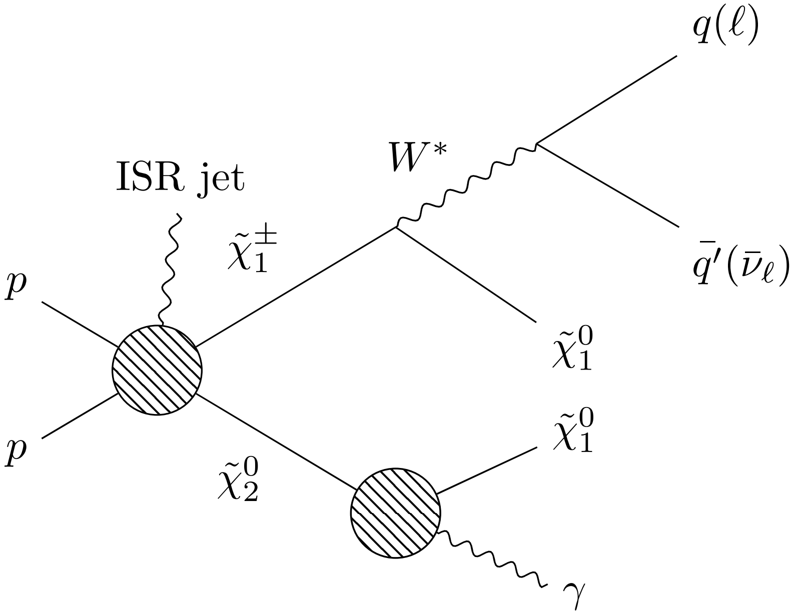
Searching for Dark Matter with Photons at the LHC



Carlos E.M. Wagner
Phys. Dept., EFI and KICP, Univ. of Chicago
HEP Division, Argonne National Lab.

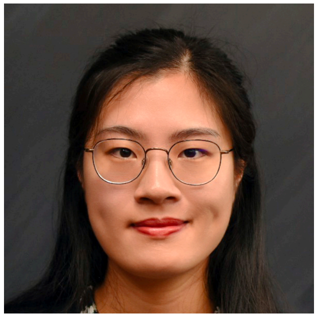
The Dark Side of the Universe - DSU2024
Corfu, September 14, 2024

Based on work performed with


Duncan Rocha

“Lighting up the LHC with Dark Matter”

S. Baum, M. Carena, T. Ou, D. Rocha, N.R. Shah,
arXiv:2303.01523, JHEP 11 (2023) 37


Tong Ou

“Dark Matter Searches with Photons at the LHC”

S. Roy, arXiv:2401.08917, JHEP 04 (2024) 106


Marcela Carena

“Machine Learning Analysis of Radiative Neutralino Decays at the LHC”

E. Arganda, M. Carena, M. De Los Rios, A.D. Perez,
D. Rocha, R.M. Sanda Seoane, arXiv:2409.xxxxx


Subhojit Roy


Nausheen Shah


Ernesto Arganda


Martin de los Rios

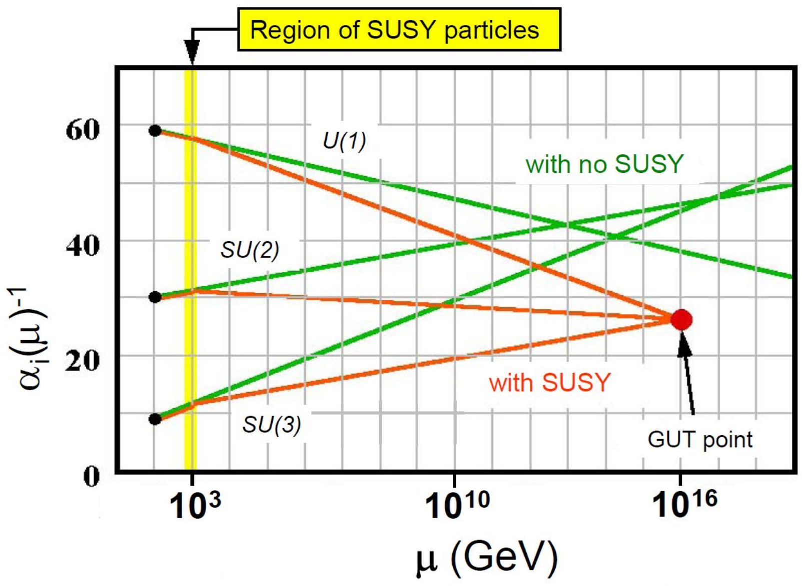

Rosa Sanda Seoane


Andres D. Perez


Sebastian Baum

Consequences of SUSY

Unification



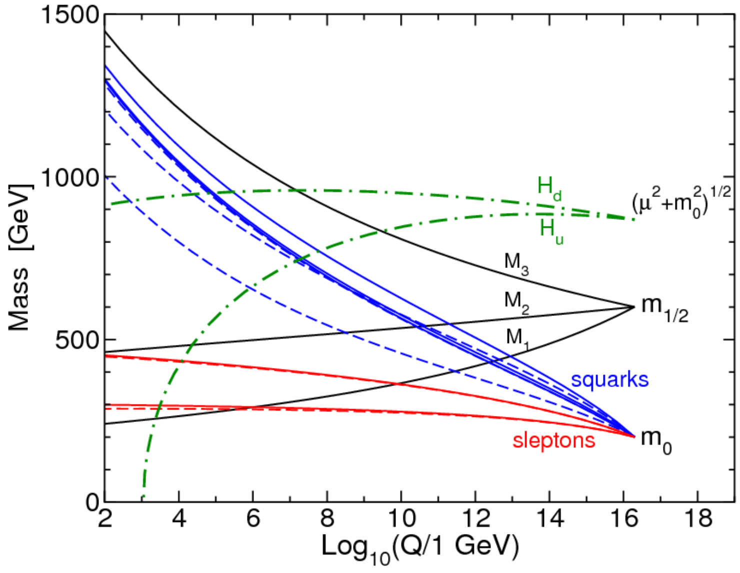
SUSY Algebra

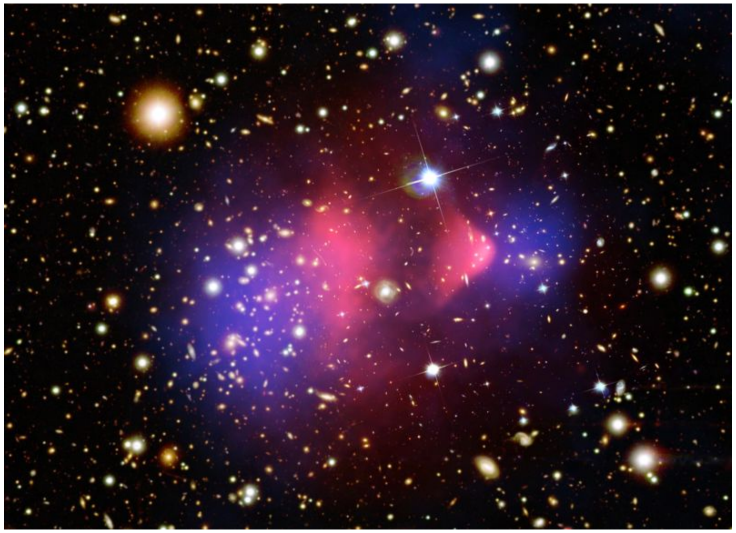
$$\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu$$

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

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

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

M_h 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

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

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

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

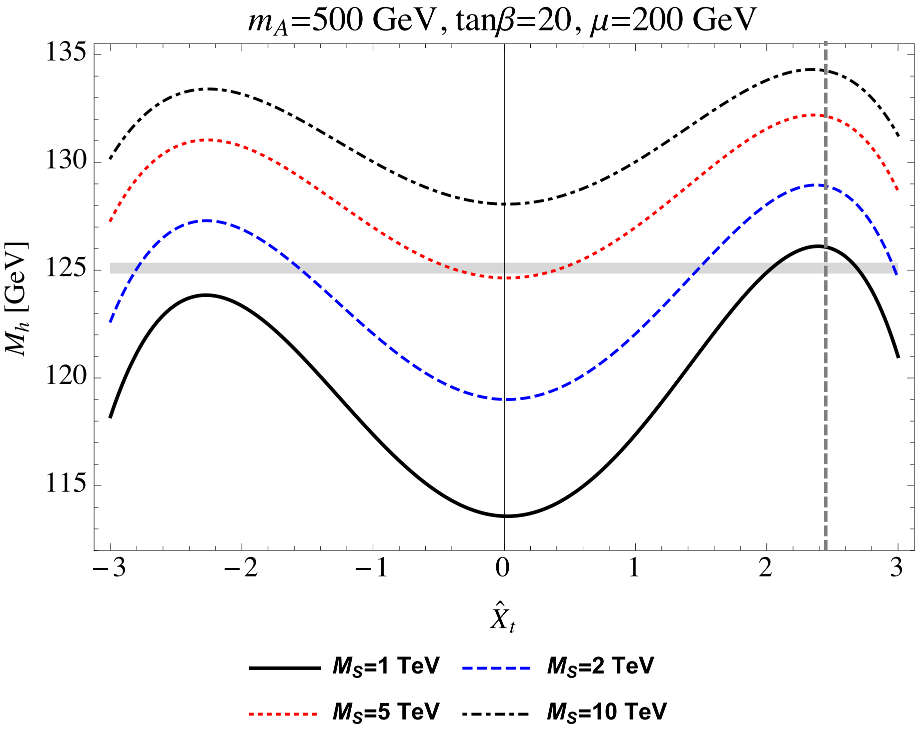
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

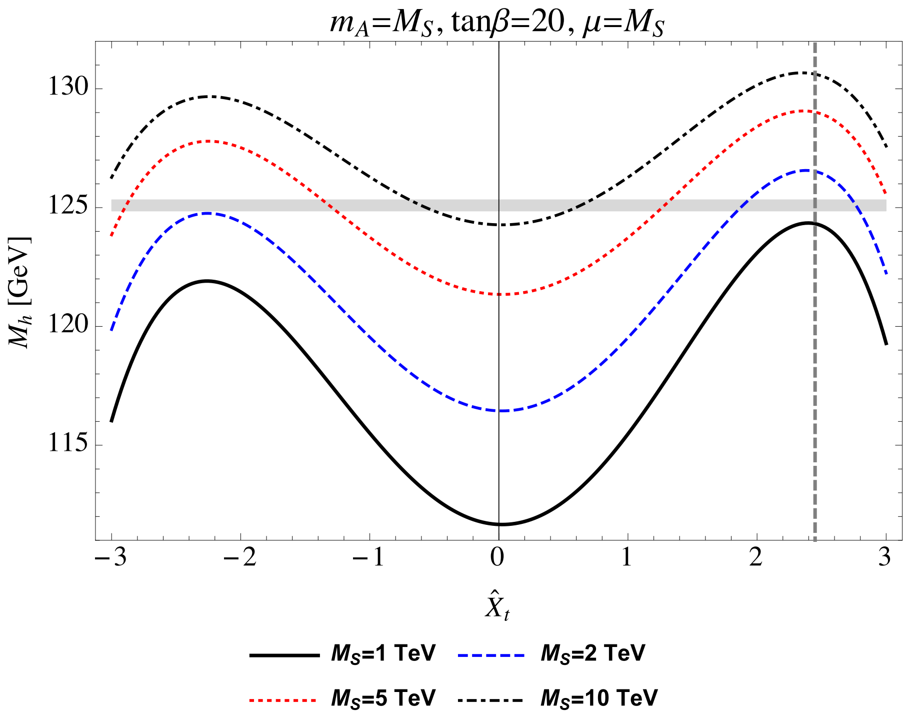
MSSM Guidance:
Stop Masses above about 1 TeV lead to the right Higgs Masss

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

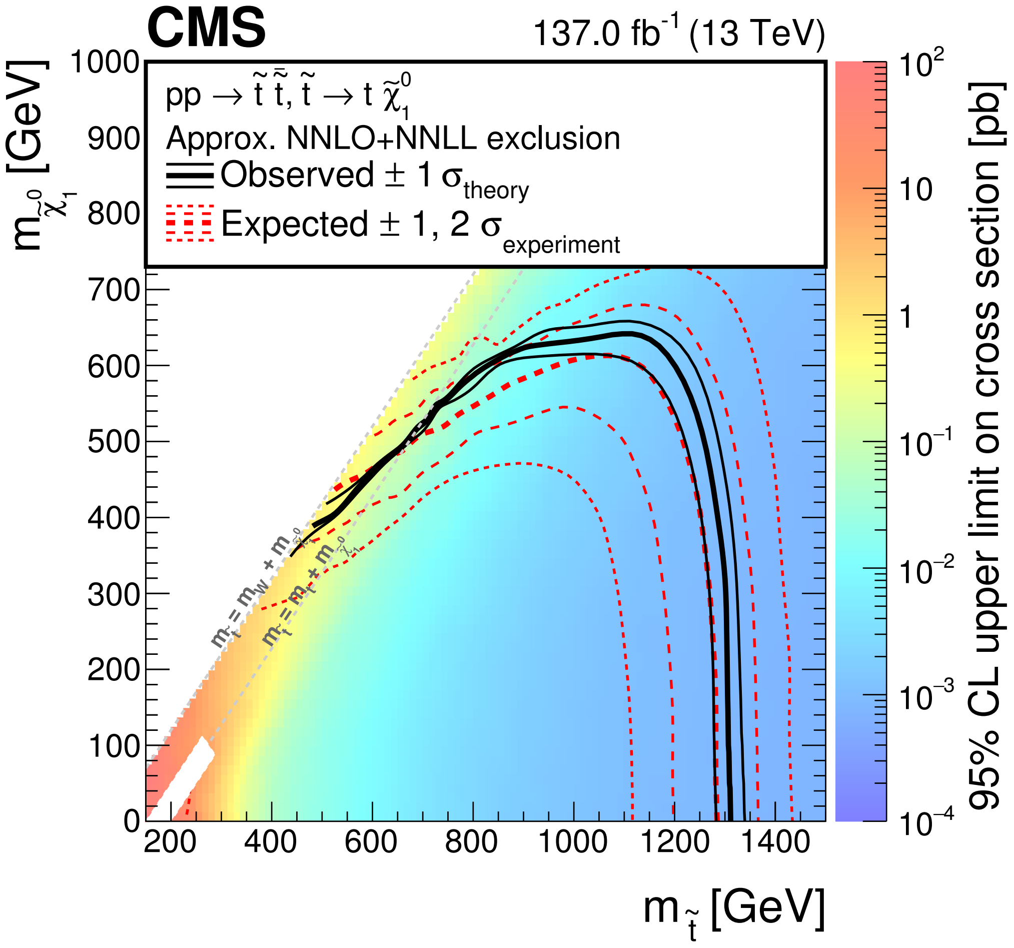


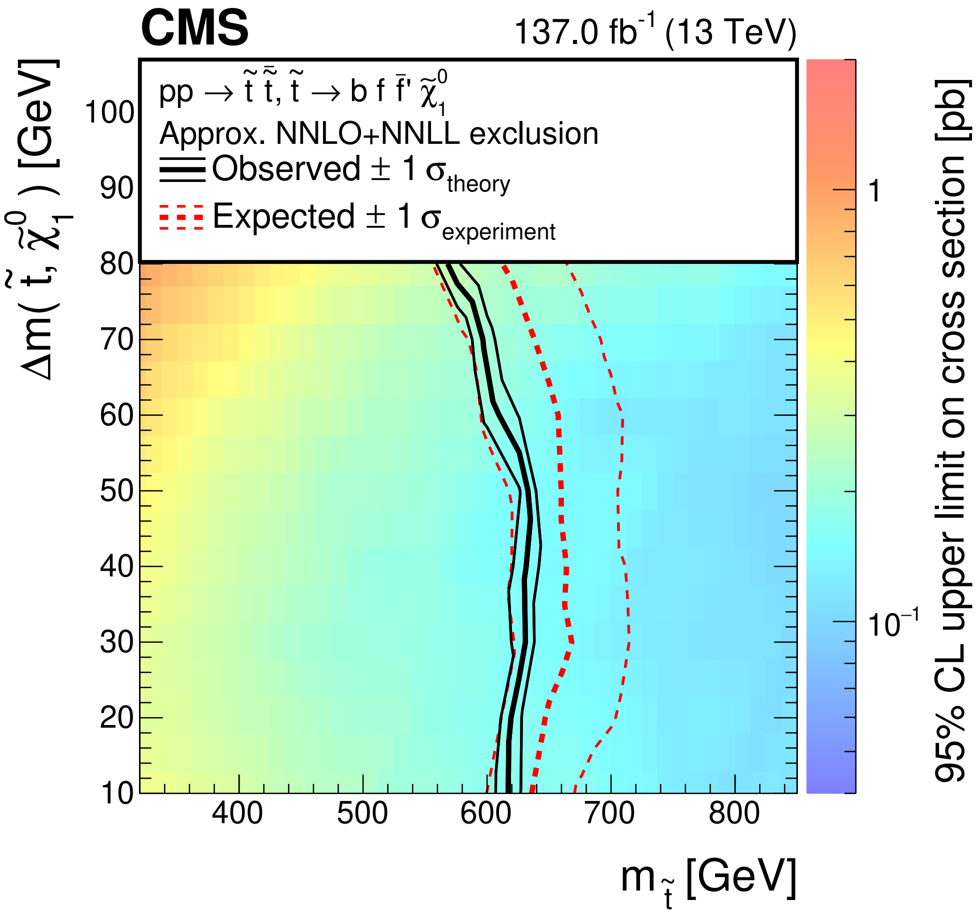


Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

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

Stop Searches



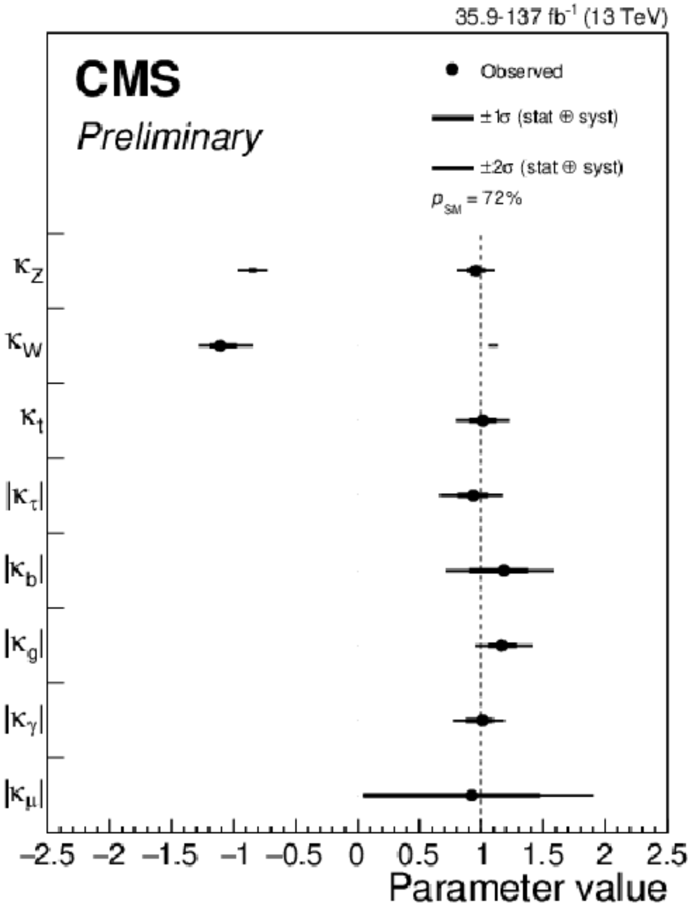


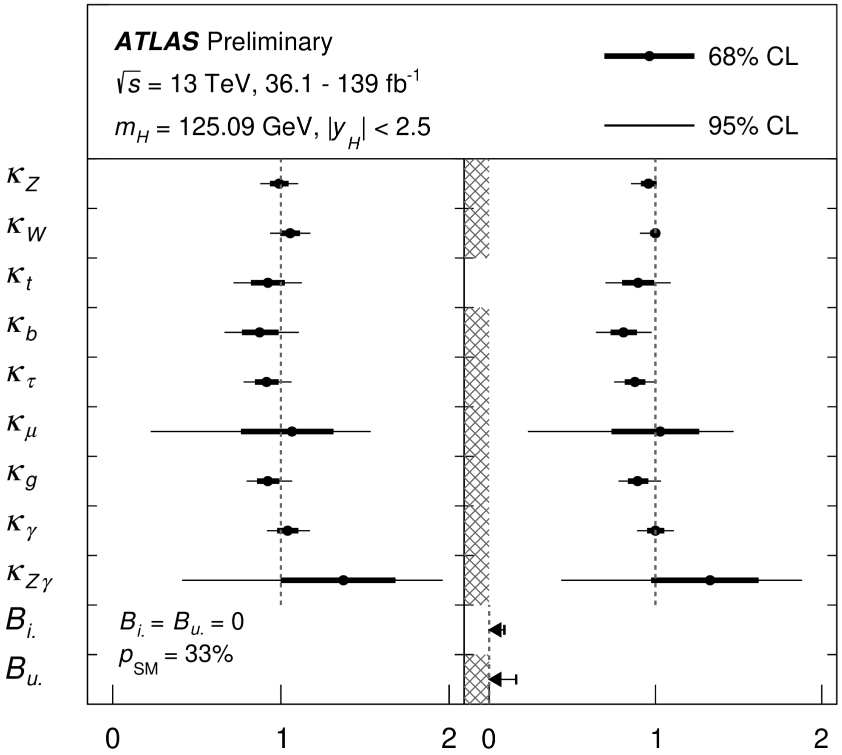
Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for sbottoms and 600 GeV for stops. Islands in one search are covered by other searches.

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

ATLAS and CMS Fit to Higgs Couplings

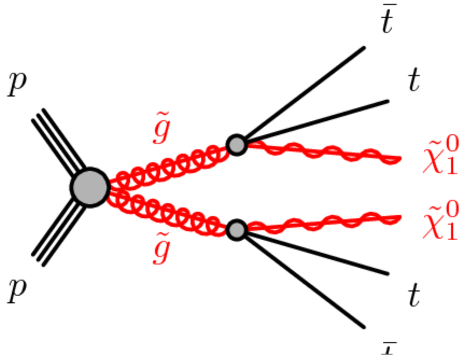
Departure from SM predictions of the order of few tens of percent allowed at this point

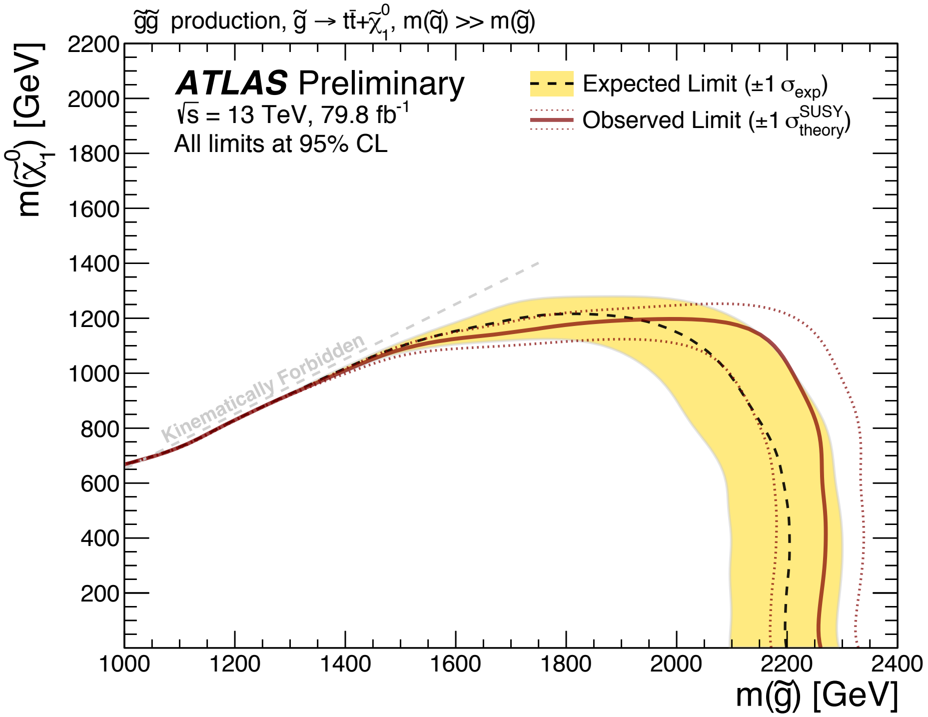


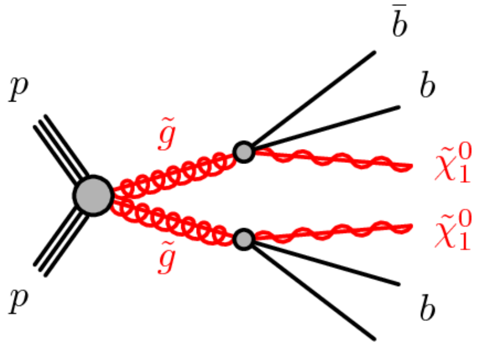


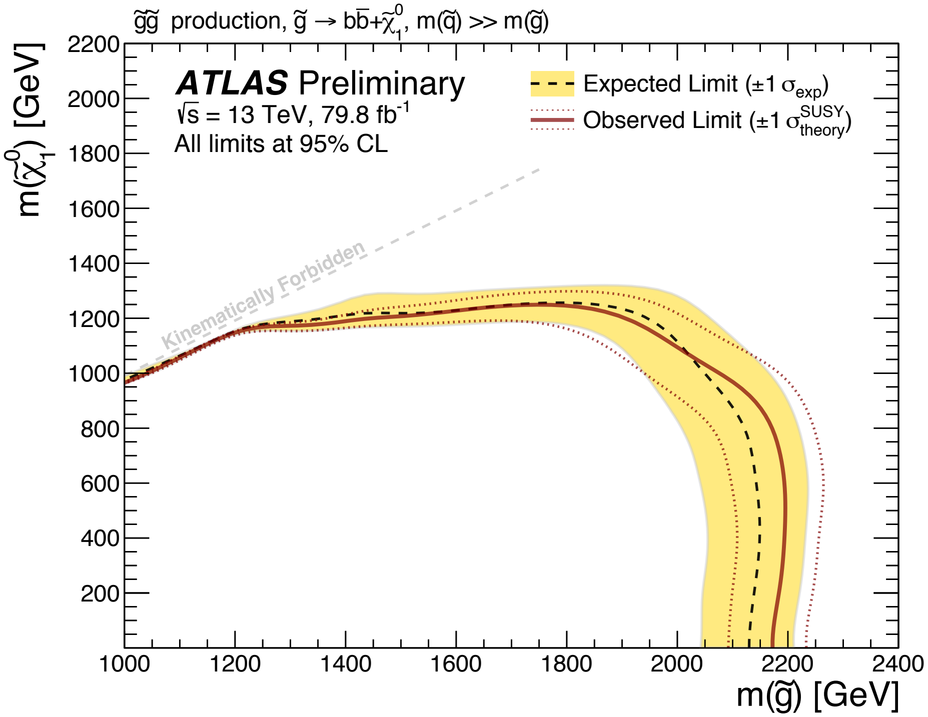
Decoupling of the heavy Higgs sector (or alignment) is preferred at this point. We shall se the heavy Higgs mass equal to the color state masses

Gluino Searches :
Gluino couples to SM via quark-squark vertices
Squarks can decay in a variety of ways









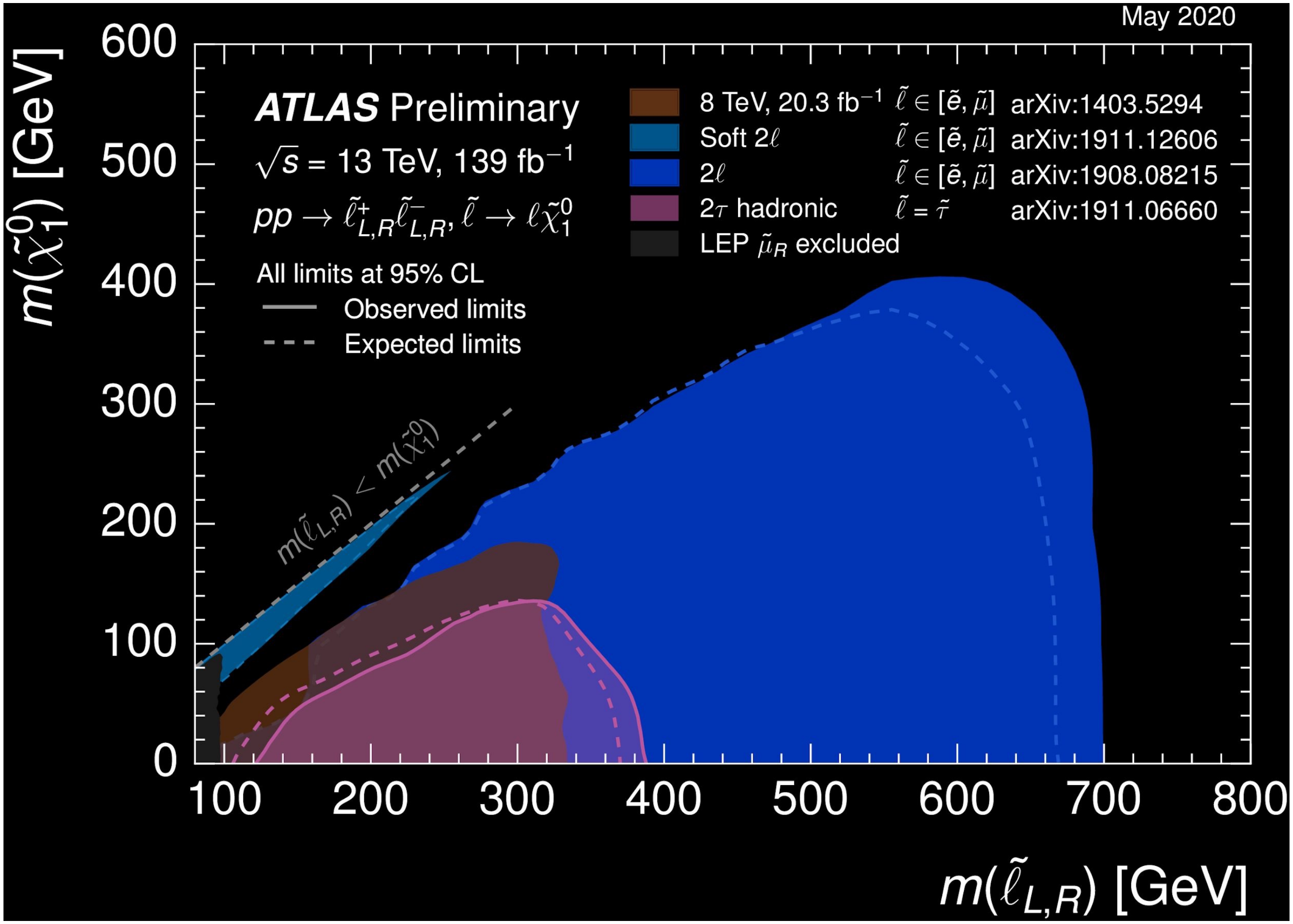
If they decay directly to third generation quarks,
gluinos must be heavier than about 2.2 TeV
We shall se the overall color particle scale at 2.5 TeV

Electroweak Sector

- Situation here is far less well defined than in the strongly interacting sector
- Sleptons, in particular staus are only weakly constraint 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.



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 $(\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_1, \tilde{H}^0_2)$ 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 real, $\quad M_1 = |M_1| e^{i\Phi_1}, \quad \mu = |\mu| e^{i\Phi_\mu}$

At tree level:

charginos $\quad M_2, \mu, \tan\beta$

neutralinos $\quad +M_1$

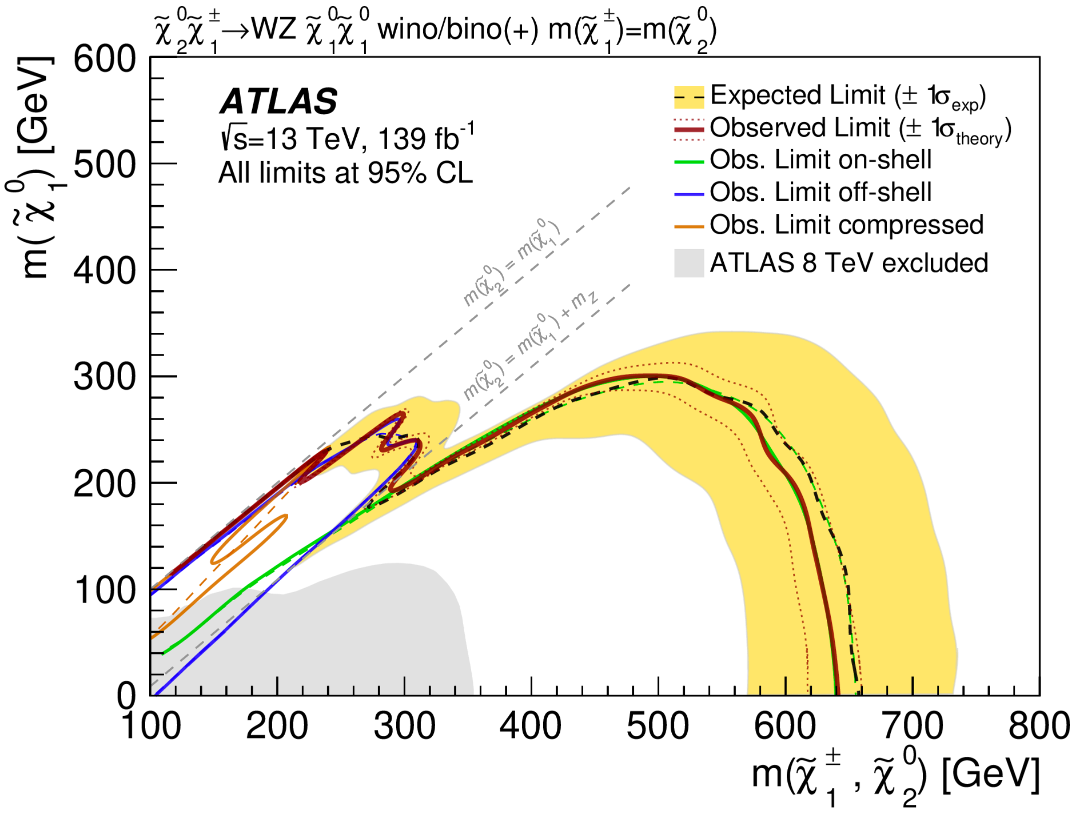
Φ_μ, Φ_1

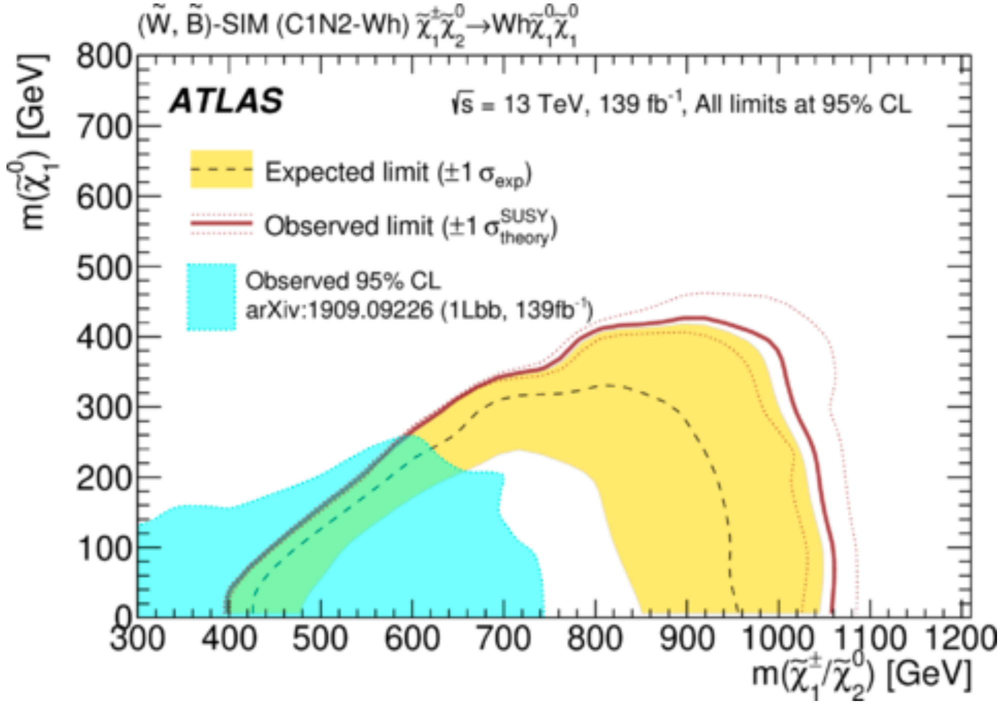
CP phases

Expected to be among the lightest sparticles

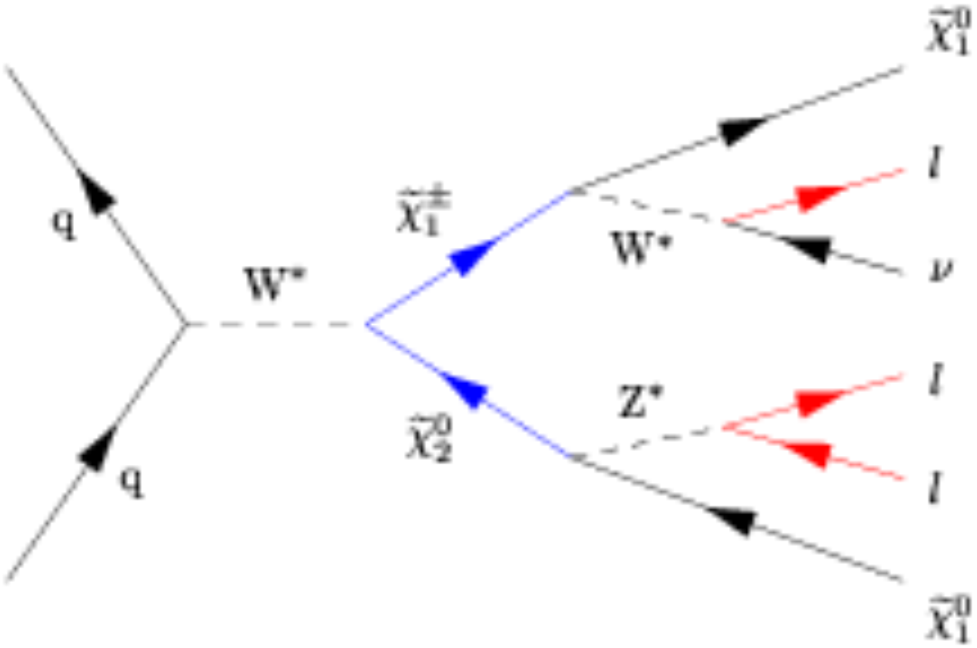
⇨ A good starting point towards SUSY parameter determination

Remarkable Improvement of Bounds away from the Compressed Region



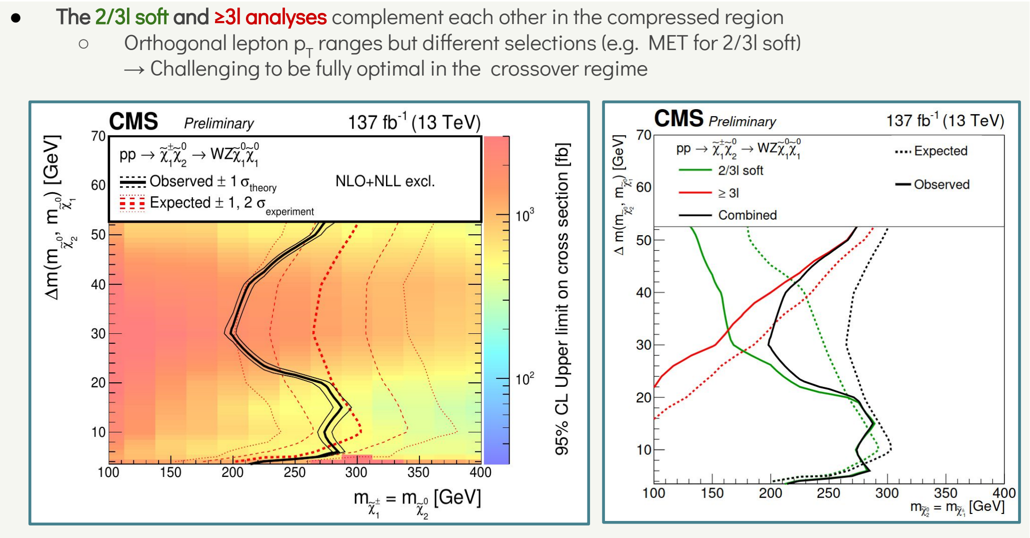


Chargino-Neutralino Production

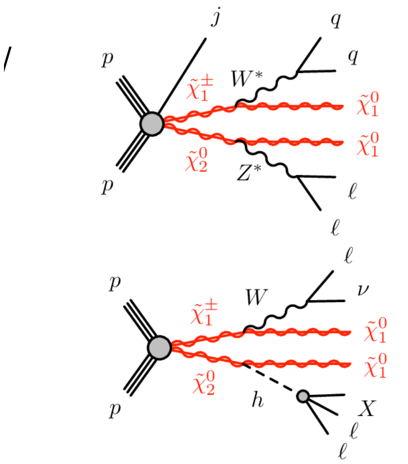


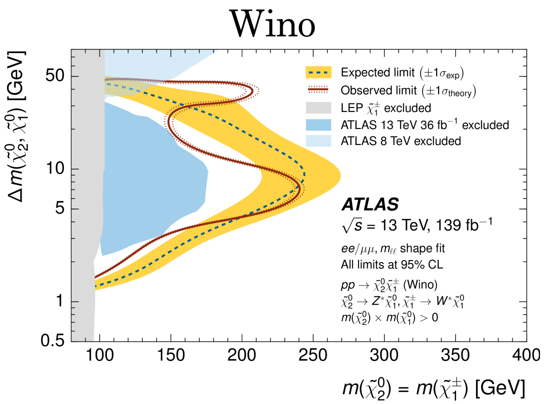
- For values of the wino and Higgsino masses larger than the weak scale, the mixing between them is small.
- Winos, in the adjoint representation of SU(2), are produced at a stronger rate than Higgsinos.
- The cross section for Wino production is about a factor 4 larger than the one for Higgsino production.
- 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”.

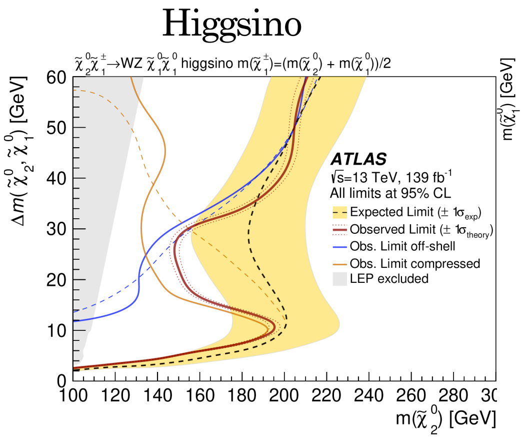
There may be surprises at the LHC

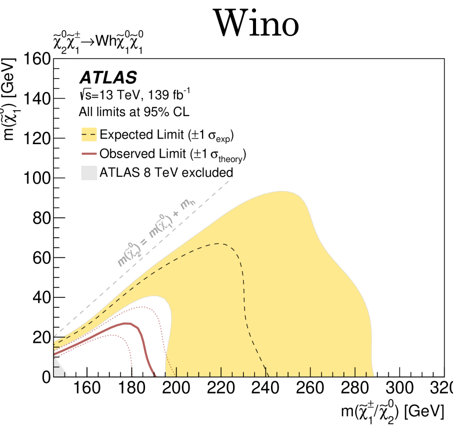


- The 2/3l soft and ≥3l analyses complement each other in the compressed region
    - Orthogonal lepton p_T ranges but different selections (e.g. MET for 2/3l soft) → Challenging to be fully optimal in the crossover regime







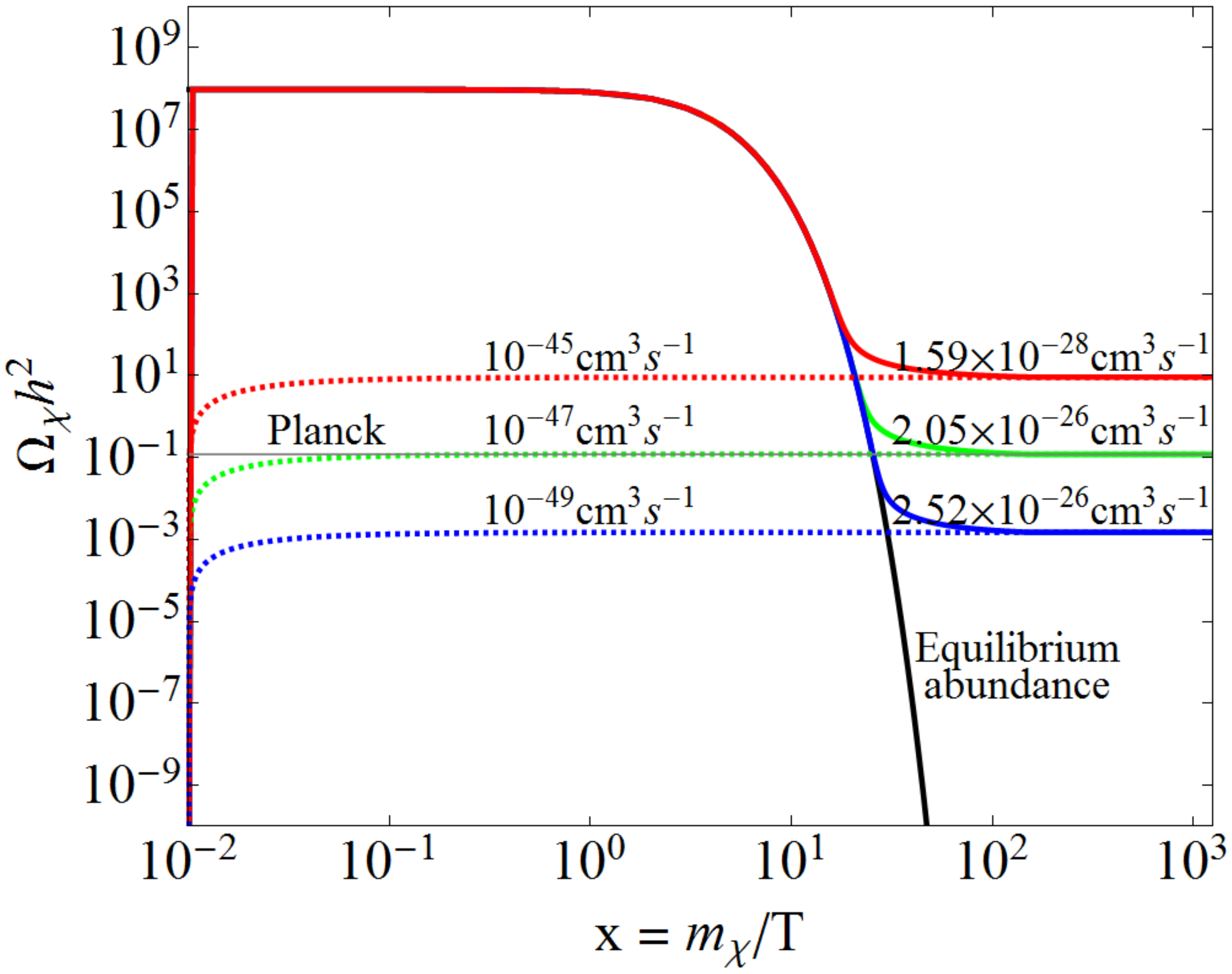


Excesses in regions consistent with co-annihilating Dark Matter

First weak evidences of SUSY electroweakino sector ?

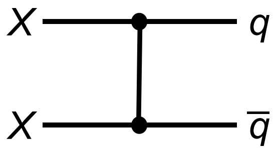
Eagerly waiting for Run3 results :)

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 ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

Weak scale size masses and couplings roughly consistent with ΩDM

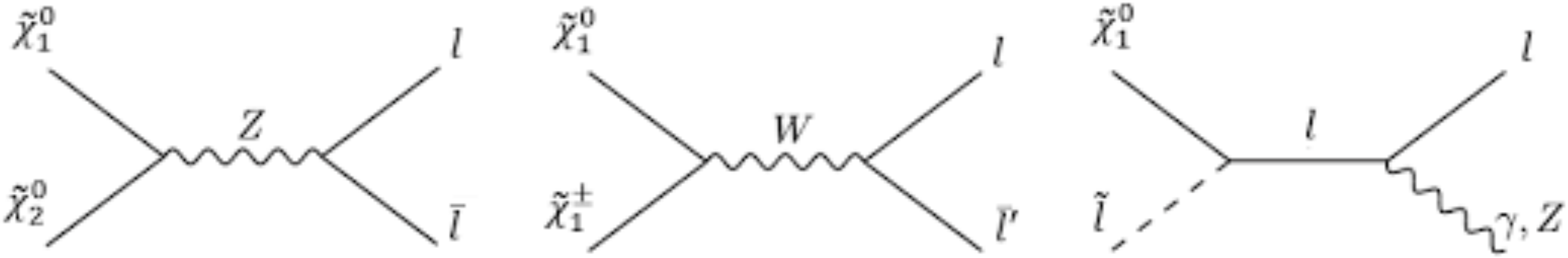
WIMPS

Drees and Nojiri, hep-ph/9207234

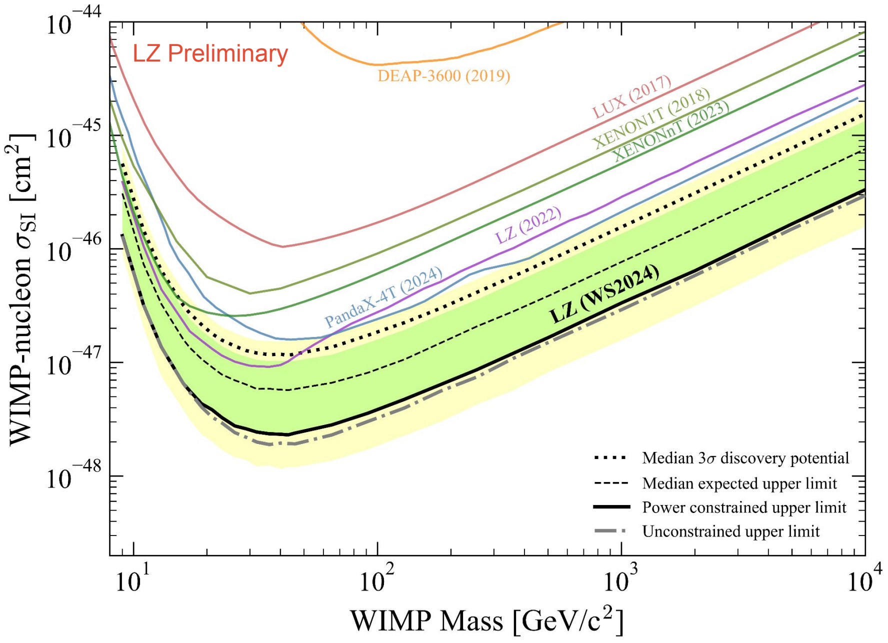
Co-annihilation

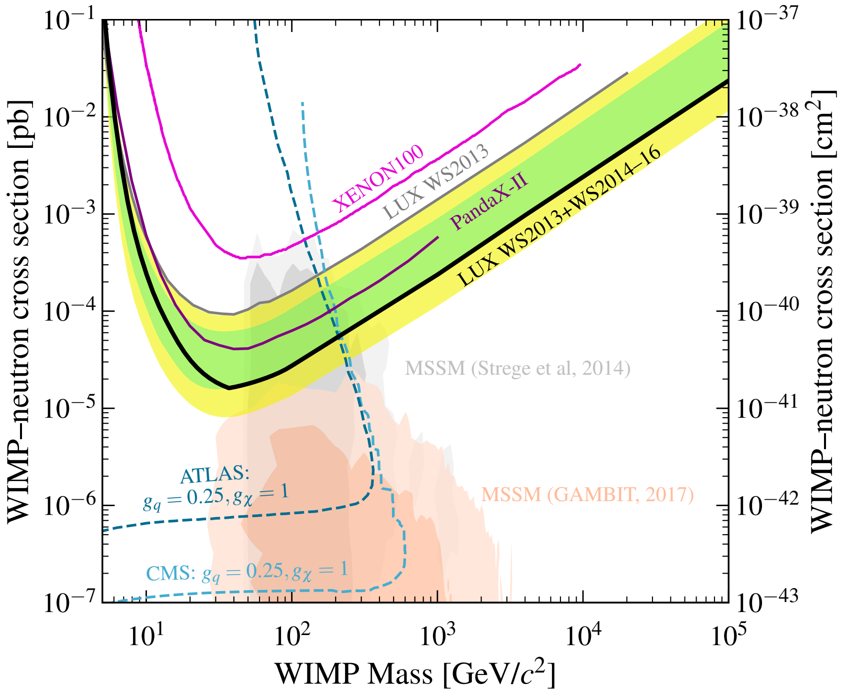
It happens when the DM can annihilate against other rapidly annihilating particles.
For it to work, the mass difference of the Dark Matter with the other weak scale weakly interacting particles must be of the order of a few tens of GeV.
It naturally leads to a compressed spectrum for new particle searches in the missing energy channel.

Some relevant channels in the case of sleptons or Winos (too light Higginos/ small μ leads to large SD cross sections).



DM : Direct Detection Bounds





$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde\chi_1^0}+2\mu/\tan\beta)\frac{1}{m_h^2}+\mu\tan\beta\frac{1}{m_H^2}+(m_{\tilde\chi_1^0}+\mu\tan\beta/2)\frac{1}{m_{\tilde Q}^2}\right]^2$$

Blind Spot :

$$2\left(m_{\tilde\chi_1^0}+2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2}\simeq-\mu\tan\beta\left(\frac{1}{m_H^2}+\frac{1}{2m_{\tilde Q}^2}\right)$$

$$\mu\times m_{\tilde\chi^0}<0$$

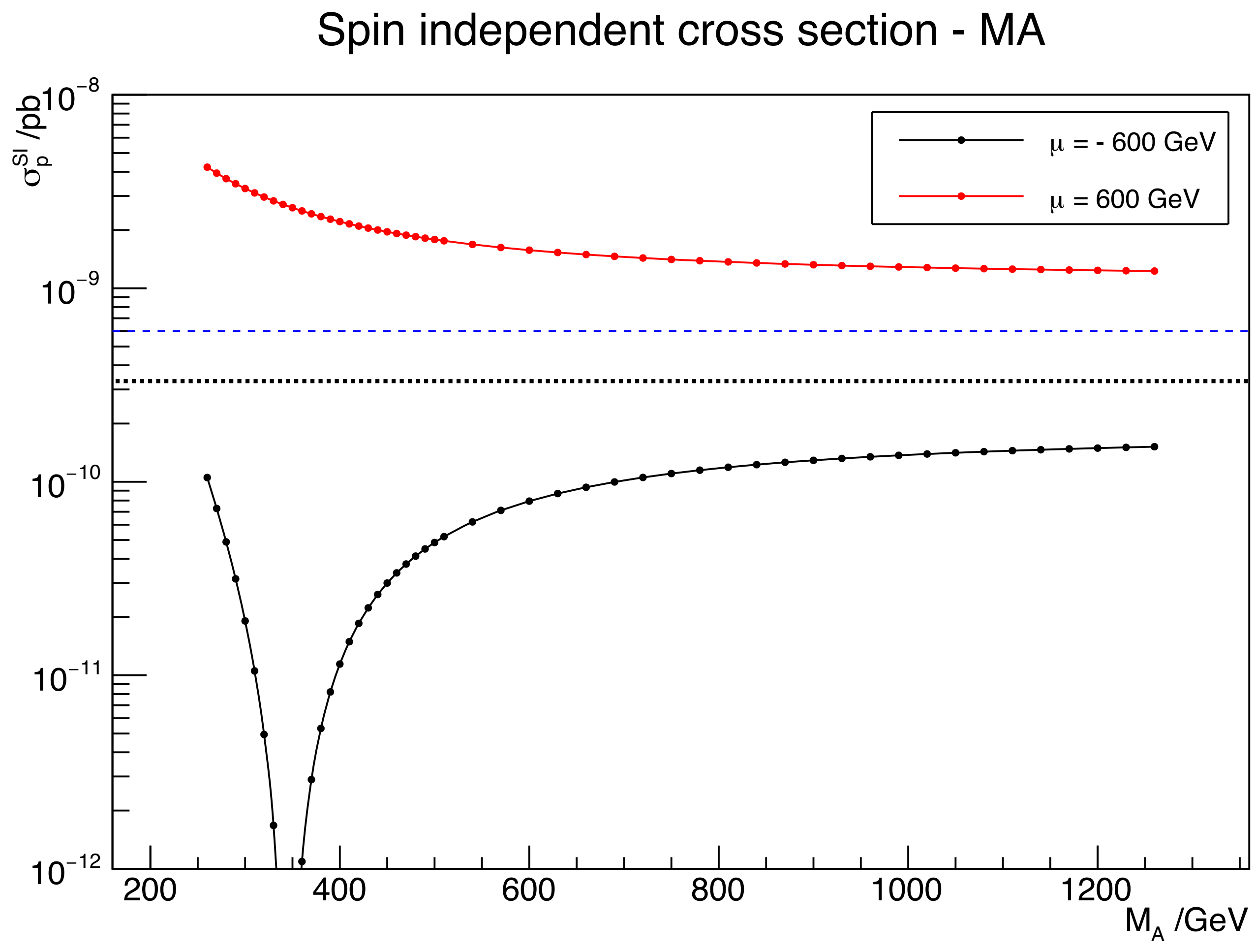
$$m_{\tilde\chi^0}\simeq M_1$$

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

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

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



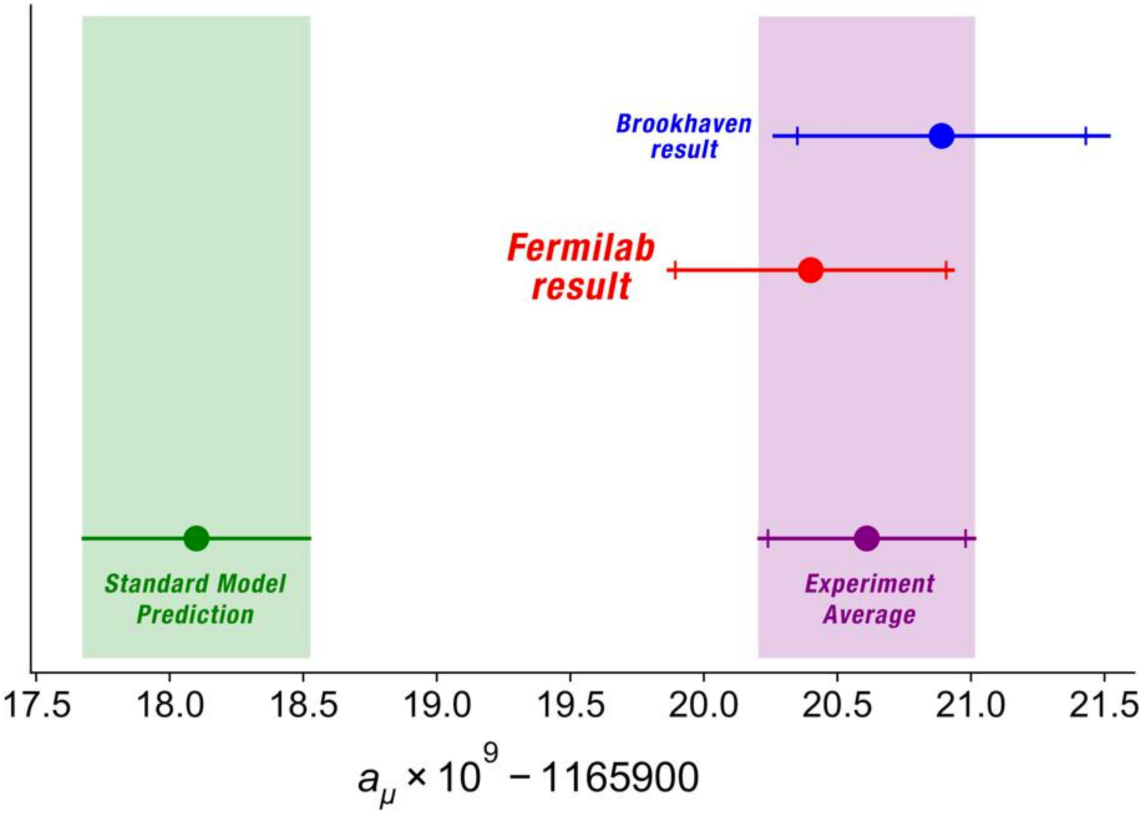
$M_1 = 400$ GeV

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.



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

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

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

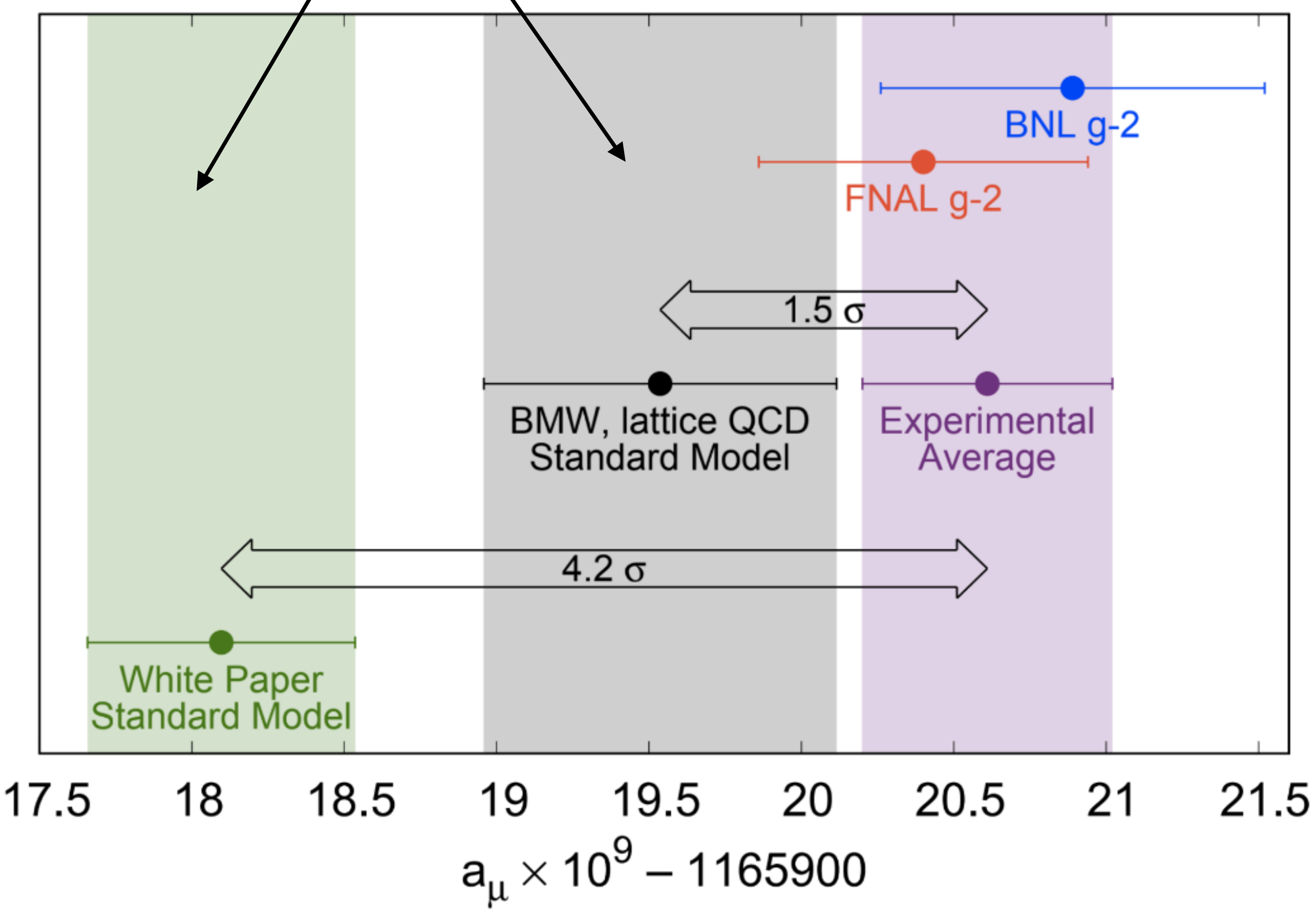
Muon g-2 : Comparison of BMW lattice computation with data driven method to fix hadronic contributions

N. Coyle, C.W.‘23

Can they be reconciled ?

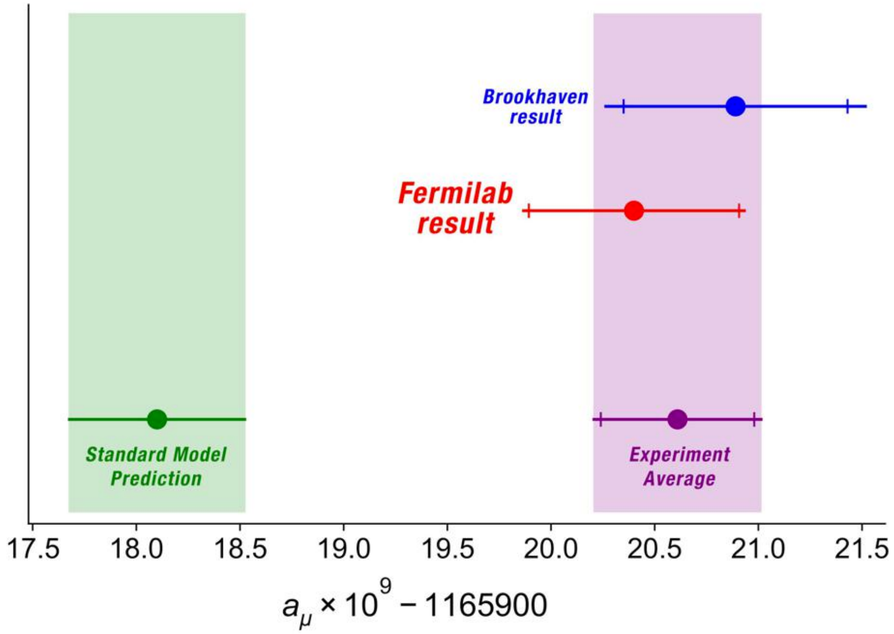
Z. Fodor ‘ 21

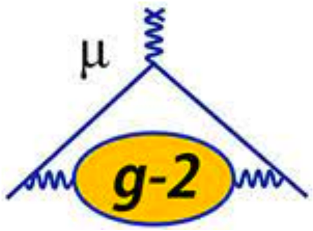
arXiv:2002.12347

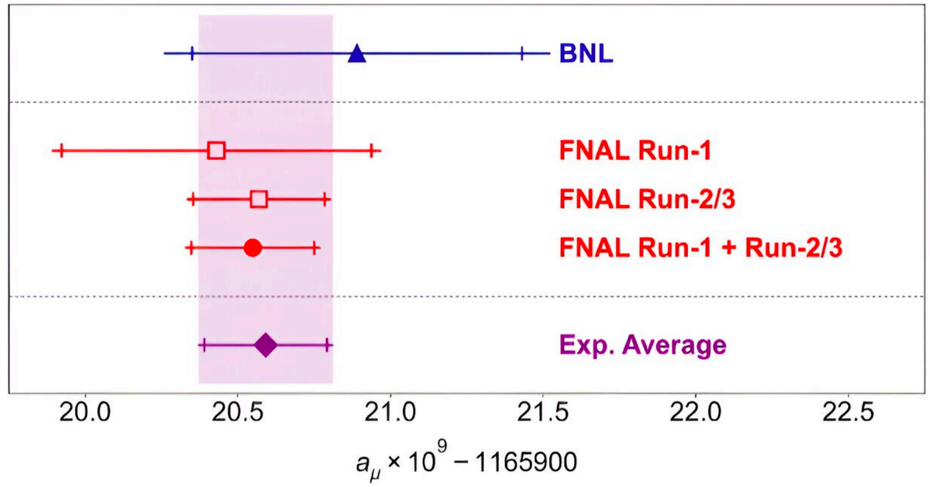


In the following, I will take the 4.2 sigma discrepancy seriously.
This question will be clarified within the next few years.

Updated result in 2023







arXiv:2104.03281

arXiv:2308.06320

Central Value did not change, experimental error decrease by a factor 1.6.
Taken at face value, discrepancy increased to 5.1 sigma.

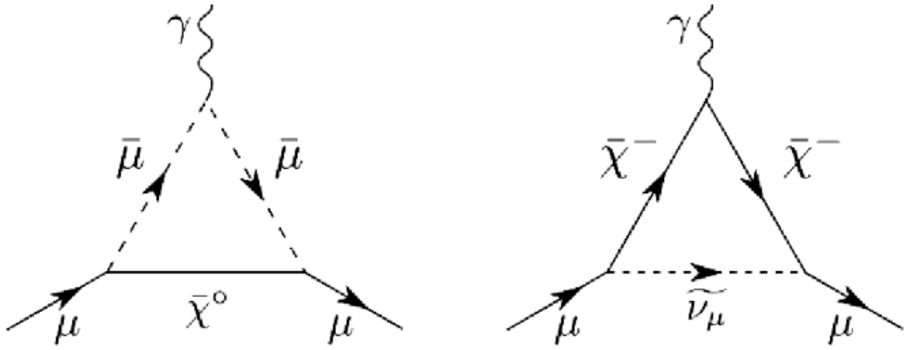
Dominant Diagrams for g-2 in Supersymmetry

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…

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

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



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

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

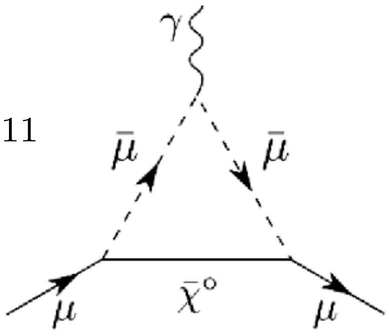
Rough Approximation

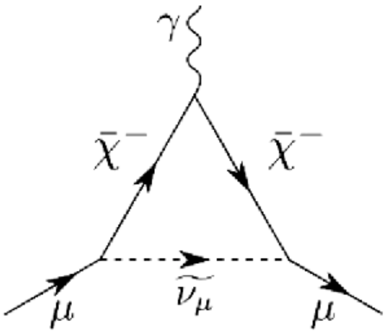
- If all weakly interacting supersymmetric particle masses were the same, and the gaugino masses had the same sign, then

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

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

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





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 μ

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 µ

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

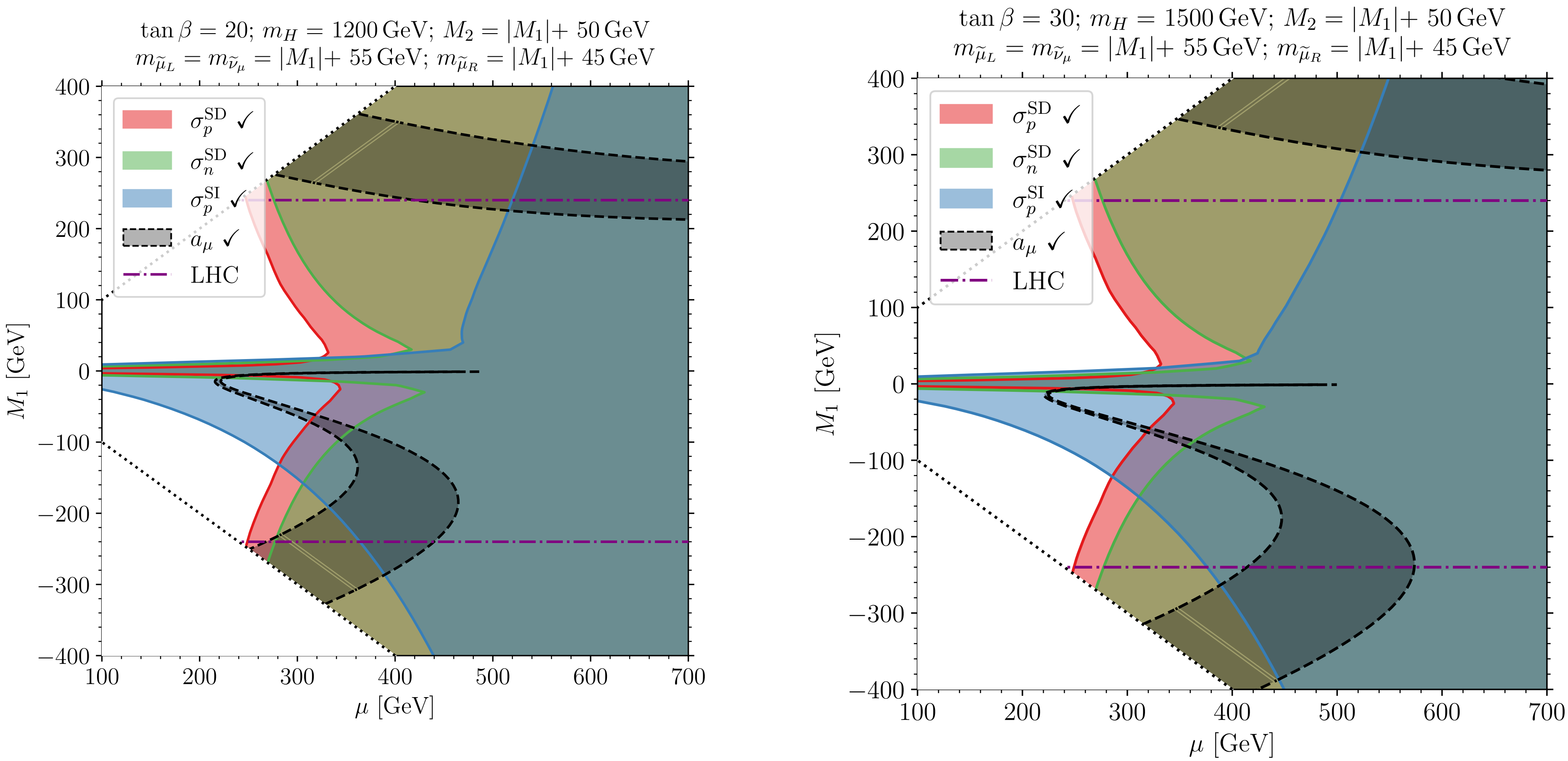
Since g-2 needs to be positive, compatibility between g-2 results and Direct detection may be either achieved for large values of µ or for smaller values of µ, when the relative sign of the gaugino masses is opposite, $M_1 \times M_2 < 0$

Baum, Carena, Shah and CW, arXiv:2104.03302

Baum, Carena, Shah and C.W., arXiv:2104.03302

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 μ between positive and negative values of the Bino mass parameter is observed.



Baum, Carena, Shah and C.W., arXiv:2104.03302

Benchmark Scenarios for negative $\mu \times M_1$

	BMSM	BMST	BMW	BMH
M_1 [GeV]	-352	-258	-274	63
M_2 [GeV]	400	310	310	700
μ [GeV]	690	475	500	470
$M_L^{1,2}$ [GeV]	360	320	350	750
M_L^3 [GeV]	500	320	350	750
$M_R^{1,2}$ [GeV]	360	320	350	750
M_R^3 [GeV]	500	320	350	750
M_A [GeV]	2000	1800	1600	3000
$\tan\beta$	60	40	35	65

	BMSM	BMST	BMW	BMH
m_χ [GeV]	350.2	255.3	271.4	61.0 (124.9)
$m_{\tilde{\tau}_1}$ [GeV]	414.4	264.2	305.3	709.5
$m_{\tilde{\mu}_1}$ [GeV]	362.7	323.0	352.8	751.3
$m_{\tilde{\nu}_\tau}$ [GeV]	496.0	313.7	344.2	747.3
$m_{\tilde{\nu}_\mu}$ [GeV]	354.4	313.7	344.2	747.3
$m_{\chi_1^\pm}$ [GeV]	392.3	296.2	297.9	469.6
Δa_μ [10^{-9}]	2.10	2.89	2.35	1.93
$\Omega_{\rm DM} h^2$	0.121	0.116	0.124	0.121
$\sigma_p^{\rm SI}$ [10^{-10} pb]	0.645	1.58	1.42	0.315
$\sigma_p^{\rm SD}$ [10^{-6} pb]	1.03	5.11	4.23	3.01
$\sigma_n^{\rm SI}$ [10^{-10} pb]	0.632	1.57	1.41	0.330
$\sigma_n^{\rm SD}$ [10^{-6} pb]	0.882	4.10	3.42	2.34

BMSM: Muon sneutrino co-annihilation channel
BMST: Stau co-annihilation channel
BMW : Wino co-annihilation scenario.
BMH : Higgs resonant annihilation channel

Wino Co-annihilation
(Compressed Chargino-Neutralino Spectrum)

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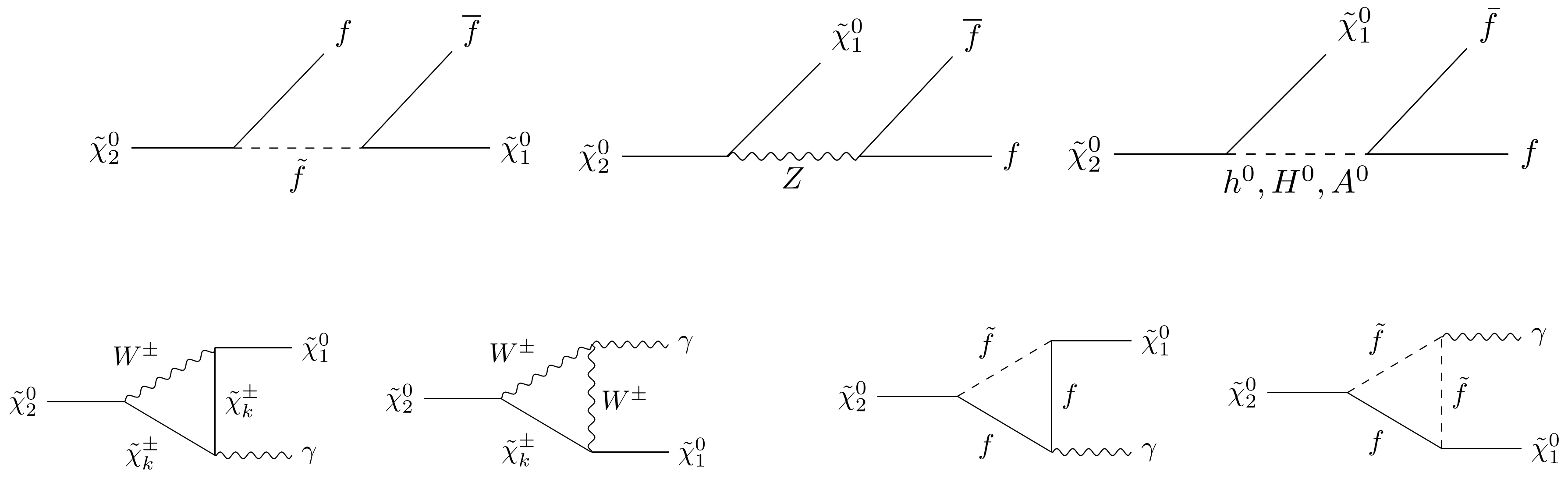
Neutralino Decay Channels



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

Three body decay rates are proportional to ϵ^5

Radiative decay rates are proportional to ϵ^3

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

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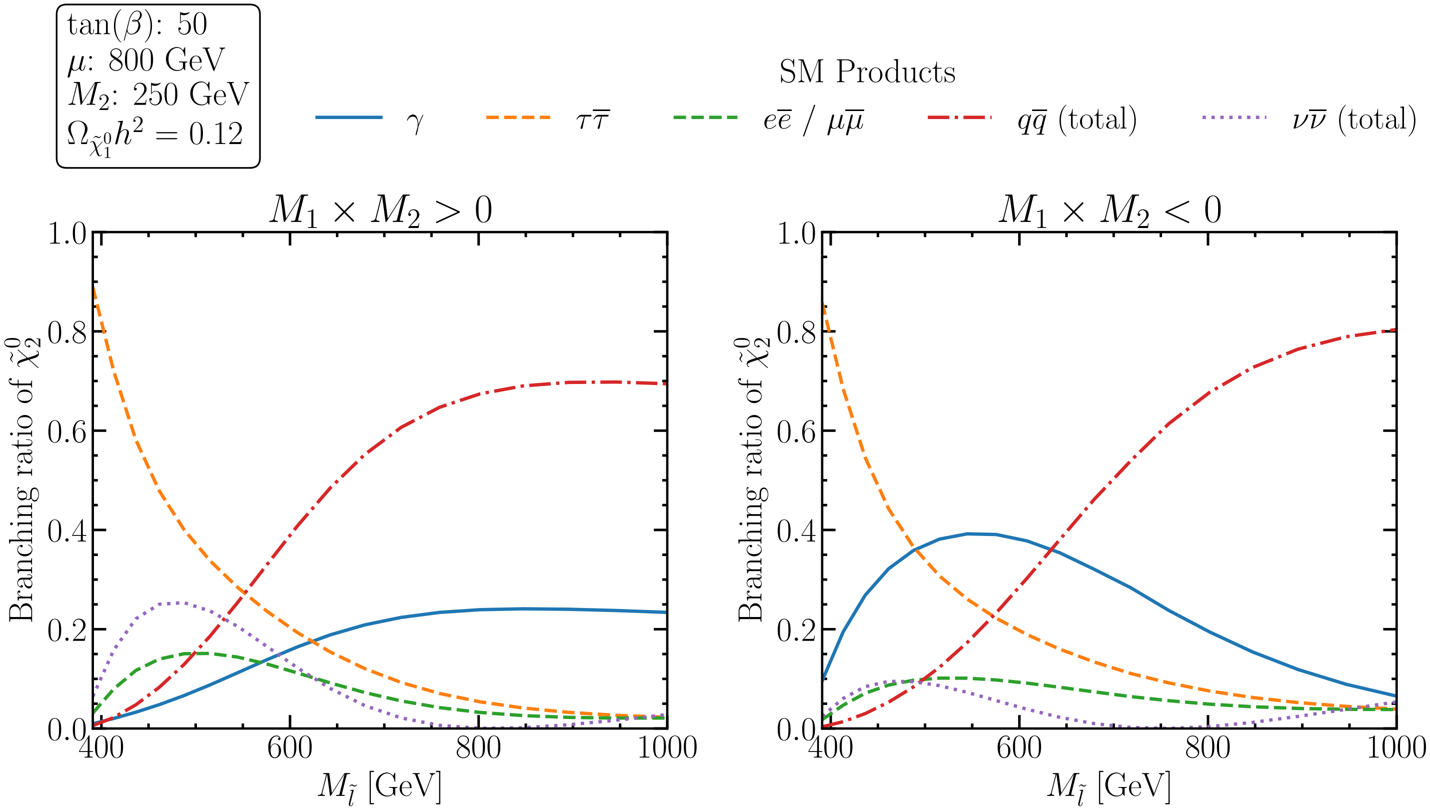
Branching Ratios



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.

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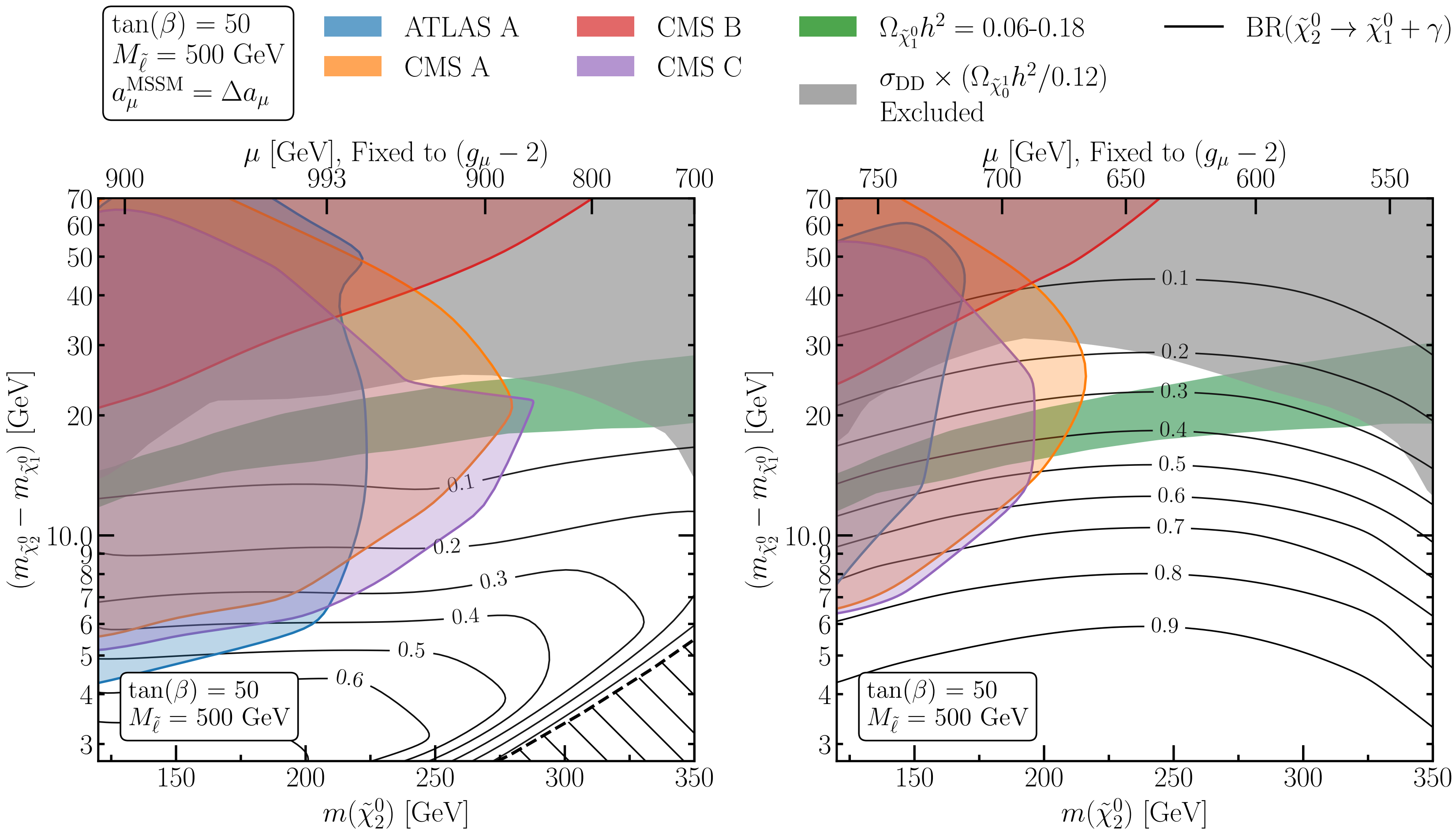
Allowed Parameter Space



$M_1 \times M_2 > 0$

$M_1 \times M_2 < 0$

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

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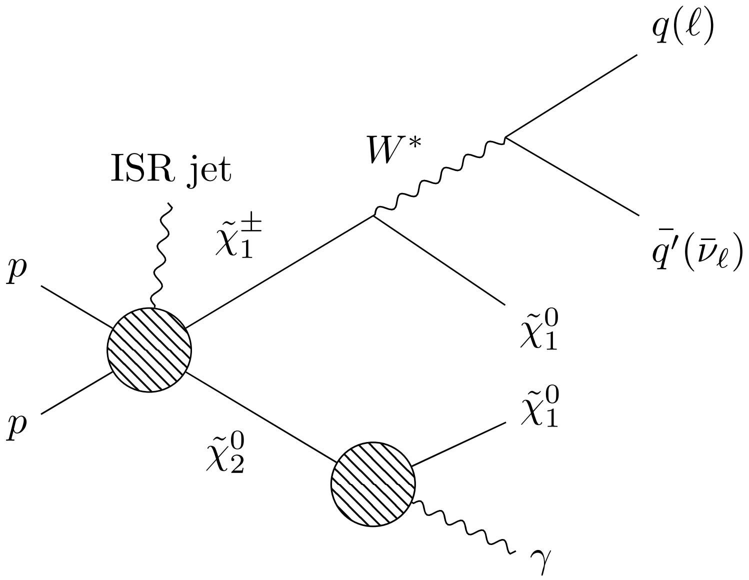
New Search Channel

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

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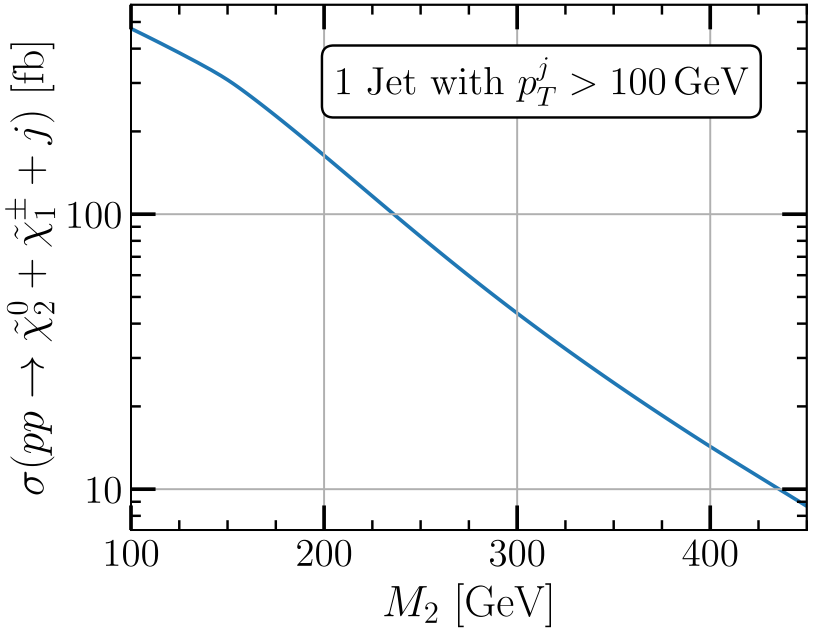
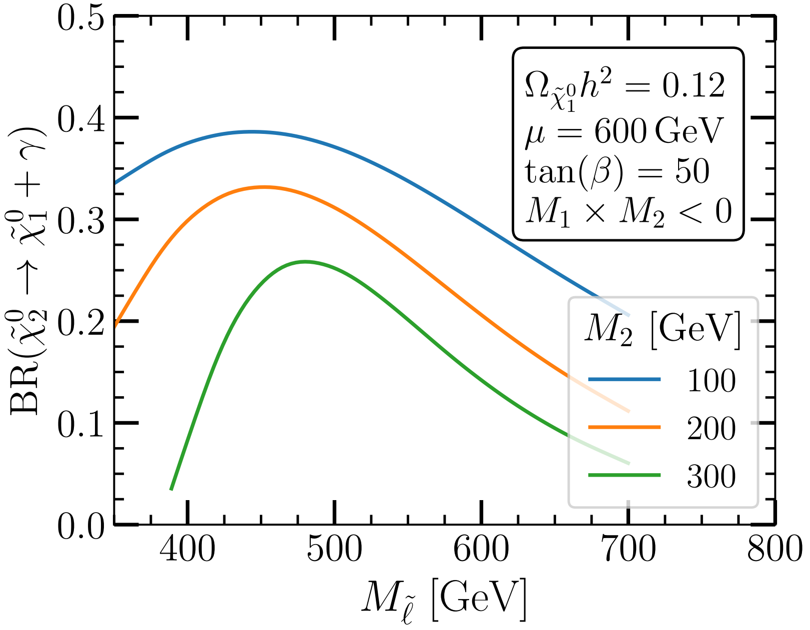
Cross Sections





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.

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Probing the Compressed region at the LHC

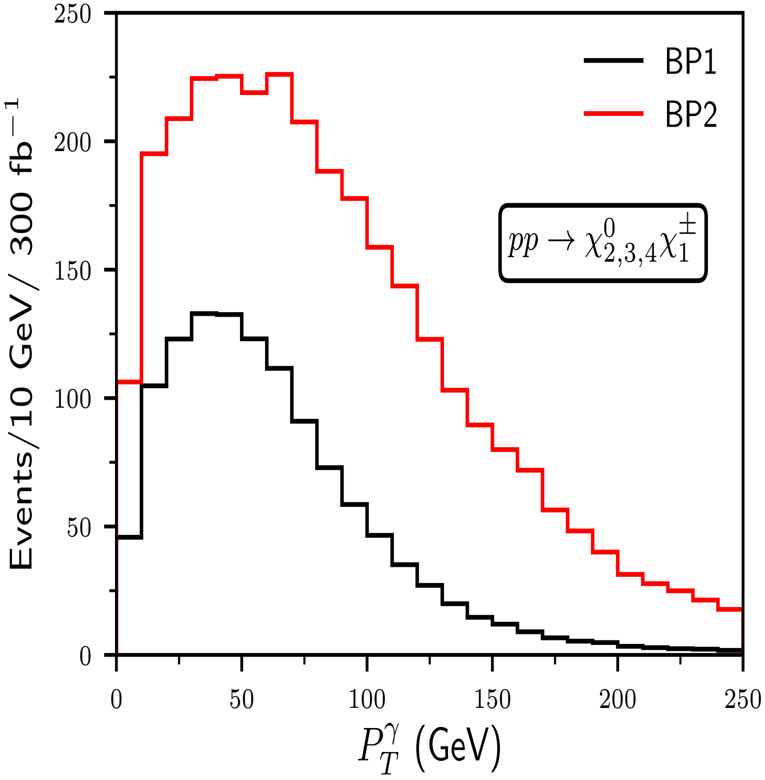
- We propose to complement the usual searches into lepton and quark final states with a search for photons and missing energy in the final state, to probe the compressed region of supersymmetric theories.
- Although the photon transverse momentum is not large, the run 3 now allow for non-trivial multi-object 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 $(pp \to \tilde{\chi}_2^0 + \tilde{\chi}_1^\pm + j)$ process.
- Let’s emphasize the the searcher multi-lepton processes that 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.

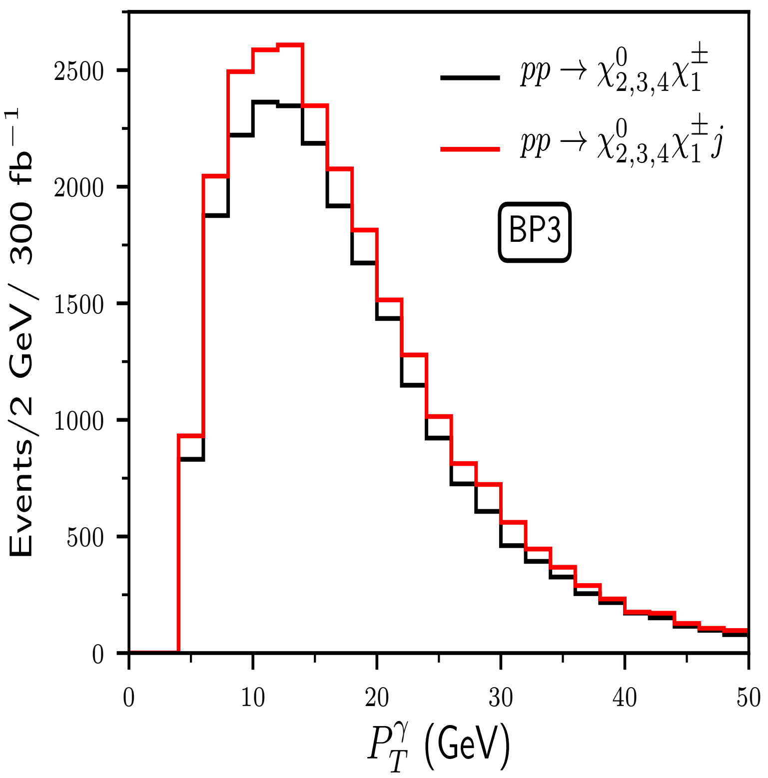
S. Roy, C.W. arXiv:2401.08917

NMSSM Case

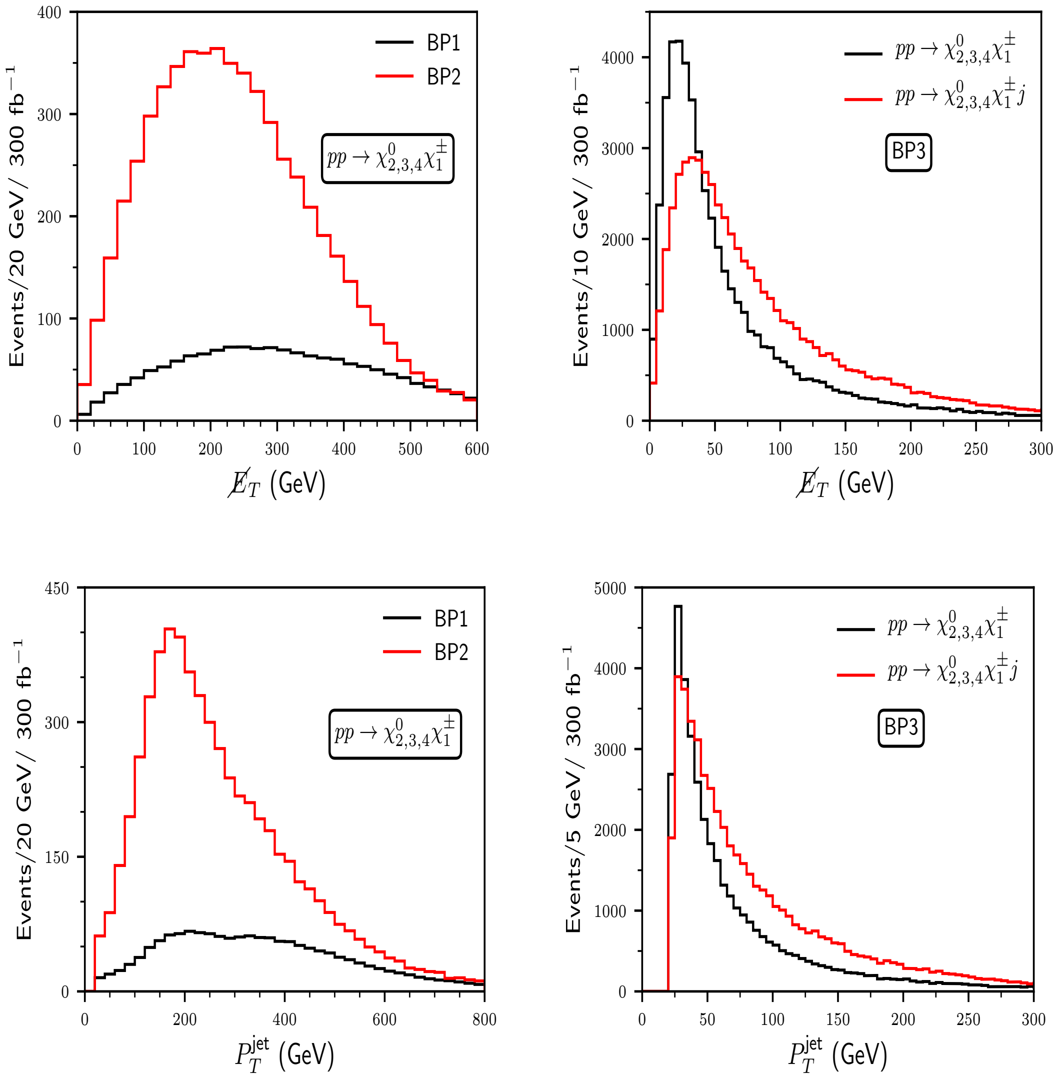
In the NMSSM you can have a similar situation with Bino and/or Singlinos co-annihilating with Winos or Higgsinos, and the story is similar.

In the NMSSM, however, you can also have Bino-singlino co-annihilation.
In such a case these particles are produced at the LHC from heavier Winos and Higgsinos and then, the photon spectrum is harder and searches become easier.





NMSSM : Other kinematic variables have expected patterns.



Blind Spot conditions are also modified in the NMSSM case

S. Roy, C.W. arXiv:2401.08917
S.Baum, M. Carena, N.R. Shah, C.W.. arXiv:1712.09873

Arganda, Carena, De Los Rios, Perez, Rocha, Sanda Seoane, C.W.,to appear soon

Machine Learning Analysis Benchmark Scenarios

$$pp \to \tilde{\chi}_1^{\pm}\,\tilde{\chi}_2^0\,j \to \tilde{\chi}_1^0\,\ell\,\nu_\ell + \tilde{\chi}_1^0\,\gamma + j$$

BP	$m_{\tilde{\chi}_2^0}$ [GeV]	$(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ [GeV]	$\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma)$	$\sigma(pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)$	$\frac{\sigma_{DD}}{\sigma_{DD,95}}$	Ωh^2
1	200	34	15%	190 fb	0.59	2.0
2	200	19	37%	190 fb	0.05	0.12
3	200	10	73%	190 fb	0.01	0.02
4	250	37	15%	92 fb	0.77	1.2
5	250	22	36%	92 fb	0.10	0.12
6	250	13	67%	92 fb	0.02	0.03
7	300	39	16%	48 fb	0.09	0.8
8	300	24	36%	48 fb	0.16	0.12
9	300	15	62%	48 fb	0.05	0.04
10	350	41	17%	27 fb	1.09	0.60
11	350	26	35%	27 fb	0.25	0.12
12	350	17	58%	27 fb	0.10	0.04
13	400	43	16%	16 fb	1.28	0.47
14	400	27	32%	16 fb	0.36	0.12
15	400	18	52%	16 fb	0.17	0.05

Arganda, Carena, De Los Rios, Perez, Rocha, Sanda Seoane, C.W.,to appear soon

Standard Cut-Based Analysis

Process	Yield
$W+\text{jets}$	60058
$W\gamma$	58462
$t\bar{t}+\text{jets}$	18051
$Z+\text{jets}$	3360
Single-top	3214
$t\bar{t}\gamma$	2498
Diboson	2340
Total background	147983

BP #	Yield	$S/\sqrt{B}$
1	202	0.52
2	459	1.19
3	637	1.65
4	111	0.28
5	235	0.61
6	334	0.86
7	66	0.17
8	129	0.33
9	179	0.46
10	40	0.10
11	74	0.19
12	102	0.26
13	23	0.05
14	41	0.10
15	57	0.14

Leptons $p_T > 10$ GeV
Photons $p_T > 10$ GeV
Jets $p_T > 20$ GeV
Missing $E_T > 100$ GeV
Central events $\eta < 2.5$

Dominant Backgrounds :
$t\bar{t}$ + jets
$W, Z + jets,\ W, Z + \gamma$
$WW,\ ZZ$

No Discovery Potential, even at the highest LHC luminosities

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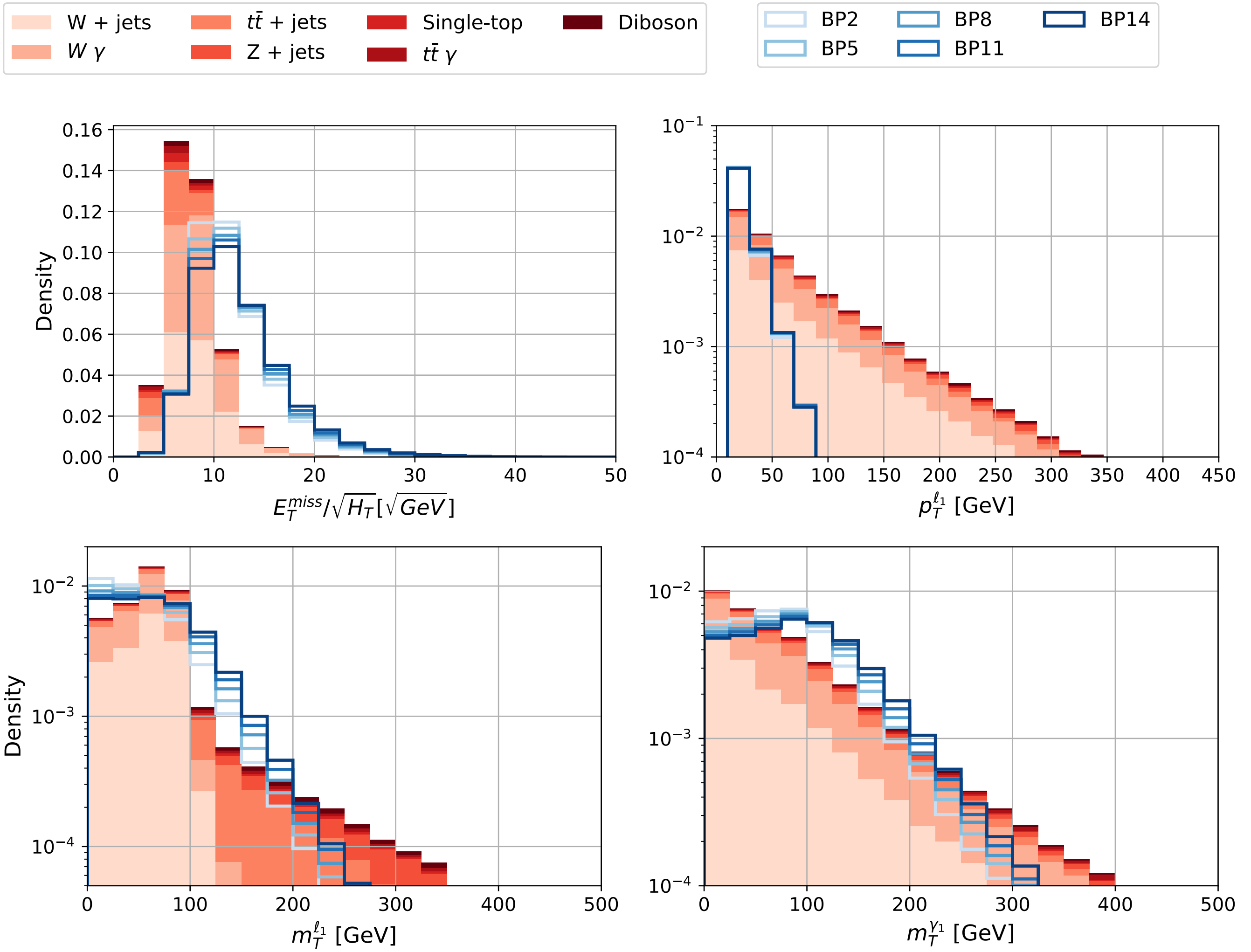
Most relevant kinematic Variables



$$m_T^A \equiv m_T\left(\mathbf{p}_T(A), \mathbf{E}_T^{\text{miss}}\right) = \sqrt{2p_T(A)E_T^{\text{miss}}\left(1-\cos\Delta\phi\left(\mathbf{p}_T(A), \mathbf{E}_T^{\text{miss}}\right)\right)}$$

$$H_T = \sum p_T^{\text{jets}} + \sum p_T^{\tau} + \sum p_T^{e} + \sum p_T^{\mu} + \sum p_T^{\gamma}\,;$$

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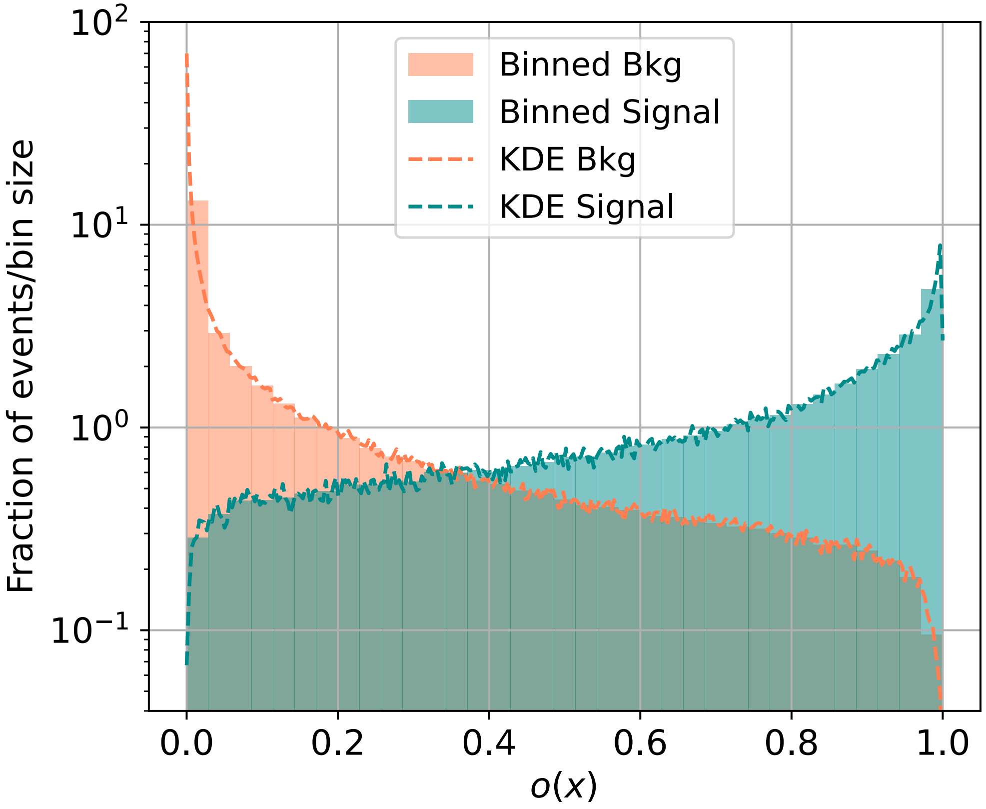
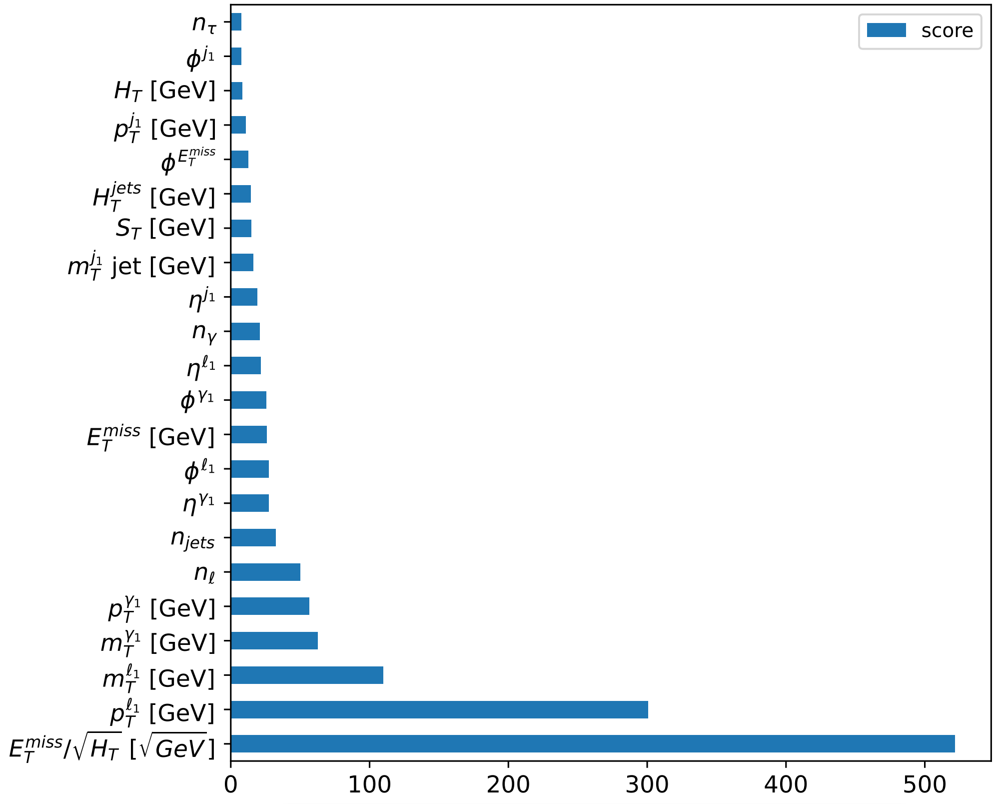
Machine Learning Output

Machine Learning Analysis makes use of the full correlation of the kinematic variables in the signal and background processes





XGBoost Feature Relevance

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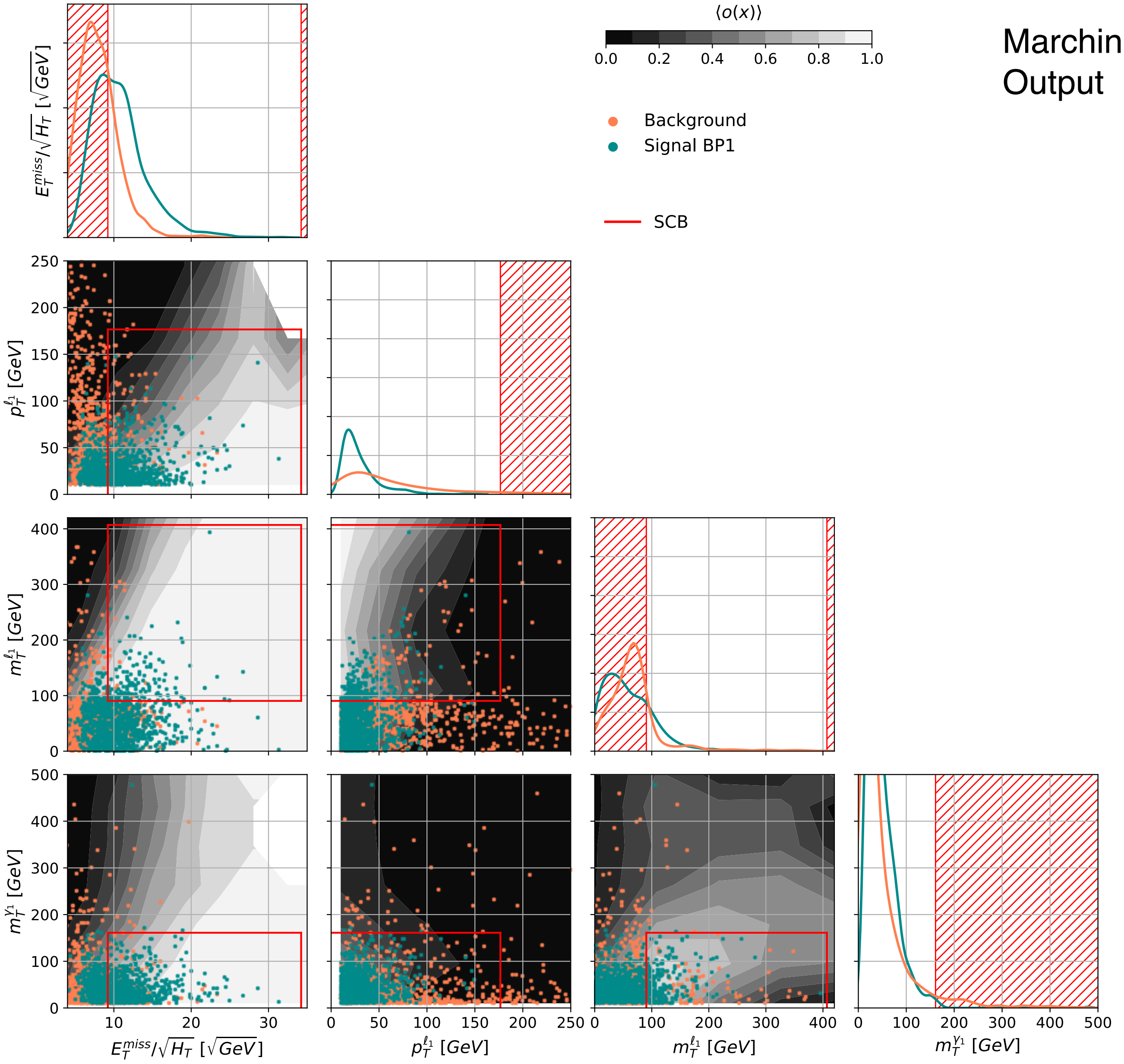
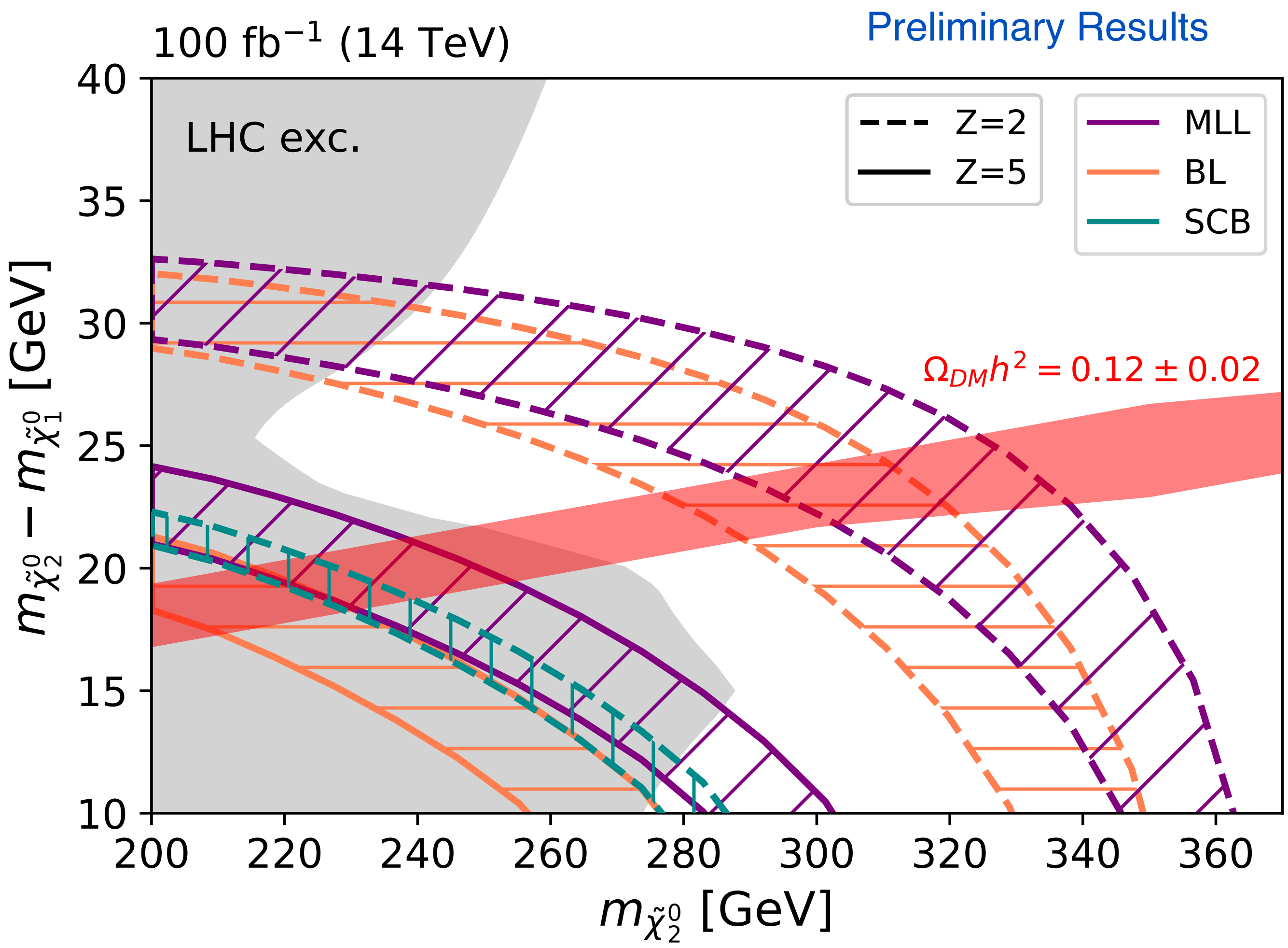
Correlations between kinematic variables



Marchine Learning Output

Arganda, Carena, De Los Rios, Perez, Rocha, Sanda Seoane, C.W.,to appear soon

Results of the ML Analysis



Results are optimistic, ignoring probable systematic errors.
One can probe currently allowed parameter space, although discovery will demand higher luminosities.

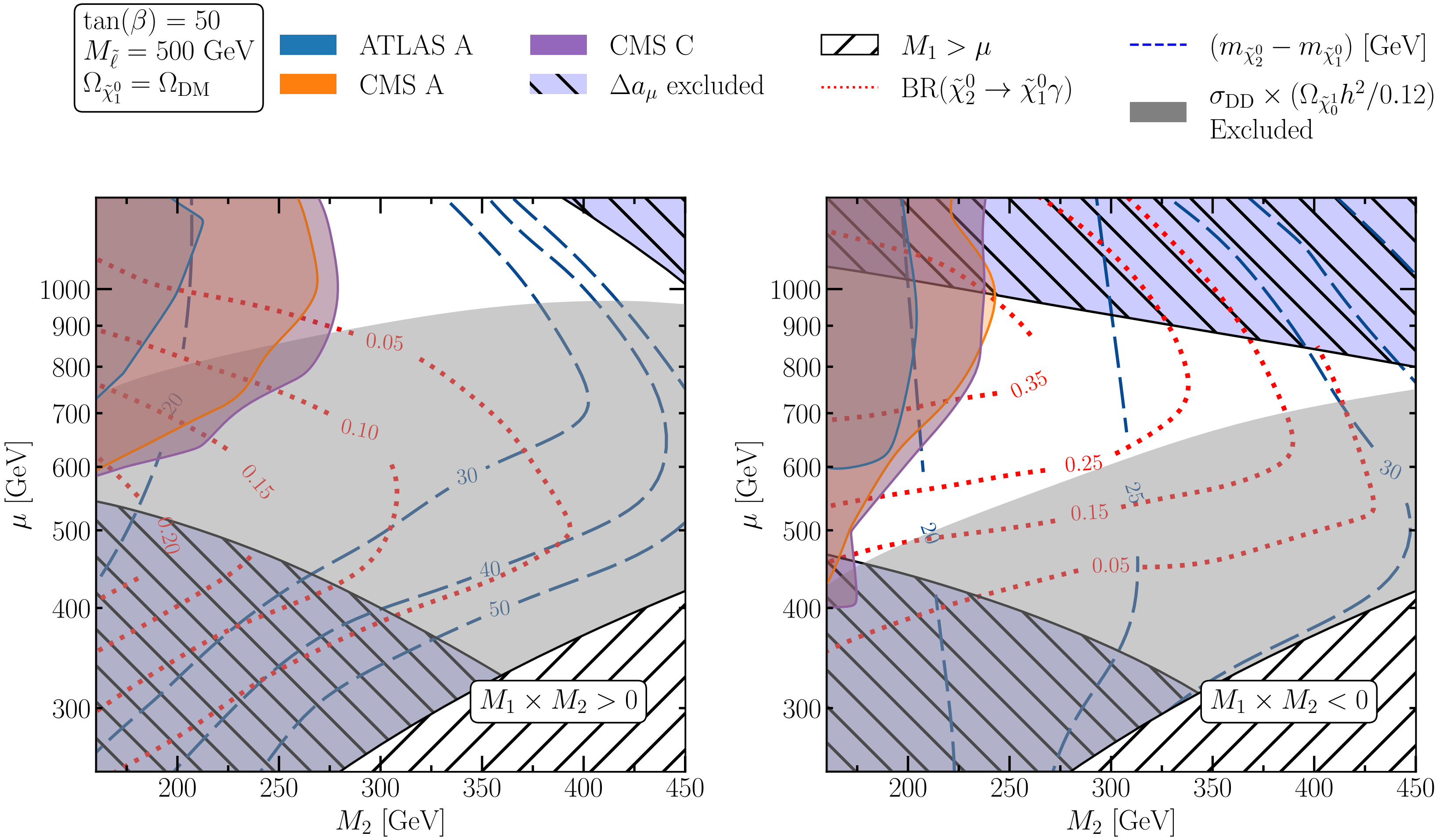
Conclusions

- Searches for supersymmetry have led to strong bounds on the existence of colored particles (gluinos) at scales below the 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 tanβ that will be smaller by the same factor, without affecting the collider cross sections or BR in a significant way.

Backup

Baum, Carena, Ou, Rocha, Shah, C.W. ’23

Allowed Parameter Space



$M_1 \times M_2 > 0$

$M_1 \times M_2 < 0$

Dark Matter fixed to explained the relic density

Same behavior in other regions of compressed parameter space

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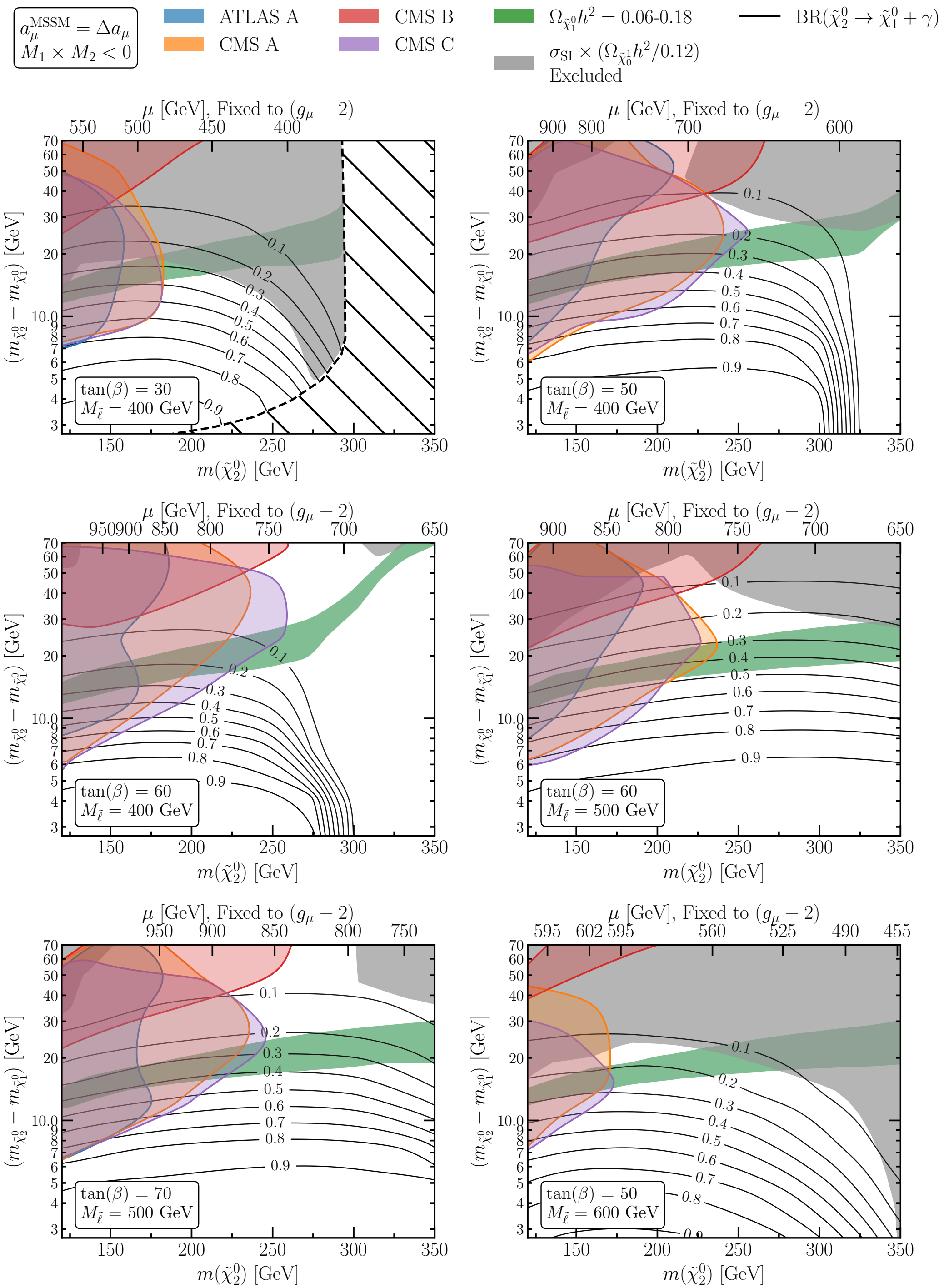

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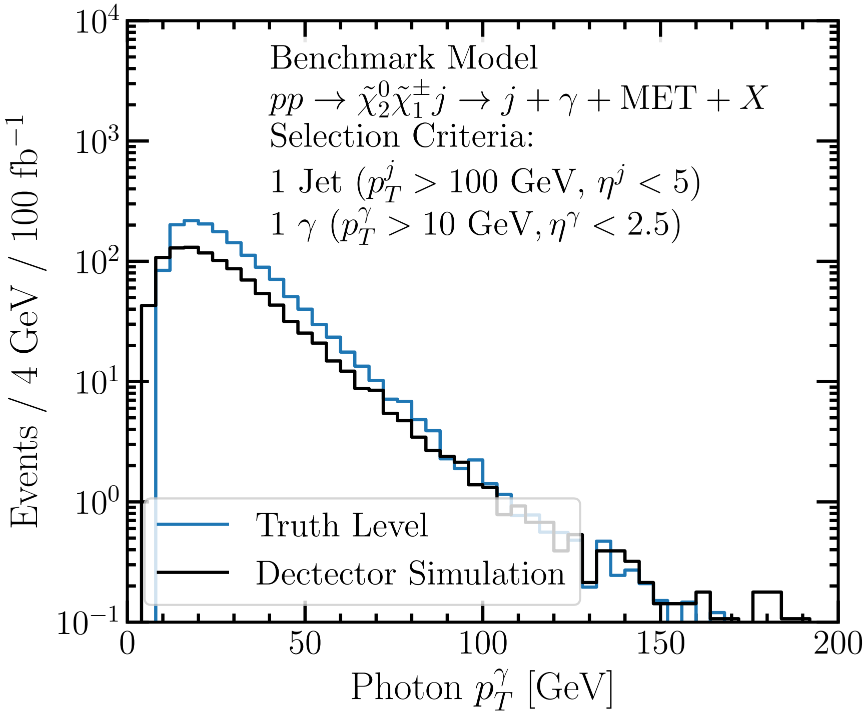
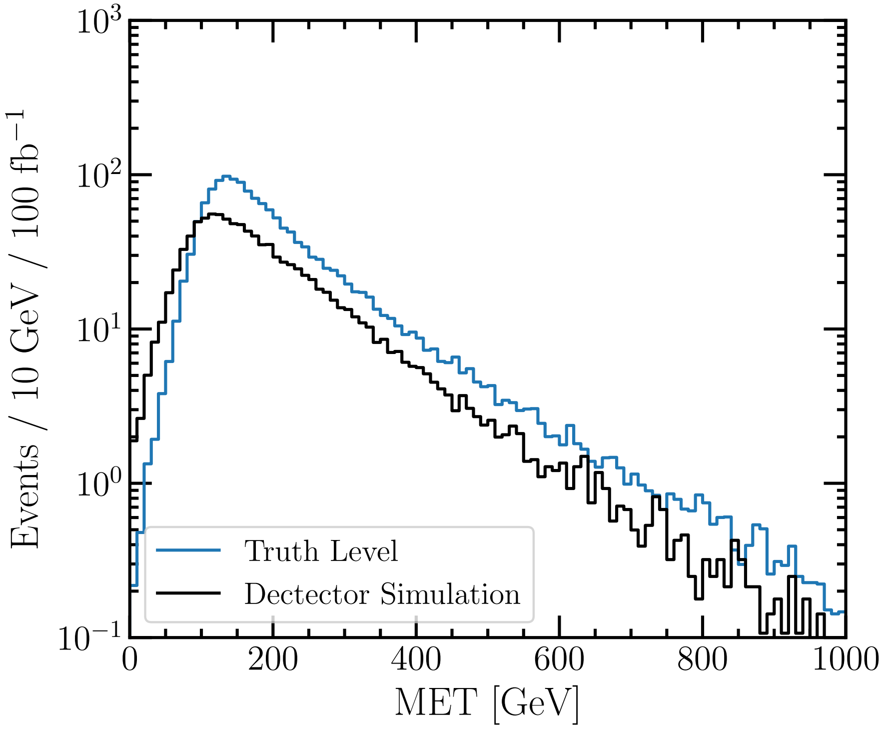
Energy and Momentum Distributions





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

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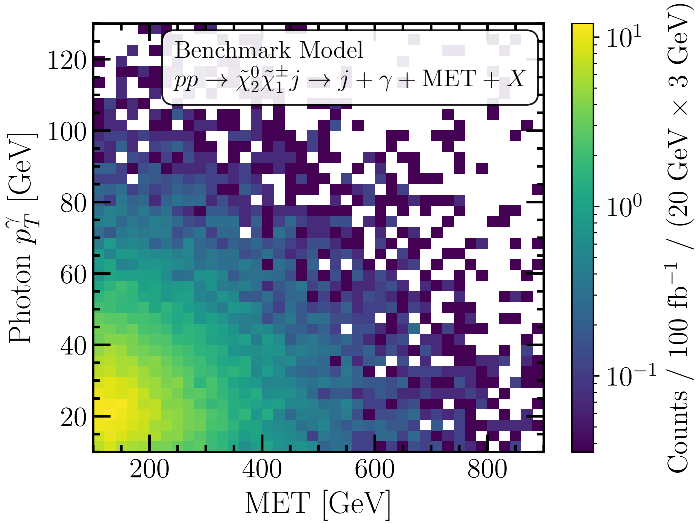
Benchmark Scenario

$$M_1 = -282\,\mathrm{GeV}$$
$$M_2 = 287\,\mathrm{GeV}$$
$$\mu = 800\,\mathrm{GeV}$$
$$M_{\tilde{l}} = 500\,\mathrm{GeV}$$
$$\tan\beta = 50$$

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

Efficiencies

		$\not\!\!E_T$ 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%

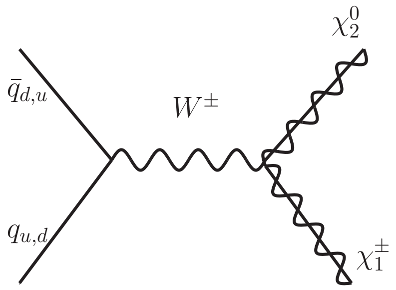


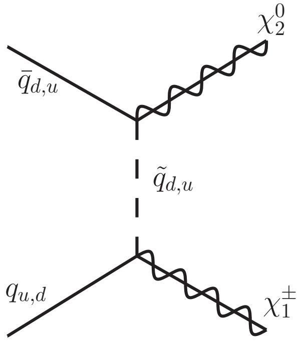
Missing E_T is strongly correlated with the ISR jet p_T

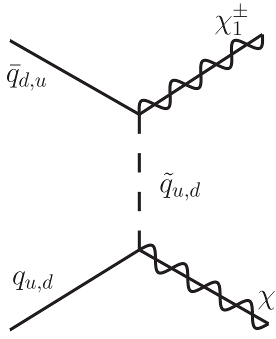
No strong correlation between missing E_T and photon p_T

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.

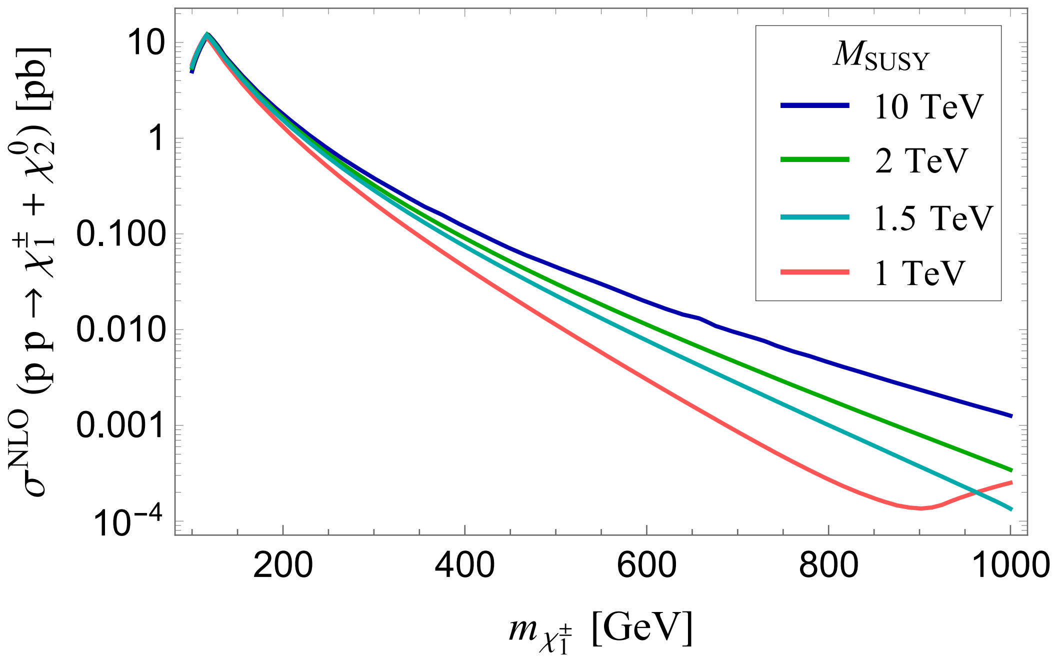
Liu, McGinnis, Wang, C.W. arXiv:2008.11847







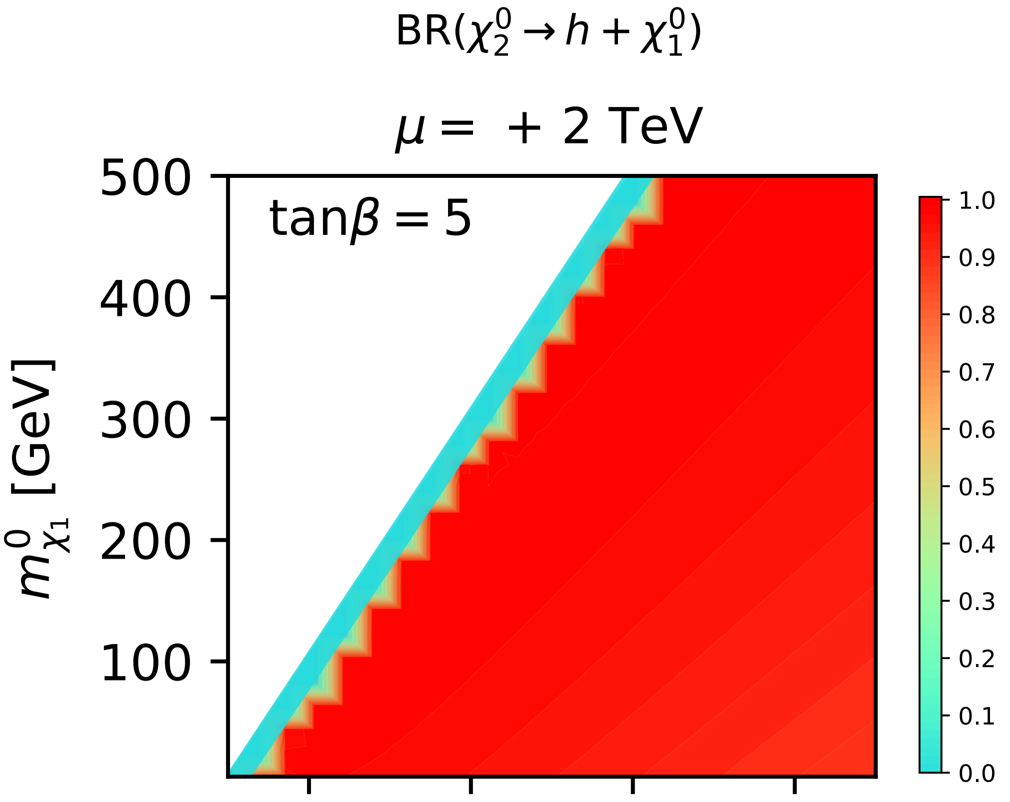
The resulting cross sections may differ in factors of a few.



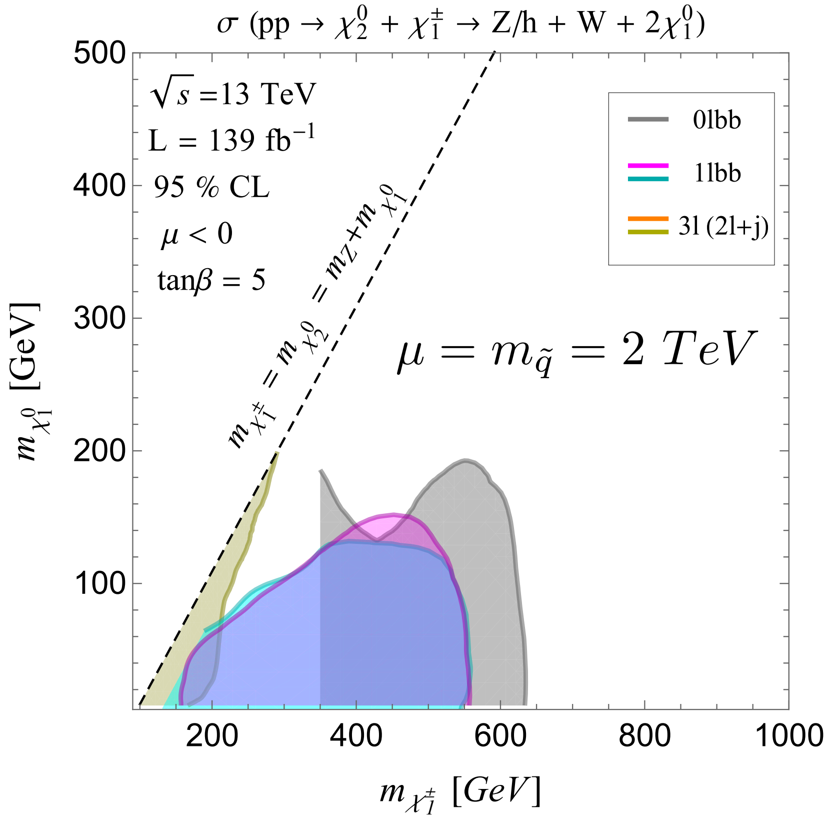
Wino Bounds for positive μ x M2

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

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



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

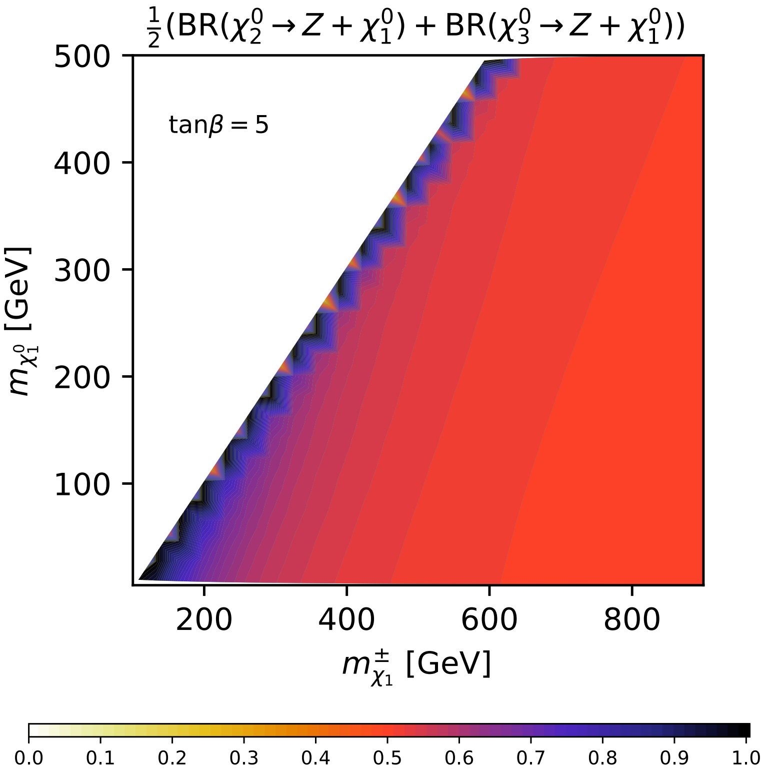


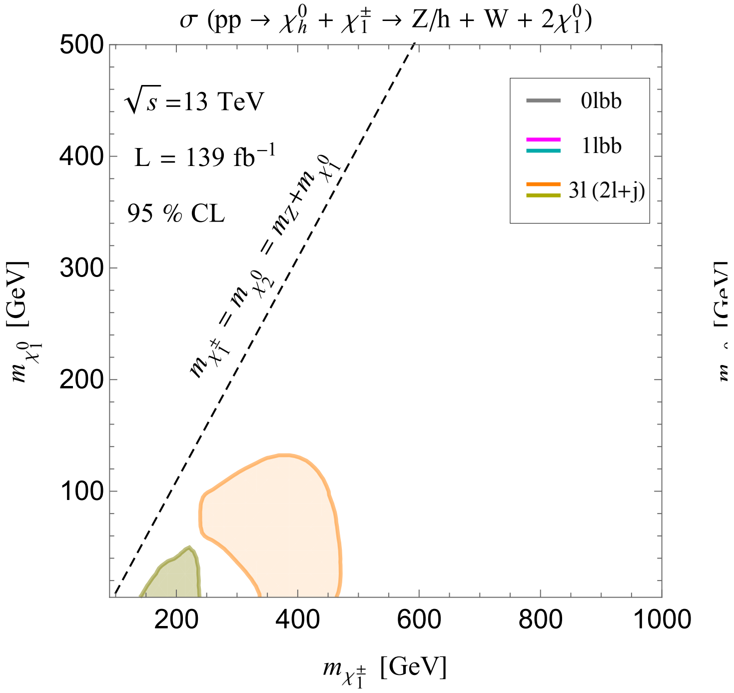
Higgsino Bounds

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.

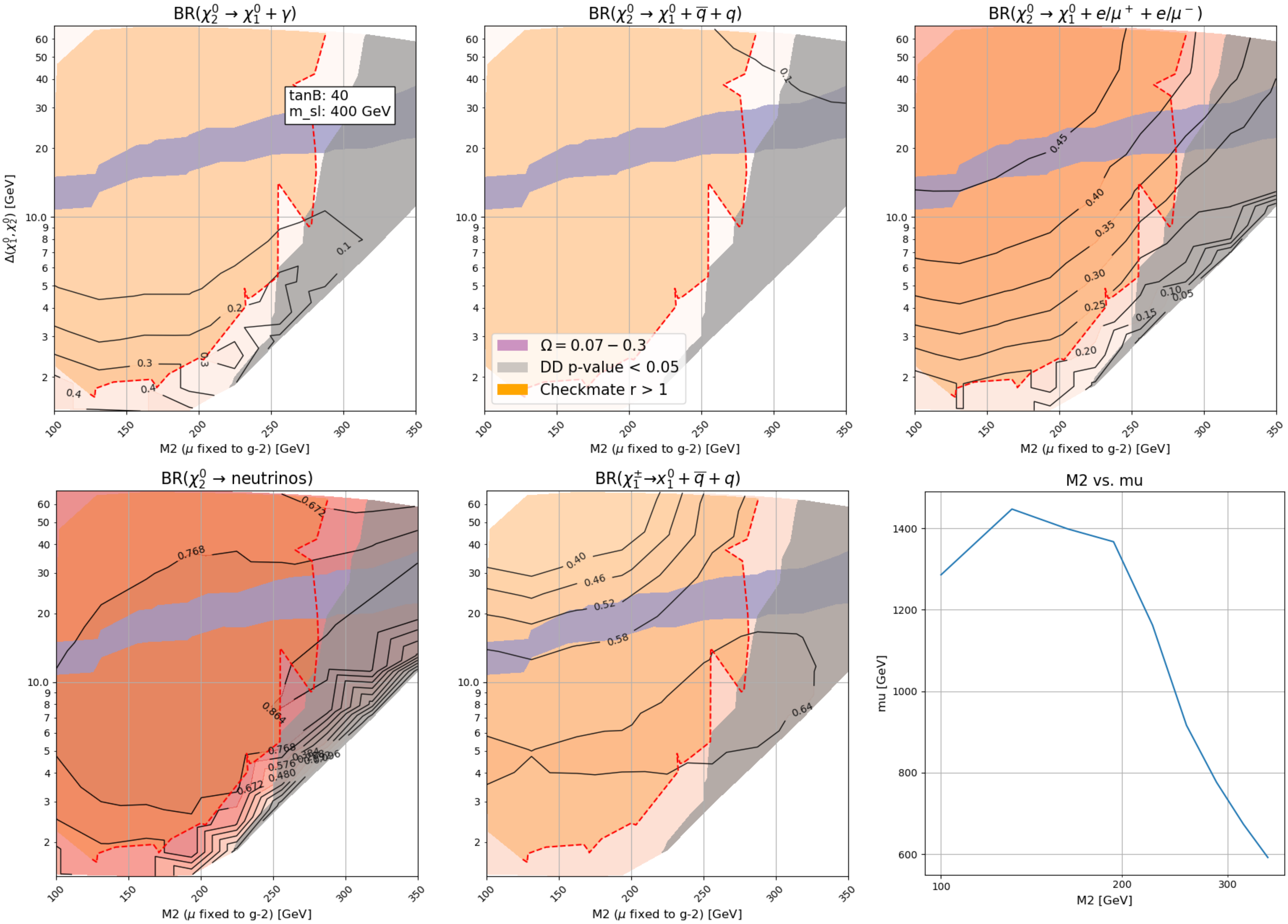
Liu, McGinnis, Wang, C.W., arXiv:2006.07389





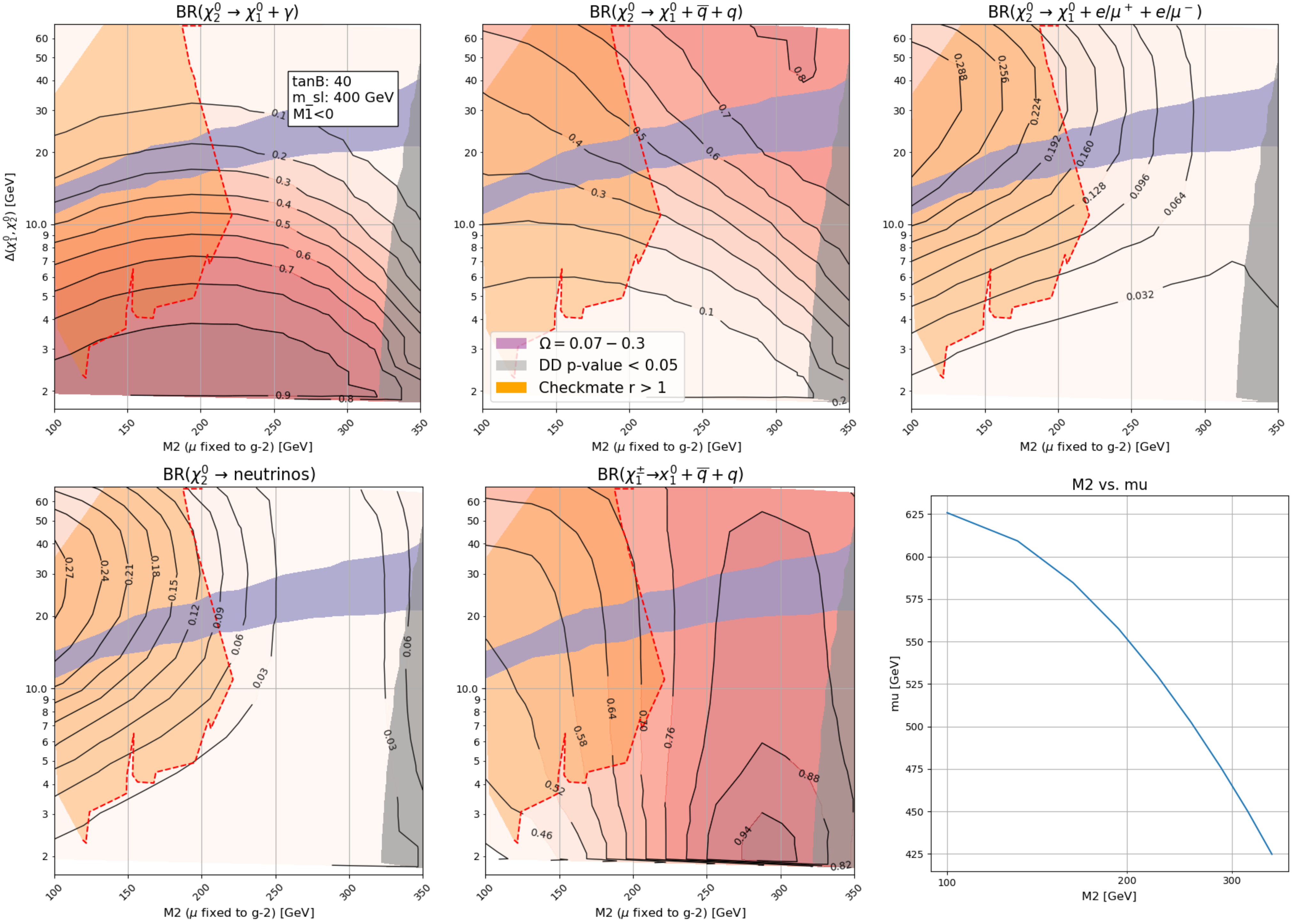
BMW : LHC Bounds

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



LHC Bounds

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



Comments on the current g-2 Anomaly

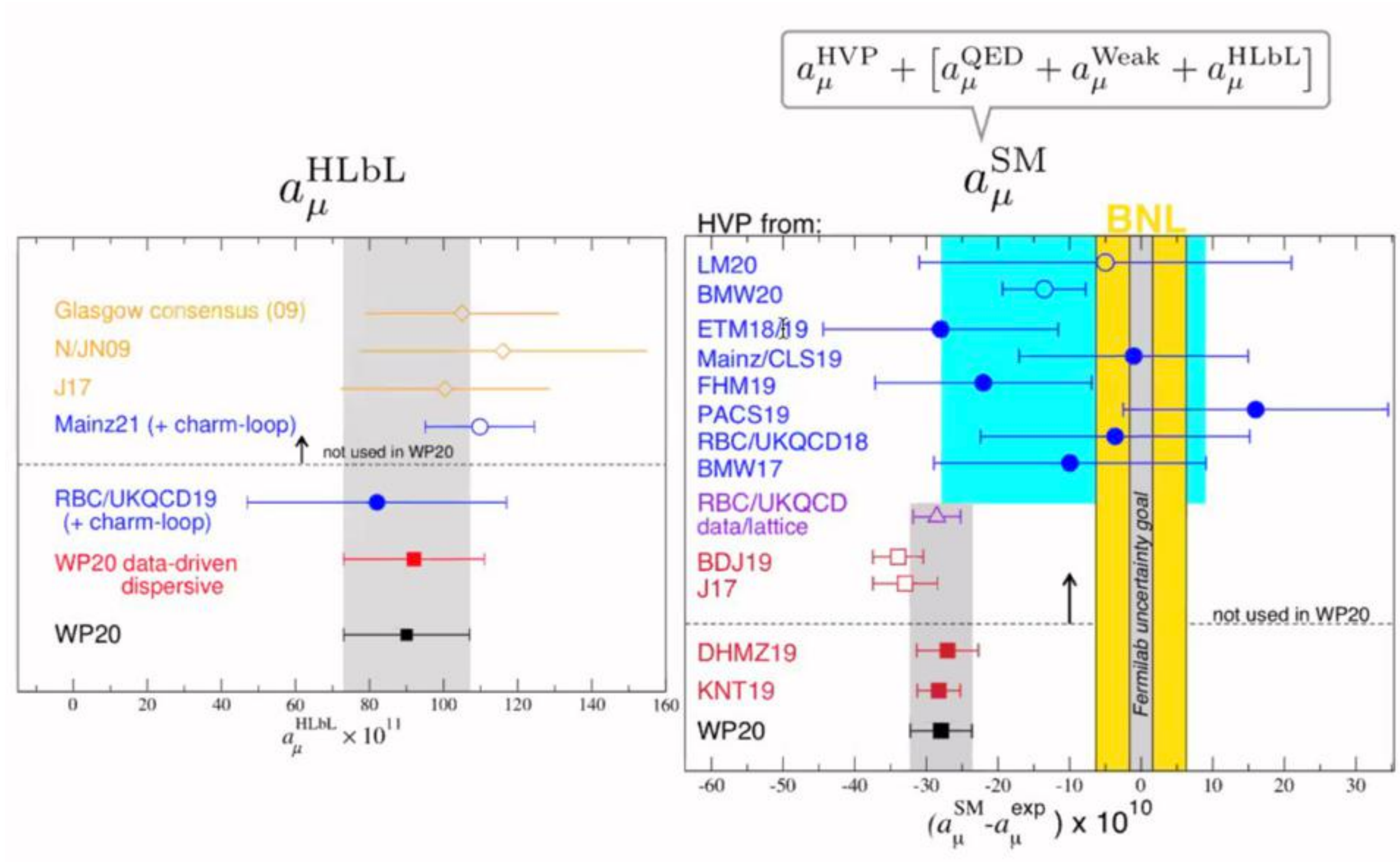
- In a sense, the current discrepancy is between the experimental determination of g-2, supported by the Brookhaven and the Fermilab g-2 experiments, and the e+e- hadronic cross section data.

- All other factors are, I believe, under good control and the uncertainties are small.

- In that sense, this anomaly should be taken very seriously. It is difficult to imagine where something could have gone wrong, even taken into account the current tension in the hadronic cross section data (KLOE vs BABAR), that cannot lead to an explanation of the measured anomaly, and has already been taken into account in the systematic errors.

- The good thing is that the g-2 collaboration will reduce the error by a factor 2 by next summer and there will be further work on the theoretical estimates.

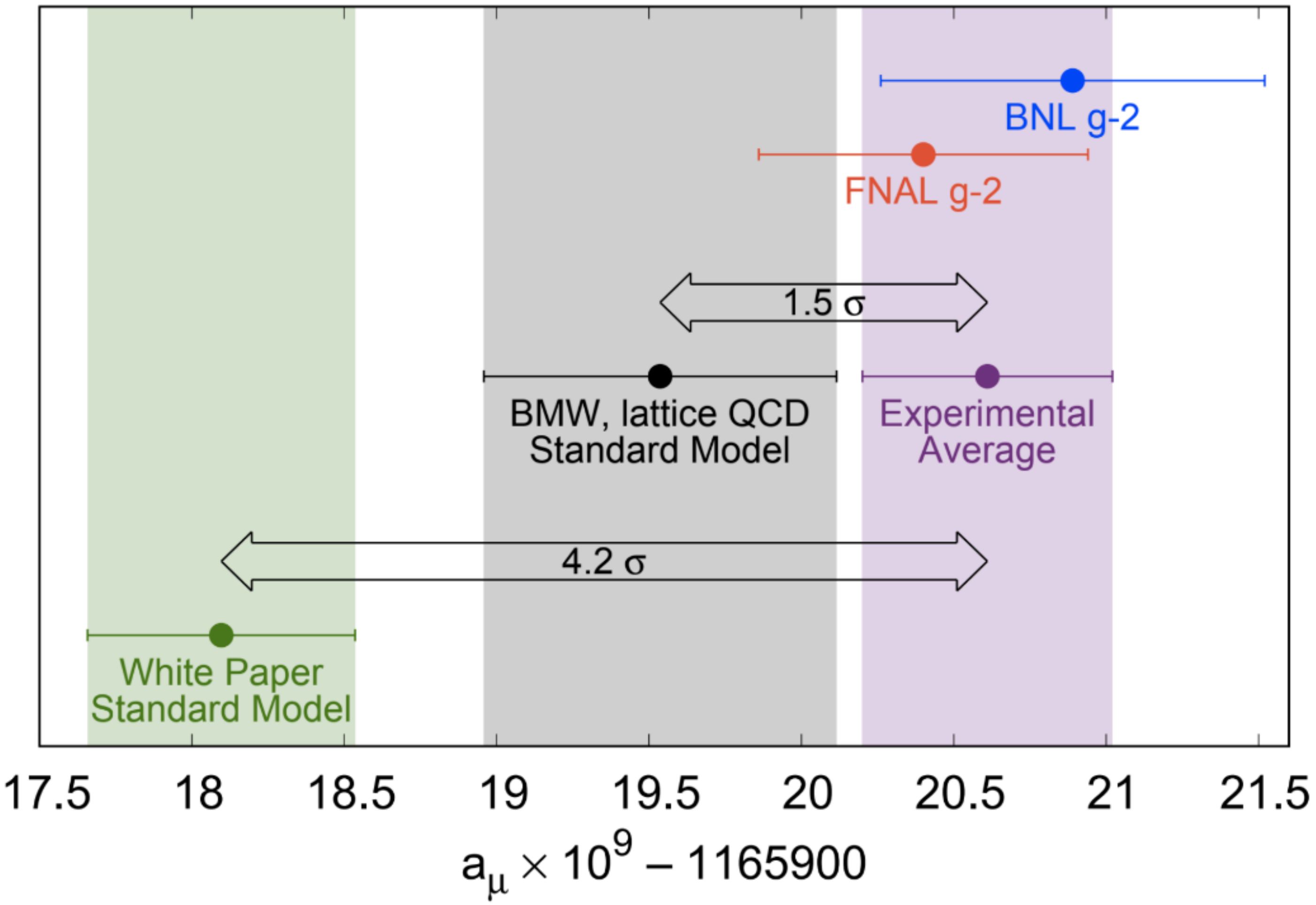
Lattice Computations



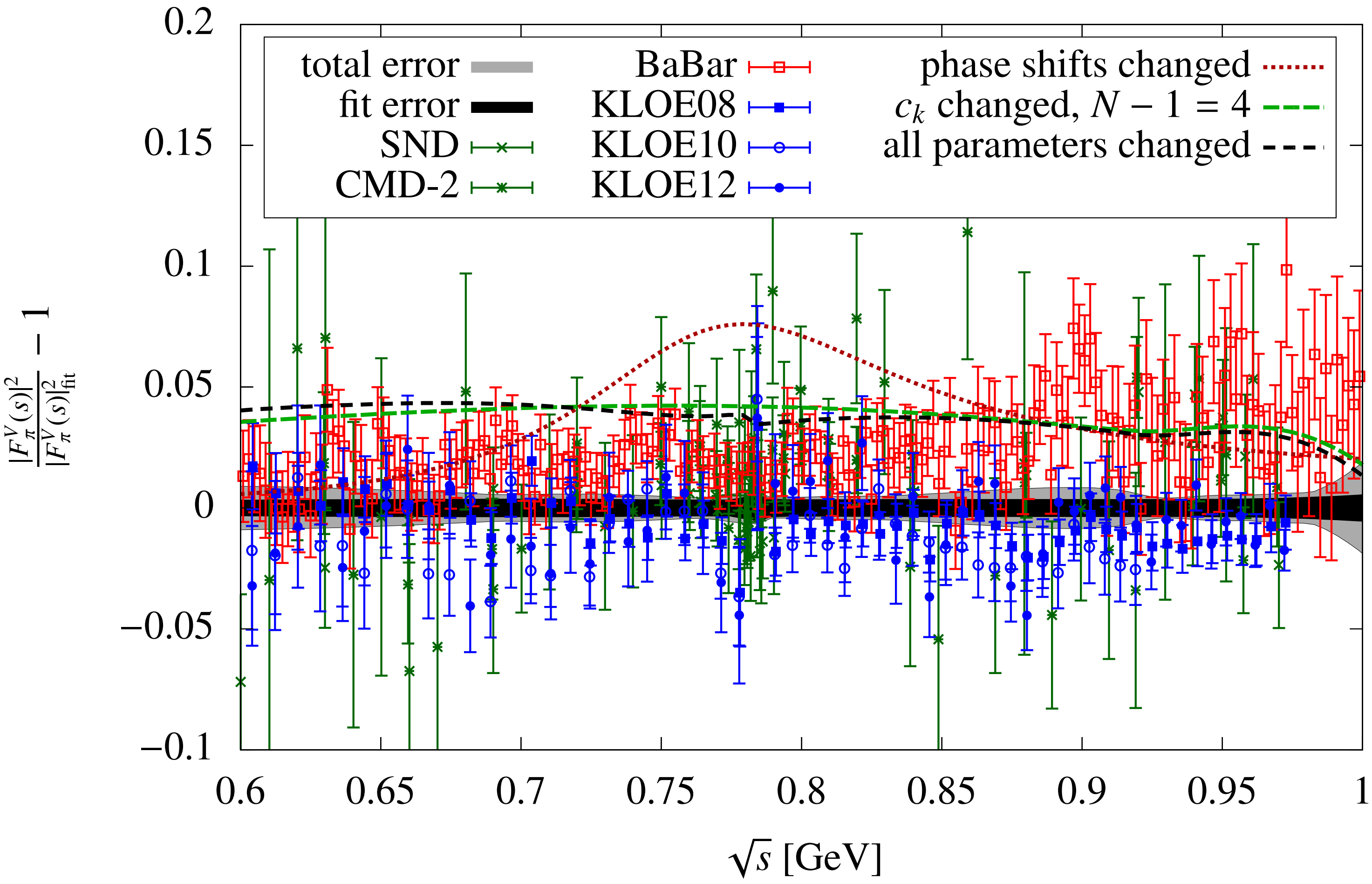
1. Lattice computations increase our confidence on the size and magnitude of the light by light contributions
2. In the computation of the hadronic vacuum polarization contributions, the BMW20 lattice collaboration finds results that reduce the tension with the g-2 experimental data. These results are hence in some tension with data driven evaluations.

Comparison of BMW lattice computation with data driven methods

Z. Fodor ' 21



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



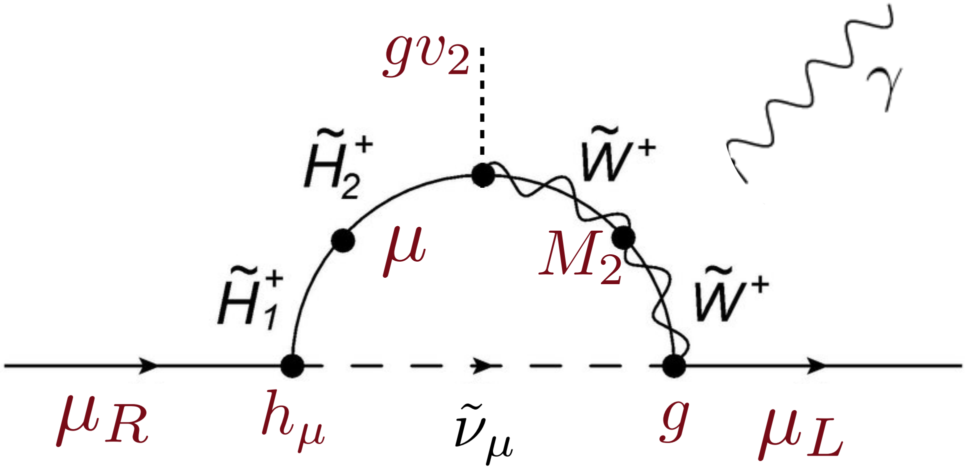
arXiv:2010.07943

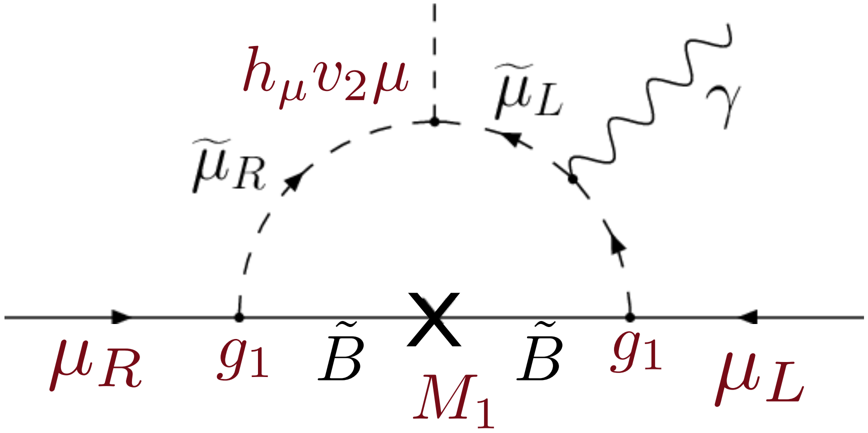
g-2 is associated with a chirality flip operator

$$\frac{e}{4m_\mu} a_\mu \left(\bar{\mu}_L \sigma_{\mu\nu} \mu_R + h.c.\right) F^{\mu\nu} \qquad \sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$$

Where do the different factors appear from ?

In the sneutrino diagram, from mixing in the chargino sector.
In the smuon diagram, from mixing among the muons.

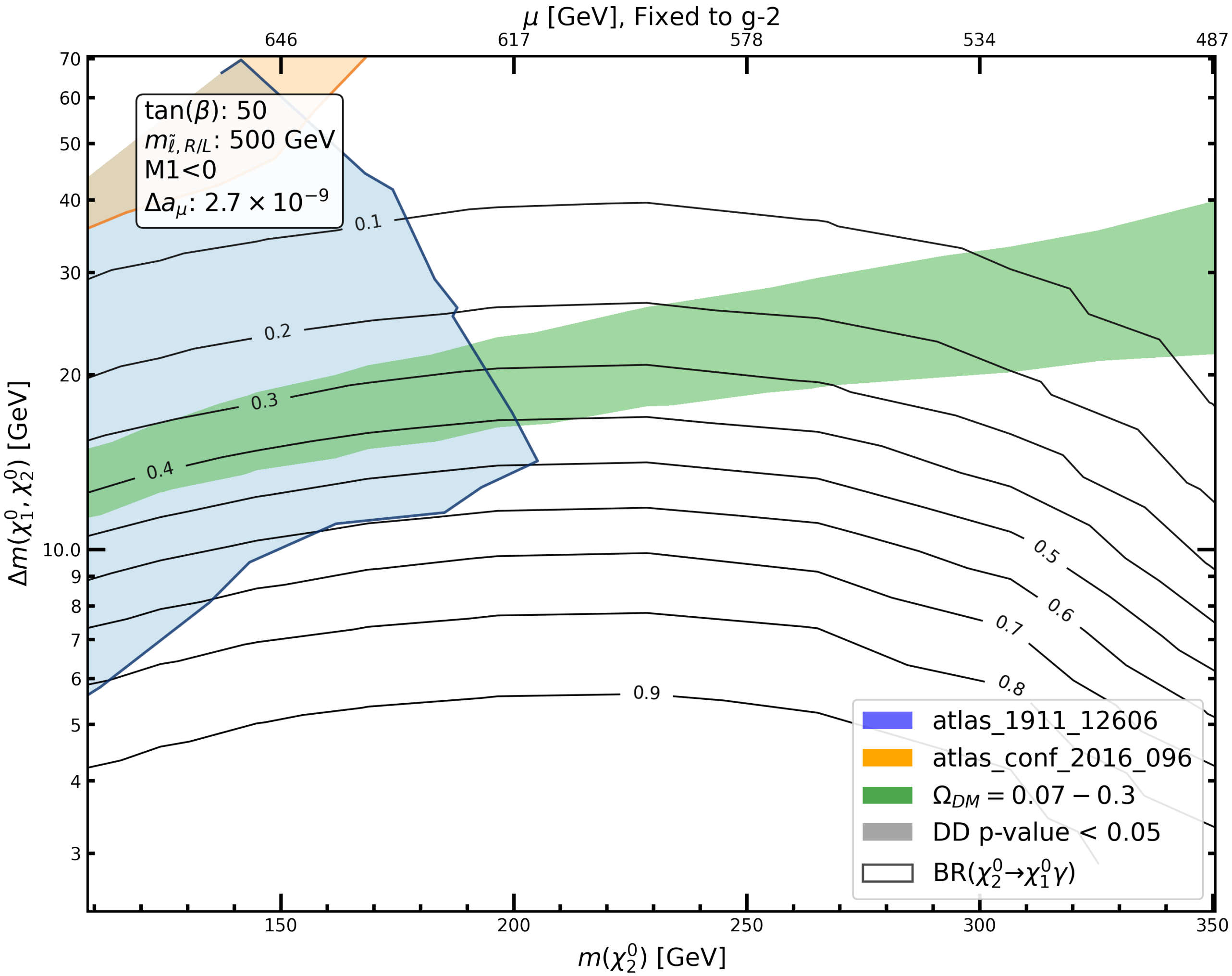




$$h_\mu v_2 = h_\mu v_1 \frac{v_2}{v_1} = m_\mu \tan\beta$$

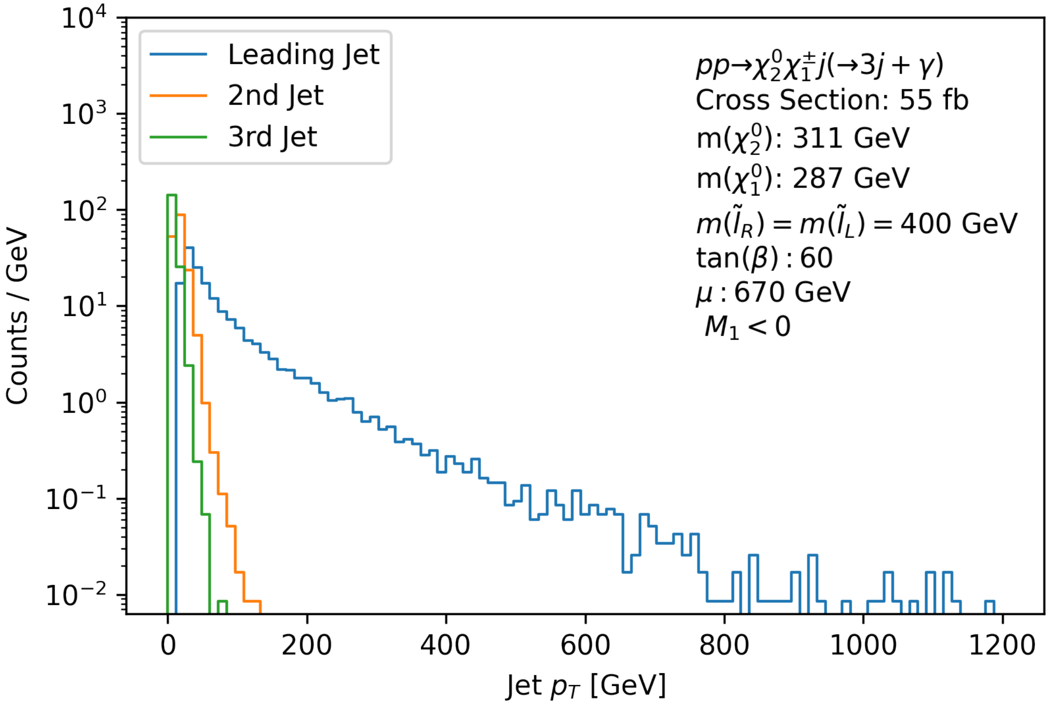
Quite interesting enhancement of the radiative decay in the compressed region.

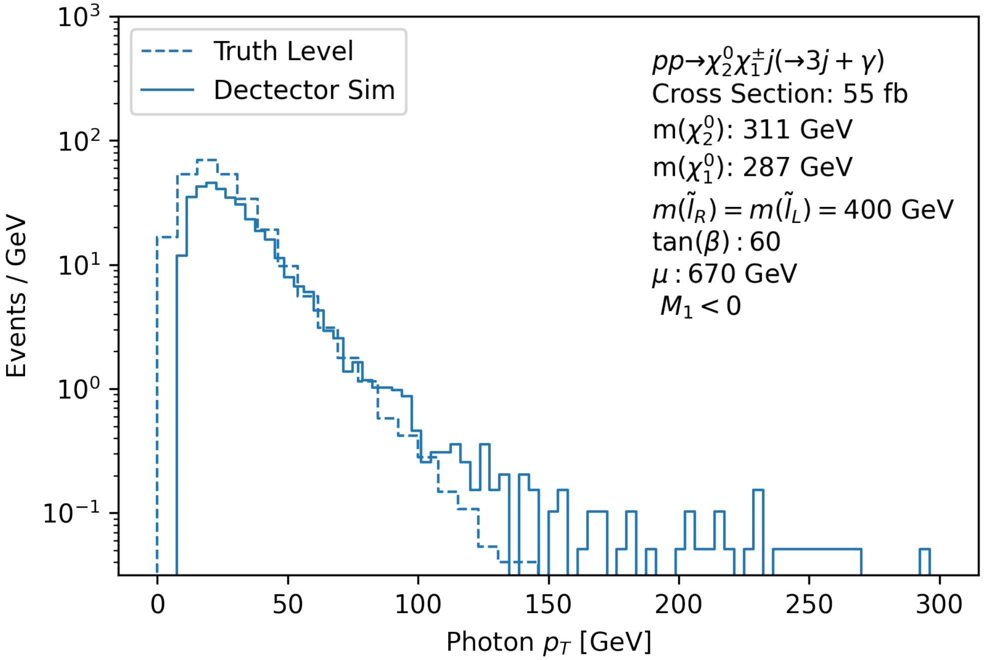
Can it be tested ? Initial state radiation relevant to get sufficient photon pT.
It would be interesting to provide a more realistic experimental analysis.



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

One must perform a simulation of the radiative decay channel. and determine if one can use it to go beyond the standard compressed scenario channels.





Soft Supersymmetry Breaking : Theoretical Prejudice

- Due to RG running of mass parameters, gluinos tend to be heavier than the other gauginos.
- The heavy gluinos tend to push up the squark masses
- The third generation SUSY breaking masses receive large negative corrections in the RG running (related to the ones driving the Higgs mass parameter negative) and tend to be the smallest ones.
- Due to its large coupling to the Higgs sector, stops are particularly relevant and have important phenomenological effects at low energies.

$$d(M_i/\alpha_i)/dt = 0,$$

$$4\pi dm_i^2/dt = -C_a^i 4M_a^2\alpha_a + |Y_{ijk}|^2[(m_i^2 + m_j^2 + m_k^2 + A_{ijk}^2)]/4\pi$$