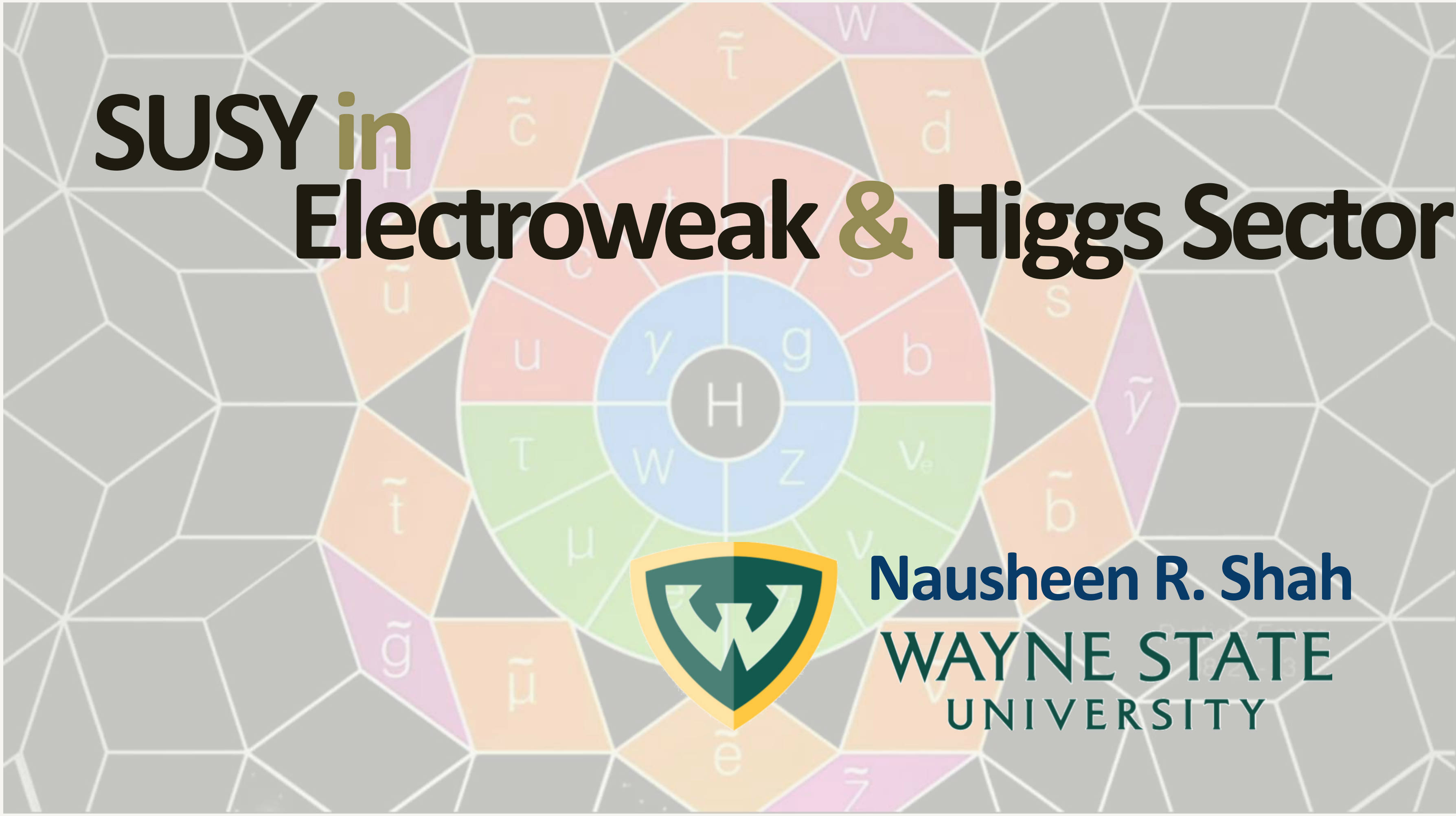
“Particle Fever” – The movie



# SUSY in Electroweak & Higgs Sector

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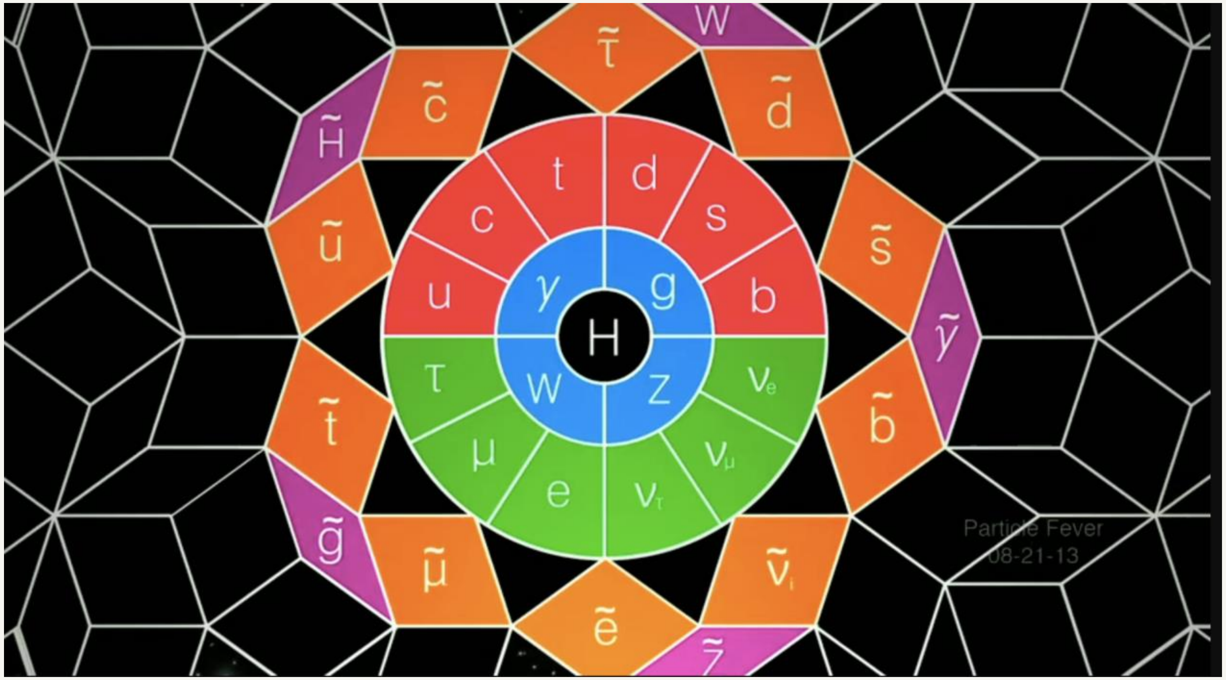
WAYNE STATE UNIVERSITY

## ATLAS/CMS Run 3 SUSY Workshop:

## New Directions for SUSY Searches with LHC Run 3 Data

Monday Nov 15, 2021

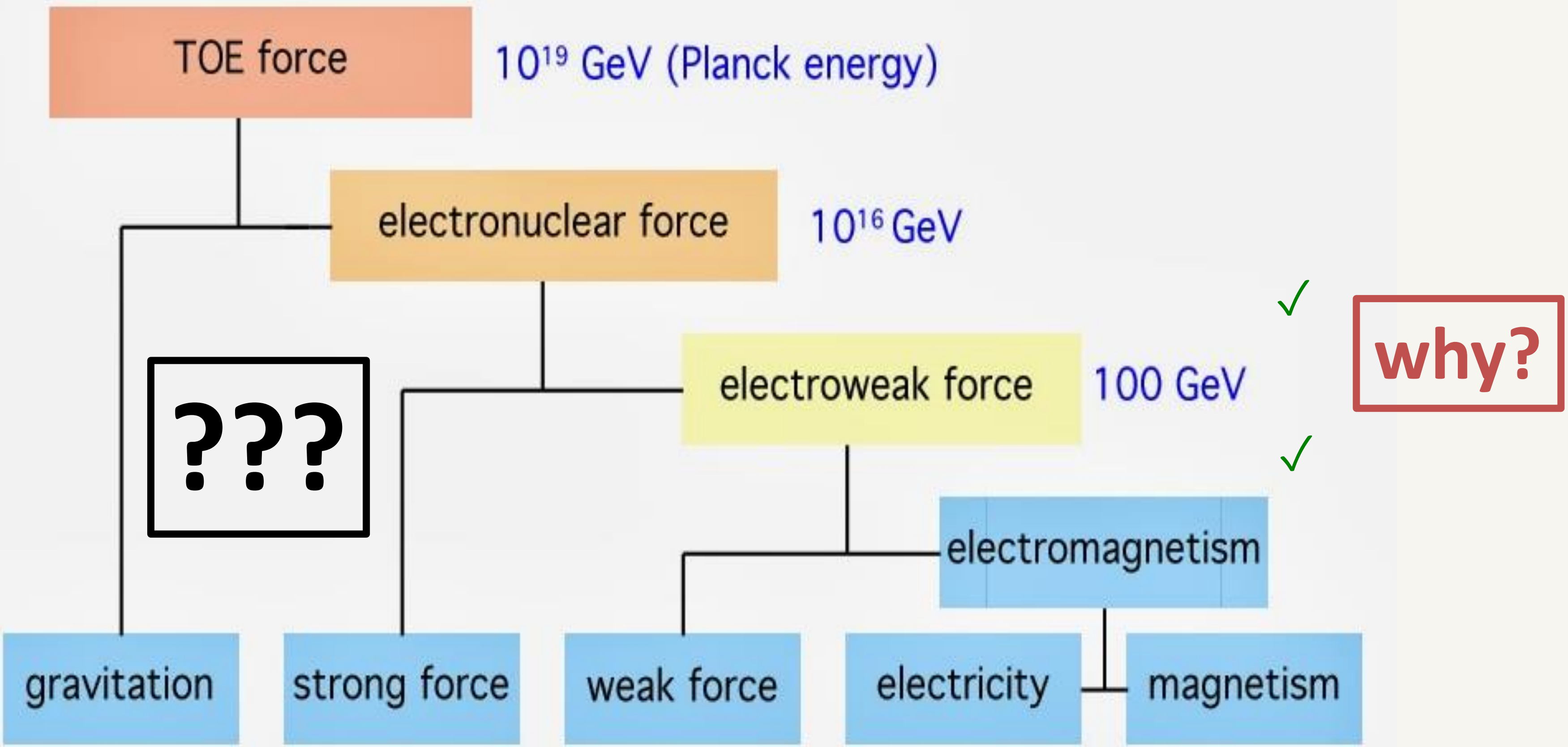
“Particle Fever” – The movie



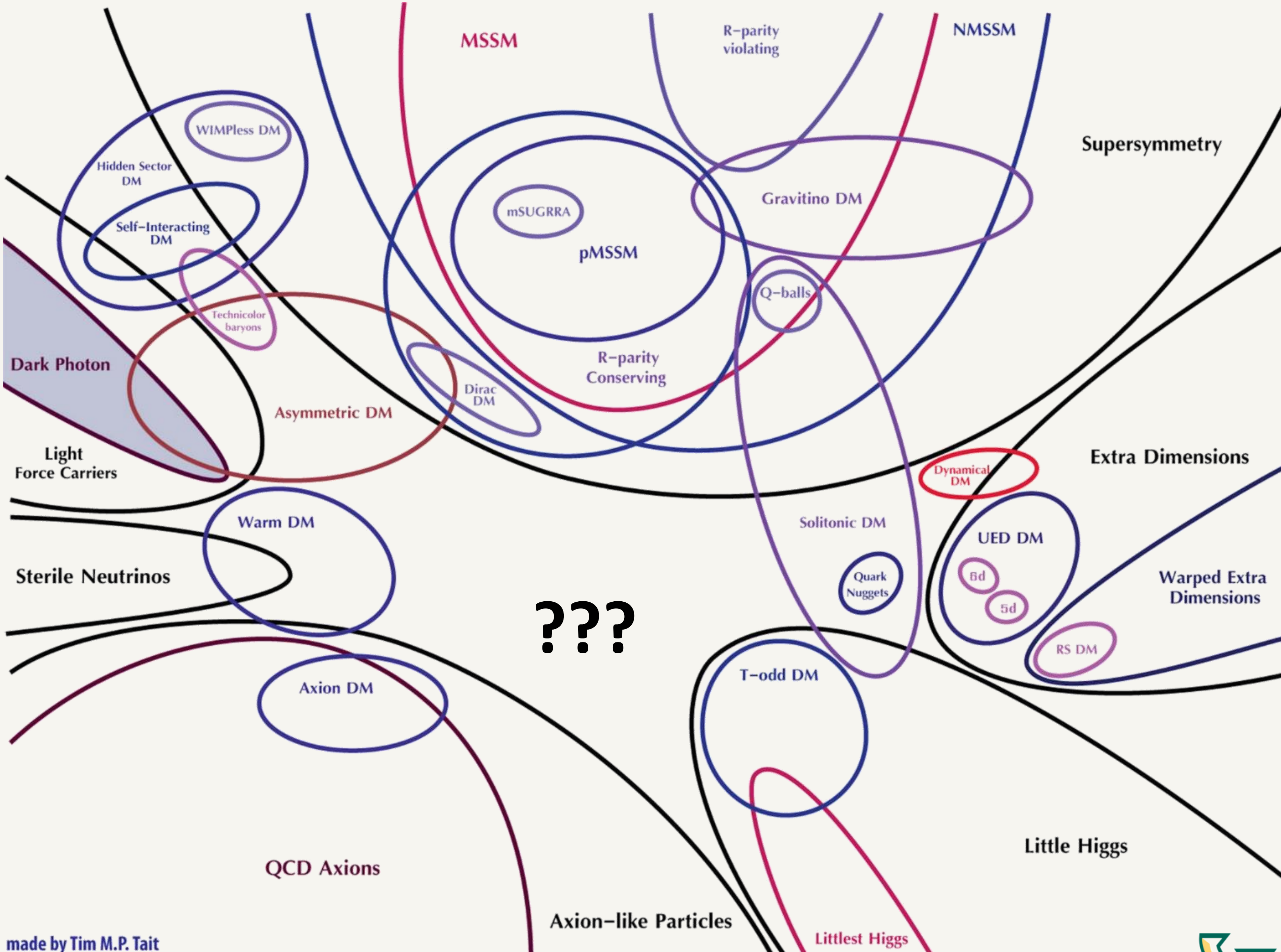

# NOTORIOUS

# SUPERSYMMETRY

# Big Picture



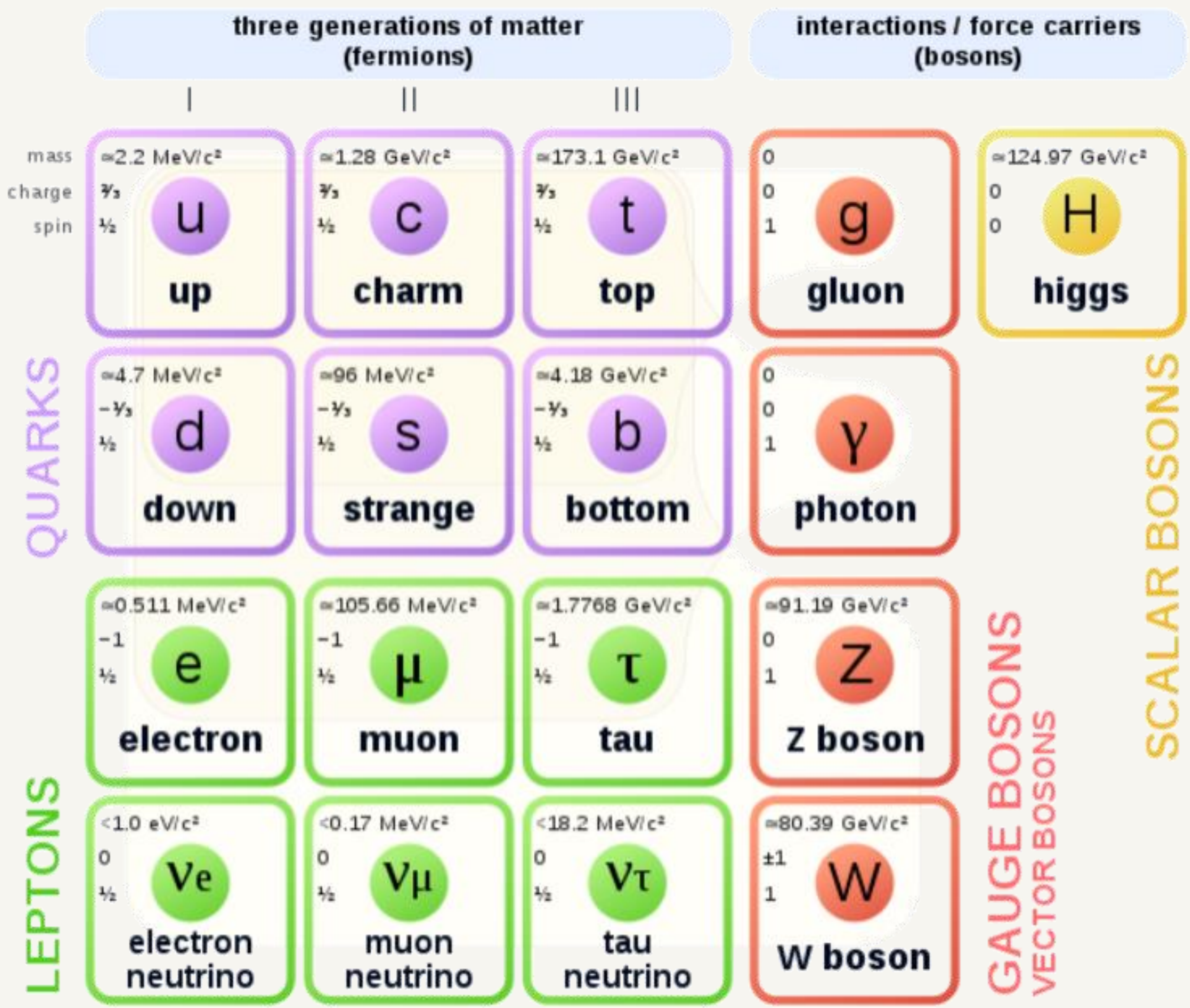

**What is Dark Matter?**


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRRA
pMSSM
Gravitino DM
Q-balls
Technicolor baryons
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
???
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
made by Tim M.P. Tait


https://www.pinterest.com/pin/304978206018018128/


https://www.pinterest.com/pin/334744184798019537/?d=t&mt=login

# The Beloved *Beautiful* (& Unnatural) Standard Model



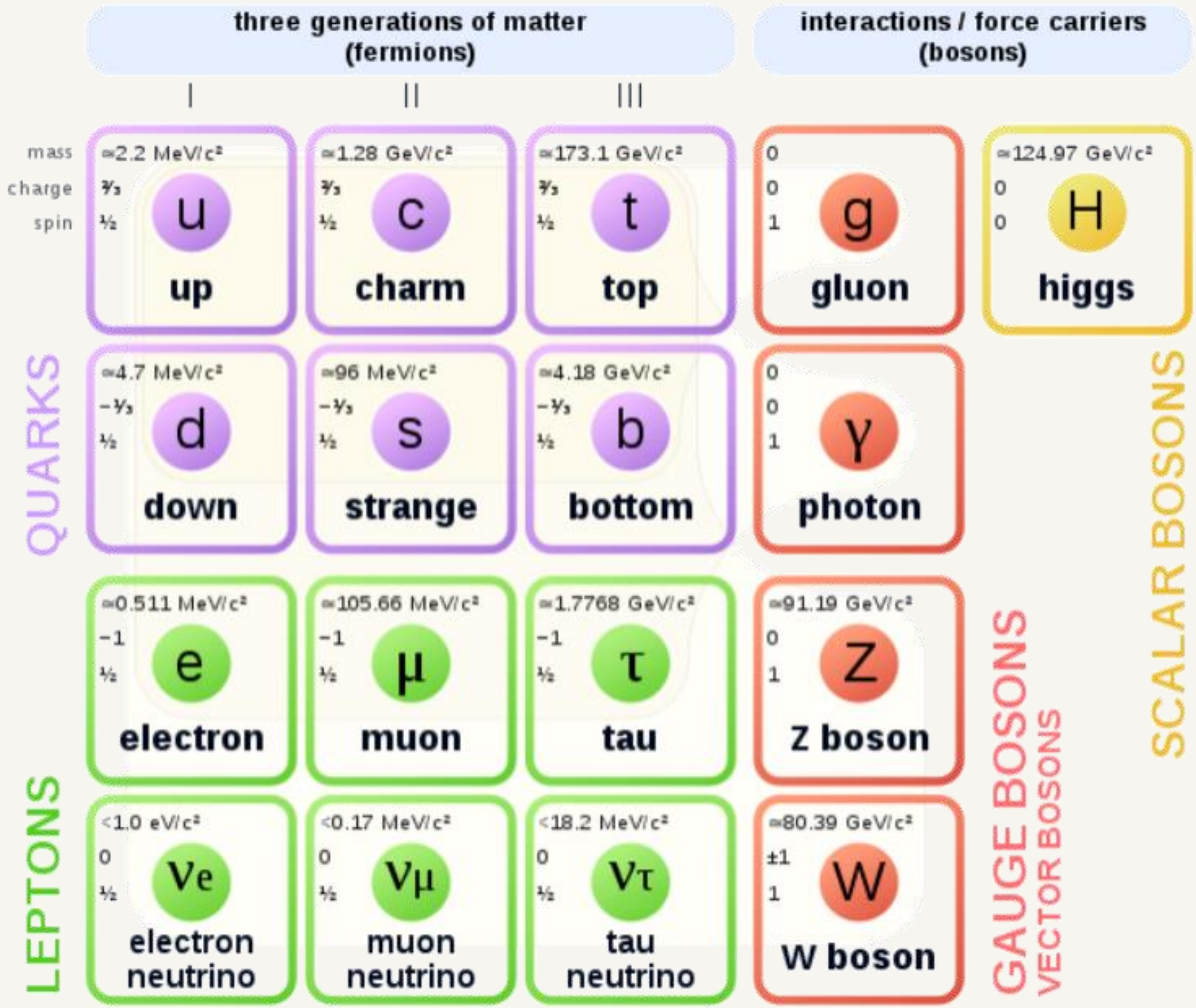

3 generations of matter
$SU(3)_C \times SU(2)_L \times U(1)_Y$

**WHY????**

https://en.wikipedia.org/wiki/Elementary_particle

# The Beloved *Beautiful* (& Unnatural)

## Standard Model




https://en.wikipedia.org/wiki/Elementary_particle

**No Dark Matter!**

**Non-Minimal**
**Unnatural**

Arbitrary Content
Arbitrary Masses
Arbitrary Mixings

**Arbitrary Higgs Mechanism**

# The Beloved *Beautiful* (& Unnatural)

## Standard Model

Only ***Left*** handed fermions charged under the weak SM gauge group.

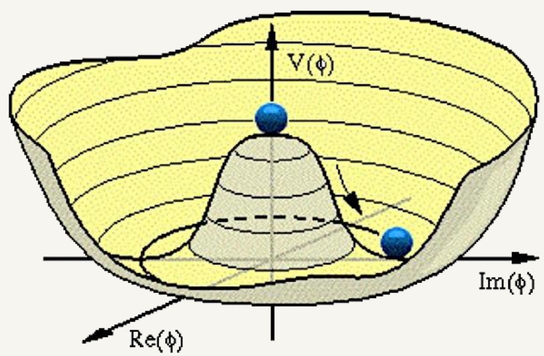
Fermion and gauge boson masses **FORBIDDEN** by symmetry.

# Whatever gives rise to fundamental particle masses has to break electroweak symmetry (EWSB).

## The Higgs Mechanism.

Spontaneous Breakdown of the symmetry:
$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

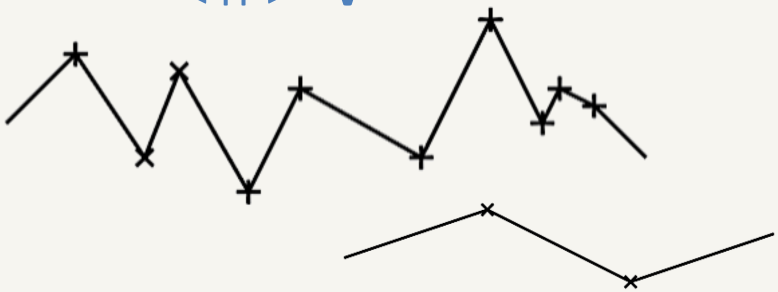
A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy.




$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

Vacuum becomes source of energy
= a source of mass

$\langle H^0 \rangle = v$

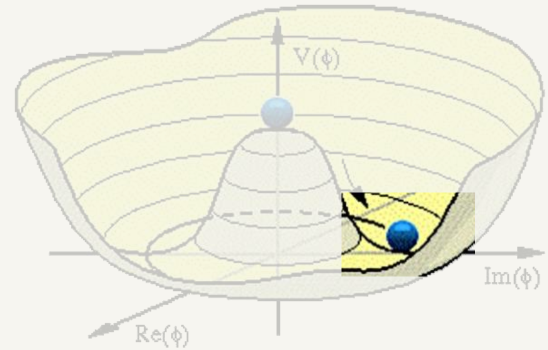


Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$M_{Z,W} = g_{Z,W}\, v$ $m_t = h_t\, v$ $m_h^2 = \lambda\, v^2$

**v = 246 GeV**

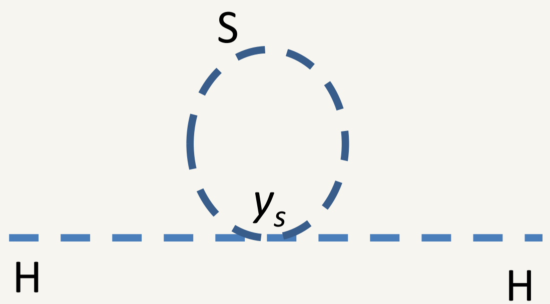
$$V(H) = m_H^2 H^\dagger H + \frac{\lambda}{2}\left(H^\dagger H\right)^2$$




$$\langle H^\dagger H \rangle = -\frac{m_H^2}{\lambda}$$

Only know location of minimum (vev)
Only know local curvature (mass)

$$Higgs\ MASS^2 = -4\, mH^2$$




NEGATIVE mass parameter ($m_H^2$).

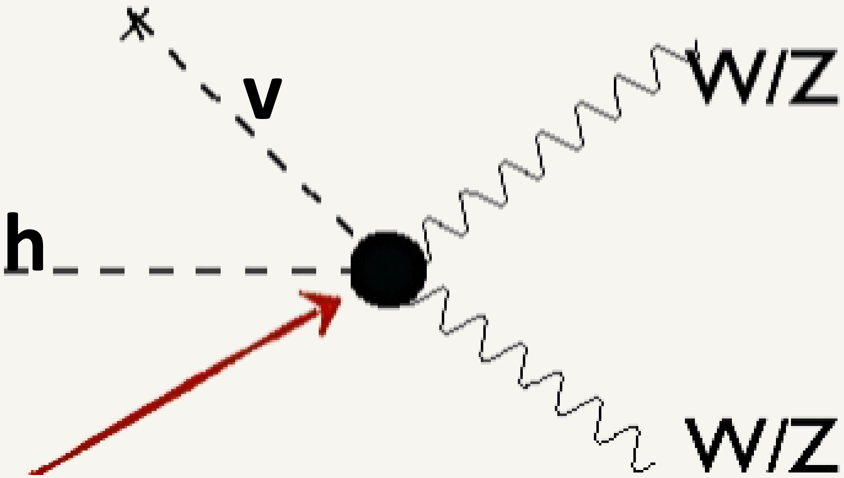
NO additional symmetry if Higgs massless.

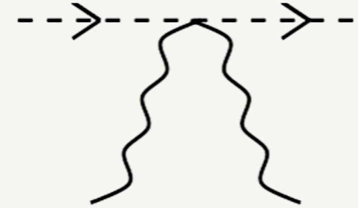
NOTHING protects Higgs Mass: UNSTABLE under quantum corrections!!

# Is it THE Higgs?

## How do scalars interact with gauge bosons?

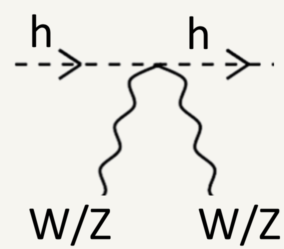
$$|D_\mu \phi|^2 = (\partial_\mu \phi + ieA_\mu \phi)(\partial^\mu \phi^* - ieA^\mu \phi^*)$$

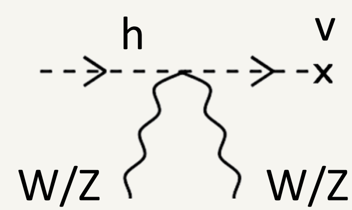


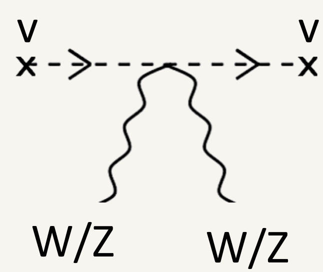



$$e^2 A^2 |\phi|^2$$

$$\phi \to h + v$$



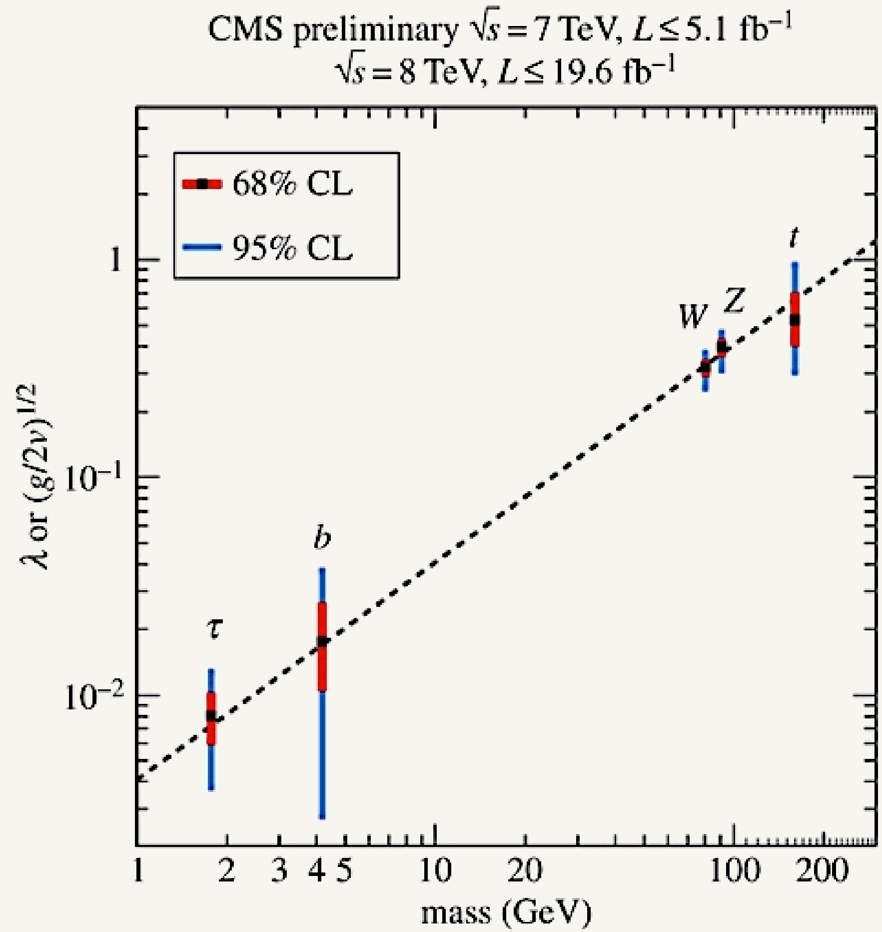

**We have seen that the Higgs couples to W/Z, with approximately the right strength!!**

# SM-Like Higgs!

**Higgs generates masses of the SM particles!**

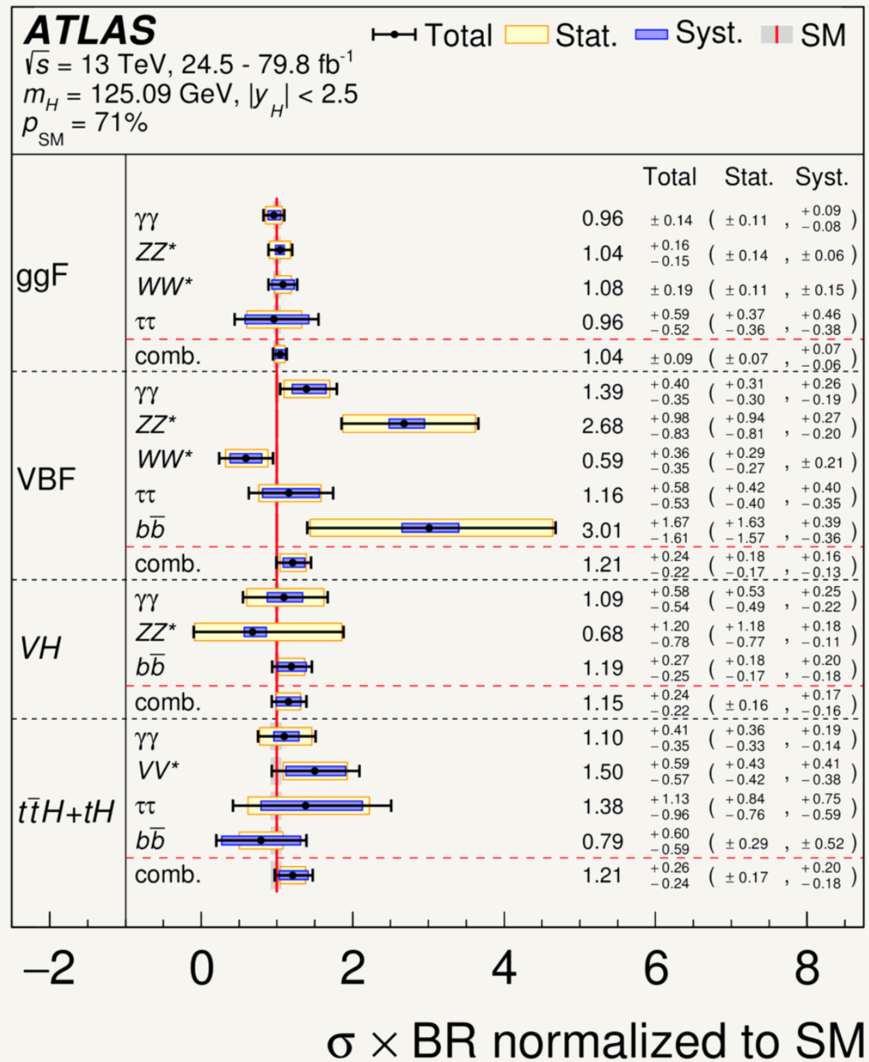
*P. Higgs:*

*"My first paper was rejected because it was not relevant for phenomenology"*



# Still large uncertainties in couplings…
# but compatible with SM expectations.

*Observed Higgs Production x Branching Ratios as a ratio to SM expectation*



# SUSY and the Higgs.

# SM Higgs is a **Doublet**

- The Higgs *FIELD* is a two component weakly charged doublet.
- $h$ is the neutral particle we think we have observed at the LHC: $h_{125}$
- $v$ is the SM vev: 174 GeV.
- $G^{+/-}$ and $G^0$ are "eaten" by the $W$ and $Z$ gauge bosons to give them mass.

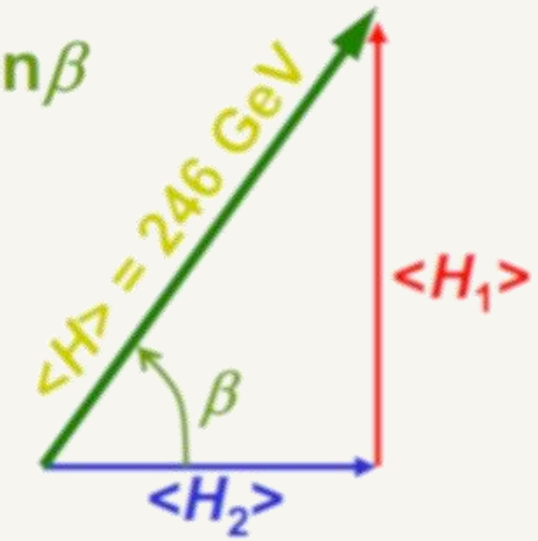
$$H_{SM} = \begin{bmatrix} G^{\pm} \\ \frac{1}{\sqrt{2}}(h + iG^0) + v \end{bmatrix}$$

But SUSY has MORE!!

**But we SEE a SM-like Higgs!**

# 2 Higgs Doublet Model (2HDM).

$\langle H_1 \rangle , \langle H_2 \rangle \rightarrow \langle H \rangle , \tan\beta$




**In SUSY Need 2 Higgs doublets:**

**$H_u$** –Couples only to up-type quarks

**$H_d$** –Couples only to down-type quarks and leptons.

- **$m_A \sim m_H$**
- **$\tan\beta = v_u / v_d$**

5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

Charged Higgs: **$H^{+,-}$**

246 GeV

$\langle H \rangle$

$\langle h \rangle \sim \langle H_{SM} \rangle$

$v \sin^2 \beta$

$$H_{SM} = \sin\beta H_u + \cos\beta H_d$$
$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

$v \cos^2 \beta$

## SM: Only 1 Higgs which then acquires a vev and leads to EWSB.

**This is what we want!**

## Lighter (*h*) is 125 GeV SM-like Higgs.

## Additional states can exist!

**Additional States can be light!**

***Haber and Gunion, '03,*** *M. Carena, I. Low, N.R.S. & C. Wagner, '13, A. Delgado, G. Nardini & M. Quiros, '13, N. Craig, J. Galloway & S. Thomas,'13, P. Dev, A. Pilaftsis '14, M. Carena, H. Haber, I. Low, N.R.S. & C. Wagner '14 & '15 etc....*

$\langle H_d \rangle = v \cos\beta$

$\langle H_u \rangle = v \sin\beta$

$\Rightarrow \langle H_{SM} \rangle = v$

$\langle H_{NSM} \rangle = 0$

**SM-like HIGGS**

**ALIGNMENT**

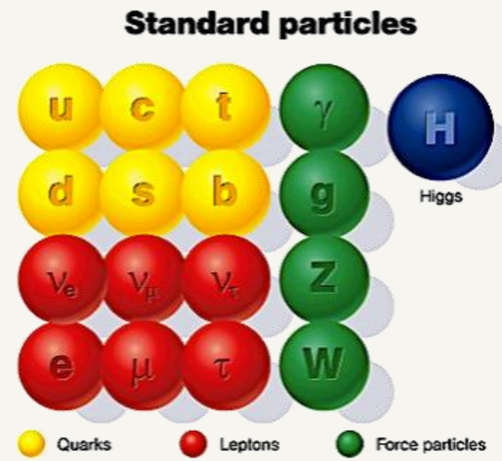
# Minimal Supersymmetric SM (MSSM).

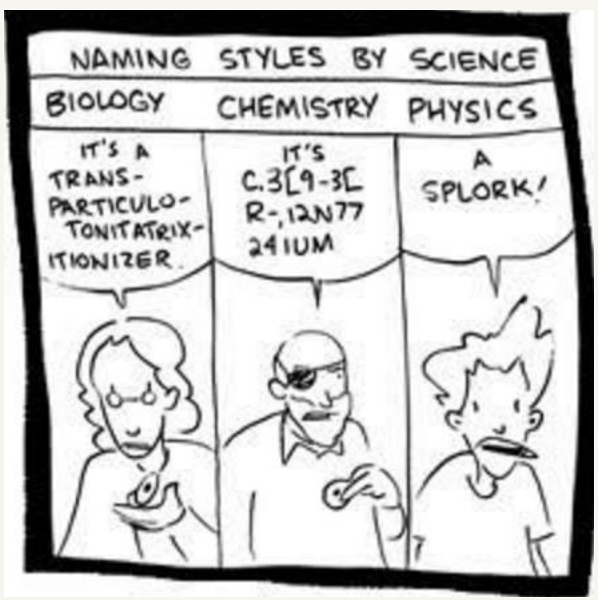
**For every fermion there is a boson of equal mass and couplings and visa versa.**

**'s'particles and 'inos** ☺

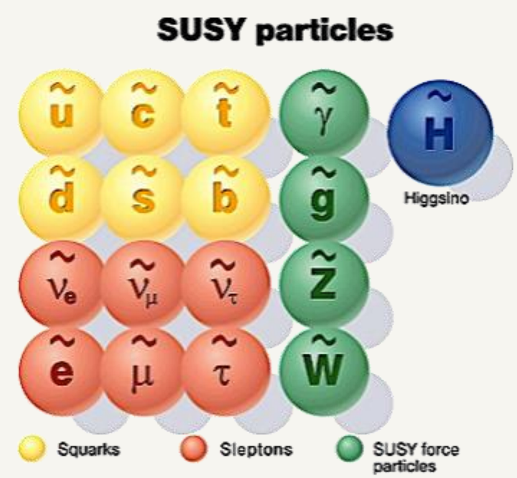
**No new couplings.**

**SUSY has to be broken.**



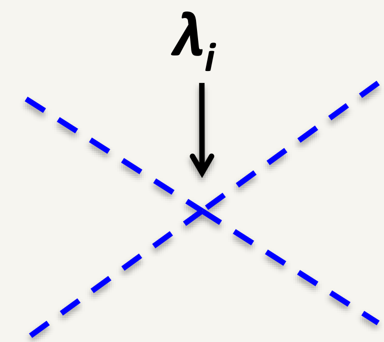

**Soft masses:**
Parametrize our Ignorance.



# Higgs Mass = 125 GeV.

$$V = m_{ij}^2 \Phi_i^\dagger \Phi_j + \lambda_i \Phi_j^\dagger \Phi_k \Phi_l^\dagger \Phi_m$$

*H. Haber and J. Gunion, '03*



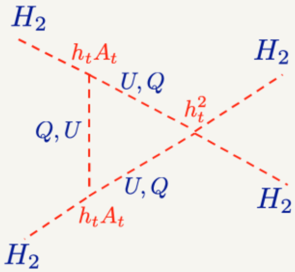

**Quartics without quantum corrections related only to SM couplings.**

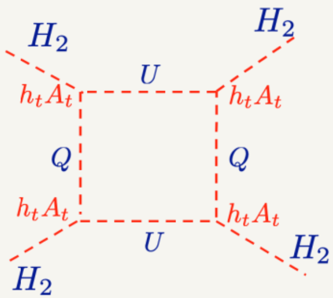
**Higgs mass bounded by $m_Z$ at tree-level.**

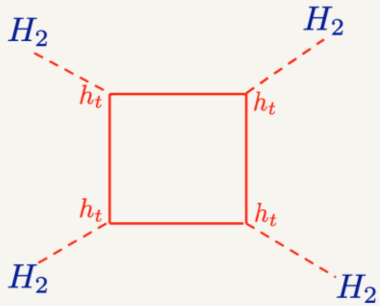
**91 ≠ 125**

**Need large radiative corrections.**

# Stop + top Quartic Contributions!




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

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

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

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

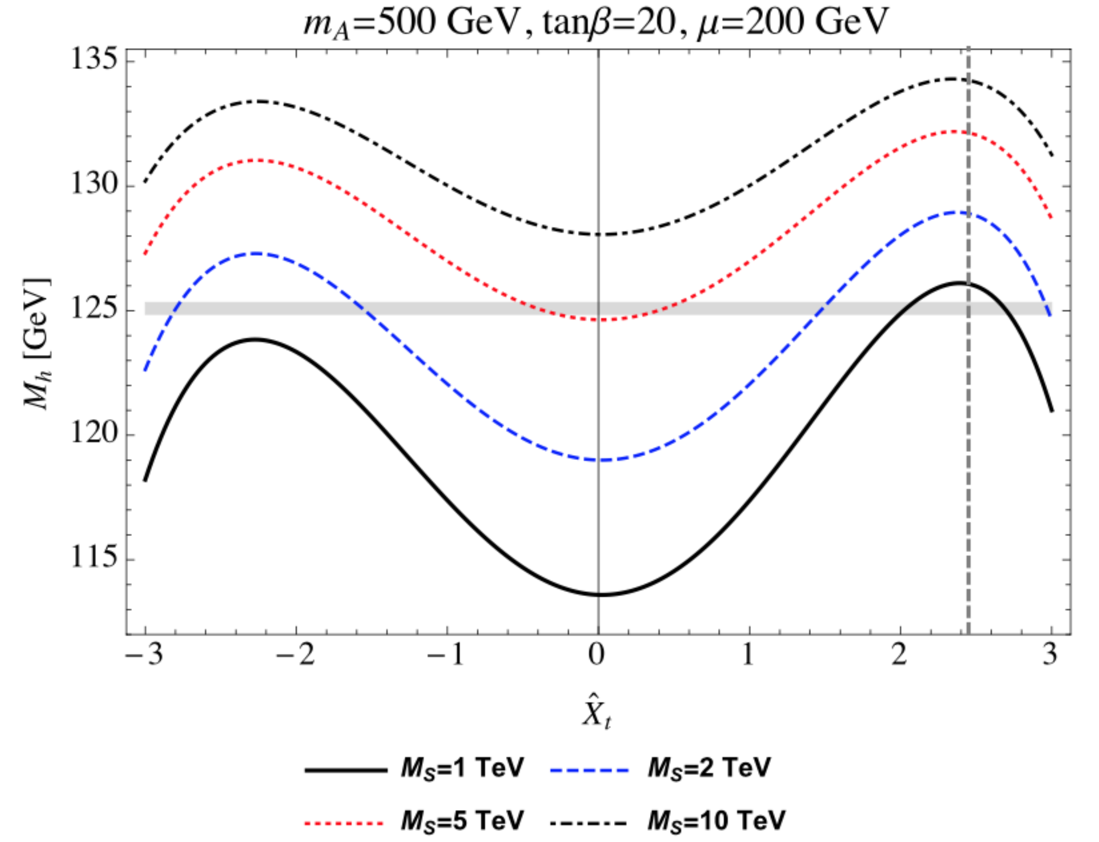
Carena, Espinosa, Quiros, Wagner, ’95,96

# Fine Tuned or Not??

Stop masses ~ few TeV

Lighter Stops demand large splitting between left- and right-handed stops.

G. Lee, C. Wagner, '15



# Alignment?

## $\cos(\beta-\alpha)=0$

$$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

Approximately for $t_\beta$ larger than a few, and $m_H > 200$ GeV:

$$\cos(\alpha-\beta) \simeq \frac{1}{\tan\beta\,(m_H^2 - m_h^2)}\left[m_h^2 + m_Z^2 + \frac{3m_t^4}{16\pi^2 v^2}\frac{\mu A_t}{m_Q^2}\left(1 - \frac{A_t^2}{6m_Q^2}\right)\tan\beta\right]$$

If $\mu A_t / m_Q^2$ small (-> decoupling):

- $\cos(\alpha-\beta)\, t_\beta \sim$ Const / $(m_H^2 - m_h^2)$

If $\mu A_t / m_Q^2$ relevant:

- Can have $\cos(\alpha-\beta) \sim 0$
- **INDEPENDENT OF $M_A$**

**Obtain**
**ALIGNMENT**
for small tan β

**⇒LARGE $A_t / m_Q$**
**⇒LARGE $\mu / m_Q$**

**Would make it difficult to test low $m_A$ and $t_\beta$ via Higgs coupling measurements**

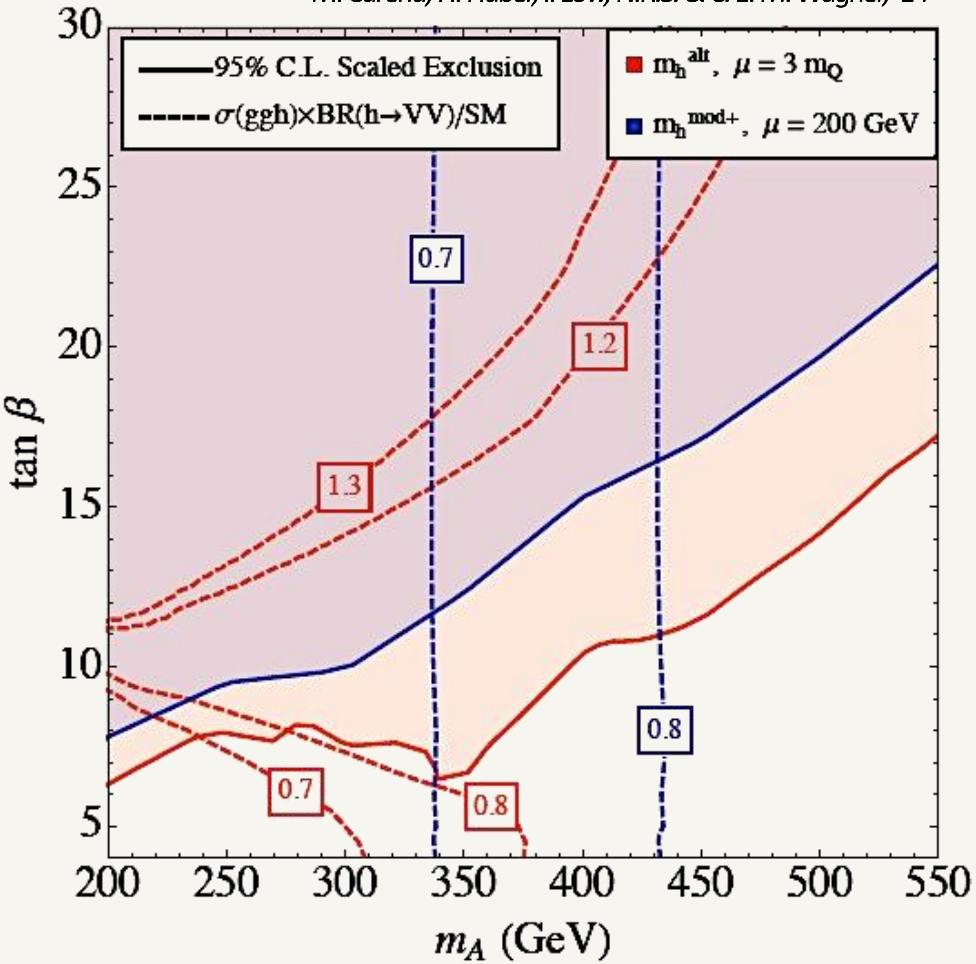
Relevant parameters for Higgs Sector: $A_t / m_Q$, $\mu / m_Q$, $m_A$, $t_\beta$
Only **Log** dependence on squark masses, $m_Q$ (relevant for $m_h$~125 GeV)

# Heavy Higgs Searches: A / H → τ τ
# Precision Higgs Physics: h → W W/Z Z

— $\sigma(bbH/A+ggH/A) \times BR(H/A \to \tau\tau)$ (8 TeV)

--- $\sigma(bbh+ggh) \times BR(h \to WW)/SM$

M. Carena, H. Haber, I. Low, N.R.S. & C. E. M. Wagner, '14




**No Alignment (Decoupling):**
H/A Direct searches Weaker
$h_{125}$ Precision measurements Stronger

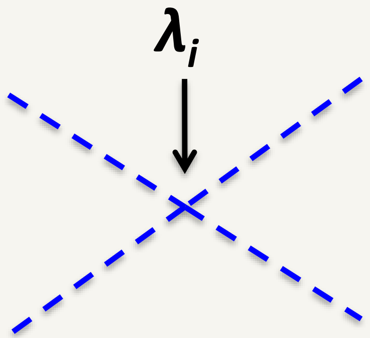
**Alignment w/o Decoupling:**
H/A Direct searches Stronger
$h_{125}$ Precision measurements Weaker

Complementarity for probing MSSM Higgs sector.

# Higgs Mass = 125 GeV.

$$V = m_{ij}^2 \Phi_i^\dagger \Phi_j + \lambda_i \Phi_j^\dagger \Phi_k \Phi_l^\dagger \Phi_m$$

*H. Haber and J. Gunion, '03*




**Quartics without quantum corrections related only to SM couplings.**

**Higgs mass bounded by $m_Z$ at tree-level.**

**91 ≠ 125**

**Need large radiative corrections.**
**…Or something else?**

# Something else: NMSSM Higgs Sector

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$-\mathcal{L}_{\text{soft}} = \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3$$

$A_\lambda$ ↔ $m_A$

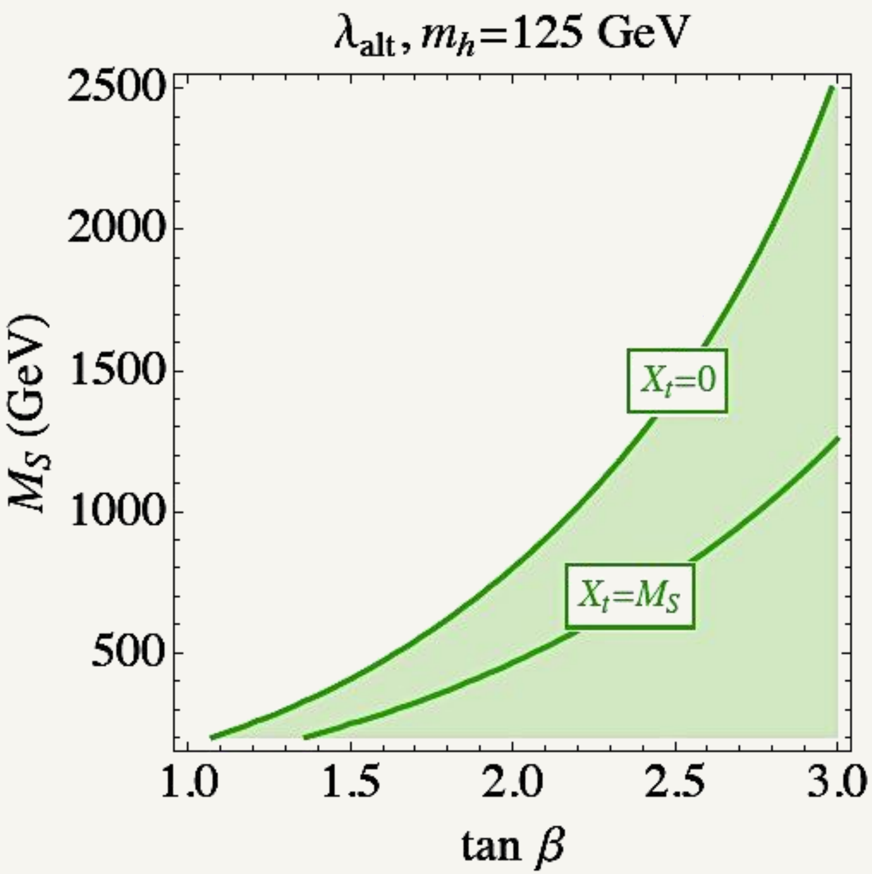
$A_\kappa$ ↔ $m_a/m_{hs}$

- **2 Doublets ($H_u$, $H_d$) + Singlet (S)**
- Singlet couples only to Higgs Sector.
- vevs: ($H_u$, $H_{d,}$, S ) =( $v_u$, $v_d$, $v_S$ =μ/ λ)

- **3 CP-Even Higgs bosons:**
  - Mixing between all three ($H_u$, $H_d$ and S).
- **2 CP-Odd Higgs bosons:**
  - Mixtures of “MSSM” $m_A$ and singlet.
- **Charged Higgs bosons**

- **Singlino** mass: 2 κ μ/λ

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15




# Alignment (No-Mixing):

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$

# Well Known

- 125 GeV Higgs
  - Tree-level contribution to Higgs mass from λ.
  - λ ~ 0.65-0.7
- Low tanβ
- Light Stops

# NMSSM:

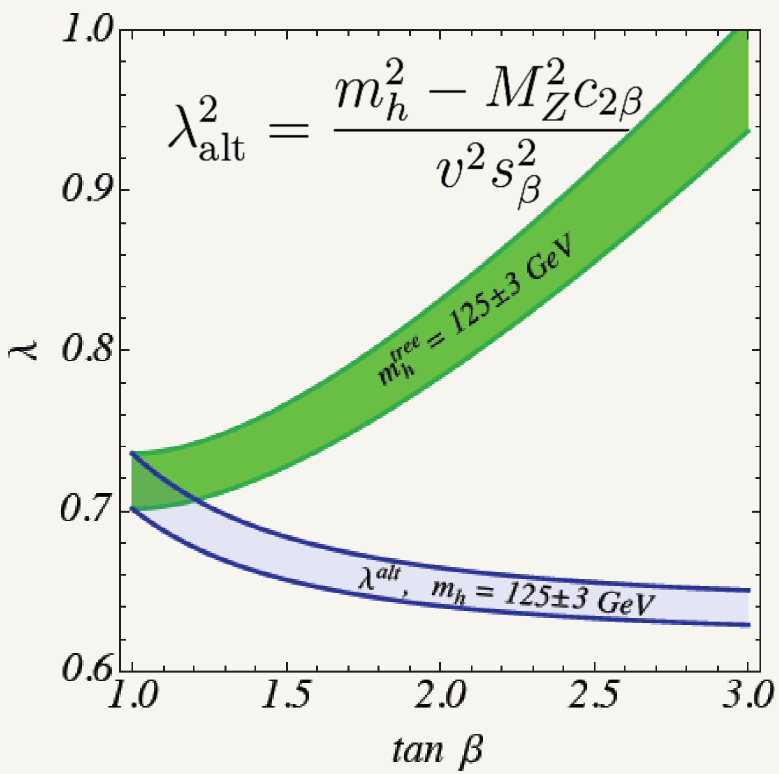
# 125 GeV Higgs Naturally!

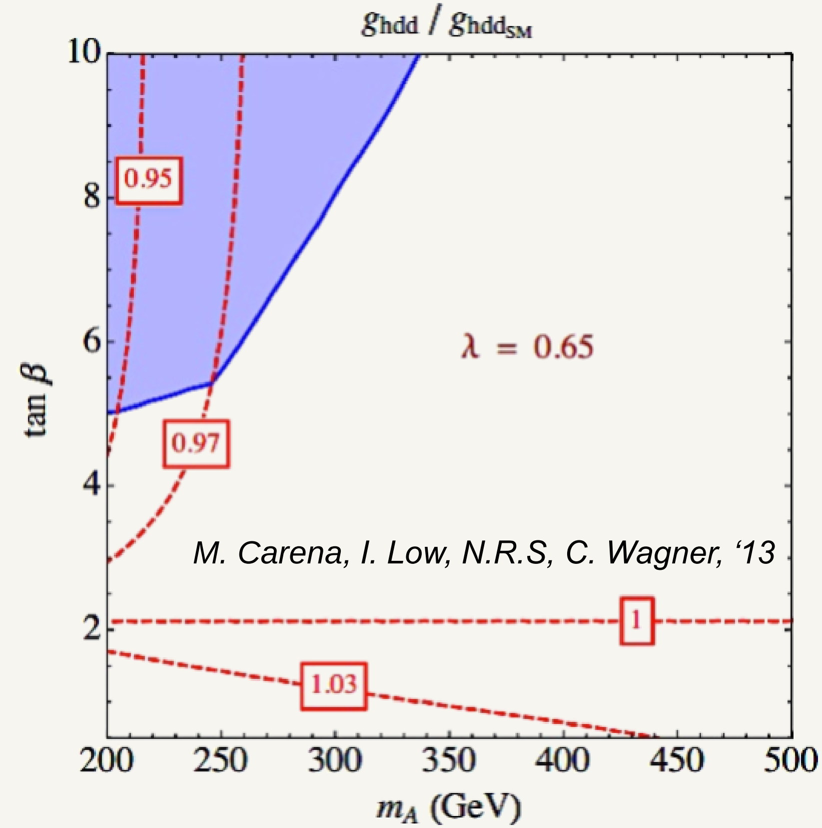
- Perturbative up to GUT scale.
  - $\lambda_{max} \sim 0.7$, $\kappa_{max} \sim \lambda/2$

**Not so well known:**

- Excellent Alignment (very little mixing)

*M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15*



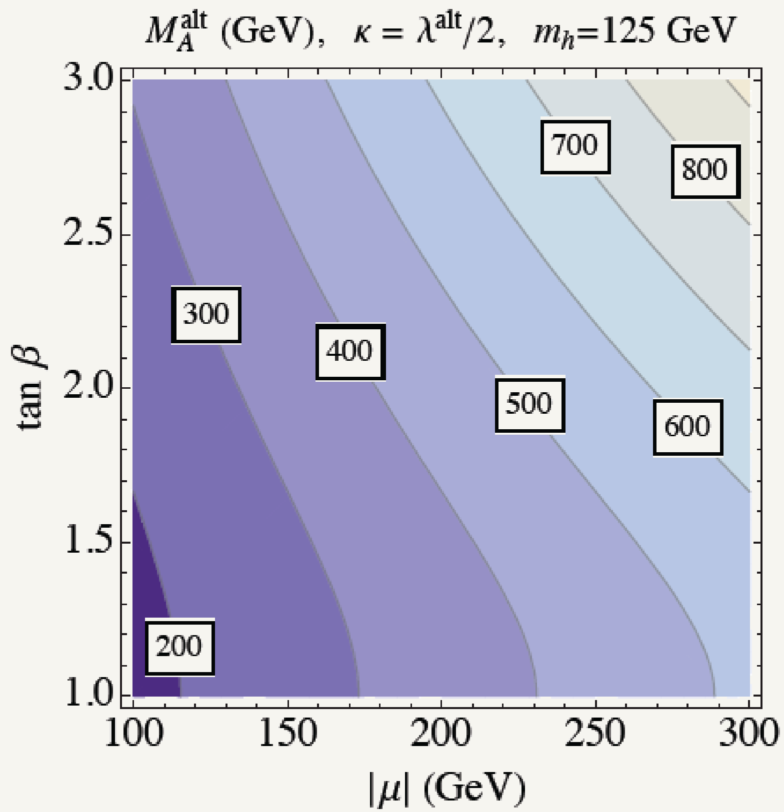



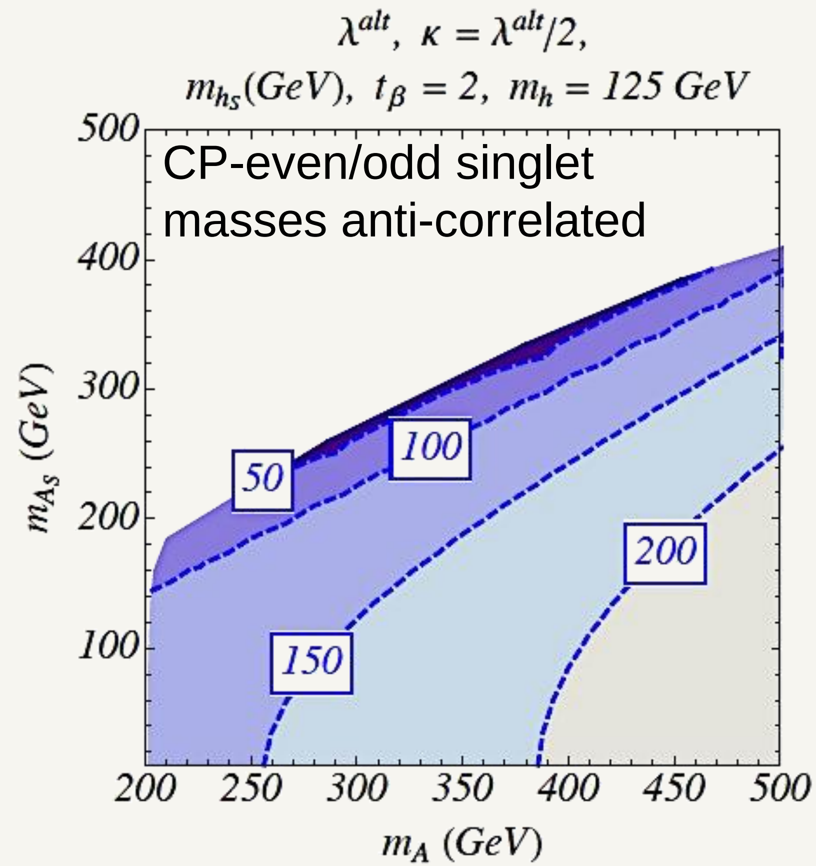

**Originate dynamically from Higgs compositeness at the GUT scale?**

*N. Coyle, C. Wagner, '19*

# SM-Like Higgs Naturally!

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15




$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$

$h_{125} = H_{SM}$

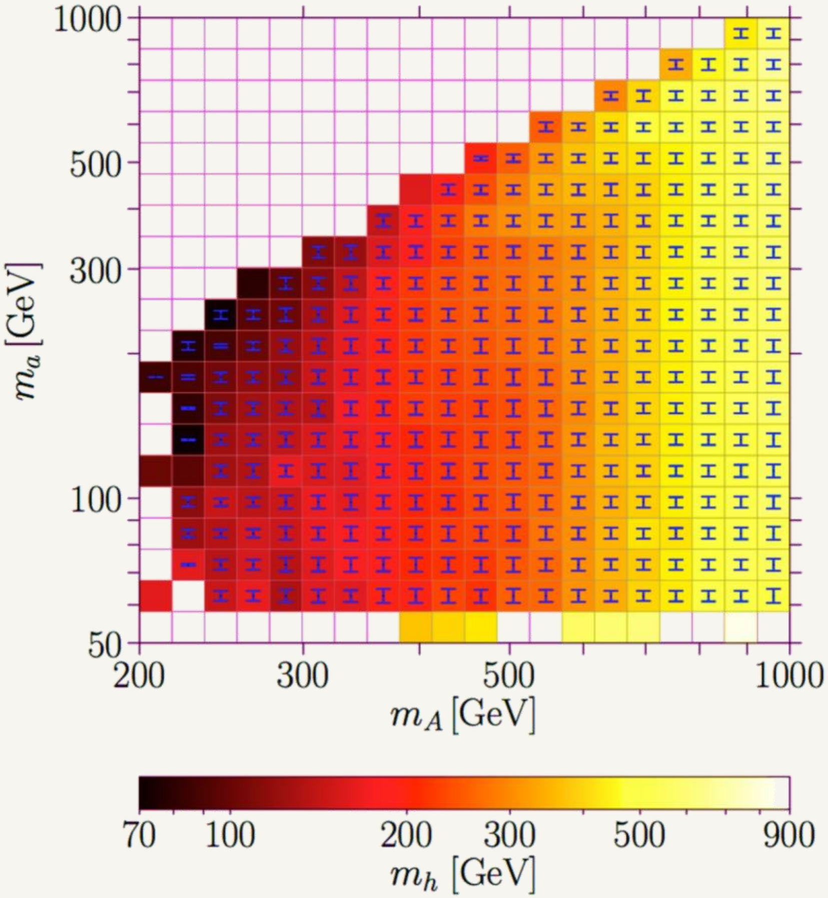
LIGHT SPECTRUM

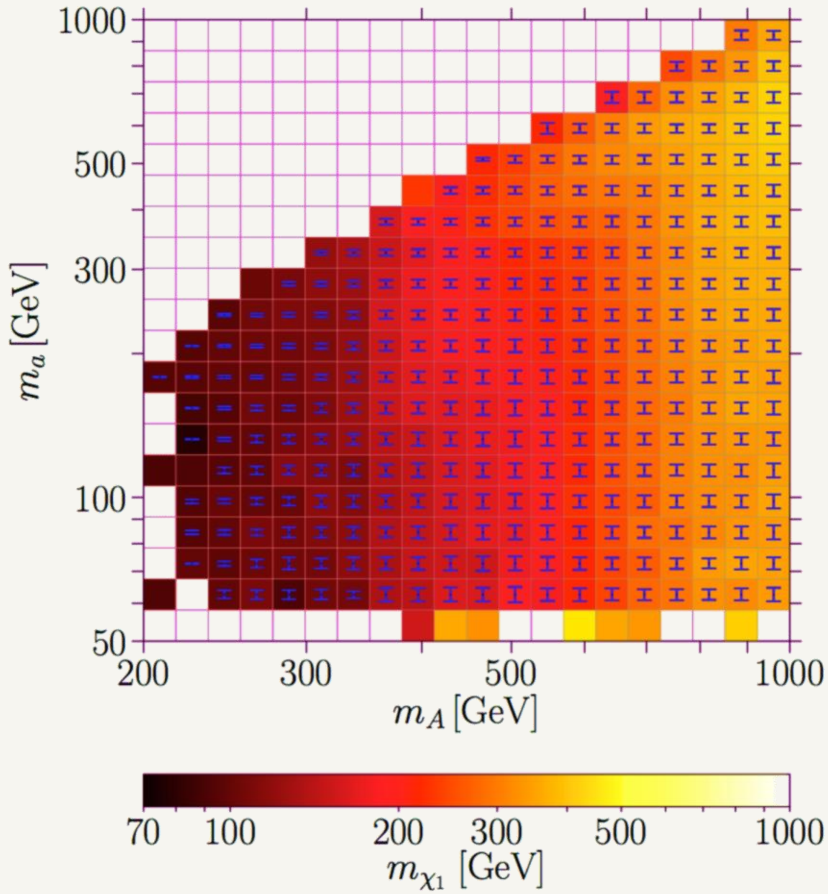
Singlino: **2 κ μ/λ ~ < μ**

# Singlet Alignment

# SM - like $h_{125}$: Mass Correlations!

*S. Baum, N.R.S, K. Freese, '19*




NMSSMTools scan with consistent $h_{125}$ pheno

So …

…

HOW ABOUT **NEUTRALINO** WIMPS FOR

Neutral Superpartners of *Higgs, Z, γ*

# DARK MATTER?

# Charginos/Neutralinos & Sleptons...

| | |
|---|---|
| SM Gauge Bosons, Higgs (2HDM in SUSY) and leptons Superpartners | Bunch of weakly coupled scalars, neutral Majorana fermions, lightest stable due to R-parity: **WIMP!** |
| B: SU(2) singlet | Bino $M_1$ $g_1$ |
| $\{W^0, W^1, W^2\}$: SU(2) triplet | Winos $M_2$ $g_2$ 1 neutral, 2 charged |
| $\{H_u\ H_d\}$: SU(2) doublets | Higgsinos $\mu$ Yukawas etc 2 neutral, 2 charged |
| $\{e, \mu, \tau\}$ | Selectron, smuon, staus $M_{\mu L,R}$ etc SM couplings |

MSSM: 4 neutral "Neutralinos", mixtures of interaction states (Also 2 charged "Charginos" mixtures of wino and Higgsinos). (Also Singlino for NMSSM)

$$\chi = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$

# Thermal Relic?

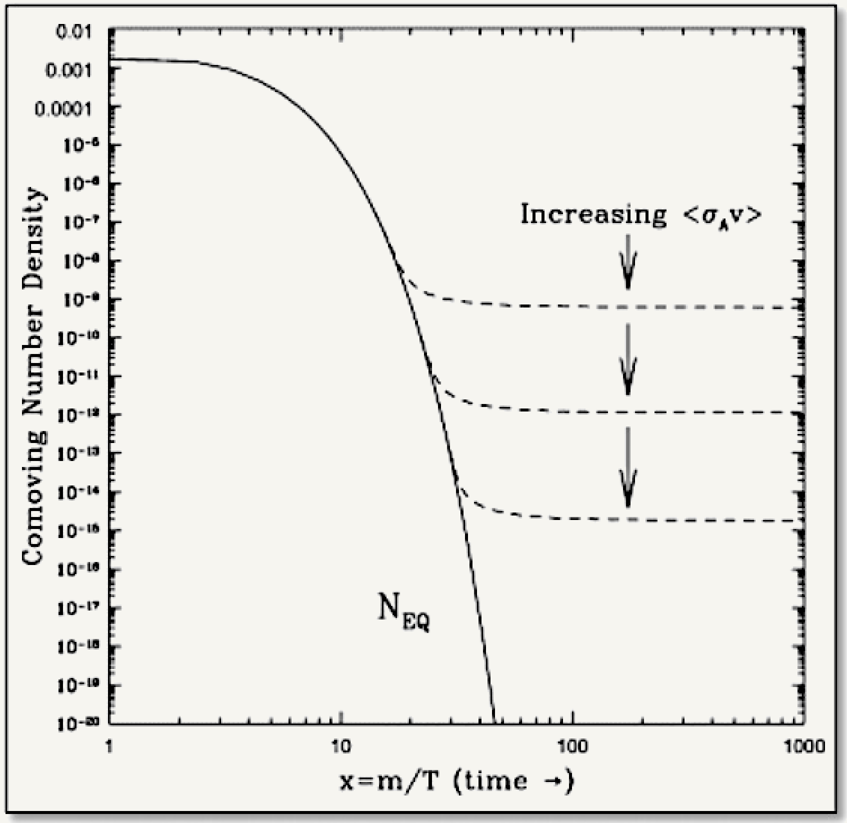
What sets the abundance of the Dark Matter observed?

Annihilations try to maintain thermal equilibrium.

Universe is Expanding!

At some point a DM particle can't "find" another DM particle to annihilate with: FREEZE-OUT.

LARGER annihilation rate means LOWER number density.



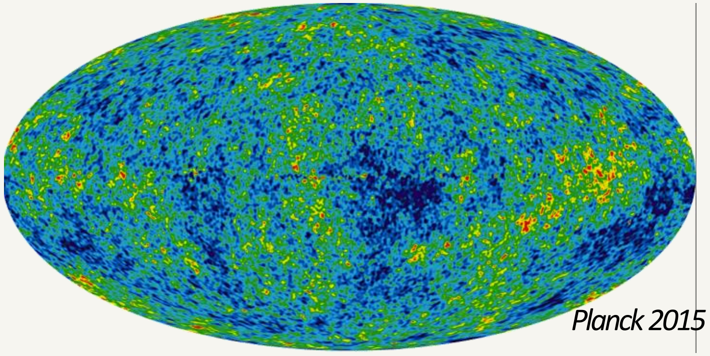

*Hooper, 09*

# WIMPs

Weakly Interacting Massive Particles

# The WIMP Miracle.

$$\sigma = \frac{\text{``}\alpha\text{''}^2}{m^2}$$



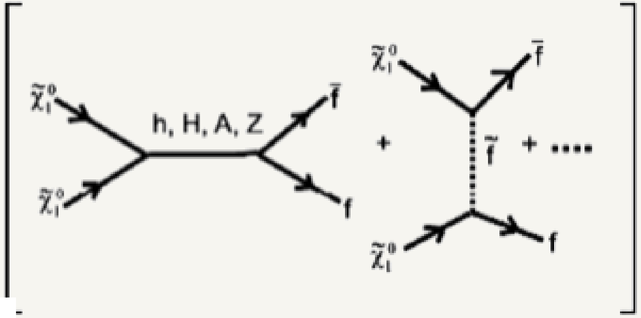

**Weak scale couplings and masses (100 GeV) !**

**$<\sigma v> \Longrightarrow$ observed $\Omega_{DM}$**

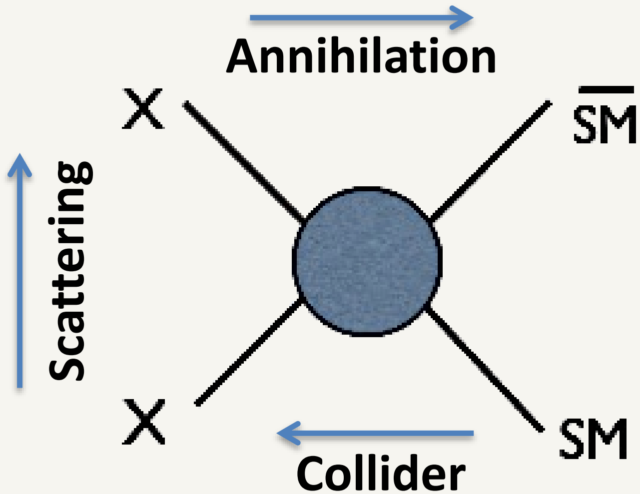
***NATURALLY* !**

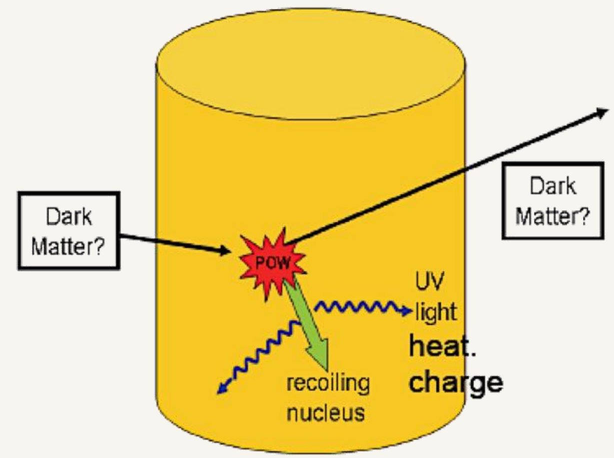
## *Break it!*

$(\Omega_{CDM})^{-1} \propto \left[ \quad \right]^2$





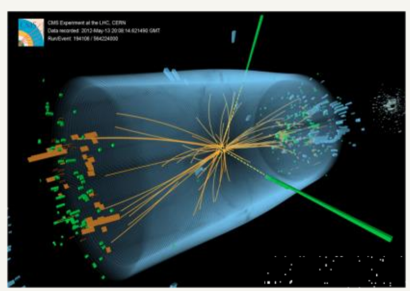


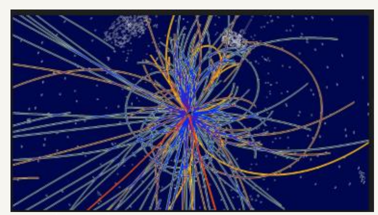




Underground detector

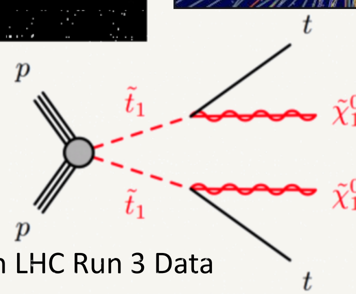
## *Shake it!*

XENON Dark Matter Project

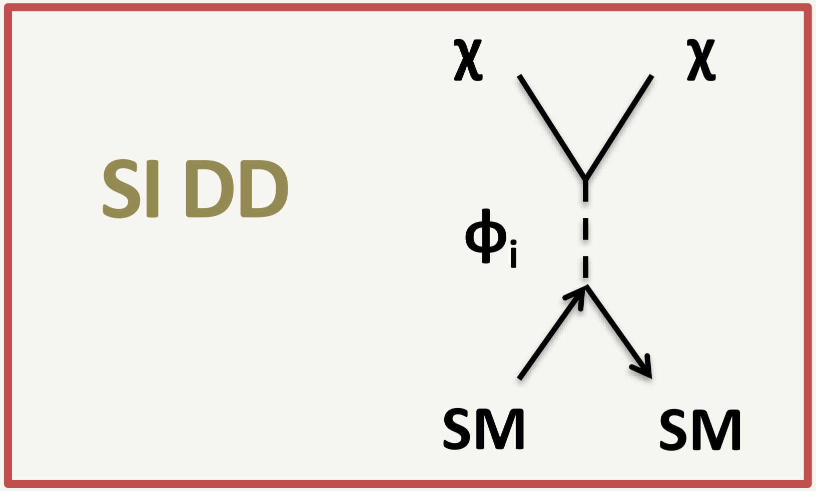


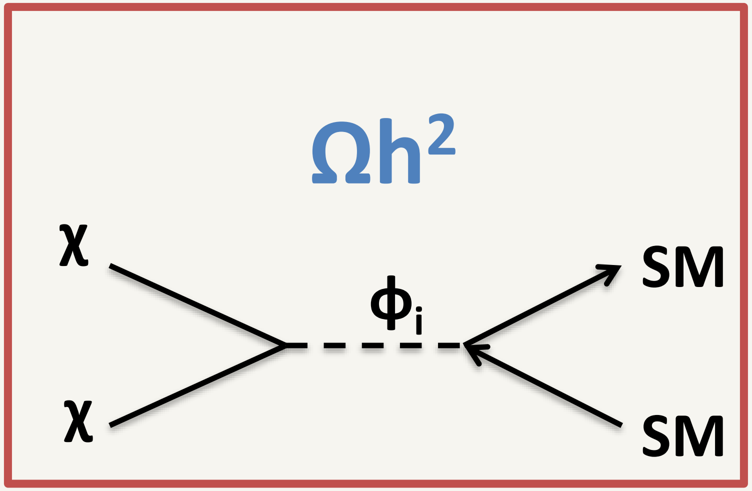


## *Make it!*

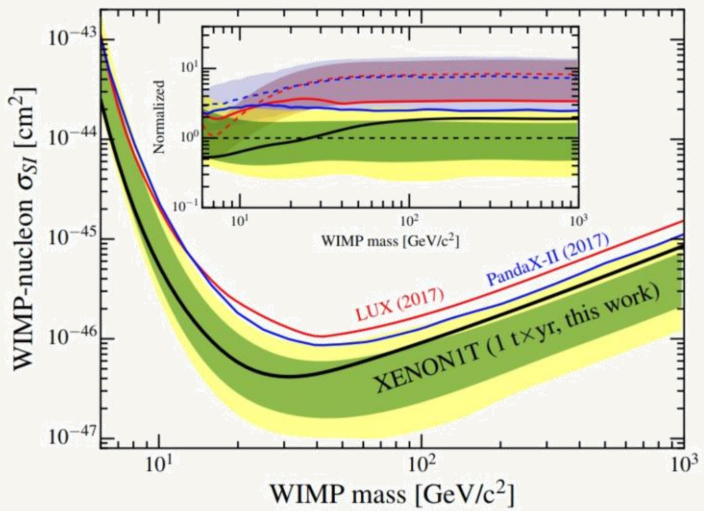


# $SI\ DD + \Omega h^2$ ??




XENON1T arXiv:1805.12562




$m_\chi$ ~ few 100 GeV

**Break the Connection!**

Multiple mediators for destructive interference

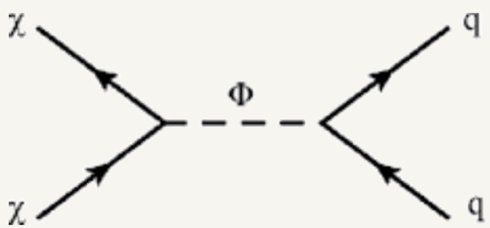
Co-annihilation/Resonance

**ALL consistent with extended Higgs sectors!!**

# Relic Density: Annihilations

**Light *Binos or Singlinos* (SM singlets) excellent candidates for Dark Matter.**

[redacted]

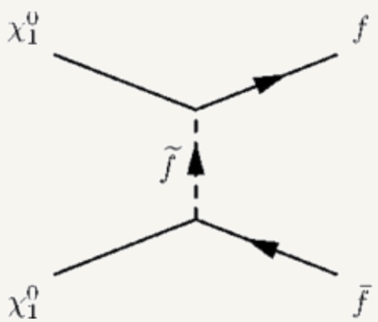



*Cheung, Papucci, Sanford, NRS, Zurek '14, Freese Lopez, NRS, Shakya '15, Carena, Osborne, NRS, Wagner '19, etc…*

*s*-channel Resonance:

DM close to half of mediating particle mass.

Constrained but possible for $h_{125}$, *Z*, & additional Higgs bosons.




*t*-channel annihilation with light stau.

Happens in a natural way at large *tanβ*.

*NRS, Pierce, Freese'1*

# Relic Density: Co - Annihilations

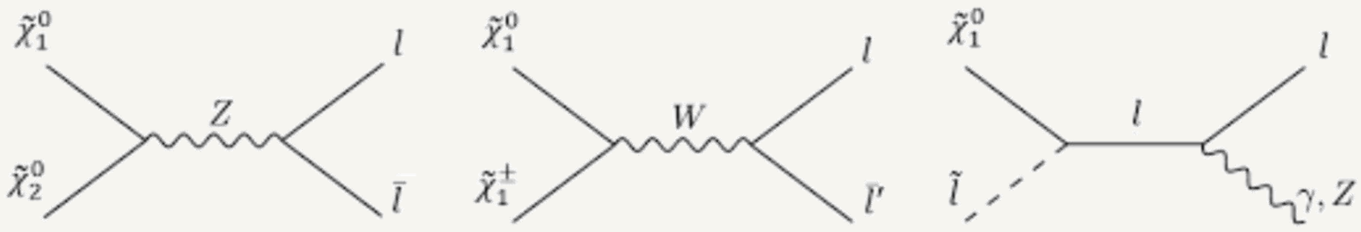
**When DM can annihilate against other rapidly annihilating particles.**

*Ibarra, Pierce, NRS, Vogl '15, Pierce, NRS, Vogl '18, Baum, Carena, NRS, Wagner '18, '21 etc*

Mass difference of Dark Matter with the other weak scale weakly interacting particles must be of the order of a few tens of GeV.

Naturally leads to compressed spectrum –> reduced sensitivity at the LHC.

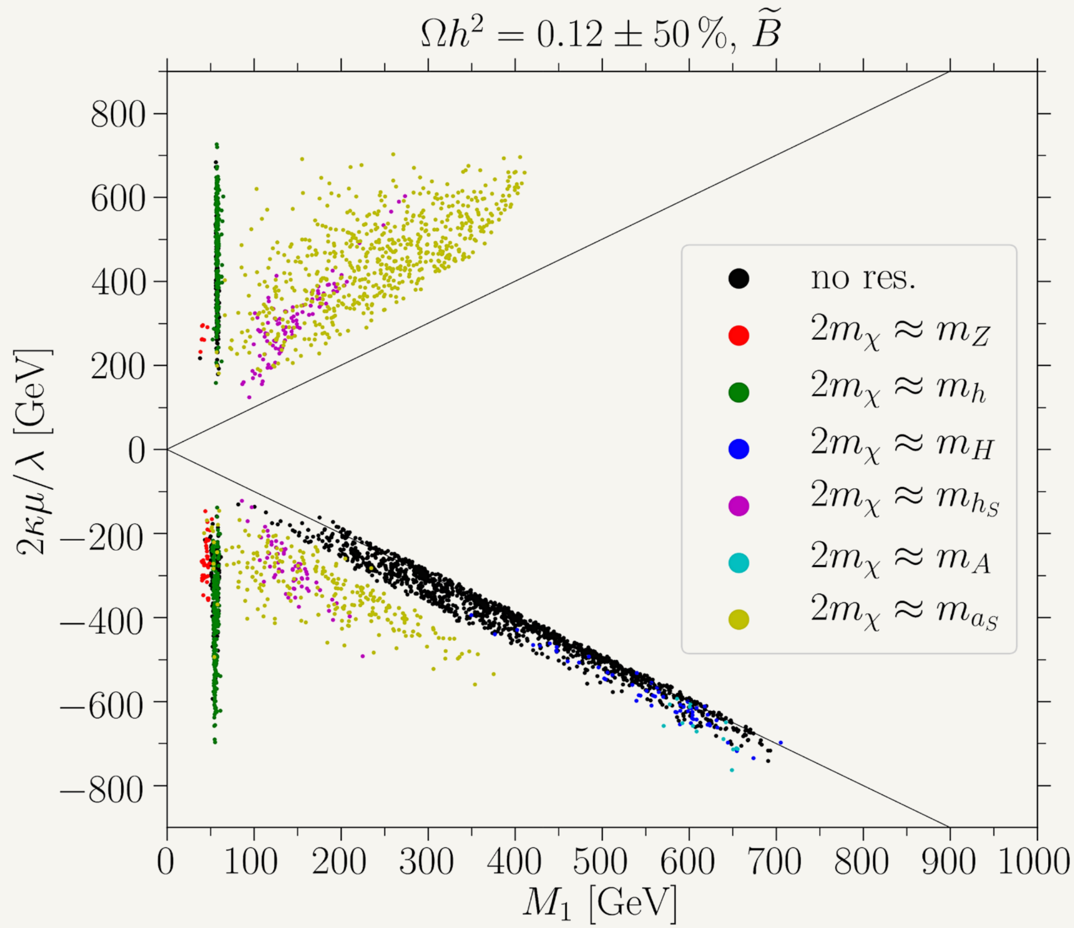
Some relevant channels in the case of sleptons or Winos (too light Higginos/ small $\mu$ leads to large SD cross sections).



# Relic Density: Co - Annihilations

*S. Baum, M. Carena, N.R.S, C. Wagner, '17*

Thermal production via co-annihilation of Bino with **singlino** or resonance




## NMSSM: ('well-tempered') Bino DM

# Direct Detection

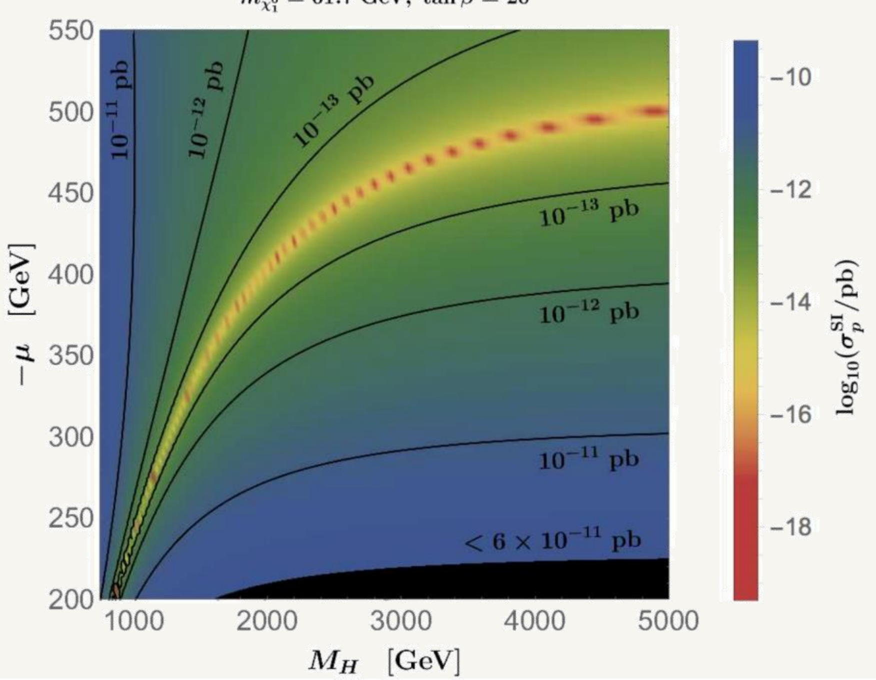
$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde\chi_1^0}+2\mu/\tan\beta)\frac{1}{m_h^2}+\mu\tan\beta\frac{1}{m_H^2}+(m_{\tilde\chi_1^0}+\mu\tan\beta/2)\frac{1}{m_{\tilde Q}^2}\right]^2$$

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

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

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

*Cheung, Hall, Ruderman '12,*
*Huang, Wagner '14,*
*Cheung, Papucci, NRS, Stanford, Zurek '14,*
*Han, Liu, Makhapadhyay, Wang '18.*




*Carena, Osborne, NRS, Wagner, '18*

Small SI DD can easily be obtained via **blind spots**.

**Negative values of (μ x $M_1$)** : *Much* weaker spin-independent direct detection bounds

**SD DD** mediated only by ***Z!*** May be probed in the near future.

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

NMSSM: similar, but different signs.


# BUT ISN'T SUSY ALREADY RULED OUT BELOW THE TEV SCALE ??

Guinos:

If decay directly to 3rd generation squarks, gluinos must be heavier than about 1.5 to 2.2 TeV

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.

Stops:

Higgs mass implies stops masses heavier than ~ 1 TeV

Combining all searches, in the simplest decay scenarios, it is hard to avoid the constraints 600 GeV - 1.2 TeV for stops.

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

# All that Weak stuff?

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.

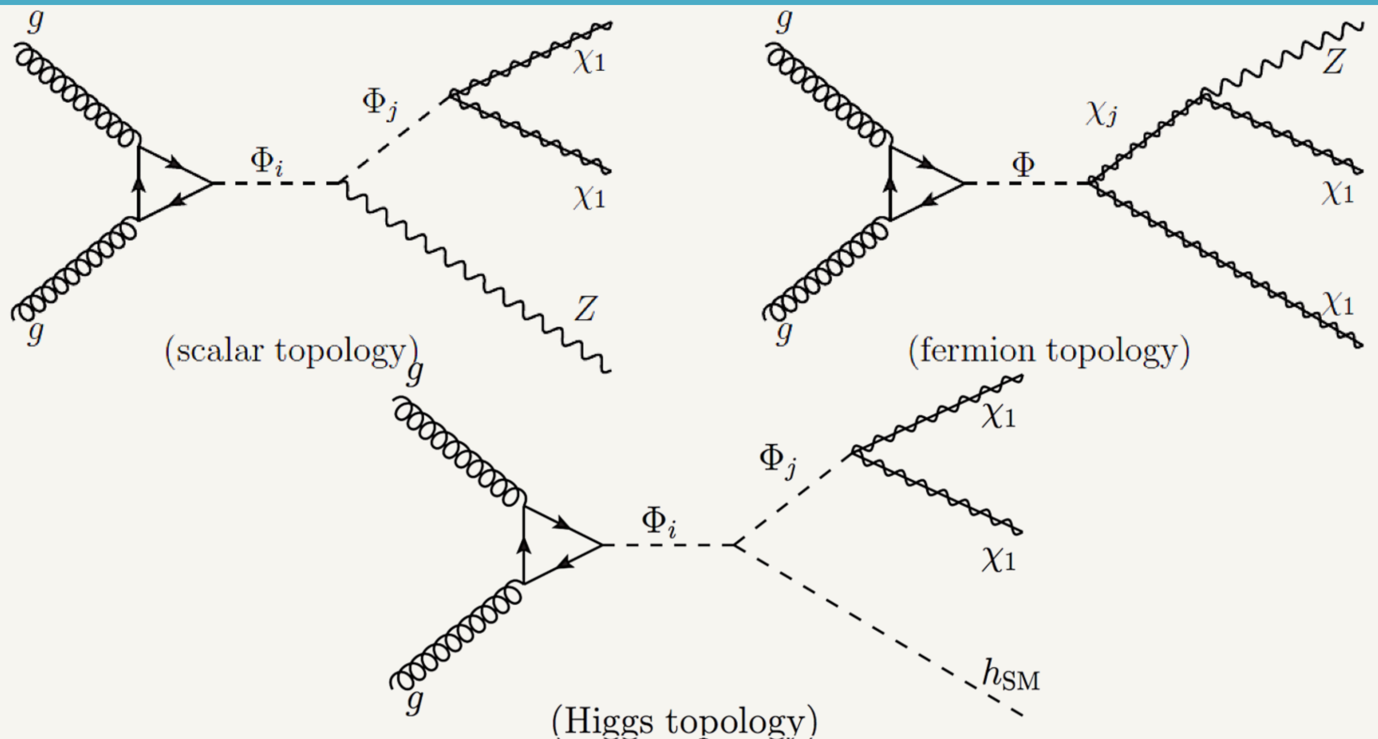
Sensitivities in the search for these particles will increase only at **high luminosities**, but bounds on Higgsinos will remain weak.

In general, a SUSY scenario with large cascade decays with light electroweakinos is the **most natural one** and the **least constrained** so far.

- Interesting cascade decays of the additional Higgs bosons in the NMSSM
  - Eg: $H_{NSM} \rightarrow h_S H_{SM}$ or $H_{NSM} \rightarrow a_S Z$

$H_{NSM} \rightarrow WW/ZZ/H_{SM} H_{SM}$ or $A \rightarrow Z H_{SM}$ suppressed due to alignment

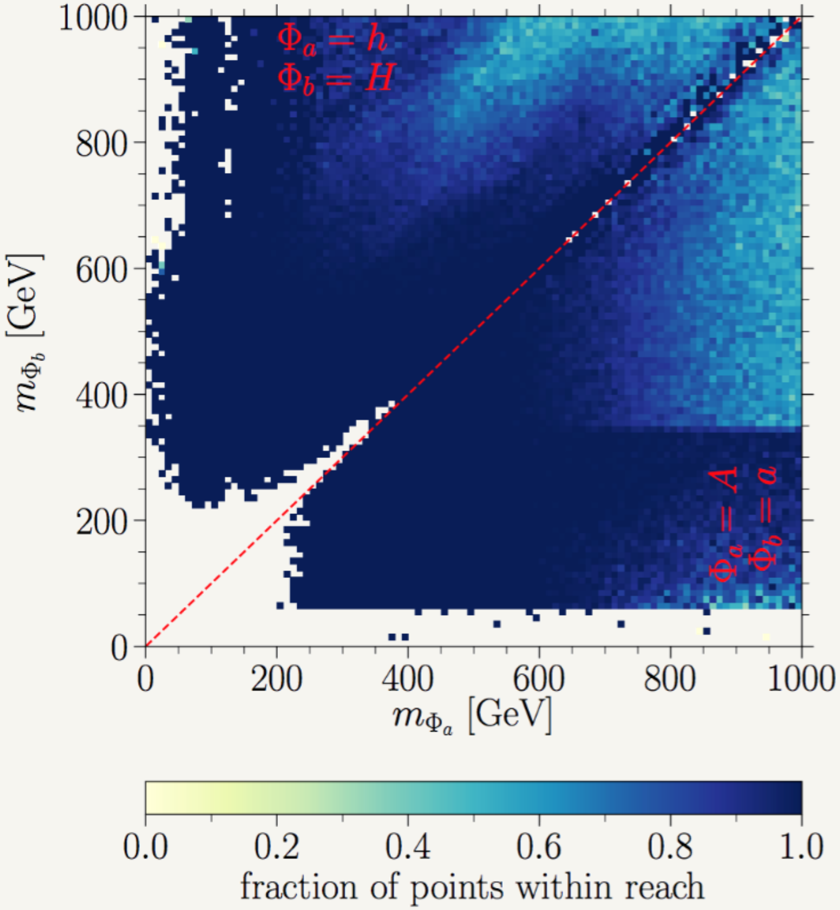
- Can have visible and invisible decays of $h_S/a_S$

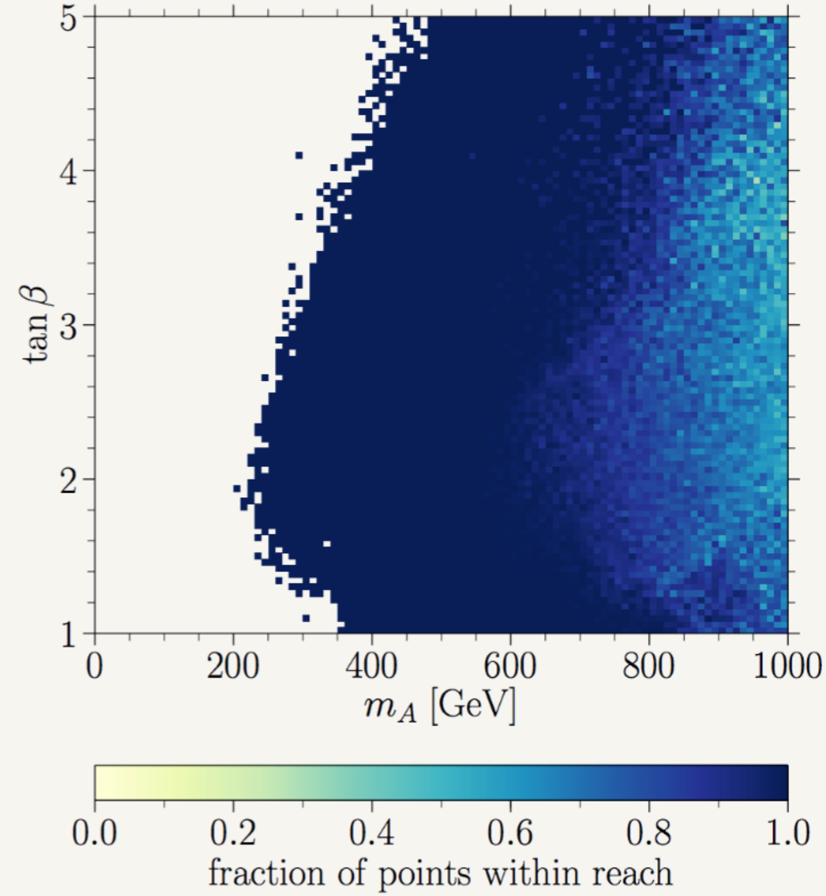


# LHC All Searches: 3000 $fb^{-1}$ NMSSM Higgs Sector

Optimistic scenario shown!

*S. Baum, N.R.S, K. Freese, '19*



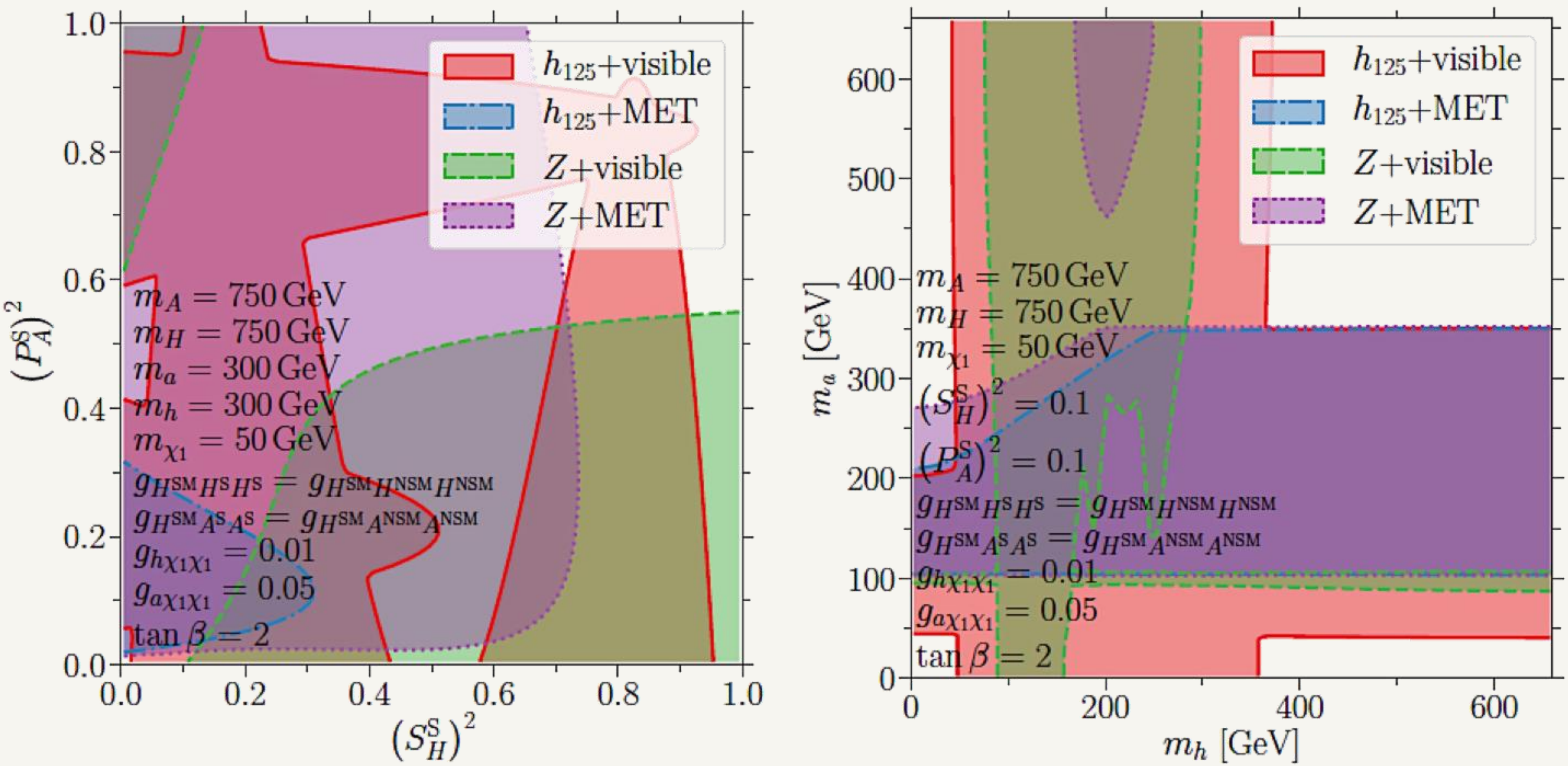




Expect **~50%** scanned region with $m_A$ < 1 TeV probed.

**~90%** if improvements by 1 order of magnitude wrt our projections, & 2 orders of magnitude in conventional search channels wrt current limits.

# Generic NMSSM: Explore 2HDM + S!!

*S. Baum & N.R.S., '18*



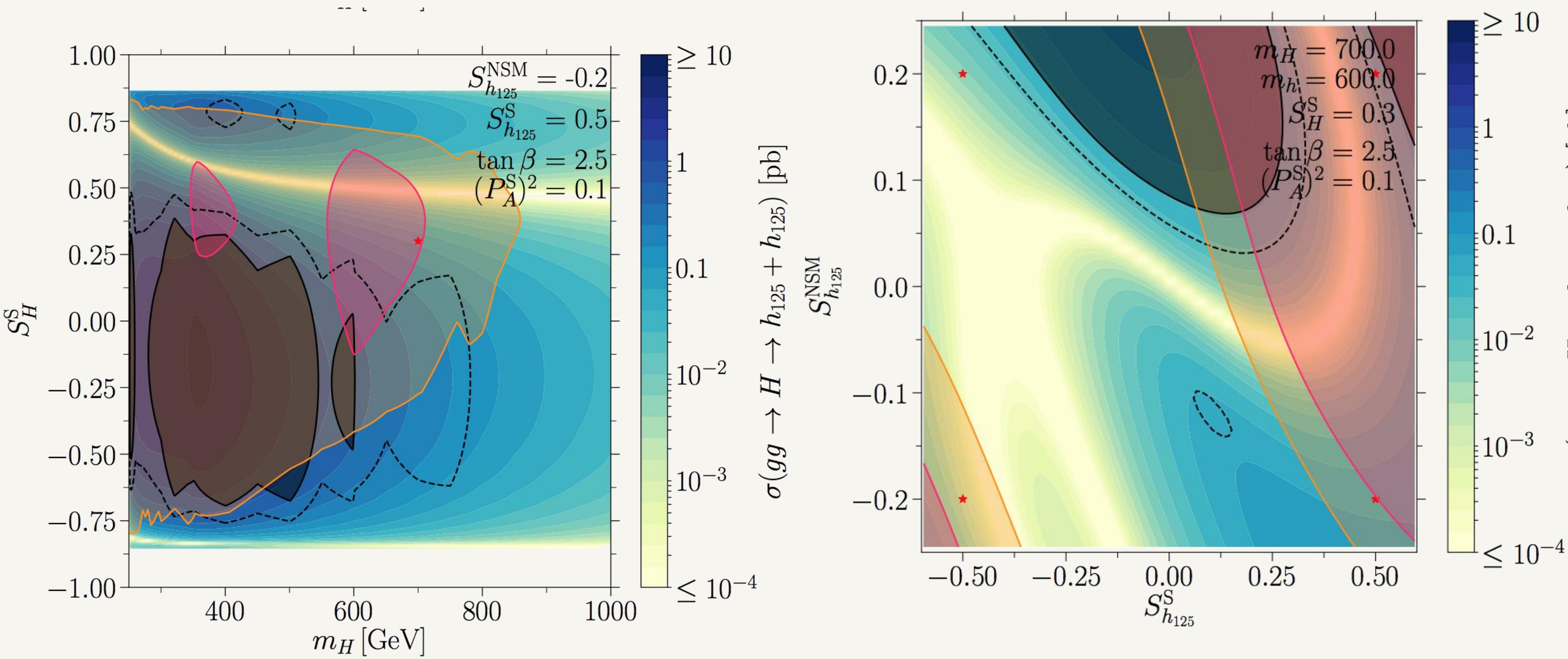

If either $m_a$ or $m_h$ > 350 GeV, can decay predominantly to tt.

**Could be hidden in $h_{125}$ tt?**

# Max Misalignment Scenario: H → $h_{125}\,h_{125}$

Compare to CMS/ATLAS limits (2019) in *bbbb, bbγγ* final states.

*S. Baum & N.R.S., '19*




Gray shaded regions excluded by (H → $h_{125}h_{125}$) searches. Black dashed lines label cross sections a factor two smaller, and hence may be probed with 300 $fb^{-1}$ of data. Red [orange] shaded area denote regions ruled out by current (H → WW) [(H → ZZ)] LHC searches

# MUCH MORE to Explore!

Stops and gluinos > TeV

Higgs & Electroweak Sector Tangled

DM + (g-2) (S. Heinemeyer talk)
+ Alignment + Higgs Mass (CPV?!)

**Experimental Simplified Model Analysis Limits** √

**Naïve Reinterpretation to Exclude** ×

**Bottle neck:**
**Data + Search strategies for compressed spectra**

**NOT Energy!**

# Snowmass - EF08: Model Specific Explorations

Convenors: Elliot Lipeles, Nausheen Shah, Jim Hirschauer

- **We are looking for people to take on specific (but manageable) responsibility for individual EF08 summary plots for the Snowmass report (current list of plots below). The work would involve:**

1) Reviewing corresponding European Strategy plot and documenting source of all numbers/lines in plots. We hope to have this done in the next few weeks. Specifically, we'd like to fill out spreadsheets that look like this:

| Machine | | | ES Report | | | | | | | Snowmass | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Collider | Energy | L (ab-1) | Presented Number/Line | Figure/Table in ES Report | Number/Line in figure | Reference | Fig | Comment on Number Source | Comment method | Update Priority | Group(s) | Status |
| **HL-LHC** | **14** | 6? | at 3 ab-1, to light quarks | 8.6 | 3.2 TeV | https://arxiv.org/pdf/1812.07831.pdf | 2.1.1 | LHC fig, 2 sigma at mX=0 | Delphes | | | |
| | | | at 3 ab-1, to light quarks compressed | 8.6 | 1.5 TeV | https://arxiv.org/pdf/1812.07831.pdf | 2.1.1 | LHC fig, 2 sigma on diagonal | Delphes | | | |
| | | | at 3 ab-1, to light top quarks | 8.6 | | https://arxiv.org/pdf/1812.07831.pdf | 2.1.6 | | CMS official | | | |
| | | | at 3 ab-1, to s top quarks | 8.6 | | unclear? | | | | | | |
| FCC-hh | 75 | **30** | at 30 ab-1, to light quarks | 8.6 | | https://link.springer.com/article/10.1140%2Fepjc%2Fs10052-019-6904-3 | 9.1 | | FCC | | | |
| | | | at 30 ab-1, to light quarks compressed | 8.6 | | "extrapolated from FCC-hh prospects" | | | | | | |
| | | | at 30 ab-1, to s top quarks | 8.6 | | https://link.springer.com/article/10.1140%2Fepjc%2Fs10052-019-6904-3 | 9.1 | | FCC | | | |
| FCC-hh | 100 | **30** | | | | | | | | | | |
| **FCC-hh** | **150** | **30** | | | | | | | | | | |

https://docs.google.com/spreadsheets/d/1KxxcOpF2PgrAe8p_3QVD910hwGHrYqRFmAIG3xEWSao/edit?usp=sharing

More Machine (e+e-, muon, e-h…)

# Snowmass - EF08: Model Specific Explorations

Convenors: Elliot Lipeles, Nausheen Shah, Jim Hirschauer

- **The work would involve (con't...):**

2) Identify new numbers/lines to include. Similarly in the next few weeks.
3) Identify changes to plots large or small with a target to have big picture changes defined by end of calendar year.
4) In 2022: track results needed, collect results in appropriate formats, and ultimately assemble the plots.

Of course, we'd also like contributions to the specific results identified in (3).

Current list of plots essentially the same as the European Strategy (Suggestions welcome for additions):

- Gluino
- Light squarks
- Stop squark
- High-Delta M electroweak (not necessary Wino-Bino, to be discussed)
- Compressed electroweak

We could potentially sub-divide the task for a plot for example into hadron and lepton colliders if you are interested.

If you want to volunteer to coordinate a plot or set of lines in a plot (e.g. all e+e-), let us know: lipeles@sas.upenn.edu, jhirsch@fnal.gov, nausheen.shah@wayne.edu

# Thank You!


**SM & DM beautiful & EMPIRICAL...**

Electroweak sector **heart** of the puzzle.

**SUSY** (may?) be the answer!

LHC: Strong constraints on strong sector...

**What are the right questions?**

LHC: Electroweak sector -> Need more data!

**Higgs/Electroweak???**

**Data + Theory: Where to look next!**

**Absence of Evidence != Evidence of Absence**

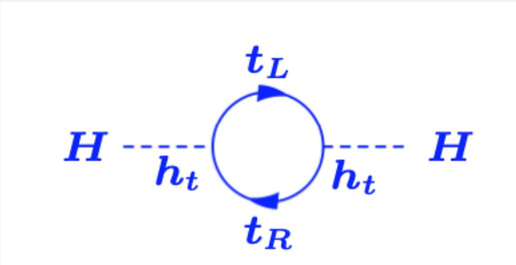
Flavors of SUSY -> Wildly different Pheno -> Much to explore!

~~"May we live in interesting times."~~

# BACK UP SLIDES

# Fine Tuning?

## Top quark contribution:

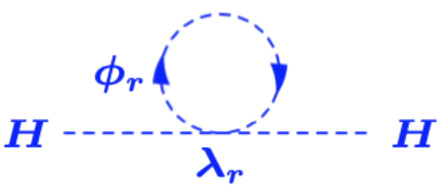


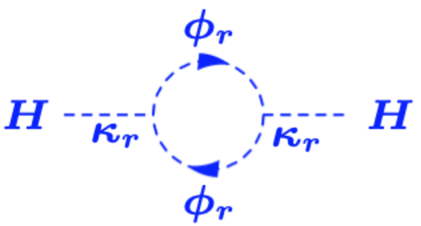

$$\left(\Delta M_H^2\right)_t = -iN_c(-ih_t)^2 \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left(\frac{i}{\not{k} - m_t} \frac{i}{\not{k} - m_t}\right)$$

$$\sim -\frac{N_c (h_t)^2}{4\pi^2}\Lambda^2 \xrightarrow[\Lambda \sim M_P \sim 10^{19}\ \mathrm{GeV}]{} -10^{37}\ \mathrm{GeV}^2$$

## Complex scalar contributions:

$$\mathcal{L} = -\lambda_r H^2 \phi_r^\dagger \phi_r$$



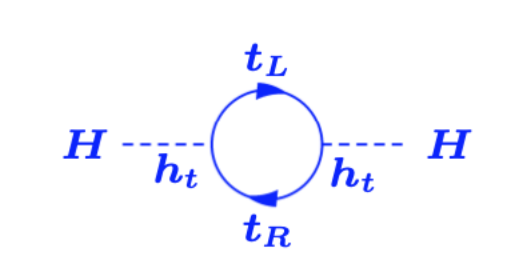




$$\left(\Delta M_H^2\right)_{\phi_r} \sim \frac{\lambda_r N_c}{8\pi^2}\Lambda^2$$

Need to CANCEL LARGE contributions to produce physical Higgs mass of 125 GeV!!

# Fine Tuning: SUSY Cancelations!

Top quark contribution:

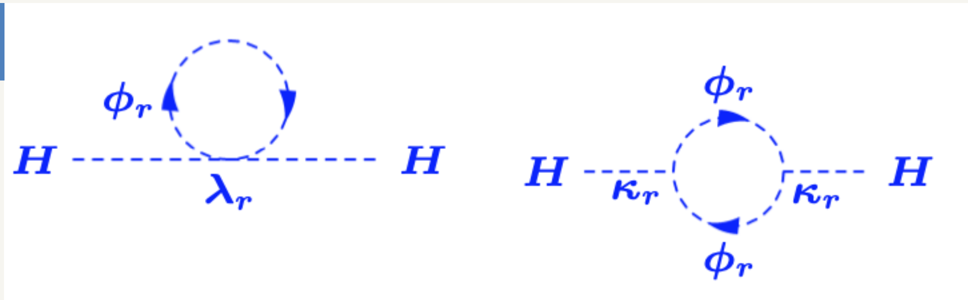



$$\left(\Delta M_H^2\right)_t = -iN_c(-ih_t)^2 \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left(\frac{i}{\not{k} - m_t} \frac{i}{\not{k} - m_t}\right)$$

$$\sim -\frac{N_c(h_t)^2}{4\pi^2}\Lambda^2 \xrightarrow[\Lambda\sim M_P\sim 10^{19}\ \mathrm{GeV}]{} -10^{37}\ \mathrm{GeV}^2$$

Complex scalar (STOP) contributions :

$$\mathcal{L} = -\lambda_r H^2 \phi_r^\dagger \phi_r$$




$$\left(\Delta M_H^2\right)_{\phi_r} \sim \frac{\lambda_r N_c}{8\pi^2}\Lambda^2$$

Quadratic divergences CANCEL if EQUALITY of couplings.

Residual (mass dependent) logarithmic contributions remain

- Interaction basis: ($H_u$, $H_d$, S)
  - $H_u$: Couples only to up-type fermions
  - $H_d$: Couples only to down-type fermions
  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u/v_d$
$\langle S \rangle = \mu/\lambda$

# CP-Even Higgs Bases

# CP-Even Higgs Bases

- Interaction basis: $(H_u, H_d, S)$
  - $H_u$: Couples only to up-type fermions
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  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u/v_d$
$\langle S \rangle = \mu/\lambda$

- "Extended" Higgs basis: $(H_{NSM}, H_{SM}, S)$
  - $H_{NSM}$: (down, up, V) = $(y_d\, t_\beta, y_u/\, t_\beta, 0)$
  - $H_{SM}$: (down, up, V) = $(y_d, y_u, g_{hVV})$

Only SM state couples to WW or ZZ!!

$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

# CP-Even Higgs Bases

- Interaction basis: $(H_u, H_d, S)$
  - $H_u$: Couples only to up-type fermions
  - $H_d$: Couples only to down-type fermions
  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u / v_d$
$\langle S \rangle = \mu / \lambda$

- "Extended" Higgs basis: $(H_{NSM}, H_{SM}, S)$
  - $H_{NSM}$: (down, up, V) = $(y_d\, t_\beta, y_u / t_\beta, 0)$
  - $H_{SM}$: (down, up, V) = $(y_d, y_u, g_{hVV})$

$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

- Mass basis: $(H^3, H^2, H^1)$

$$H^i = S^i_{NSM} H_{NSM} + S^i_{SM} H_{SM} + S^i_S H_S$$

# CP-Even Higgs Bases

- Interaction basis: $(H_u, H_d, S)$
  - $H_u$: Couples only to up-type fermions
  - $H_d$: Couples only to down-type fermions
  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u / v_d$
$\langle S \rangle = \mu / \lambda$

- "Extended" Higgs basis: $(H_{NSM}, H_{SM}, S)$
  - $H_{NSM}$: (down, up, V) = $(y_d\, t_\beta, y_u / t_\beta, 0)$
  - $H_{SM}$: (down, up, V) = $(y_d, y_u, g_{hVV})$

$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

- Mass basis: $(H_3, H_2, H_1) \longrightarrow (H, h125, h)$

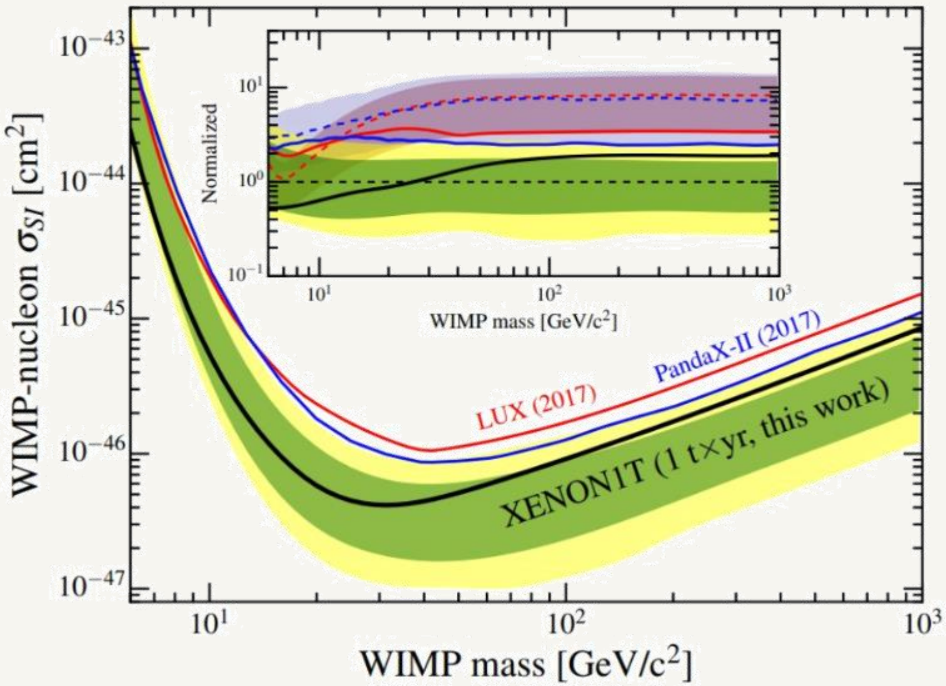
$$H_i = S_i^{NSM} H_{NSM} + S_i^{SM} H^{SM} + S_i^S H_S$$

CP-odd mix similarly:
$A_i = P_i^{NSM} A_{NSM} + P_i^S A_S$

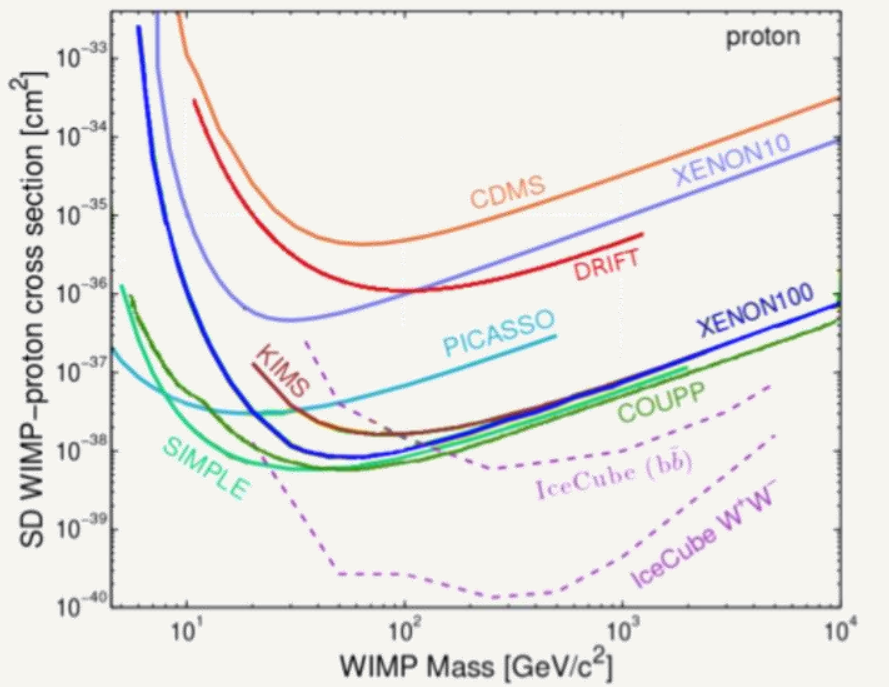
# Current Bounds from Direct Dark Matter Detection

## Current Limits

$$1\ \text{pb} = 10^{-36}\ \text{cm}^2, \qquad 1\ \text{zb} = 10^{-45}\ \text{cm}^2$$




Spin Independent Interactions

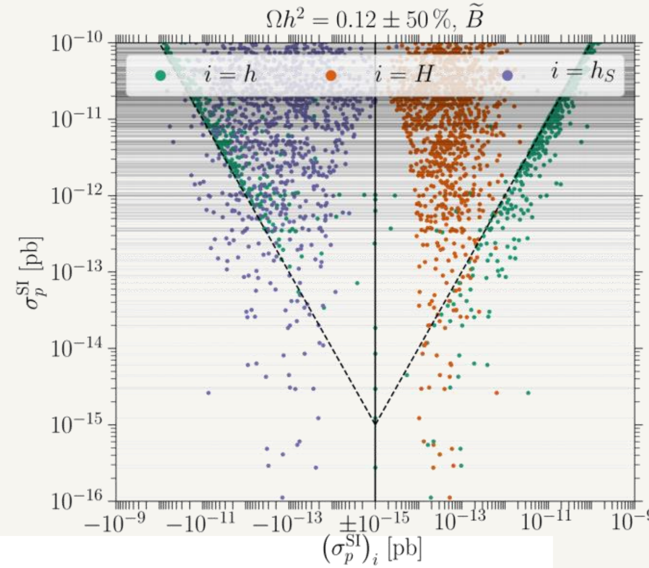



Spin Dependent Interactions

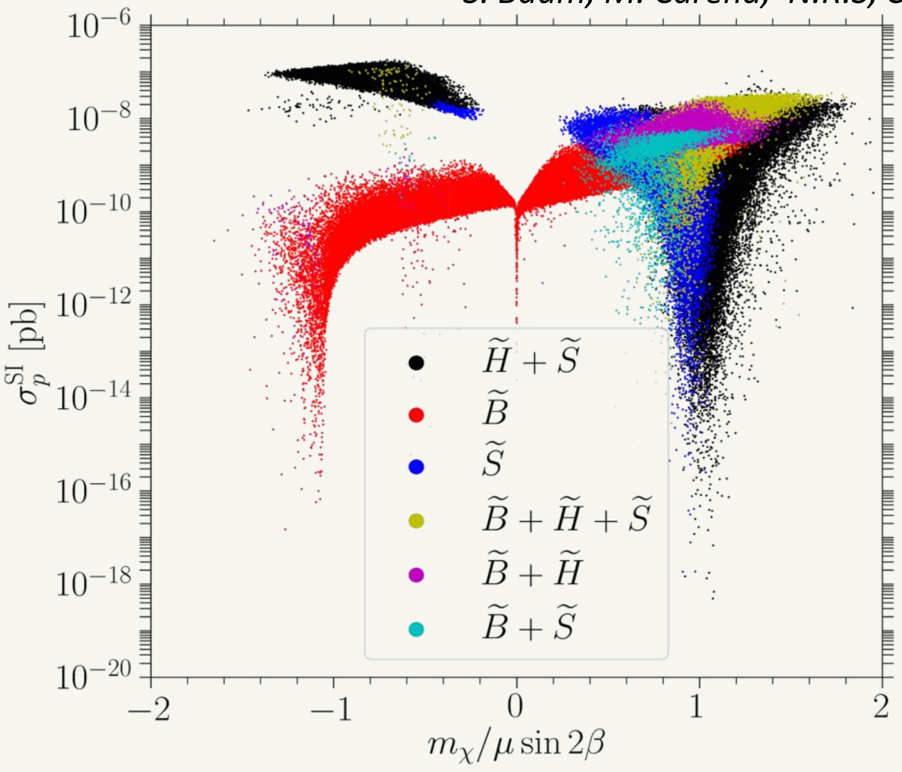
# NMSSM: SI Direct Detection

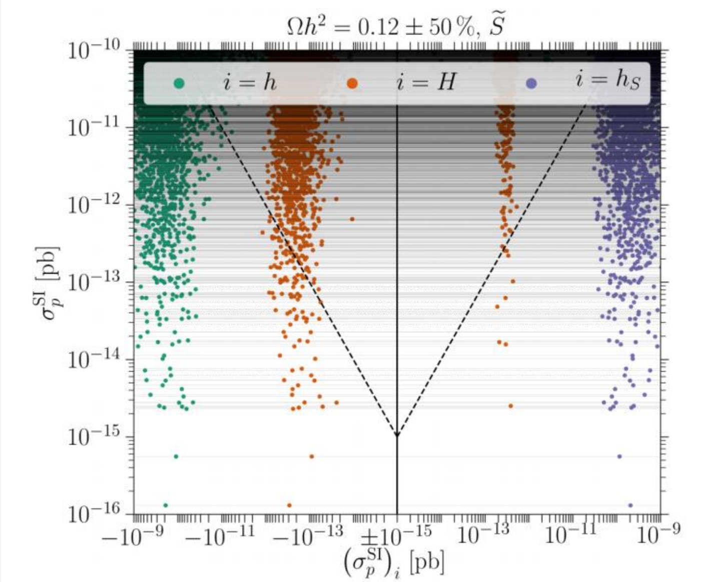
SI Direct Detection cross section suppressed by:
Cheung, Papucci, Sanford, NRS, Zurek, `14; Huang, Wagner, 2014, etc.

- Proximity to $h_{125}$ blind spot
- Destructive interference between CP-even Higgs mass eigenstates

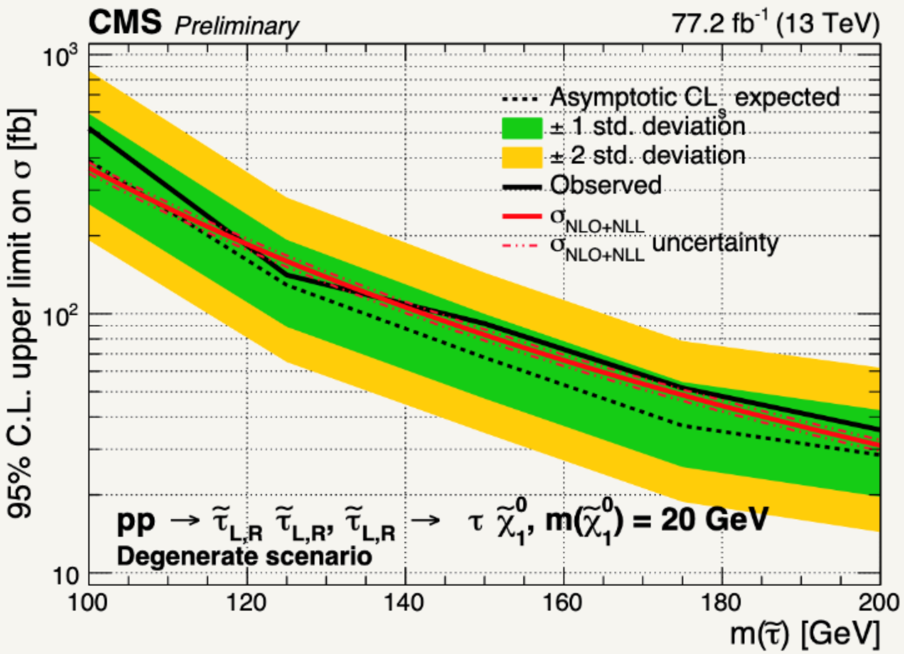


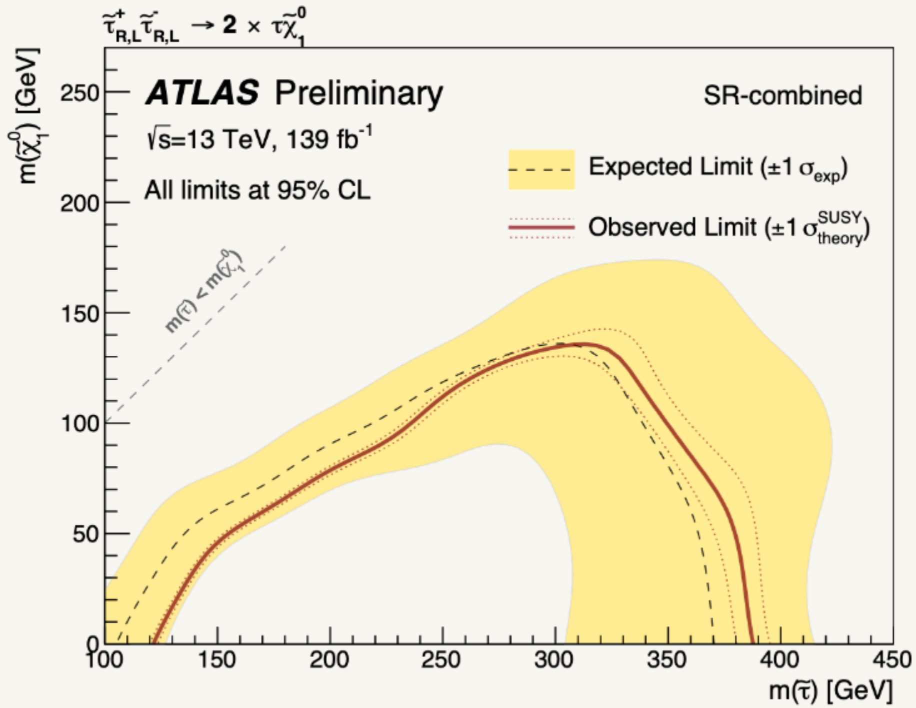

*S. Baum, M. Carena, N.R.S, C. Wagner, '17*



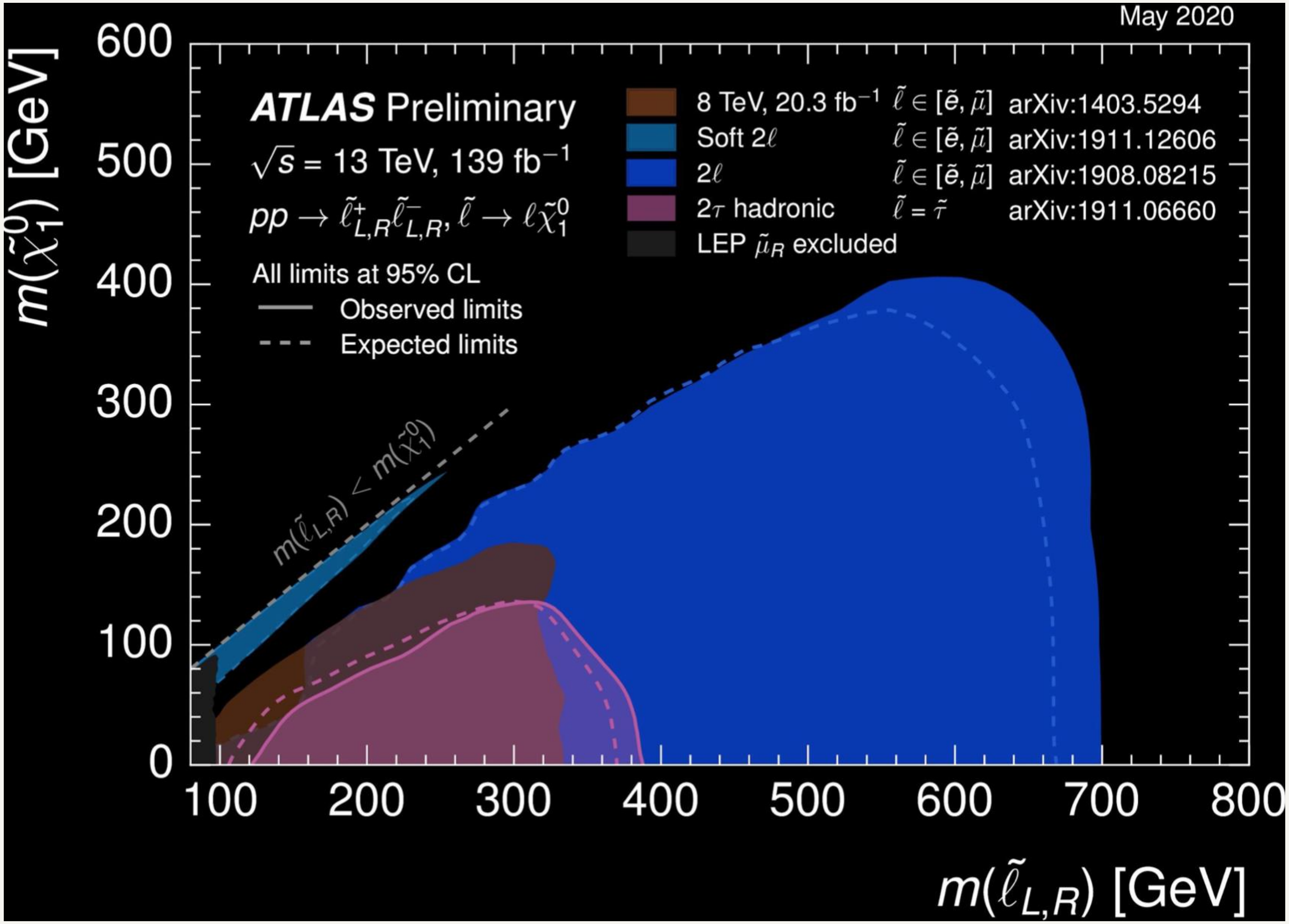
# Stau searches: Bounds depend on mixing!




Weak limit at this point, we are now exploring limits beyond LEP.
Observe that this assumes degenerate stau masses.

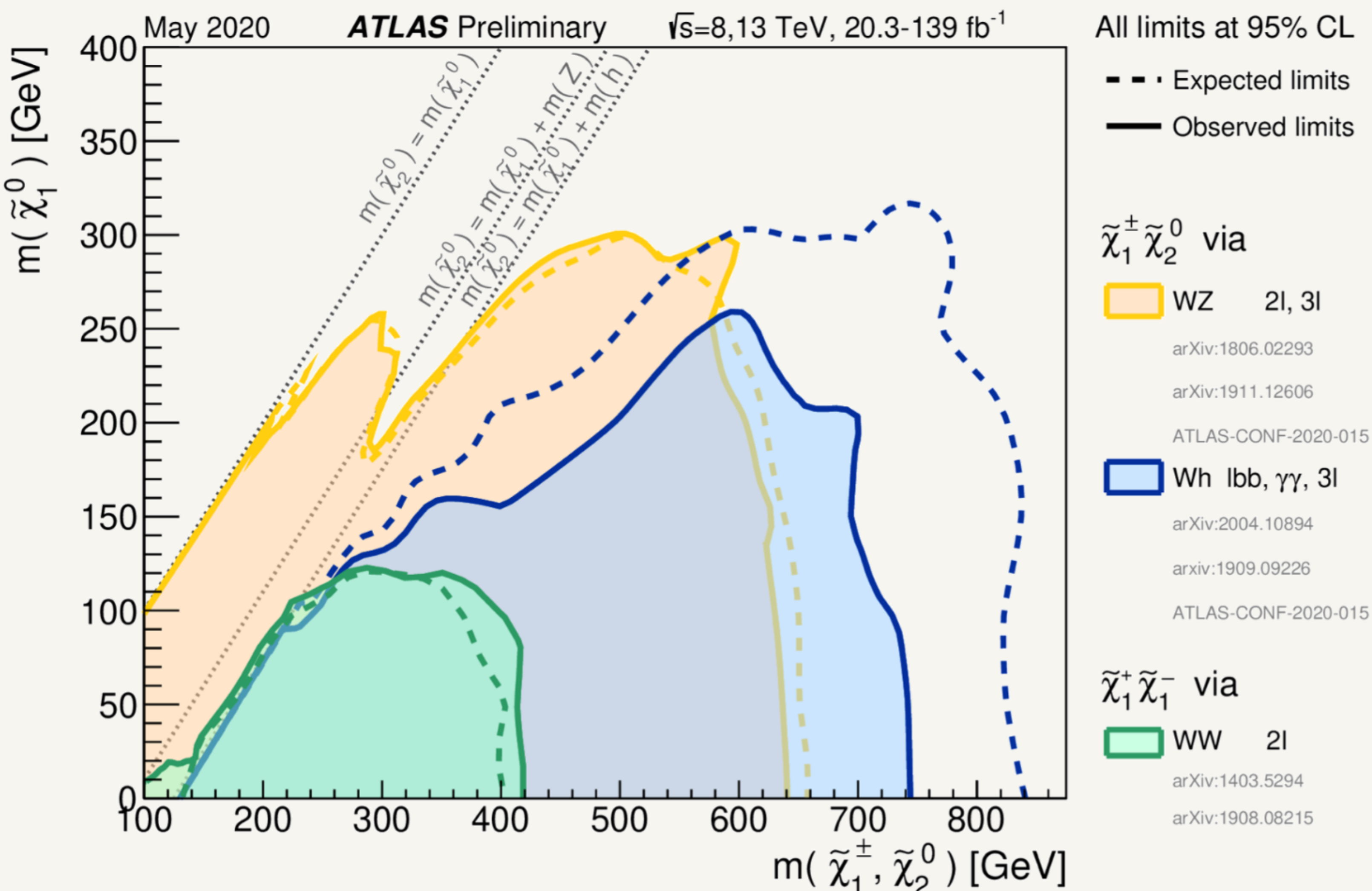
# Slepton Searches



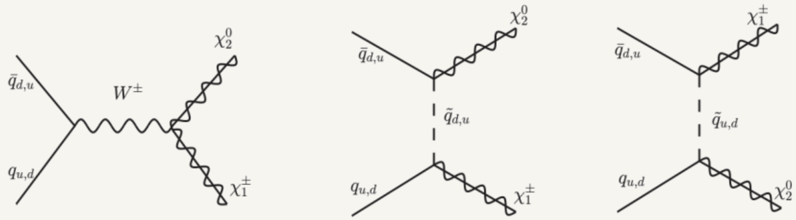

Assuming all leptons are degenerate, bound can be as large as 700 GeV. Bounds are significantly relaxed if mass difference between sleptons and neutralinos is smaller than ~100 GeV.

# Current Electroweakino Mass Bounds

## Wino NLSP, BR = 1

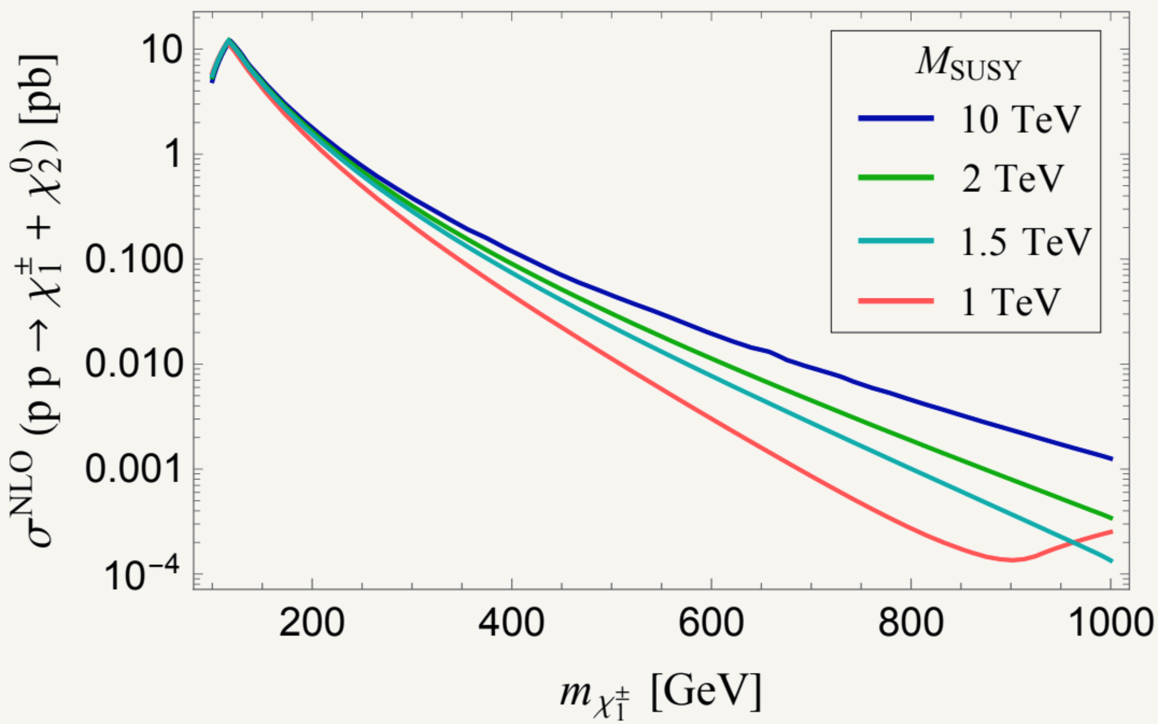


# But also… The Squarks!




In evaluating these bounds the squarks have been decoupled.
**But** cross section depends on the squark masses due to a *t* and *u* channel contribution to them

Liu, McGinnis, Wang, Wagner arXiv:2008.11847




The resulting cross sections may differ by factors of a few!