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SUSY Search

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LHC

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Outline:

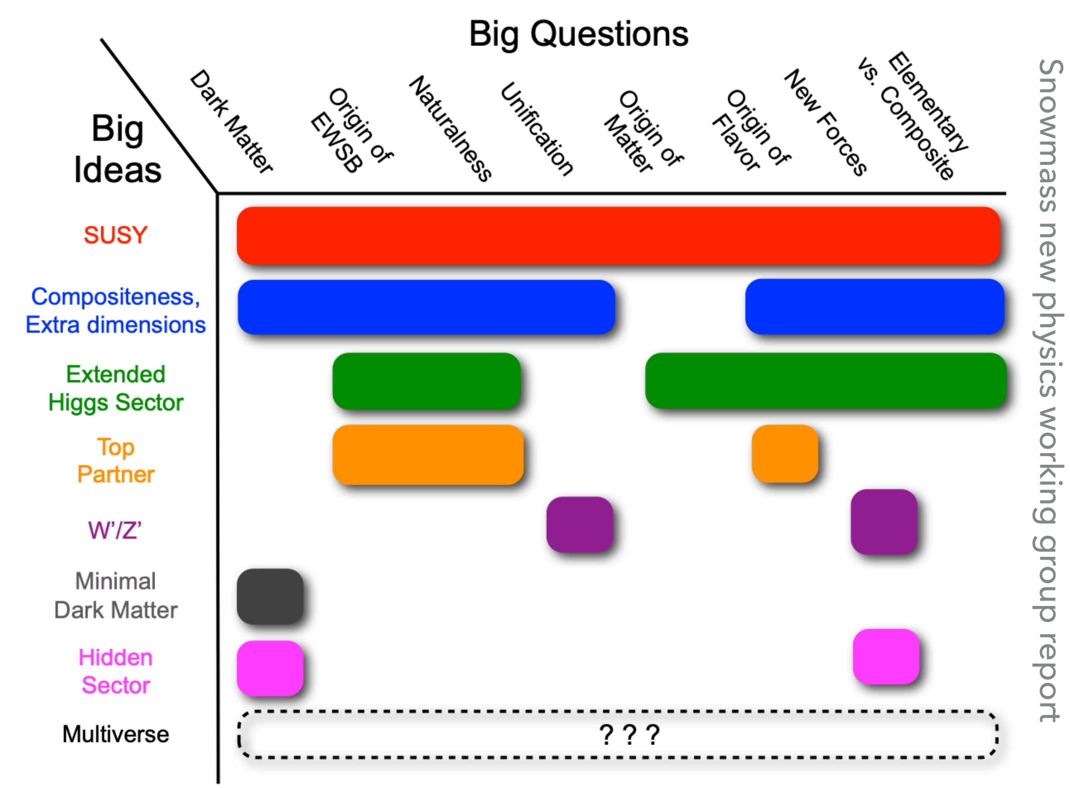
- **General strategy for searching SUSY**
- **SUSY searches in run2**
- **Towards to run3**
- **One more thing…**

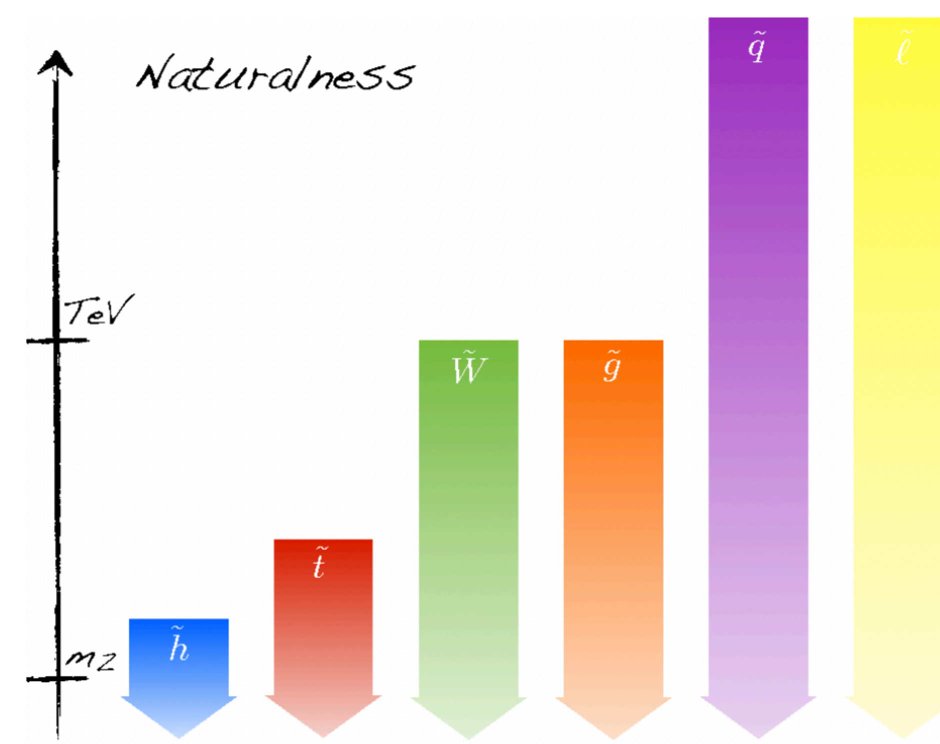
Why SUSY:

- Despite the huge success of the SM theory, physics beyond SM is strongly motivated:
  - hierarchy problem, dark matter, quantum description of gravity, the GUT e.t.c…
- Supersymmetry (SUSY) extend the SM and connect SM Fermions & Bosons with their super partner into a set of super-multiplets
  - Solving hierarchy problem if only soft breaking of supersymmetry (mass constraint within TeV scale, could be produced in the LHC)
  - Provide stable DM candidate (Lightest-SUSY-Particle) if R-parity is conserving (RPC)

$$P_R = (-1)^{3B+L+2S}$$

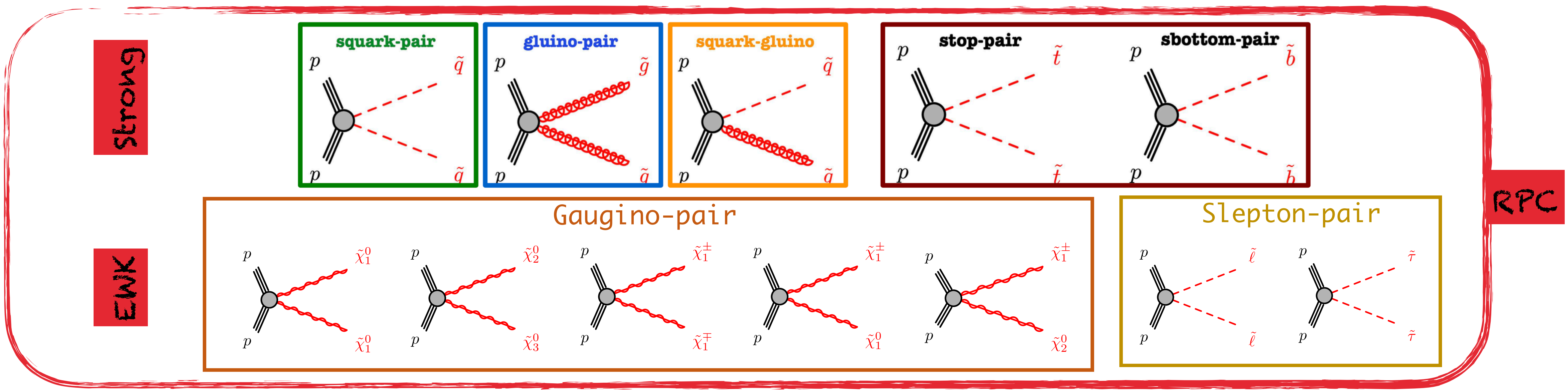
  - Including graviton & gravitino needed for the GUT…





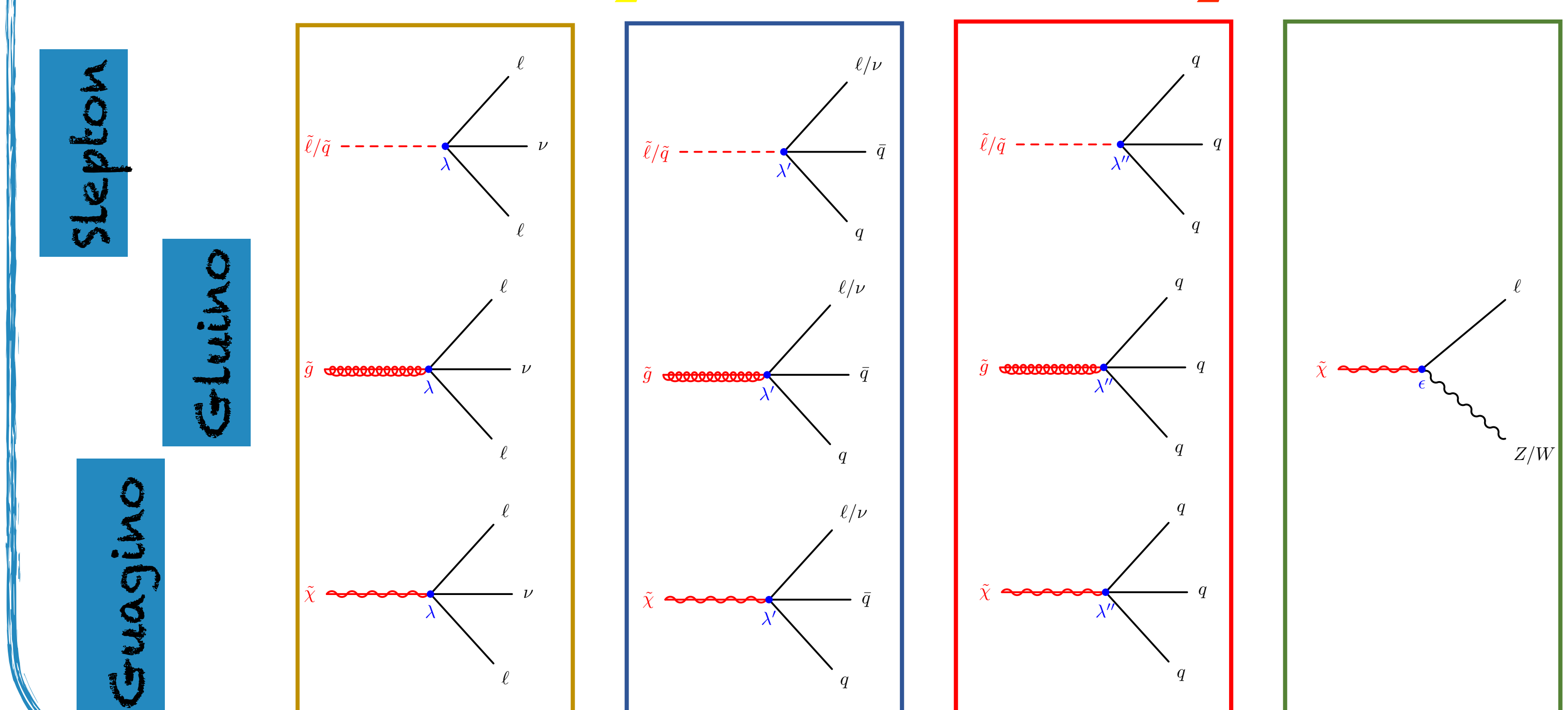
General strategy of searching SUSY:

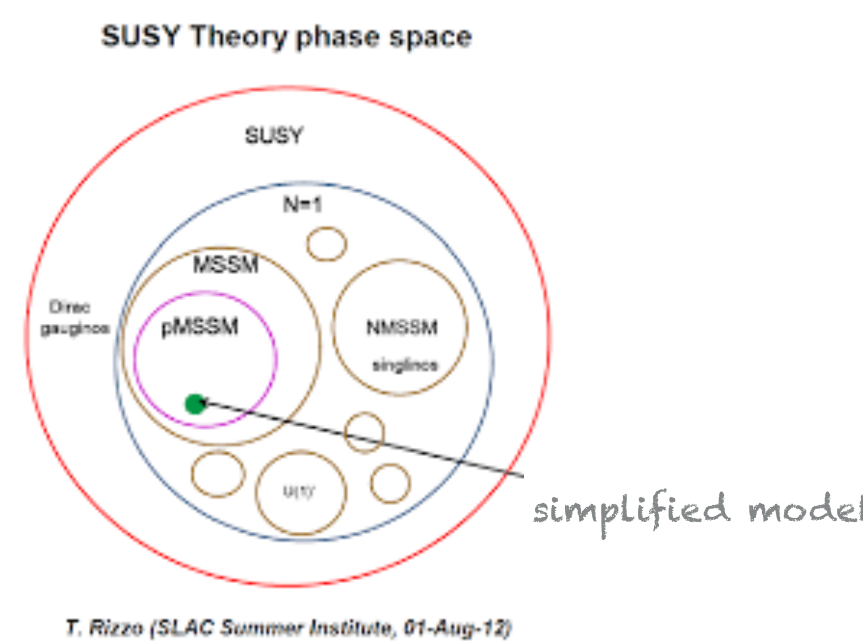
- Dozens of analysis team covering all aspects of SUSY scenarios and models: further separated via final states



$$W = W_{MSSM} + W_R;\ W_R = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

RPV





General strategy of searching SUSY:

Finding signal regions

- Dedicated SRs are designed for targeting signal models to enhance the signal sensitivity
- Different sets of SRs are designed to target at different phase space (e.g: boost, compressed)
- "Multi-bin" strategy is applied to maximize the exclusion power
- Best CLs value for each point are chosen from those inclusively SRs

BKG estimations

- Dominant bkgs:
  - Estimated directly from data events in control regions (CRs):
    - Data-Driven (DD) methods e.g: ABCD, MxM and FakeFactor methods
  - Corrected by data in CRs
  - Estimations will be validated by comparing to data events in validation regions
- Minor bkgs: Estimated directly via MC simulations

Systematics estimations

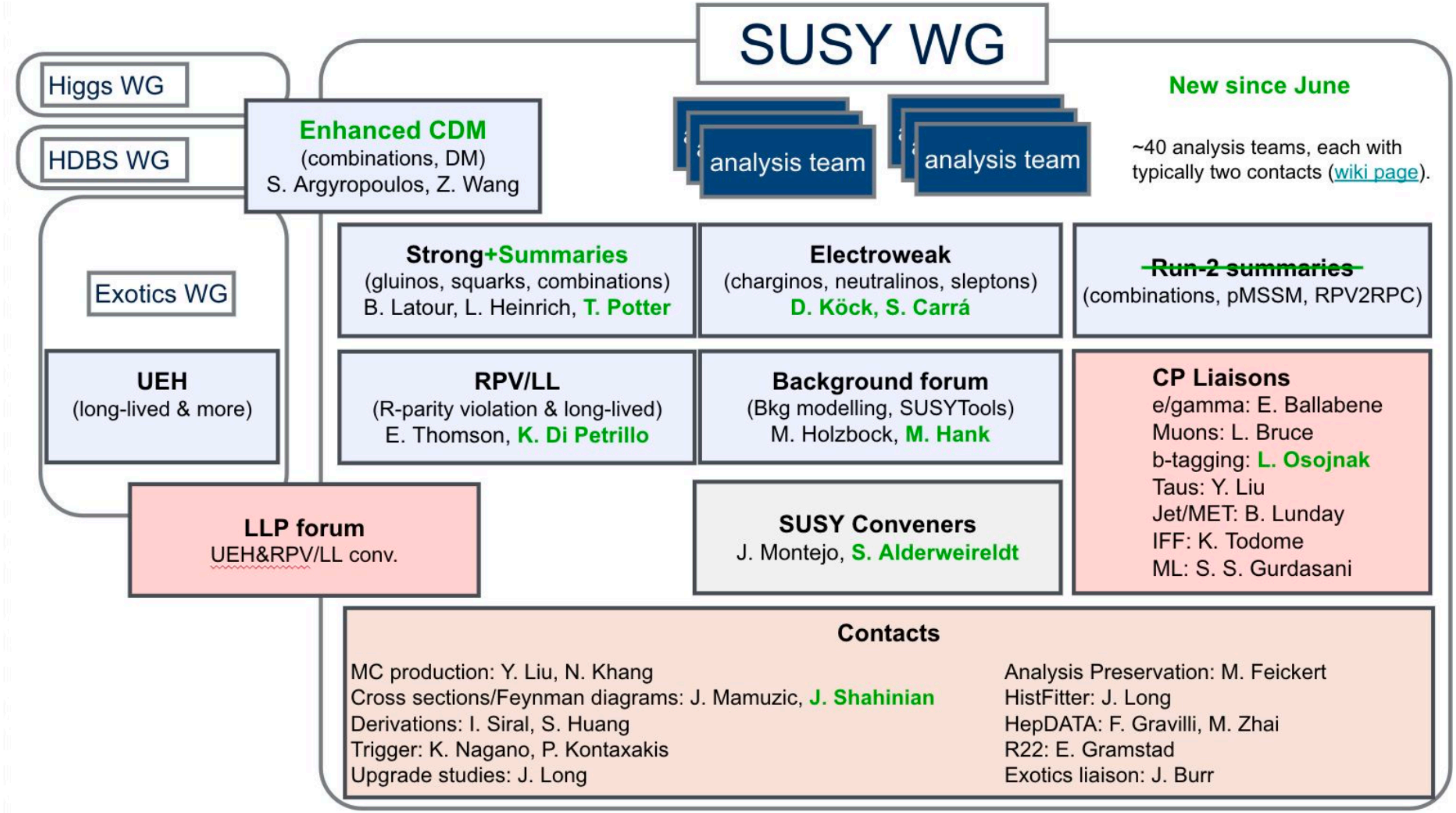
- Experimental uncertainties:
  - Uncertainties coming from the imperfection of the simulation, obtained by all kinds of correction factors e.g: Lumi, pileup …
  - Uncertainties coming from DD estimation methods
- Theoretically uncertainties:
  - Uncertainties coming from the parameter choices of used MC sample e.g: renormalization and factorization scales, PDF …

Statistical interpretations

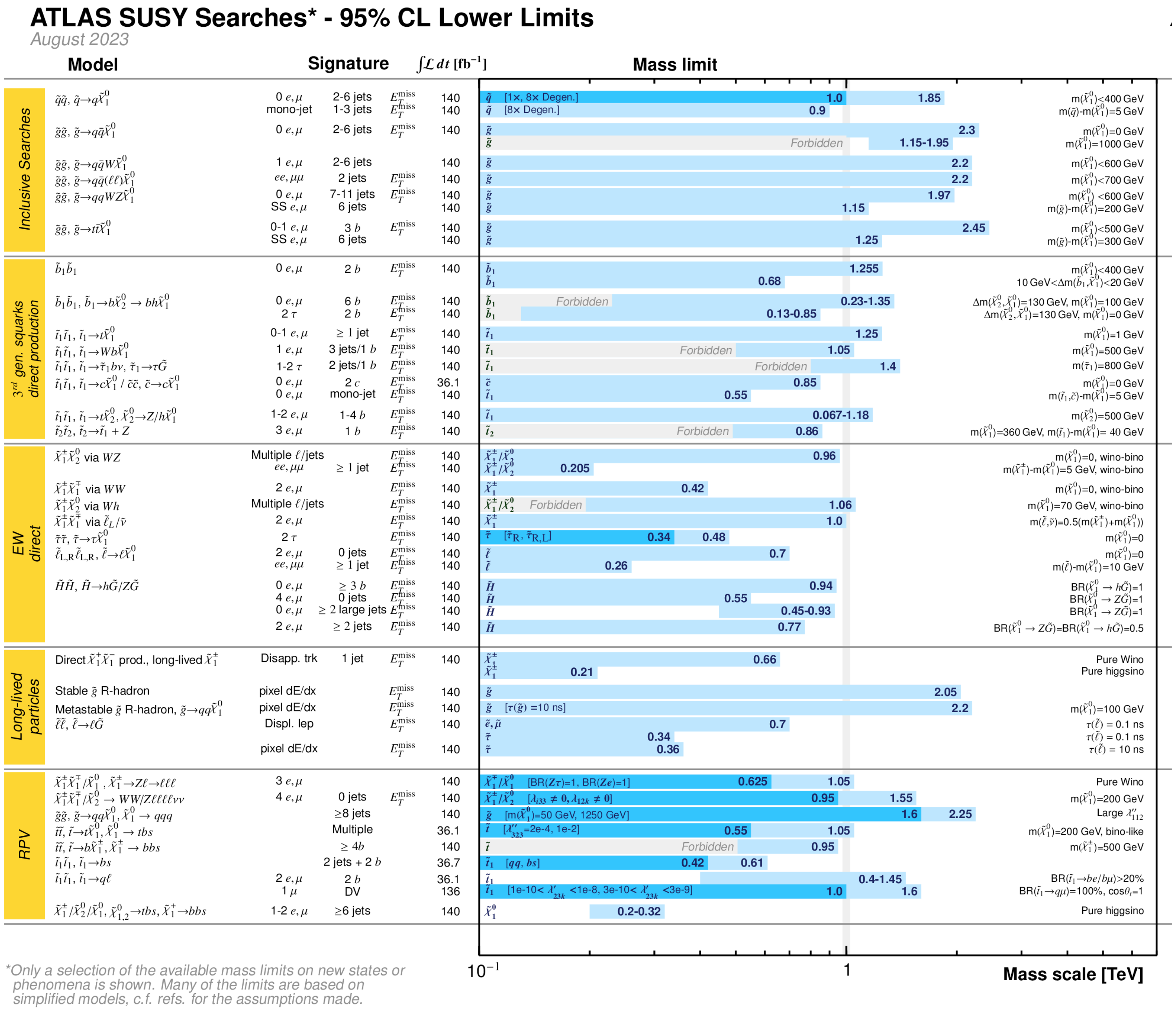
- With estimations of BKGs and data events in SRs, excess or agreement could be seen
- 95% CLs exclusion limits will be drawn for targeted models on phase space if there is no excess observed

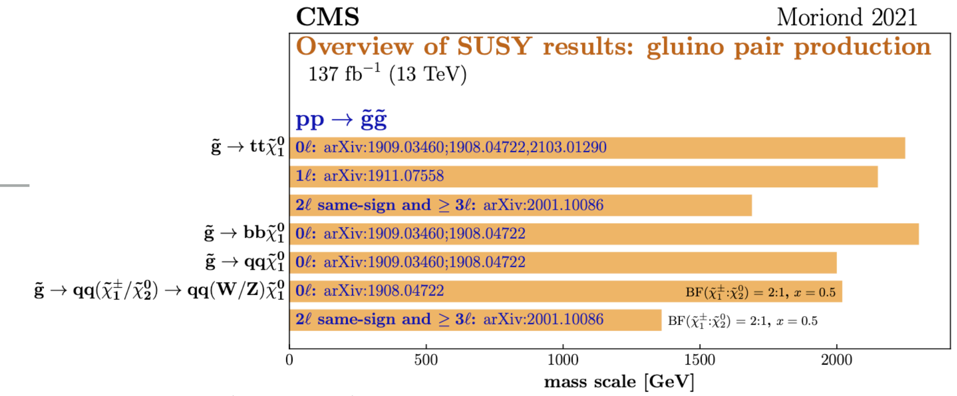
General strategy of searching SUSY:

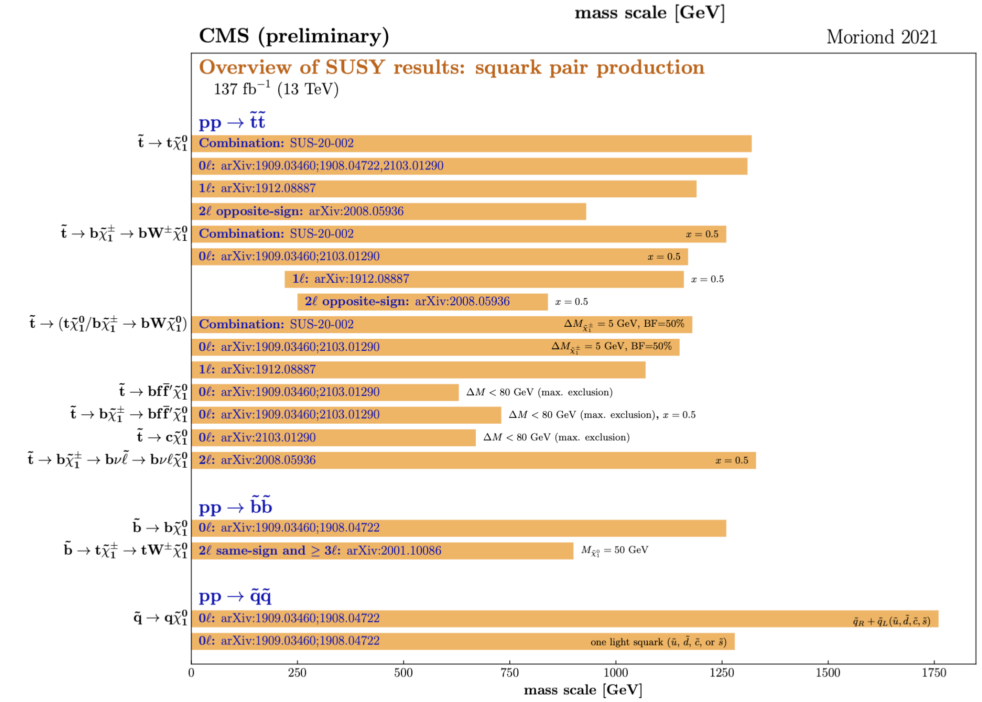
The SUSY group structure

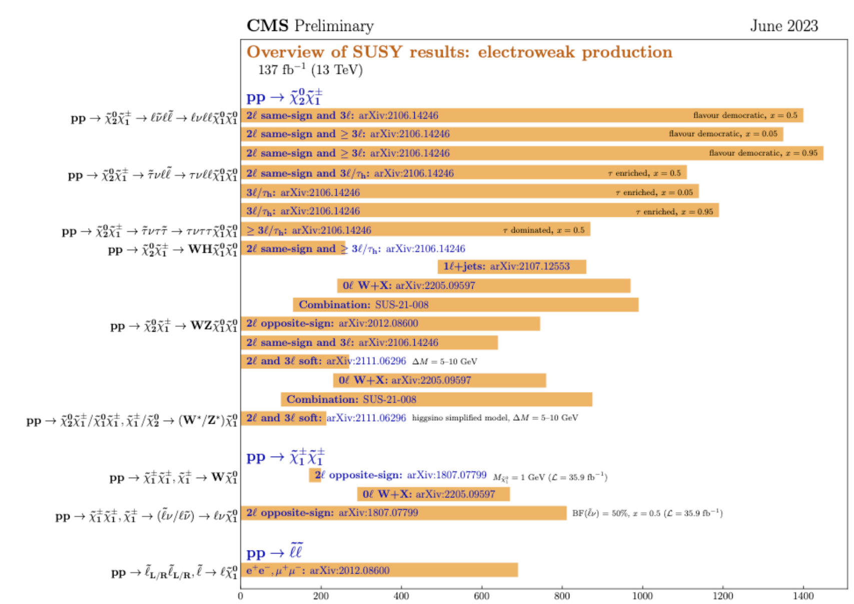


Current searching results:







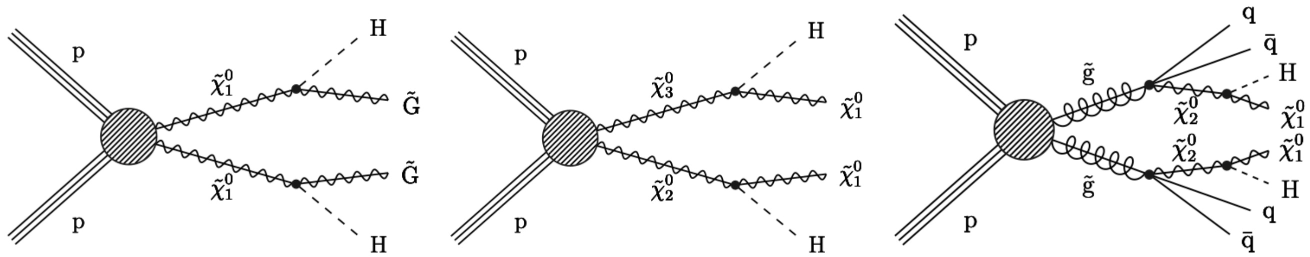


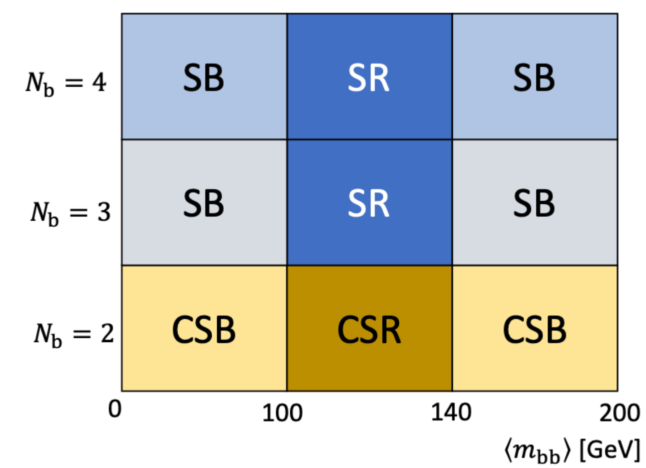
- No significant excess observed yet
- BTY, 2/3σ excess are normal in SUSY searches
- Up to ~2.5/1.2/1/0.7 TeV $\tilde{g}/\tilde{q}_{(3rd)}/\tilde{\chi}/\tilde{l}$ got excluded

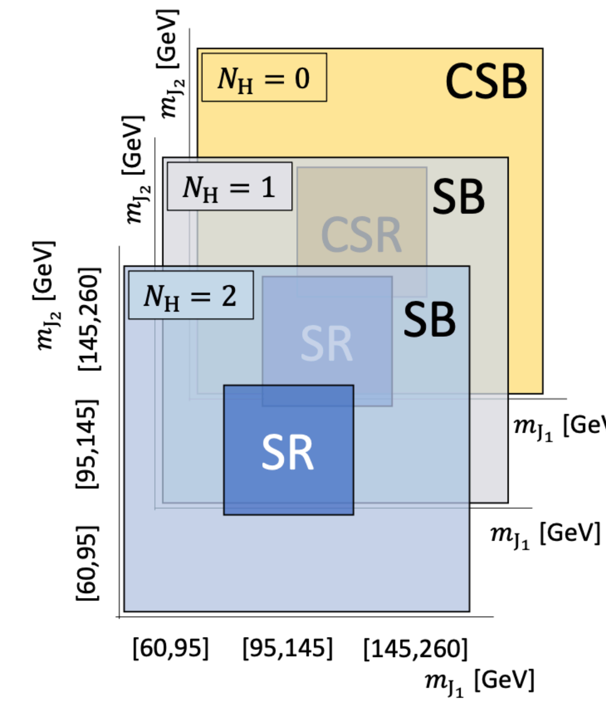
SUSY excess observed in run2:

HIGGSINO WITH TWO HIGGS SEARCHES IN MULTI-BJETS EVENTS

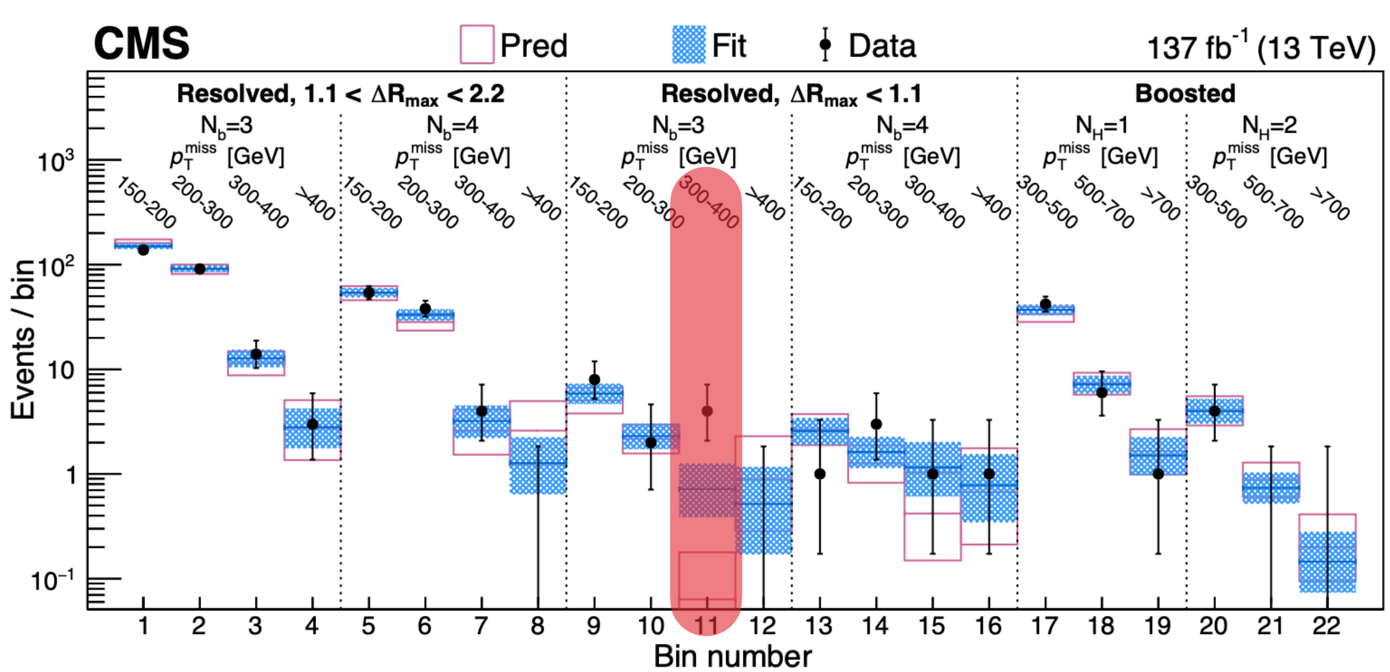
JHEP05(2022)014

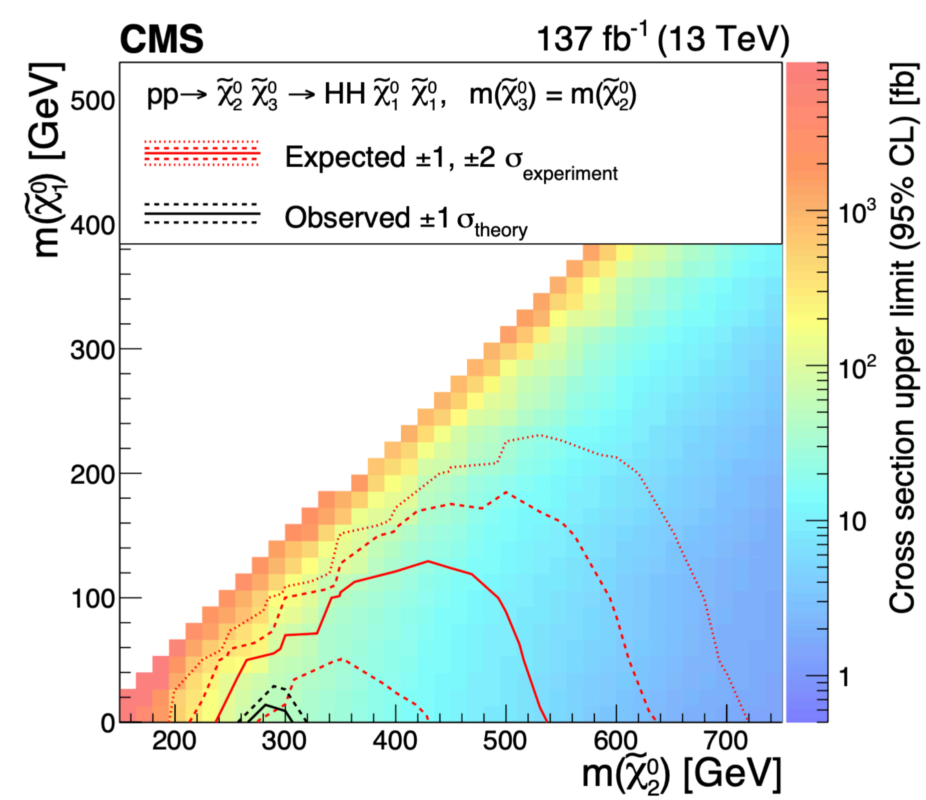






- Events are categorized by boosted two bjets or resolved two bjets
- Backgrounds were estimated using sideband and controlled by control regions: $N_{SR}^{pred} = \kappa \frac{N_{CSR}}{N_{CSB}} N_{SB}$
- **Excess observed in bin11, reaching to 2.1σ**
- **Even it doesn't looks like an SUSY excess, but still good sign to investigate**

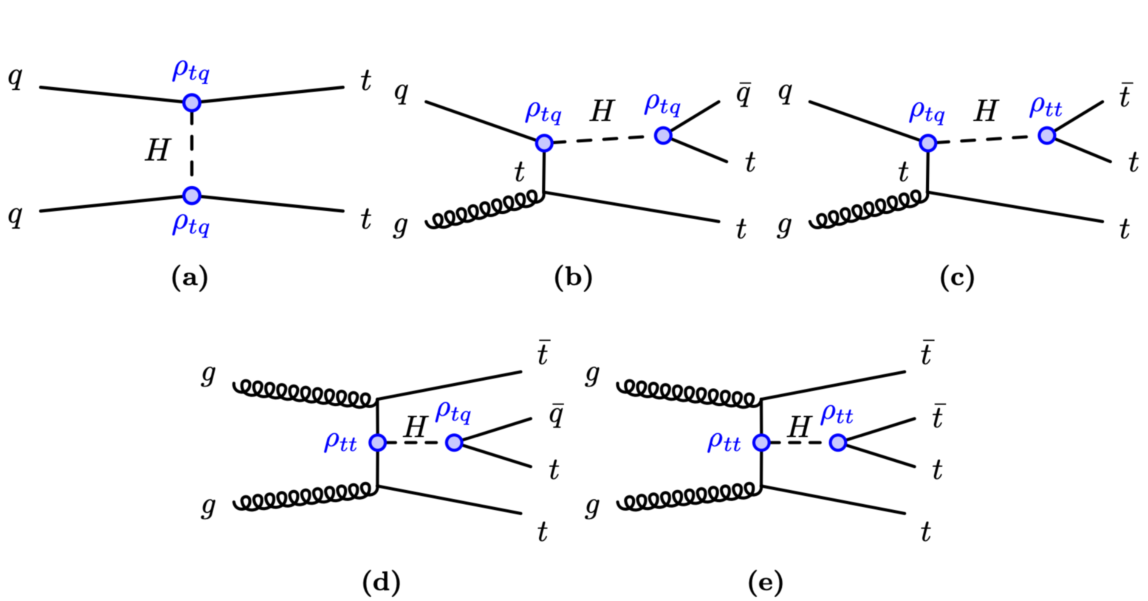


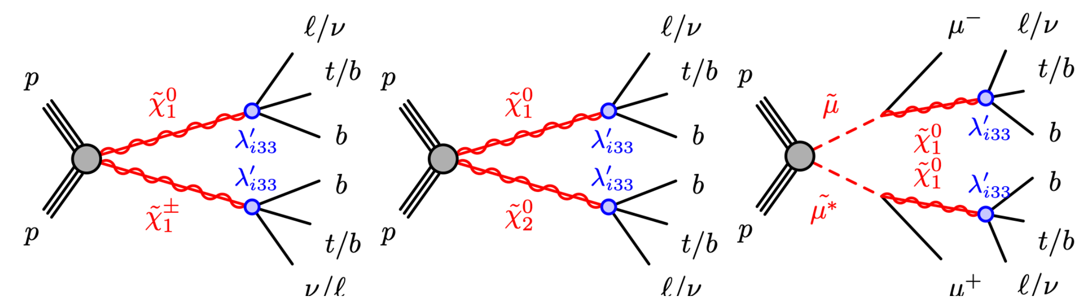


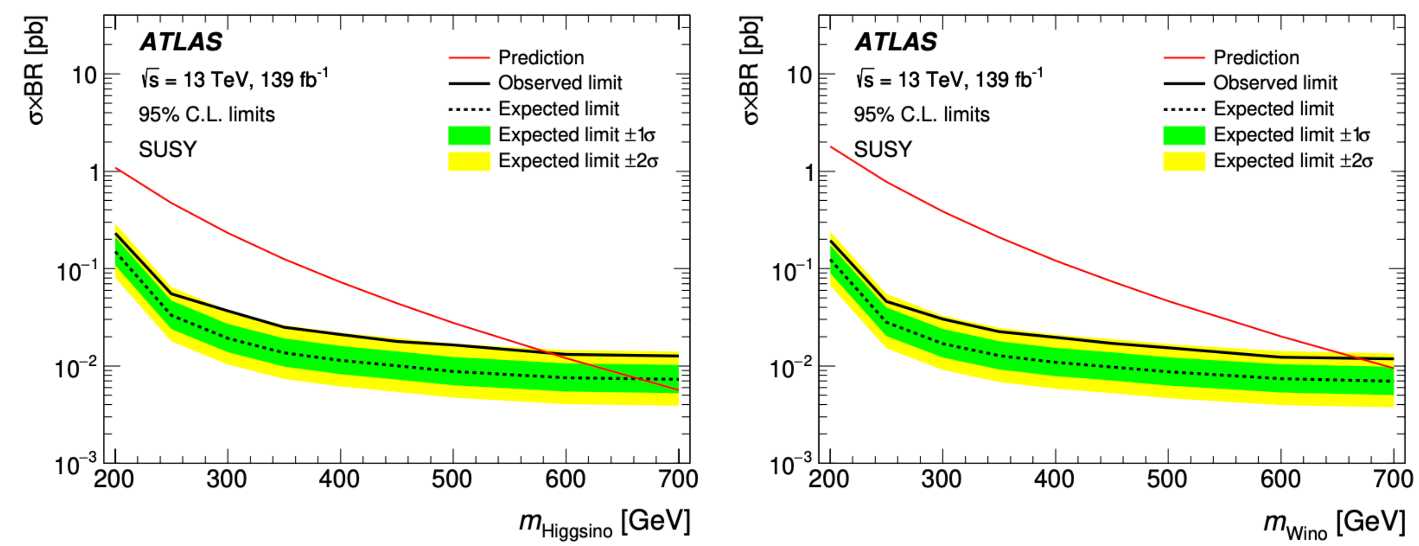
SUSY excess observed in run2:

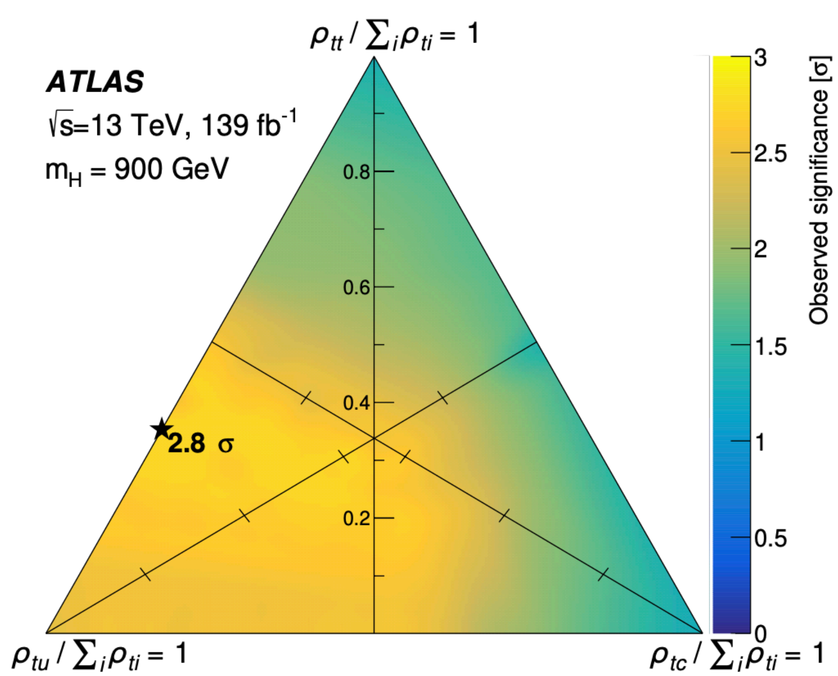
G2HDM & SUSY IN MULTI-LEP + BJETS

JHEP12(2023)081







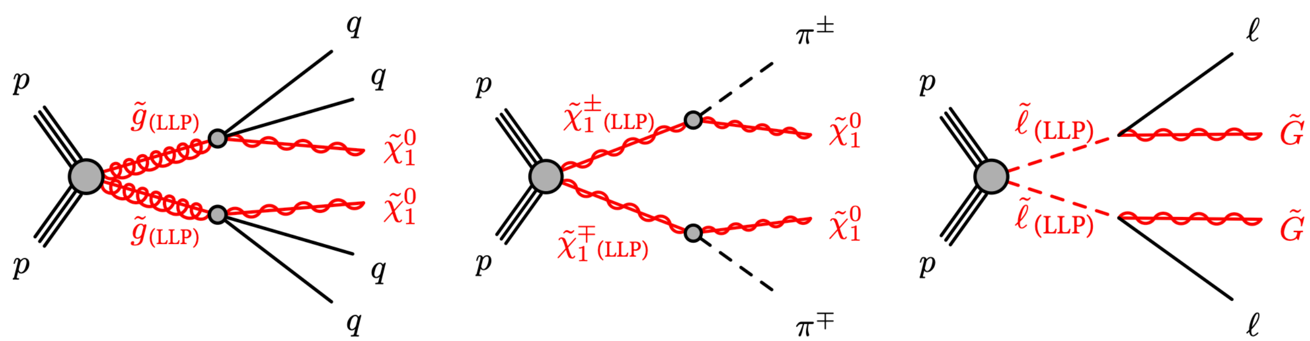


- g2HDM models with varied coupling strength & m_H
- SUSY models with prompt RPV decay and varied mass of the relevant particles
- SRs categorized by N_l & N_{bjet} & DNN scores
- **Largest deviation (2.8σ) observed for g2HDM**
- Exclusion $\tilde{\chi}$ up to ~700 GeV
- **SUSY searches can be guidelines for all NP phenomena**

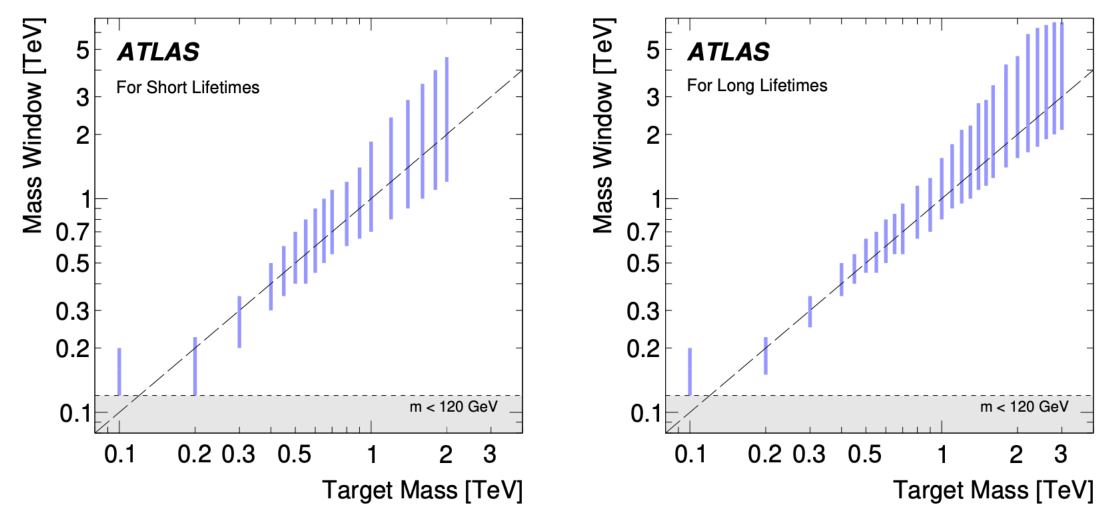
SUSY excess observed in run2:

LONG-LIVED CHARGED SUSY PARTICLES IN DE/DX MEASUREMENT

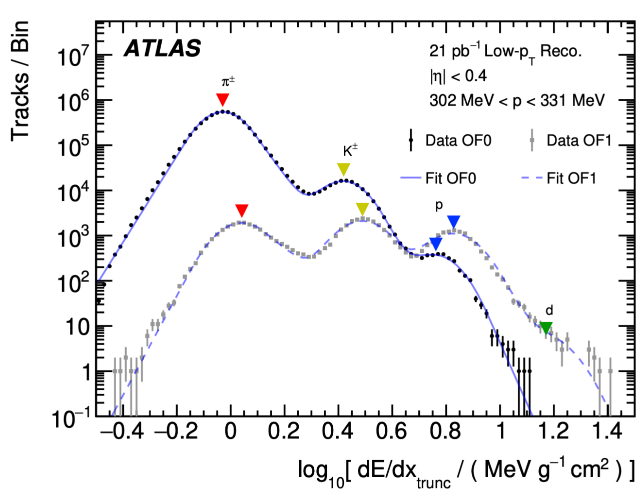
JHEP12(2023)158

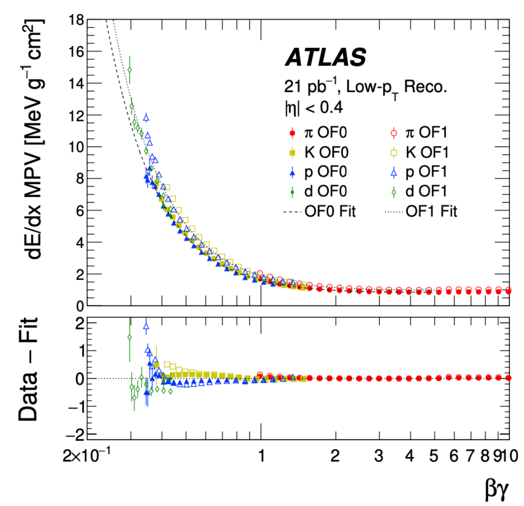


Category	Item		Description
			● ● ●
Pixel dE/dx	Inclusive	Low:	$dE/dx \in [1.8, 2.4]$ MeV $g^{-1}cm^2$
		High:	$dE/dx > 2.4$ MeV $g^{-1}cm^2$
	Binned	IBL0_Low:	$dE/dx \in [1.8, 2.4]$ MeV $g^{-1}cm^2$ and $OF_{IBL} = 0$
		IBL0_High:	$dE/dx > 2.4$ MeV $g^{-1}cm^2$ and $OF_{IBL} = 0$
		IBL1:	$dE/dx > 1.8$ MeV $g^{-1}cm^2$ and $OF_{IBL} = 1$



- Massive long-lived and charged particle leaves track in the inner track detector
- With pixel tracker, dE/dX can be measured for each track
- With Bethe-Bloch equation ($dE/dX = f(\beta\gamma)$), and pT one can obtain the particle mass from the track





$$\mathrm{MPV}_{dE/dx}(\beta\gamma) = \frac{1 + (\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1 \log_{10}(\beta\gamma) + c_2 \left[\log_{10}(\beta\gamma)\right]^2\right)$$

- **Excess observed in in the high-dE/dx and high-mass range**
- **Reach to 3.6σ in the SR for $M_x = 1.4TeV$**
- **This search not only suits for SUSY models but is also sensitive to every similar case**
- **Unfortunately, the excess was killed by the following studies using TOF info to obtain the $\beta\gamma$**

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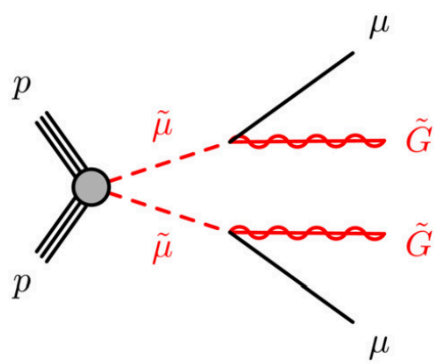
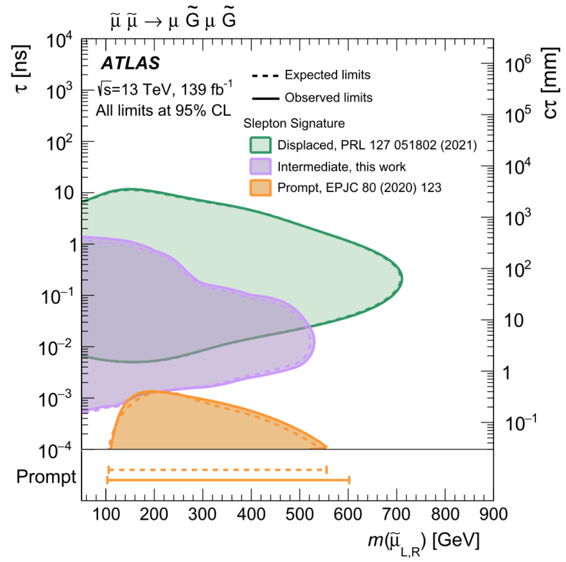
SUSY highlights in run2:

LONG-LIVED $\tilde{\mu}$



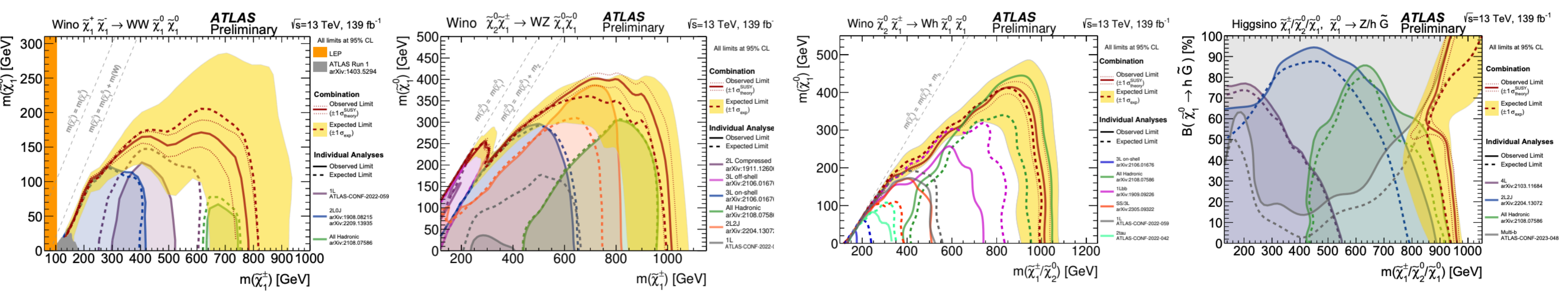


[PLB 846 (2023) 138172](#)

- First time fill the gap between the prompt and long-lived scenario using reinterpretation
- More will come in recent days in RPC-RPV studies

$\tilde{\chi}/\tilde{l}$ COMBINATION

Production mode	Wino $\tilde{\chi}_1^+\tilde{\chi}_1^-$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	Higgsino GGM $\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_{1,2}^0, \tilde{\chi}_1^0\tilde{\chi}_2^0$
Decay mode	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$	$\tilde{\chi}_1^0 \to Z/h\tilde{G}$
Searches				
All Hadronic [23]	✓	✓	✓	✓
1L [24]	✓	✓		
1Lbb [25]			✓	
2L Compressed [26]		✓		
2L0J $\Delta m > m(W)$ [27]	✓			
2L0J $\Delta m \sim m(W)$ [28]	✓			
2L2J [29]		✓		✓
2tau [30]			✓	
3L [31]		✓	✓	
SS/3L [32]		✓	✓	
4L [33]				✓
Multi-b [34]				✓

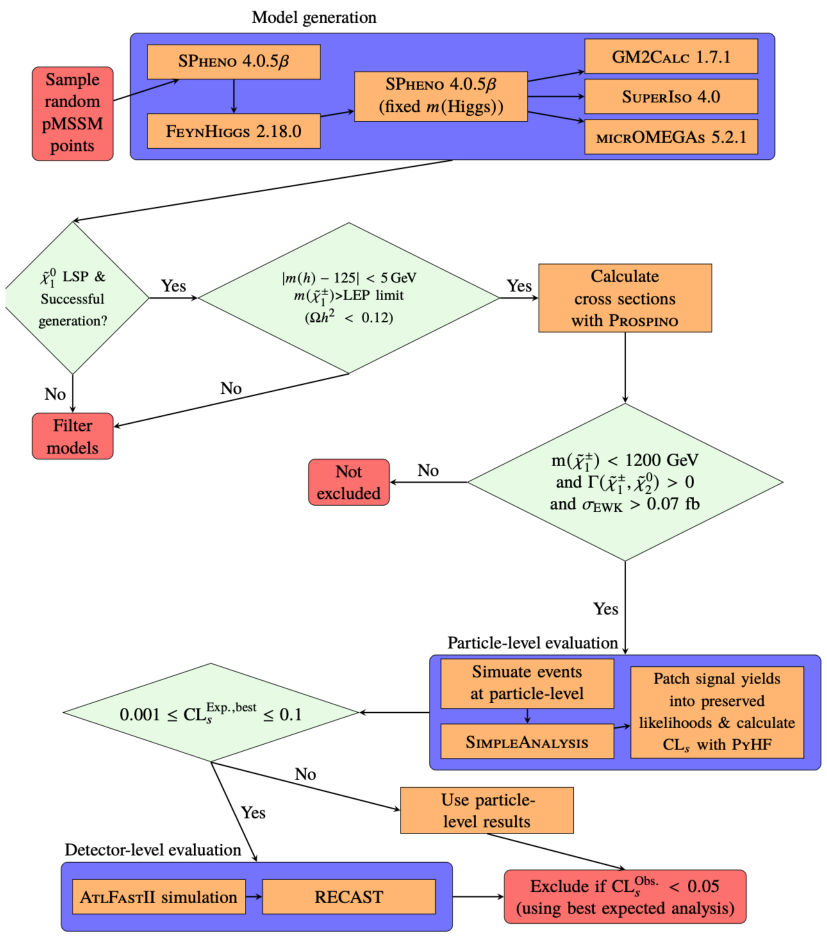


[ATLAS-CONF-2023-046](#)

- First time to have a combination in SUSY, full use the published results
- $\tilde{l}$ studies also performed, but no extra sensitivity was gained
- Lots of studies on combination ahead: $\tilde{l}$, $\tilde{g}$, $\tilde{q}$, $\tilde{t}$ and $\tilde{b}$

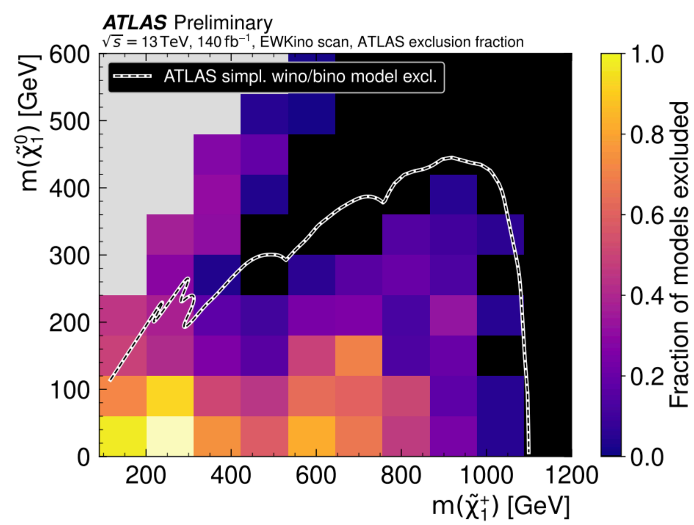
SUSY highlights in run2:

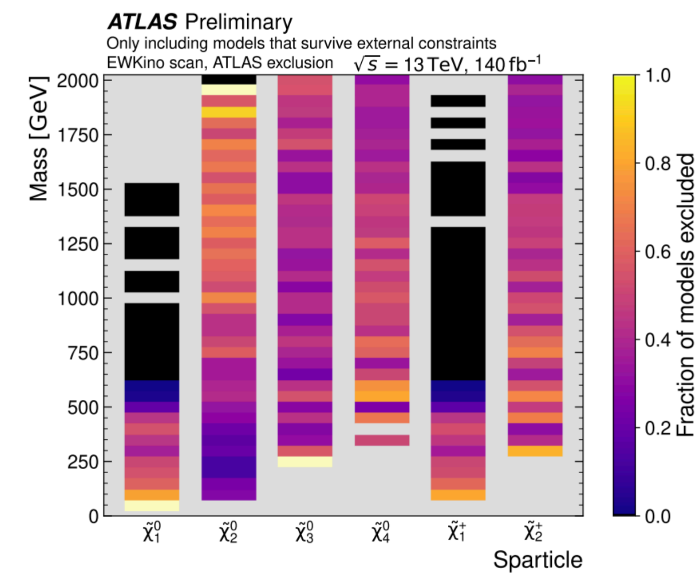
EWK PMSSM-19 SCANNING



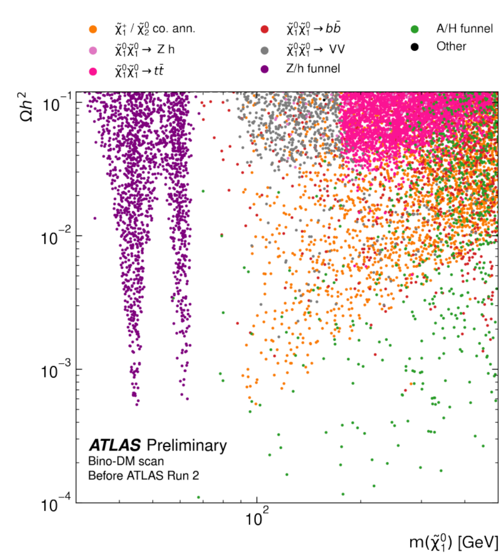
Parameter	min	max	Note
$M_{\tilde L_1}$ $(=M_{\tilde L_2})$	10 TeV	10 TeV	Left-handed slepton (first two gens.) mass
$M_{\tilde e_1}$ $(=M_{\tilde e_2})$	10 TeV	10 TeV	Right-handed slepton (first two gens.) mass
$M_{\tilde L_3}$	10 TeV	10 TeV	Left-handed stau doublet mass
$M_{\tilde e_3}$	10 TeV	10 TeV	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 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

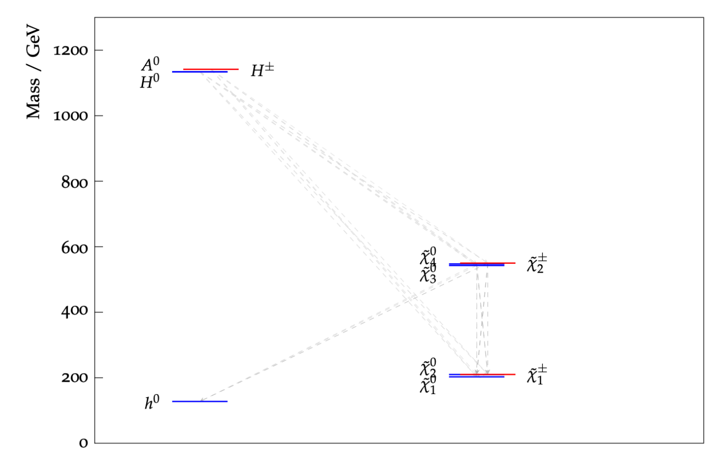
Analysis	Simplified models targeted
FullHad [24]	Wino $\tilde\chi_1^\pm\tilde\chi_2^0$ via WZ, Wino $\tilde\chi_1^\pm\tilde\chi_2^0$ via Wh, Wino $\tilde\chi_1^+\tilde\chi_1^-$ via WW, Higgsino GGM
1Lbb [15]	Wino $\tilde\chi_1^\pm\tilde\chi_2^0$ via Wh
2L0J [19]	Wino $\tilde\chi_1^+\tilde\chi_1^-$ via WW, slepton pairs
2L2J [25]	Wino $\tilde\chi_1^\pm\tilde\chi_2^0$ via WZ, Higgsino GGM
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 $\tilde\chi_1^\pm\tilde\chi_2^0\tilde\chi_1^0$, Higgsino GGM
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 $\tilde\chi_1^\pm\tilde\chi_1^0$





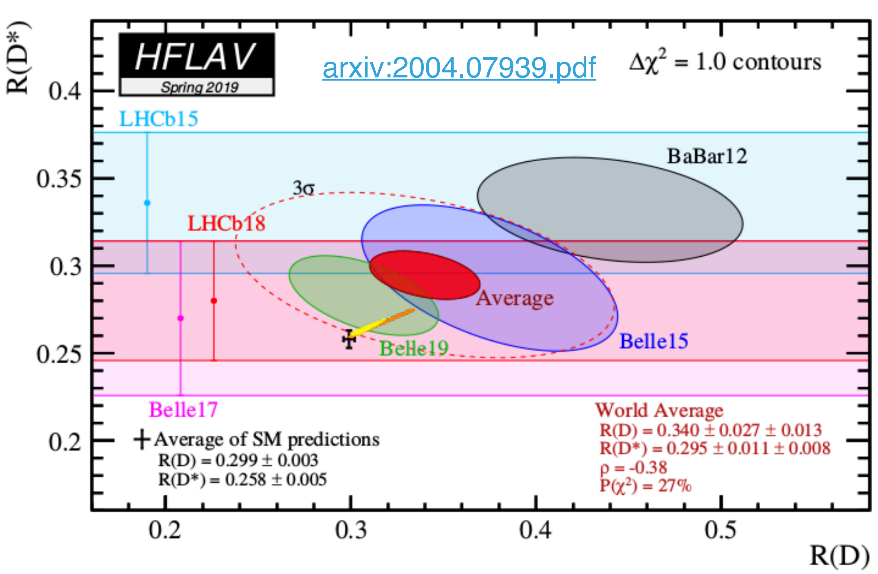
- More scanning results are coming: general scanning and strong scanning
- **Strong relationship with phenomenologists**
- **Recasting (reana) is applied and can be published for use in the future**
- Other highlights like Unfolding SUSY searches:
    - W^+W^- measurement using unfolded SUSY 2L0J search [EPJC]



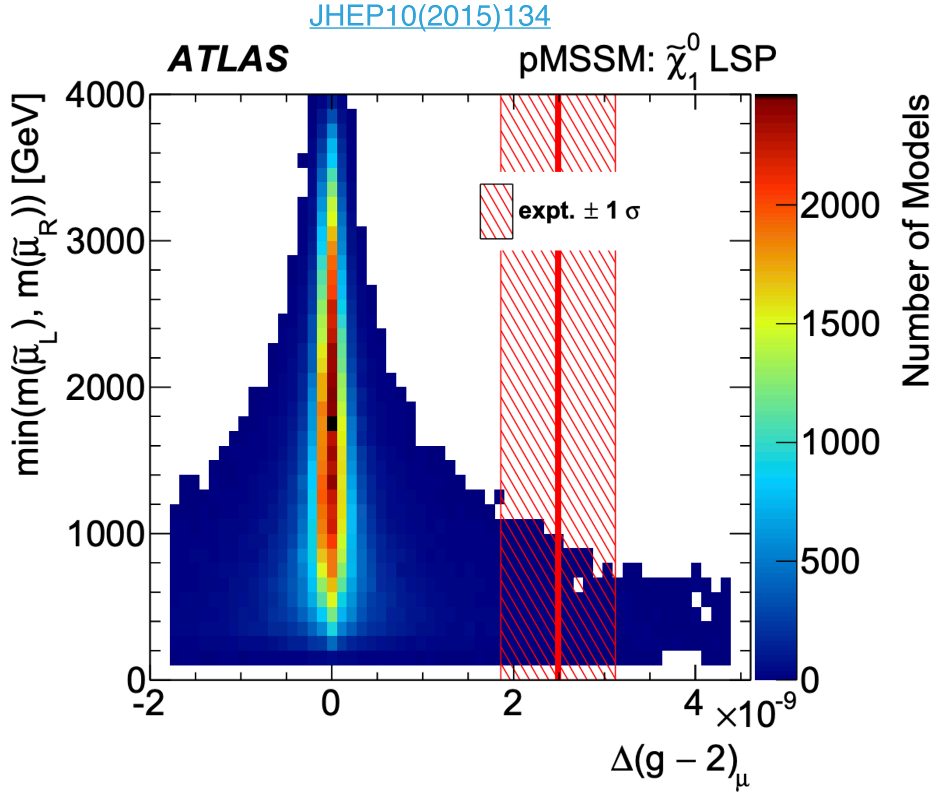


Guidelines for searches in run3

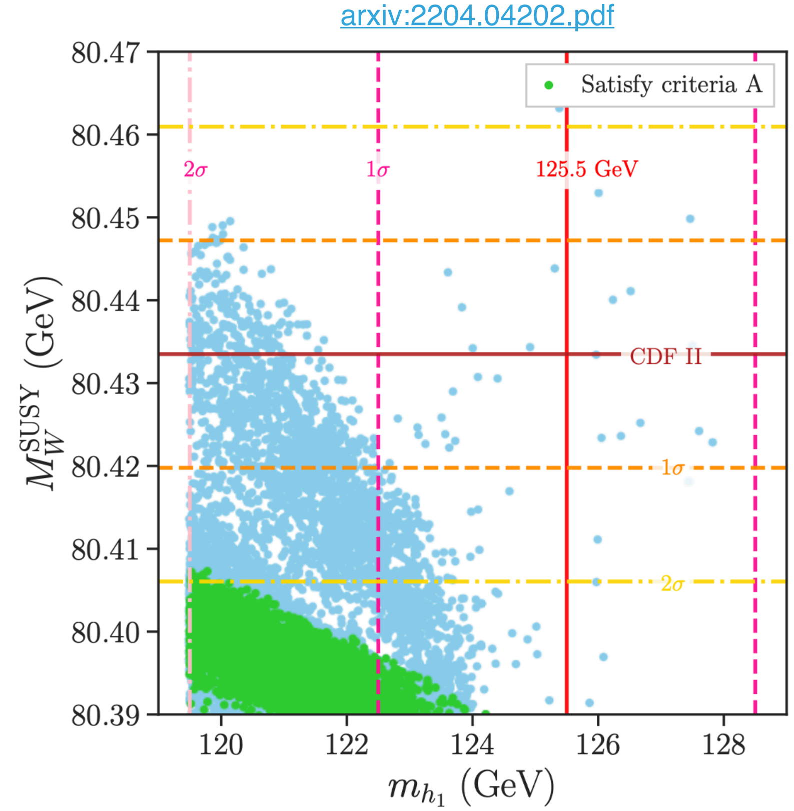
- Novelty:
    - 13 TeV/139 fb-1 to 13.6 TeV/~250fb-1 won't have a significant improve in searches
    - Focus more on the "new" "model-driven" strategy instead of the "signature-driven"
- Excess/Anomalies:
    - B anomalies, mu g-2 and W mass all can constraint the pMSSM phase space
    - Follow-ups on the excess observed before
- Holes in pMSSM scanning:
    - Will use the coming pMSSM scanning results as a guideline to search for the SUSY models
    - With "clustering" tech to choose the benchmark models
    - Compressed regions are expected to be highlighted



JHEP10(2015)134



arxiv:2204.04202.pdf



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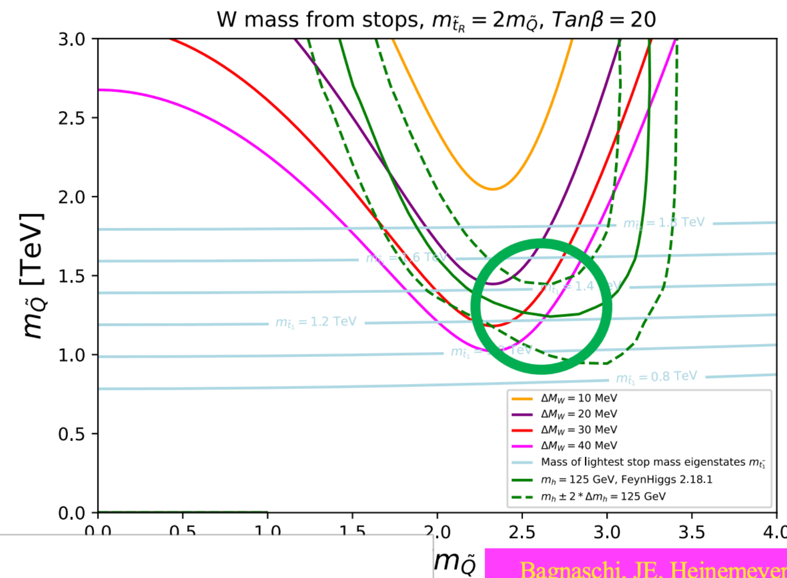
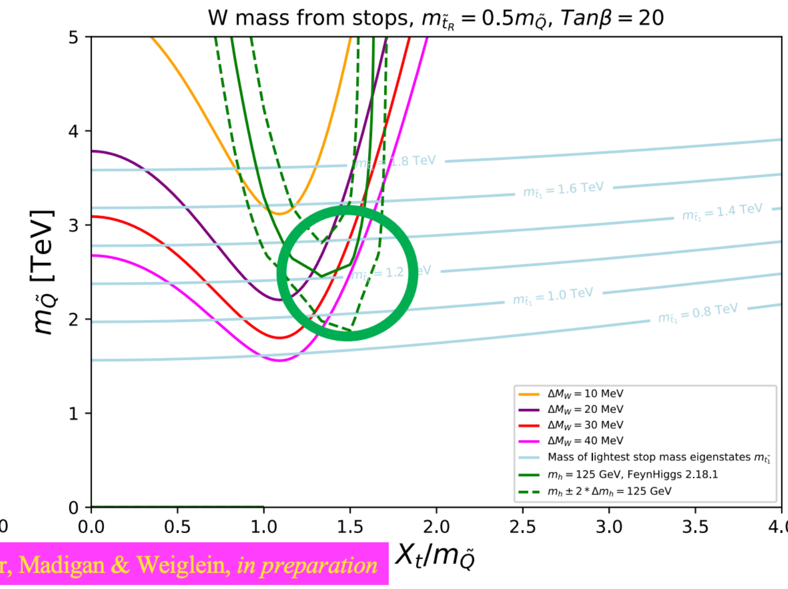
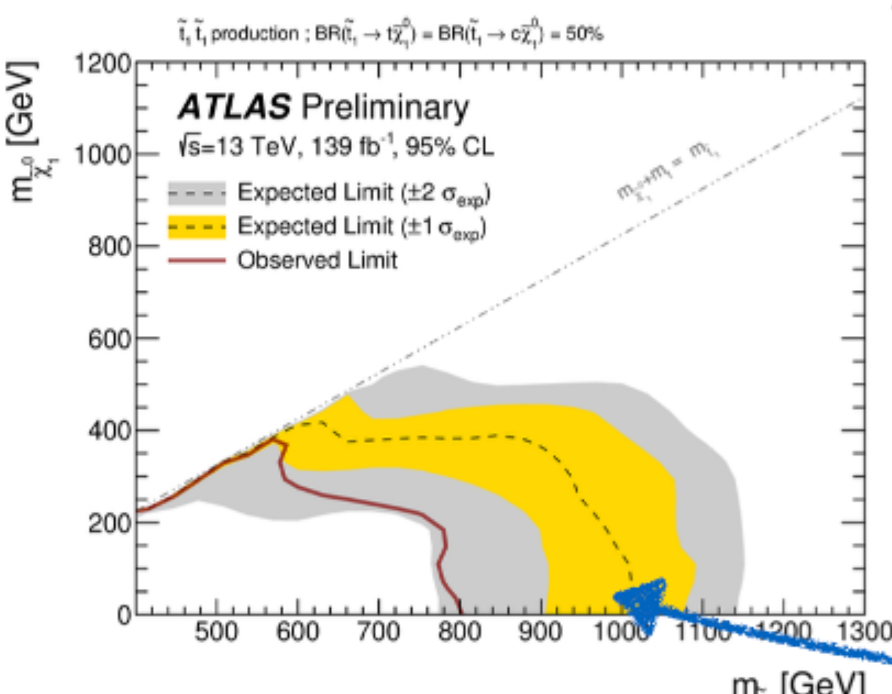
Stop searches in run3:

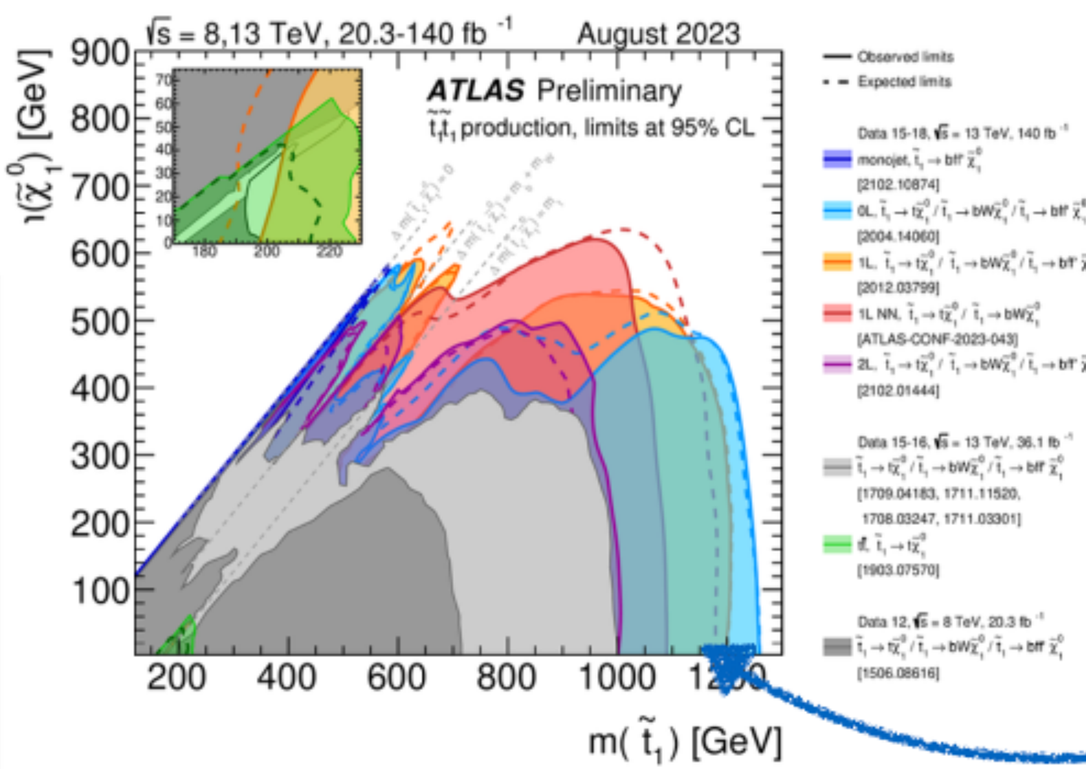
m_H compatible with $m_{stop} \sim 1.5$ TeV





Bagnaschi, JE, Heinemeyer, Madigan & Weiglein, *in preparation*

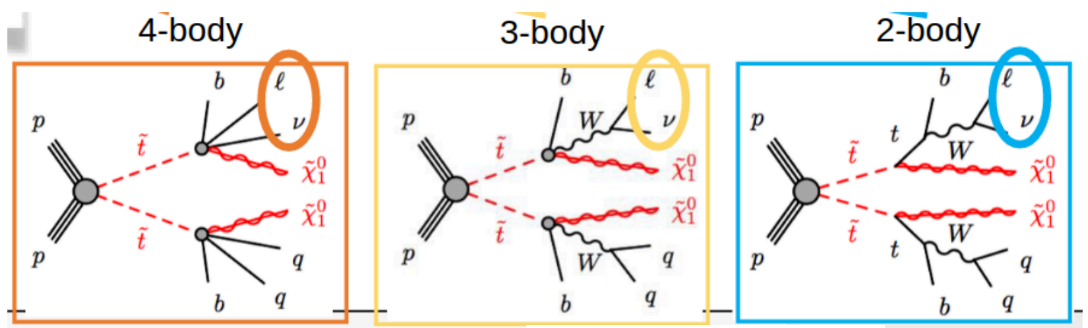


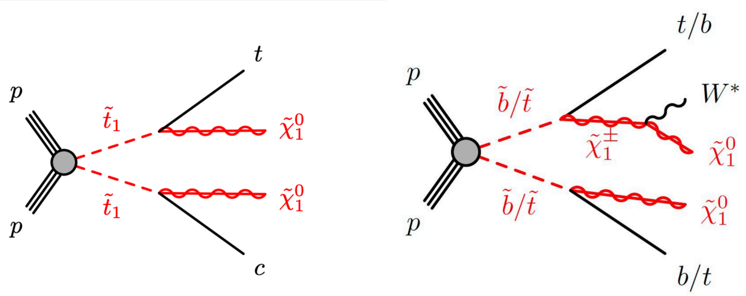


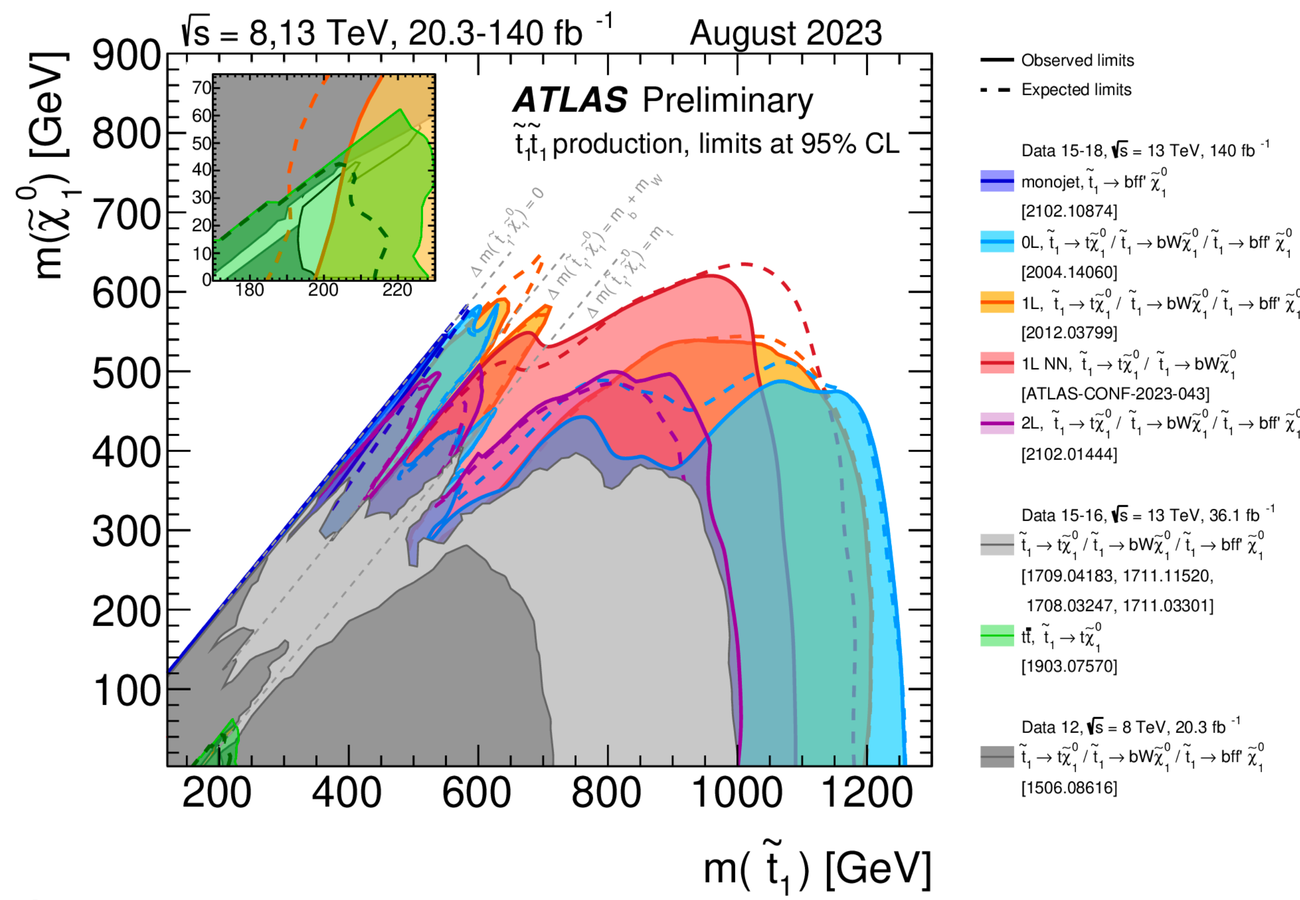
Maybe we start seeing some excesses? :)

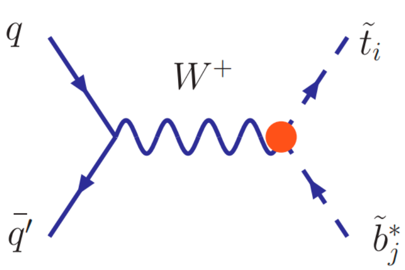
Stop searches in run3:

- Need to probe all possible stop productions and decay modes and run combinations!

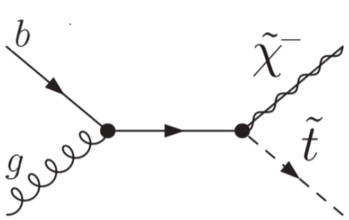




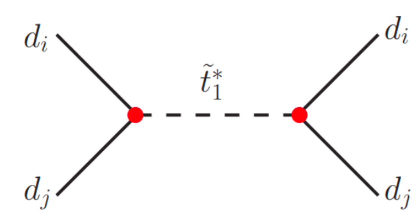




- Observing mixed-flavor squark production could probe the (semi-) Weak vertex directly: $W - \tilde{q}_L - \tilde{q}'_L \; (W - g - \tilde{q}_L - \tilde{q}'_L)$



- Expected to be found @ HL-LHC

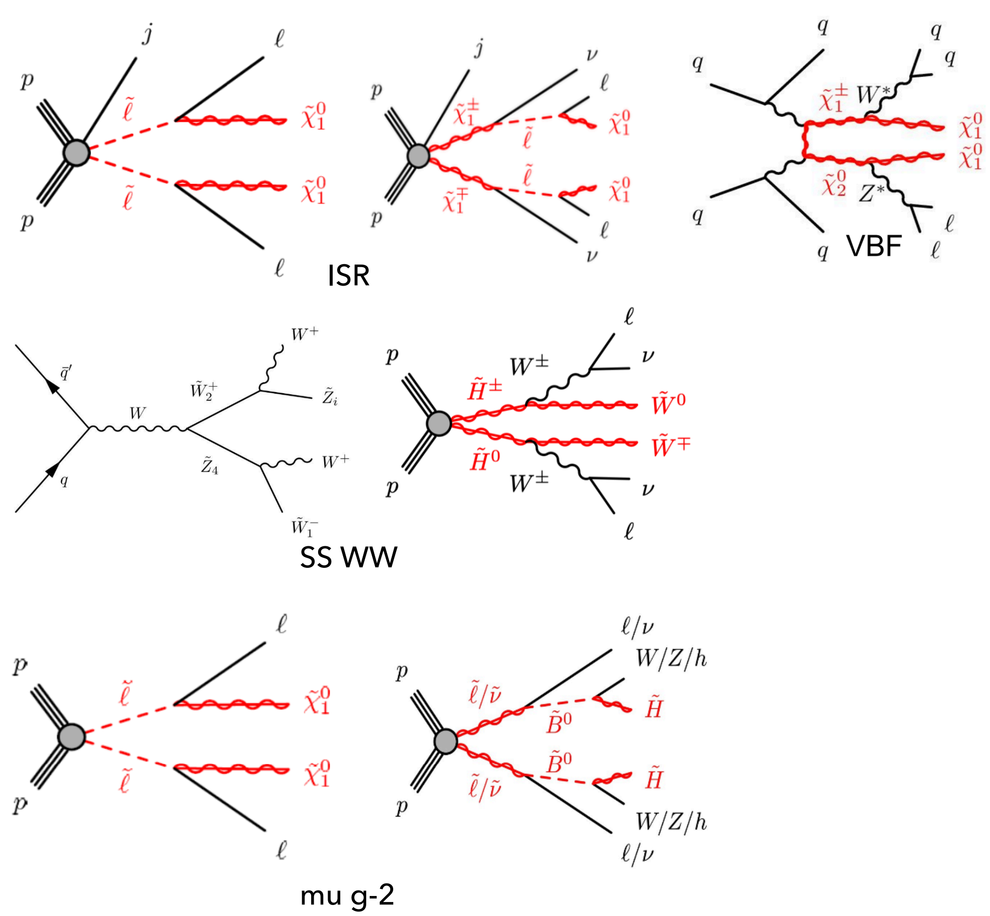


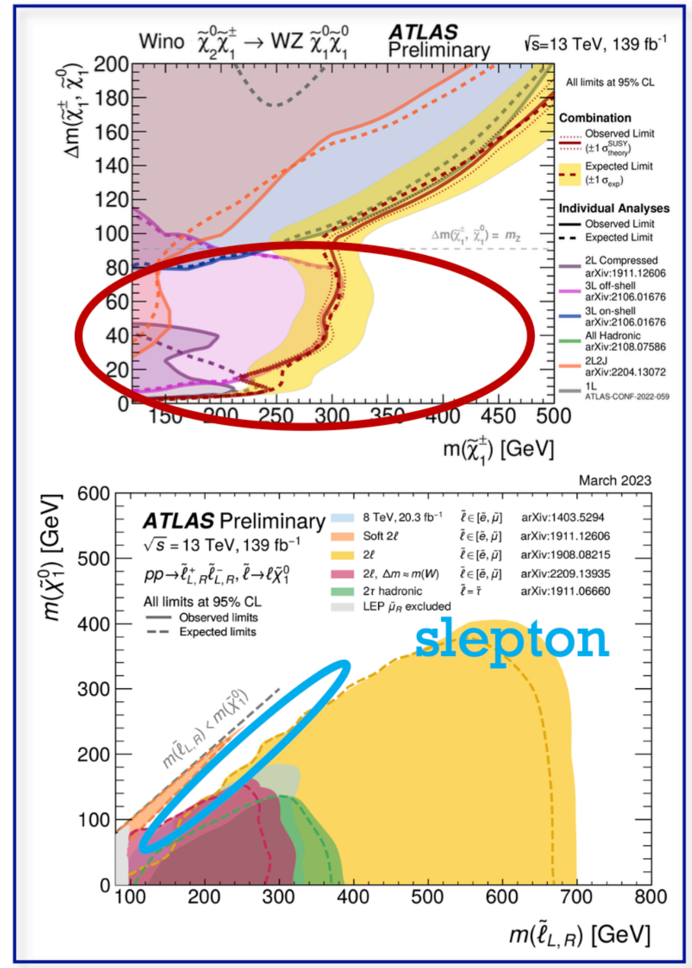
- Xsec of the resonant squark production at the LHC can easily exceed pair-production
- UDD yielding the resonant stop, where the constraints are weaker than the light version allowing larger coupling (a.k.a prompt decay case)
- Contribute to FCNCs, potentially contributing to flavor physics observables

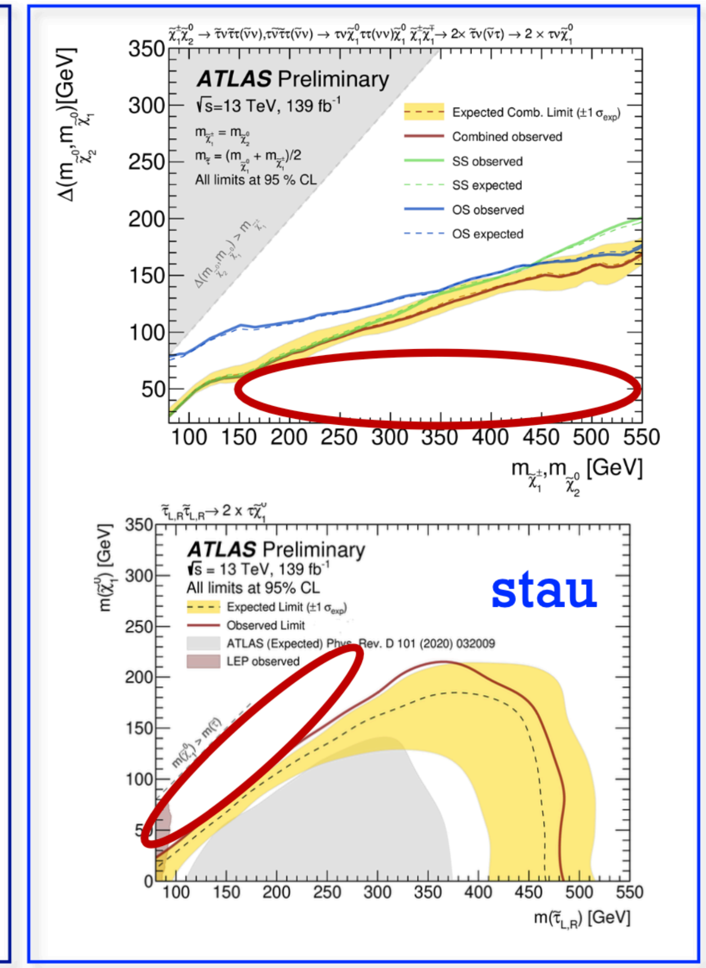
++ ANY HOLES OBSERVED IN PMSSM SCANNING

中山大學 SUN YAT-SEN UNIVERSITY

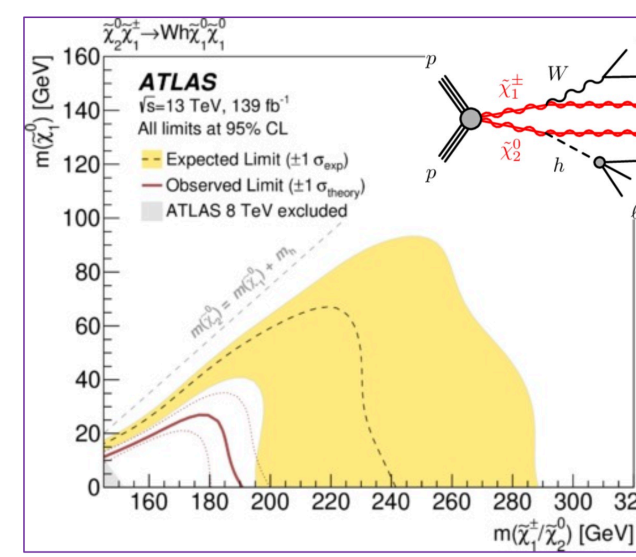
EWK searches in run3:







- Compressed scenarios are challenging due to soft object, small xsec from ISR jet, similar signatures between sig and bkg…
- Light $\tilde{\chi}_i^{\pm}$ and light $\tilde{\mu}$ can explain the μ g-2
- Follow-ups on the excess in run2: (soft 2l,3l)



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~ 2σ excess

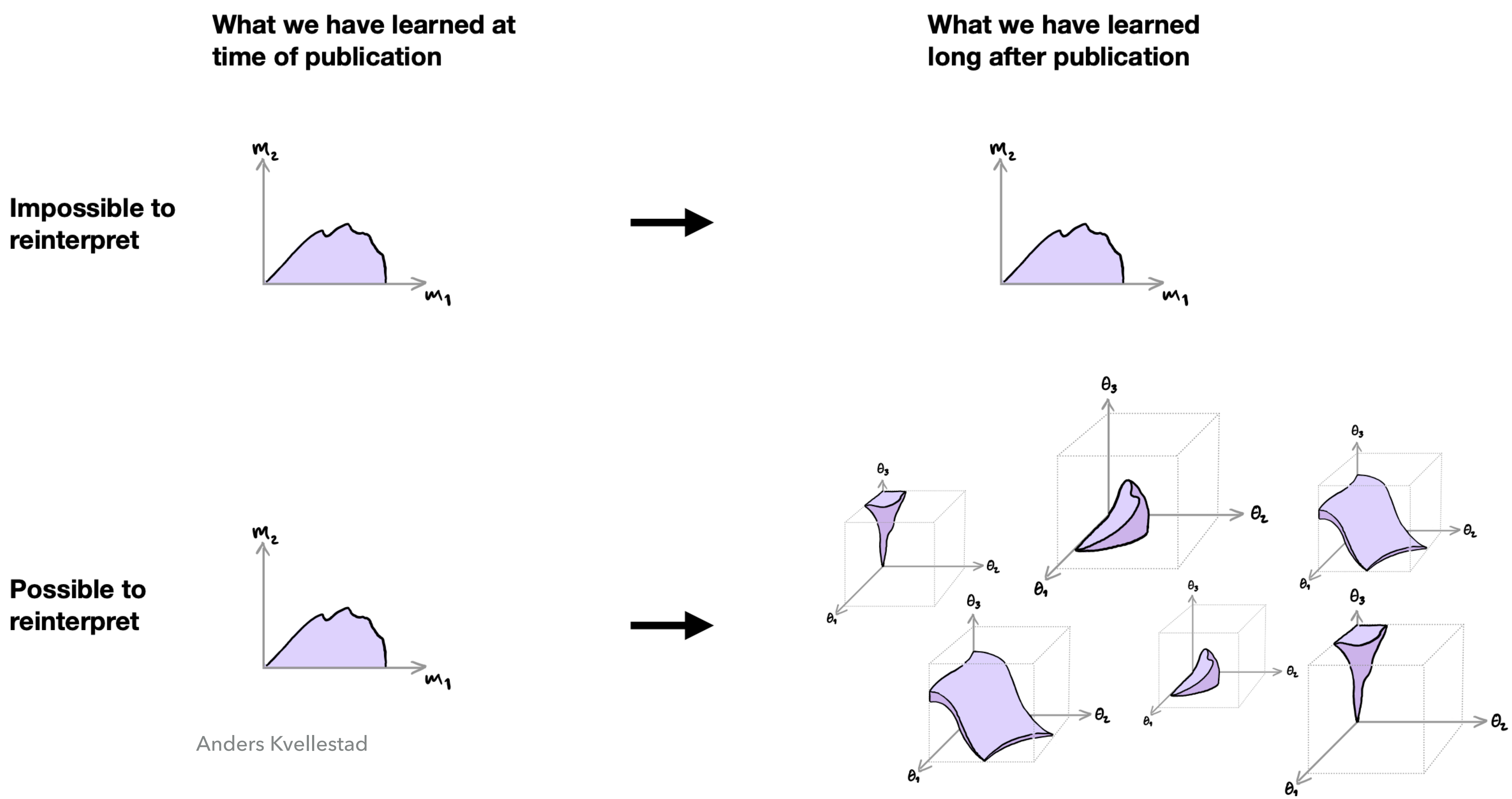
SUSY towards to run3:

- "SUSY is the most **complete** microscopic theory conceived so far to go beyond the SM":
  - In principle can be used to compute any* observable quantity
  - In principle contains the ingredients to deal with all/most issues that the SM cannot address
  - "Supersymmetric models are extremely compelling theoretically"
- "SUSY is the most **complete** "LHC" of experimental signals conceived so far to go beyond the SM":
  - It is quite hard to find an experimental signature that can be attained in another model and cannot be attained in SUSY
  - The model also comes with "some" way to judge how likely it is the particular signal at hand
  - The model allows to derive the experimental implications of observing such signal
- Being "complete" in the theory and experimental sense:
  - You can use it to stress-test the capability of your present (or future) accelerator+experiment
  - Create a solid ground for exchange about **reinterpretation**/**preservation** of the searches

Searches for supersymmetric models are extremely useful
(even if SUSY is not realized in Nature)
Reinterpretation/Preservation is the key

Reinterpretation & Preservation:

- Key point for future "generation":
  - SUSY could be hidden in the existing data
  - NP could be hidden in the existing SRs
- Probe much more of SUSY theory space afterwards
- Probe much more of BSM theory space afterwards
- Identify best-fit scenarios afterwards



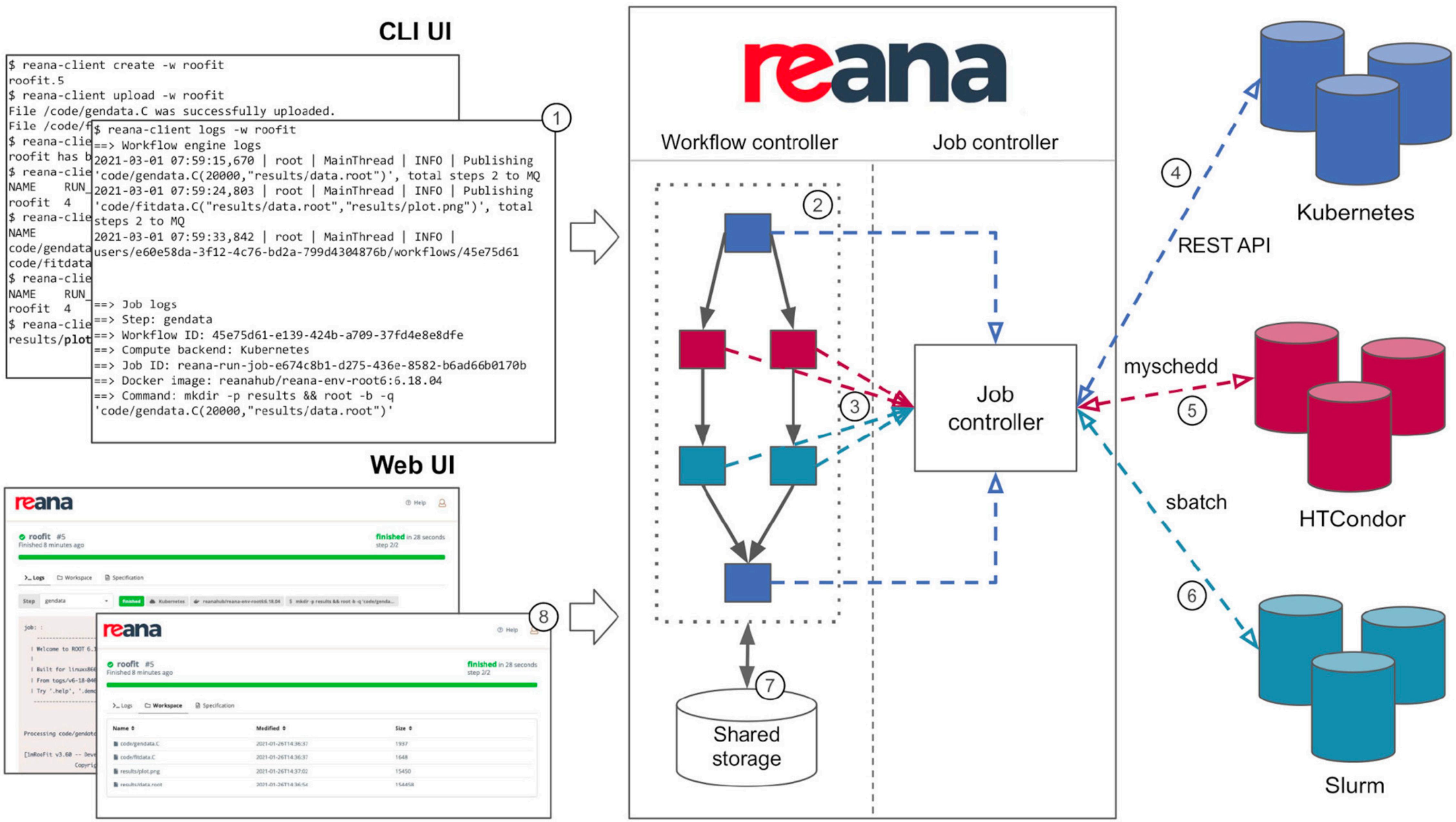
Anders Kvellestad

Reinterpretation & Preservation:

- What we have so far?
  - SModelS, HiggsTools, DarkCast:
    - Medium accuracy, less simulations
  - MadAnalysis, CheckMate, GAMBIT(ColliderBit), Contour+Rivet:
    - Medium accuracy, medium simulations
- **No tools for full simulation and can not access to analysis details**

Reinterpretation & Preservation: reana

- reana: is a reproducible analysis platform allowing scientists to run containerised data analysis pipelines on remote compute clouds.



Reinterpretation & Preservation: reana

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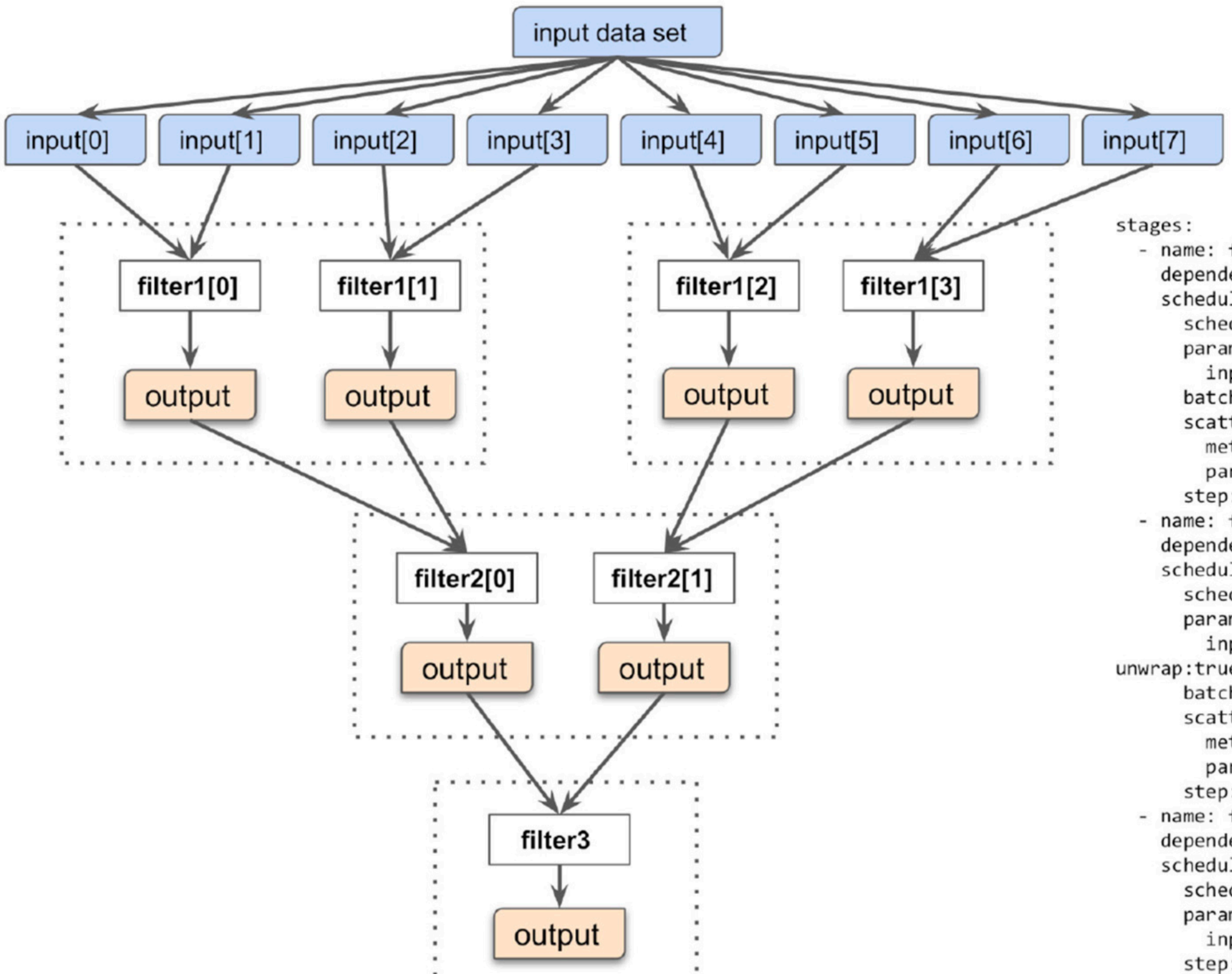


```
stages:
  - name: filter1
    dependencies: [init]
    scheduler:
      scheduler_type: multistep-stage
      parameters:
        input: {stages: init, output: input, unwrap: true}
      batchsize: 2
      scatter:
        method: zip
        parameters: [input]
      step: {$ref: steps.yaml#/filter}
  - name: filter2
    dependencies: [filter1]
    scheduler:
      scheduler_type: multistep-stage
      parameters:
        input: {stages: filter1, output: output,
unwrap:true}
      batchsize: 2
      scatter:
        method: zip
        parameters: [input]
      step: {$ref: steps.yaml#/filter}
  - name: filter3
    dependencies: [filter2]
    scheduler:
      scheduler_type: singlestep-stage
      parameters:
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      step: {$ref: steps.yaml#/filter}
```

Reinterpretation & Preservation: reana

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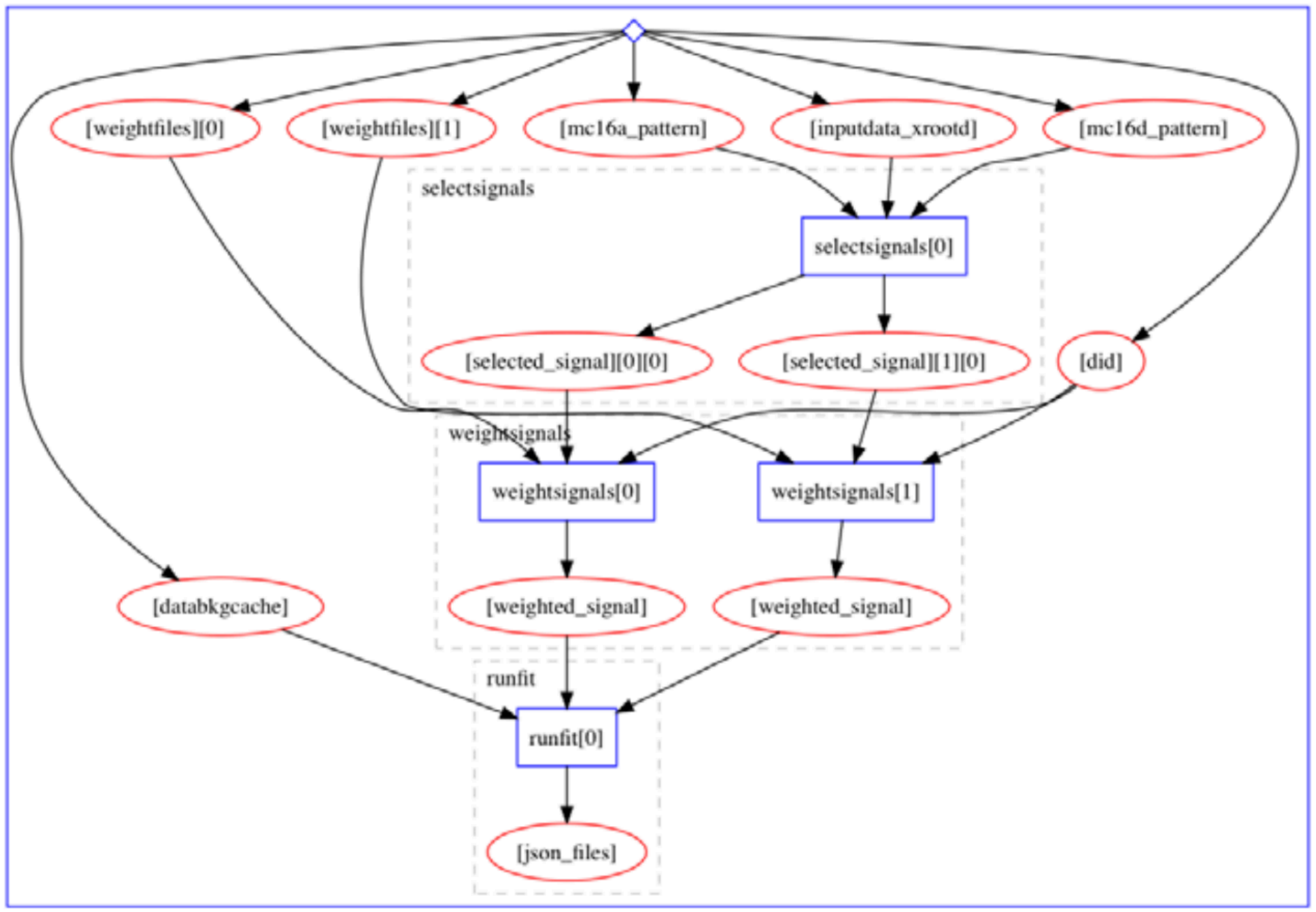

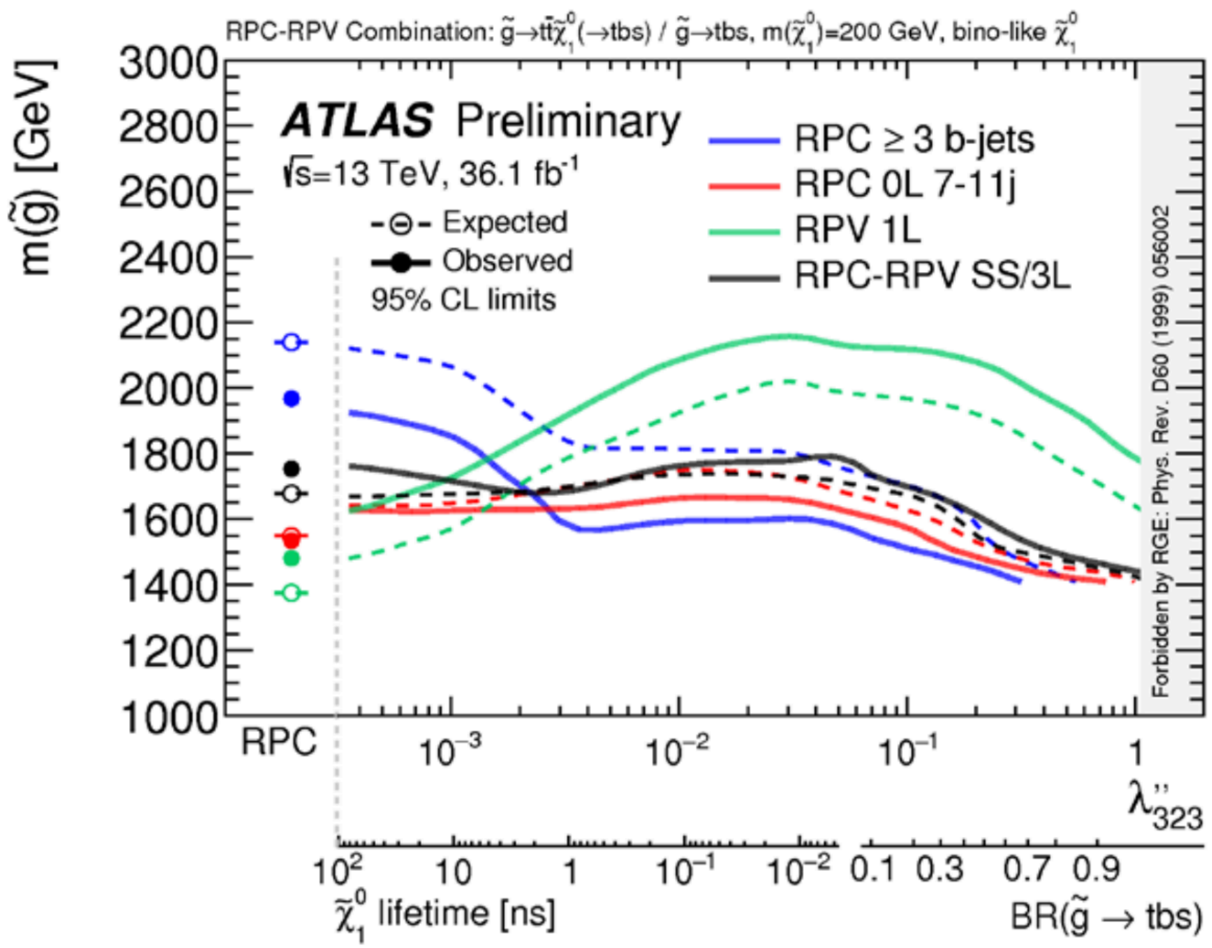

- The platform now is being used and tested internally:
  - pMSSM efforts
  - Combination efforts
  - Other reinterpretation efforts

- The platform now is being used and tested internally:
  - Almost all run2 SUSY analysis preserved their workflows
  - Will be published for use in the near future

Summary:

- Very completed searches have been performed for the run2 datasets:
  - Covering almost all the scenarios using simplified models
  - Null (almost) results so far with few excesses here or there
  - Up to ~2.5/1.2/1/0.7 TeV $\tilde{g}/\tilde{q}_{(3rd)}/\tilde{\chi}/\tilde{l}$ got excluded
- Warping up the run2 searches:
  - Combinations: $\tilde{\chi}$ & $\tilde{l}$ & $\tilde{t}$
  - RPC-RPV: Fill the gaps between the long-lived and prompt decays
  - pMSSM scanning: Understanding the current search power in the full picture
- Brainstorms to the run3 and future:
  - Novelty: new models, new phase space
  - Guided by the anomalies
- Reinterpretations & Preservation:
  - Build a bridge between experimentalists and theorists

SUSY IS STILL ALIVE AND CAN BE VERY USEFUL

THE END