Beyond the Standard Model physics at colliders

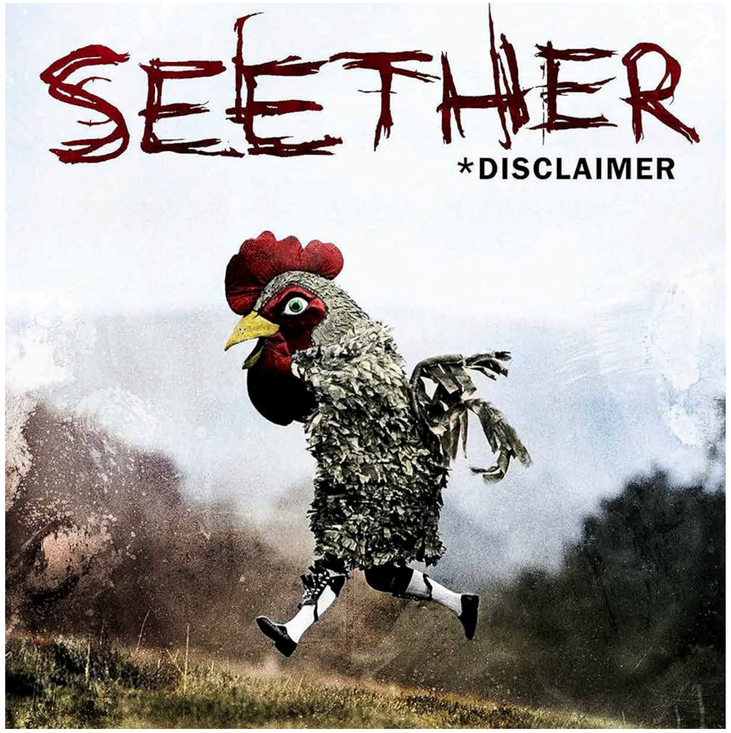
Benjamin Fuks

LPTHE / Sorbonne Université

SUSY 2024

Institute of Theoretical Physics (Madrid) – 14 June 2024

Disclaimer



Very broad topic

- Dozens of new results every week
- 25-minute talk
- Subjective choices to be made
  - ➙ A lot of interesting papers not covered
- SUSY-connected picks
  - ➙ It is a SUSY conference!
  - ➙ Choices have been made…

Where are we with SUSY ?

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 the analyses

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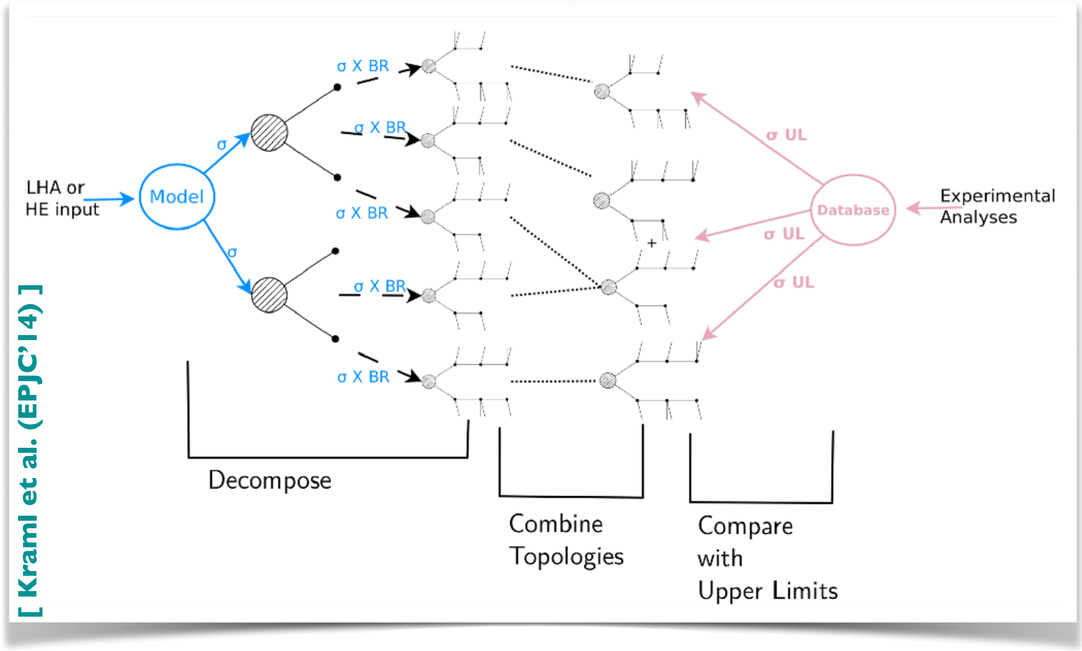
Reinterpretation based on Simplified Model Spectra (SMS)

- 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

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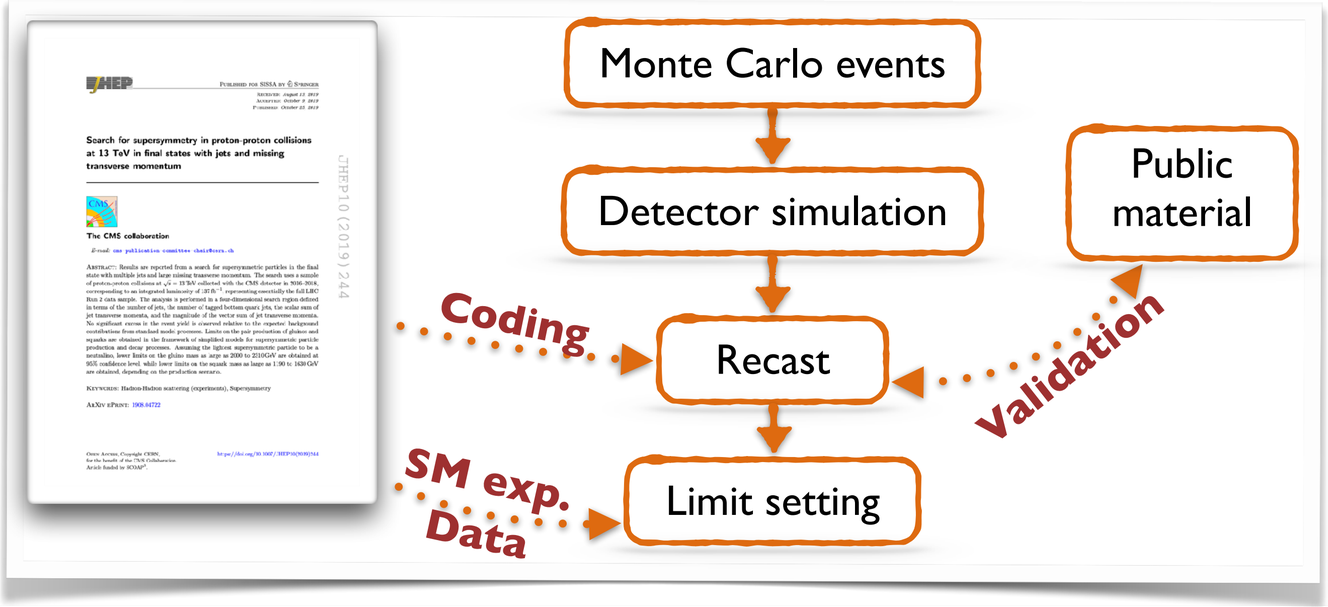
Reinterpretation based on simulations

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



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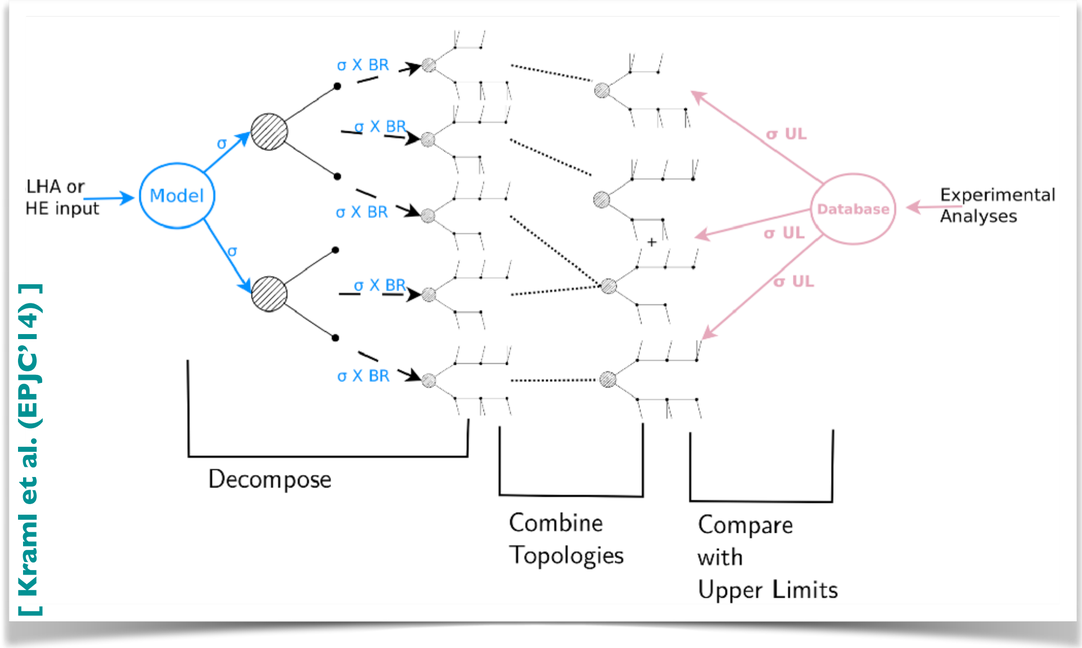

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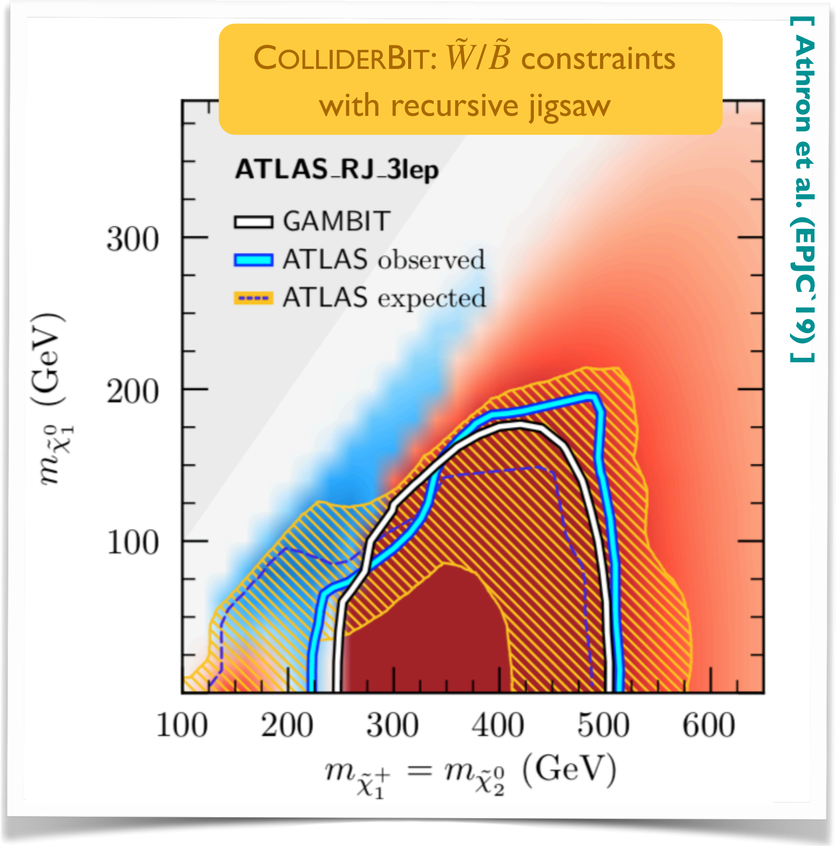
Validating LHC recast in public tools



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

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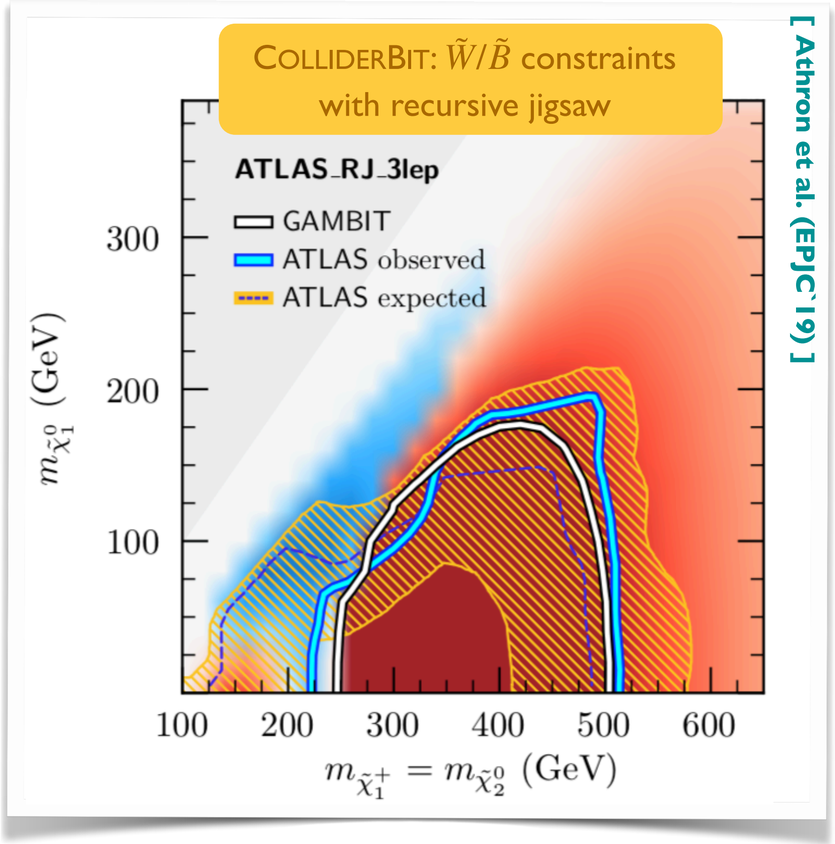

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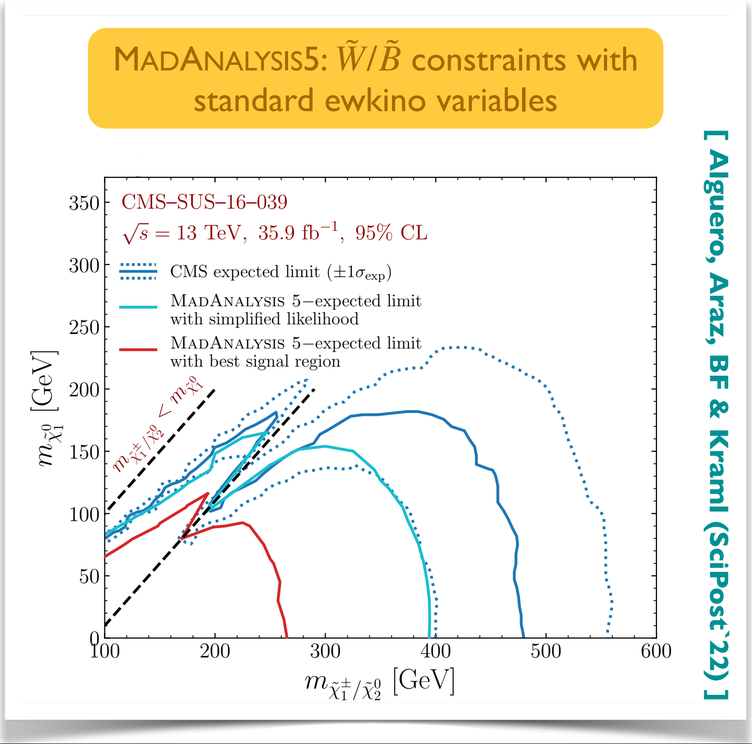
Better limit settings procedures

- 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)]



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

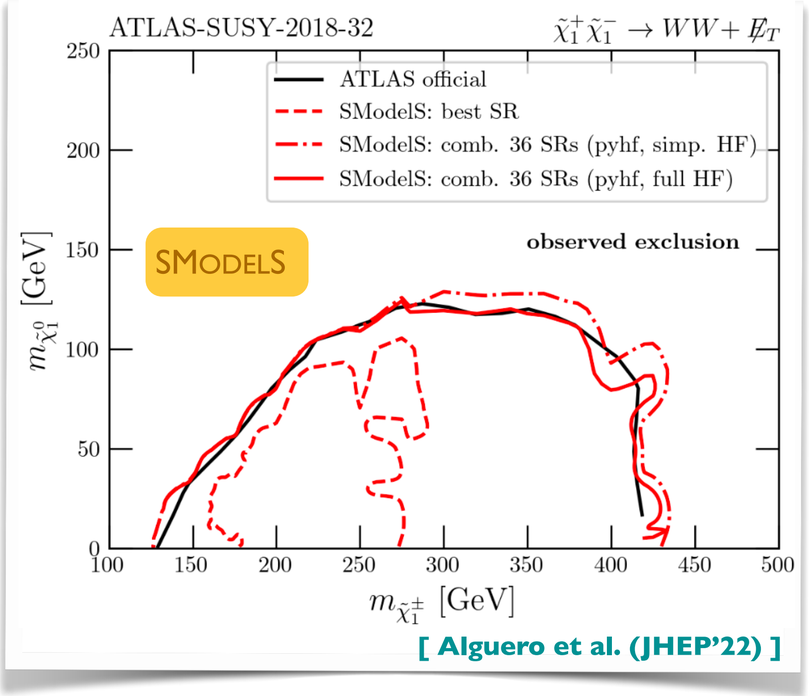
Talk by Y.Villamizar

[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)]



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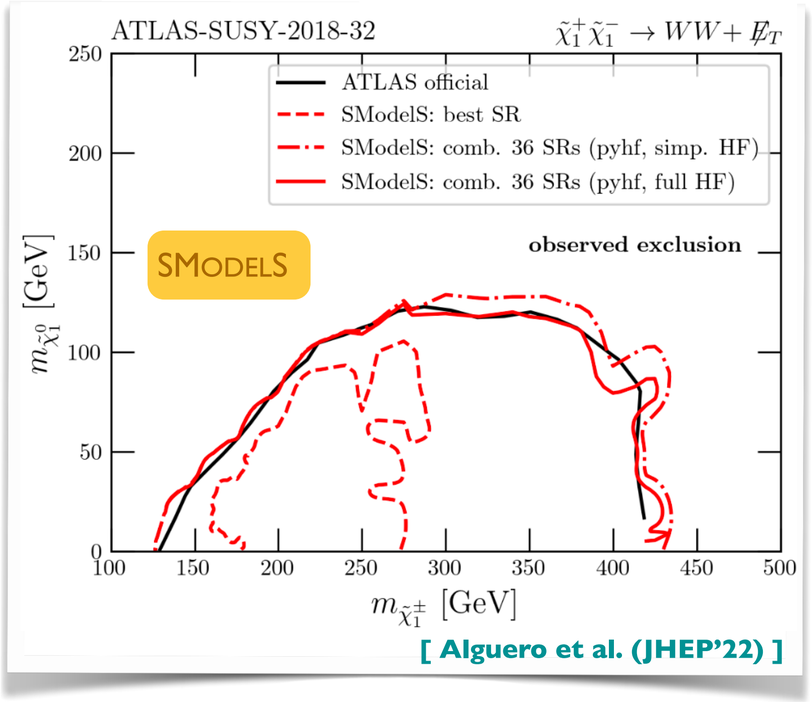

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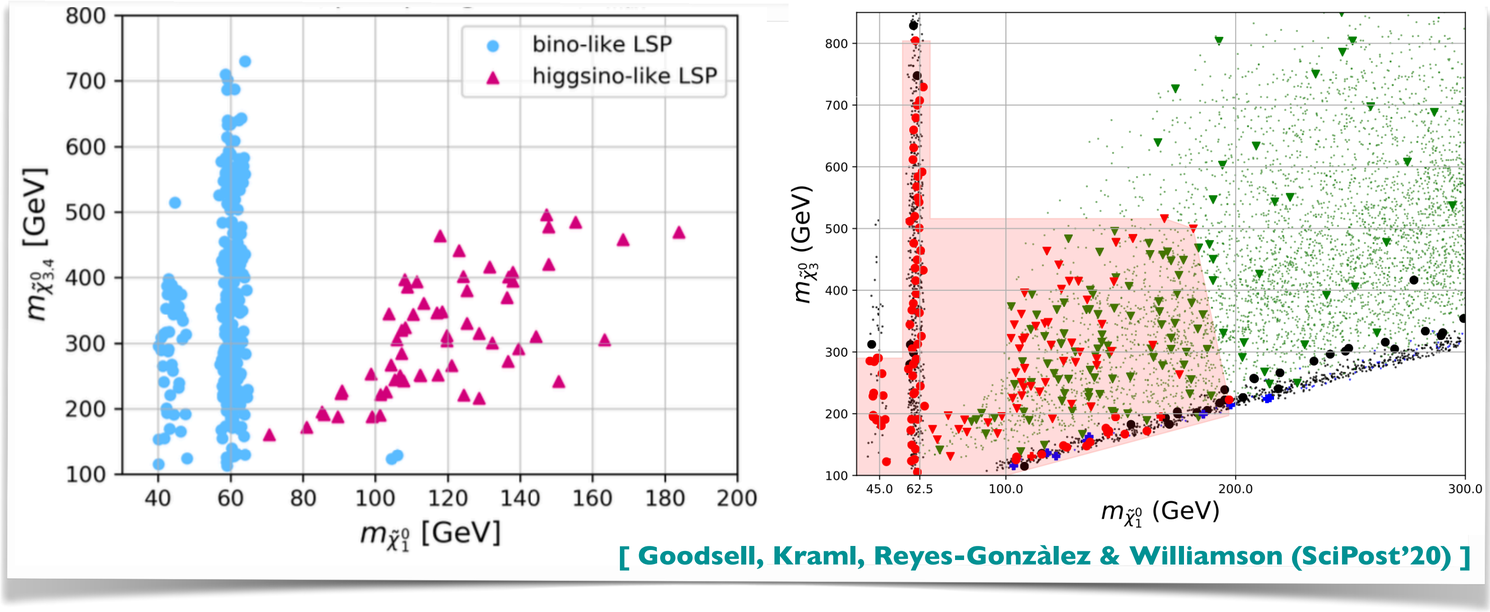

[Goodsell, Kraml, Reyes-Gonzàlez & Williamson (SciPost'20)]

Application: Dirac gauginos at the LHC

- Model not considered by ATLAS/CMS
  - ➙ Full scan of the EW sector of the model
  - ➙ Varied 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]
- HackAnalysis [*O(10)* analyses, from IN2P3]
  - ⋆ Validation example (CMS-EXO-19-010)
    - ➙ Disappearing tracks and winos
    - ➙ Cut-flow comparisons
- MadAnalysis5/SFS [*O(15)* analyses, from GitHub/MA5DataVerse]
- Rivet [*O(30)* analyses, from HepForge]

[Balász et al. (EPJC`17)]
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[Buckley et al. (2010); Bierlich et al. (SciPost`20)]

Talks by A. Feike, A. Kvellestad, T. Murphy

HackAnalysis

	700 GeV, 10 cm, region 2018A		
	ϵ_i^{CMS}	ϵ_i^{sim}, HEPMC	ϵ_i^{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 $p_{\text{T}}^{\text{miss}}$ filters	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
$p_{\text{T}}^{\text{miss}} > 120\,\text{GeV}$	$1.4^{+0.02}_{-0.02} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$	$1.5^{+0.01}_{-0.01} \times 10^{-1}$
≥ 1 jet with $p_{\text{T}} > 110\,\text{GeV}$ 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 $\Delta\phi_{\text{jet, jet}} > 2.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
$\lvert\Delta\phi(\text{leading jet}, \mathbf{p}_{\text{T}}^{\text{miss}})\rvert > 0.5$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$	$1.1^{+0.01}_{-0.01} \times 10^{-1}$
≥ 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 $p_{\text{T}} > 55\,\text{GeV}$	$4.7^{+0.10}_{-0.10} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$	$4.6^{+0.06}_{-0.06} \times 10^{-2}$
≥ 1 track passing fiducial selections	$3.1^{+0.08}_{-0.08} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$	$3.6^{+0.05}_{-0.05} \times 10^{-2}$
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≥ 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 $\lvert d_{xy}\rvert < 0.02\,\text{cm}$	$5.1^{+0.34}_{-0.34} \times 10^{-3}$	$6.0^{+0.23}_{-0.23} \times 10^{-3}$	$6.2^{+0.23}_{-0.23} \times 10^{-3}$
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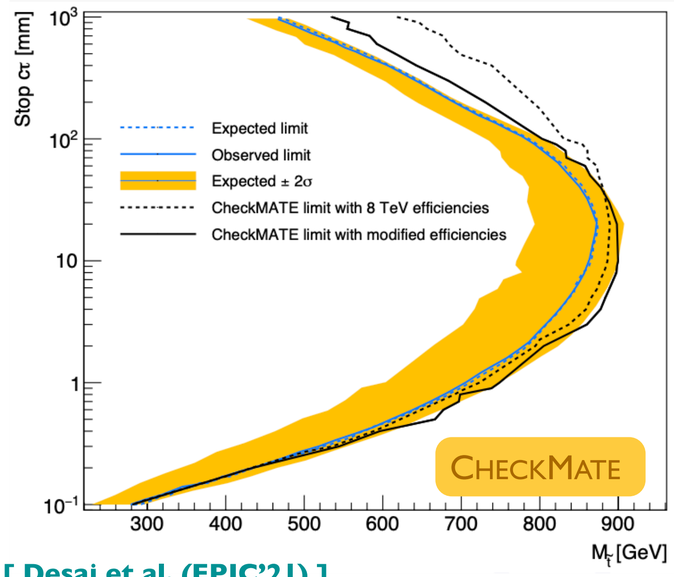

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Simulation-based; Delphes 3 detector modelling

- MadAnalysis 5 [*O(50)* analyses, from GitHub/MA5DataVerse]
- CheckMate [*O(50)* analyses, from GitHub]
  - ⋆ Validation example (CMS-EXO-16-022)
    - ➙ Displaced stop in an $e\mu$ pair
    - ➙ Detailed information crucial

[Derks et al. (CPC`17)]
[Dumont, BF, Kraml et al. (EPJC`15)]
[Conte & BF (IJMPA`19)]

Recasting SUSY searches to study... SUSY

LHC recasting

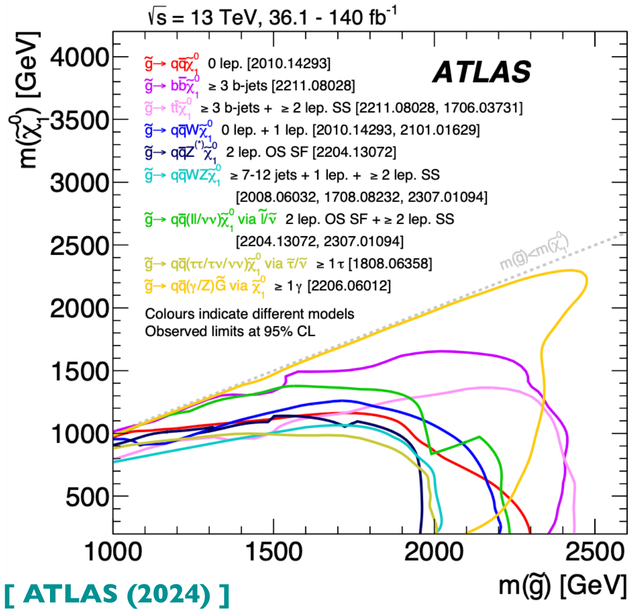
- Constraining SUSY models
  - ➙ Beyond those addressed in LHC searches
  - ➙ Minimal and non-minimal setups

SUSY and the MSSM are not excluded!

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)]

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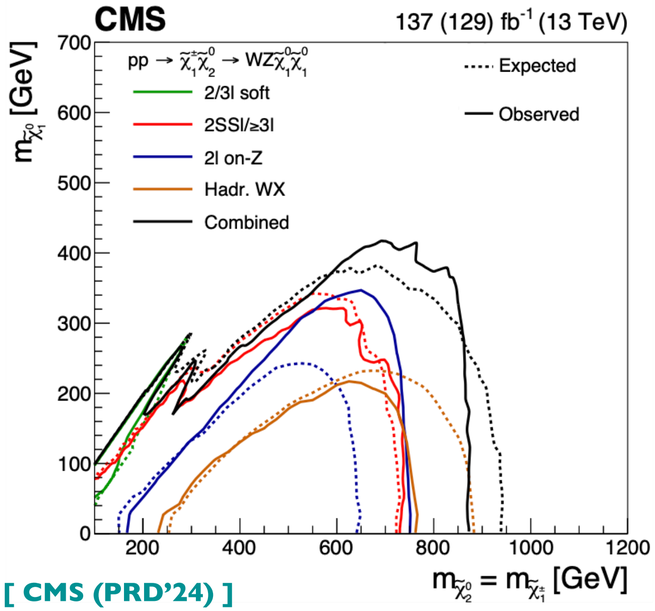

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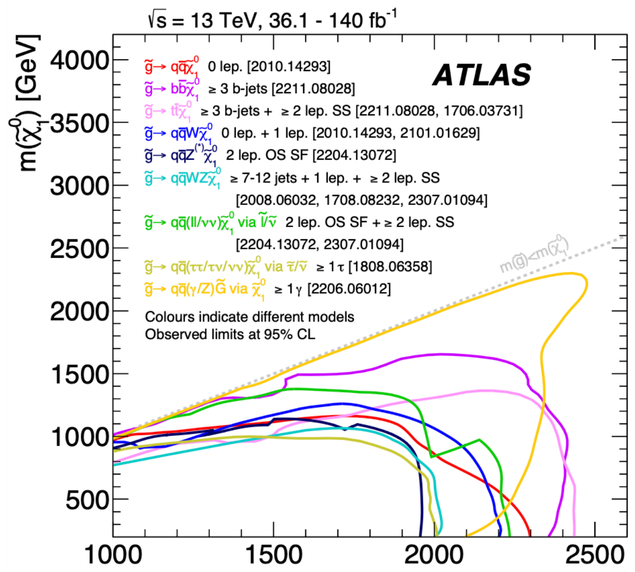

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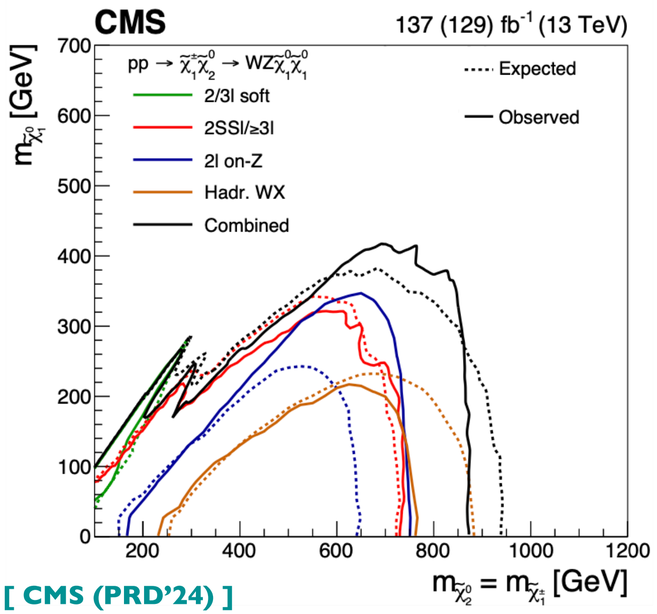
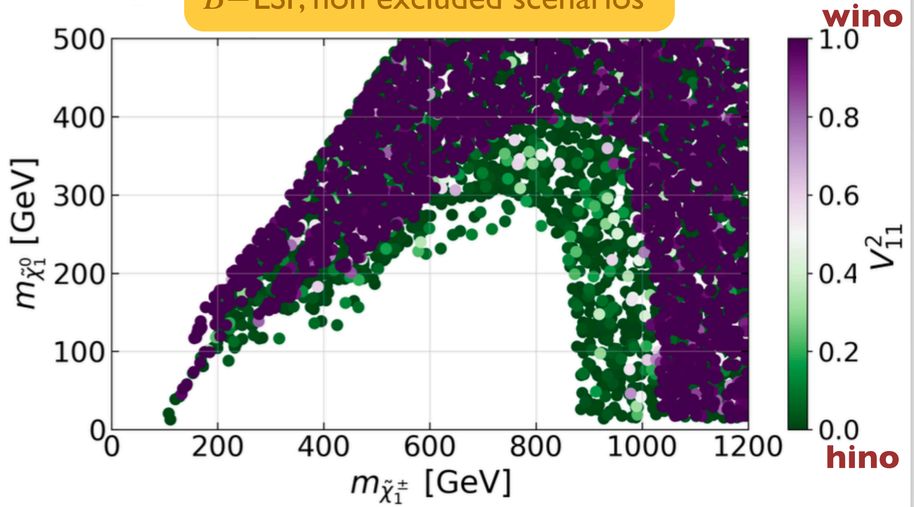


[CMS (PRD'24)]

Is SUSY in bad shape ?

- Not really: MSSM-inspired simplified models
  - ➙ Most superpartners decoupled
  - ➙ Specific decay table
  - ➙ Simplistic scenarios
- Signatures typically more complex
  - ➙ Constraints not necessarily that strong
- Example: EWino search recasts with SModelS
  - ➙ Scan over $\{M_1, M_2, \mu, \tan\beta\}$

$\tilde{B}$—LSP, non excluded scenarios

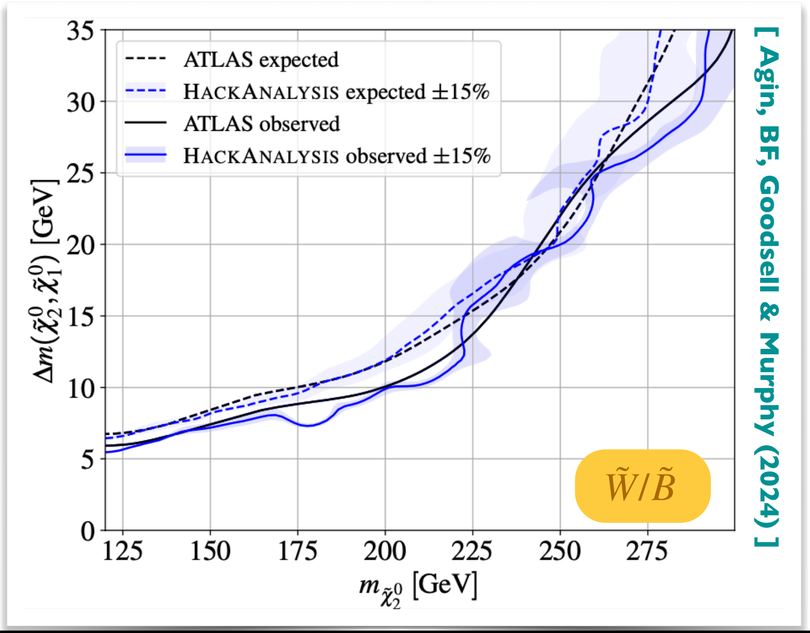


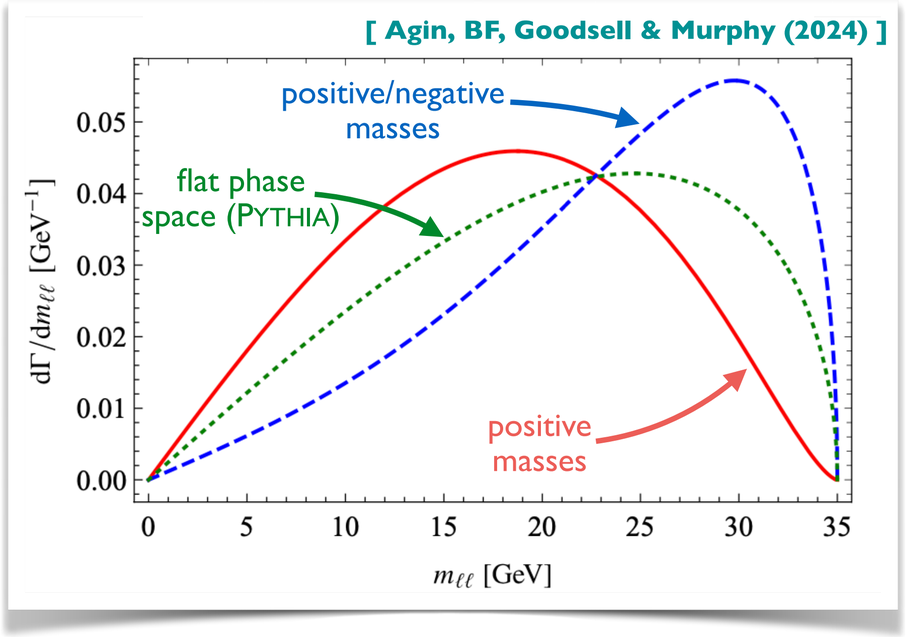
[Altakach, Kraml, Lessa, Narasimha, Pascal et al. (SciPost'24)]

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 in progress)
- Equivalent CMS search: CMS-SUS-18-004





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 (MadAnalysis5 in progress)
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Constraints/impact on realistic SUSY models

A lot of pheno interests in those excesses

Talks by S. Heinemeyer, T. Murphy

- 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, $(g-2)_{\mu,e}$

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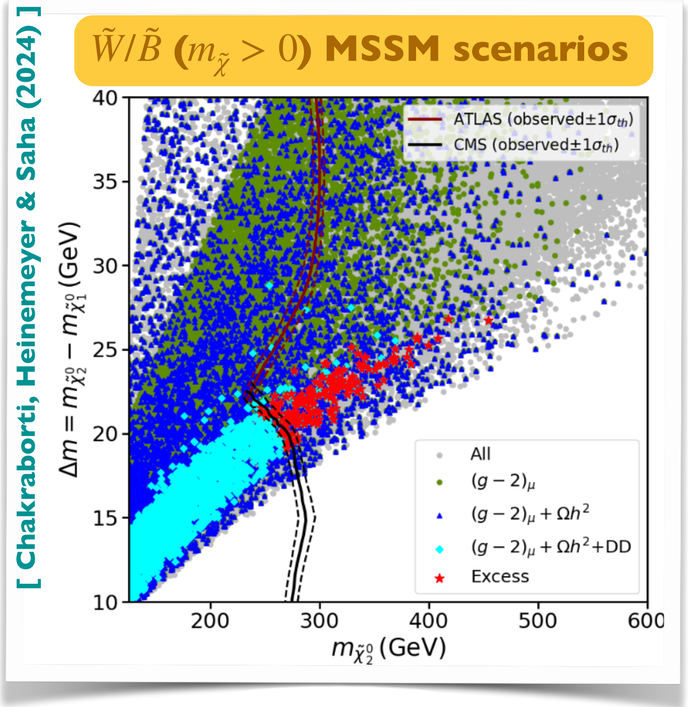
  - ➙ Dark matter, Higgs and flavour physics, $(g-2)_{\mu,e}$



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 $m_{\tilde{\ell}} \equiv$ new Δa_μ value

Constraints/impact on realistic SUSY models

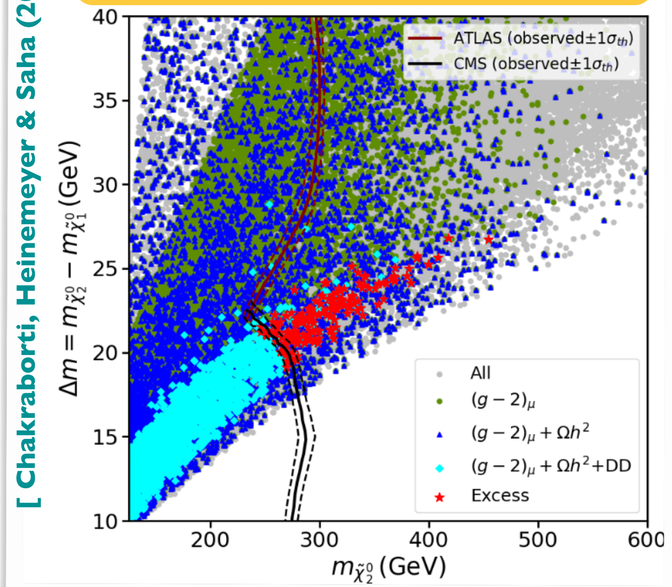
A lot of pheno interests in those excesses

- 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, $(g-2)_{\mu,e}$

Talks by S. Heinemeyer, T. Murphy

$\tilde{W}/\tilde{B}$ **($m_{\tilde{\chi}} > 0$) MSSM scenarios**

[Chakraborti, Heinemeyer & Saha (2024)]



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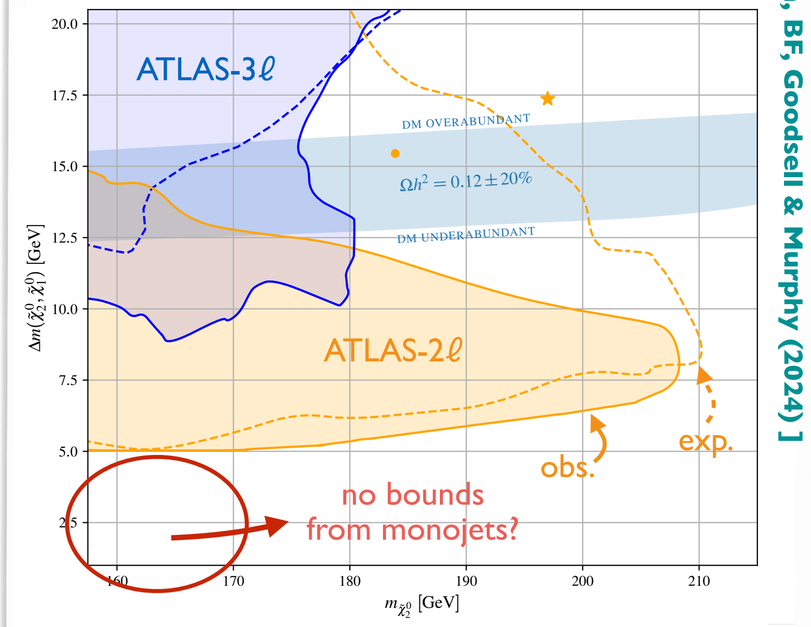
$\tilde{S}/\tilde{H}$ **($m_{\tilde{\chi}} \lesssim 0$) NMSSM scenarios**

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



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

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: $pp \rightarrow \tilde{q}\tilde{q}^* + \tilde{q}^{(*)}\tilde{\chi} + \tilde{\chi}\tilde{\chi}$
- 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

Talk by A. Feike

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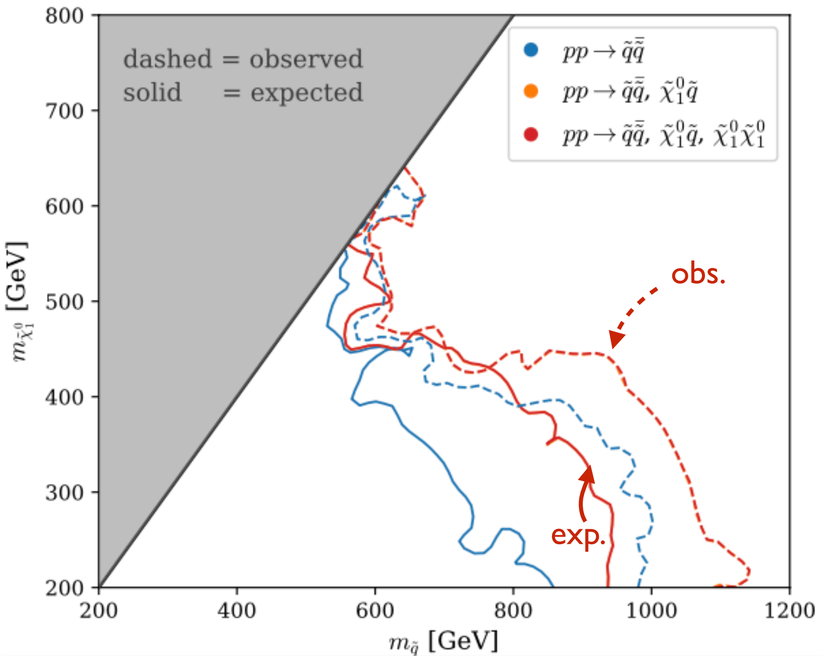
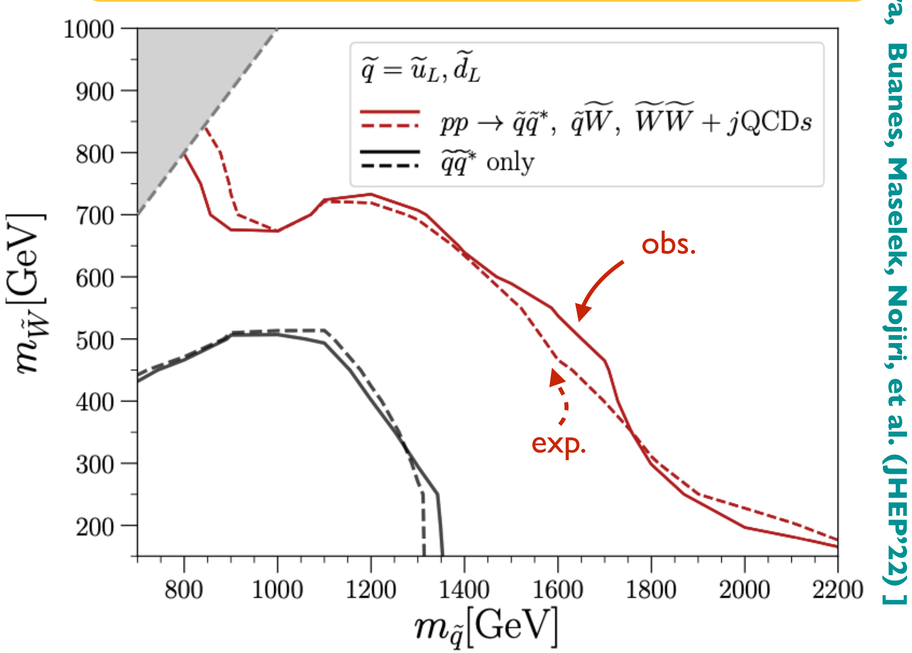
Talk by A. Feike

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



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

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



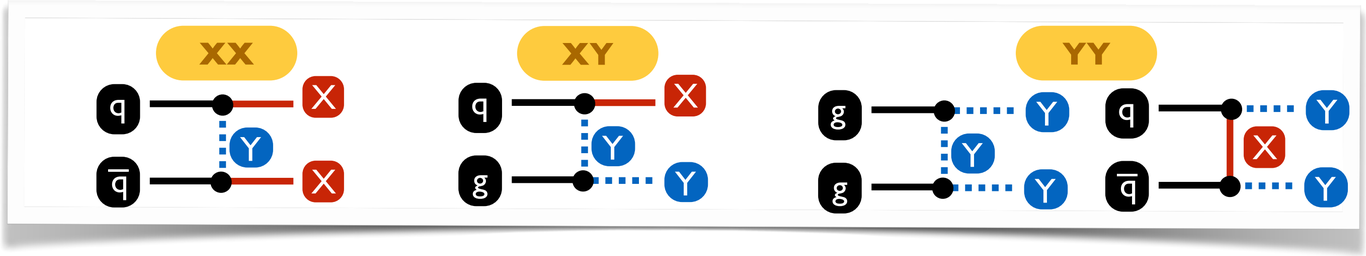
[Lara, Buanes, Maselek, Nojiri, et al. (JHEP'22)]

- 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

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 $H_T/\not{H}_T$)

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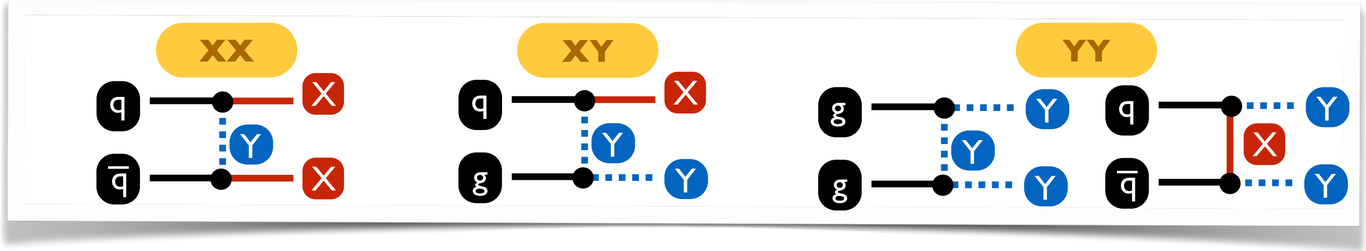

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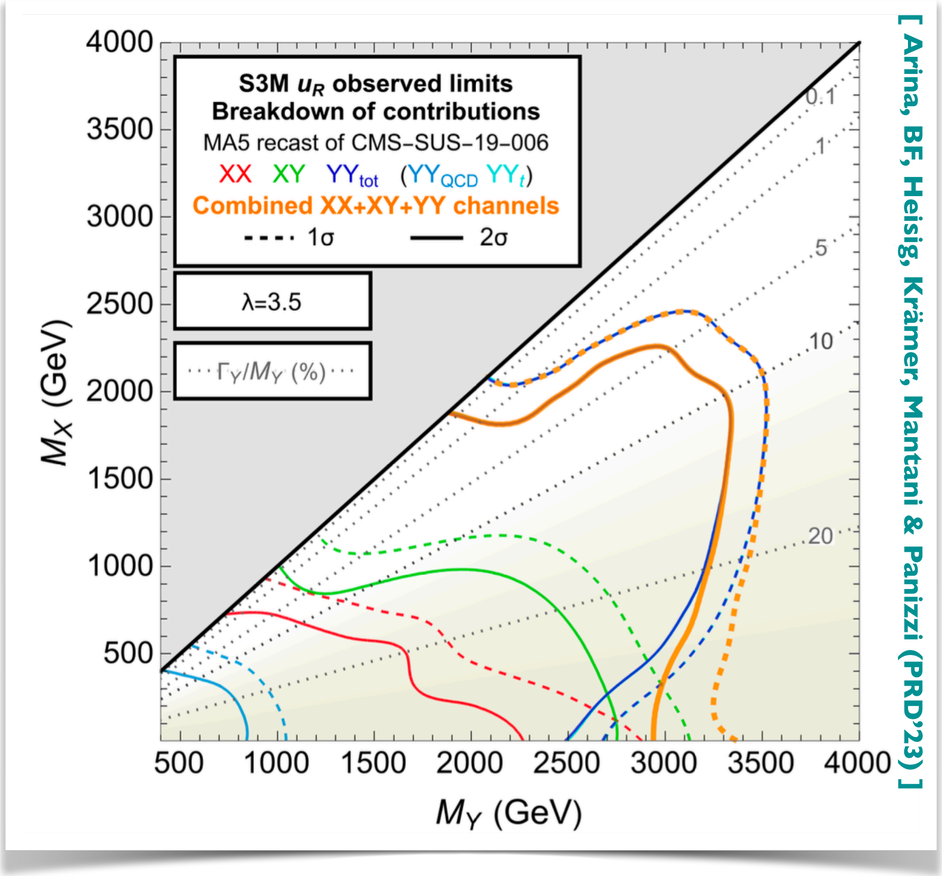
- Example: $\lambda \simeq 3.5$ (cosmology favoured); CMS-SUS-19-006 (inclusive $H_T/\not{H}_T$)

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



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

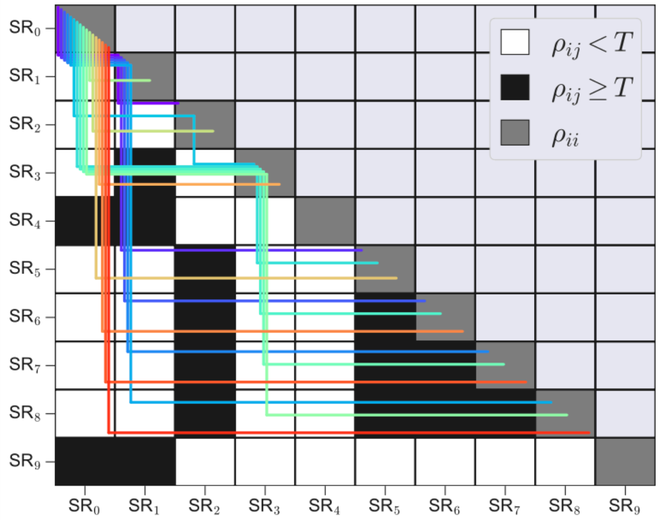
[Araz, Buckley, BF et al. (SciPost`23)]

The TACO approach - testing analysis correlations

- One step further: combination of analyses
  - ➙ Overlap matrix ≡ approximate correlation matrix
  - ➙ Path finding (set of non-overlapping regions)

Talk by A. Feike

[weighted hereditary depth-first search algorithm]



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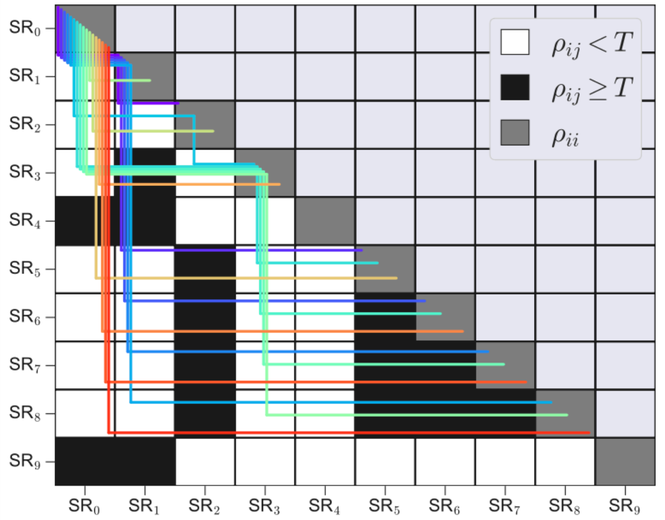
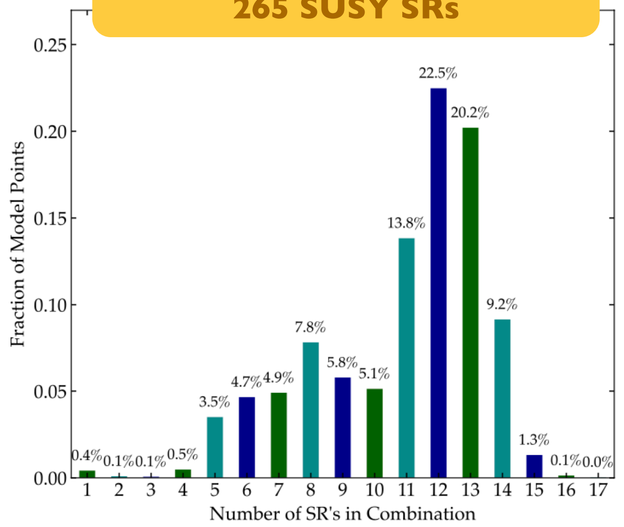
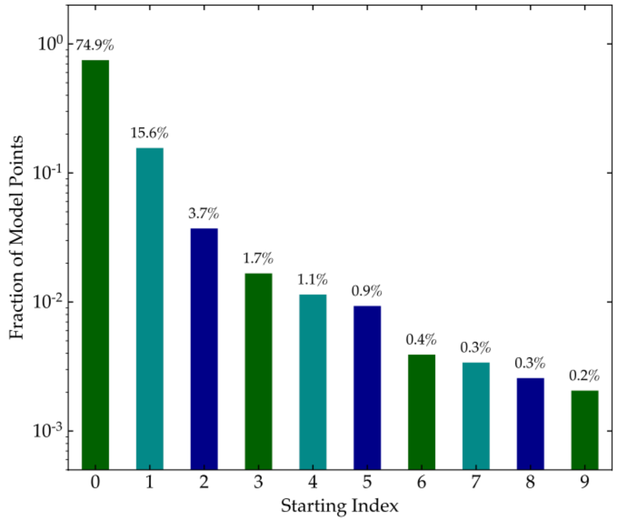
Application 1: the ATLAS 2015 pMSSM-19 scan

- 100s SRs: a few matter
- Going beyond ATLAS/CMS combinations
- Always a specific driving SR
  - ➙ Not powerful enough alone
  - ➙ *O(10)* regions combined



27,000 ATLAS wino models
265 SUSY SRs





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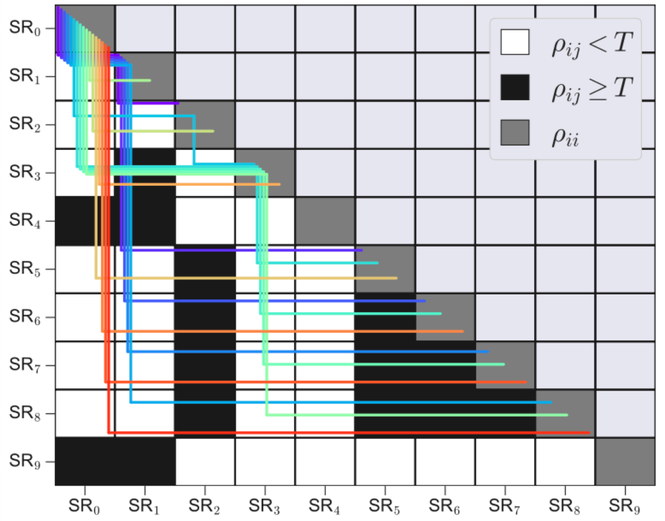
Application 2: *t*-channel DM

- Considered analyses: jets +$\not{E}_T$
  - ➙ Combination possible (non-overlapping SRs exist)
- Advantage of quantified measure of overlap
  - ➙ with respect to a naive guess



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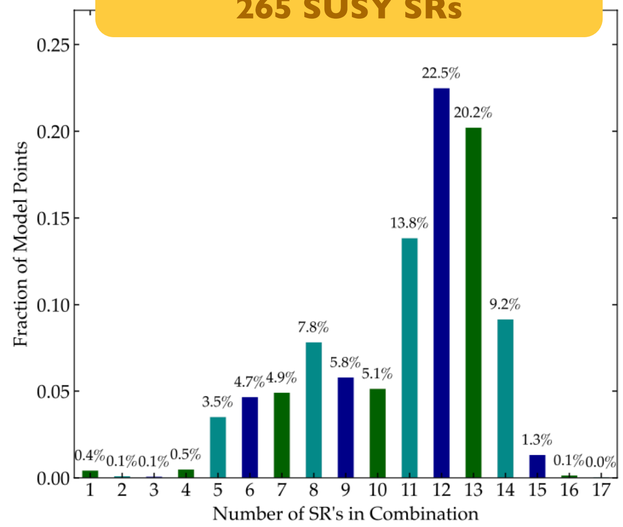
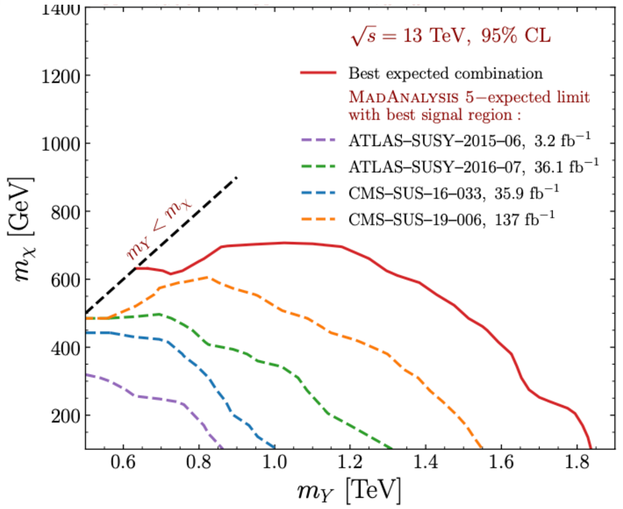
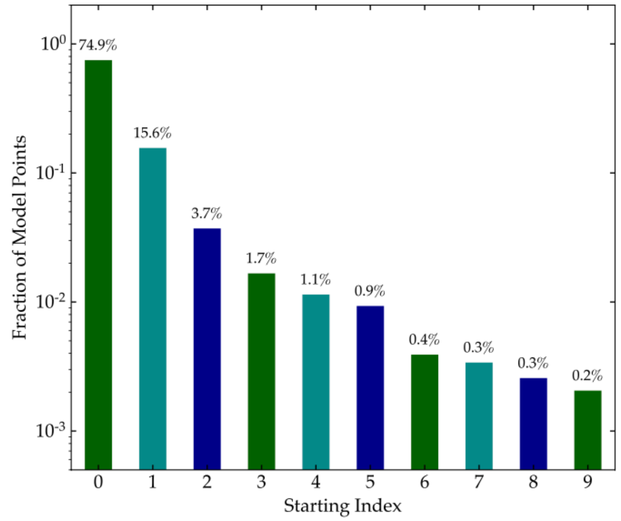


Majorana DM+$\tilde{q}$ *vs.* jets+$\not{E}_T$



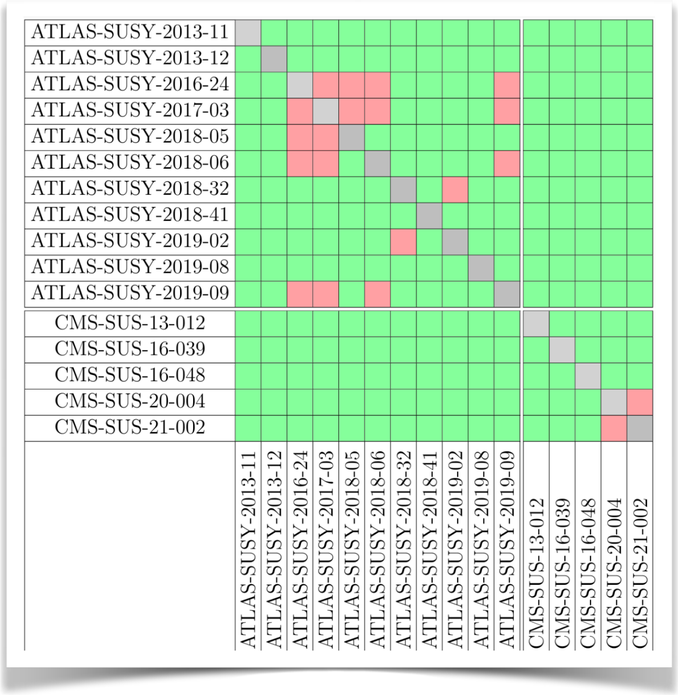


Analysis combination with SModelS

[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



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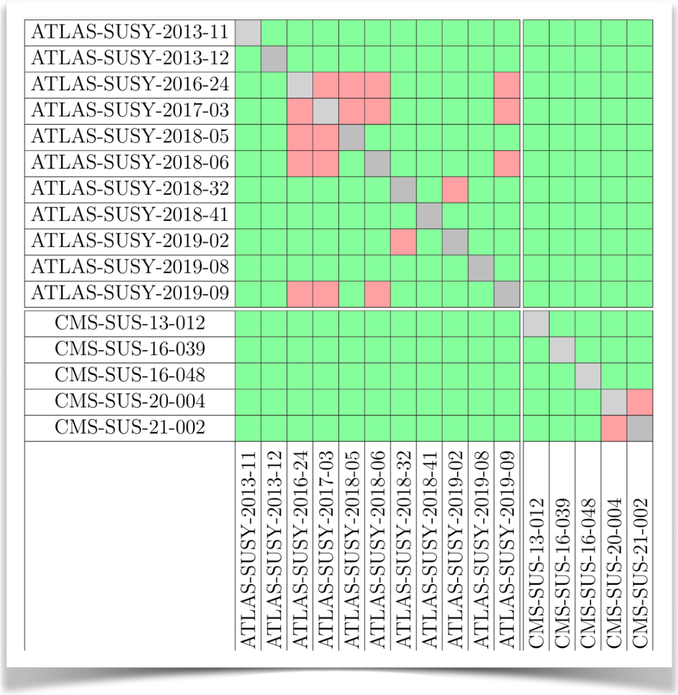

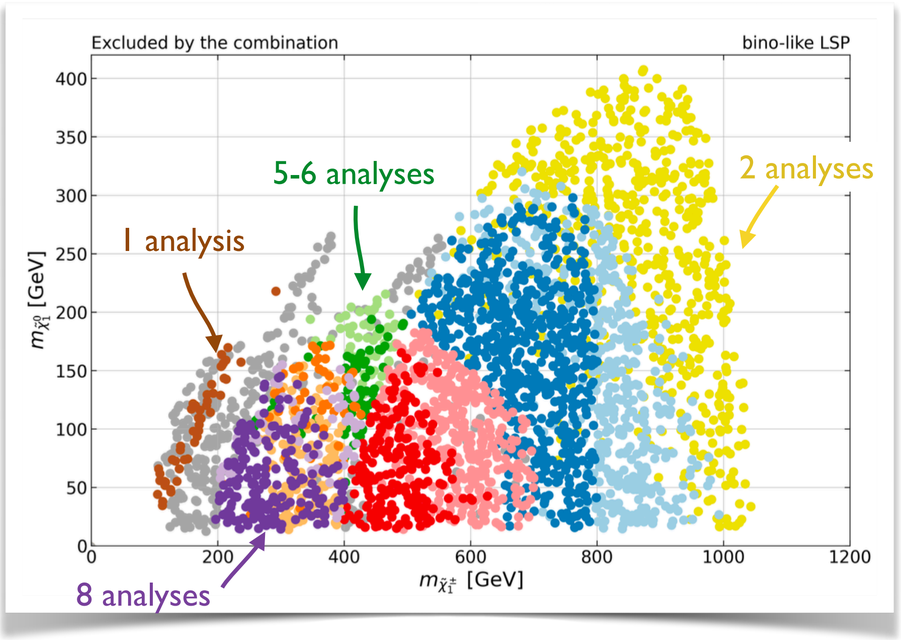

Application: the ewkino sector

- 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
- Useful for SUSY (despite of no $\not{E}_T$)
  ➙ Dirac gluinos!

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	$\frac{y_{8S}^2}{2m_{S_8}^2}$	/	/
$\tilde{S}_8$	$-\frac{y_{8P}^2}{2m_{\tilde{S}_8}^2}$	$-\frac{4y_{8P}^2}{9m_{\tilde{S}_8}^2}$	$\frac{y_{8P}^2}{3m_{\tilde{S}_8}^2}$

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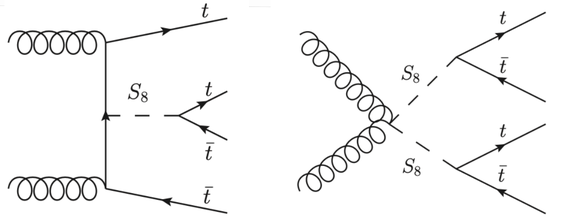
BSM impact on four-top production

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



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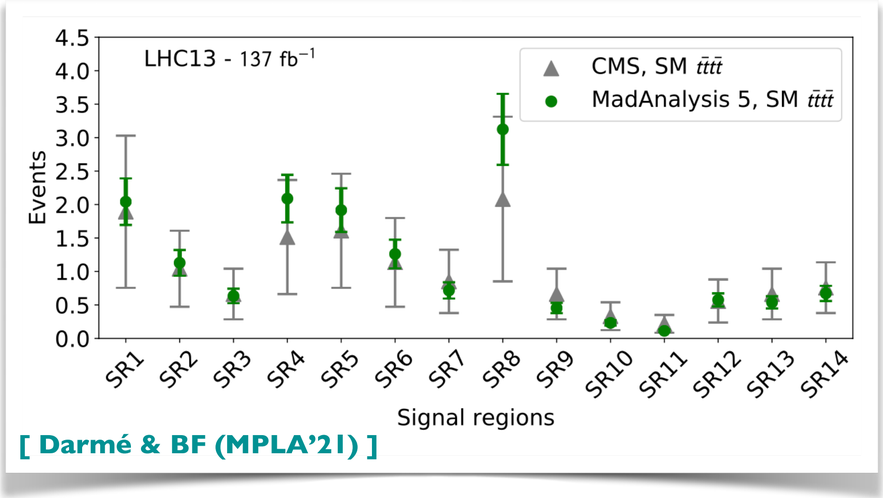

[Darmé & BF (MPLA'21)]

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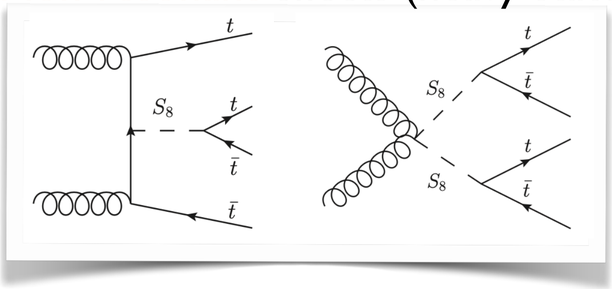


CMS-TOP-18-003

- 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)]

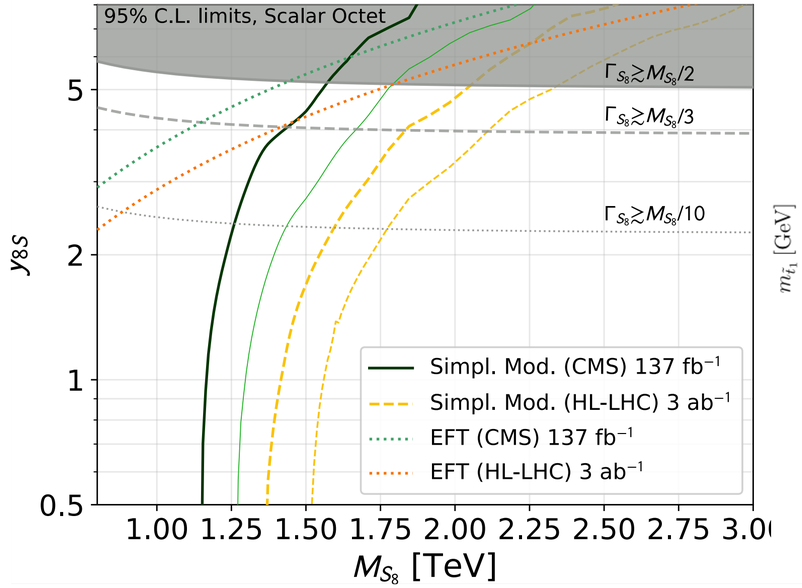
- MadAnalysis 5 implementation

Probing sgluons with four tops @ LHC

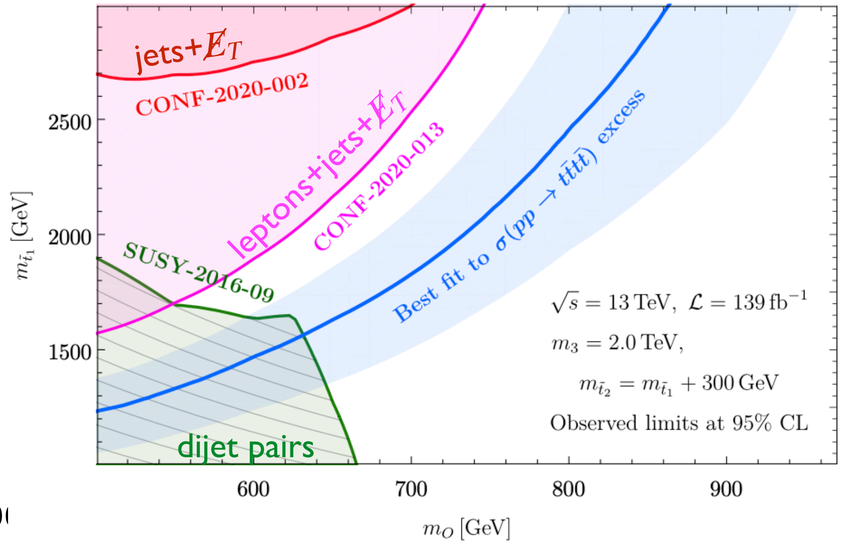
Recasting four-top measurements

- 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)]



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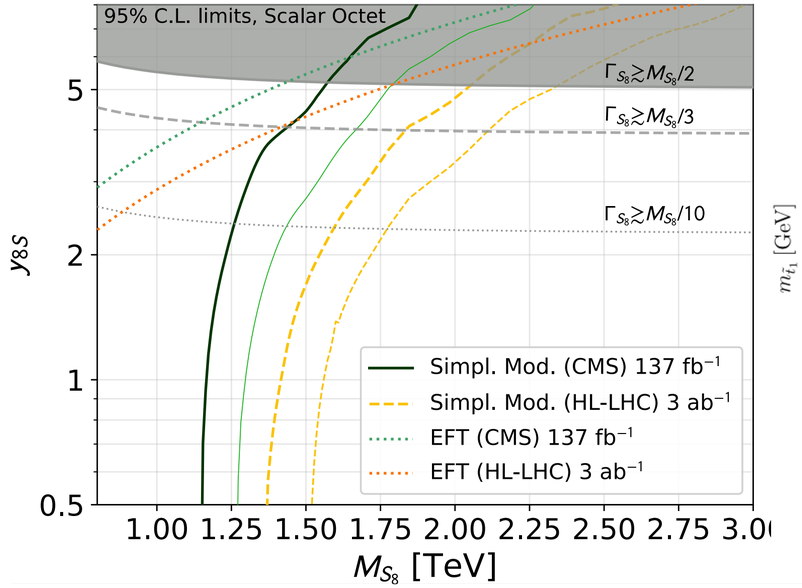

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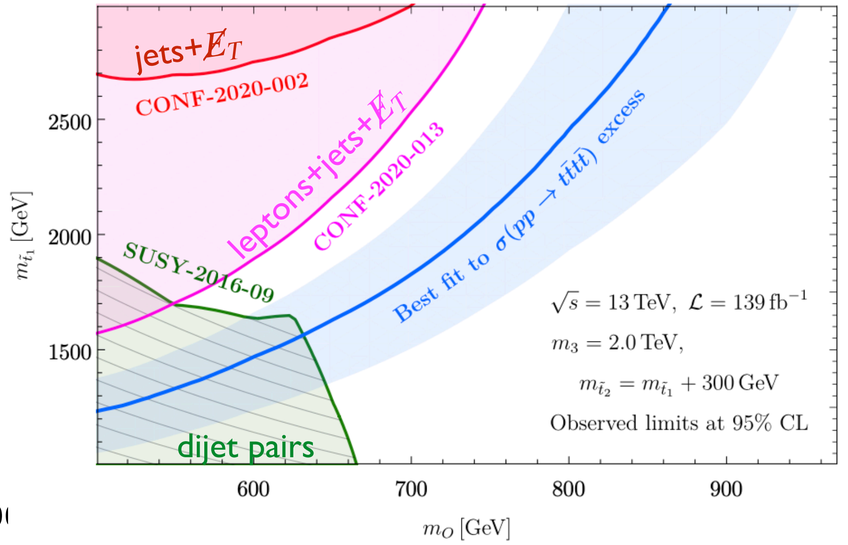
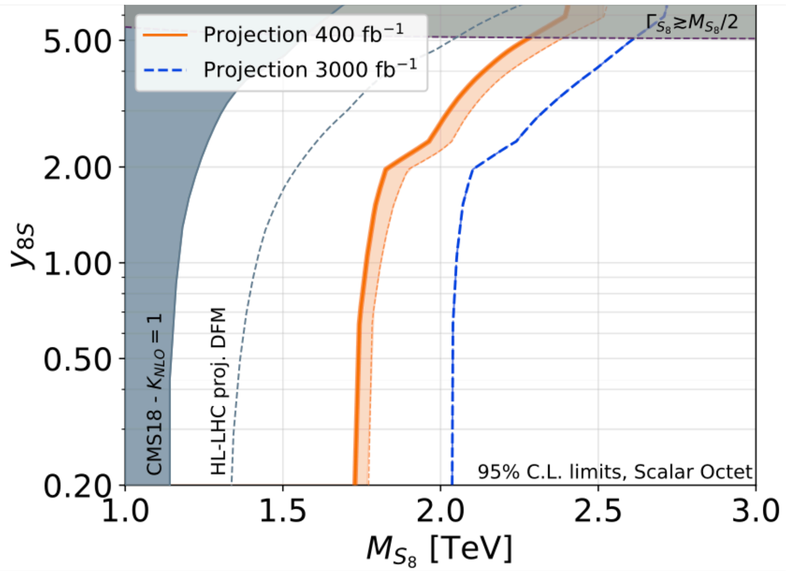


[Darmé, BF, Li et al. (2024)]



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