

# A few words about Herbi



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**Herbi-Fest, March 27, 2023**  
**University of Bonn**

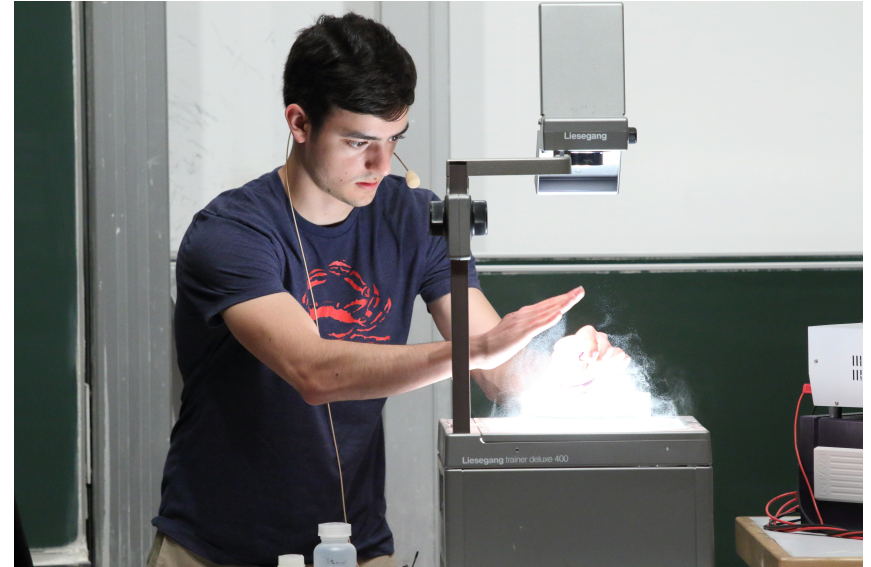
# Herbi and Physics

- My connection to Herbi dates to our early postdoc years.
- We both shared love for Supersymmetry, and we remain among the few believers in it (although there are many others here).





Herbi also became a friend of our son Sebastian, who had the plan of being here today but will arrive tomorrow due to the Deutsche Bahn (EVG) Streik



## PHYSICS SHOW 2016

arXiv:1607.07478

“What’s (the) Matter?”,

A Show on Elementary Particle Physics with 28

Demonstration Experiments

Herbi K. Dreiner<sup>\*1,2</sup>, Max Becker<sup>3</sup>, Mikolaj Borzyszkowski<sup>4</sup>, Maxim Braun<sup>1</sup>, Alexander Faßbender<sup>1</sup>, Julia Hampel<sup>1</sup>, Maïke Hansen<sup>1</sup>, Dustin Hebecker<sup>1,5</sup>, Timo Heepenstrick<sup>6</sup>, Sascha Heinz<sup>1</sup>, Katharina Hortmanns<sup>1</sup>, Christian Jost<sup>3</sup>, Michael Kortmann<sup>1</sup>, Matthias U. Kruckow<sup>4</sup>, Till Leuteritz<sup>1</sup>, Claudia Lütz<sup>3</sup>, Philip Mahlberg<sup>3</sup>, Johannes Müllers<sup>3</sup>, Toby Opferkuch<sup>1,2</sup>, Ewald Paul<sup>1</sup>, Peter Pauli<sup>3</sup>, Merlin Rossbach<sup>3</sup>, Steffen Schaepe<sup>1</sup>, Tobias Schiffer<sup>1</sup>, Jan F. Schmidt<sup>1</sup>, Jana Schüller-Ruhl<sup>4</sup>, Christoph Schürmann<sup>1</sup>, Lorenzo Ubaldi<sup>1,7</sup>, and Sebastian Wagner-Carena<sup>8</sup>

This photo is from three years ago, in Santa Cruz, celebrating Sebastian's birthday and the imminent release of Howie, Steve and Herbi's book (that we are celebrating again now.).



To be fair, a partial version of their book was published a few (fifteen) years ago, in 2008, [arXiv:0812.1594](https://arxiv.org/abs/0812.1594) !

The iPhone was a novelty on those days and there were high hopes for SUSY at the LHC.

## Herbi carries also an old passion (42 articles) :

### R-parity violation at hadron colliders

[Herbert K. Dreiner](#)([Oxford U.](#)), [Graham G. Ross](#)([Oxford U.](#)) (Jul 8, 1991)

Published in: *Nucl.Phys.B* 365 (1991) 597-613

### Bounds on R-parity violating couplings at the weak scale and at the GUT scale

[B.C. Allanach](#)([Cambridge U., DAMTP](#)), [A. Dedes](#)([Rutherford](#)),

[Herbert K. Dreiner](#)([Rutherford](#)) (Jun, 1999)

Published in: *Phys.Rev.D* 60 (1999) 075014 • e-Print: [hep-ph/9906209](#) [hep-ph]

### An Introduction to explicit R-parity violation      667 citations !

[Herbert K. Dreiner](#)([Rutherford](#)) (Jul, 1997)

Published in: *Adv.Ser.Direct.High Energy Phys.* 21 (2010) 565-583 •

e-Print: [hep-ph/9707435](#) [hep-ph]

## And it is not dying out

### Nucleon decay in the R-parity violating MSSM

[Nidal Chamoun](#)([HIAST](#)), [Florian Domingo](#)([U. Bonn, Phys. Inst., BCTP](#)),

[Herbert K. Dreiner](#)([U. Bonn, Phys. Inst., BCTP](#)) (Dec 21, 2020)

Published in: *Phys.Rev.D* 104 (2021) 1, 015020 • e-Print: [2012.11623](#) [hep-ph]



# I agree with the need to study R-Parity violation

- As a joke, I postulated Wagner's theorem :
- Any collider anomaly, no matter how strange it is, may be explained with Supersymmetry with R-Parity violation (and by extension with leptoquarks).
- Important corollary of the Wagner's Theorem : Any anomaly that demands R-Parity violation to be explained is either a statistical fluctuation or an experimental error and will soon disappear.
- It is now being quoted in physics talks :) . I apologize to Herbi for the bad mouthing of R-Parity violation.



# Double Checking Herbi's recent most cited articles

CheckMATE: Confronting your Favourite New Physics Model with LHC Data

[Manuel Drees](#)([Bonn U.](#)), [Herbi Dreiner](#)([Bonn U.](#)), [Daniel Schmeier](#)([Bonn U.](#)),

[Jamie Tattersall](#)([Heidelberg U.](#) and [Bonn U.](#)),

[Jong Soo Kim](#)([Madrid, IFT](#) and [Adelaide U.](#)) (Dec 9, 2013)

Published in: *Comput.Phys.Commun.* 187 (2015) 227-265 • e-Print: 1312.2591 [hep-ph]

321 citations

How low can SUSY go? Matching, monojets and compressed spectra

[Herbi Dreiner](#) ([Bonn U.](#)), [Michael Kramer](#)([RWTH Aachen U.](#)),

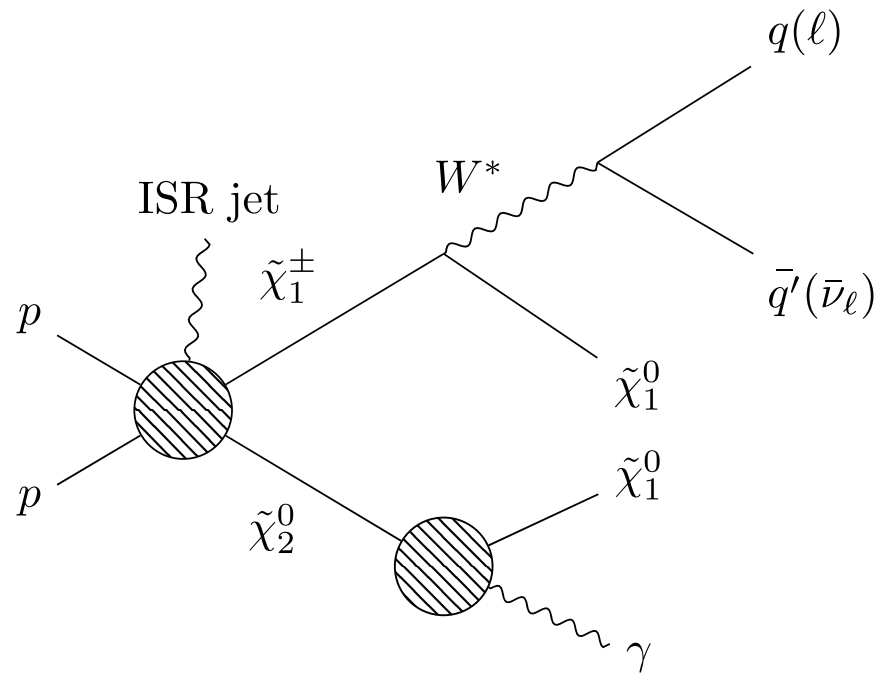
[Jamie Tattersall](#)([Bonn U.](#)) (Jul, 2012)

Published in: *EPL* 99 (2012) 6, 61001 • e-Print: 1207.1613 [hep-ph]

132 citations

I will come back to these two subjects during my science talk !

# Signals of Electroweakino Searches at the LHC

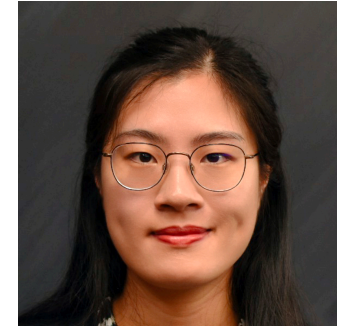
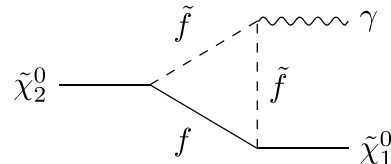
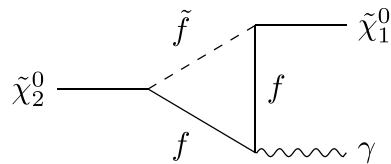


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# Based on work performed with



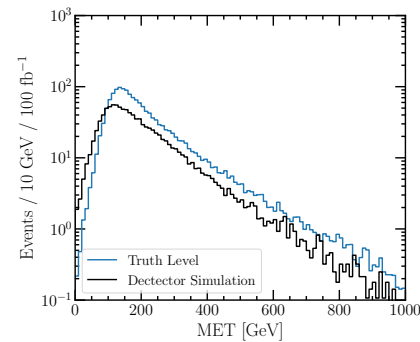
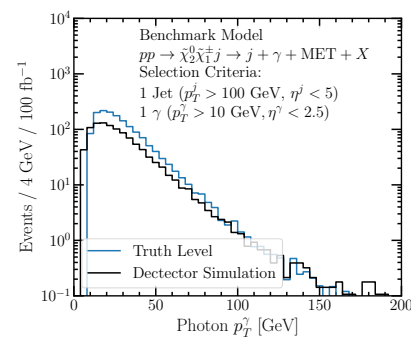
Duncan Rocha



Tong Ou



Marcela Carena



Sebastian Baum



Nausheen Shah

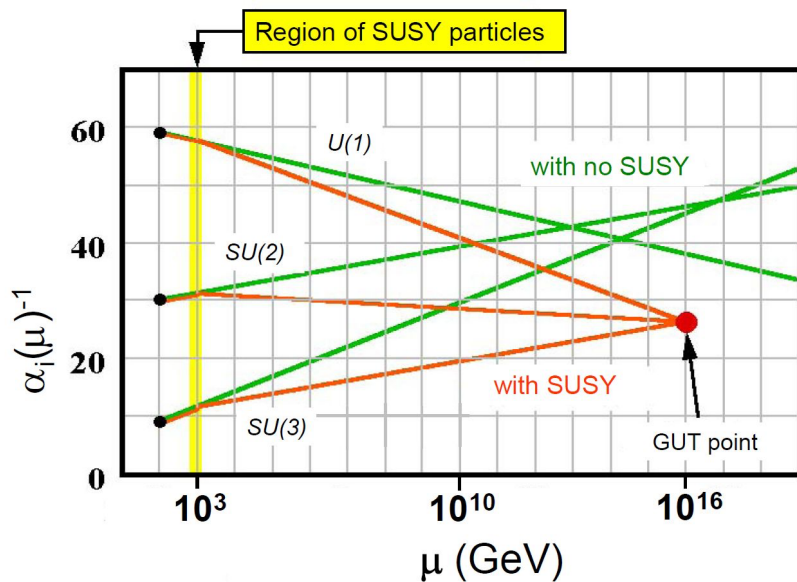
“Lighting up the LHC with Dark Matter”

Authors: Sebastian Baum, Marcela Carena, Tong Ou,  
Duncan Rocha, Nausheen R. Shah, Carlos E. M. Wagner  
arXiv: 2303.01523



# Consequences of SUSY

## Unification



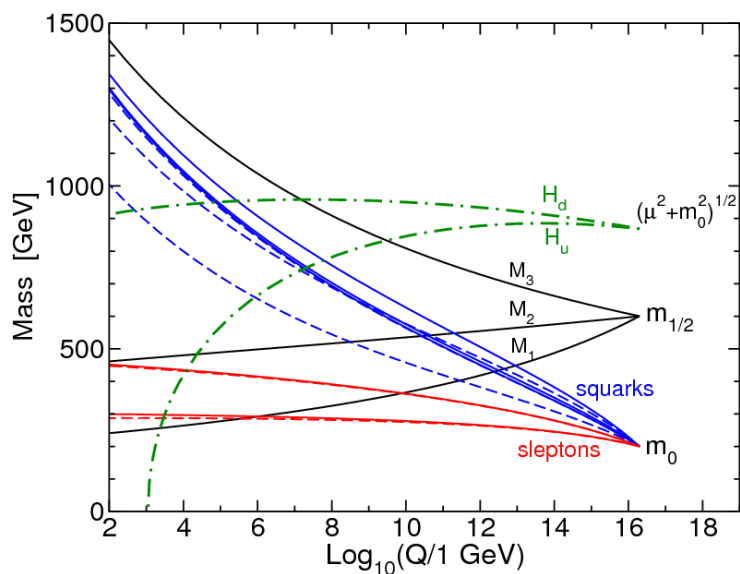
## SUSY Algebra

$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

$$[Q_\alpha, P_\mu] = [\bar{Q}_{\dot{\alpha}}, P_\mu] = 0$$

## Quantum Gravity ?

## Electroweak Symmetry Breaking



If R-Parity is Conserved the Lightest SUSY particle is a good Dark Matter candidate

## Stop Searches : MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

\* CP-odd Higgs mass  $m_A$

$$* \tan \beta = \frac{v_u}{v_d}$$

\* the top quark mass

\* the stop masses and mixing

$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

$M_h$  depends logarithmically on the averaged stop mass scale  $M_{\text{SUSY}}$  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

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

$$t = \log(M_{\text{SUSY}}^2 / m_t^2) \quad \tilde{X}_t = \frac{2X_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \quad \underline{X_t = A_t - \mu / \tan \beta \rightarrow \text{LR stop mixing}}$$

Carena, Espinosa, Quiros, C.W.'95,96

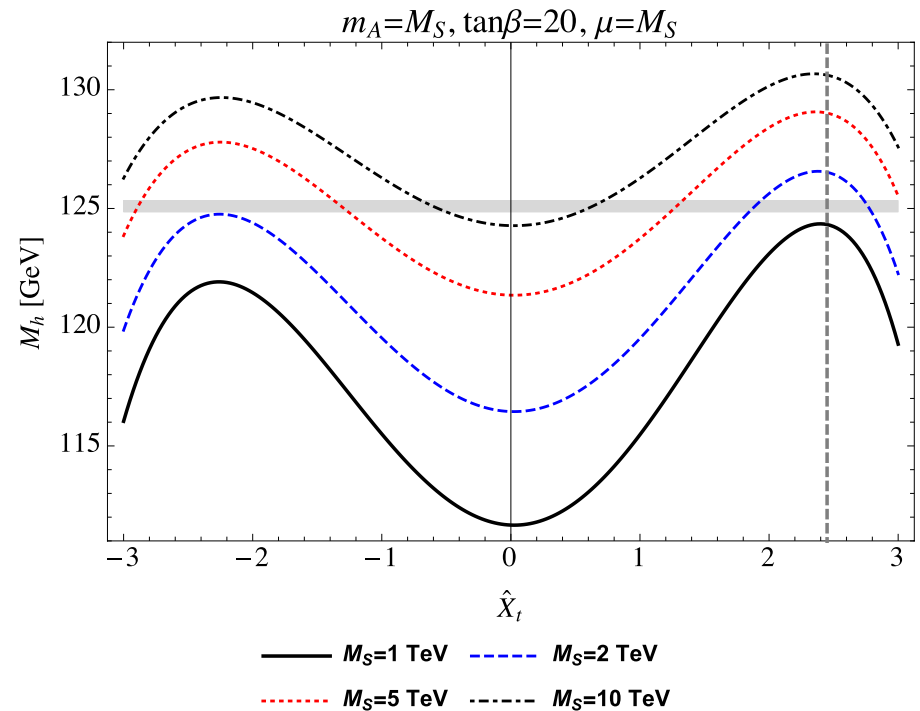
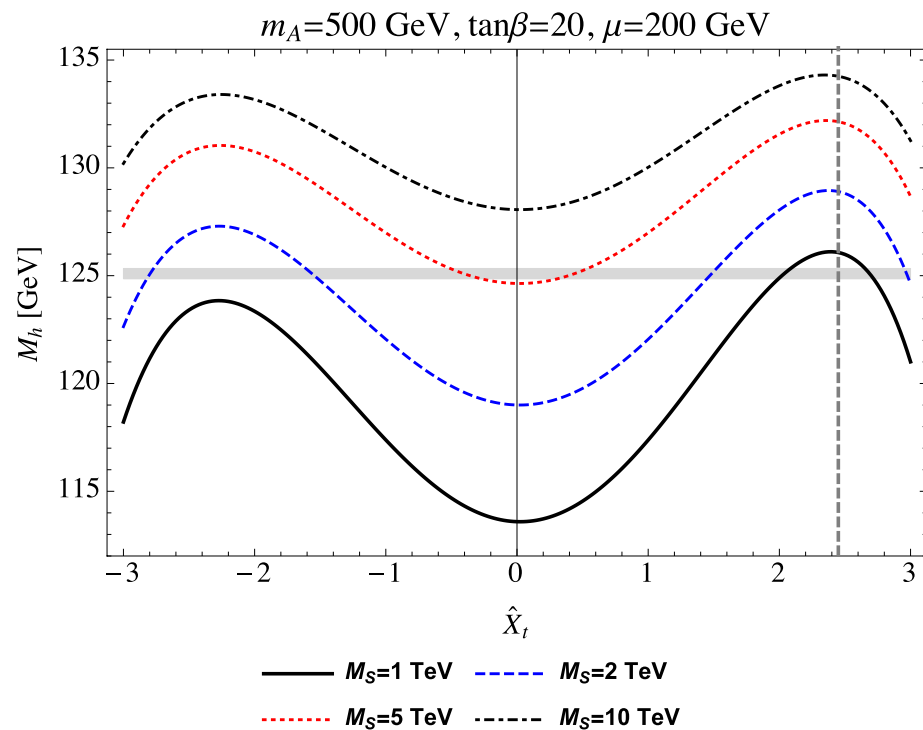
Analytic expression valid for  $M_{\text{SUSY}} \sim m_Q \sim m_U$

# MSSM Guidance: Stop Masses above about 1 TeV lead to the right Higgs Masss

P. Slavich, S. Heinemeyer et al, arXiv:2012.15629

P. Draper, G. Lee, C.W.'13, Bagnaschi et al' 14, Vega and Villadoro '14, Bahl et al'17

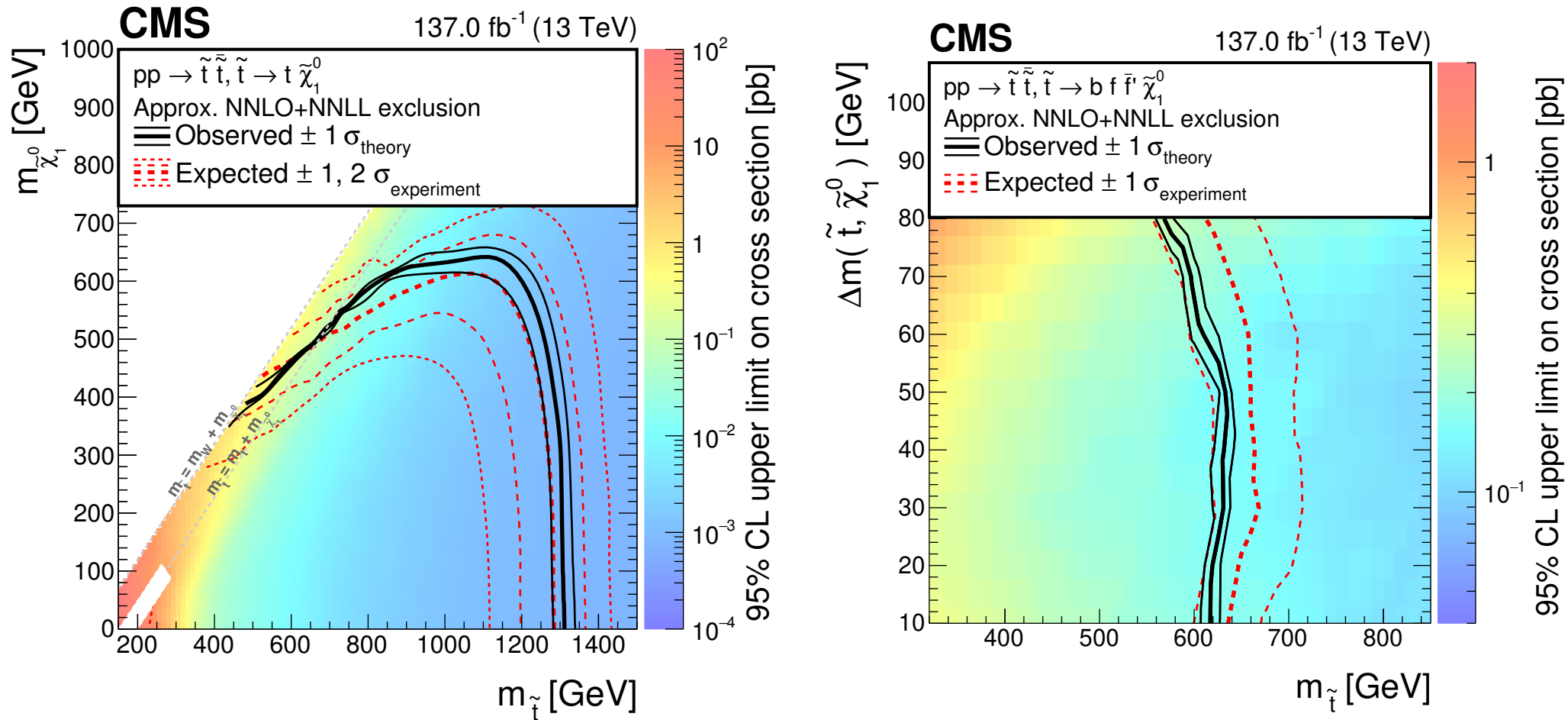
G. Lee, C.W. arXiv:1508.00576



Necessary stop masses increase for lower values of  $\tan\beta$ , larger values of  $\mu$  smaller values of the CP-odd Higgs mass or lower stop mixing values.

Lighter stops demand large splittings between left- and right-handed stop masses

# Stop Searches



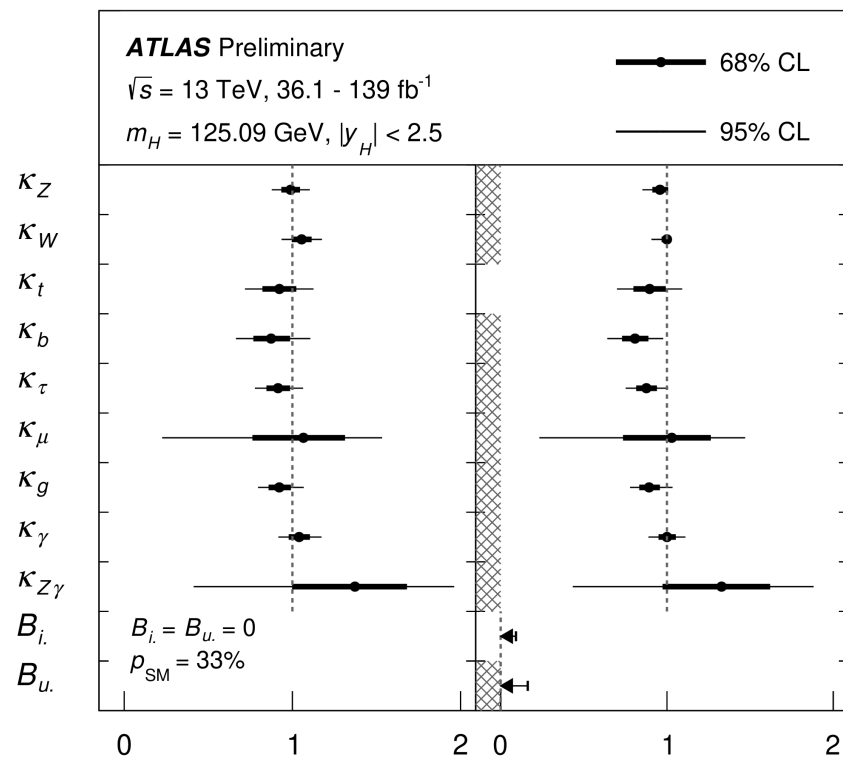
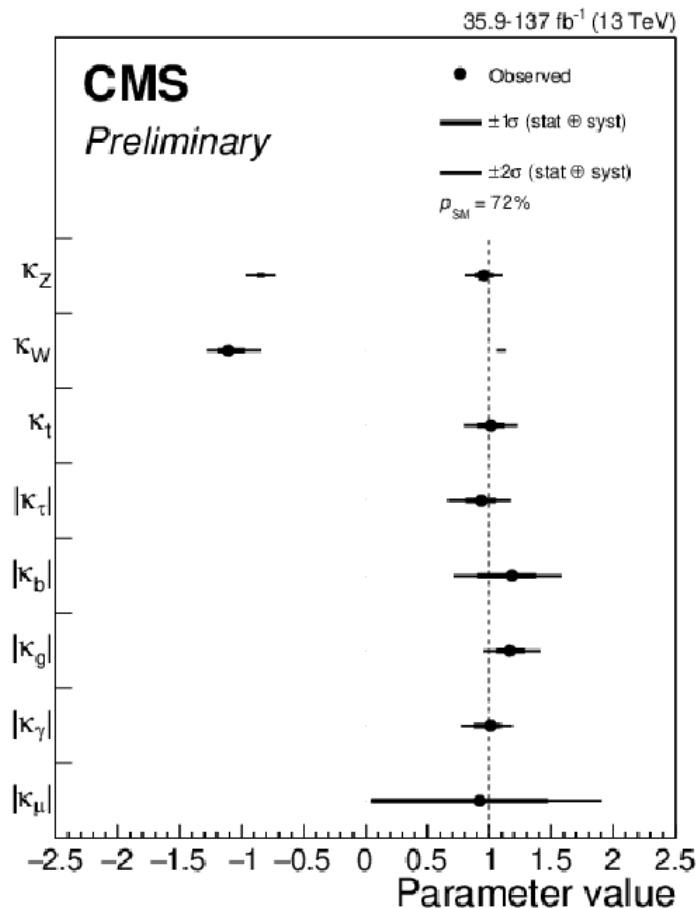
Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

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



# ATLAS and CMS Fit to Higgs Couplings

Departure from SM predictions of the order of  
few tens of percent allowed at this point



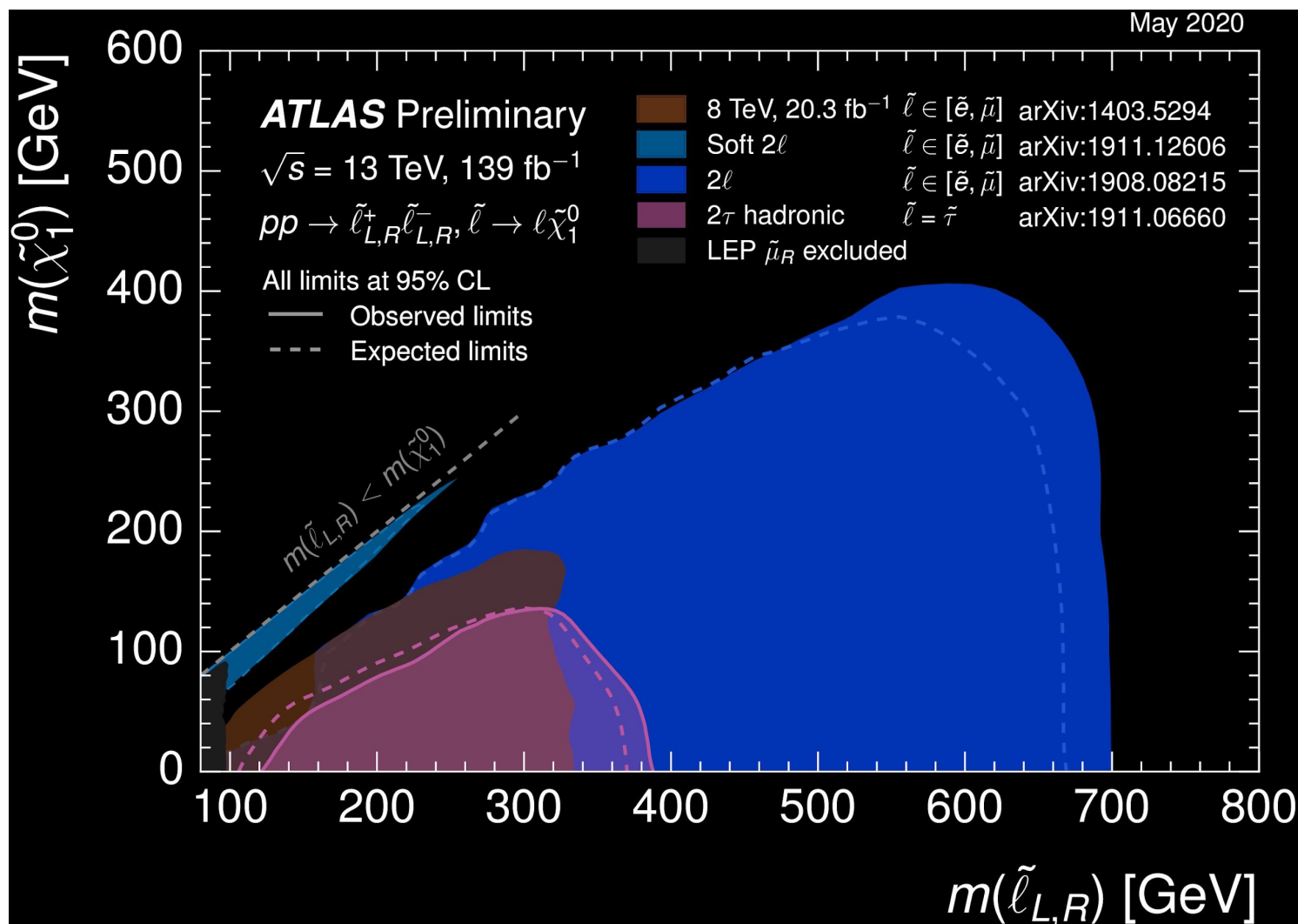
Decoupling of the heavy Higgs sector (or alignment)  
is preferred at this point. We shall set the heavy Higgs  
mass equal to the color state masses, of order 2.5 TeV

# Electroweak Sector

- Situation here is far less well defined than in the strongly interacting sector
- Sleptons, in particular staus are only weakly constrained beyond the LEP limits
- 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 the highest hopes for detection of SUSY at the weak scale.

# Slepton Searches

Assuming **all sleptons are degenerate**, bound can be as large as 700 GeV. However, the bounds are highly relaxed if the spectrum is somewhat compressed and if the sleptons don't decay directly to the LSP



# MSSM charginos and neutralinos

## Mass matrices

charginos

in  $(\tilde{W}^-, \tilde{H}^-)$  basis

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

neutralinos

in  $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$  basis

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

$$M_2 \text{ real}, \quad M_1 = |M_1|e^{i\Phi_1}, \quad \mu = |\mu|e^{i\Phi_\mu}$$

At tree level:

$$\begin{array}{l} \text{charginos} \\ \text{neutralinos} \end{array} \quad M_2, \mu, \tan \beta \quad + M_1$$

$\Phi_\mu, \Phi_1$   
CP phases

Expected to be among the lightest sparticles

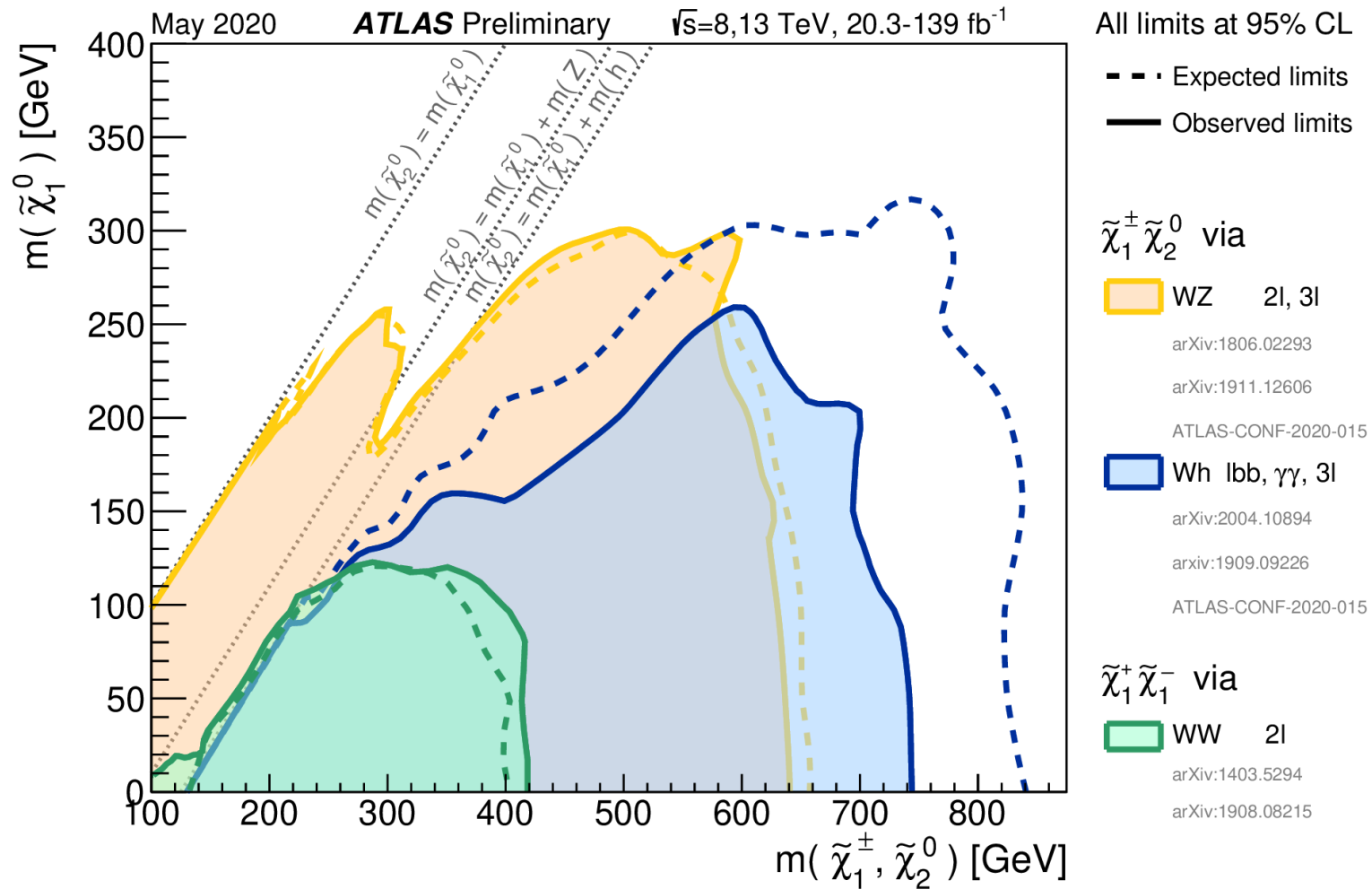


A good starting point towards SUSY parameter determination

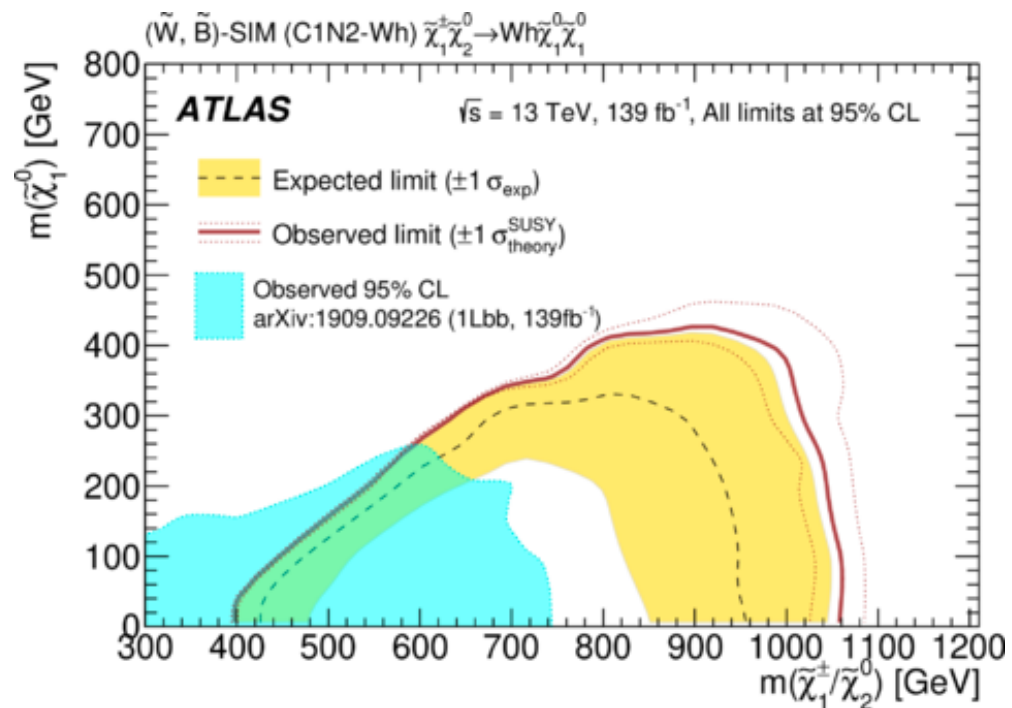
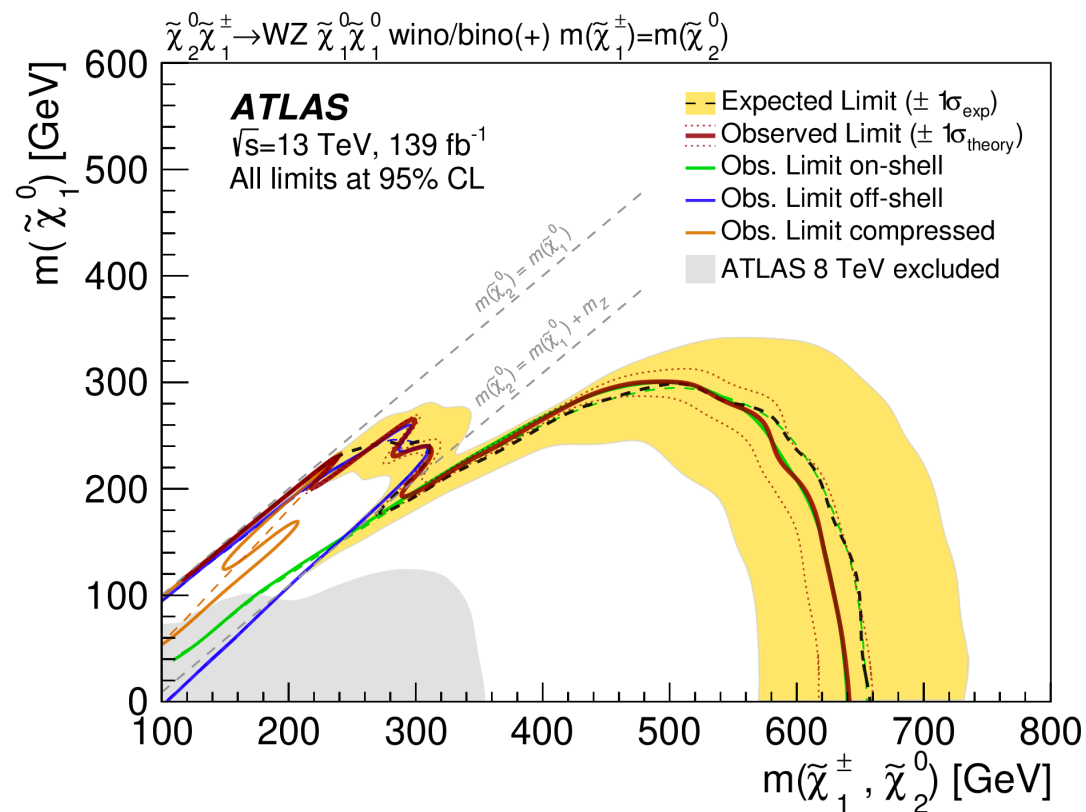


# Current Electroweakino Mass Bounds

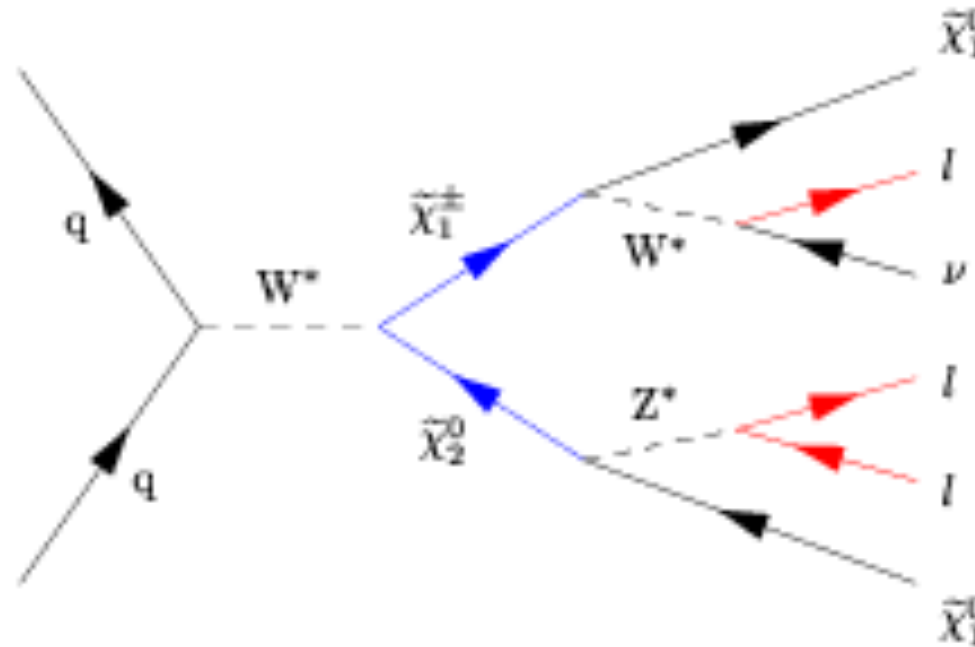
## Wino NLSP BR = 1



## Remarkable Improvement of Bounds away from the Compressed Region



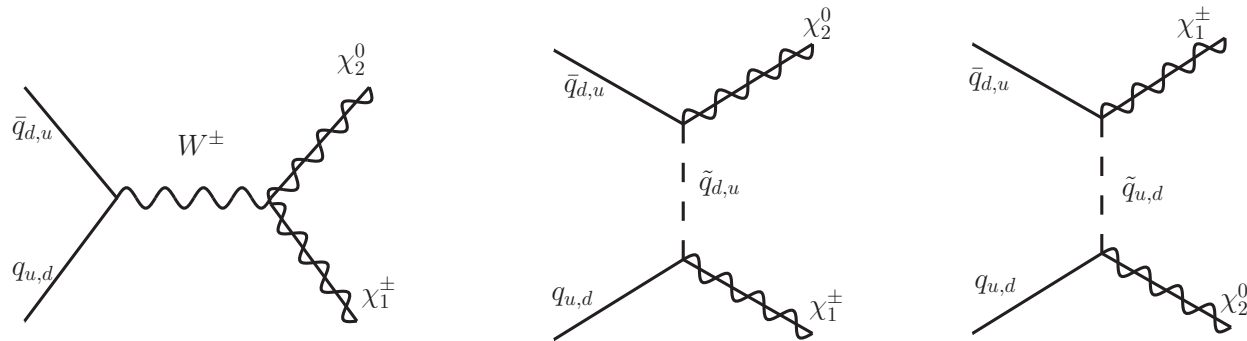
# Chargino-Neutralino Production



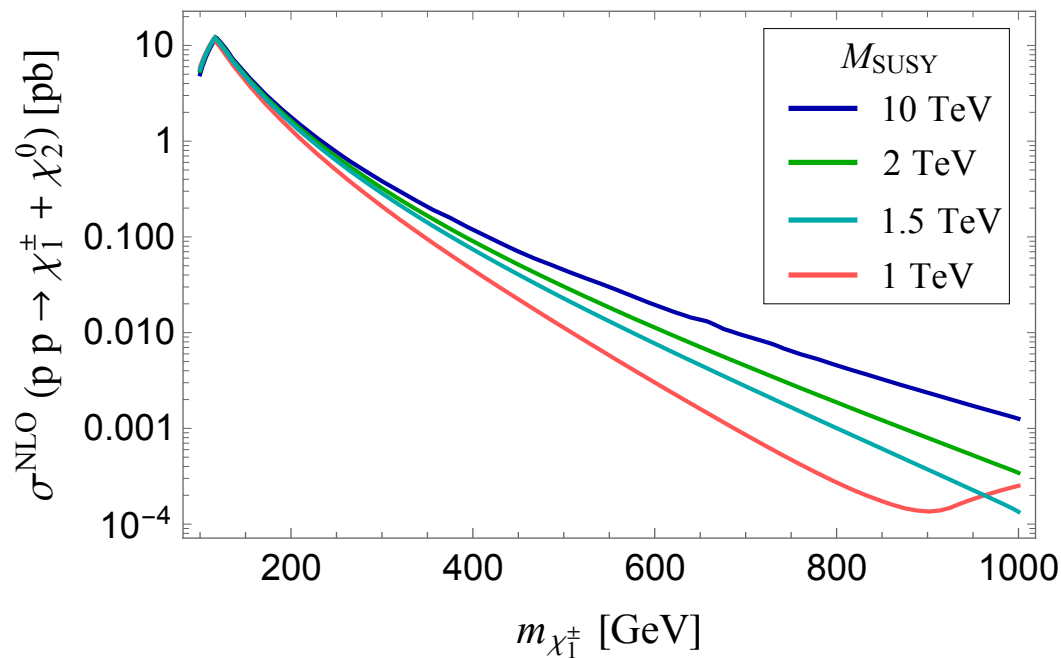
- For values of the wino and Higgsino masses larger than the weak scale, the mixing between them is small.
- Winos, in the adjoint representation of  $SU(2)$ , are produced at a stronger rate than Higgsinos.
- The cross section for **Wino production** is about a factor 4 larger than the one for **Higgsino production**.
- Mixing increases for smaller mass differences, leading to a reduction of the wino cross section, and to the **addition of new channels**, some of them mixed “Wino-Higgsino”.

However, in evaluating these bounds the squarks have been taken to decouple. But the cross section depends on the squark masses due to a t and u channel contribution to them.

Liu, McGinnis, Wang, C.W. arXiv:2008.11847



The resulting cross sections may differ in factors of a few.



# Wino Bounds for positive $\mu \times M2$

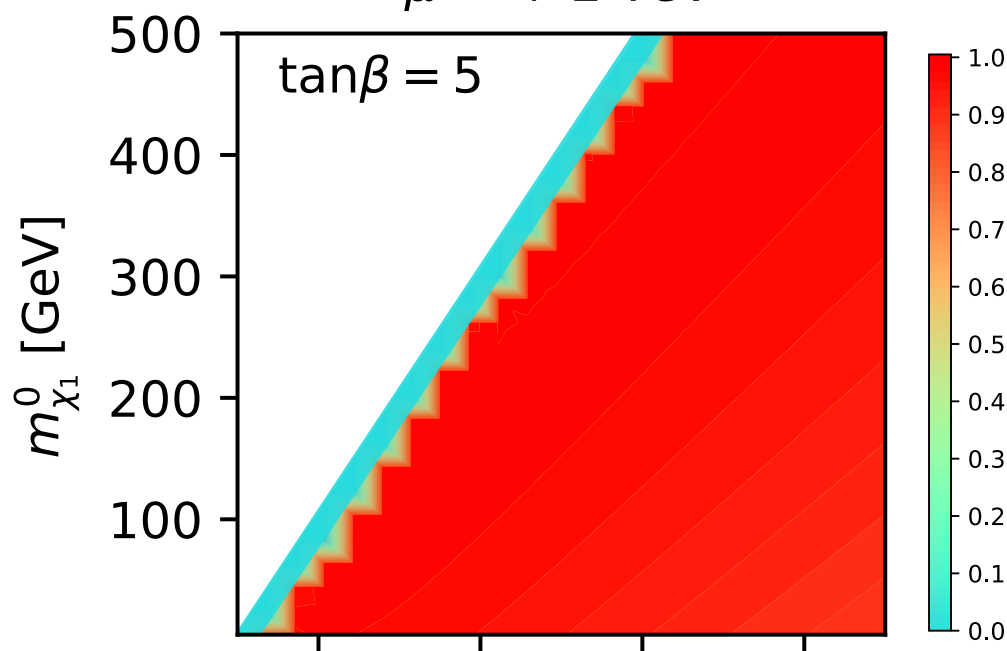
Liu, McGinnis, Wang, C.W. arXiv:2008.11847

Also, 100 percent BR into  $W/W^*$  and  $Z/Z^*$  have been assumed.

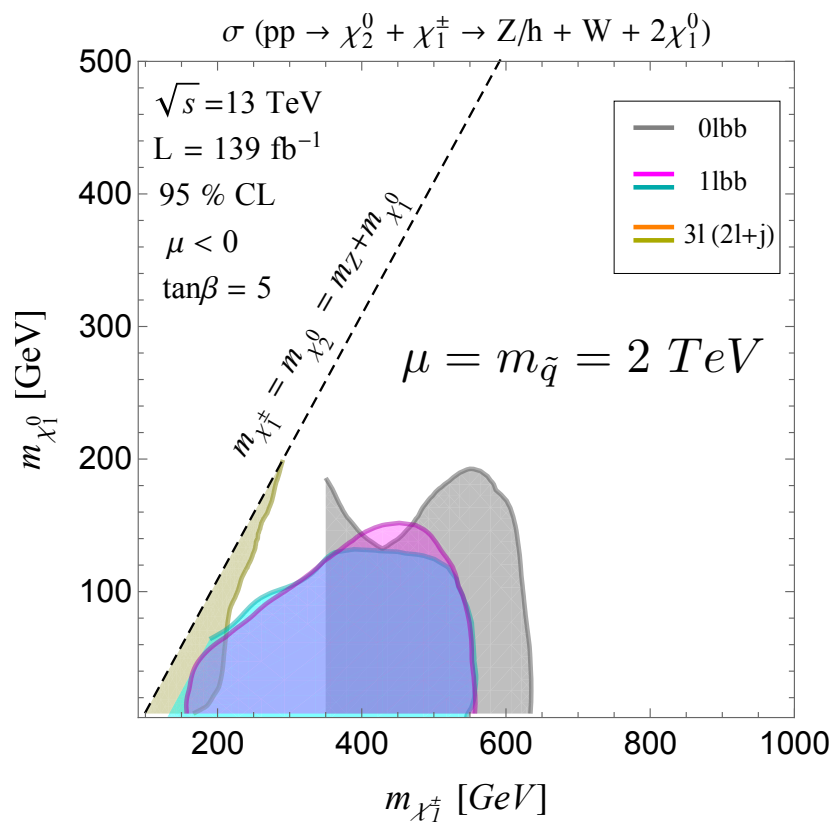
$$\text{BR}(\chi_2^0 \rightarrow h + \chi_1^0)$$

$$\mu = +2 \text{ TeV}$$

$$\tan\beta = 5$$



Recasting of ATLAS bounds lead to weak constraints in the (somewhat) compressed region.



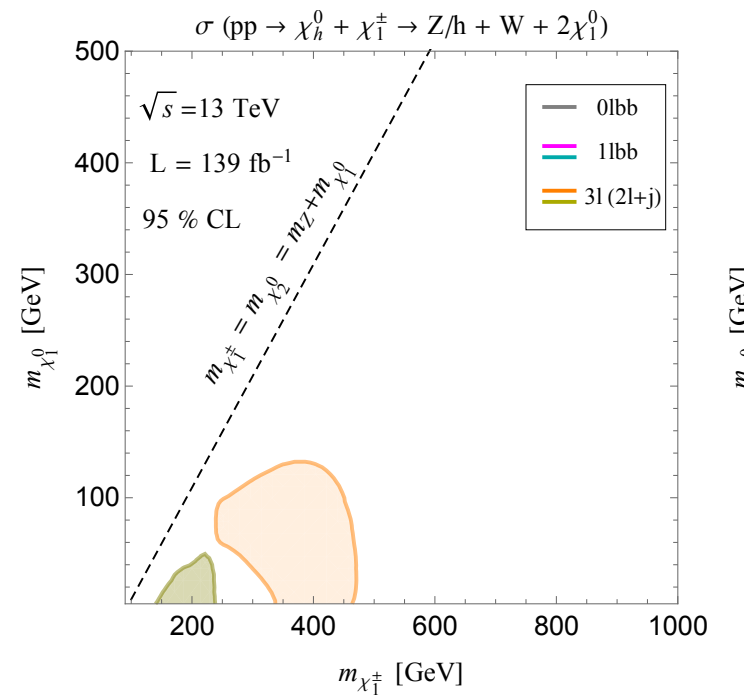
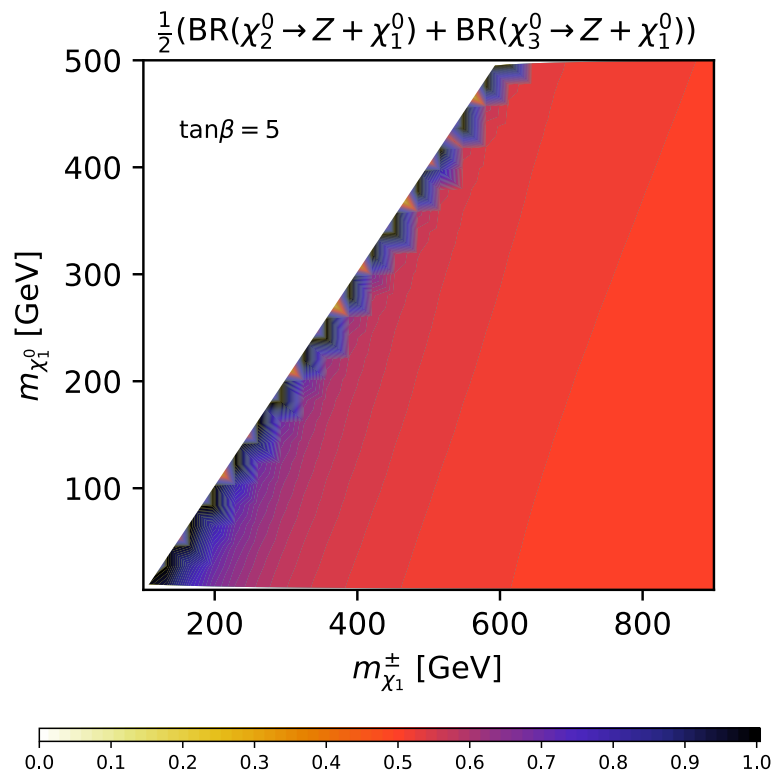


# Higgsino Bounds

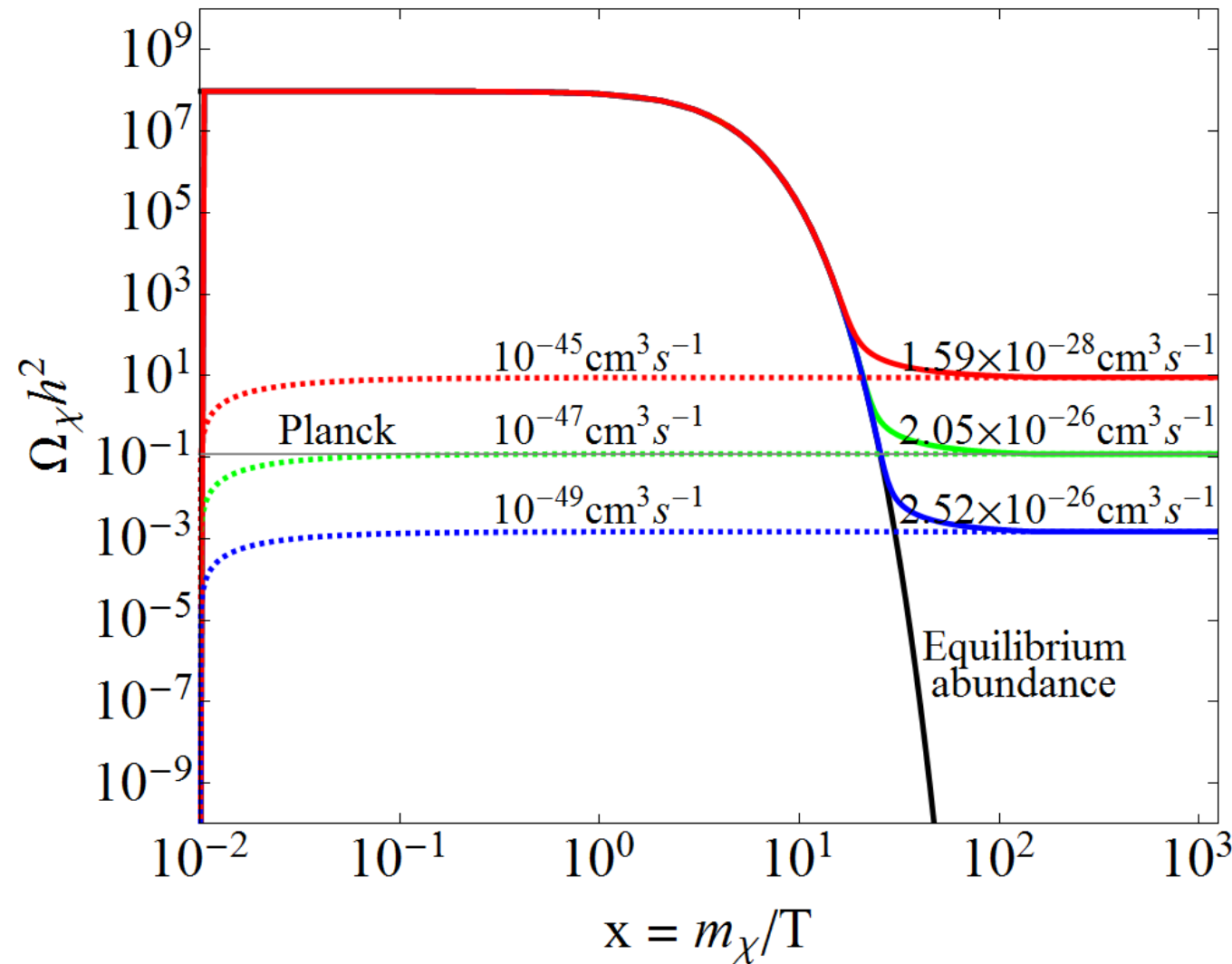
Large M2 : Higgsino Cross section almost a factor four smaller than the Wino cross section. BR of the second lightest neutralino is about 50 percent into  $h$  and  $Z$ . Bounds are significantly weaker than in the Wino case.

Conclusion is that in the compressed region limits are quite weak whenever the lightest neutralino mass is larger than about 200 GeV.

Liu, McGinnis, Wang, C.W., arXiv:2006.07389

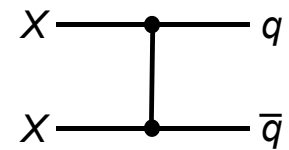


# Dark Matter as a Big Bang Relic



Kolb and Turner  
The Early Universe

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



$$m_X \sim 100 \text{ GeV}, g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$$

Weak scale size masses and couplings roughly consistent with  $\Omega_{\text{DM}}$

**WIMPS**

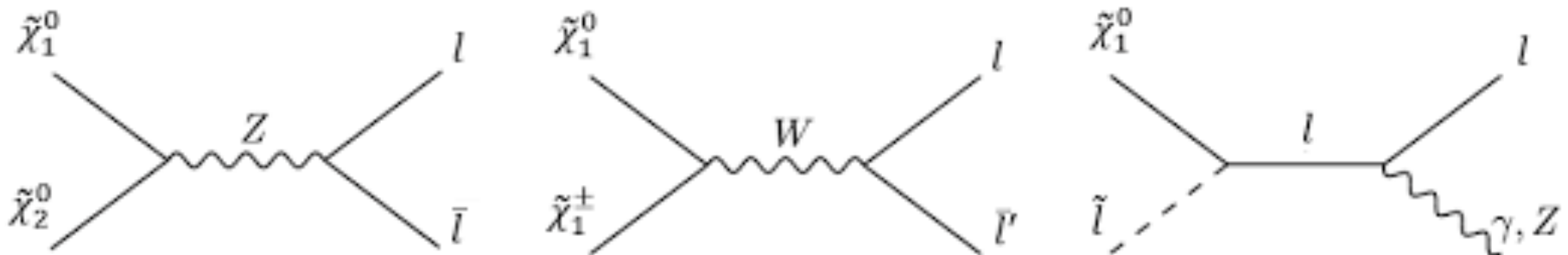
## Co-annihilation

It happens when the DM can annihilate against other rapidly annihilating particles.

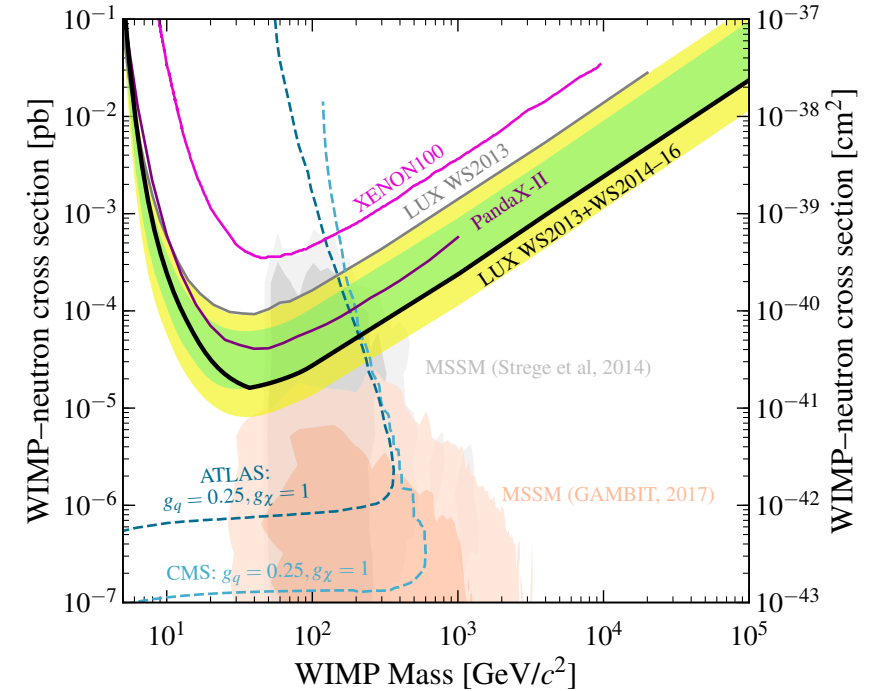
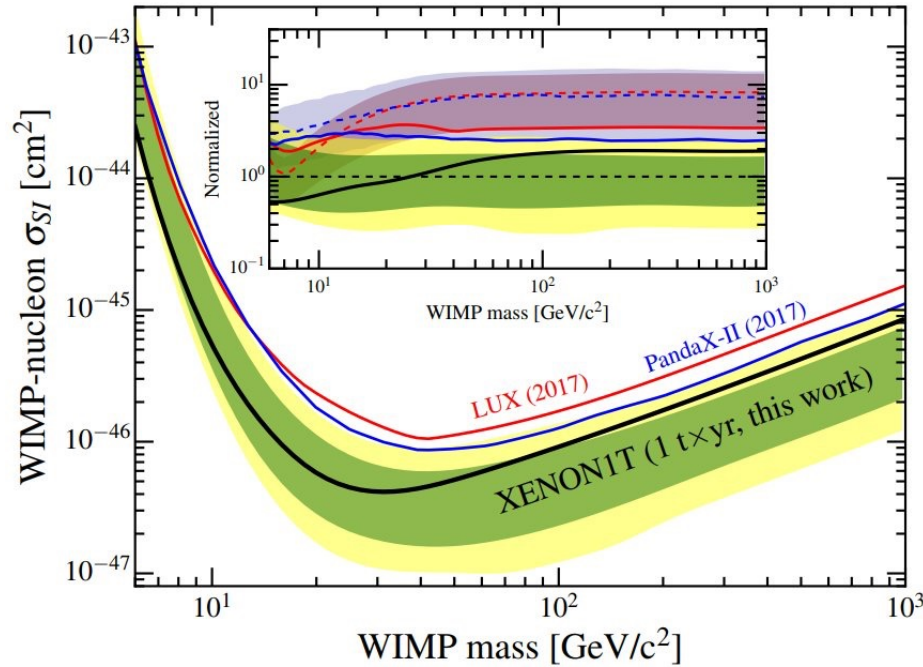
For it to work, the mass difference of the Dark Matter with the other weak scale weakly interacting particles must be of the order of a few tens of GeV.

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 Higgsinos/ small  $\mu$  leads to large SD cross sections).



# DM : Direct Detection Bounds



$$\sigma_p^{\text{SI}} \propto \frac{m_Z^4}{\mu^4} \left[ 2(m_{\tilde{\chi}_1^0} + 2\mu/\tan\beta) \frac{1}{m_h^2} + \mu \tan\beta \frac{1}{m_H^2} + (m_{\tilde{\chi}_1^0} + \mu \tan\beta/2) \frac{1}{m_{\tilde{Q}}^2} \right]^2$$

Blind Spot :

$$2 \left( m_{\tilde{\chi}_1^0} + 2 \frac{\mu}{\tan\beta} \right) \frac{1}{m_h^2} \simeq -\mu \tan\beta \left( \frac{1}{m_H^2} + \frac{1}{2m_{\tilde{Q}}^2} \right) \quad \begin{array}{l} \mu \times m_{\tilde{\chi}_1^0} < 0 \\ m_{\tilde{\chi}_1^0} \simeq M_1 \end{array}$$

Cheung, Hall, Pinner, Ruderman'12, Huang, C.W.'14, Cheung, Papucci, Shah, Stanford, Zurek'14, Han, Liu, Mukhopadhyay, Wang'18

$$\sigma^{\text{SD}} \propto \frac{m_Z^4}{\mu^4} \cos^2(2\beta)$$

# Blind Spots in the Spin-Independent Cross Section

J. Ellis, K. Olive, Y. Santoso, V.C. Spanos '05

H. Baer, A. Mustayev, E. Park, X. Tata '06

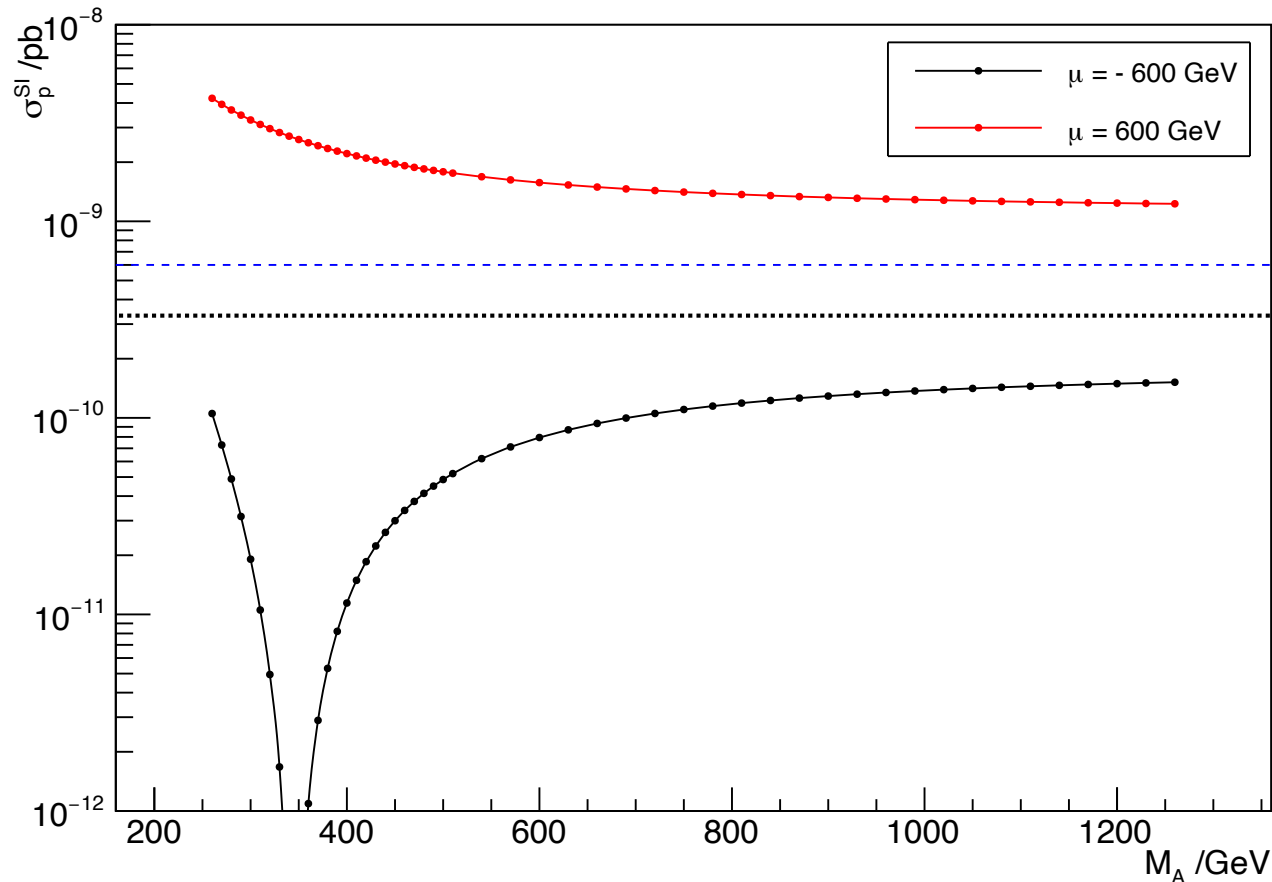
P. Huang, C.W.'14

C. Cheung, D. Sanford, M. Papucci, N.R. Shah, K. Zurek '14

P. Huang, R. Roglans, D. Spiegel, Y. Sun, C.W.'17

S. Baum, M. Carena, N.R. Shah, S. Baum '18

Spin independent cross section - MA



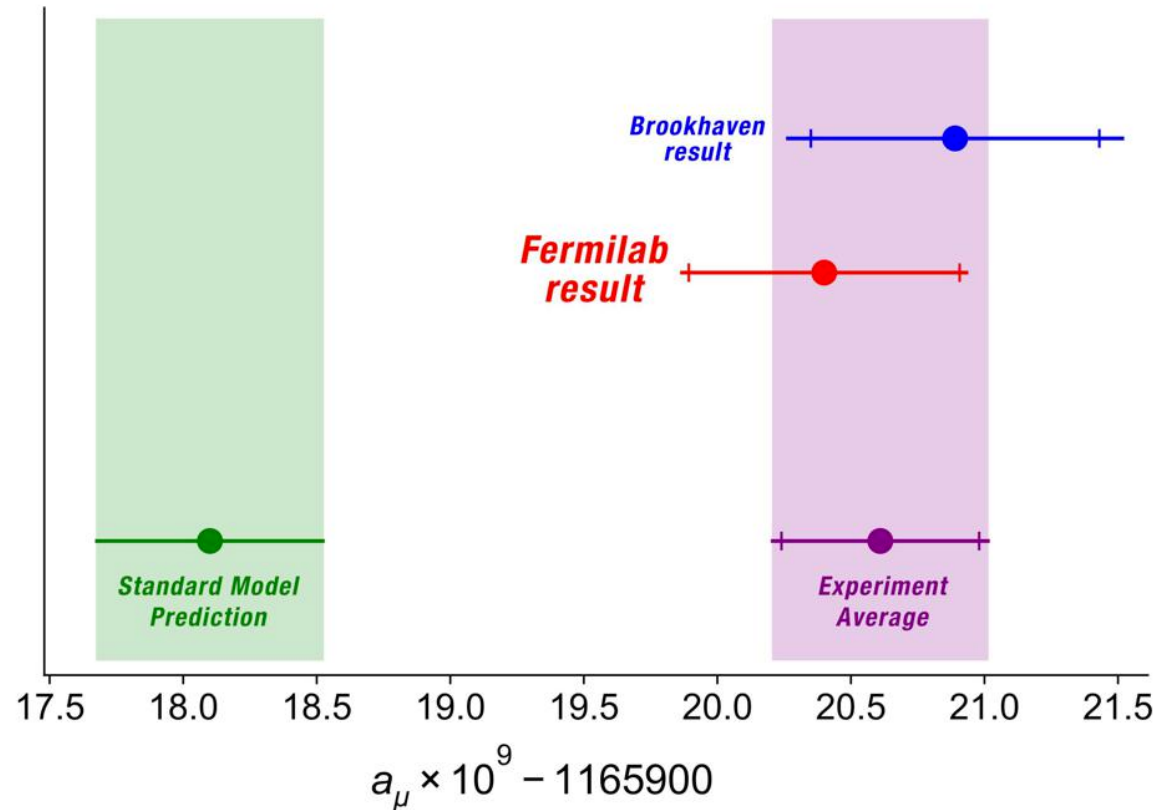
$$M_1 = 400 \text{ GeV}$$

Remember, however,  
that the DD cross section  
is suppressed by

$$\sigma \propto \mu^{-4}$$

The muon g-2 collaboration confirms the Brookhaven result.  
 Deviation of 4.2 standard deviations from SM Expectations.  
**A very important result**, that will be further tested in the coming years.

Observe that the g-2 errors are mainly statistical ones.



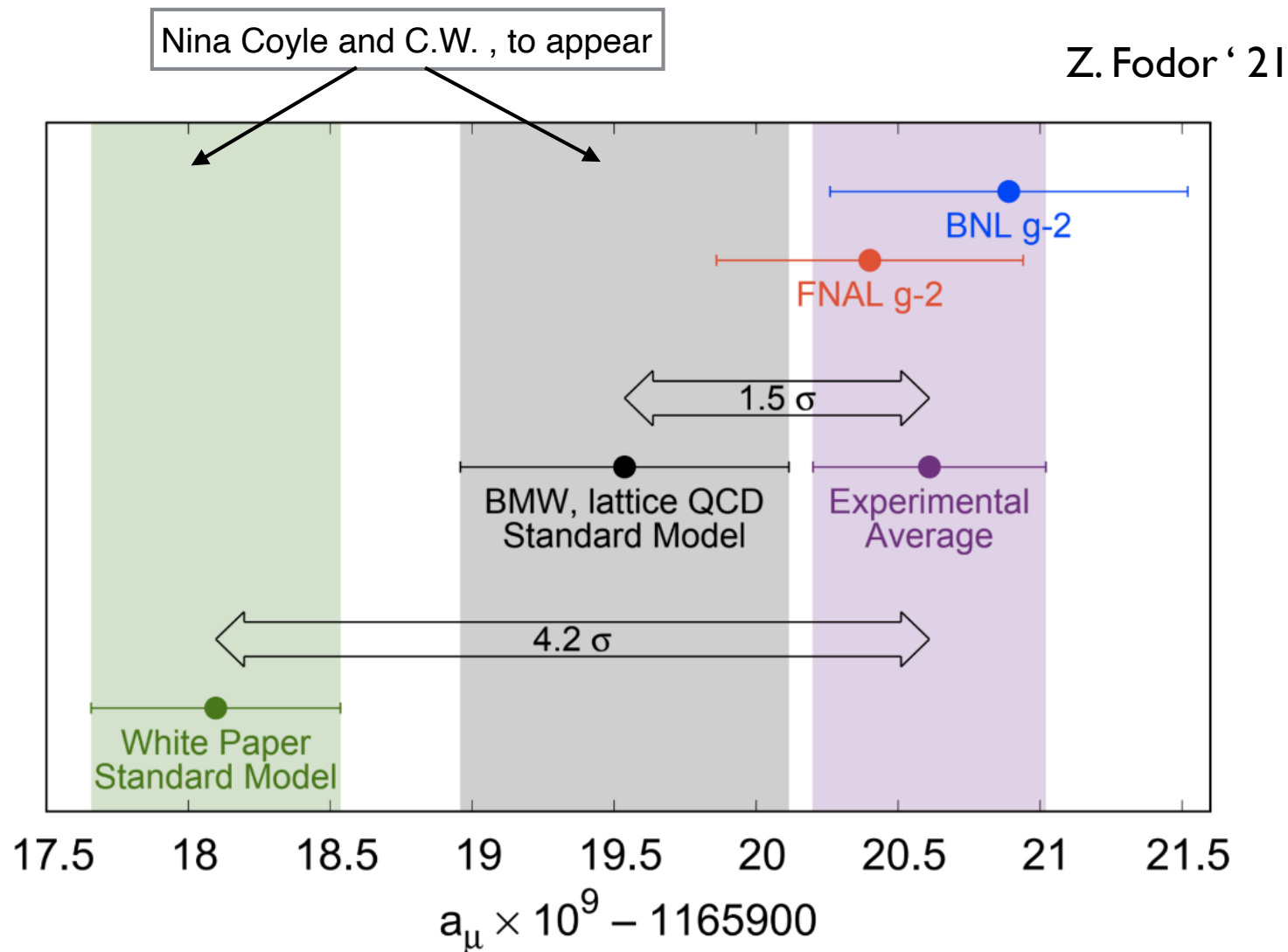
$$a_\mu^{\text{SM}} = 116\,591\,810(43) \times 10^{-11}$$

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

$$a_\mu^{\text{exp}} = 116\,592\,061(41) \times 10^{-11}$$



# Comparison of BMW lattice computation with data driven methods



In the following, I will take the 4.2 sigma discrepancy seriously.  
This question will be clarified within the next few years.

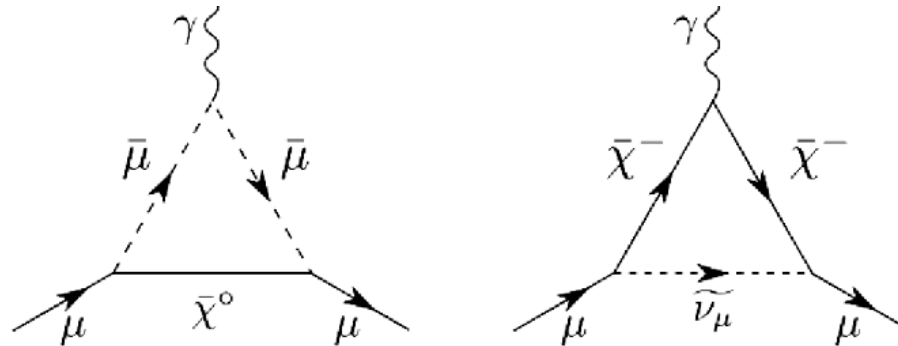
# Dominant Diagrams for g-2 in Supersymmetry

See T. Moroi and J. Ellis talks

Barbieri, Maiani'82, Ellis et al'82, Grifols and Mendez'82  
Moroi'95, Carena, Giudice, CW'95, Martin and Wells'00...

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

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



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

$$f_{\chi^0}(x) = \frac{x^2 - 1 - 2x \ln(x)}{(1-x)^3};$$

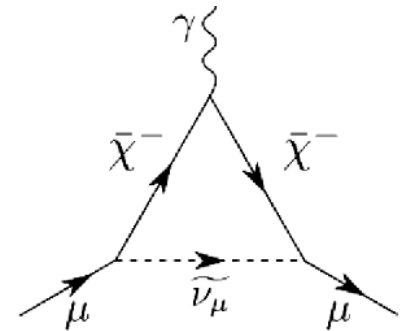
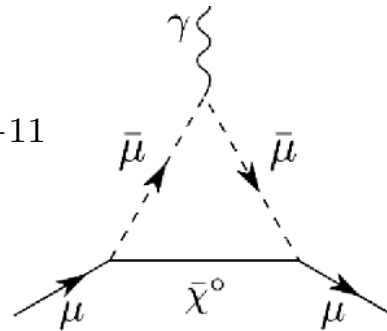
# Rough Approximation

- If all **weakly interacting** supersymmetric particle masses were the same, and the gaugino masses had the same sign, then

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

- This implies that, for  **$\tan \beta = 10$** , particle masses of order **250 GeV** could explain the anomaly, while for values of  **$\tan \beta = 60$**  (consistent with the unification of the top and bottom Yukawa) these particle masses could be of order **700 GeV**.

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



## g-2 and Direct Detection

Reduction of the DD cross section is obtained for negative values of  $\mu \times M_1$

The direct detection cross sections can also be suppressed for large values of  $\mu$

g-2 has two contributions, the Bino one proportional to  $\mu \times M_1$  and the other (chargino) proportional to  $\mu \times M_2$

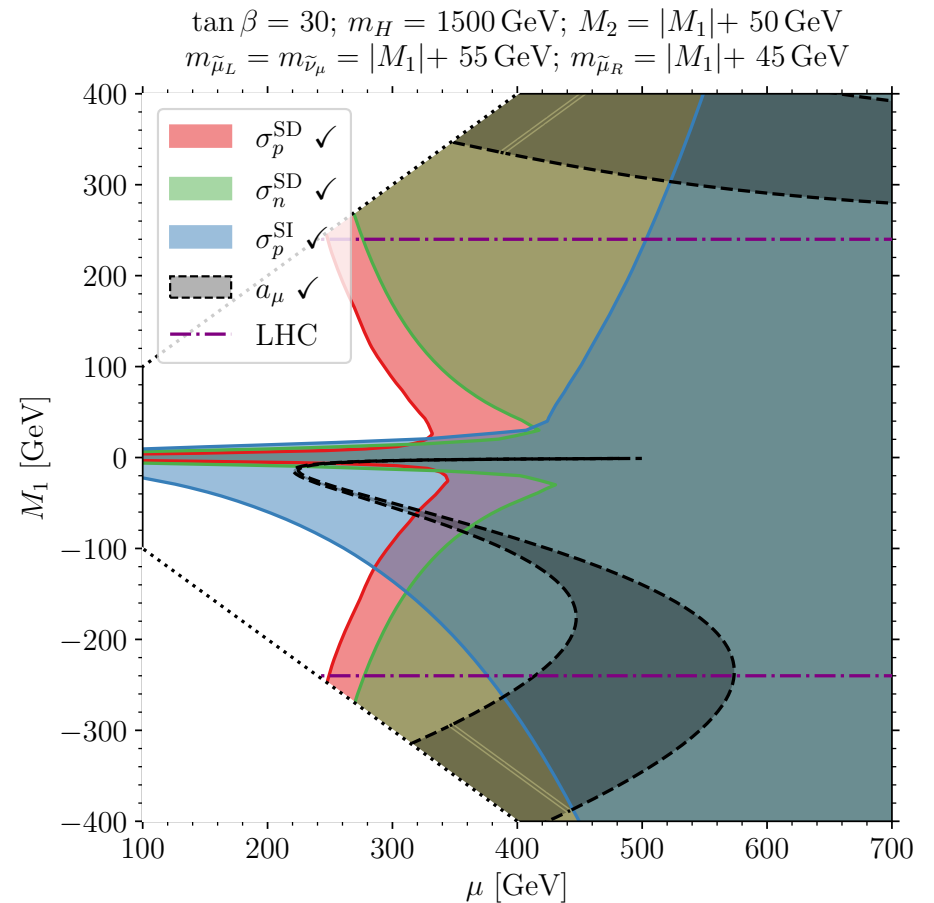
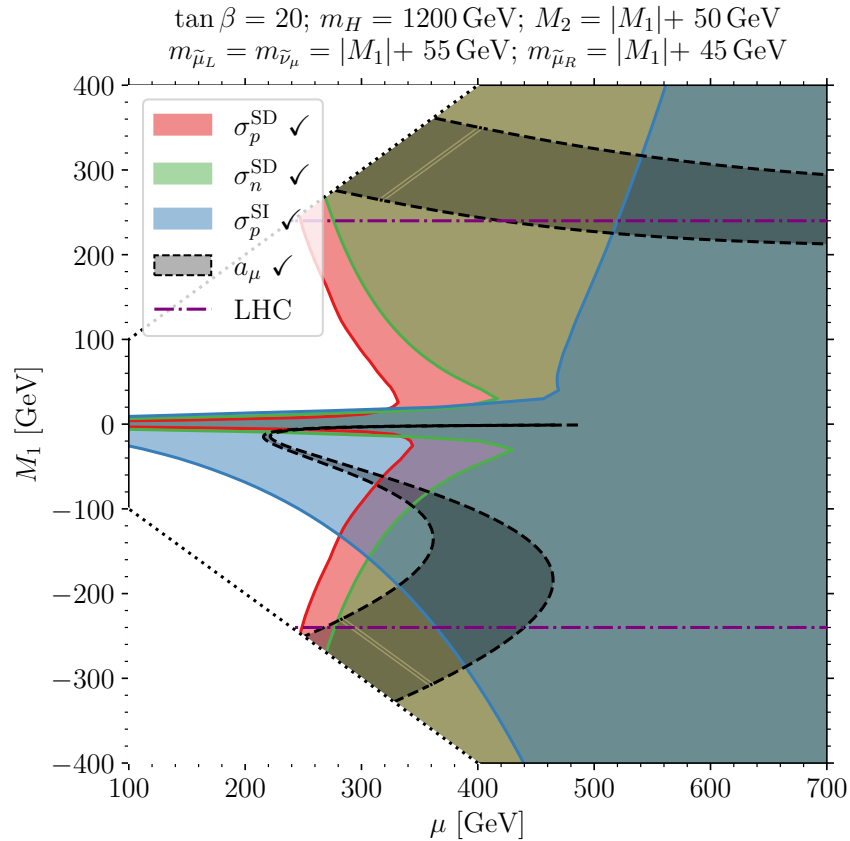
The Bino contribution to g-2 is negative at the proximity of the blind spot but becomes subdominant at smaller values of  $\mu$

The chargino contribution is the dominant one for masses of the same order and is suppressed at large  $\mu$

Since g-2 needs to be positive, compatibility between g-2 results and Direct detection may be either achieved for large values of  $\mu$  or for smaller values of  $\mu$ , when the relative sign of the gaugino masses is opposite,  $M_1 \times M_2 < 0$

# Compatibility of Direct Detection and g-2 Constraints for a representative example of a compressed spectrum. Stau co-annihilation is assumed

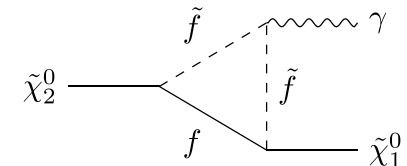
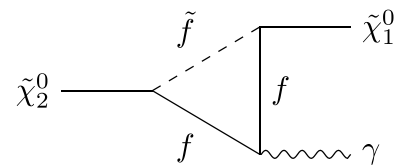
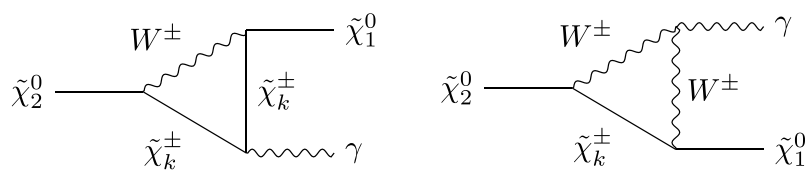
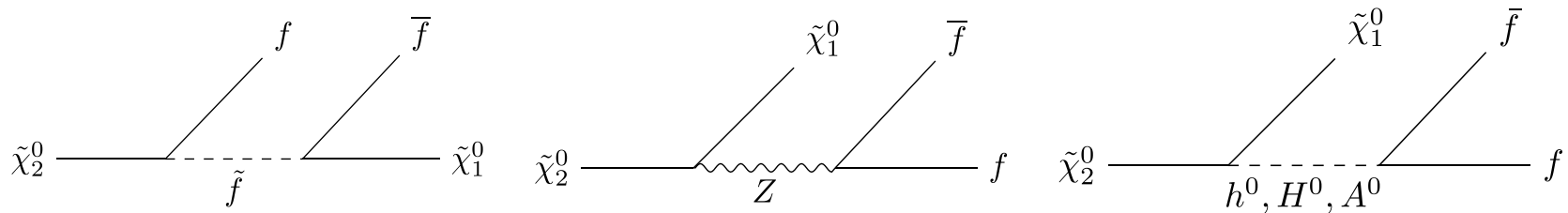
Large hierarchy of values of  $\mu$  between positive and negative values of the Bino mass parameter is observed.



# Wino Co-annihilation (Compressed Chargino-Neutralino Spectrum)



# Neutralino Decay Channels



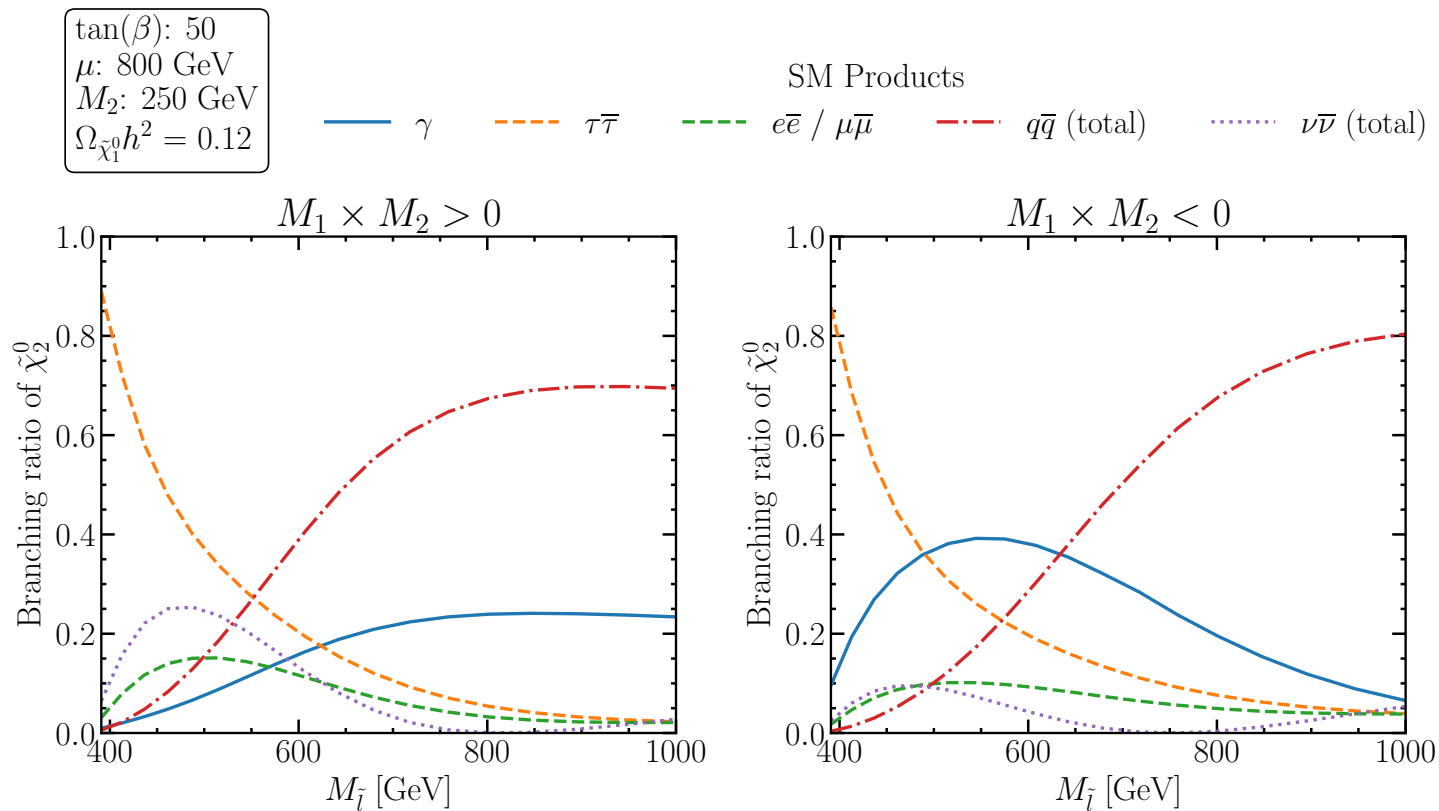
Defining  $\epsilon = \frac{m_{\tilde{\chi}_2^0}}{m_{\tilde{\chi}_1^0}} - 1$ ,

Three body decay rates are proportional to  $\epsilon^5$

Radiative decay rates are proportional to  $\epsilon^3$

Small mass differences : Radiative decay mode tends to be the dominant one

# Branching Ratios



$M_1$  is fixed to get the proper neutralino relic density

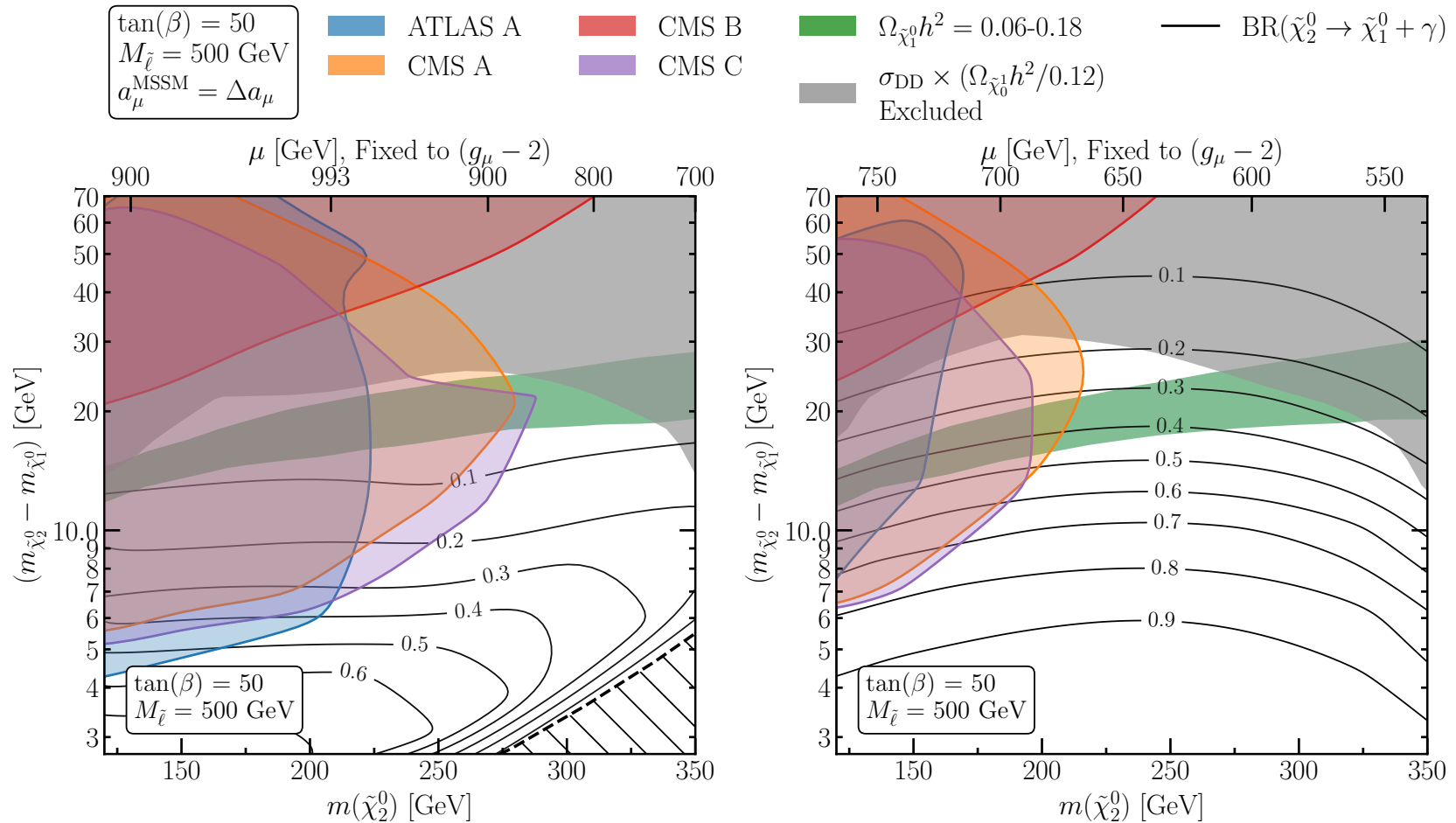
Quite interesting enhancement of the radiative decay in the compressed region.

Can it be tested ? Initial state radiation relevant to get sufficient missing ET.

# Bounds on SUSY particles

- In supersymmetric theories, the spectrum consists of many particles, which decay into lighter supersymmetric particles, leading to missing energy and several standard model particles in the final state.
- When setting bounds, then, one should recast the existing analyses and impose them in the final state obtained by the sum of all supersymmetric particles produced at the LHC.
- In the following, we shall assume that the strongly interacting particles are sufficiently heavy, so that their contribution to SUSY signals is small.
- We shall use the program **CHECKMATE**, to analyze the LHC bounds on the SUSY spectrum. **CHECKMATE** uses **Madgraph** or **Pythia** (for hadronization) and **Delphes** to generate MC events and detector effects, and compare the events with a library of 39 different ATLAS and CMS searches at run 2.
- Comparison of these bounds with simplified model analysis are generally difficult due to the multiple channel decays and decay chains that occurs in a realistic SUSY model.

# Allowed Parameter Space



$$M_1 \times M_2 > 0$$

$$M_1 \times M_2 < 0$$

Not only the allowed parameter space is larger for opposite sign gauginos, but the radiative decays branching ratio becomes significantly larger.

# Allowed Parameter Space

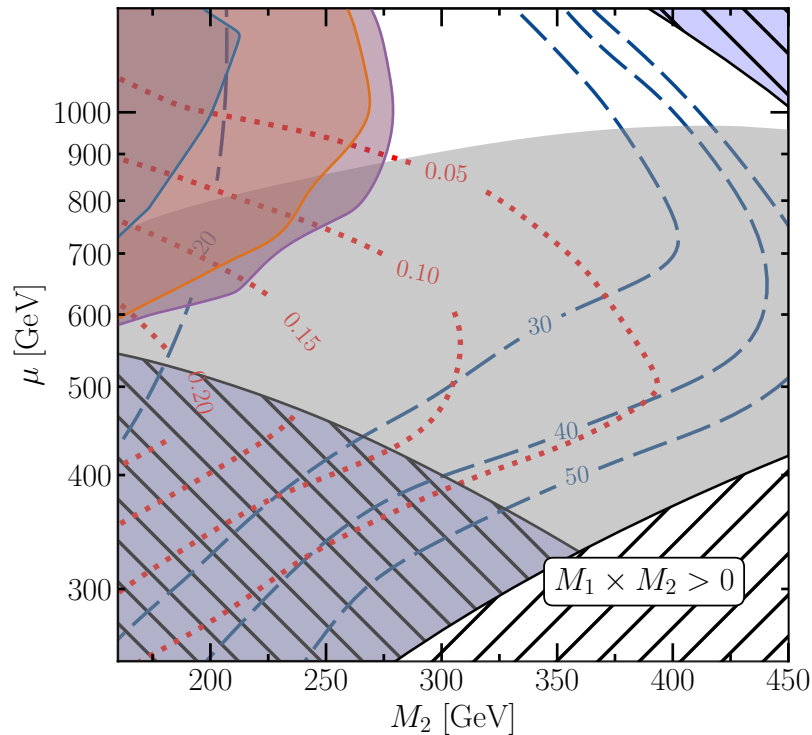
$$\begin{aligned} \tan(\beta) &= 50 \\ M_{\tilde{\ell}} &= 500 \text{ GeV} \\ \Omega_{\tilde{\chi}_1^0} &= \Omega_{\text{DM}} \end{aligned}$$

ATLAS A

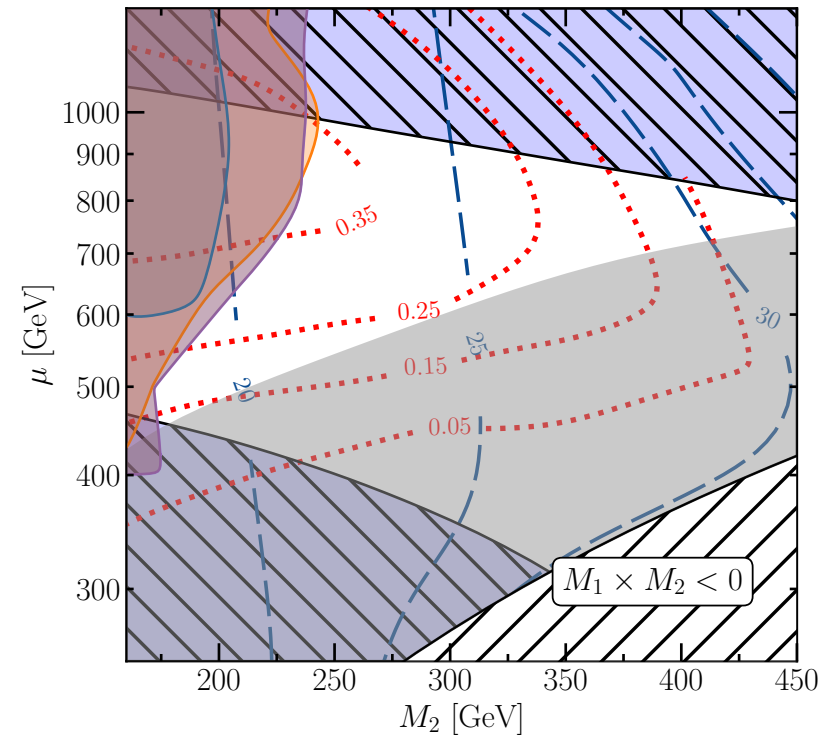
CMS A

CMS C

 $\Delta a_\mu$  excluded

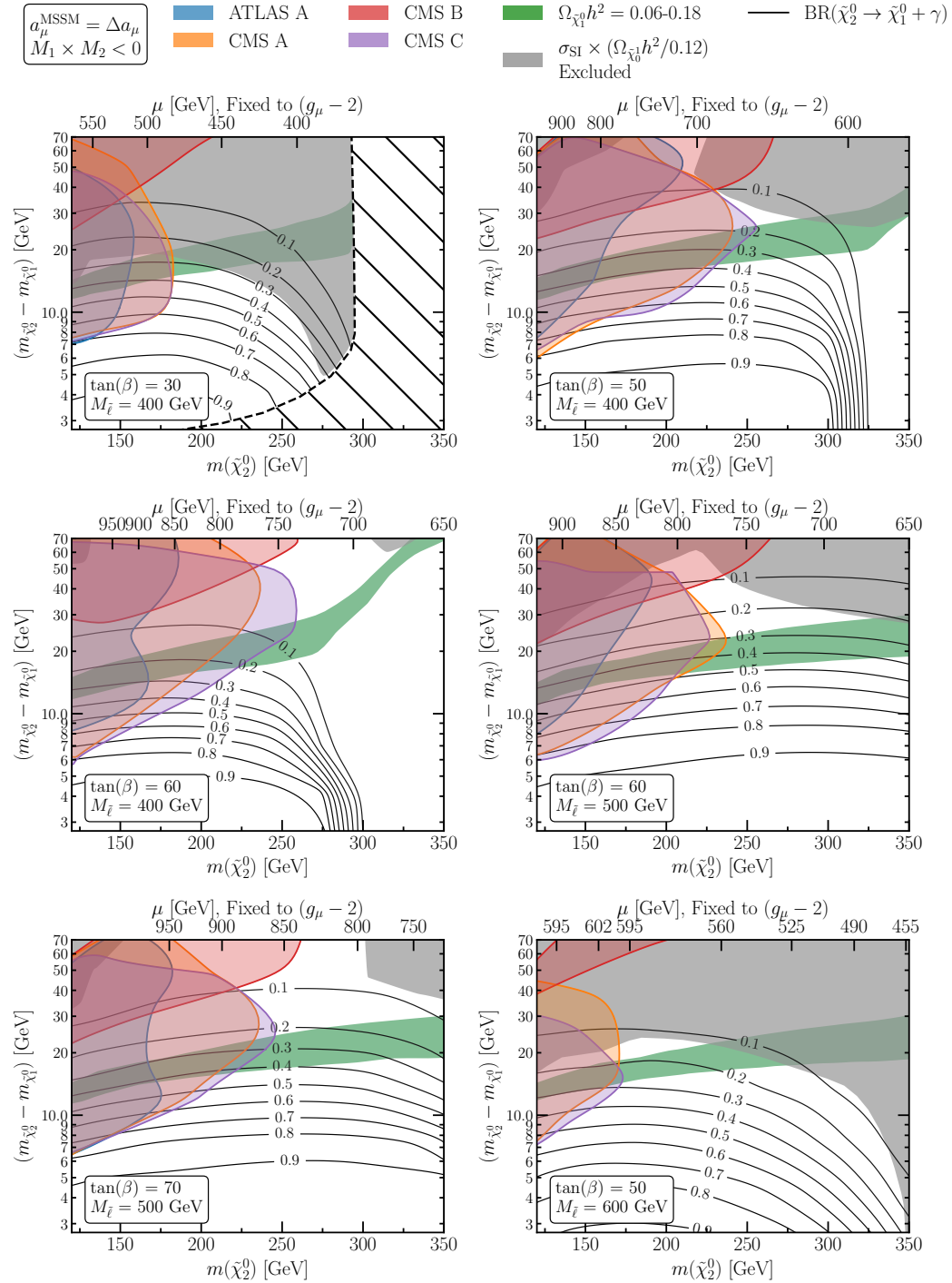
 $M_1 > \mu$ 
 $\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma)$ 
 $(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) [\text{GeV}]$ 
 $\sigma_{\text{DD}} \times (\Omega_{\tilde{\chi}_1^0} h^2 / 0.12)$   
Excluded


$$M_1 \times M_2 > 0$$



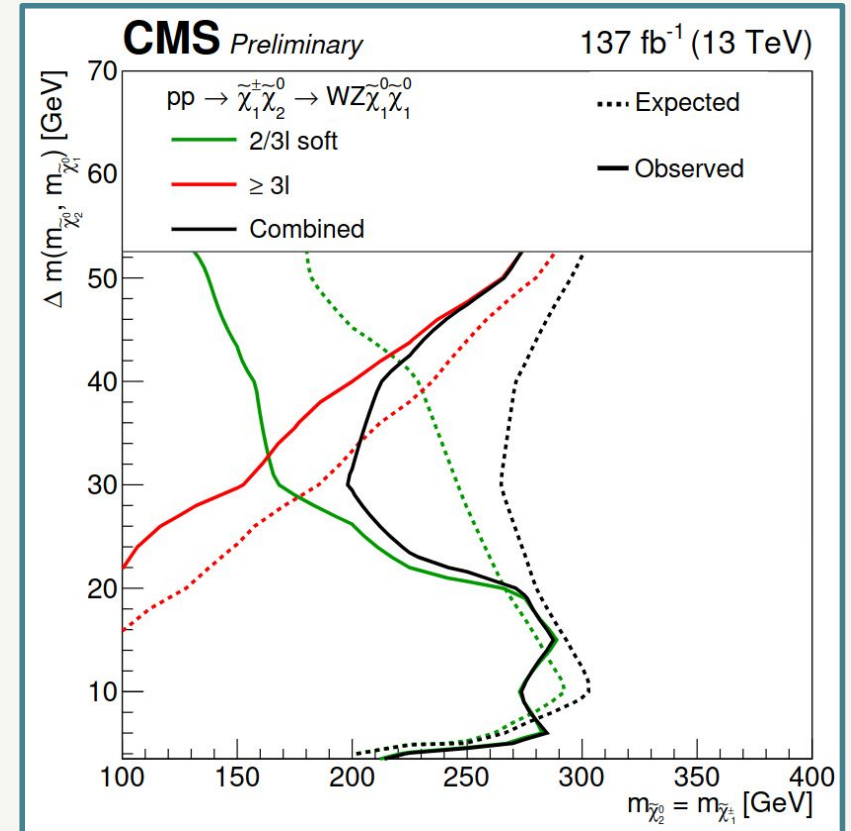
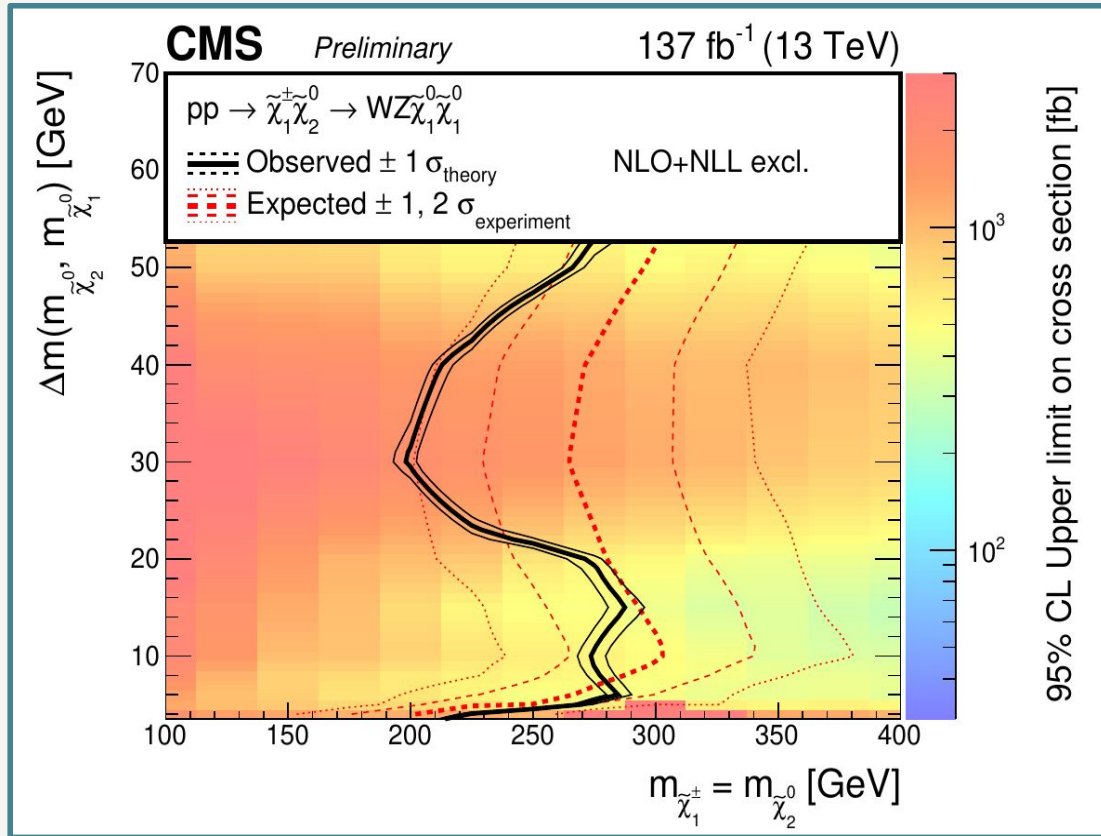
$$M_1 \times M_2 < 0$$

Dark Matter fixed to explained the relic density





- The **2/3l soft** and  **$\geq 3l$  analyses** complement each other in the compressed region
  - Orthogonal lepton  $p_T$  ranges but different selections (e.g. MET for 2/3l soft)
  - Challenging to be fully optimal in the crossover regime

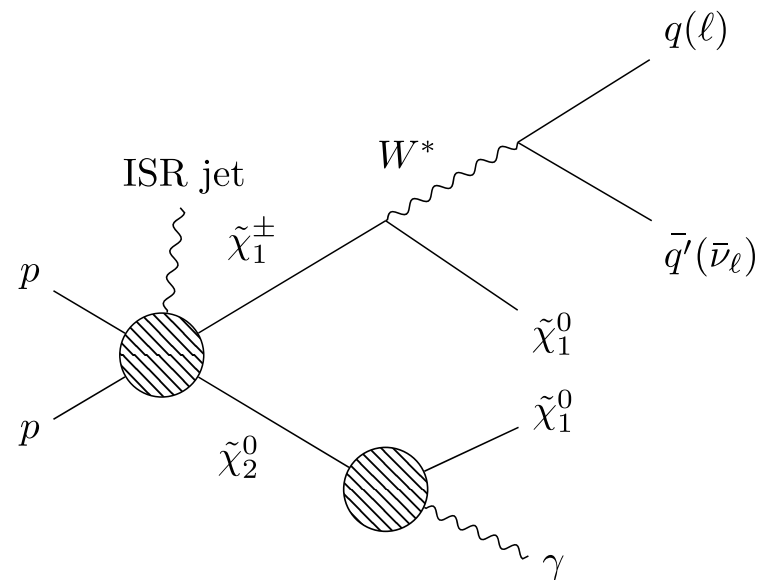


*The combination closes the gap between the analyses around  $\Delta m \sim 40$  GeV*  
*We observe a mild excess ( $\sim 2\sigma$ ) at  $\Delta m \sim 30-40$  GeV - due to both 2/3l soft and  $\geq 3l$  analyses*



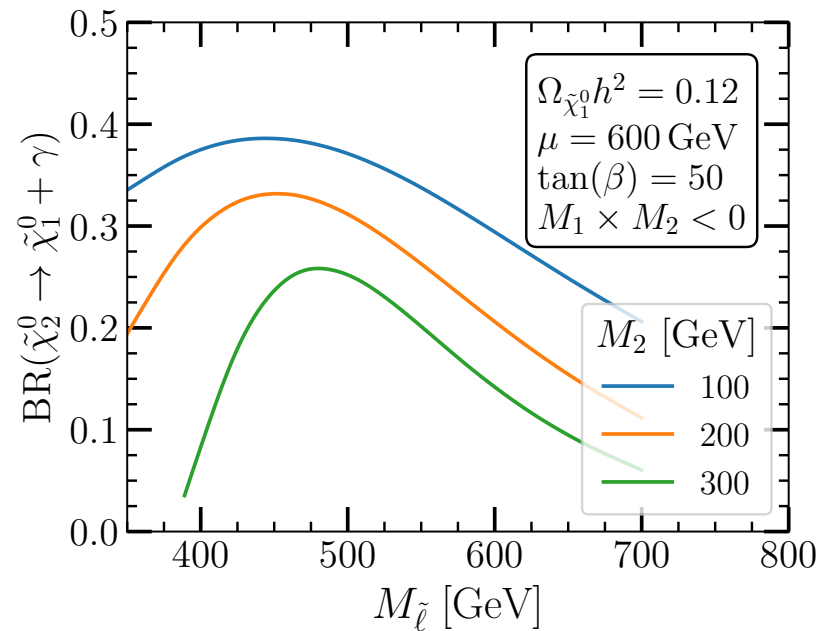
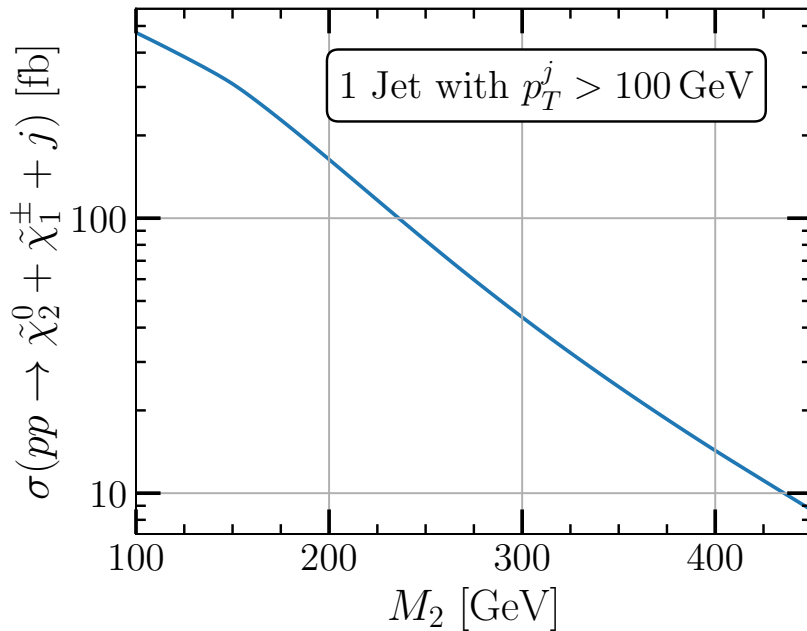
# New Search Channel

We propose to search for electroweakinos in this new search channel



One can trigger in events with sufficient Missing  $E_T$  and a somewhat hard photon in the final state

# Cross Sections

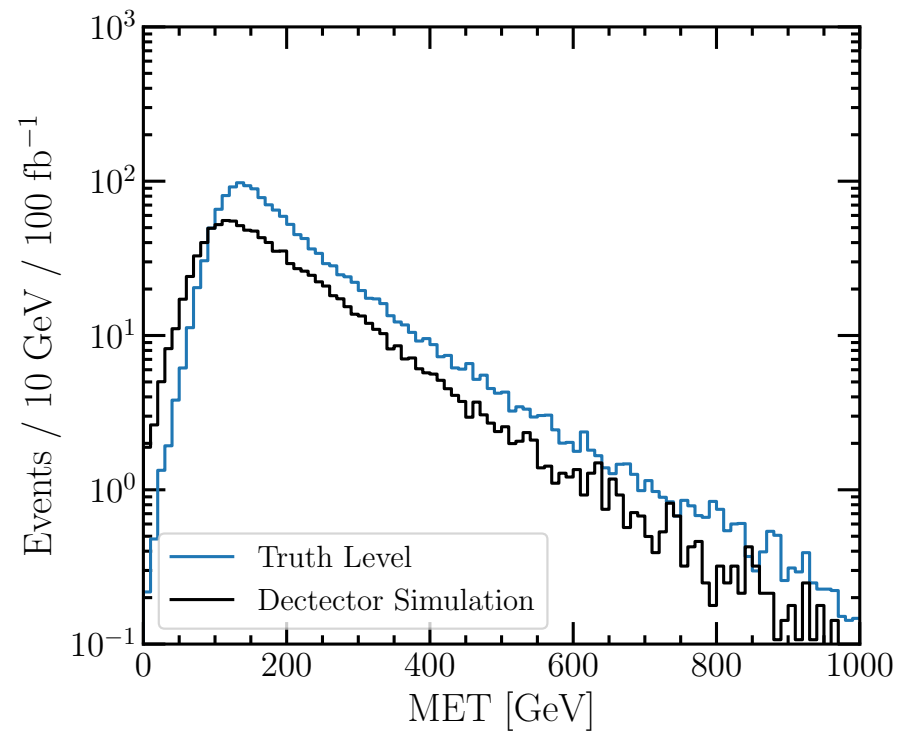
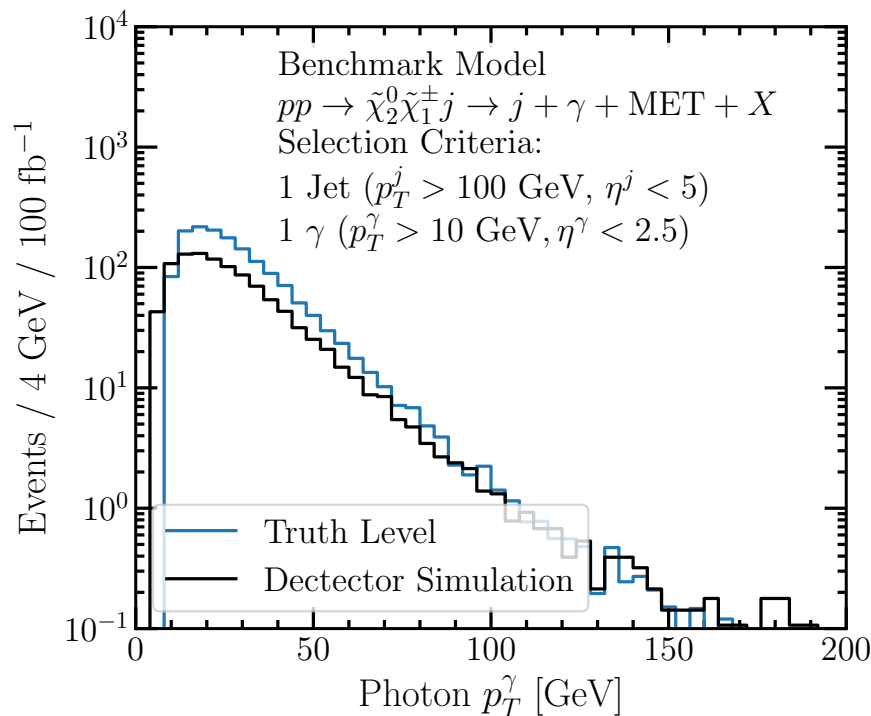


Cross section depend strongly on the overall scale of the charged and neutral Wino masses. Characteristic cross sections of order of tens of fb.

The branching ratio of the radiative decays also depends on the slepton masses. For smaller slepton masses, the stau contribution to the three body decay becomes prominent and suppresses the radiative decay branching ratio.

For large slepton masses, the lack of slepton contribution to the radiative decay loop amplitude also suppresses this branching ratio.

# Energy and Momentum Distributions



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

# Benchmark Scenario

$$M_1 = -282 \text{ GeV}$$

$$M_2 = 287 \text{ GeV}$$

$$\mu = 800 \text{ GeV}$$

$$M_{\tilde{t}} = 500 \text{ GeV}$$

$$\tan \beta = 50$$

$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx 300 \text{ GeV}$$

$$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 24.1 \text{ GeV}$$

$$\text{BR}(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma) = 36 \%$$

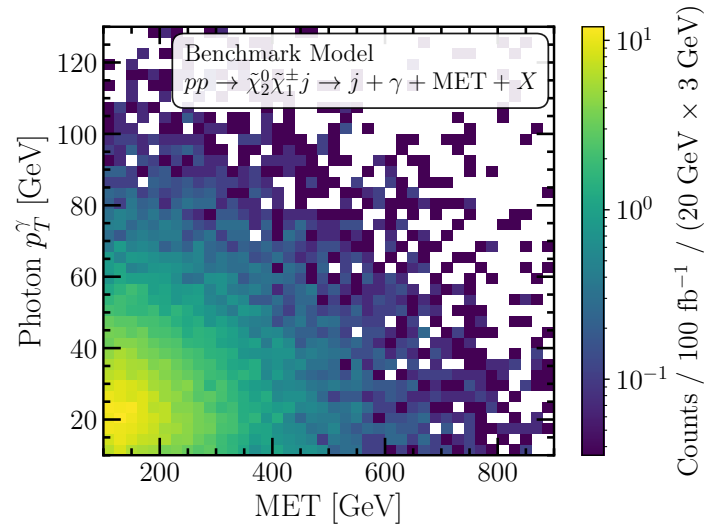
$$a_\mu^{\text{MSSM}} = 1.7 \times 10^{-9}$$

$$\Omega_{\tilde{\chi}_1^0} h^2 = 0.118$$

$$\sigma(pp \rightarrow \tilde{\chi}_1^\pm + \tilde{\chi}_2^0 + j) = 48 \text{ fb}$$

## Efficiencies

|                        |    | $\cancel{E}_T$ cut [GeV] |      |       |
|------------------------|----|--------------------------|------|-------|
|                        |    | 150                      | 300  | 500   |
| $p_T^\gamma$ cut [GeV] | 0  | 60%                      | 17%  | 3.9%  |
|                        | 40 | 15%                      | 6.0% | 1.7%  |
|                        | 70 | 3.2%                     | 1.6% | 0.64% |



Missing  $E_T$  is strongly correlated with the ISR jet  $p_T$

No strong correlation between missing  $E_T$  and photon  $p_T$

## Probing the Compressed region at the LHC

- We propose to complement the usual searches into lepton and quark final states with a search for photons and missing energy in the final state, to probe the compressed region of supersymmetric theories.
- Although the photon transverse momentum is not large, the run 3 now allow for non-trivial multi-object triggers with considerably lower thresholds than the photon  $p_T$  or missing energy only triggers.
- A combined trigger would be particularly useful to search for the relatively soft photon and missing  $E_T$  final state arising from the  $(pp \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^\pm + j)$  process.
- Let's emphasize that the searcher multi-lepton processes, which is generally used to probe this region is hampered precisely by the large radiative decay branching ratio.
- A study of the SM backgrounds will be necessary to fully quantify the reach of the photon plus missing  $E_T$  search propose here.

# Conclusions

- Searches for supersymmetry have led to strong bounds on the existence of colored particles (gluinos) at scales below the 1 to 2 TeV scale.
- Stop searches, in particular, are starting to probe the region of parameter space that is consistent with a 125 GeV Higgs boson in the MSSM.
- Searches for weakly interacting particles have started to cover a similar region of parameter space, which however depends strongly on the assumed decays.
- The compressed region, that leads to a proper DM relic density is starting to be probed through a combination of LHC and DM direct detection experiments
- We propose to complement the standard searches with a search for a radiatively decaying second neutralino, which is enhanced in the region consistent with the observed DM relic density, a relevant correction to the anomalous magnetic moment of the muon and a reduction of the DD cross section.
- Let us just mention that if the necessary  $g-2$  correction would be smaller by a factor 2, all our results remain the same, apart from the values of  $\tan\beta$  that will be smaller by the same factor, without affecting the collider cross sections or BR in a significant way.



Happy Birthday, Herbi !

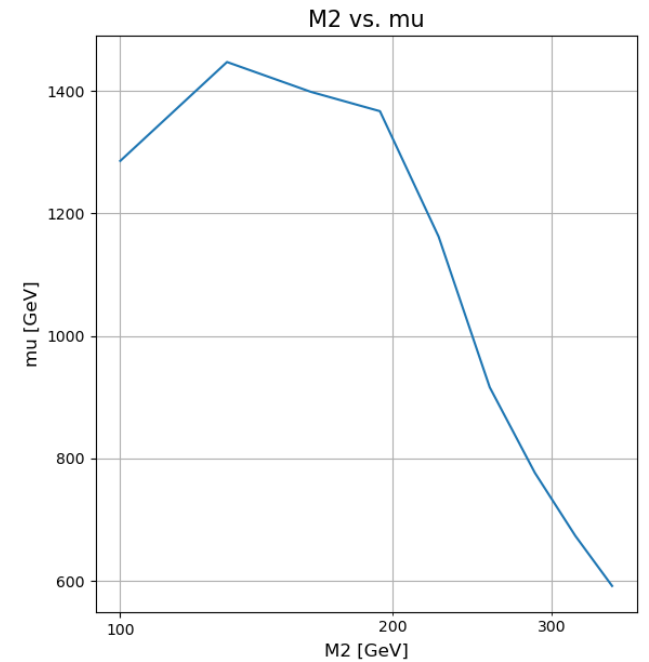
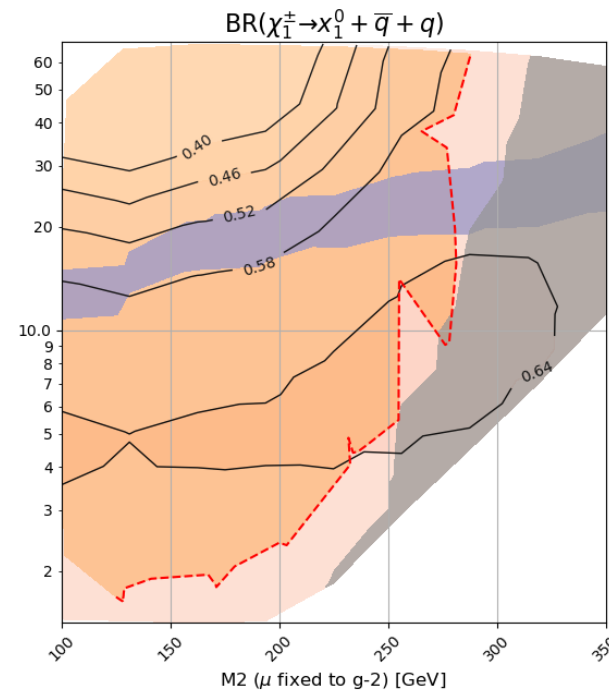
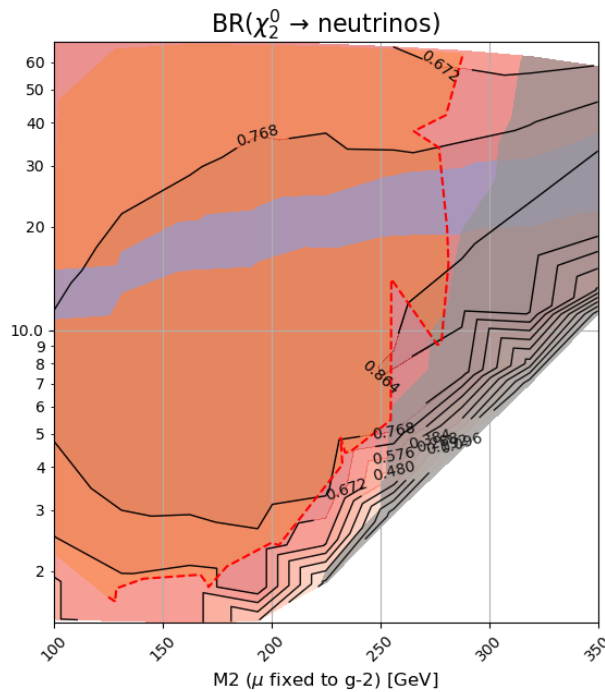
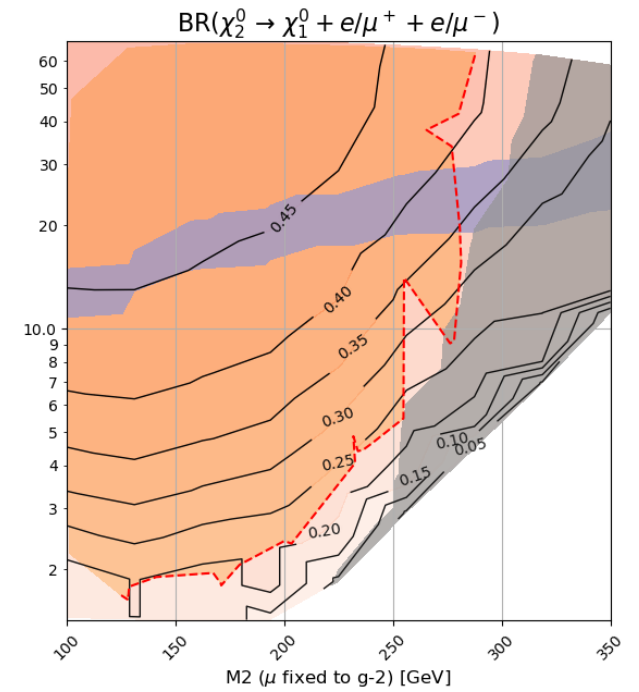
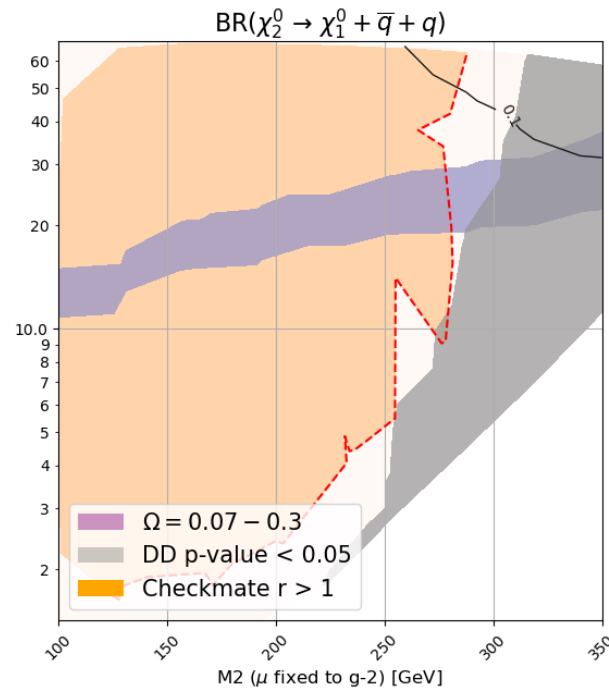
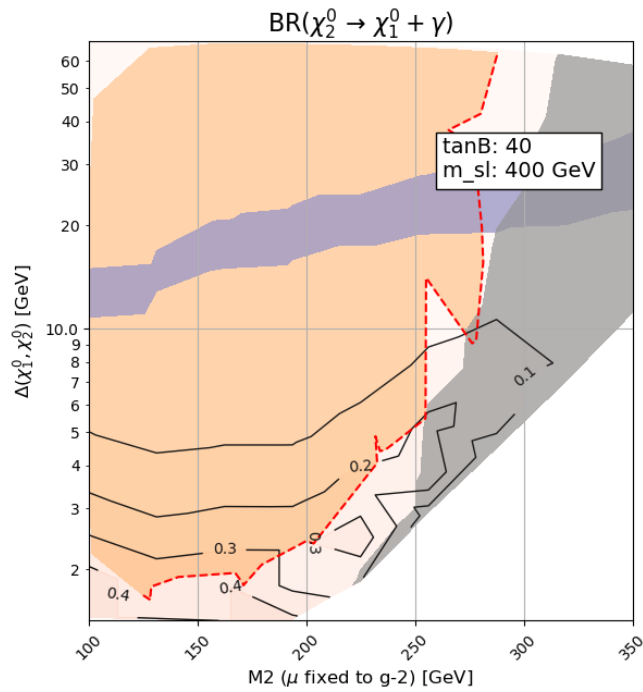




Backup

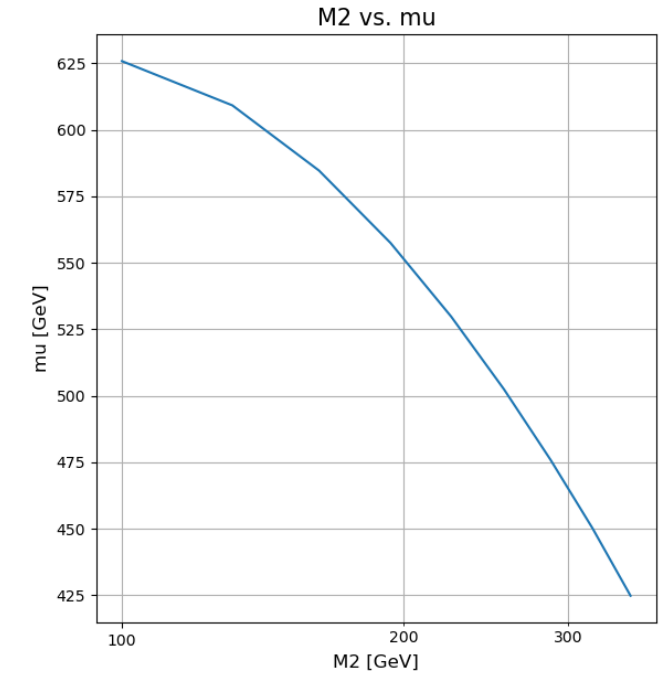
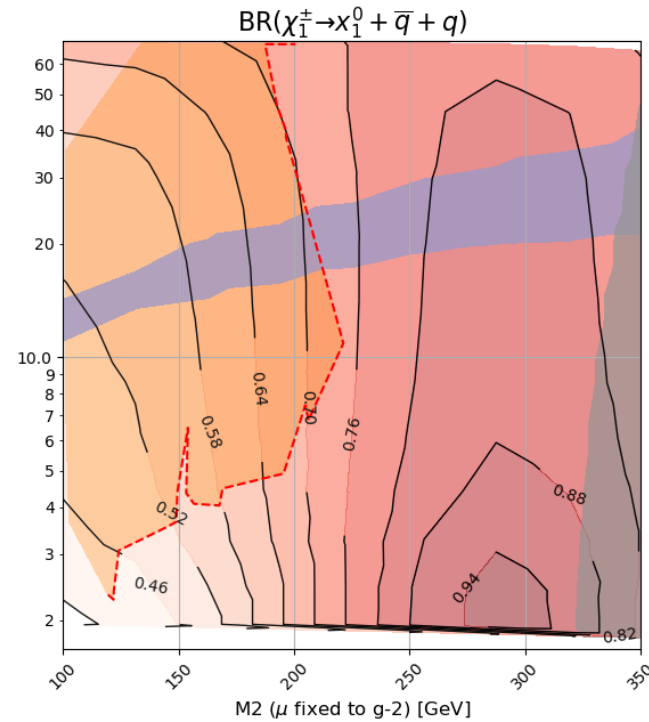
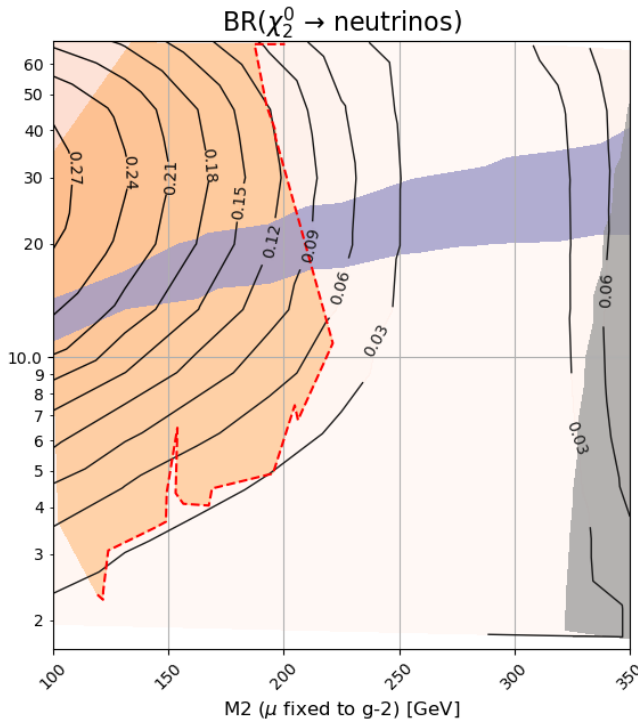
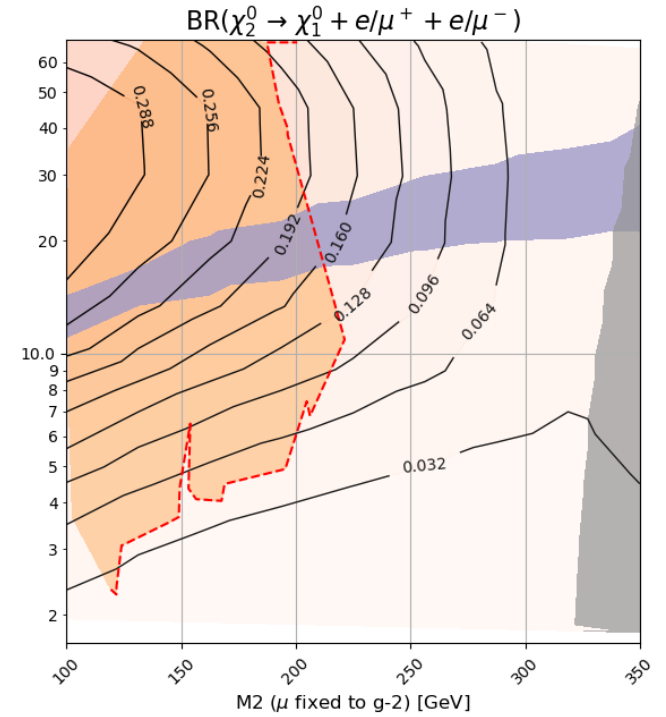
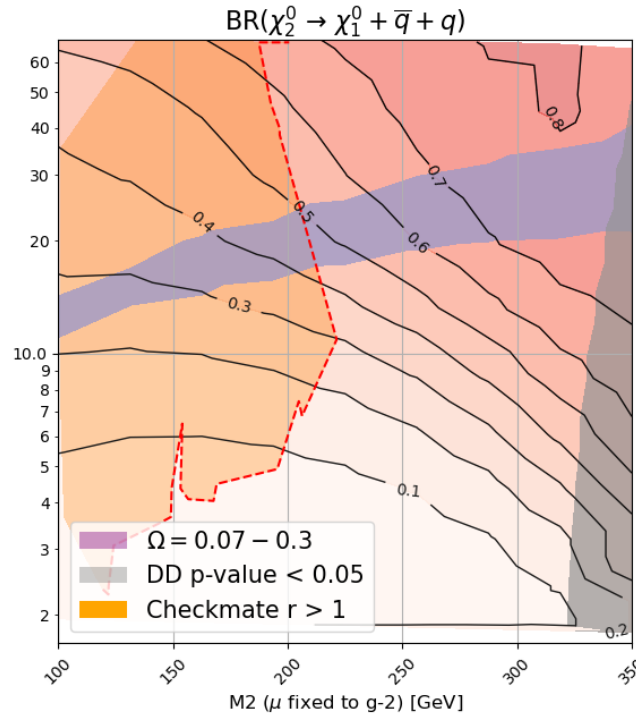
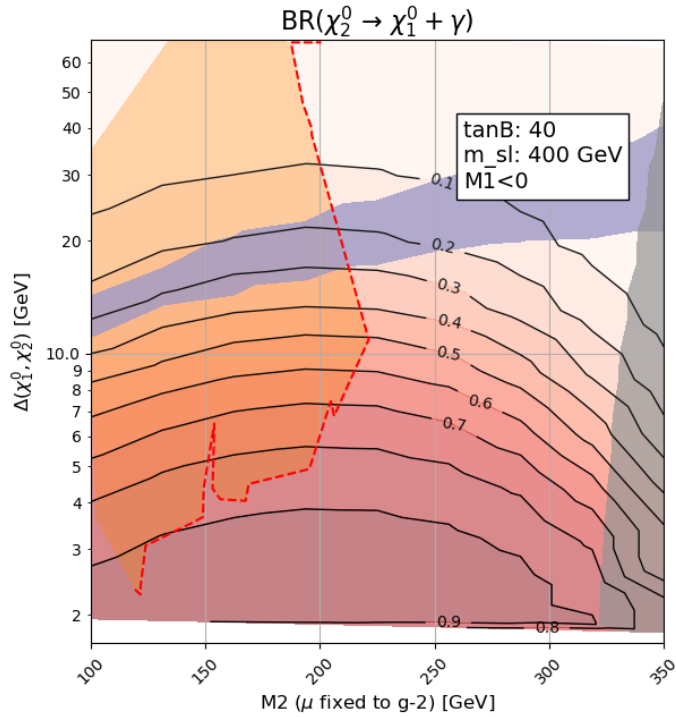
# BMW : LHC Bounds

Baum, Carena, Shah, Wagner  
Rocha, Ou, to appear

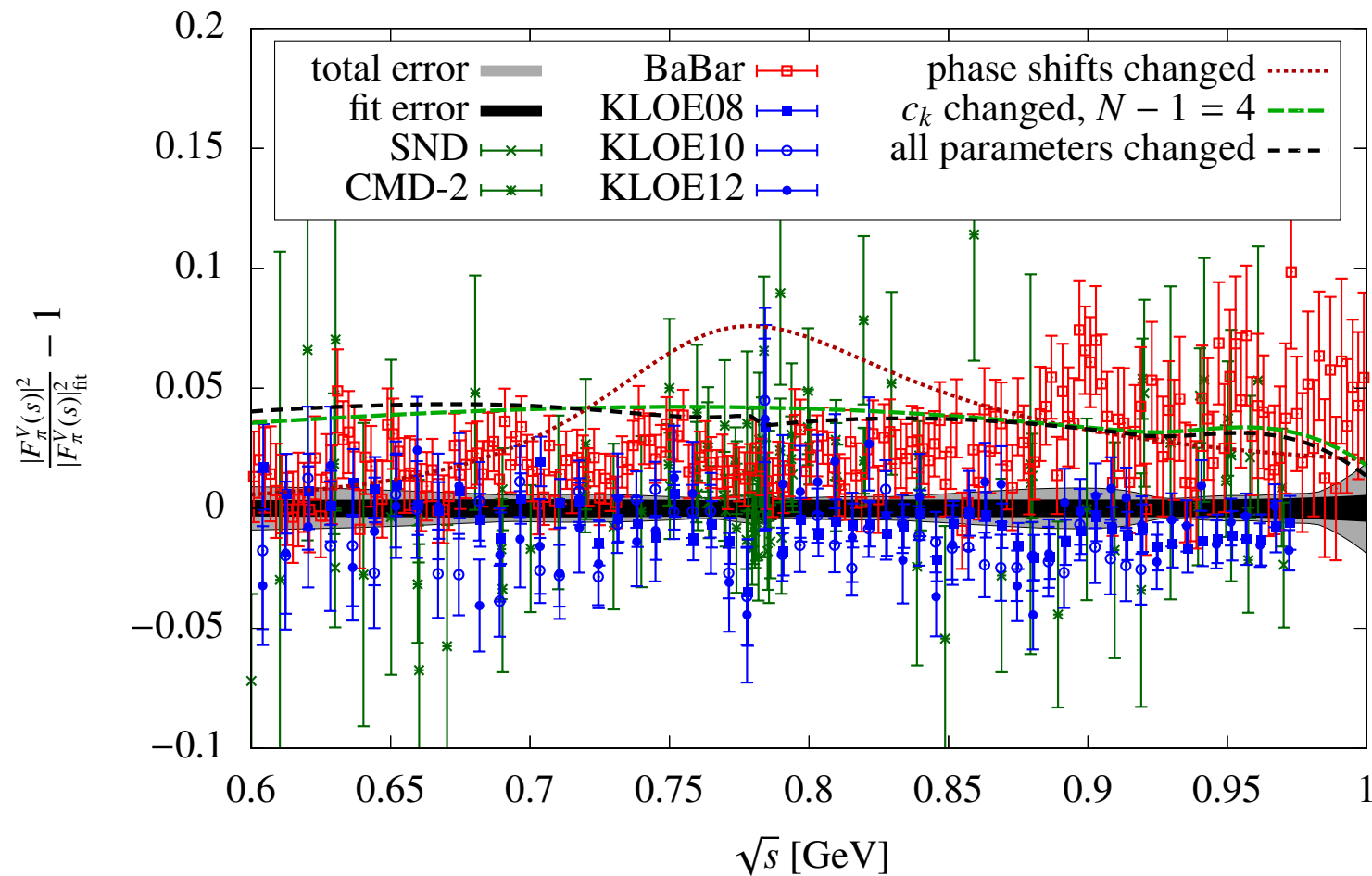


# LHC Bounds

S. Baum, M. Carena, N. Shah, C. Wagner  
D. Rocha, T. Ou, to appear



What would be the value of the hadronic cross sections necessary for compatibility with lattice values ?



arXiv:2010.07943