Dark Matter and the Electroweak Sector in Supersymmetry

Marcela Carena

Fermilab/UChicago

University of Southampton, July 20, 2023

Outline

- The missing answers in the Standard Model; the theory landscape evolving with the LHC
- Supersymmetry and Dark Matter basics
- All we can achieve within Supersymmetry with minimal particle content:

➔ The Minimal Supersymmetric Standard Model ((MSSM)

The MSSM SM-like Higgs

The MSSM WIMP miracle

The muon g-2 anomaly?

Searching for Dark Matter and electroweakinos in the compressed mass region at the LHC: a new channel via radiative decays

- Outlook on SUSY

A lot of Particle Physics is Missing in the Standard Model

- Why Electroweak Symmetry Breaking occurs?
  What is the history of the Electroweak Phase Transition ?
- The reason for the **Hierarchy in Fermion Masses and their Flavor Structure**
- The Nature of **Dark Matter**
- The origin of the **Matter-Antimatter Asymmetry**
- The generation of **Neutrino Masses**
- The cause of the Universe's accelerated expansion **- Dark Energy**
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

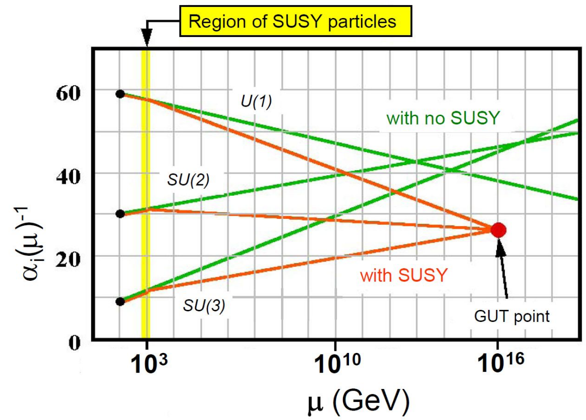
The SM is silent about all the above BUT,
LHC data could provide decisive clues to help us decipher many of these mysteries

Particle theorist's view of the road ahead: @LHC start in 2009

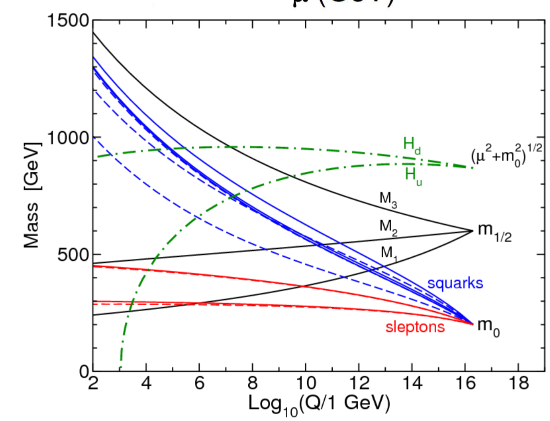
Particle theorist's view of the road ahead: @LHC RUN 3 in 2023

A few Words on SUSY theories' good features

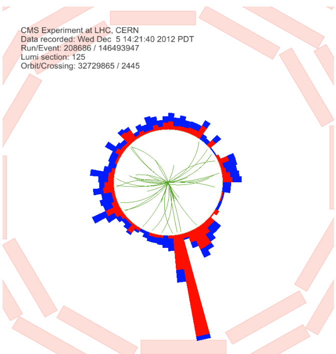
- Unification of couplings
- SUSY Algebra → Quantum gravity?
- Radiative Electroweak Symmetry Breaking
- An elementary Higgs boson with corrections to its mass screened at the scale of SUSY breaking



- Requires at least 2 Higgs Doublets and can easily accommodate more additional Higgs-like particles



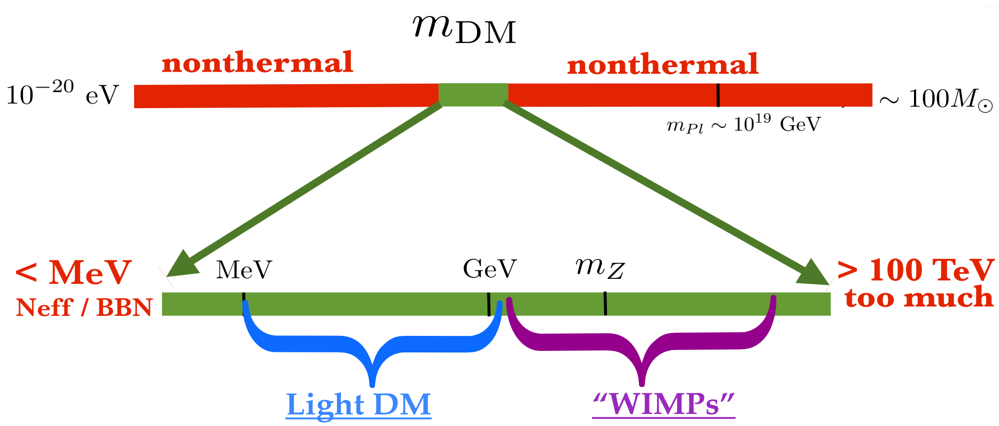
- Extended Higgs sectors, plus other particles, can affect the history of EWSB and provide new possible sources of CP violation which may facilitate baryogenesis at the electroweak scale



- If R-Parity is conserved, the Lightest SUSY Particle is a good Dark Matter candidate; it can be searched for at the LHC via MET signals; together with other possible SUSY partners

A few words on Dark Matter

Thermal Equilibrium in the early Universe narrows the viable Dark Matter mass range



WIMPs: weak scale size masses and couplings roughly consistent with $\Omega_{\rm DM}$

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

Kolb and Turner

- SUSY provides viable WIMP DM

- SUSY WIMPs are a mixture of fermionic supersymmetric-partners of the SM EW gauge bosons (electroweakinos) and extended Higgs sectors (higgsinos)

In the MSSM

- Neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)$=mass eigenstates of $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_u^0, \widetilde{H}_d^0)$.

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

- Charginos $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$=mass eigenstates of $(\widetilde{W}^\pm, \widetilde{H}_{u/d}^\pm)$.

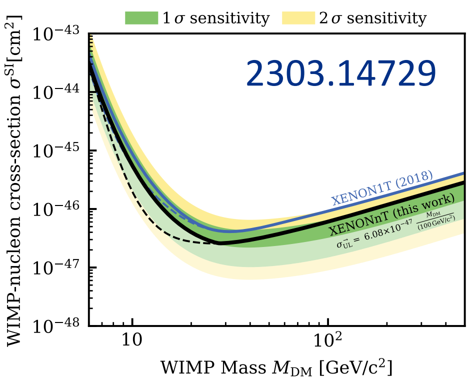
$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

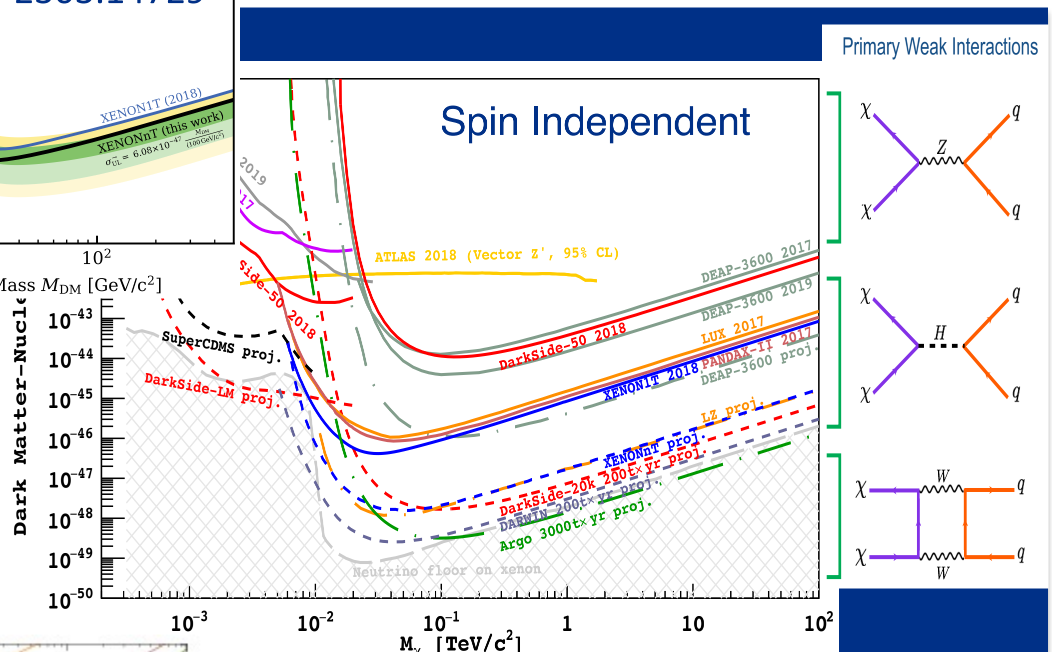
M_2 real, $\quad M_1 = |M_1| e^{i\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$ $\quad$ Φ_μ, Φ_1 CP phases

Fermilab

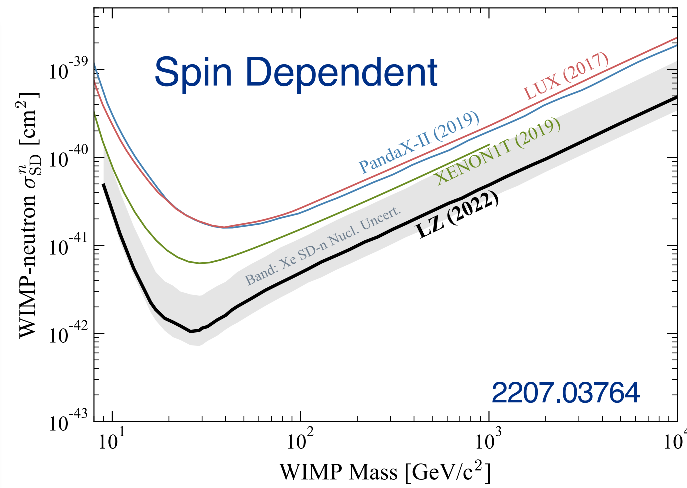
Dark Matter Direct Detection

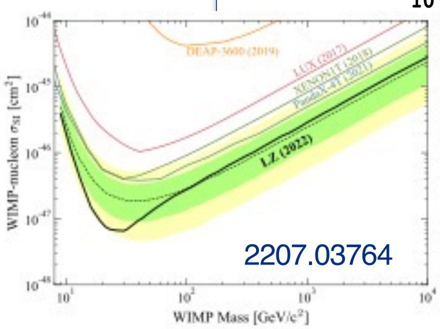
Already probing the Higgs Portal/s





Marching down to the Neutrino Floor

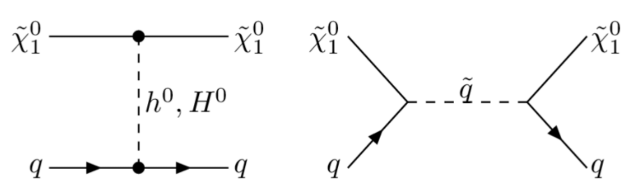




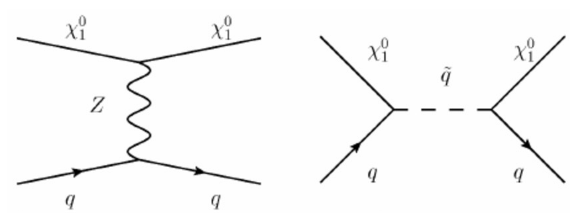
Depending on the DM interactions, different experiments can set the most stringent limits

In the MSSM

SI:



SD:



The Higgs boson as a tool for SUSY theory exploration

MSSM Guidance:

- the lightest Higgs-boson mass depends strongly on m_A, $\tan\beta = v_u/v_d$ and m_{top}
- It also depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t.

  [and on sbottom/stau sectors for large tan beta]

For moderate to large values of tan beta and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]$$

M.C., Espinosa, Quiros, Wagner '95

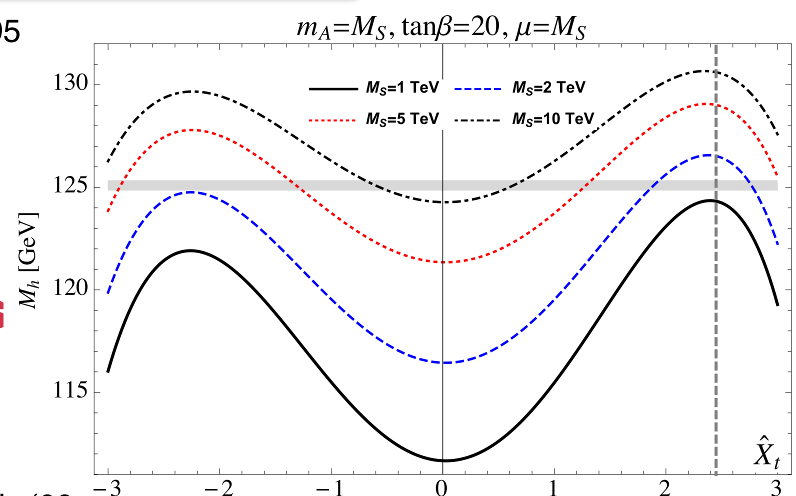
$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

$$t = \log(M_{SUSY}^2/m_t^2)$$

$$\tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)$$

$X_t = A_t - \mu/\tan\beta \rightarrow$ LR stop mixing

Stop masses above about 1 TeV yield the measured Higgs mass



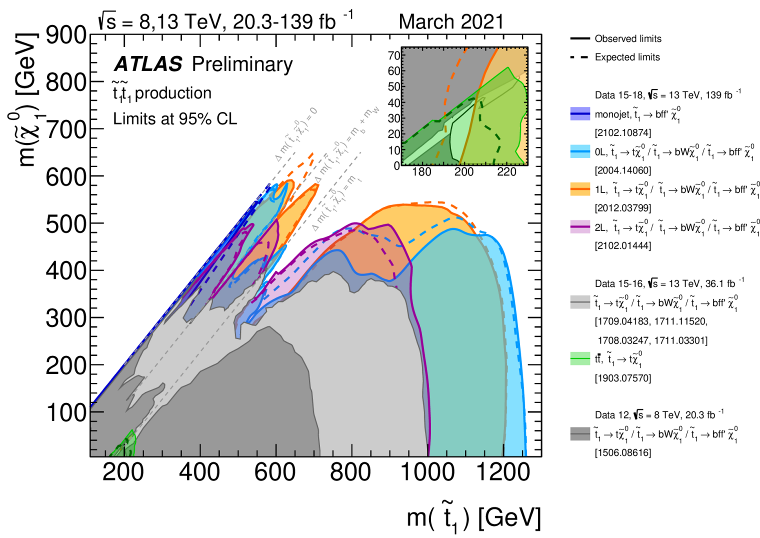
M.C. Haber, Heinemeyer, Hollik, Wagner, Weiglein '00

SUSY- Higgs MSSM situation starting LHC Run 3

- **Stop Searches**

Combining all searches, in simplest decay scenarios, it is hard to avoid constraints of several hundred GeV to 1 TeV (for $m_{LSP} < 350$ GeV) for stop (sbottom) searches

➔ We are starting to explore the mass region suggested by Higgs mass determination



- **ATLAS and CMS fit to Higgs Couplings**

	ATLAS Run 2 (ATLAS-CONF-2021-53)	CMS Run 2 (CMS-PAS-HIG-19-005)	Current precision
κ_γ	1.04 ± 0.06	$1.01^{+0.09}_{-0.14}$	6%
κ_W	1.06 ± 0.06	$-1.11^{+0.14}_{-0.09}$	6%
κ_Z	0.99 ± 0.06	0.96 ± 0.07	6%
κ_g	$0.92^{+0.07}_{-0.06}$	$1.16^{+0.12}_{-0.11}$	7%
κ_t	0.92 ± 0.10	1.01 ± 0.11	11%
κ_b	0.87 ± 0.11	$1.18^{+0.19}_{-0.27}$	11%
κ_τ	0.92 ± 0.07	0.94 ± 0.12	8%

Departure of SM predictions of order a few tens of percent allowed

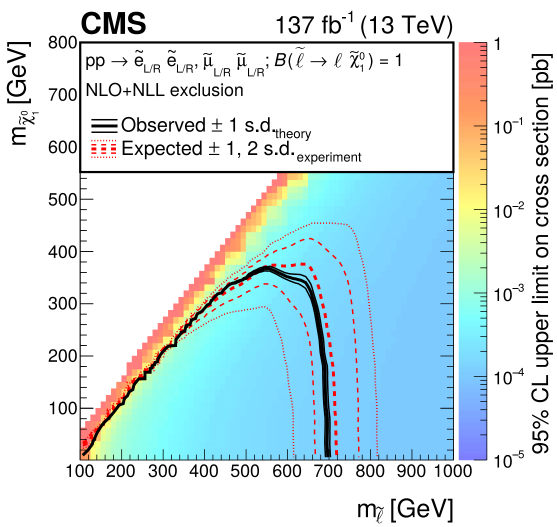
➔ One neutral Higgs of mass 125 GeV needs to **approximately** do the job of the SM Higgs boson; **ALIGNMENT**

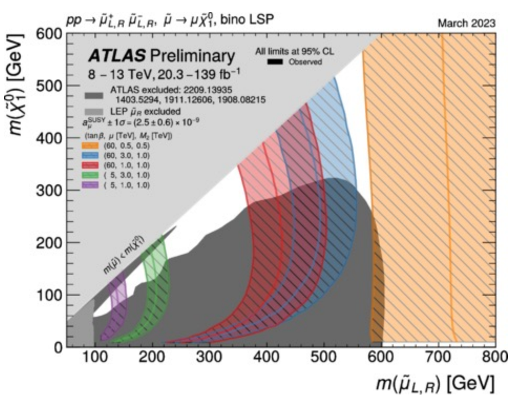
See Haber's talk

Either specific relation among Higgs bosons' quartics or decoupling of the heavy Higgs sector

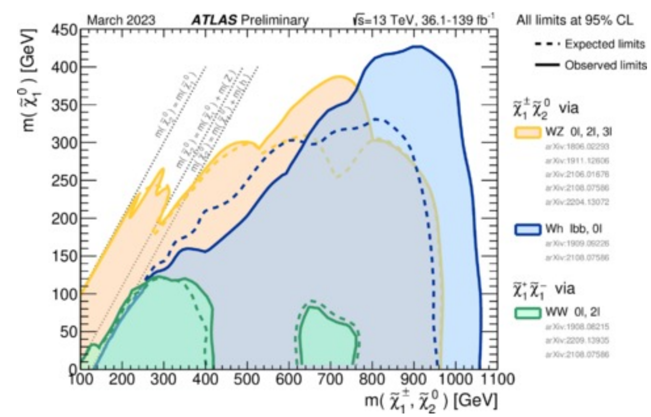
SUSY- Electroweak Sector at the start of Run 3

- Situation far less well defined than in the strongly interacting sector
- Sleptons mass bounds can be as large as 700 GeV (staus below 390 GeV)
- Winos as NLSP's are the strongest constrained particles.
- Sensitivities in the search for these particles is permanently increasing with higher luminosities.
- In general, a scenario with large cascade decays with light electroweakinos is the most natural one and one of the highest hopes for detecting SUSY at the weak scale.





Bounds are highly relaxed if the spectrum is somewhat compressed (or if sleptons don't decay directly to LSP)



Current Electroweakino bounds

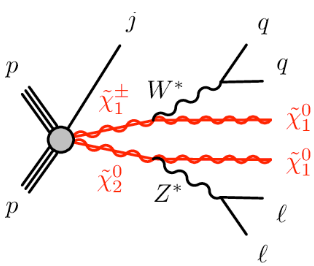
Wino NLSP with BR = 1 assumed, not necessarily the case, specially for the WZ decay channel

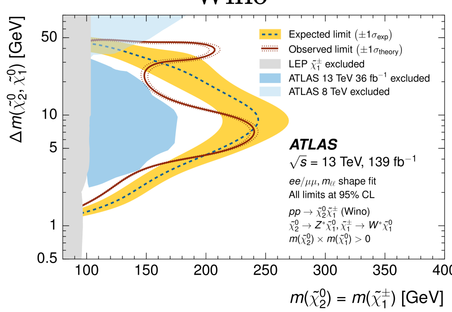
SUSY Dark Matter under scrutiny at the LHC

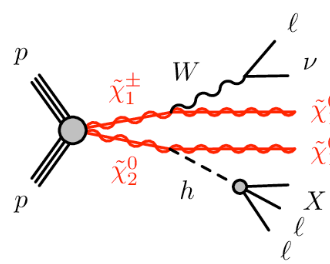
Chargino –Neutralino Production

Talk of Judita Mamužić

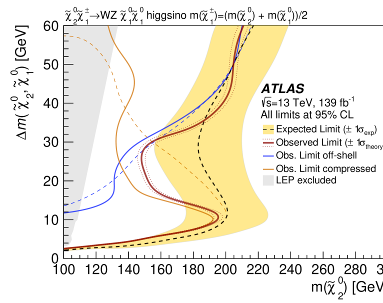
Wino



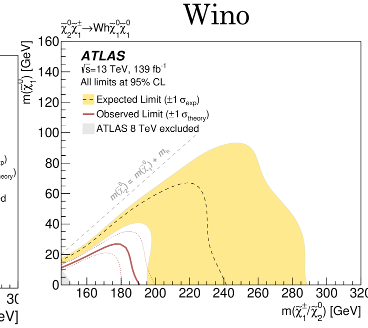




Higgsino



Wino



- $2l$: ~2σ for wino WZ Δm = 20 GeV
- $3l$: ~2σ for wino Wh DFOS

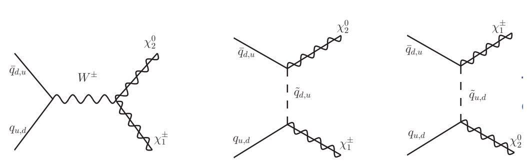
- $2l$ + $3l$: <2σ for higgsino Δm = 25 GeV
- CMS: ~2σ for higgsino Δm ~ 20 GeV

•Winos, in the adjoint rep. of SU(2), are produced at a stronger rate than Higgsinos.

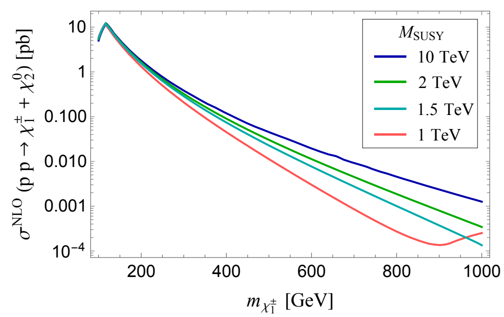
➔The cross section for Wino production is about a factor 4 larger than the Higgsino one.

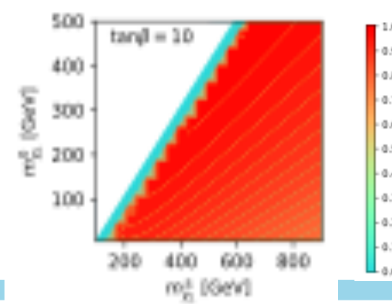
Caveats of LHC analyses that enhance the reach:

- Squarks taken to be decoupled, leading to larger production cross sections
- BR ratio of Wino/Higgsino into SM bosons assumed 1 for each analysis; not the case



Liu, McGinnis, Wang, Wagner: 2008.11847





BR (Wino → h + LSP)

for mu x M_2 > 0

Fermilab

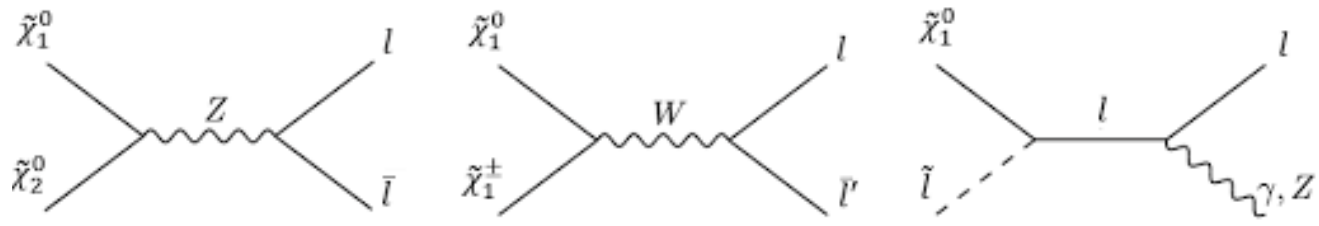
Electroweak scale SUSY DM and the Thermal Relic Density

- An MSSM LSP at the electroweak scale needs to be Bino-like to reproduce the right relic density; EW scale Wino and Higgsino LSPs annihilate too efficiently

- In particular, Bino-like LSP needs to annihilate against other rapidly annihilating particles => **Co-annihilation**

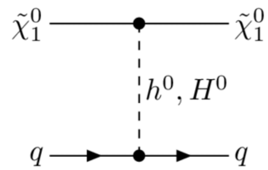
For co-annihilation to work, the mass difference of the Dark Matter with the other weakly interacting particles must be of the order of a few tens of GeV.

- It naturally leads to a compressed spectrum for new particle searches in the missing energy channel.
- Some relevant channels in the case of sleptons or Winos (too light Higginos/small μ leads to large SD cross sections).



Blind Spots in Direct Dark Matter Detection

- Probing the Higgs portal
  close to Alignment:



$$\mathcal{M}_p^{SI} \propto \frac{v}{\mu^2}\left[2\frac{(M_1+\mu\sin 2\beta)}{m_h^2} - \frac{\mu\cos 2\beta}{m_H^2}\tan\beta\right],$$

for moderate to large tanβ implies

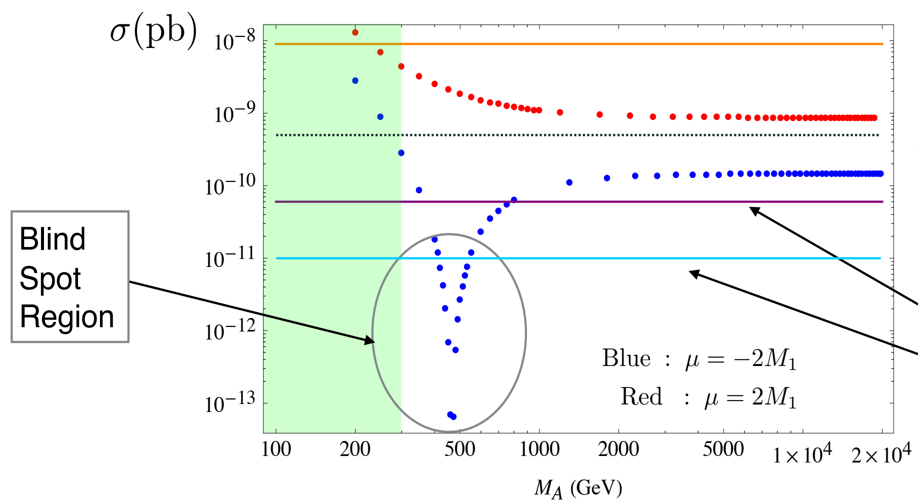
Destructive interference between h and H contributions for M_1 x μ < 0 (cos2β negative)

Still room for a SUSY WIMP miracle:

Cross section greatly reduced when the parameters fulfilled the approximate relation

$$2\ (m_\chi + \mu\sin 2\beta)\frac{1}{m_h^2} \simeq -\ \mu\tan\beta\frac{1}{m_H^2}$$

$$\mu \times m_{\tilde{\chi}^0} < 0 \qquad m_{\tilde{\chi}^0} \simeq M_1$$ relaxes SIDD bounds



Recall, however, the μ dependence of the SD part ➔ $\sigma^{SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$

Ellis, Olive, Santoso, Spanos'05; Baer, Mustayev, Park, Tata '06; **Huang, Wagner'14**; Cheung, Sanford, Papucci, Shah, K. Zurek '14; Huang, Roglans, Spiegel, Sun, Wagner.'17 Baum, MC.., Shah, Wagner' '18

The WIMP miracle and the muon g-2 in the MSSM

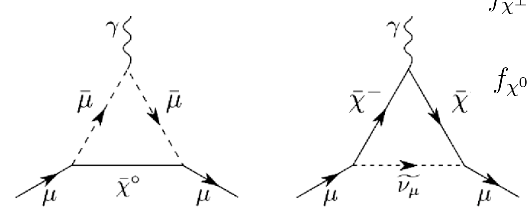
SUSY contributions to g-2

Barbieri, Maiani'82, Ellis et al'82, Grifols and Mendez'82; Moroi'95, M.C., Giudice, Wagner'95, Martin,Wells'00...

See Wagner's talk

$$a_\mu^{\tilde{\chi}^\pm - \tilde{\nu}_\mu} \simeq \frac{\alpha m_\mu^2 \mu M_2 \tan\beta}{4\pi \sin^2\theta_W m_{\tilde{\nu}_\mu}^2} \left[\frac{f_{\chi^\pm}\left(M_2^2/m_{\tilde{\nu}_\mu}^2\right) - f_{\chi^\pm}\left(\mu^2/m_{\tilde{\nu}_\mu}^2\right)}{M_2^2 - \mu^2} \right],$$

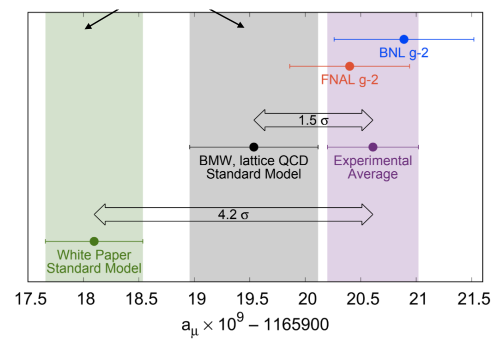
$$a_\mu^{\tilde{\chi}^0 - \tilde{\mu}} \simeq \frac{\alpha m_\mu^2 M_1 (\mu \tan\beta - A_\mu)}{4\pi \cos^2\theta_W \left(m_{\tilde{\mu}_R}^2 - m_{\tilde{\mu}_L}^2\right)} \left[\frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_R}^2\right)}{m_{\tilde{\mu}_R}^2} - \frac{f_{\chi^0}\left(M_1^2/m_{\tilde{\mu}_L}^2\right)}{m_{\tilde{\mu}_L}^2} \right]$$



$$f_{\chi^\pm}(x) = \frac{x^2 - 4x + 3 + 2\ln(x)}{(1-x)^3}, \quad f_{\chi^0}(x) = \frac{x^2 - 1 - 2x\ln(x)}{(1-x)^3};$$

Taking the 4.2 sigma discrepancy seriously

$$\Delta a_\mu \equiv (a_\mu^{\rm exp} - a_\mu^{\rm SM}) = (251 \pm 59) \times 10^{-11}$$



Assuming all weakly interacting supersymmetric particle masses are the same and M_1 x $M_2 > 0$

➔ $$(\Delta a_\mu)^{\rm SUSY} \simeq 150 \times 10^{-11} \left(\frac{100 \text{ GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

One can explain the anomaly within the MSSM:
for values of tanβ ~ 10 – 60 and SUSY particle masses in the 250-700 GeV range

Fitting Dark Matter Direct Detection and muon g-2 results

- Reduction (proximity to blind spot) of SIDD cross section obtained for $\mu \times M_1 < 0$
- Direct Detection cross sections (SD/SI) are suppressed for large values of μ

- Muon g-2 has two contributions:
  - Bino one proportional to $\mu \times M_1$ - that is negative at the proximity of the blind spot but becomes subdominant at smaller values of μ
  - Chargino one proportional to $\mu \times M_2$ -that is the dominant one for gaugino masses of the same order and is suppressed at large μ

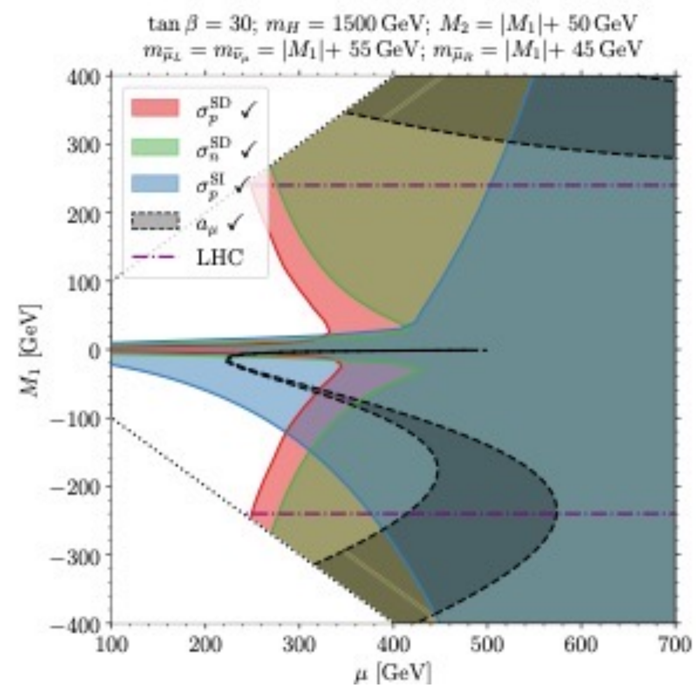
Since contributions to g-2 need to be positive ➔ compatibility between Direct Detection and muon g-2 results is achievable either for

- large values of μ (or)

  Chakraborti, Heinemeyer, Saha, arXiv:2006.15157; 2103.13403

- smaller μ values, IF $M_1 \times M_2 < 0$ ⟶

  Baum, M.C., Shah, Wagner, arXiv:2104.03302



Some hierarchy of μ values between positive and negative M_1 is observed

Trailing the electroweakinos at the LHC

The many good features of the compressed bino-wino region

- yields a dark matter WIMP solution
- is at the current/future reach of Direct Detection experiments
- can explain the possible muon g-2 anomaly for opposite sign of gaugino masses

AND can be searched for at the LHC Run 3/HL-LHC

Trailing the electroweakinos at the LHC

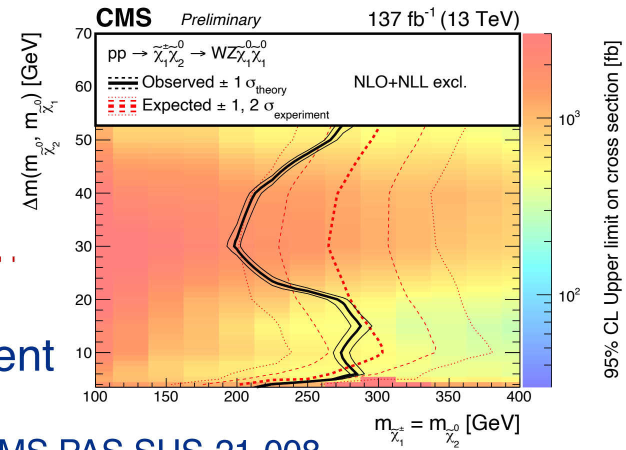
The many good features of the compressed bino-wino region

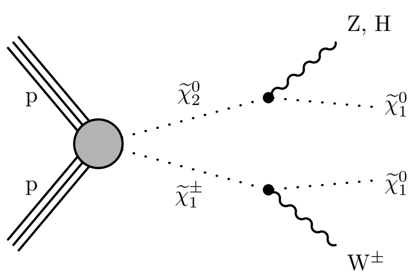
- yields a dark matter WIMP solution
- is at the current/future reach of Direct Detection experiments
- can explain the possible muon g-2 anomaly for opposite sign gaugino masses

AND can be searched for at the LHC Run 3/HL-LHC

In fact,

there are hints of mild (2σ) excesses in both experiments …



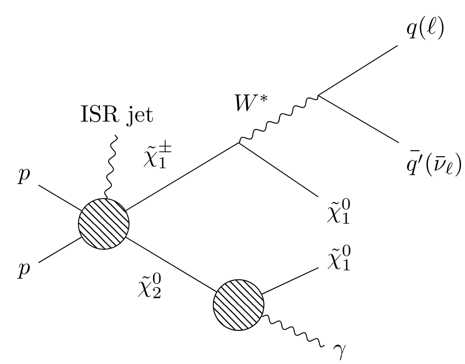


The 2/3l soft and ≥ 3l analyses complement each other in the compressed region.

CMS PAS SUS-21-008

Here, I would like to consider a new search channel in the region of interest

The radiative decay of the NLSP



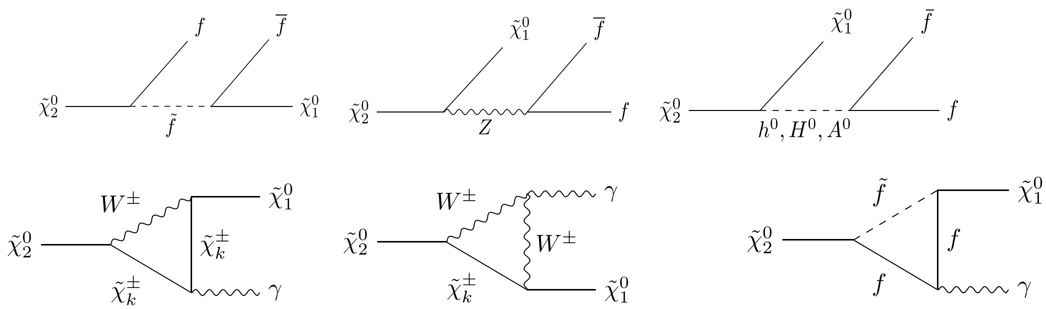
NLSP neutralino decay channels and Branching Ratios

Focusing on the compressed region, define the mass splitting parameter ε → $\varepsilon \equiv \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{\chi}_1^0}} - 1$
to understand the importance of the radiative decays

Tree-level decays

vs

radiative decays

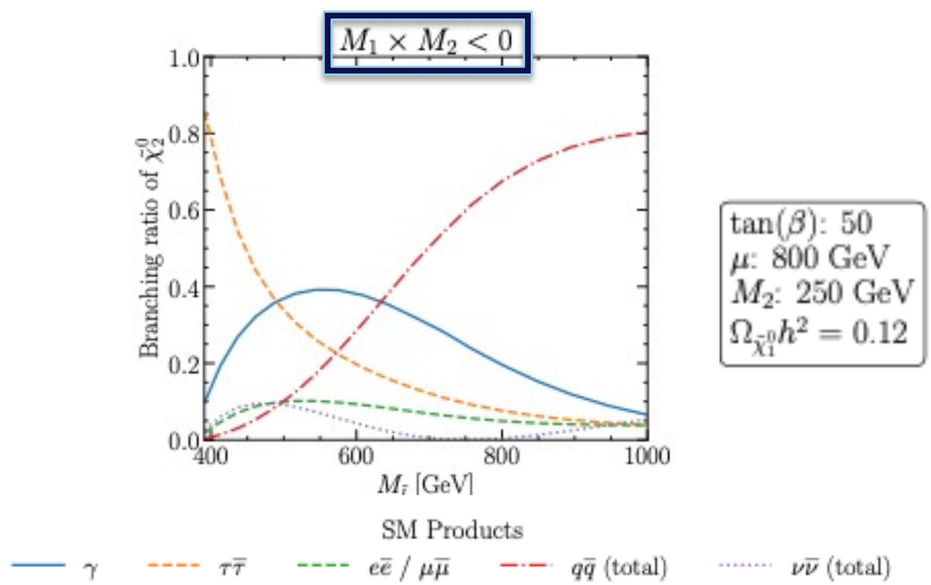


Kinematic suppression: As the mass difference shrinks, the tree-level decay rate is prop. to ε^5 while loop-level radiative decay prop. to ε^3 → radiative decay prominent in compressed region.

Branching Ratios

obtained with SUSY-HIT

- M_1 chosen to get proper relic density
- Dominant radiative decay from fermion-sfermion loop with effective coupling enhanced for $M_1 \times M_2 < 0$

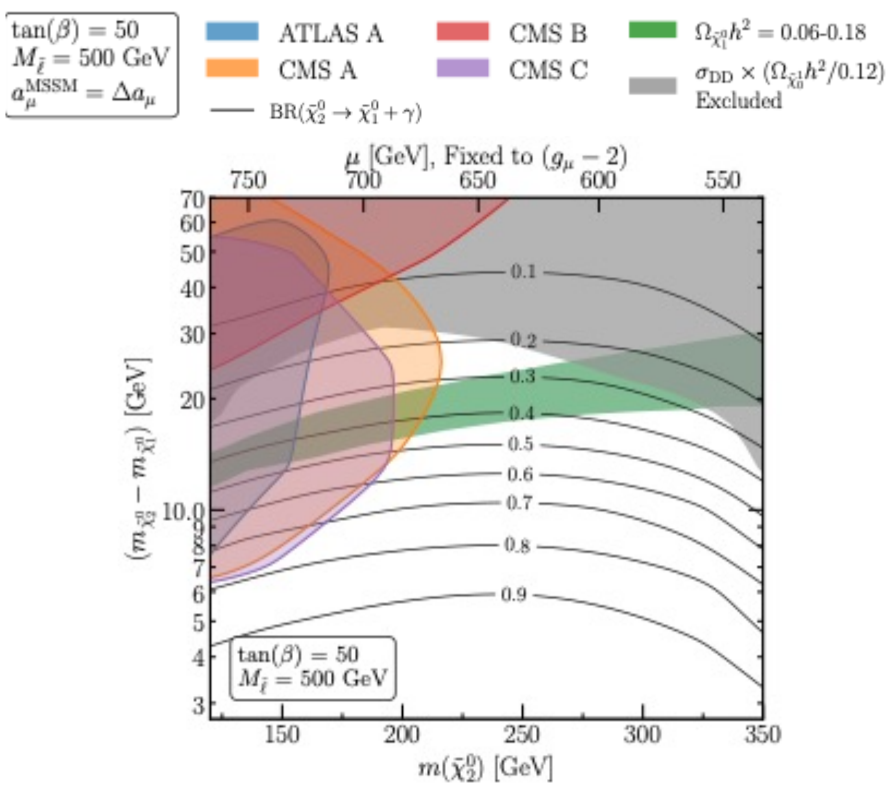


Can this be tested at the LHC?

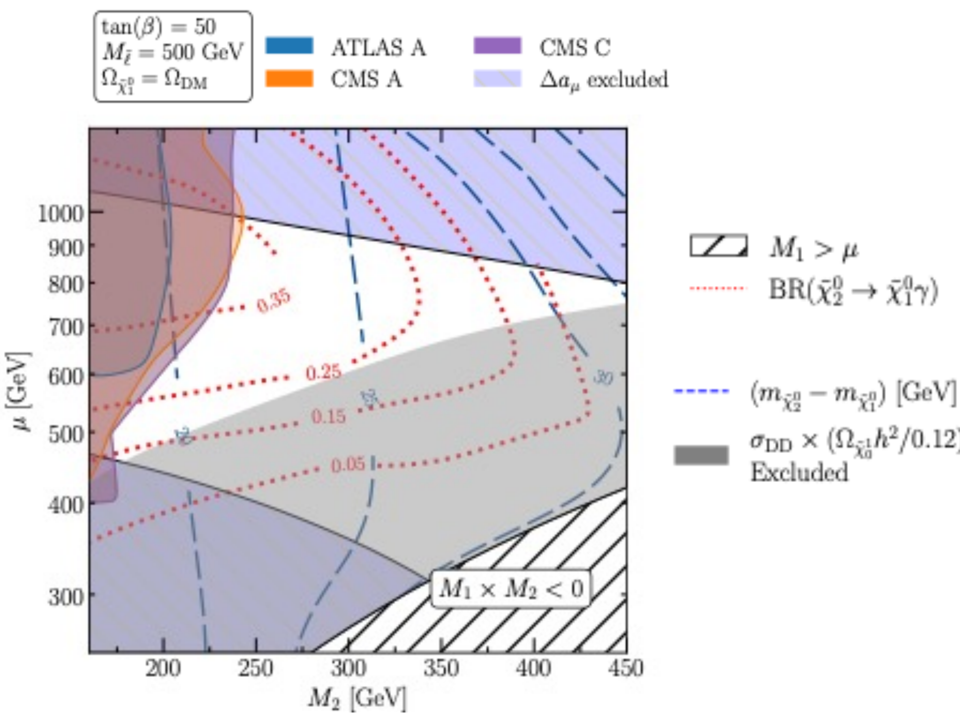
Allowed Parameter Space - fixing $M_1 \times M_2 < 0$ -

- LHC searches in the compressed region, taking into account bounds on the whole SUSY spectrum while assuming sufficiently heavy strong interacting particles
- Compute relic density and consider direct detection bounds (SI and SD)
- Consider parameter space compatible with the potential muon g-2 anomaly
- Compute BR (NLSP → SLP + γ)

Baum, M.C., Ou, Rocha, Shah, Wagner, arxiv 2303.01523



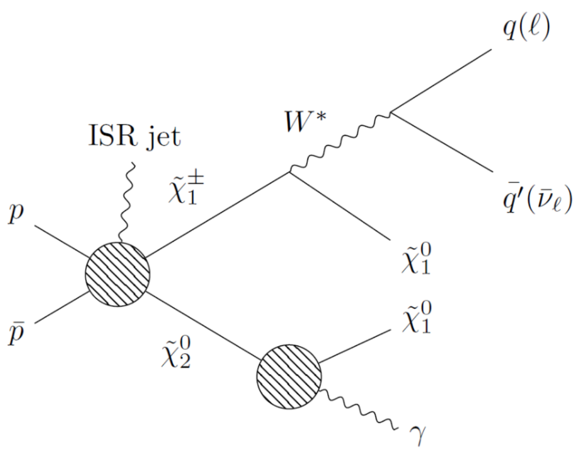
DM fixed to obtain relic density

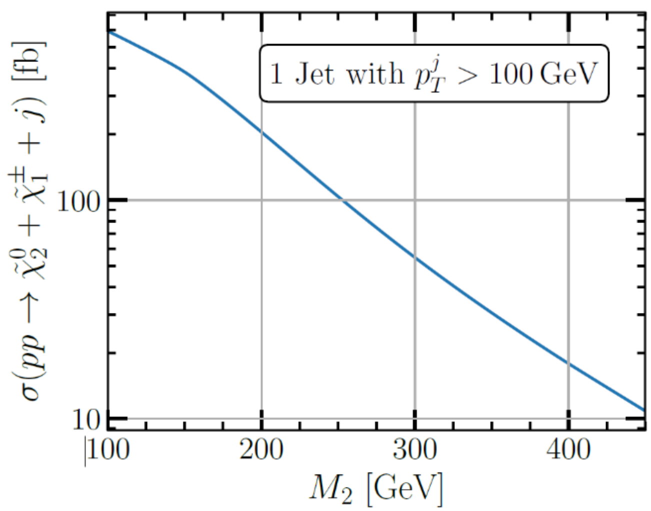


We use SUSY-HIT, MicrOMEGAS 3.2, CheckMATE 2.3, with Madgraph and Pythia, and Delphes

Lighting up the LHC with Dark Matter

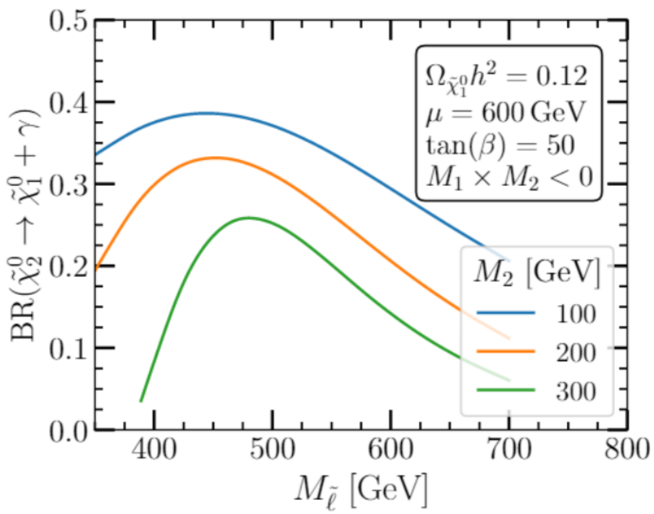
A soft photon $[E \sim \mathcal{O}(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})]$ + missing E_T [boosted by a hard ISR jet]





Strong dependence on electroweakino mass.

Characteristic cross sections of order of tens of fb



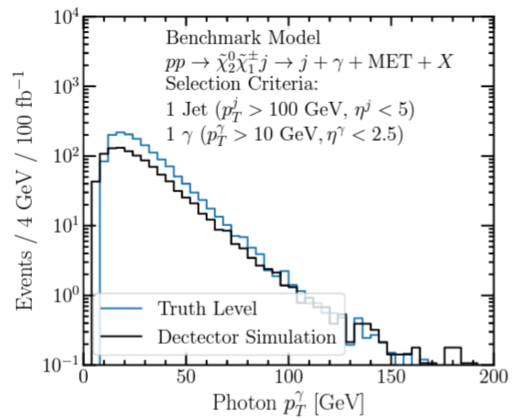
radiative decay BR depends on the slepton masses.

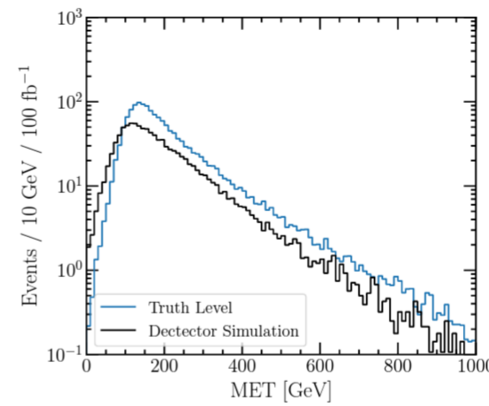
- For small slepton mass parameter, the stau contribution to the three body decay becomes prominent and suppresses the radiative decay
- For large slepton mass parameter, the lack of slepton contribution to the radiative decay loop amplitude suppresses this BR.

Lighting up the LHC with Dark Matter: Benchmark case

- Benchmark parameters and kinematic distributions. In the event selection, we request a hard ISR jet with pTj > 100 GeV to boost the missing energy.

$M_1 = -282\,\mathrm{GeV}$	$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx 300\,\mathrm{GeV}$
$M_2 = 287\,\mathrm{GeV}$	$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 24.1\,\mathrm{GeV}$
$\mu = 800\,\mathrm{GeV}$	$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma) = 36\,\%$
$M_{\tilde{l}} = 500\,\mathrm{GeV}$	$a_\mu^{\mathrm{MSSM}} = 1.7 \times 10^{-9}$
$\tan\beta = 50$	$\Omega_{\tilde{\chi}_1^0} h^2 = 0.118$
	$\sigma(pp \to \tilde{\chi}_1^\pm + \tilde{\chi}_2^0 + j) = 48\,\mathrm{fb}$

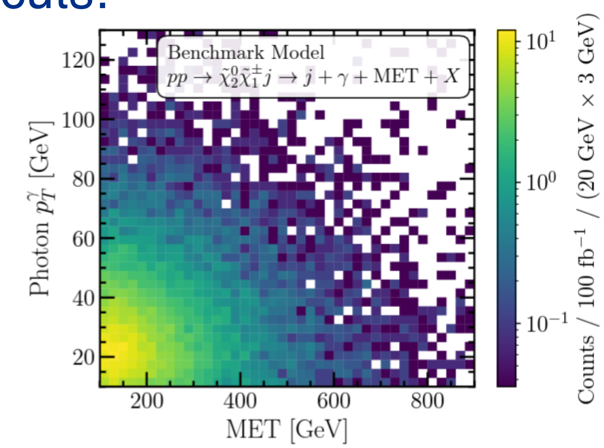




The photon p_T peaks at values close to the neutralino mass difference
The missing Energy is correlated with the ISR jet p_T

Potential Kinetic cuts:

		$\not{E}_T$ cut [GeV]		
		150	300	500
p_T^γ cut [GeV]	0	60%	17%	3.9%
	40	15%	6.0%	1.7%
	70	3.2%	1.6%	0.64%



There are various sources of backgrounds: em backgrounds, jet energy mis-measurements,…

We evaluate the efficiencies of possible MET and $p_T\gamma$ cuts. Due to the absence of correlations between them, a multi-object trigger might be suitable for this search

Outlook

Supersymmetry, guided by the Higgs boson discovery and informed by LHC searches offers a path to uncover mysteries of particle physics

Even the minimal SUSY extension of the SM can accommodate Dark Matter and the possible muon g-2 anomaly

SUSY searches have led to bounds on colored particles in the 1 to 2 TeV range

Stop searches are starting to probe the region of parameter space consistent with a 125 GeV MSSM SM-like Higgs boson

Sensitivity in electroweak interacting particle searches is advancing rapidly at the LHC

The so-called compressed mass region leading to a good WIMP-DM candidate, is starting to be probed via a combined effort of LHC and Direct detection DM searches: Here we propose a new radiative decay search for the Wino NLSP to complement ongoing multilepton searches

Other SUSY extensions, such as the NMSSM, can in addition to a DM candidate, also provide an explanation to Baryogenesis at the Electroweak phase transition
– an exciting possibility with falsifiable signals at current/future experiments -

Extras

Data on SM-like Higgs signal strengths ➔Alignment

For a general 2HDM (H_1, H_2), **the couplings of h/H to V = W,Z are**

$$\mathbf{h} = -\sin\alpha\ \mathbf{H_1^0} + \cos\alpha\ \mathbf{H_2^0}$$
$$\mathbf{H} = \cos\alpha\ \mathbf{H_1^0} + \sin\alpha\ \mathbf{H_2^0}$$

$$\mathbf{HVV} = (\mathbf{hVV})^{\mathbf{SM}} \cos(\beta-\alpha)$$
$$\mathbf{hVV} = (\mathbf{hVV})^{\mathbf{SM}} \sin(\beta-\alpha)$$

In a 2HDM type II (e.g. MSSM), H_1 couples to down-quarks and charged leptons, while H_2 couples to up-quarks. **$\langle H_i \rangle = v_i$ tan $\beta = v_2/v_1$**

$$\mathbf{g_{hdd(hll)}} = \frac{\mathbf{m_{d(l)}}}{\mathbf{v}} \frac{(-\sin\alpha)}{\cos\beta} \qquad \mathbf{g_{Hdd(Hll)}} = \frac{\mathbf{m_{d(l)}}}{\mathbf{v}} \frac{\cos\alpha}{\cos\beta}$$

$$\mathbf{g_{huu}} = \frac{\mathbf{m_{uu}}}{\mathbf{v}} \frac{\cos\alpha}{\sin\beta} \qquad \mathbf{g_{Huu}} = \frac{\mathbf{m_{u}}}{\mathbf{v}} \frac{\sin\alpha}{\sin\beta}$$

In 2HDM type I, all fermions couple to H_2

If the mixing in the CP-even sector yields cos (β-α) = 0 ➔ cosα = sinβ

The lightest Higgs coupling to fermions and gauge bosons is SM-like.

This situation is called ALIGNMENT Gunion and Haber ’03

H and A couplings scale like 1/ tanβ with the exception of the down-quark/lepton couplings enhanced by tanβ in Type II (SUSY)

Alignment Conditions in General 2HDMs

General 2HDM
Higgs potential

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2$$
$$+\lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+\left\{\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)]\Phi_1^\dagger \Phi_2 + \text{h.c.}\right\} ,$$

Minimization conditions define m_A, m_{H+} and $m_{h/H}$ in terms of quartic couplings, one mass parameter and tanβ

Eigenstate Eq.

$$\underbrace{\begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}}_{\approx 0} = -\frac{v^2}{m_A^2} \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix} + \frac{m_h^2}{m_A^2} \begin{pmatrix} -s_\alpha \\ c_\alpha \end{pmatrix}$$

≈ 0 ➔ cos (β-α) = 0

Alignment occurs for **large values of m_A ➔ Decoupling OR**

specific conditions independent of M_A ➔ Alignment without decoupling

If no CP violation in the Higgs sector

Valid for any 2HDM

$$(m_h^2 - \lambda_1 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^2 = v^2 (3\lambda_6 t_\beta + \lambda_7 t_\beta^3) ,$$
$$(m_h^2 - \lambda_2 v^2) + (m_h^2 - \tilde{\lambda}_3 v^2) t_\beta^{-2} = v^2 (3\lambda_7 t_\beta^{-1} + \lambda_6 t_\beta^{-3})$$

Craig, Galloway, Thomas'13   M.C, Low, Shah, Wagner '13

Electroweak baryogenesis with Supersymmetry

A more extended Higgs sector: two Higgs doublets + a singlet

both charged under the EW gauge group

provides flexibility enhancing the PT strength

The multiple field space scalar potential makes the study of phase transitions challenging

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + |\lambda H_u \cdot H_d + \kappa S^2|^2$$
$$+ \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + \frac{g_1^2 + g_2^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2$$

we consider the 3-dim. field space

$$\langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix} \quad \langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$
$$\langle S \rangle = v_S$$

CP even interaction states $\{H^{\text{SM}}, H^{\text{NSM}}, H^S\}$ $\rightarrow$ CP even mass states $\{h_{125}, H, h_S\}$

Higgs basis

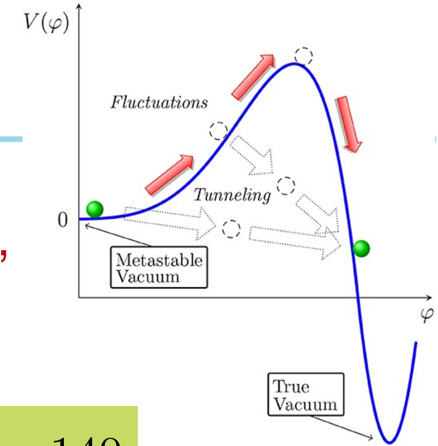
The EW vacuum: $\langle H^{\text{SM}} \rangle = v, \quad \langle H^{\text{NSM}} \rangle = 0, \quad \langle H^{\text{SM}} \rangle = v_S$

After minimization conditions, replacing mass parameters by vev's and suppressing mixing of H^{NMS} and H^S with H^{SM} to be consistent with Higgs 125 GeV phenomenology

Parameter space: $\left\{v \equiv \sqrt{v_d^2 + v_u^2}\,,\ \tan\beta \equiv v_u/v_d\,,\ \mu \equiv \lambda v_S,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa\right\} \mapsto \{\mu,\ \tan\beta,\ \kappa,\ A_\kappa\}$

After considering temperature and quantum effects, many benchmarks yield the desired EW vacuum structure and sphaleron rate suppression at the critical temperature

Nucleation is more than critical



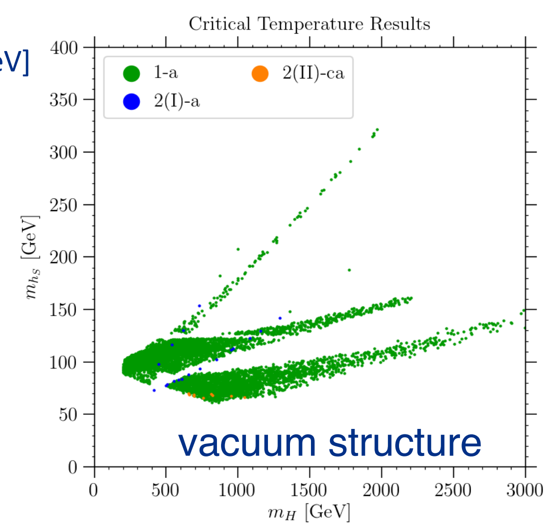
Vacuum structure gives little information about tunneling probability.

➔ the higher the barrier, and the larger the distance between minima, the lower the nucleation rate

The bubble nucleation rate per unit volume: $\Gamma/V \propto T^4 e^{-S_3/T}$

requiring the nucleation probability to be approx. one per Hubble volume and Hubble time leads to the nucleation condition ⟶ $\frac{S_3(T_n)}{T_n} \simeq 140$

M_{hs} [GeV]

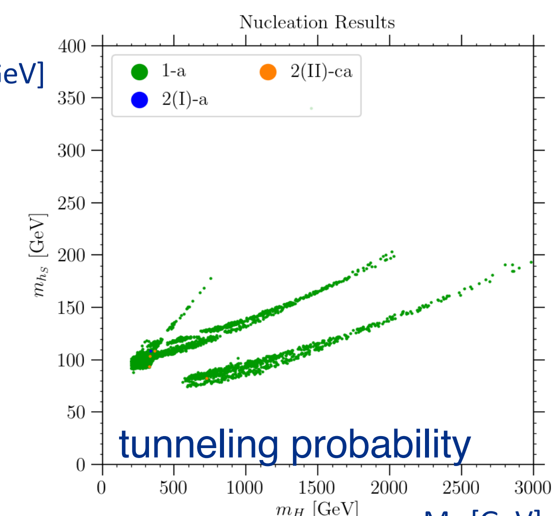


M_H [GeV]

T_c ⟶ T_n

Baum, M.C. Shah, Wagner, Wang, JHEP 04(2018) 069

M_{hs} [GeV]



M_H [GeV]

Collider and Dark Matter opportunities

- Strong EWPT with a non-SM-like Higgs boson (m_H > 200GeV) and a lighter singlet h_s
- These states are hard to probe in colliders due to alignment and decays into electroweakinos; best search channel $H \rightarrow h_{125} + h_S$
- The most promising dark matter scenario is a bino-like lightest neutralino