LHC Recasting
Reinterpretation of the LHC results

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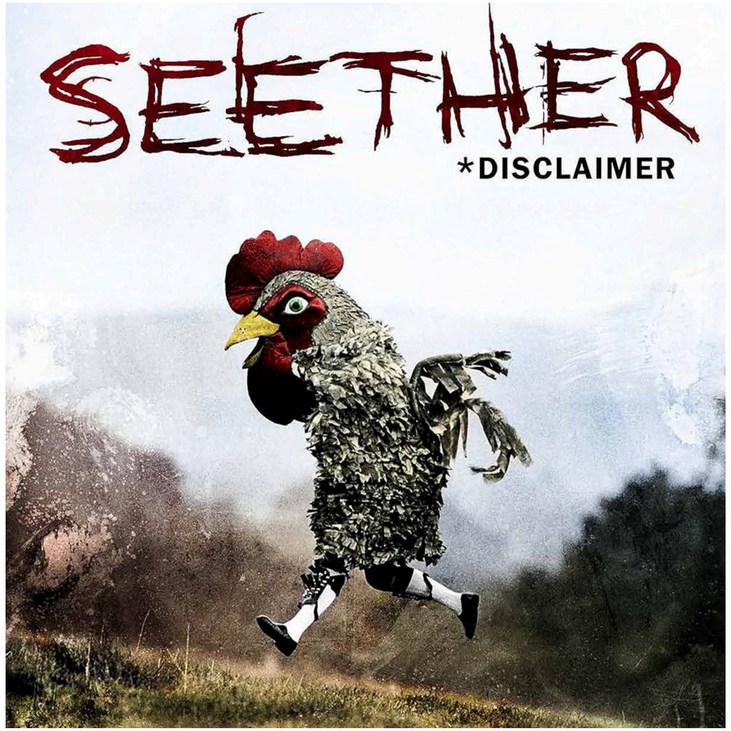
LPTHE / Sorbonne Université

The 14th IDPASC school

15 – 25 July 2025

Disclaimer…

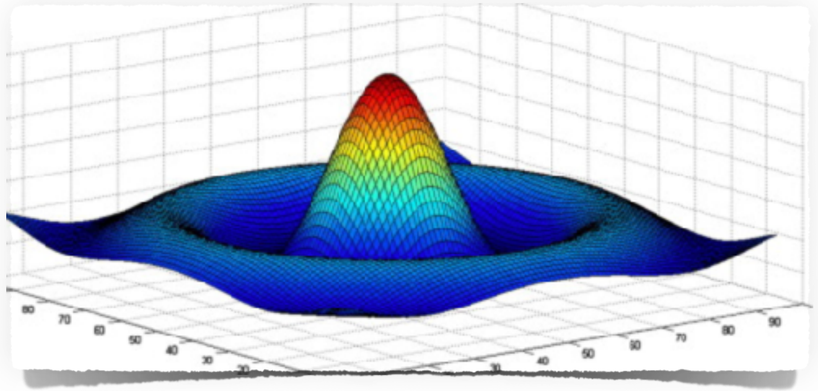


Very broad topic

- Dozens of new results every week
- 1-hour lecture
- Subjective choices to be made…

  ➙ A lot of interesting topics not covered

Going beyond the Standard Model?



SM extremely successful

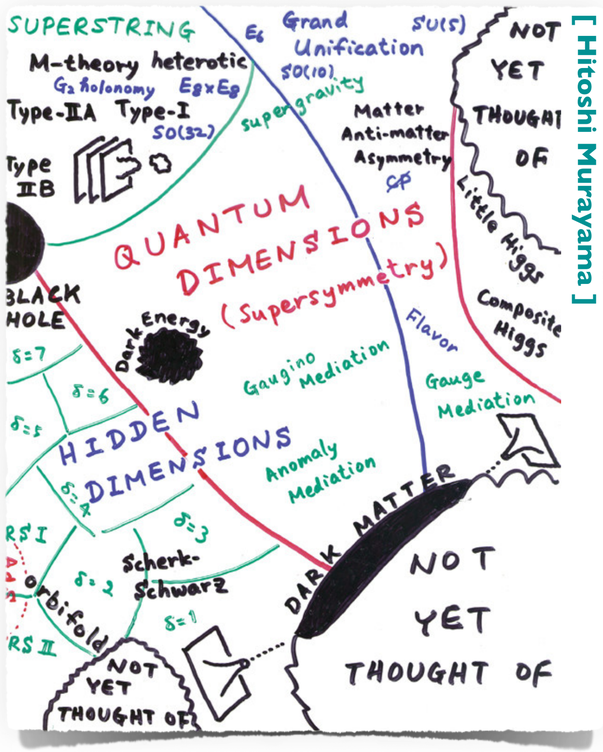
- Agreement with a century of data
- No clear sign of new phenomena

Why going beyond ?

- Practical limitations
- Conceptual issues
- Few experimental anomalies

Some issues of the SM

- Naturalness of the theory / hierarchy problem
- Neutrino masses
- Dark matter
- Gauge structure of the theory
- Origins of CP violation
- Matter/antimatter asymmetry
- Lepton/quark mixings and masses
- Dark energy
- Four-dimensionality of space-time
- Gravity



[Hitoshi Murayama]

SM ≡ tip of the iceberg

- BSM exploration to solve its issues
- No clear path
  - → Supersymmetry / Dark matter ≡ (excellent) ways
  - → Signals comprising missing transverse energy

Supersymmetry as a general QFT

Most general quantum field theory

- SUSY natural in any generic QFT with a generic symmetry
- Nœther and spin-statistics ➞ the Poincaré superalgebra
- Unification of the external and internal symmetries
  ➞ Algebra: $\mathfrak{iso}(1,3) \times \mathfrak{g}_{\text{int}} \oplus$ fermionic part

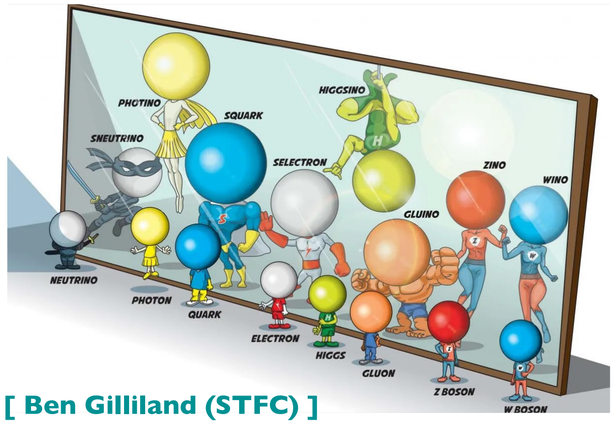
[Coleman, Mandula (PhysRev '67)]
[Haag, Lopuszanski, Sohnius (NPB '75)]
[BF (Habilitation Thesis, 2014)]

$$
\begin{aligned}
[M^{\mu\nu}, M^{\rho\sigma}] &= -i(\eta^{\nu\sigma}M^{\rho\mu} - \eta^{\mu\sigma}M^{\rho\nu} + \eta^{\nu\rho}M^{\mu\sigma} - \eta^{\mu\rho}M^{\nu\sigma}) \,, \\
[M^{\mu\nu}, P^{\rho}] &= -i(\eta^{\nu\rho}P^{\mu} - \eta^{\mu\rho}P^{\nu}) \,, \\
[T_a, T_b] &= i f_{ab}{}^{c} T_c \,, \\
[Q_\alpha, M^{\mu\nu}] &= \sigma^{\mu\nu}{}_{\alpha}{}^{\beta}\, Q_\beta \,, \qquad [\bar{Q}^{\dot\alpha}, M^{\mu\nu}] = \bar{\sigma}^{\mu\nu\dot\alpha}{}_{\dot\beta}\, \bar{Q}^{\dot\beta} \,, \\
\{Q_\alpha, \bar{Q}_{\dot\alpha}\} &= 2\sigma^{\mu}{}_{\alpha\dot\alpha} P_\mu \,, \\
[Q_\alpha, R] &= Q_\alpha \,, \qquad [\bar{Q}_{\dot\alpha}, R] = -\bar{Q}_{\dot\alpha} \,, \\
[P^\mu, P^\nu] &= [P_\mu, Q_\alpha] = [P_\mu, \bar{Q}^{\dot\alpha}] = \{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0 \,, \\
[T_a, P^\mu] &= [T_a, M^{\mu\nu}] = [Q_\alpha, T_a] = [\bar{Q}_{\dot\alpha}, T_a] = 0 \,.
\end{aligned}
$$

Representations of the Poincaré superalgebra

- Minimality: 1 supercharge
- SM states associated with superpartners of opposite statistics

$$Q|F\rangle = |B\rangle \qquad Q|B\rangle = |F\rangle$$



[Ben Gilliland (STFC)]

Supersymmetry broken

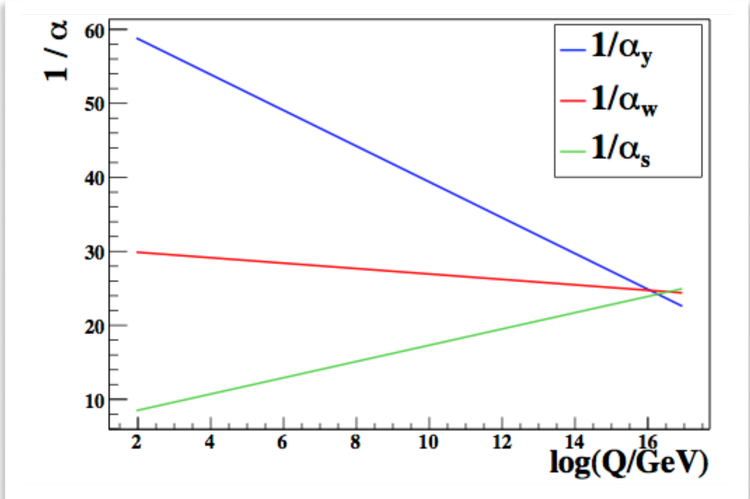
- No observation of a SUSY state with a SM mass
- Unknown breaking mechanism
  ➞ 100s free parameters
  ➞ Simplest options: 5−10 parameters
  (supergravity, gauge mediation, …)

SUSY as a cure to the SM problems

Scalar masses protected with respect to quantum corrections

- Hierarchy problem fixed
- SUSY breaking soft
- Superpartners not too heavy ➙ strong motivation for the LHC

[Witten (NPB '81)]



RG running of the gauge couplings

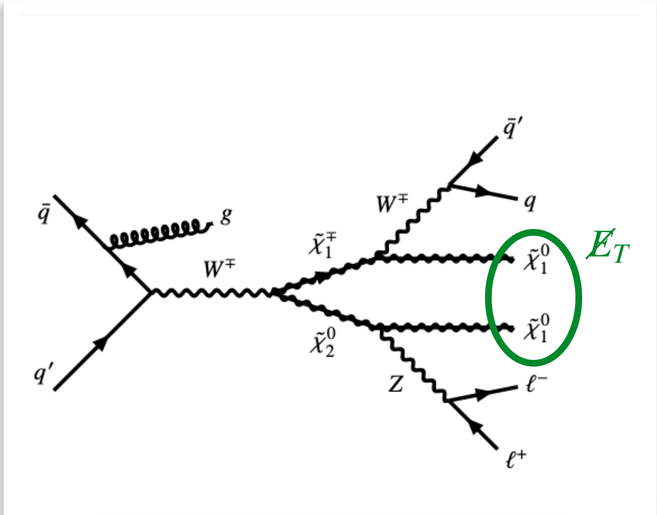
- Superpartners in the loops
- Unification at high energies

[Ibanez, Ross (PLB '81)]
[Dimopoulos, Raby, Wilczek (PRD '81)]

R-parity conservation

[Farrar, Fayet (PLB'78)]

- SM states: R=+1 / SUSY partners: R = -1
- Proton stability
- Lightest SUSY state: DM candidate (if neutral/colourless)
- Missing transverse energy and pair production at colliders

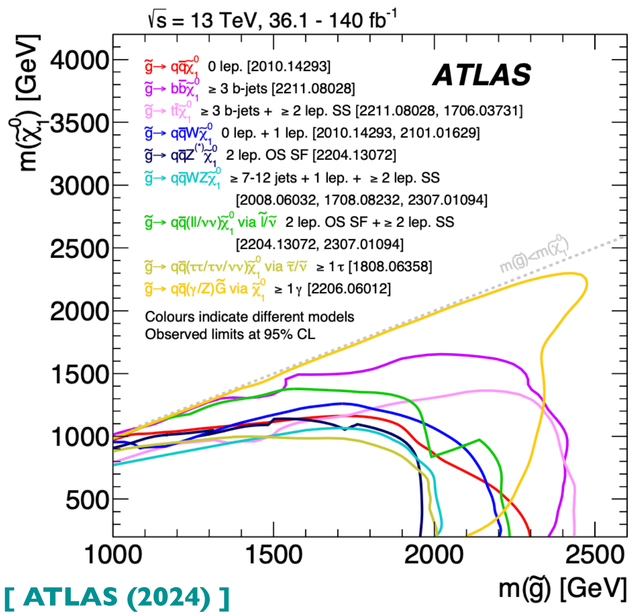


Where are we with supersymmetry? – Simplified models

Typical MSSM searches at the LHC (with *R*-parity)

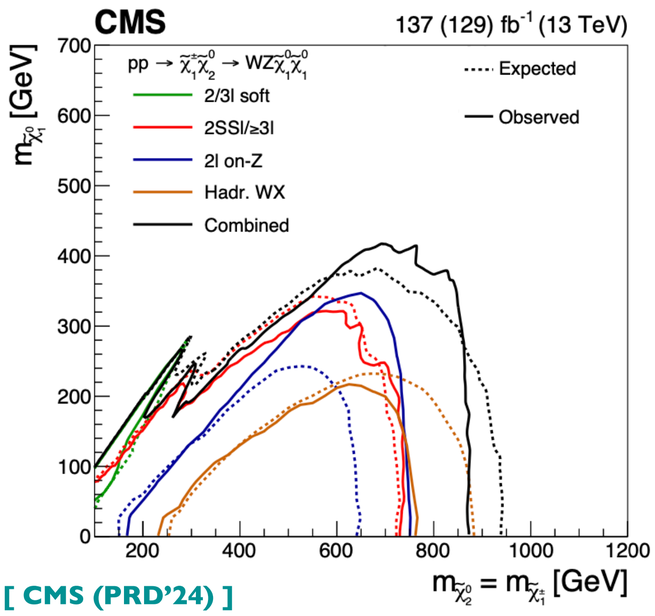
- Missing energy and visible objects (jets, leptons, *etc.*)
  - ➙ Stringent bounds deep in the TeV regime
  - ➙ Both for strong and EW superpartners

$\tilde{g}$ constraints with jets, leptons and MET



[ATLAS (2024)]

$\tilde{W}/\tilde{B}$ constraints with jets, leptons and MET

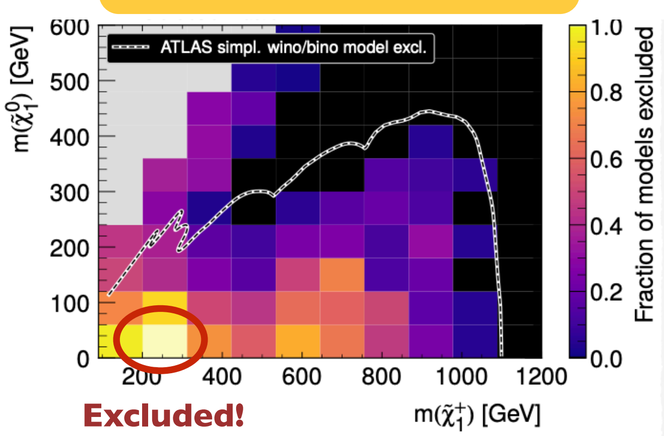


[CMS (PRD'24)]

Is SUSY in bad shape ?

- Not really: MSSM-inspired simplified models
  - ➙ Most superpartners decoupled
  - ➙ Specific decay table
- Signatures typically more complex
  - ➙ Constraints not necessarily that strong
- Example: ATLAS pMSSM scan (20,000 scenarios)
  - ➙ Points survival (almost) at all masses

Non excluded $\tilde{B}/\tilde{W}$ scenarios



[ATLAS (JHEP'24)]

What's next?

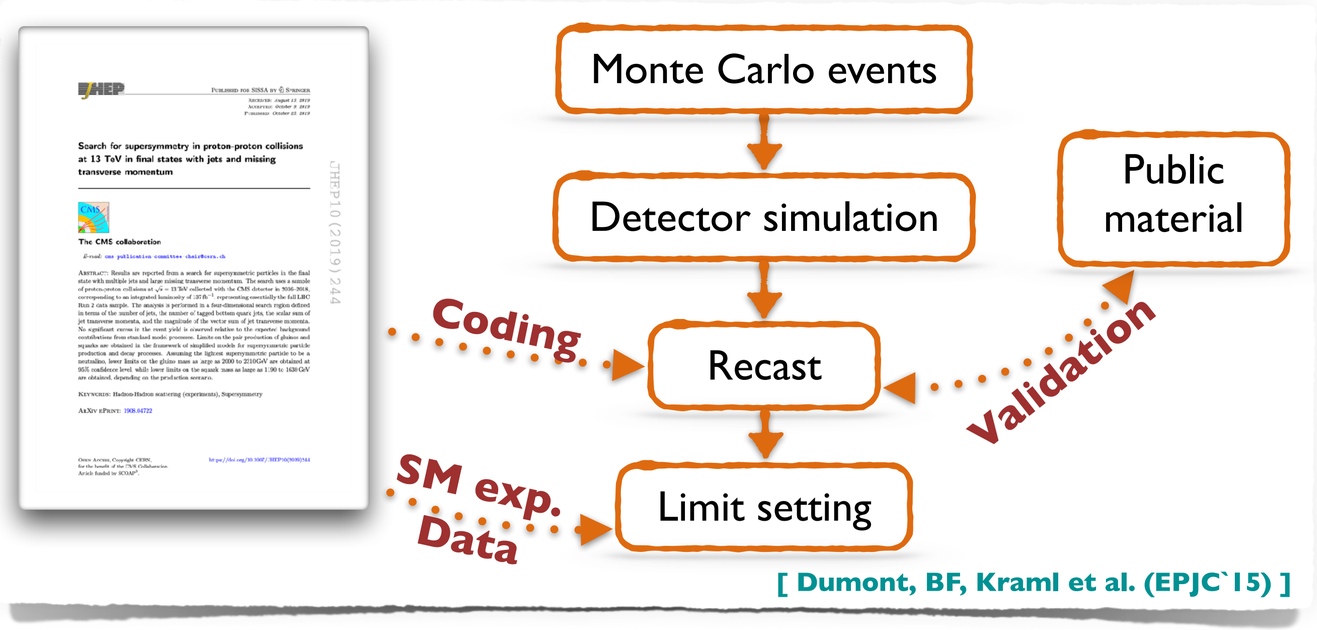
Searches for SUSY will continue (during Run 3 and beyond)

- Great: SUSY ↔ test ground for many BSM theories
  ➞ Shared signatures with numerous models
- Requires ability to reproduce/recycle the analyses

What's next?

Reinterpretation based on simulations

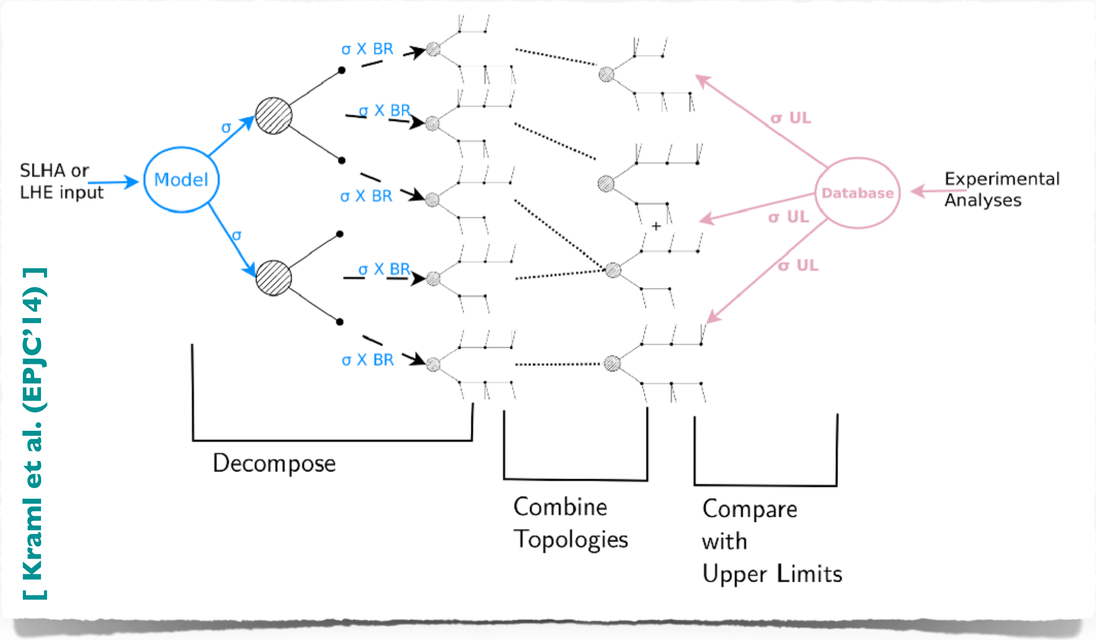
- Detector modelling mimicking ATLAS / CMS
- Development of full frameworks
  - ➙ Implementations of searches (and validation)
  - ➙ Event yields from simulated signals



[Dumont, BF, Kraml et al. (EPJC`15)]

Reinterpretation based on Simplified Model Spectra (SMS)

- Decomposition of theory signatures into SMS signatures
- Fiducial cross sections on the basis of public efficiency maps
- Comparison to published upper bounds
  - ➙ Validation: reproduction of existing bounds



- Often conservative: different kinematics, asymmetric decays
- Rather fast, fair estimates of bounds

Analysis implementations in tools – challenges

Picking up an experimental publication
- Reading / understanding

✅ Relatively easy

Writing the analysis code in the tool internal language

Accurate information for proper validation
- Efficiencies (trigger, $e^{\pm}$, $\mu^{\pm}$, *b*-tagging, JES, *etc.*)
- Detailed cut-flows for well-defined benchmarks
  - ➙ Information for all SRs
  - ➙ Exact definition of benchmarks (spectra)
  - ➙ Event generation information (cards, tunes)
- Digitised histograms (*e.g.* on HEPDATA)
- Reproduction of exclusion contours

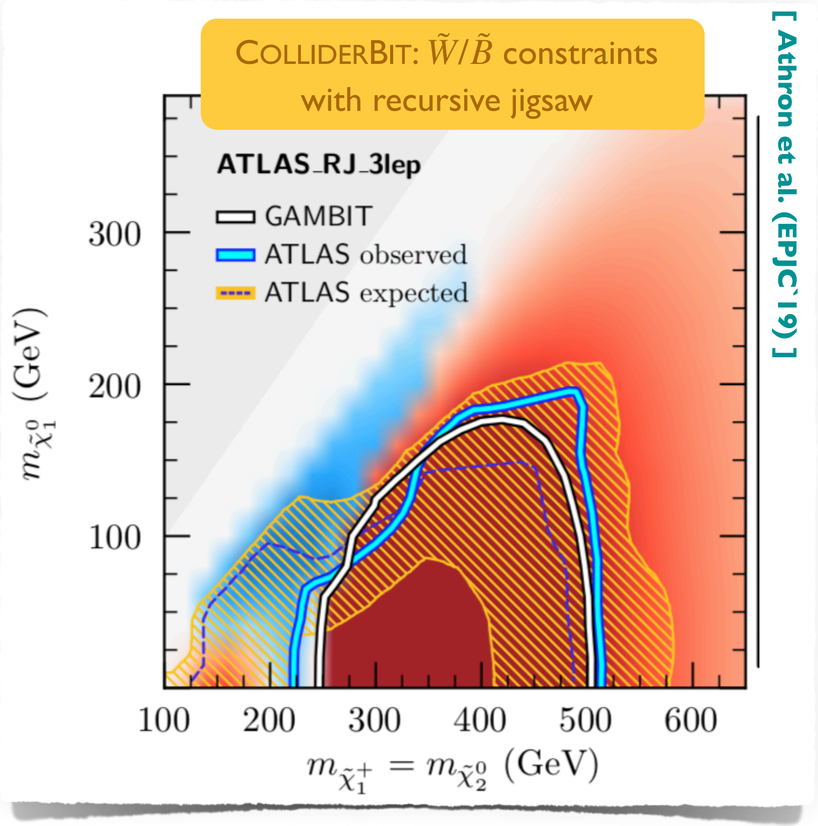
⚠️ Essential
❌ Often difficult!

Wishlist for high-quality recasts
- Background estimates
  - ➙ usually provided (not systematic)
- Efficiencies
  - ➙ To be provided as tables / functional forms
  - ➙ To be broken down in sub-efficiencies (trigger, *etc.*)
  - ➙ Efficiency maps for SMS-based recasting
- Validation material (crucial):
  - ➙ SLHA files, MG5_aMC cards, PYTHIA8 cards, *etc.*
  - ➙ Cut-flows for given benchmarks
  - ➙ Not systematic (sequence, details, all SRs)

Improved recast material over the years
- Publications clearer, HEPDATA widely used
- Better EXP/TH communication
- Still improvable

[The Reinterpretation Forum (SciPost`20)]

Validating LHC recast in public tools



ColliderBit: $\tilde{W}/\tilde{B}$ constraints with recursive jigsaw

[Athron et al. (EPJC'19)]

Excellent agreement with ATLAS

- Wino/bino scenarios ($\tilde{W}$ decays into EW bosons)
- Not necessarily easy to get
- Using the '*best expected region*'
  ➙ Often off when correlations matter

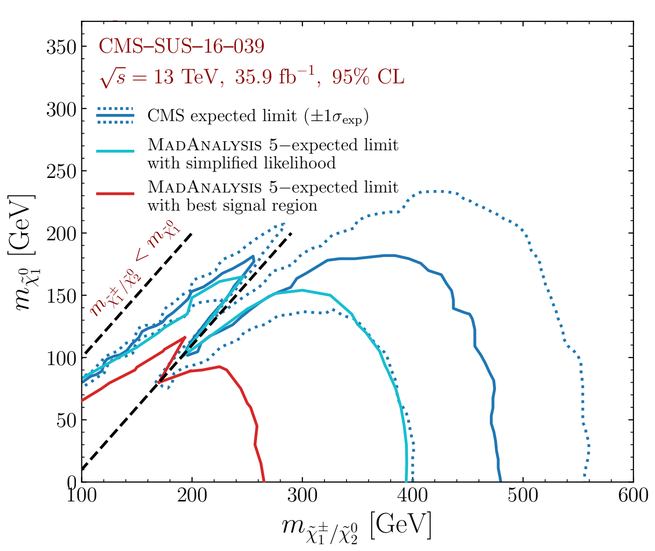
Better limit settings procedures

- Signal region combination
  ➙ CMS correlation matrices (Gaussian-approximate likelihoods)

$$\mathscr{L}_S(\mu,\theta) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i + \theta_i)^{n_i}\, e^{-(\mu s_i + b_i + \theta_i)}}{n_i!} \exp\left(-\frac{1}{2}\theta^T \mathbf{V}^{-1}\theta\right)$$

[CMS-NOTE-2017-001; Buckley et al. (JHEP`19)]

  ➙ ATLAS (full) PyHF likelihoods [Heinrich, Feickert, Stark & Cranmer (JOSS'21)]



MadAnalysis5: $\tilde{W}/\tilde{B}$ constraints with standard ewkino variables

[Alguero, Araz, BF & Kraml (SciPost'22)]

Combination mandatory

- Wino/bino scenarios ($\tilde{W}$ decays into EW bosons)
- 100+ SRs; signal over ≠SRs
- Sensitivity reduced with the '*best region*' only
- Covariance matrices and PyHF models crucial

SMS-based *public* tools

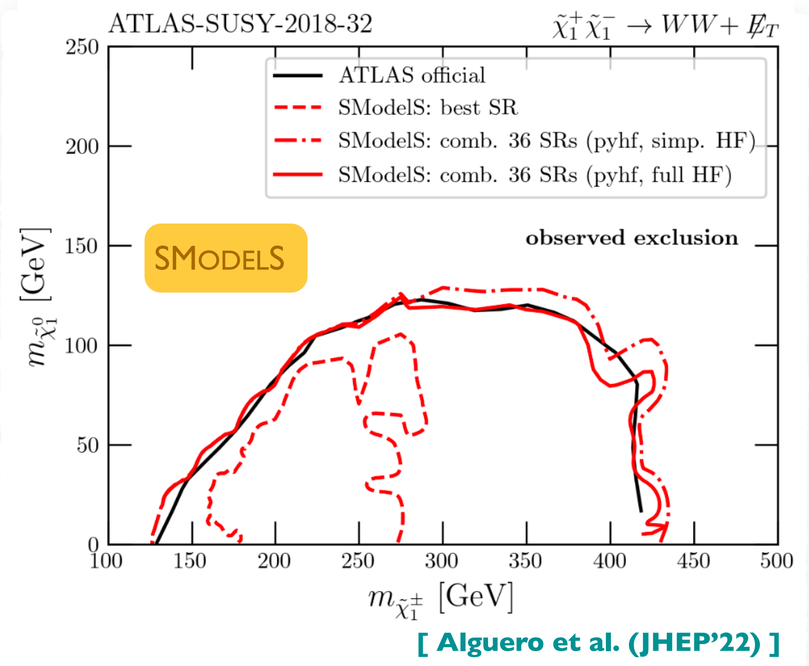
SMS-based

- SMODELS [*O*(100) analyses, from GITHUB]
  - ⋆ Validation example (ATLAS-SUSY-2018-32)
    - ➙ $\tilde{W}/\tilde{B}$ scenario with 2 leptons and $\not{E}_T$
    - ➙ PYHF model crucial

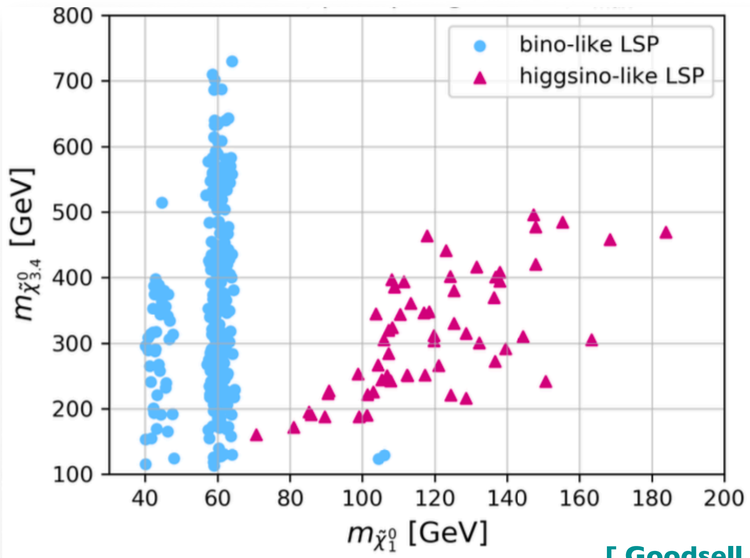
[Kraml et al. (EPJC'14); Alguero et al. (JHEP'22)]
[Altakach et al. (SciPost'24)]

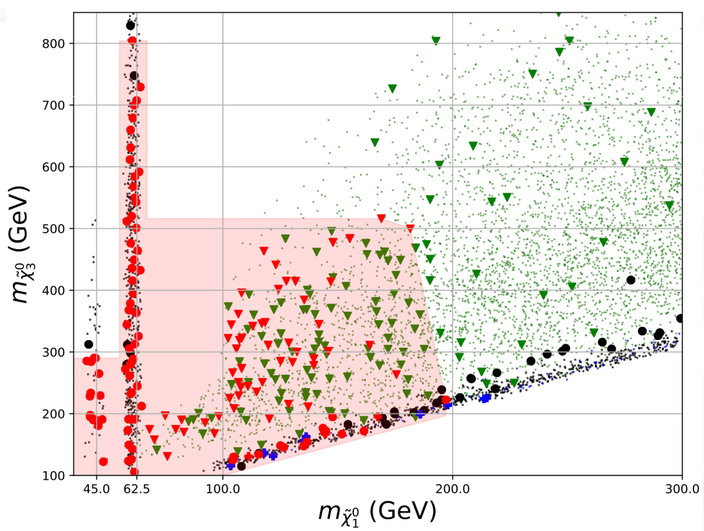
- Dark photons: DARKCAST [from GITLAB]

[Ilten et al. (JHEP'18)]



[Alguero et al. (JHEP'22)]





[Goodsell, Kraml, Reyes-Gonzàlez & Williamson (SciPost'20)]

Application: Dirac gauginos at the LHC

- Model not considered by ATLAS/CMS
  - ➙ Full scan of the EW sector of the model
  - ➙ Constraints (EWPT, relic density, *etc.*)
- Points excluded by SMODELS (with $r \geq 1$)
  - ➙ DM funnels
  - ➙ Larger set of analyses than other tools
- Comparison with full recasts (from MADANALYSIS 5)
  - ➙ SMS approach more conservative and faster
  - ➙ Full recasts sensitive to complex spectra/signatures

Simulation-based *public* tools

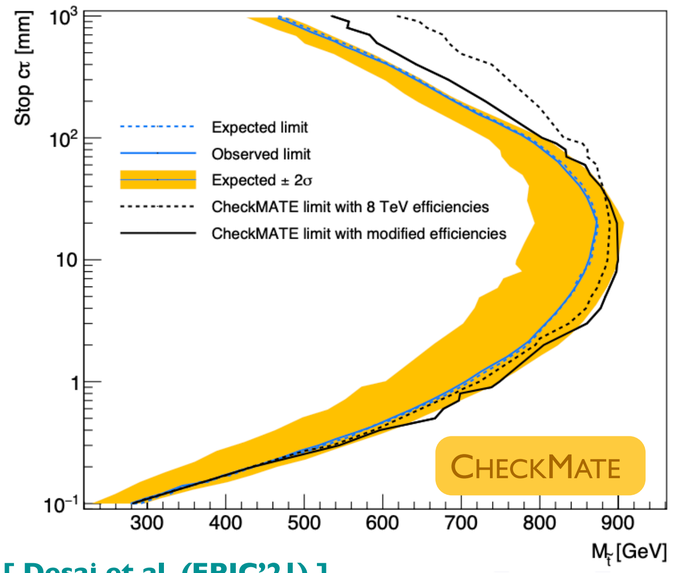
Simulation-based; detector modelling with transfer functions

- ColliderBit [*O(40)* analyses, from HepForge] [Balász et al. (EPJC`17)]
- HackAnalysis [*O(10)* analyses, from IN2P3] [Goodsell & Priya (EPJC`22)]
  - ⋆ Validation example (CMS-EXO-19-010)
    - ➙ Disappearing tracks and winos
    - ➙ Cut-flow comparisons
- MadAnalysis5/SFS [*O(15)* analyses, from GitHub/MA5DataVerse] [Araz, BF & Polykratis (EPJC`21) ; Araz, BF, Goodsell & Utsch (EPJC`22)]
- Rivet [*O(30)* analyses, from HepForge] [Buckley et al. (2010); Bierlich et al. (SciPost`20)]

HackAnalysis

	700 GeV, 10 cm, region 2018A		
	$\epsilon_i^{\mathrm{CMS}}$	$\epsilon_i^{\mathrm{sim}}$, HEPMC	$\epsilon_i^{\mathrm{sim}}$, HEPMC, no pileup
Total	$1.0^{+0.00}_{-0.00}$	$1.0^{+0.00}_{-0.00}$	$1.0^{+0.00}_{-0.00}$
Trigger	$1.5^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
Passes $p_{\mathrm{T}}^{\mathrm{miss}}$ filters	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
$p_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 jet with $p_{\mathrm{T}} > 110\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.4$	$1.3^{+0.02}_{-0.02} \times 10^{-1}$	$1.3^{+0.01}_{-0.01} \times 10^{-1}$	$1.3^{+0.01}_{-0.01} \times 10^{-1}$
==0 pairs of jets with $\Delta\phi_{\mathrm{jet,\,jet}} > 2.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
$\lvert\Delta\phi(\text{leading jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert > 0.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 track with $\lvert\eta\rvert < 2.1$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 track with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$	$4.7^{+0.10}_{-0.10} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$
≥ 1 track passing fiducial selections	$3.1^{+0.08}_{-0.08} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$
≥ 1 track with ≥ 4 pixel hits	$1.7^{+0.06}_{-0.06} \times 10^{-2}$	$2.7^{+0.05}_{-0.05} \times 10^{-2}$	$2.7^{+0.05}_{-0.05} \times 10^{-2}$
≥ 1 track with no missing inner hits	$1.7^{+0.06}_{-0.06} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$
≥ 1 track with no missing middle hits	$1.5^{+0.05}_{-0.05} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$	$2.0^{+0.04}_{-0.04} \times 10^{-2}$
≥ 1 track with relative track isolation $< 5\%$	$5.3^{+0.34}_{-0.34} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $\lvert d_{\mathrm{xy}}\rvert < 0.02\,\mathrm{cm}$	$5.1^{+0.34}_{-0.34} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $\lvert d_z\rvert < 0.5\,\mathrm{cm}$	$5.1^{+0.31}_{-0.31} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
≥ 1 track with $\Delta R(\text{track, jet}) > 0.5$	$4.9^{+0.31}_{-0.31} \times 10^{-3}$	$5.9^{+0.22}_{-0.22} \times 10^{-3}$	$6.1^{+0.23}_{-0.23} \times 10^{-3}$

[Goodsell & Priya (EPJC`22)]



[Desai et al. (EPJC'21)]

Simulation-based; Delphes 3 detector modelling

- MadAnalysis 5 [*O(50)* analyses, from GitHub/MA5DataVerse] [Dumont, BF, Kraml et al. (EPJC`15)]
- CheckMate [*O(50)* analyses, from GitHub] [Conte & BF (IJMPA`19) ] [ Derks et al. (CPC`17)]
  - ⋆ Validation example (CMS-EXO-16-022)
    - ➙ Displaced stop in an $e\mu$ pair
    - ➙ Detailed information crucial

Recasting SUSY searches to study… SUSY?

LHC recasting

- Constraining SUSY models
  - ➙ Beyond those addressed in LHC searches
  - ➙ Minimal and non-minimal setups

Excesses in SUSY searches at the LHC

- Quantifying
- Interpreting
- Tools needed!

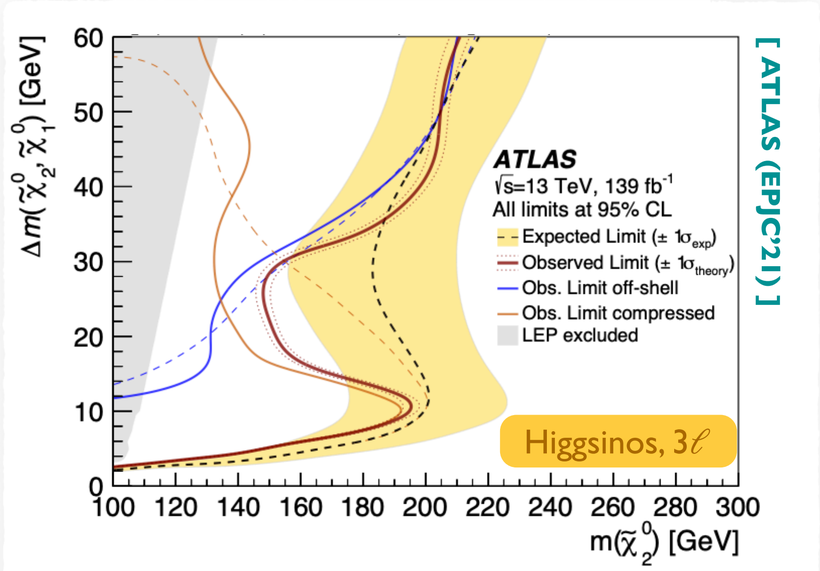
Compressed ewkino excesses at the LHC

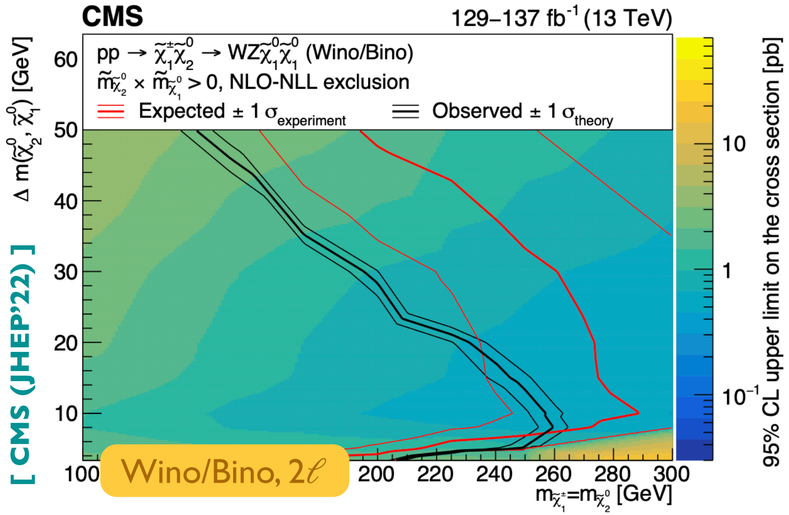
Numerous LHC searches for ewkinos with leptons and $\not{E}_T$

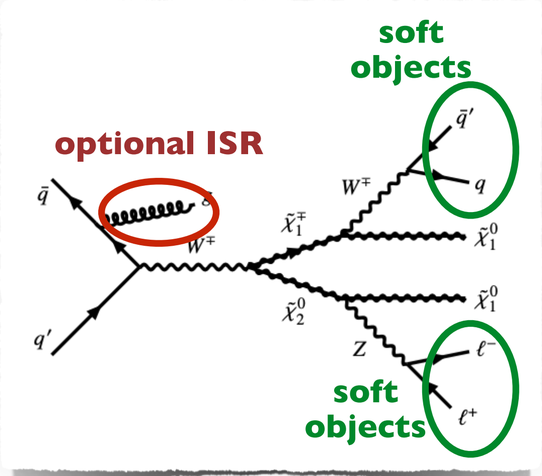
- Many signatures
  - → 3 leptons + $\not{E}_T$ (ATLAS-SUSY-2019-09, CMS-SUS-19-012)
  - → 2 soft leptons + $\not{E}_T$ (ATLAS-SUSY-2018-16, CMS-SUS-18-004)
  - → Combination (CMS-SUS-21-008)
- Interpretations in various simplified models
  - → Light higgsinos
  - → Light bino/wino (+/- ≡ sign of the mass)

$$\tilde{\chi}^0_{1,2} \sim -\frac{1}{\sqrt{2}}\left(\mp\tilde{H}^0_u + \tilde{H}^0_d\right), \qquad \tilde{\chi}^\pm_1 \sim \tilde{H}^\pm_{u,d}$$

$$\tilde{\chi}^0_1 \sim i\tilde{B}, \qquad \tilde{\chi}^0_2 \sim i\tilde{W}^3, \qquad \tilde{\chi}^\pm_1 \sim \tilde{W}^\pm$$







Excesses compatible with a compressed spectrum

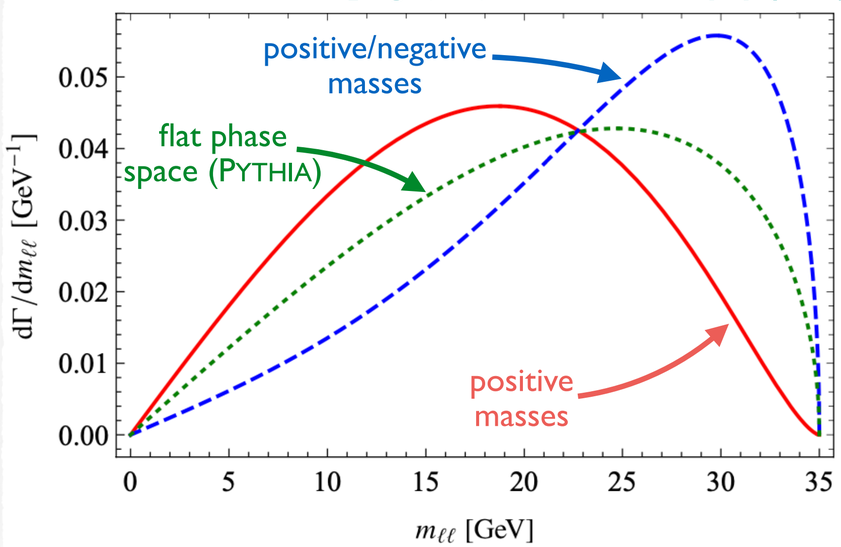
- Mass differences of 10-30 GeV
- Overlapping excesses?
- What about monojets?
- What about complete models?

A few words on soft lepton excesses...

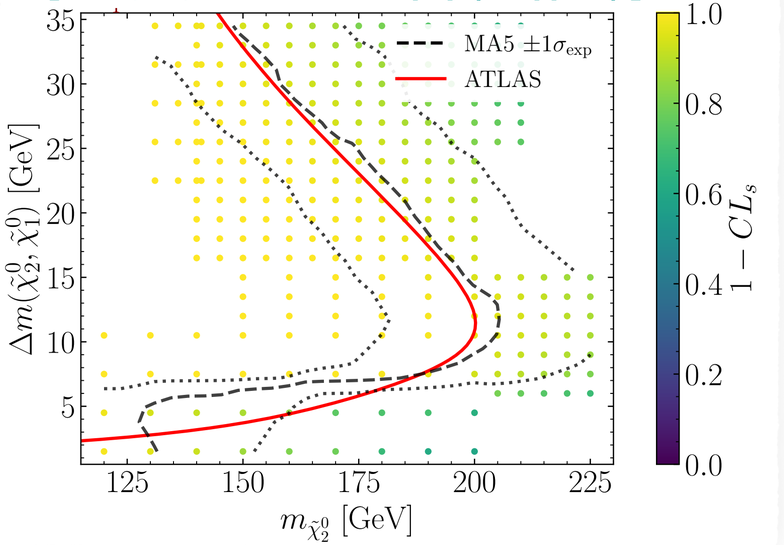
ATLAS-SUSY-2018-16: Soft di-lepton + $\not{E}_T$

- Selection (the second lepton could be a track)
  - ➙ 1OSSF pair + $\not{E}_T$ + at least 1 hard jet
  - ➙ Object isolation, m_T, jigsaw, *etc.*; bins in $m_{\ell\ell}$
  - ➙ PyHF model file
- Recasting challenges
  - ➙ Using RestFrames (*cf.* jigsaw variables) ≡ strong impact on exclusions
  - ➙ Event generation details important for compressed spectra
  - ➙ Validated recast in HackAnalysis / MadAnalysis5
- Equivalent CMS search: CMS-SUS-18-004

[Agin, BF, Goodsell & Murphy (2024)]



[Araz, BF, Goodsell & Murphy (to appear)]



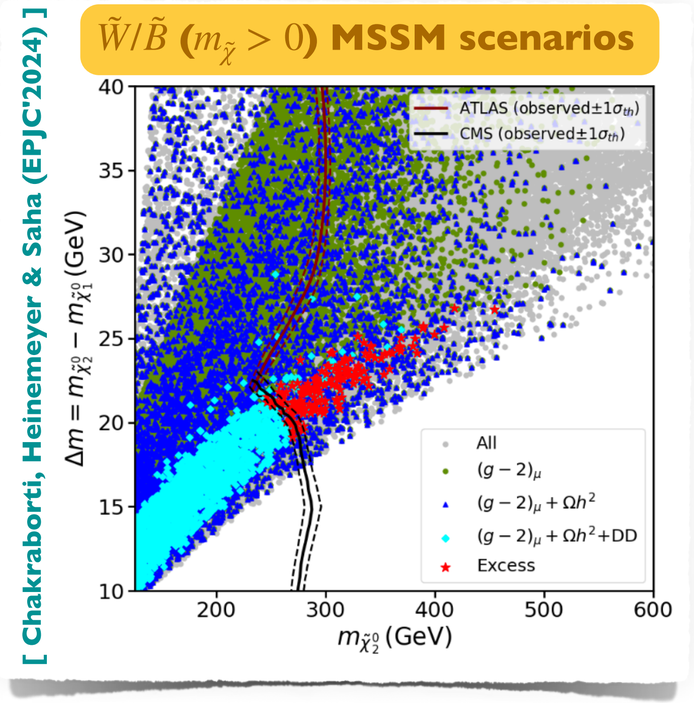
ATLAS-SUSY-2019-09: 3 leptons + $\not{E}_T$

- Selection
  - ➙ 3 leptons including 1 OSSF pair + small/large $\not{E}_T$ + with/without jets
  - ➙ Object isolation, lepton properties, on-shell/off-shell Z boson; bins in $m_{\ell\ell}$
  - ➙ PyHF model file
- Recasting challenges
  - ➙ Event generation details important for compressed spectra
  - ➙ Validated recast in HackAnalysis and MadAnalysis5
- Equivalent CMS search: CMS-SUS-19-012

Constraints/impact on realistic SUSY models

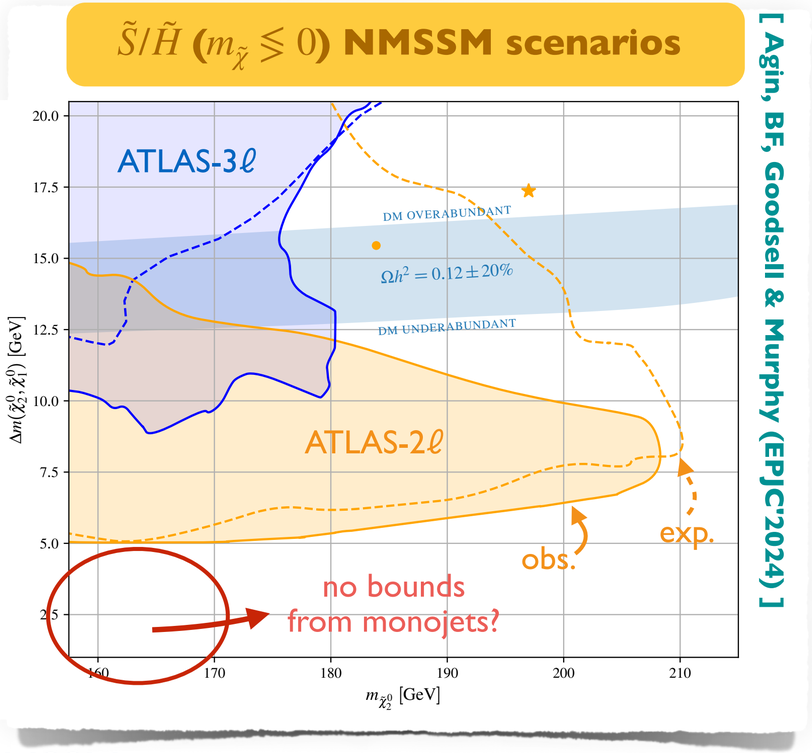
A lot of pheno interests in those excesses

- Interpretation in various models
  - ➙ Realistic or less simplified MSSM scenarios
  - ➙ NMSSM setups
  - ➙ Non-SUSY models
- Connection with other observables
  - ➙ Dark matter, Higgs and flavour physics, $(g-2)_{\mu,e}$



MSSM scan of the EW sector

- Large set of constraints
  - ➙ LHC
  - ➙ DM relic and DD bounds
  - ➙ Δa_μ [⚠️ no new lattice results]
- Points in red
  - ➙ Could explain the excess
  - ➙ Tuning $m_{\tilde{\ell}}$ ≡ new Δa_μ value



NMSSM scan

- $\tilde{S}$-like LSP (*cf.* DM) ↔ 4 light ewkinos
- Excess compatibility can accommodate DM
  - ➙ *cf.* best fit points
- Monojet bounds in principle complementary
  - ➙ Existing excesses
  - ➙ Common explanation unclear

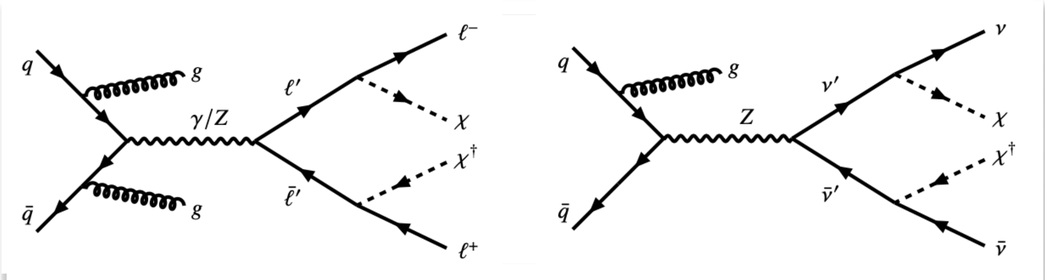
Non-supersymmetric explanations?

[Agin, BF, Goodsell & Murphy (EPJC`24)]

Scalar DM with a doublet vector-like leptons

$$\mathcal{L} \supset \lambda_I \chi(\bar{\nu}'\nu_{LI} + \bar{\ell}'\ell_{LI}) + \text{H.c.}$$

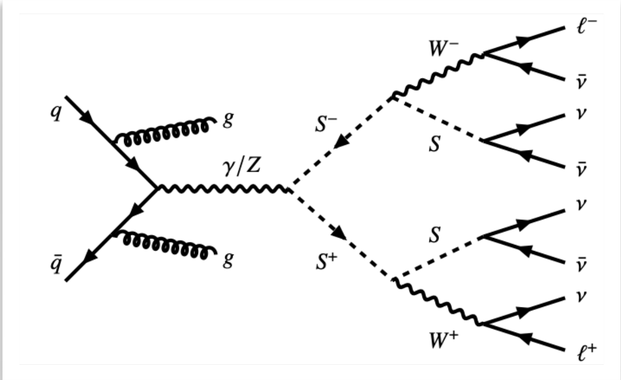
- Non-SUSY higgsino-like setup (fermionic weak doublet)
- LHC signals: two-body decays to leptons



- Spectrum of interest: compressed by [0, 30] GeV
  → Soft leptons at the LHC

Type II Seesaw

- Neutrino mass modelling
- Non-SUSY wino-like setup (scalar weak triplets)
  → 1 SM Higggs field Φ + 1 BSM scalar Δ
  → 4 CP-even scalars (h, S, $S^{\pm}$, $S^{\pm\pm}$)
  → Small splitting possible ↔ small Φ/Δ mixing
- LHC signals: cascade-decays to leptons
  → Via off-shell weak bosons
  → Many (too many?) soft leptons

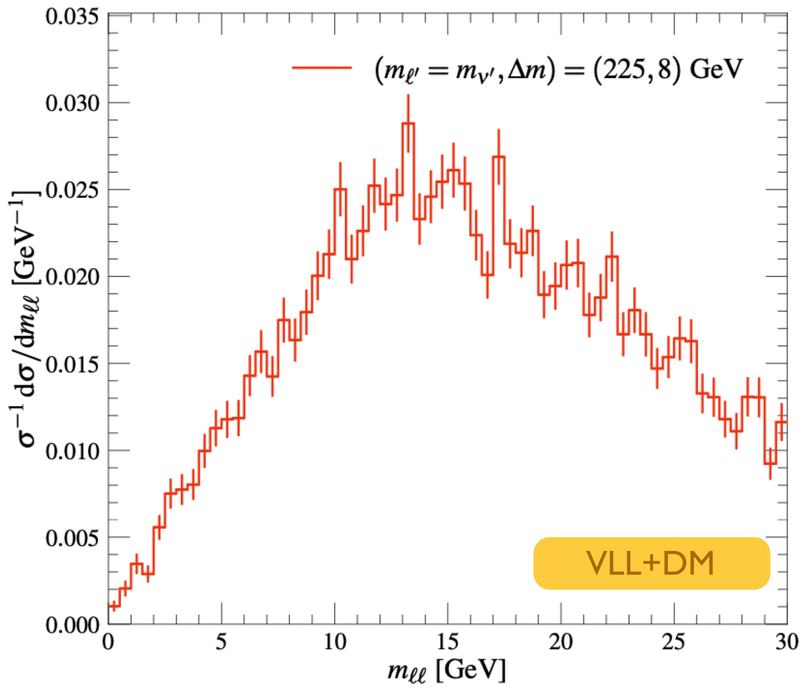


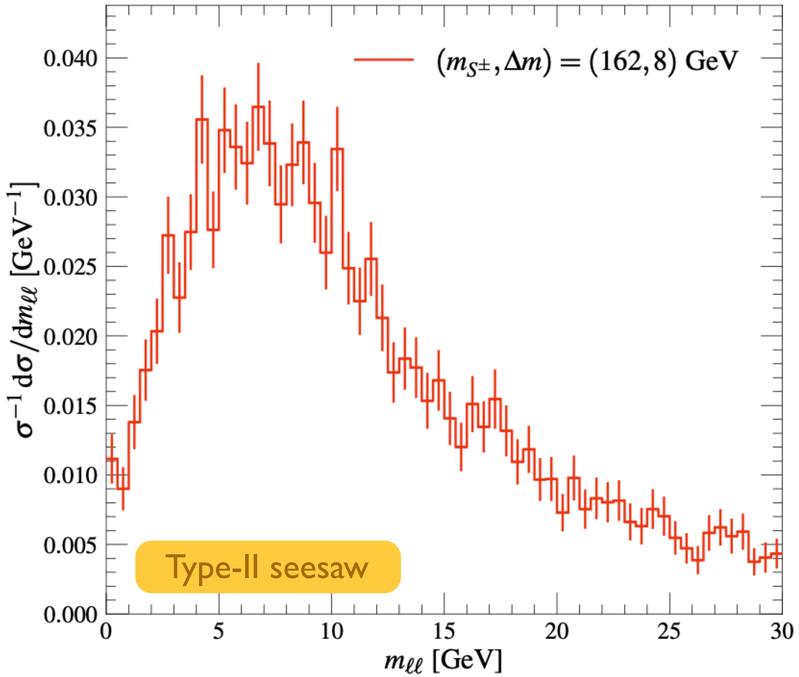
Non-supersymmetric explanations: not so far!

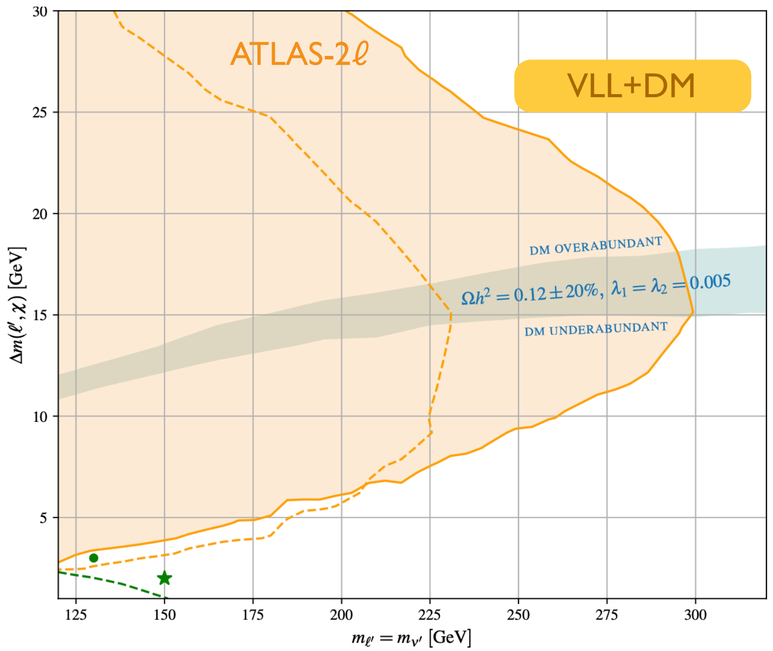
[Agin, BF, Goodsell & Murphy (EPJC`24)]

Too hard tails in the dilepton invariant mass spectra

- VLL+DM: events expected to populating high $m_{\ell\ell}$ bins
- Type-II: similar to ewkino models







VLL+DM model

- No leptonic excess, strong exclusion
  - ➙ 3-body BSM decays in order
- Survival of the monojet excess!
  - ➙ Very light BSM states ($\mu \sim 1.1 - 1.25; p \sim 0.04$)

Type-II model

- No sensitivity
  - ➙ Busy final states ⬌ small efficiencies
- Excess present!

	CL_s^{exp}	CL_s^{obs}	p-value	$\hat{\mu}$
ATLAS 2ℓ	0.387	0.620	0.050	2.06
ATLAS 3ℓ	0.611	0.615	≥ 0.5	0.62
CMS monojet	0.270	0.395	0.081	1.17
ATLAS monojet	0.553	0.399	0.277	0.72

More realistic models ↔ more complex signatures

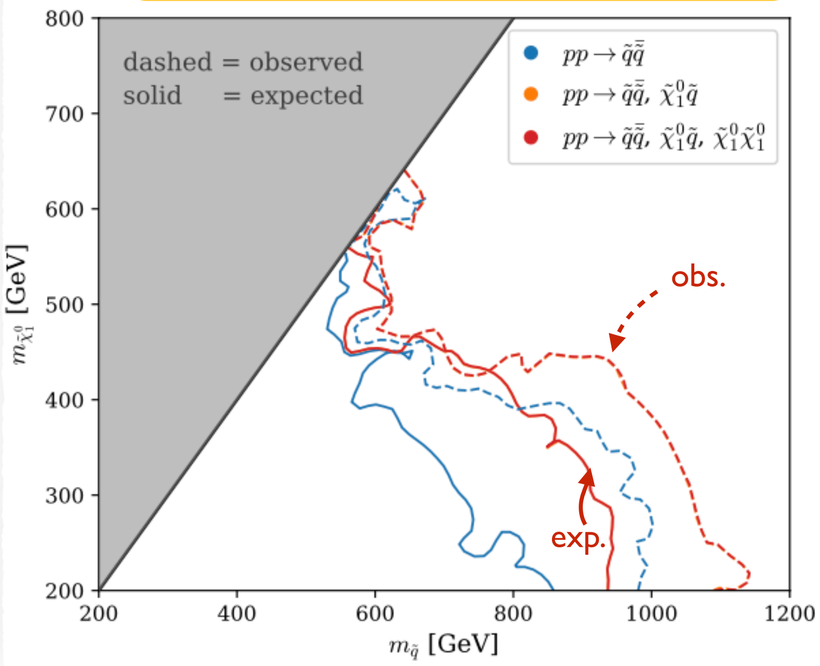
More realistic scenarios - general features

- Several states possibly light and relevant
  ➙ Even true within simplified models
- Impact on BSM signal modelling

Examples: SM + $\tilde{q}$ + $\tilde{B}/\tilde{W}$

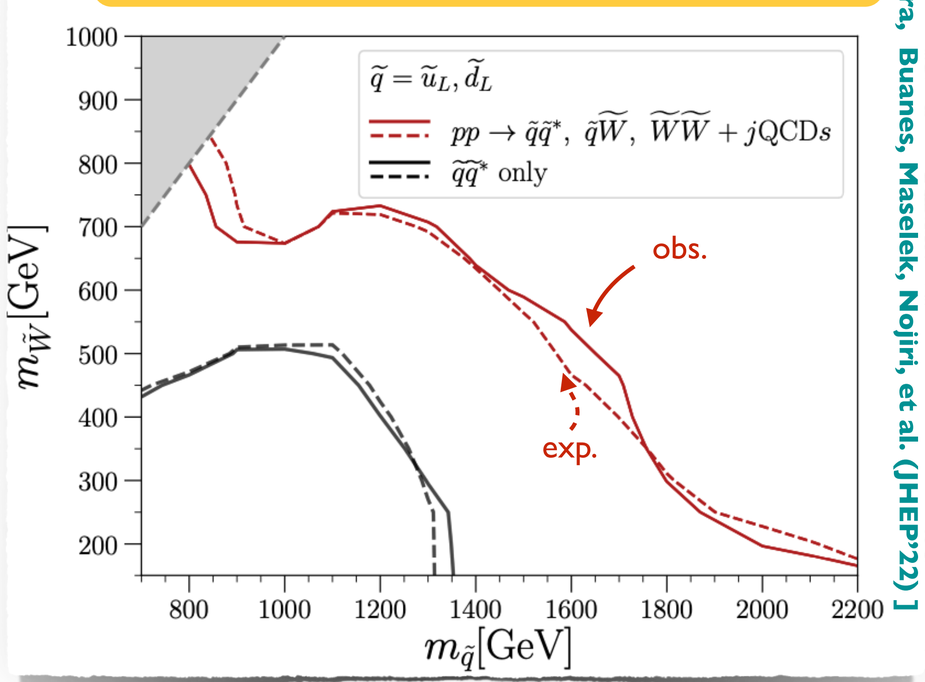
- Three-component signal at the LHC: $pp \to \tilde{q}\tilde{q}^* + \tilde{q}^{(*)}\tilde{\chi} + \tilde{\chi}\tilde{\chi}$
- Impact on multijet + $\not{E}_T$ searches
  ➙ ATLAS-SUSY-2018-22: jets, effective mass, jet/met relative properties
  ➙ CMS-SUS-19-006: jets, inclusive $H_T/\not{H}_T$ search

SM + $\tilde{u}_R$ + $\tilde{B}$ & CMS-SUS-19-006



[Feike, Fiaschi, BF, Klasen & Neuwirth (JHEP'2024)]

SM + $\tilde{u}_L/\tilde{d}_L$ + $\tilde{W}$ & ATLAS-SUSY-2018-22



[Lara, Buanes, Maselek, Nojiri, et al. (JHEP'22)]

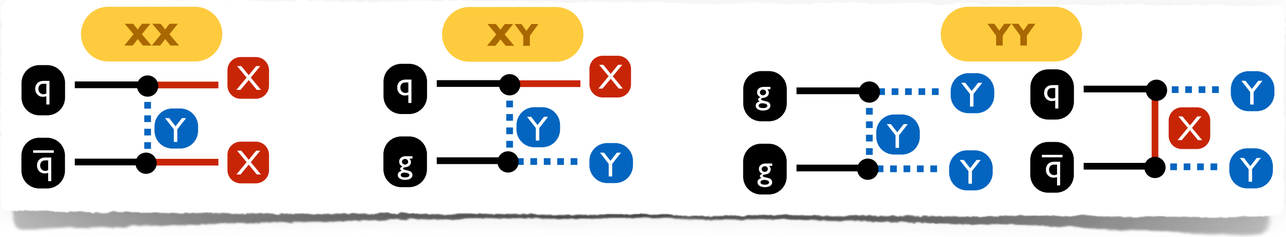
- All signal components needed
  ➙ $pp \to \tilde{q}\tilde{\chi}$ always matters
  ➙ $pp \to \tilde{\chi}\tilde{\chi}$ matters
  ($\tilde{W}$-LSP scenarios only)
- Bounds underestimated significantly
  ➙ Gain on $m_{\tilde{q}}$: 100-1000 GeV
  ➙ Gain on $m_{\tilde{\chi}}$: 100s GeV

DM simplified models - beyond SUSY

[Arina, BF, Panizzi et al. (2025)]

Signal modelling even more crucial for some DM simplified models

- *t*-channel DM, SUSY-inspired but with relaxed couplings
  - ➙ X ≡ Majorana DM; Y ≡ $\tilde{q}$; λ free

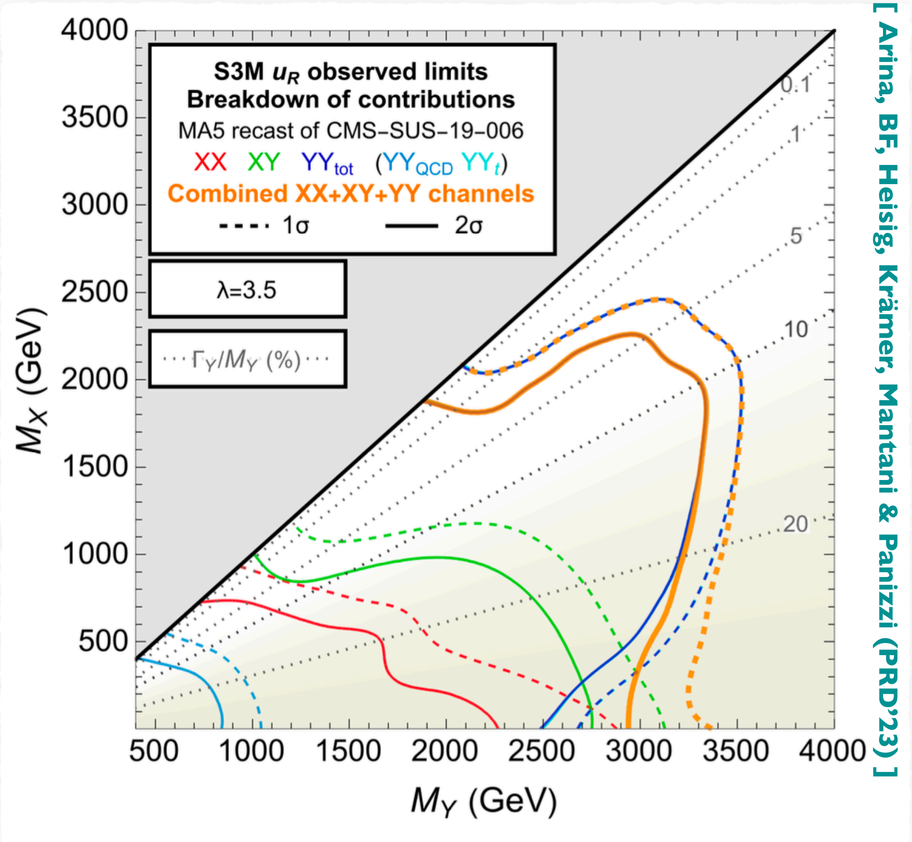


- All signal components to be included in LHC simulations
  - ➙ Y pairs (QCD + non-QCD diagrams)
  - ➙ DM pairs
  - ➙ Associated pairs (XY)
- Example: $\lambda \simeq 3.5$ (cosmology favoured); CMS-SUS-19-006 (inclusive $H_T/\not{H}_T$)

Naive simulations ⇔ bounds underestimated by 2 TeV!

- QCD-induced 'squark production': $M_Y \lesssim 800$ GeV
- Full 'squark production': $M_Y \lesssim 3$ TeV
- Light DM: associated production important

BSM signal *correct* modelling crucial



[Arina, BF, Heisig, Krämer, Mantani & Panizzi (PRD'23)]

Combinations of LHC analyses

Theory-driven combinations

- Beyond those done in experiments
- Could be done in a good enough manner
  - ➙ Has to be conservative
  - ➙ Ideas on global status of models

Analysis combination with TACO

[Araz, Buckley, BF et al. (SciPost`23)]

The TACO approach - testing analysis correlations

- One step further: combination of analyses
  - ➙ Overlap matrix ≡ approximate correlation matrix
  - ➙ Path finding (set of non-overlapping regions) [weighted hereditary depth-first search algorithm]

Study 1: the ATLAS 2015 pMSSM-19 scan

- 100s SRs considered
- Going beyond ATLAS/CMS combinations
- A specific SR not powerful enough alone
  - ➙ *O(10)* regions combined

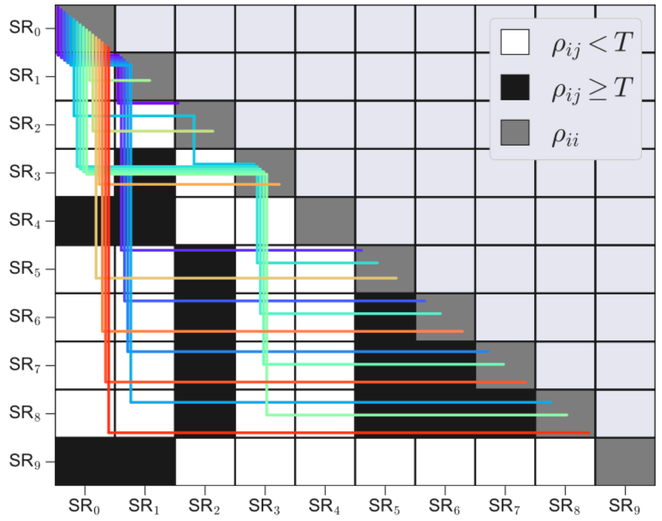
[Araz, Buckley, BF et al. (SciPost`23)]

Studies 2 & 3: squarks and ewkinos; *t*-channel DM

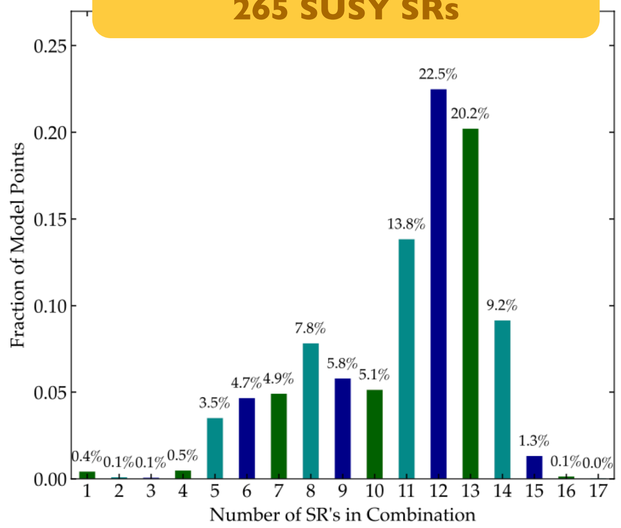
- Considered analyses: jets +$\not{E}_T$
  - ➙ Combination possible (non-overlapping SRs exist)
- Advantage of quantified measure of overlap
  - ➙ Stronger bounds by 100s GeV

[Araz, Buckley, BF et al. (SciPost`23)]

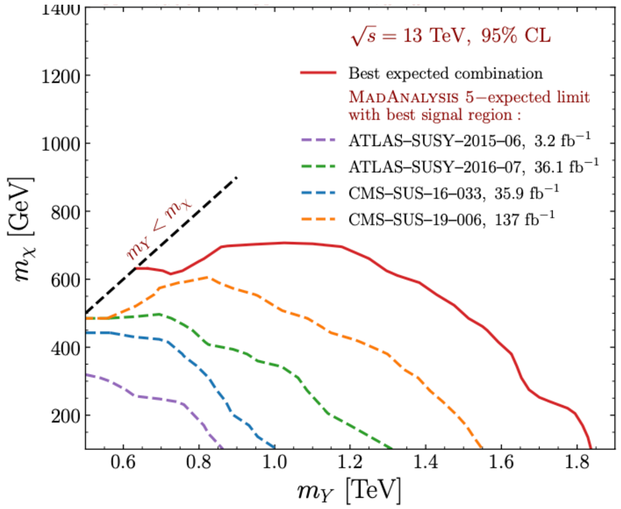
[Feike, Fiaschi, BF, Klasen & Neuwirth (JHEP`24)]



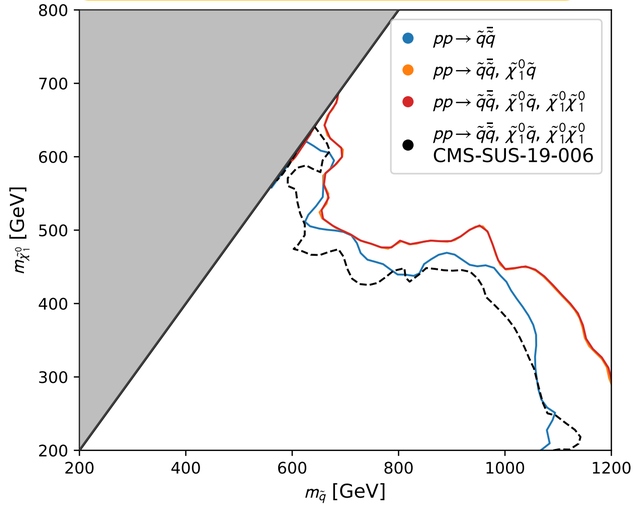
27,000 ATLAS wino models
265 SUSY SRs



Majorana DM+$\tilde{q}$ *vs.* jets+$\not{E}_T$



Ewkino/squark *vs.* jets+$\not{E}_T$

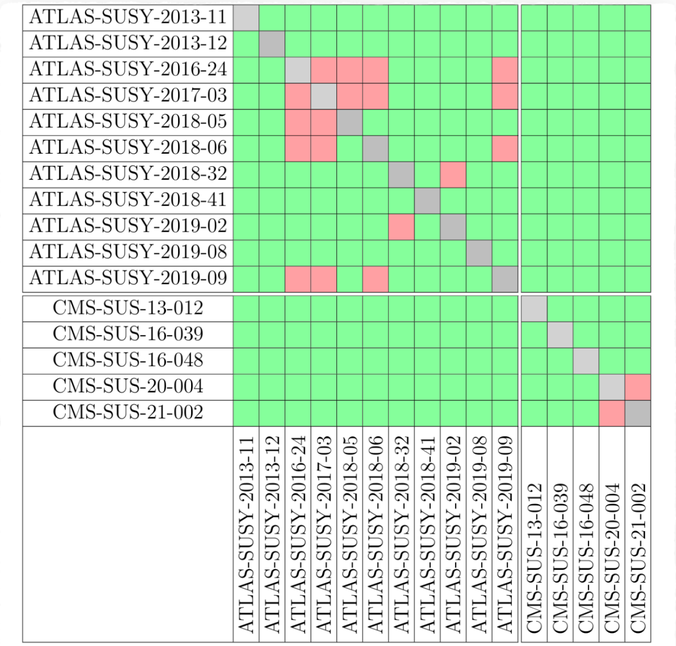


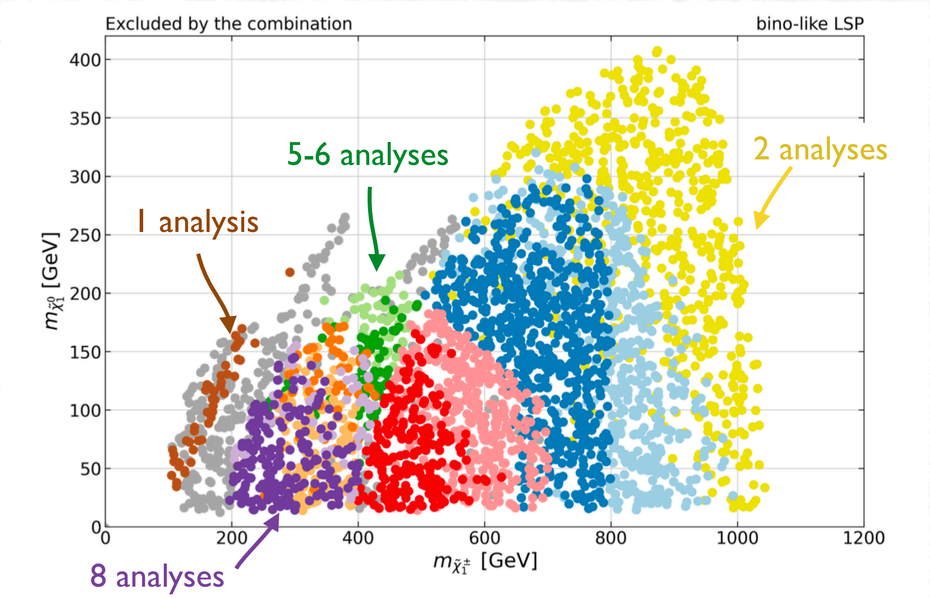
Analysis combination with SMODELS

[Altakach, Kraml, Lessa, Narasimha, Pascal et al. (SciPost'24)]

The SMODELS approach

- Overlap matrix pre-defined from 3 assumptions
  - ➙ Analyses from different runs non-overlapping
  - ➙ ATLAS and CMS analyses non-overlapping
  - ➙ SR definitions scrutinised
  - ➙ Inter-analysis correlations ignored
- Subset of most sensitive analyses ➙ best combination





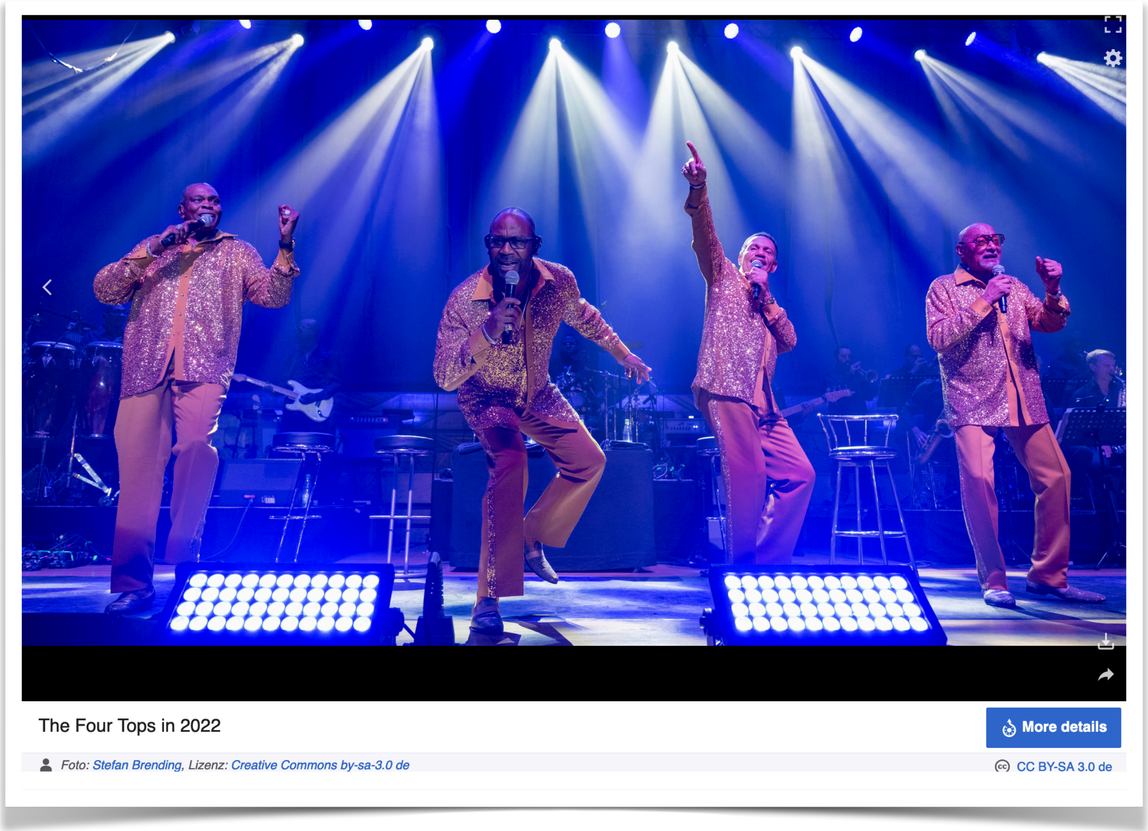
Application: the ewkino sector

- Scan over $\{M_1, M_2, \mu, \tan\beta\}$ [O(20k) points]
- Colour code ≡ different combinations
  - ➙ Better coverage of the different parameter space regions
  - ➙ Combination more relevant for light states
- Pros:
  - ➙ Better assessment of the sensitivity
  - ➙ Compensation of over/under fluctuations
- Beware: overlap matrix determined from assumptions
  - ➙ Also with TACO: unavoidable

New player: four-top production

Four-top production is coming...

- Already run 2 SM measurements
  ➙ Large room for BSM physics
- Precision with run 3



Sgluon-induced four-top production

New top-philic particles

- Non-minimal SUSY: top-philic sgluon [(pseudo-)scalar colour-octet]

S=0	S=1/2	S=1
S_8	$\tilde{g}$	G_μ

proportional to m_t

$$\mathcal{L}_{S_8} = \frac{1}{2} D_\mu S_8^A D^\mu S_8^A - \frac{1}{2} m_{S_8}^2 S_8^A S_8^A + \bar{t}\left[y_{8S} + i\, y_{8P}\gamma^5\right] T^A S_8^A\, t$$

Heavy new states

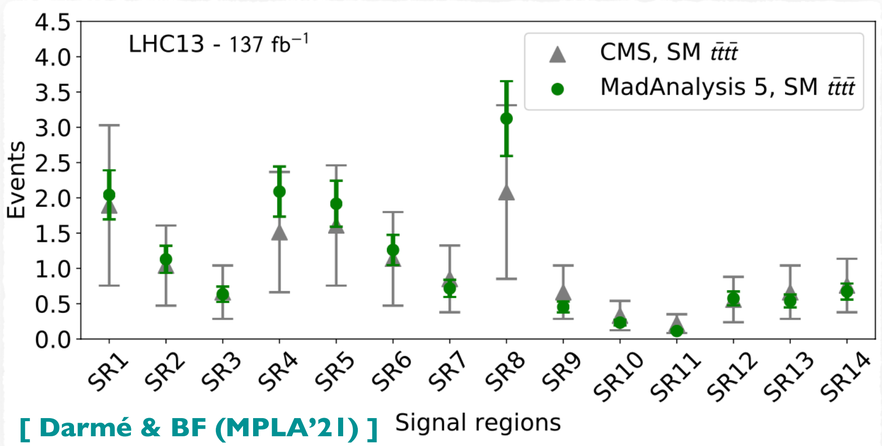
- EFT operators (beyond the SMEFT)

$$\mathcal{O}_S^8 = \bar{t}T^A t\ \bar{t}T^A t$$ SU(2)$_L$ breaking

$$\mathcal{O}_{LR}^1 = \bar{t}_L\gamma^\mu t_L\ \bar{t}_R\gamma_\mu t_R$$

$$\mathcal{O}_{LR}^8 = \bar{t}_L T^A\gamma^\mu t_L\ \bar{t}_R T^A\gamma_\mu t_R$$

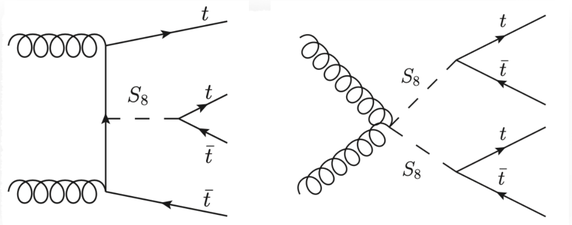
Heavy Mediator	$\mathcal{O}_S^8$	$\mathcal{O}_{LR}^1$	$\mathcal{O}_{LR}^8$
S_8	$\frac{y_{8S}^2}{2m_{S_8}^2}$	/	/
$\tilde{S}_8$	$-\frac{y_{8P}^2}{2m_{\tilde{S}_8}^2}$	$-\frac{4y_{8P}^2}{9m_{\tilde{S}_8}^2}$	$\frac{y_{8P}^2}{3m_{\tilde{S}_8}^2}$



[Darmé & BF (MPLA'21)]

BSM impact on four-top production

- Resonant effects (light states)
  - ➙ Associated and pair production contributions
  - ➙ Different kinematics ⬌ two handles
- Non-resonant effects (heavy states)



CMS-TOP-18-003

- Run 2 measurement of σ_{tttt}
- 14 SRs: *cf.* (*b*-)jet/lepton multiplicities
- H_T spectra measured
  - ➙ BSM-improvement: high-H_T bin

[Darmé, BF & Goodsell (PLB'18)]

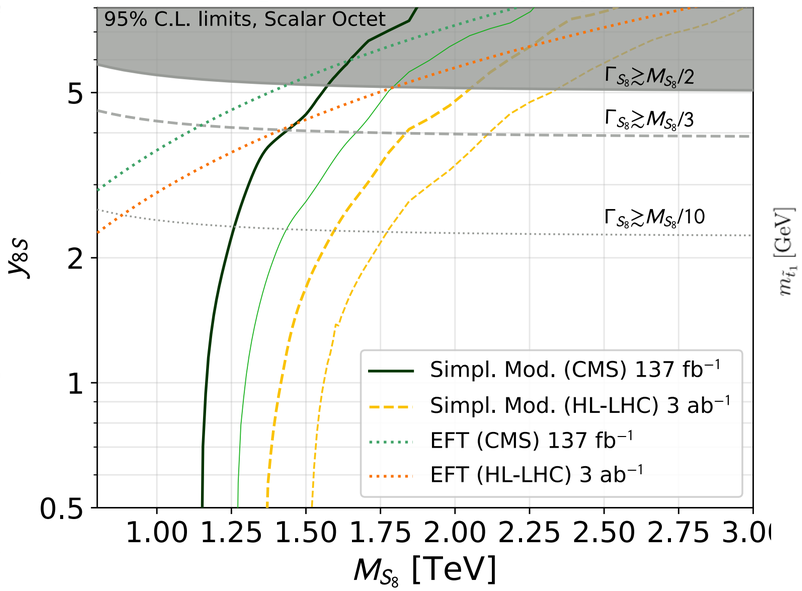
- MADANALYSIS 5 implementation

Probing sgluons with four tops @ LHC

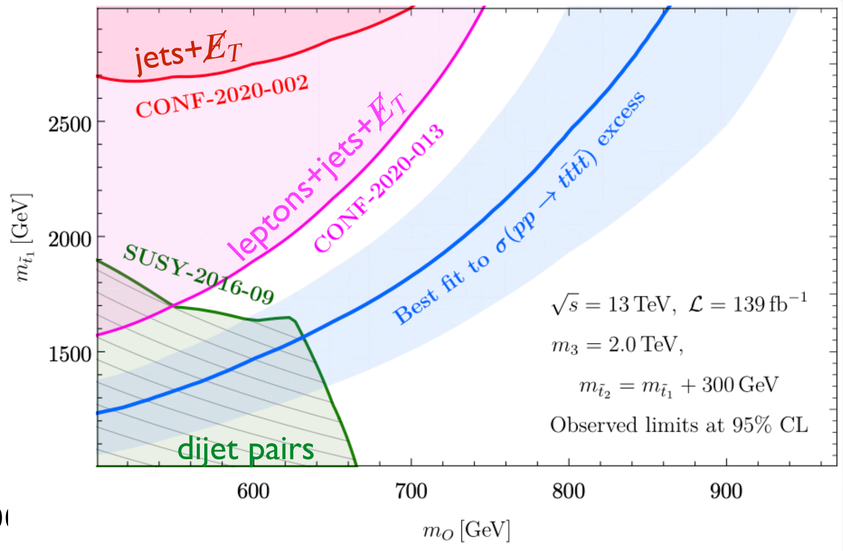
Recasting four-top measurements

- Mass limits $\gtrsim$ 1.10 TeV
  - ➙ Pair-production driven
  - ➙ Up to 1.5 TeV @ HL-LHC
  - ➙ Stronger bounds for large Yukawas
- EFT approach not viable
  - ➙ Typical $\sqrt{s}$ too large wrt Λ
  - ➙ Overly conservative
- Competitive with other searches
  - ➙ Connection with stops

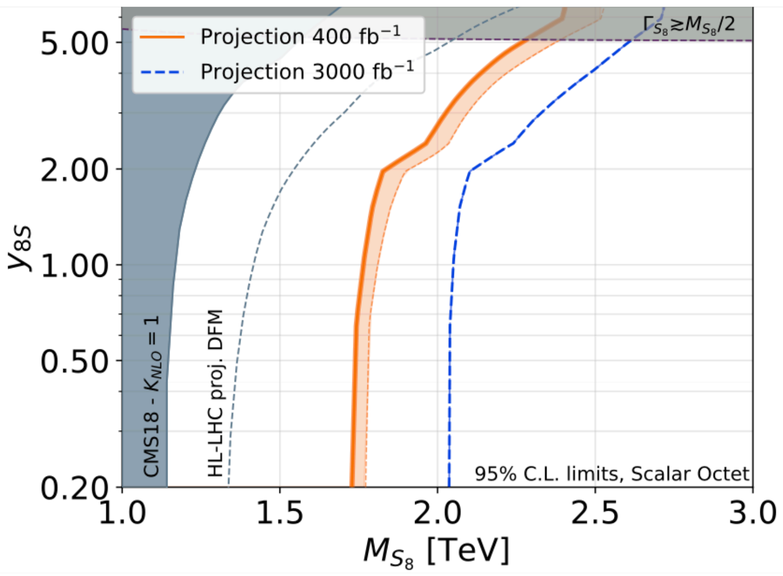
[Darmé, BF & Maltoni (JHEP'21)]



[Carpenter, Murphy & Smilie (JHEP'22)]



[Darmé, BF, Li et al. (PRD'25)]



Sgluons heavy ⬌ boosted four-top production

- Reconstruction of the four-top system
  - ➙ Reconstruction of boosted and leptonic tops
  - ➙ Tagging 3/4 tops + SS2L cases
  - ➙ 66% of all signal event tagged!
- Tailored cuts (pair/associated production)
  - ➙ Pair of resonance constraints (pair)
  - ➙ Top relative direction constraints (single)

- Reaching 2 TeV @ HL-LHC
  - ➙ Even for small Yukawas

Summary - outlook

SUSY searches ↔ excellent templates for BSM searches

- Large set of shared signatures with numerous models
- Crucial to reproduce analyses (aka *LHC recasting*)

LHC recasting paves the way to interesting studies

- Non-simplified models; non-minimal models
- Understanding excesses [soft leptons? monojets? extra scalars?]

A lot of development over the past decade

- Two classes of public tools (SMS or simulation based)
- Validation ↔ detailed material
  - ➙ Great progress over the years!
  - ➙ Being transparent crucial
- Combination of SRs/analyses now possible
- ML-based searches ↔ the next frontier
  - ➙ ONNX-released networks
  - ➙ Already available in some tools [*not covered here*]

Reproducibility

- Key principle in the scientific method
- Need for the TH/EXP communities to move together