Simplified Models of Heavy Higgs Bosons Decaying to Supersymmetric Particles

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*Master thesis
(work in progress)

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Der Wissenschaftsfonds.

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ÖAW

The Current Situation

- **Where are we?**
  - Well-motivated New Physics searches without success

    $\rightarrow$ Constraints on the MSSM parameter space[1]
  - Current searches of heavy Higgs bosons assume only SM decay channels[2]
- **Where to go?**
  - Are there supersymmetric decays of Higgs bosons which offer additional search channels?[3]

[1] Belanger, Ghosh, Godbole, and Kulkarni, "Light stop in the MSSM after LHC Run 1".

[2] Arbey, Battaglia, and Mahmoudi, "Supersymmetric Heavy Higgs Bosons at the LHC".

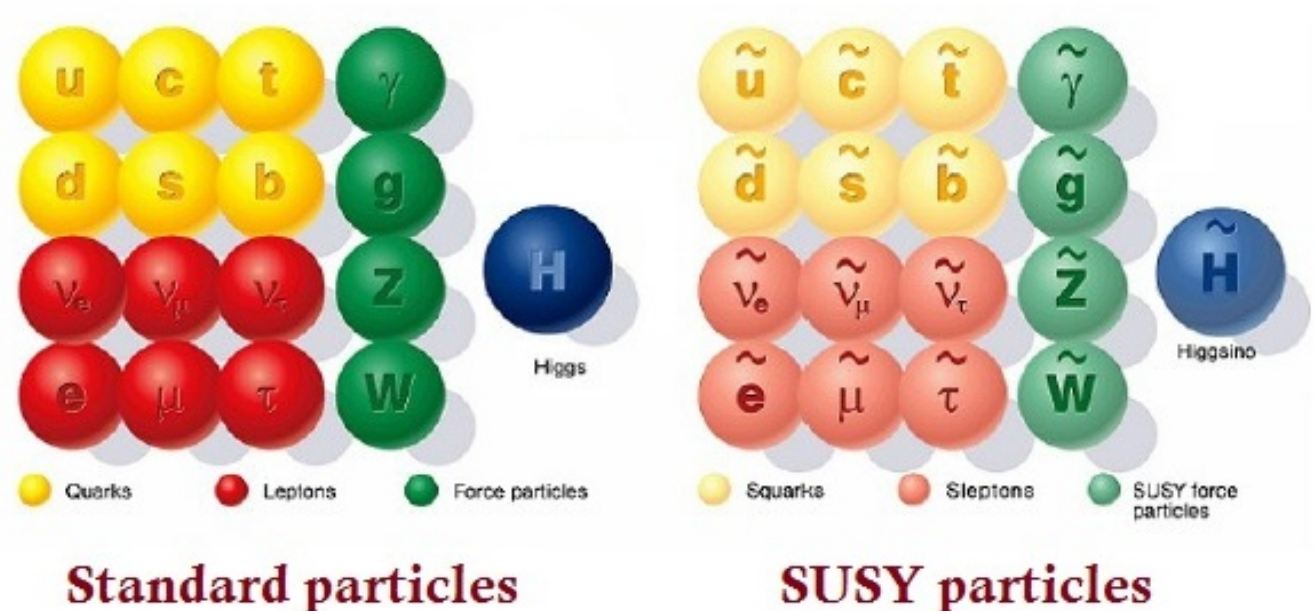
[3] Barman, Bhattacherjee, Chakraborty, and Choudhury, "Study of MSSM heavy Higgs bosons decaying into charginos and neutralinos".

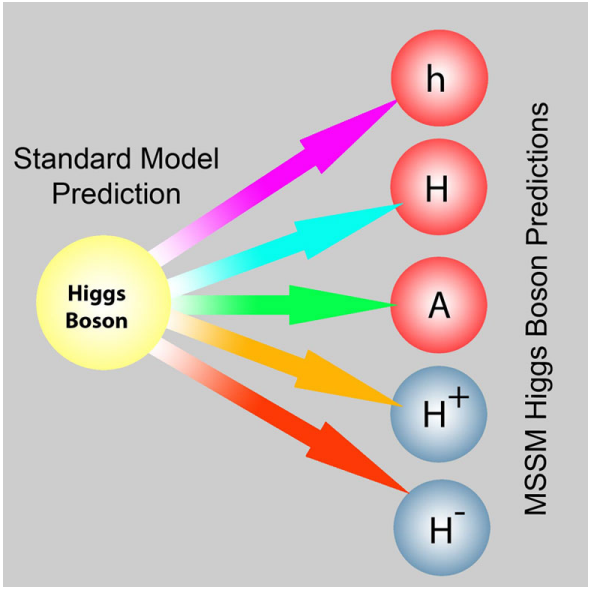
Content

Content

Supersymmetry

- Bosonic superpartners of fermions: squarks, sleptons
- Fermionic superpartners of bosons: gluinos, neutralinos, charginos
- Five Higgs bosons





Minimal Supersymmetric Standard Model

- **Constrain the number of MSSM parameters with simple assumptions**
  - R-Parity conservation with neutral LSP as DM candidate
  - Electroweak/Soft Symmetry Breaking
  - No new CP-violation, no FCNC at tree-level
  - ...

  $\rightarrow$ only 19 additional free parameters in pMSSM

$$\tan\beta \quad M_{1,2,3} \quad \mu \quad M_A \quad M_{\tilde{q},\tilde{l}} \quad M_{\tilde{Q},\tilde{L}} \quad M_{\tilde{u}_R,\tilde{d}_R,\tilde{e}_R} \quad M_{\tilde{t}_R,\tilde{b}_R,\tilde{\tau}_R} \quad A_{t,b,\tau}$$

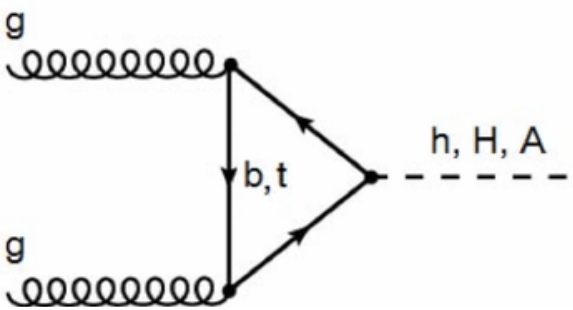
- **Higgs Masses Determined by M_A and $\tan\beta$ at Tree Level**

$$M_{H,h}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2(2\beta)}\right]$$

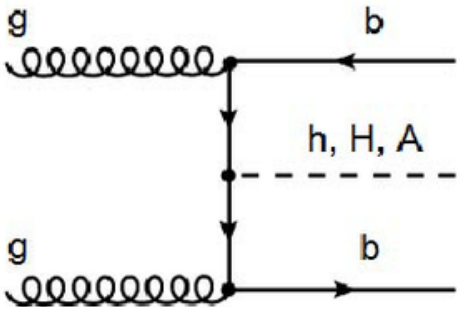
$$\xrightarrow[\text{(decoupling limit)}]{M_A \gg M_Z} M_H \approx M_A$$

Heavy Higgs Production and Couplings

- **Main Heavy Higgs Production Mechanisms @ LHC**



(gluon fusion)



(bottom-quark annihilation)

- **Normalized Higgs Couplings and the Decoupling Limit** $M_A \gg M_Z$

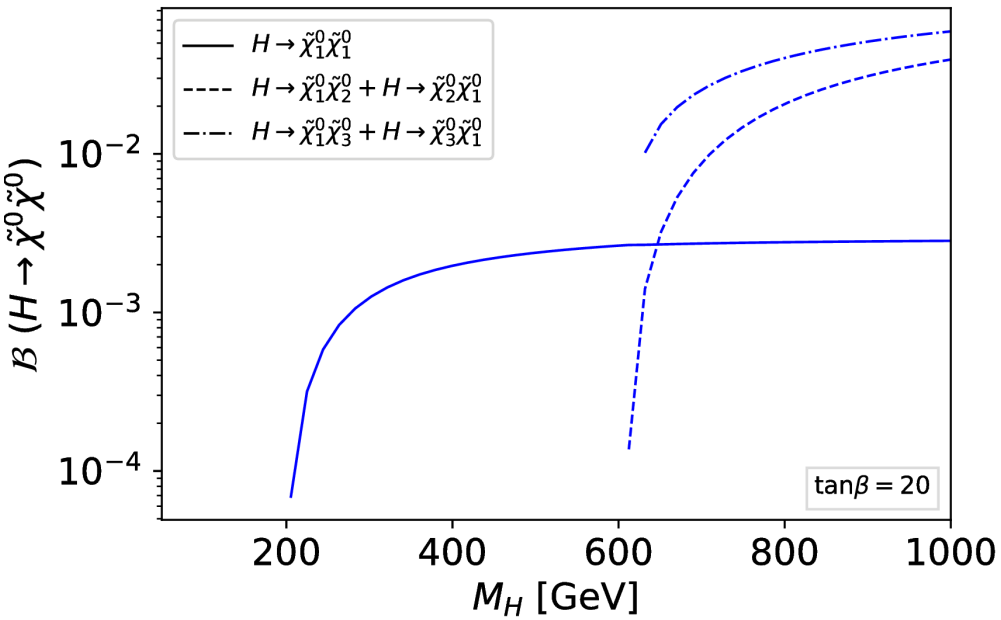
Φ	$g_{\Phi u\bar{u}}/g^{\rm SM}_{\Phi u\bar{u}}$	$g_{\Phi d\bar{d}}/g^{\rm SM}_{\Phi d\bar{d}}$	$g_{\Phi VV}/g^{\rm SM}_{\Phi VV}$
h	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$

Heavy Higgs Decay Width to Electroweakinos

- **Heavy Higgs Decay Width**

$$\Gamma(H \to \tilde{\chi}_i \tilde{\chi}_j) \sim M_H \left[\left((g^L_{Hij})^2 + (g^R_{Hij})^2 \right) \left(1 - \frac{M^2_{\tilde{\chi}_i}}{M^2_H} - \frac{M^2_{\tilde{\chi}_j}}{M^2_H} \right) \boxed{- 4\epsilon_i \epsilon_j g^L_{Hij} g^R_{Hij} \frac{M_{\tilde{\chi}_i} M_{\tilde{\chi}_j}}{M^2_H}} \right]$$

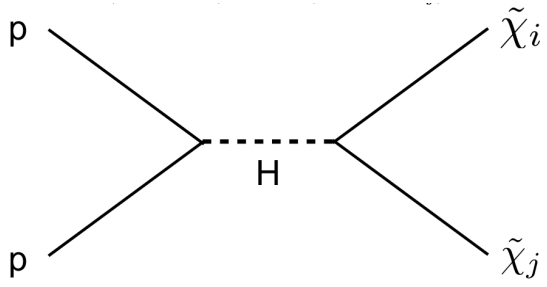
ϵ_i ... sign of ith EWino mass EV



High $\mathcal{B}(H \to \tilde{\chi}\tilde{\chi})$ for

- $\epsilon_i \neq \epsilon_j$
- $sign(g^L_{Hij}) \neq sign(g^R_{Hij})$

$\to$ Prefered asymmetric decay $(i \neq j)$



EWino Mass Eigenvalues

- **Elektroweakino Masses:** Diagonalizing the
  - Neutralino Mass Matrix

$$\mathcal{M}_{\mathcal{N}} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

  - Chargino Mass Matrix

$$\mathcal{M}_{\mathcal{C}} = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & \mu \end{pmatrix}$$

- **Elektroweakino Characterization**

Bino-like LSP	Higgsino-like LSP	Wino-like LSP
$M_1 \ll M_2, \mu$	$\mu \ll M_1, M_2$	$M_2 \ll M_1, \mu$

Content

pMSSM Point Selection

- **Sample Size:**

Type	Sample Size (ATLAS)	Sample Size
Bino-like LSP	103.410	32.566
Higgsino-like LSP	126.684	65.083
Wino-like LSP	80.233	(43.680)

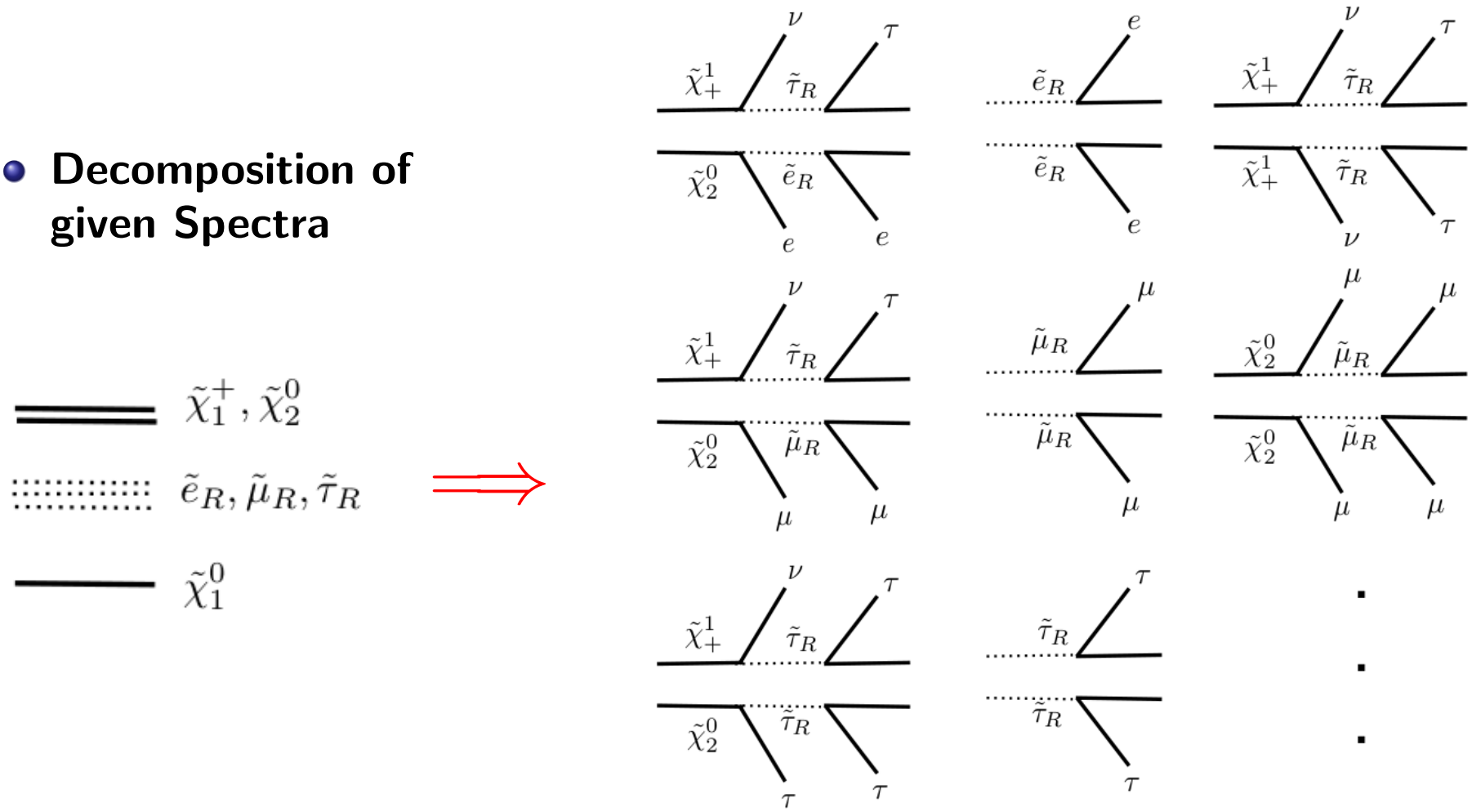
- **Experimental Constraints**
  - Dark Matter Relic Density
  - LEP constraints on SUSY
  - ATLAS constraints on SUSY

- `SuperISO - 3.6` ← Flavor Sector
- `HiggsSignals - 1.4.0` ← Light Higgs Mass & Signal Rate
- `HiggsBounds - 4.3.1` ← Cross Section Limit for Heavy Higgs
- `SModelS - 1.1.1` ← Possible Decay of H to Sparticles
  ← Lifetime of Sparticles

Content

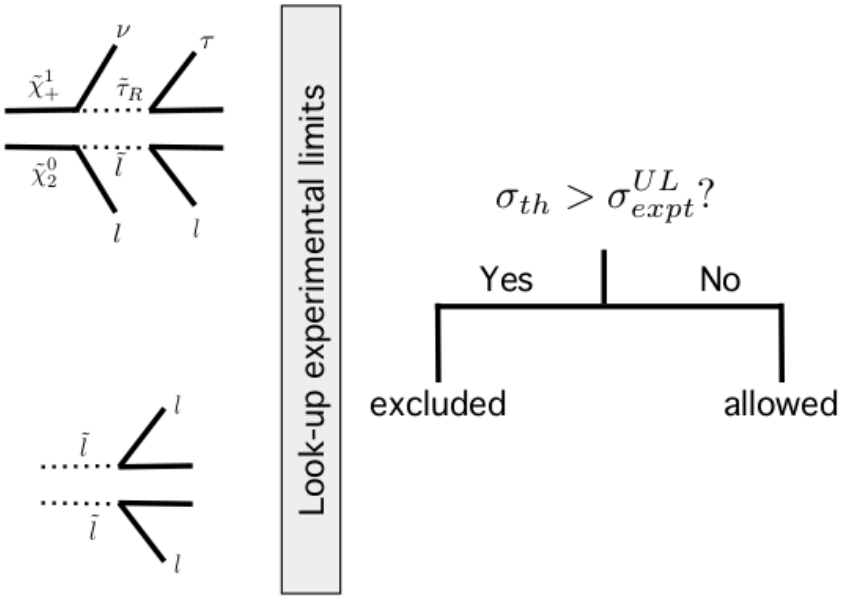
SModelS

- **Decomposition of given Spectra**

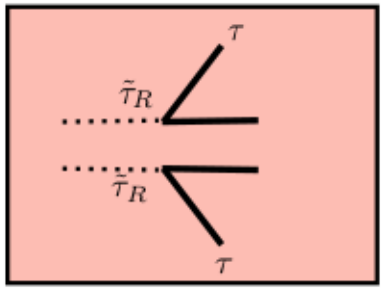


SModelS

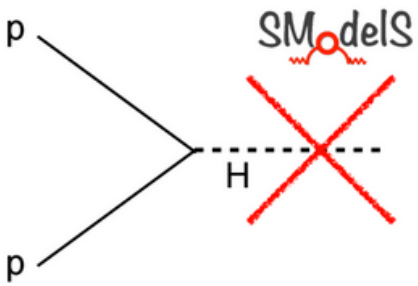
- **Constraining using LHC Results**

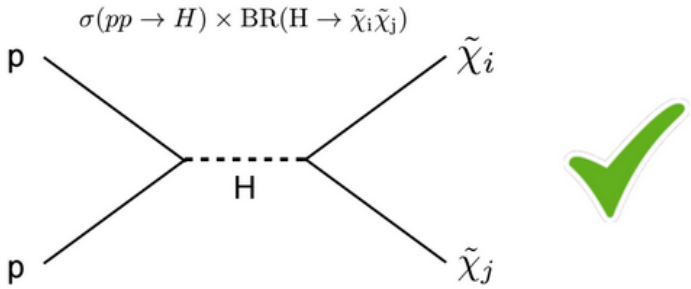


- **Identifying Missing Topologies**



- **Workaround for Resonant Searches**





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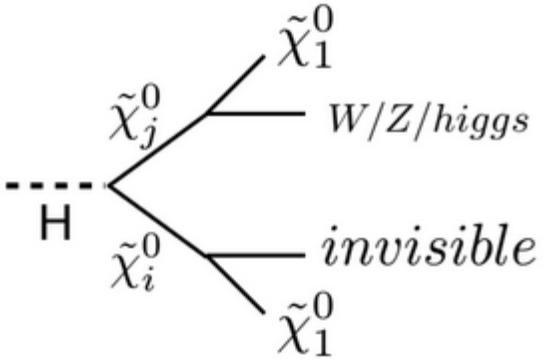
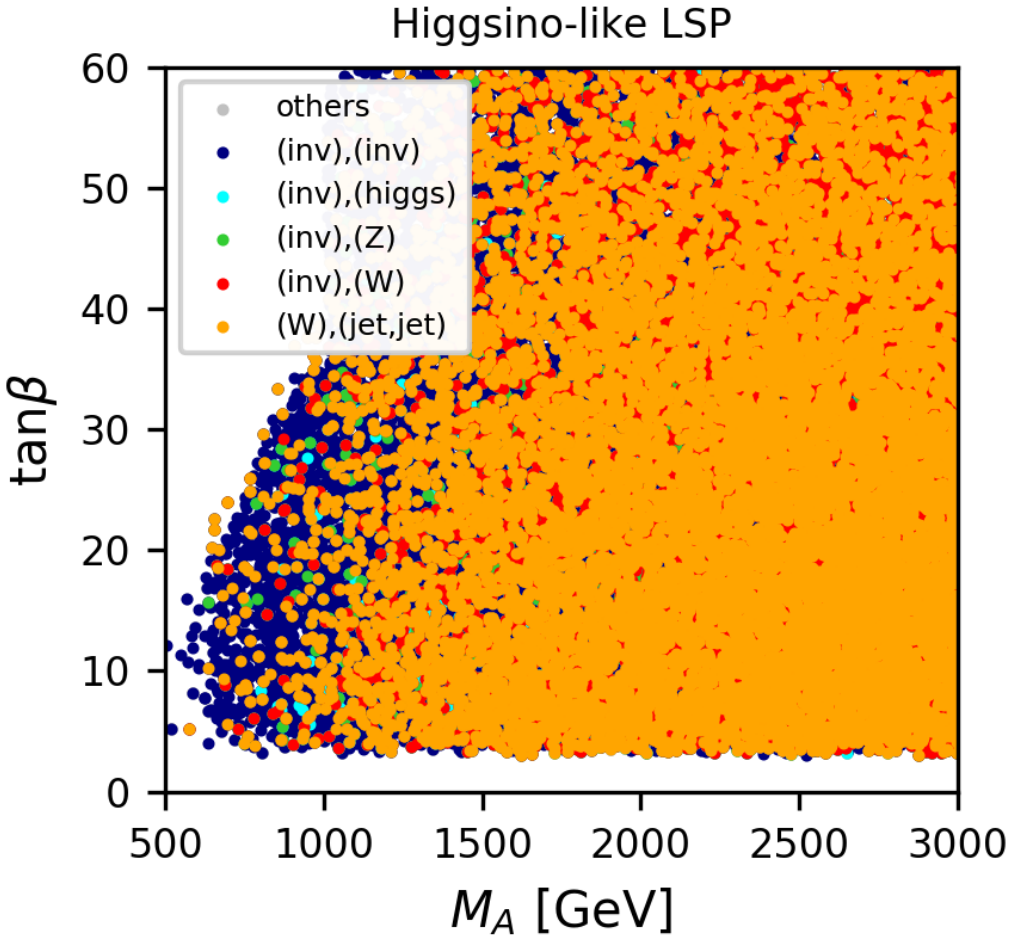
Missing Topologies

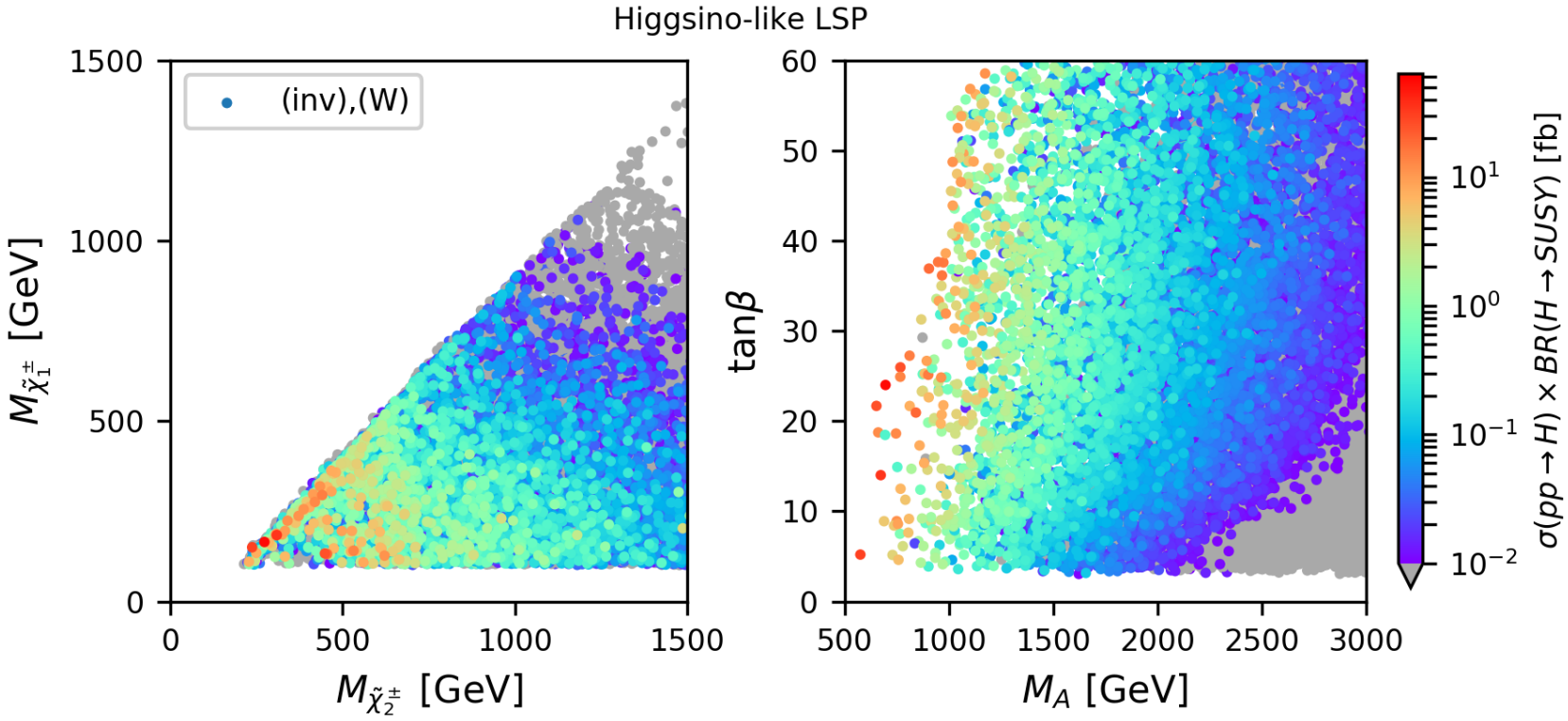
- Higgsino (Bino) dataset
- Mono-X are most **dominant** and **frequent** missing topologies
- Additional signatures due to off-shell X





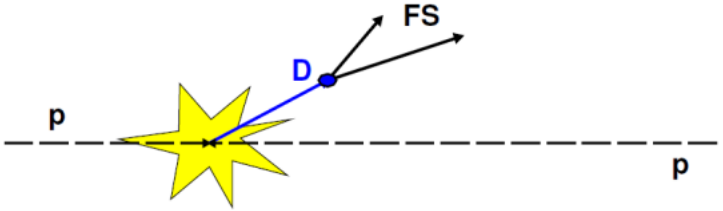
Mono-X Results @ $\sqrt{s} = 14$ TeV

- Large cross sections up to $\mathcal{O}(10\text{ fb})$ if kinematically allowed
- Heavy Higgs searches @ HL-LHC?
- Re-interpretation of current mono-X searches for resonant heavy Higgs?

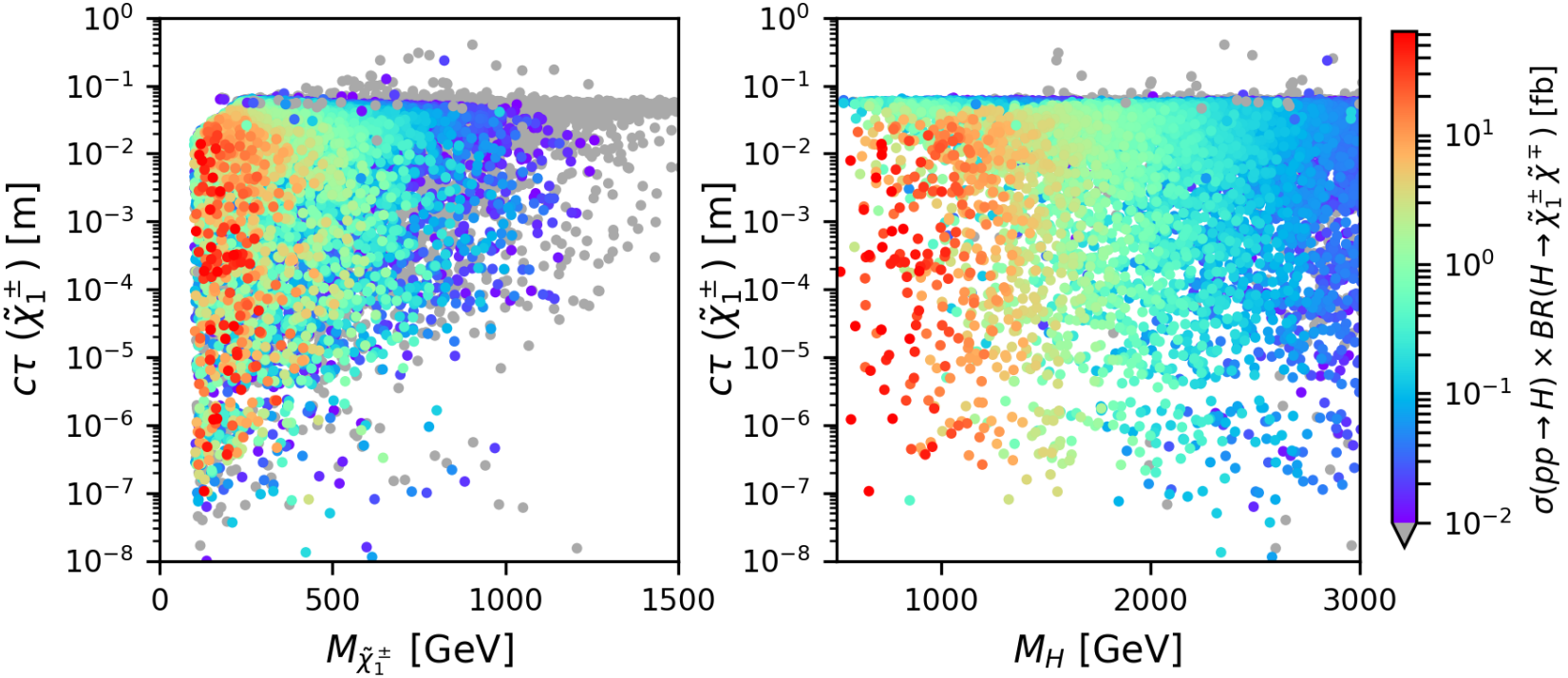


Wino Results @ $\sqrt{s} = 14$ TeV

- Large cross sections up to $\mathcal{O}(10\text{ fb})$
- Displaced vertices due to long-lived light charginos $\tilde{\chi}_1^{\pm}$ ($\sim 95\%$ of Wino-Set)



$\rightarrow$ can't be handled by `SModelS` yet $\rightarrow$ **stay tuned!**



Conclusion

- Search for heavy Higgses is an important avenue for BSM searches
- We use `SModelS` to classify supersymmetric decays of heavy Higgses

- Complicated dependencies of Higgs decays reduce to simple detector signatures
- We find potentially large cross sections mono-X signatures
- Promising results for HL-LHC with 3 ab^{-1} integrated luminosity

- We propose a reinterpretation of current DM mono-X analyses
- Displaced vertex analyses also promising for heavy Higgs searches

Publication

- More details? Publication is in preparation!

Characterising simplified models for heavy Higgs decays to supersymmetric particles

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[2] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfer Gasse 18, 1050 Wien, Austria*

The search for heavy Higgs bosons is an important step to probe the parameter space of the Minimal Supersymmetric Standard Model. We define simplified models for heavy Higgs bosons decaying to supersymmetric particles by using the SModelS framework. We use the allowed points from ATLAS pMSSM dataset for this purpose. Furthermore, we characterize the parameter space resulting in maximal signal in a given decay mode at the LHC 14 TeV. Systematically studying the possible decay modes, we propose a reinterpretation of current mono-X analyses (mono-Higgs, -W, -Z).

Thank you for your attention!
Any questions?

Backup

Backup - pMSSM Parameter Assumptions

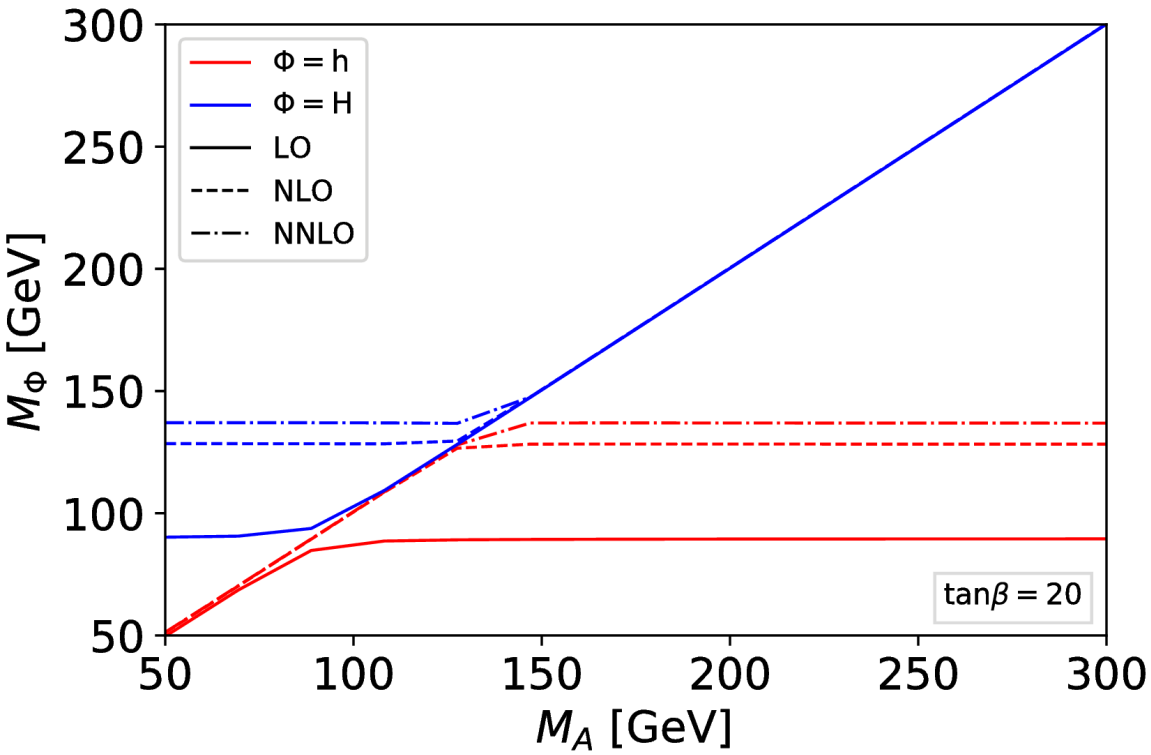
- R-Parity conservation
- Neutral Lightest Supersymmetric Particle (LSP)
- Elektroweak Symmetry Breaking
- Real soft parameters (no new CP-violation)
- No FCNC at tree-level
- Negligible trilinear couplings $A_{q,l}$ at low energy for 1st- and 2nd-gen sparticles
- Degenerate 1st- and 2nd-gen sparticle states with negligible Yukawa couplings

$\rightarrow$ **19 free parameters:**
$\tan\beta$, $M_{1,2,3}$, μ, M_A, $M_{\tilde{q},\tilde{l}}$, $M_{\tilde{Q},\tilde{L}}$, $M_{\tilde{u}_R,\tilde{d}_R,\tilde{e}_R}$, $M_{\tilde{t}_R,\tilde{b}_R,\tilde{\tau}_R}$, $A_{t,b,\tau}$

Backup - MSSM Higgs Masses

- **Strong Influences of 3rd-gen (S)Quarks in Loop-Corrections**

  $\rightarrow M_{\tilde{Q}}, M_{\tilde{t}_R,\tilde{b}_R}, A_{t,b}$ parameter dependence



Backup - Two Higgs Doublets

- Two Higgs doublets are required in SUSY models

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} \left(\nu_d + \phi_d^0 + i\chi_d^0\right)/\sqrt{2} \\ \phi_d^- \end{pmatrix} \qquad \langle H_d \rangle = \frac{\nu_d}{\sqrt{2}}$$

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} \phi_u^+ \\ \left(\nu_u + \phi_u^0 + i\chi_u^0\right)/\sqrt{2} \end{pmatrix} \qquad \langle H_u \rangle = \frac{\nu_u}{\sqrt{2}}$$

$$\nu^2 = \nu_d^2 + \nu_u^2 = \nu_{\mathrm{SM}}^2 = (246\ \mathrm{GeV})^2$$

$$\tan\beta = \frac{\nu_u}{\nu_d}$$

Backup - Higgs Bosons in MSSM

- CP-even Higgs bosons h, H
- CP-odd Higgs boson A
- charged Higgs bosons H^+, H^-
- neutral Goldstone boson G^0
- charged Goldstone bosons G^+, G^-

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi_d^0 \\ \phi_u^0 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \chi_d^0 \\ \chi_u^0 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \phi_d^\pm \\ \phi_u^\pm \end{pmatrix}$$

Backup - pMSSM Point Selection

- **Pre-Defined Experimental Constraints**
  - Flavor Sector
  - Dark Matter Relic Density
  - Lower Limit on Lightest Chargino Mass
  - Lower Limit on Lightest Charged Sparticle Mass
  - Lower Limit on Lightest Squark Mass
  - Mass Window for Light Higgs

- **Additional Experimental Constraints**
  - `SuperISO - 3.6` ← Flavor Sector
  - `HiggsSignals - 1.4.0` ← Light Higgs Mass & Signal Rate
  - `HiggsBounds - 4.3.1` ← Cross Section Limit for Heavy Higgs
  - `SModelS - 1.1.1` ← Possible Decay of H to Sparticles
  - ← Lifetime of Sparticles

Backup - pMSSM Parameter Range

Lower Limit		Parameter		Upper Limit	Description
90 GeV	$\leq$	$M_{\tilde{l}_1} = M_{\tilde{l}_2}$	$\leq$	4000 GeV	Left-handed 1st- and 2nd-gen slepton
90 GeV	$\leq$	$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	$\leq$	4000 GeV	Right-handed 1st- and 2nd-gen slepton
90 GeV	$\leq$	$M_{\tilde{L}_3}$	$\leq$	4000 GeV	Left-handed 3rd-gen slepton
90 GeV	$\leq$	$M_{\tilde{\tau}_R}$	$\leq$	4000 GeV	Right-handed 3rd-gen slepton
200 GeV	$\leq$	$M_{\tilde{q}_1} = M_{\tilde{q}_2}$	$\leq$	4000 GeV	Left-handed 1st- and 2nd-gen squark
200 GeV	$\leq$	$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	$\leq$	4000 GeV	Right-handed 1st- and 2nd-gen up-type squark
200 GeV	$\leq$	$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	$\leq$	4000 GeV	Right-handed 1st- and 2nd-gen down-type squark
100 GeV	$\leq$	$M_{\tilde{Q}_3}$	$\leq$	4000 GeV	Left-handed 3rd-gen squark
100 GeV	$\leq$	$M_{\tilde{t}_R}$	$\leq$	4000 GeV	Right-handed 3rd-gen up-type squark
100 GeV	$\leq$	$M_{\tilde{b}_R}$	$\leq$	4000 GeV	Right-handed 3rd-gen down-type squark
0 GeV	$\leq$	$\lvert M_1 \rvert$	$\leq$	4000 GeV	Bino mass parameter
70 GeV	$\leq$	$\lvert M_2 \rvert$	$\leq$	4000 GeV	Wino mass parameter
80 GeV	$\leq$	$\lvert \mu \rvert$	$\leq$	4000 GeV	Higgsino mass parameter
200 GeV	$\leq$	M_3	$\leq$	4000 GeV	Gluino mass parameter
0 GeV	$\leq$	$\lvert A_t \rvert$	$\leq$	8000 GeV	Trilinear top quark coupling
0 GeV	$\leq$	$\lvert A_b \rvert$	$\leq$	4000 GeV	Trilinear bottom quark coupling
0 GeV	$\leq$	$\lvert A_\tau \rvert$	$\leq$	4000 GeV	Trilinear τ lepton coupling
100 GeV	$\leq$	$\lvert M_A \rvert$	$\leq$	4000 GeV	CP-odd Higgs boson mass
1	$\leq$	$\tan\beta$	$\leq$	60	Ratio of the Higgs vev

Backup - Constraints

- Pre-defined Constraints

Lower Limit		Parameter		Upper Limit	Description
-0.0005	$\leq$	$\Delta\rho$	$\leq$	0.0017	Electroweak parameter
-17.7×10^{-10}	$\leq$	$\Delta(g-2)_\mu$	$\leq$	43.8×10^{-10}	Anomalous magnetic moment of the muon
2.69×10^{-4}	$\leq$	$\mathcal{B}(b \to s\gamma)$	$\leq$	3.87×10^{-4}	Branching ratio FCNC
1.6×10^{-9}	$\leq$	$\mathcal{B}(B_s \to \mu\mu)$	$\leq$	4.2×10^{-9}	Branching ratio $B_s \to \mu\mu$
66×10^{-6}	$\leq$	$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	$\leq$	161×10^{-6}	Branching ratio $B^+ \to \tau^+\nu_\tau$
		$\Omega_{\tilde{\chi}_1^0} h^2$	$\leq$	0.1208	Cold dark matter energy density
		$\Gamma_{\text{inv(SUSY)}}(Z)$	$\leq$	2 MeV	Z-boson decay width to invisible
100 GeV	$\leq$	$M_{\tilde{\chi}^\pm}$			Lightest charged sparticle mass
103 GeV	$\leq$	$M_{\tilde{\chi}_1^\pm}$			Lightest chargino mass
200 GeV	$\leq$	$M_{\tilde{q}}$			Lightest squark mass
124 GeV	$\leq$	M_h	$\leq$	128 GeV	Light Higgs boson mass

Backup - pMSSM Point Selection

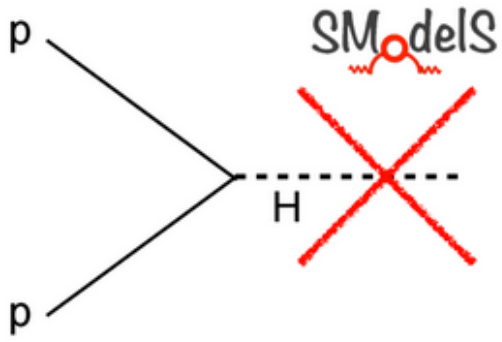
Losses	Bino-like	Higgsino-like	Wino-like
Sample Size (ATLAS)	103.410	126.684	80.233
Valid Sample Size (ATLAS)	61.370	77.981	43.680
SuperISO (2σ)	- 1.504	- 1.988	
HiggsBounds (2σ)	- 109	- 160	
HiggsSignals (2σ)	- 9.765	- 1.199	
SModelS Direct Search $(\sigma_{\text{th}} > \sigma_{\text{exp}}^{\text{UL}})$	- 517	- 2.440	
SModelS Res. Higgs Search	- 0	- 0	
Long-Lived Sparticles $(c\tau > 1 \text{ mm})$	- 4.571	- 1.792	(- 39.243)
No Decay Mode to SUSY	- 12.338	- 5.319	
Valid Sample Size (total)	32.566	65.083	(43.680)

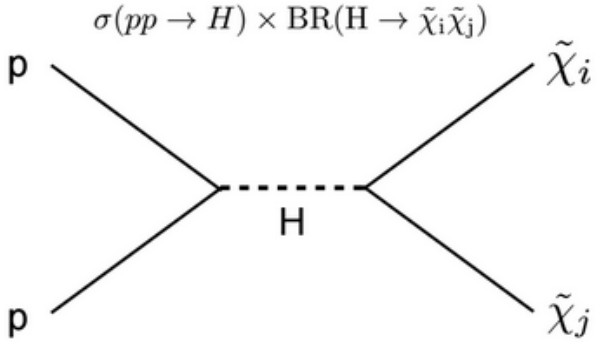
Backup - SModelS

- Database of ATLAS and CMS SUSY results
- Decomposing parameter set to Simplified Model Spectrum (SMS) topologies
- Identifying new signatures/missing topologies
- MET in the final state

$\rightarrow$ Constrains parameter sets with existing LHC limits ($\sigma_{\text{th}} > \sigma_{\text{exp}}^{\text{UL}}$?)

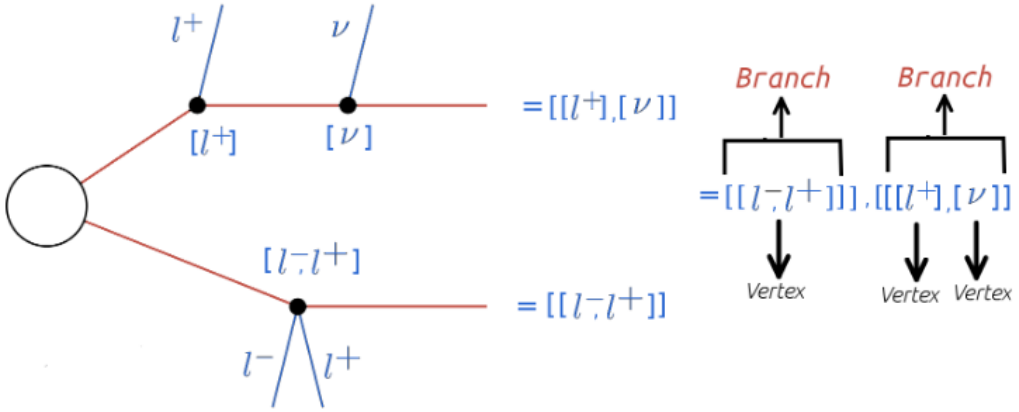
- Use a workaround to use `SModelS` for resonant searches:



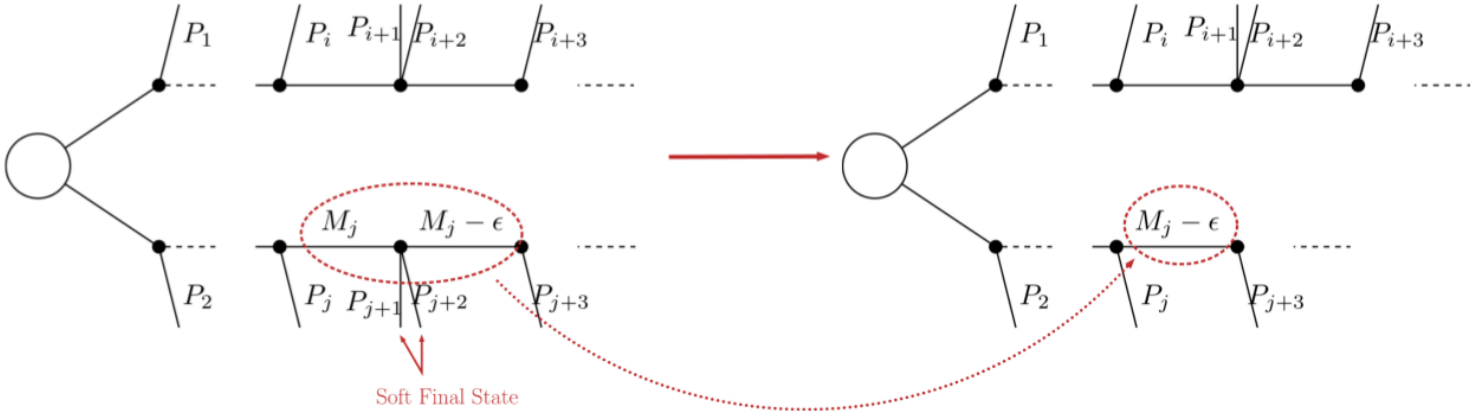


Backup - SModelS

- `SModelS` **Bracket Notation**

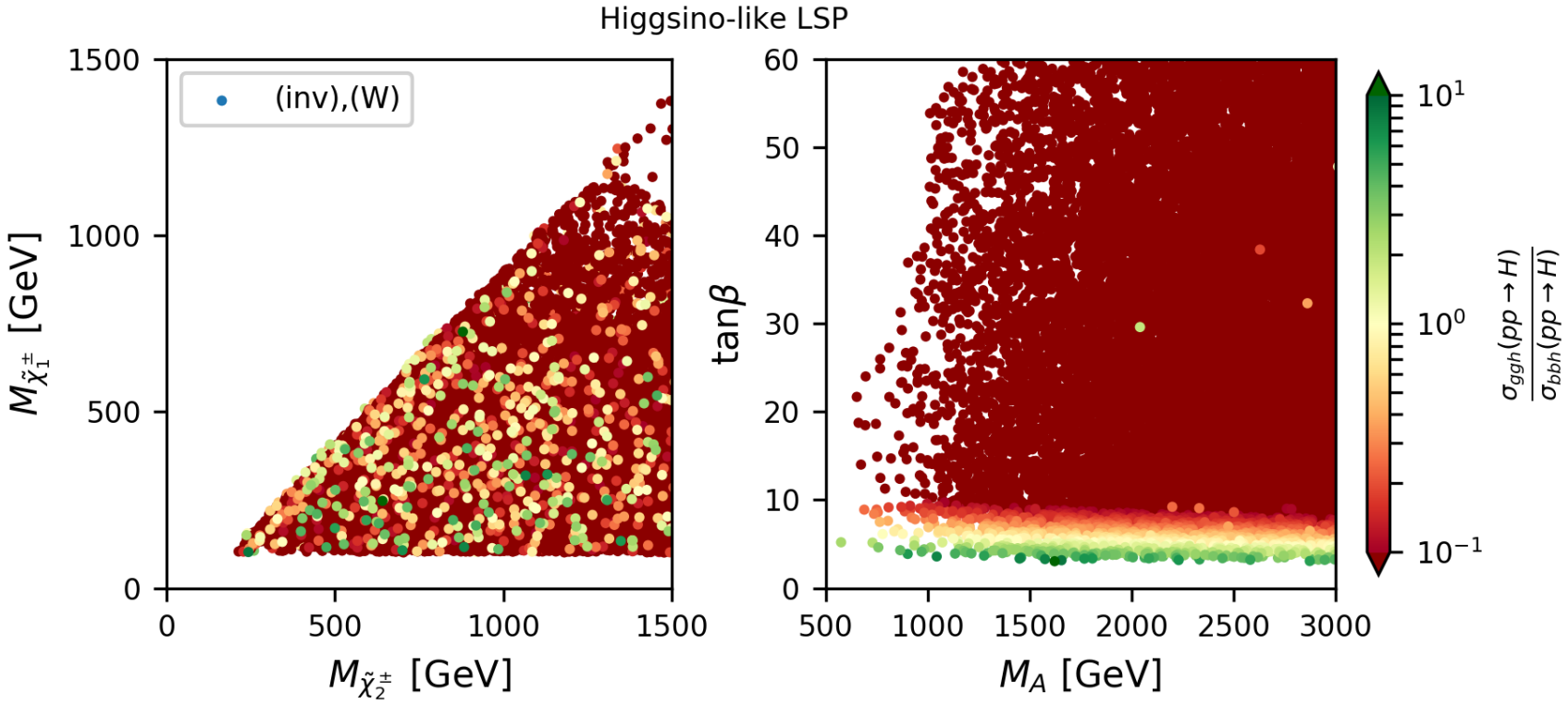


- `SModelS` **Mass Compression** ($\Delta M < 5$ GeV)



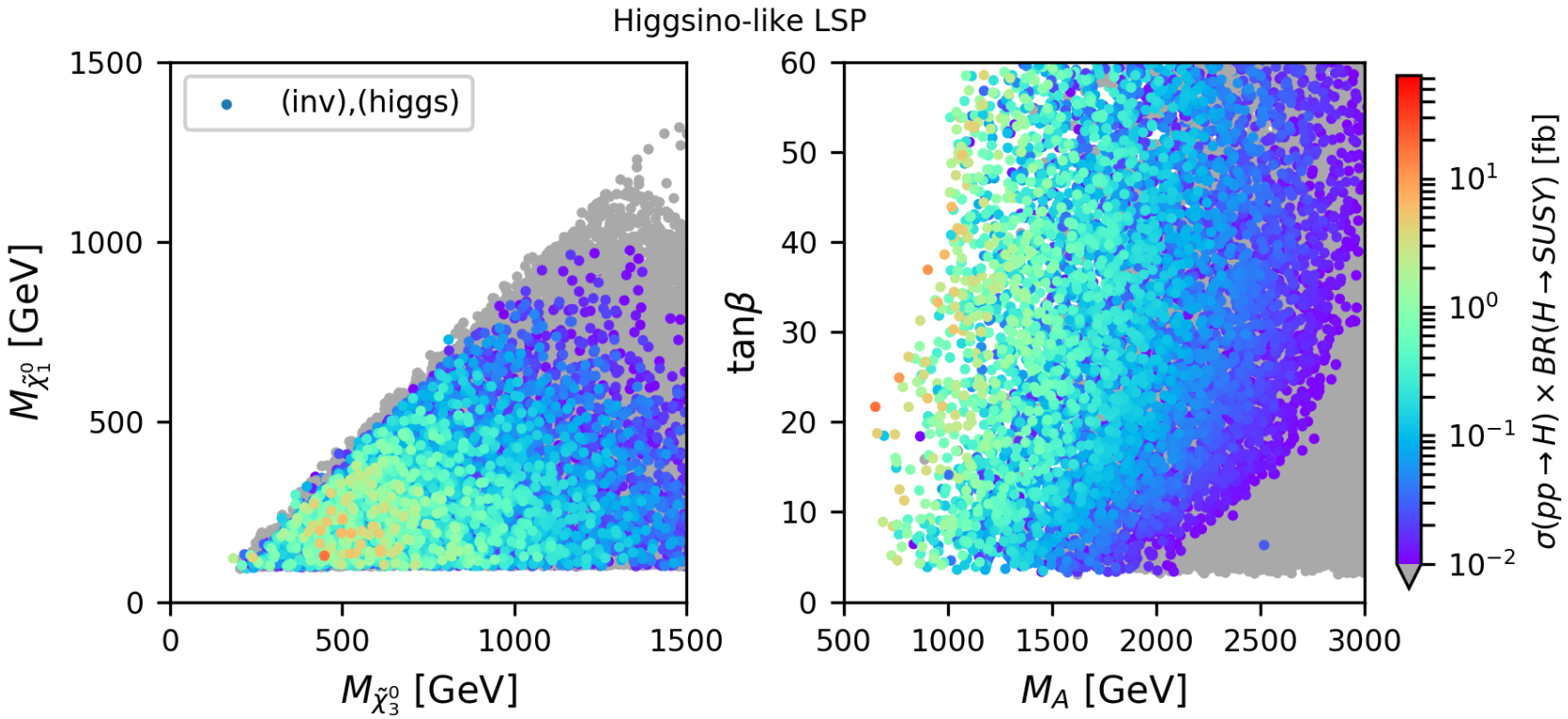
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Detailed studies of heavy Higgs production channel
- Almost entirely due to bottom-quark annihilation
  $\rightarrow$ up to two additional b-jets!



Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP



Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

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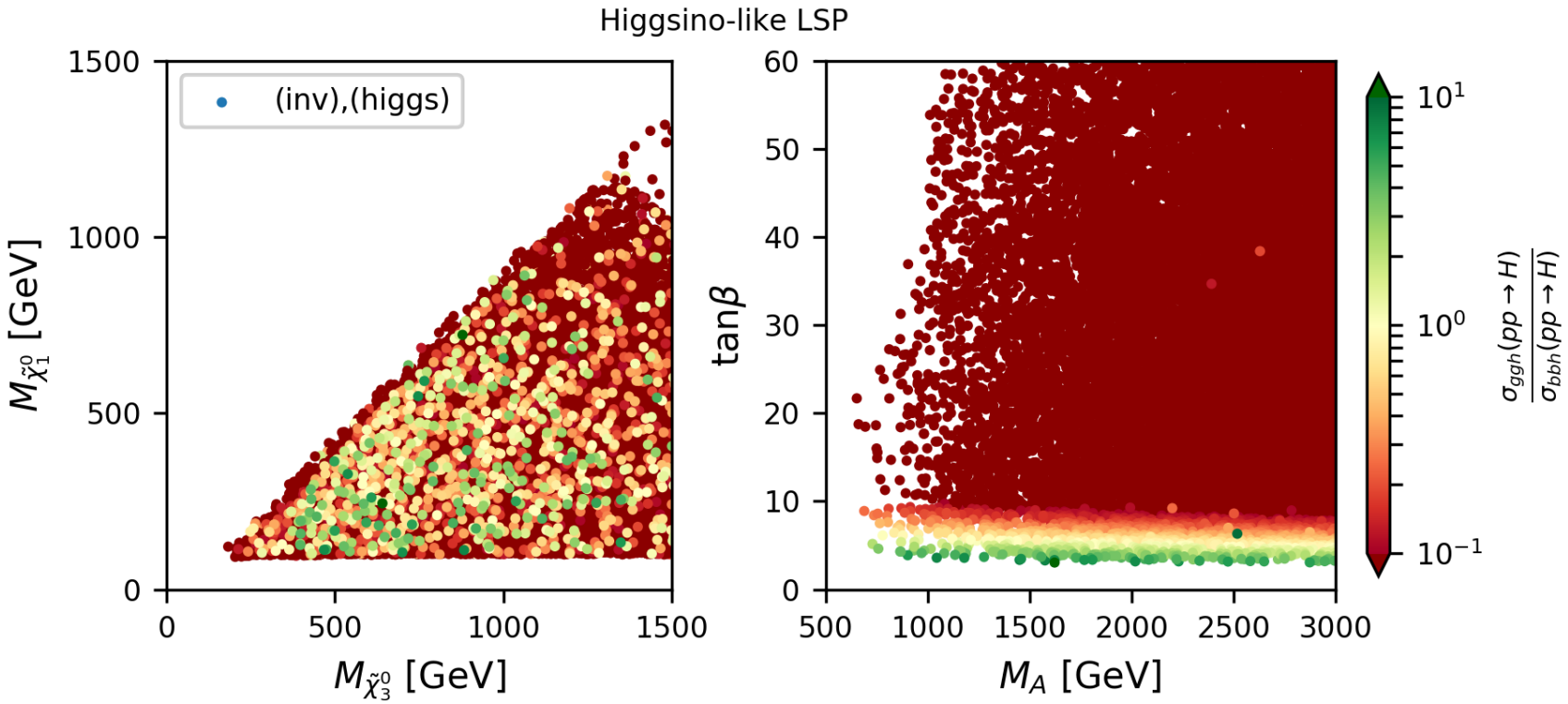
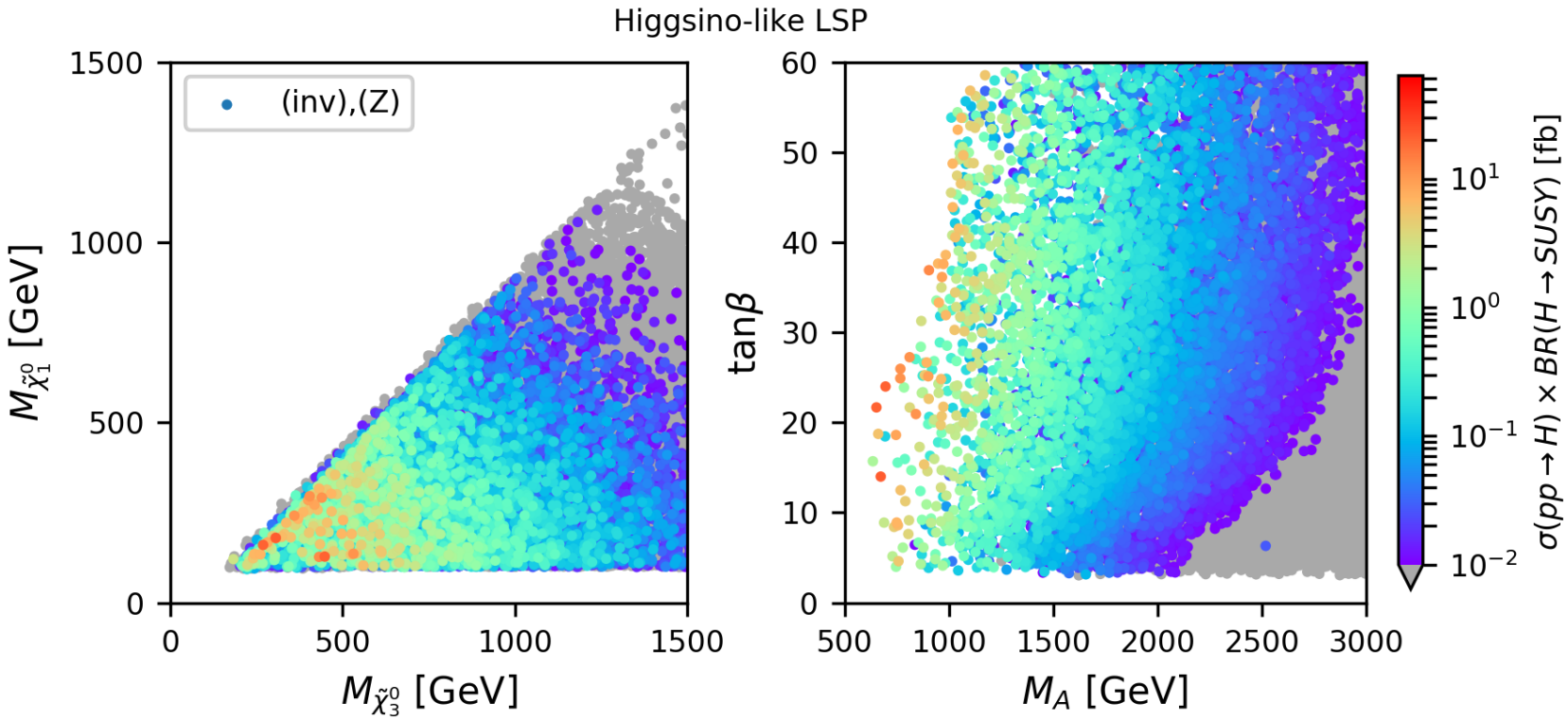


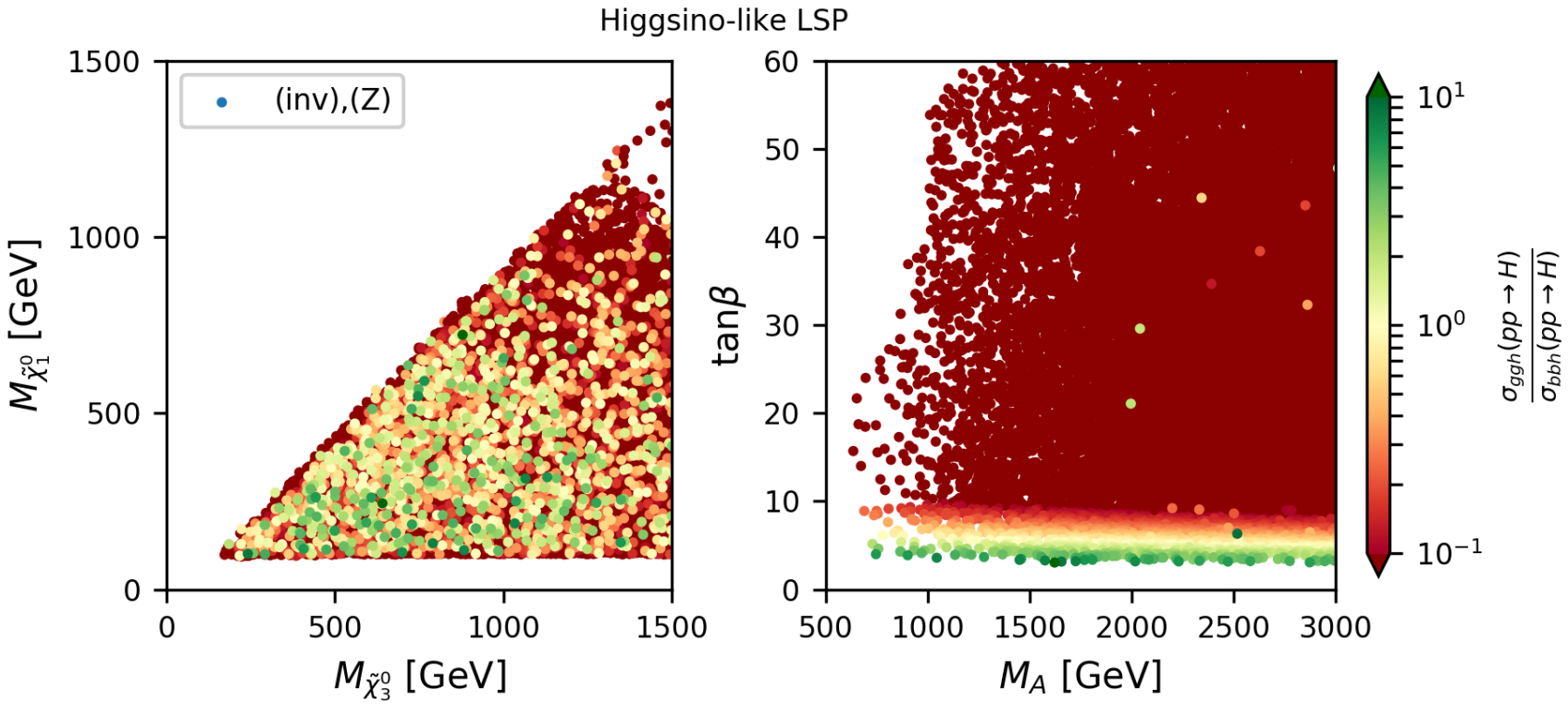
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP



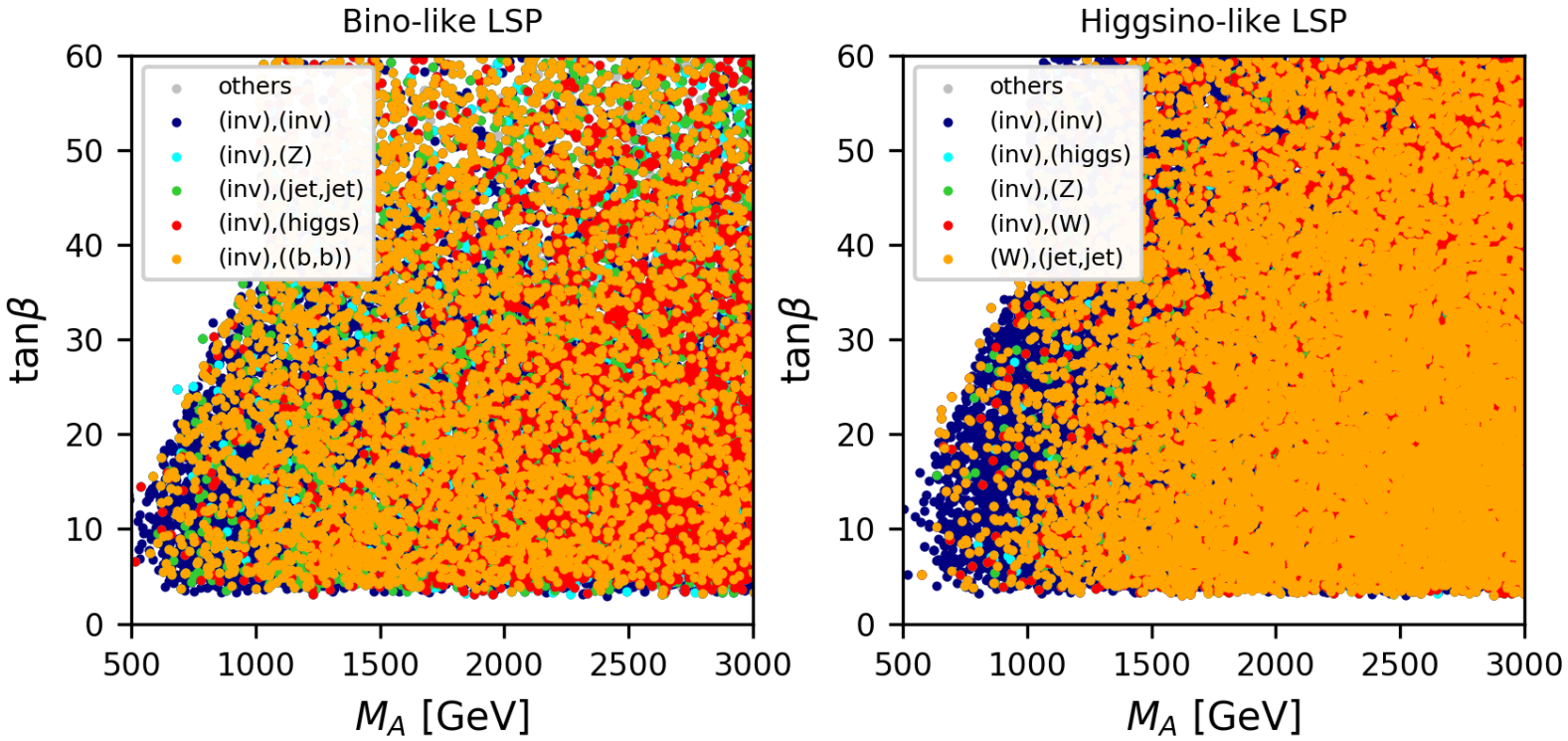
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Higgsino-like LSP



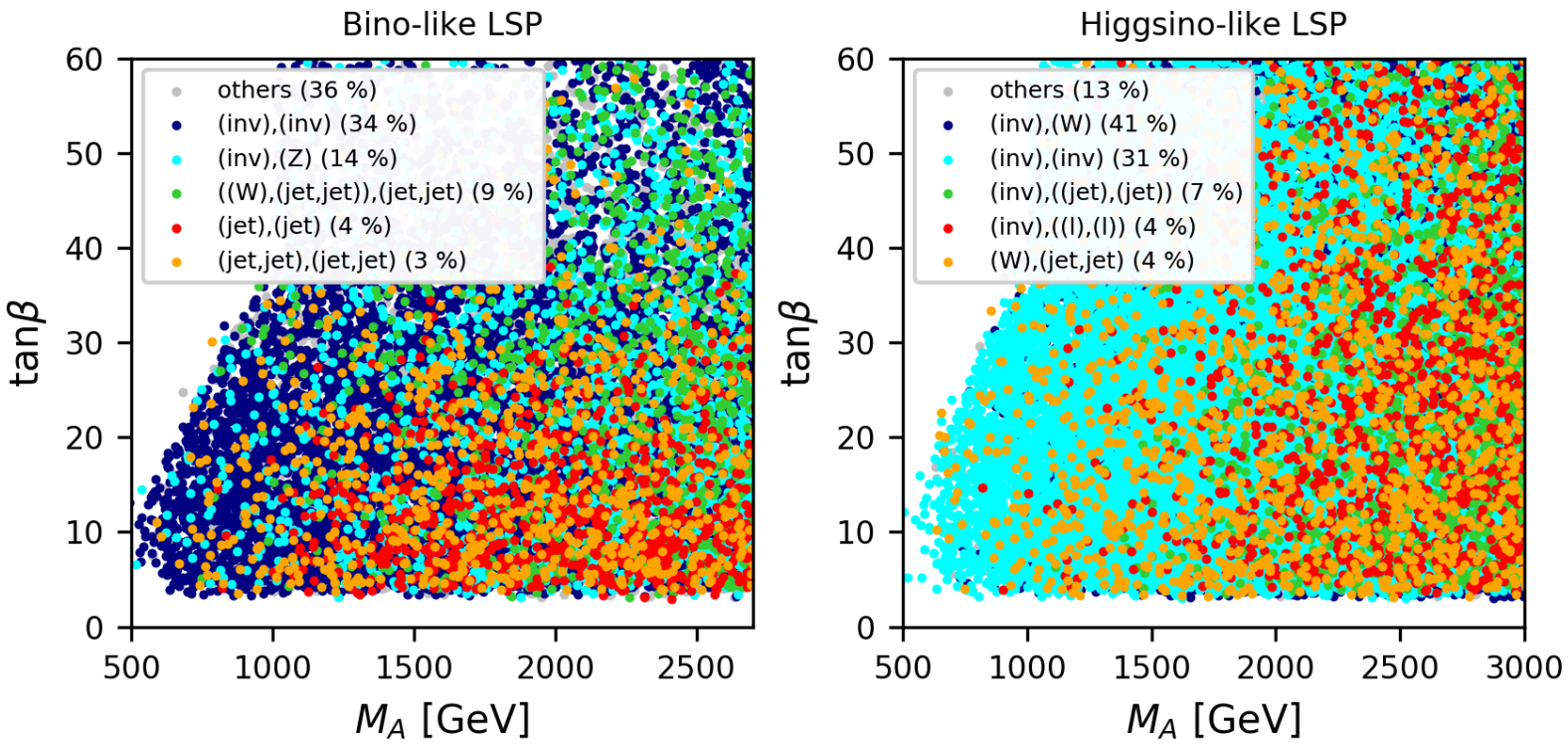
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Most frequent missing topologies



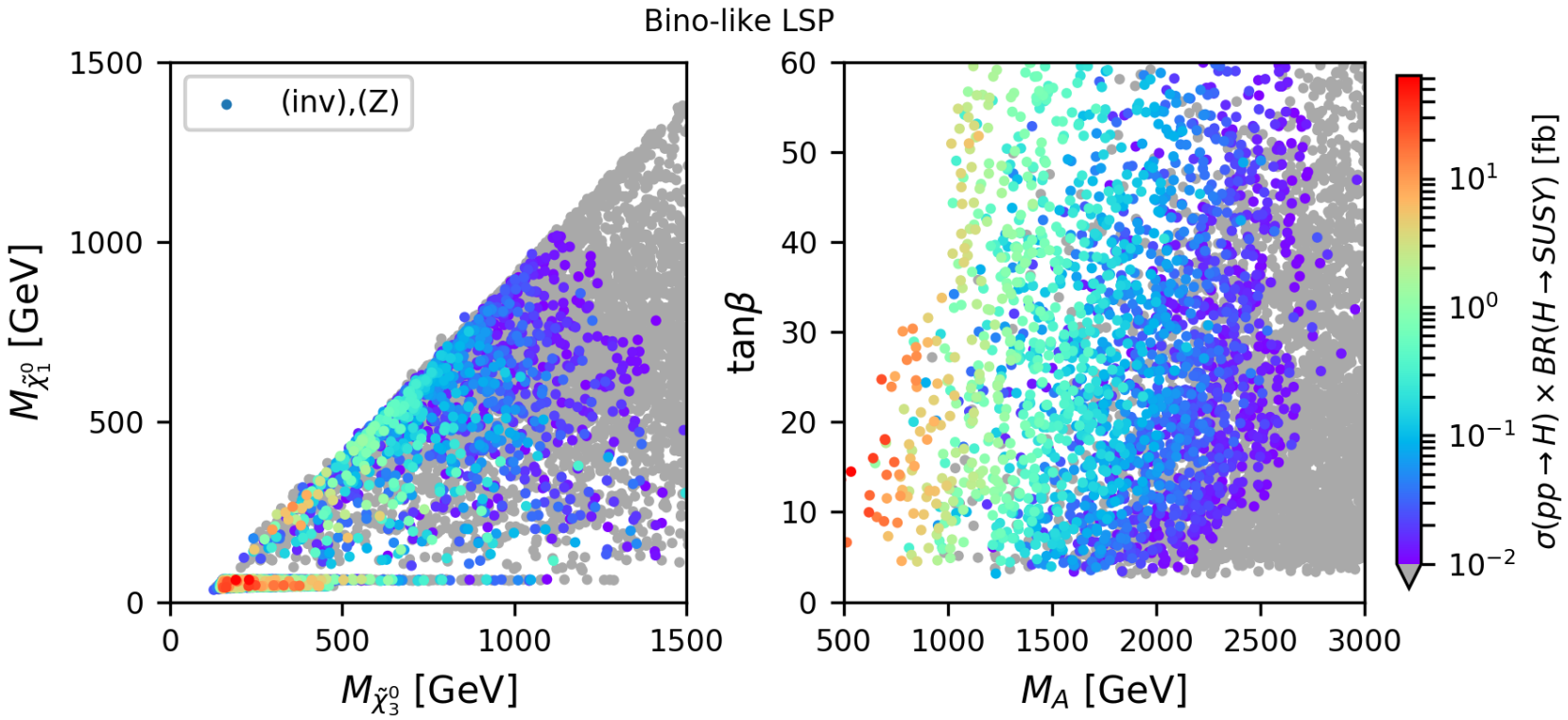
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Most dominating missing topologies
  (highest missing topology cross section of the parameter-set)



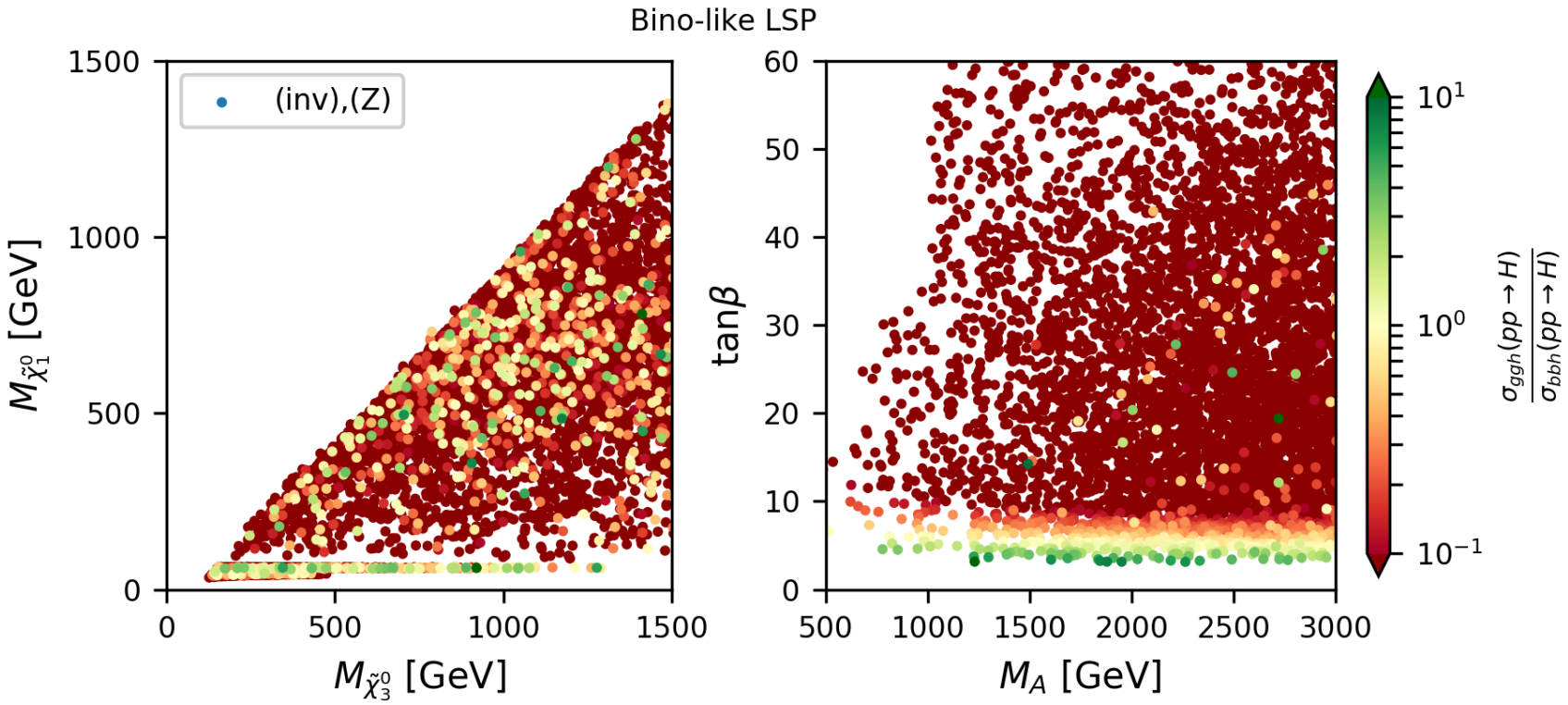
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP



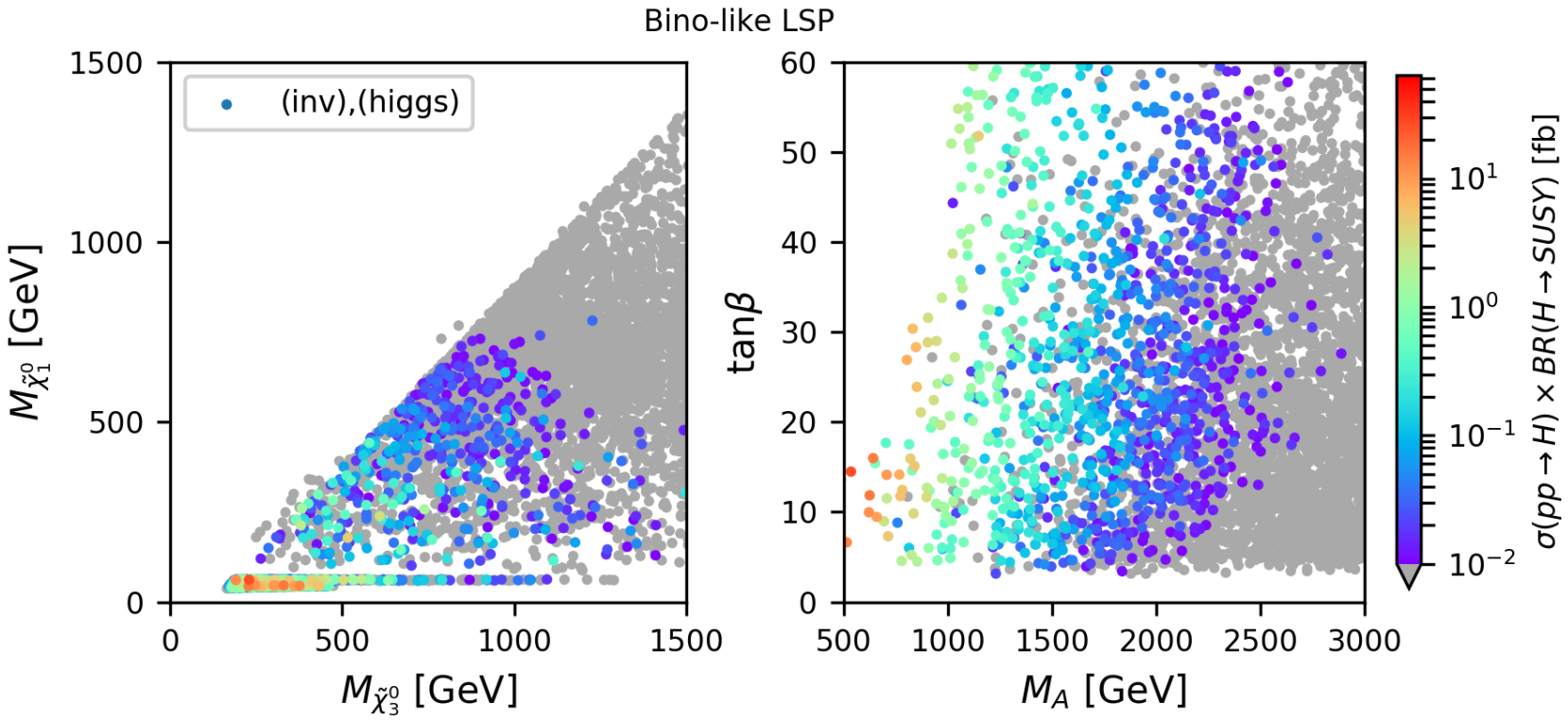
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP



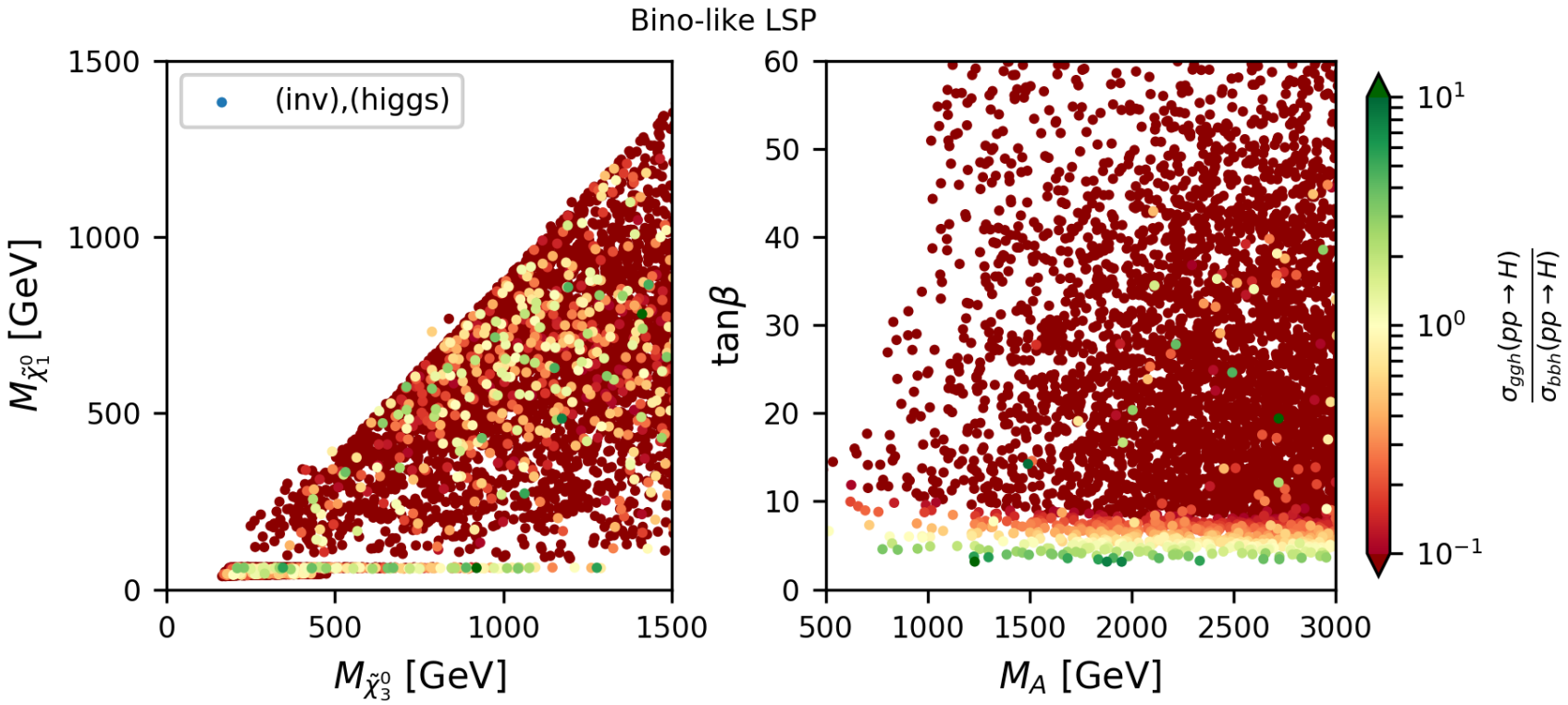
Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP



Backup - Mono-X Results @ $\sqrt{s} = 14$ TeV

- Bino-like LSP



Backup - Wino Results @ $\sqrt{s} = 14$ TeV

- Wino-like LSP