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Seeking an explanation of compressed spectrum excesses at the LHC

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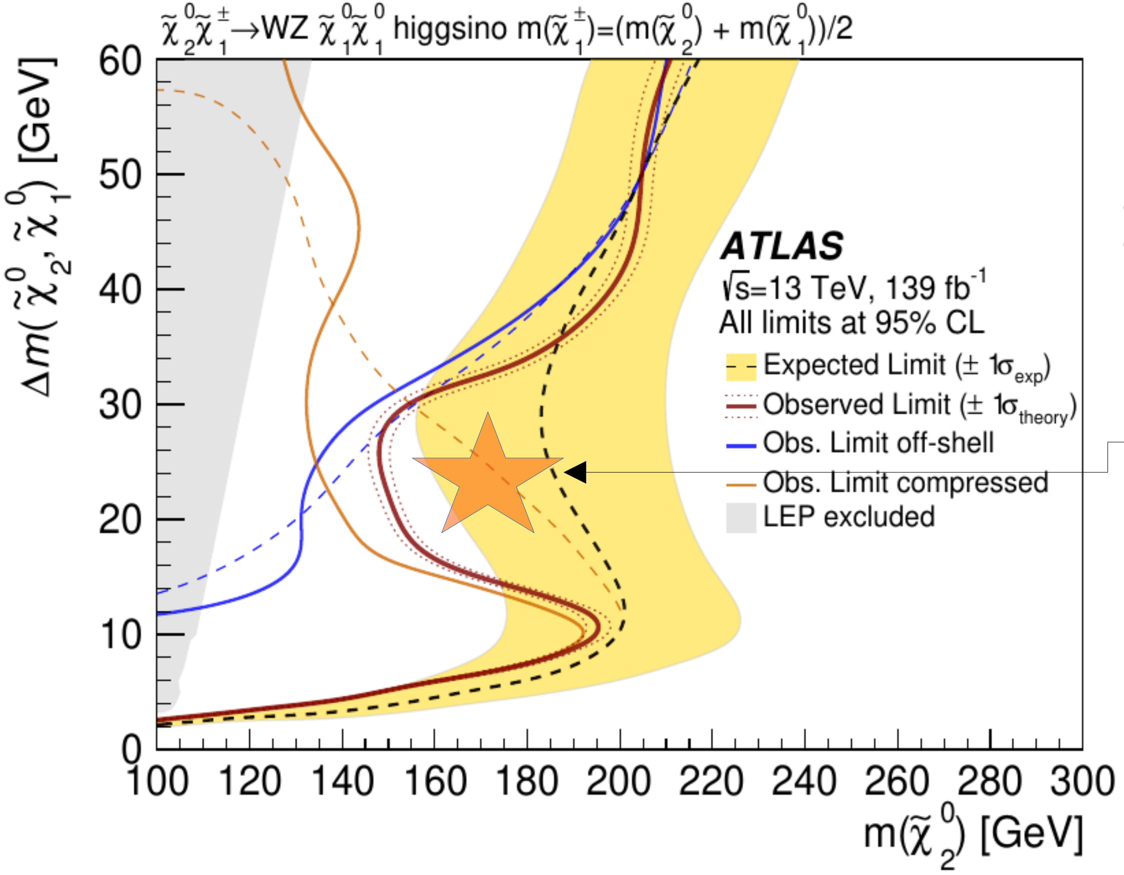
Overview

- Four related excesses at the LHC
- Anatomy of the excesses
- SUSY models to explain them
- Non-SUSY models to (not) explain them
- An interesting SUSY model to explain monojet and entirely different excesses
- Future directions

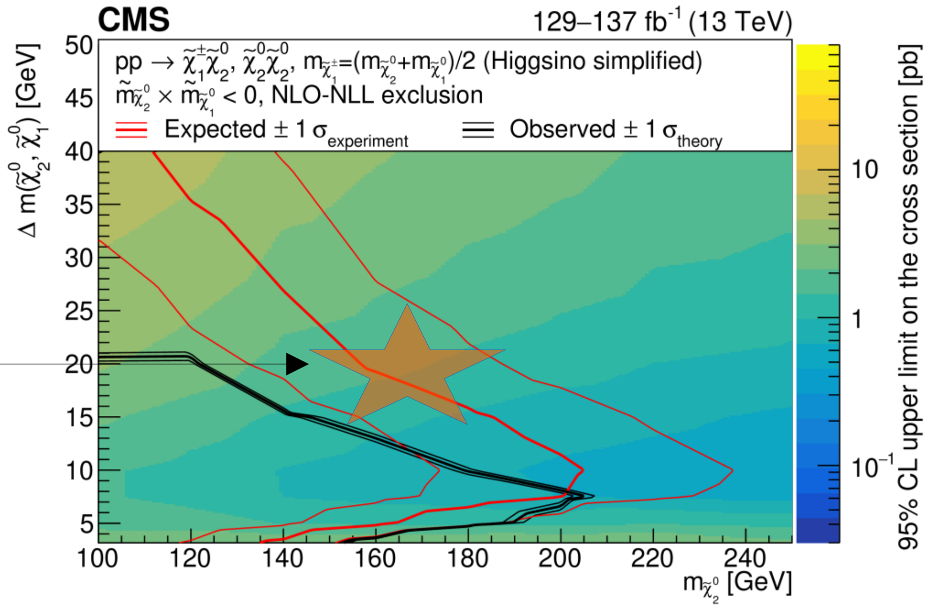
Based on:

- Initial hints in monojets: 2311.17149 with D. Agin, B. Fuks and T. Murphy.
- Models to explain the excesses: 2404.12423 with D. Agin, B. Fuks and T. Murphy.
- HackAnalysis 2: 2406.10042
- Frustrated DM: 2409.03014 with B. Fuks and T. Murphy.

Excesses in soft lepton searches

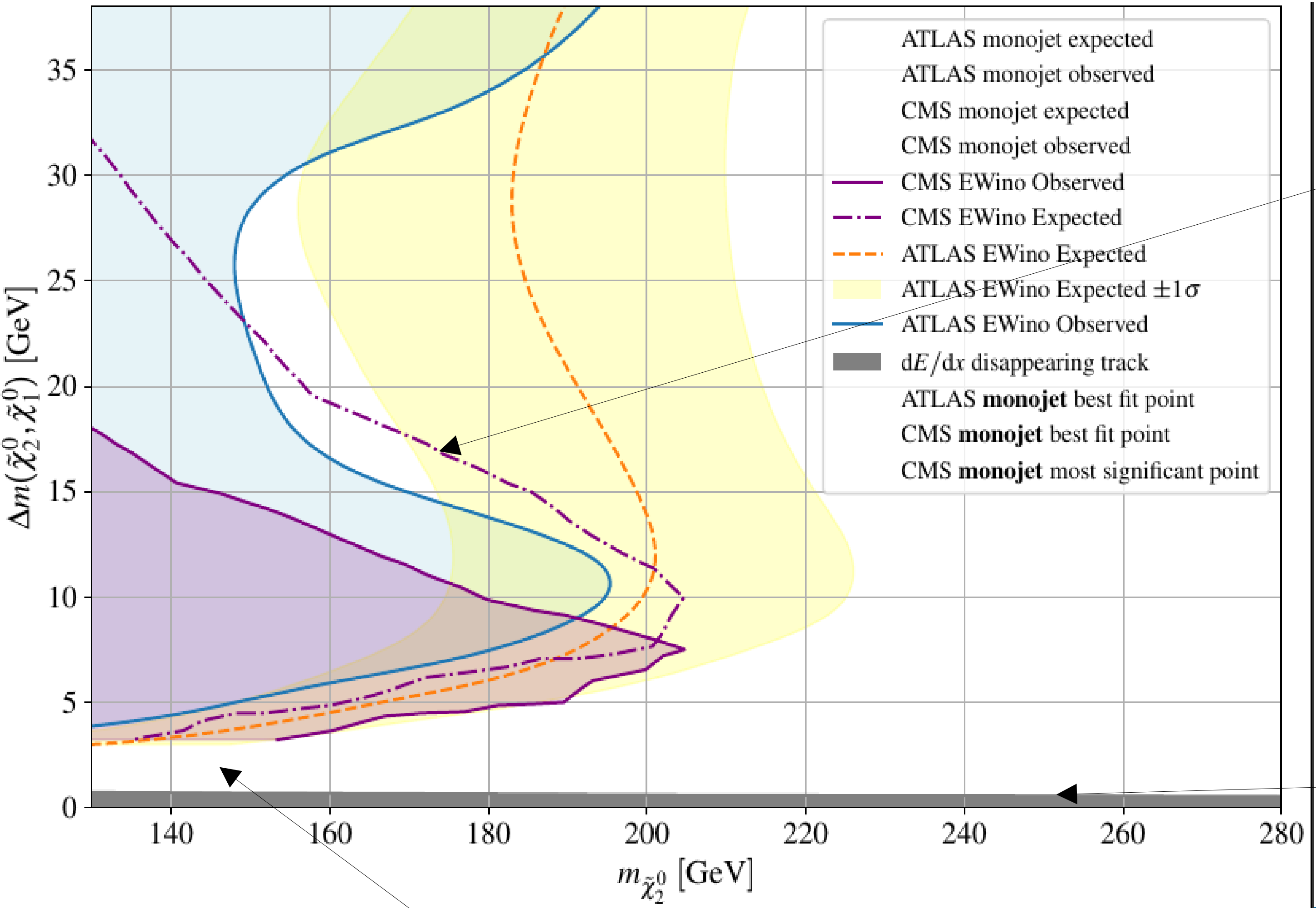


Combination from ATLAS-SUSY-2019-09



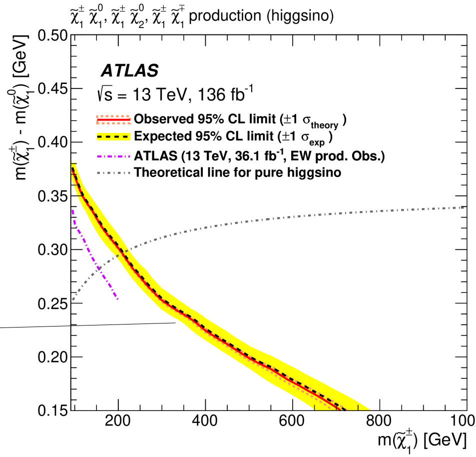
Equivalent limits on Higgsinos from CMS-SUS-18-004

Side-by side: ‘higgsino hole’ is obvious



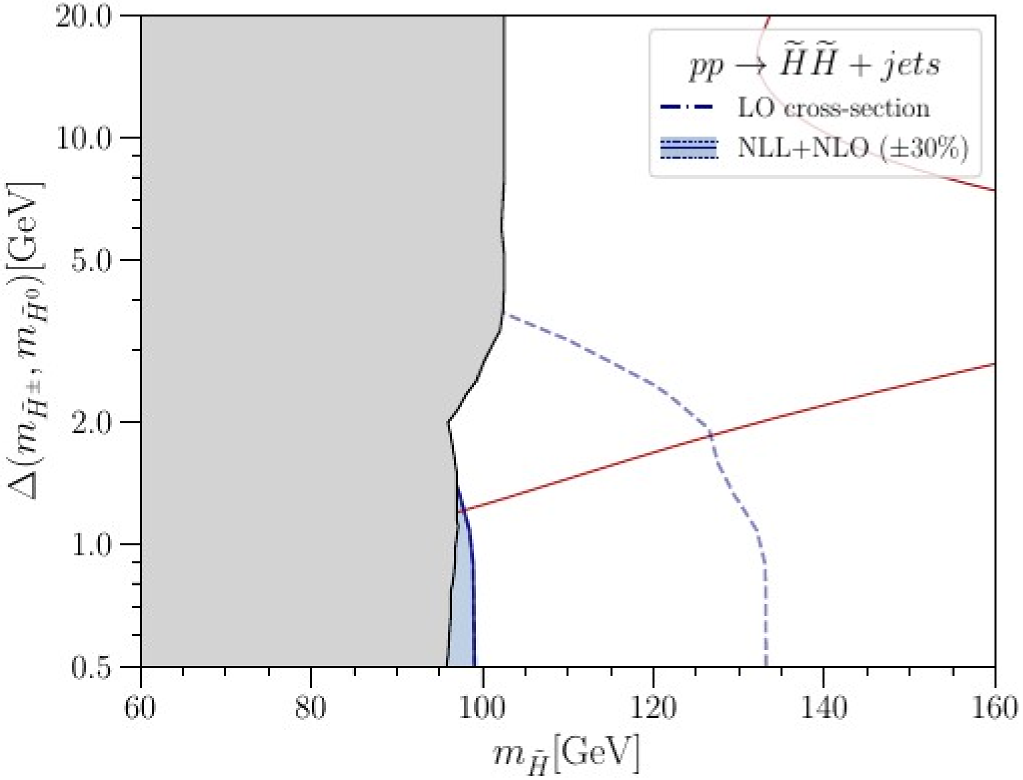
Clearly both searches have compatible excesses!

c.f. disappearing tracks at very low splittings:



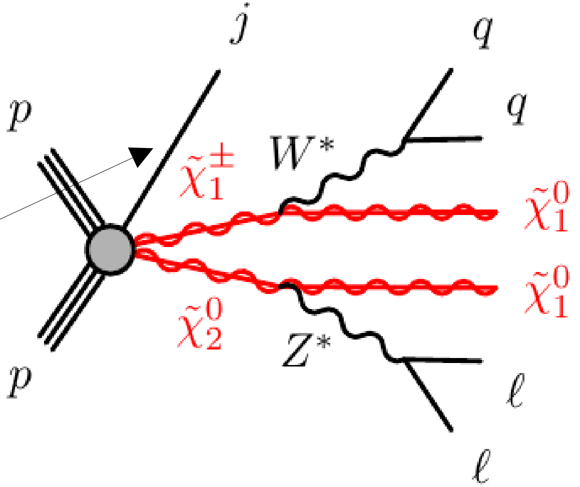
Is there really a hole down to the LEP limit at low splittings?

Other constraints?



In 2208.01651 it was proposed to use the ATLAS multijet search, which only gives a tiny improvement over LEP

The simplified scenarios used (we focussed on ‘higgsino’) involve W/Z decays of charginos/neutralinos, e.g.:



Higgsino scenario: $m_{\tilde{\chi}_1^{\pm}} = \frac{1}{2}(m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0}) = m_{\tilde{\chi}_1^0} + \frac{1}{2}\Delta m$

Can’t we look at the monojet + MET?

Classic claim that ‘higgsinos aren’t constrained by monojets’ comes because for *pure* higgsinos only one process is relevant:

$$pp \to \tilde{\chi}_1^0 \tilde{\chi}_0^2$$

All the others leave charged tracks

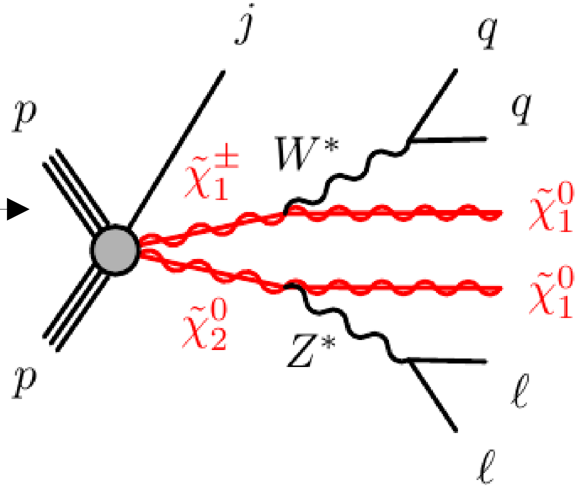
But when we have a mass splitting should include:

$$pp \to \tilde{\chi}_1^0 \tilde{\chi}_0^2, \tilde{\chi}_1^0 \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$$

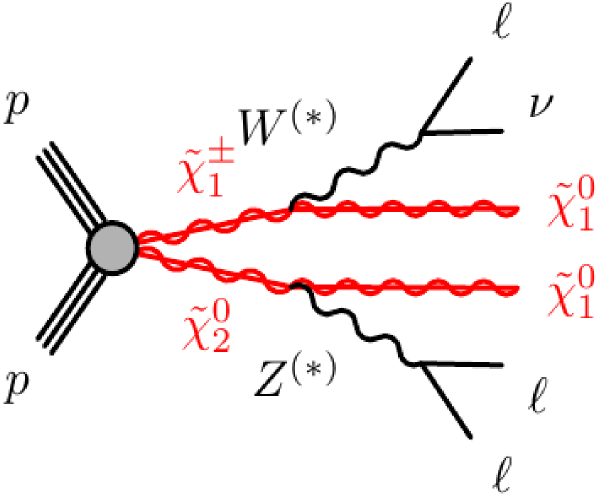
Above the disappearing track limit have prompt decays + soft leptons/jets

Searches for:

- 2 soft leptons + ISR jet + (some) MET
  - ATLAS-SUSY-2018-16, CMS-SUS-18-004 where the excess is seen



- 3 soft leptons + either MET *or lepton trigger*
  - ATLAS-SUSY-2019-09 with small/unclear excess



To test this we used recasts of ATLAS and CMS monojet searches in MadAnalysis (and for speed converted them to HackAnalysis):

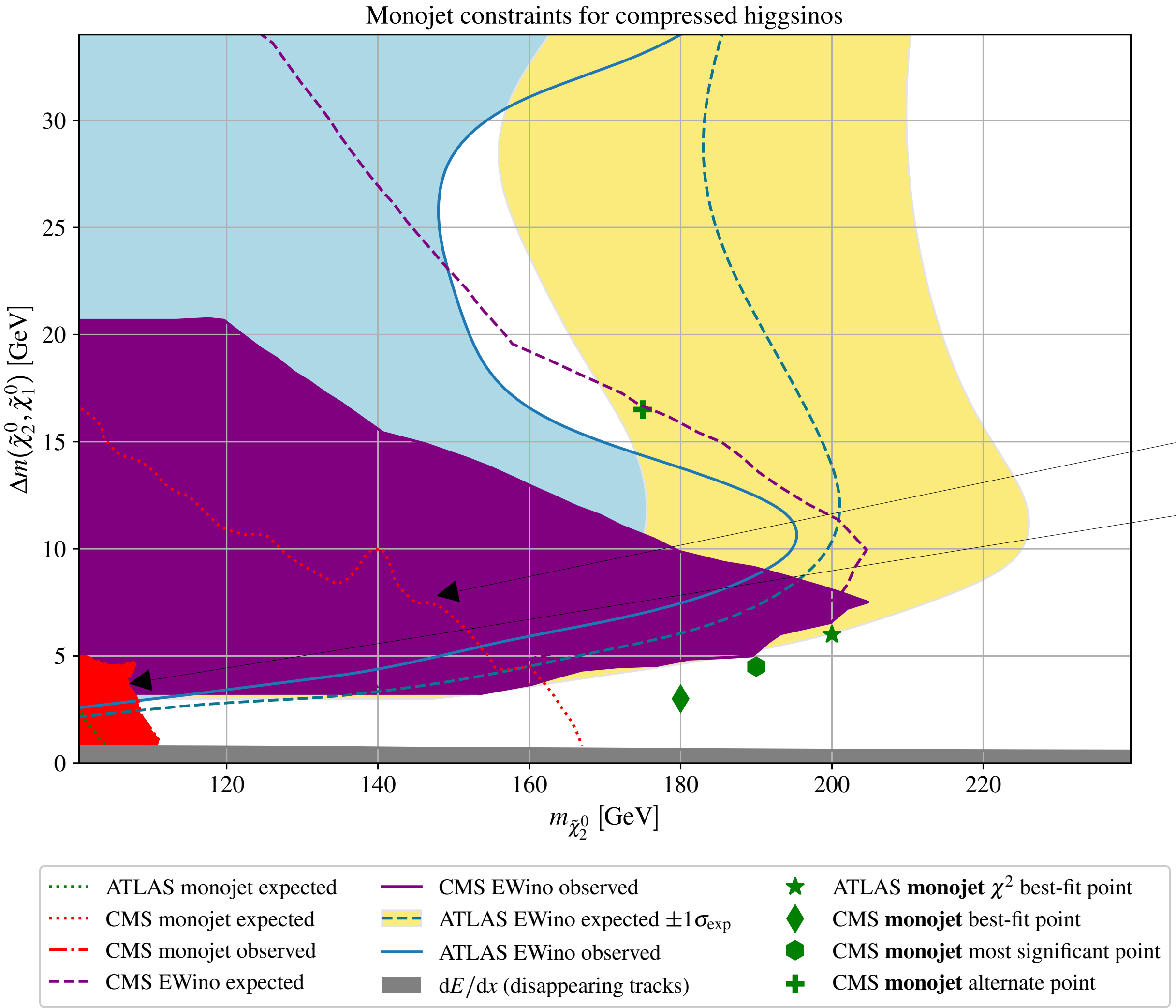
CMS-EXO-20-004

- MET > 250 GeV
- DeepAK algorithm to categorise leading jet as mono-W/Z/j
- Veto on leptons pT > 10 GeV
- Veto on bjets
- **Recast provided by CMS!!!**
- **Simplified likelihood also provided!!**

ATLAS-EXOT-2018-06

- MET > 200 GeV
- 13 exclusive bins in MET, largest > 1200 GeV
- Veto on leptons/photons pT > 7 GeV
- *Up to 3 additional jets allowed*
- **Recast performed by us (Diyar Agin)**
- **No likelihood information provided**

Excesses in Monojet searches



- Close the Higgsino hole!
- ATLAS search much less powerful
- But: **found a massive difference between expected and observed limits …**

…. in ***both*** *ATLAS and CMS analyses*

How significant are they?

- Typical statistical procedure involves either setting *limits* or computing *significances*
- Since we have an excess and have a simplified likelihood model provided by CMS, we can compute these using standard tools (spey)
- Procedure involves finding optimum signal strength $\hat{\mu}$ – this has nothing to do with the actual model
- Our best-fit points for CMS only are:

$$q_0 \equiv -2 \ln \frac{\mathcal{L}(0, \hat{\hat{\theta}}(0))}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad \text{for} \quad \hat{\mu} \geq 0$$

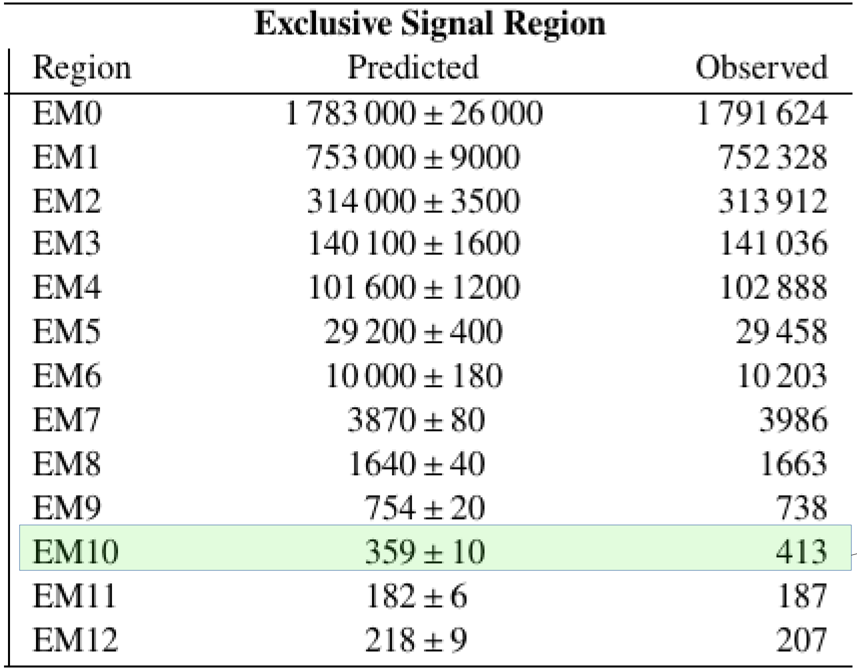
$$\begin{aligned} L(\boldsymbol{\alpha}, \boldsymbol{\delta})\pi(\boldsymbol{\delta}) &= \prod_{I=1}^{P} \Pr\Big(n_I^{\text{obs}} \,\Big|\, n_I(\boldsymbol{\alpha}, \boldsymbol{\delta})\Big)\pi(\boldsymbol{\delta}) \\ &\approx \prod_{I=1}^{P} \Pr\Big(n_I^{\text{obs}} \,\Big|\, a_I(\boldsymbol{\alpha}) + b_I(\boldsymbol{\alpha})\theta_I + c_I(\boldsymbol{\alpha})\theta_I^2\Big) \cdot \frac{\mathrm{e}^{-\frac{1}{2}\boldsymbol{\theta}^{\mathrm{T}}\boldsymbol{\rho}^{-1}(\boldsymbol{\alpha})\boldsymbol{\theta}}}{\sqrt{(2\pi)^P}} \end{aligned}$$

◆ $m_{\tilde{\chi}_2^0} = 180 \text{ GeV}, \ \Delta m = 3 \text{ GeV}, \ \hat{\mu} = 1, \ p = 0.048$

✚ $m_{\tilde{\chi}_2^0} = 175 \text{ GeV}, \ \Delta m = 16.5 \text{ GeV}, \ \hat{\mu} = 1.5, \ p = 0.04$

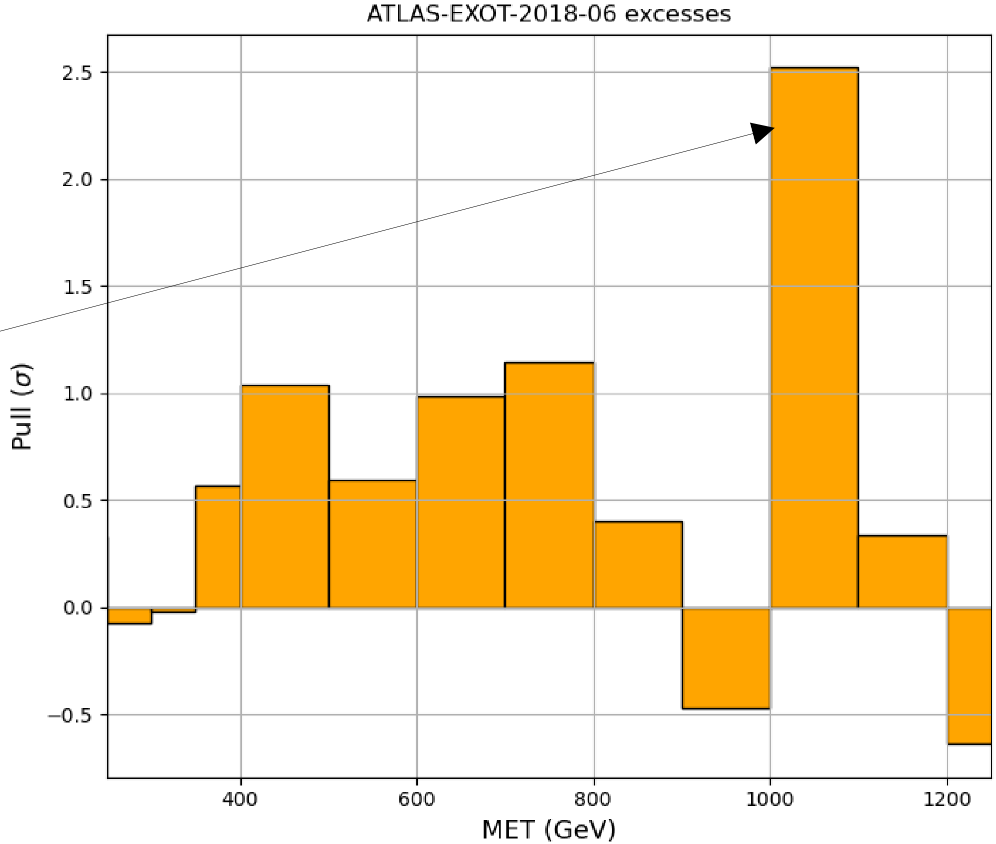
So a model that gives excess soft leptons can also explain monojet excesses!

Decrypting the monojet excesses



Exclusive Signal Region		
Region	Predicted	Observed
EM0	1 783 000 ± 26 000	1 791 624
EM1	753 000 ± 9000	752 328
EM2	314 000 ± 3500	313 912
EM3	140 100 ± 1600	141 036
EM4	101 600 ± 1200	102 888
EM5	29 200 ± 400	29 458
EM6	10 000 ± 180	10 203
EM7	3870 ± 80	3986
EM8	1640 ± 40	1663
EM9	754 ± 20	738
EM10	359 ± 10	413
EM11	182 ± 6	187
EM12	218 ± 9	207

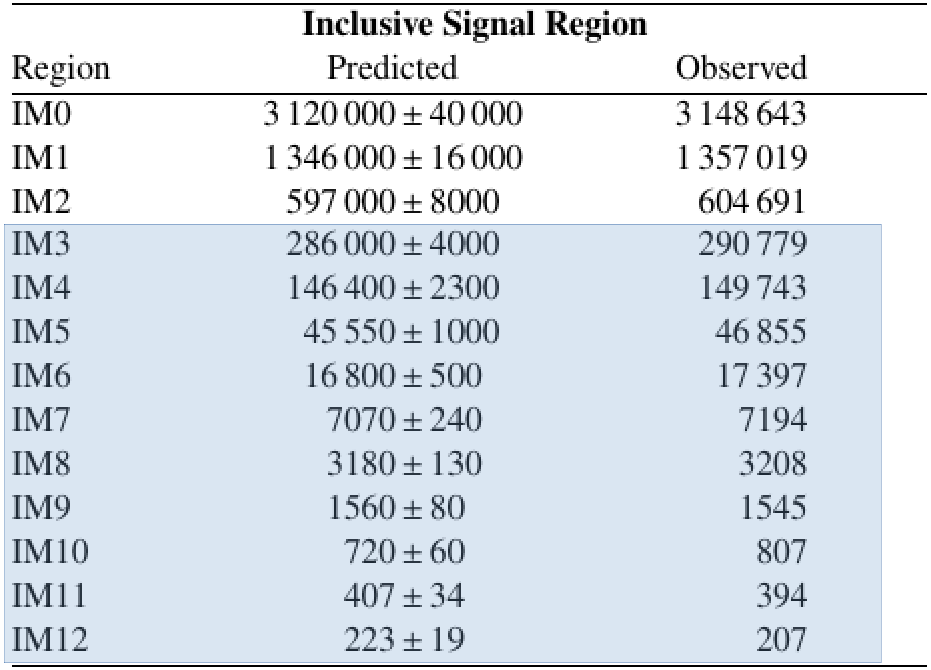
ATLAS have several small excesses and one large one



Corresponds to MET
between 1 and 1.1 TeV

But it is still just about visible when binned as inclusive regions:

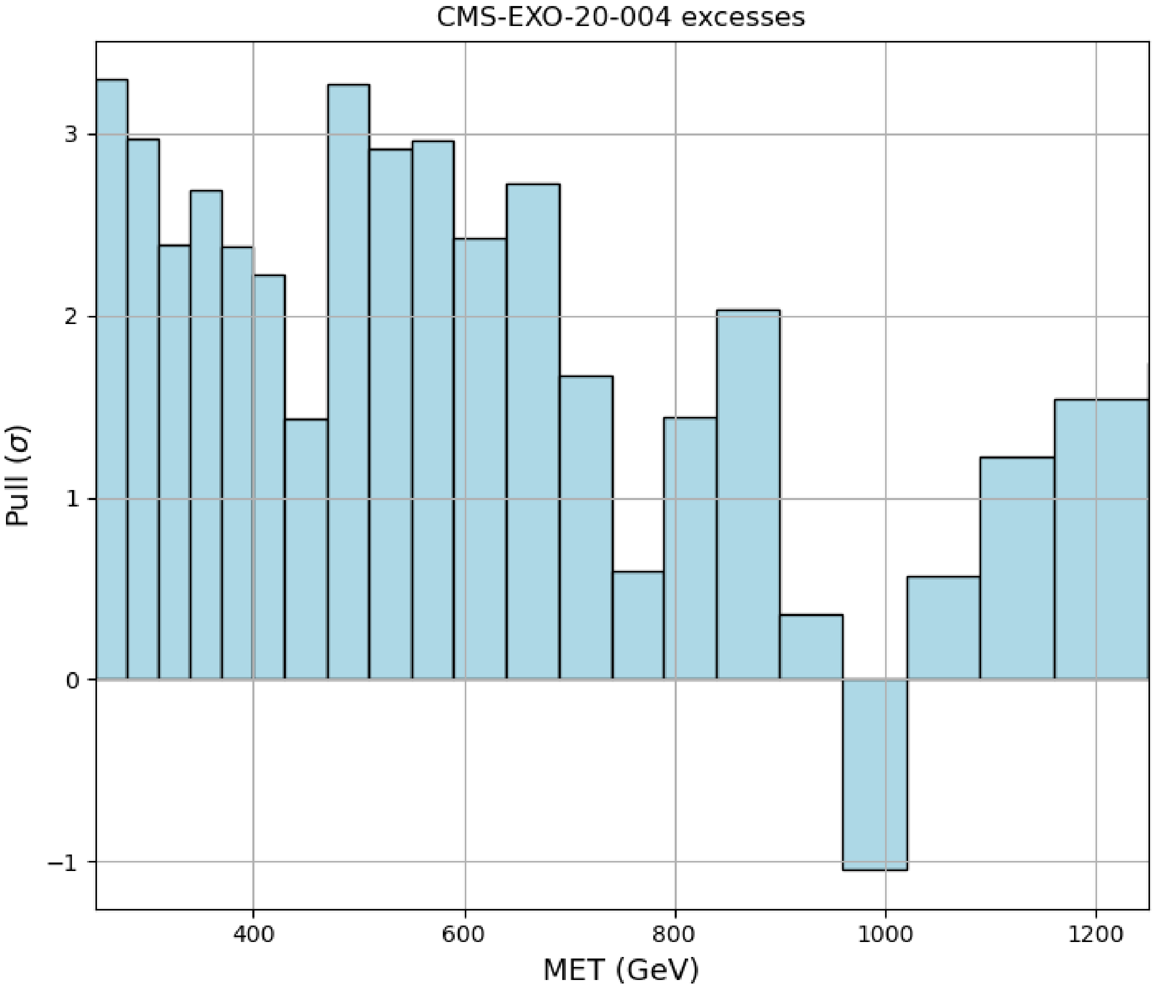
Corresponds to excess MET above 350 GeV



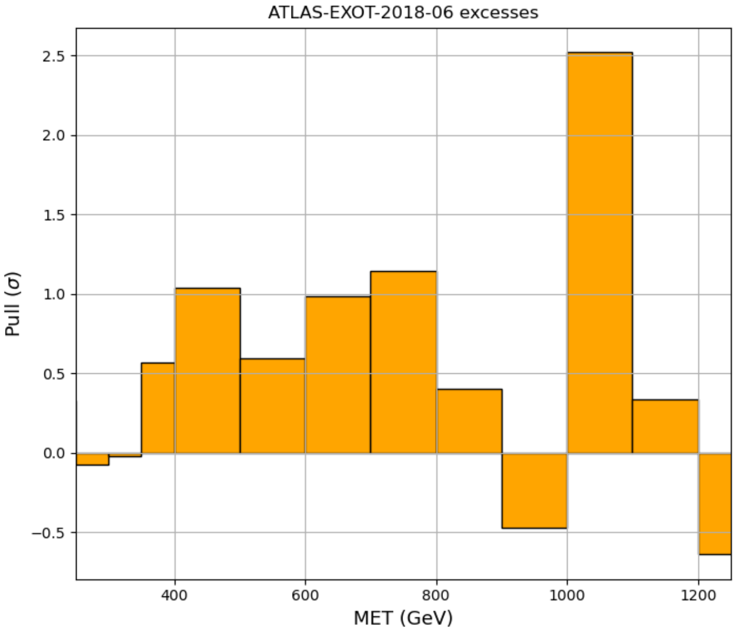
Inclusive Signal Region

Region	Predicted	Observed
IM0	3 120 000 ± 40 000	3 148 643
IM1	1 346 000 ± 16 000	1 357 019
IM2	597 000 ± 8000	604 691
IM3	286 000 ± 4000	290 779
IM4	146 400 ± 2300	149 743
IM5	45 550 ± 1000	46 855
IM6	16 800 ± 500	17 397
IM7	7070 ± 240	7194
IM8	3180 ± 130	3208
IM9	1560 ± 80	1545
IM10	720 ± 60	807
IM11	407 ± 34	394
IM12	223 ± 19	207

No such tables in the CMS paper … but we can inspect the accompanying HEPData and find many excesses in both low and high MET regions.



… and since we have statistical info, can look for ‘best fit’ points



Where is the excess best fit?

We're used to providing exclusion curves … now would like to present data showing where models are most compatible with data.

This is nicely done by using the *Bayes Factor Surface* (*see e.g.* arXiv:2401.11710) by showing contours of the ratio of Bayesian evidence.

$$B_{10} \equiv \frac{Z(\mu = 1)}{Z(\mu = 0)}$$

$$Z(\mu) \equiv \int d\phi p(\mathrm{data}|\mu, \phi) p(\phi|\mu)$$

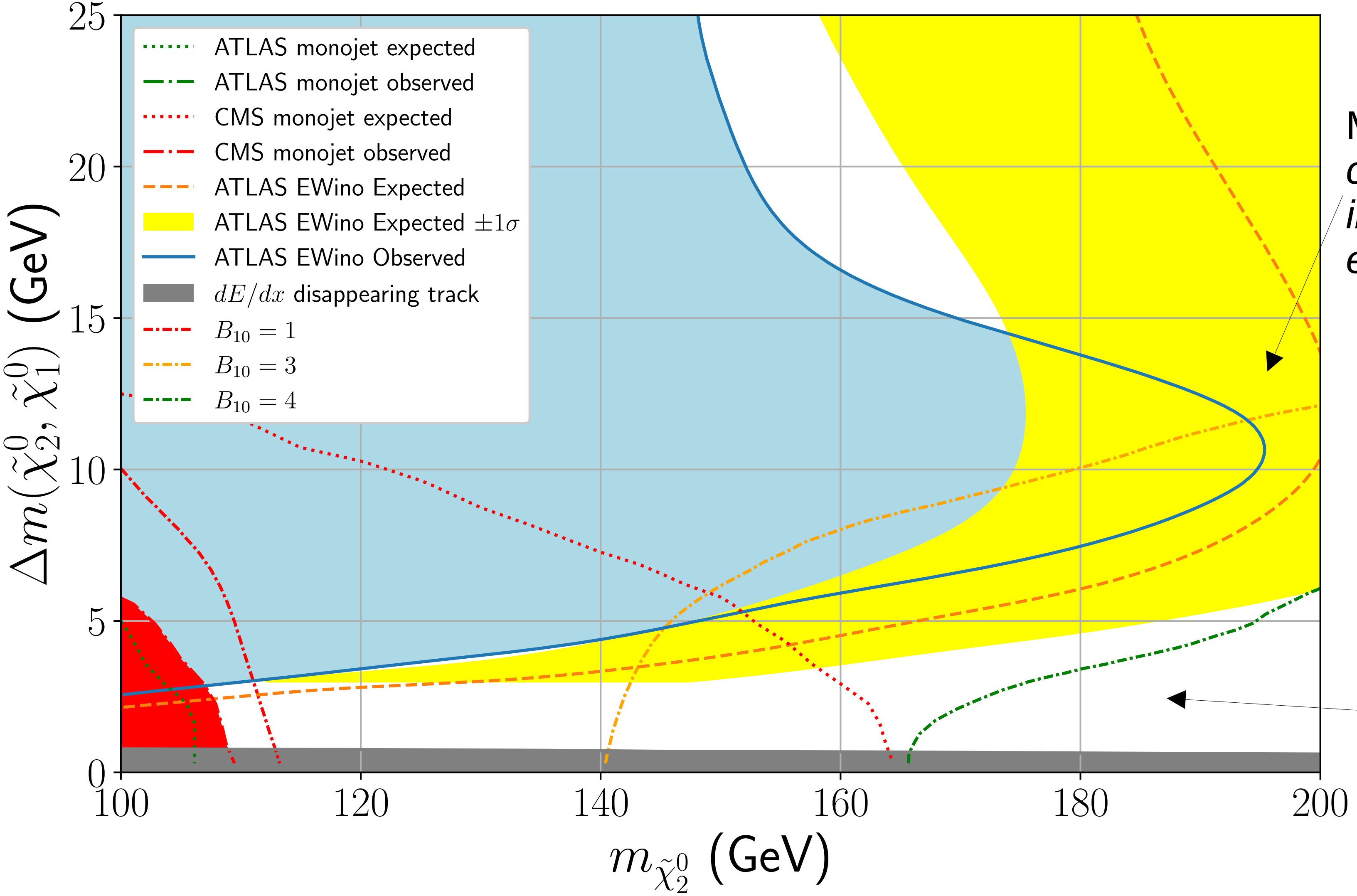
With modern HEP stats tools we can't actually compute this! Instead compute ratio of likelihoods, maximising the nuisance parameters

$$B_{10} \approx \frac{\mathcal{L}(\mu = 1)}{\mathcal{L}(\mu = 0)}$$

Idea is to show relative compatibility of data compared to SM. The larger it is, the better.

But if it is less than 1, the point is ~ excluded

Bayes factors for the CMS monojet search recast in HackAnalysis: (2406.10042)



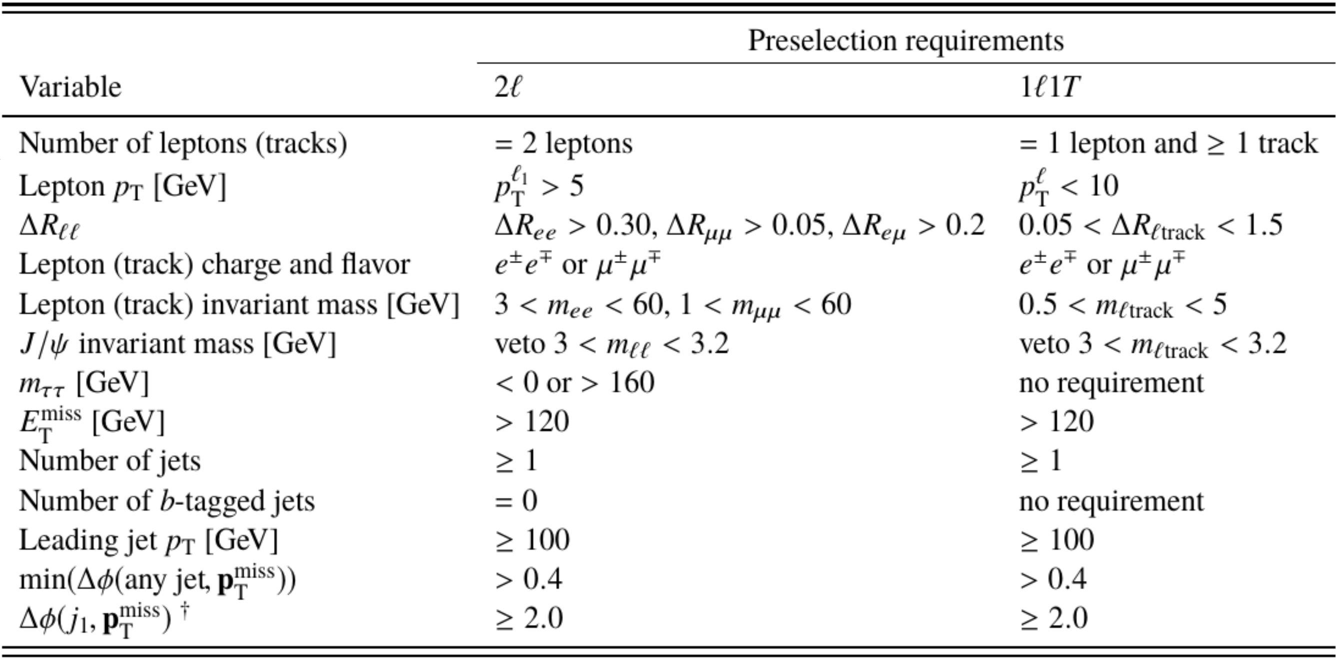
Monojets *improve compatibility of data in the soft lepton excess region!*

Monojets fit even better in this region

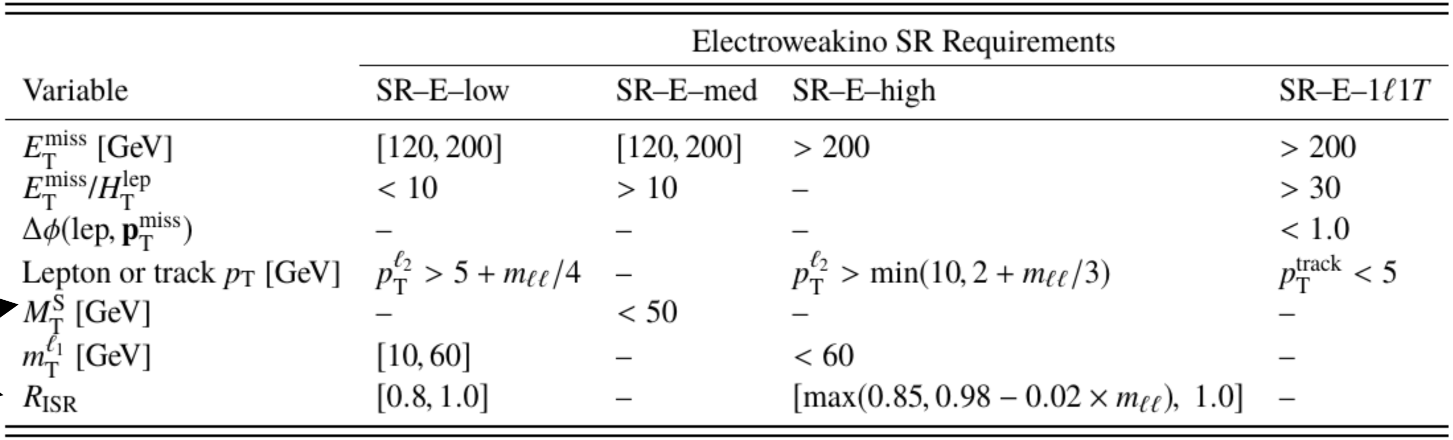
… now for soft leptons

ATLAS-SUSY-2018-16

Here are the preselection cuts,
And signal region cuts



	Preselection requirements	
Variable	2ℓ	$1\ell 1T$
Number of leptons (tracks)	= 2 leptons	= 1 lepton and ≥ 1 track
Lepton p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_1} > 5$	$p_{\mathrm{T}}^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of *b*-tagged jets	$= 0$	no requirement
Leading jet p_{T} [GeV]	≥ 100	≥ 100
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ †	≥ 2.0	≥ 2.0

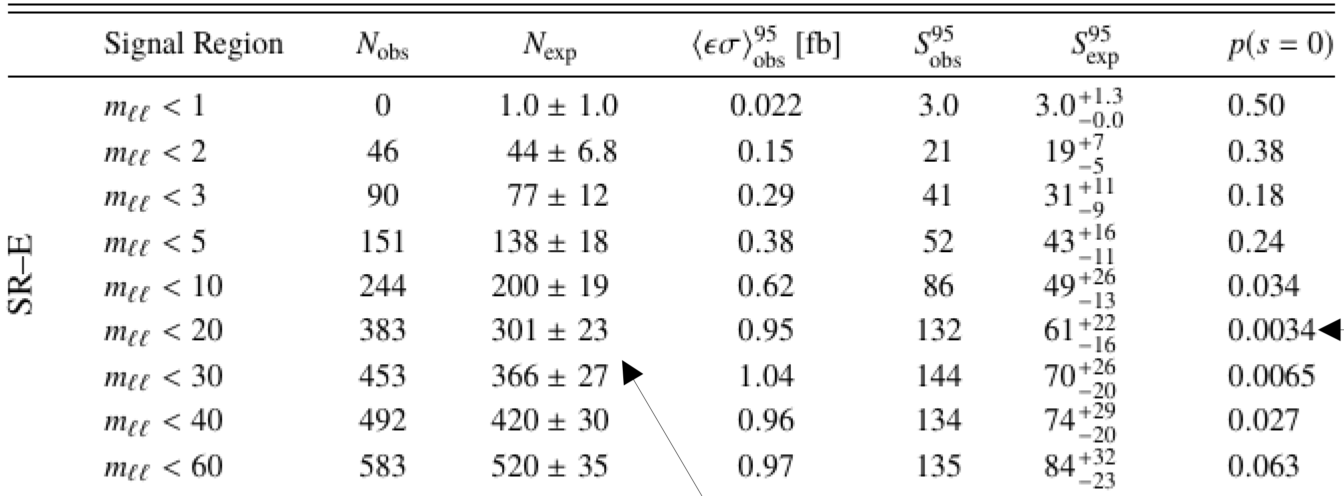


	Electroweakino SR Requirements			
Variable	SR–E–low	SR–E–med	SR–E–high	SR–E–$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[120, 200]$	$[120, 200]$	> 200	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	< 10	> 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	–	–	–	< 1.0
Lepton or track p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_2} > 5 + m_{\ell\ell}/4$	–	$p_{\mathrm{T}}^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_{\mathrm{T}}^{\mathrm{track}} < 5$
$M_{\mathrm{T}}^{\mathrm{S}}$ [GeV]	–	< 50	–	–
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	$[10, 60]$	–	< 60	–
R_{ISR}	$[0.8, 1.0]$	–	$[\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}),\ 1.0]$	–

Restframes quantities to identify ISR jet

The signal regions are binned by dilepton invariant mass:

From ATLAS-SUSY-2018-16



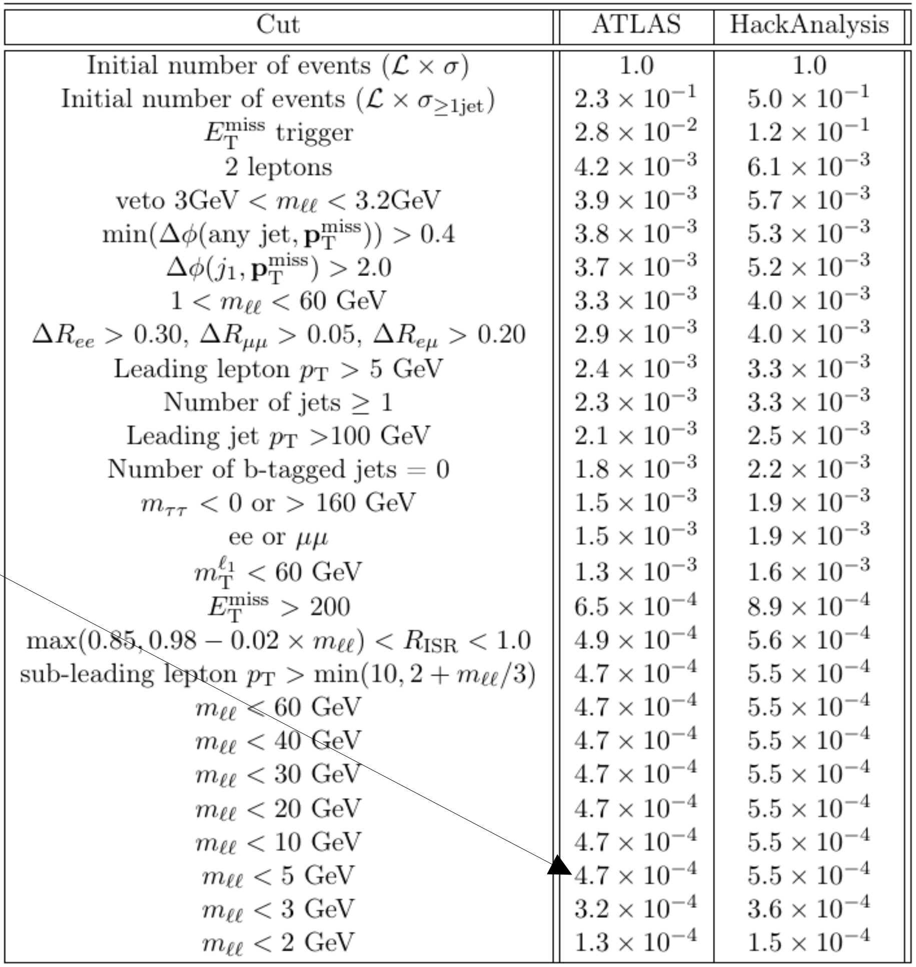
	Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
SR–E	$m_{\ell\ell} < 1$	0	1.0 ± 1.0	0.022	3.0	$3.0^{+1.3}_{-0.0}$	0.50
	$m_{\ell\ell} < 2$	46	44 ± 6.8	0.15	21	19^{+7}_{-5}	0.38
	$m_{\ell\ell} < 3$	90	77 ± 12	0.29	41	31^{+11}_{-9}	0.18
	$m_{\ell\ell} < 5$	151	138 ± 18	0.38	52	43^{+16}_{-11}	0.24
	$m_{\ell\ell} < 10$	244	200 ± 19	0.62	86	49^{+26}_{-13}	0.034
	$m_{\ell\ell} < 20$	383	301 ± 23	0.95	132	61^{+22}_{-16}	0.0034
	$m_{\ell\ell} < 30$	453	366 ± 27	1.04	144	70^{+26}_{-20}	0.0065
	$m_{\ell\ell} < 40$	492	420 ± 30	0.96	134	74^{+29}_{-20}	0.027
	$m_{\ell\ell} < 60$	583	520 ± 35	0.97	135	84^{+32}_{-23}	0.063

2.7σ local excess for ‘signal model with unconstrained normalisation’

Maybe a different model would give a stronger significance?

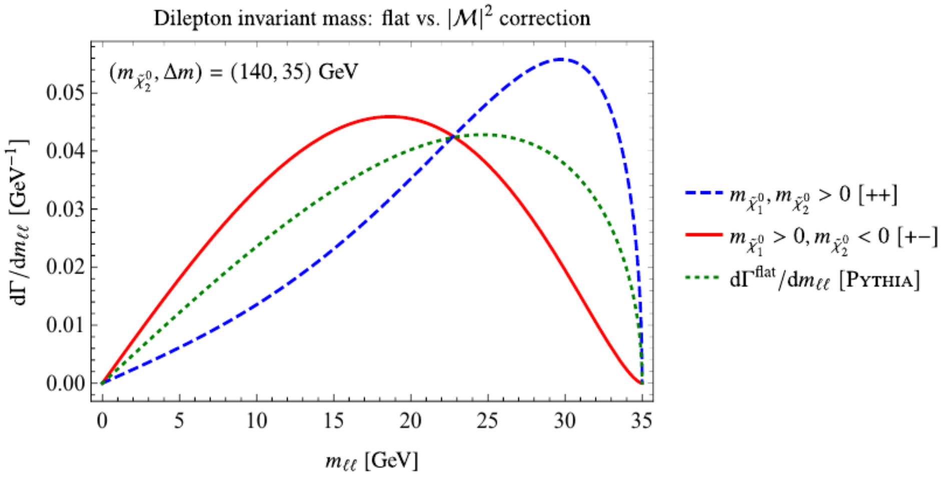
Recasting – and using – the ATLAS soft lepton searches is challenging:

- 2-lepton search uses RestFrames – contains > 50 c++ files, needs root + minuit
- Need detailed invariant-mass reconstruction of decay products → not possible with generation of events in pythia
- Tiny efficiencies → simulate large numbers of events
- 3-lepton search uses MET significance



Cut	ATLAS	HackAnalysis
Initial number of events ($\mathcal{L} \times \sigma$)	1.0	1.0
Initial number of events ($\mathcal{L} \times \sigma_{\geq 1\text{jet}}$)	2.3×10^{-1}	5.0×10^{-1}
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	2.8×10^{-2}	1.2×10^{-1}
2 leptons	4.2×10^{-3}	6.1×10^{-3}
veto 3GeV $< m_{\ell\ell} <$ 3.2GeV	3.9×10^{-3}	5.7×10^{-3}
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})) > 0.4$	3.8×10^{-3}	5.3×10^{-3}
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 2.0$	3.7×10^{-3}	5.2×10^{-3}
$1 < m_{\ell\ell} < 60$ GeV	3.3×10^{-3}	4.0×10^{-3}
$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.20$	2.9×10^{-3}	4.0×10^{-3}
Leading lepton $p_{\mathrm{T}} > 5$ GeV	2.4×10^{-3}	3.3×10^{-3}
Number of jets ≥ 1	2.3×10^{-3}	3.3×10^{-3}
Leading jet p_{T} >100 GeV	2.1×10^{-3}	2.5×10^{-3}
Number of b-tagged jets = 0	1.8×10^{-3}	2.2×10^{-3}
$m_{\tau\tau} < 0$ or > 160 GeV	1.5×10^{-3}	1.9×10^{-3}
ee or $\mu\mu$	1.5×10^{-3}	1.9×10^{-3}
$m_{\mathrm{T}}^{\ell_1} < 60$ GeV	1.3×10^{-3}	1.6×10^{-3}
$E_{\mathrm{T}}^{\mathrm{miss}} > 200$	6.5×10^{-4}	8.9×10^{-4}
$\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}) < R_{\mathrm{ISR}} < 1.0$	4.9×10^{-4}	5.6×10^{-4}
sub-leading lepton $p_{\mathrm{T}} > \min(10, 2 + m_{\ell\ell}/3)$	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 60$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 40$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 30$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 20$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 10$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 5$ GeV	4.7×10^{-4}	5.5×10^{-4}
$m_{\ell\ell} < 3$ GeV	3.2×10^{-4}	3.6×10^{-4}
$m_{\ell\ell} < 2$ GeV	1.3×10^{-4}	1.5×10^{-4}

Table 5: Signal region comparison for ATLAS-SUSY-2018-16 signal region `SR_E_high`.



Digression on tools: why HackAnalysis?

Exist several major frameworks for ‘full’ recasting:

- RIVET: amazing for SM processes, great support by ATLAS members, no root, YODA for histograms. For BSM all detector stuff is abstracted into “projections.” Relies on being handed hepmc files (nb weight treatment).
- MadAnalysis: gold standard for transparency and reproducability. Can use either Delphes or SFS (no root required, but hepmc instead).
- CheckMATE: good ideas for running points quickly, loads of analyses being added, mainly intended to be used as a black box, requires root and Delphes.
- GAMBIT: intended for global scans as black box, great ideas for fast detector simulation, some compromises in favour of speed vs accuracy.
- ADL: no need to introduce here, relies on root & hepmc.

In 2020, I wanted to recast the CMS disappearing track search, and none of them were usable: if you want some feature (finite size of detector, disappearing tracks in this case) you better contact the authors.

CMS-EXO-19-010: cuts

- Triggers followed by a cut on MET (120 GeV) – *without muons*
- At least one high-pT jet (110 GeV), no jets within $|\Delta\Phi| < 0.5$ of the MET vector
- Remaining cuts are all on the tracks: pT > 55 GeV
- Sufficiently isolated
- No missing hits in the pixel detector, no missing inner hits
- Sufficiently separated ($\Delta R < 0.5$) from jets, ($\Delta R < 0.15$) from electrons, *muons*
- Must actually disappear! That means, >2 missing outer hits, < 10 GeV calorimeter energy around the track.
- Extra complication: data split into 6 different data taking periods! 2015, 2016A/B, 2017, 2018A/B (due to malfunctioning parts of detector)
- Signal regions depend on number of tracker layers that have been hit!

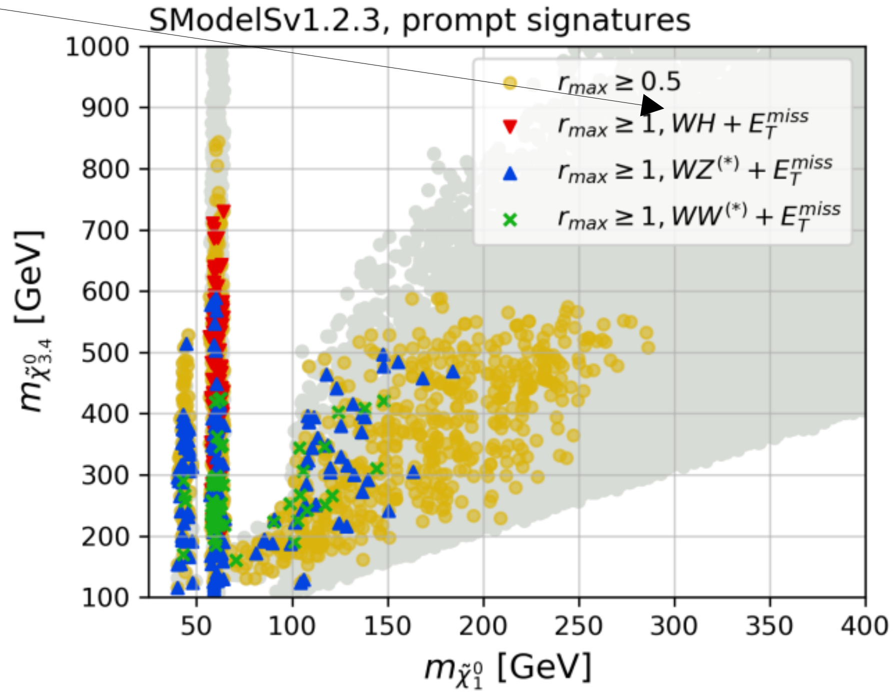
Pileup!

Long-lived charginos get mistaken for muons and get included in MET calculation!

Pixels, hits, track isolation, forget about using any standard detector simulation!

- I was also interested in electroweakino searches for Dirac Gaugino models (SciPostPhys.9.4.047 with Kraml, Reyes and Williamson)
- I tried to use GAMBIT, was proposed “ColliderBit standalone solo” but could not use it. (Issues with the pythia code produced by MadGraph, etc etc).
- Some of the most powerful relevant analyses weren’t extant anyway.

- For the recast of ATLAS-SUSY-2018-09 in MadAnalysis:
  - EWino searches have fairly small efficiencies → need to simulate large numbers of events.
  - At the time needed to use Delphes → generate large root files, tinkering with the efficiencies during development of the recast was **painful.**
  - Implementing dynamic isolation requirements (as ATLAS required) impossible in Delphes (in-built routines were removing too many leptons), so have to do it in the analysis anyway.
  - At the time there was no pyhf interface in MadAnalysis

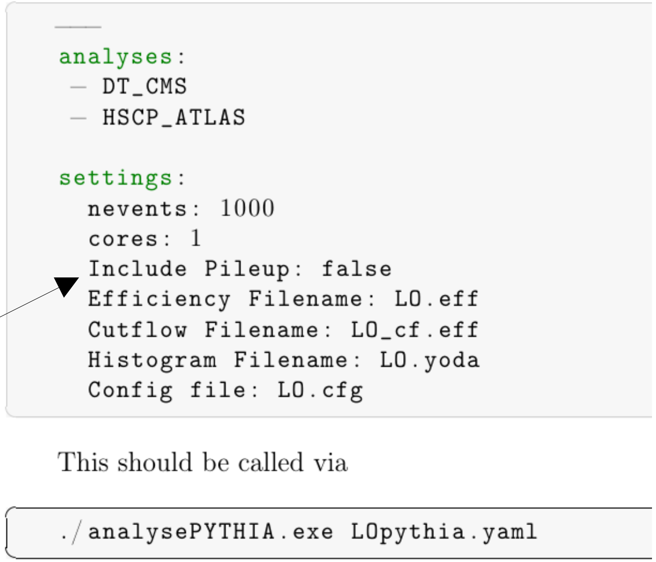


Goals for HackAnalysis:

- Major recasting packages have become monolithic: they do what they are intended to do incredibly well, but it’s hard to get them to do something else. I want to be able to add new features easily and without breaking something. E.g.:
  - RestFrames
  - Pileup in fast sim
  - FastJet features such as pileup subtraction, etc etc
  - Finite detector size
- Would be ideal to take advantage of the best ideas of each.
- Want to speed up development of new analyses (mainly) for MadAnalysis – this means no compromises in precision.
- Ideally should be as simple as possible to port to other frameworks.
- Therefore also want a minimum of external dependencies (e.g. root can be difficult to install/unavailable on clusters).

Intro to HackAnalysis

- Implementation of MadAnalysis-style analysis structure (init(), Execute(), Finalise(); AddRegionSelection(..), AddCut(..)) so you can almost convert to MA5 syntax with a perl script … but based on `heputils` – can take advantage of GAMBIT binning functions/efficiency functions/syntax.
- YODA for plotting/histogramming (and can also read efficiency information in YODA files provided on HEPData).
- Basic Makefile rather than configure scripts, cmake etc – easier to add your own code.
- External dependencies: YODA, hepmc2, fastjet, pythia, openmp. ONNX and zlib as options.
- Four running modes:
  - analysePYTHIA.exe for pythia event generation (super fast + dirty)
  - analysePYTHIA_LHE.exe for reading lhe files + showering internally
  - analyseHEPMC.exe mainly for compatibility/checking against MA5
  - analyseHAEVENT.exe for reading pre-processed events
- Piloted by a `yaml` file
- Can include pileup (code for generating min bias events included)



```
---
analyses:
 - DT_CMS
 - HSCP_ATLAS

settings:
  nevents: 1000
  cores: 1
  Include Pileup: false
  Efficiency Filename: LO.eff
  Cutflow Filename: LO_cf.eff
  Histogram Filename: LO.yoda
  Config file: LO.cfg
```

This should be called via

```
./analysePYTHIA.exe LOpythia.yaml
```

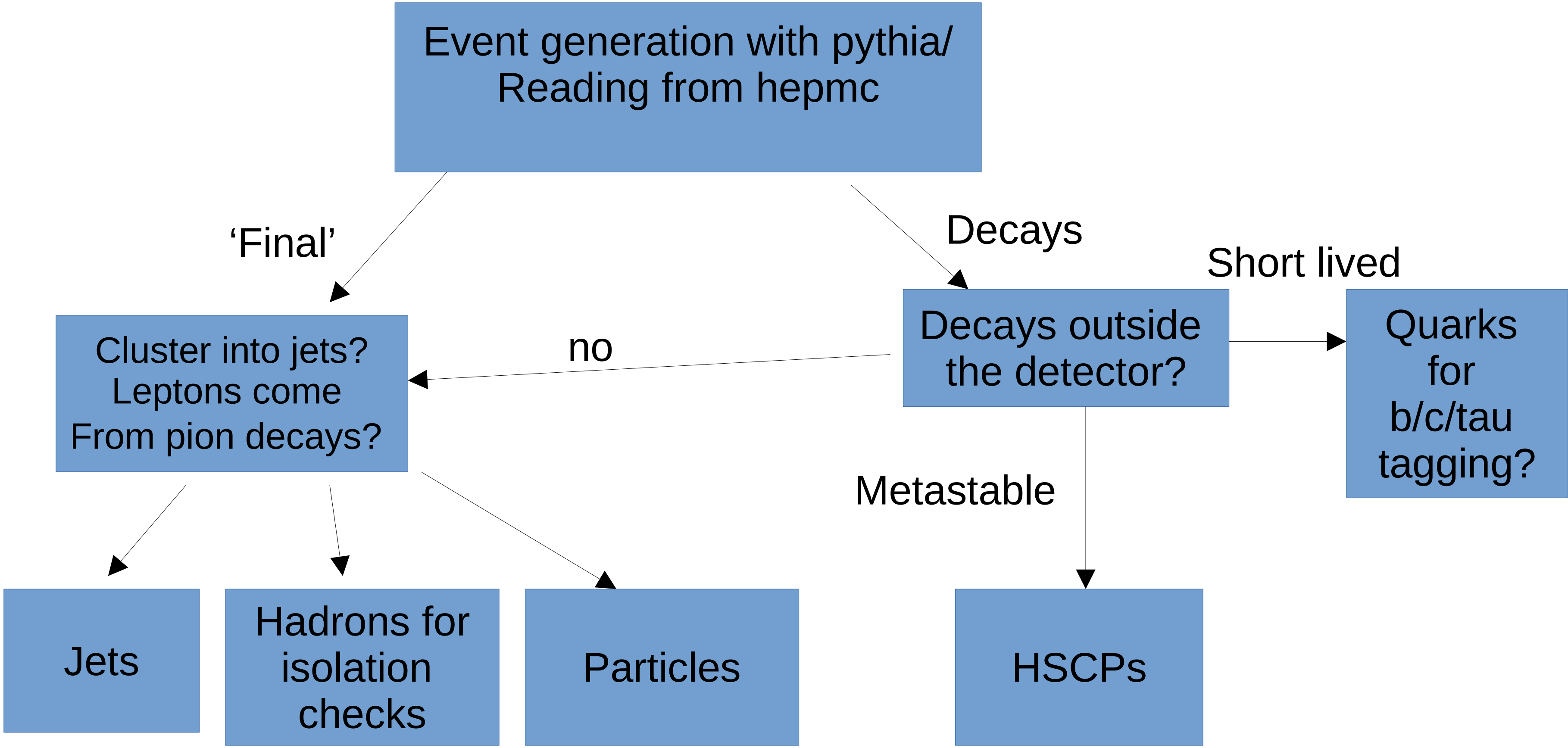
HackAnalysis 2 new features

Described in the manual arXiv:2406.10042

- Simple inclusion of new particles via a QNUMBERS file (or directly in yaml input)
- Multiple ‘detector’ simulations
- Compressed event format
- Automatic systematic uncertainties
- RestFrames, Eigen, Nelder-Mead minimiser, MT2
- ONNX interface
- Json output for cutflows, weight info, etc: can be used for merging runs
- Scripts for merging runs, printing cutflows in LaTeX
- Python scripts for running stats (exclusion/signal strength limits/p-values/likelihoods) through pyhf, spey and toy-based single bin
- Interface with BSMArt for scanning – handling the generation of events in MadGraph, gridpack generation, etc – and convergence checking
- New and old analyses

Write your own filling function! Maximum flexibility to use e.g. avanced fastjet features without breaking something, etc etc

Detector ‘filling’ routines



Event generation with pythia/
Reading from hepmc

‘Final’

Decays

Short lived

Cluster into jets?
Leptons come
From pion decays?

no

Decays outside
the detector?

Quarks
for
b/c/tau
tagging?

Metastable

Jets

Hadrons for
isolation
checks

Particles

HSCPs

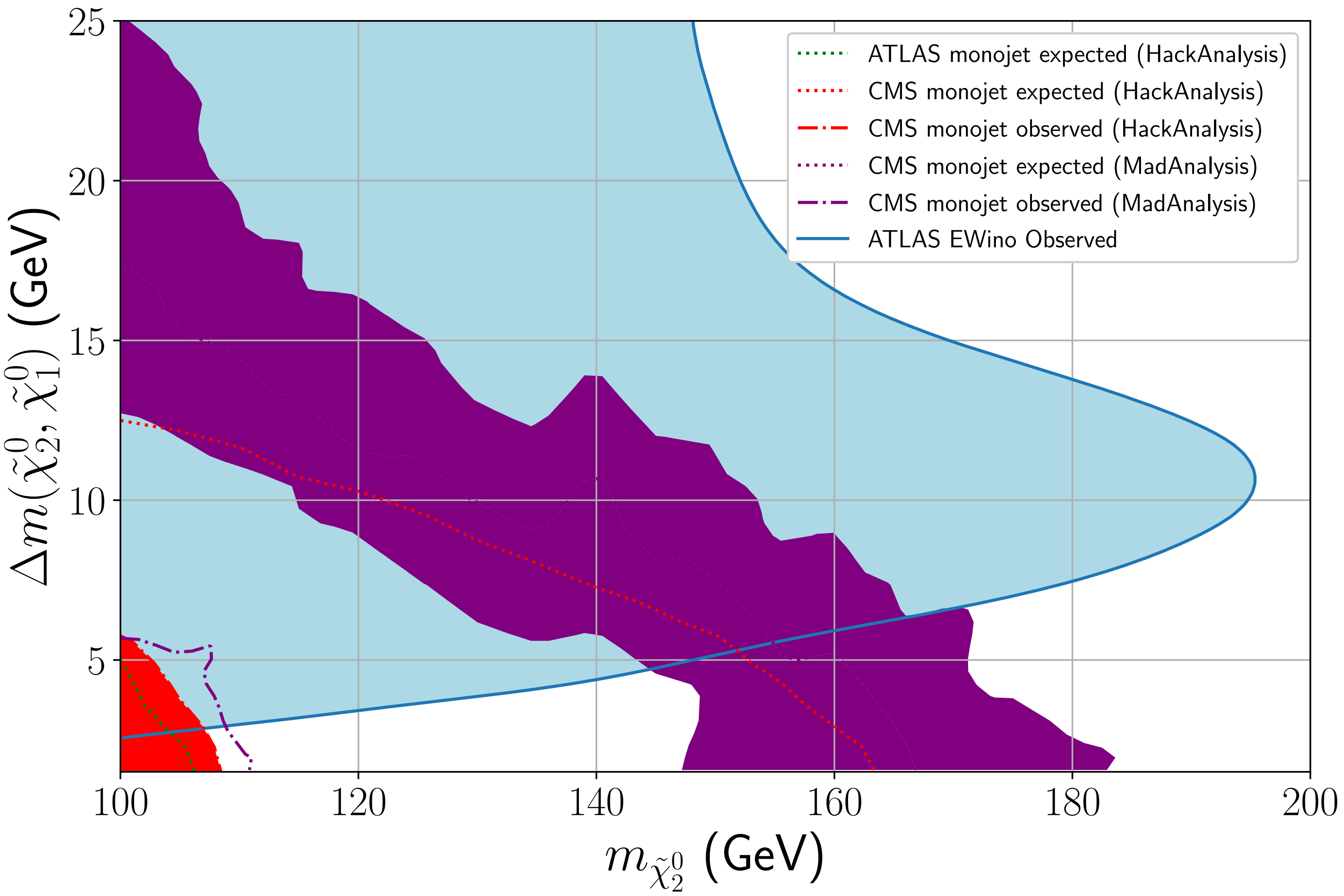
Gridpacks, batches

Many features to make running/prototyping as fast as possible:

- Generate gridpack in MadGraph → run in ‘read-only’ mode, one gridpack run per core to generate lhe events. One .lhe file per core.
    - Can then shower directly running pythia.
    - With gridpacks can easily run batches of points of any size.
    - If not too large: put MG5 output + gridpacks on ramdisk (/dev/shm) → no writing to disk at all during run!
    - Extra bonus: can then do convergence checks after each batch
- Store events in a compressed reco format. E.g. 100k event sample:
    - 7.2 GB `.hepmc` (!!!)
    - 19 MB `.lhe.gz`
    - 10 MB `.ha.gz`
- Store one reco file/core → can rerun sample in multicore mode. Incredibly fast.
- Can choose to keep hadrons for isolation or discard.

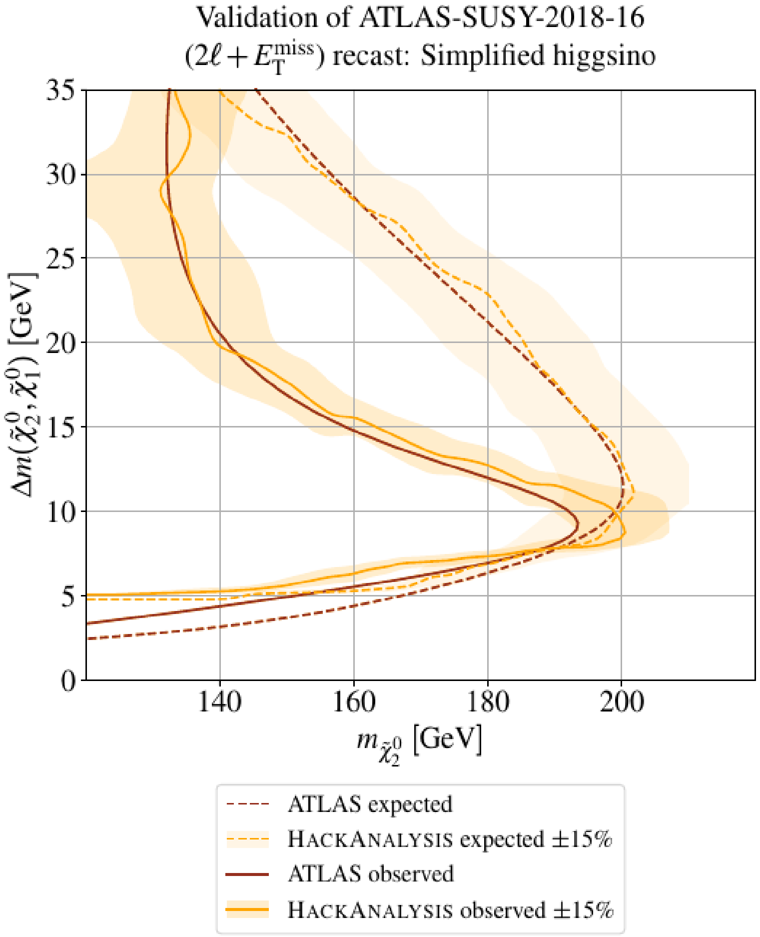
E.g. running 19.2M events/point using gridpack mode via BSMArt takes about 4 hours/point/batch of 3.2M events on 8 cores on lxplus …

vs 16 hours to run 2M events via MadAnalysis

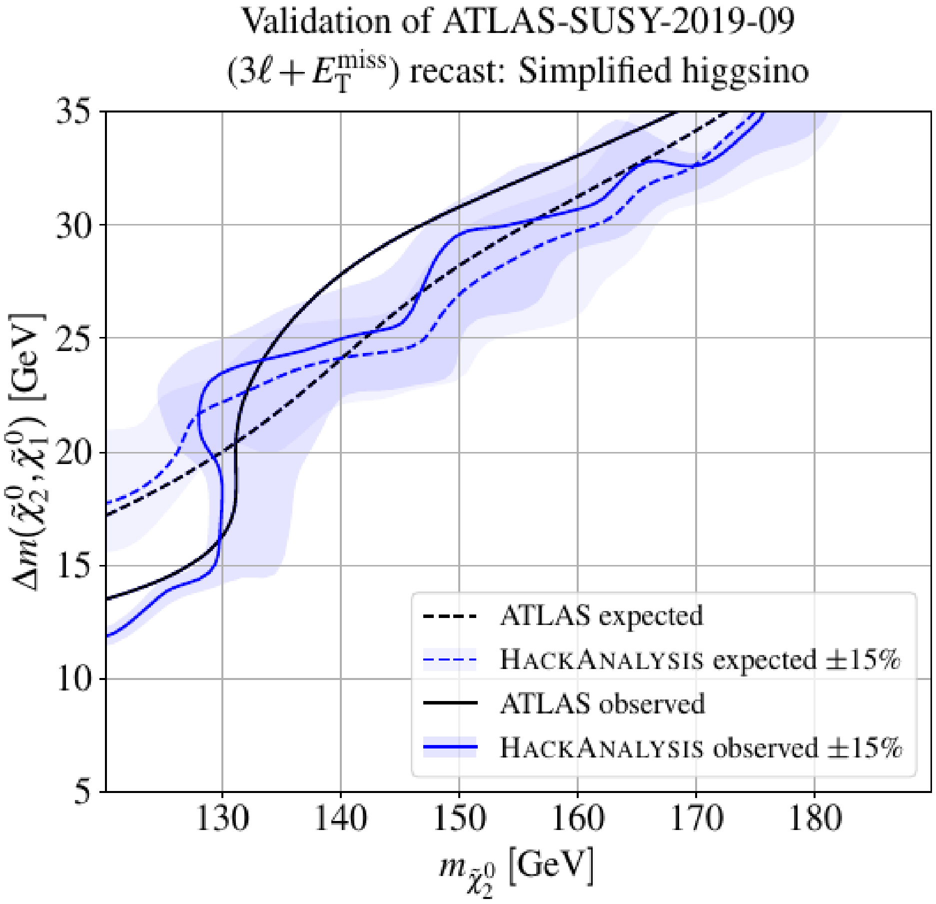


And this is without using ramdisk/batches

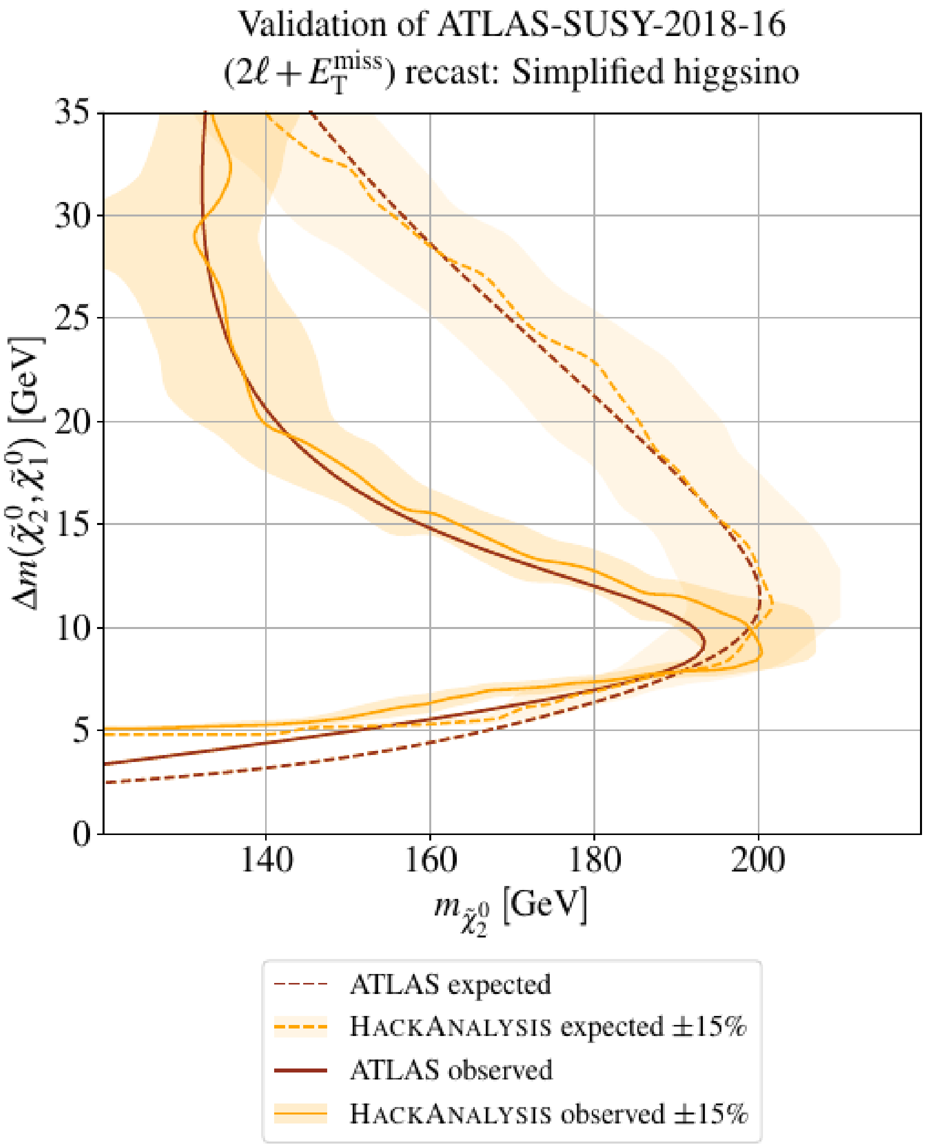
Similarly needed large numbers of events to validate the soft lepton analyses, using same workflow

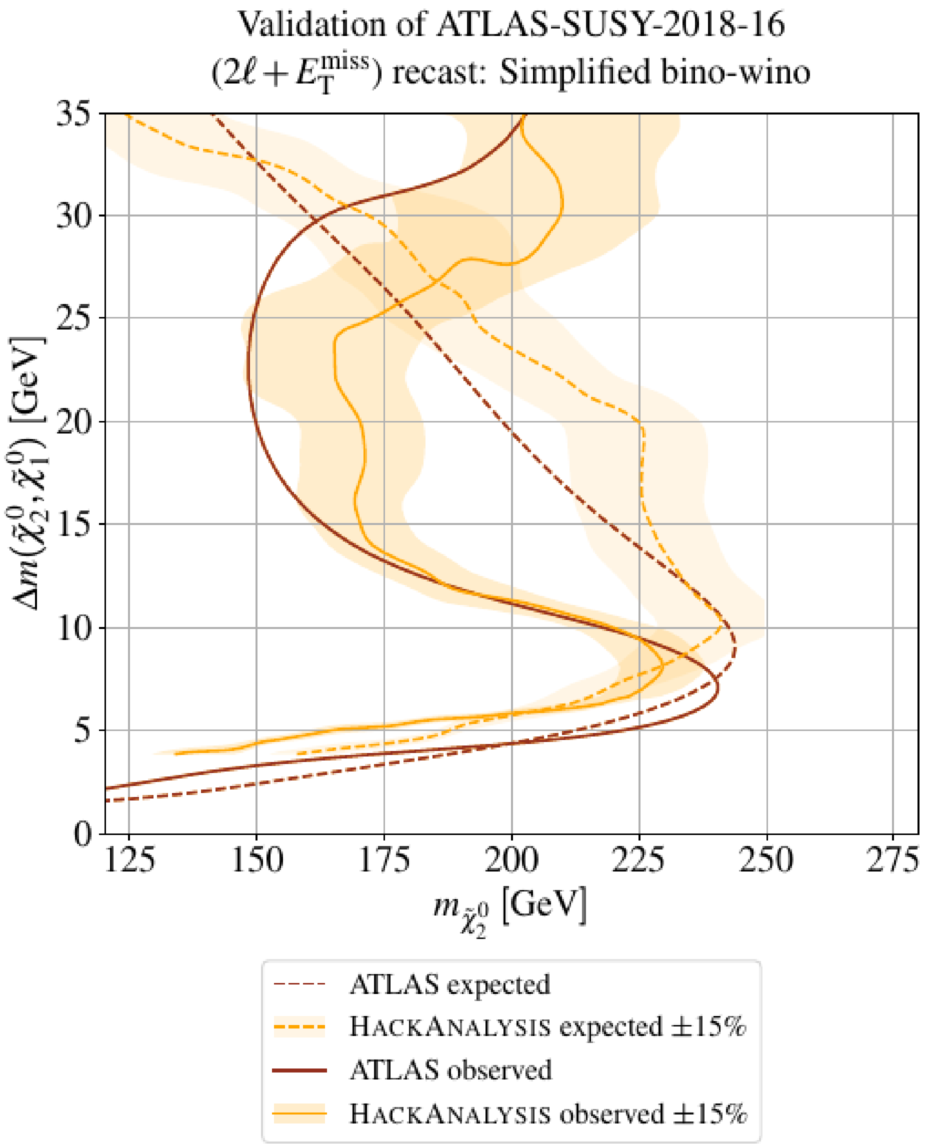


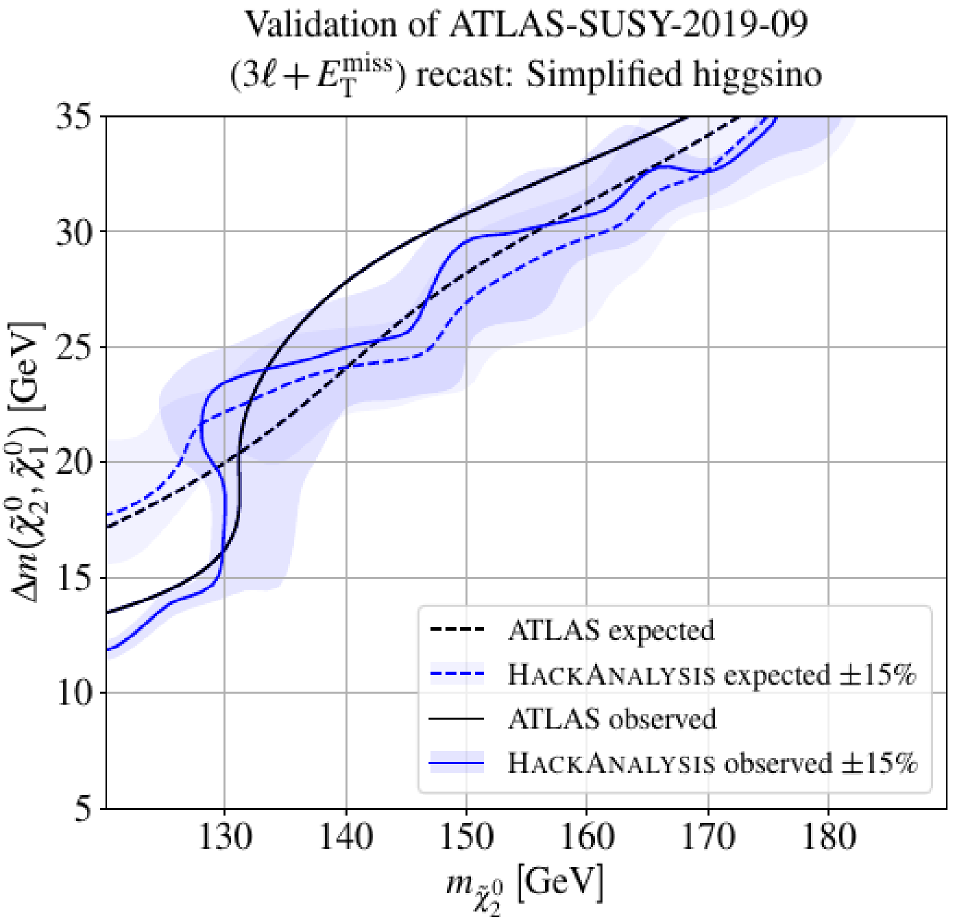
2 soft leptons



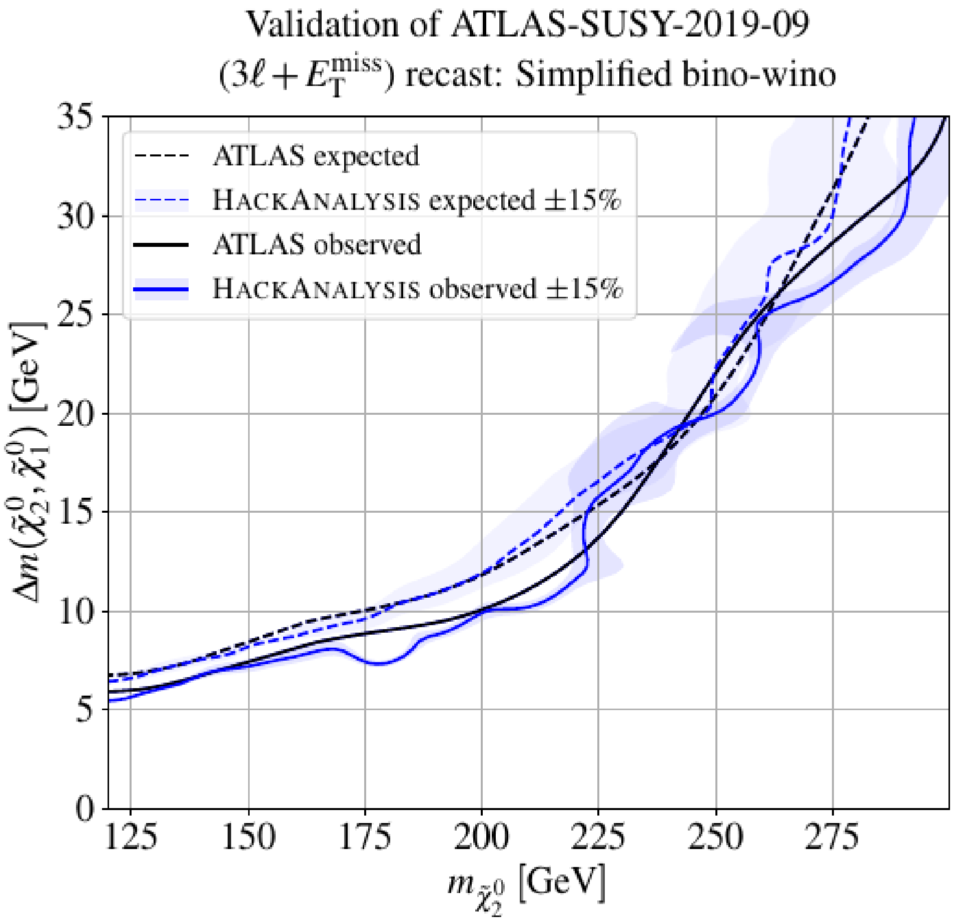
3 soft leptons


Validation of ATLAS-SUSY-2018-16
($2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$) recast: Simplified higgsino


Validation of ATLAS-SUSY-2018-16
($2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$) recast: Simplified bino-wino


Validation of ATLAS-SUSY-2019-09

($3\ell + E_{\mathrm{T}}^{\mathrm{miss}}$) recast: Simplified higgsino


Validation of ATLAS-SUSY-2019-09

($3\ell + E_{\mathrm{T}}^{\mathrm{miss}}$) recast: Simplified bino-wino

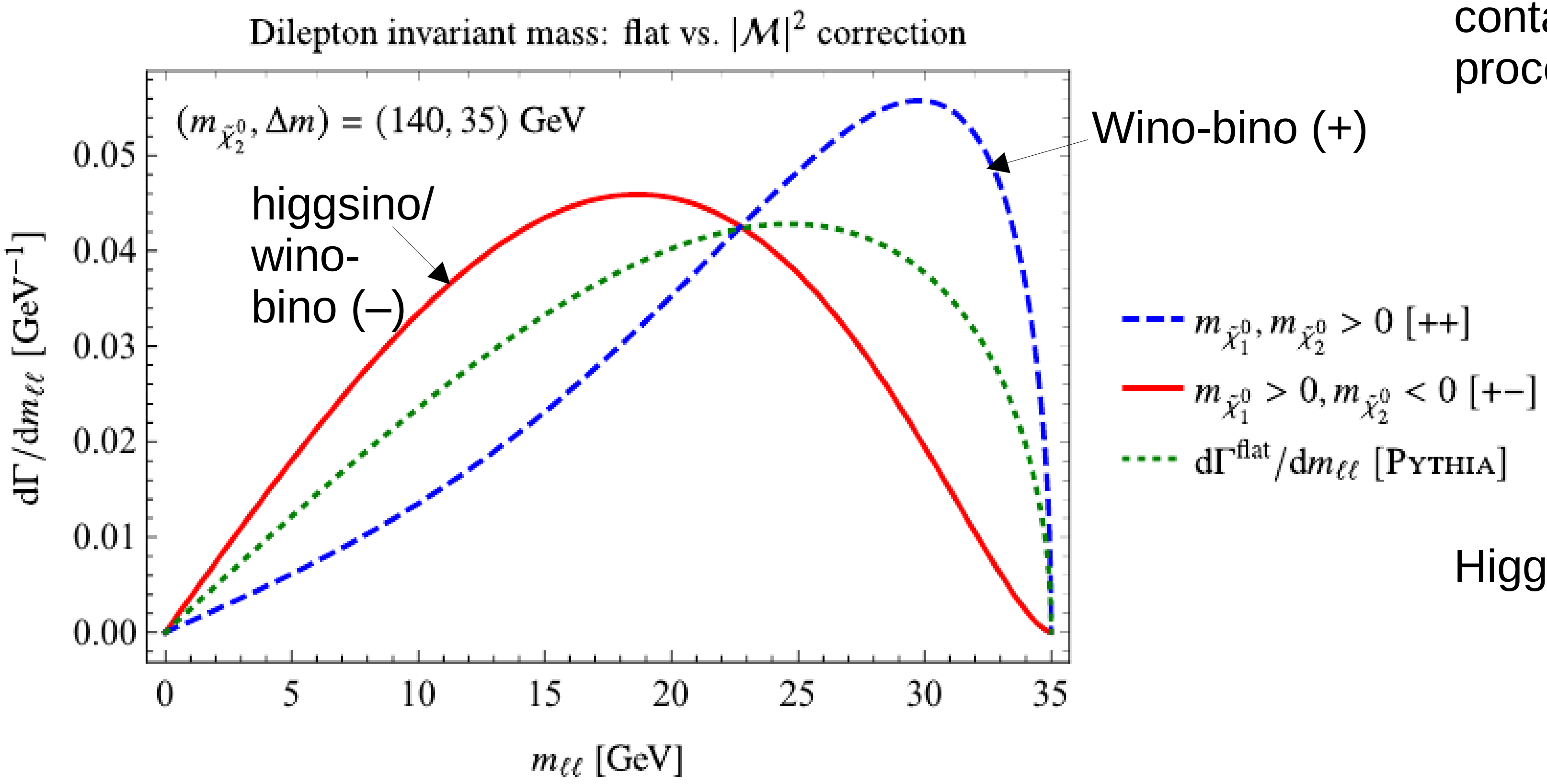
Here we see that the wino-bino fits more poorly
because of the extra leptons and different distribution

Models for the excesses

- Which MSSM scenario is better: higgsino or wino/bino?
- Other SUSY models?
- Non-SUSY models?
- Can we add dark matter?
- Could they be ruled out by other constraints/searches (e.g. multijets?)
- Could they also explain other anomalies?

Different particles have decays have different distributions of lepton invariant mass:

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \ell^- + \ell^+$$



higgsino/
wino-
bino (–)

Wino-bino (+)

This is important because some bins have (large) under-fluctuations.

Also wino-bino model contains only the process with charginos:

$$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$$

Higgsino also contains:

$$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$$

Application 1: realistic MSSM models

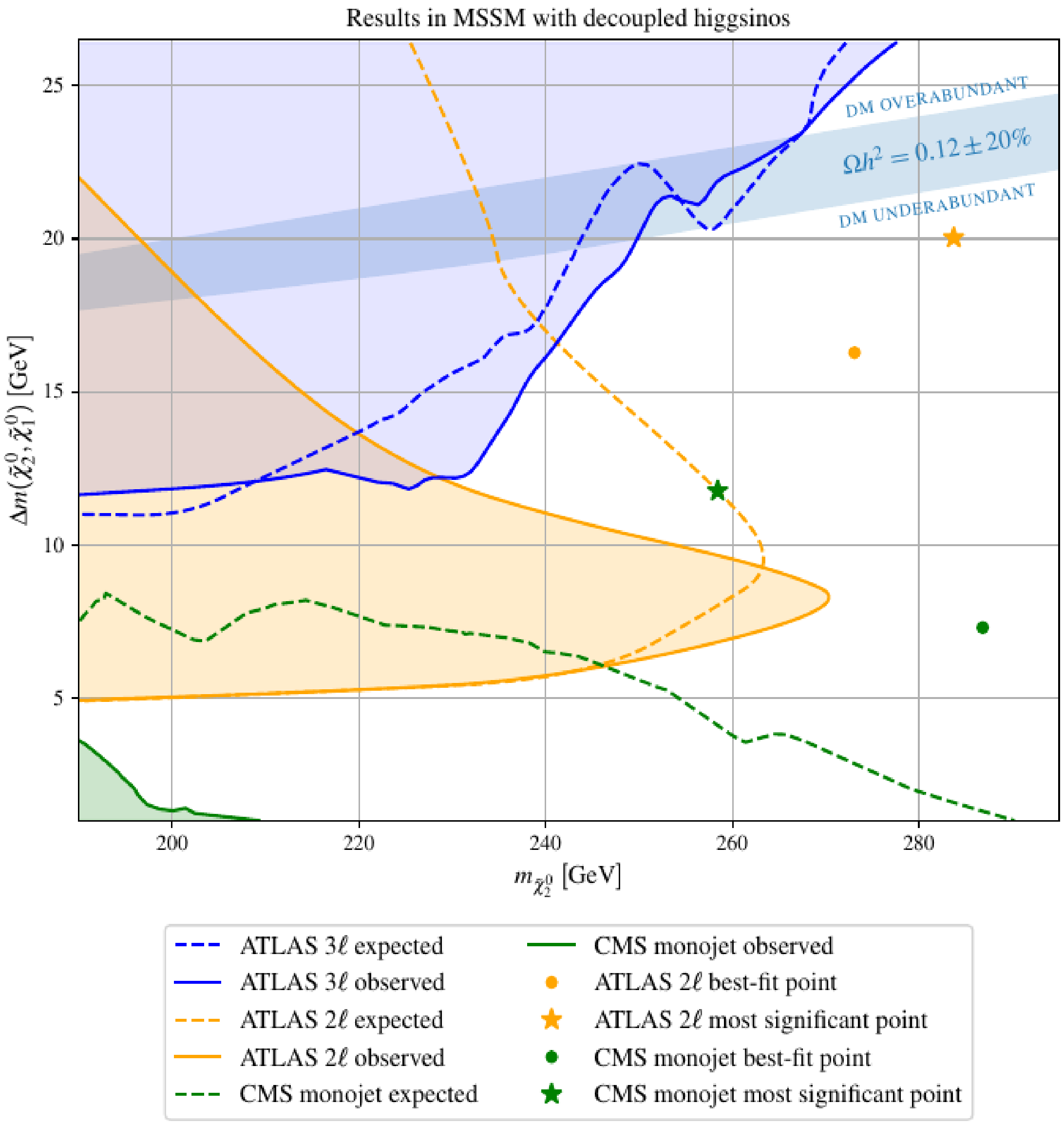
- Typical cross-sections for EWinos around 200 GeV are about 1pb
- Searches are therefore sensitive to efficiencies around $10^{-4} - 10^{-5}$
- In toy higgsino model, decay of Z → leptons with ~ 10% branching ratio
- When generating samples for the toy model, can bias event generation – only need to simulate O(1M) events to get sufficient statistics:

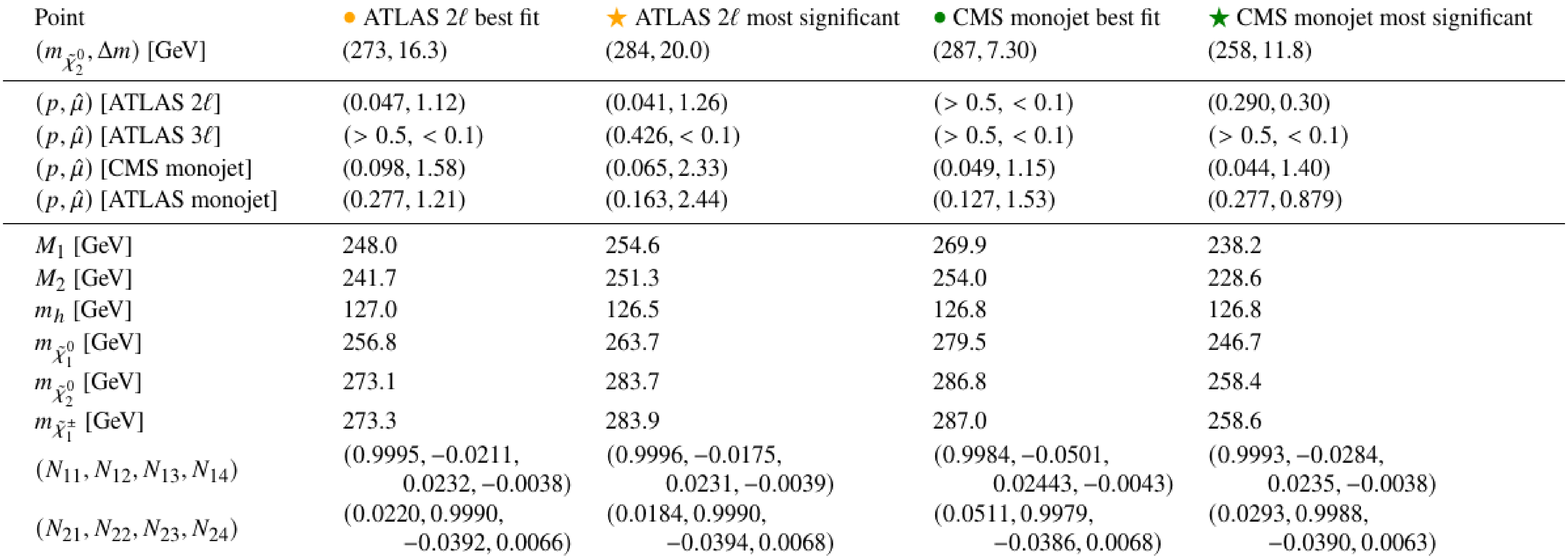
$$\text{rel. uncert.} = \frac{1}{\sqrt{\epsilon N}} \longrightarrow N \sim 0.01/\epsilon \text{ for } 10\%$$

BUT:

- Realistic MSSM points have complicated decay chains involving intermediate EWinos.
- End up having to simulate O(10M) events per point (lose half from MLM matching too)
- Had to develop machinery to efficiently handle this throughput!

We examined ‘realistic’ wino-bino points, now with all three analyses:



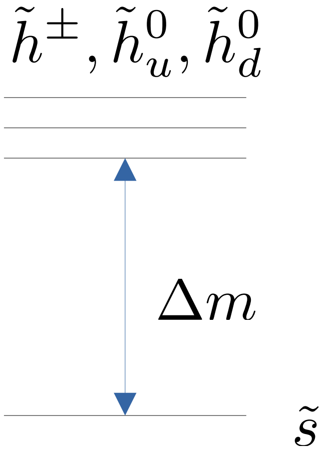


Point	● ATLAS 2ℓ best fit	★ ATLAS 2ℓ most significant	● CMS monojet best fit	★ CMS monojet most significant
$(m_{\tilde{\chi}_2^0}, \Delta m)$ [GeV]	(273, 16.3)	(284, 20.0)	(287, 7.30)	(258, 11.8)
$(p, \hat{\mu})$ [ATLAS 2ℓ]	(0.047, 1.12)	(0.041, 1.26)	(> 0.5, < 0.1)	(0.290, 0.30)
$(p, \hat{\mu})$ [ATLAS 3ℓ]	(> 0.5, < 0.1)	(0.426, < 0.1)	(> 0.5, < 0.1)	(> 0.5, < 0.1)
$(p, \hat{\mu})$ [CMS monojet]	(0.098, 1.58)	(0.065, 2.33)	(0.049, 1.15)	(0.044, 1.40)
$(p, \hat{\mu})$ [ATLAS monojet]	(0.277, 1.21)	(0.163, 2.44)	(0.127, 1.53)	(0.277, 0.879)
M_1 [GeV]	248.0	254.6	269.9	238.2
M_2 [GeV]	241.7	251.3	254.0	228.6
m_h [GeV]	127.0	126.5	126.8	126.8
$m_{\tilde{\chi}_1^0}$ [GeV]	256.8	263.7	279.5	246.7
$m_{\tilde{\chi}_2^0}$ [GeV]	273.1	283.7	286.8	258.4
$m_{\tilde{\chi}_1^\pm}$ [GeV]	273.3	283.9	287.0	258.6
$(N_{11}, N_{12}, N_{13}, N_{14})$	(0.9995, −0.0211, 0.0232, −0.0038)	(0.9996, −0.0175, 0.0231, −0.0039)	(0.9984, −0.0501, 0.02443, −0.0043)	(0.9993, −0.0284, 0.0235, −0.0038)
$(N_{21}, N_{22}, N_{23}, N_{24})$	(0.0220, 0.9990, −0.0392, 0.0066)	(0.0184, 0.9990, −0.0394, 0.0068)	(0.0511, 0.9979, −0.0386, 0.0068)	(0.0293, 0.9988, −0.0390, 0.0063)

Now we can start to quantify complementarity of the excesses ...

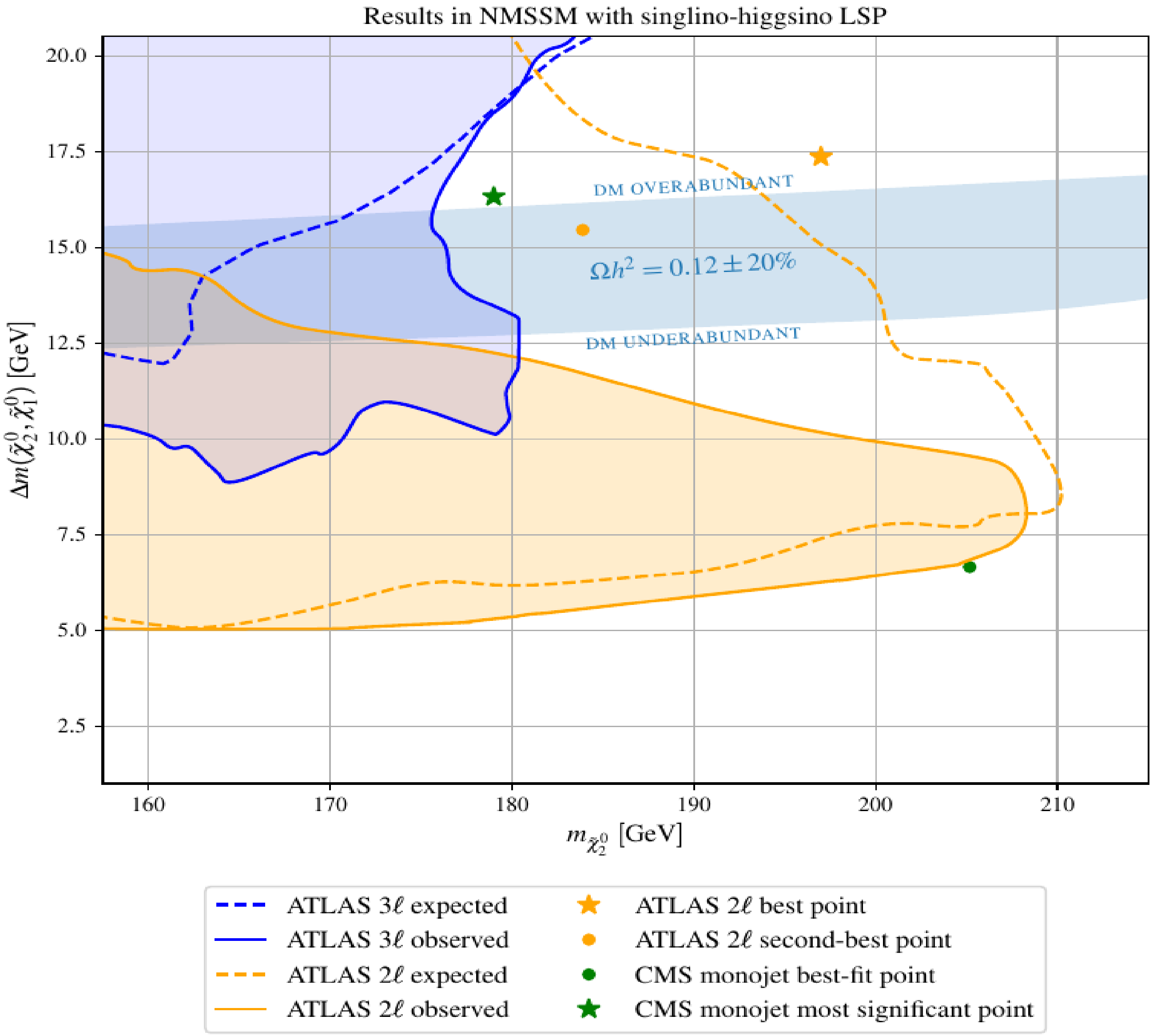
NMSSM scenario

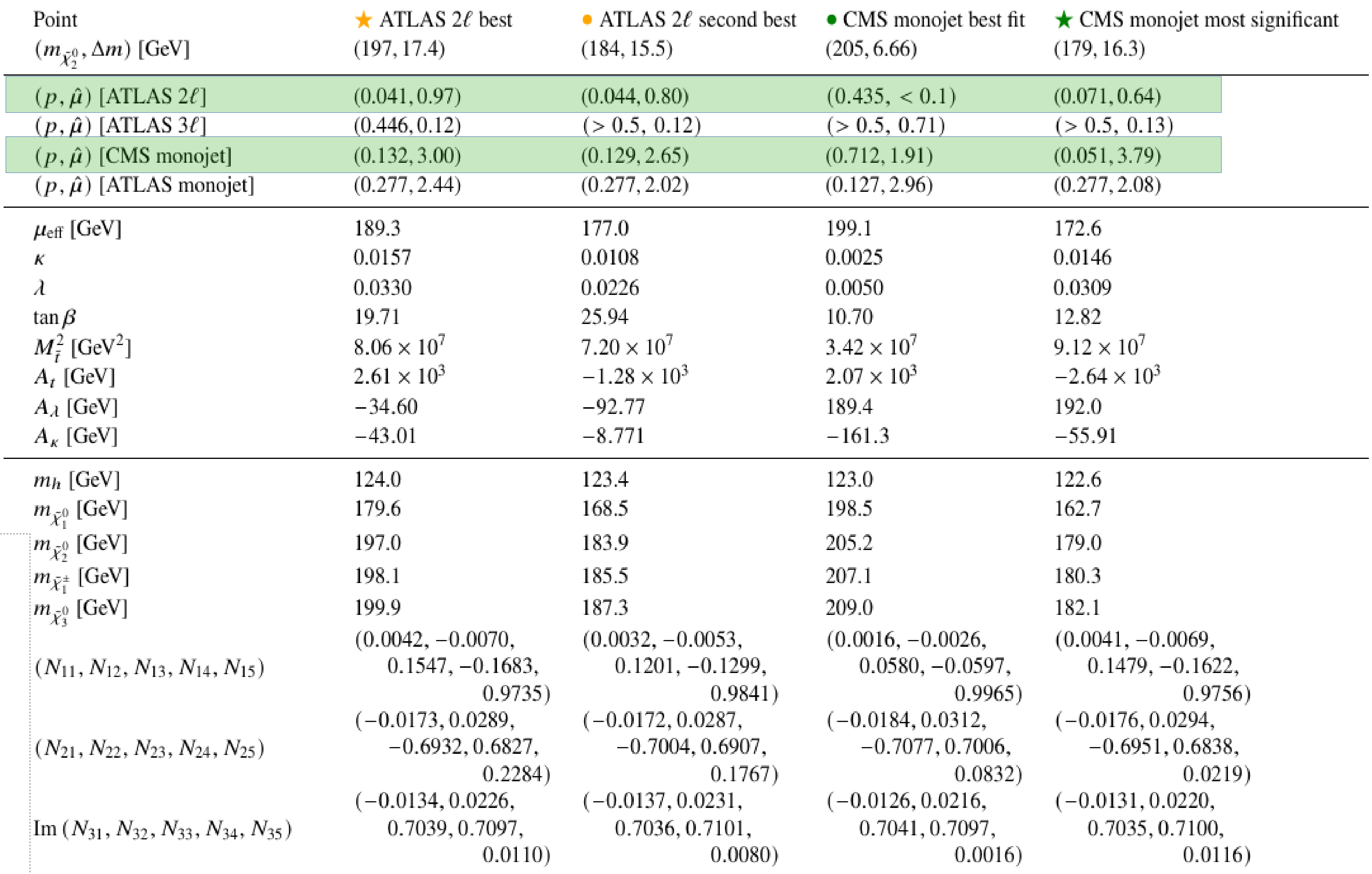
Singlino LSP with roughly degenerate higgsinos



This allows DM and lots of soft leptons …

… but worsens fit for monojets



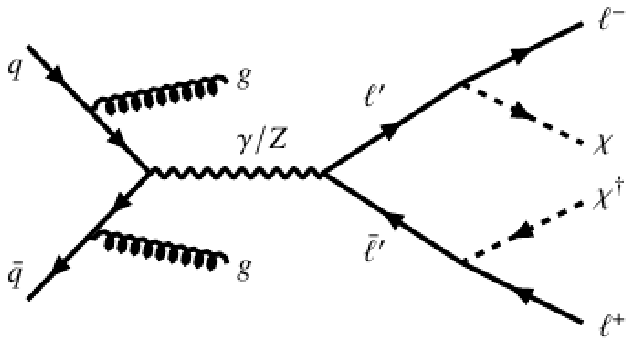


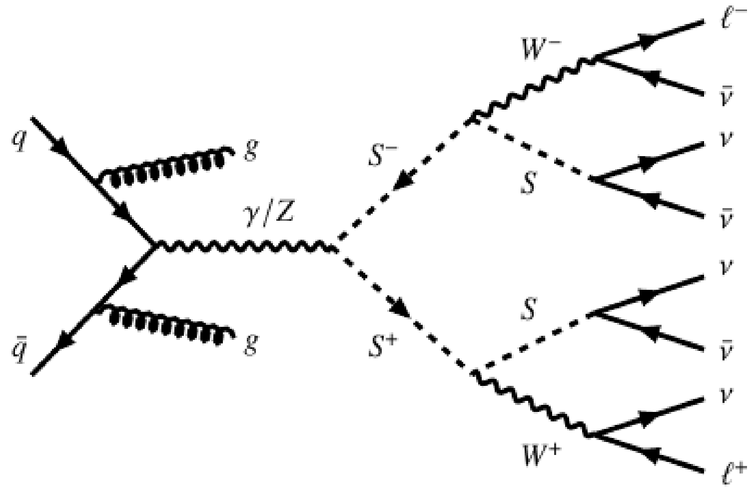
Point	★ ATLAS 2ℓ best	● ATLAS 2ℓ second best	● CMS monojet best fit	★ CMS monojet most significant
$(m_{\tilde{\chi}_2^0}, \Delta m)$ [GeV]	$(197, 17.4)$	$(184, 15.5)$	$(205, 6.66)$	$(179, 16.3)$
$(p, \hat{\mu})$ [ATLAS 2ℓ]	$(0.041, 0.97)$	$(0.044, 0.80)$	$(0.435, <0.1)$	$(0.071, 0.64)$
$(p, \hat{\mu})$ [ATLAS 3ℓ]	$(0.446, 0.12)$	$(>0.5, 0.12)$	$(>0.5, 0.71)$	$(>0.5, 0.13)$
$(p, \hat{\mu})$ [CMS monojet]	$(0.132, 3.00)$	$(0.129, 2.65)$	$(0.712, 1.91)$	$(0.051, 3.79)$
$(p, \hat{\mu})$ [ATLAS monojet]	$(0.277, 2.44)$	$(0.277, 2.02)$	$(0.127, 2.96)$	$(0.277, 2.08)$
$\mu_{\rm eff}$ [GeV]	189.3	177.0	199.1	172.6
κ	0.0157	0.0108	0.0025	0.0146
λ	0.0330	0.0226	0.0050	0.0309
$\tan\beta$	19.71	25.94	10.70	12.82
$M_{\tilde{t}}^2$ [GeV^2]	8.06×10^7	7.20×10^7	3.42×10^7	9.12×10^7
A_t [GeV]	2.61×10^3	-1.28×10^3	2.07×10^3	-2.64×10^3
A_λ [GeV]	-34.60	-92.77	189.4	192.0
A_κ [GeV]	-43.01	-8.771	-161.3	-55.91
m_h [GeV]	124.0	123.4	123.0	122.6
$m_{\tilde{\chi}_1^0}$ [GeV]	179.6	168.5	198.5	162.7
$m_{\tilde{\chi}_2^0}$ [GeV]	197.0	183.9	205.2	179.0
$m_{\tilde{\chi}_1^\pm}$ [GeV]	198.1	185.5	207.1	180.3
$m_{\tilde{\chi}_3^0}$ [GeV]	199.9	187.3	209.0	182.1
$(N_{11}, N_{12}, N_{13}, N_{14}, N_{15})$	$(0.0042, -0.0070, 0.1547, -0.1683, 0.9735)$	$(0.0032, -0.0053, 0.1201, -0.1299, 0.9841)$	$(0.0016, -0.0026, 0.0580, -0.0597, 0.9965)$	$(0.0041, -0.0069, 0.1479, -0.1622, 0.9756)$
$(N_{21}, N_{22}, N_{23}, N_{24}, N_{25})$	$(-0.0173, 0.0289, -0.6932, 0.6827, 0.2284)$	$(-0.0172, 0.0287, -0.7004, 0.6907, 0.1767)$	$(-0.0184, 0.0312, -0.7077, 0.7006, 0.0832)$	$(-0.0176, 0.0294, -0.6951, 0.6838, 0.0219)$
$\mathrm{Im}\,(N_{31}, N_{32}, N_{33}, N_{34}, N_{35})$	$(-0.0134, 0.0226, 0.7039, 0.7097, 0.0110)$	$(-0.0137, 0.0231, 0.7036, 0.7101, 0.0080)$	$(-0.0126, 0.0216, 0.7041, 0.7097, 0.0016)$	$(-0.0131, 0.0220, 0.7035, 0.7100, 0.0116)$

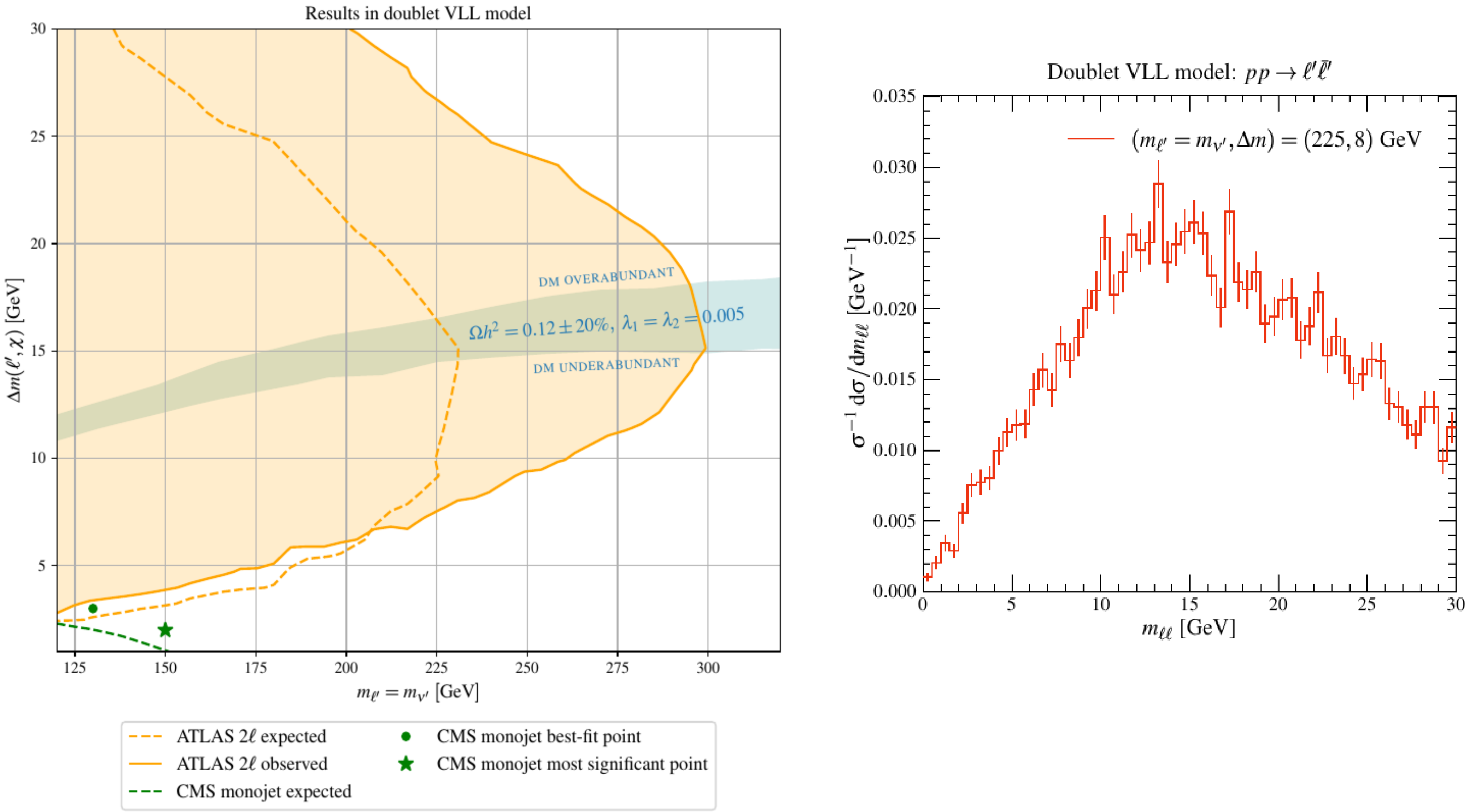
A different hierarchy with smaller singlino-chargino splitting like 2404.19338 (Ellwanger et al) might give better results: to be continued!

Non-SUSY models?

- Scalar DM with vector-like leptons
- Type-II see-saw model
- These ***generically fit worse than the SUSY models***






Results in doublet VLL model
$\Delta m(\ell',\chi)$ [GeV]
30
25
20
15
10
5
125
150
175
200
225
250
275
300
$m_{\ell'} = m_{\nu'}$ [GeV]
DM OVERABUNDANT
$\Omega h^2 = 0.12 \pm 20\%,\ \lambda_1 = \lambda_2 = 0.005$
DM UNDERABUNDANT
ATLAS 2ℓ expected
ATLAS 2ℓ observed
CMS monojet expected
CMS monojet best-fit point
CMS monojet most significant point
Doublet VLL model: $pp \to \ell'\bar{\ell}'$
$(m_{\ell'} = m_{\nu'}, \Delta m) = (225, 8)$ GeV
$\sigma^{-1}\, d\sigma/dm_{\ell\ell}$ [GeV^{-1}]
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
5
10
15
20
25
30
$m_{\ell\ell}$ [GeV]

Frustrated DM model

2409.03014, with Benj Fuks & Taylor Murphy

- Consider now a model with an electroweak triplet scalar Δ.
- This model has been shown to explain a possible excess in diphotons at 152 GeV at 4.3σ (2404.14492)
- Such a model would not produce monojets.
- But it could have a natural coupling to a vector-like pair of triplet fermions T and $\bar{T}$
- And an interesting coupling to a Dirac singlet fermion X, $\bar{X}$.

$$V(\Phi,\Delta) = \mu^2|\Phi|^2 + \frac{1}{2}\lambda(\Phi^\dagger\Phi)^2 + \frac{1}{2}\mu_\Delta^2\,\mathrm{tr}\,\Delta^2 + \frac{1}{4}\lambda_\Delta\,\mathrm{tr}\,\Delta^4 + \sqrt{2}\delta_\Delta\Phi^\dagger\Delta\Phi + \frac{1}{2}\kappa_\Delta\,\Phi^\dagger\Phi\,\mathrm{tr}\,\Delta^2.$$

$$-\mathcal{L}_{\mathrm{int}} = y_T\,\mathrm{tr}\,\bar{T}\Delta T + y_X\bar{X}\,\mathrm{tr}\,\Delta T + \mathrm{H.c.},$$

This model should fit the data much better than the SM ...

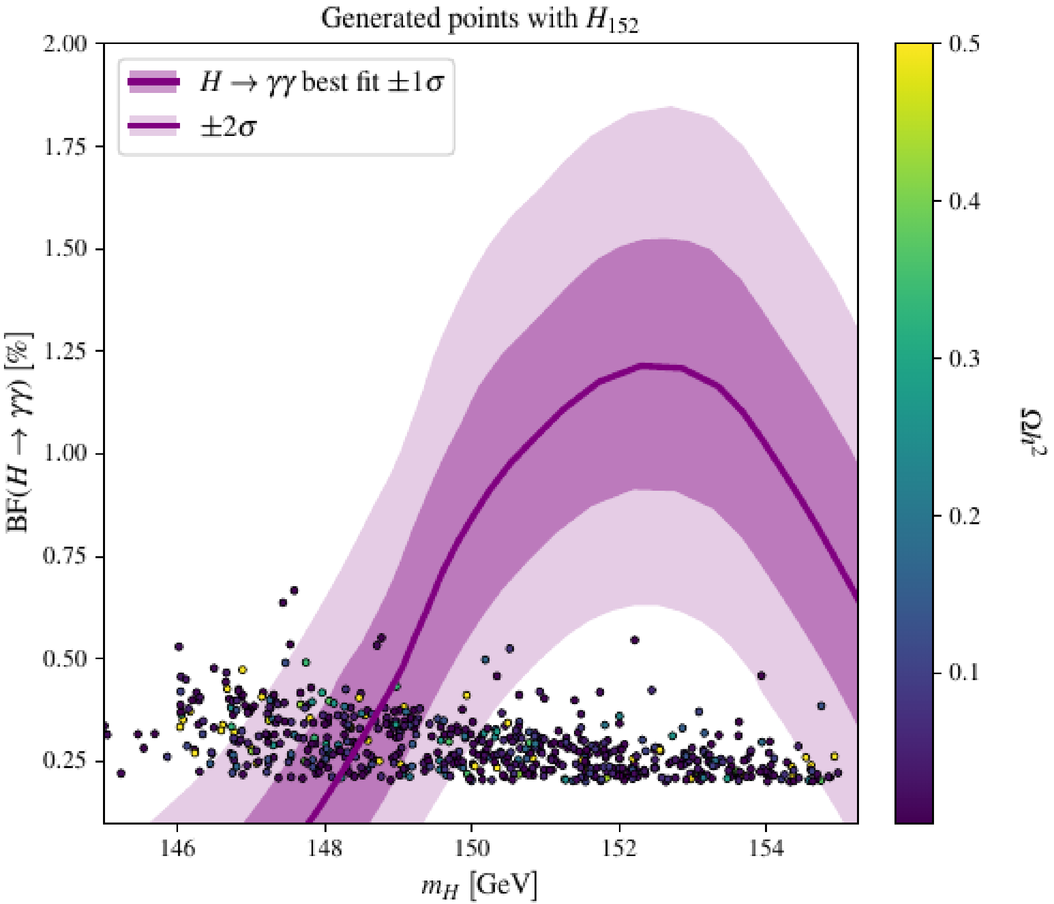
Frustrated DM

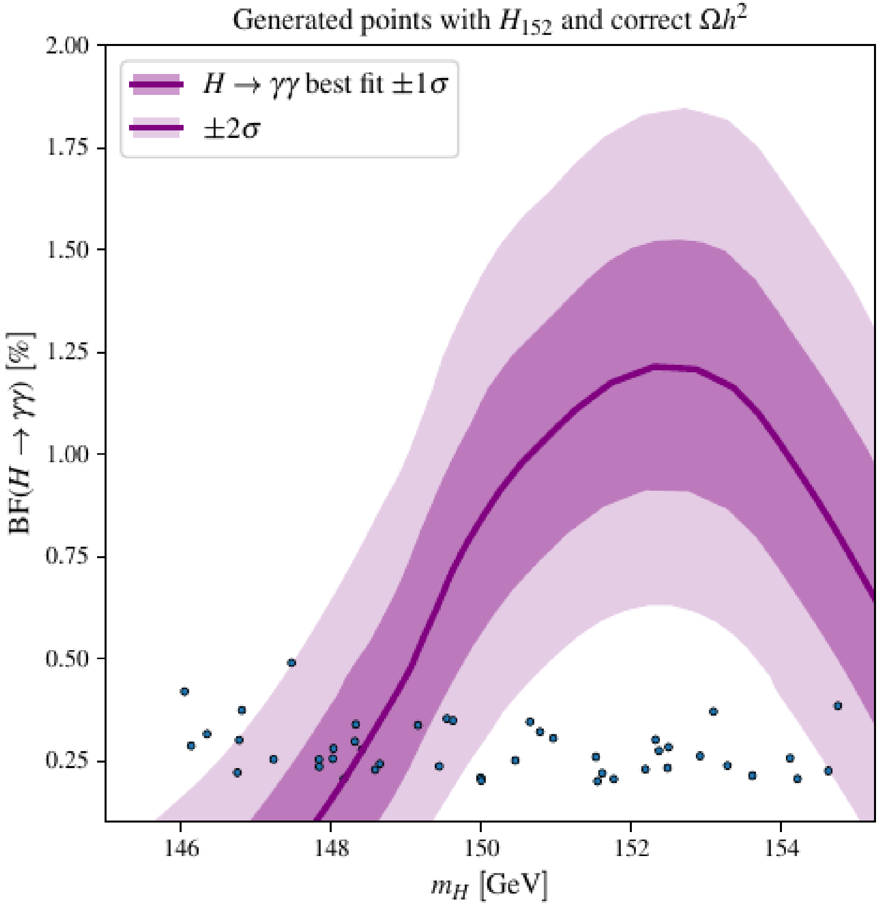
- Introduced in 2205.06824 (Carpenter & Murphy)
- Models where it is not possible to write down a direct interaction between SM *fermions* and DM at tree level
- Original model involved sextets; in our case the triplet can only couple to the Higgs in the SM sector.

Scanned the parameter space with BSMArt using HiggsTools + MicrOMEGAs

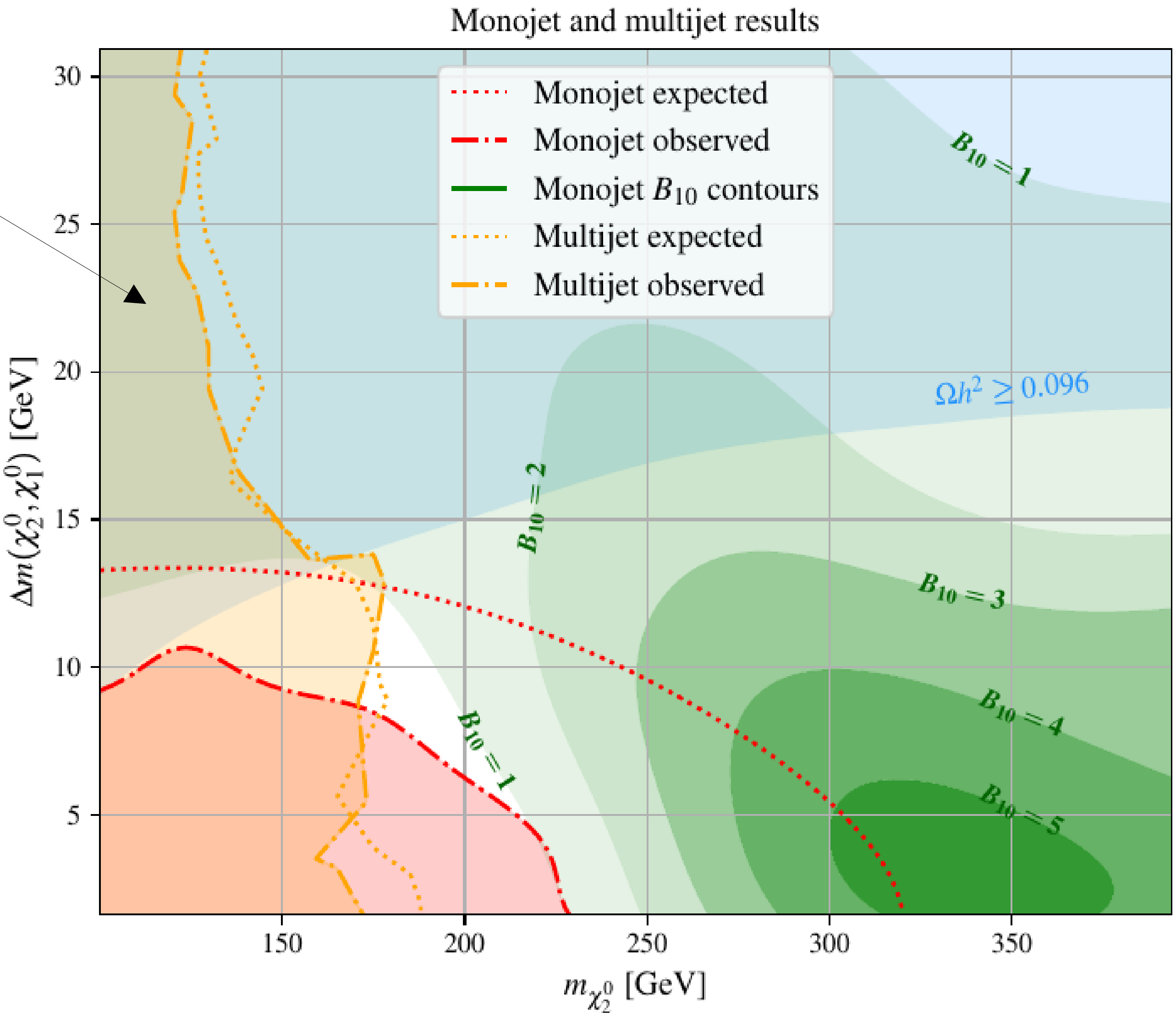
$$\begin{aligned} \lambda &\in [0.2, 0.3], & \lambda_\Delta &\in [0, 3.5], \\ \delta_\Delta &\in [0, 2]\ \text{GeV}, & \kappa_\Delta &\in [0, 3.5], \\ v_\Delta &\in [1, 10]\ \text{GeV}, & y_T &\in [0, 1], \\ y_X &\in [0, 1], & m_X &\in [95, 400]\ \text{GeV}, \end{aligned}$$

and $m_T \in [96, 435]$ GeV such that $m_T - m_X \in [1, 35]$ GeV.





The CMS multijet recast in MadAnalysis cuts out an uninteresting portion of the parameter space – it is rather complementary to the monojets!



Using the monojet recast in HackAnalysis we can generate enough events to get smooth Bayes factor contours using spey!

We refrain from being too sensationalist and doing a combined fit with the triplet to diphoton significance!

Conclusions

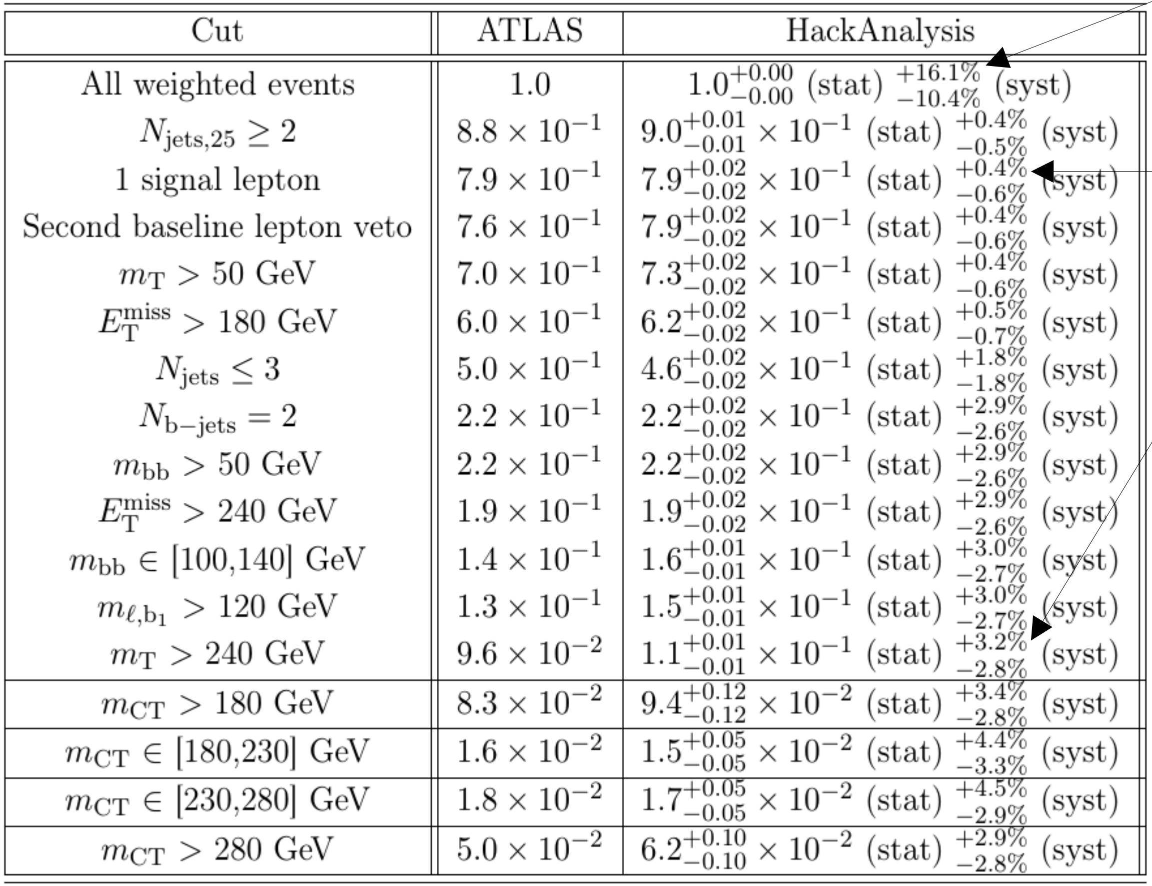
- Have 4 independent analyses with 1 – 3σ excesses that are compatible!
- We focussed first on one Higgsino scenario because it is simplest, but it is a fake model: has no DM; to get mass splitting need bino/wino component, which changes the cross-sections etc.
- ATLAS + CMS both also considered a bino-wino scenario which is similarly fake
- We examined several realistic SUSY scenarios including DM – but far from exhaustively.
- Non-SUSY models tend to work worse! (This was a surprise).
- So far we have found *no non-SUSY model that works for monojets, soft leptons and DM! (except of course from a copy of the SUSY spectrum).*
- Did find an interesting model with DM, monojets and also explains the 152 GeV excess!
- Have shown that multijet searches *don't cover the interesting regions of parameter space.*

Outlook

- Want more and better models!
- Clearly need MET + jet(s) [but how much?]
- Are these excesses heralds of SUSY?!!
- Need to finish recasting the CMS soft lepton search.
- Then we can combine significances for everything (modulo technical challenges).
- Also porting all recasts to MadAnalysis (available soon!)

BACKUP

Automatic systematic uncertainties, TeX outputs:

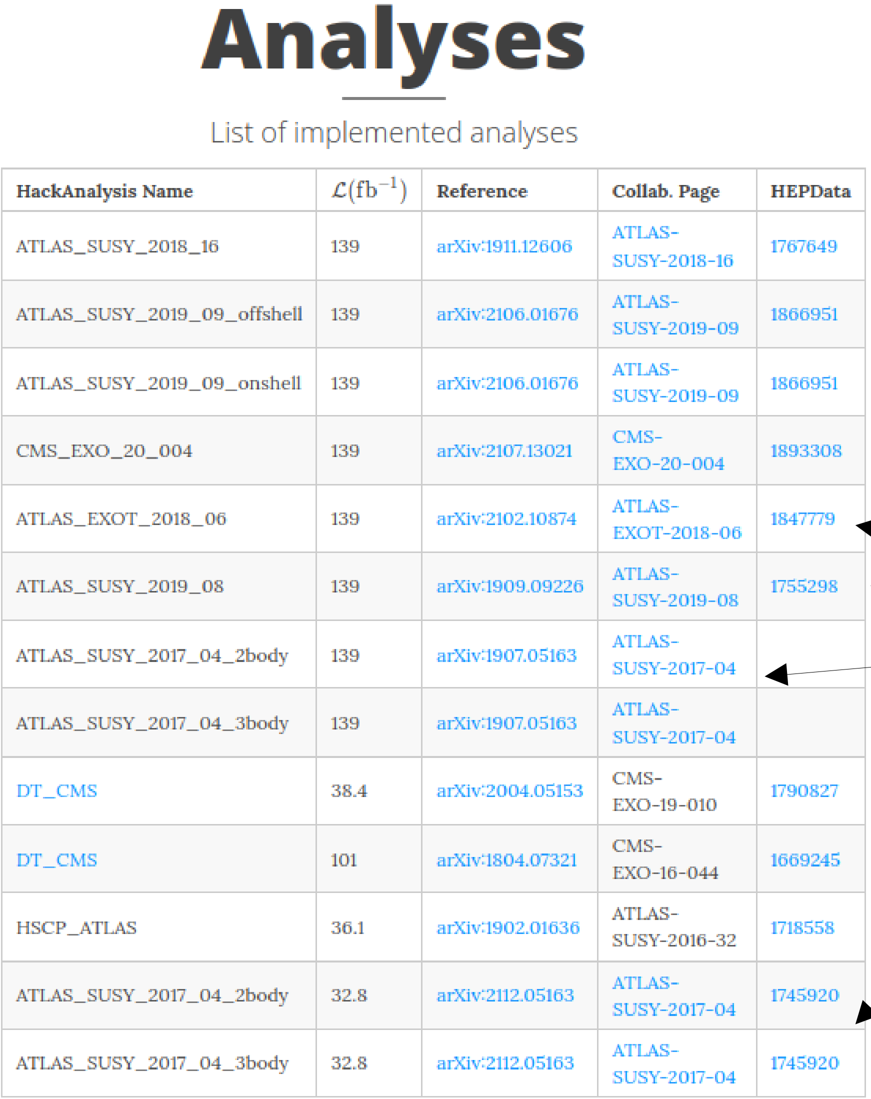


Cut	ATLAS	HackAnalysis
All weighted events	1.0	$1.0^{+0.00}_{-0.00}$ (stat) $^{+16.1\%}_{-10.4\%}$ (syst)
$N_{\text{jets},25} \geq 2$	8.8×10^{-1}	$9.0^{+0.01}_{-0.01} \times 10^{-1}$ (stat) $^{+0.4\%}_{-0.5\%}$ (syst)
1 signal lepton	7.9×10^{-1}	$7.9^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+0.4\%}_{-0.6\%}$ (syst)
Second baseline lepton veto	7.6×10^{-1}	$7.9^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+0.4\%}_{-0.6\%}$ (syst)
$m_{\mathrm{T}} > 50$ GeV	7.0×10^{-1}	$7.3^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+0.4\%}_{-0.6\%}$ (syst)
$E_{\mathrm{T}}^{\mathrm{miss}} > 180$ GeV	6.0×10^{-1}	$6.2^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+0.5\%}_{-0.7\%}$ (syst)
$N_{\text{jets}} \leq 3$	5.0×10^{-1}	$4.6^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+1.8\%}_{-1.8\%}$ (syst)
$N_{\text{b}-\text{jets}} = 2$	2.2×10^{-1}	$2.2^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+2.9\%}_{-2.6\%}$ (syst)
$m_{\text{bb}} > 50$ GeV	2.2×10^{-1}	$2.2^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+2.9\%}_{-2.6\%}$ (syst)
$E_{\mathrm{T}}^{\mathrm{miss}} > 240$ GeV	1.9×10^{-1}	$1.9^{+0.02}_{-0.02} \times 10^{-1}$ (stat) $^{+2.9\%}_{-2.6\%}$ (syst)
$m_{\text{bb}} \in [100{,}140]$ GeV	1.4×10^{-1}	$1.6^{+0.01}_{-0.01} \times 10^{-1}$ (stat) $^{+3.0\%}_{-2.7\%}$ (syst)
$m_{\ell,\mathrm{b}_1} > 120$ GeV	1.3×10^{-1}	$1.5^{+0.01}_{-0.01} \times 10^{-1}$ (stat) $^{+3.0\%}_{-2.7\%}$ (syst)
$m_{\mathrm{T}} > 240$ GeV	9.6×10^{-2}	$1.1^{+0.01}_{-0.01} \times 10^{-1}$ (stat) $^{+3.2\%}_{-2.8\%}$ (syst)
$m_{\mathrm{CT}} > 180$ GeV	8.3×10^{-2}	$9.4^{+0.12}_{-0.12} \times 10^{-2}$ (stat) $^{+3.4\%}_{-2.8\%}$ (syst)
$m_{\mathrm{CT}} \in [180{,}230]$ GeV	1.6×10^{-2}	$1.5^{+0.05}_{-0.05} \times 10^{-2}$ (stat) $^{+4.4\%}_{-3.3\%}$ (syst)
$m_{\mathrm{CT}} \in [230{,}280]$ GeV	1.8×10^{-2}	$1.7^{+0.05}_{-0.05} \times 10^{-2}$ (stat) $^{+4.5\%}_{-2.9\%}$ (syst)
$m_{\mathrm{CT}} > 280$ GeV	5.0×10^{-2}	$6.2^{+0.10}_{-0.10} \times 10^{-2}$ (stat) $^{+2.9\%}_{-2.8\%}$ (syst)

Table 3: ATLAS-SUSY-2019-08, Signal regions HM for parameter point $m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0} = (750, 100)$ GeV. The final lines correspond to regions HMdisc,HMlow,HMmed and HMhigh respectively.

First cut: overall systematics

Subsequent cuts: uncertainty on cut efficiency



Analyses

List of implemented analyses

HackAnalysis Name	$\mathcal{L}(\text{fb}^{-1})$	Reference	Collab. Page	HEPData
ATLAS_SUSY_2018_16	139	arXiv:1911.12606	ATLAS-SUSY-2018-16	1767649
ATLAS_SUSY_2019_09_offshell	139	arXiv:2106.01676	ATLAS-SUSY-2019-09	1866951
ATLAS_SUSY_2019_09_onshell	139	arXiv:2106.01676	ATLAS-SUSY-2019-09	1866951
CMS_EXO_20_004	139	arXiv:2107.13021	CMS-EXO-20-004	1893308
ATLAS_EXOT_2018_06	139	arXiv:2102.10874	ATLAS-EXOT-2018-06	1847779
ATLAS_SUSY_2019_08	139	arXiv:1909.09226	ATLAS-SUSY-2019-08	1755298
ATLAS_SUSY_2017_04_2body	139	arXiv:1907.05163	ATLAS-SUSY-2017-04	
ATLAS_SUSY_2017_04_3body	139	arXiv:1907.05163	ATLAS-SUSY-2017-04	
DT_CMS	38.4	arXiv:2004.05153	CMS-EXO-19-010	1790827
DT_CMS	101	arXiv:1804.07321	CMS-EXO-16-044	1669245
HSCP_ATLAS	36.1	arXiv:1902.01636	ATLAS-SUSY-2016-32	1718558
ATLAS_SUSY_2017_04_2body	32.8	arXiv:2112.05163	ATLAS-SUSY-2017-04	1745920
ATLAS_SUSY_2017_04_3body	32.8	arXiv:2112.05163	ATLAS-SUSY-2017-04	1745920

Intention is not to create a competitor database

Idea: prototype + scan in HA2, then export

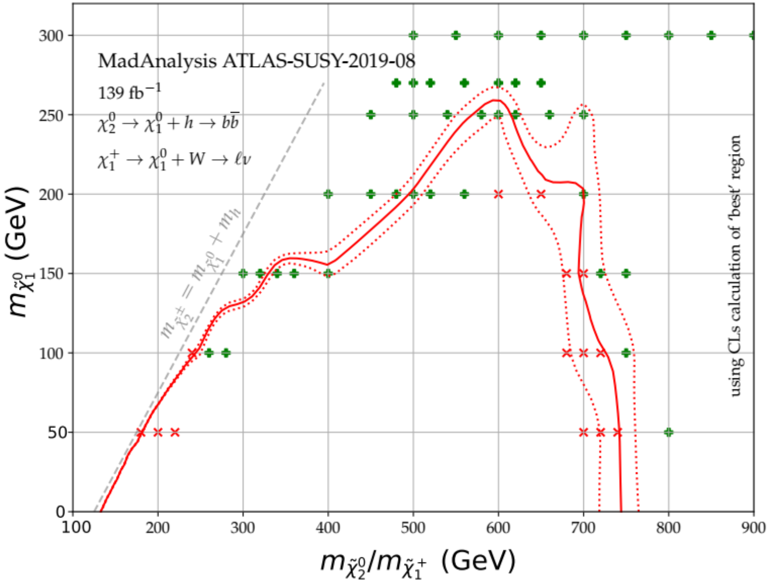
Alternative workflow is I develop the HA2 version at the same time as a MA5 one (e.g. by student …) for cross-checks

Recast of ATLAS-SUSY-2019-08

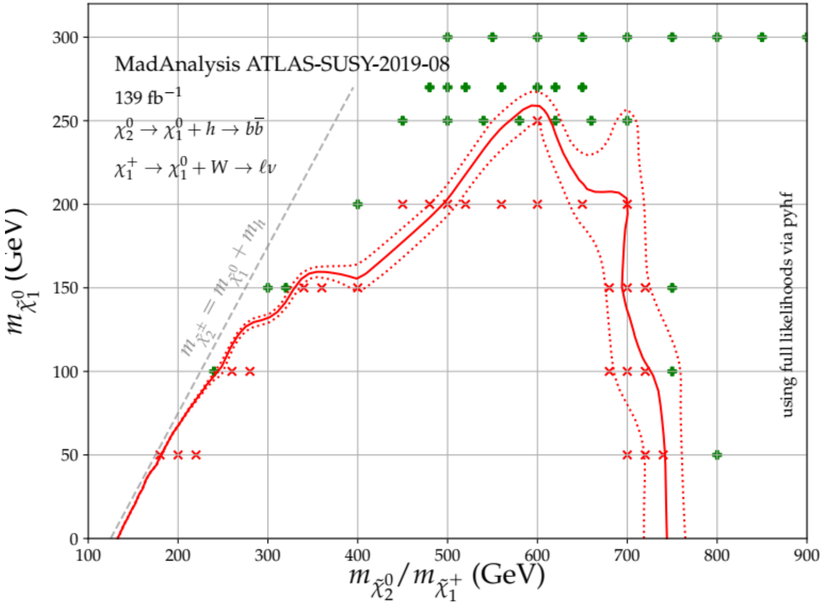
WH signature through Higgs to bb and W to leptons @ 139fb^{-1}

Looked for a Wino NLSP and Bino LSP in **MSSM**

Full likelihoods in pyhf

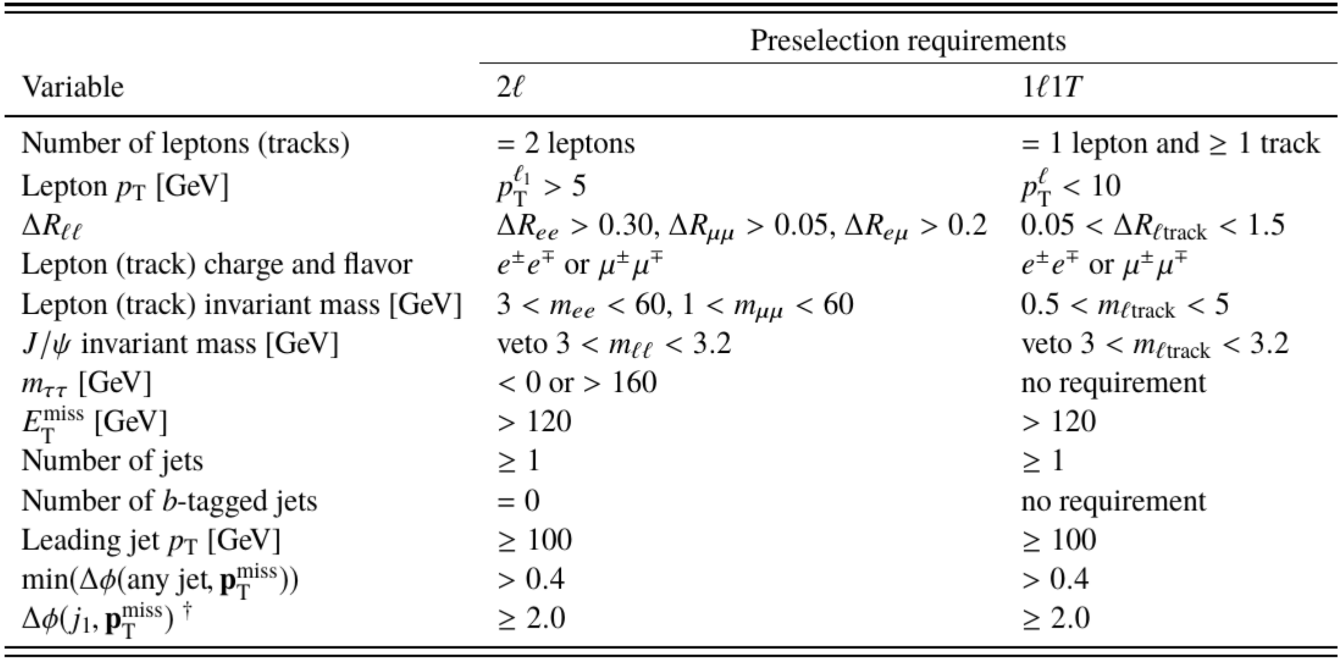


Exclusions using 'best' region

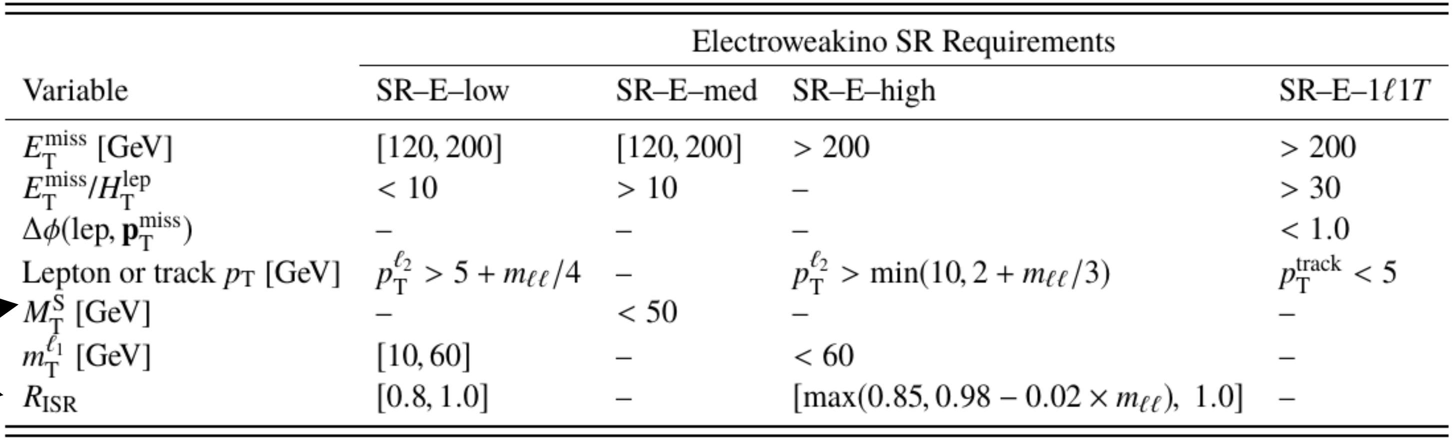


Exclusions using private implementation + pyhf

ATLAS-SUSY-2018-16



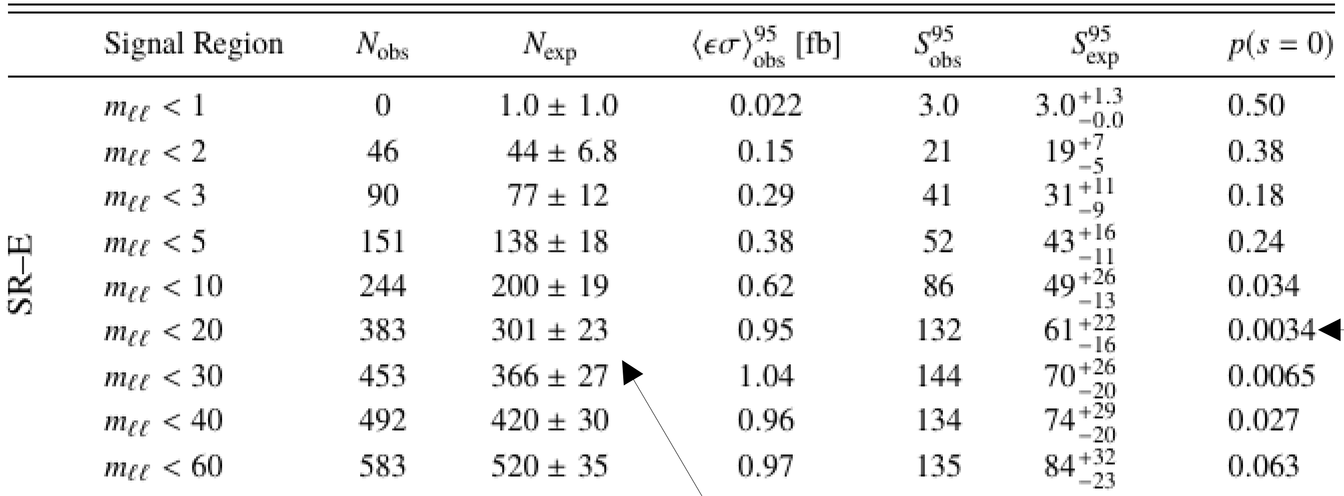
Variable	Preselection requirements	
	2ℓ	$1\ell 1T$
Number of leptons (tracks)	= 2 leptons	= 1 lepton and ≥ 1 track
Lepton p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_1} > 5$	$p_{\mathrm{T}}^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of b-tagged jets	$= 0$	no requirement
Leading jet p_{T} [GeV]	≥ 100	≥ 100
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ †	≥ 2.0	≥ 2.0



Variable	Electroweakino SR Requirements			
	SR–E–low	SR–E–med	SR–E–high	SR–E–$1\ell 1T$
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$[120, 200]$	$[120, 200]$	> 200	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/H_{\mathrm{T}}^{\mathrm{lep}}$	< 10	> 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	–	–	–	< 1.0
Lepton or track p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_2} > 5 + m_{\ell\ell}/4$	–	$p_{\mathrm{T}}^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_{\mathrm{T}}^{\mathrm{track}} < 5$
$M_{\mathrm{T}}^{\mathrm{S}}$ [GeV]	–	< 50	–	–
$m_{\mathrm{T}}^{\ell_1}$ [GeV]	$[10, 60]$	–	< 60	–
R_{ISR}	$[0.8, 1.0]$	–	$[\max(0.85, 0.98 - 0.02 \times m_{\ell\ell}),\ 1.0]$	–

Restframes quantities to identify ISR jet

From ATLAS-SUSY-2018-16



	Signal Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$p(s=0)$
SR–E	$m_{\ell\ell} < 1$	0	1.0 ± 1.0	0.022	3.0	$3.0^{+1.3}_{-0.0}$	0.50
	$m_{\ell\ell} < 2$	46	44 ± 6.8	0.15	21	19^{+7}_{-5}	0.38
	$m_{\ell\ell} < 3$	90	77 ± 12	0.29	41	31^{+11}_{-9}	0.18
	$m_{\ell\ell} < 5$	151	138 ± 18	0.38	52	43^{+16}_{-11}	0.24
	$m_{\ell\ell} < 10$	244	200 ± 19	0.62	86	49^{+26}_{-13}	0.034
	$m_{\ell\ell} < 20$	383	301 ± 23	0.95	132	61^{+22}_{-16}	0.0034
	$m_{\ell\ell} < 30$	453	366 ± 27	1.04	144	70^{+26}_{-20}	0.0065
	$m_{\ell\ell} < 40$	492	420 ± 30	0.96	134	74^{+29}_{-20}	0.027
	$m_{\ell\ell} < 60$	583	520 ± 35	0.97	135	84^{+32}_{-23}	0.063

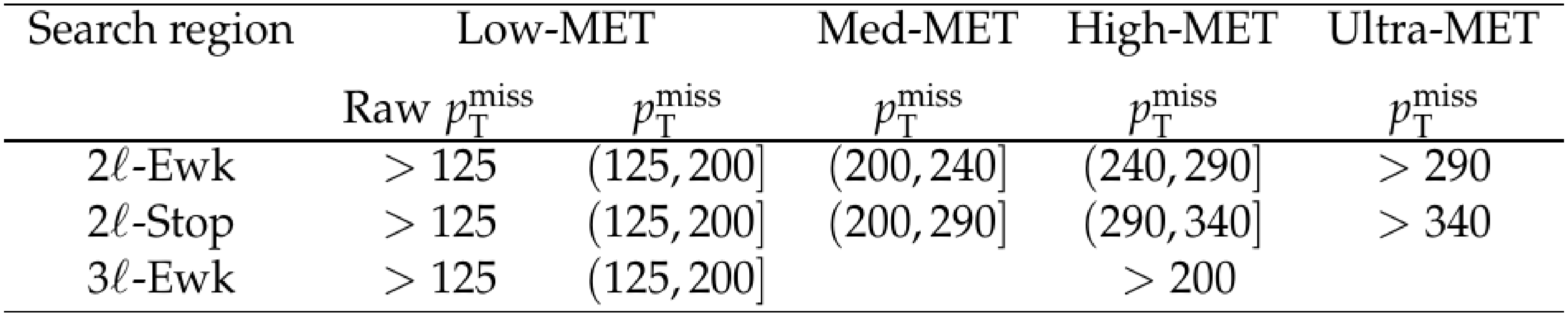
2.7σ local excess for ‘signal model with unconstrained normalisation’

Maybe a different model would give a stronger significance?
(what we’re looking into now ...)

CMS Analysis details

Targets the same W-Z channel, but now ‘all-in-one’ analysis with whole of Run 2 data subsuming preliminary one:

CMS-SUS-18-004



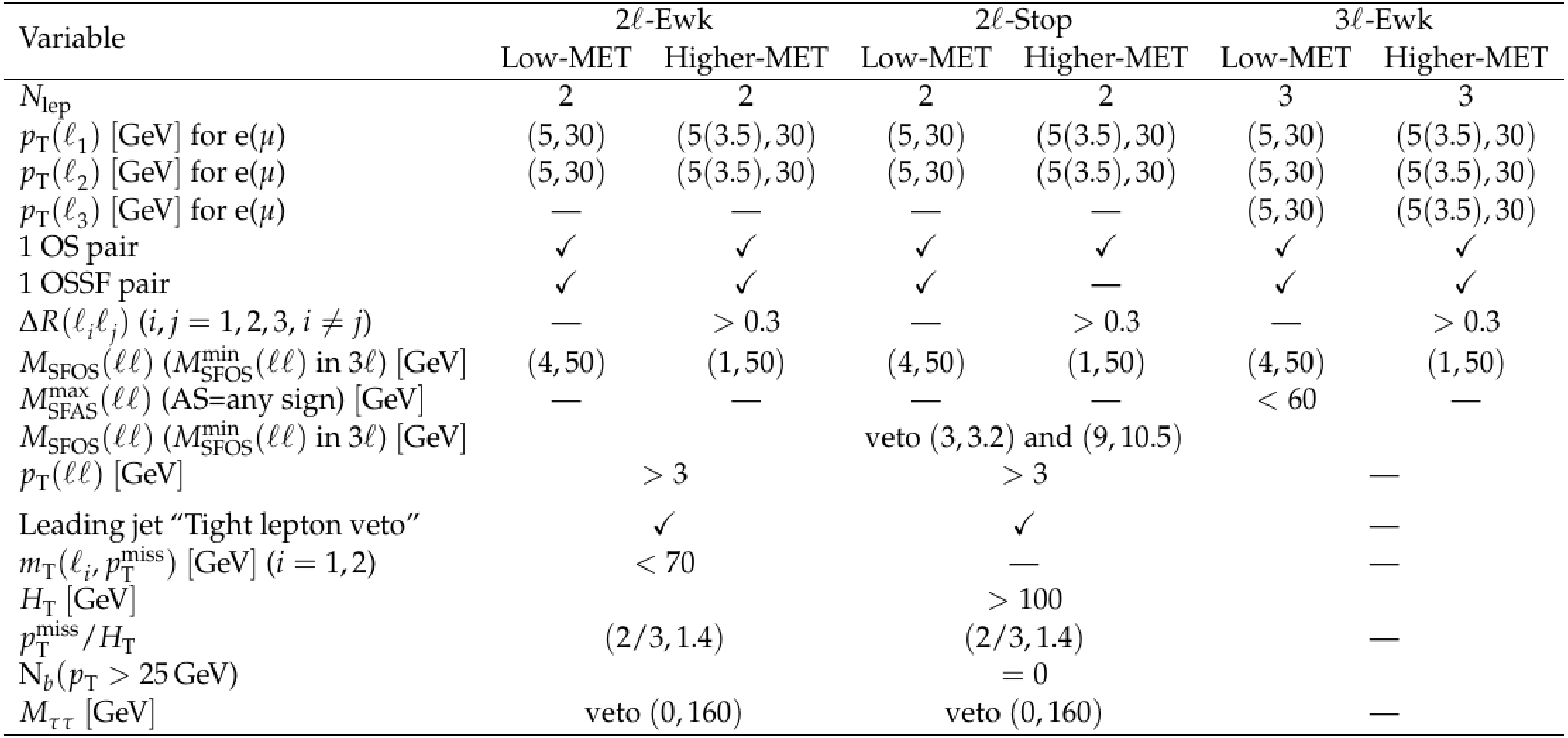
Search region	Low-MET		Med-MET	High-MET	Ultra-MET
	Raw $p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$
2ℓ-Ewk	> 125	$(125, 200]$	$(200, 240]$	$(240, 290]$	> 290
2ℓ-Stop	> 125	$(125, 200]$	$(200, 290]$	$(290, 340]$	> 340
3ℓ-Ewk	> 125	$(125, 200]$	> 200		

Very similar to ATLAS

Except: maximum pT for leptons

…. and no RestFrames

Naively should be more permissive regarding models



Variable	2ℓ-Ewk		2ℓ-Stop		3ℓ-Ewk	
	Low-MET	Higher-MET	Low-MET	Higher-MET	Low-MET	Higher-MET
N_{lep}	2	2	2	2	3	3
$p_{\text{T}}(\ell_1)$ [GeV] for e(μ)	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$
$p_{\text{T}}(\ell_2)$ [GeV] for e(μ)	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$	$(5, 30)$	$(5(3.5), 30)$
$p_{\text{T}}(\ell_3)$ [GeV] for e(μ)	—	—	—	—	$(5, 30)$	$(5(3.5), 30)$
1 OS pair	✓	✓	✓	✓	✓	✓
1 OSSF pair	✓	✓	✓	—	✓	✓
$\Delta R(\ell_i \ell_j)$ $(i, j = 1, 2, 3, i \neq j)$	—	> 0.3	—	> 0.3	—	> 0.3
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]	$(4, 50)$	$(1, 50)$	$(4, 50)$	$(1, 50)$	$(4, 50)$	$(1, 50)$
$M^{\text{max}}_{\text{SFAS}}(\ell\ell)$ (AS=any sign) [GeV]	—	—	—	—	< 60	—
$M_{\text{SFOS}}(\ell\ell)$ ($M^{\text{min}}_{\text{SFOS}}(\ell\ell)$ in 3ℓ) [GeV]	veto $(3, 3.2)$ and $(9, 10.5)$					
$p_{\text{T}}(\ell\ell)$ [GeV]	> 3		> 3		—	
Leading jet "Tight lepton veto"	✓		✓		—	
$m_{\text{T}}(\ell_i, p_{\text{T}}^{\text{miss}})$ [GeV] $(i = 1, 2)$	< 70		—		—	
H_{T} [GeV]	> 100					
$p_{\text{T}}^{\text{miss}} / H_{\text{T}}$	$(2/3, 1.4)$		$(2/3, 1.4)$		—	
$\text{N}_b(p_{\text{T}} > 25\,\text{GeV})$	$= 0$					
$M_{\tau\tau}$ [GeV]	veto $(0, 160)$		veto $(0, 160)$		—	