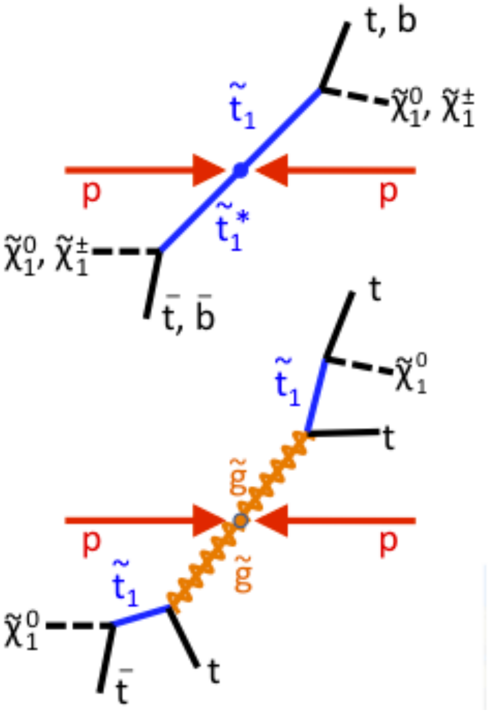
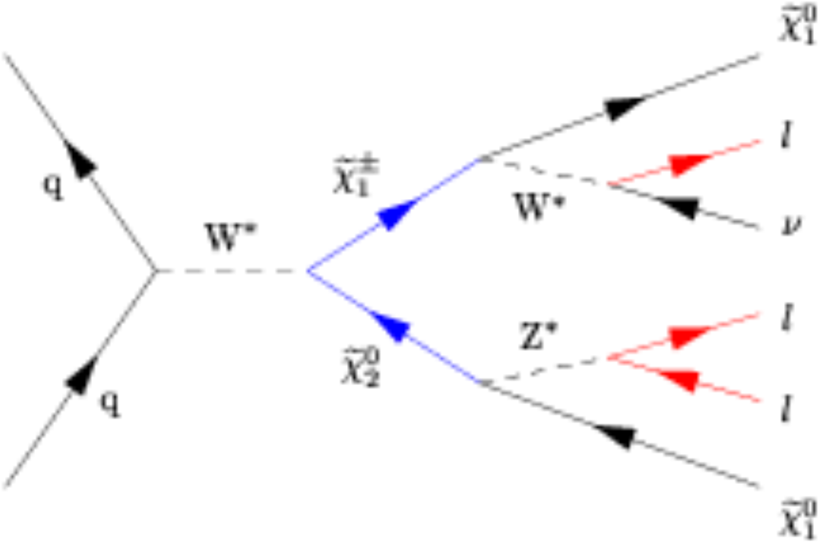
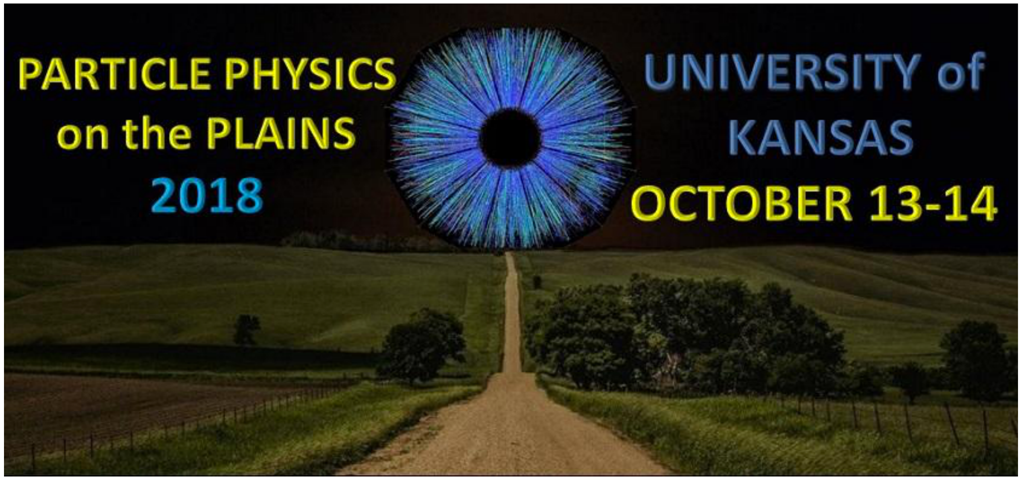
Reflections on SUSY Searches at the LHC





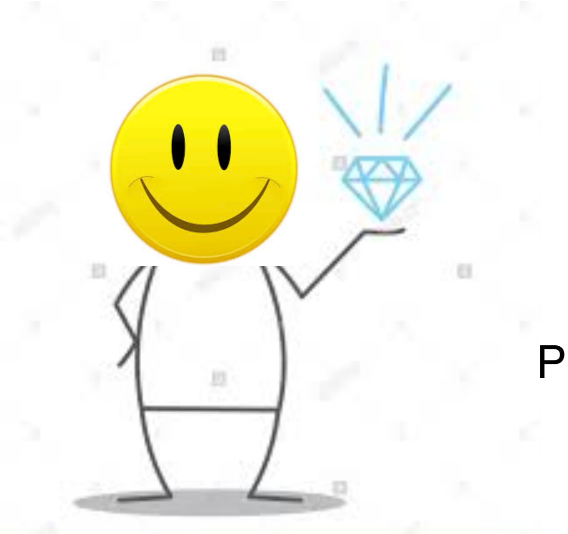
Carlos E.M. Wagner
EFI and KICP, University of Chicago
Argonne National Laboratory



It was in the world, and though the Universe was made by it, the world did not recognize it.

Adaptation, John 1:10

Nils Runeberg, "Dem Hemlige Fraelsaren", J. L. Borges, "Three versions of Judas"

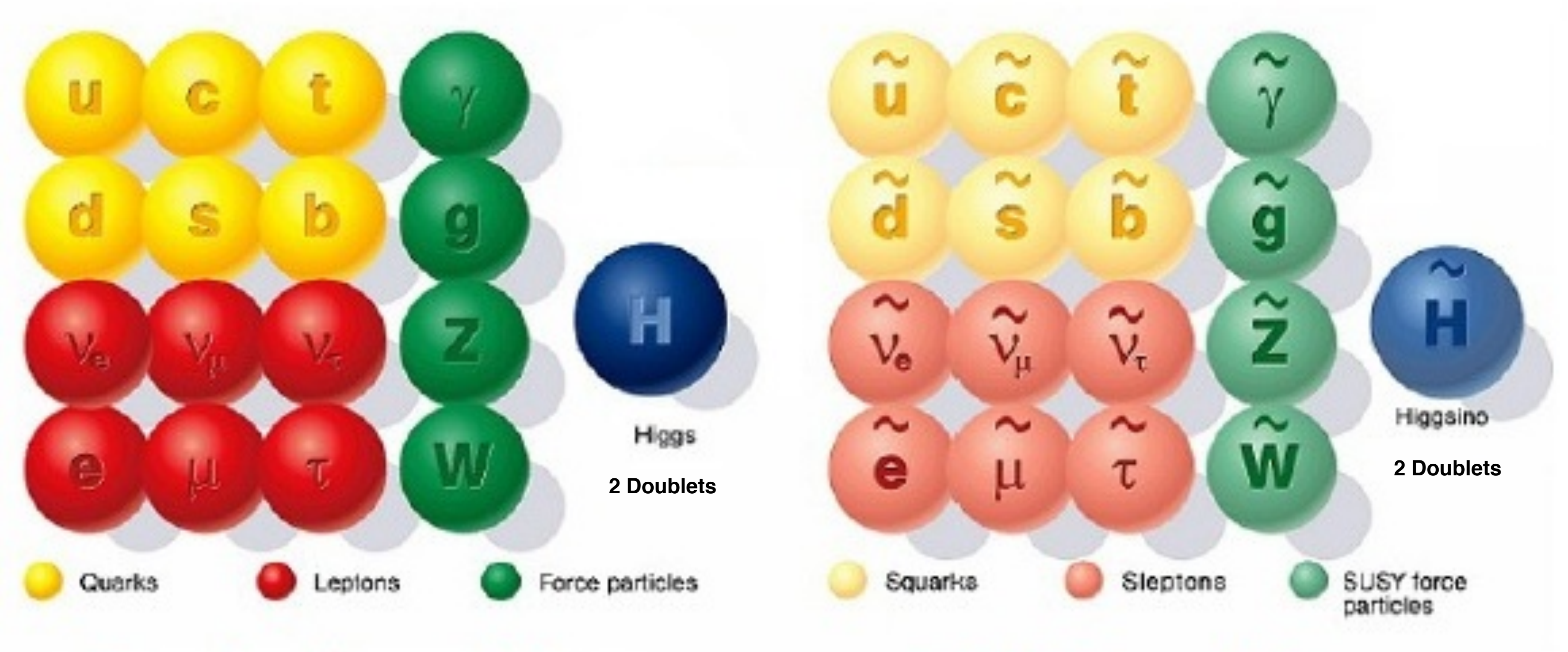


Peisi

Based on the recent work

M. Carena, N. Shah, J. Osborne, C. Wagner, arXiv:1809.11082

SUPERSYMMETRY



Standard particles

SUSY particles

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

$$\text{Two Higgs doublets necessary} \rightarrow \tan\beta = \frac{v_2}{v_1}$$

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy: $\delta m_H^2 \approx (-1)^{2S_i} \frac{n_i g_i^2}{16\pi^2} \Lambda^2$
- Supersymmetry algebra contains the generator of space-time translations.
  Possible ingredient of theory of quantum gravity.
- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.
- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.
- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Strongly Interacting Sector

- ATLAS and CMS have conducted a series of searches for squarks and gluinos
- No significant excess has been found
- In general, bound on gluinos vary, depending on the spectrum and decays, between 1 and 2 TeV
- Bounds on degenerate first and second generation squarks also at the TeV level
- Bounds on s-bottoms for simplest decay modes vary between 700 GeV and 1.2 TeV
- Bounds on stops for the simplest decay modes vary between 500 GeV and 1.2 TeV
- An overall spectrum at about or not far above the TeV scale still possible, particularly in the stop sector.

Theoretical Prejudice

- Due to RG running of mass parameters, heavier gluinos tend to push up the squark masses

- SUSY breaking square mass contributions tend to be much larger than the top mass squared and hence there is no correlation between squark and quark 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 lightest.

- In addition, the lightest stop mass is pushed down by mixing effects.

- Due to its large coupling to the Higgs sector, stops are particularly relevant and have important phenomenological effects at low energies.

- It is common to assume that the first and second generation masses, which have an impact on flavor violation processes, are heavy.

MSSM Guidance ?

Lightest SM-like Higgs mass strongly depends on:

- CP-odd Higgs mass m_A
- tan beta
- the top quark mass

- the stop masses and mixing

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

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

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

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

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

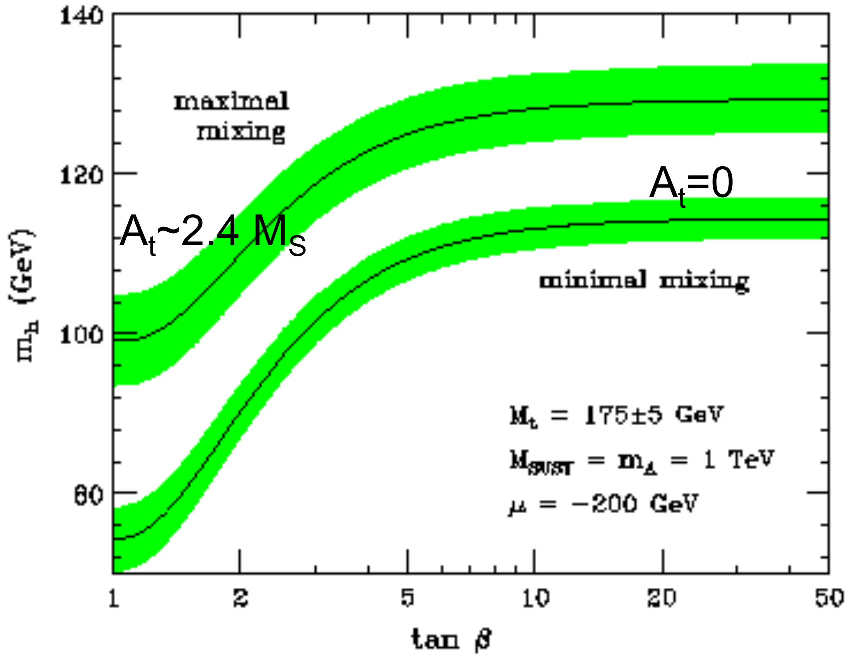
Analytic expression valid for $M_{SUSY} \sim m_Q \sim m_U$

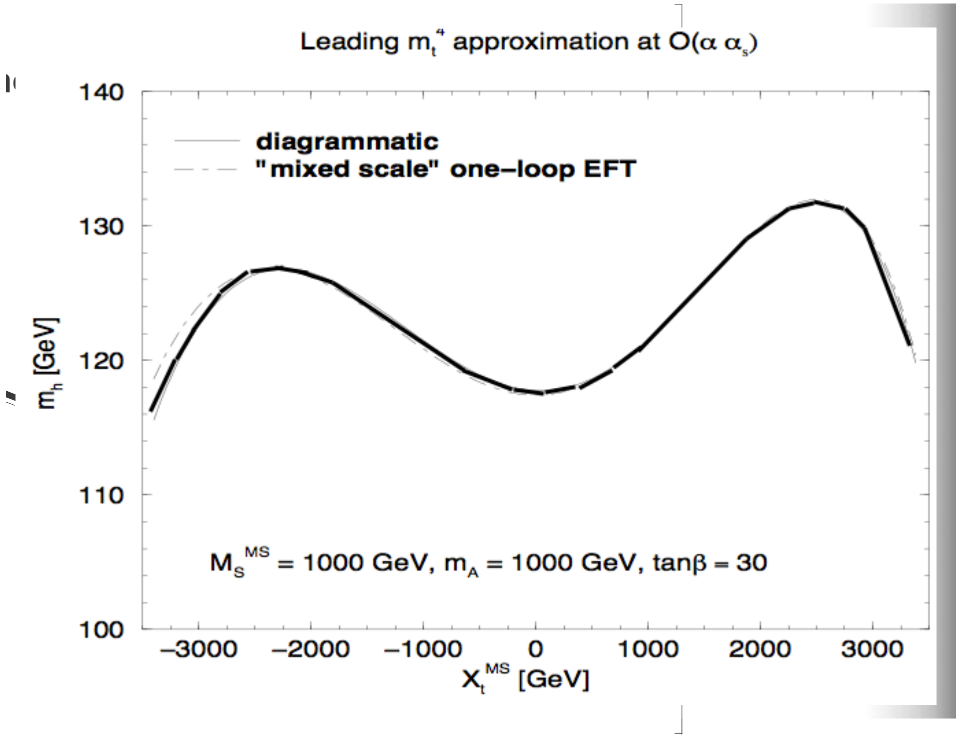
Standard Model-like Higgs Mass

Long list of two-loop computations: Carena, Degrassi, Ellis, Espinosa, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, C.W., Weiglein, Zhang, Zwirner

Carena, Haber, Heinemeyer, Hollik, Weiglein, C.W.'00

For masses of order 1 TeV, diagrammatic and EFT approach agree well, once the appropriate threshold corrections are included

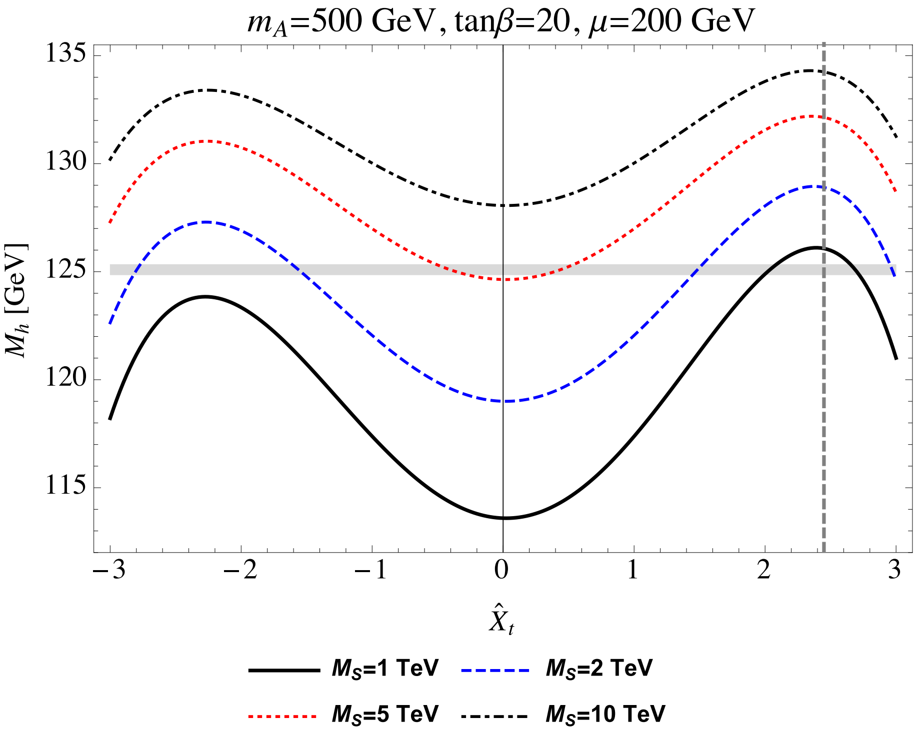


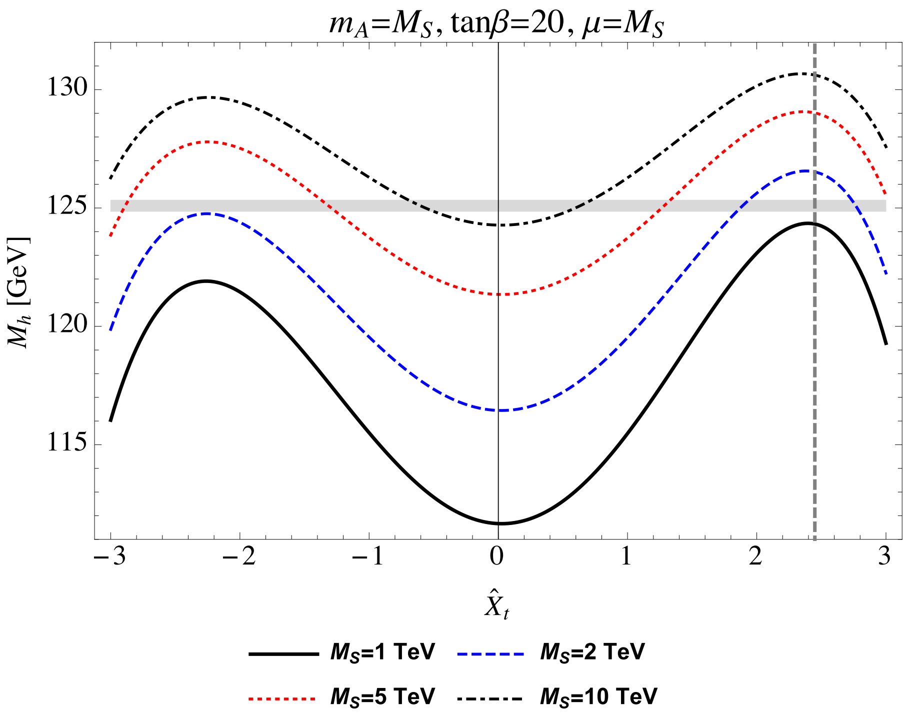


$$X_t = A_t - \mu/\tan\beta, \qquad X_t = 0 : \text{ No mixing}; \qquad X_t = \sqrt{6} M_S : \text{ Max. Mixing}$$

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

G. Lee, C.W. arXiv:1508.00576



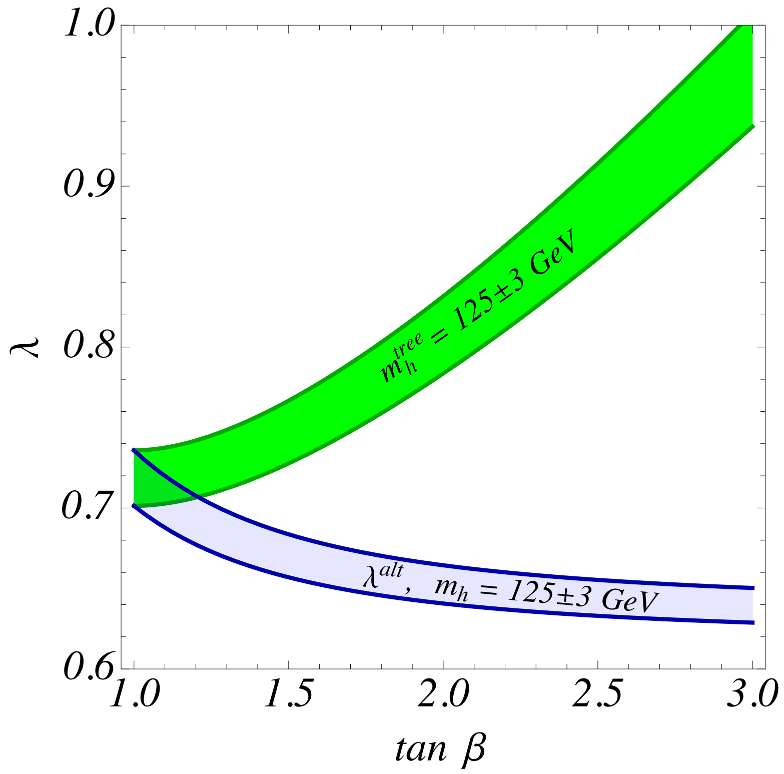


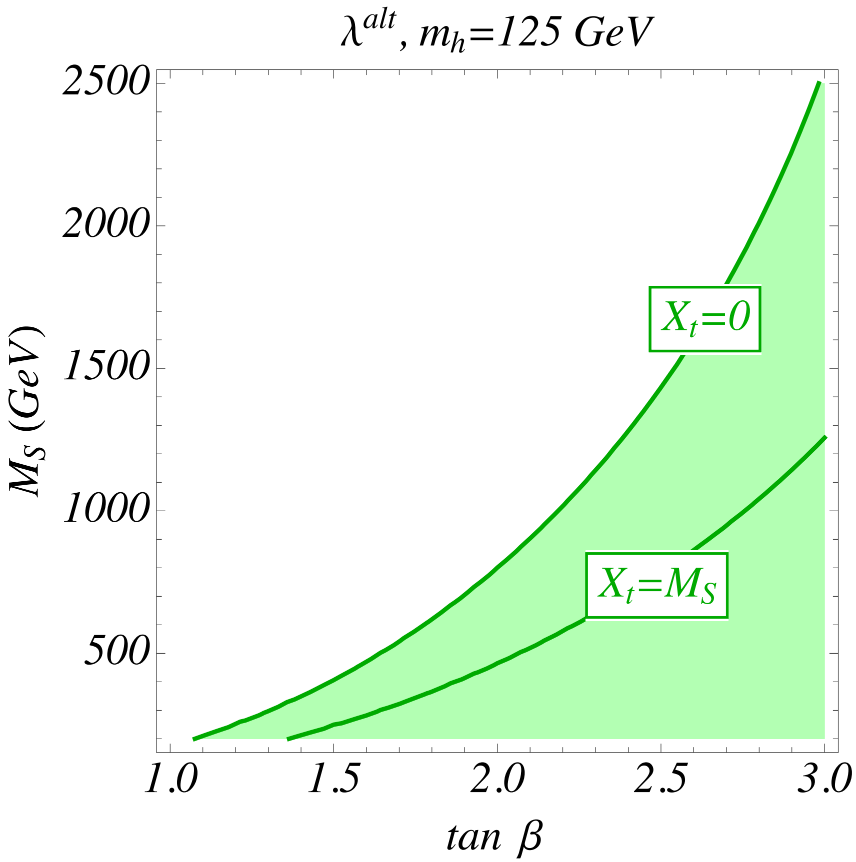
Necessary stop masses increase for lower values of tanβ, larger values of μ smaller values of the CP-odd Higgs mass or lower stop mixing values.

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

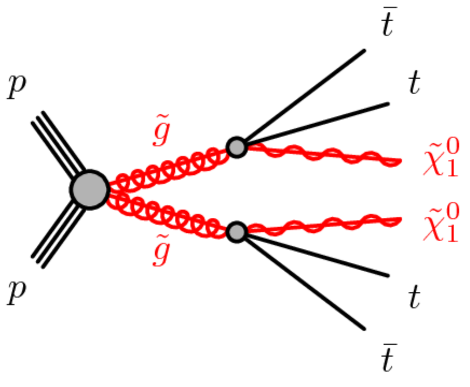
Lighter stops in Extended Models : NMSSM

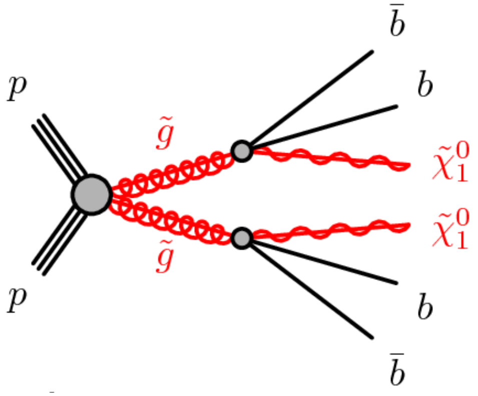
M. Carena, H. Haber, I. Low, N.R. Shah and C.W. arXiv:1510.09137

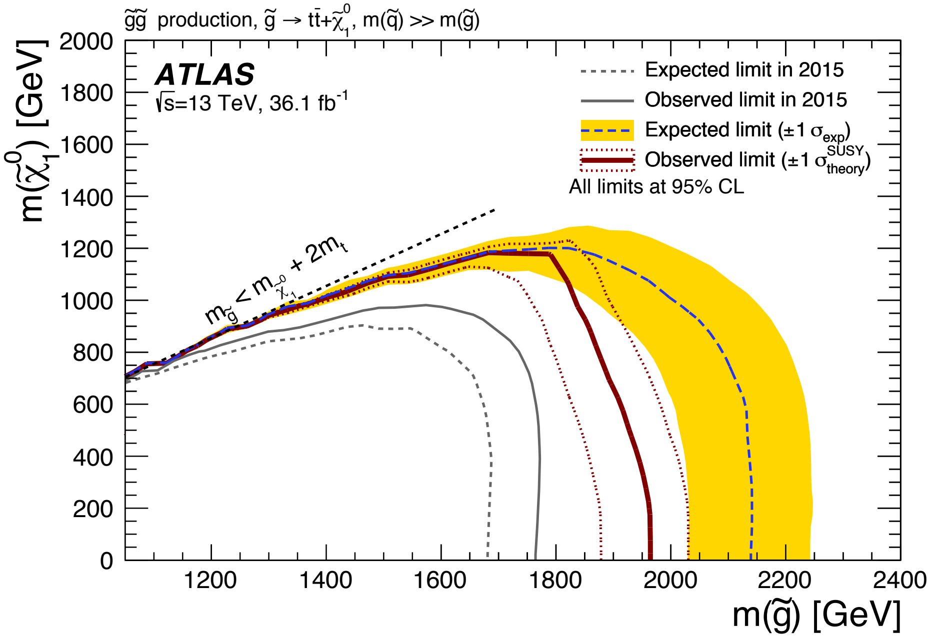




Gluino Searches :
Gluino couples to SM via quark-squark vertices
Squarks can decay in a variety of ways

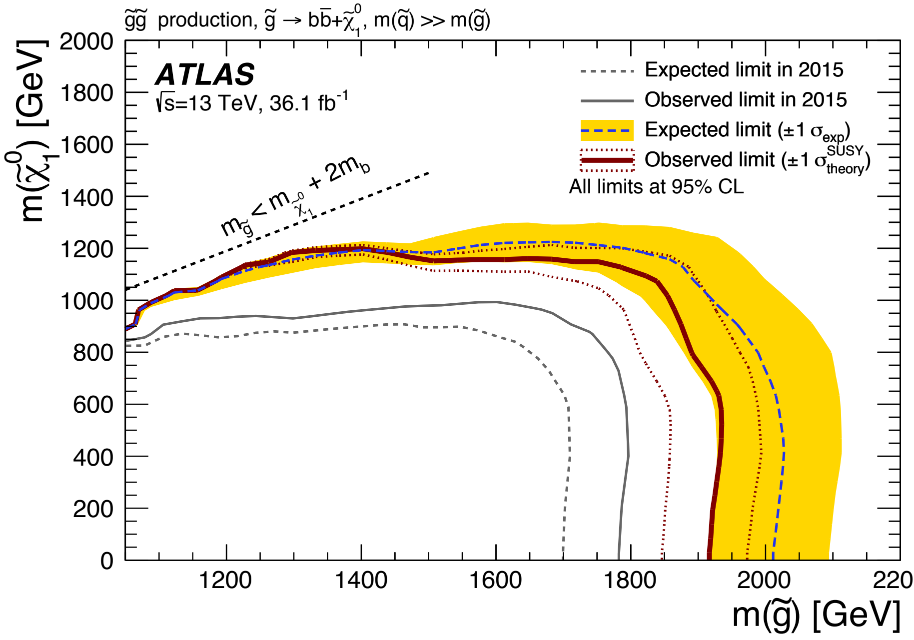






Excess in channel with four tops ?

Events with b's, jets, leptons and Missing ET



Events with b's and Missing Energy

CMS Analysis not sensitive to the Excess Region

Where was the excess ?

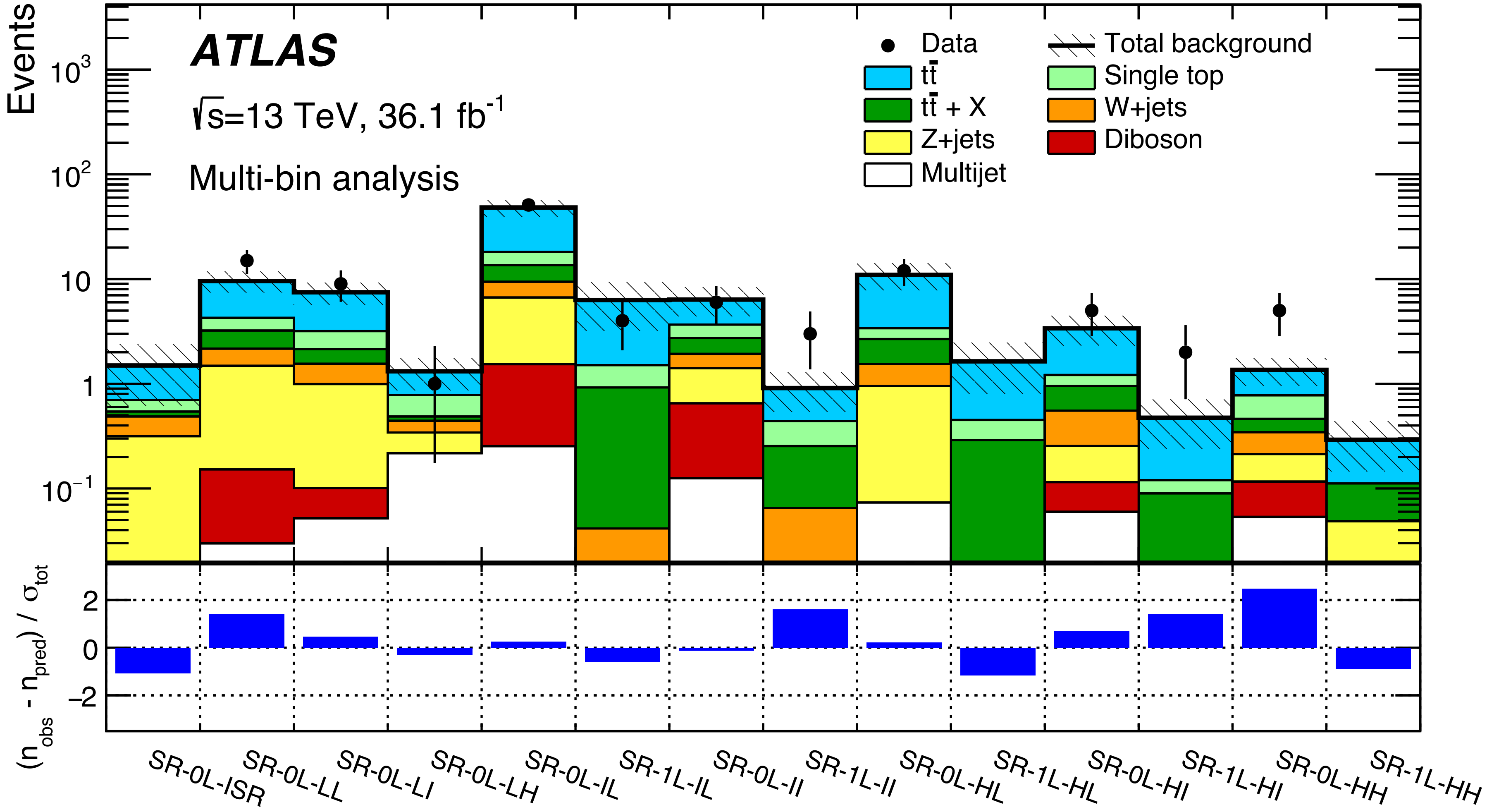


Table 4: Definition of the high-N_{jet} SRs, CRs and VRs of the multi-bin analysis. All kinematic variables are expressed in GeV except $\Delta\phi^{4\text{j}}_{\text{min}}$, which is in radians.

High-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_{\text{T}}^{\text{jet}} > 30$ GeV

Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4\text{j}}_{\text{min}}$	m_{T}	N_{jet}	$m_{\text{T,min}}^{b\text{-jets}}$	M_J^{Σ}	$E_{\text{T}}^{\text{miss}}$	m_{eff}
High-m_{eff} (HH) (Large Δm)	SR-0L	$= 0$	> 0.4	–	≥ 7	> 100	> 200	> 400	> 2500
	SR-1L	≥ 1	–	> 150	≥ 6	> 120	> 200	> 500	> 2300
	CR	≥ 1	–	< 150	≥ 6	> 60	> 150	> 300	> 2100
	VR-0L	$= 0$	> 0.4	–	≥ 7	< 100 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 100$	> 2100
	VR-1L	≥ 1	–	> 150	≥ 6	< 140 if $m_{\text{eff}} > 2300$	–	< 500	> 2100
Intermediate-m_{eff} (HI) (Intermediate Δm)	SR-0L	$= 0$	> 0.4	–	≥ 9	> 140	> 150	> 300	$[1800, 2500]$
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	> 150	> 300	$[1800, 2300]$
	CR	≥ 1	–	< 150	≥ 8	> 60	> 150	> 200	$[1700, 2100]$
	VR-0L	$= 0$	> 0.4	–	≥ 9	< 140 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 140$	$[1650, 2100]$
	VR-1L	≥ 1	–	> 150	≥ 8	< 140 if $E_{\text{T}}^{\text{miss}} > 300$	–	< 300 if $m_{\text{T,min}}^{b\text{-jets}} > 140$	$[1600, 2100]$
Low-m_{eff} (HL) (Small Δm)	SR-0L	$= 0$	> 0.4	–	≥ 9	> 140	–	> 300	$[900, 1800]$
	SR-1L	≥ 1	–	> 150	≥ 8	> 140	–	> 300	$[900, 1800]$
	CR	≥ 1	–	< 150	≥ 8	> 130	–	> 250	$[900, 1700]$
	VR-0L	$= 0$	> 0.4	–	≥ 9	< 140	–	> 300	$[900, 1650]$
	VR-1L	≥ 1	–	> 150	≥ 8	< 140	–	> 225	$[900, 1650]$

Intermediate-N_{jet} regions

Criteria common to all regions: $N_{b\text{-jets}} \geq 3$, $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV

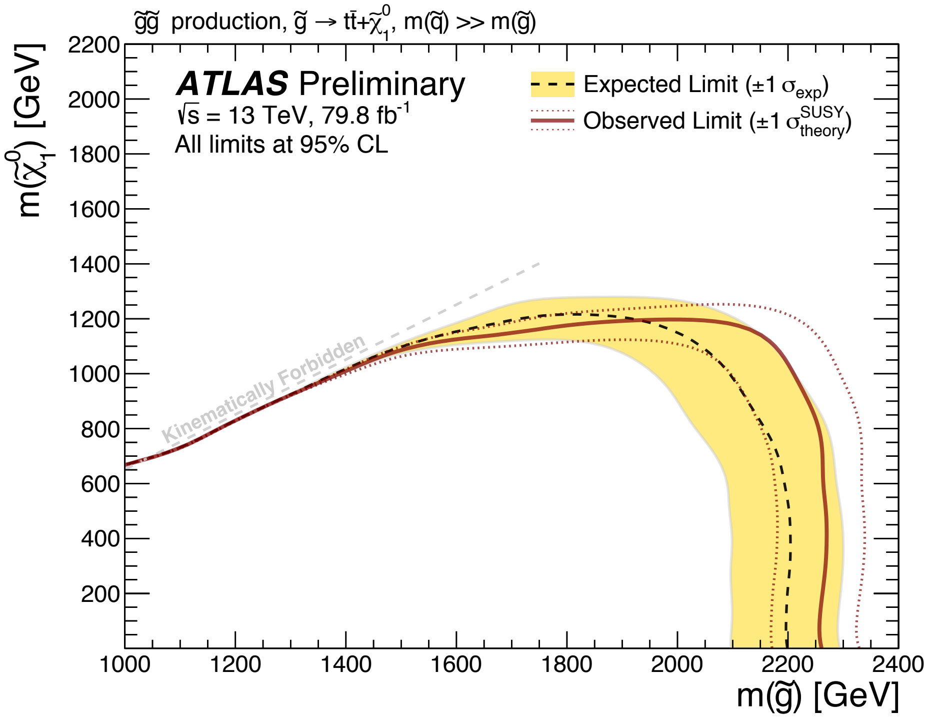
Targeted kinematics	Type	N_{lepton}	$\Delta\phi^{4\mathrm{j}}_{\mathrm{min}}$	m_{T}	N_{jet}	$\mathrm{j}_1 = b$ or $\Delta\phi^{\mathrm{j}_1} \leq 2.9$	$m^{b\text{-jets}}_{\mathrm{T,min}}$	M_J^{Σ}	$E_{\mathrm{T}}^{\mathrm{miss}}$	m_{eff}
Intermediate-m_{eff} (II) (Intermediate Δm)	SR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	> 140	> 150	> 300	$[1600, 2500]$
	SR-1L	≥ 1	–	> 150	$[6, 7]$	–	> 140	> 150	> 300	$[1600, 2300]$
	CR	≥ 1	–	< 150	$[6, 7]$	✓	> 110	> 150	> 200	$[1600, 2100]$
	VR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	< 140	–	> 300	$[1450, 2000]$
	VR-1L	≥ 1	–	> 150	$[6, 7]$	–	< 140	–	> 225	$[1450, 2000]$
Low-m_{eff} (IL) (Low Δm)	SR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	> 140	–	> 300	$[800, 1600]$
	SR-1L	≥ 1	–	> 150	$[6, 7]$	–	> 140	–	> 300	$[800, 1600]$
	CR	≥ 1	–	< 150	$[6, 7]$	✓	> 130	–	> 300	$[800, 1600]$
	VR-0L	$= 0$	> 0.4	–	$[7, 8]$	✓	< 140	–	> 300	$[800, 1450]$
	VR-1L	≥ 1	–	> 150	$[6, 7]$	–	< 140	–	> 300	$[800, 1450]$

New ATLAS Results

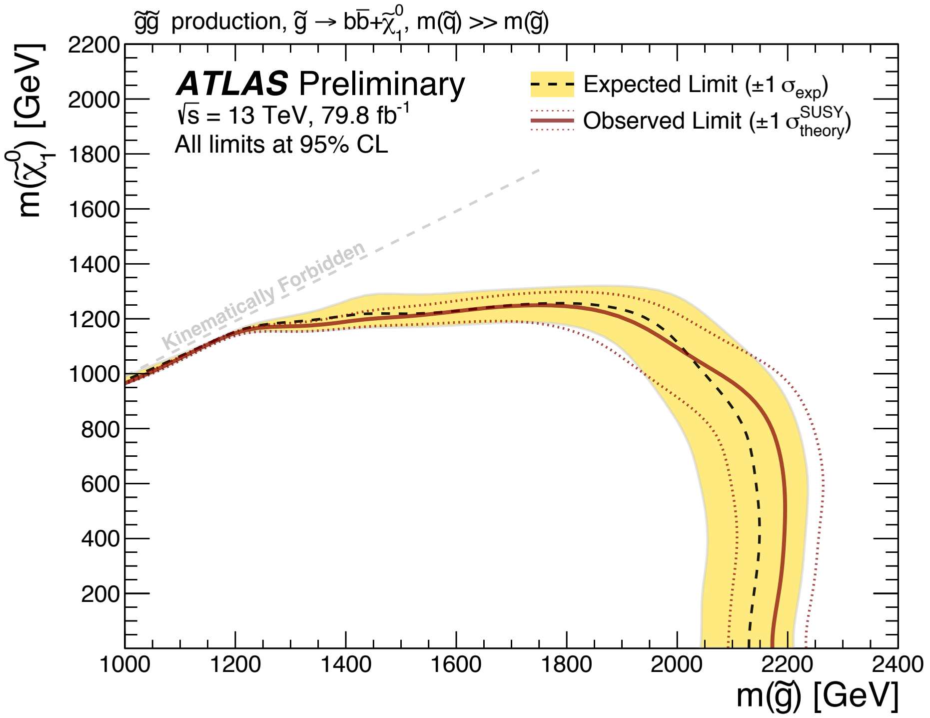
ATLAS CONF Note

ATLAS-CONF-2018-041

24th July 2018



(a)

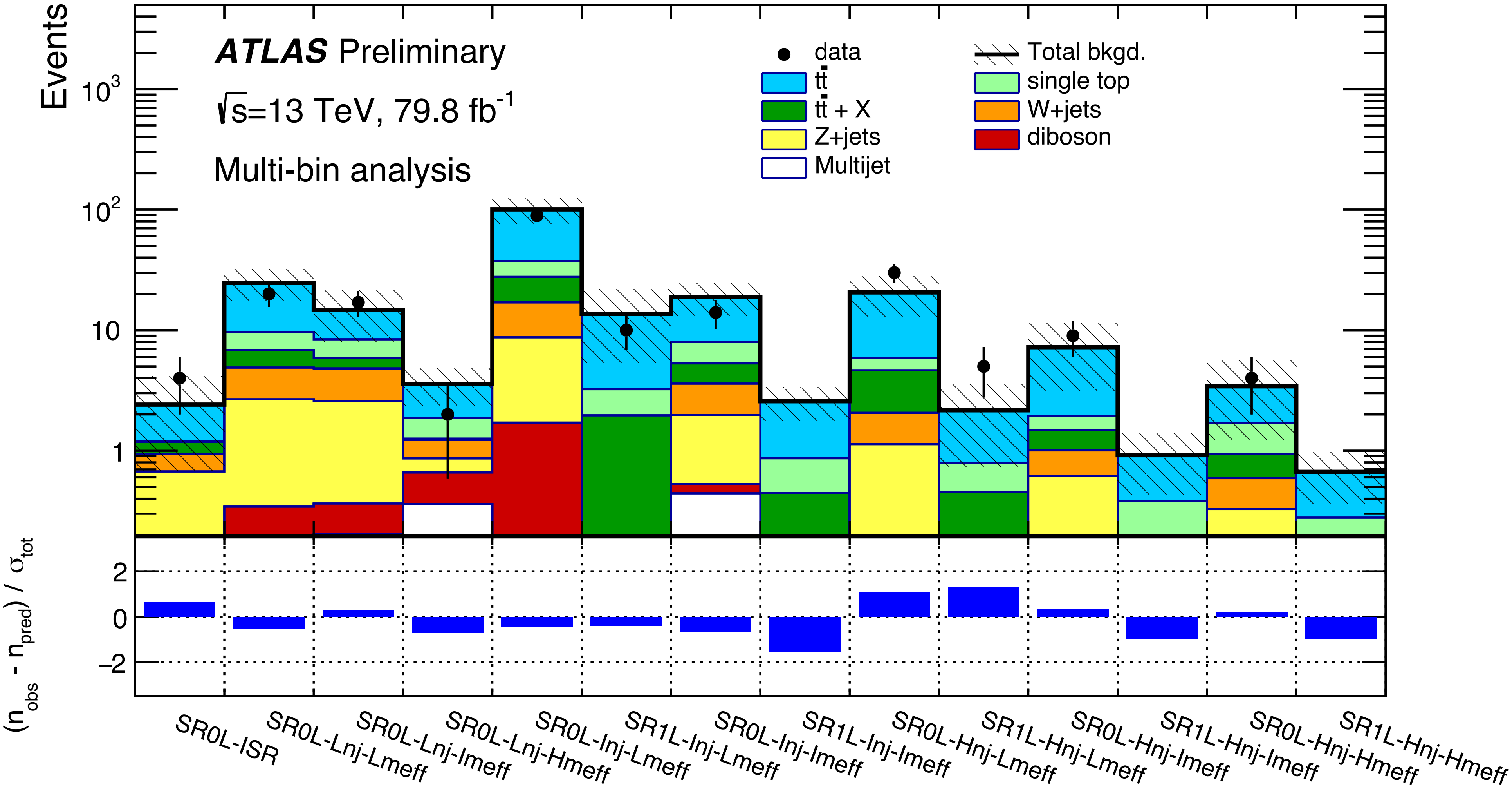


(b)

What happened to the apparent excess ?

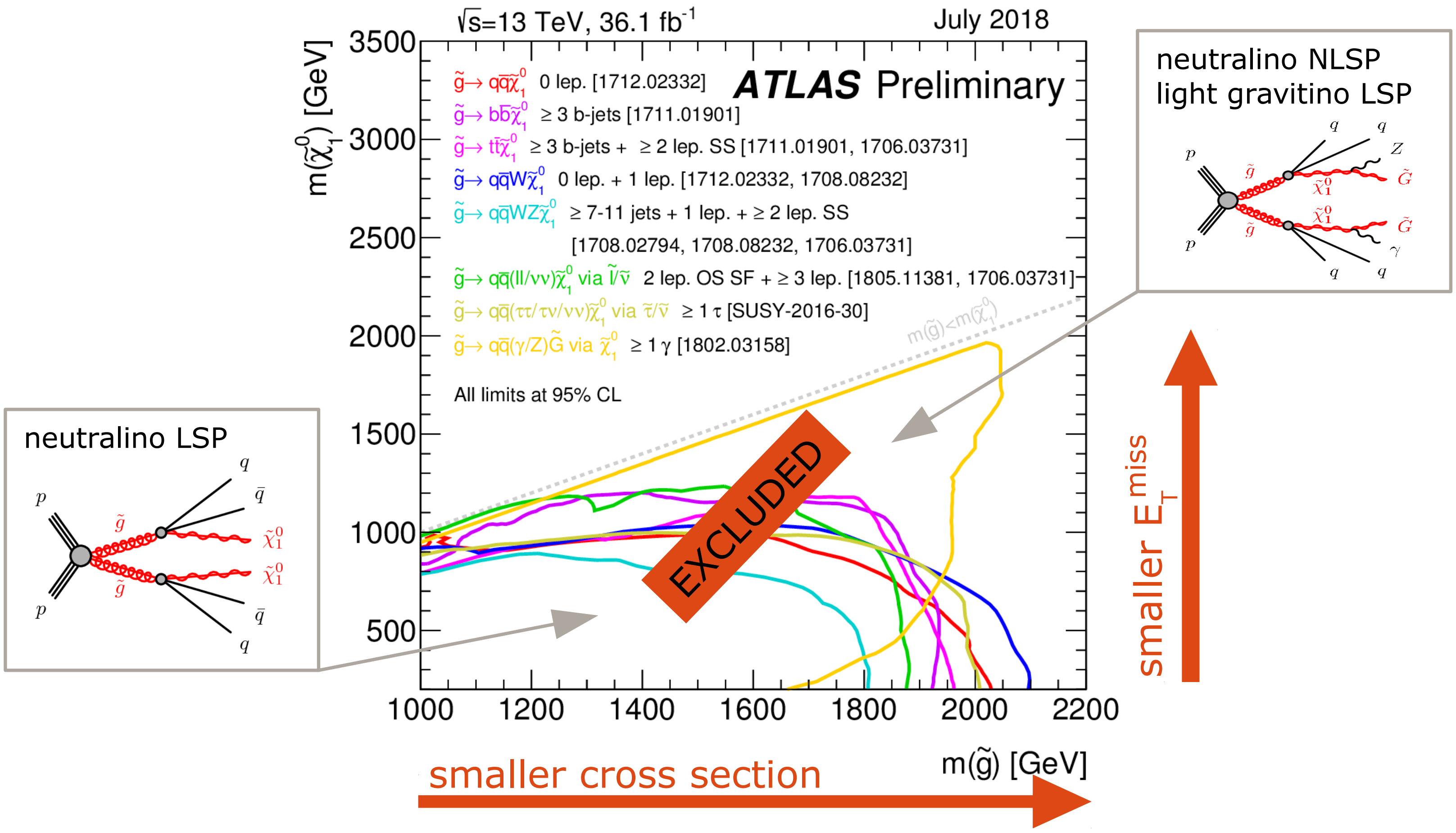
No Significant Excesses seen

Slight Excesses in Regions Inconsitent with previous ones



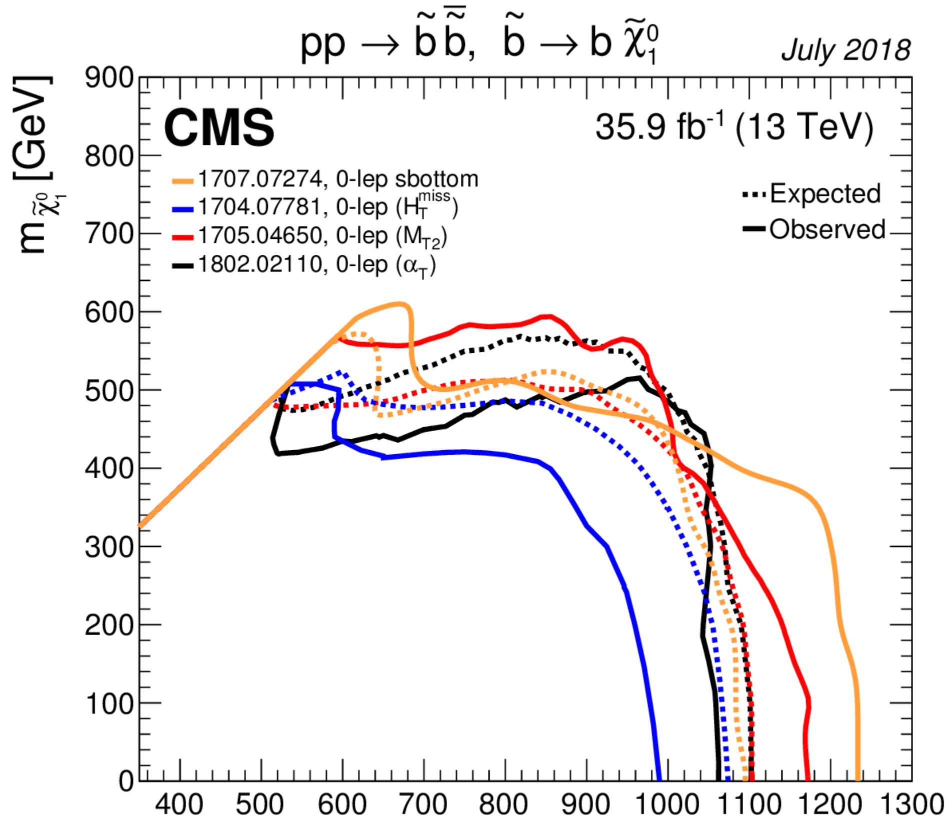
Gluino Searches

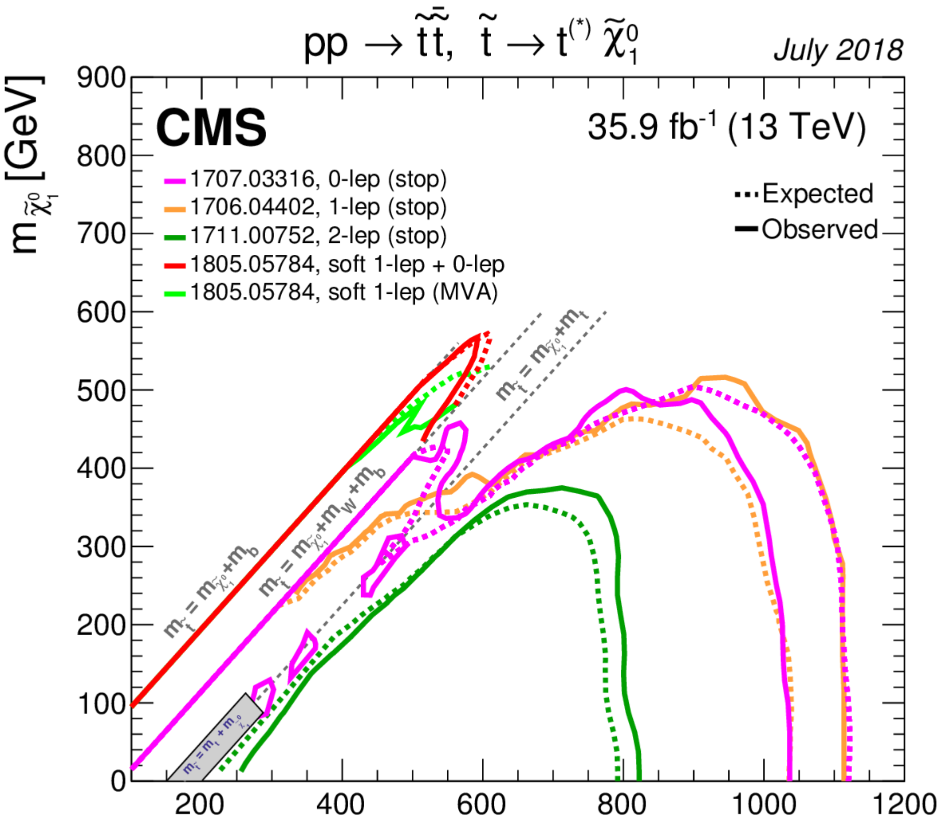
Summary by Sara Strandberg at ICHEP 18.



Channels with cascade decays into intermediate chargino/neutralino states and compressed spectrum present the weakest limits, and the bound falls short of 2 TeV for non-compressed spectrum. Bound of 2.2 TeV in the most extreme case. Hard to evade the TeV bound.

Stop-sbottom Searches



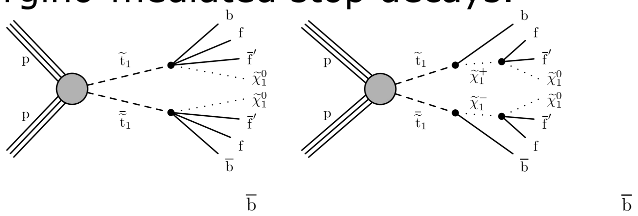


Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints of 700 GeV for bottoms and 550 GeV for stops. Islands in one search are apparently covered by other searches.

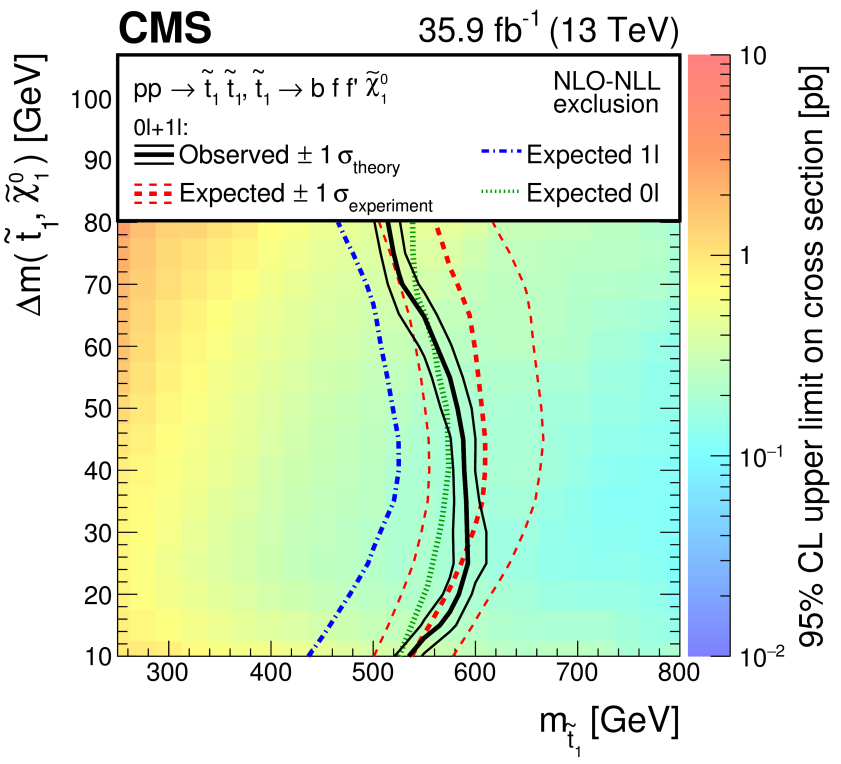
Stop searches in Compressed Spectrum

- Target compressed scenarios with 4-body or chargino-mediated stop decays.

CMS-SUS-17-005



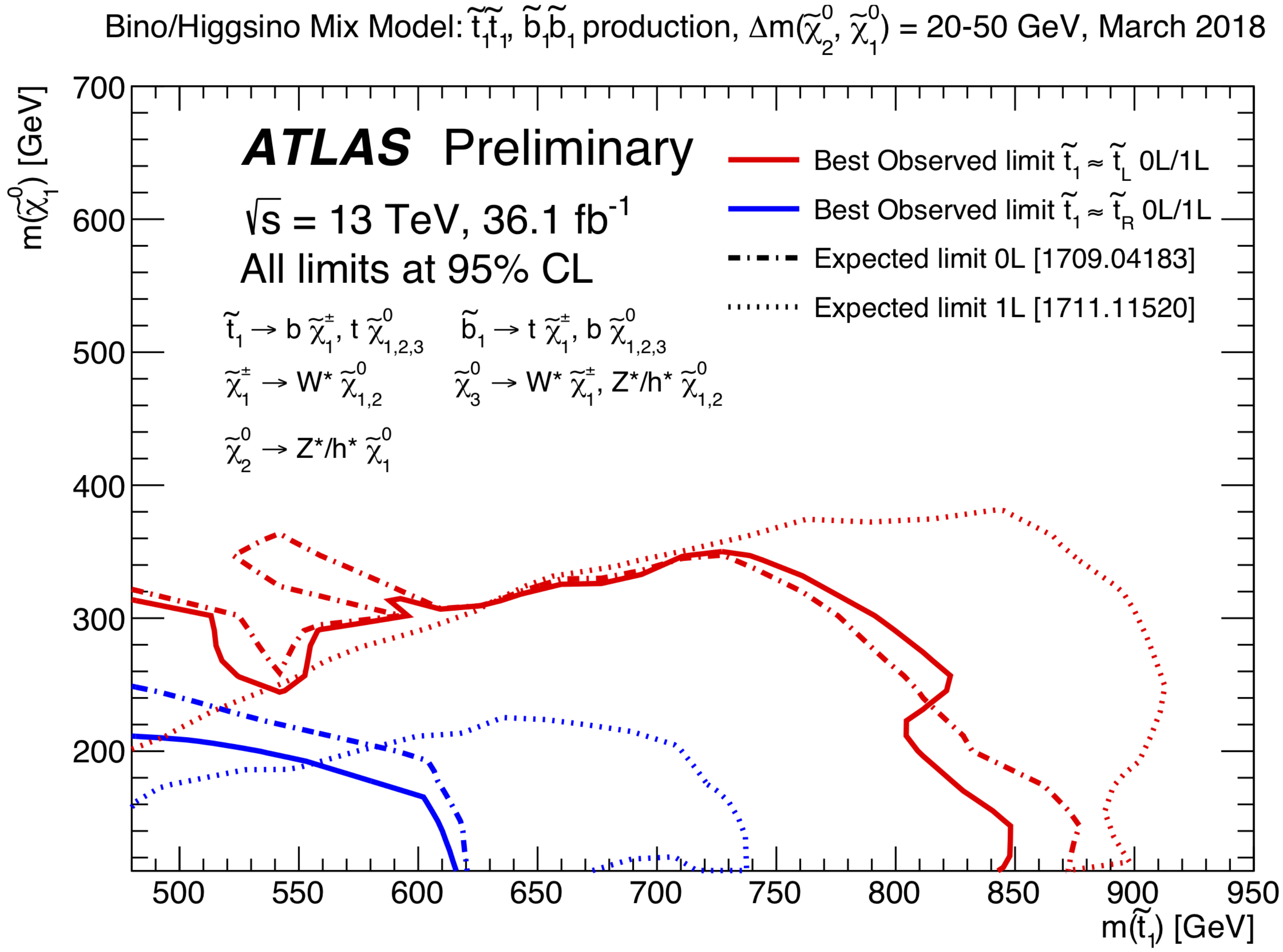
- Require hard (p_T > 100 GeV) ISR jet to boost system and recover some E_T^{miss}.
- Soft leptons (p_T^{μ} > 3.5 GeV and p_T^{e} > 5 GeV).



Again, bound of 500 GeV hard to beat !

Stop bound may be somewhat relaxed in more complex cascade decays, but not by much

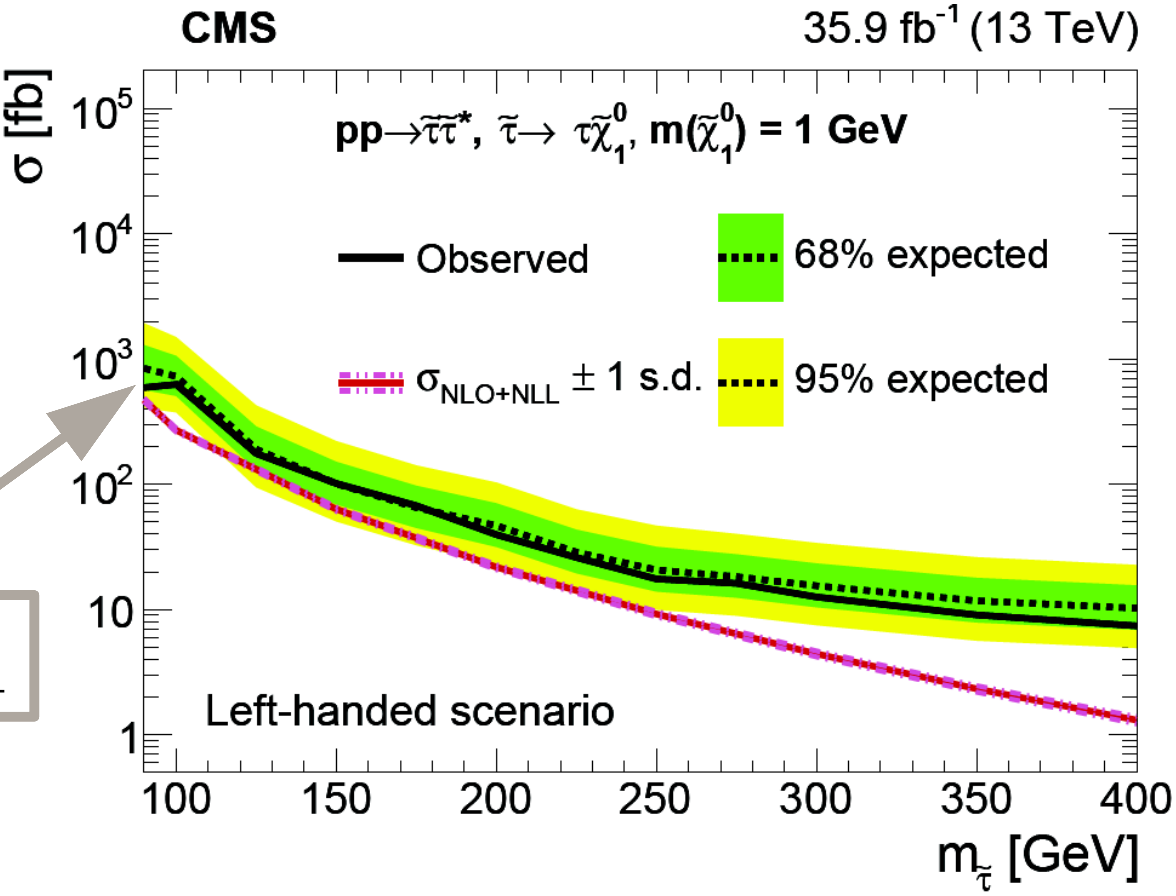
(need to study these results. Excess in 1L channels?)



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, although an intriguing excess observed at ATLAS demands some attention
- Higgsinos as NLSP's are mostly unconstrained.
- Sensitivities in the search for these particles will increase only at high luminosities, but bounds on Higgsinos will remain weak.
- I will flash results of some searches and concentrate on the interesting recent ATLAS result.
- In general, a scenario with large cascade decays with light electroweakinos is the most natural one and the highest hope for SUSY at the weak scale.

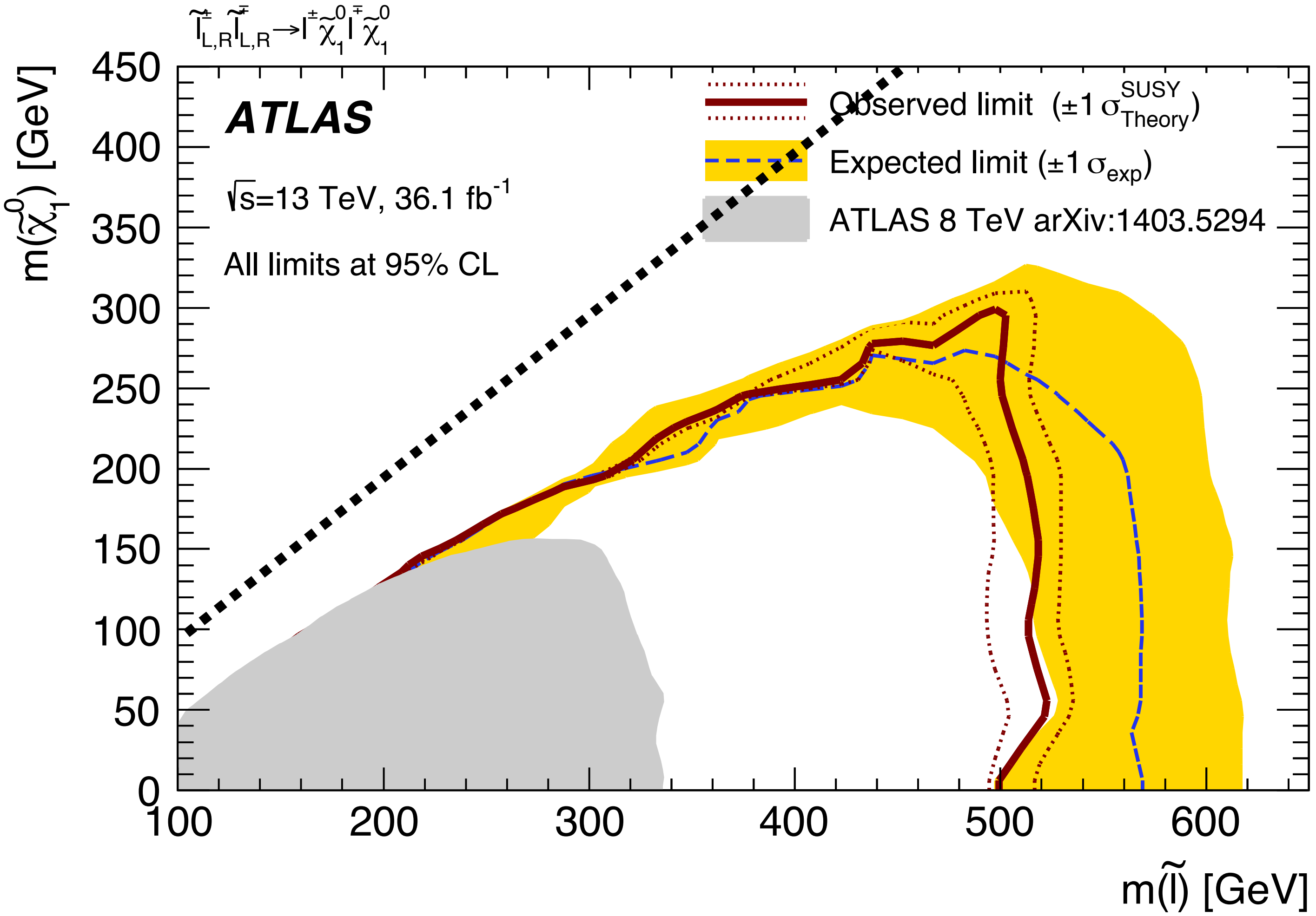
Stau Searches : Approaching sensitivity for (left-handed) stau production. Bounds depend on stau mixing.



$1.26\times\sigma_{NLO+NLL}$

NO Limit at this point

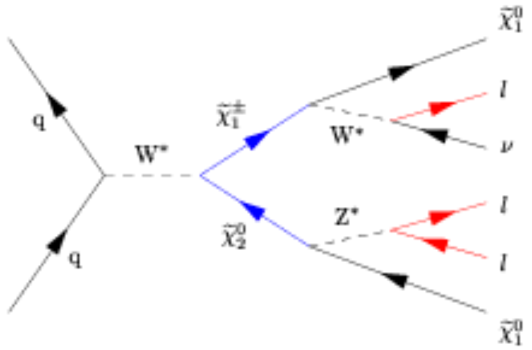
Slepton production
All four light generation leptons mass degenerate

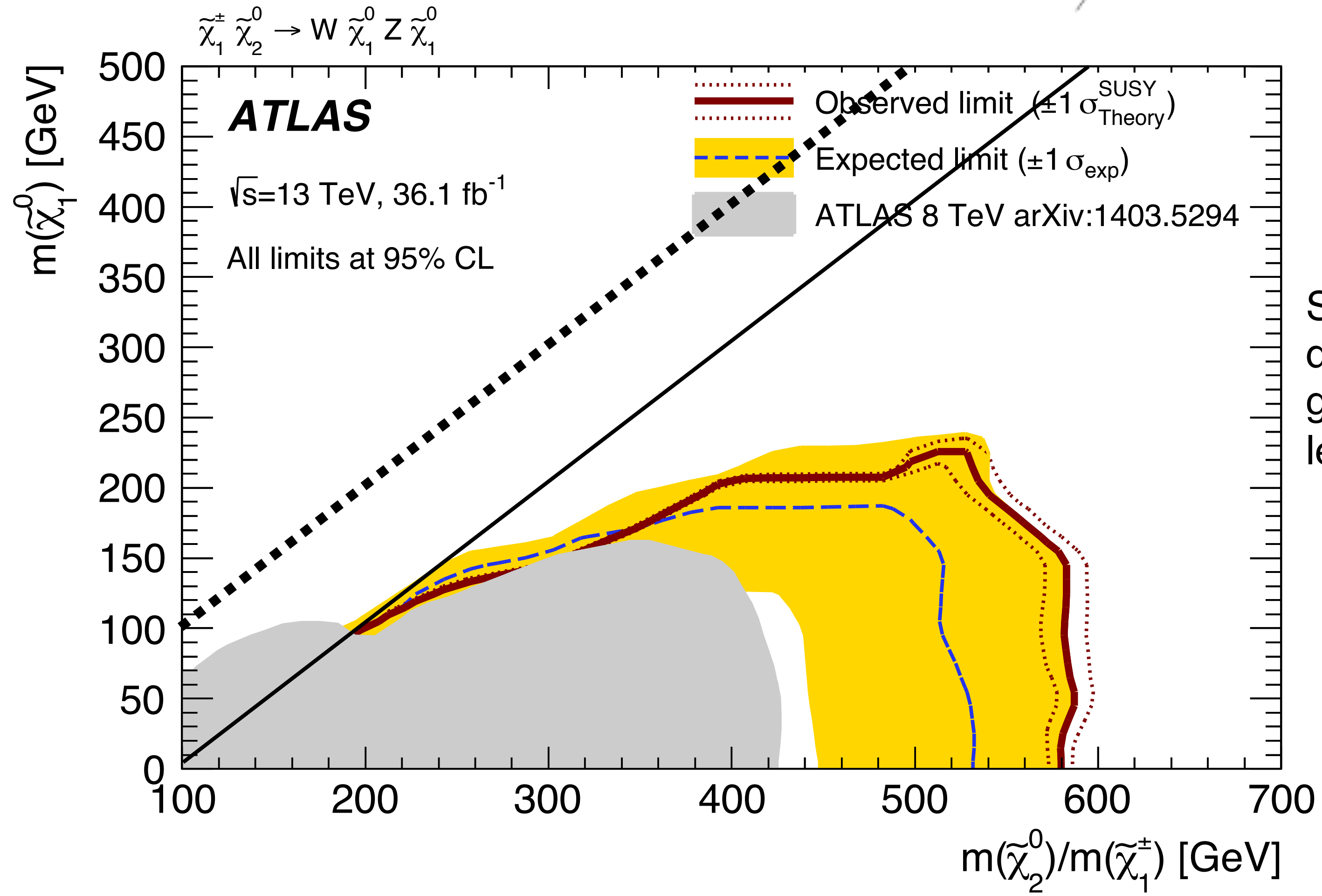


Limits may be different in the case of cascade decays of the leptons into lighter electroweakino states.

Electroweakino Production

2 lepton and 3 lepton final states. On-shall Z production





Small cross sections due to small BR of gauge bosons to leptons

Comments : Wino production cross section assumed.

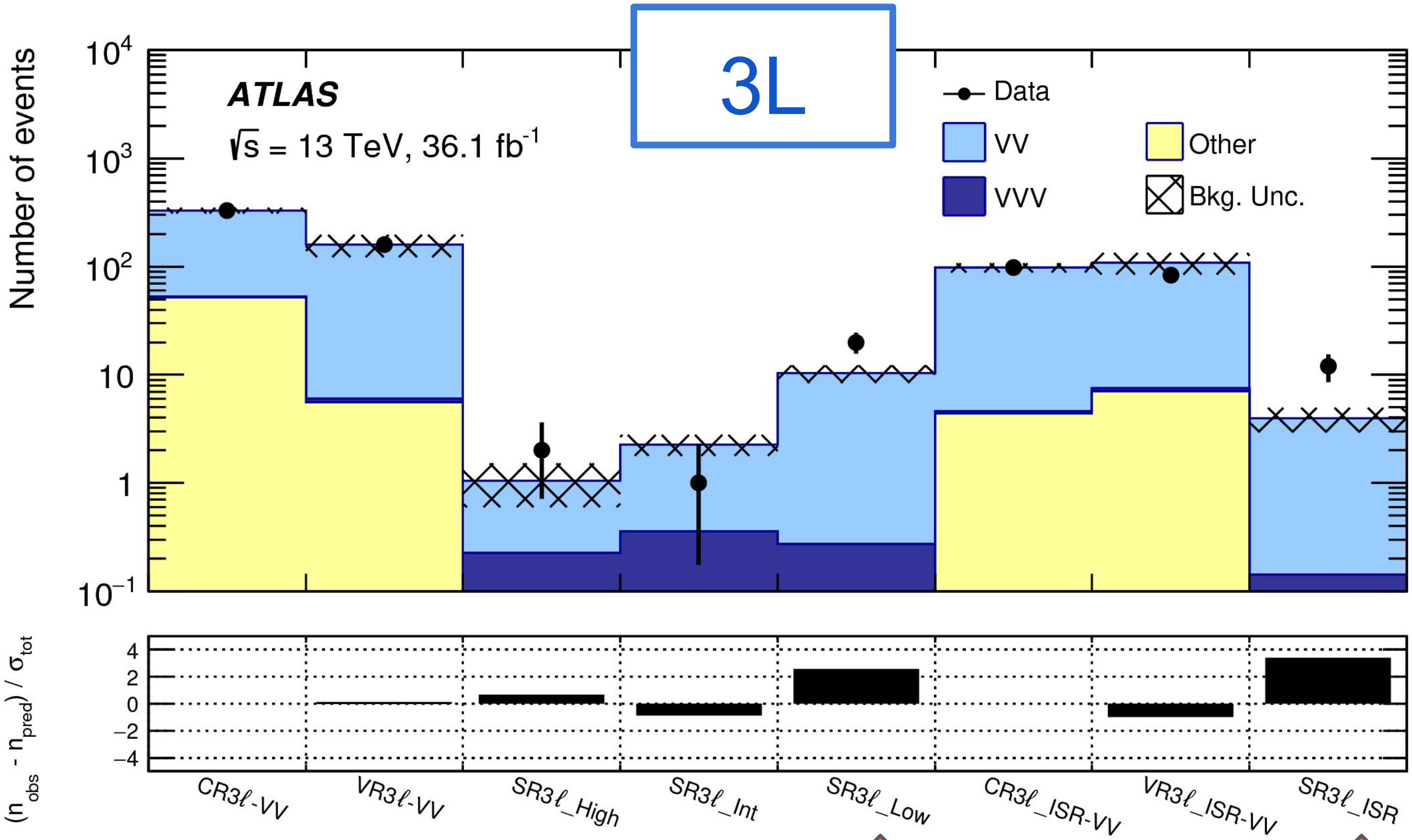
Limits disappear in the case of Higgsino production.

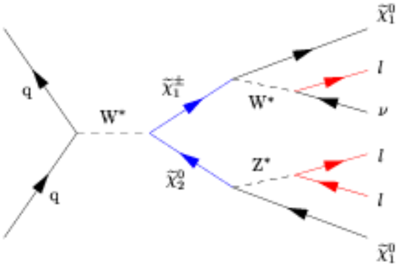
Backgrounds estimated from Monte Carlo

Recent ATLAS Analysis

Z. Zinonos ICHEP Conference

arXiv:1806.02293





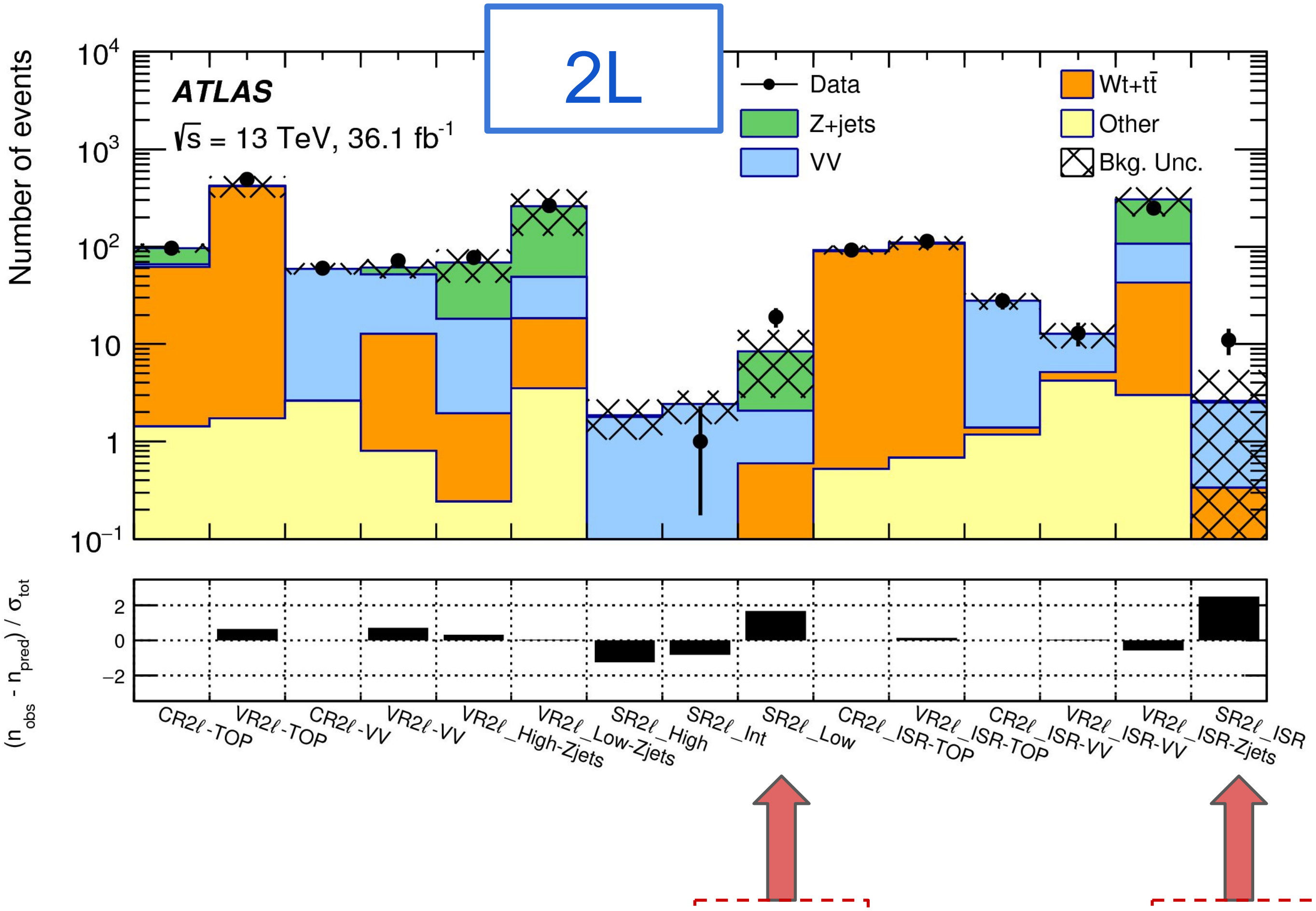
2.1σ

3.0σ

Recent ATLAS Analysis

Z. Zinonos ICHEP Conference

arXiv:1806.02293



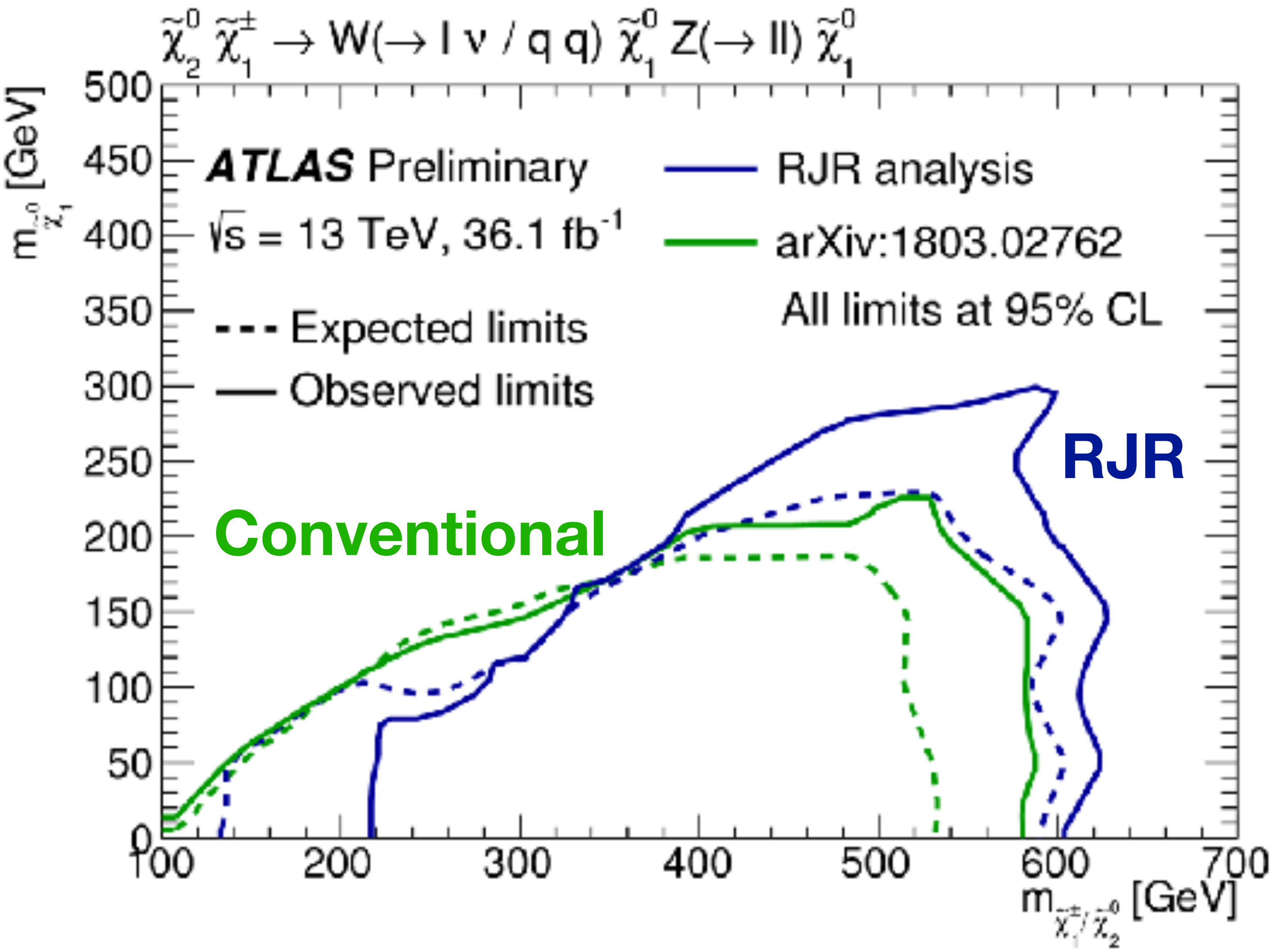
local significance: 1.4σ 2.0σ

Where is the Excess ?

Signal region	SR2ℓ_High	SR2ℓ_Med	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	0	1	19	11
Total background events	1.9 ± 0.8	2.4 ± 0.9	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$
Signal region	**SR3ℓ_High**	**SR3ℓ_Med**	**SR3ℓ_Low**	**SR3ℓ_ISR**
Total observed events	2	1	20	12
Total background events	1.1 ± 0.5	2.3 ± 0.5	10 ± 2	3.9 ± 1.0

Low Effective Masses.
Low Masses/Mass Splittings
Compressed region/ISR jets

Comparison between RJR and “Conventional” searches



Important difference between these searches :
In RJR analysis, backgrounds are computed from data
In Conventional Searches from Monte Carlo

BG estimation:

Shion-Chen, LHCP Conference

- **Diboson (main BG), ttbar** → Semi data-driven

  Normalize MC to data in control regions (CRs),

  where some of selections are loosened reversed wrt SRs

  Normalization factors: 0.9~1.1

- **Z+jets (main BG in 2L)** → Data driven ("γ-replace")

  Pick γ+jets events / replace γ into simulated Z→ℓℓ,

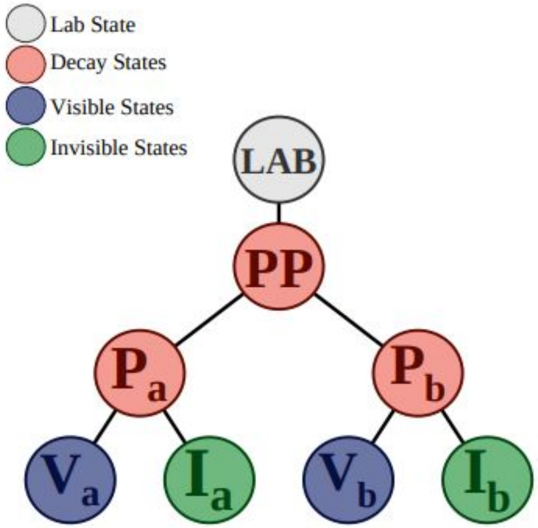
  w/ corrections for γ/Z difference, trigger pre-scale etc.

Recursive jigsaw in a nutshell

A method for decomposing measured properties event-by-event to provide a basis of kinematic variables.

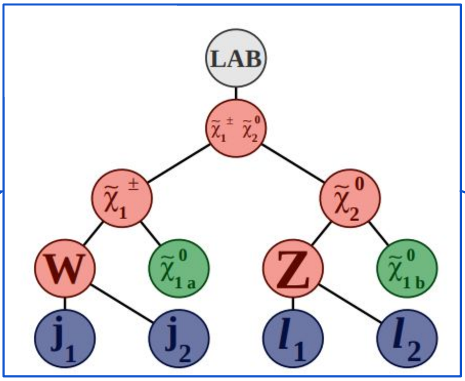
→ Achieved by approximating the rest frames of intermediate particle states in each event.

→ A natural basis of kinematic observables calculated by recursively evaluating the momentum and energy of different objects in these reference frames.



Phys. Rev. D 96 (2017) 112007

Reconstructed objects: leptons, jets, E_T^{miss} as input



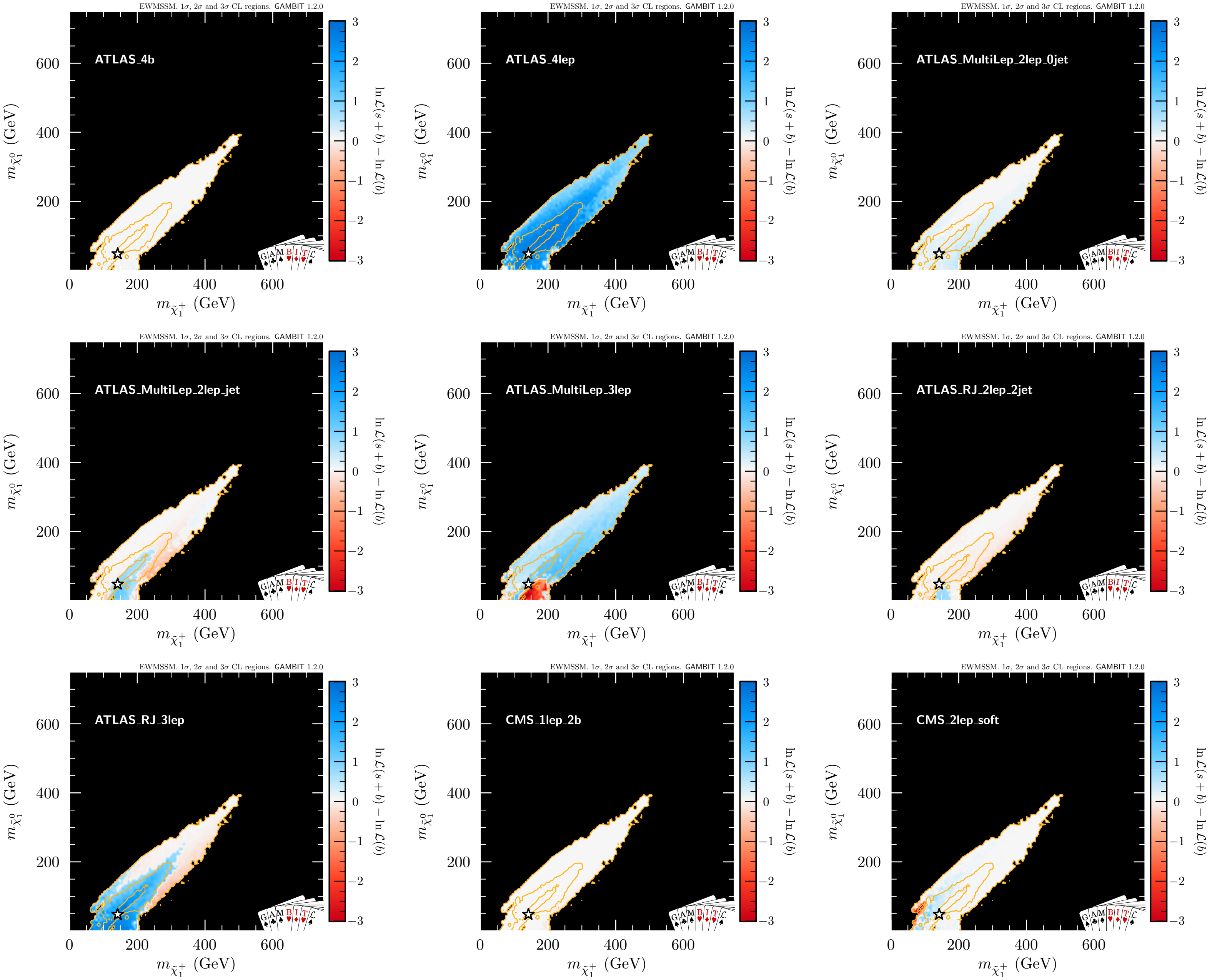
Assignment to decay tree

Set of kinematic observables discriminating S from B

Fit to the Data

RJR Optimized for region where
$m_{\tilde{\chi}_2} - m_{\tilde{\chi}_1} \simeq 100$ GeV

GAMBIT Collaboration,
arXiv:1807.03208, 1809.02097



Claim that bounds from conventional searches become weaker once realistic spectrum is taken into account.

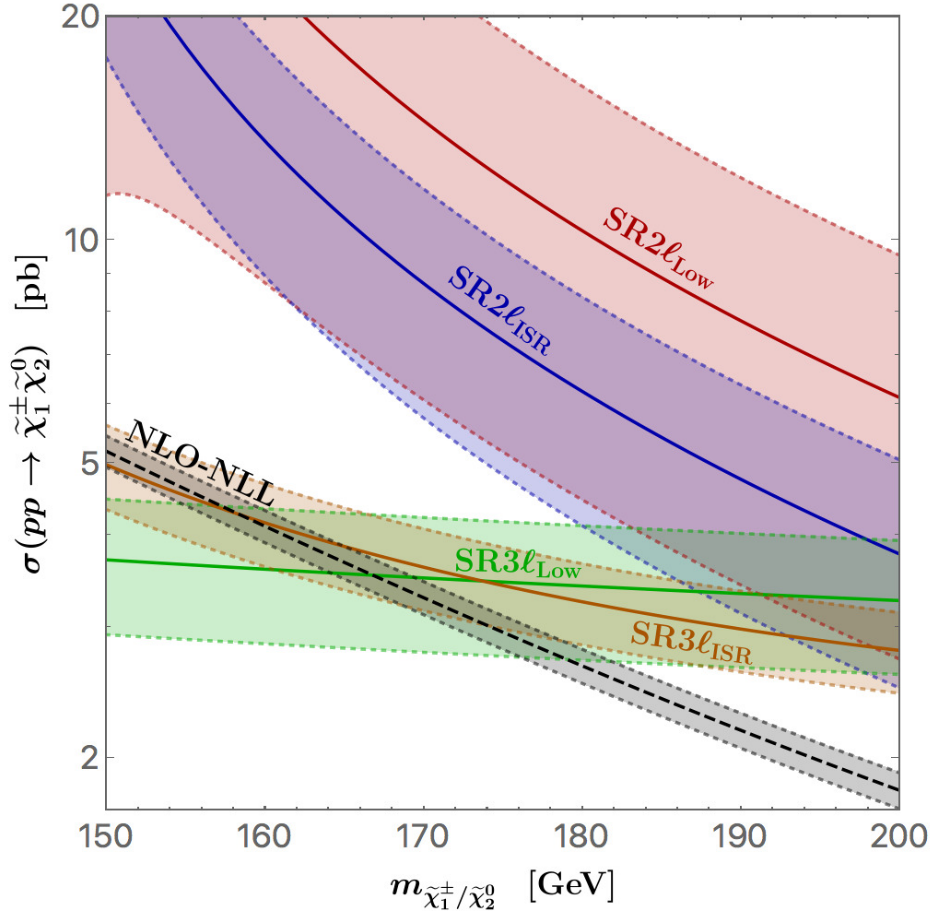
Cross Sections Consistent with Observed Excesses

Carena, Osborne, Shah, C.W. '18

Concentrated on the region consistent with 3-leptons plus missing energy that is the most sensitive one.

Masses of about 165 GeV and cross section of about 3pb.

Additional region with masses of 200 GeV interesting, too.



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 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 $\quad +M_1$

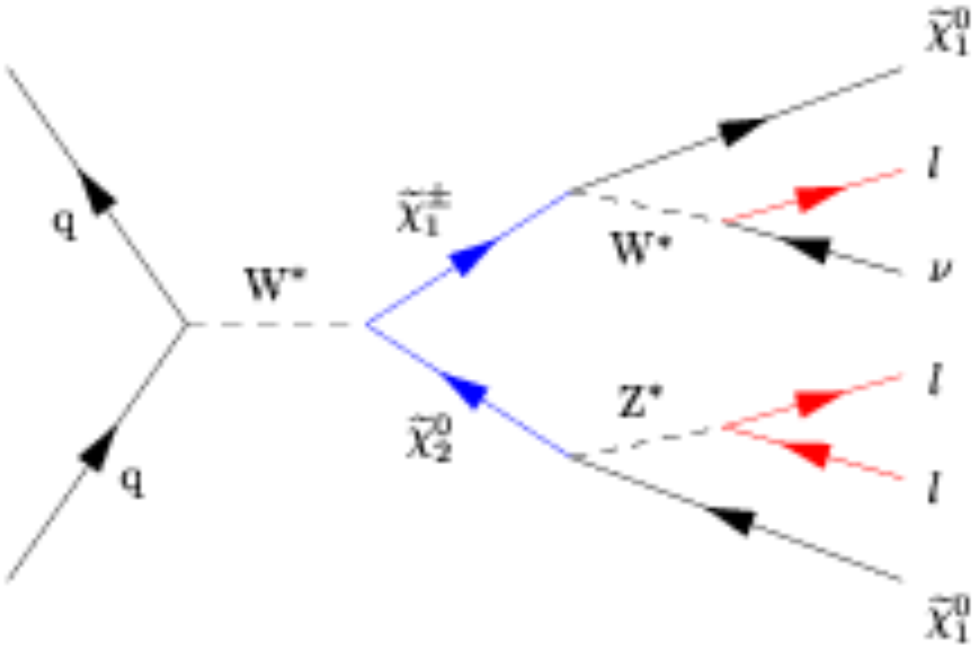
$\Phi_\mu,\ \Phi_1$

CP phases

Expected to be among the lightest sparticles

⇒ A good starting point towards SUSY parameter determination

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”.

MSSM Cross Sections

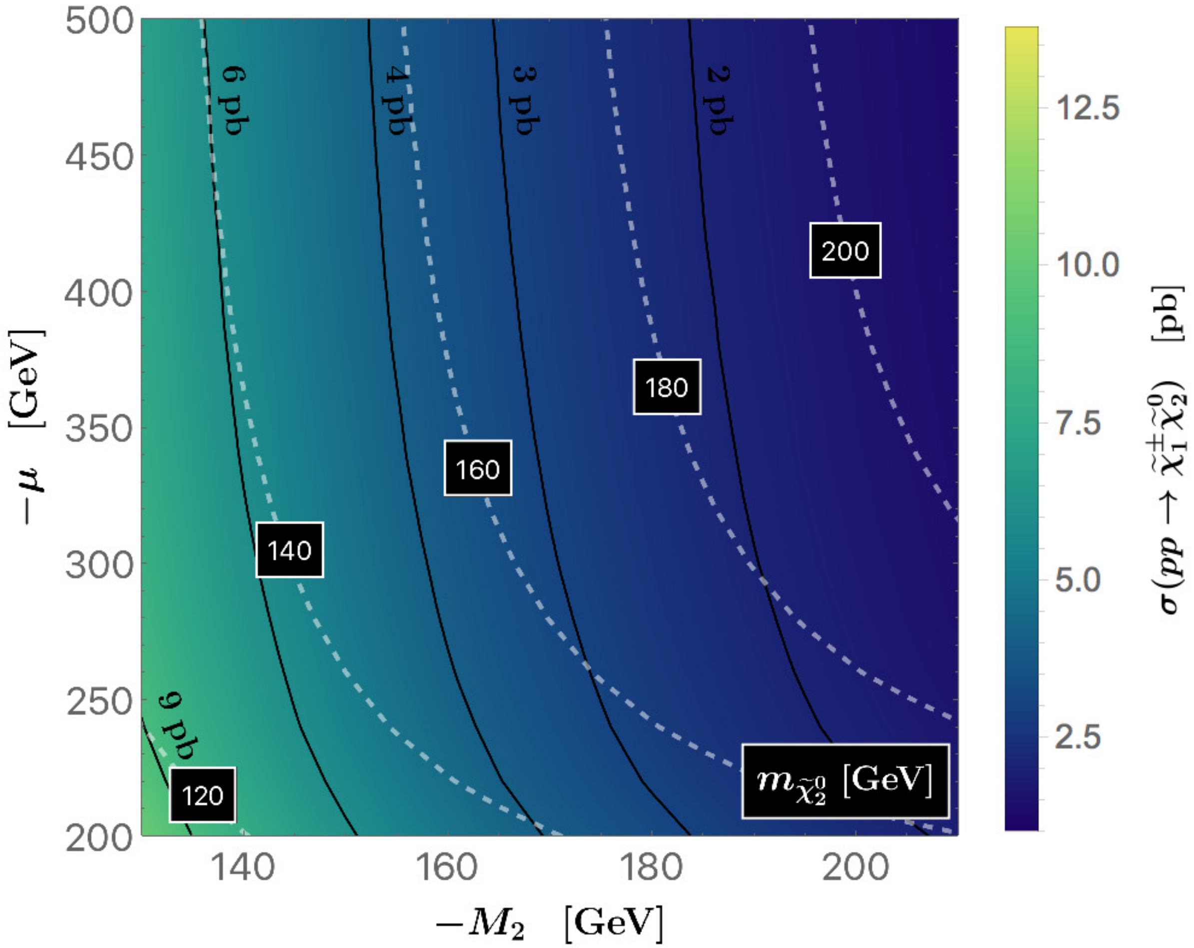
Carena, Osborne, Shah, C.W. ‘18

Strong dependence on M2

Weak Dependence on mu.

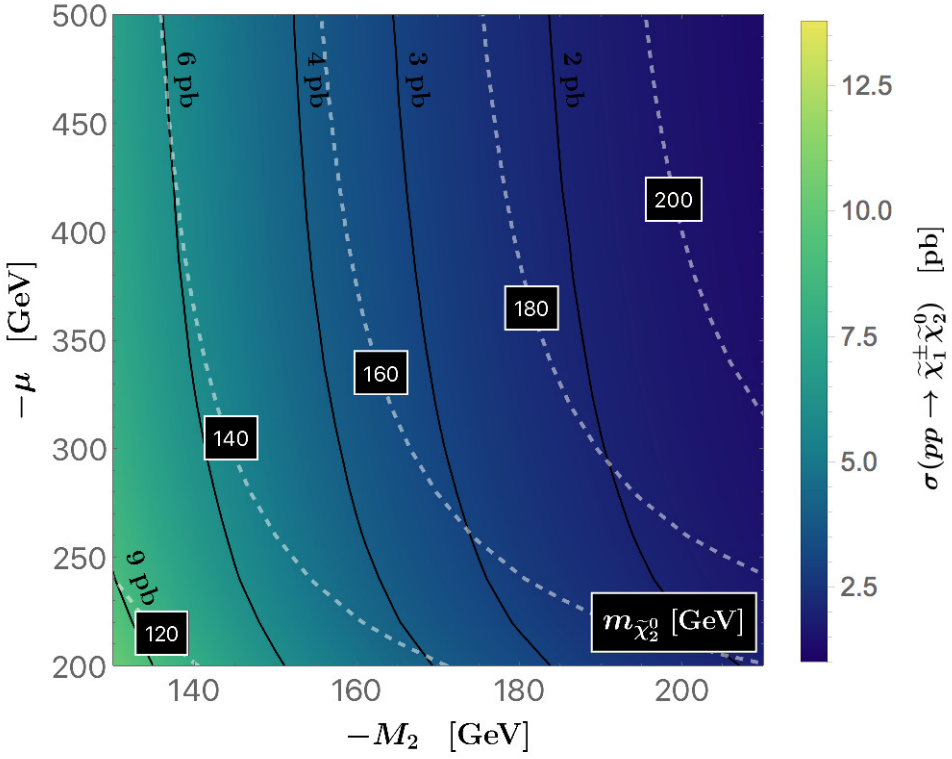
Wino cross section larger by about a factor 4 than the Higgsino one.

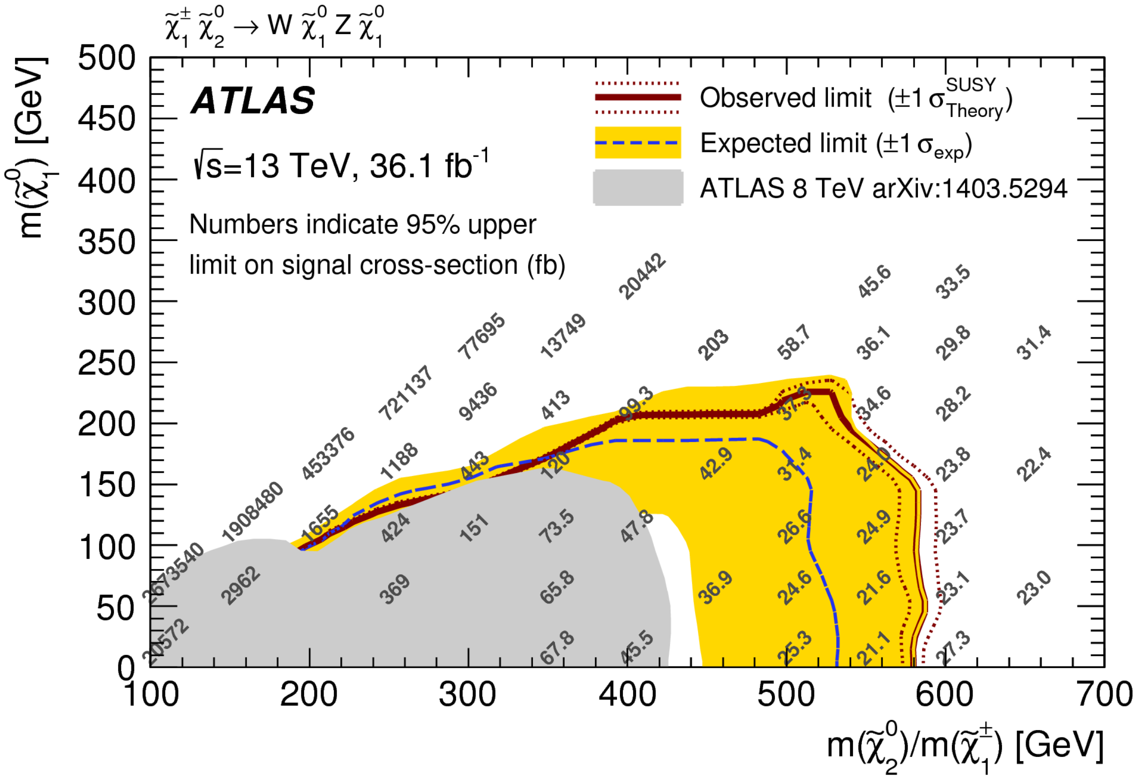
Values of $\mu \simeq 300$ GeV lead to the desired cross sections.



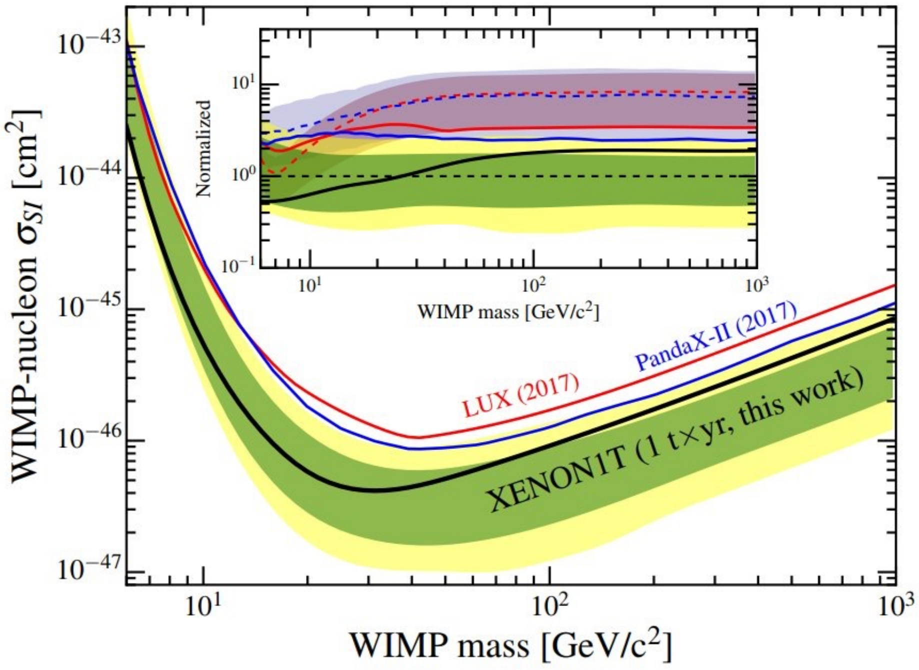
Comparison with Limits from Conventional Searches

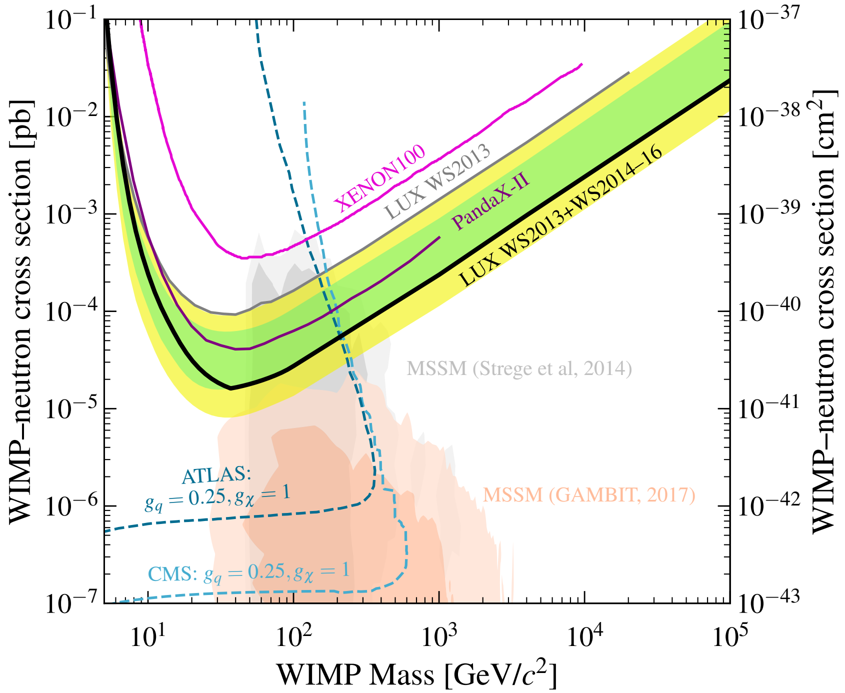
Chargino Masses of about 165 GeV and Neutralino Masses of about 65 GeV, with cross sections of about 3 pb are in marginal tension with conventional searches and lead to an explanation of the RJR excess within 1 standard deviation.





DM : Direct Detection Bounds





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

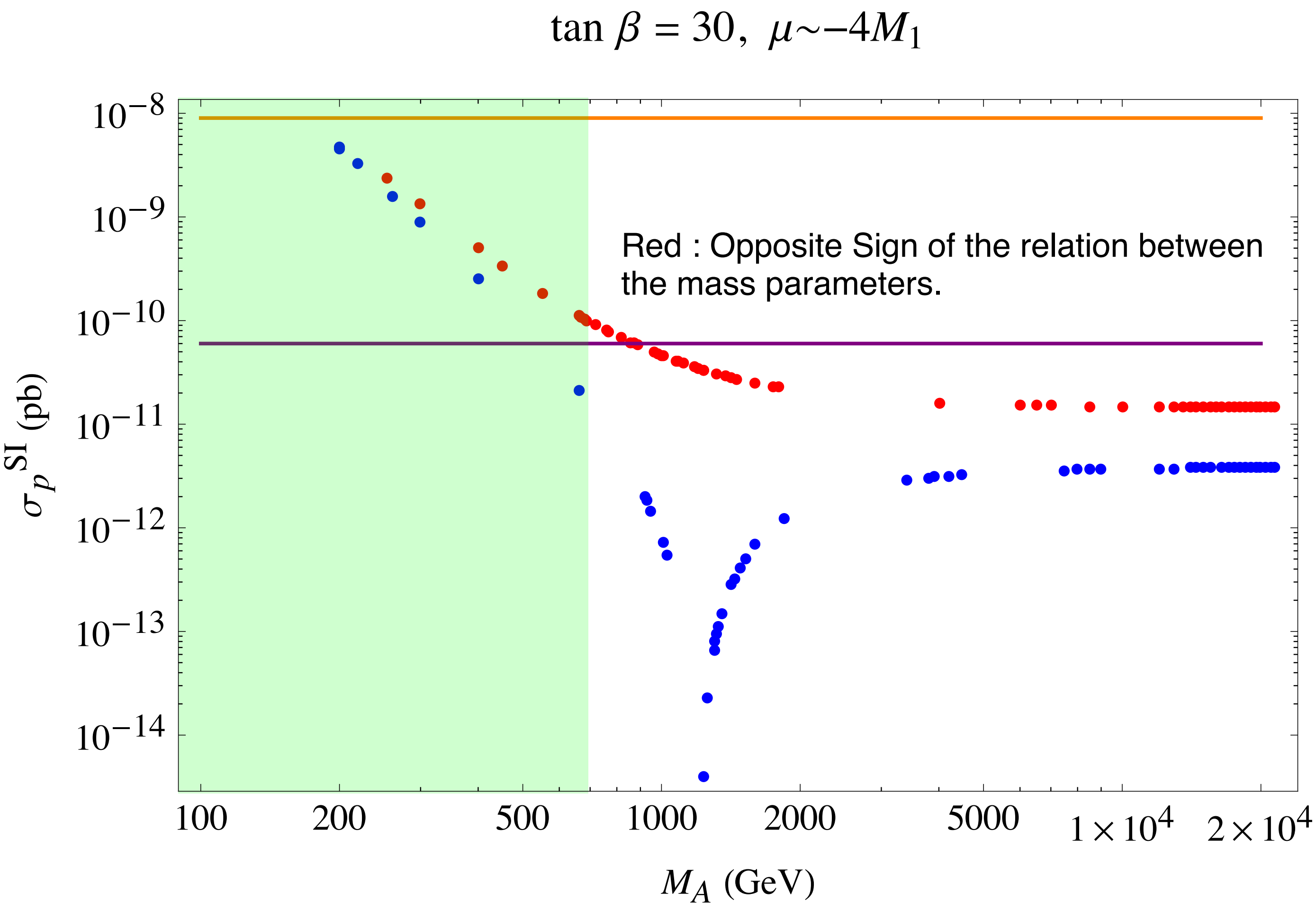
Blind Spot :
$$2\left(m_{\tilde{\chi}_1^0}+2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2}\simeq-\mu\tan\beta\left(\frac{1}{m_H^2}+\frac{1}{2m_{\tilde{Q}}^2}\right)$$

Cheung, Hall, Pinner, Ruderman'12, Huang, C.W.'14, Cheung, Papucci, Shah, Stanford,Zurek'14

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

Blind Spots in the Spin-Independent Cross Section

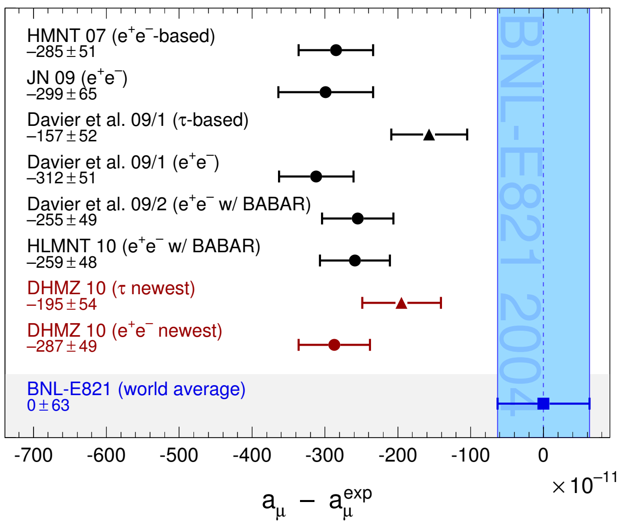
P. Huang, C.W.'14



Red : Opposite Sign of the relation between the mass parameters.

Muon Anomalous Magnetic Moment

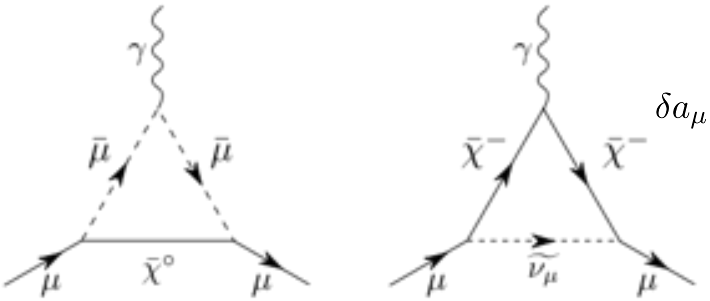
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level



$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm theory} = 268(63)(43) \times 10^{-11}$$

3.6σ Discrepancy

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2}\frac{m_\mu^2}{\widetilde{m}^2}\mathrm{Sgn}(\mu M_2)\tan\beta \simeq 130 \times 10^{-11}\left(\frac{100\ \mathrm{GeV}}{\widetilde{m}}\right)^2 \mathrm{Sgn}(\mu M_2)\tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

Benchmark Point

Carena, Osborne, Shah, C.W. '18

$$\text{Blind Spots}: \mu \times M_1 < 0$$
$$(g-2)_\mu : \mu \times M_2 > 0$$

Param.	[GeV]	Param.	[GeV]	Param.	[GeV]	Param.	[GeV]
μ	-300	M_2	-172	$M_{\widetilde{L}}$	400	M_H	1500
M_1	63.5	M_3	2000	$M_{\widetilde{Q}}$	2000	A_t	3000

Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]	Part.	m [GeV]
h	125.84	$\widetilde{\chi}_1^\pm$	165.0	$\widetilde{\nu}_e$	395.0	$\widetilde{u}_R$	2069.8
H	1500.03	$\widetilde{\chi}_2^\pm$	333.6	$\widetilde{\nu}_\mu$	395.0	$\widetilde{u}_L$	2069.5
H_3	1500.00	$\widetilde{\tau}_1$	389.5	$\widetilde{\nu}_\tau$	395.0	$\widetilde{d}_R$	2070.3
$H^\pm$	1502.38	$\widetilde{\tau}_2$	415.0	$\widetilde{g}$	2129.2	$\widetilde{d}_L$	2071.0
$\widetilde{\chi}_1^0$	61.7	$\widetilde{e}_R$	402.4	$\widetilde{t}_1$	1927.7	$\widetilde{s}_R$	2070.3
$\widetilde{\chi}_2^0$	164.8	$\widetilde{e}_L$	402.6	$\widetilde{t}_2$	2131.6	$\widetilde{s}_L$	2071.0
$\widetilde{\chi}_3^0$	314.2	$\widetilde{\mu}_R$	402.4	$\widetilde{b}_1$	2067.1	$\widetilde{c}_R$	2069.8
$\widetilde{\chi}_4^0$	331.2	$\widetilde{\mu}_L$	402.6	$\widetilde{b}_2$	2074.1	$\widetilde{c}_L$	2069.5

$\sigma(pp \to \chi_1^\pm \chi_2^0) = 2.92$ pb

$\Omega_{\rm CDM} h^2 = 0.121$

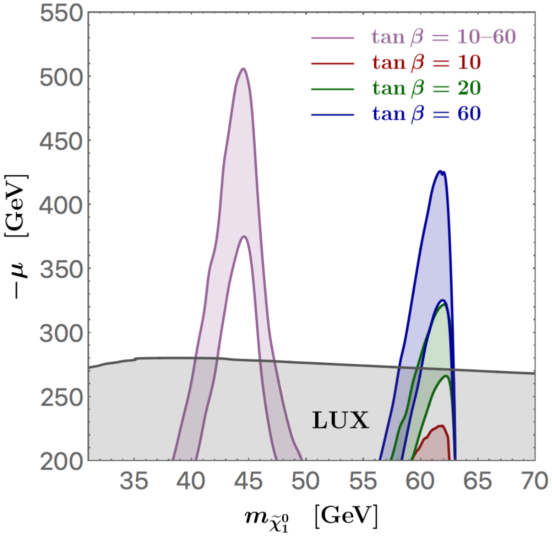
$a_\mu^{\rm MSSM} = 248 \times 10^{-11}\,.$

$$\sigma_p^{\rm SI} = 6.82 \times 10^{-13}\ \text{pb}\,, \qquad \sigma_p^{\rm SD} = 1.70 \times 10^{-5}\ \text{pb}\,,$$
$$\sigma_n^{\rm SI} = 4.70 \times 10^{-13}\ \text{pb}\,, \qquad \sigma_n^{\rm SD} = 1.33 \times 10^{-5}\ \text{pb}\,.$$

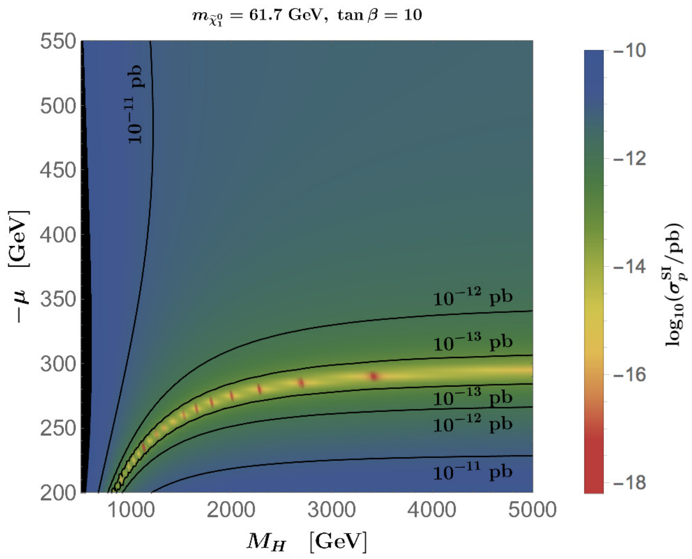
Carena, Osborne, Shah, C.W. ‘18

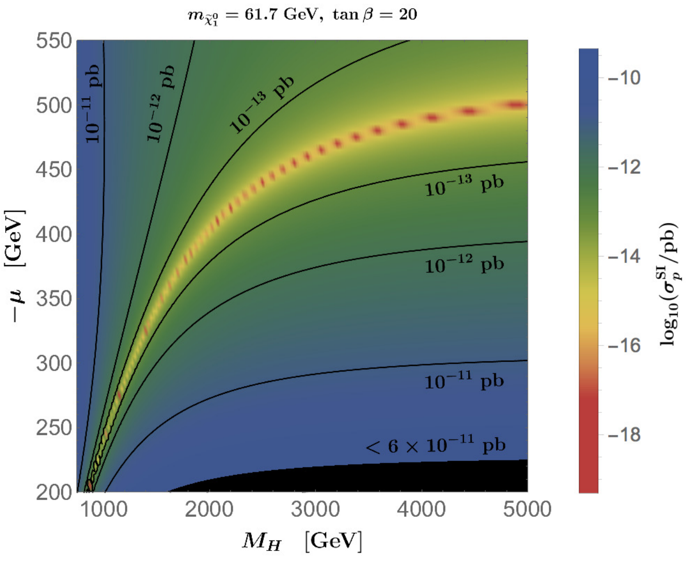
Dark Matter Phenomenology

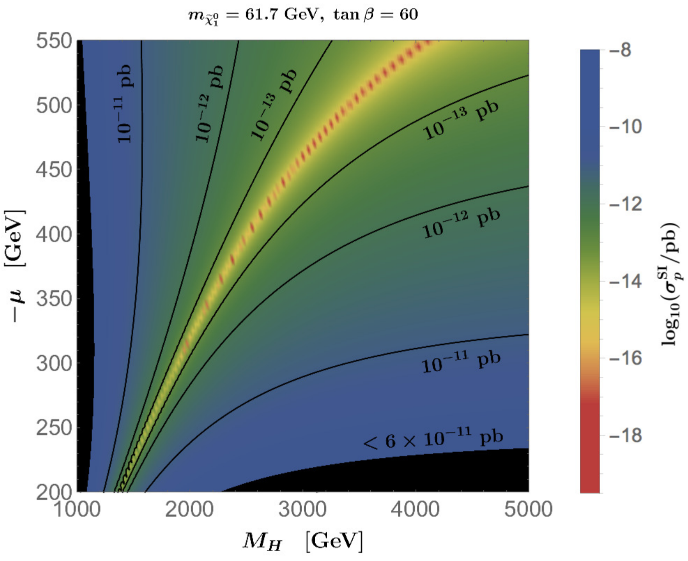
Higgs and Z Resonant Annihilation Regions
SD Cross Section Bounds satisfied
provided $|\mu| > 270$ GeV



Existence of Blind Spot Regions Suppresses the SI cross section below the current limits in most of the parameter space.







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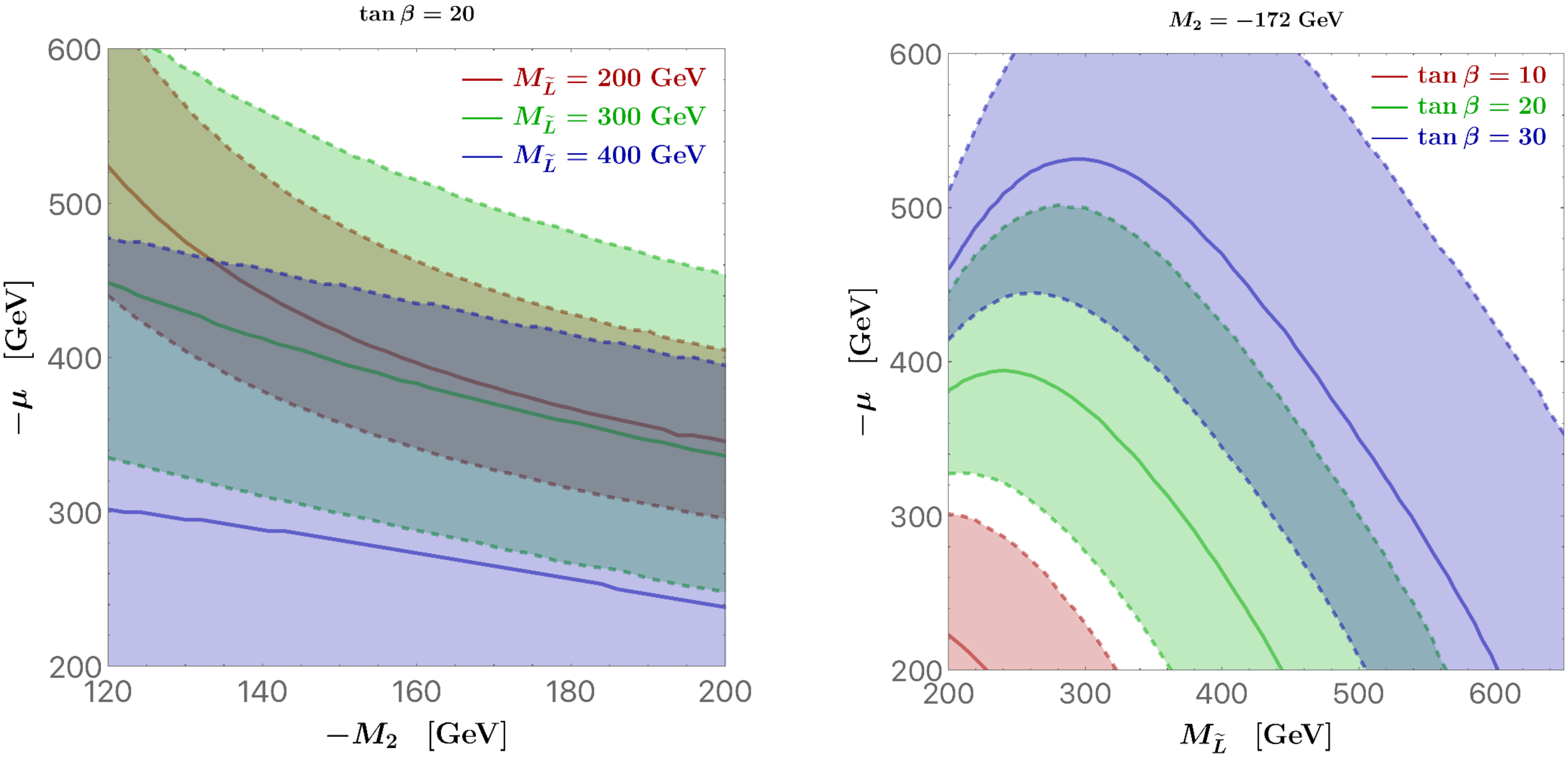
Anomalous Magnetic Moment $(g-2)_\mu$

As expected, s-leptons with masses of the order of 400 GeV lead to an explanation of g-2 for the benchmark point.

Dependence on tan(beta) follows the expected behavior



Conclusions

- Constraints on New Physics at the LHC have become increasingly strong
- No direct evidence of new physics
- No clear deviation of Higgs coupling from SM expectations
- Strongly interacting particles are restricted to be heavier than about 1 TeV
- Is there a chance of observing light, weakly interacting particles ?
- Case of low energy SUSY : Clearly there is still a chance !
- Is the RJR excess a hint ? Not clear, but time will tell
- One thing is for sure : If there is SUSY at the weak scale, it could lead to a solution of the DM problem without any tension with present experimental constraints.
- g-2 can also be explained. Not to mention all the "benefits" of SUSY

May we live in Interesting Times !

Backup

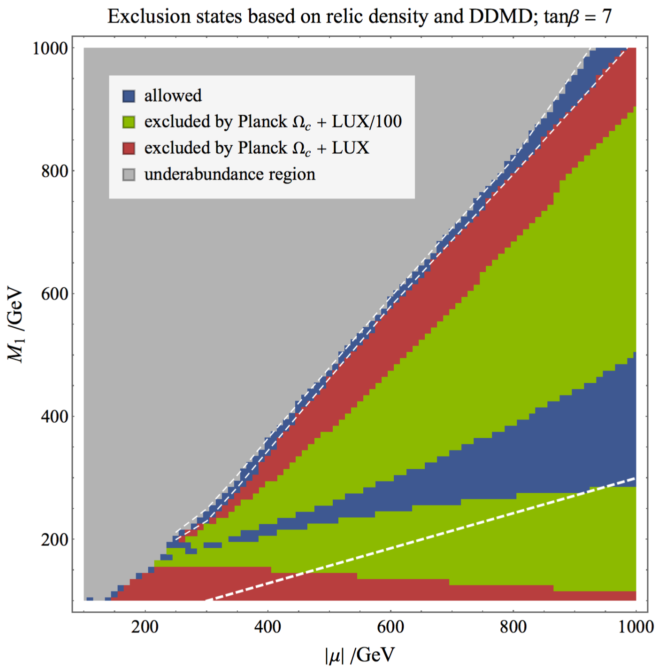
Dark Matter ?

- Bino (mixed with Higgsino) Dark Matter can lead to the right relic density for masses of a few hundred GeV, without upsetting other constraints, in a variety of ways, including co-annihilation and resonant annihilations.

- Higgsinos, with heavier gauginos, demand masses of order of the TeV

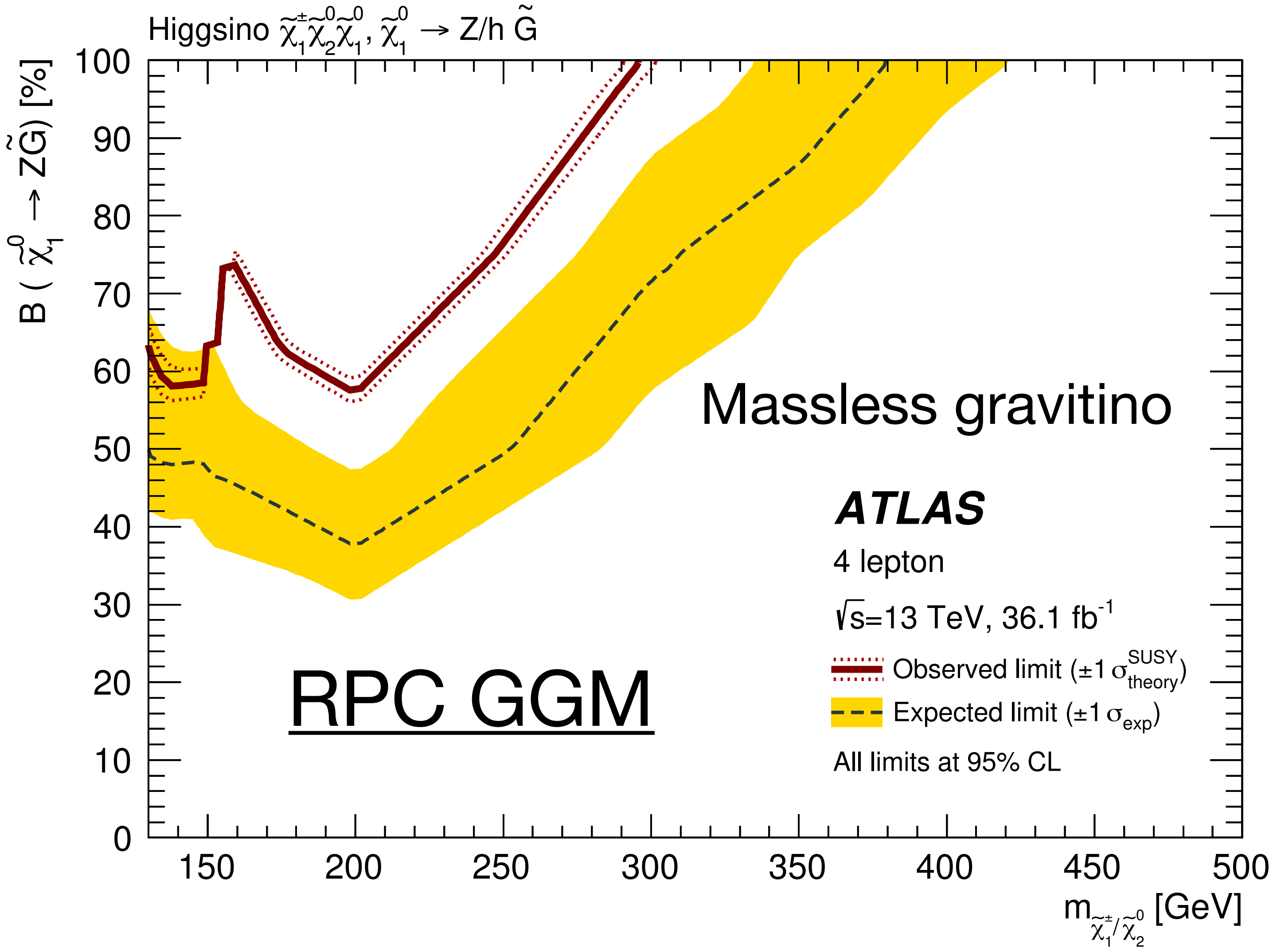
- Winos may be heavier, with masses of order of 2 TeV to get the right relic density.

- Only guidance : Masses of the order of the weak scale are consistent with a Dark Matter interpretation. No specific mass range suggested.



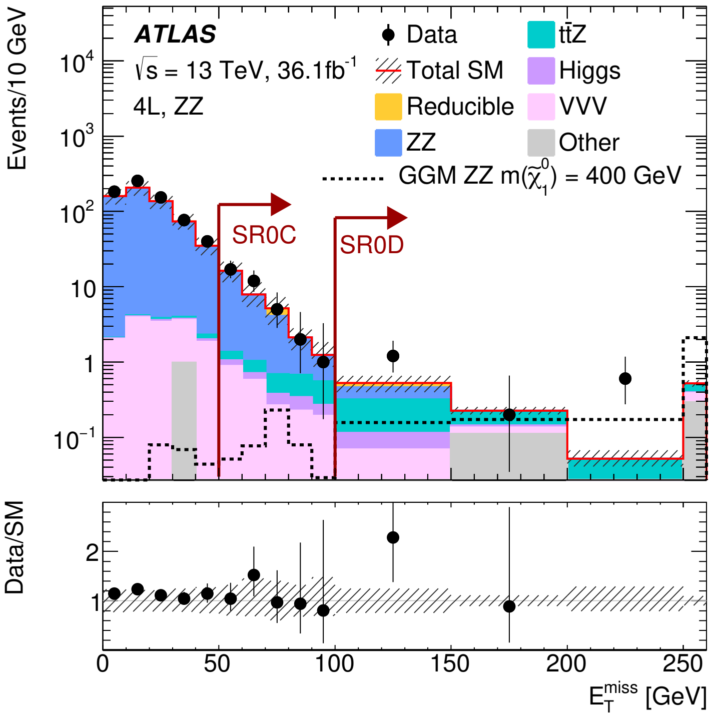
P. Huang, R. Roglans, D. Spiegel, Y. Sun, C.W.
arXiv:1711.05743

Four lepton Searches



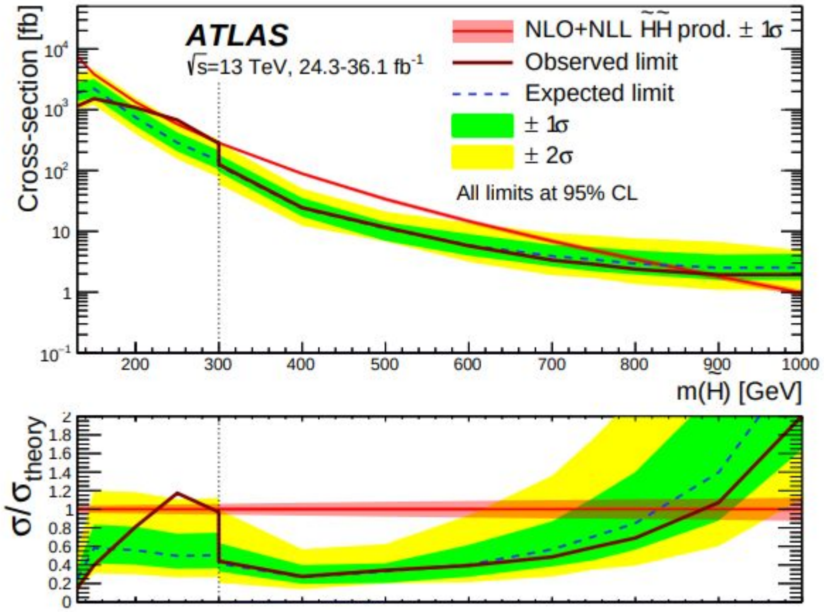
BG dominated by irreducible component (ZZ, ttZ)

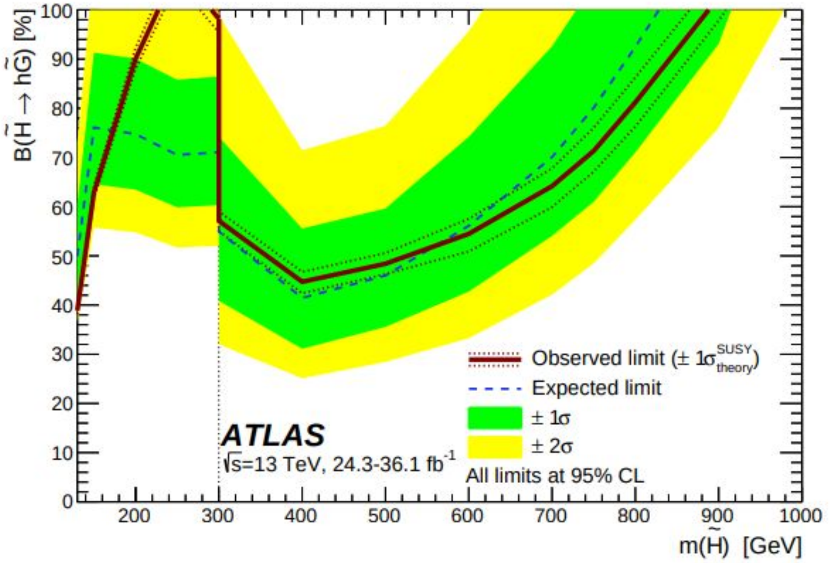
Sample	SR0A	SR0B	SR0C	SR0D	SR1	SR2
Observed	13	2	47	10	8	2
SM Total	10.2 ± 2.1	1.31 ± 0.24	37 ± 9	4.1 ± 0.7	4.9 ± 1.6	2.3 ± 0.8
ZZ	2.7 ± 0.7	0.33 ± 0.10	28 ± 9	0.84 ± 0.34	0.35 ± 0.09	0.33 ± 0.08
$t\bar{t}Z$	2.5 ± 0.6	0.47 ± 0.13	3.2 ± 0.4	1.62 ± 0.23	0.54 ± 0.11	0.31 ± 0.08
Higgs	1.2 ± 1.2	0.13 ± 0.13	0.9 ± 0.8	0.28 ± 0.25	0.5 ± 0.5	0.32 ± 0.32
VVV	0.79 ± 0.17	0.22 ± 0.05	2.7 ± 0.6	0.64 ± 0.14	0.18 ± 0.04	0.20 ± 0.06
Reducible	2.4 ± 1.4	$0.000^{+0.005}_{-0.000}$	$0.9^{+1.4}_{-0.9}$	$0.23^{+0.38}_{-0.23}$	3.1 ± 1.5	1.1 ± 0.7
Other	0.53 ± 0.06	0.165 ± 0.018	0.85 ± 0.19	0.45 ± 0.10	0.181 ± 0.022	0.055 ± 0.012



Higgsino : Higgs Final States

Higgsino multi-b

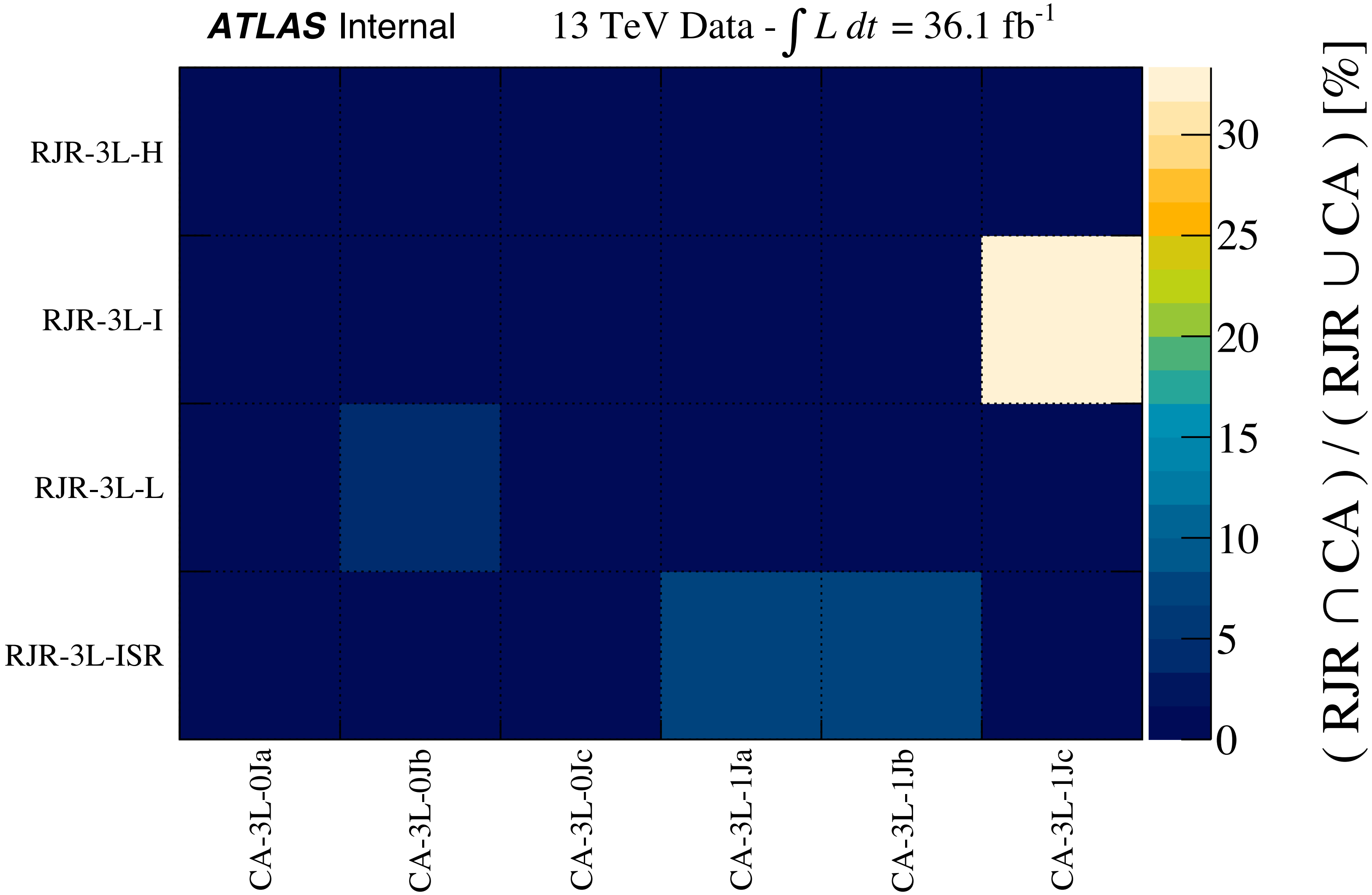




Four bottom final states
Reconstruction of the two Higgses by 2b invariant masses

Excess in region where background is obtained by data driven methods

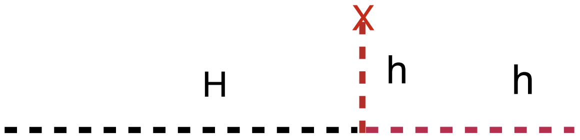
Small Overlap between Conventional and RJR SR

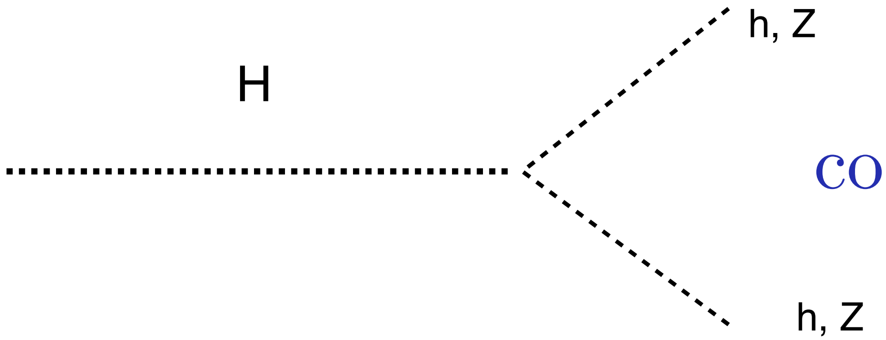


Higgs Sector

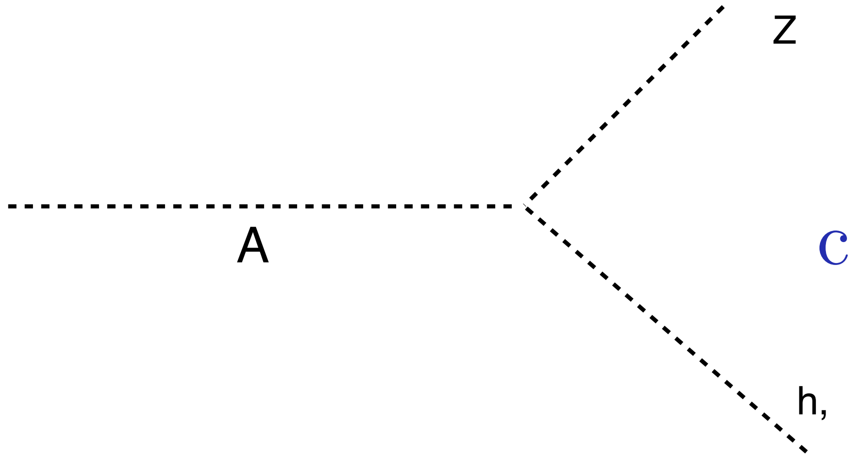
H and A Decay to Boson Pairs

Suppressed at Alignment





$$\cos(\beta - \alpha)$$



$$\cos(\beta - \alpha)$$

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

Inverting the sign of the bottom coupling

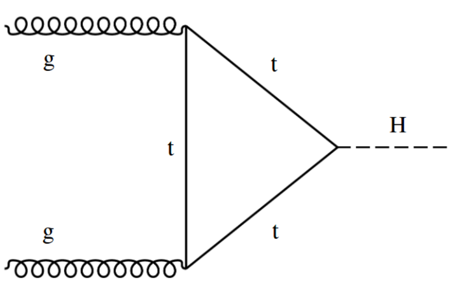
$$t_\beta \; c_{\beta-\alpha} \approx 2.$$

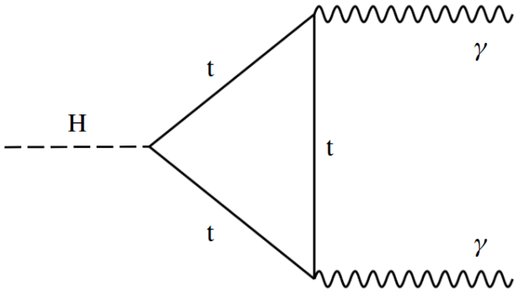
$$[(\lambda_3 + \lambda_4 + \lambda_5) - \lambda_2 + \lambda_7 t_\beta]v^2 \simeq 2(m_H^2 - m_h^2).$$

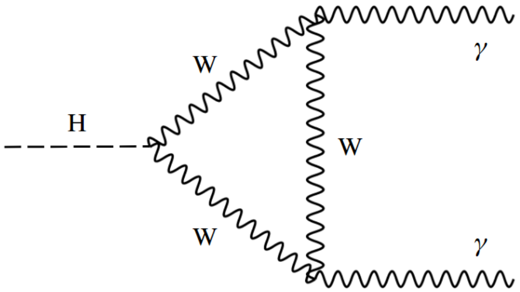
N. Coyle, B. Li, C.W.' arXiv:1802.09122

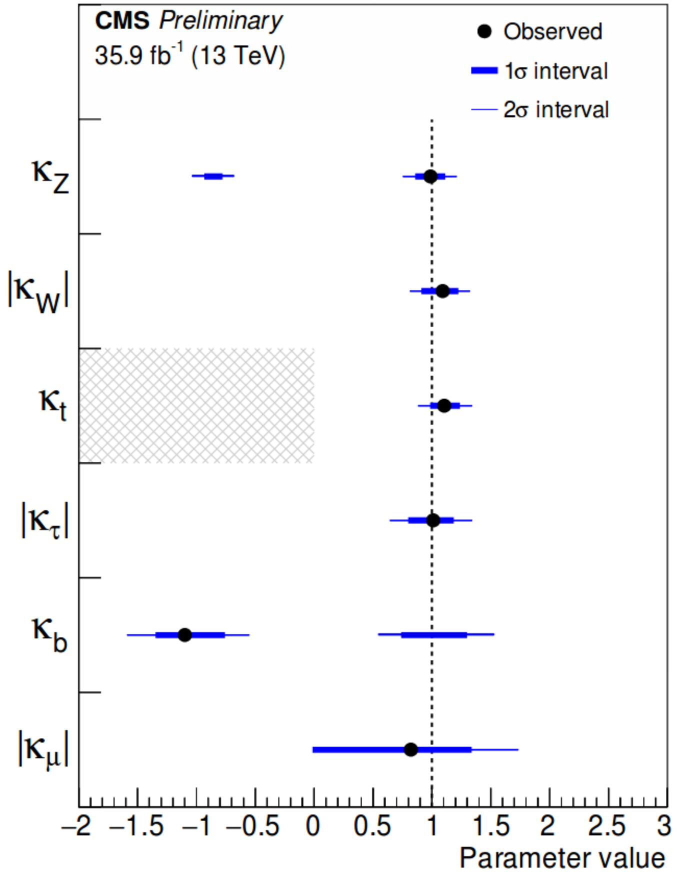
Couplings: Resolved Loops

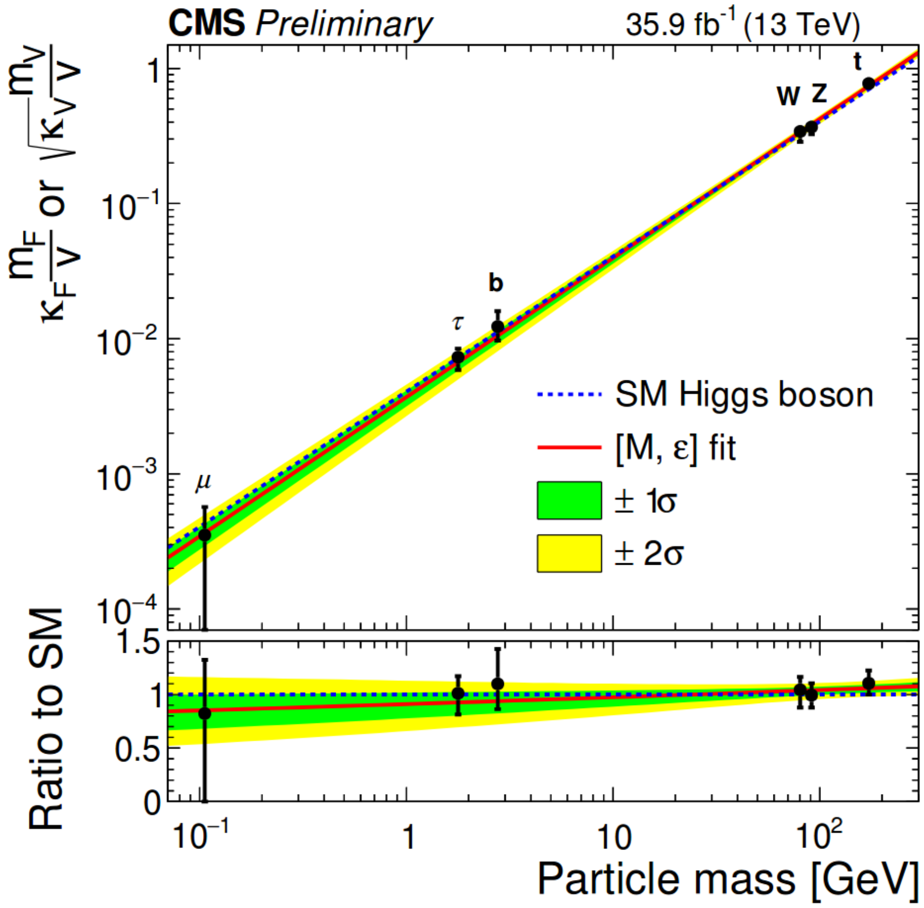
CMS-PAS-HIG-17-031











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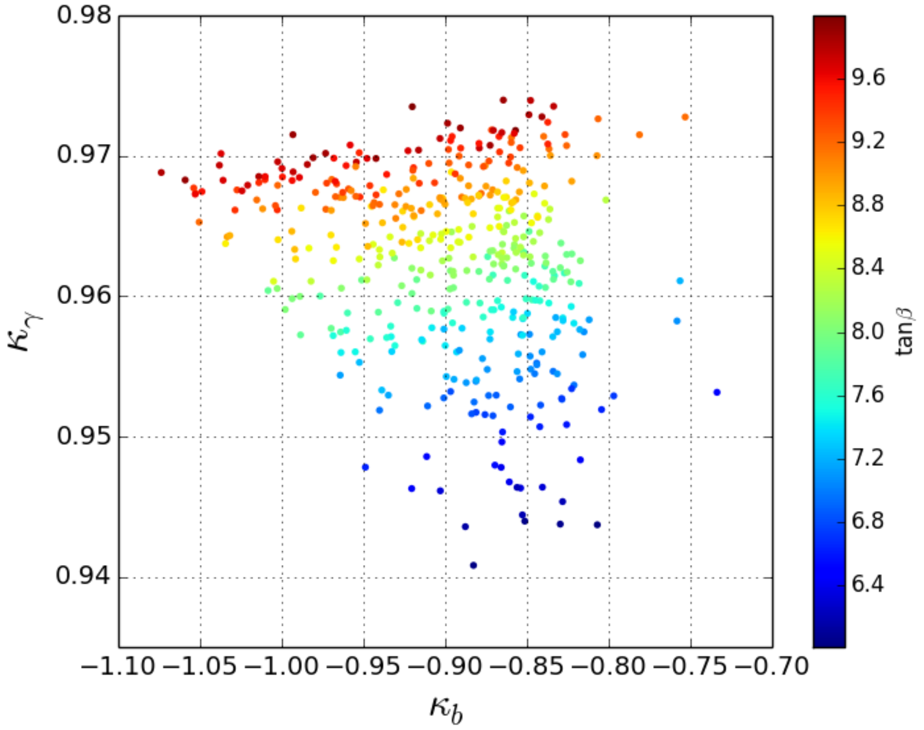
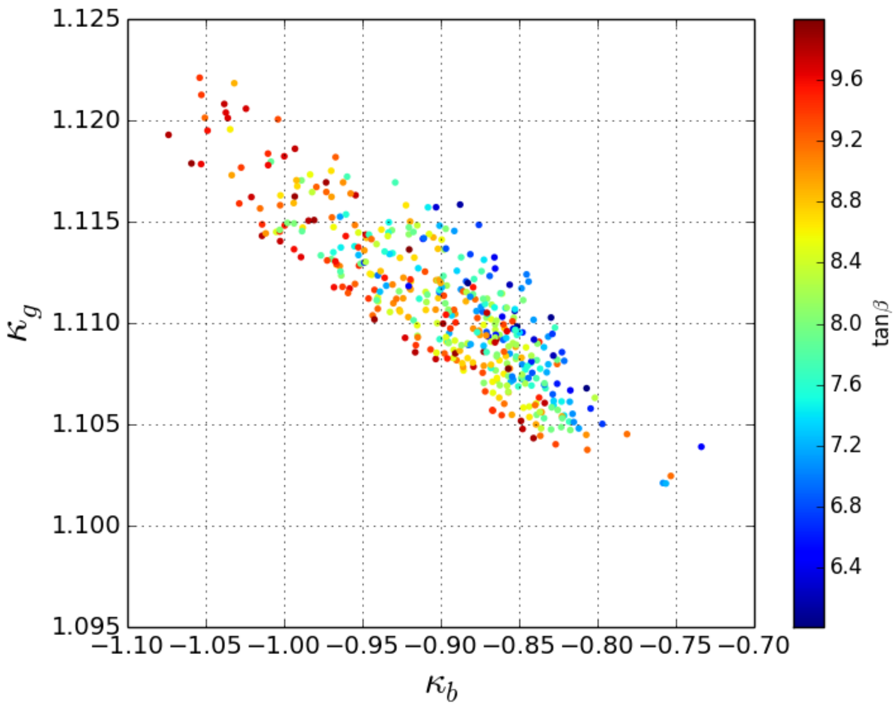
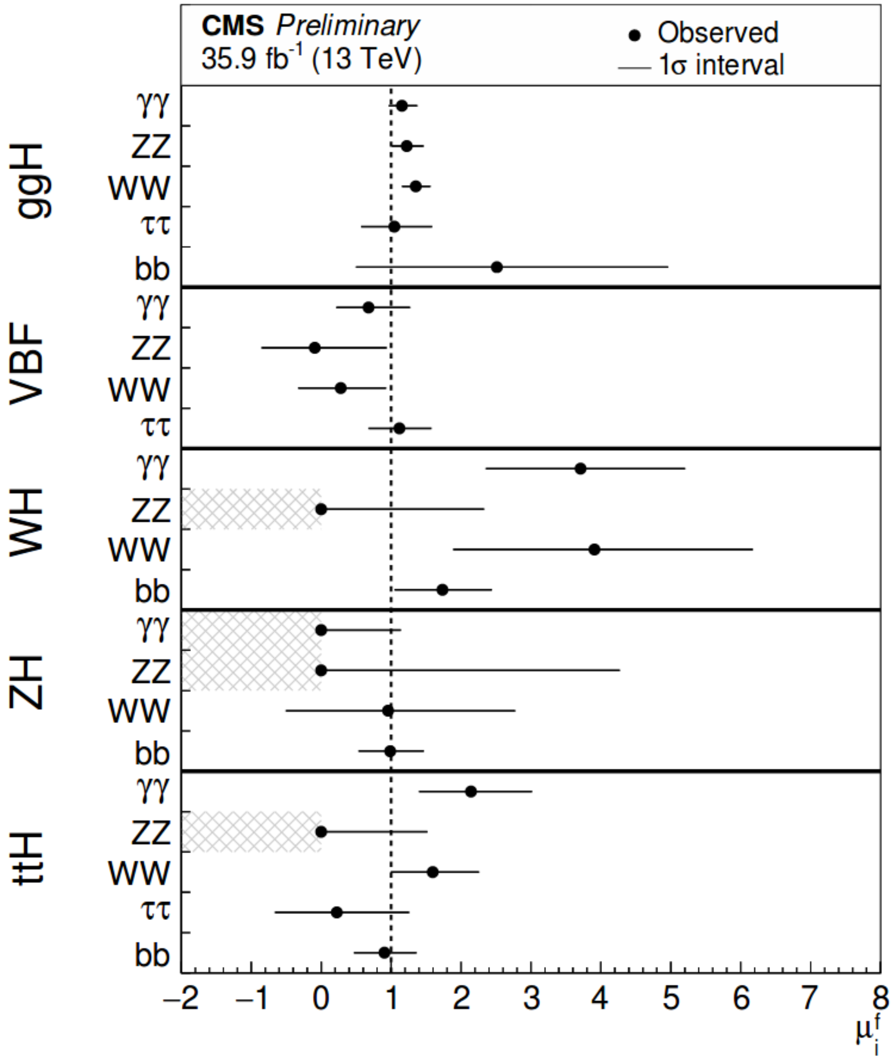
Effects on gluon Fusion

- Changing the sign of the bottom coupling changes the gluon fusion rate by about 12 percent !
- Assuming that no other effect is present, the LHC collaborations announce a precision of about 5 percent for the gluon coupling by the end of the LHC run. So, under this assumption this effect may be tested.





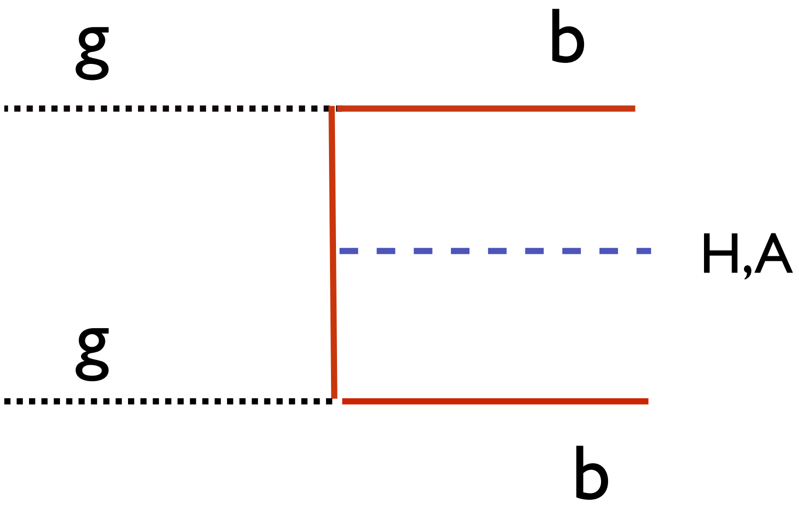
CMS Combination



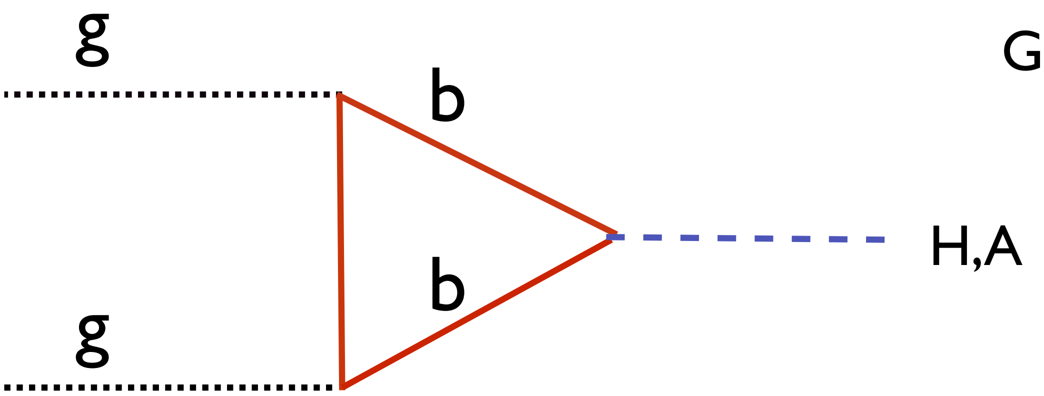
D. Sperka's talk, Moriond EW

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



Associated Production



Gluon Fusion

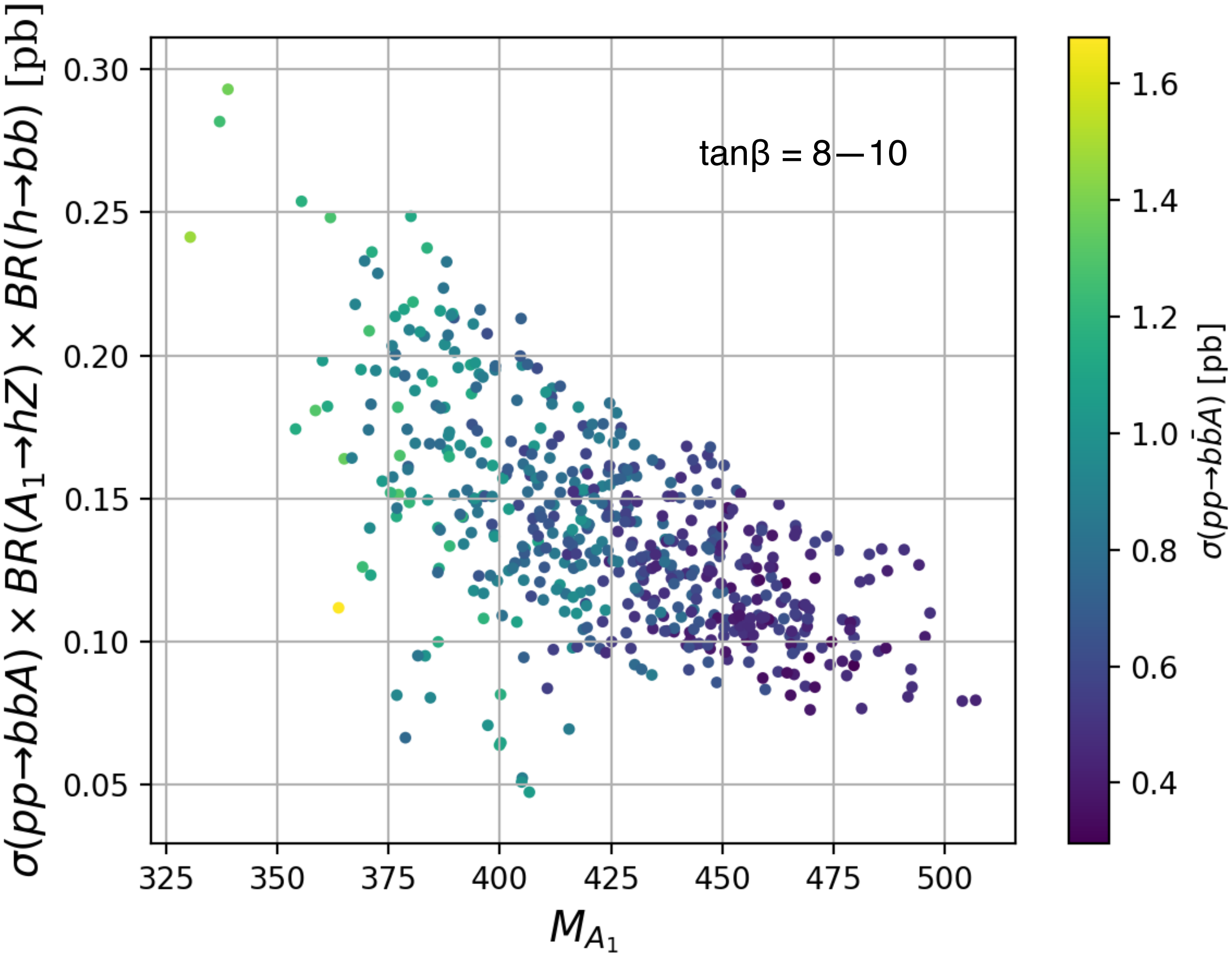
$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan\beta}{(1+\Delta_b)v}, \qquad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan\beta}{v}$$

B. Li, N. Coyle, C.W. ’18

More general Parameters : Superpotential Tadpole

One may reduce the mass gap with the charged Higgs, and due to the large misalignment, decays into Higgs and gauge bosons open up.

$$\delta W = \xi_F S$$



$$\cos(\beta-\alpha)\simeq 2/\tan\beta$$

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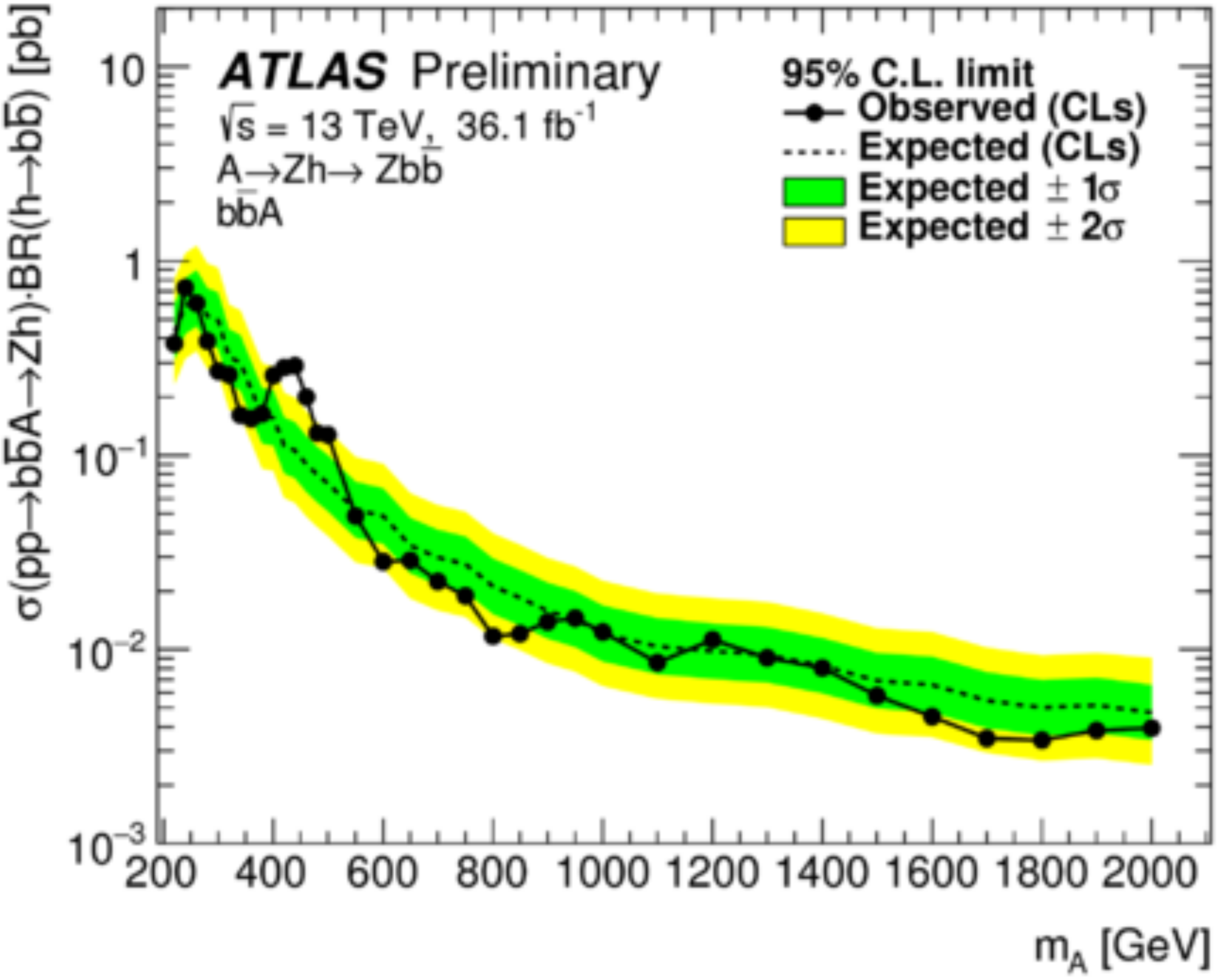
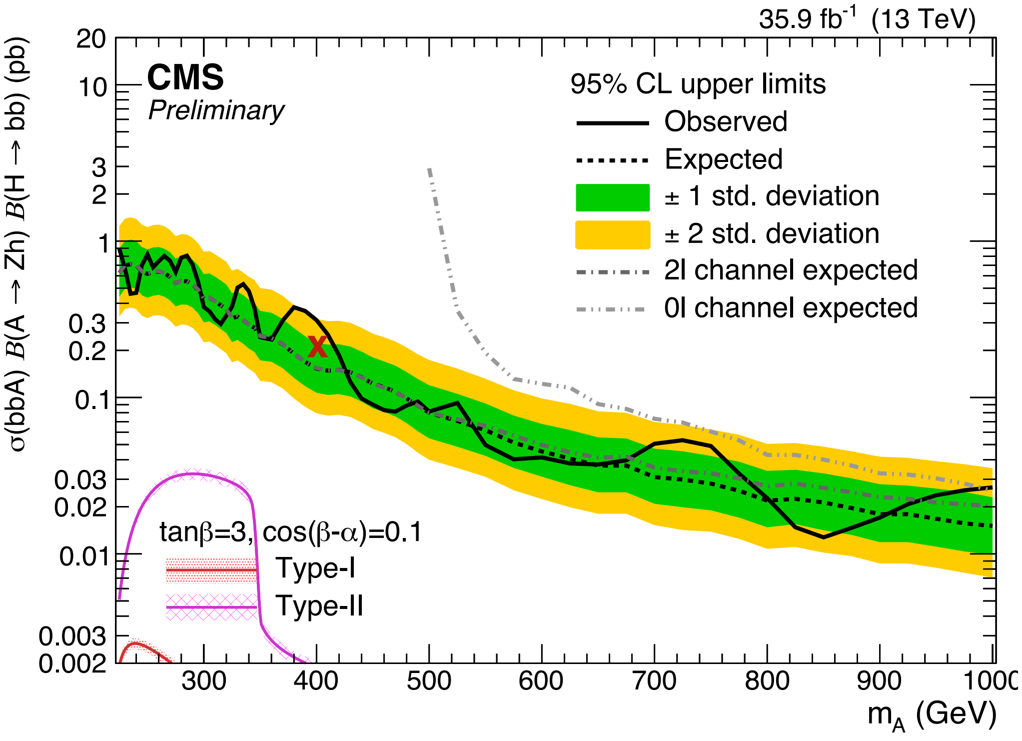
Consistent with ATLAS Excess

ATLAS-CONF-17-055

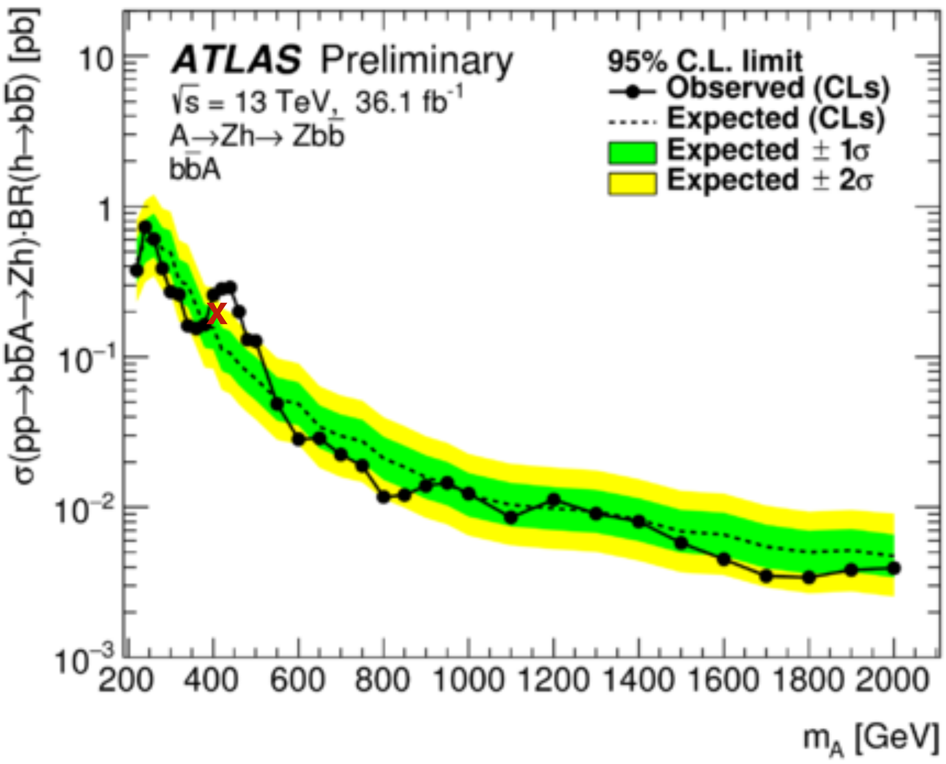


Recent CMS Analysis
Cross indicates a BM point

CMS-PAS-HIG-18-005
July 2018

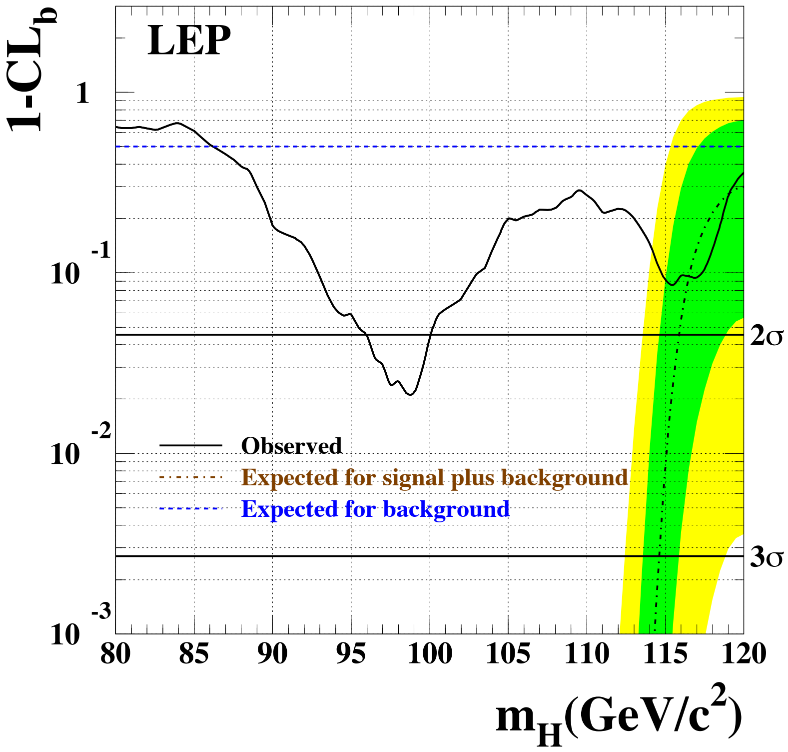


ATLAS-CONF-17-055

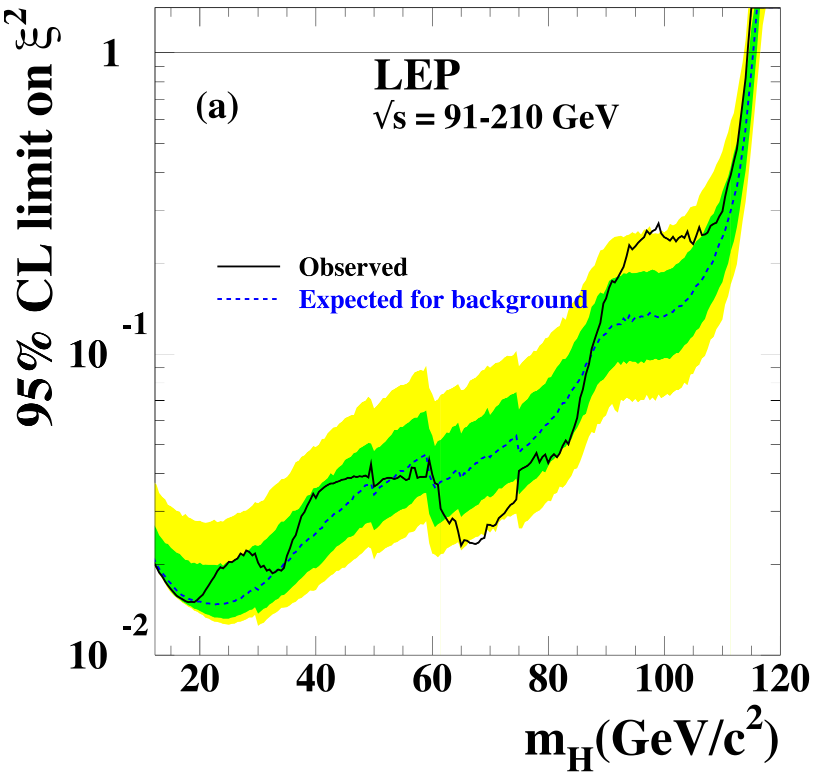


LEP2 Excess

LHWG-2003-011

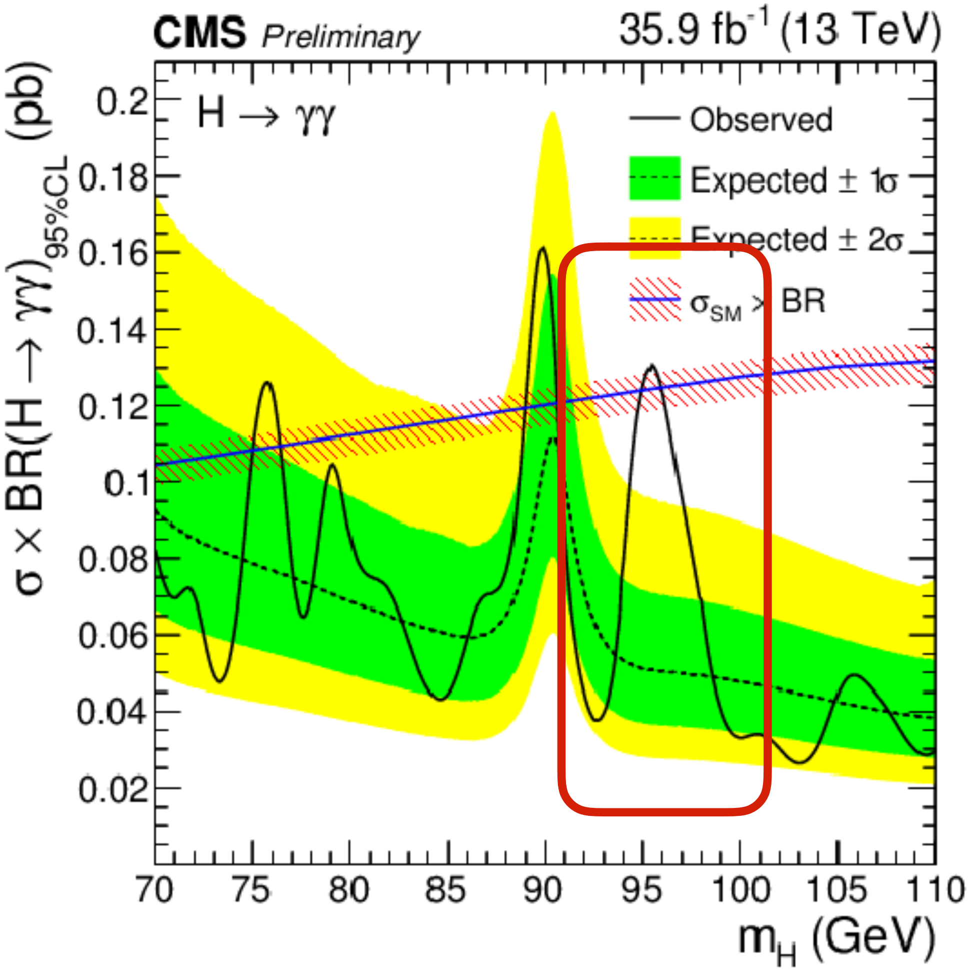


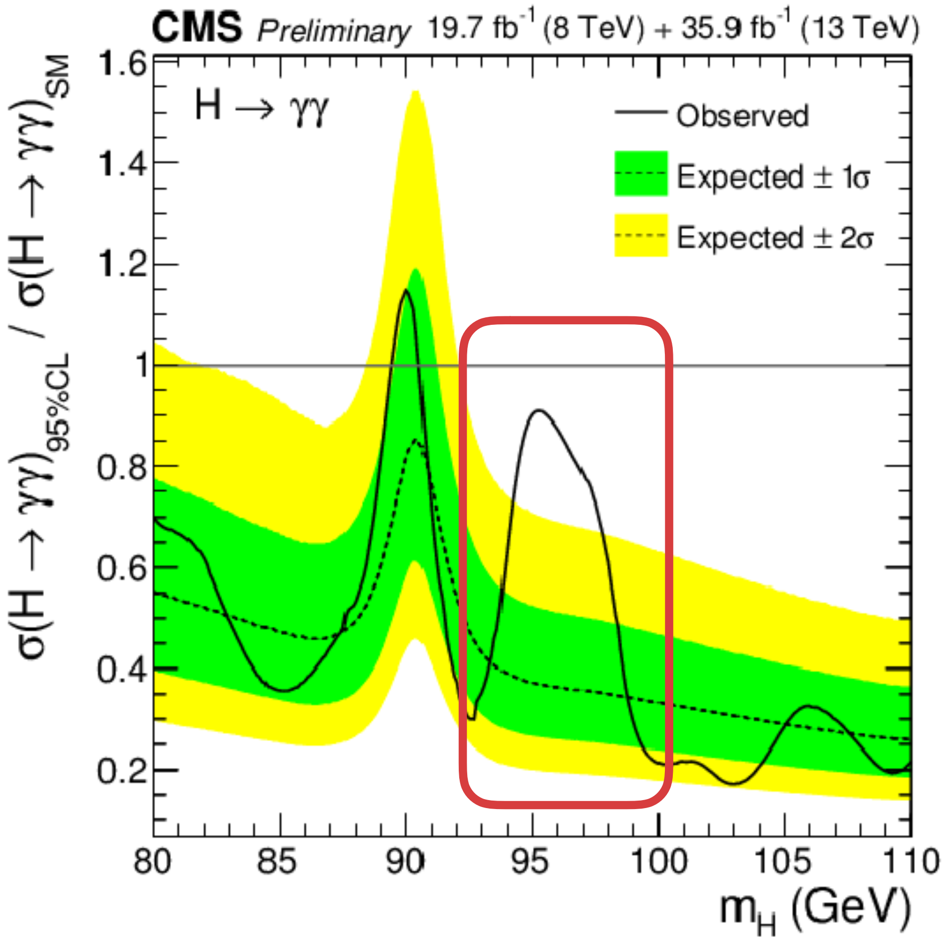
$$\xi^2 = g^2_{ZZh}/g^2_{ZZh_{SM}} \times \frac{\mathrm{BR}(s \to b\bar{b})}{\mathrm{BR}(h^{\mathrm{SM}} \to b\bar{b})}$$



See X. Wang’s Talk at PASCOS2018

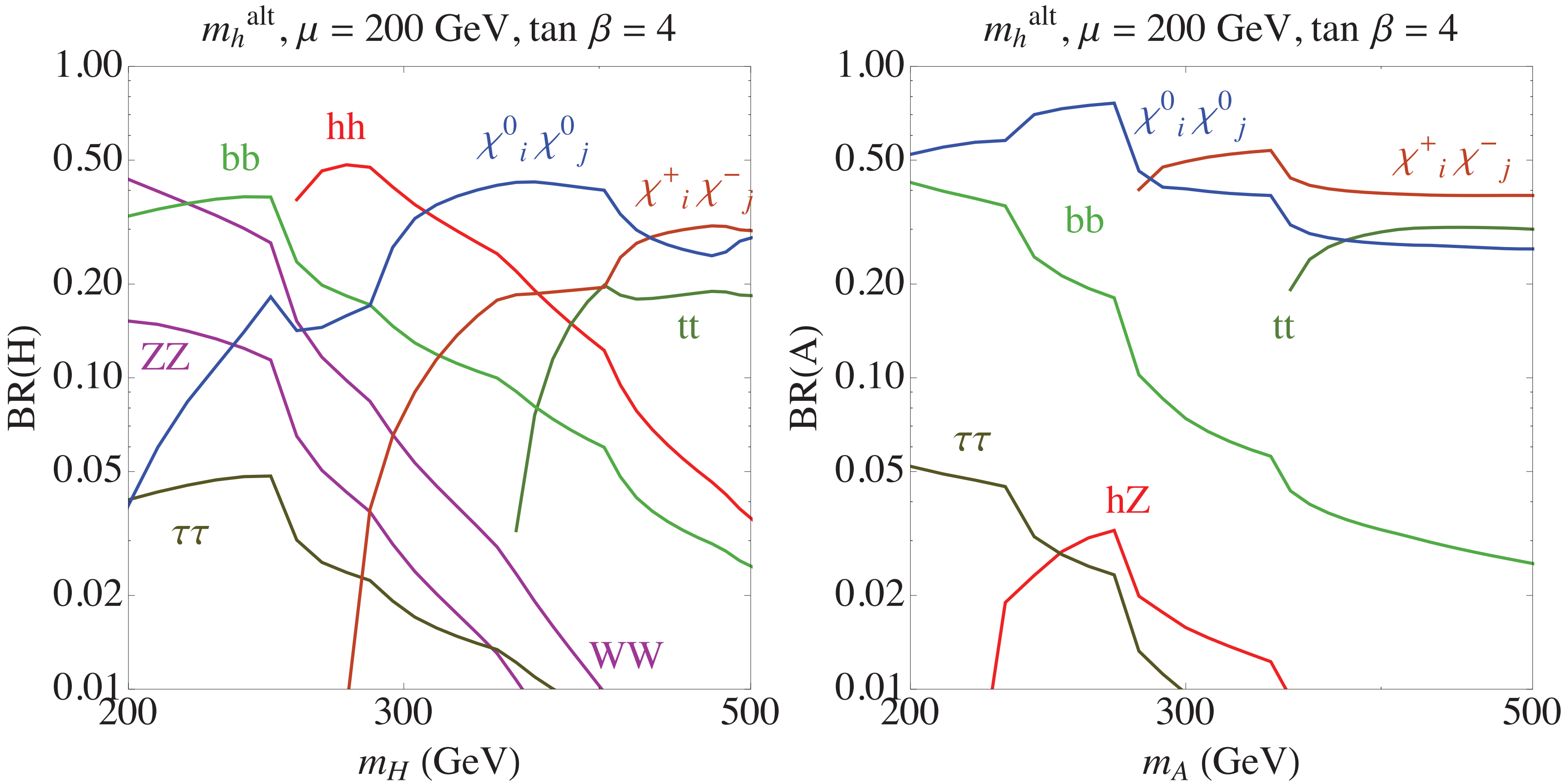
Related to CMS Excess ?





Light Charginos and Neutralinos can significantly modify M the CP-odd Higgs Decay Branching Ratios

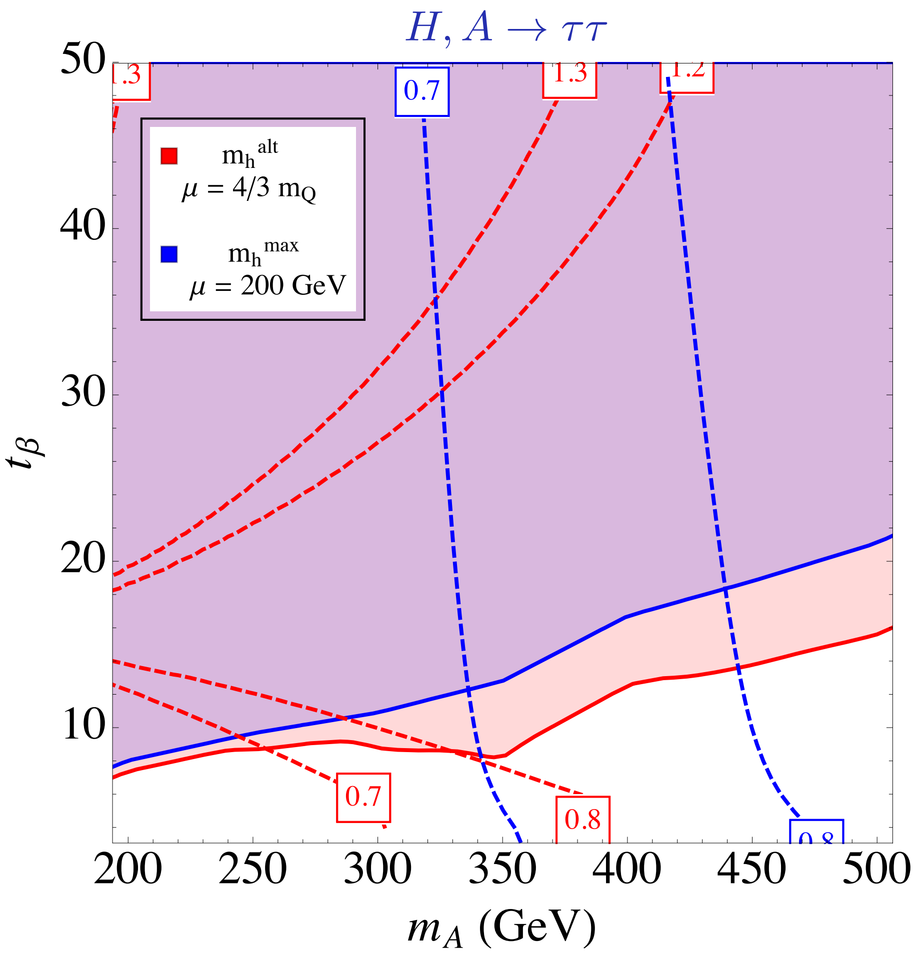
Carena, Haber, Low, Shah, C.W.'14



At small values of μ ($M_2 \simeq 200$ GeV here), chargino and neutralino decays prominent. Possibility constrained by direct searches.

Complementarity between precision measurements and search for new Higgs going to τ pairs

Carena, Haber, Low, Shah, C.W.'14



Limits coming from measurements of h couplings become weaker for larger values of μ

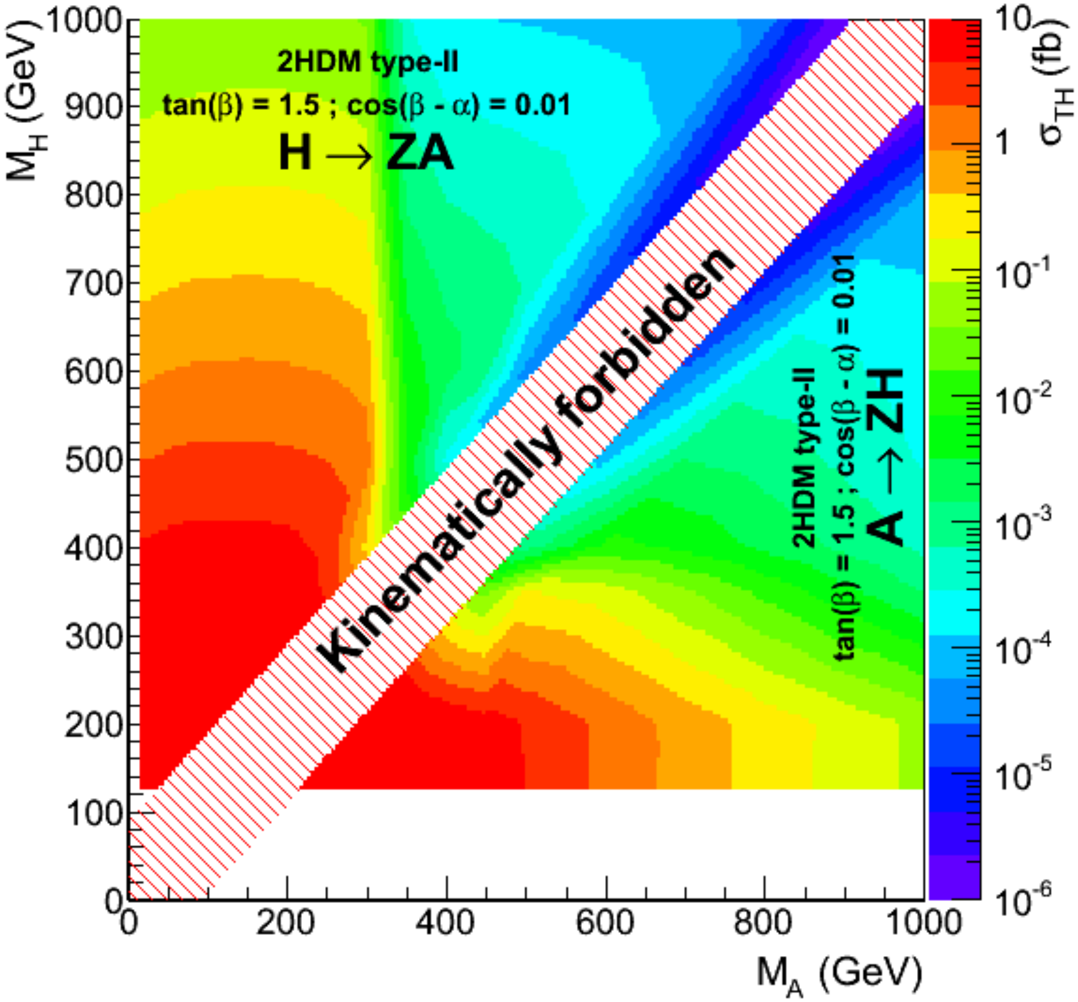
Limits coming from direct searches of $H, A \to \tau\tau$ become stronger for larger values of μ

Bounds on m_A are therefore dependent on the scenario and at present become weaker for larger μ

With a modest improvement of direct search limit one would be able to close the wedge, below top pair decay threshold

Search for (psudo-)scalars decaying into lighter ones

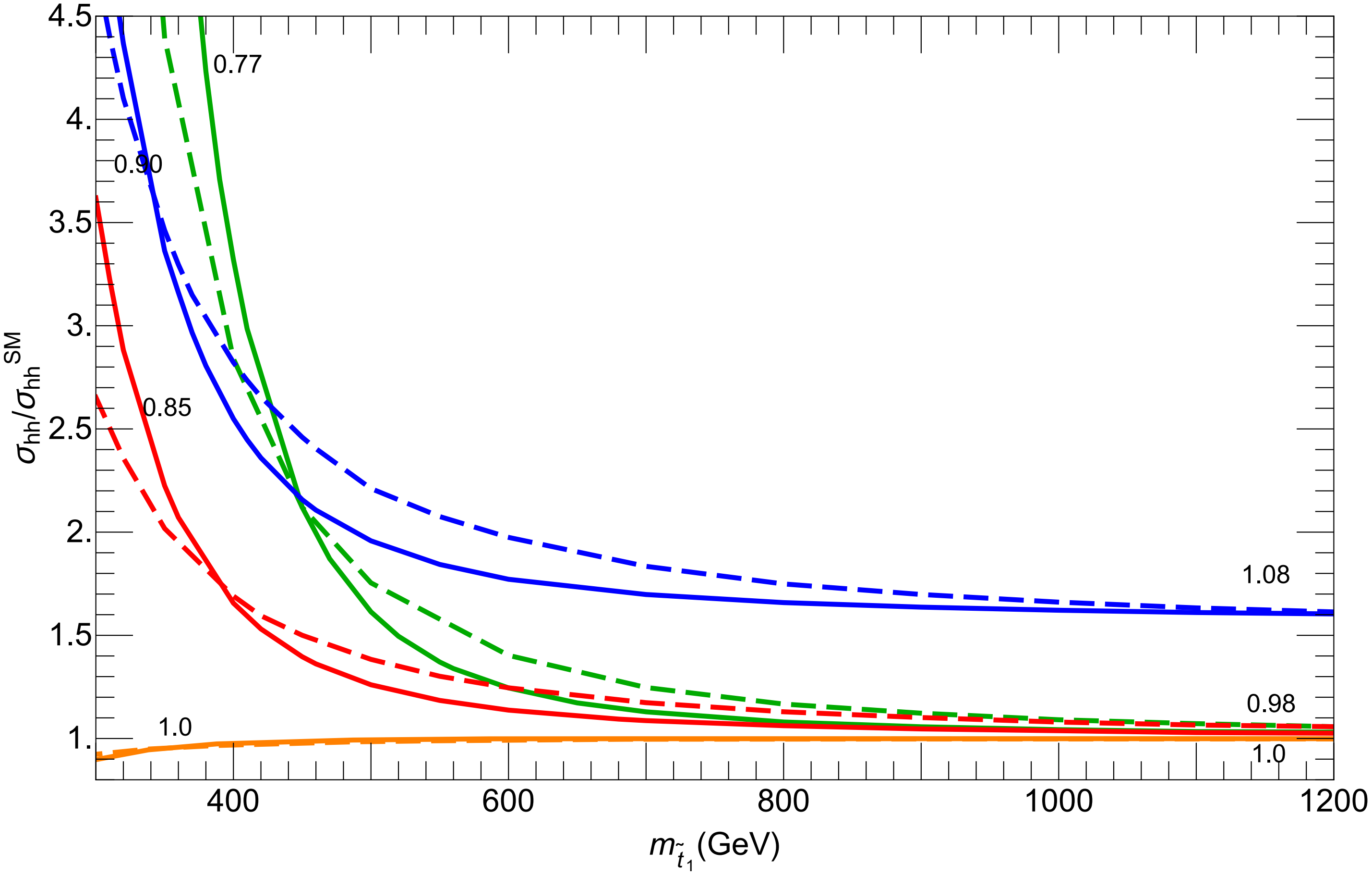
CMS-PAS-HIG-15-001



It is relevant to perform similar analyses replacing the Z by a SM Higgs !

Stop Effects on Di-Higgs Production Cross Section

Huang, Joglekar, Li, C.W.'17



Orange : Stop corrections to kappa_g decoupled

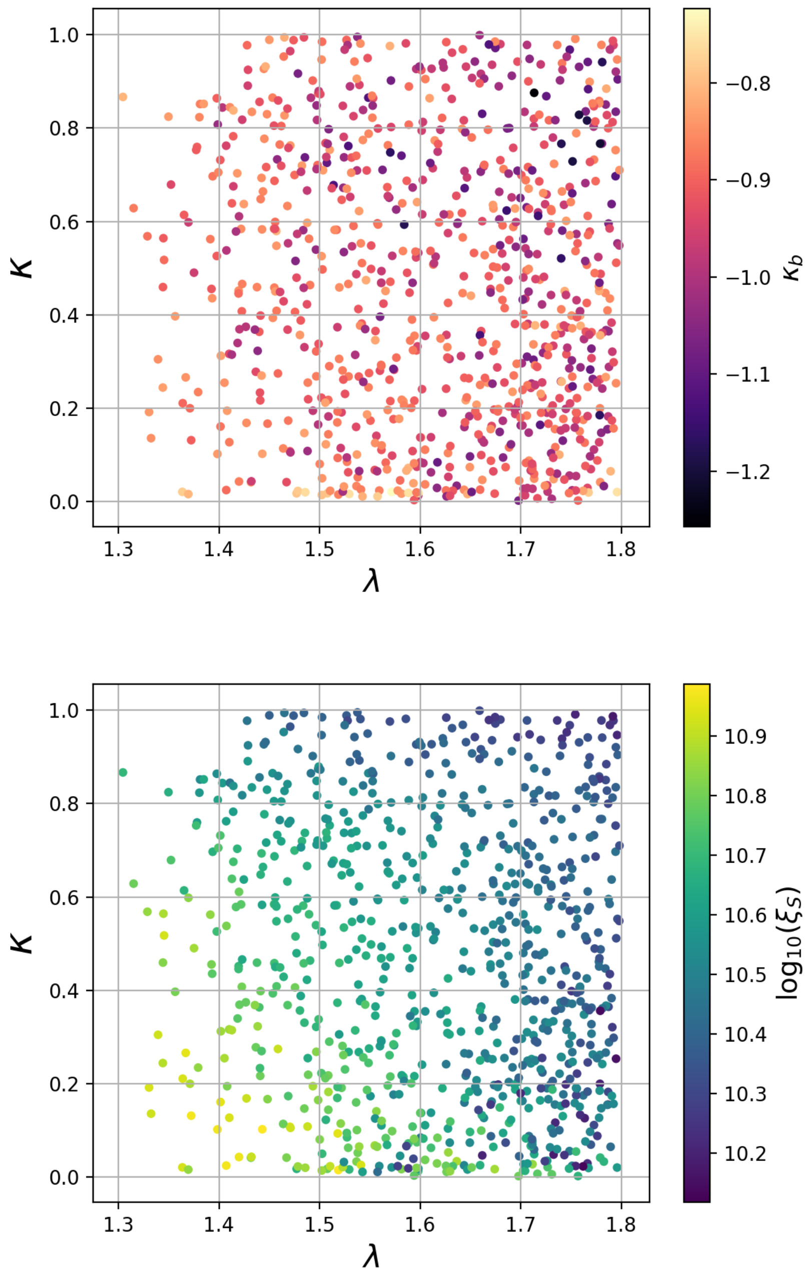
Red : X_t fixed at color breaking vacuum boundary value, for light mA

Green : X_t fixed at color breaking boundary value, for mA = 1.5 TeV

Blue : Same as Red, but considering \kappa_t = 1.1

Values of the dimensionless couplings

B. Li, N. Coyle, C.W. '18



Necessary values to invert the bottom coupling

$\delta W = \xi_F S$

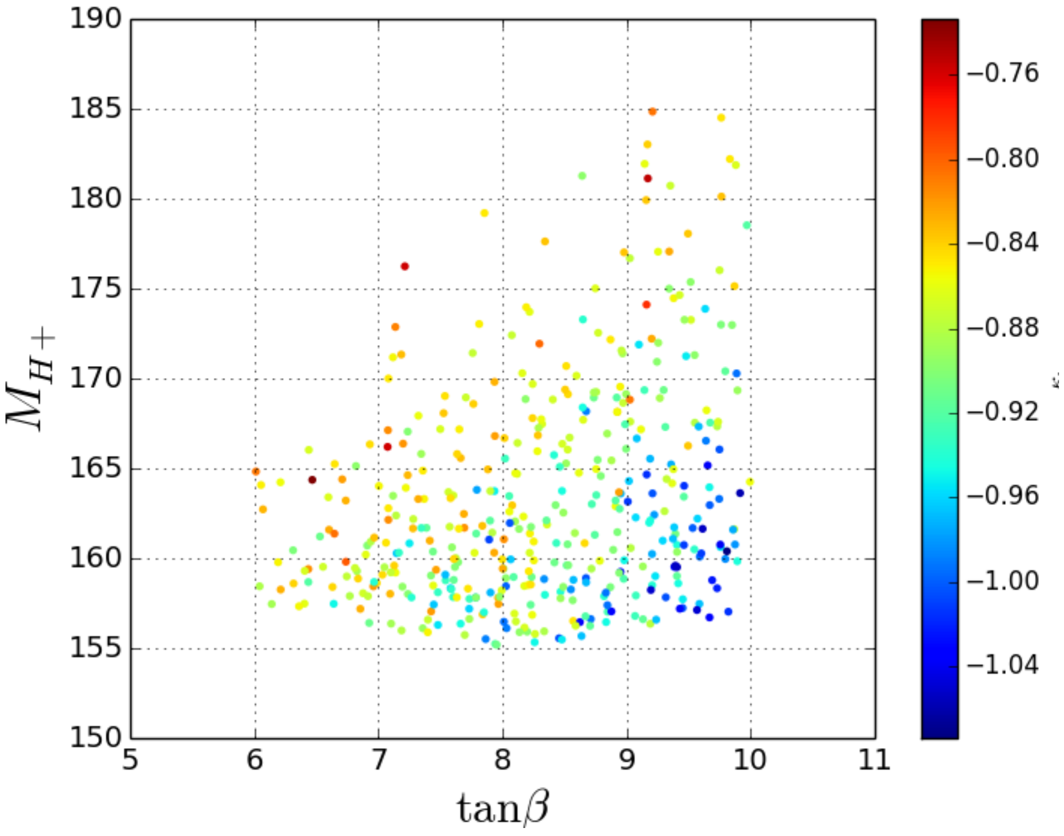
B. Li, N. Coyle, C.W. '18

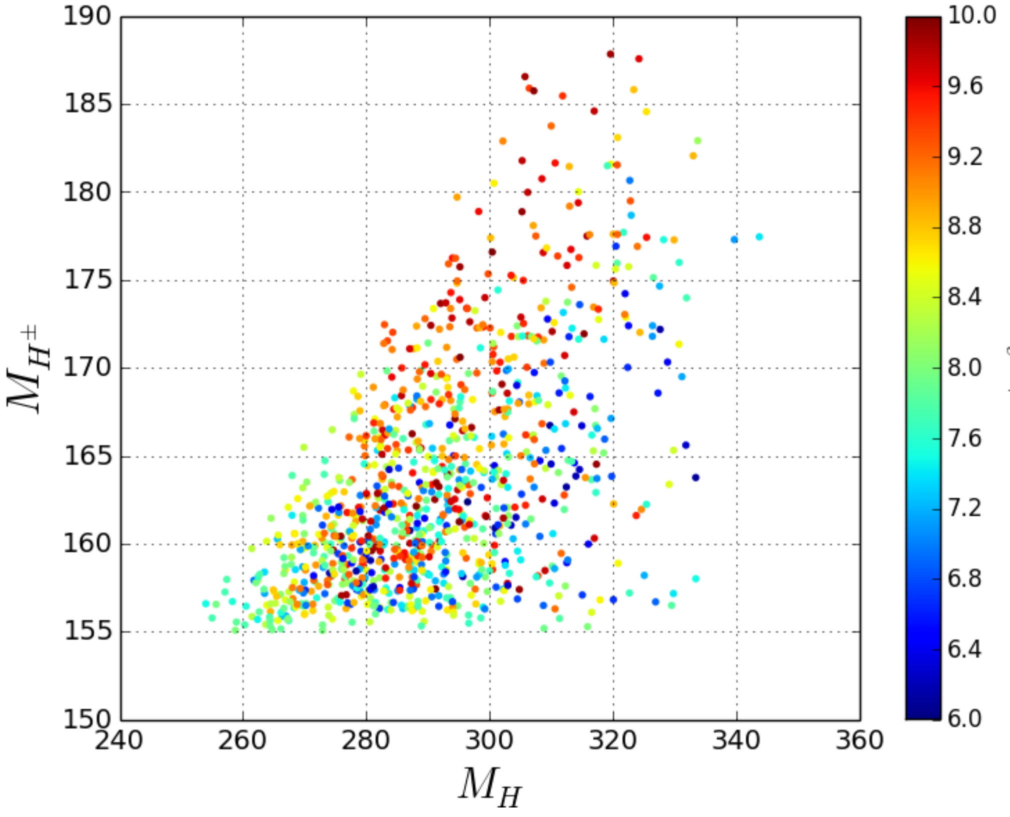
Low charged Higgs masses

Part of the reason for large value of λ is the relation between the CP-odd and charged Higgs masses in these theories, namely

$$m_{H^+}^2 \simeq m_A^2 - \lambda^2 v^2 \qquad v = 174\ GeV$$

Constraints on Charged Higgs Mass coming from $t \to bH^+$ considered





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Novelty : Decay into charged Higgs Bosons

Large values of λ imply that the charged Higgs mass becomes significantly lower than the neutral MSSM-like Higgs masses.