

Prospects for electroweakinos at the HL- LHC

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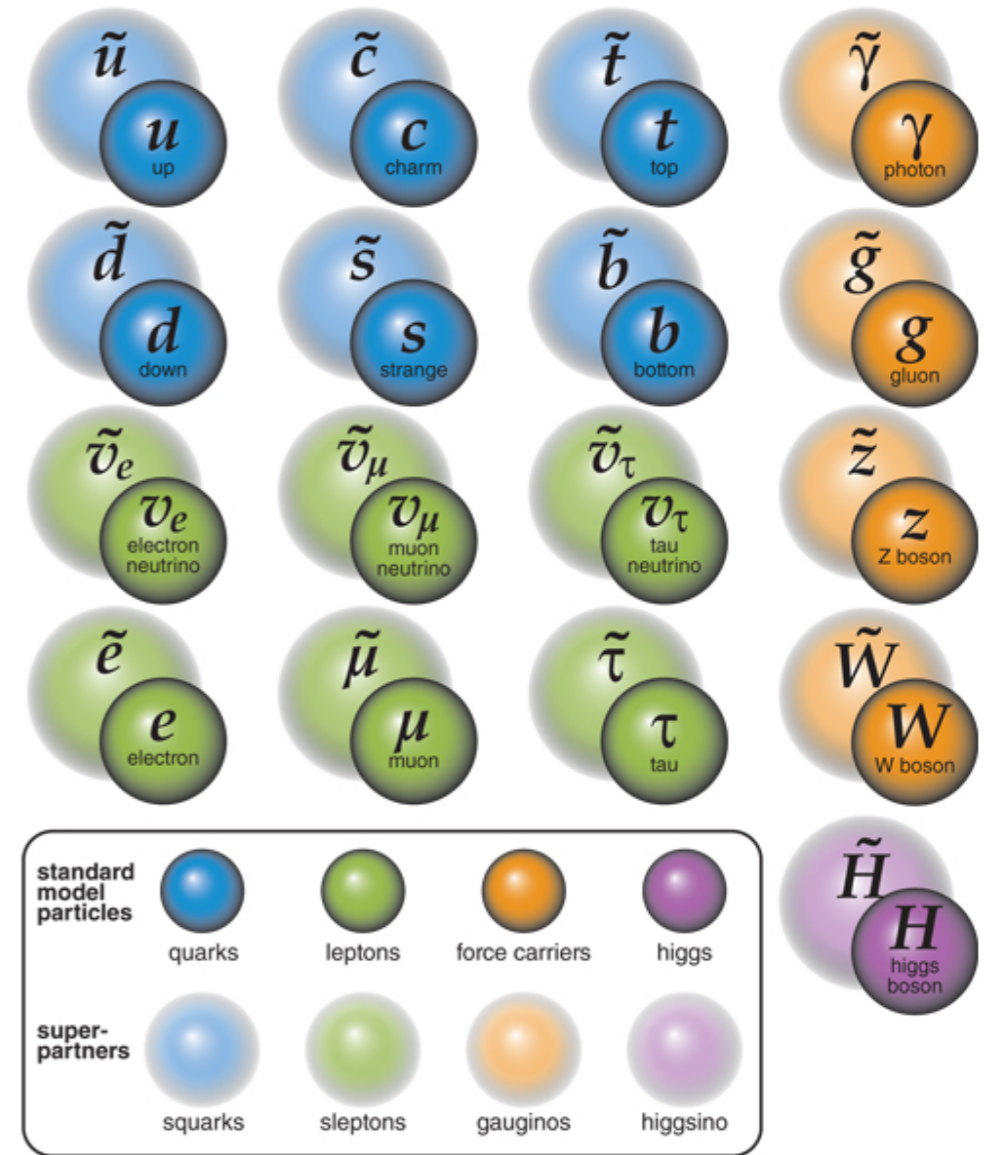
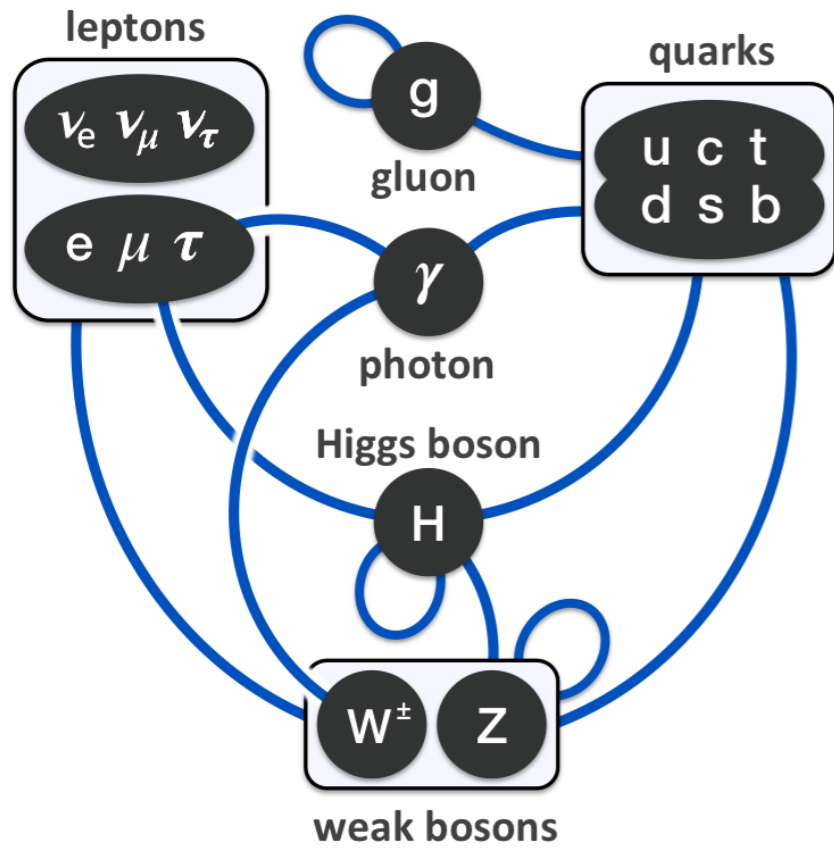
Based on collaboration with
Jiu Liu, Carlos Wagner, and
Xiaoping Wang

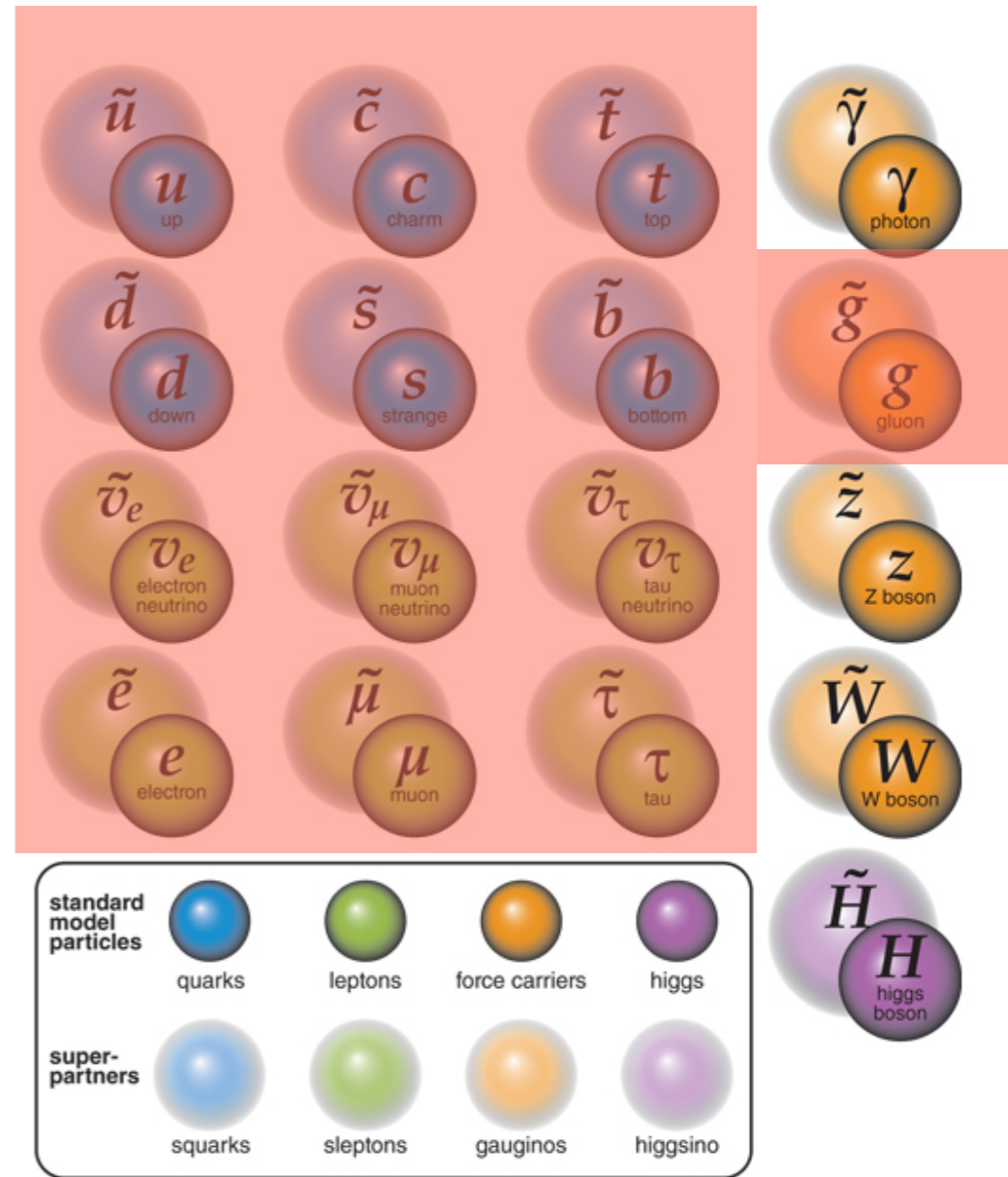
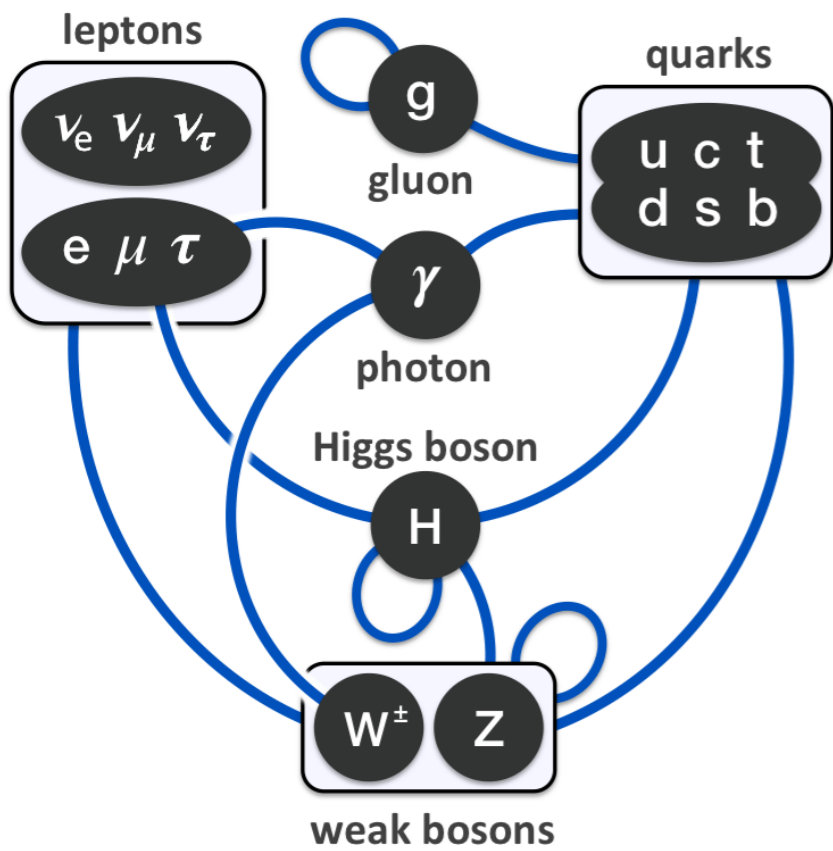
[arXiv:2008.11847](https://arxiv.org/abs/2008.11847) [hep-ph]

[arXiv:2006.07389](https://arxiv.org/abs/2006.07389) [hep-ph]

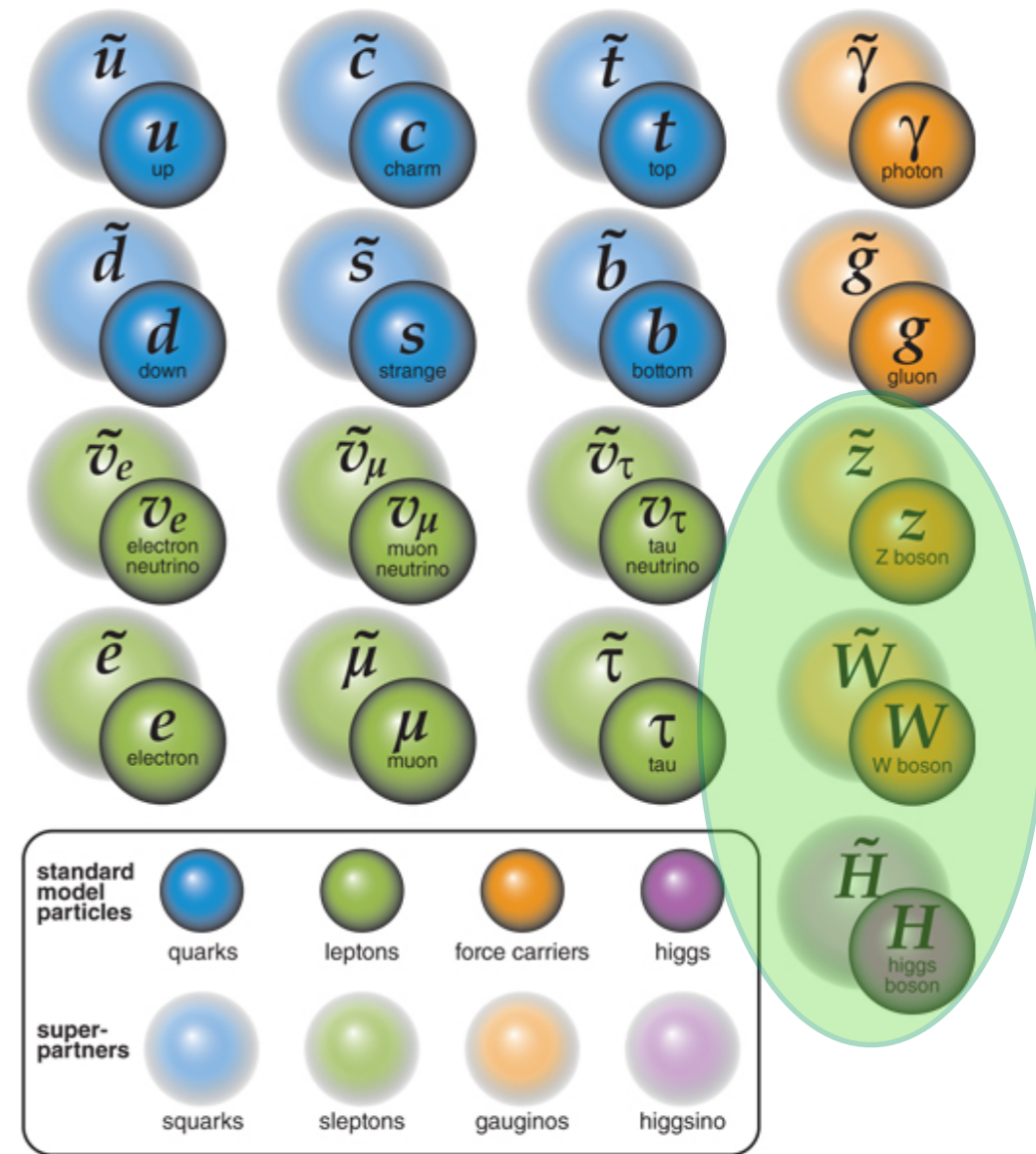
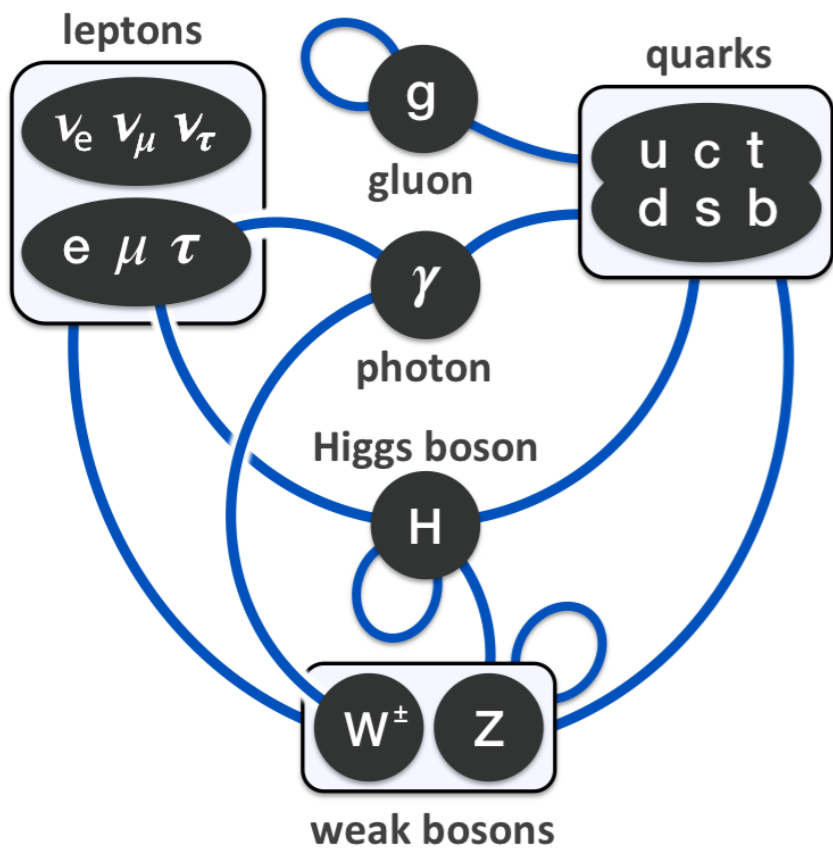


Motivation





Scalars & in particular strongly interacting superpartners studied in great detail so far, stringent limits



Plenty of room to explore weakly interacting sfermions

Current status

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

ATLAS Preliminary

$\sqrt{s} = 13$ TeV

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$]	Mass limit	Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets E_T^{miss} 139 36.1	\tilde{q} [10x Degen.] \tilde{q} [1x, 8x Degen.] 0.43 0.71 1.9	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	ATLAS-CONF-2019-040 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, μ	2-6 jets E_T^{miss} 139	\tilde{g} \tilde{g} Forbidded 2.35 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, μ	2-6 jets E_T^{miss} 139	\tilde{g} \tilde{g} 2.2 1.2	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2020-047 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets E_T^{miss} 36.1	\tilde{g} \tilde{g} 1.2 1.97	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV	ATLAS-CONF-2020-002 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, μ SS e, μ	7-11 jets 6 jets E_T^{miss} 139 139	\tilde{g} \tilde{g} 1.15 2.25	$m(\tilde{\chi}_1^0) < 600$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	ATLAS-CONF-2020-002 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ SS e, μ	3 b 6 jets E_T^{miss} 79.8 139	\tilde{g} \tilde{g} 1.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/\tilde{\chi}_1^\pm$	Multiple Multiple	36.1 139	\tilde{b}_1 Forbidded \tilde{b}_1 Forbidded 0.9 0.74	$m(\tilde{\chi}_1^0) = 300$ GeV, BR($h\tilde{\chi}_1^0$)=1 $m(\tilde{\chi}_1^\pm) = 300$ GeV, BR($h\tilde{\chi}_1^\pm$)=1	1708.09266, 1711.03301 1909.08457
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, μ 2 τ	6 b 2 b E_T^{miss} 139 139	\tilde{b}_1 Forbidded \tilde{b}_1 0.23-1.35 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, μ	≥ 1 jet E_T^{miss} 139	\tilde{t}_1 \tilde{t}_1 1.25 0.44-0.59	$m(\tilde{\chi}_1^0) = 1$ GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, μ	3 jets/1 b E_T^{miss} 139	\tilde{t}_1 \tilde{t}_1 1.16 0.46	$m(\tilde{\chi}_1^0) = 400$ GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1 $\tau + 1 e, \mu, \tau$	2 jets/1 b E_T^{miss} 36.1	\tilde{t}_1 \tilde{t}_1 1.16 0.43	$m(\tilde{\tau}_1) = 800$ GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, μ	2 c E_T^{miss} 36.1	\tilde{t}_1 \tilde{t}_1 0.85 0.46	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 1805.01649 1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	0 e, μ	mono-jet E_T^{miss} 36.1	\tilde{t}_1 \tilde{t}_1 0.067-1.18 0.86	$m(\tilde{\chi}_2^0) = 500$ GeV $m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	SUSY-2018-09 SUSY-2018-09
	$\tilde{b}_2\tilde{b}_2, \tilde{b}_2 \rightarrow \tilde{t}_1 + Z$	0 e, μ 3 e, μ	1-4 b 1 b E_T^{miss} 139 139	\tilde{b}_2 Forbidded \tilde{b}_2 0.86		
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e, μ $ee, \mu\mu$	≥ 1 jet E_T^{miss} 139 139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205 0.64	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV	ATLAS-CONF-2020-015 1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e, μ	E_T^{miss} 139	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$ 0.42	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e, μ	2 $b/2 \gamma$ E_T^{miss} 139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidded $\tilde{\chi}_1^\pm$ 0.74 1.0	$m(\tilde{\chi}_1^0) = 70$ GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{L}/\tilde{\nu}$	2 e, μ	E_T^{miss} 139	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$ [$\tilde{\tau}_L, \tilde{\tau}_R, L$] 0.16-0.3 0.12-0.39	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 τ	E_T^{miss} 139	$\tilde{\tau}$ $\tilde{\tau}$ 0.7 0.256	$m(\tilde{\chi}_1^0) = 0$	1911.06660
	$\tilde{t}_{1,R}\tilde{t}_{1,R}, \tilde{t} \rightarrow t\tilde{\chi}_1^0$	2 e, μ $ee, \mu\mu$	0 jets ≥ 1 jet E_T^{miss} 139 139	\tilde{t} \tilde{t} 0.7 0.256	$m(\tilde{\chi}_1^0) = 0$	1908.08215 1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, μ 4 e, μ	$\geq 3 b$ 0 jets E_T^{miss} 36.1 139	\tilde{H} \tilde{H} 0.13-0.23 0.29-0.88 0.55	BR($\tilde{\chi}_1^0 \rightarrow h\tilde{G}$)=1 BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)=1	1806.04030 ATLAS-CONF-2020-040
	Long-lived particles	Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet E_T^{miss} 36.1	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm$ 0.15 0.46	Pure Wino Pure higgsino
Stable \tilde{g} R-hadron		Multiple	36.1	\tilde{g} \tilde{g} 2.0		1902.01636, 1808.04095
Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$		Multiple	36.1	\tilde{g} [$\tau(\tilde{g}) = 10$ ns, 0.2 ns] \tilde{g} 2.05 2.4	$m(\tilde{\chi}_1^0) = 100$ GeV	1710.04901, 1808.04095
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell\ell$	3 e, μ	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] $\tilde{\chi}_1^\pm$ 0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, e\tau, \mu\tau$	3.2	$\tilde{\nu}_\tau$ $\tilde{\nu}_\tau$ 1.9	$\lambda'_{511} = 0.11, \lambda'_{132/133/233} = 0.07$	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, μ	0 jets E_T^{miss} 36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda'_{33} \neq 0, \lambda'_{12k} \neq 0$] $\tilde{\chi}_1^\pm$ 0.82 1.33	$m(\tilde{\chi}_1^0) = 100$ GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	4-5 large- R jets Multiple	36.1 36.1	\tilde{g} [$m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV] \tilde{g} [$\lambda'_{112} = 2e-4, 2e-5$] \tilde{g} 1.05 1.3 2.0	Large λ'_{112} $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	36.1	\tilde{t} [$\lambda'_{323} = 2e-4, 1e-2$] \tilde{t} 0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow bbs$	$\geq 4b$	139	\tilde{t} Forbidded \tilde{t} 0.95	$m(\tilde{\chi}_1^0) = 500$ GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	36.7	\tilde{t}_1 [qq, bs] \tilde{t}_1 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, μ 1 μ	2 b DV 36.1 136	\tilde{t}_1 \tilde{t}_1 0.4-1.45 1.0 1.6	BR($\tilde{t}_1 \rightarrow be/b\mu$) > 20% BR($\tilde{t}_1 \rightarrow q\mu$) = 100%, $\cos\theta_t = 1$	1710.05544 2003.11956

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹ 1 Mass scale [TeV]

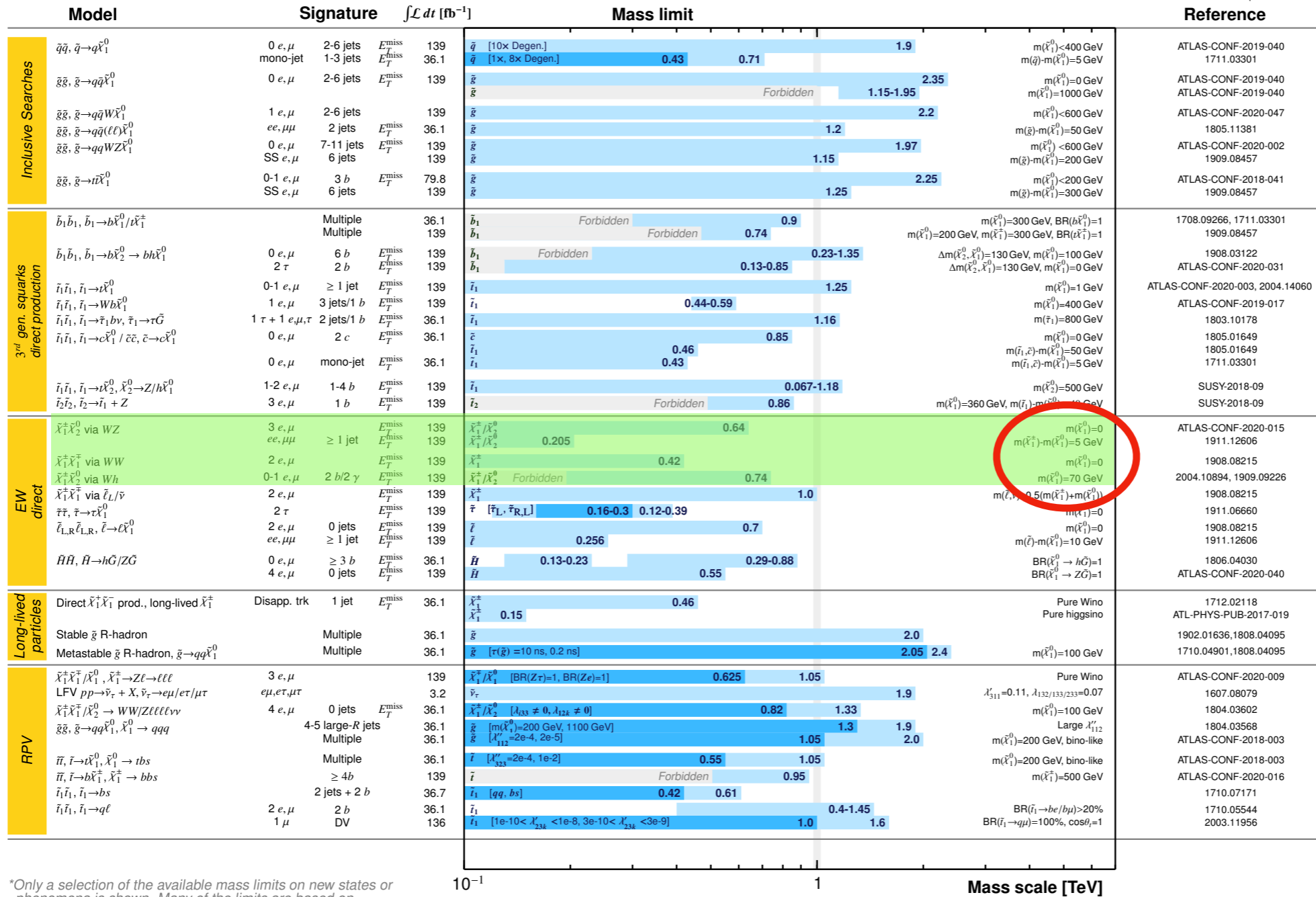
For my talk: EWino direct channels *without* sleptons. Looking at final states resulting from W + Z/h decays: bounds ranging ~200-700 GeV

Current status

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults>

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2020

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV



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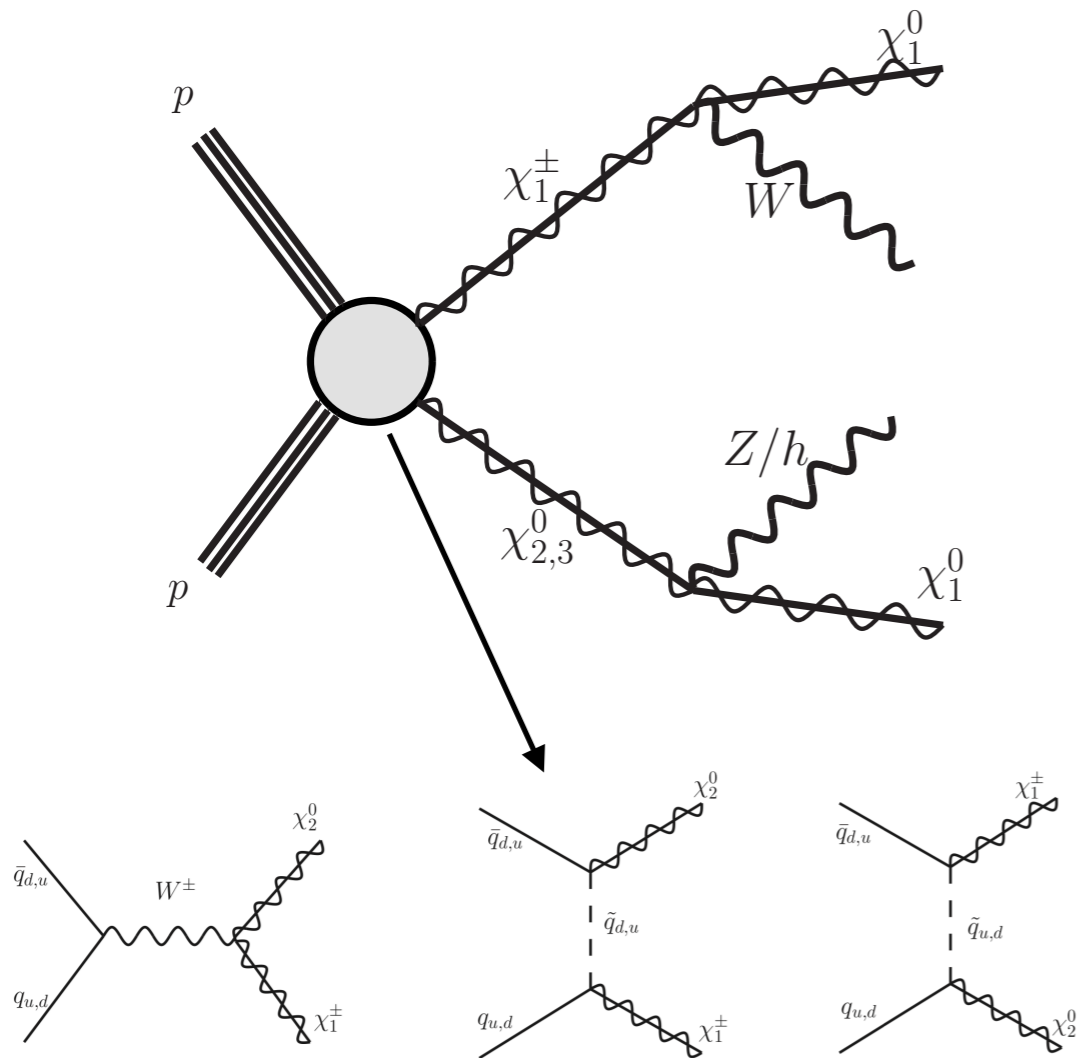
Fine print: simplified models with specific spectrum and/or BRs=100%
MSSM dynamics: spectrum *and* BRs determined by same parameters. Different channels give complementary information

Search channels

Looking at EW direct production without sleptons, decaying through $W + Z/h$

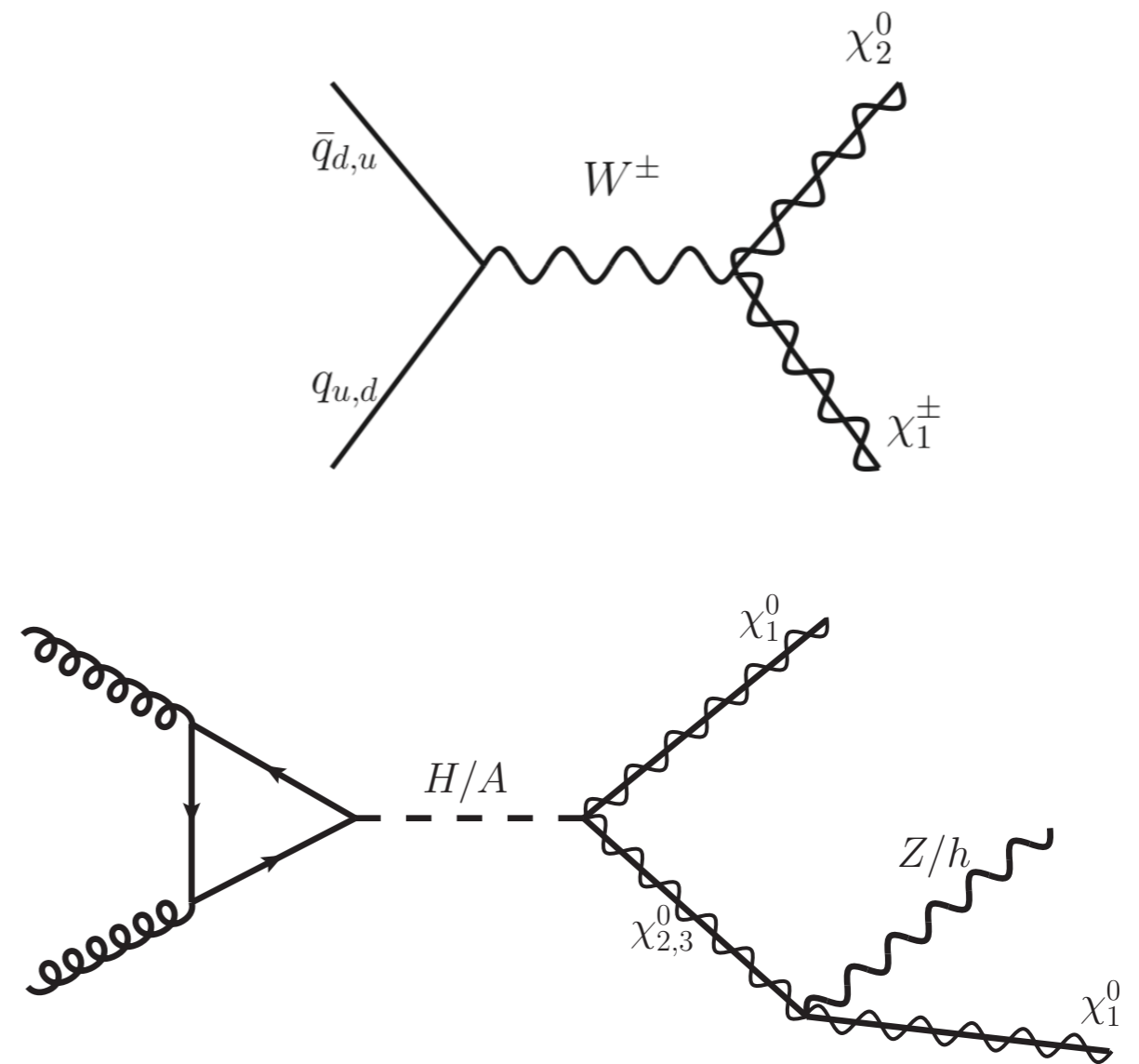
Wino scenario

$$M_1 \lesssim M_2 \ll |\mu|$$



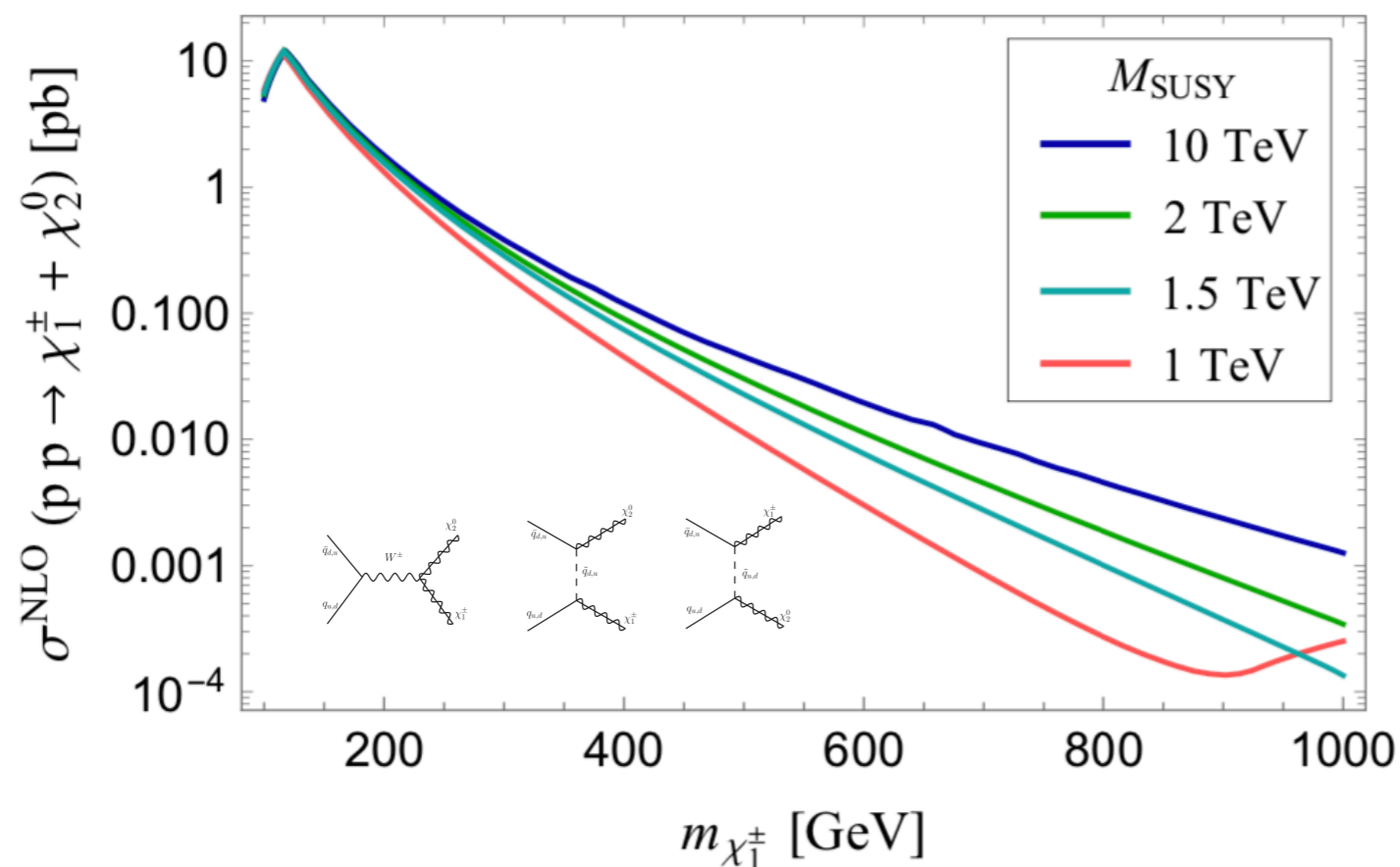
Higgsino-Bino scenario

$$M_1 \lesssim |\mu| \ll M_2$$



Wino scenario

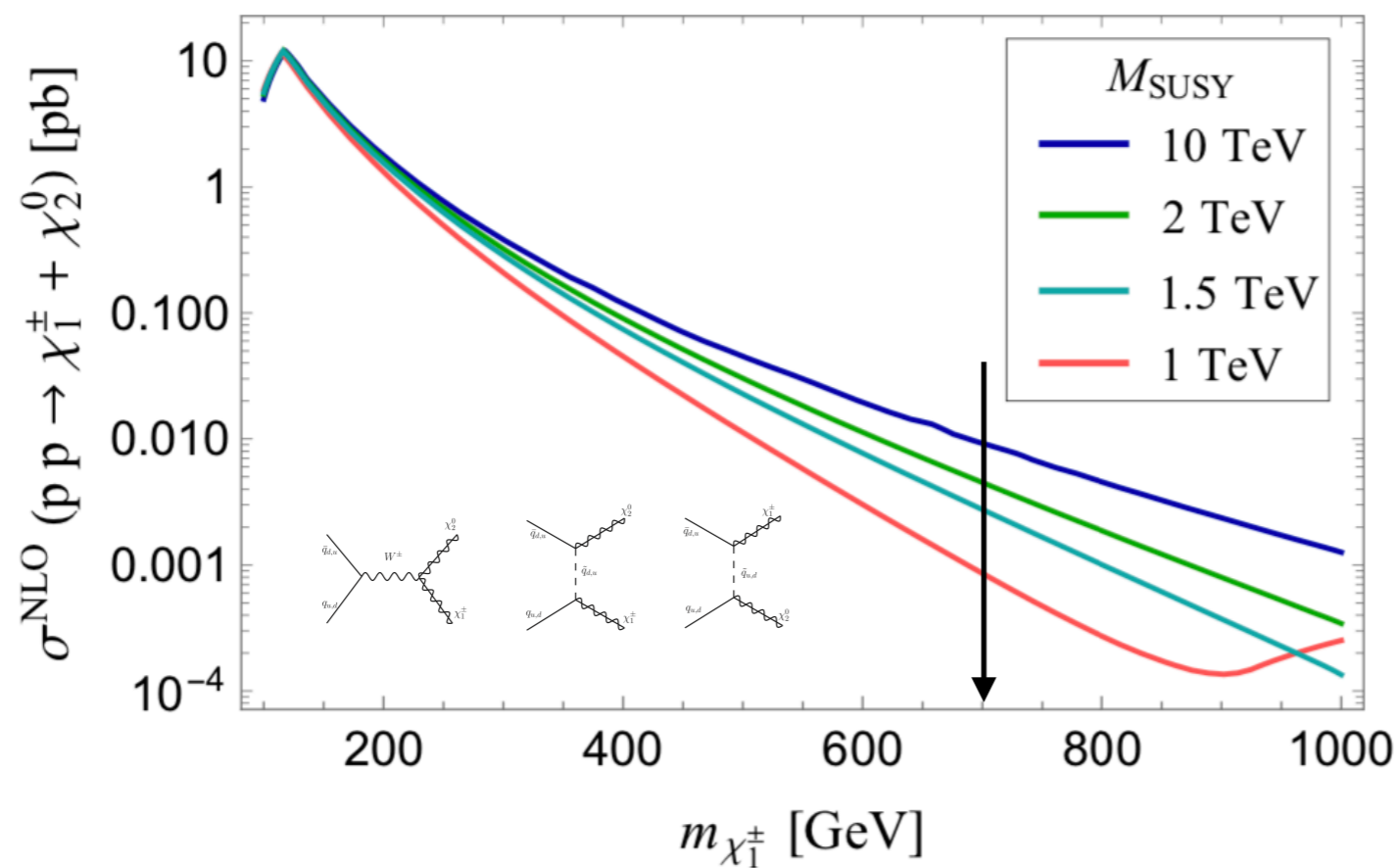
- Wino scenario (large components of \tilde{W}):
 - Traditional search channel considered by ATLAS and CMS collaborations
 - Cross sections actually connected to SUSY strong sector - major implications for EWino bounds!



M_{SUSY} = overall scale of scalar super partners. 1 - 10 TeV suggested by measured value of Higgs mass

Wino scenario

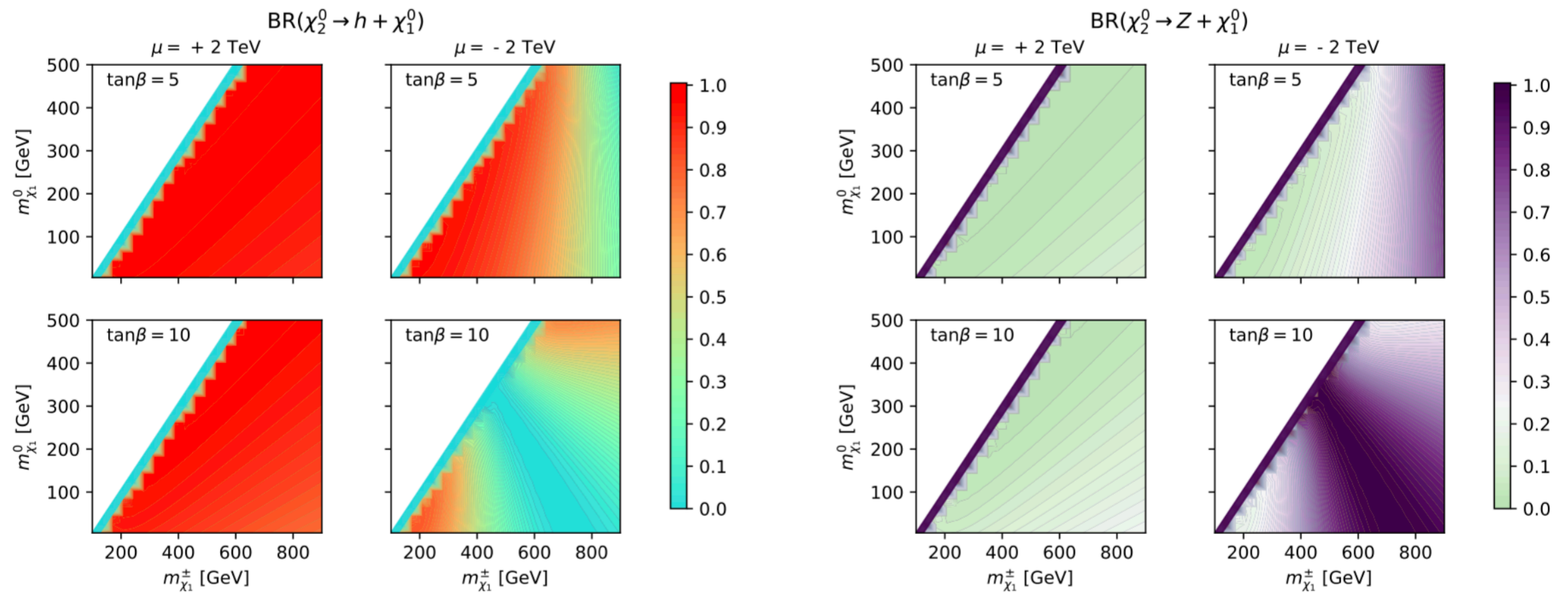
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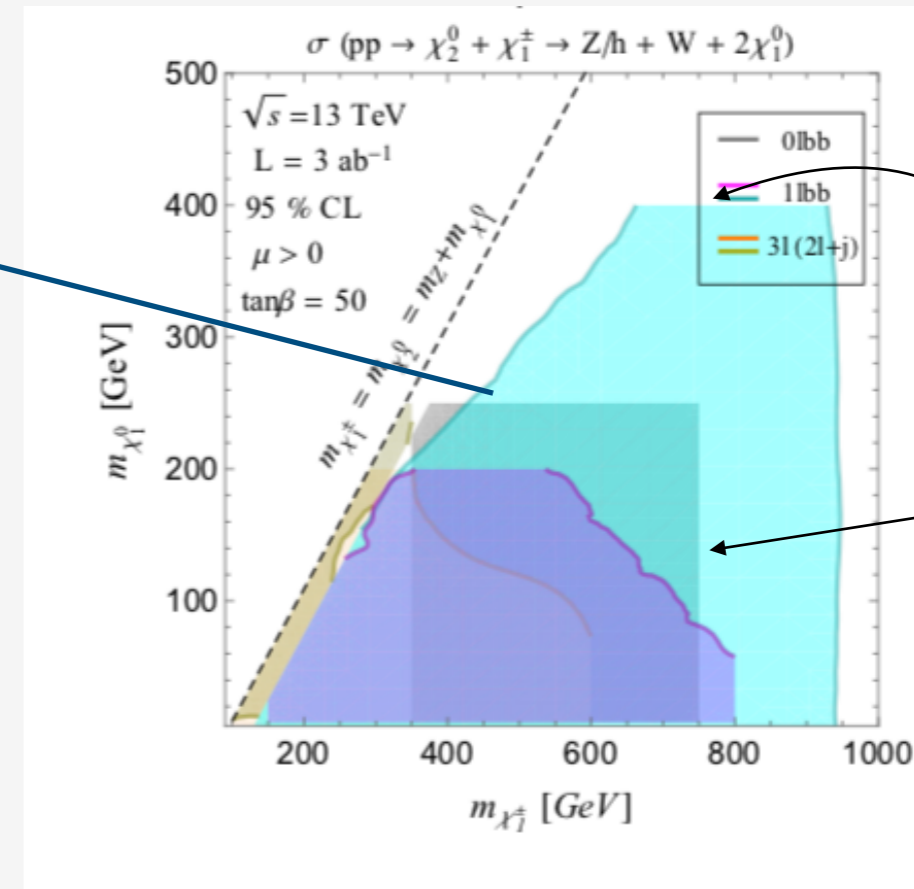
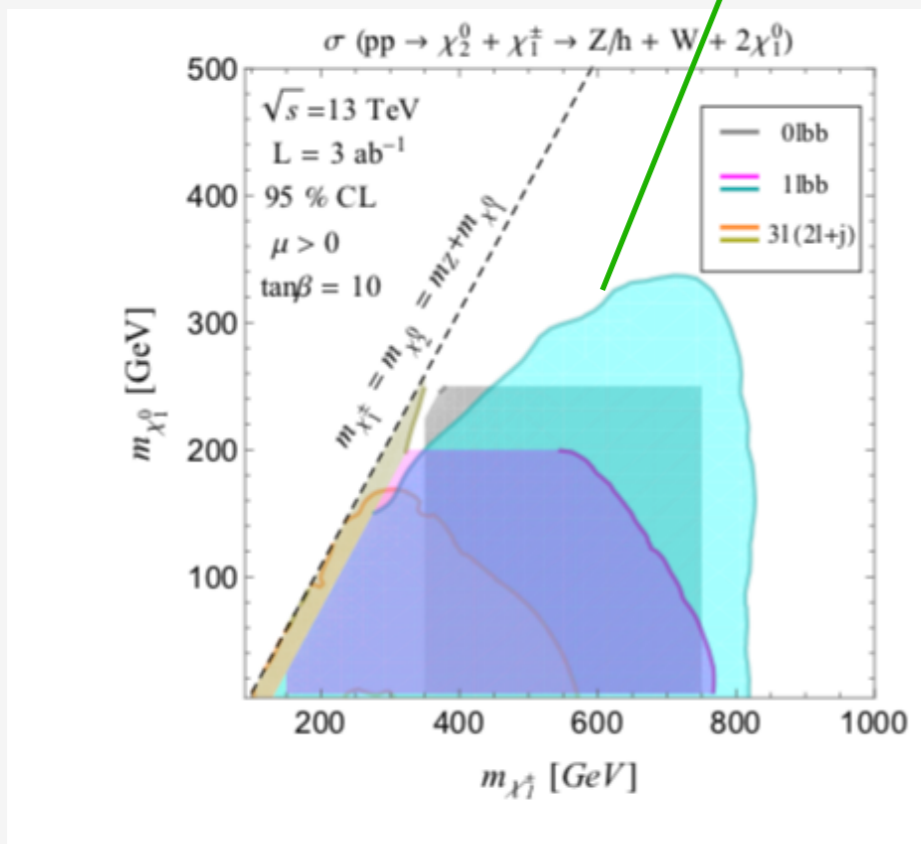
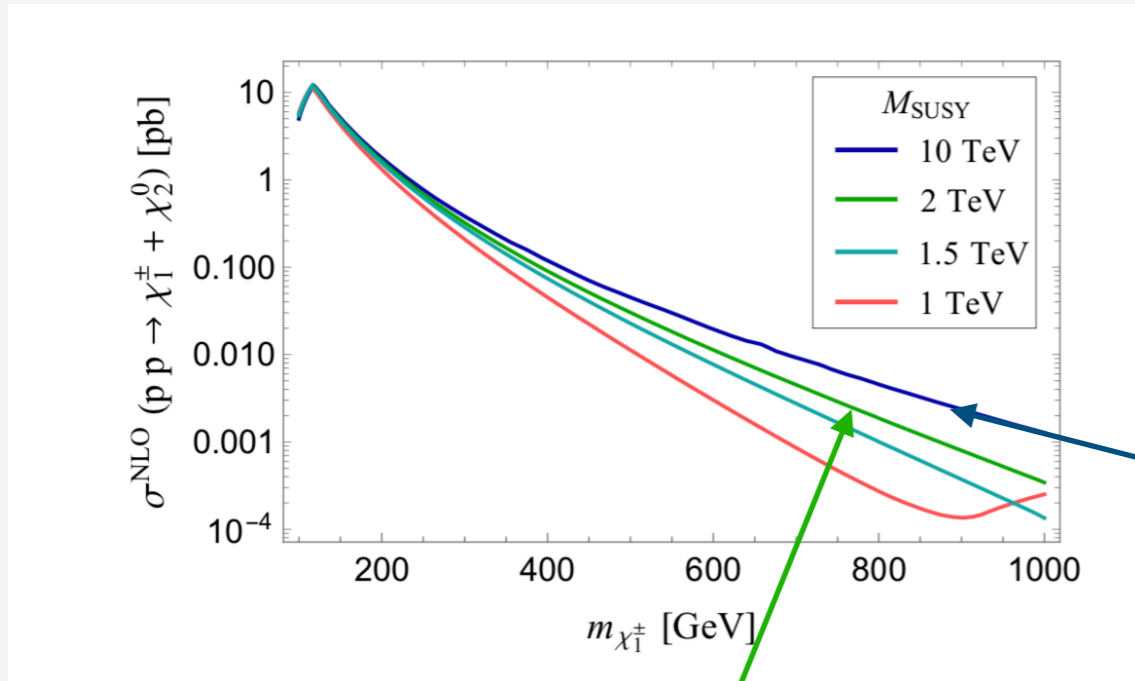
Wino scenario

- Wino scenario (large components of \tilde{W}):
 - Sign of μ matters



Take away: trilepton searches good for compressed region or special region of parameters. Fairly robust ultimate reach for $m_{\chi_1^\pm}$ from $W+h$ channels

Wino scenario



Currently unexplored region

Wino summary

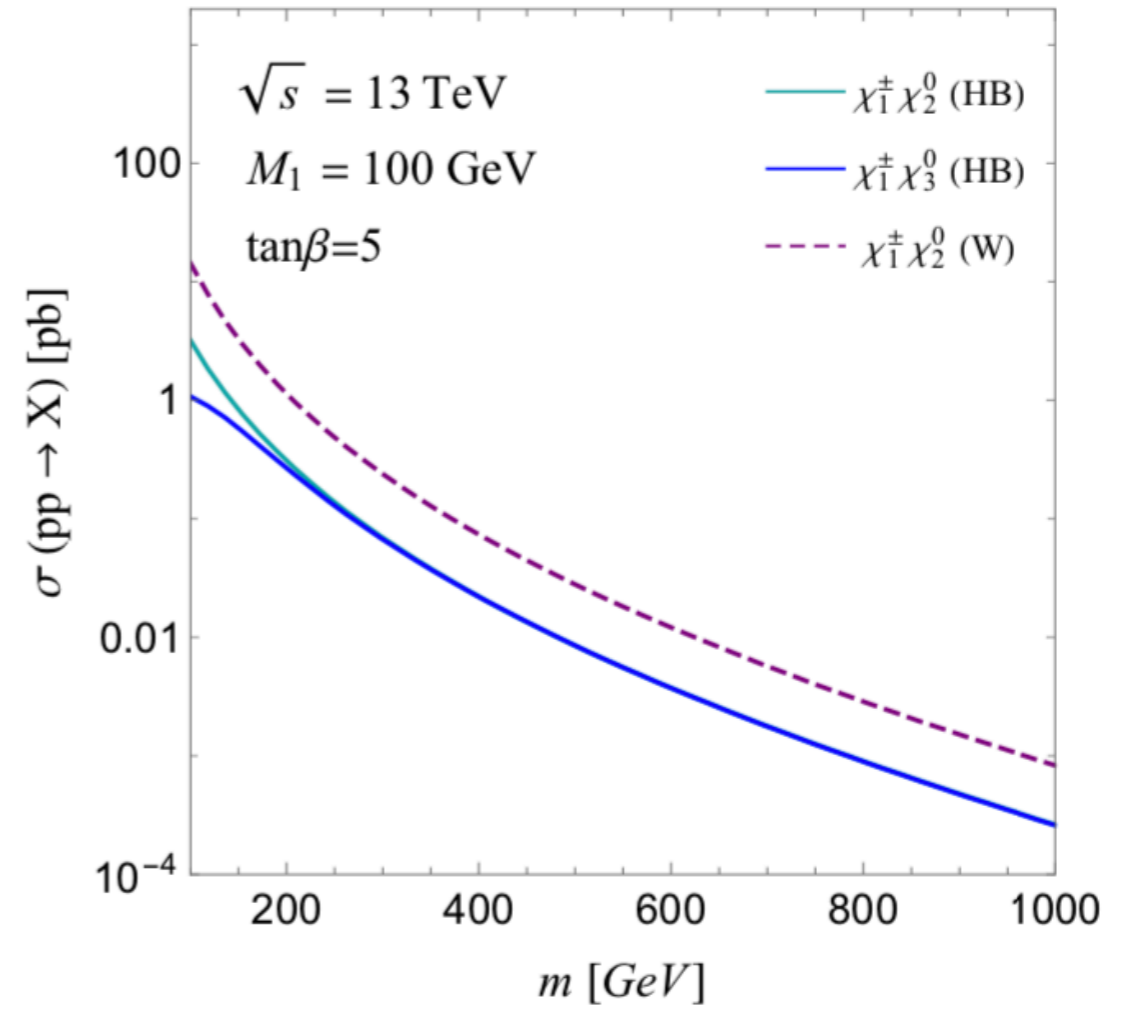
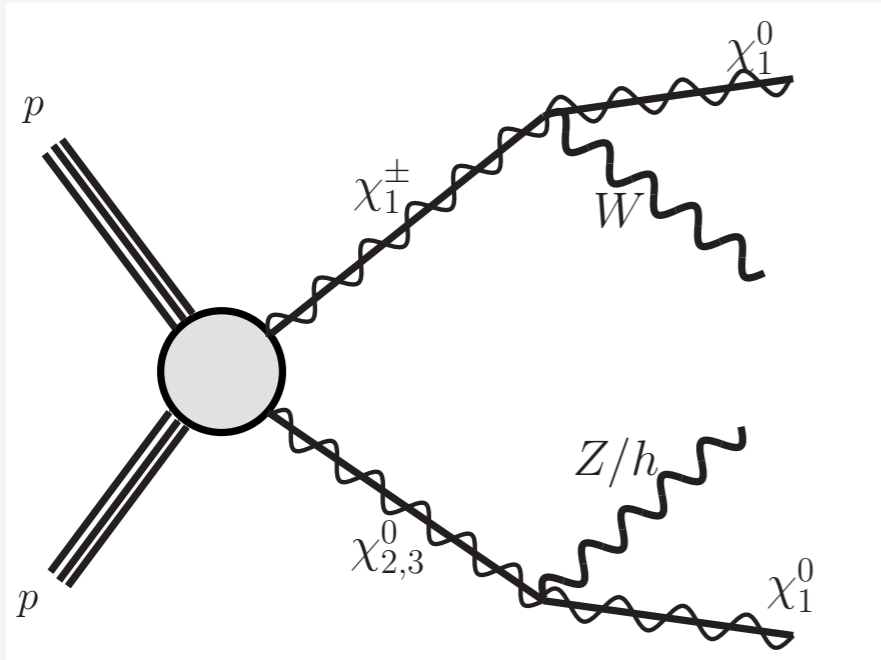
$$M_1 \lesssim M_2 \ll |\mu|$$

- Direct EW searches gives indirect info on squark sector through prod x-section
- Sign of μ can have drastic consequences in branching ratios

Assuming the optimal case for the HL-LHC, when $M_{SUSY} \rightarrow 10$ TeV, projection of current analyses gives reach of $m_{\chi_1^\pm} \simeq 1$ TeV, $m_{\chi_1^0} \simeq 400$ GeV

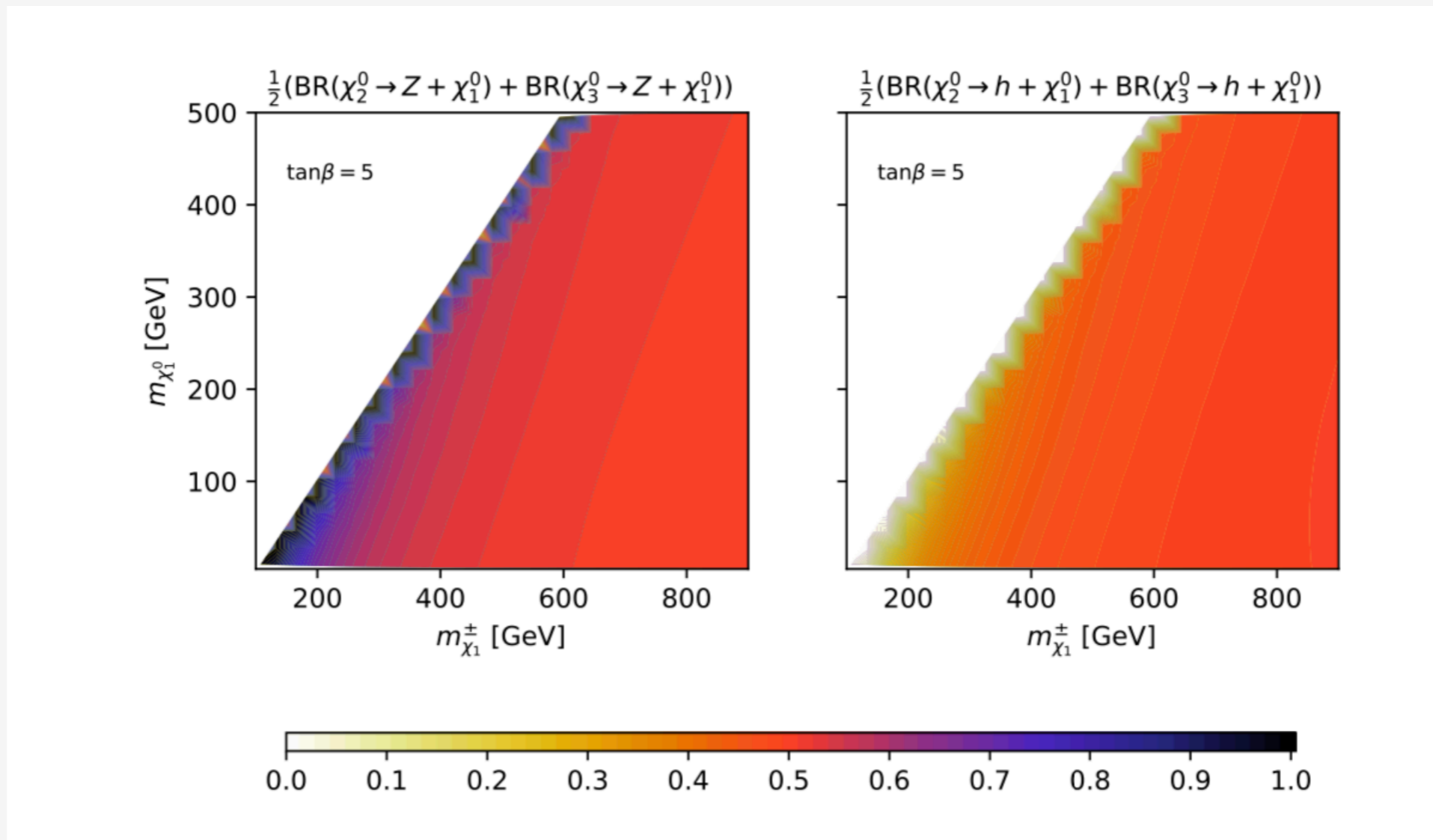
Higgsino-Bino scenario

$$M_1 \lesssim |\mu| \ll M_2$$



χ_2^0 & χ_3^0 give comparable contributions now, $m_{\chi_1^\pm} \simeq m_{\chi_2^0} \simeq m_{\chi_3^0}$

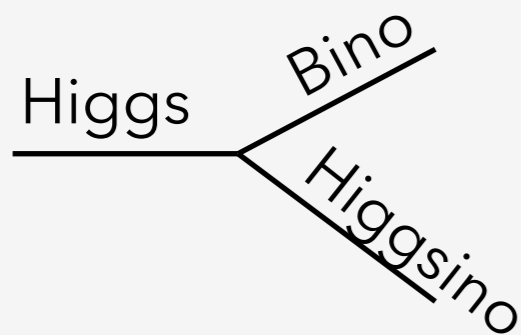
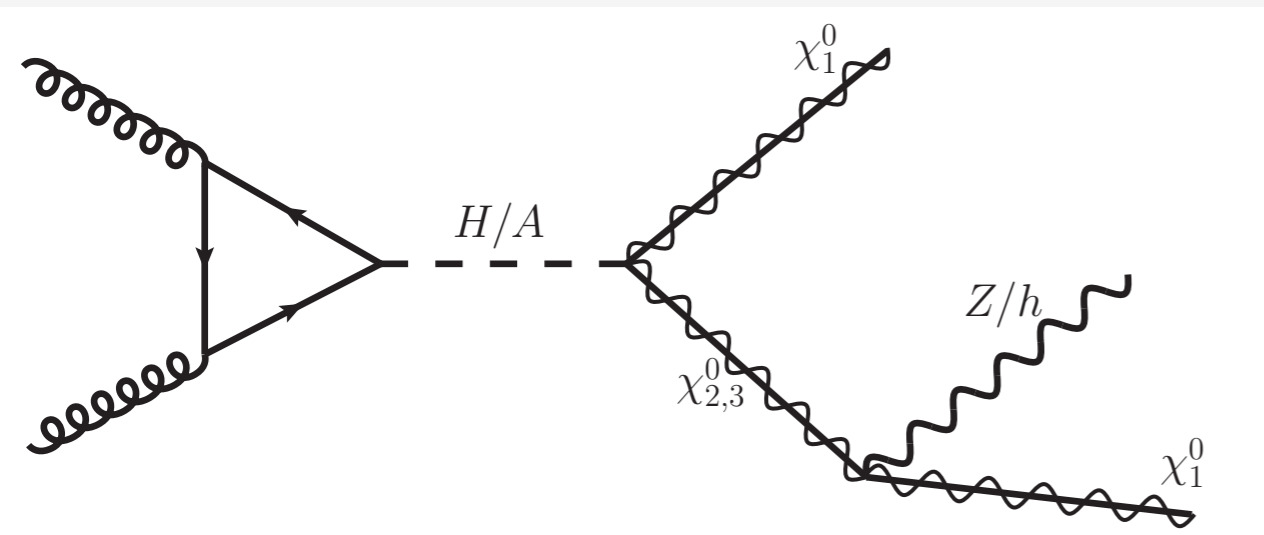
Higgsino-Bino scenario



Simple pattern of overall branching ratio to Z or h

Higgsino-Bino scenario

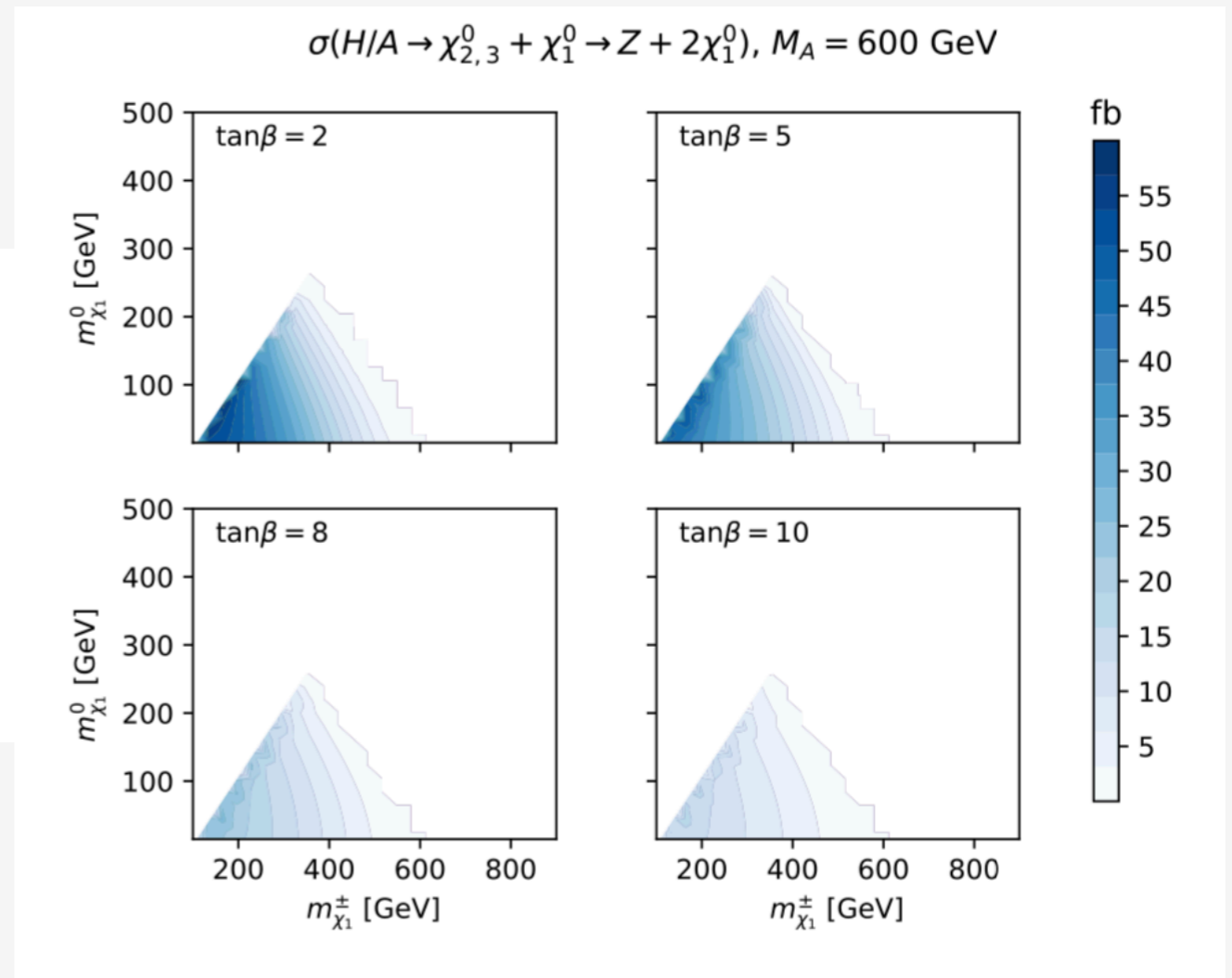
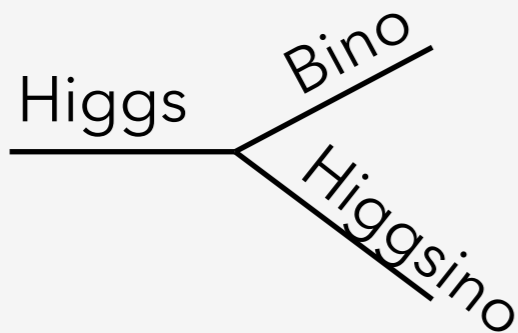
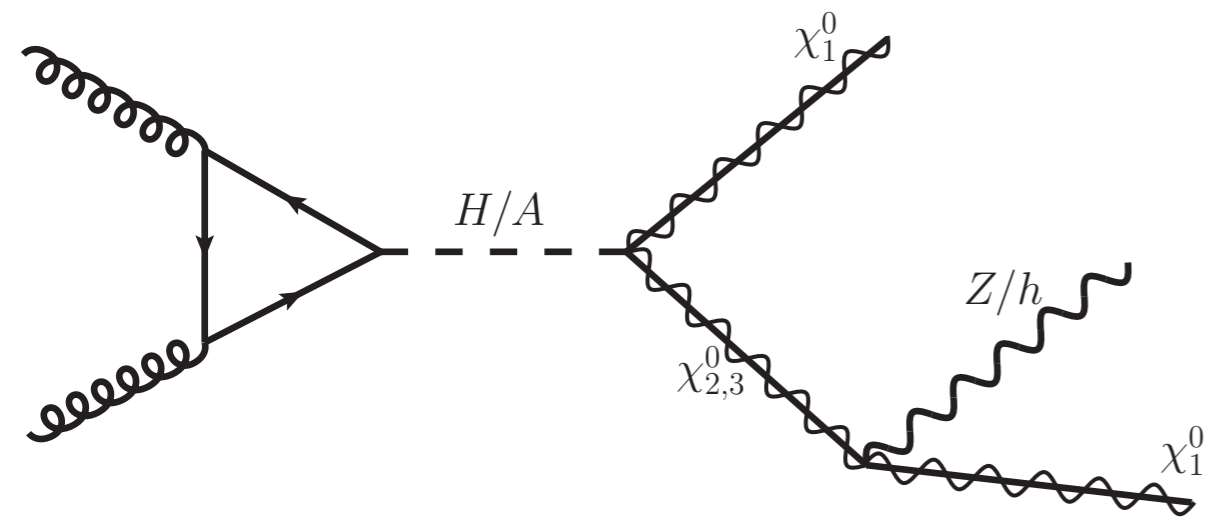
Complementary channel



~ coupling not suppressed by mixing

Higgsino-Bino scenario

Complementary channel

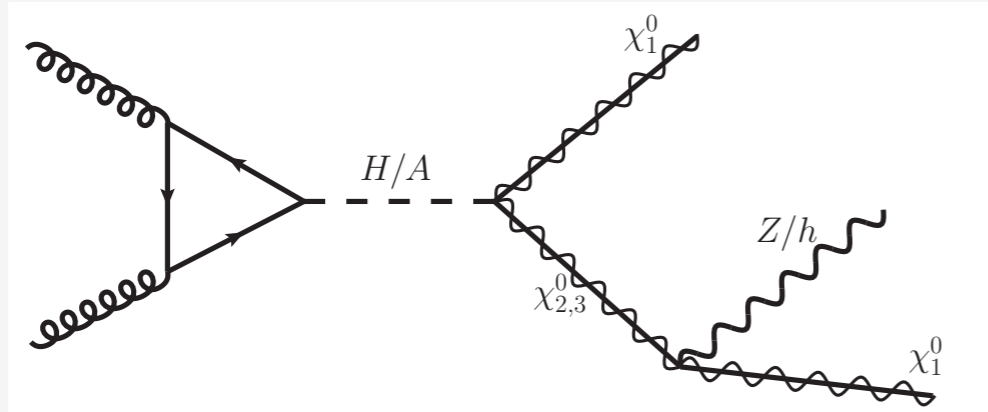


$\mathcal{O}(1 - 10)$ fb size x-section

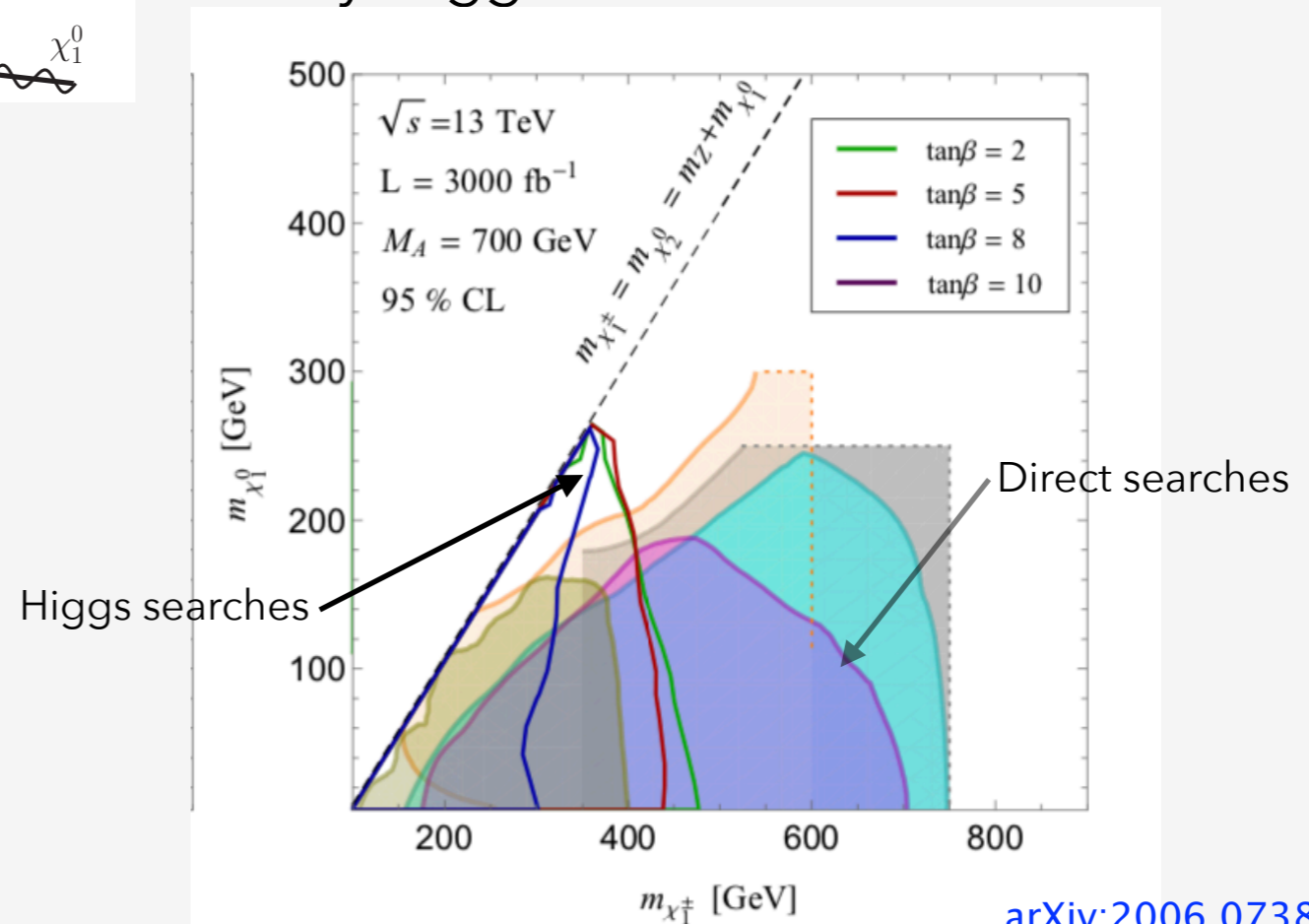
Very different kinematics due to heavy resonance

Higgsino-Bino scenario

- Higgsino-Bino scenario (large components of \tilde{H}):
 - Alternative search channel NOT yet explored (in detail) by ATLAS and CMS



Not only relevant for EWinos, but gives additional handle on the heavy Higgs sector in the MSSM



Higgsino-Bino summary

$$M_1 \lesssim |\mu| \ll M_2$$

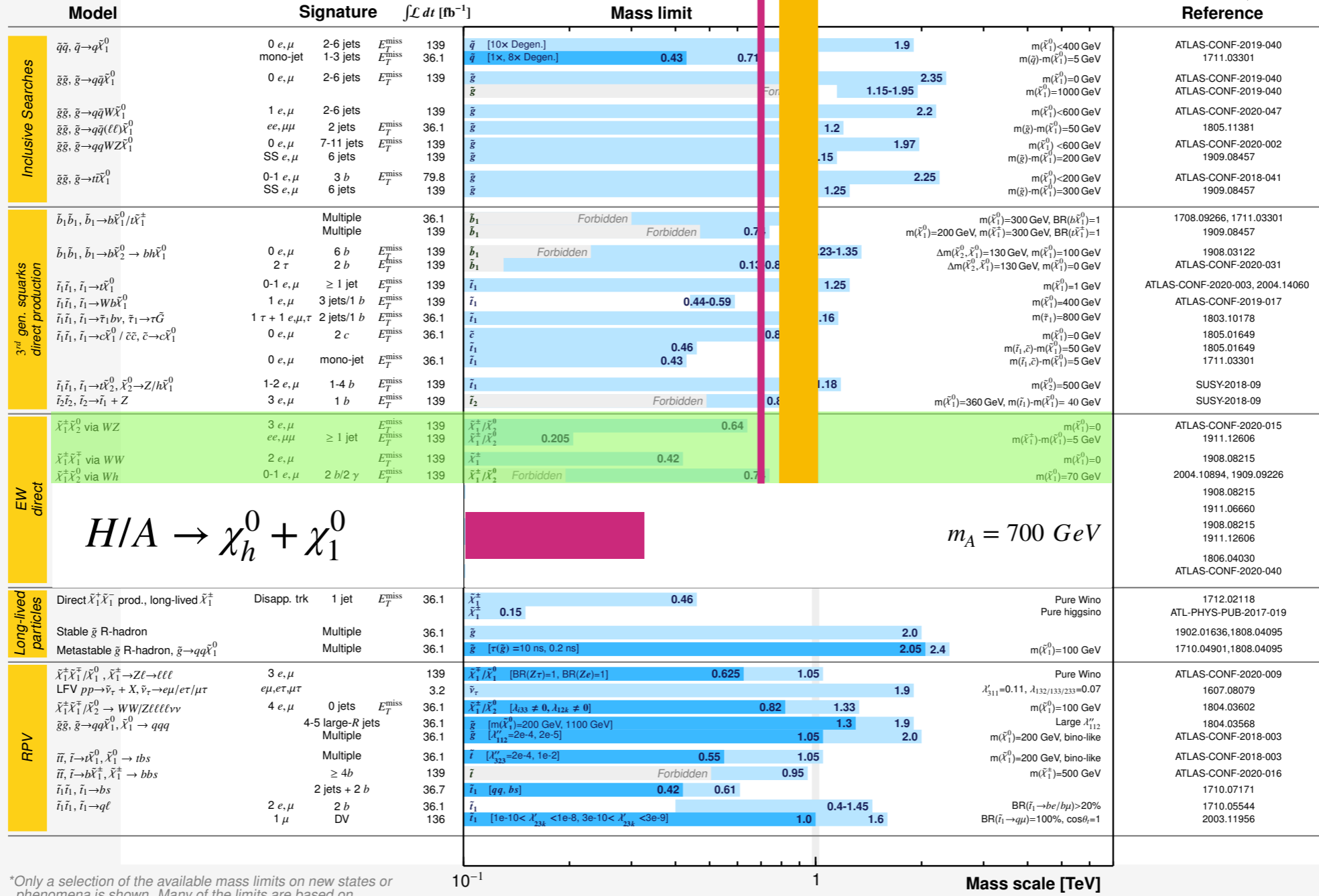
- Weaker direct production (no squark channel) than in Wino case
- Pattern of mixing allows alternative search channel with complementary region to explore decays. Additionally probes Higgs sector

Optimal case of $m_A = 700$ GeV, gives significant reach in compressed region

$$m_{\chi_1^\pm} \simeq 400 \text{ GeV}, m_{\chi_1^0} \simeq 300 \text{ GeV}$$

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*Current bounds highly relaxed in H-B scenario

Summary

- Traditional EW search channels can probe different mixing scenarios btw a Wino/bino-like spectrum and Higgsino/Bino-like spectrum
- Each case requires different kind of search strategy (branching ratios, production channels, kinematics)
- HL-LHC has strong potential to explore all of these regions, probing multiple aspects of SUSY models: Higgs sector, EWino mixings, squarks (indirectly)

We will learn a lot about EWinos at the HL-LHC :)