ATLAS pMSSM efforts

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A typical ATLAS Summary plot

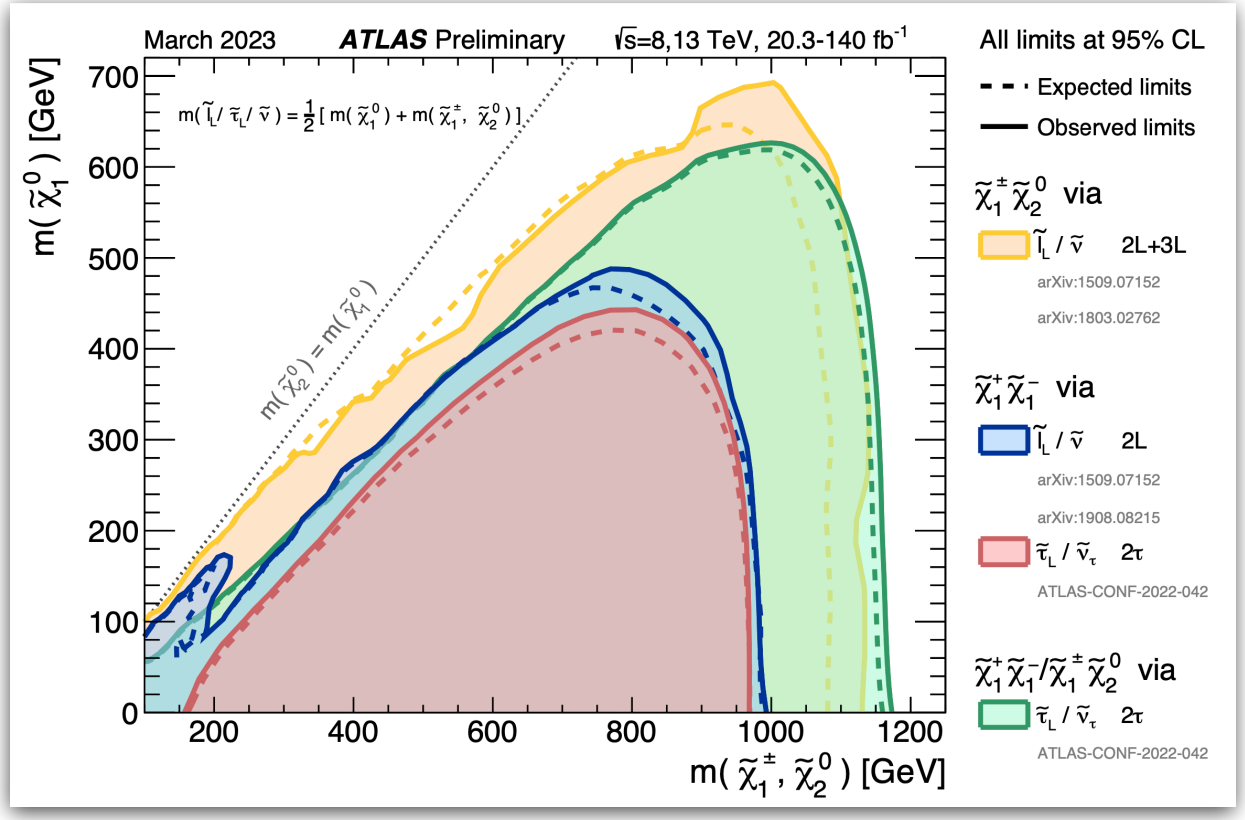
Question: What does this plot mean for ATLAS coverage of SUSY?

Very difficult to answer!

1. Rely on specific simplified models
   - fixed masses and BFs
2. Can be different between searches

Compare in bigger parameter space

- Re-interpret results in (19d)-pMSSM



[src1], [src2]

Re-interpret results in higher dimensions

[src1], [src2]

Re-interpret results in higher dimensions

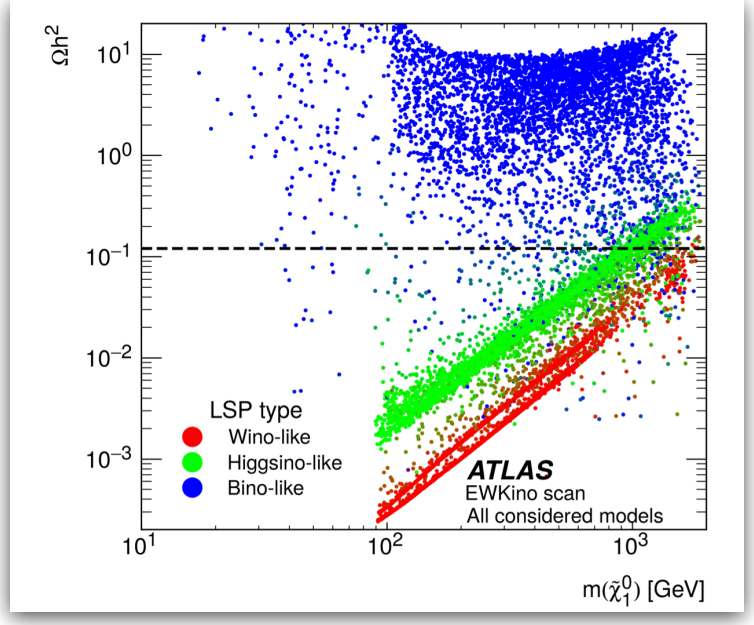
There may be holes in our map!

→ Design new searches to fill them

JHEP 2024 (2024) 106

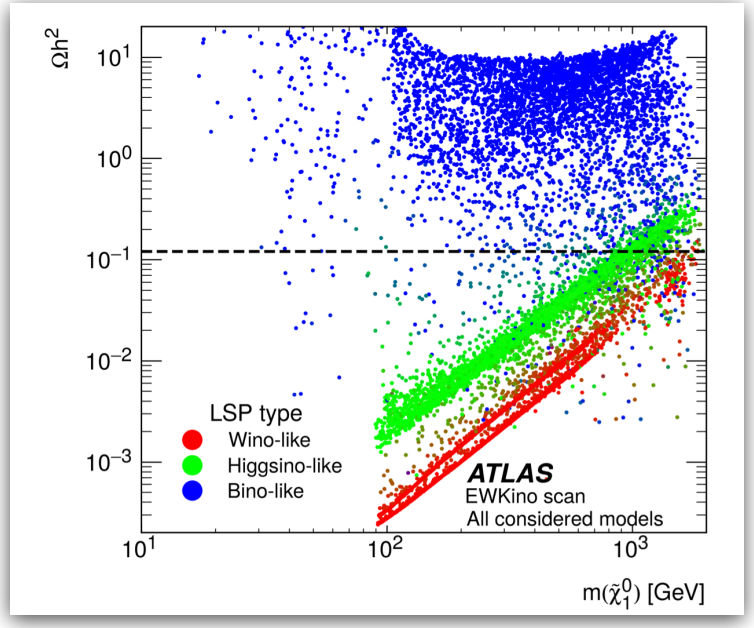
How to ATLAS pMSSM in Four Easy Steps

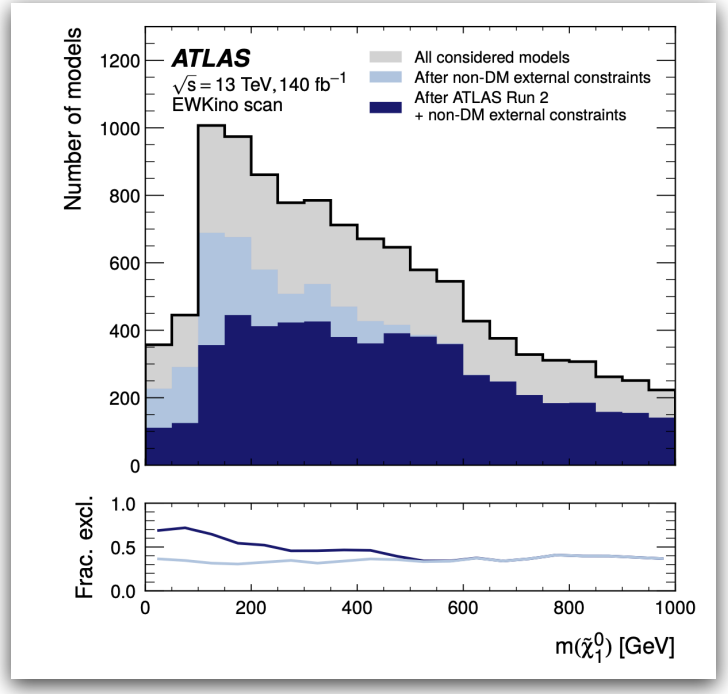
1. Fill pMSSM parameter space with models (random flat prior)



How to ATLAS pMSSM in Four Easy Steps

1. Fill pMSSM parameter space with models (random flat prior)
2. Evaluate ATLAS' sensitivity to each model





How to ATLAS pMSSM in Four Easy Steps

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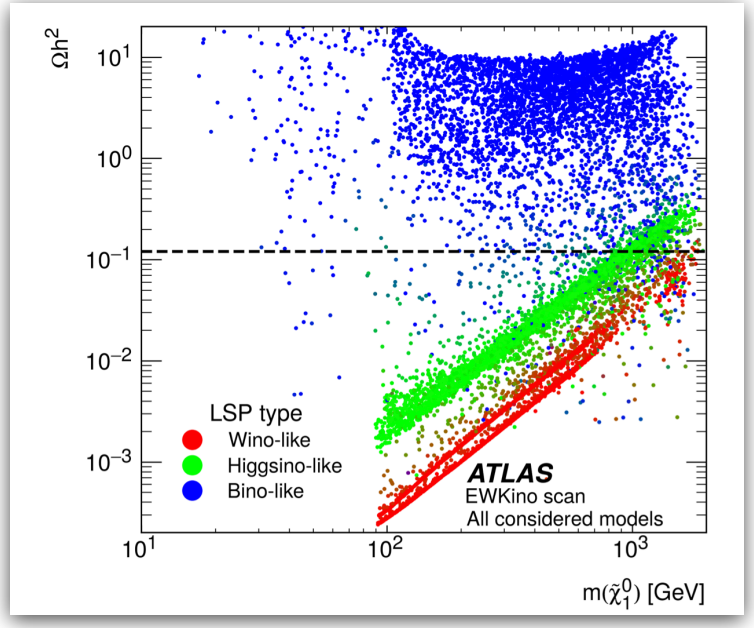
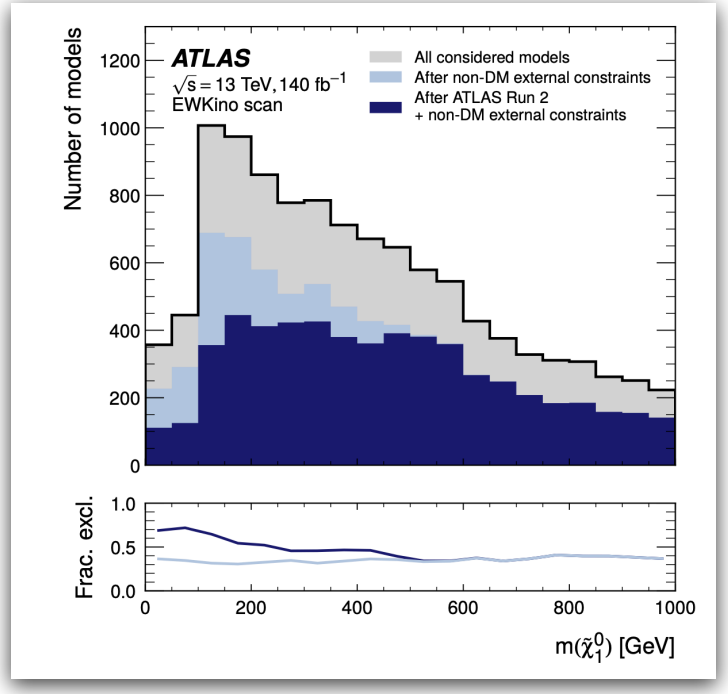
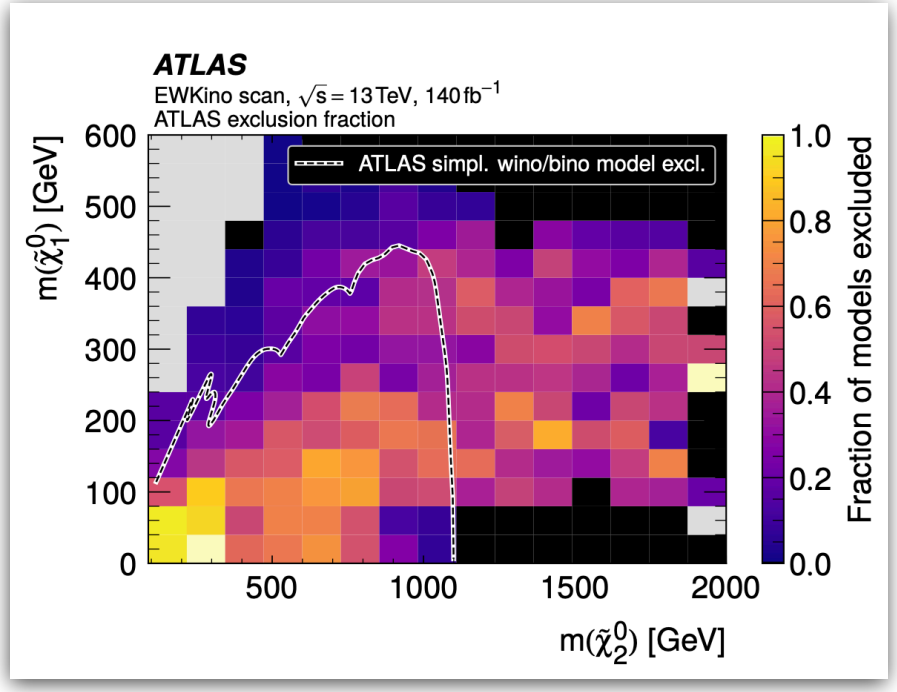
3. Compare to Simplified Models

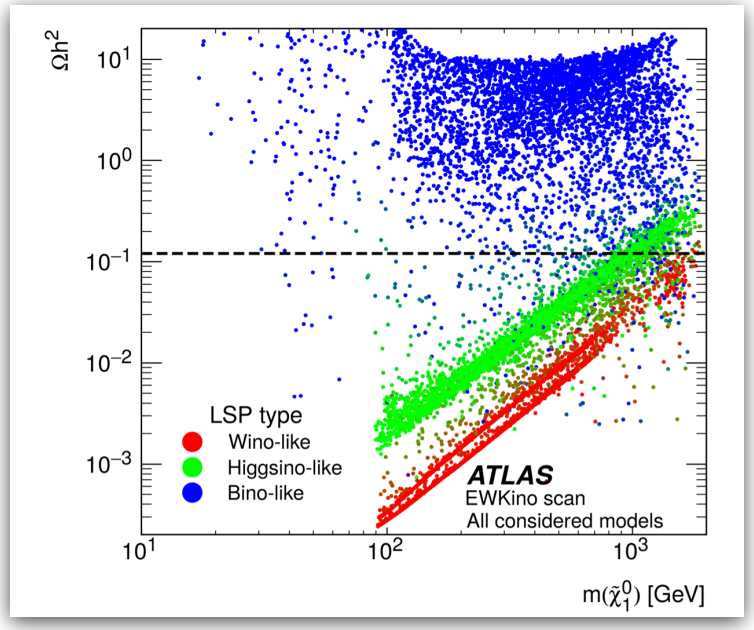


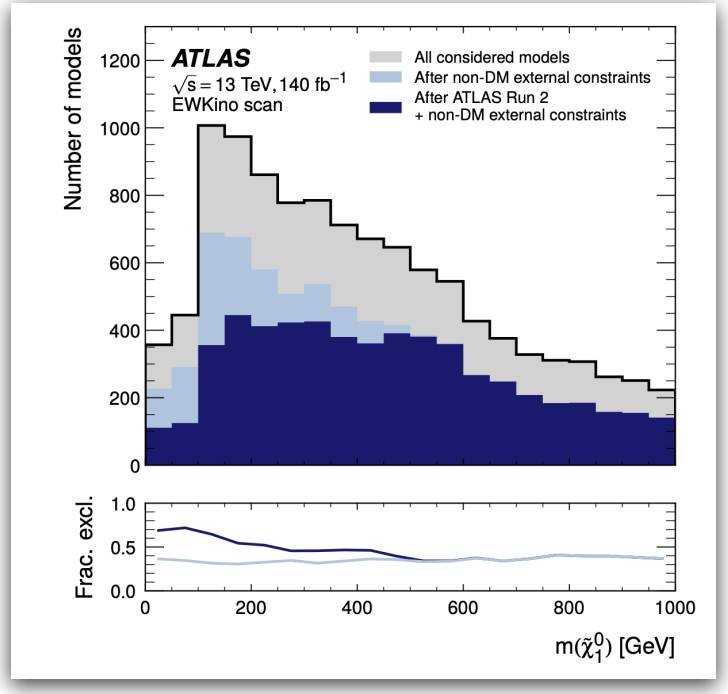


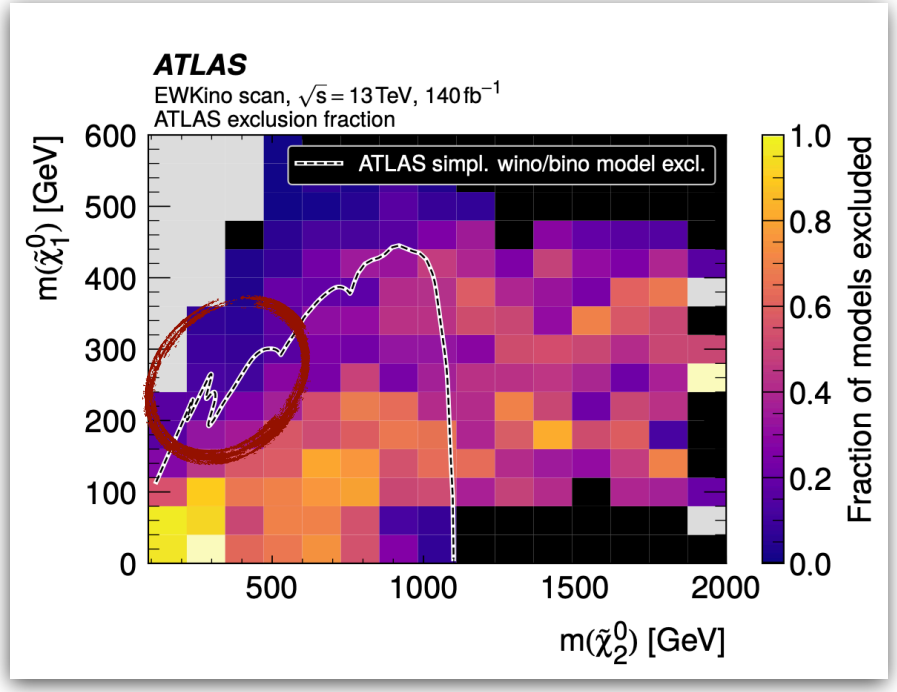


How to ATLAS pMSSM in Four Easy Steps

1. Fill pMSSM parameter space with models (random flat prior)
2. Evaluate ATLAS' sensitivity to each model
3. Compare to Simplified Models
4. Find holes

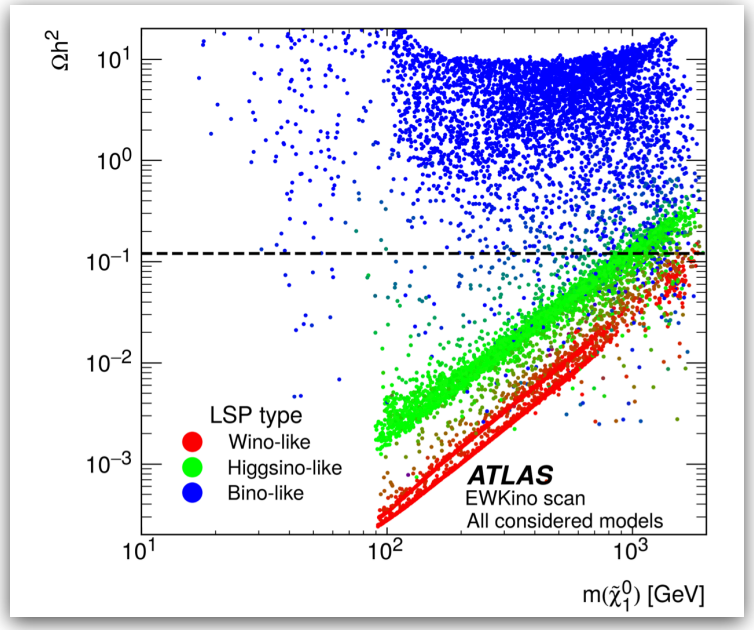


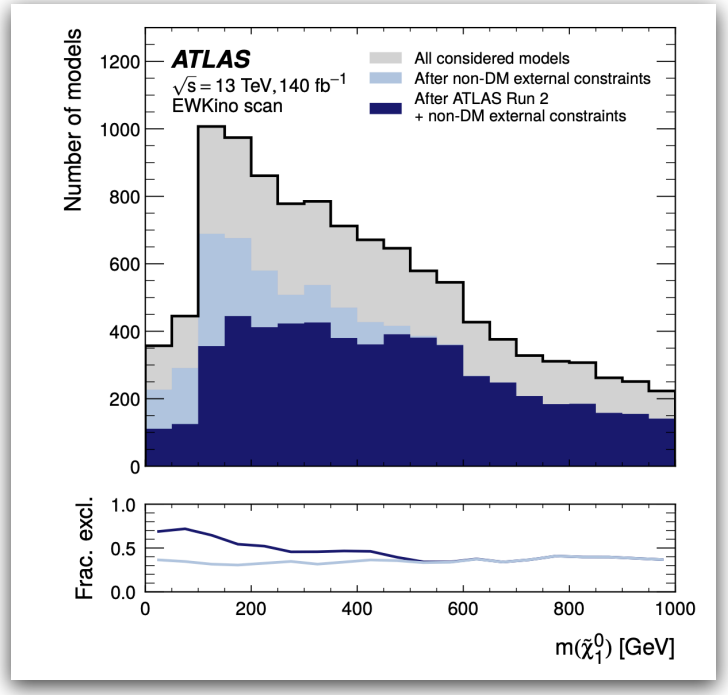


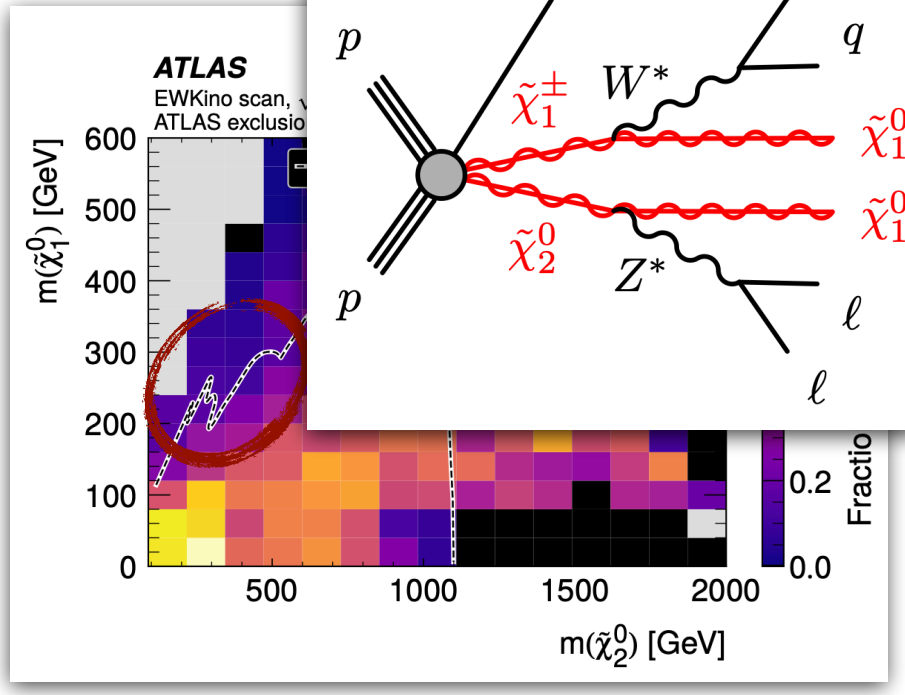


How to ATLAS pMSSM in Four Easy Steps

1. Fill pMSSM parameter space with models (random flat prior)
2. Evaluate ATLAS' sensitivity to each model
3. Compare to Simplified Models
4. Find holes, design new searches

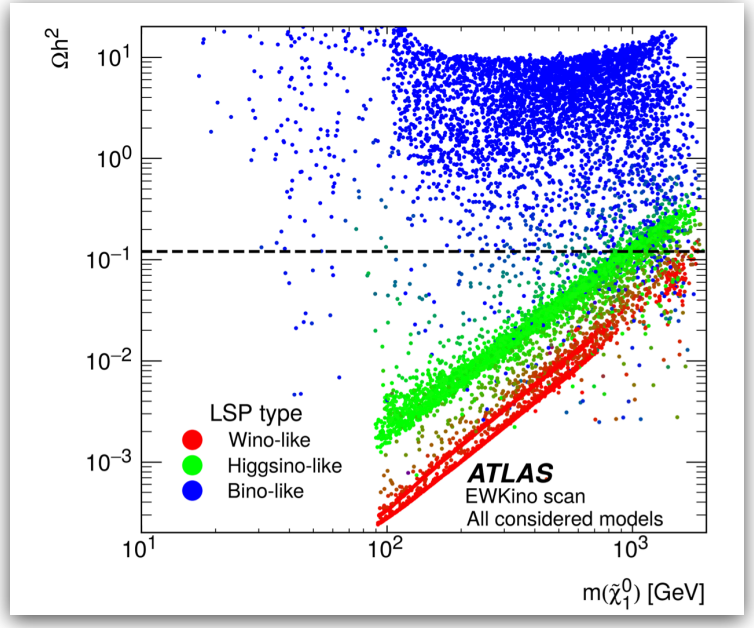


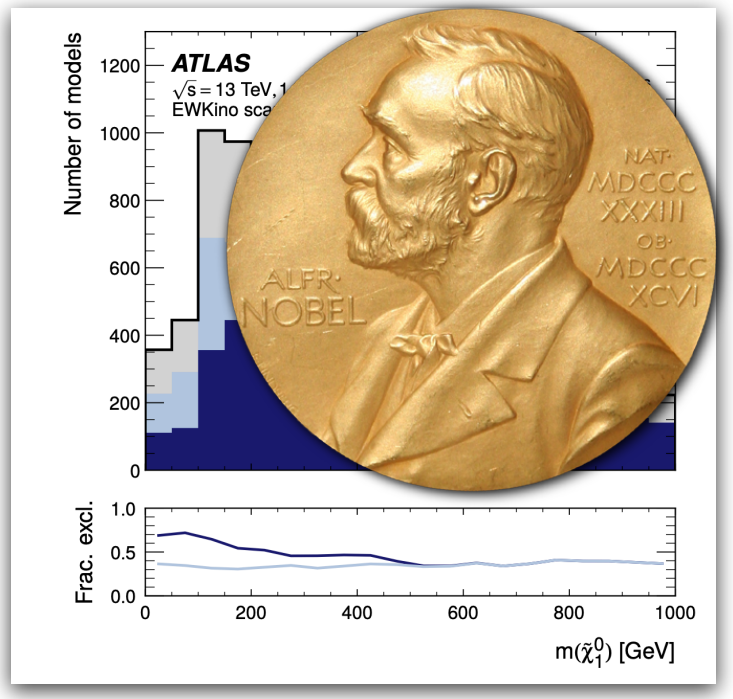


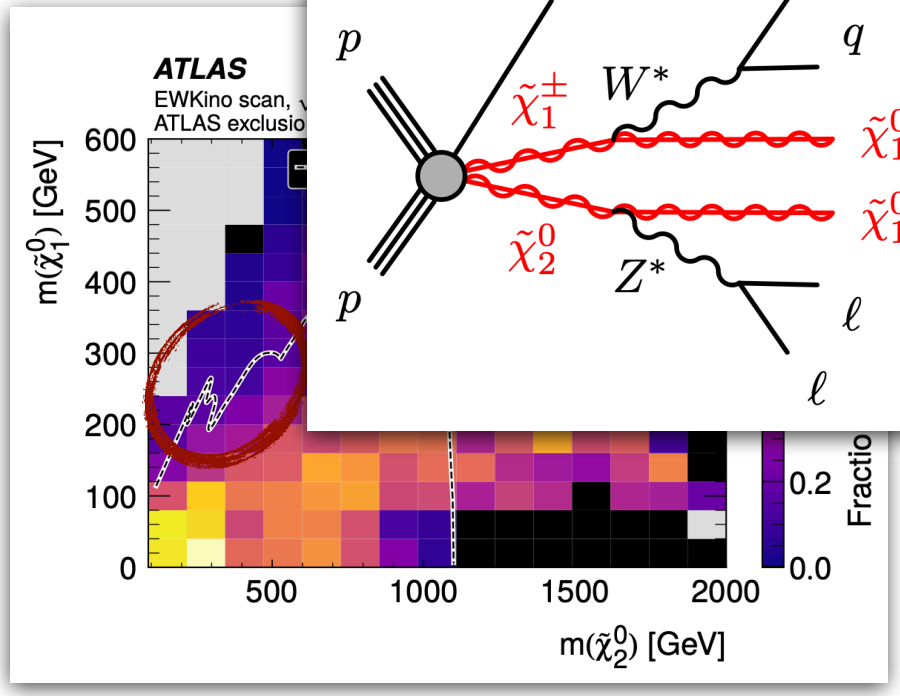


How to ATLAS pMSSM in Four Easy Steps

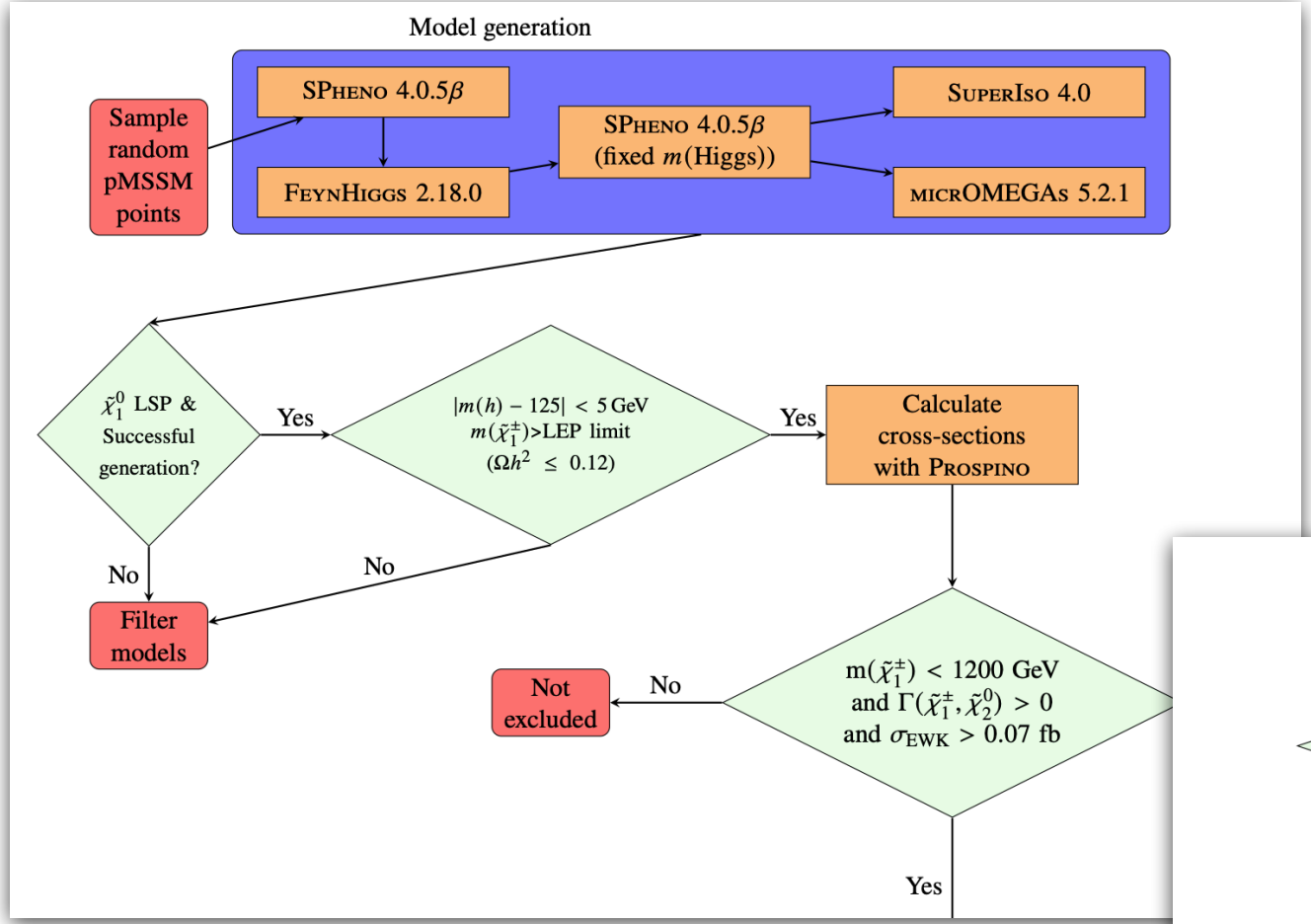
1. Fill pMSSM parameter space with models (random flat prior)
2. Evaluate ATLAS' sensitivity to each model
3. Compare to Simplified Models
4. Find holes, design new searches, win Nobel Prize

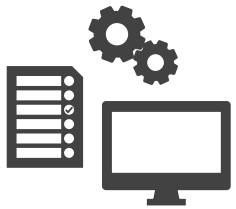






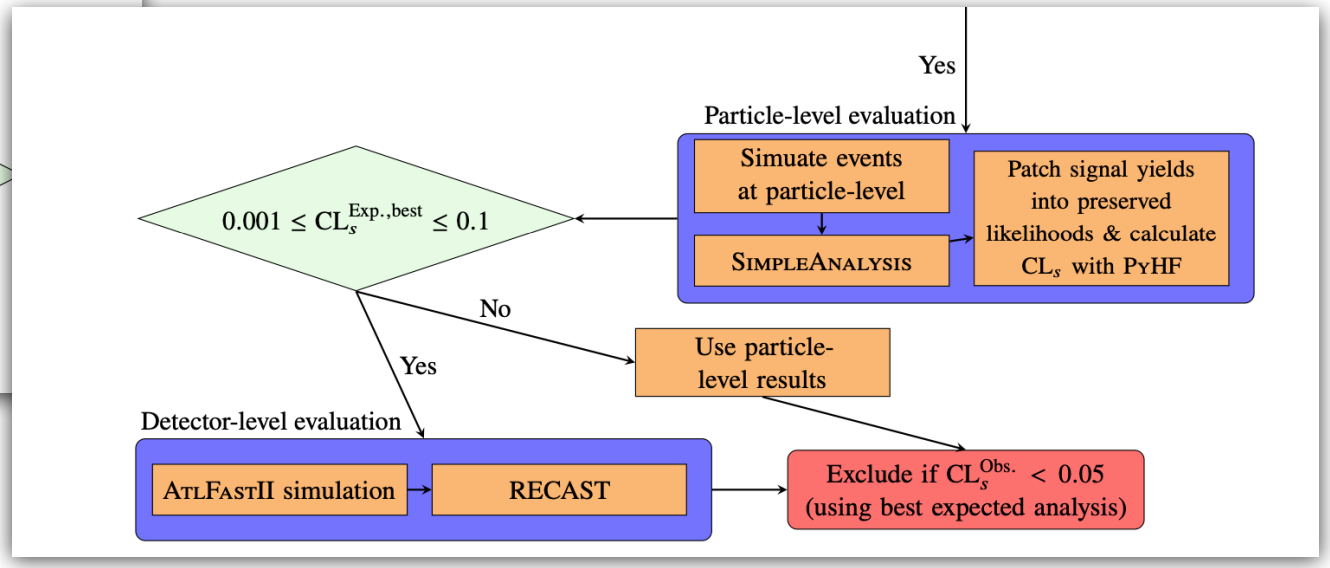
May sound simple in theory…





: 2017 - 2024

Pipeline was under development for ~6 years



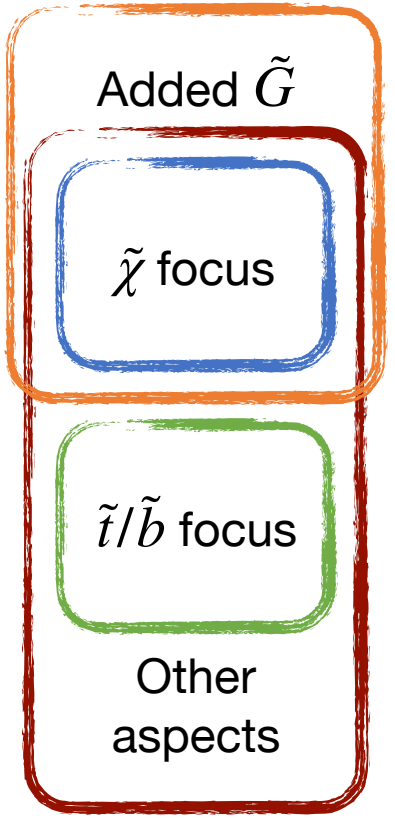
ATLAS pMSSM scans

"Big" summary scans:

- **Electroweak** scan (JHEP 2024 (2024) 106):
  - Focus on EWK-inos & searches for EWK production
- **3G scan**: strong production, focus on 3rd gen squarks
- **General scan**: strong EWK production, 19D pMSSM

GMSB-focussed scan is also in the works:

- Added gravitino $\tilde{G}$ means richer phenomenology



Will focus on Electroweak scan in this talk!

Electroweak pMSSM scan

Published in: JHEP 2024 (2024) 106

EWK scanning setup

5D EWKino scan; **Include 3rd gen** sector to not bias Higgs mass

- 20k models generated
- **2,460 models satisfy all constraints**

Parameter	Min	Max	Note
$M_{\tilde{L}_1}$ $(=M_{\tilde{L}_2})$	10 TeV	10 TeV	Left-handed slepton (first two gens.) mass
$M_{\tilde{e}_1}$ $(=M_{\tilde{e}_2})$	10 TeV	10 TeV	Right-handed slepton (first two gens.) mass
$M_{\tilde{L}_3}$	10 TeV	10 TeV	Left-handed stau doublet mass
$M_{\tilde{e}_3}$	10 TeV	10 TeV	Right-handed stau mass
$M_{\tilde{Q}_1}$ $(=M_{\tilde{Q}_2})$	10 TeV	10 TeV	Left-handed squark (first two gens.) mass
$M_{\tilde{u}_1}$ $(=M_{\tilde{u}_2})$	10 TeV	10 TeV	Right-handed up-type squark (first two gens.) mass
$M_{\tilde{d}_1}$ $(=M_{\tilde{d}_2})$	10 TeV	10 TeV	Right-handed down-type squark (first two gens.) mass
$M_{\tilde{Q}_3}$	2 TeV	5 TeV	Left-handed squark (third gen.) mass
$M_{\tilde{u}_3}$	2 TeV	5 TeV	Right-handed top squark mass
$M_{\tilde{d}_3}$	2 TeV	5 TeV	Right-handed bottom squark mass
M_1	−2 TeV	2 TeV	Bino mass parameter
M_2	−2 TeV	2 TeV	Wino mass parameter
μ	−2 TeV	2 TeV	Bilinear Higgs boson mass parameter
M_3	1 TeV	5 TeV	Gluino mass parameter
A_t	−8 TeV	8 TeV	Trilinear top coupling
A_b	−2 TeV	2 TeV	Trilinear bottom coupling
A_τ	−2 TeV	2 TeV	Trilinear τ-lepton coupling
M_A	0 TeV	5 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

EWK scanning setup

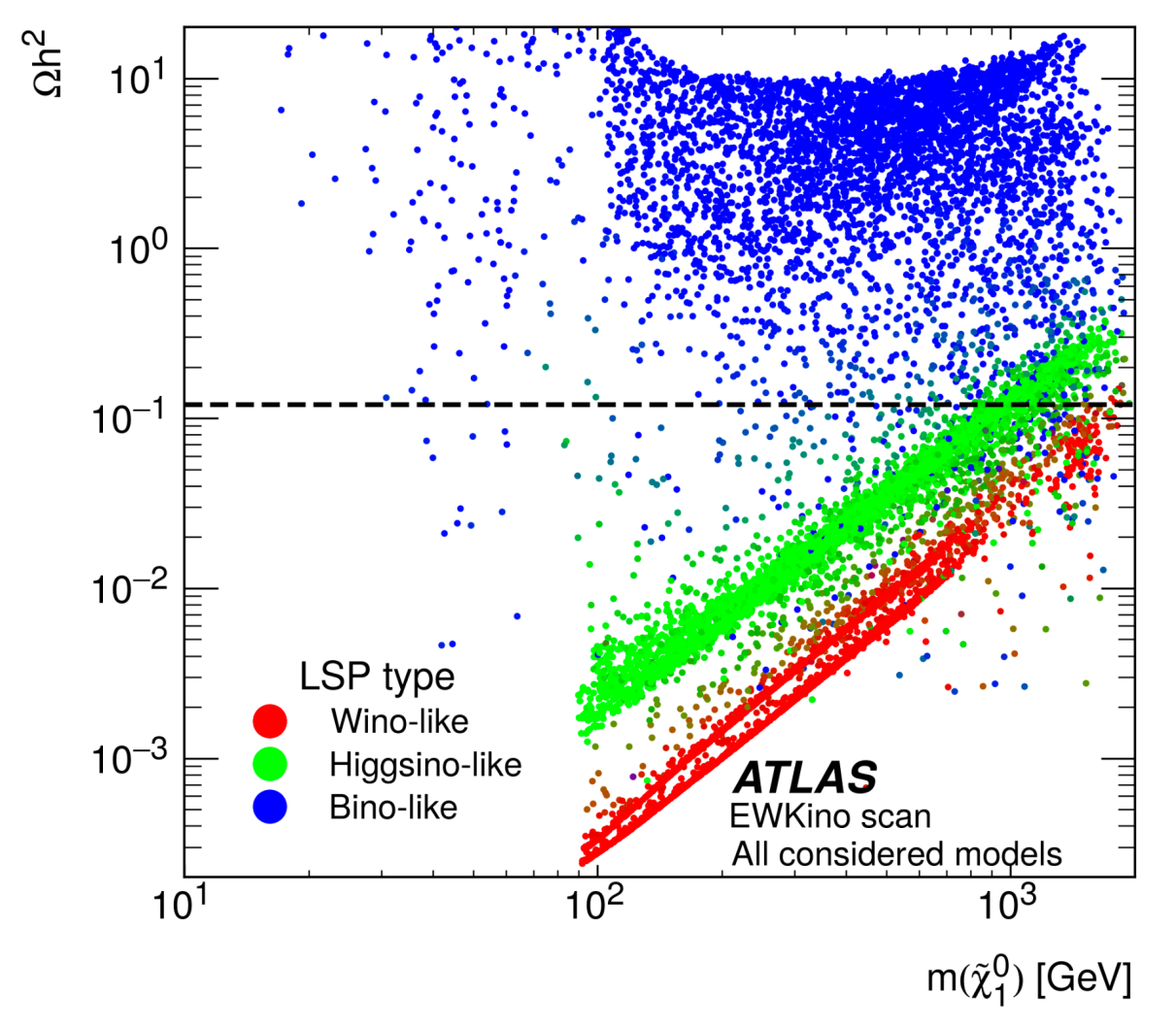
5D EWKino scan; **Include 3rd gen** sector to not bias Higgs mass

- 20k models generated
- **2,460 models satisfy all constraints**

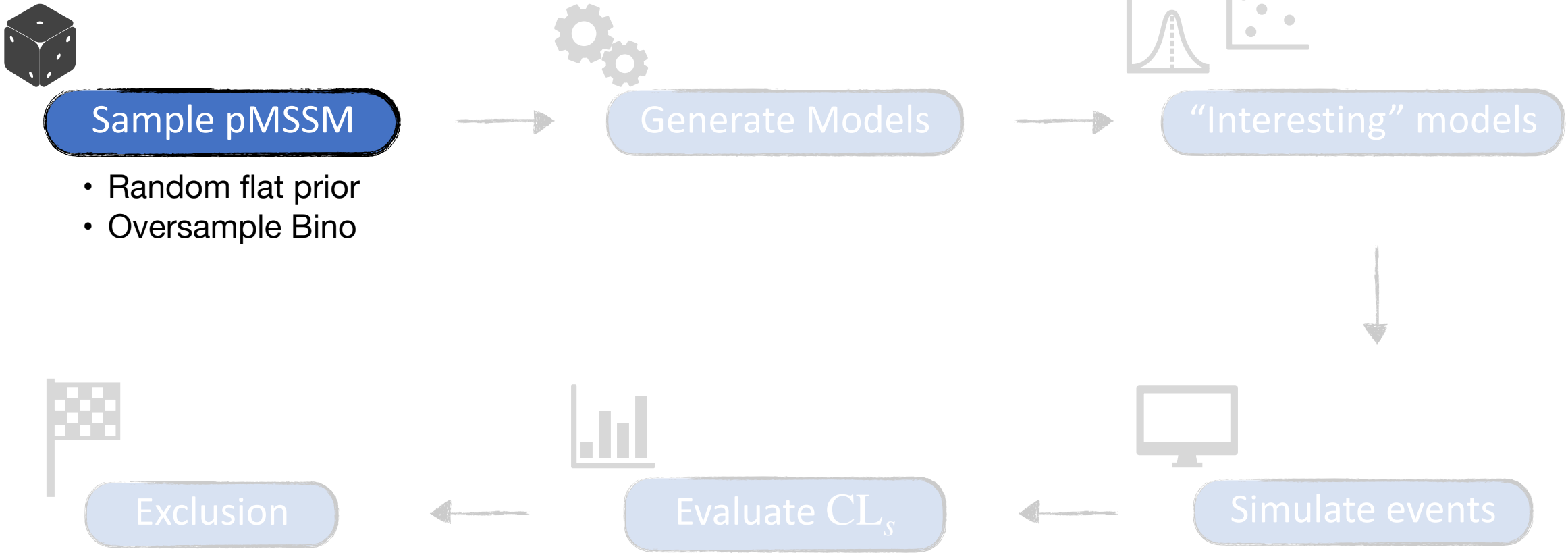
Oversample **Bino-like DM** models: $\Omega h^2 < 0.12$

- ~440k models generated
- **1,769 models satisfy all constraints**

More in Backup



The pMSSM pipeline



- Random flat prior
- Oversample Bino

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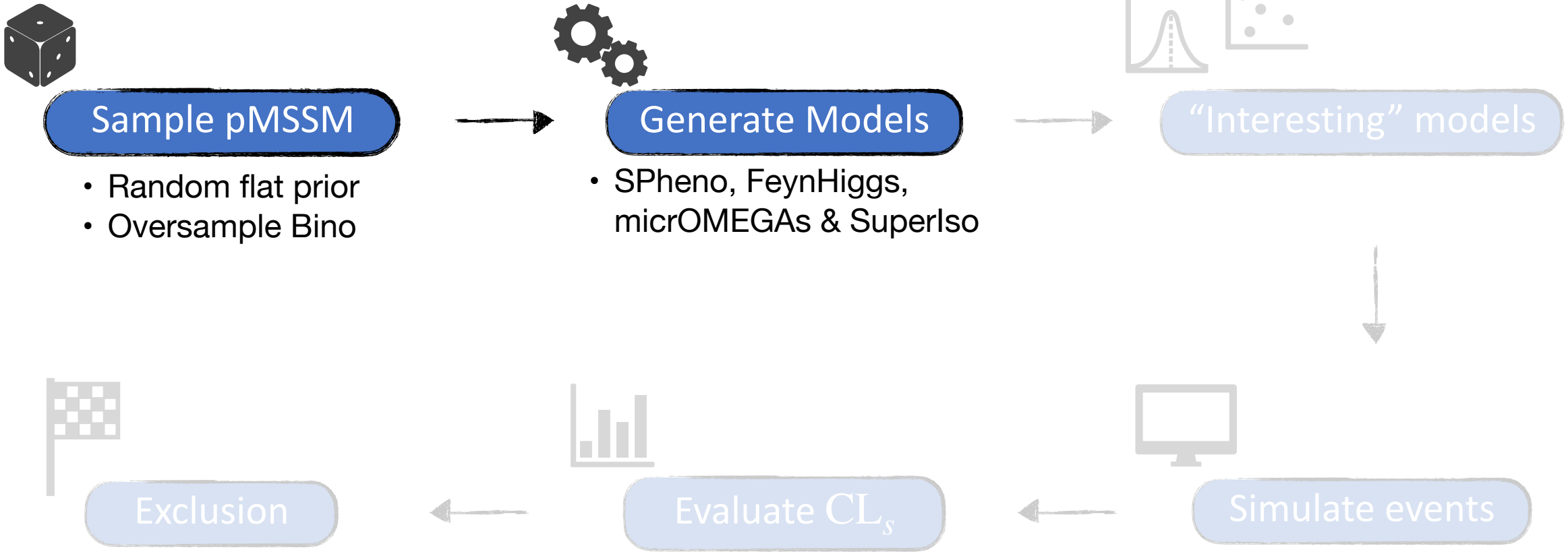


Details in Backup

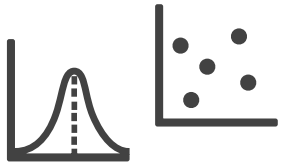
The pMSSM pipeline

Sample pMSSM

- Random flat prior
- Oversample Bino

Generate Models

- SPheno, FeynHiggs, micrOMEGAs & SuperIso



"Interesting" models

- m_h, $m(\tilde{\chi}_1^{\pm})$ LEP limit

Simulate events

Evaluate CL_s

Exclusion

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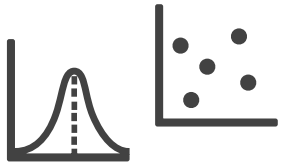

"Interesting" models

- m_h, $m(\tilde{\chi}_1^{\pm})$ LEP limit

Simulate events

- Truth-level: SimpleAnalysis
- Detector-level: RECAST for models with unclear excl.

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- Using pyHF
- Use $\mathrm{CL}_s^{\mathrm{best,exp.}}$ to pick $\mathrm{CL}_s^{\mathrm{obs.}}$

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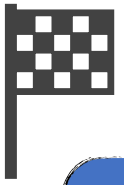


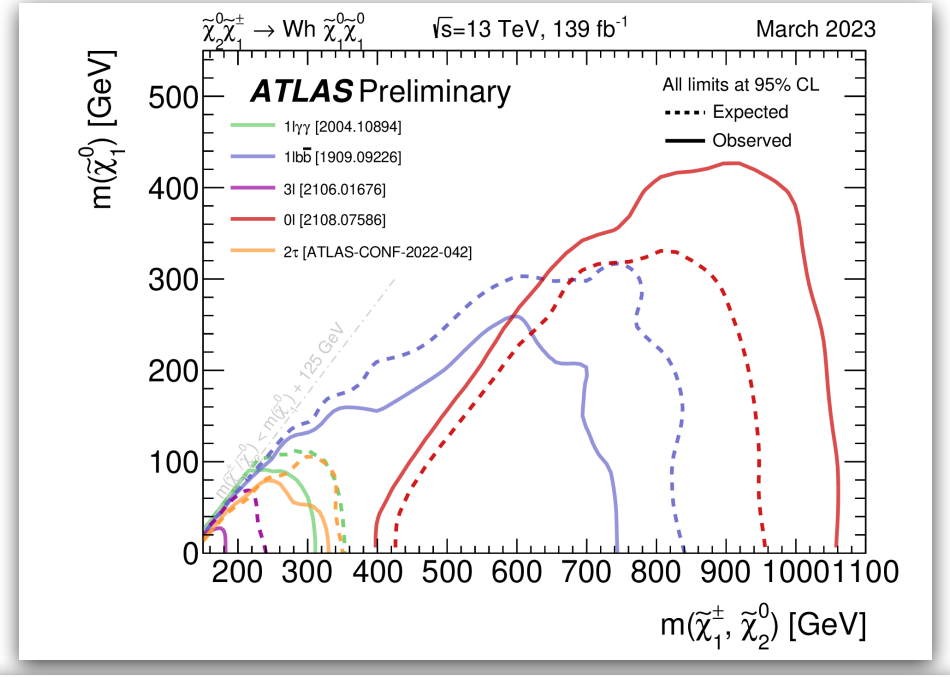
Exclusion

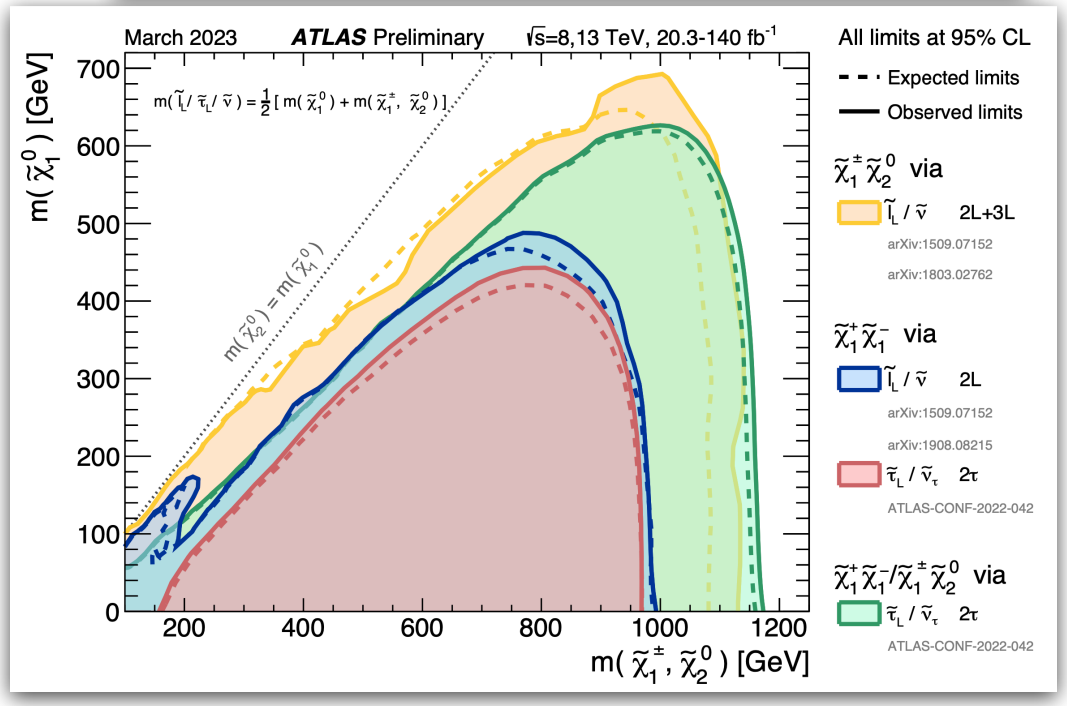
- Uncovered models?

Ewk Analyses

Consider many ATLAS Run 2 searches targeting various EWK final states

Analysis	Relevant simplified models targeted
FullHad [24]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW
1Lbb [15]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh
2L0J [19]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW, slepton pairs
2L2J [25]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ
3L [23]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$
4L [22]	Higgsino GGM
Compressed [20]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$
Disappearing-track [27]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$

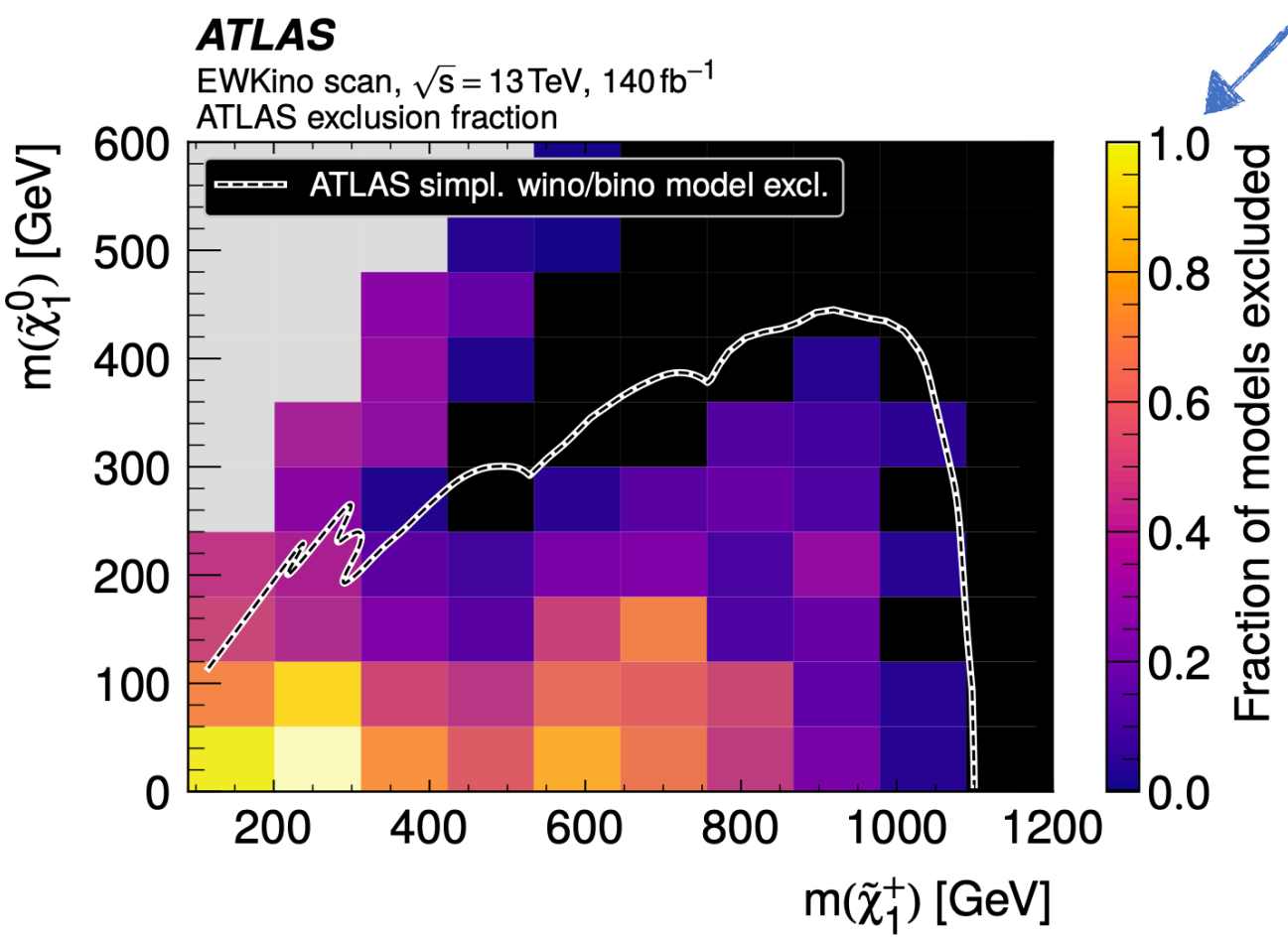




Plots: ATL-PHYS-PUB-2023-025
Table: JHEP 2024 (2024) 106

A typical Result

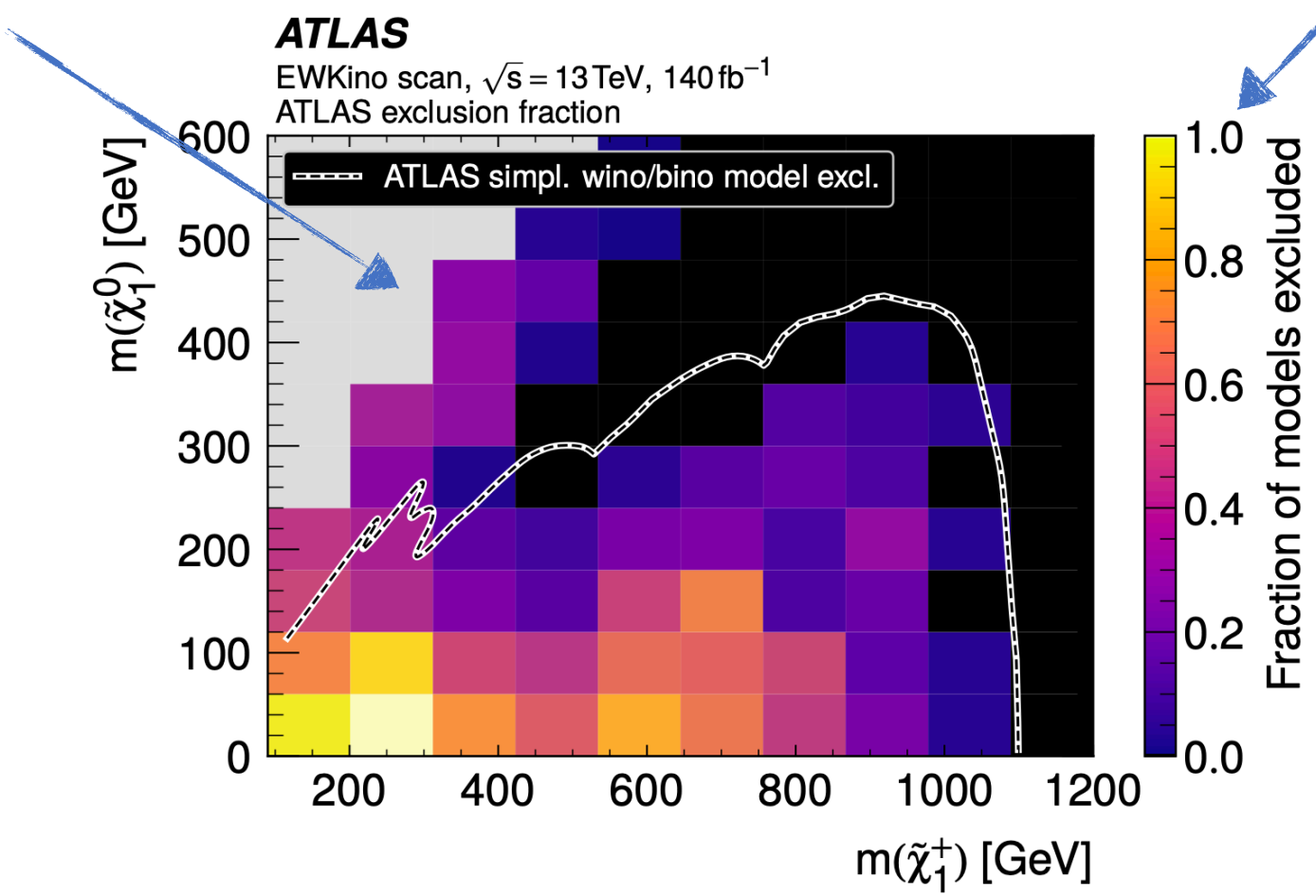
Fraction of models excluded:
- Indicator of coverage



A typical Result

Fraction of models excluded:
- Indicator of coverage

Better coverage outside contour:
- Higher dimensions
  → more particles
- Can pick up on decays of other particles



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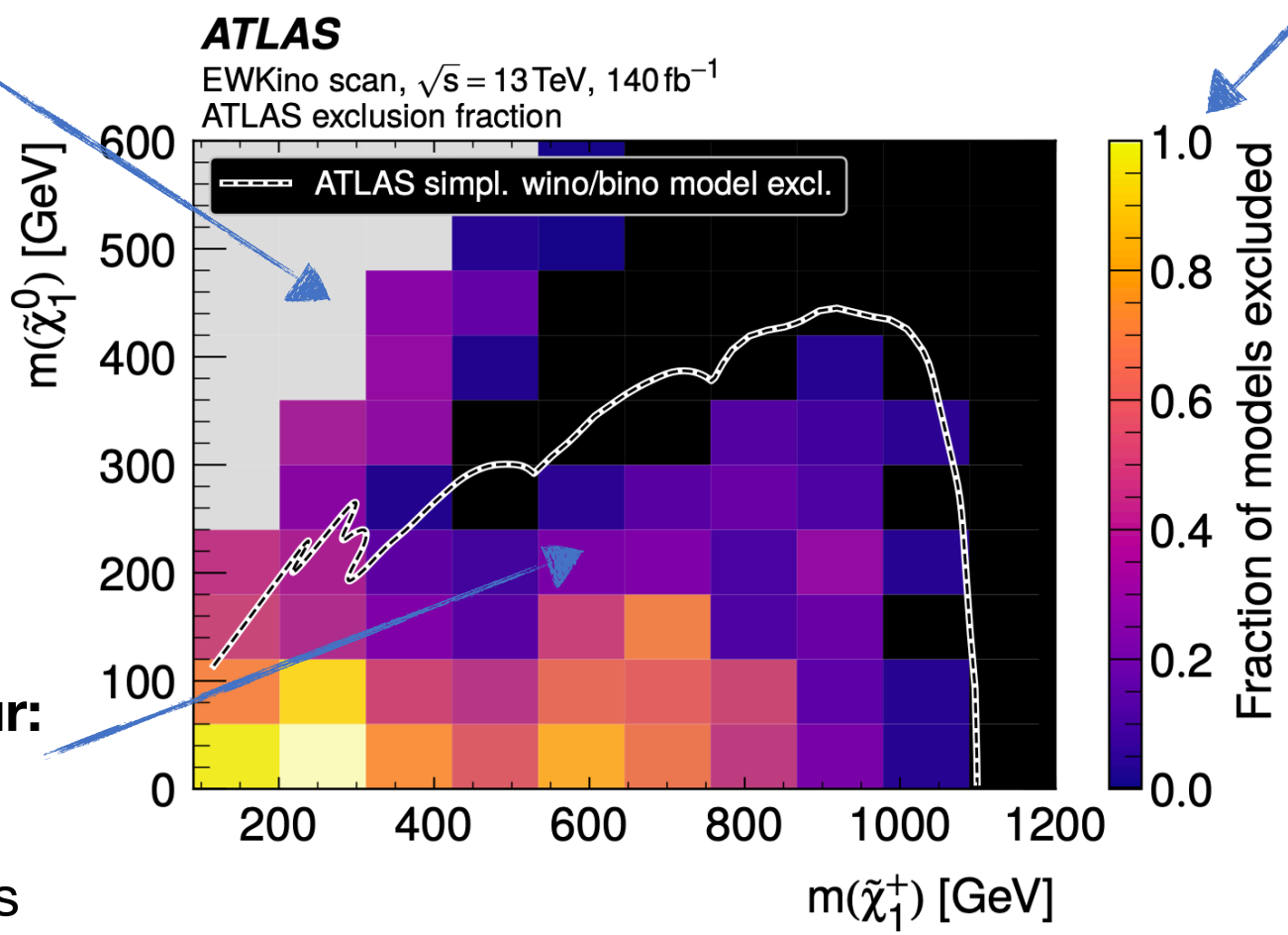


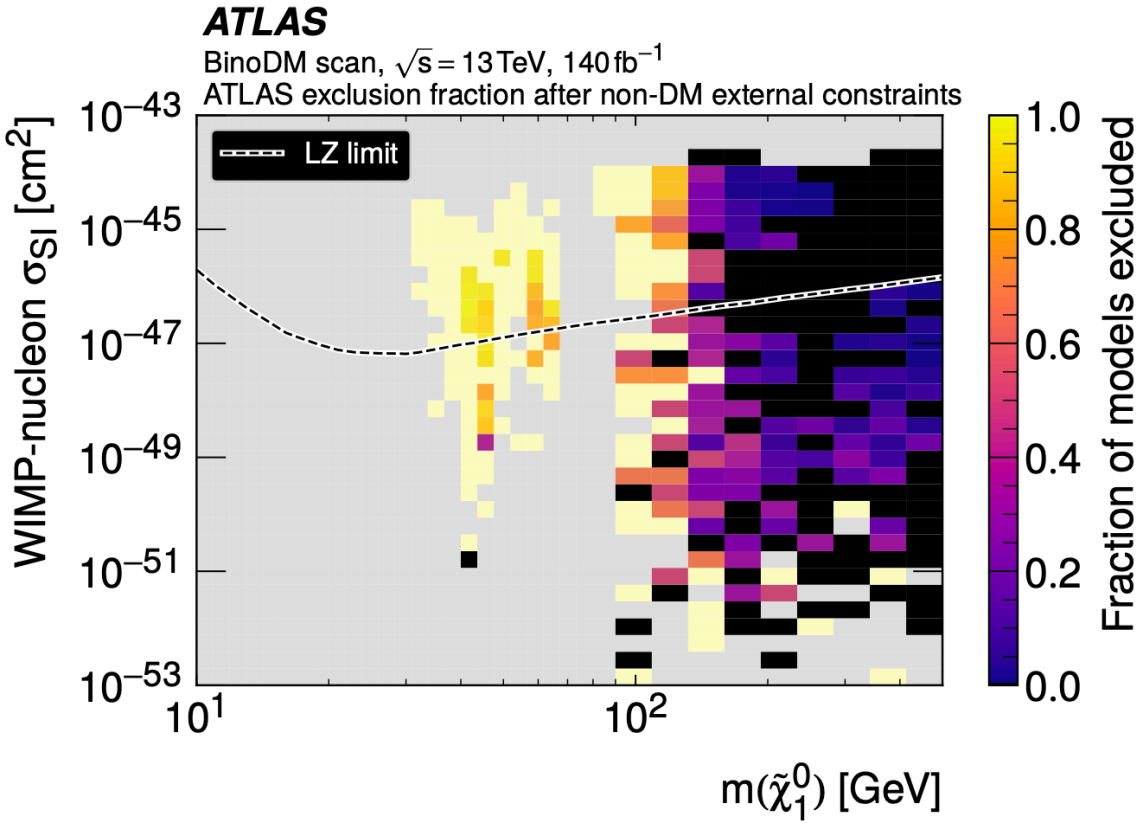
Worse coverage inside contour:
- Higher dimensions
  → more particles
- More mixed decays of particles hinder detection

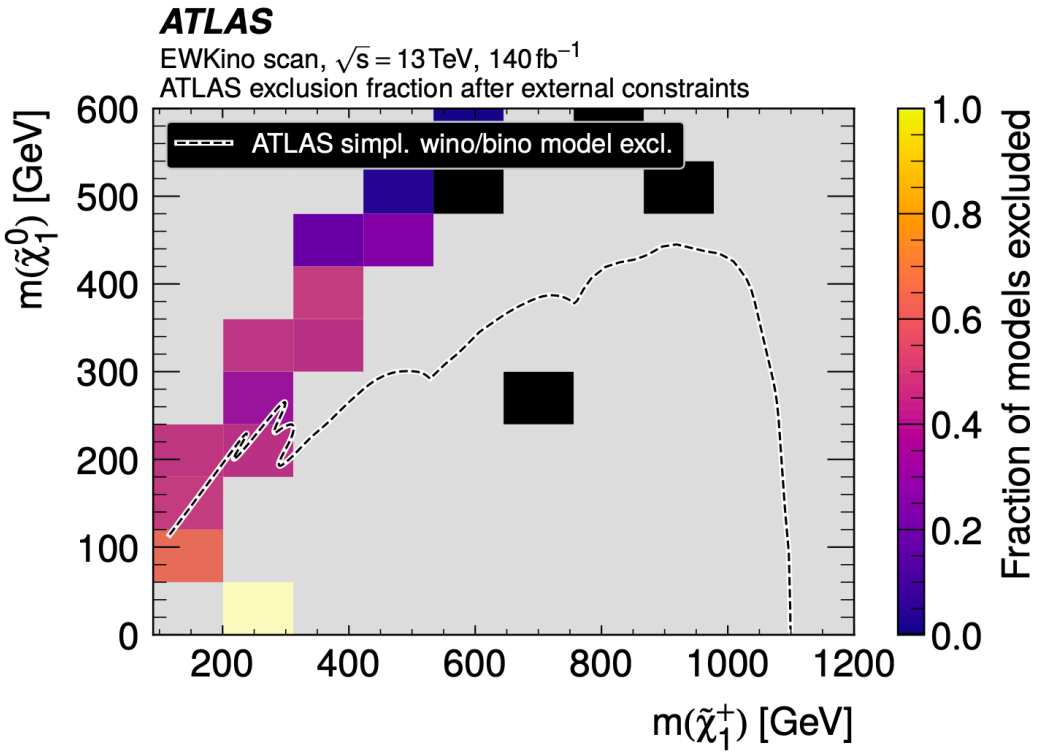
Much better coverage than in Run 1

Nice complementarity between ATLAS and direct detection experiments [1, 2]

However: Very few models which satisfy all constraints

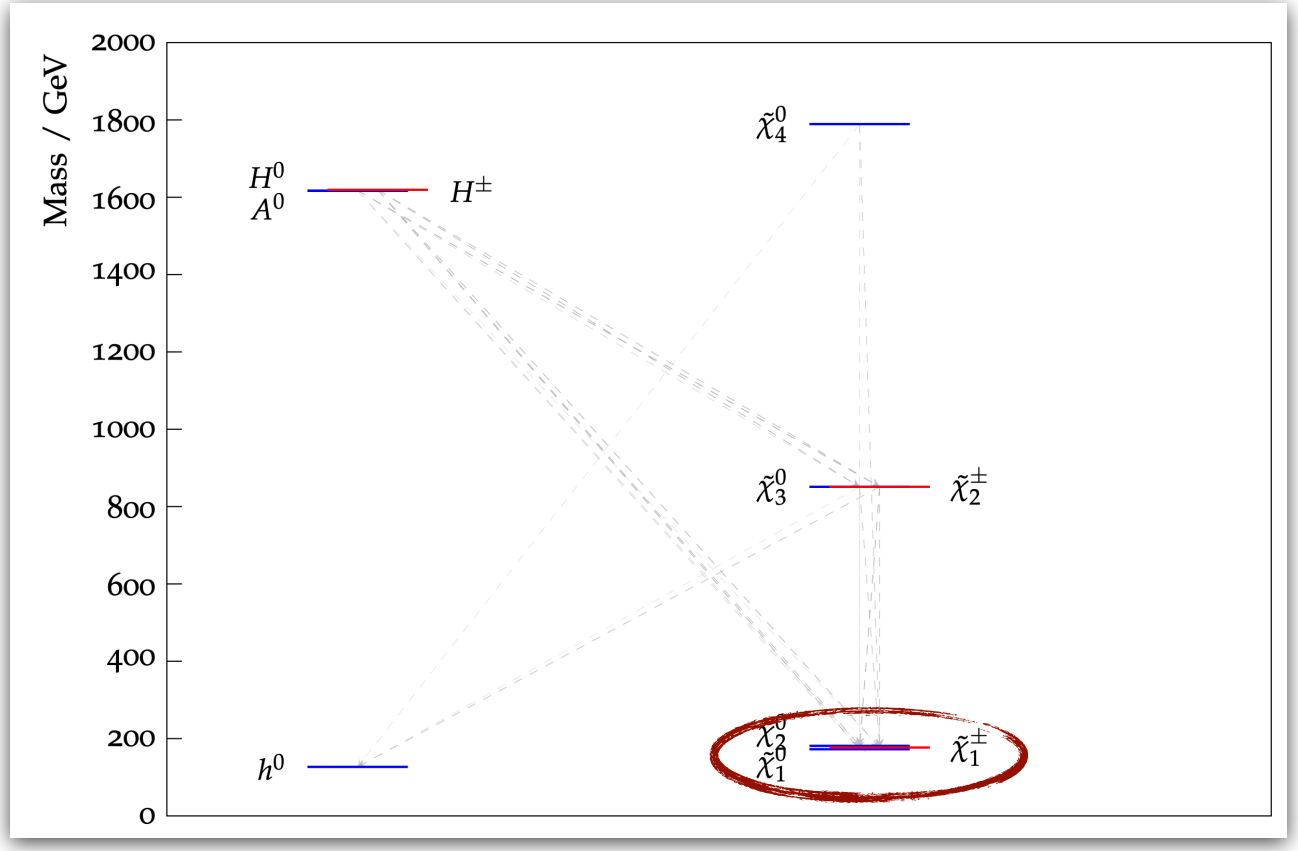
→ random flat sampling to blame!





Surviving Benchmark models

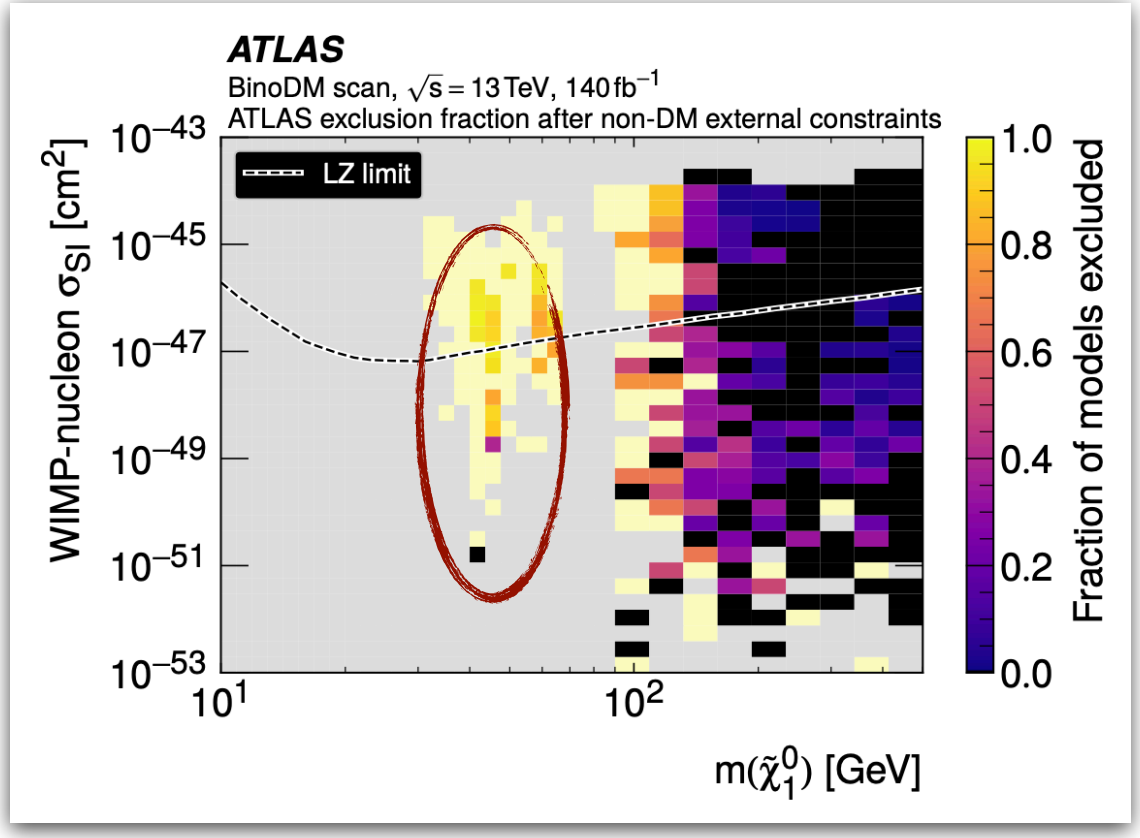
1. Models with small mass splitting and small $\mathrm{BF}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)$
   - Instead dominated by $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$
   - A new search is already being looked into!



Surviving Benchmark models

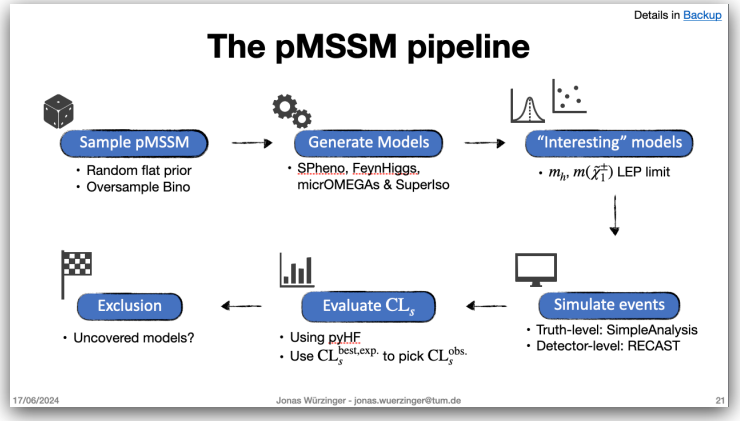
1. Models with small mass splitting and small $\mathrm{BF}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)$

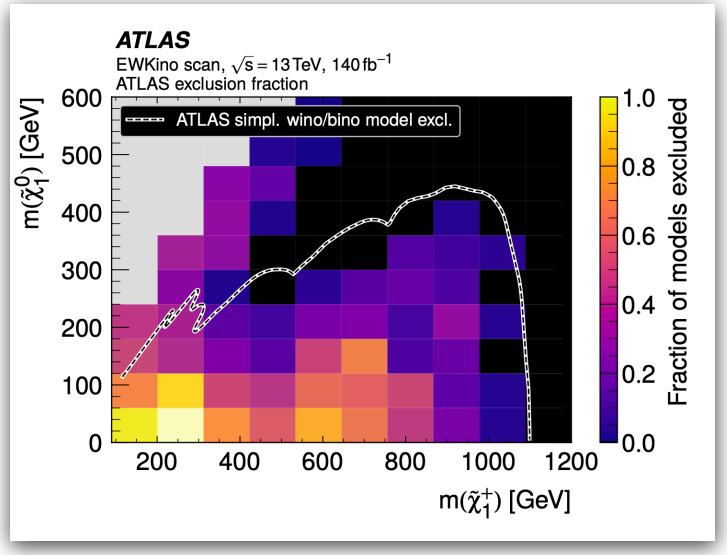
2. Models in the Z/h funnel region can have almost pure higgsino-$\tilde{\chi}_1^0$
   - Lower σ wrt. simplified models
   - Target this by improving sensitivity to $\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$



Taking a step back…

1. **Complex re-interpration pipeline is in place**
   - Random flat prior; easy to use, quite difficult to get enough models
2. **Using frac. of excluded models for coverage**
   - Better coverage inside contour, worse outside
   - What does $\mathrm{frac}. = 0.75$ mean?
3. **Can identify benchmark models for new searches**
   - Does require hand-selecting models





Did we miss any interesting/unexpected models?

$\tilde{\chi}_2^0 \to Z/h\tilde{\chi}_1^0$

$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma$

Gaussian Processes (GPs)

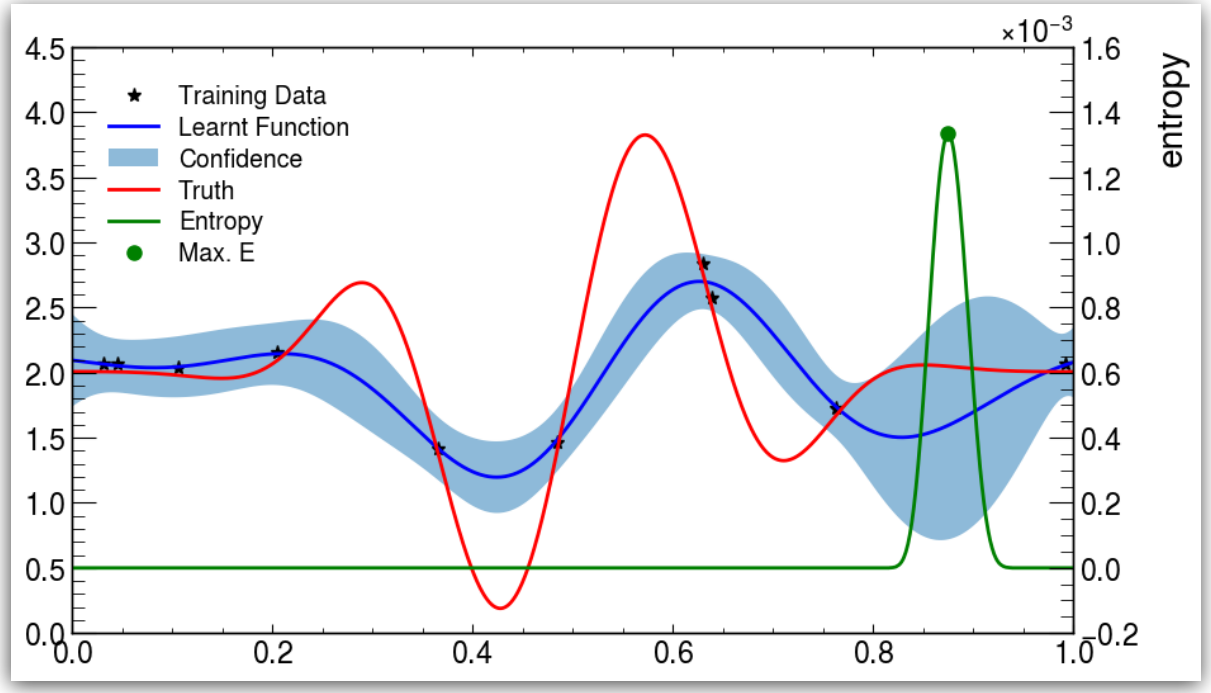
Problems: Expensive (detector) sim., flat prior breaks down

- How well do we know the “coverage” of SUSY after this scan?

Can use Gaussian Process (GP)

- Assume observations follow joint Normal distribution $f(\theta) \sim \mathrm{GP}(m, k)$
- Condition on observation to make predictions
- Intrinsic measure of uncertainty

Active Learning: Use unc. to identify where to generate more data

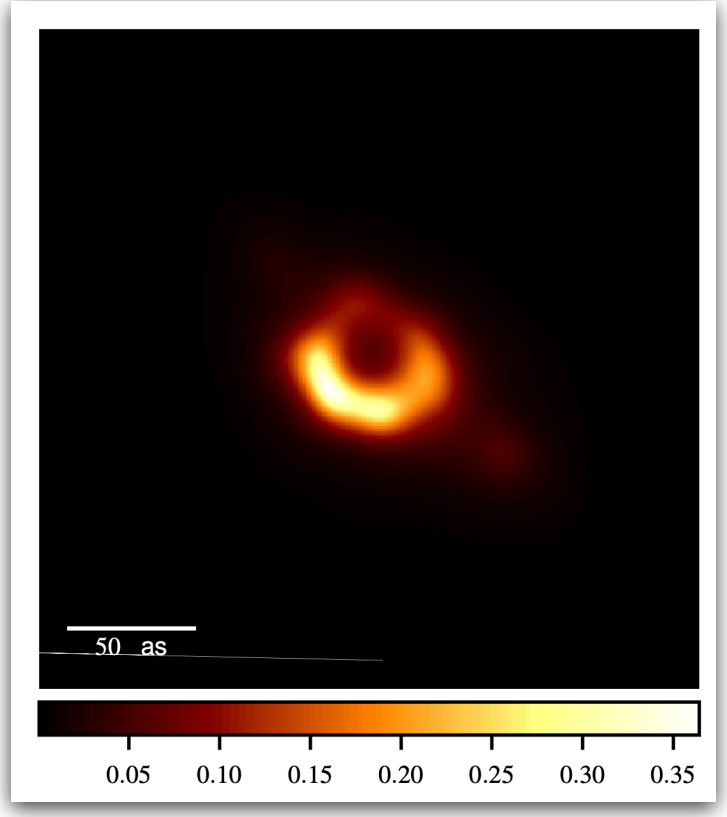


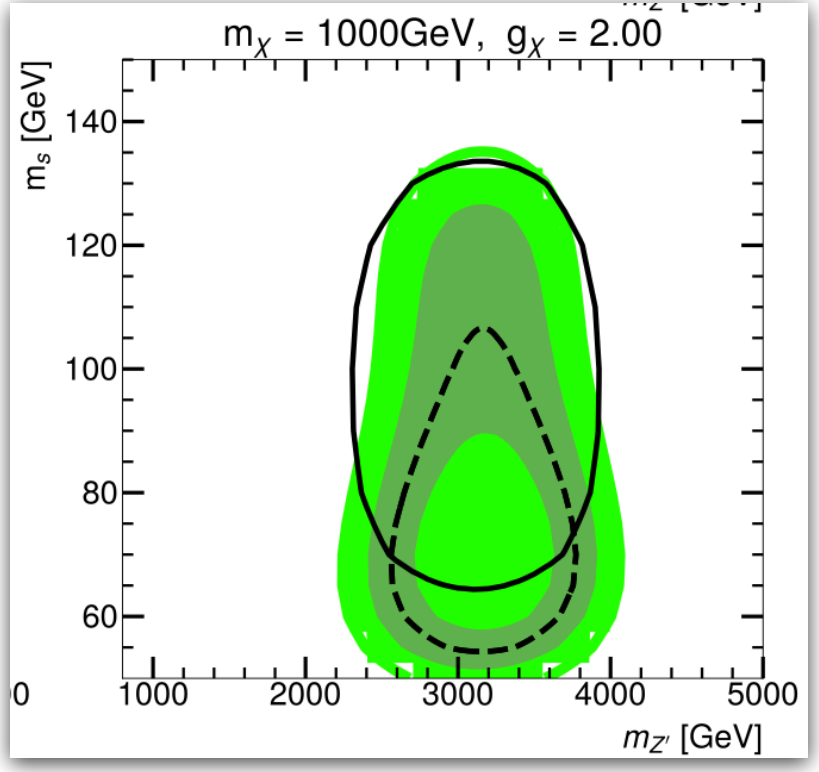
Gaussian Processes in practice

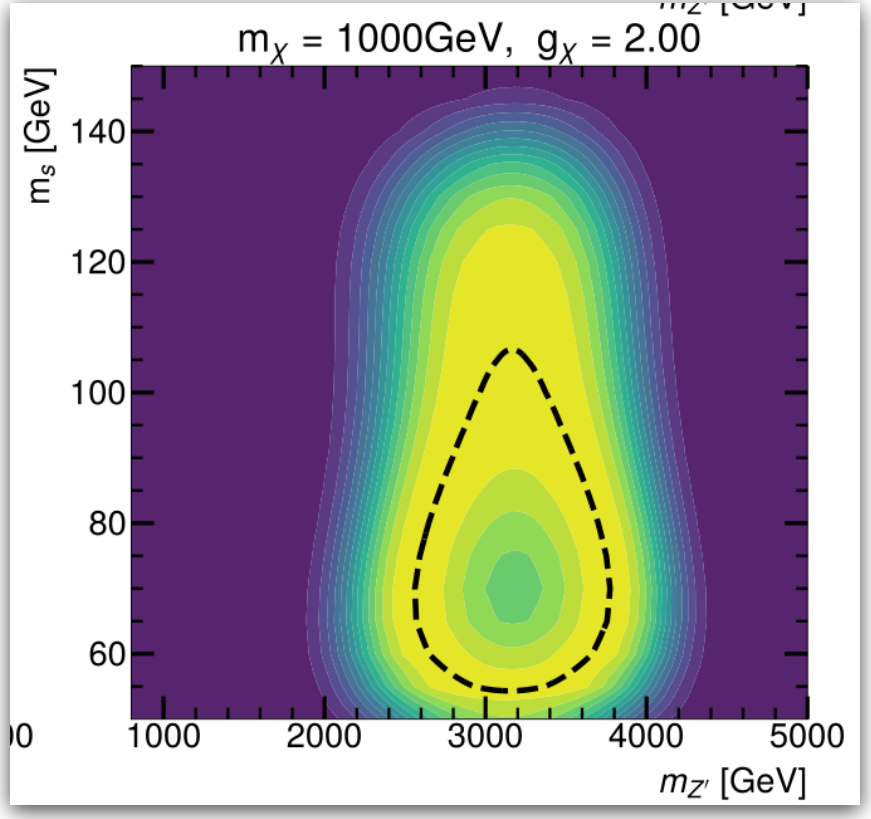
NIFTy: First ever video reconstruction of black holes
- Improved image reconstruction, now picked up by EHT

ATL-PHYS-PUB-2022-045: Dark Higgs Active Learning reinterpretation
- Very efficient contour finding through use of entropy

D. Voß (Master's student): working on GPs for pMSSM!

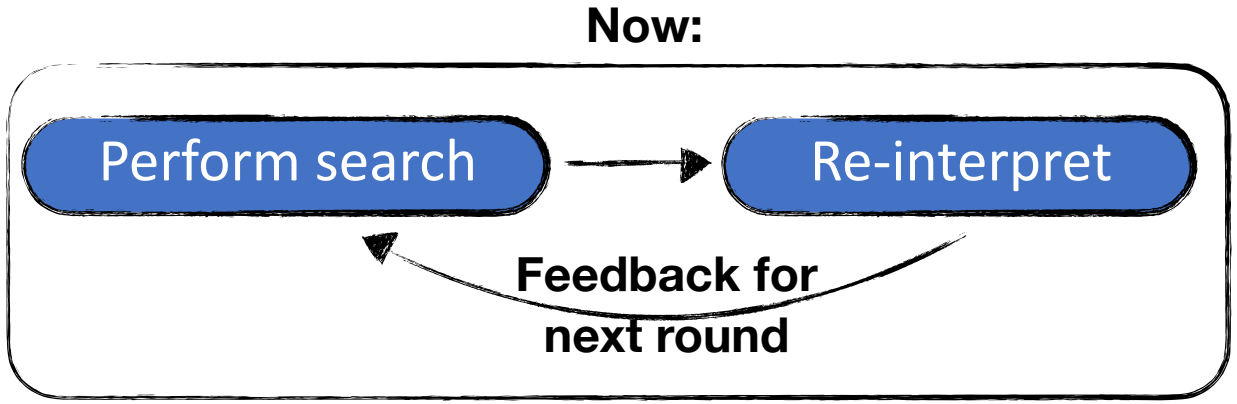


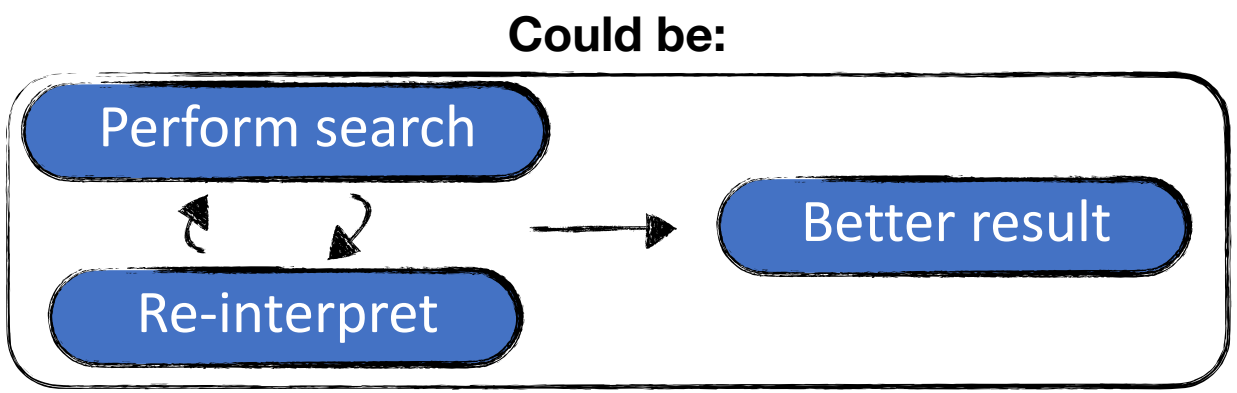




Other Scans & Studies

1. General, 3G and GMSB pMSSM scans to follow soon
2. L. Renn: Automate comb. of pMSSM SR using TACO algorithm
3. Re-written ATLAS model gen.: Full control over code, fully dockerised
4. ATLAS: In-time re-interpretations for better optimised ongoing searches
   - Will drastically improve re-interpretation experience in ATLAS!





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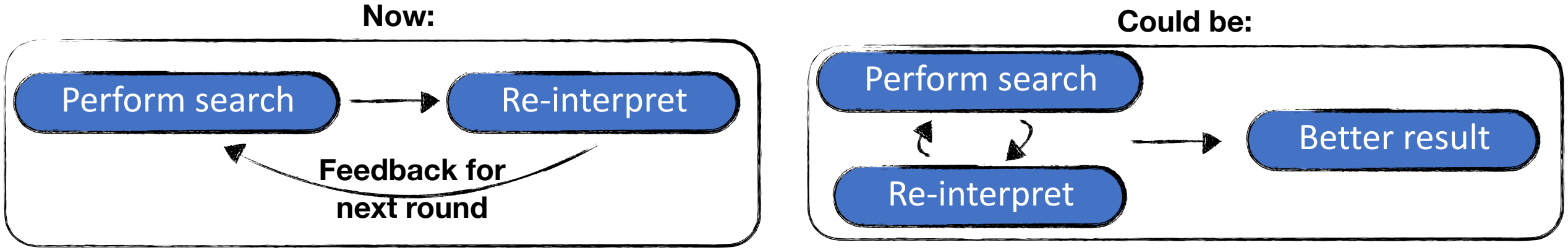

There is much more to do with the ATLAS data!

Backup

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EWK Scan Selections: Table 4

Scan name	EWKino	BinoDM
$\|M_1\|$ range	0 – 2 TeV	0 – 500 GeV
LSP type	Neutralino	Bino-like neutralino
Number of models generated:		
Sampled	20 000	437 500
Successful generation	16 667	370 017
Correct LSP type	15 321	286 267
Satisfy DM relic density constraint $\Omega h^2 \leq 0.12$	N/A	11 122
Satisfy LEP chargino mass constraint	13 969	10 174
120 GeV $<$ m(h) $<$ 130 GeV	12 280	8 897
Satisfy non-DM external constraints	7 956	5 752
Satisfy all external constraints	2 460	1 769

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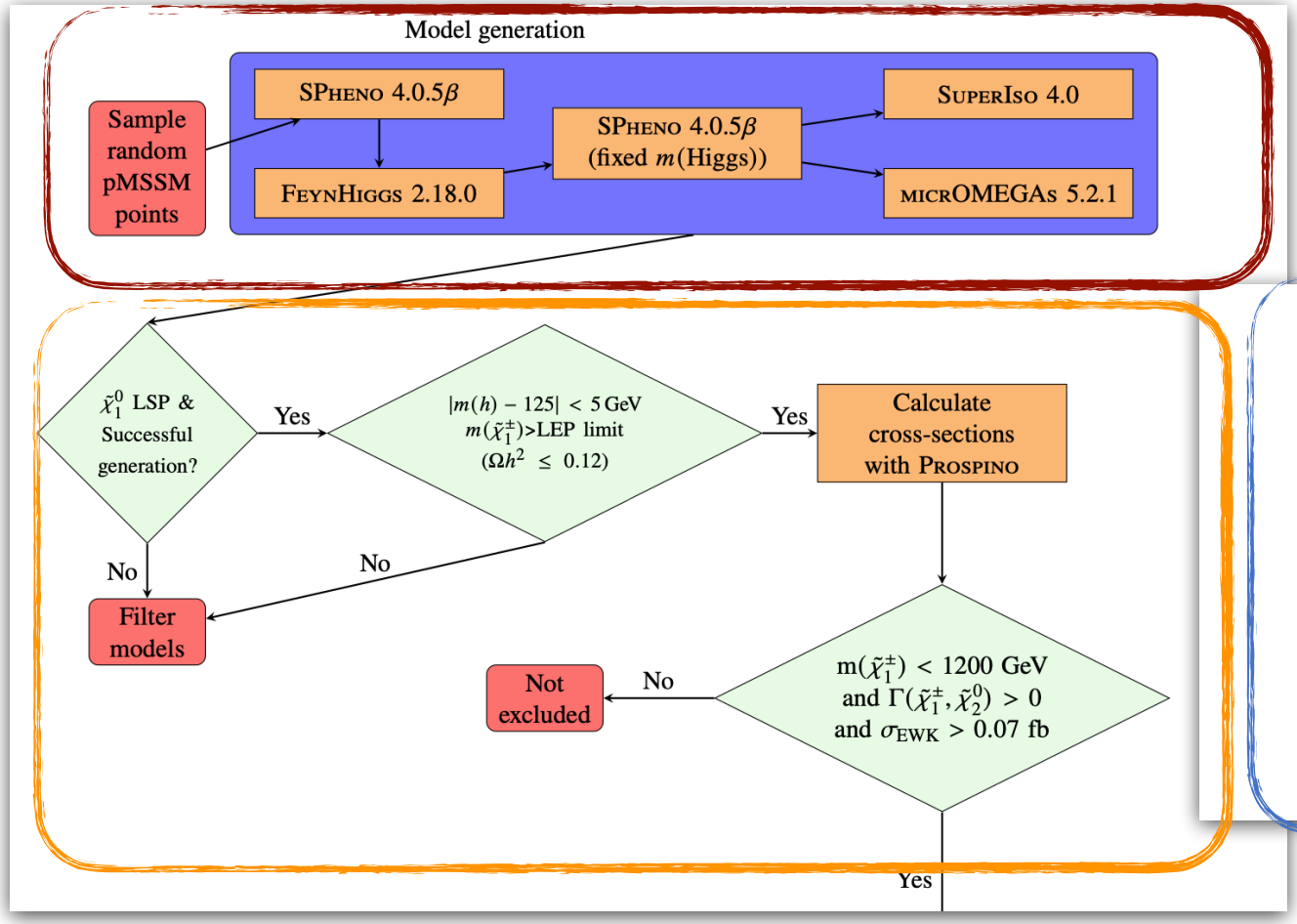
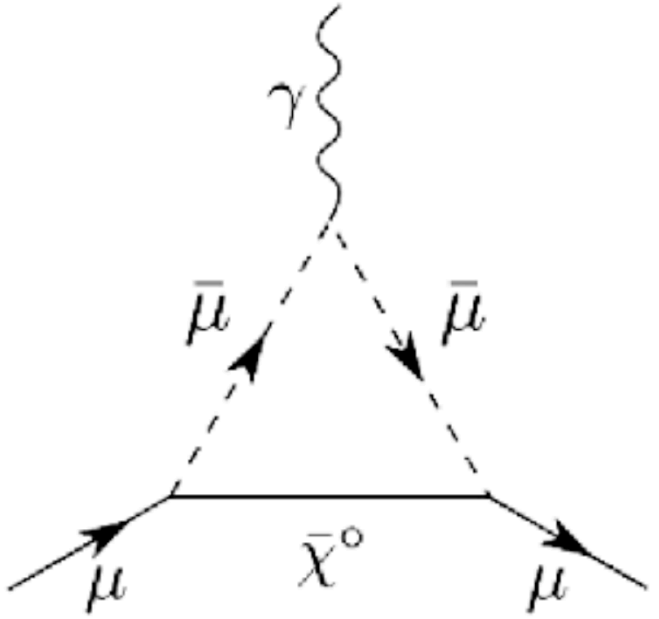
pMSSM pipeline

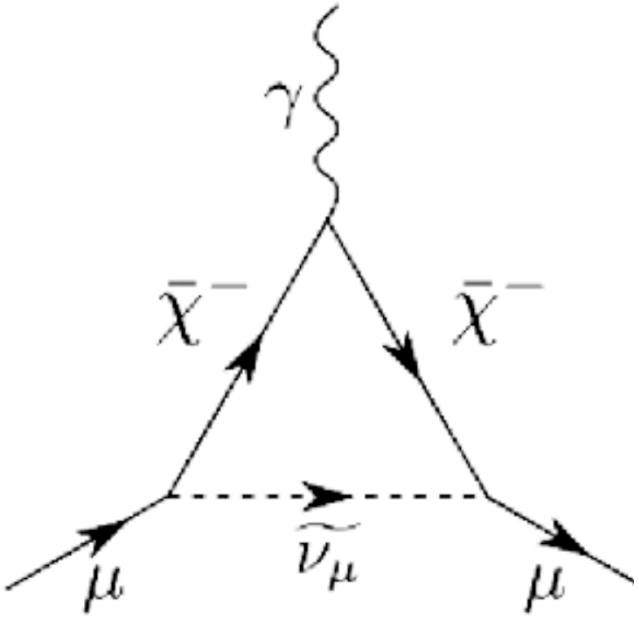
Generate models → Select "interesting" models → Simulate & evaluate



Why a GMSB scan?

1. Explicit SUSY breaking mechanism
2. $\tilde{\chi}_1^0$ does **NOT** have to be LSP anymore
   - Looser DM constraints
   - Different $(g-2)_\mu$ contributions through $\tilde{H} \rightarrow \tilde{\mu} \rightarrow \tilde{G}$
3. Allows us to re-interpret GMSB searches





Still ongoing, already puts simplified GMSB models into question

Already identified possible interesting targets for new searches

Other Scans & Studies

L. Renn: Automate comb. of pMSSM SR using TACO algorithm

- Test overlap of SRs → safe comb?
- Significantly improves coverage!
- More work needed