SUPERSYMMETRY AT COLLIDERS

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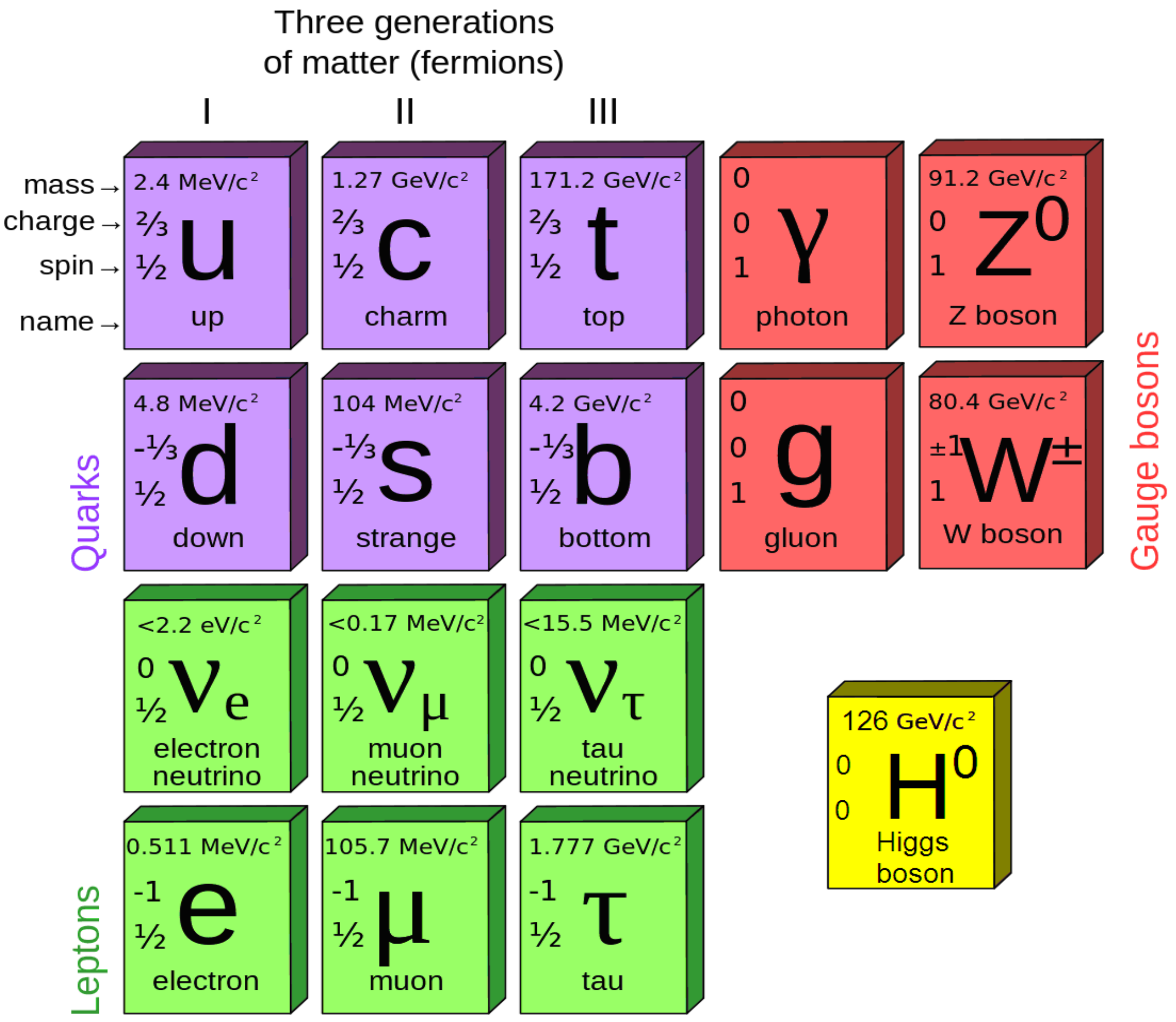
Fundamental Interactions at Future Colliders 2024, Trieste, Italy

September 18, 2024

The Standard Model



Three generations
of matter (fermions)

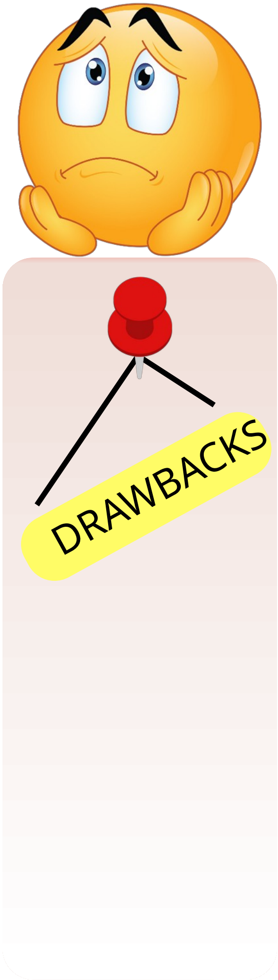
	I	II	III		
mass → charge → spin → name →	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	91.2 GeV/c^2 0 1 Z^0 Z boson
Quarks	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	80.4 GeV/c^2 ±1 1 $W^{\pm}$ W boson
	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino		
Leptons	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau		

Gauge bosons

126 GeV/c^2
0
0
H^0
Higgs boson

V. D. Barger et.al., Collider Physics (1996)

Drawbacks of the Standard Model



✦The Higgs mass instability problem in the Electroweak (EW) sector

Supersymmetry (SUSY)

✦The Strong CP Problem

$U(1)_{PQ}$ symmetry (Axion)

✦Existence of Dark Matter

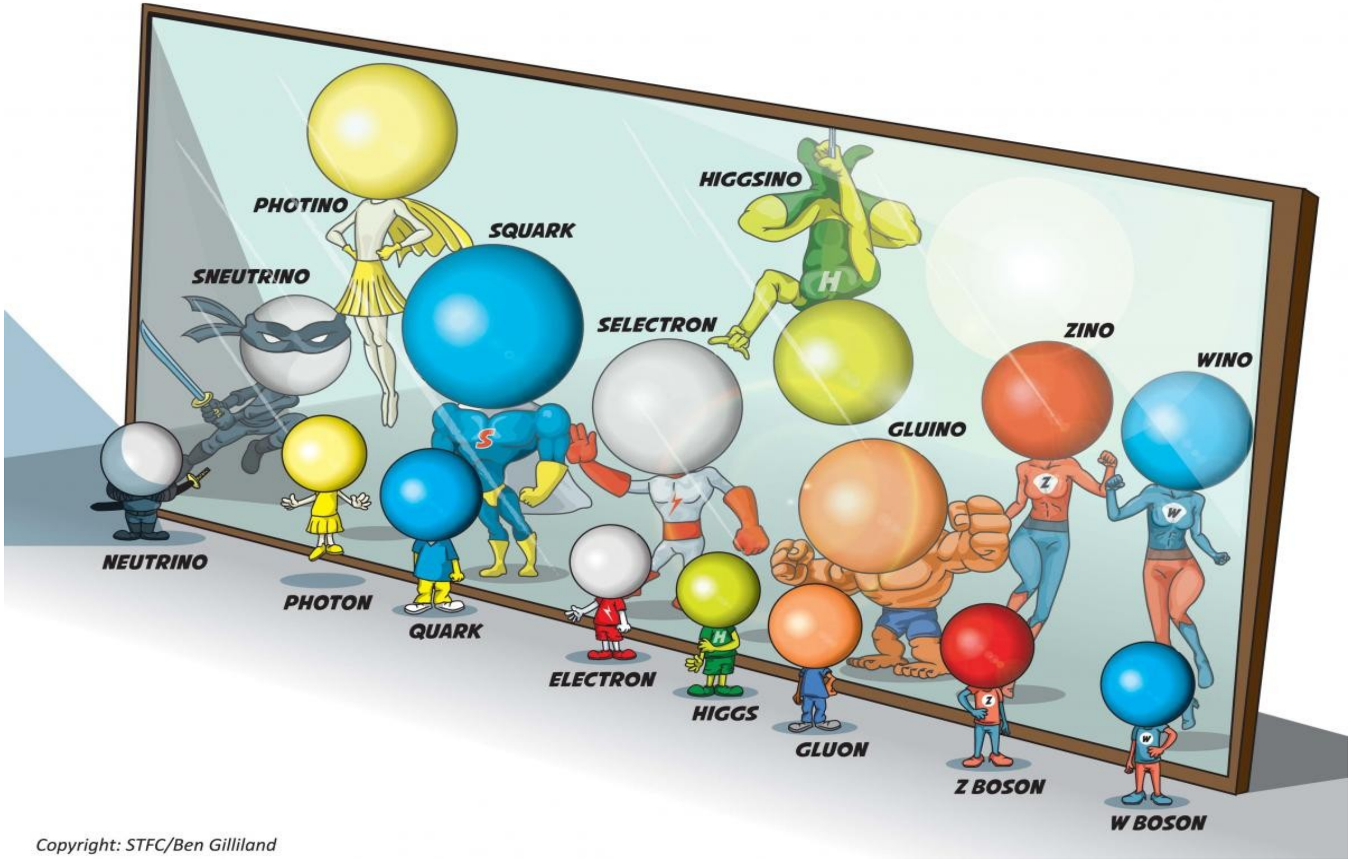
Lightest SUSY Particle (LSP) from R-Parity Conserving (RPC) SUSY+ Axion

M. Bauer et. al., Lect.Notes Phys. (2019)
A. Hook, PoS TASI2018
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)
V. D. Barger et.al., Collider Physics (1996)

A BSM Scenario: Supersymmetry (SUSY)

SUSY = SM + Superpartner with spin = spin(SM) $\pm$ 1/2

MINIMAL SUPERSYMMETRIC STANDARD MODEL (MSSM)



Copyright: STFC/Ben Gilliland

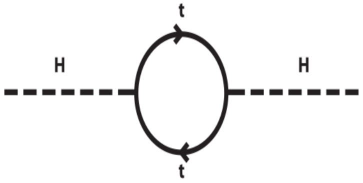
SM Fermion $\xrightarrow{\text{Superpartner}}$ Boson

SM Boson $\xrightarrow{\text{Superpartner}}$ Fermion

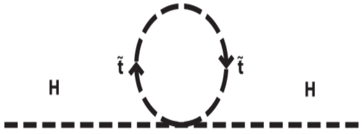
H. Baer et. al., Cambridge University Press, 2006.
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)

SUSY and its advantages

Main Motivation: *Cancellation of Quadratic Divergence in Higgs Mass*



$$\Delta m_H^2 = \frac{-|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2 + \underbrace{\dots}_{} \longrightarrow \propto m_t^2 log\Lambda_{UV}$$



$$\Delta m_H^2 = \frac{|\lambda_t|^2}{8\pi^2}\Lambda_{UV}^2 + \underbrace{\dots}_{} \longrightarrow \propto m_{\tilde{t}}^2 log\Lambda_{UV}$$

Quadratic divergences must be canceled to stabilize the Higgs mass in the ultraviolet complete theory

H. Baer et. al., Cambridge University Press, 2006.
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)

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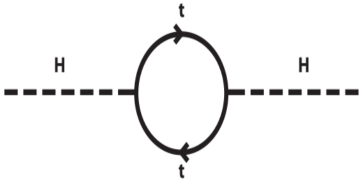

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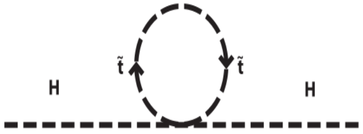

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Other Advantanges

★ **Dark Matter** → **Lightest Supersymmetric Particle (LSP)** → **R-Parity Conserving SUSY**

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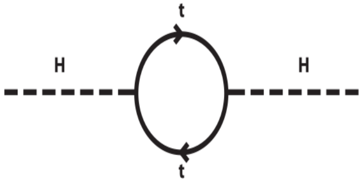

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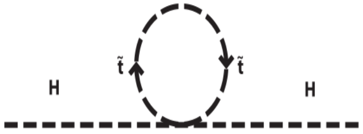

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R-parity (SM particles) = +1; **R-parity (sparticles) = -1**

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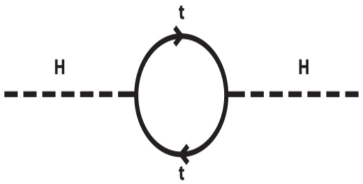

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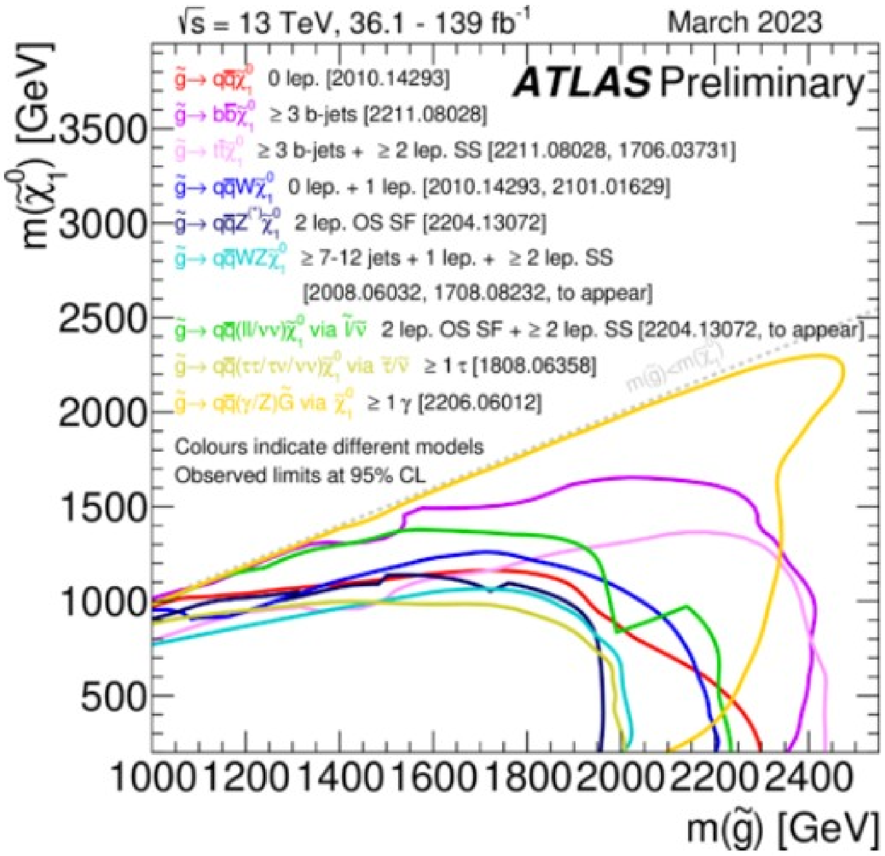
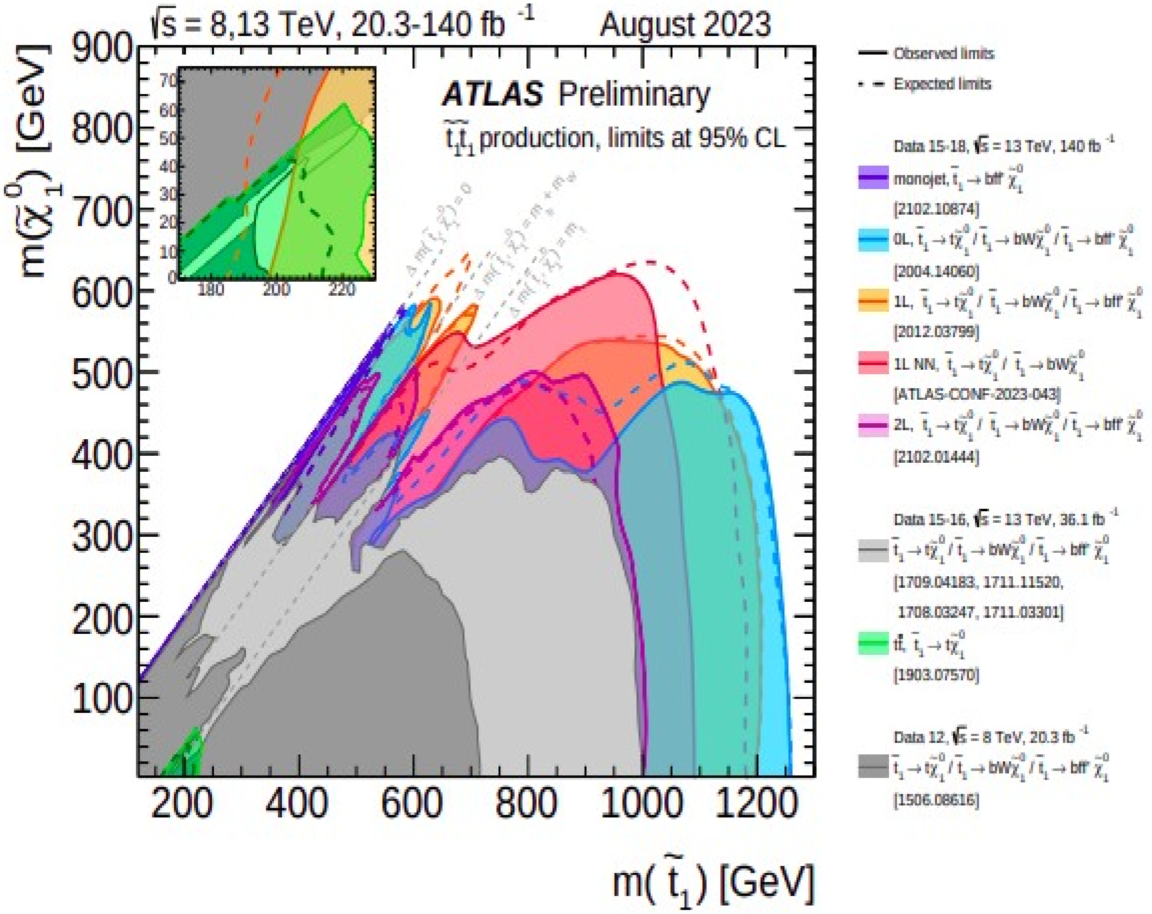
$(-1)_R \to (-1)_R\ (1)_R$ (allowed);
$(1)_R \to (-1)_R\ (-1)_R$ (kinematically forbidden);
$(-1)_R \to (1)_R\ (1)_R$ (forbidden by RPC)

H. Baer et. al., Cambridge University Press, 2006.
S.P. Martin, Adv.Ser.Direct.High Energy Phys. (2010)

Where are the sparticles?

none seen so far at LHC





$$m_{\tilde{g}} > 2.25\ \text{TeV}$$

$$m_{\tilde{t}_1} > 1.3\ \text{TeV}$$

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Naturalness in SUSY

No **SPARTICLES** yet!

$$m_{sparticles} \gg m_{SM particles}$$

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Notion of Practical Naturalness :

An Observable $\mathcal{O}$ is natural if all independent contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.

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$$\Delta_{\rm EW} = {\rm max}_i |C_i|/(M_Z^2/2)$$

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u\left(\tilde{t}_{1,2}\right)$$

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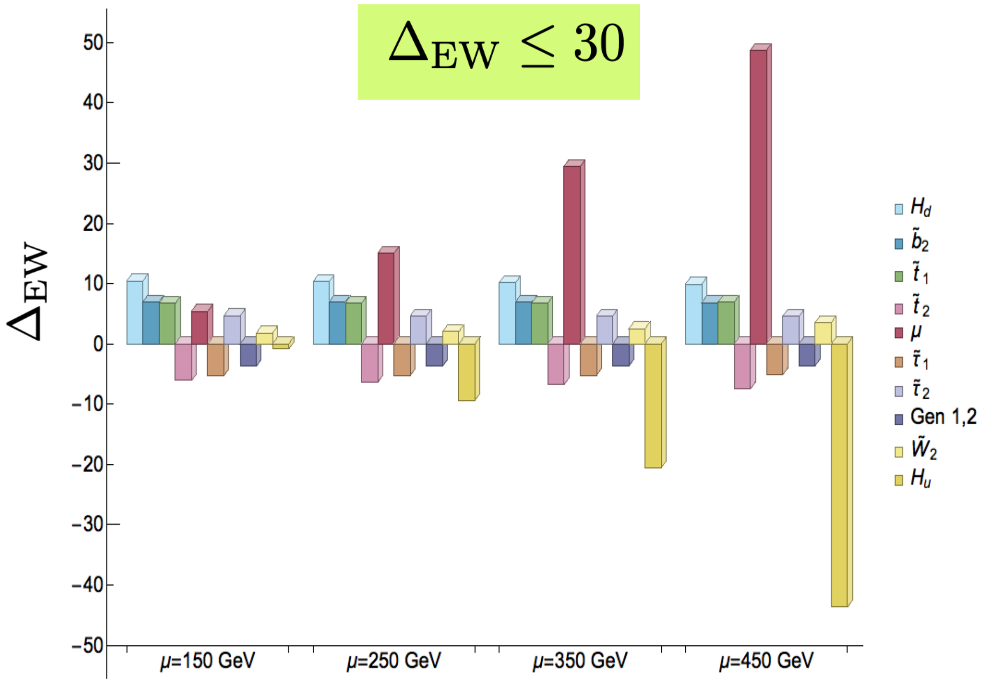

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$\Delta_{EW} <$ **30 ?**

$\Delta_{EW} < 30$ → Anthropic requirements needed to sustain life

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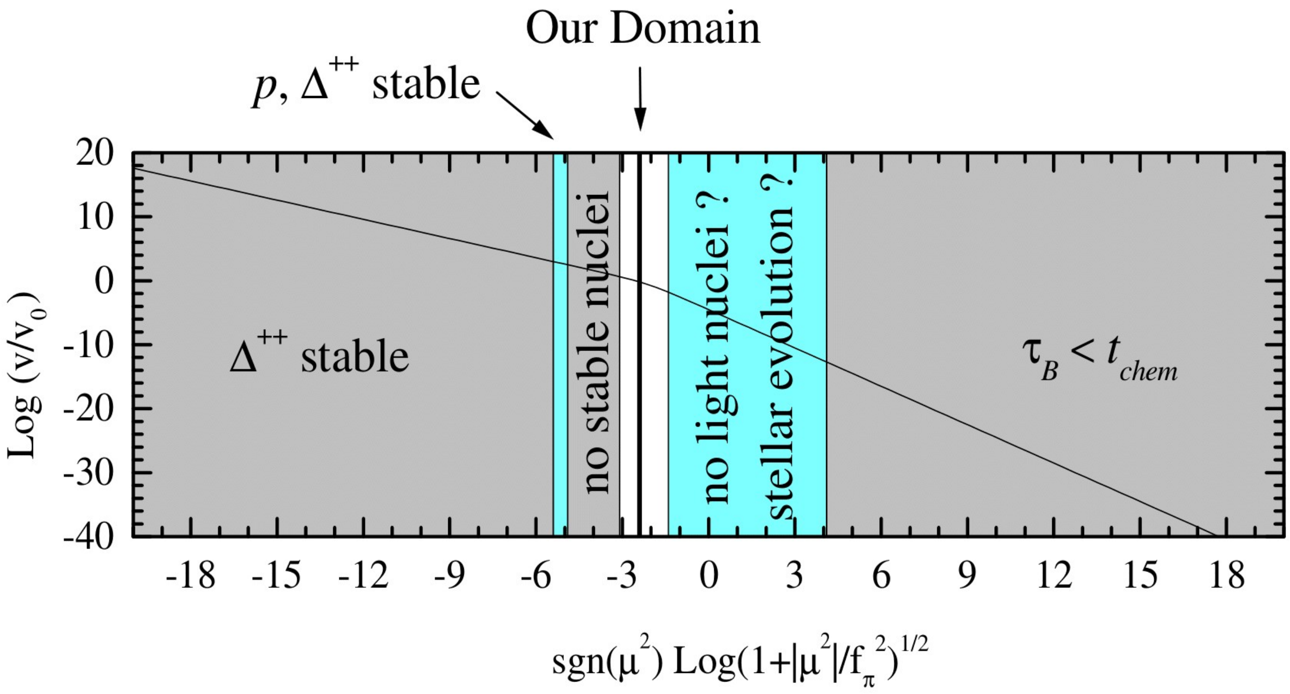

Agrawal, Barr, Donoghue, Seckel, Phys. Rev. D 57, 5480

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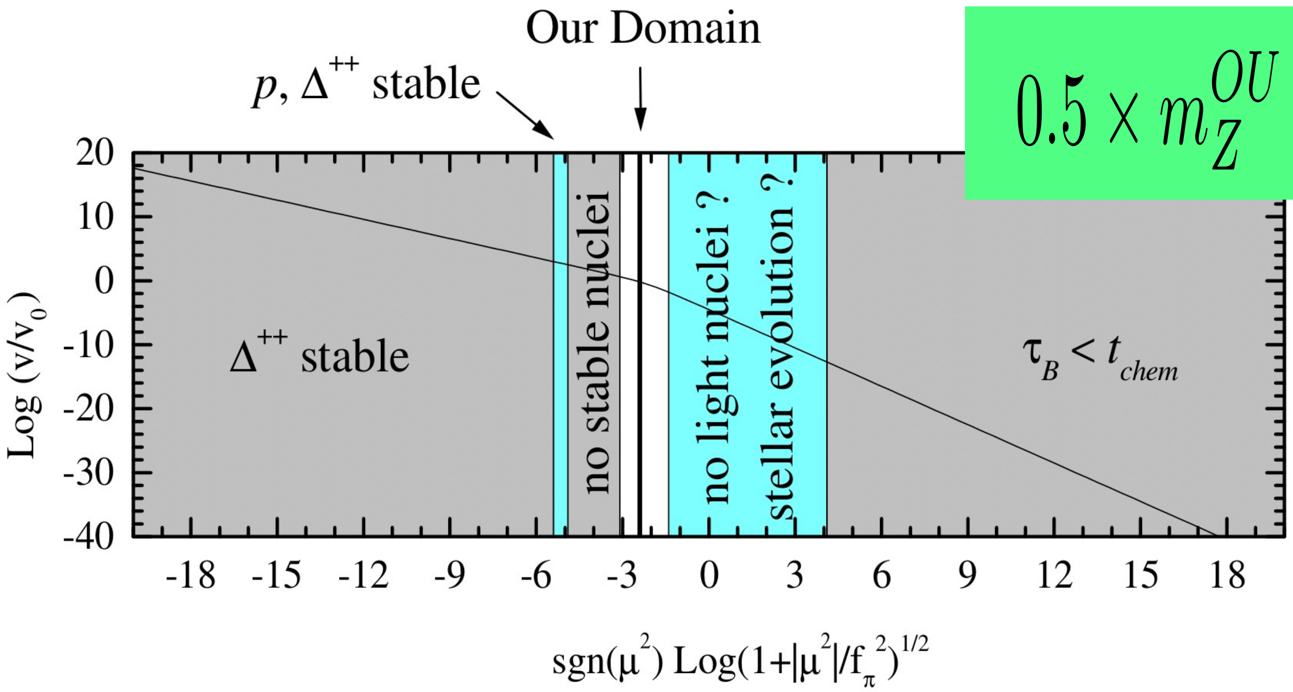

$$0.5 \times m_Z^{OU} \le m_Z^{PU} \le 5 \times m_Z^{OU}$$

Agrawal, Barr, Donoghue, Seckel, Phys. Rev. D 57, 5480

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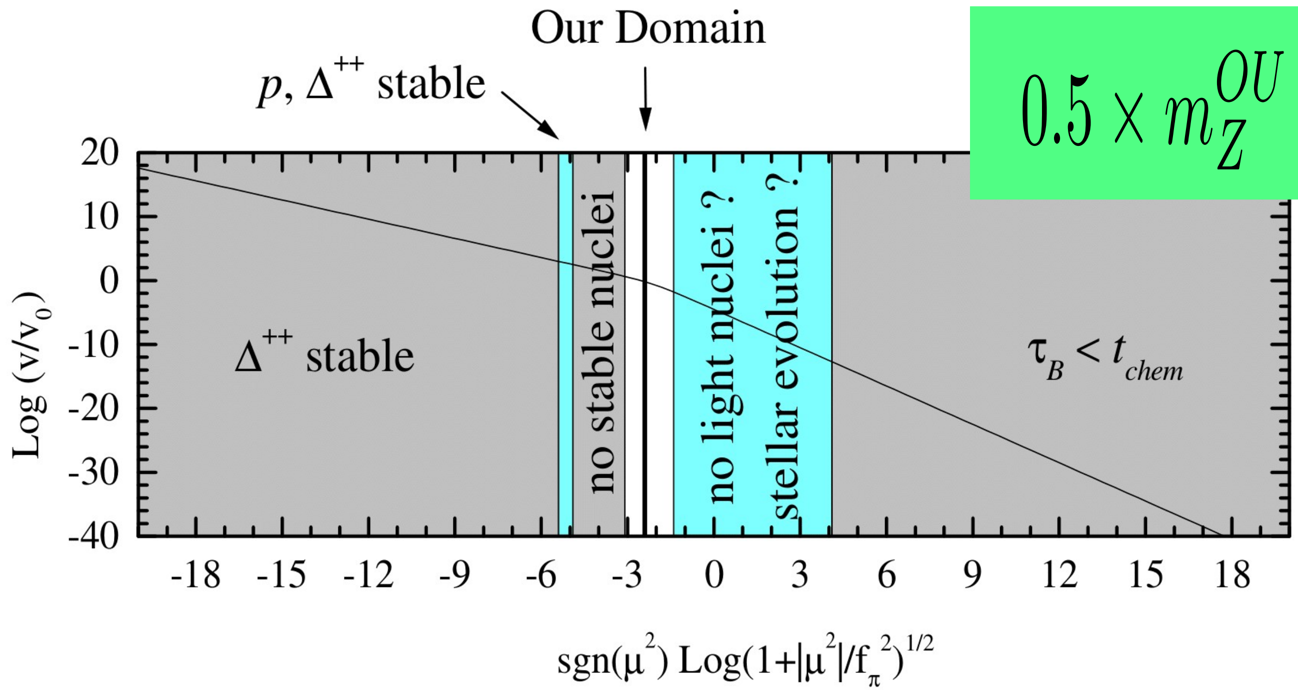

$$0.5 \times m_Z^{OU} \leq m_Z^{PU} \leq 5 \times m_Z^{OU}$$

$$\Delta_{EW} = 30 \longrightarrow \quad 4 \times m_Z^{OU}$$

Agrawal, Barr, Donoghue, Seckel, Phys. Rev. D 57, 5480

Supersymmetry Breaking

$$m_{sparticles} \gg m_{SMparticles}$$

BROKEN IN HIDDEN SECTOR

H. Baer et. al., Cambridge University Press, 2006.

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BROKEN IN HIDDEN SECTOR

SUSY BREAKING EFFECTS MEDIATED TO VISIBLE SECTOR VIA:

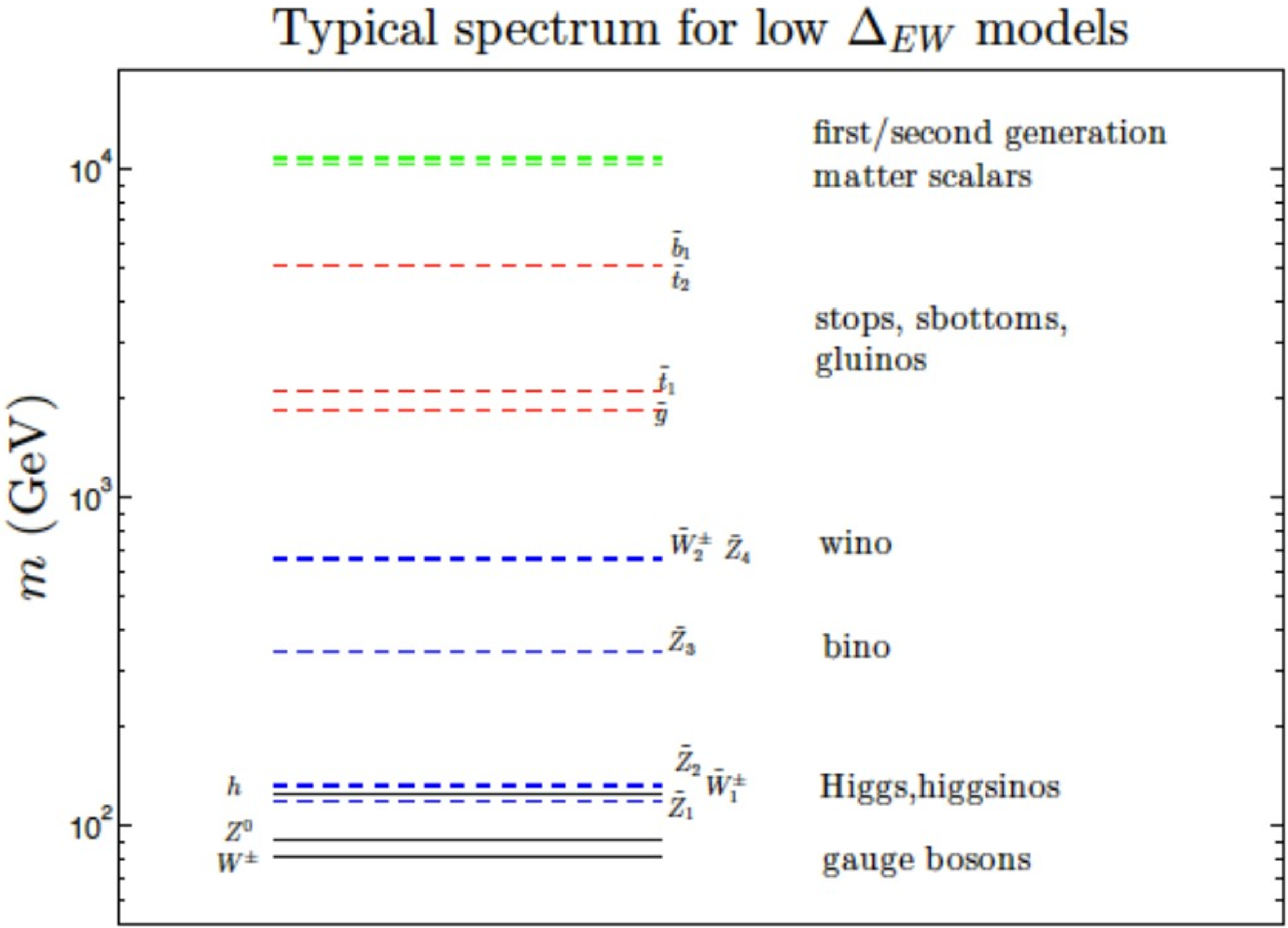
- Gravity-Mediation
- Anomaly-Mediation
- Mirage-Mediation = Anomaly + Gravity Mediation

- Gauge-Mediation
- Gaugino-Mediation

} → **UNNATURAL**

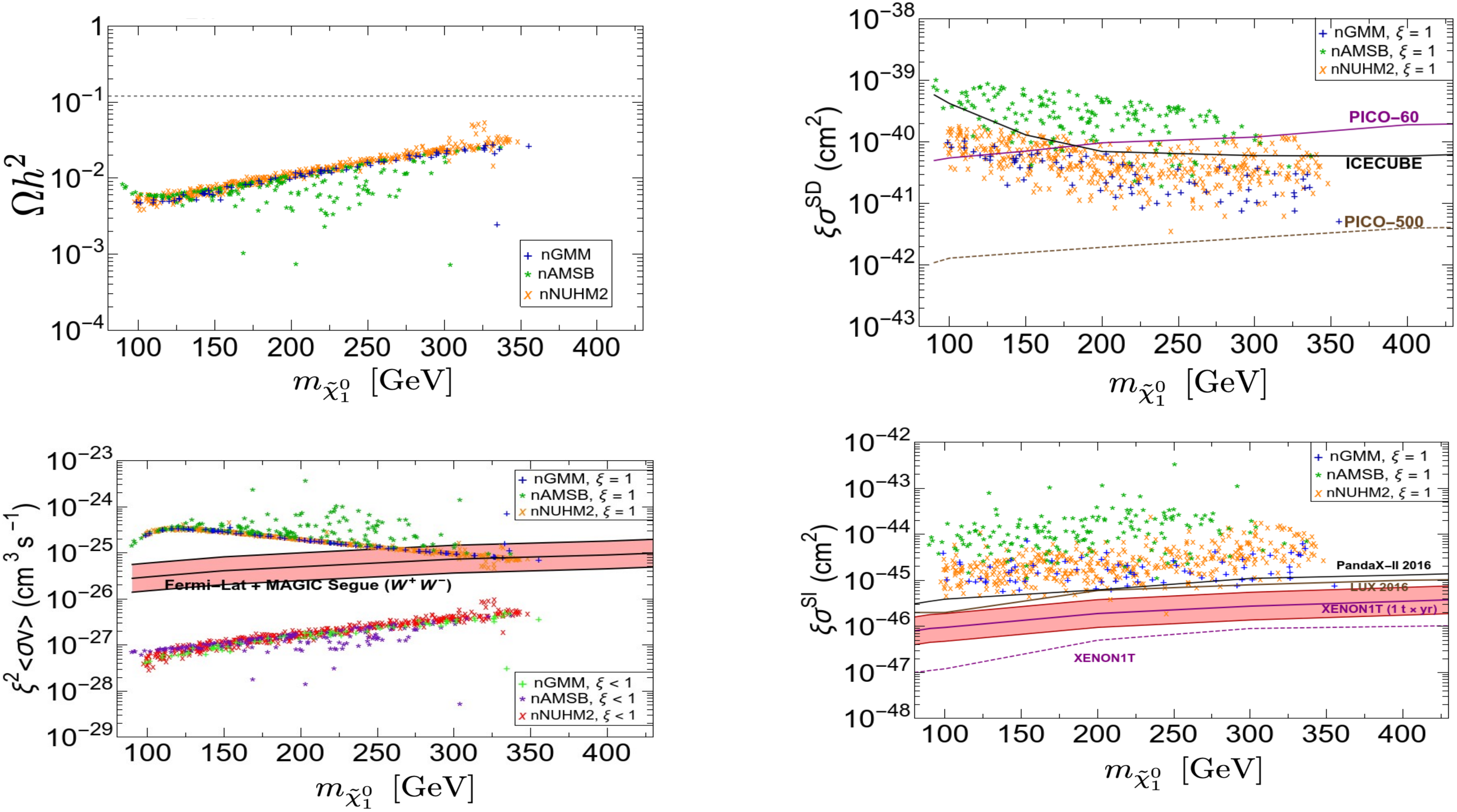
H. Baer et. al., Cambridge University Press, 2006.

Typical Mass Spectra of Natural SUSY Models



Dark Matter in SUSY

$$\Delta_{\rm EW} < 30 \;\&\; 122 < m_h < 128~{\rm GeV}$$

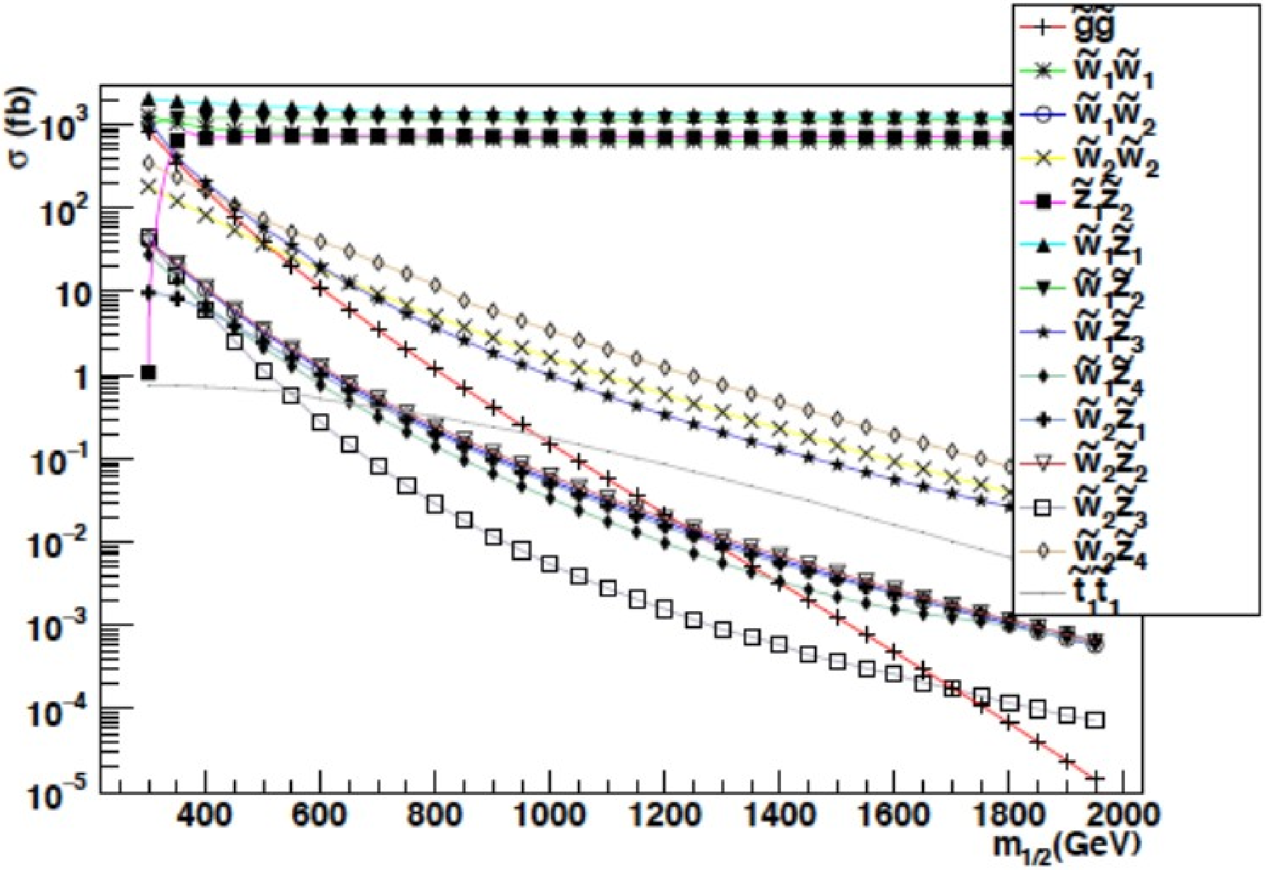


Dark matter = LSP from RPC SUSY+Axion

Baer, Barger, DS, Tata, Eur. Phys. J. C 78 (2018) 10, 838

Sparticles Production at LHC

For a typical natural SUSY model line at $\sqrt{s}$ = 14 TeV



higgsinos

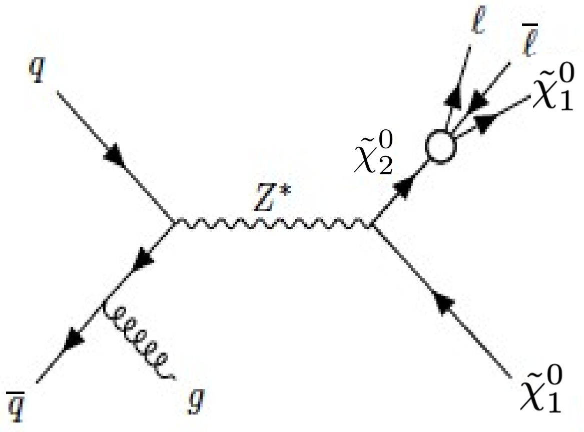
gauginos

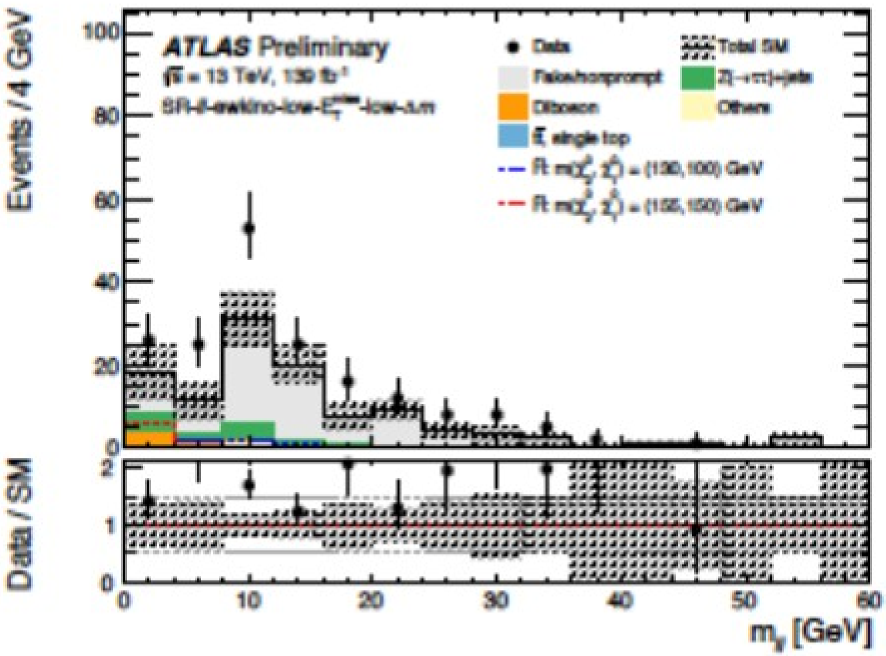
stops

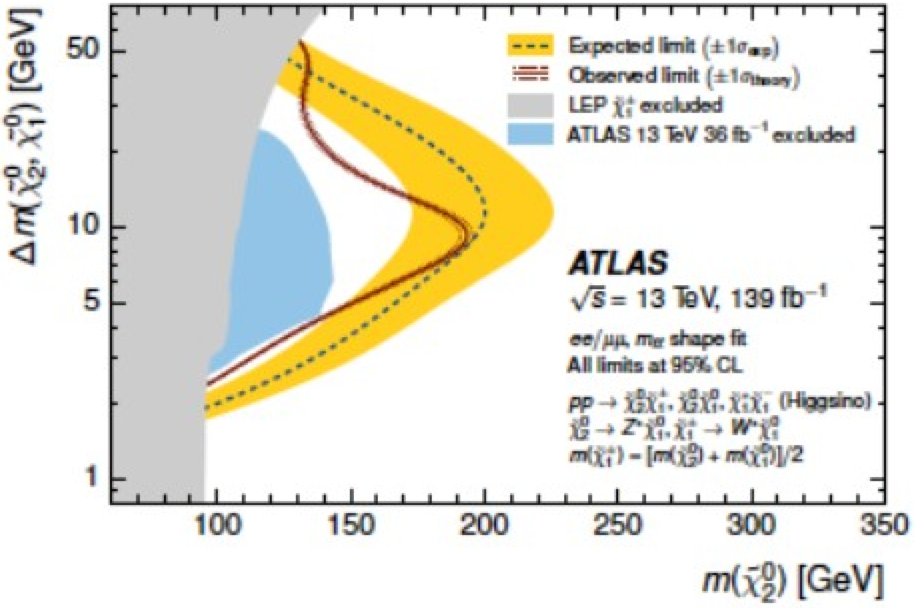
gluinos

Higgsino pair-production dominant but only soft visible energy released from higgsino decays

HL-LHC best bet: Higgsino pair production



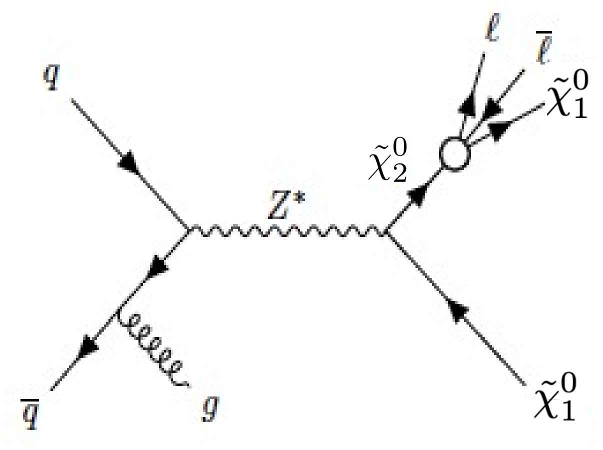




Baer, Barger, Huang, JHEP 11 (2011) 031;
Z. Han, Kribs, Martin, Menon, Phys.Rev.D 89 (2014) 7, 075007;
Baer, Mustafayev, Tata, Phys.Rev.D 90 (2014) 11, 115007;
C. Han, Kim, Munir, Park, JHEP 04 (2015) 132;
Baer, Barger, Savoy, Tata, Phys.Rev.D 94 (2016) 3, 035025;
Baer, Barger, Salam, DS, Tata, Phys.Lett.B 810 (2020) 135777;
Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

signal in this channel should emerge slowly as more integrated luminosity accrues;
both CMS and ATLAS have ~2-sigma excess in this channel: keep watch!

Higgsino Pair-Production at Hl-LHC



SM Backgrounds: $\tau\bar{\tau}j$, $t\bar{t}$, WWj, $W\ell\bar{\ell}j$, $Z\ell\bar{\ell}j$

BENCHMARK POINTS

- BM1 (NUHM2): $m_{\tilde{\chi}_2^0} = 157.6$ GeV, $m_{\tilde{\chi}_1^0} = 145.4$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 12.2$ GeV, $\Delta_{EW} = 13.9$
- BM2 (NUHM2):$m_{\tilde{\chi}_2^0} = 310.1$ GeV, $m_{\tilde{\chi}_1^0} = 293.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 16.4$ GeV, $\Delta_{EW} = 21.7$
- BM3 (GMM'): $m_{\tilde{\chi}_2^0} = 207.0$ GeV, $m_{\tilde{\chi}_1^0} = 202.7$ GeV, $\Delta m = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 4.3$ GeV, $\Delta_{EW} = 26.0$

Despite large cross-section of pair production of higgsinos, the signal is swamped by backgrounds because the decay products are soft. Hence the focus is on monojet + soft dilepton + $\not{E}_T$ signal, triggered by monojet.

Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

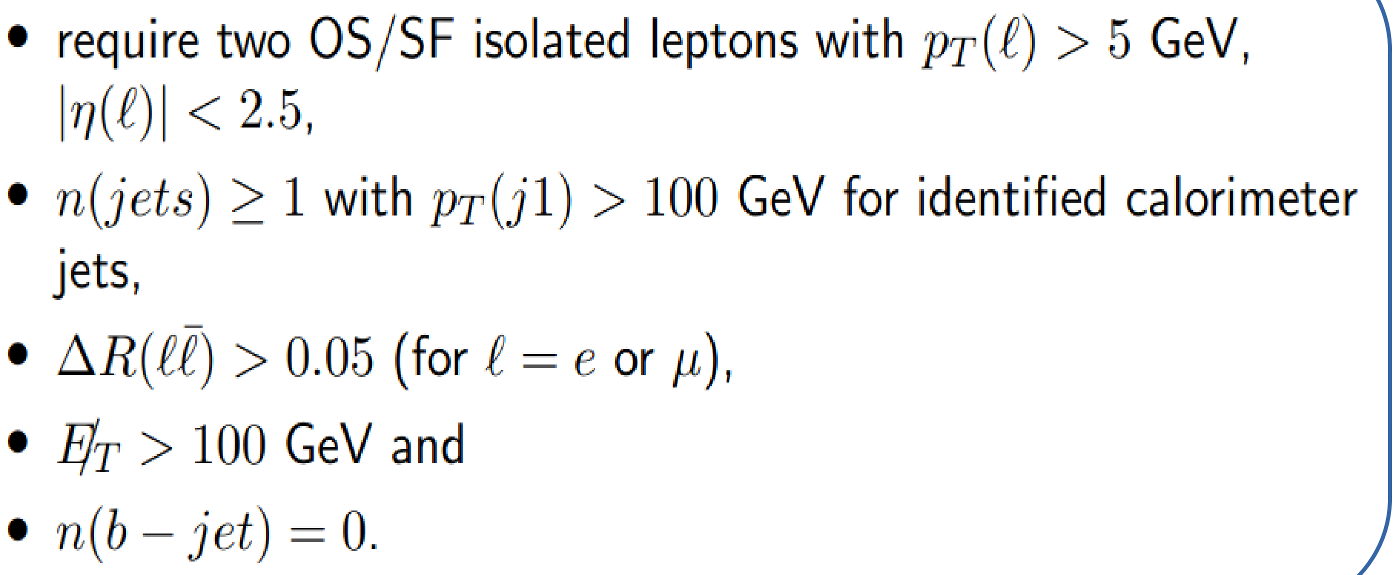
Cuts

BASIC CUTS

$p_T(j) >$ 80 GeV, $p_T(\ell) >$ 1 GeV, $\Delta R(\ell\bar{\ell}) >$ 0.01,

$m(\ell\bar{\ell}) >$ 1 GeV for the backgrounds $\gamma^*, Z^* \to \ell\bar{\ell}$

C1-Cuts



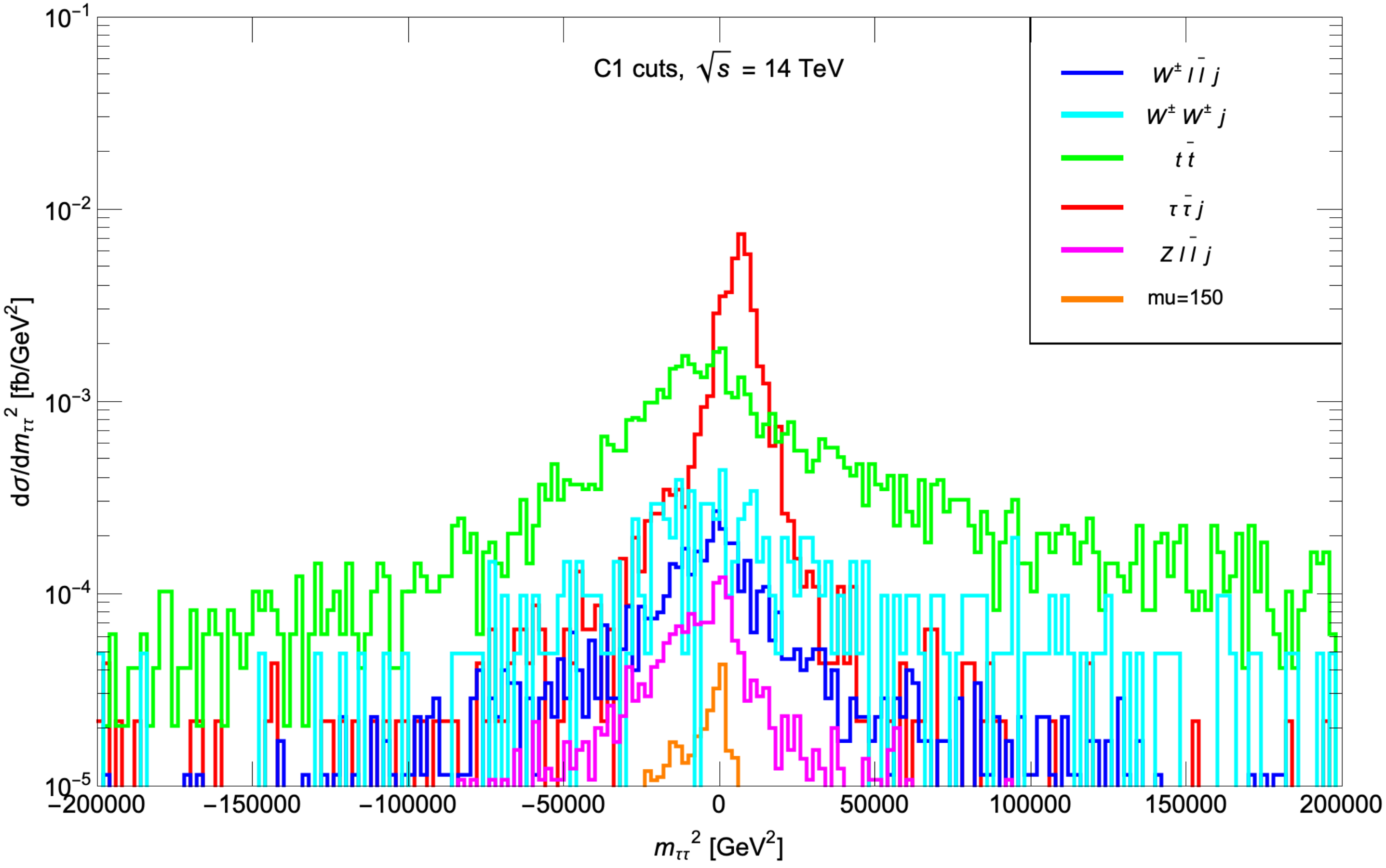
- require two OS/SF isolated leptons with $p_T(\ell) > 5$ GeV, $|\eta(\ell)| < 2.5$,
- $n(jets) \geq 1$ with $p_T(j1) > 100$ GeV for identified calorimeter jets,
- $\Delta R(\ell\bar{\ell}) > 0.05$ (for $\ell = e$ or μ),
- $\not{E}_T > 100$ GeV and
- $n(b - jet) = 0$.

Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Cuts

$$m_{\tau\tau}^2 = (1+\xi_1)(1+\xi_2)m_{\ell\ell}^2$$

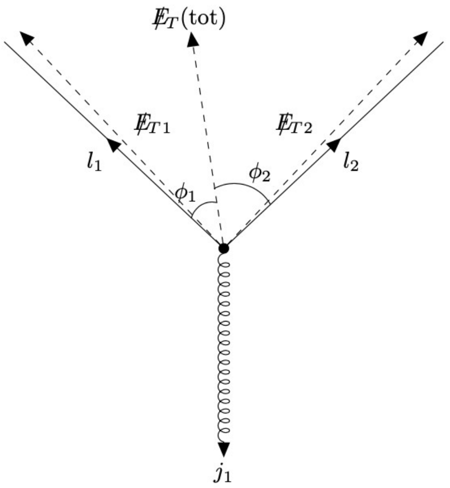
$$-\sum_{jets}\vec{p}_T(j) = (1+\xi_1)\vec{p}_T(\ell_1) + (1+\xi_2)\vec{p}_T(\ell_2)$$

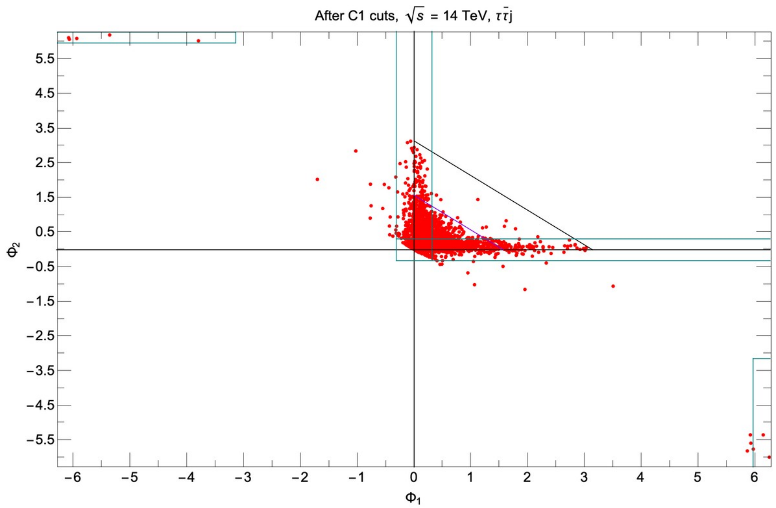


$m_{\tau\tau}^2 < 0$

Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Angle Cuts

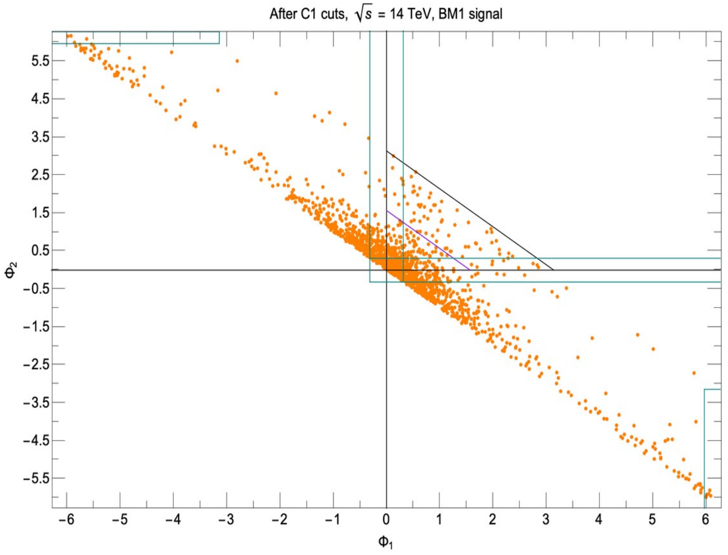


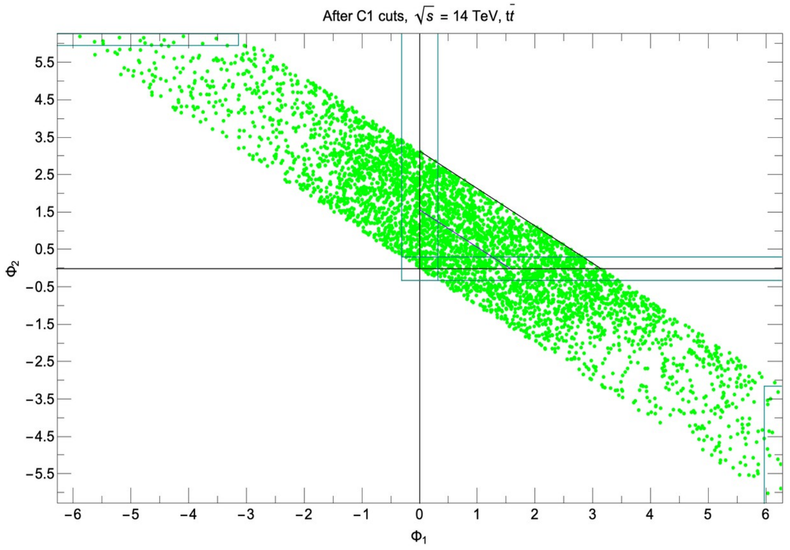

After C1 cuts, $\sqrt{s}$ = 14 TeV, $\tau\bar{\tau}j$

Veto: φ_1, φ_2 > 0,
$\varphi_1 + \varphi_2 < \pi/2$

Veto: $|\varphi_{1,2}| < \pi/10$

Veto: Corner strips


After C1 cuts, $\sqrt{s}$ = 14 TeV, BM1 signal


After C1 cuts, $\sqrt{s}$ = 14 TeV, $t\bar{t}$

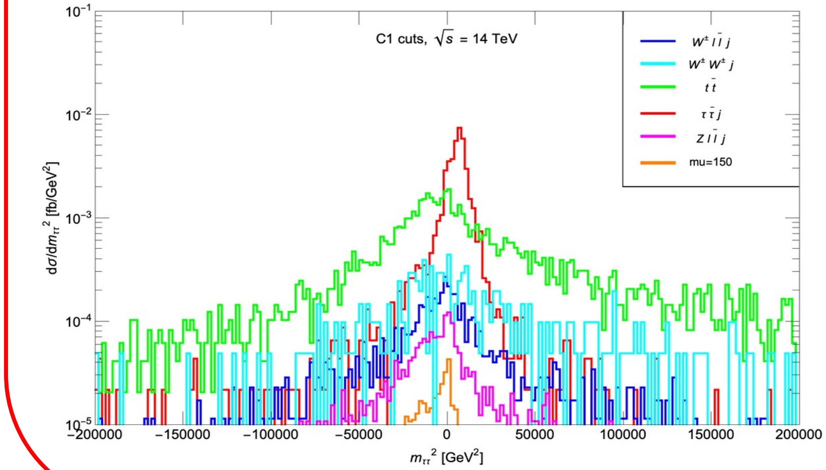
Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Cuts

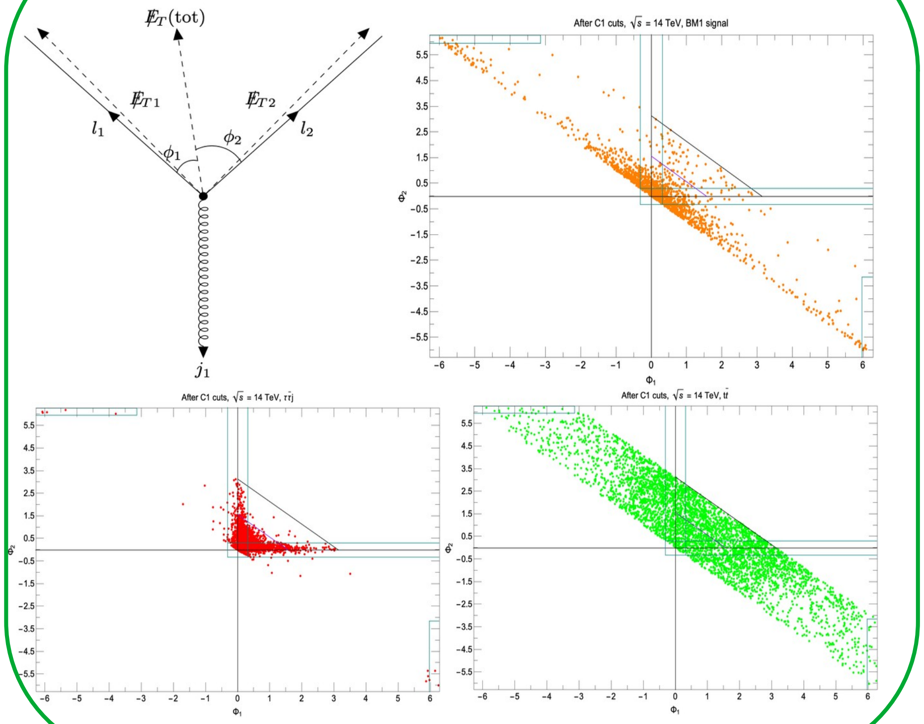
$m^2_{\tau\tau}$

$$m^2_{\tau\tau} = (1+\xi_1)(1+\xi_2)m^2_{\ell\ell}$$

$$-\sum_{jets} \vec{p}_T(j) = (1+\xi_1)\vec{p}_T(\ell_1) + (1+\xi_2)\vec{p}_T(\ell_2)$$



Angle Cuts



cuts/process	$BM1$	$BM2$	$BM3$ GMM'	$\tau\bar{\tau}j$	$t\bar{t}$	WWj	$W\ell\bar{\ell}j$	$Z\ell\bar{\ell}j$
BC	83.1	9.3	31.3	43800.0	41400	9860.0	1150.0	311
$C1$	1.2	0.19	0.07	94.2	179	35.9	14.7	5.9
$C1 + m^2_{\tau\tau} < 0$	0.92	0.13	0.043	23.1	75.6	12.8	7.7	3.2
$C1 + angle$	0.68	0.12	0.04	1.8	130	22	11.0	4.9

Table: Cross sections (in fb) for signal benchmark points and the various SM backgrounds listed in the text after various cuts.

Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Cuts

C3-Cuts

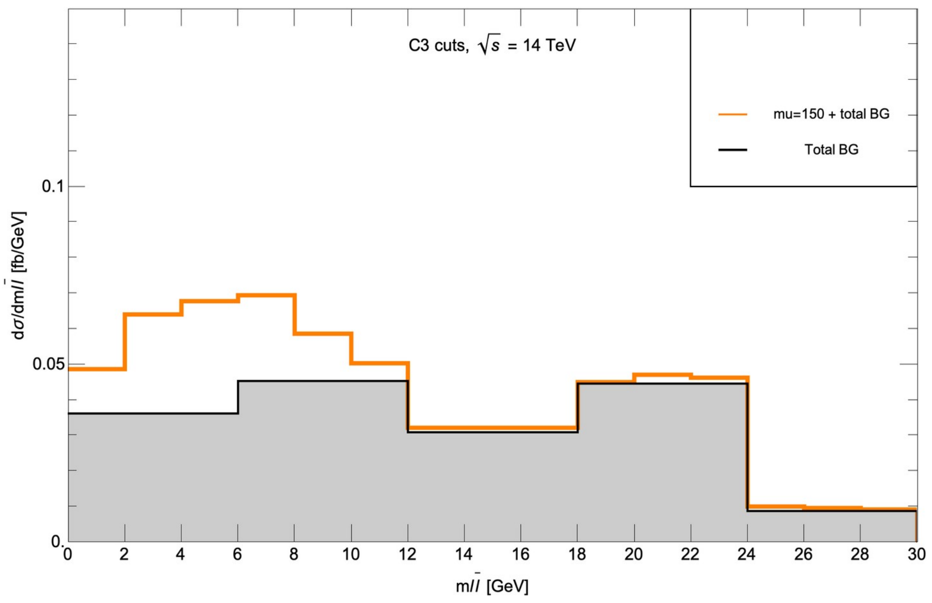
- **C1** plus angle cuts
- $p_T(\ell_2) : 5 - 15$ GeV
- $\not{E}_T / H_T(\ell\bar{\ell}) > 4$,
- $n(jets) = 1$
- $H_T(\ell\bar{\ell}) < 60$ GeV
- $m(\ell\bar{\ell}) < 50$ GeV
- $\Delta\phi(j1, \not{E}_T) > 2.0$
- $m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV
- $p_T(j1)/\not{E}_T < 1.5$
- $|p_T(j1) - \not{E}_T| < 100$ GeV

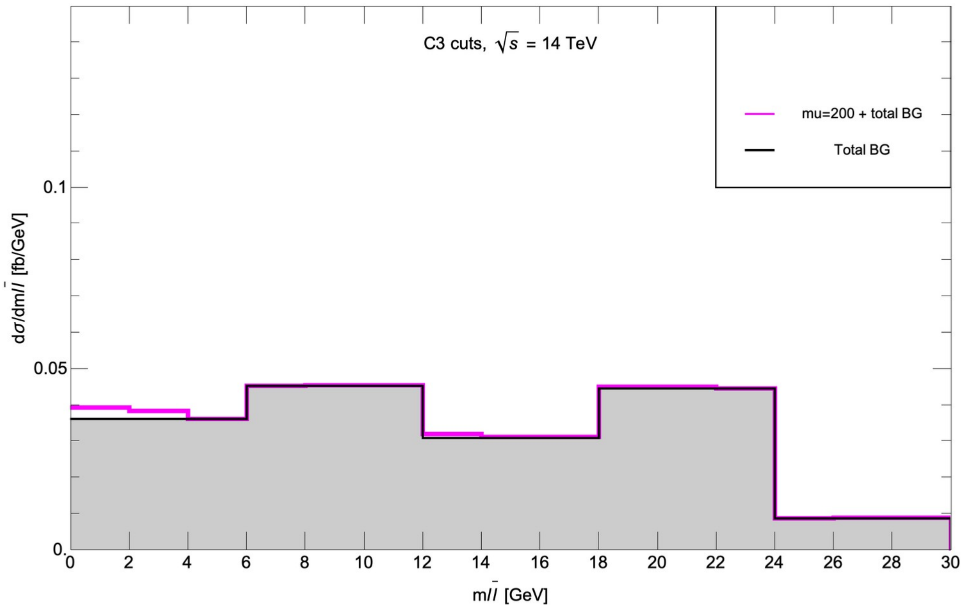
Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

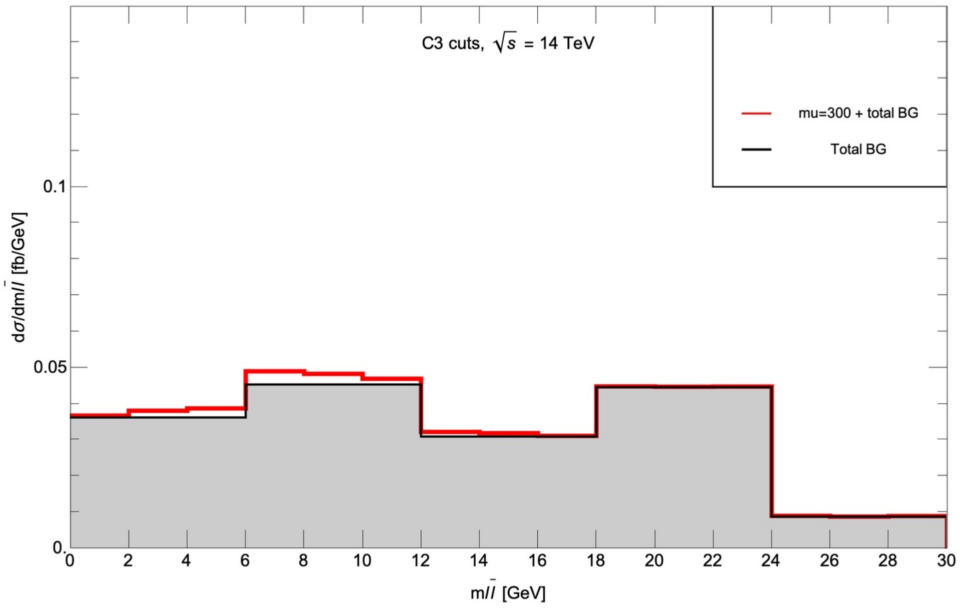
Cuts

C3-Cuts

- **C1** plus angle cuts
- $p_T(\ell_2)$: 5 – 15 GeV
- $\not{E}_T/H_T(\ell\bar{\ell}) > 4$,
- $n(jets) = 1$
- $H_T(\ell\bar{\ell}) < 60$ GeV
- $m(\ell\bar{\ell}) < 50$ GeV
- $\Delta\phi(j1, \not{E}_T) > 2.0$
- $m_{cT}(\ell\bar{\ell}, \not{E}_T) < 100$ GeV
- $p_T(j1)/\not{E}_T < 1.5$
- $|p_T(j1) - \not{E}_T| < 100$ GeV

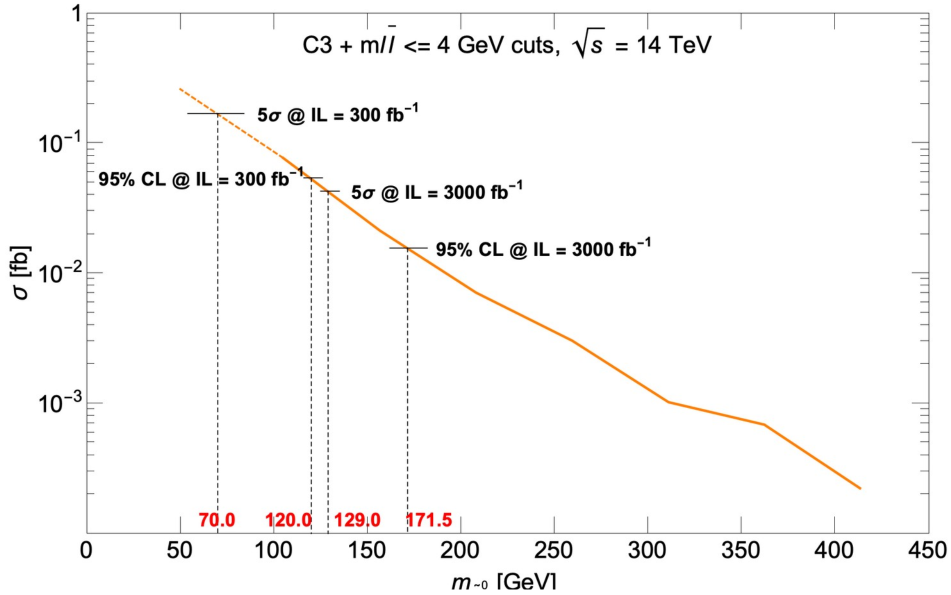


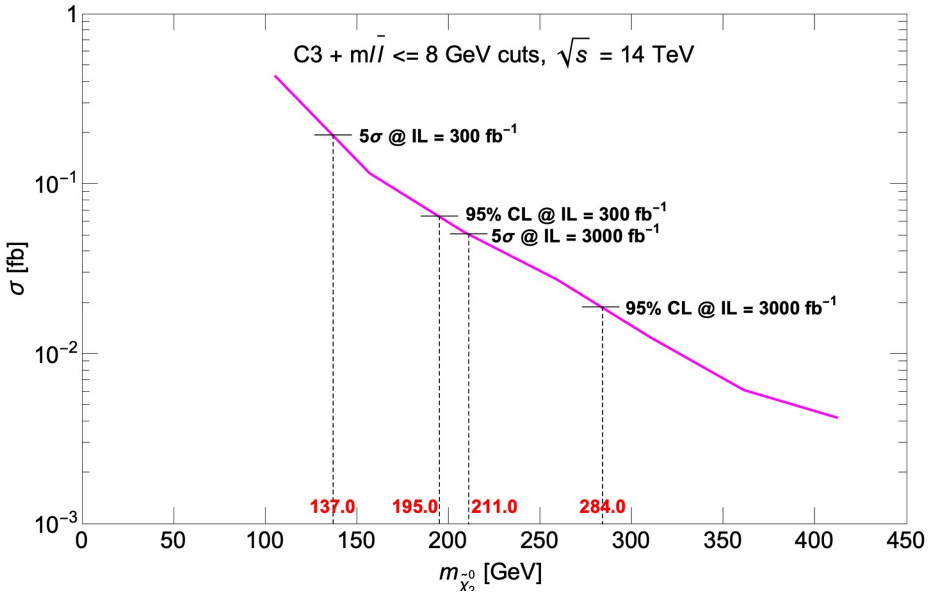


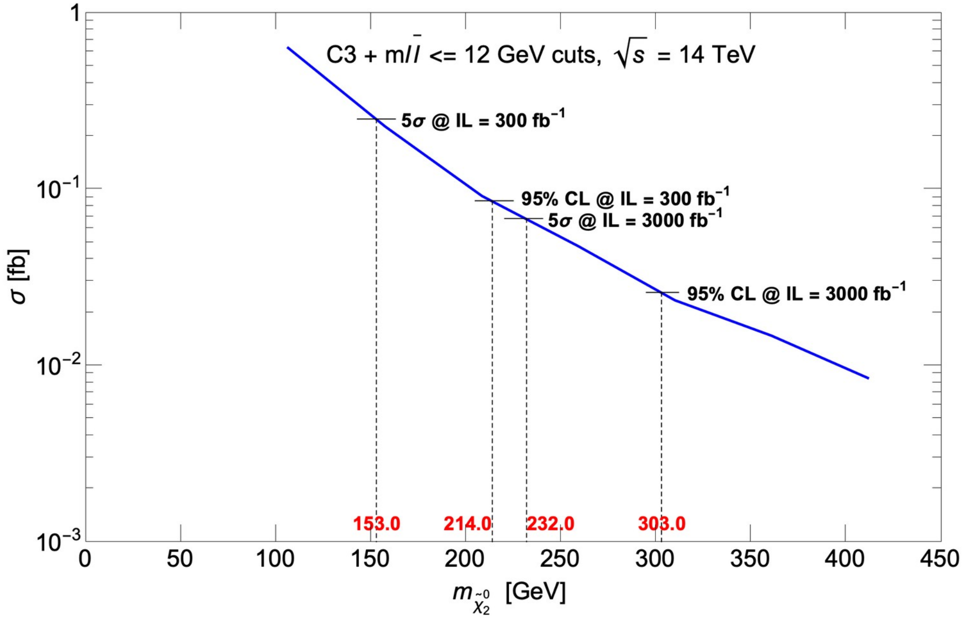


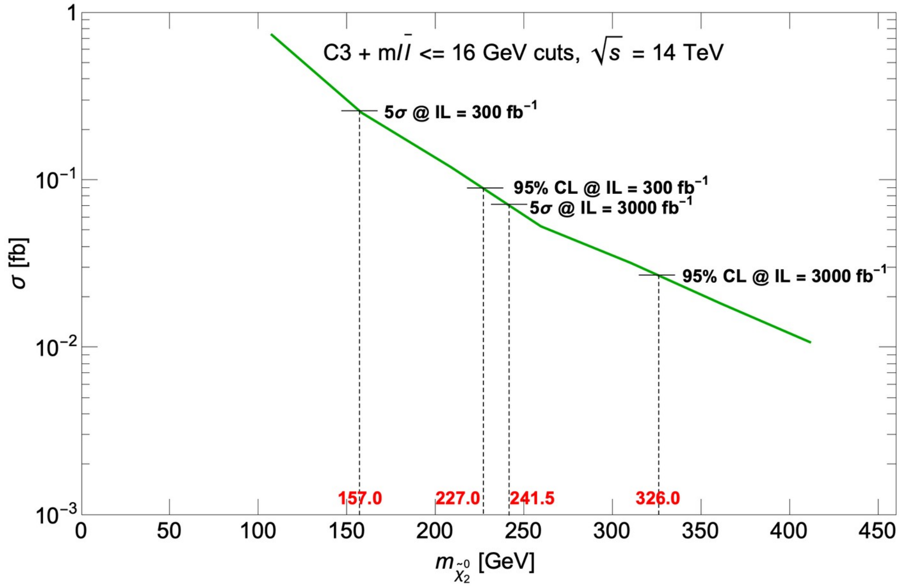
Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Mass Reach





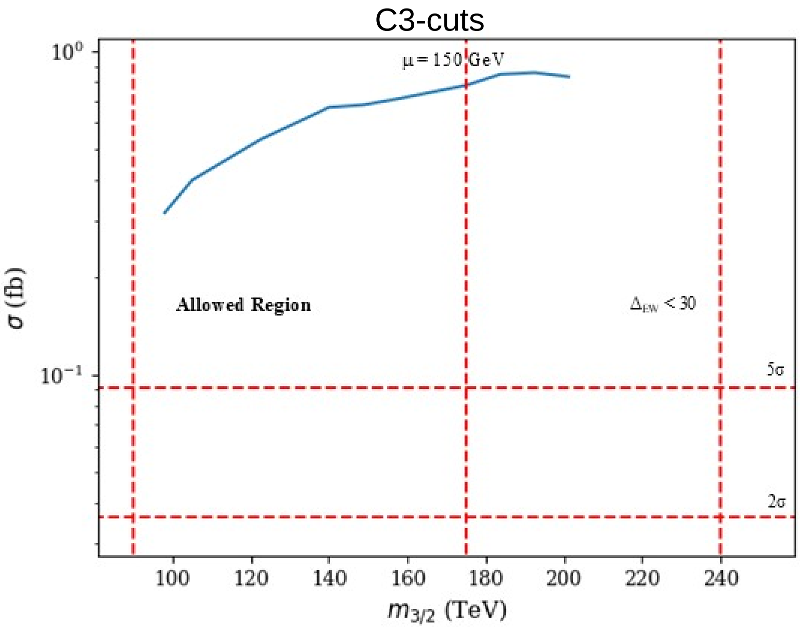


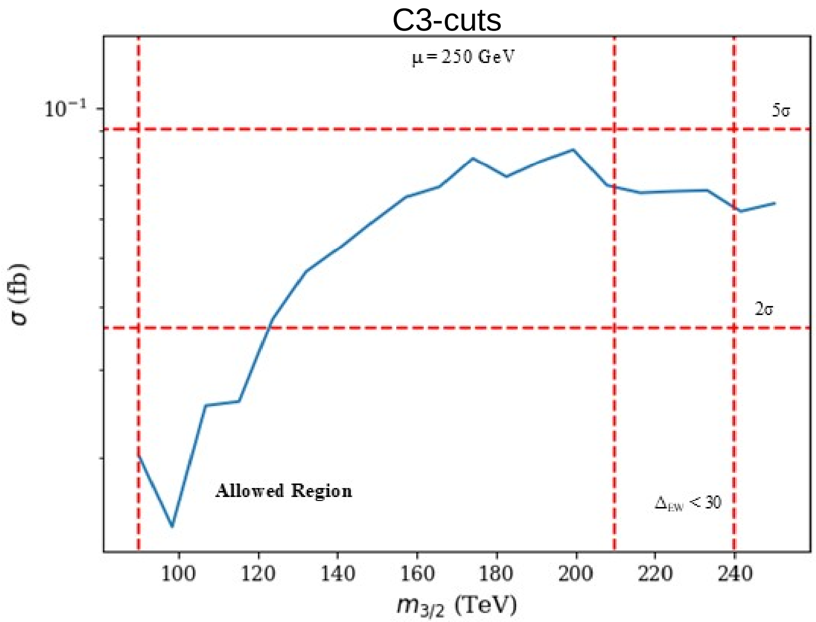


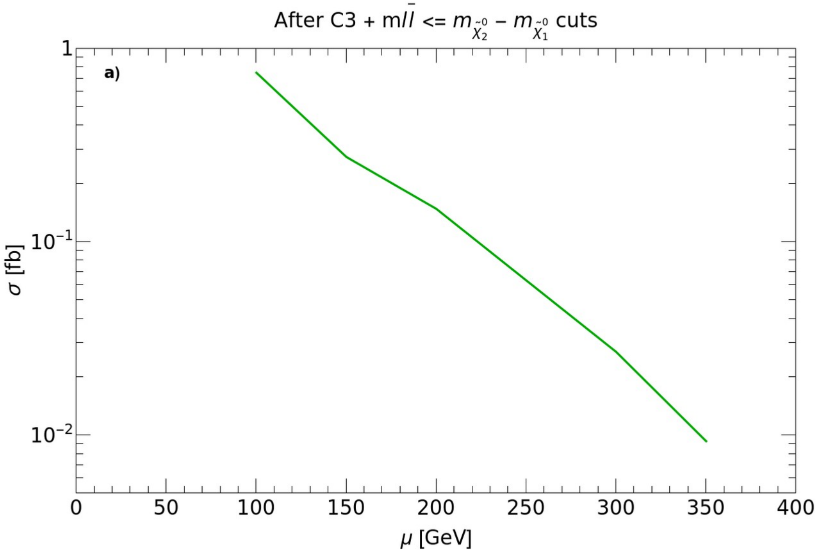
Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

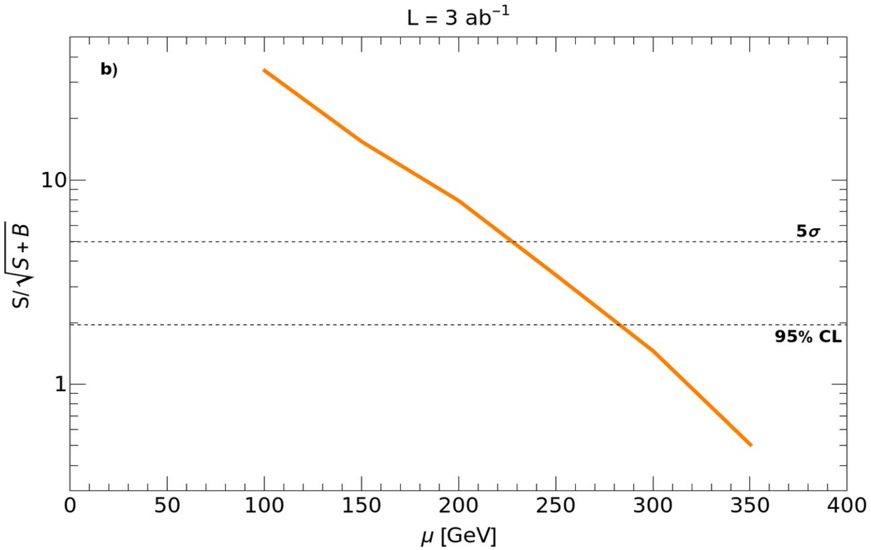
Mass Reach (nAMSB model)

Model Line: $m_0\left(3\right) = m_{3/2}/35, m_0\left(1,2\right) = 2m_0\left(3\right), A_0 = 1.2m_0\left(3\right), tan\beta = 10, m_A = 2TeV$


C3-cuts

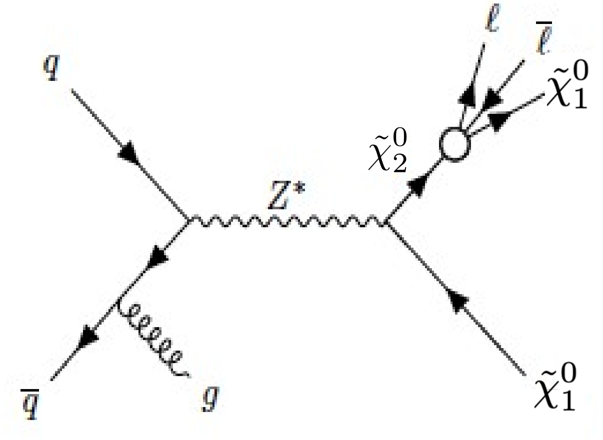

C3-cuts

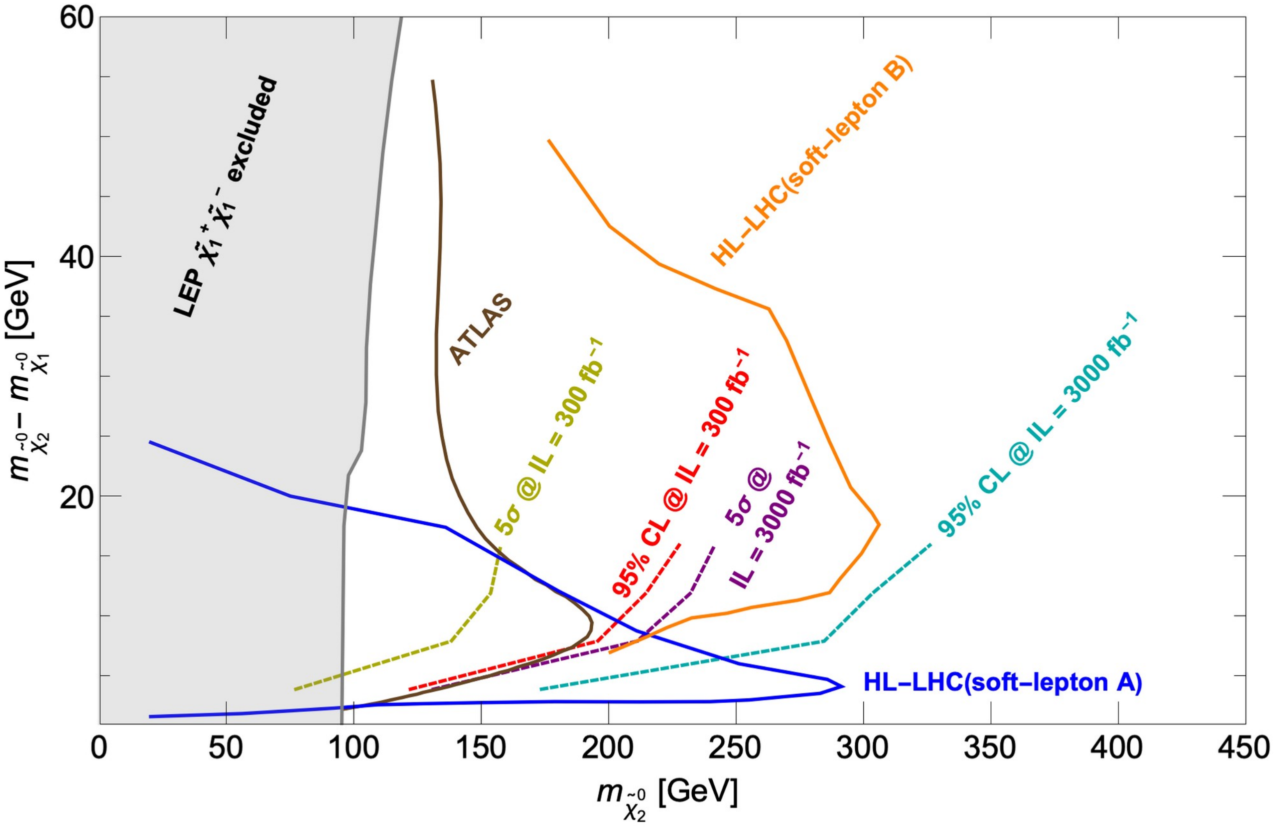

After C3 + $m_{l\bar{l}} <= m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ cuts


L = 3 ab^{-1}

Baer, Barger, Bolich, Dutta, DS 2408.03276

Higgsino Pair-Production at LHC



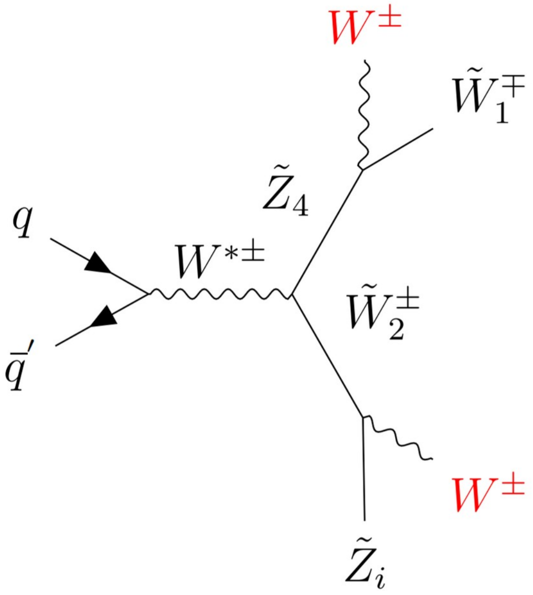


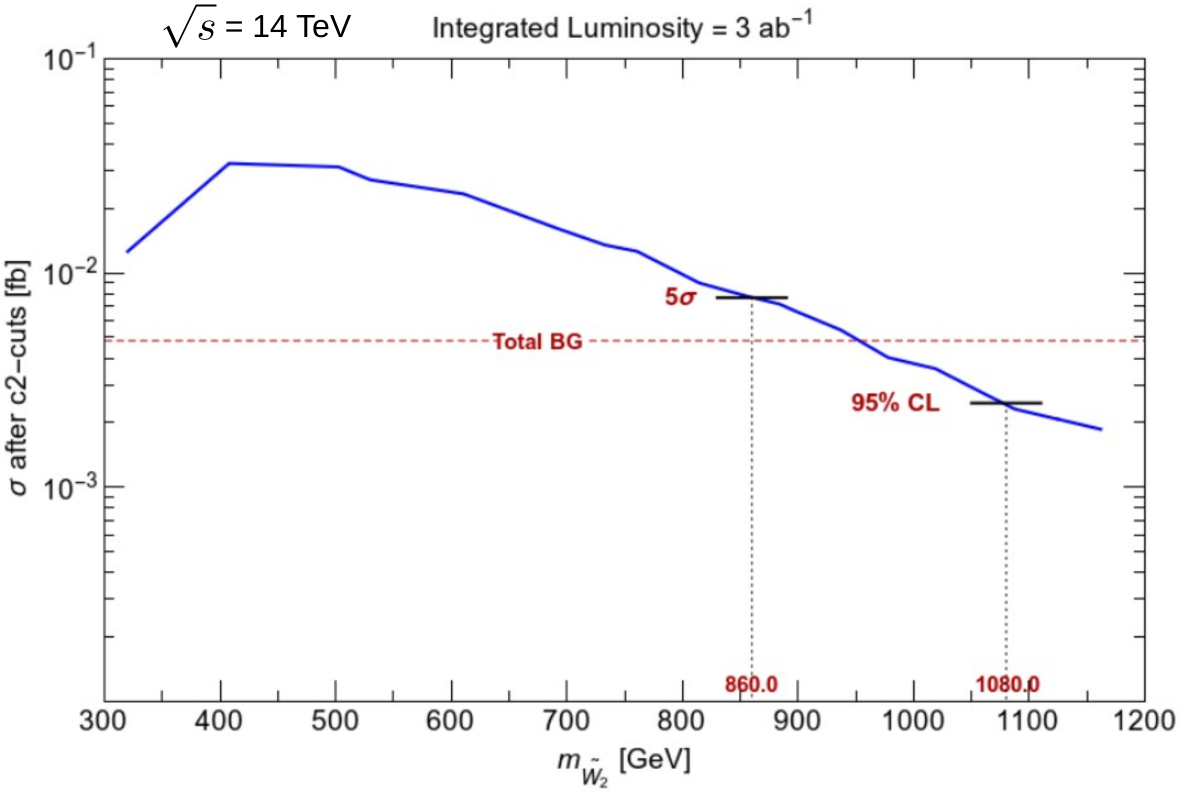
Natural SUSY: Higgsinos almost fully covered by HL-LHC

Baer, Barger, DS, Tata, Phys. Rev. D 105 (2022) 9, 095017

Wino Pair-Production at HL-LHC

Distinctive new same-sign diboson (SSdB) for natural SUSY models with light higgsinos

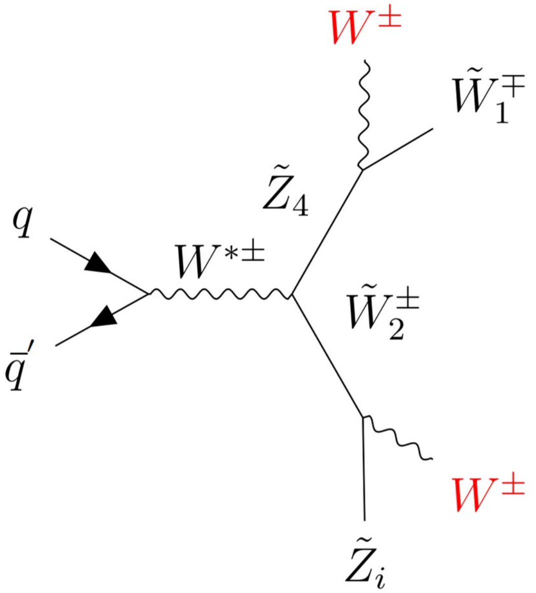


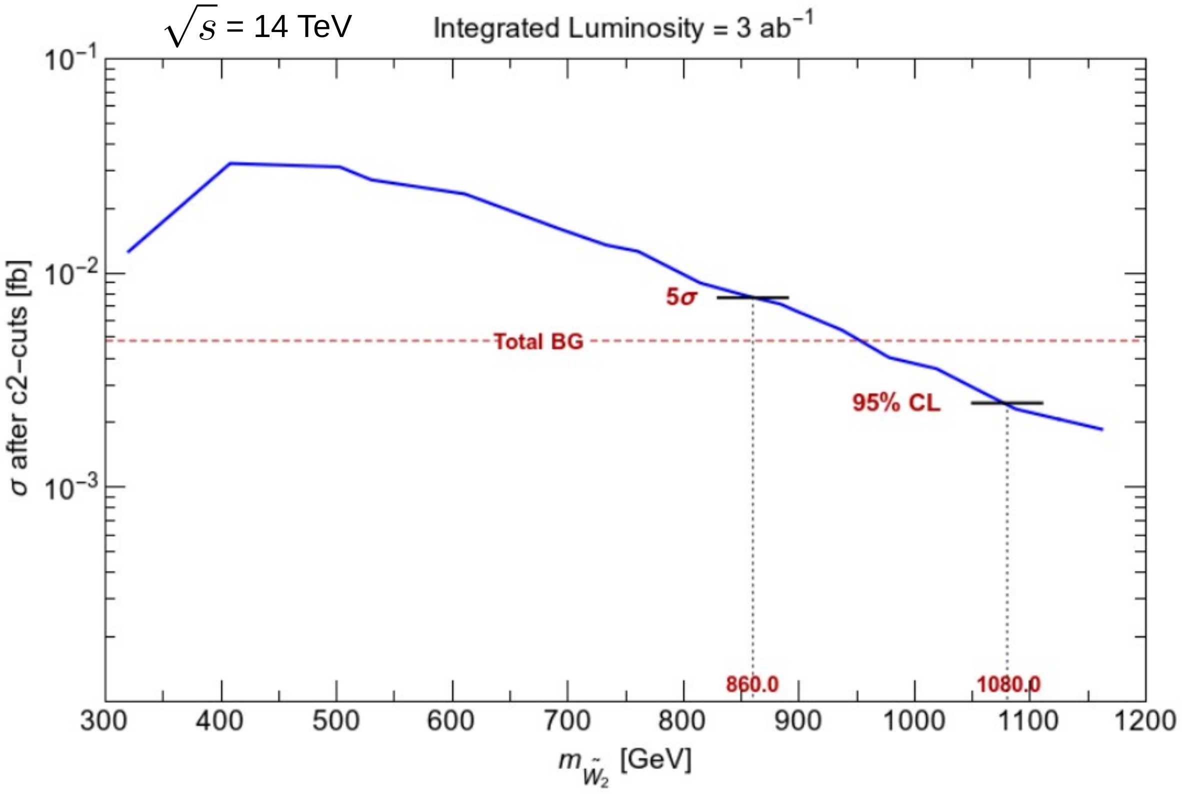


Baer, Barger, Gainer, Savoy, DS, Tata, Phys.Rev.D 97 (2018) 3, 035012

Wino Pair-Production at HL-LHC

Distinctive new same-sign diboson (SSdB) for natural SUSY models with light higgsinos

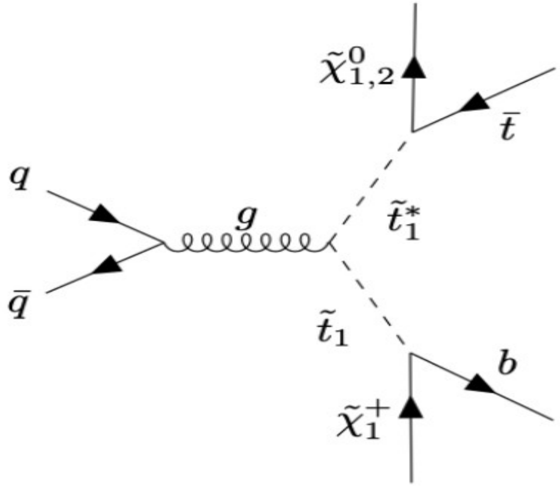




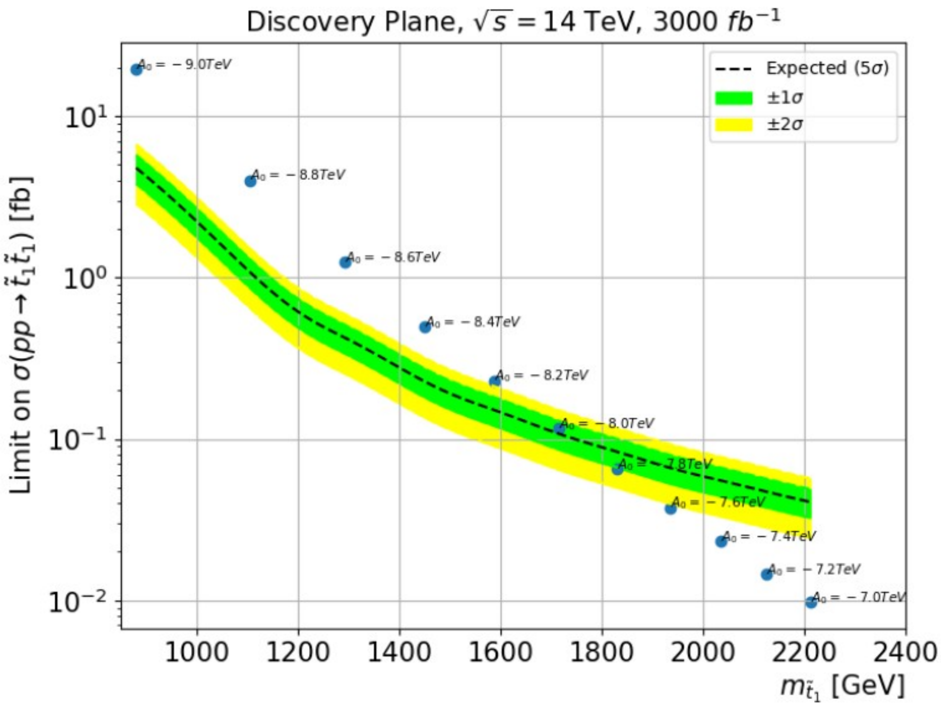
HL-LHC can see m(wino) followed by decay to light higgsinos ~0.8-1.1 TeV @5sigma/ 95% CL

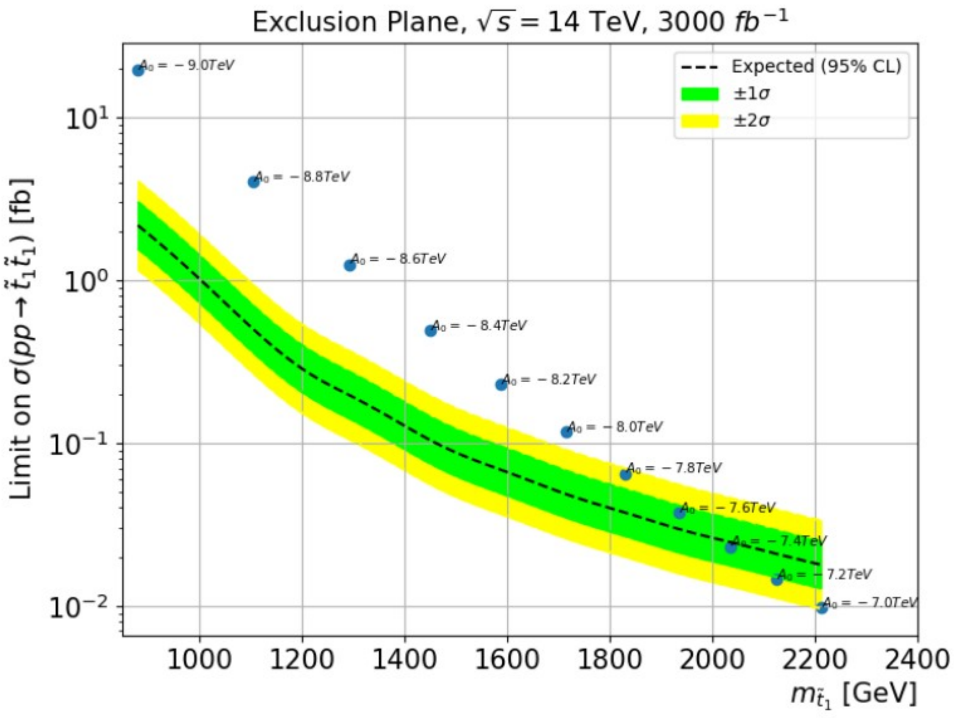
Baer, Barger, Gainer, Savoy, DS, Tata, Phys.Rev.D 97 (2018) 3, 035012

Top squark searches



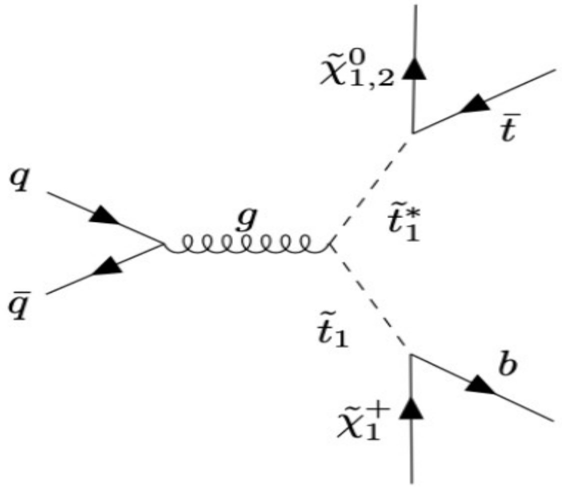
Model Line: $m_0 = 5$ TeV, $m_{1/2} = 1.2$ TeV, $tan\,\beta = 10$,
$\mu = 250$ GeV, $m_A = 2$ TeV,
$A_0 =$ -7 TeV to -9 TeV





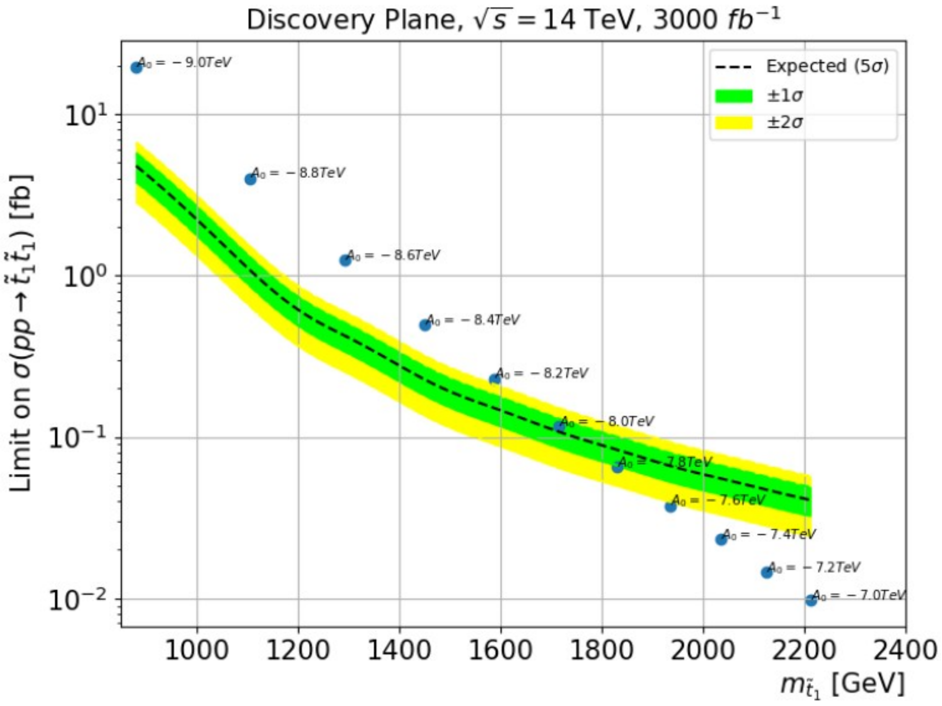
Baer, Barger, Dutta, DS, Zhang, Phys.Rev.D 108 (2023) 7

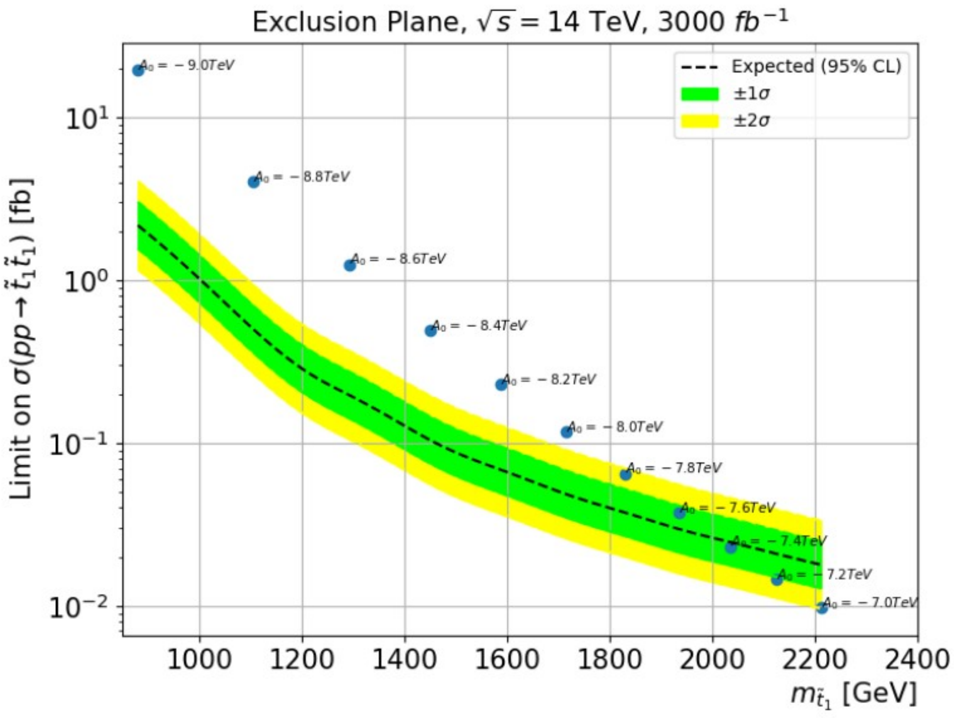
Top squark searches



Model Line: $m_0 = 5$ TeV, $m_{1/2} = 1.2$ TeV, $tan\,\beta = 10$,
$\mu = 250$ GeV, $m_A = 2$ TeV,
$A_0 =$ -7 TeV to -9 TeV

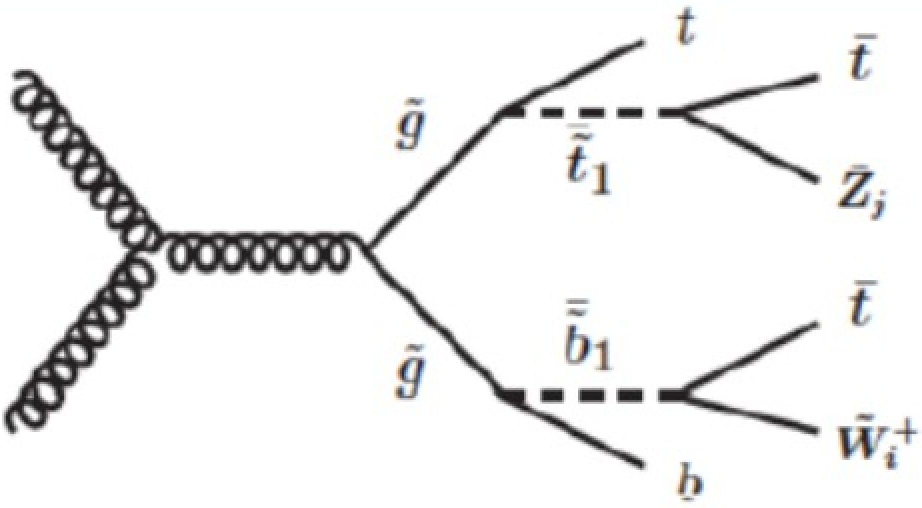
HL-LHC can see m(t1)~1.7-2 TeV @5sigma/ 95% CL


Discovery Plane, $\sqrt{s} = 14$ TeV, 3000 fb^{-1}

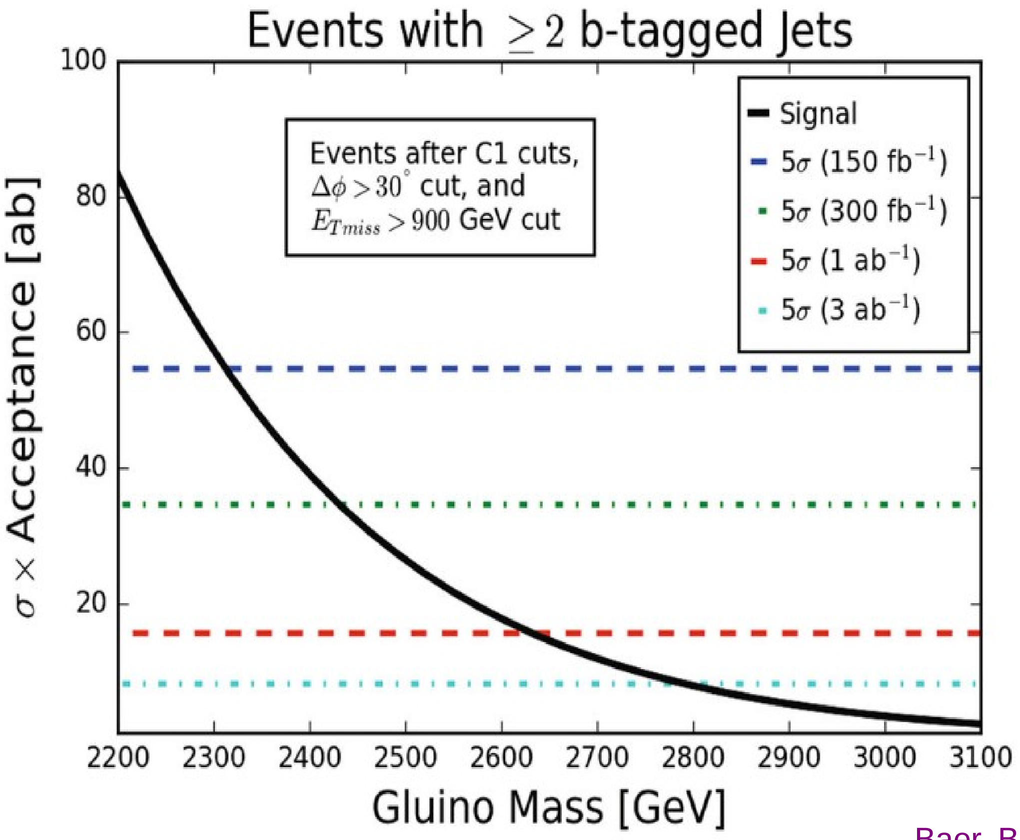

Exclusion Plane, $\sqrt{s} = 14$ TeV, 3000 fb^{-1}

Baer, Barger, Dutta, DS, Zhang, Phys.Rev.D 108 (2023) 7

Gluino pair cascade decay signatures



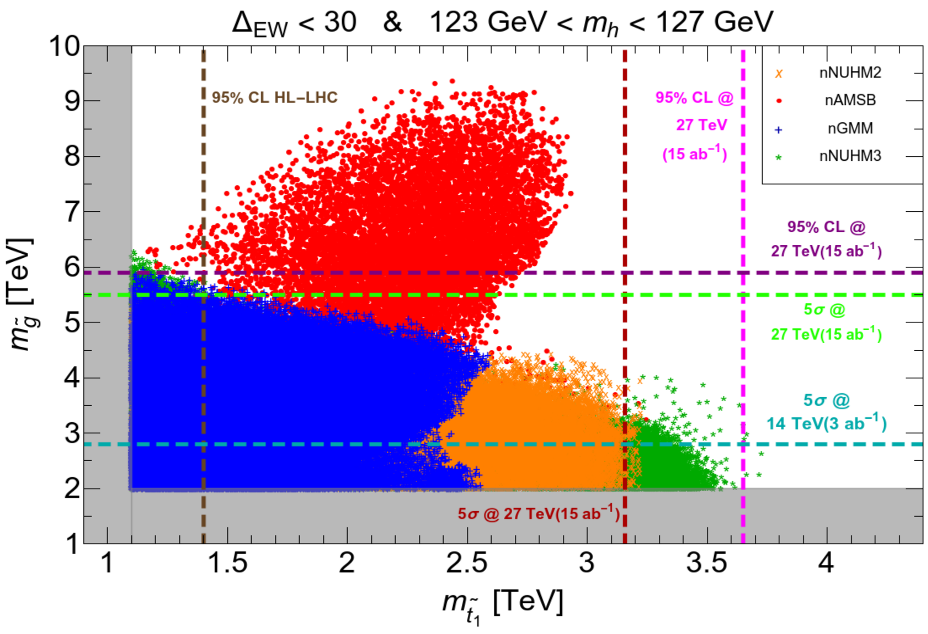
$\sqrt{s}$ = 14 TeV

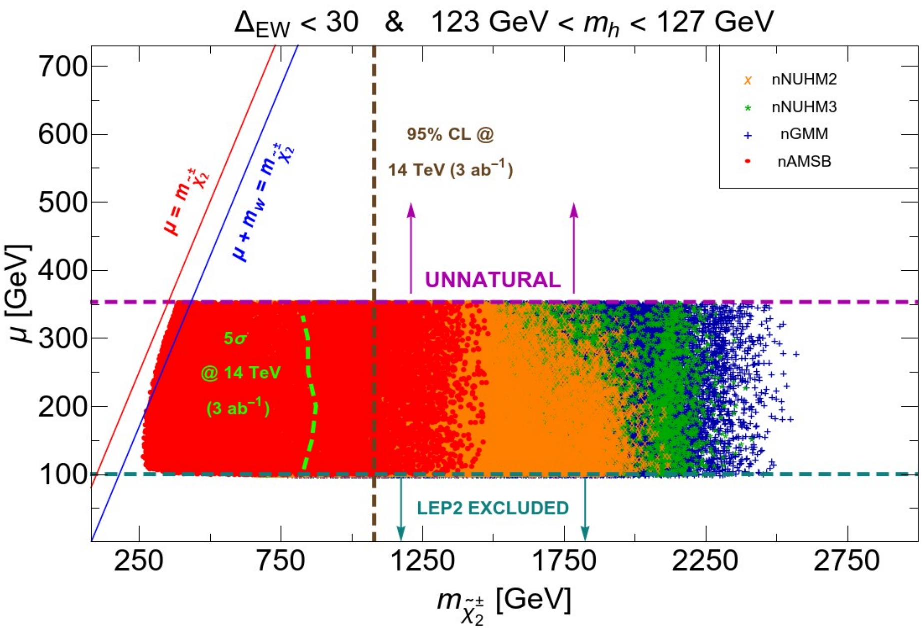


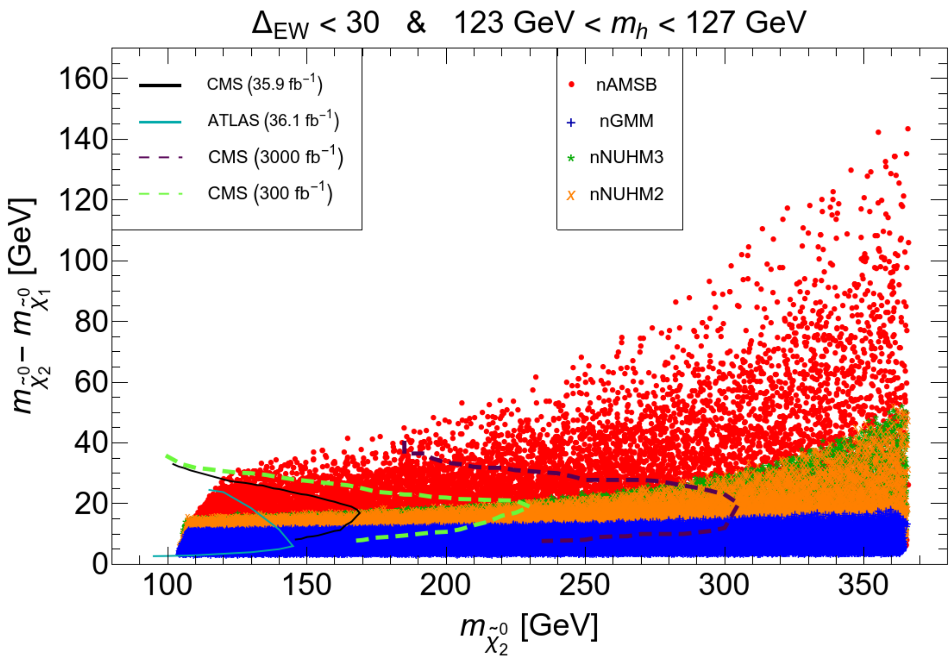
HL-LHC to probe m(gl)~2.8 TeV
FCC-hh(100) to probe m(gl)~10 TeV

Baer, Barger, Gainer, Huang, Savoy, DS, Tata, Eur.Phys.J.C 77 (2017) 7, 499

LHC Confronts SUSY







Exploration of Parameter Space of Natural Supersymmetric models

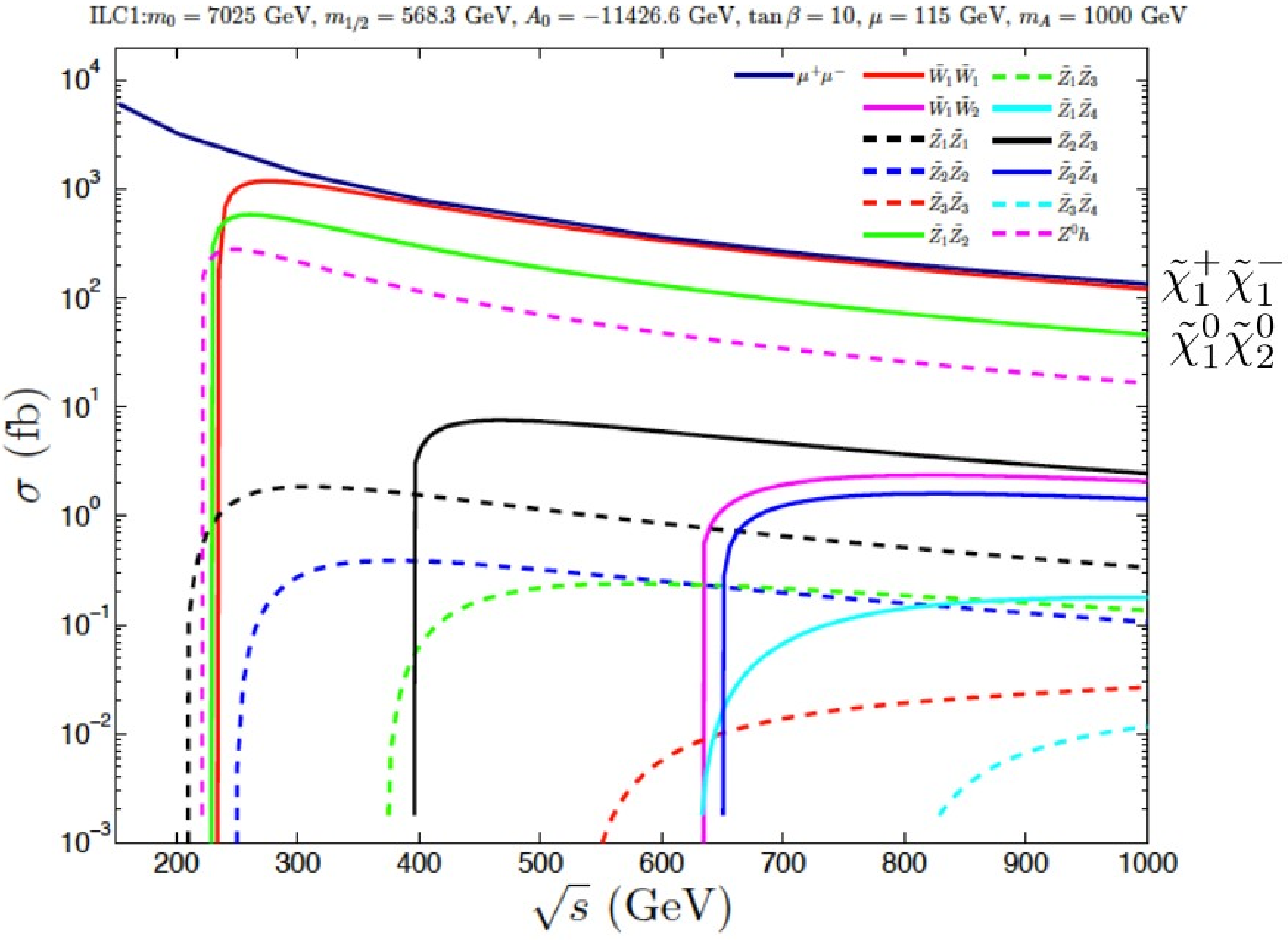
Higgsinos at HL-LHC

Gluinos and top squarks and winos at FCC-hh

European strategy update report in 2018

Baer, Barger, Gainer, DS, Serce Phys. Rev. D 98 (2018) 7, 075010

Smoking gun signature: Light higgsinos at ILC

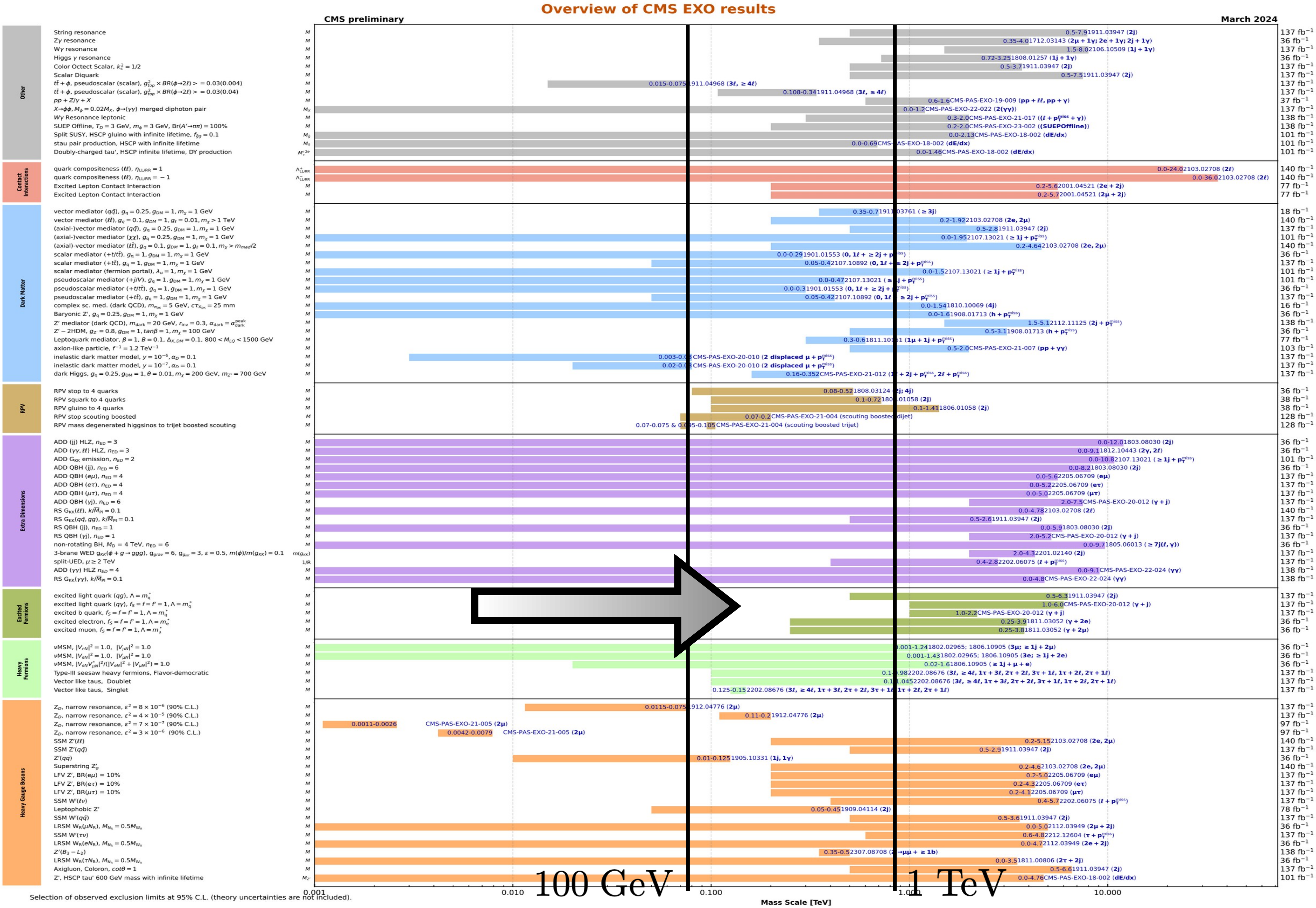


$\sigma_{\text{(higgsino)}} >> \sigma_{\text{(Zh)}}$

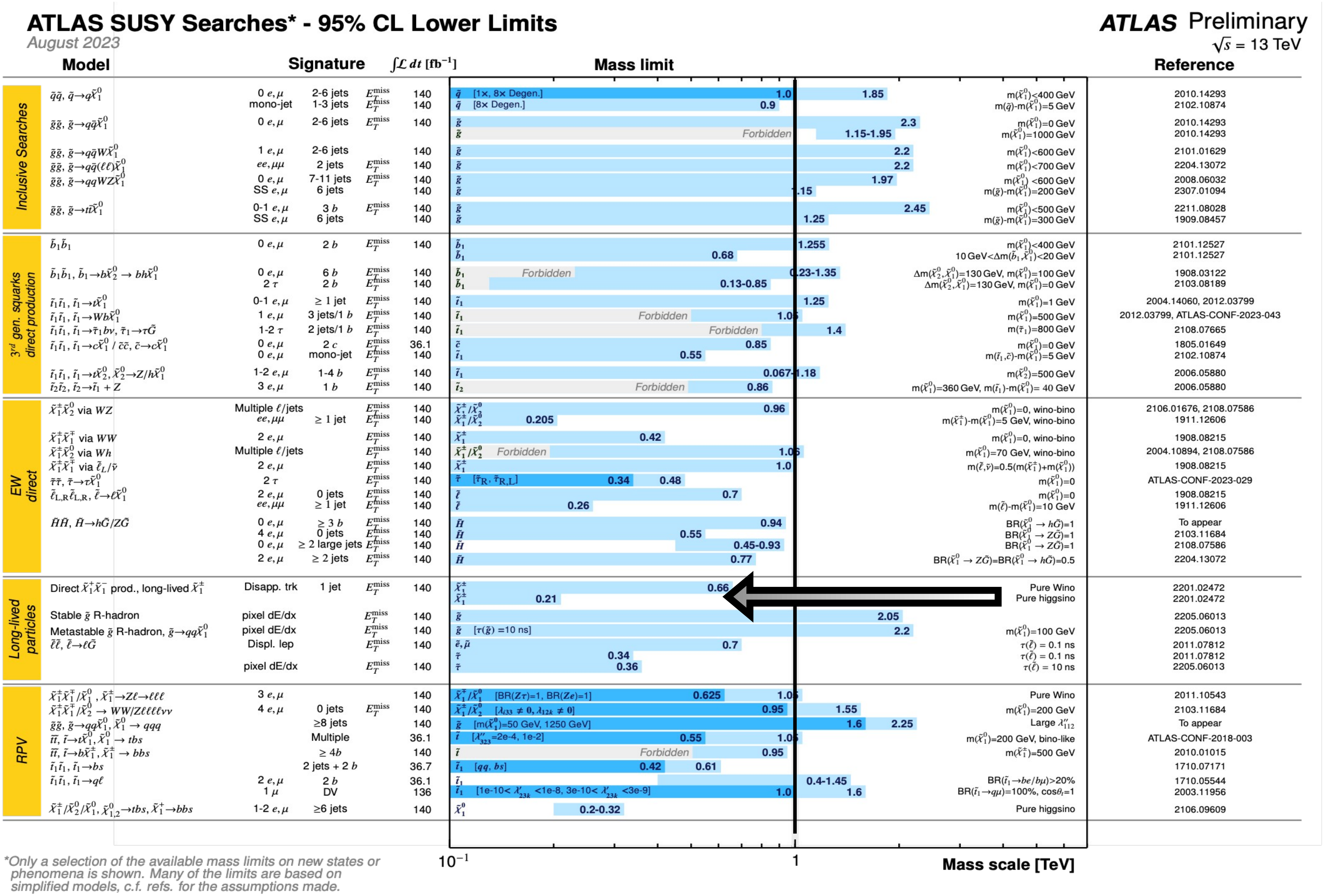
3-15 GeV higgsino mass gaps
no problem in clean ILC environment

Baer, Barger, Mickelson, Mustafayev, Tata, JHEP 06 (2014) 172

Has LHC excluded Light new Physics?



Has LHC excluded Light new Physics?



ATLAS SUSY Searches* - 95% CL Lower Limits

August 2023

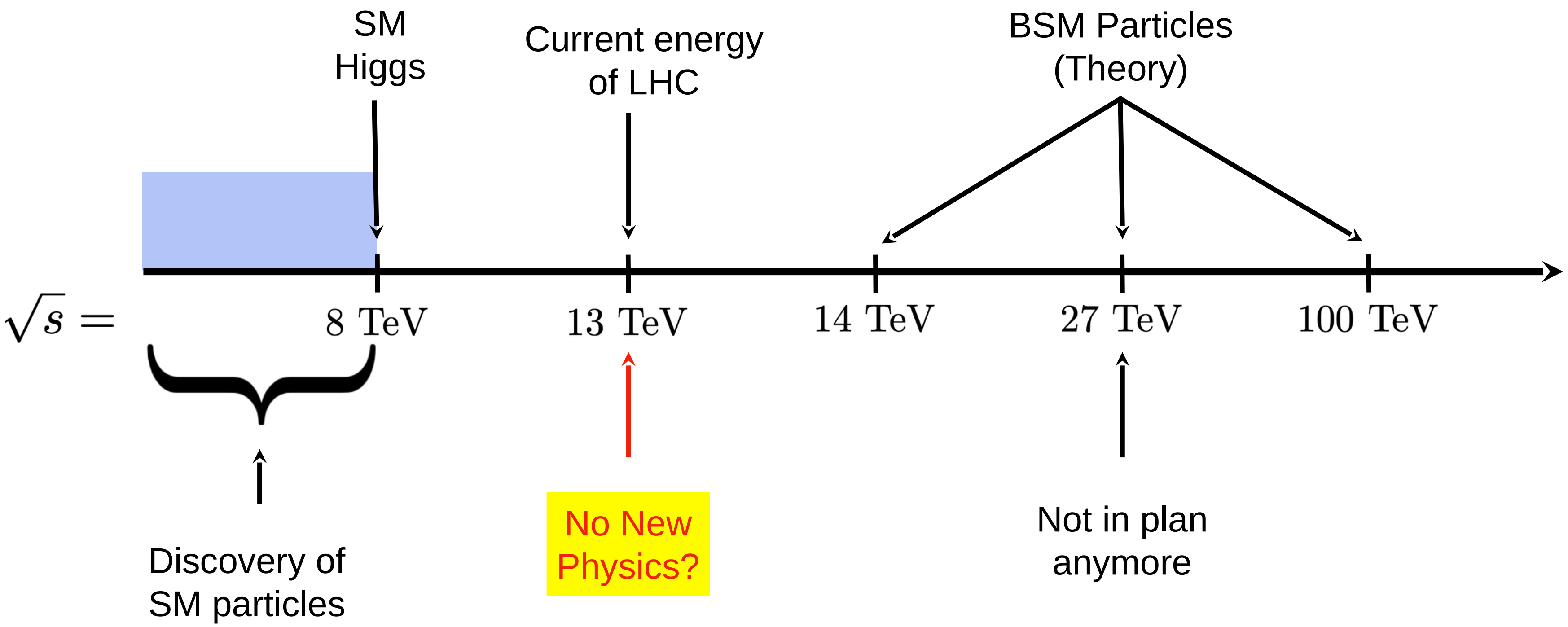
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde q$ [1×, 8× Degen.] 1.0 1.85	m($\tilde\chi^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	140	$\tilde q$ [8× Degen.] 0.9	m($\tilde q$)-m($\tilde\chi^0_1$)=5 GeV	2102.10874
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde g$ 2.3	m($\tilde\chi^0_1$)=0 GeV	2010.14293
						$\tilde g$ Forbidden 1.15-1.95	m($\tilde\chi^0_1$)=1000 GeV	2010.14293
	$\tilde g\tilde g$, $\tilde g\to q\bar qW\tilde\chi^0_1$	1 e,μ	2-6 jets		140	$\tilde g$ 2.2	m($\tilde\chi^0_1$)<600 GeV	2101.01629
	$\tilde g\tilde g$, $\tilde g\to q\bar q(\ell\ell)\tilde\chi^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	140	$\tilde g$ 2.2	m($\tilde\chi^0_1$)<700 GeV	2204.13072
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	140	$\tilde g$ 1.97	m($\tilde\chi^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde g$ 1.15	m($\tilde g$)-m($\tilde\chi^0_1$)=200 GeV	2307.01094
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	140	$\tilde g$ 2.45	m($\tilde\chi^0_1$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde g$ 1.25	m($\tilde g$)-m($\tilde\chi^0_1$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$	0 e,μ	2 b	$E_T^{\rm miss}$	140	$\tilde b_1$ 1.255	m($\tilde\chi^0_1$)<400 GeV	2101.12527
						$\tilde b_1$ 0.68	10 GeV<Δm($\tilde b_1$,$\tilde\chi^0_1$)<20 GeV	2101.12527
	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_2\to bh\tilde\chi^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	140	$\tilde b_1$ Forbidden 0.23-1.35	Δm($\tilde\chi^0_2$,$\tilde\chi^0_1$)=130 GeV, m($\tilde\chi^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	140	$\tilde b_1$ 0.13-0.85	Δm($\tilde\chi^0_2$,$\tilde\chi^0_1$)=130 GeV, m($\tilde\chi^0_1$)=0 GeV	2103.08189
	$\tilde t_1\tilde t_1$, $\tilde t_1\to t\tilde\chi^0_1$	0-1 e,μ	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde t_1$ 1.25	m($\tilde\chi^0_1$)=1 GeV	2004.14060, 2012.03799
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	140	$\tilde t_1$ Forbidden 1.05	m($\tilde\chi^0_1$)=500 GeV	2012.03799, ATLAS-CONF-2023-043
	$\tilde t_1\tilde t_1$, $\tilde t_1\to\tilde\tau_1 b\nu$, $\tilde\tau_1\to\tau\tilde G$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	140	$\tilde t_1$ Forbidden 1.4	m($\tilde\tau_1$)=800 GeV	2108.07665
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$ / $\tilde c\tilde c$, $\tilde c\to c\tilde\chi^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde c$ 0.85	m($\tilde\chi^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	140	$\tilde t_1$ 0.55	m($\tilde t_1$,$\tilde c$)-m($\tilde\chi^0_1$)=5 GeV	2102.10874
	$\tilde t_1\tilde t_1$, $\tilde t_1\to t\tilde\chi^0_2$, $\tilde\chi^0_2\to Z/h\tilde\chi^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	140	$\tilde t_1$ 0.067-1.18	m($\tilde\chi^0_2$)=500 GeV	2006.05880
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	140	$\tilde t_2$ Forbidden 0.86	m($\tilde\chi^0_1$)=360 GeV, m($\tilde t_1$)-m($\tilde\chi^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde\chi^\pm_1\tilde\chi^0_2$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.96	m($\tilde\chi^0_1$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1/\tilde\chi^0_2$ 0.205	m($\tilde\chi^\pm_1$)-m($\tilde\chi^0_1$)=5 GeV, wino-bino	1911.12606
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1$ 0.42	m($\tilde\chi^0_1$)=0, wino-bino	1908.08215
	$\tilde\chi^\pm_1\tilde\chi^0_2$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1/\tilde\chi^0_2$ Forbidden 1.06	m($\tilde\chi^0_1$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde\chi^\pm_1\tilde\chi^\mp_1$ via $\tilde\ell_L/\tilde\nu$	2 e,μ		$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1$ 1.0	m($\tilde\ell$,$\tilde\nu$)=0.5(m($\tilde\chi^\pm_1$)+m($\tilde\chi^0_1$))	1908.08215
	$\tilde\tau\tilde\tau$, $\tilde\tau\to\tau\tilde\chi^0_1$	2 τ		$E_T^{\rm miss}$	140	$\tilde\tau$ [$\tilde\tau_R$, $\tilde\tau_{R,L}$] 0.34 0.48	m($\tilde\chi^0_1$)=0	ATLAS-CONF-2023-029
	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde\ell$ 0.7	m($\tilde\chi^0_1$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde\ell$ 0.26	m($\tilde\ell$)-m($\tilde\chi^0_1$)=10 GeV	1911.12606
	$\tilde H\tilde H$, $\tilde H\to h\tilde G/Z\tilde G$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	140	$\tilde H$ 0.94	BR($\tilde\chi^0_1\to h\tilde G$)=1	To appear
		4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde H$ 0.55	BR($\tilde\chi^0_1\to Z\tilde G$)=1	2103.11684
		0 e,μ	≥ 2 large jets	$E_T^{\rm miss}$	140	$\tilde H$ 0.45-0.93	BR($\tilde\chi^0_1\to Z\tilde G$)=1	2108.07586
		2 e,μ	≥ 2 jets	$E_T^{\rm miss}$	140	$\tilde H$ 0.77	BR($\tilde\chi^0_1\to Z\tilde G$)=BR($\tilde\chi^0_1\to h\tilde G$)=0.5	2204.13072
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1$ 0.66	Pure Wino	2201.02472
						$\tilde\chi^\pm_1$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde g$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde g$ 2.05		2205.06013
	Metastable $\tilde g$ R-hadron, $\tilde g\to qq\tilde\chi^0_1$	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde g$ [$\tau(\tilde g)$ =10 ns] 2.2	m($\tilde\chi^0_1$)=100 GeV	2205.06013
	$\tilde\ell\tilde\ell$, $\tilde\ell\to\ell\tilde G$	Displ. lep		$E_T^{\rm miss}$	140	$\tilde e,\tilde\mu$ 0.7	$\tau(\tilde\ell)$ = 0.1 ns	2011.07812
						$\tilde\tau$ 0.34	$\tau(\tilde\ell)$ = 0.1 ns	2011.07812
		pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde\tau$ 0.36	$\tau(\tilde\ell)$ = 10 ns	2205.06013
RPV	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_1$, $\tilde\chi^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde\chi^\mp_1/\tilde\chi^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde\chi^\pm_1\tilde\chi^\mp_1/\tilde\chi^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde\chi^\pm_1/\tilde\chi^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde\chi^0_1$)=200 GeV	2103.11684
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^0_1$, $\tilde\chi^0_1\to qqq$		≥8 jets		140	$\tilde g$ [m($\tilde\chi^0_1$)=50 GeV, 1250 GeV] 1.6 2.25	Large λ''_{112}	To appear
	$\tilde t\tilde t$, $\tilde t\to t\tilde\chi^0_1$, $\tilde\chi^0_1\to tbs$		Multiple		36.1	$\tilde t$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde\chi^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde t\tilde t$, $\tilde t\to b\tilde\chi^\pm_1$, $\tilde\chi^\pm_1\to bbs$		≥ 4b		140	$\tilde t$ Forbidden 0.95	m($\tilde\chi^\pm_1$)=500 GeV	2010.01015
	$\tilde t_1\tilde t_1$, $\tilde t_1\to bs$		2 jets + 2 b		36.7	$\tilde t_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde t_1\tilde t_1$, $\tilde t_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde t_1$ 0.4-1.45	BR($\tilde t_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde t_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde t_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde\chi^\pm_1/\tilde\chi^0_2/\tilde\chi^0_1$, $\tilde\chi^0_{1,2}\to tbs$, $\tilde\chi^+_1\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde\chi^0_1$ 0.2-0.32	Pure higgsino	2106.09609

*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.

New Physics: Light or Heavy?



Energy line of SM and BSM particles

Searches for new physics ⟶ Future colliders

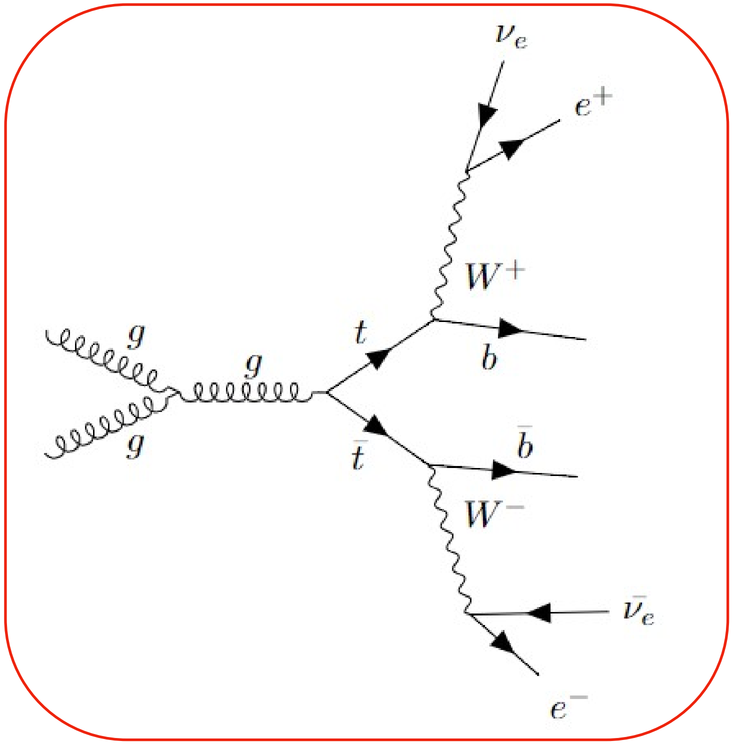
Our proposal: Study well-known observables to reveal New Physics

This work: Precise measurement of top quark observables

Light New Physics from $t\bar{t}$

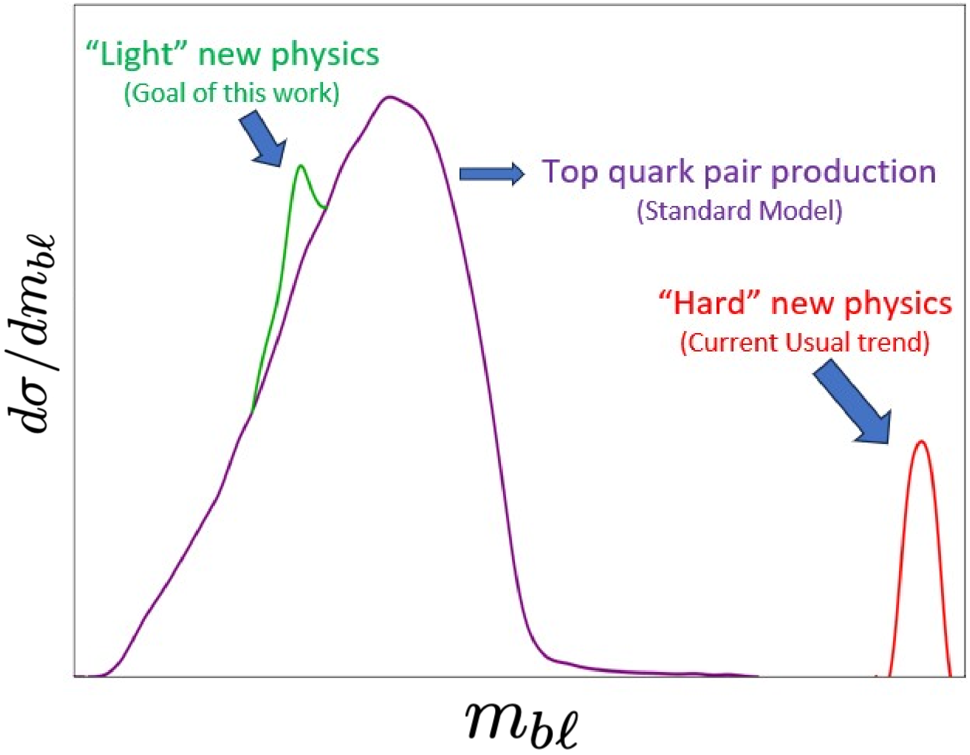
The **LHC**, being a **“top quark factory”**, helps in precise measurement of various properties of the top quark

SM Process



Pair-production of top quarks with each top t decaying to b and $W^\pm$ which further decays leptonically

Invariant mass of the b -jet and the lepton ($m_{b\ell}$)



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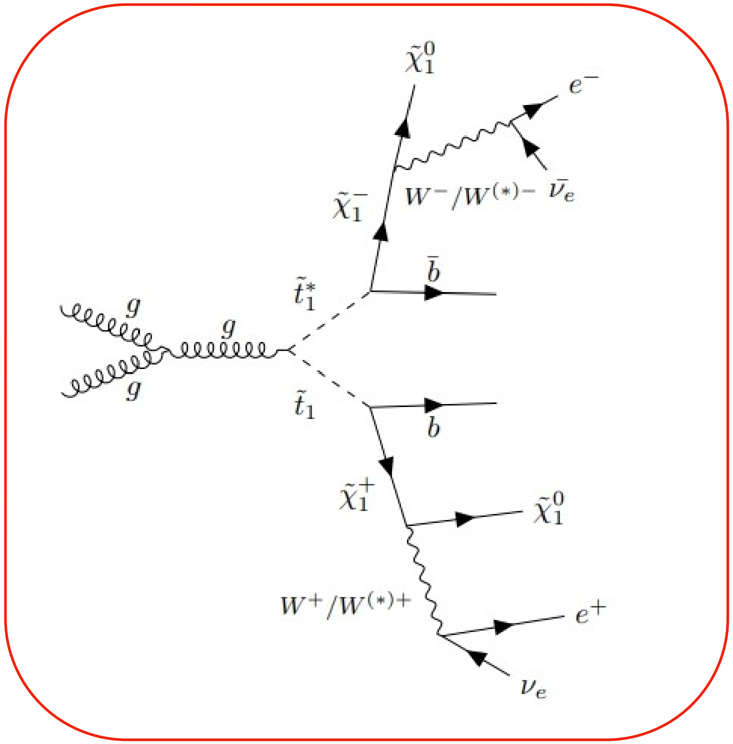
Targeted New Physics Scenario

Any BSM scenario with final state: opposite sign dileptons + 2 b -jets + $\not{E}_T$

Example: Minimal supersymmetric standard model (MSSM)

MSSM Process



Pair-production of the lightest stop $\tilde{t}_1$, with each $\tilde{t}_1$ decaying to the lightest chargino $\tilde{\chi}_1^\pm$ and b, and each $\tilde{\chi}_1^\pm$ decaying to the lightest SUSY particle (LSP) $\tilde{\chi}_1^0$ leptonically via a real or a virtual $W^\pm$ boson

Several parameter space points generated using SPheno - 4.0.3 interfaced with SARAH -4.15.1

$$m_{\tilde{t}_1} = 180, 200, 220 \text{ GeV}$$
$$M_1 : 5 \text{ GeV} - 1 \text{ TeV}$$
$$\mu : 100 \text{ GeV} - m_{\tilde{t}_1}$$

$$m_{\tilde{q}} \approx m_{\tilde{l}} \approx 3.5 \text{ TeV} \neq m_{\tilde{t}_1}$$
$$m_{\tilde{g}} \approx 3.6 \text{ TeV}$$
$$122 \text{ GeV} \leq m_h \leq 128 \text{ GeV}$$

Lightest SUSY Particle (LSP) : $\tilde{\chi}_1^0$
Next-to-Lightest SUSY Particle (NLSP) : $\tilde{\chi}_1^\pm$

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Bounds from Experiments

Important!

A new physics scenario should not be excluded by

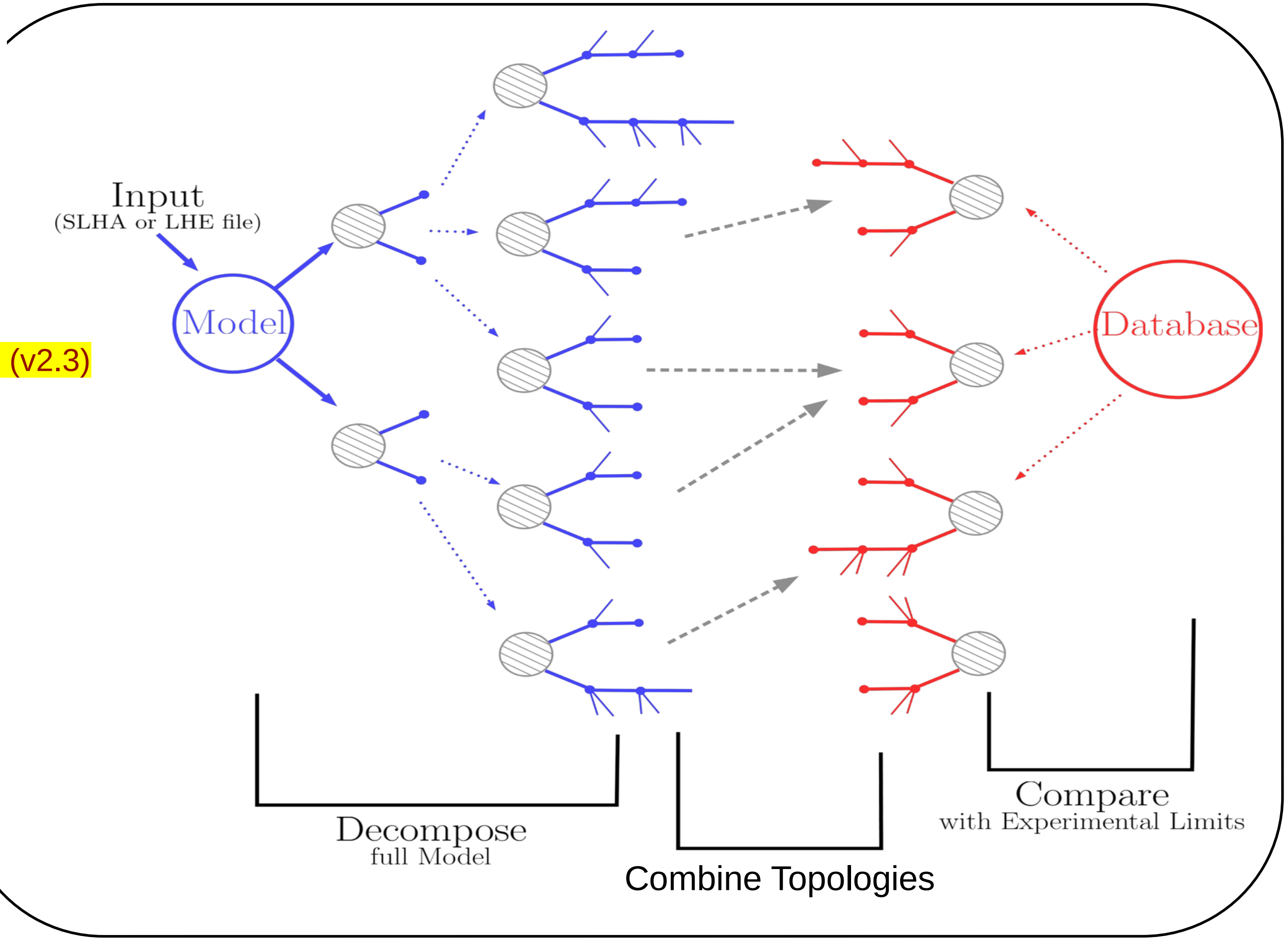
→ experimental searches **SPECIFICALLY** designed for this scenario, **AS WELL AS**

→ experimental searches **NOT** designed for this scenario

arXiv:1312.4175 (v1.0) → arXiv:2306.17676 (v2.3)

$r > 1$
Excluded

$r < 1$
Not Excluded



https://smodels.github.io/
https://smodels.readthedocs.io/en/stable/
https://indico.cern.ch/event/1375202/ - April 25th 2024 - Roberto Franceschini - LHC top WG

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Simulation

All the parameter space points are simulated with Pythia — 8.3 with PDF=NNPDF2.3 QCD+QED LO.

Cuts imposed (motivated by experimental papers)

$$p_T(\ell) \geq 25 \text{ GeV},\ |\eta(\ell)| < 2.5,\ R(j) = 0.4,\ p_T(j) \geq 25 \text{ GeV},\ |\eta(j)| < 2.5,$$
$$\Delta R(\ell j) > 0.2,\ \Delta R(\ell\ell) > 0.1,\ \Delta R(jj) > 0.4$$

Jet clustering: Anti-k_T jet algorithm

From $m_{b\ell}$ distribution :

$$\text{Significance} = \sqrt{\sum_i \left[S_i / \left(B_i \times u_{B_i}\right)\right]^2} \quad \text{at } \mathcal{L} = 139\ fb^{-1}$$

$S_i = \text{No. of signal events in the } i^{th} \text{ bin}$

$B_i = \text{No. of background events in the } i^{th} \text{ bin}$

$u_{B_i} = \text{Relative uncertainty in the background in the } i^{th} \text{ bin}$

(extracted from ATLAS and CMS)

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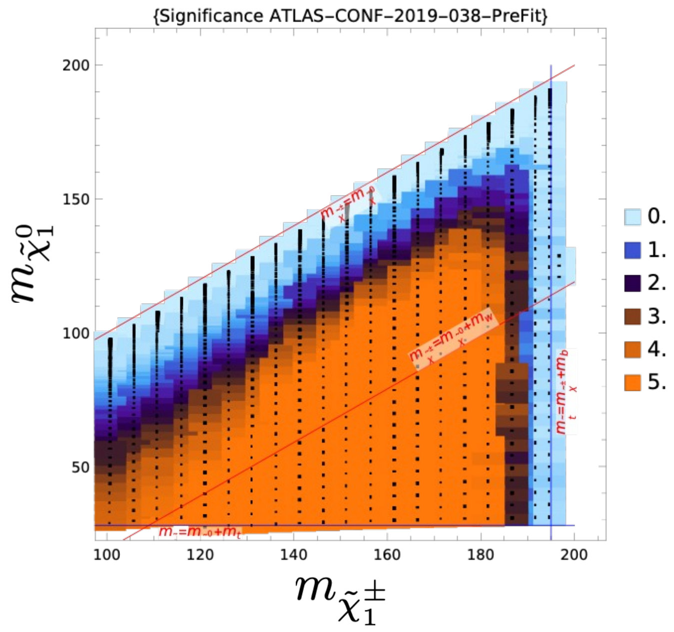
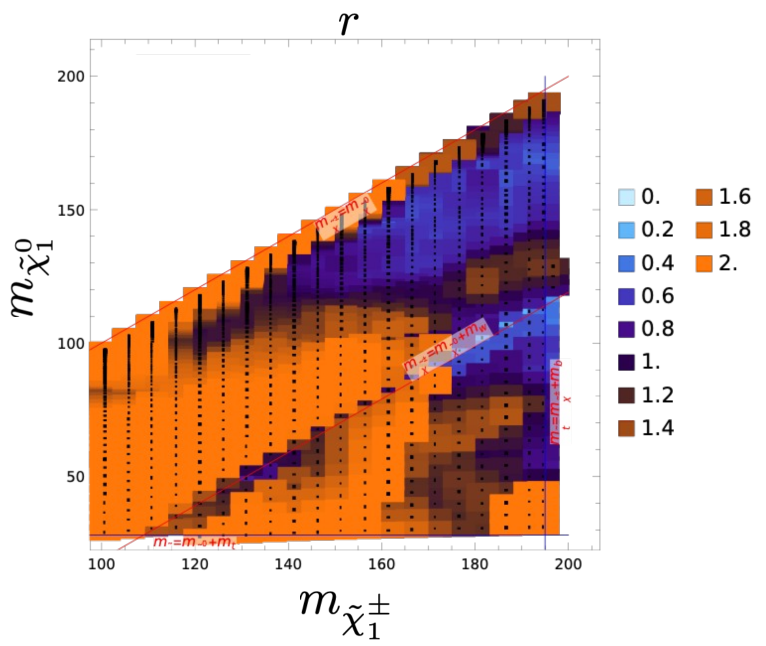
Tech. Rep. ATLAS-CONF-2019-038

M. Aaboud et. al. (ATLAS), Eur. Phys. J. C 78, 129 (2018)

A. M. Sirunyan et. al. (CMS), Eur. Phys. J. C 79, 368 (2019)

Benchmark Points $(m_{\tilde{t}_1} = 200\ \text{GeV})$





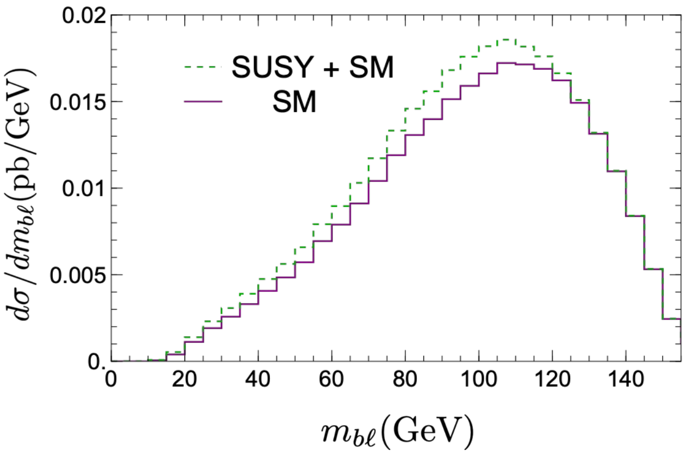
Significance with u_B from ATLAS

Values of r calculated using SModelS — 2.3.3

Significance ≥ 5

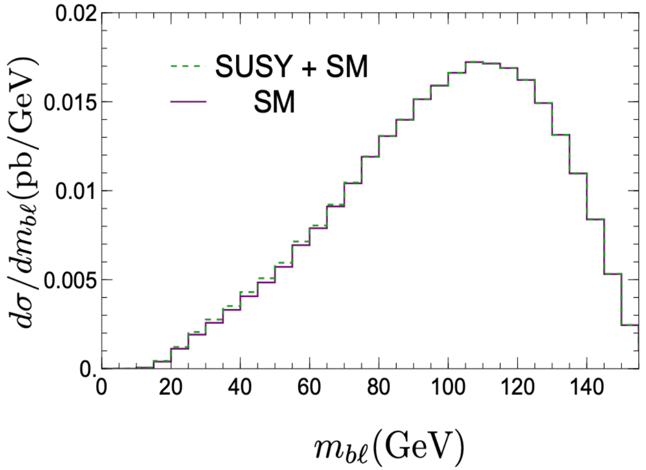
DISCOVERY!!

$m_{\tilde{t}_1} = 200\text{GeV}, m_{\tilde{\chi}_1^\pm} = 136.2\text{GeV}, m_{\tilde{\chi}_1^0} = 49.9\text{GeV}, r = 0.83$



Significance with u_B from ATLAS ~ 10.8

$m_{\tilde{t}_1} = 200\text{GeV}, m_{\tilde{\chi}_1^\pm} = 156.42\text{GeV}, m_{\tilde{\chi}_1^0} = 123.3\text{GeV}, r = 0.72$



Significance with u_B from ATLAS~ 2.6

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Conclusion

Natural SUSY at HL-LHC :

- **Light Higgsinos → Parameter space almost fully covered**
- **Winos decaying to light Higgsinos → 0.8-1.1 TeV @ 5sigma / 95% CL**
- **Lightest stop quark → 1.7-2 TeV @ 5sigma / 95% CL**
- **Gluinos → 2.8 TeV @ 5sigma**

Parameter space for winos, lightest stop and gluino to be fully covered by FCC-hh

However, before moving on to future colliders we must ensure there is no new physics hidden in already measured observables. Here we show that a thorough study of well-known kinematic observables may hint towards the existence of Light New Physics.

THANK YOU