separated from background using the **razor variables M_R and R^2**, for which signal shows up as a peak or endpoint over a smoothly falling background

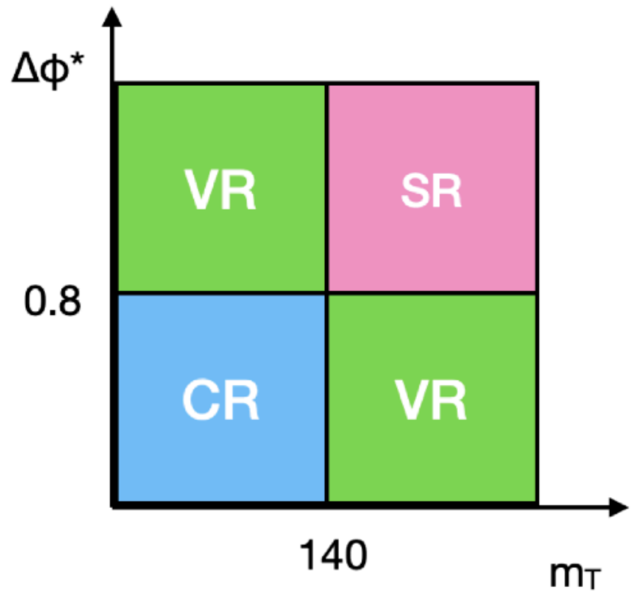
$$M_R \equiv \sqrt{\left(|\vec{p}_{j1}| + |\vec{p}_{j2}|\right)^2 - \left(p_z^{j1} + p_z^{j2}\right)^2},$$

$$M_T^R \equiv \sqrt{\frac{p_T^{miss}\left(p_T^{j1} + p_T^{j2}\right) - \vec{p}_T^{\,miss} \cdot \left(\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2}\right)}{2}}.$$

$$R \equiv \frac{M_T^R}{M_R}$$

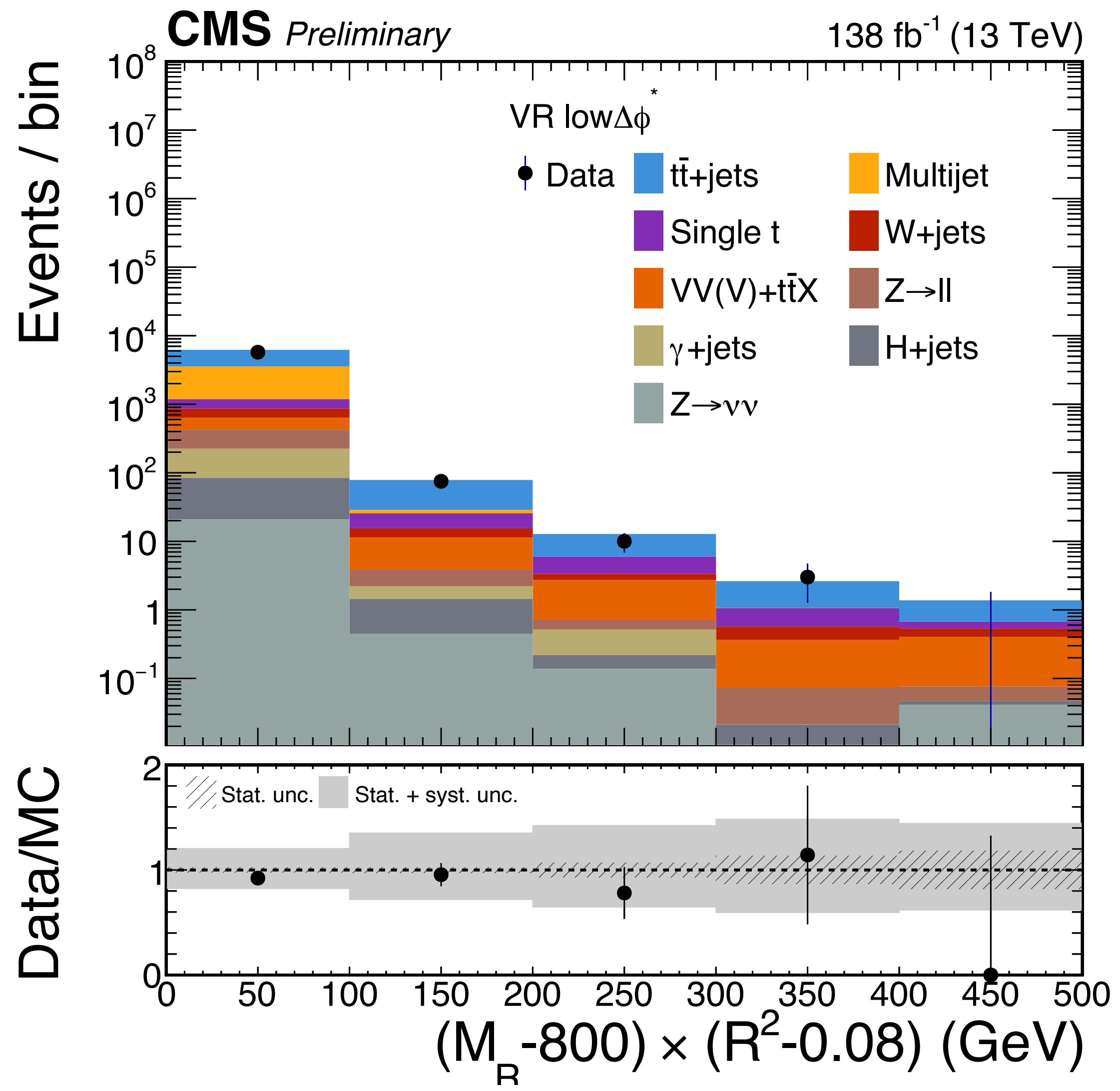
Signal regions with leptonic jets

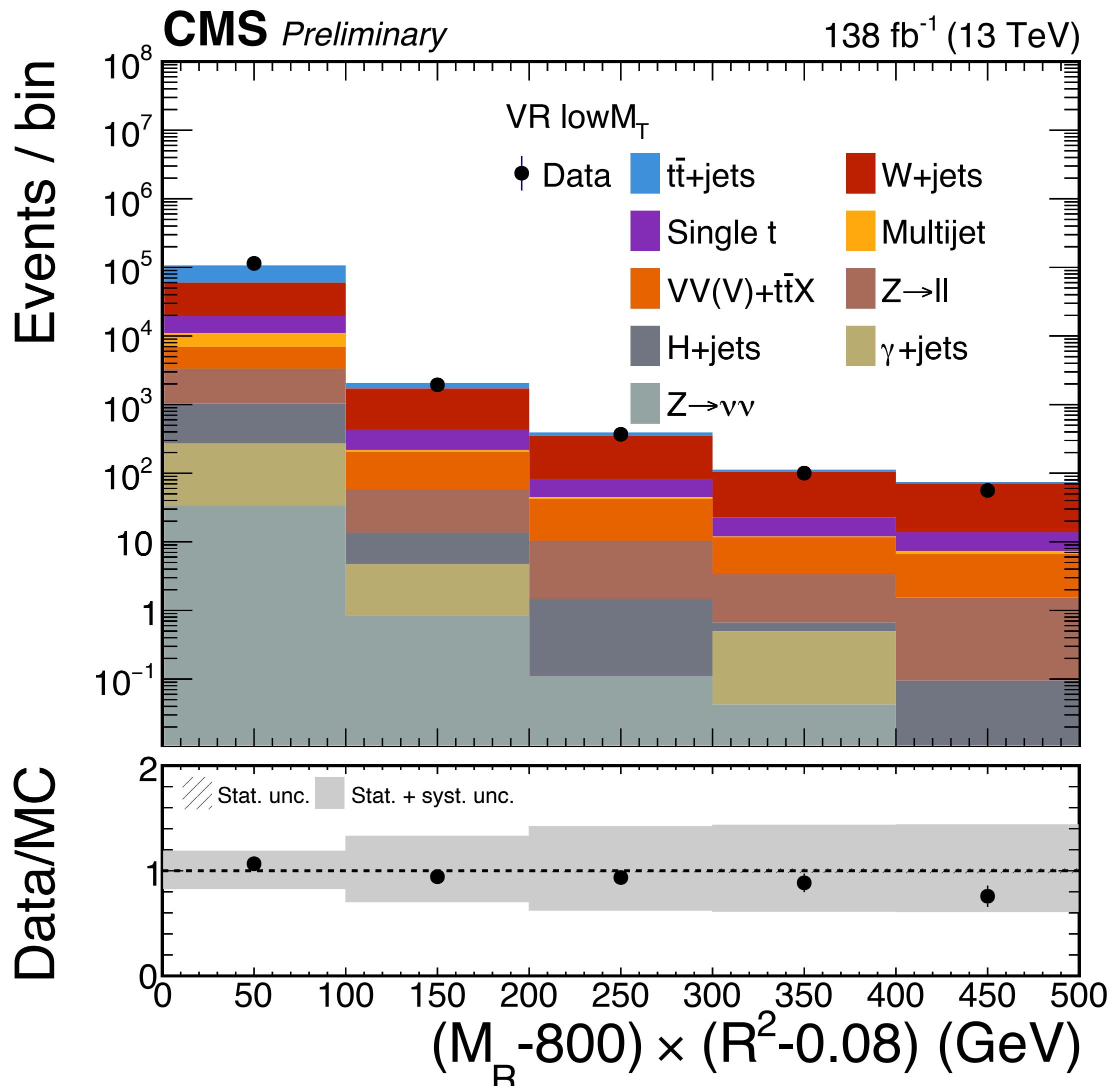
- Search has many signal regions, most relevant for RPV models are the ones with **leptonic jets:**
  - Jets ($p_T > 300\,\mathrm{GeV}$) with non-isolated leptons within a ΔR of 0.8 from the jet axis
- Backgrounds, including at high N_j, are estimated by extracting **correction factors per M_R-R^2 bin** from a range of data CRs and applying them in the SRs
  - top, W+jets: control regions with inverted m_T and $\Delta\phi^*$ requirements
  - Multijet: corrections shared with hadronic signal regions.
- Correction factors are validated in dedicated validation regions



	Preselection
good primary vertices	> 0
number of AK8 jets	≥ 1
number of AK4 jets	≥ 2
M_R	$> 800\,\mathrm{GeV}$
R^2	> 0.08

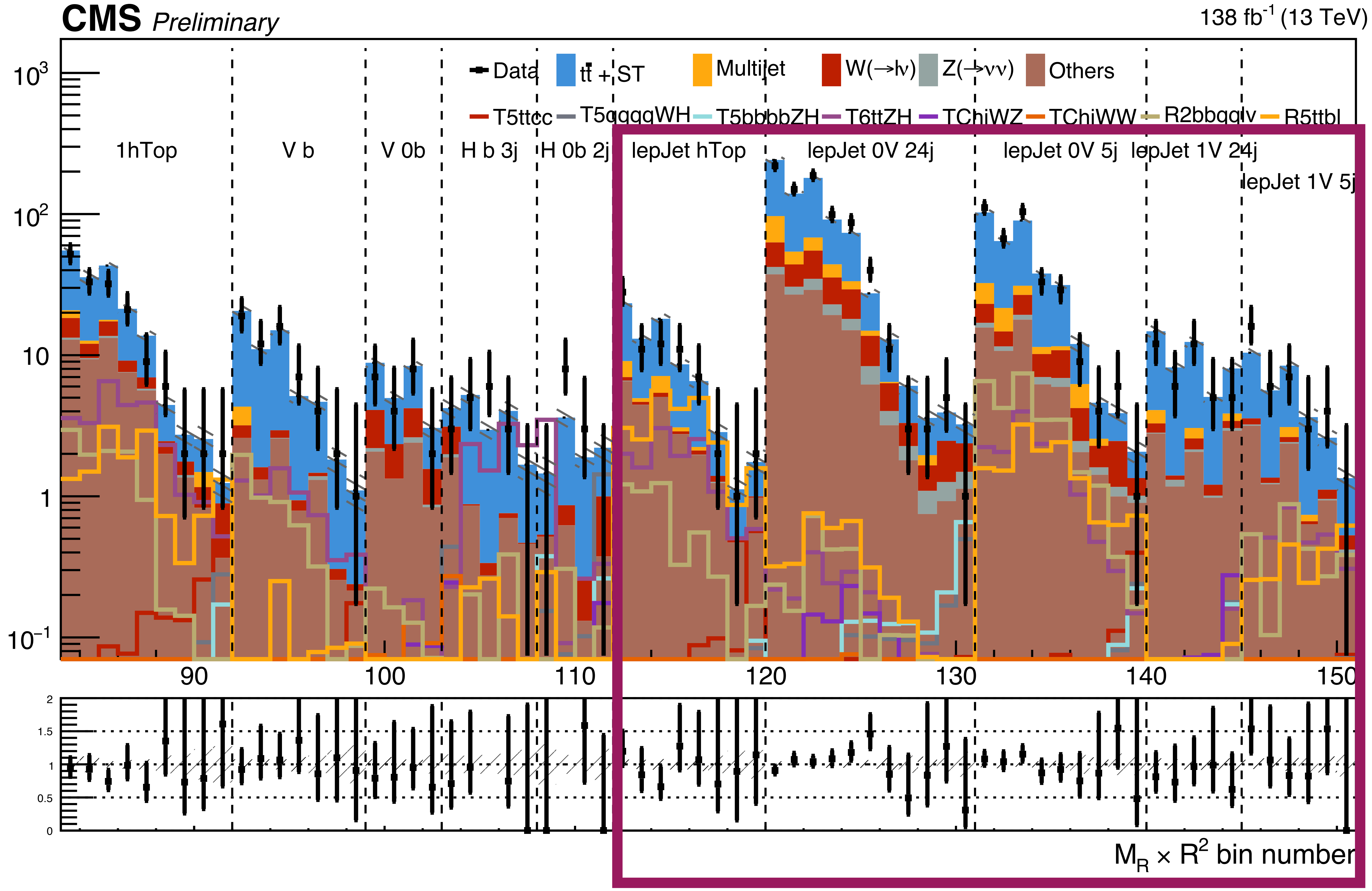
SR categories:	had	lep	lepJet
number of iso select leptons ℓ_{isel} : e, μ	$= 0$	$= 1$	–
number of iso tracks	$= 0$	$= 0$	$= 0$
number of leptonic jets	$= 0$	$= 0$	≥ 1
$\Delta\phi_R \equiv \Delta\phi_{\mathrm{megajets}}$	< 2.8	–	–
m_T	–	$> 120\,\mathrm{GeV}$	$> 140\,\mathrm{GeV}$
$\Delta\phi_{J,W} \equiv \Delta\phi(\vec{j}^{\,\mathrm{lead}}_{\mathrm{AK8}}, \vec{\ell} + \vec{p}_T^{\,\mathrm{miss}})$	–	–	> 0.8

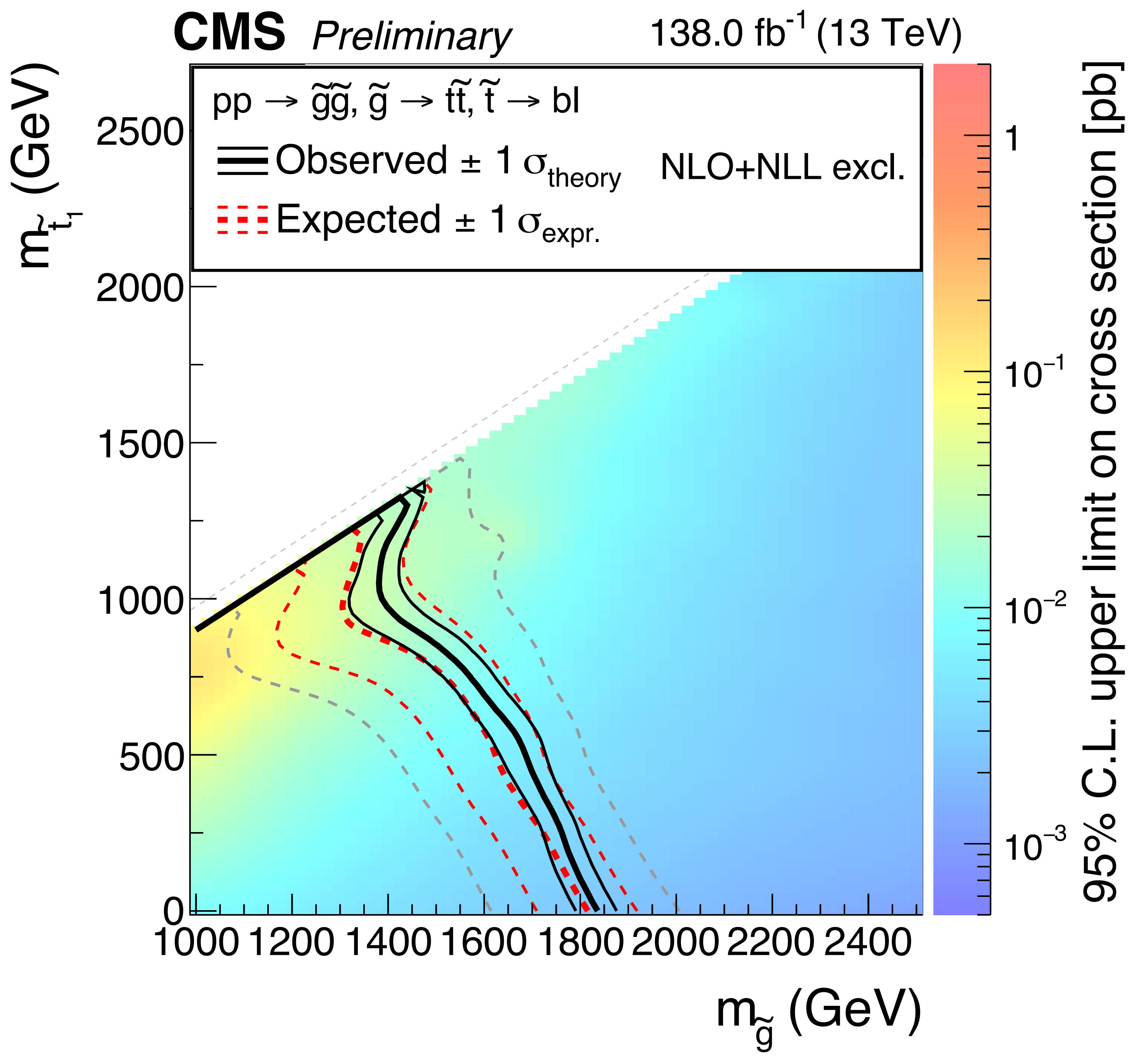


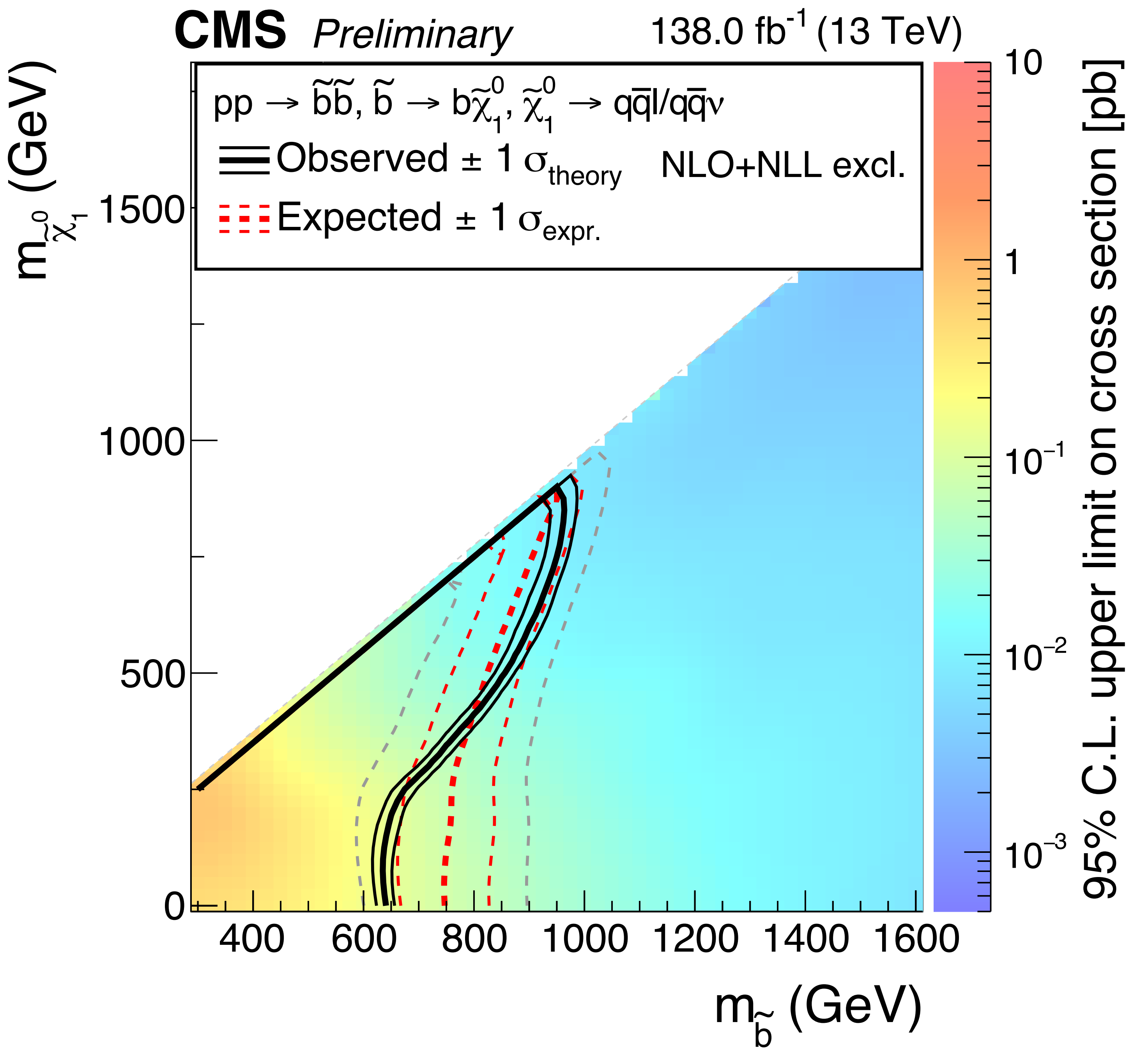


SUS-23-014: Results

- Final results are computed by a simultaneous fit to all signal regions, incorporating the correction factors
- Good agreement between data and prediction is observed
- Exclude $\tilde{g}$ ($\tilde{b}$) masses up to 1800 (900) GeV, for the considered models







Summary

- We are continuing our search for BSM physics, focusing on tricky corners where signal may have been hiding.
- I presented **three recent results** in the context of R-parity violating and stealth SUSY
- All search in final states without $p_{\mathrm{T}}^{\mathrm{miss}}$ but with large jet multiplicity or boosted objects
- Data and prediction generally matched well, so **no evidence of new physics at this time**
- Modeling of additional jets is challenging!
  - SUS-23-015 used the similarity of jet scaling patterns to correct the background for 3-lepton events using 1-, 2-, and 4-lepton events
  - SUS-23-001 developed a novel method, ABCDisCoTEC, to discriminate signal from background while producing two variables that can be used to estimate the background at high Njets with the ABCD method
  - The **developed methods are general and will enable future searches!**

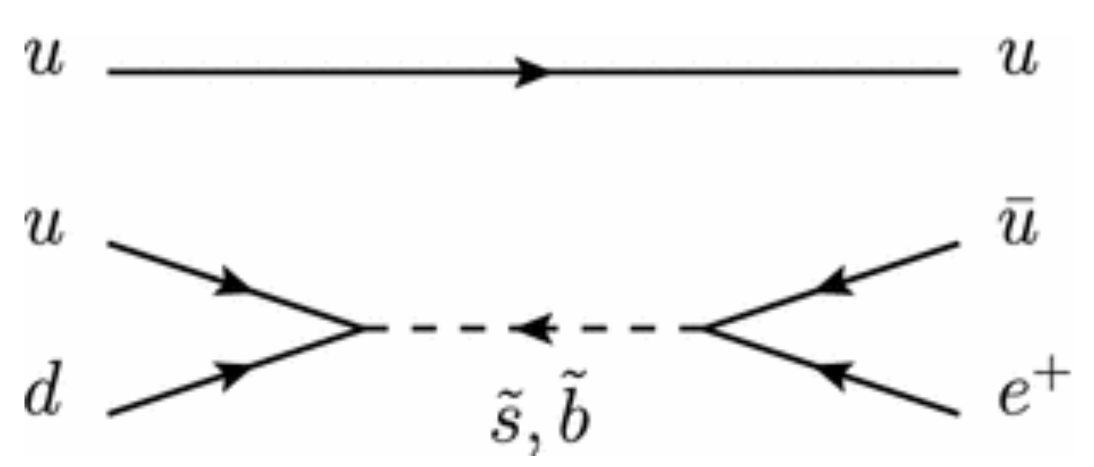
Backup

SUSY with R-parity violation

Dreiner et al (JHEP07(2023)215)

- General MSSM contains terms that violate lepton or baryon number conservation, which could lead to rapid proton decay

$$W_{RpV} = \epsilon_{ab}[\lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^b \bar{D}_k + \kappa_i L_i^a H_u^b] \qquad \not{L}$$
$$+\lambda''_{ijk}\epsilon_{xyz}\bar{U}_i^x \bar{D}_j^y \bar{D}_k^z \qquad \not{B}$$

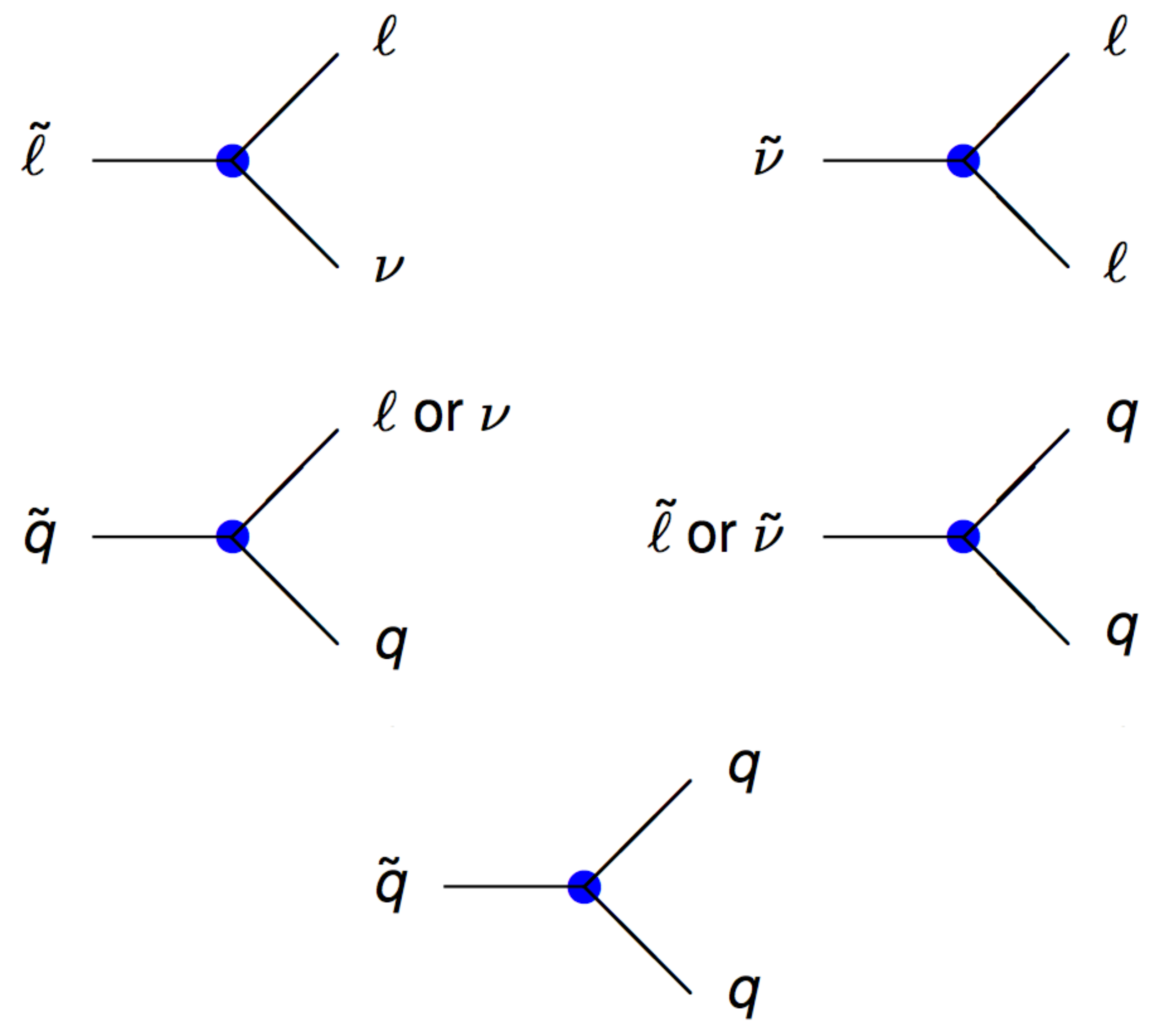


- Typically, these terms are removed by the introduction of R-parity conservation (+1 for SM particles, -1 for SUSY partners)
- However, if only 1 possible coupling is nonzero at a time, we avoid the troubles of proton decay
- Typically: p_T^{miss} is exchanged for visible SM particles
  - Many possibilities! 45 couplings, many possible LSPs...
  - Can result in events with high object multiplicity

LLE

LQD

UDD

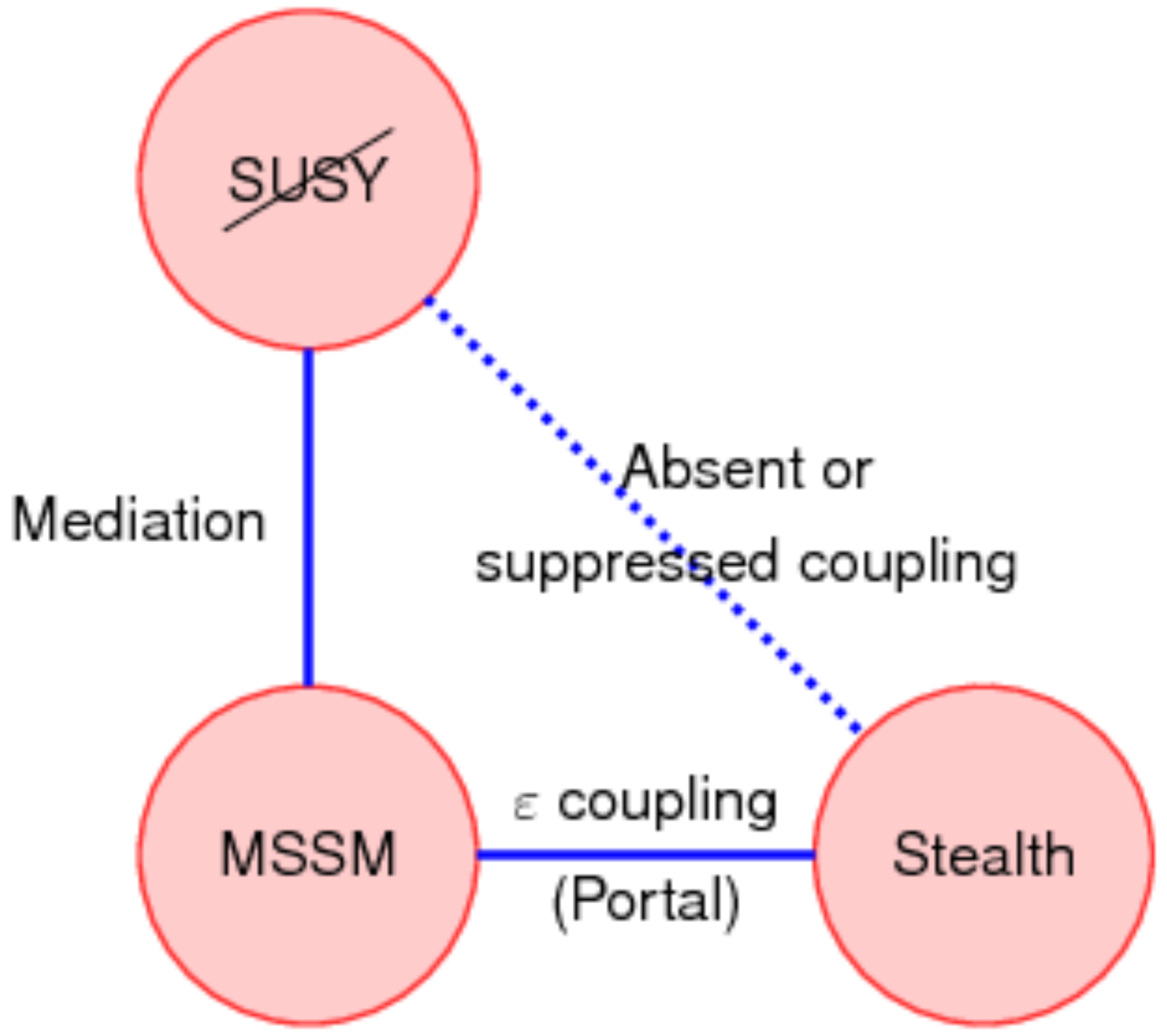


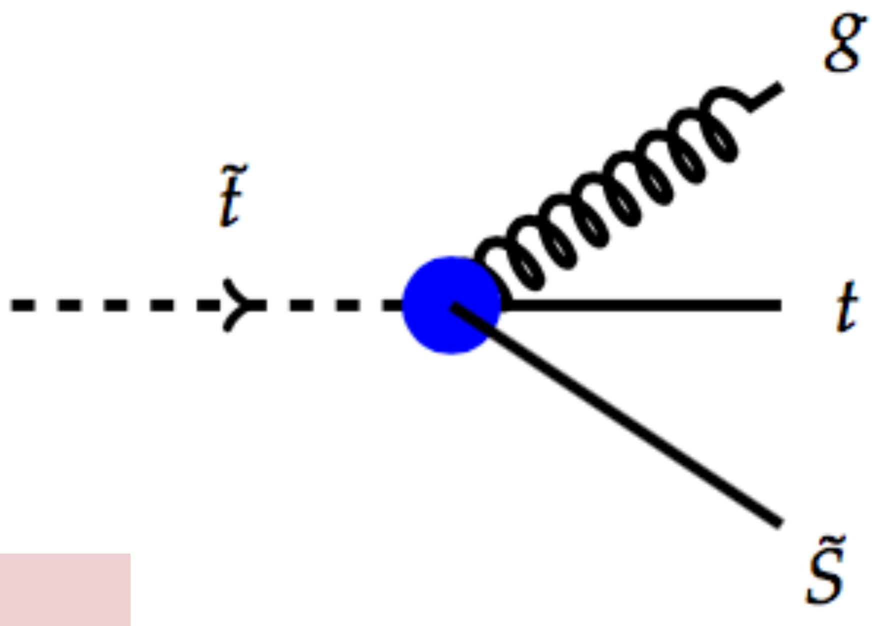
Analyses covered here consider UDD couplings λ'', resulting in the decay $\tilde{\chi}_1^0 \rightarrow qqq$, leading to additional jets in the final state; or LQD couplings λ' resulting in additional jets and leptons

Stealth Supersymmetry

Fan et al (JHEP11(2011)012)
Fan et al (JHEP07(2016)016)

- Augment MSSM with a hidden "stealth" sector in which SUSY is conserved
  - Minimal case: nearly degenerate singlet S and partner (singlino $\tilde{S}$)
  - Singlino decay: $\tilde{S}$ → S+gravitino ($\tilde{G}$)
  - Singlet decay depends on portal
    - Through mixing with the Higgs: S → $b\bar{b}$, S → $\gamma\gamma$
    - Through loops of vector-like particles: S → gg
- Small coupling between normal and hidden sectors results in all sparticles quickly decaying to lightest ordinary SUSY particle (LOSP), then the LOSP decays via the hidden sector
- Typically: p_T^{miss} is exchanged for additional visible objects, e.g. jets



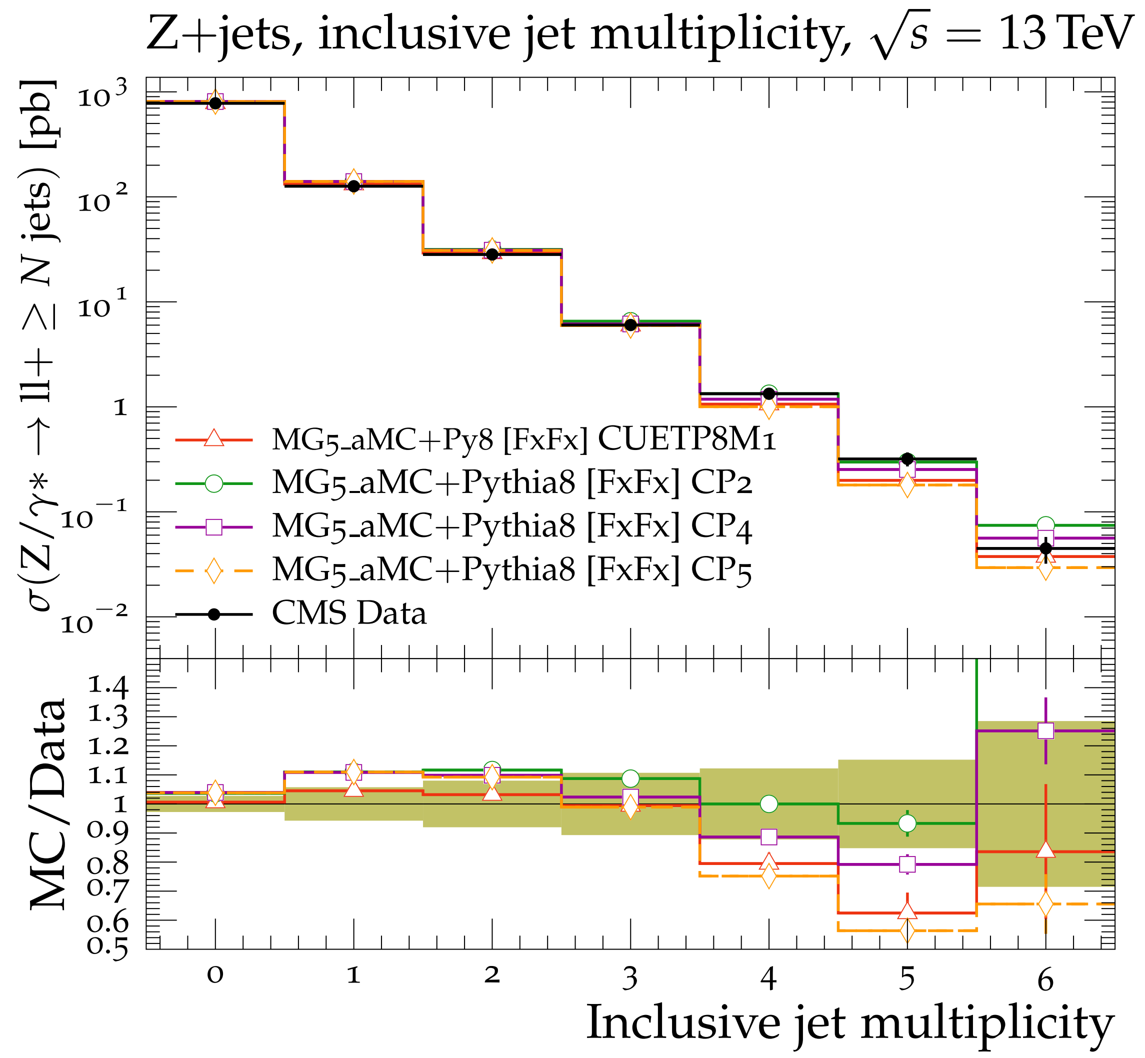


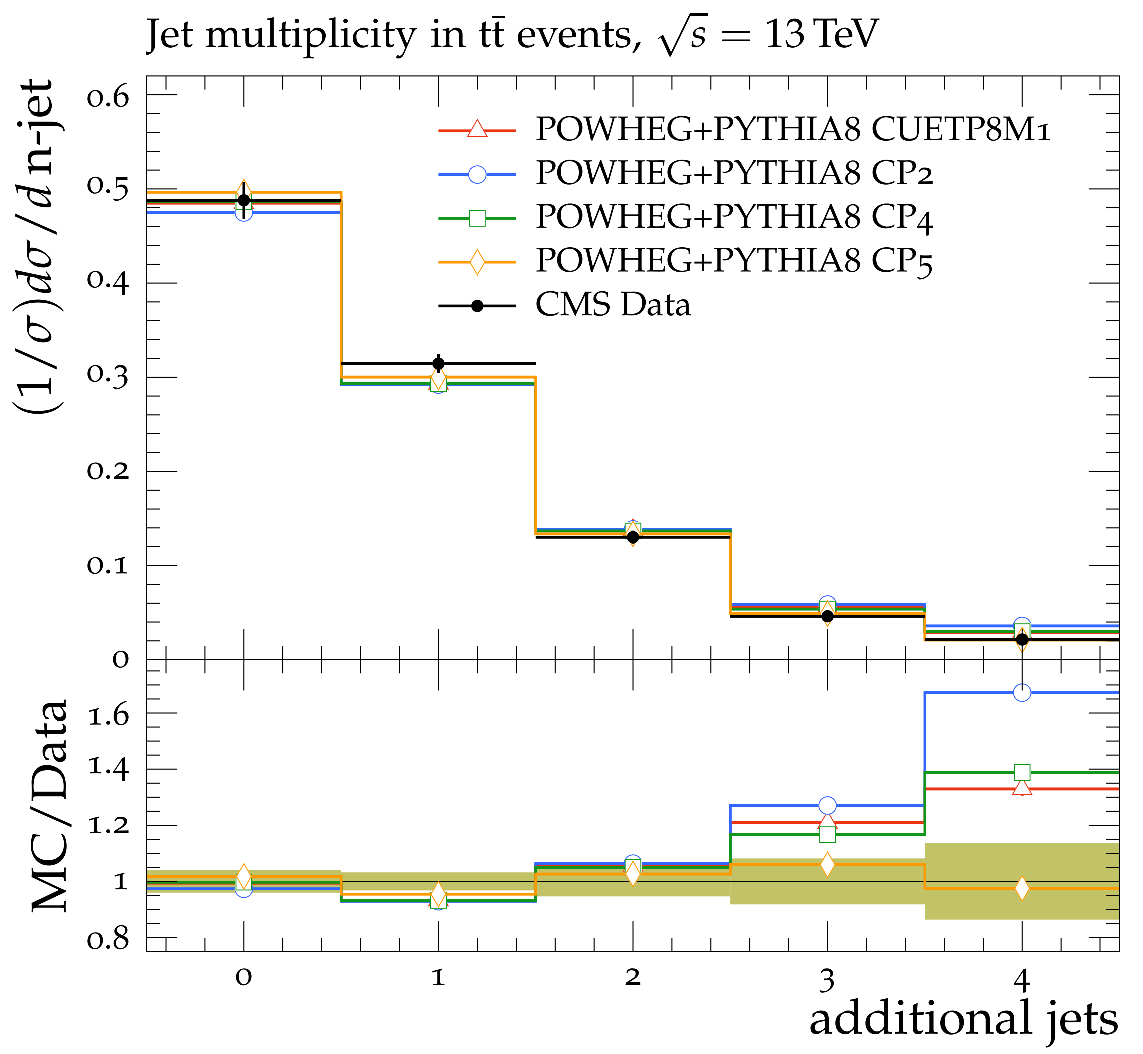
SUS-23-001 considers top squark decay, with S → gg decays, resulting in 3 additional gluons per top squark

Common challenge: jet multiplicity modeling

- The modeling of the jet multiplicity is notoriously difficult, and comes with large theory uncertainties
- To search for new physics at high N_j, such as in RPV or stealth SUSY, one cannot solely rely on MC for background modeling!
- We need a **data-driven background prediction for high N_j**
  - Use **jet scaling patterns**
    - Ratio of number of events in adjacent N_j bins becomes a constant at high N_j (“staircase scaling”)
    - Similar for different processes since it is driven by ISR/FSR
    - SUS-23-015 uses this method
  - Use **control regions at high N_j**, e.g. via ABCD method
    - This method is used by SUS-23-001
      - Previous version of this analysis (SUS-19-004) used jet scaling patterns

Examples from GEN-17-001





Implementing ABCDisCoTEC

SUS-23-001 arxiv:2506.08825 | MLG-23-003 arxiv:2506.08826

- Steps to complete after network is trained:
  - **Pick the boundaries** defining the A, B, C, and D regions
    - Optimized for signal significance, taking into account all systematic uncertainties
  - Apply simulation-based correction for any predicted non-closure
    - Include range of uncertainties in this correction
  - **Validate the level of non-closure of the method in data**
    - Method comes with built-in validation regions
    - Derive systematic uncertainty to cover for any discrepancies found between non-closure in data vs simulation