Supersymmetry after Higgs discovery (Status/Prospects)

Kick-off meeting : 08/30/2016

Masahiro Ibe (ICRR&IPMU)

What have we learned from LHC results ?

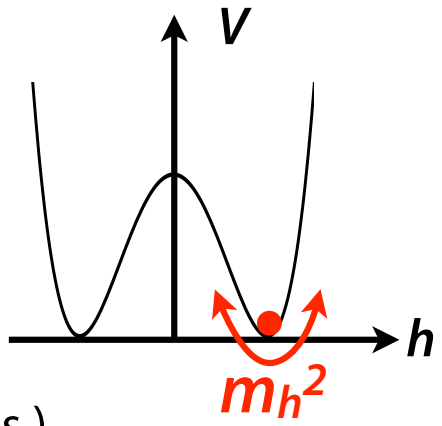
- ✔ Higgs exists
- ✔ Higgs is more like an elementary scalar

  Higgs can be fit by the simplest implementation

$$V = - m_{higgs}^2/2\, h^\dagger h + \lambda/4\, (h^\dagger h)^2$$

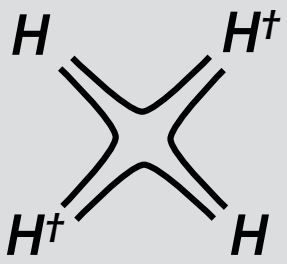
$$m_{higgs} = \lambda^{1/2}\, v \;[\, v=174.1GeV]$$

$$m_{higgs} \sim 125GeV \longrightarrow \lambda \sim 0.5$$



(We knew $v=174.1GeV$ before the discovery of Higgs)

e.g.) Naive composite Higgs :



λ is expected to be very large ($\simeq 4\pi$)

(Exceptional models : NGB Higgs
→ Top Yukawa coupling is difficult...)

What have we learned from LHC results ?

- ✔ No New Physics beyond the SM has been confirmed …

  [Some tentative hints are/were reported though]

- ✔ Wide range of alternatives to the Standard Model have been excluded…

  [e.g. Higgsless models]

Could the Standard Model Be the Ultimate Theory?

Answer is NO

There should be new physics which addresses at least

- ✔ Quantum Gravity
- ✔ Neutrino Masses
- ✔ Dark Matter
- ✔ Baryon Asymmetry of the Universe
- ✔ Inflation
- ✔ Strong CP problem
- ✔ Anomalies (muon ***g-2***, ***B***-physics etc)

Are some of these entries accessible at the LHC ?

Possibly, but not sure…

Most of the above entries can be solved in decoupled (ultra-violet) theories…

Why New Physics at the LHC ?

We want to know why the weak scale << M_{PL} .

Let us suppose that the Higgs couples to ***X*** in the UV theories.

$$\Delta L = \lambda_X |h|^2 |X|^2$$

$$\rightarrow \Delta m_h^2 = \frac{\lambda_X}{16\pi^2}\left[\Lambda_{\rm UV}^2 - m_X^2\left(\log\left(\frac{\Lambda_{\rm UV}^2}{m_X^2}\right) + (\text{finite})\right)\right]$$

→ Even aside from the quadratic divergence, the Higgs boson mass is sensitive to the UV scale m_X !

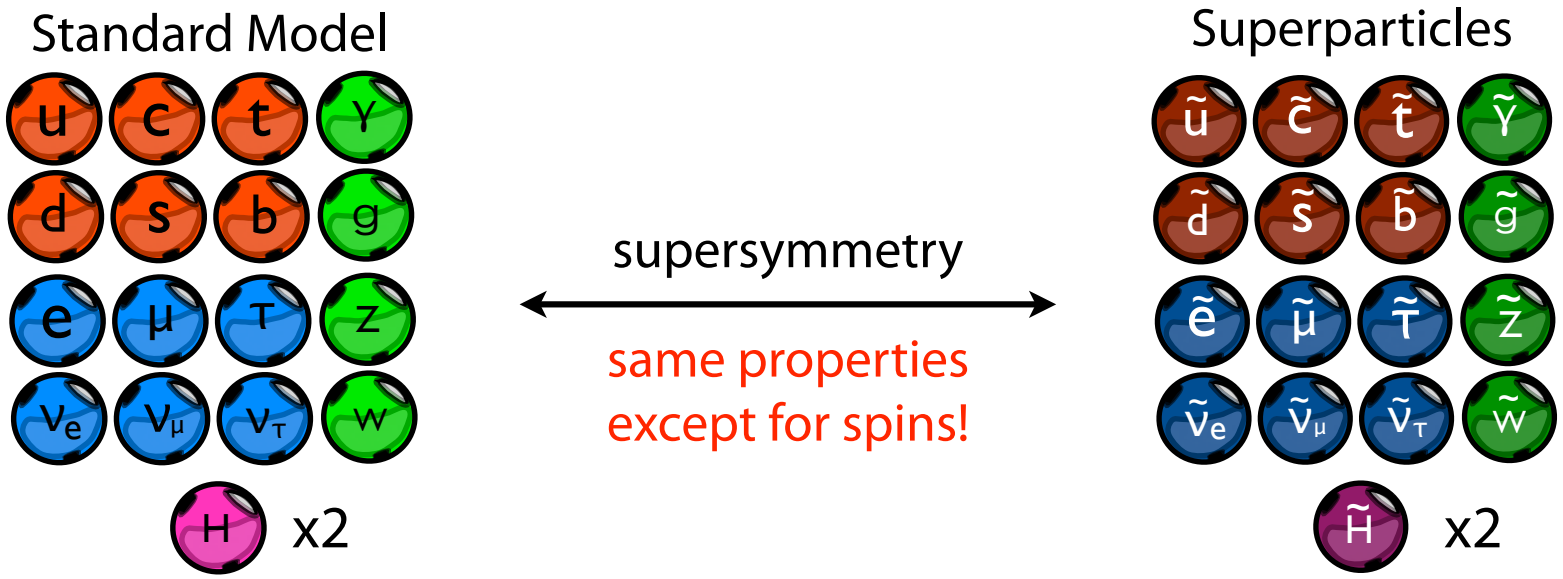
If M_W << M_{PL} is explainable, there should be new physics close to M_W which renders the SM being UV insensitive.

→ New Physics Accessible at the LHC !

[No verifiable conflicts happen even if no new physics exist…]

Supersymmetric Standard Model

✔ We just enlarge spacetime symmetry to supersymmetry !



Higgs mass term can be protected !

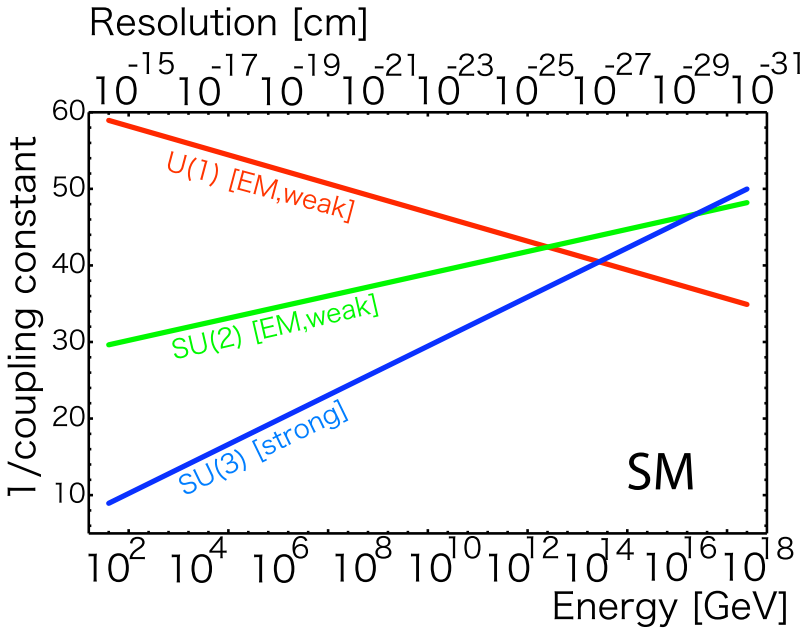
Higgs mass term = Higgsino mass term
Higgsino mass term can be protected by the chiral symmetry!
Hierarchy problem is solved if SUSY breaking is around M_W.

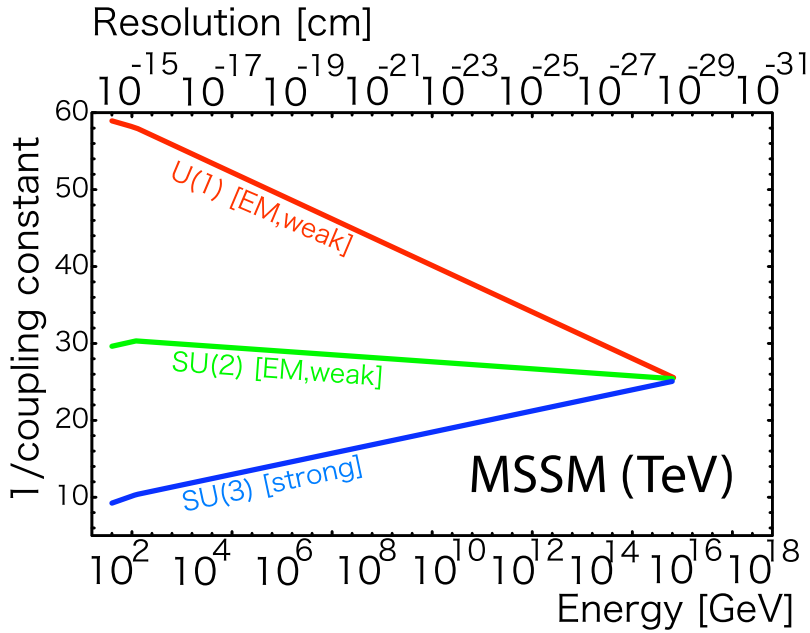
['79 Maiani, '81 Witten, '81 Kaul]

Supersymmetric Standard Model

✔ Big Bonus !

Just by introducing the superpartners at around ***TeV***, the gauge coupling unification become more precise!





Supersymmetric standard model is perfectly consistent with GUT !

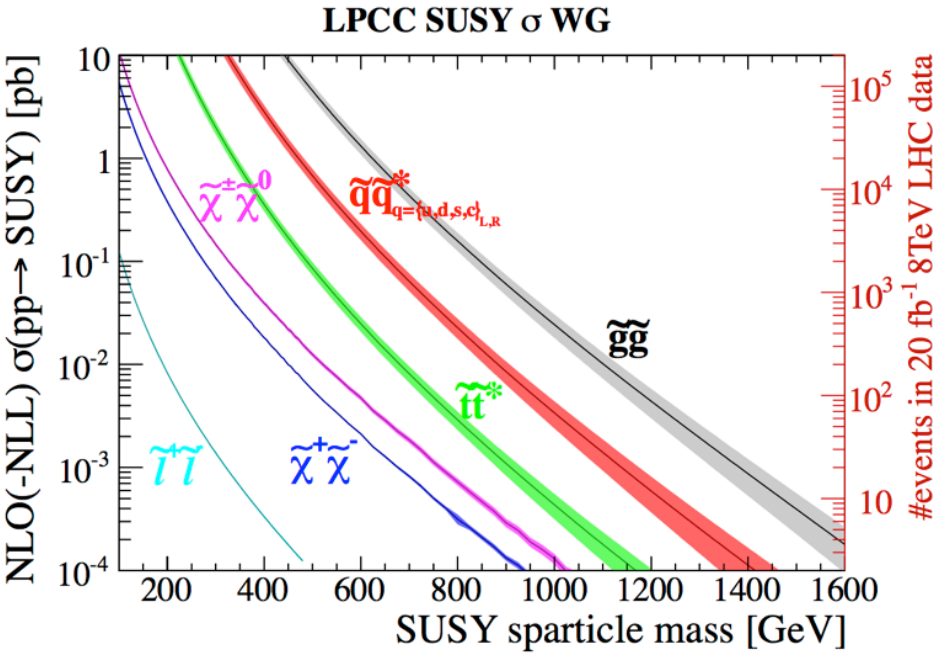
Supersymmetric Standard Model

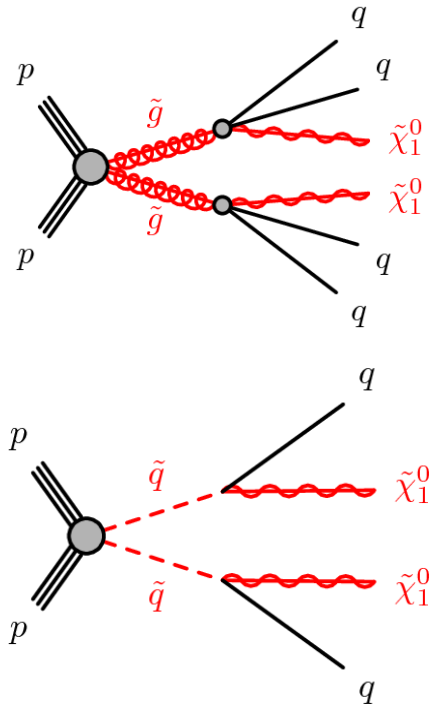
✔ Searchable at the LHC !

Supersymmetry = Spacetime symmetry

All the Standard Model particles are accompanied by superpartners.

→ Lots of colored new particles (***gluino***, ***squarks***)





at ***13TeV***, the cross section is ***x10*** larger !

Big Blow to supersymmetry?

The Higgs boson ~ 125GeV requires multi-TeV SUSY ?

In the MSSM, the tree-level Higgs boson mass is given by the gauge coupling constants.

$$V = - m_{higgs}^2/2\, h^\dagger h + \lambda/4\, (h^\dagger h)^2$$

A combination of the SUSY breaking masses and the Higgsino mass

$\lambda = (g'^2+g^2)/2\, \cos^2 2\beta$ from gauge couplings

The predicted Higgs boson mass is around Z-boson mass,

$$m_H = \lambda^{1/2}\, v \sim m_Z \cos 2\beta$$

at the tree-level.

Big Blow to supersymmetry?

The Higgs boson ~ 125GeV requires multi-TeV SUSY ?

The radiative corrections to the Higgs boson mass logarithmically depend on the stop masses.

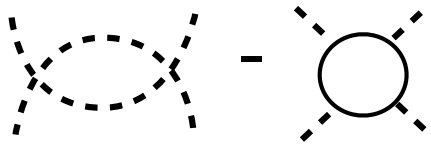
$$m_{h^0}^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi} y_t^2 m_t^2 \sin^2\beta \left(\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{X_t^4}{m_{\tilde{t}}^4} \right)$$

($X_t = A_t - \mu \cot\beta$)

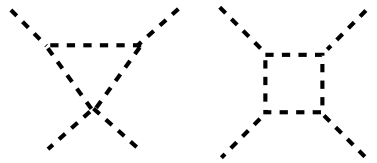
Tree-level quartic term:

$$\lambda = \frac{1}{2}(g_1^2 + g_2^2)\cos^2 2\beta$$

One-loop log enhanced:



One-loop finite:



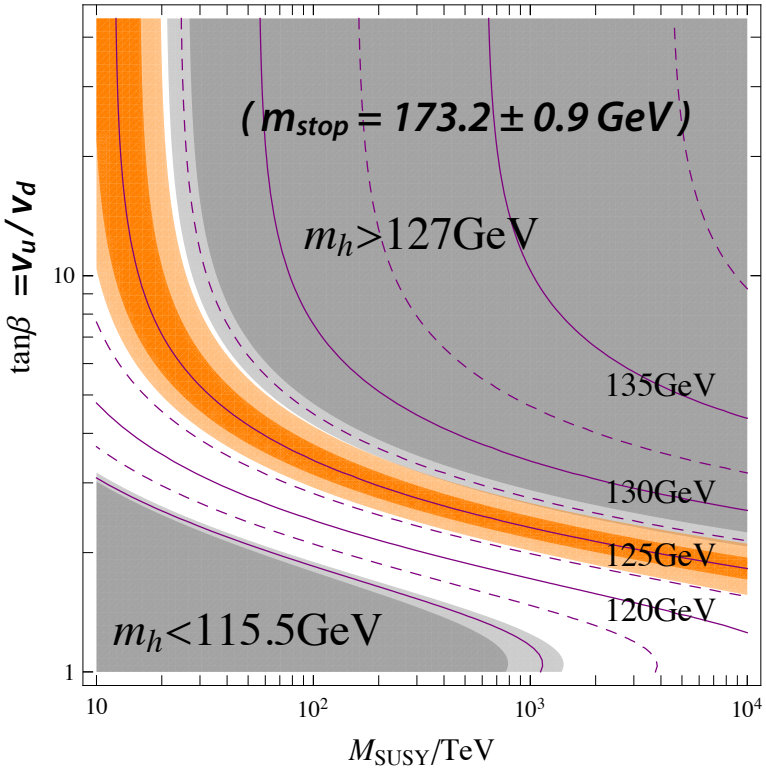
['91 Okada, Yamaguchi, Yanagida, '91 Haber, Hempfling, '91 Ellis, Ridolfi, Zwirner]

The observed Higgs boson mass requires a rather large SUSY breaking effects!

Big Blow to supersymmetry?

The Higgs boson ~ 125GeV requires multi-TeV SUSY ?

The simplest interpretation: $m_H \sim 125$ GeV suggests that the sfermion (stop) masses are above **O(10-1000)TeV** *['91 Okada, Yamaguchi, Yanagida]*.

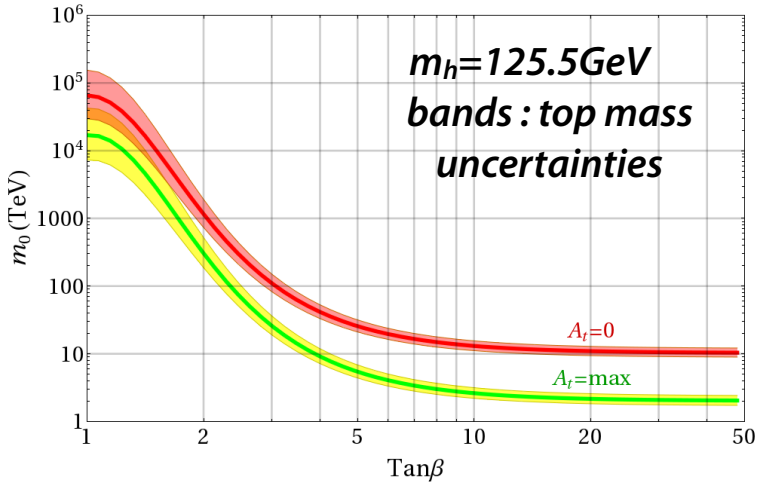


['12, MI, Matsumoto,Yanagida (μ_H=O(M_{susy}))]

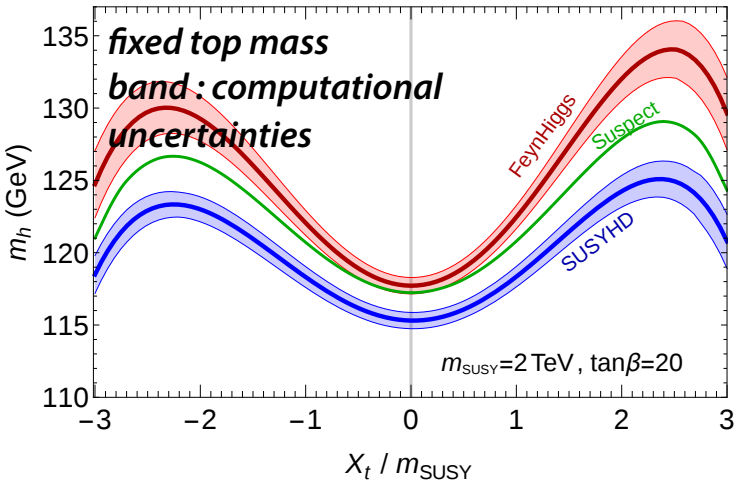
Big Blow to supersymmetry?

The Higgs boson ~ 125GeV with a few TeV SUSY ?

✔ A large ***stop A-term*** (trilinear coupling) can enhance the Higgs boson mass !



['12 Arvanitaki, Craig, Dimopoulos, Villadoro]



['15 Vega, Villadoro]

✔ Having a large ***stop A-term*** (trilinear coupling) at the low energy scale is not very easy.

$$16\pi^2 \frac{d}{dt} a_t = a_t \left[18 y_t^* y_t + y_b^* y_b - \frac{16}{3} g_3^2 - 3 g_2^2 - \frac{13}{15} g_1^2 \right] + 2 a_b y_b^* y_t + y_t \left[\frac{32}{3} g_3^2 M_3 + 6 g_2^2 M_2 + \frac{26}{15} g_1^2 M_1 \right],$$

[e.g. GMSB realization '11 MI, Evans, Yanagida]

[see '15 Kitano, Murayama, Tobioka with KK-effect]

[Extra matter can also enhance A-term see '16 Moroi, Yanagida, Yokozaki]

→ As a whole, ***m_{squark} > TeV*** is required

Big Blow to supersymmetry?

The Higgs boson ~ 125GeV with a few TeV SUSY ?

✔ Extra Vector Matter (e.g. ***10*** representation ***['92 Moroi, Okada]***)

$$\mathbf{10} = (Q_E, \bar{U}_E, \bar{E}_E) \ , \quad \bar{\mathbf{10}} = (\bar{Q}_E, U_E, E_E)$$

$$W = M_T \bar{Q}_E Q_E + M_T \bar{U}_E U_E + M_T \bar{E}_E E_E + \lambda_u H_u Q_E \bar{U}_E$$

Higgs quartic potential receives an additional radiative contributions !

$$\Delta V \simeq \frac{\Delta\lambda^2}{2} |H_u|^4 \qquad \Delta\lambda \simeq \frac{\lambda_u^2}{16\pi^2} \left(6 \log \frac{M_{SUSY}^2}{M_T^2} - 5 \right)$$

→ ***125GeV*** Higgs mass can be achieved as long as the extra matters have large SUSY soft masses in the ***TeV*** range.

If the soft masses of the MSSM and the extra matter have the same origin, the squarks are also in the ***TeV*** range though…

Big Blow to supersymmetry?

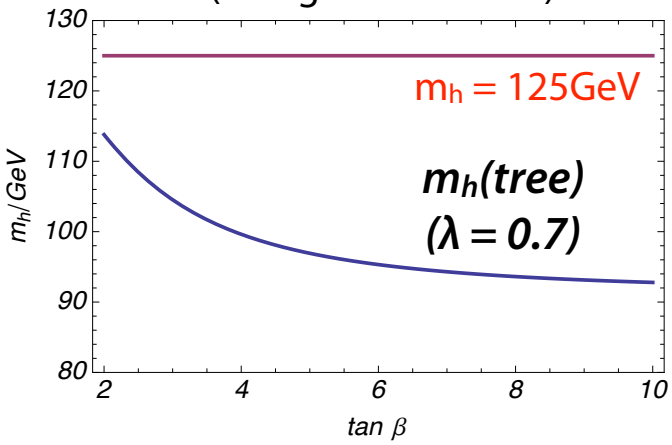
The Higgs boson ~ 125GeV with a few TeV SUSY ?

✔ Singlet Extension (NMSSM) *[see '10 Maniatis for review]*

We add a tree-level quartic term to the Higgs scalar potential :

$$W = \lambda N H_u H_d + \frac{1}{3}\kappa N^3 \quad \rightarrow \quad \Delta V \simeq \frac{\lambda^2}{4}\sin^2 2\beta\,(h^\dagger h)^2$$

(Rough estimation)



Accordingly, the tree-level Higgs mass is lifted :

$$(m_{H_1}^{\rm NMSSM})^2 < m_Z^2\left(\cos^2(2\beta) + \frac{2|\lambda|^2\sin^2(2\beta)}{g_1^2+g_2^2}\right)$$

Still, we need some radiative contributions to achieve ***125GeV*** from the squarks in a ***TeV*** range.

(***λ < 0.7*** from perturbativity)

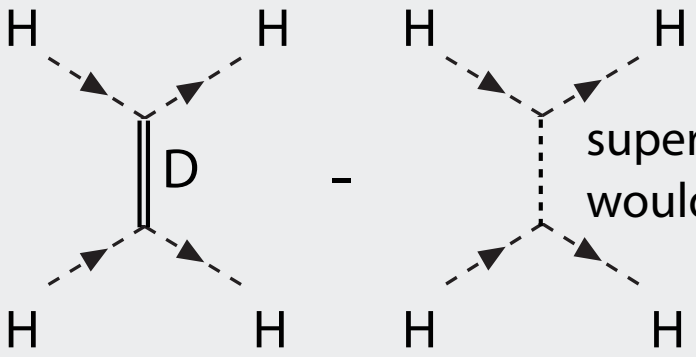
[For the scenarios where the lightest Higgs is not the observed one see ***'13 Christensen, Han, Liu, Su***] .

Big Blow to supersymmetry?

The Higgs boson ~ 125GeV with a few TeV SUSY ?

✔ Extended Gauge Symmetry *['06 Maloney, Pierce, Wacker]*

If the gauge symmetry of the MSSM is extended, the Higgs obtains tree-level quartic ***D-term*** potential



superpartner of would-be NGB

$$\sim \frac{g^2}{2}\frac{M_{\rm SUSY}^2}{M_{Z'}^2+M_{\rm SUSY}^2}(|H_u|^2-|H_d|^2)^2$$

$M_{Z'}$: Mass of new gauge boson

We need a rather large ***g*** and at least ***TeV*** soft mass to the gauge symmetry breaking sector.

If the soft masses of the MSSM and the gauge breaking sector have the same origin, the squarks are again in the ***TeV*** range.

Big Blow to supersymmetry?

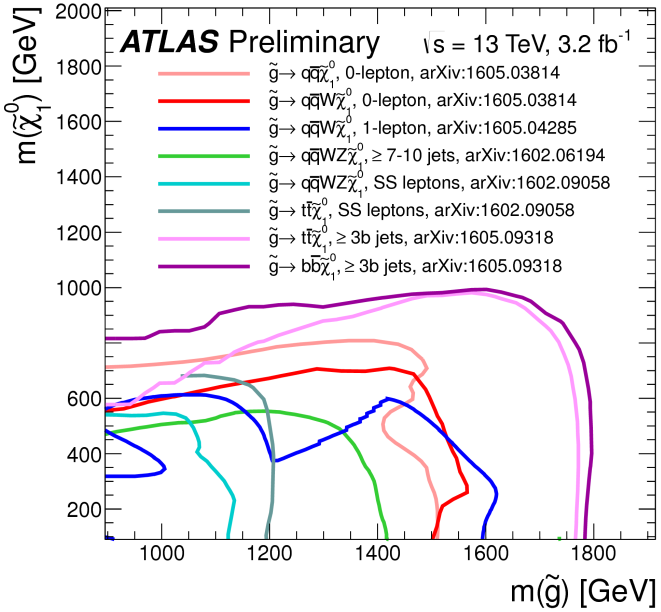
The observed Higgs boson mass disfavors the squark (stop) masses in the ***hundreds GeV*** range…

- This is a big blow to supersymmetry…

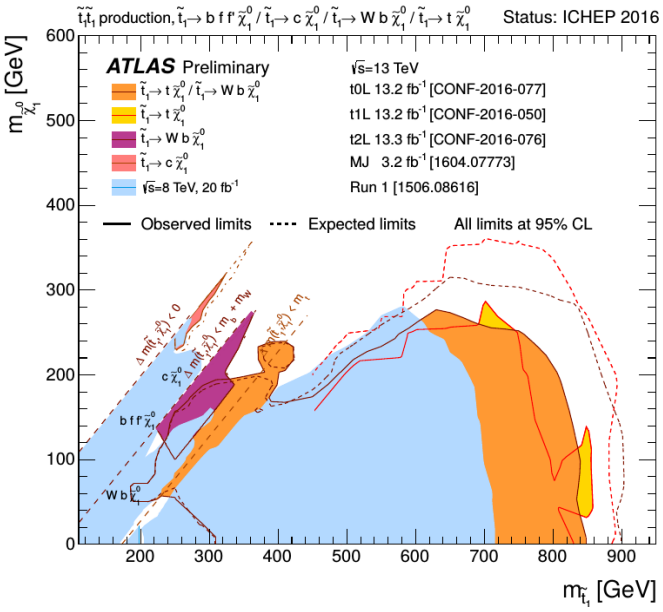
  [Before the LHC, we expected that the SUSY is easier to be discovered than the Higgs boson !!]

- Although it's a big blow, at the same time, the null SUSY discovery so far is not very surprising in view of the ***125GeV*** Higgs.

[ATLAS Summary, 13TeV]



[light stop search (ICHEP)]



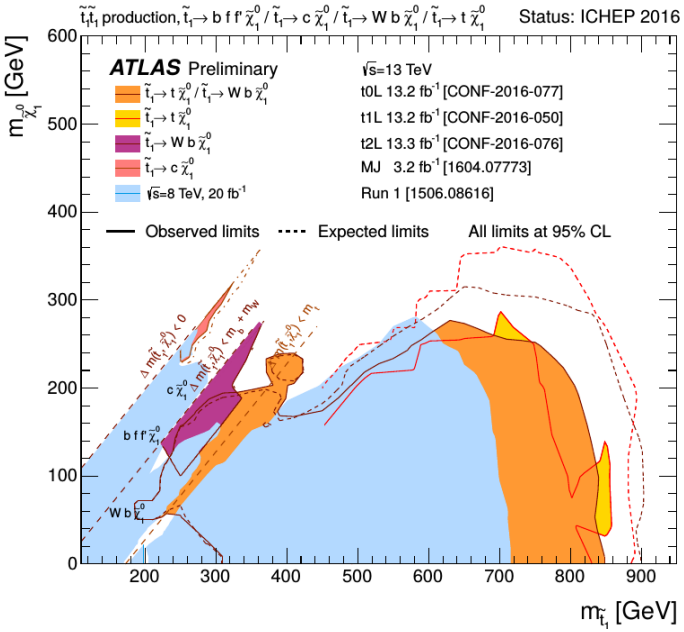
How about the naturalness ?

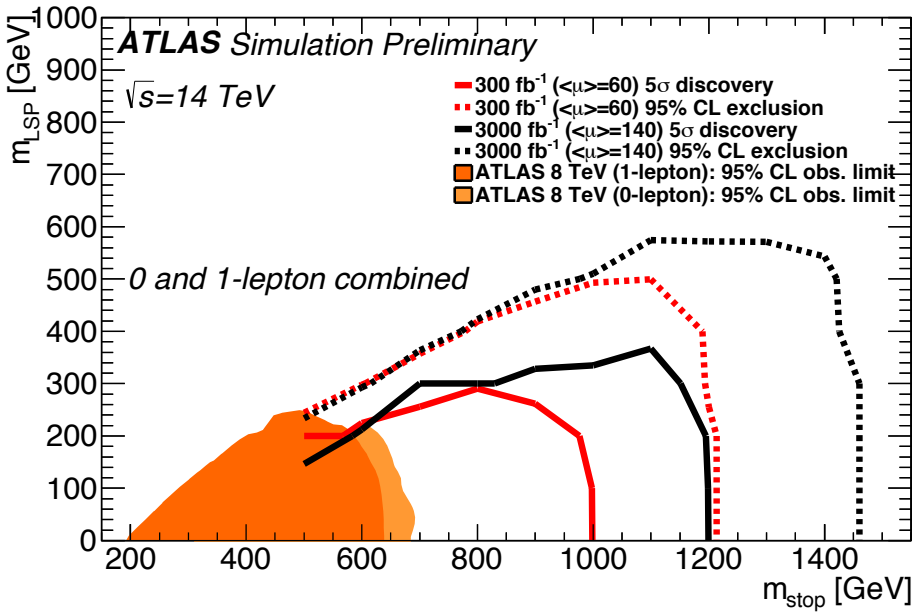
Natural SUSY (m_{stop}, m_{Hu}, m_{Hd}, $\mu \sim O(100)$GeV)

- ✔ Parameter regions are getting smaller by direct searches.
- ✔ The explanation of the Higgs boson mass is not easy.
- ✔ We need to avoid fine-tuning to achieve ***the natural spectrum.***
- ✔ Model building is getting more complicated…

(but should not give up this possibility)

[ATL-PHYS-PUB-2013-011]





How about the naturalness ?

SUSY (in particular the stops) in the TeV range.

Is it natural to have <*H*> = ***174 GeV*** from the ***TeV*** mass parameters ?

It is actually more or less a matter of taste.

We do not complain the naturalness once the squarks are discovered in the ***TeV*** range !

(Still, we would wonder why SUSY is not in the weak scale in this case.)

✔ We look forward further searches at the LHC !

$M_{gluino} \sim M_{squark} > 1.8$ ***TeV (Run1)***

$M_{gluino} > 1.8$ ***TeV*** for $M_{squark} \gg$ ***TeV (13TeV,13.3fb^{-1})***

[Future discovery reaches: $M_{gluino} \sim M_{squark} \sim 2.8$ ***TeV (14TeV, 300fb^{-1})***

$M_{gluino} \sim M_{squark} \sim 3.2$ ***TeV (14TeV, 3000fb^{-1})***

$M_{gluino} \sim M_{squark} \sim 6.8$ ***TeV (33TeV, 3000fb^{-1})]***

[arXiv:1310.0077]

How about the naturalness ?

SUSY (in particular the stops) in the TeV range.

✔ SUSY in the ***TeV*** range might be more natural than it appears.

→ Focus point mechanism ***['99 Feng, Matchev, Moroi]***

When soft breaking parameters of $O(M_{SUSY})$ at the UV satisfy a special (and motivated) condition, m_{Hu}^2 can be much smaller than M_{SUSY}.

$$m_{Hu}^2 = \varepsilon M_{SUSY}^2 \quad (\varepsilon << 1)$$

['99 Feng, Matchev, Moroi : $m_{Hu}^2 = m_{Hd}^2 = m_{Q3}^2 = m_{U3}^2$ >> gaugino mass]

['13 Yokozaki, Yanagida : M3 : M2 = 0.4 : 1 in gaugino mediation]

[Models in gauge mediation, see e.g. '15 Murayama, Yokozaki, Yanagida]

For a large ***tanβ***, the weakscale is of O(m_{Hu}^2) :

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}\Big|_{m_{\rm weak}} \approx -\mu^2 - m_{H_u}^2\big|_{m_{\rm weak}}$$

The weakscale can be obtained from the ***TeV*** SUSY naturally !

✔ ***Higgsino searches in O(100)GeV range are important !***

How about the naturalness ?

SUSY (in particular the stops) in the O(10-1000) TeV range.

- ✓ This is the simplest interpretation of the ***125GeV*** Higgs boson mass.
- ✓ We do not think that $\langle H \rangle = 174\text{GeV}$ is ***naturally explained*** by the models the mass parameters of ***O(10-1000) TeV***.

(may be a matter of taste again though…)

One simple answer is : SUSY with ***O(10-1000)TeV*** is much much better than the Standard Model.

SM : $m_{higgs}^2/M_{GUT}^2 \sim 10^{-(24\text{-}28)}$

MSSM : $m_{higgs}^2/M_{SUSY}^2 \sim 10^{-(4\text{–}8)}$

Not very convincing though…

How about the naturalness ?

SUSY (in particular the stops) in the O(10-1000) TeV range.

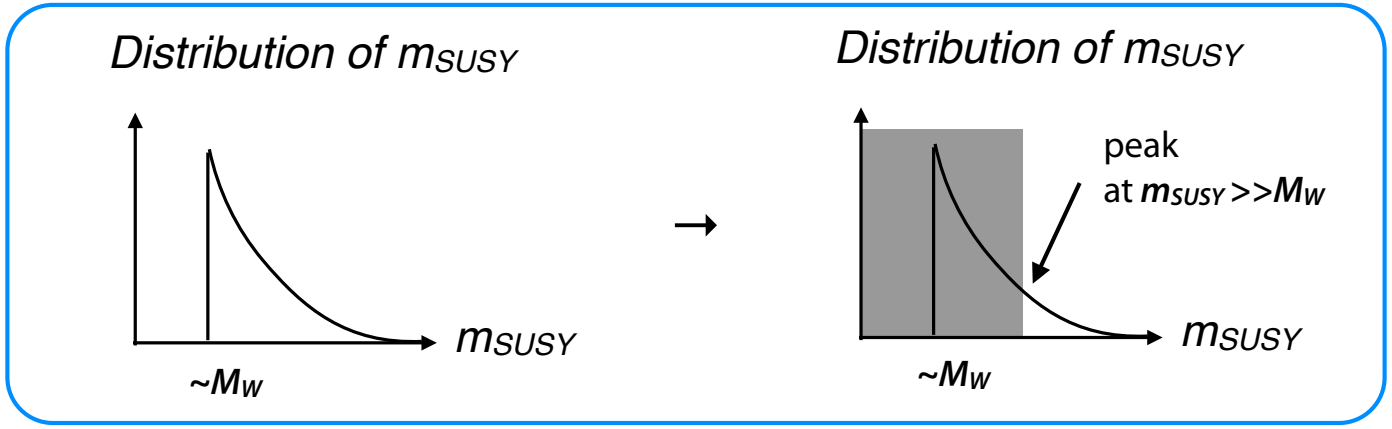
- Clearly, we need more consideration.

  So far, I do not have very convincing arguments...

- Combination with Landscape/habitability arguments ?

  For $\langle H \rangle = 174\,GeV$, it seems better to have SUSY in the electroweak scale.

  If some habitable conditions put lower limits on the SUSY scale, then the peak of the distribution of M_{SUSY} can be much higher than M_W.



Arguments depend on a lot of assumptions…

Difficult to be confirmed experimentally…

Once additional light scalar bosons requiring fine-tuning are discovered, this explanation becomes much less convincing.

High Scale SUSY

What do we get once we accept ***O(10-1000)TeV*** SUSY ?

Are those scenarios interesting ?

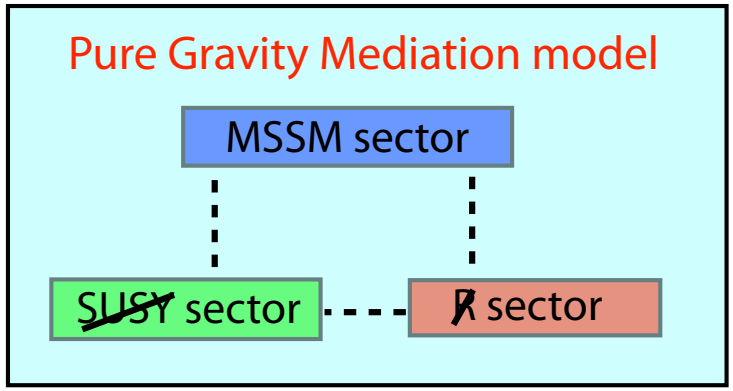
- ✔ This is the simplest interpretation of the ***125GeV*** Higgs boson mass.
- ✔ Gaugino masses are not necessarily ***O(10-1000)TeV*** .
- ✔ They can be often suppressed by symmetries such as ***R-symmetry*** !

→ The models with ***O(10-1000)TeV*** SUSY are testable at the LHC !

- ✔ There are interesting models which is motivated by consistencies in cosmology !

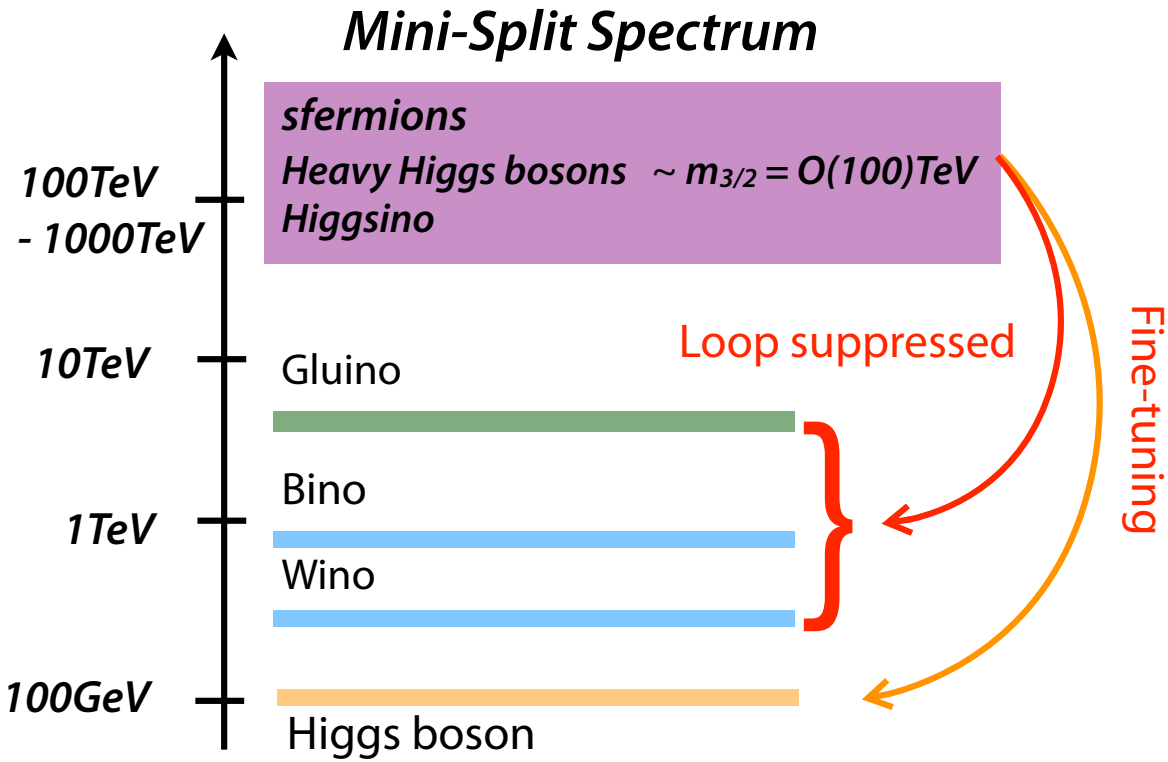
High Scale SUSY at 100TeV - PeV

- ✔ Consistent with cosmology (good DM candidate, no Gravitino/Polonyi problem)
- ✔ Model building is very simple !
- ✔ Fine-tuning problem between ***O(10-1000)TeV*** and ***O(100)GeV…***



They are connected by generic Planck suppressed operators with each other.

['04 Wells, 06'MI,Moroi,Yanagida,12 MI, Yanagida, '12 Arkani-hamed, Gupta, Kaplan, Weiner, Zorawski…]



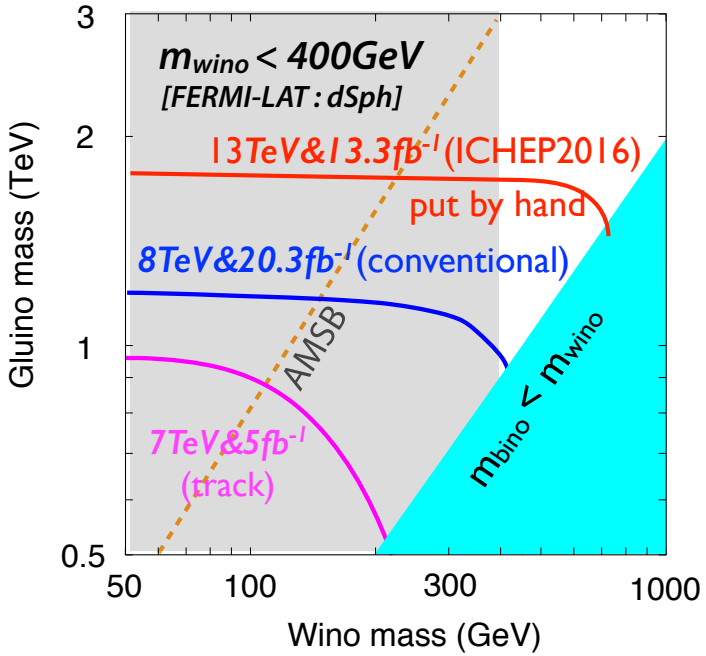
Gaugino Masses are One-Loop Suppressed !

Gaugino Masses = Anomaly Mediation + Higgsino Mediation

['99 Giudice, Luty, Murayama, Rattazzi, '99 Gherghetta, Giudice, Wells]

High Scale SUSY at 100TeV - PeV

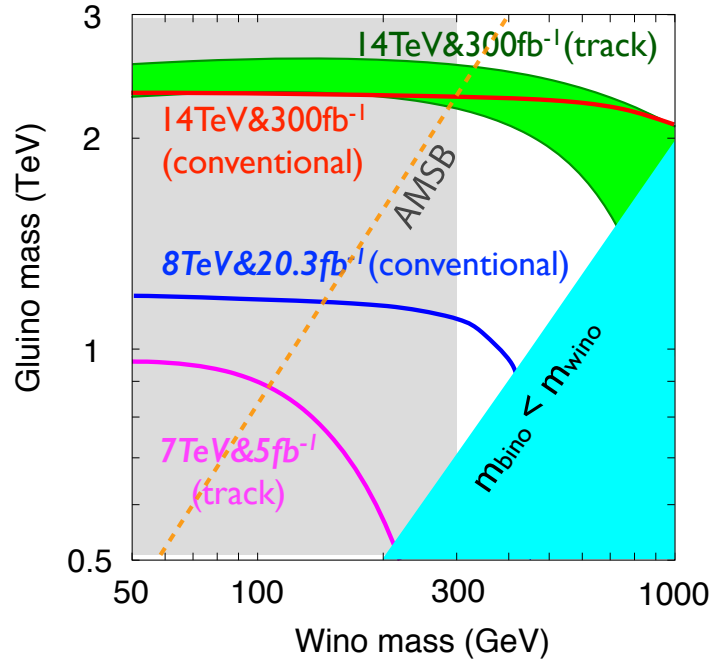
Current limits via gluino production *['12, Bhattacherjee, Feldstein, MI, Matsumoto, Yanagida]*



✔ Multi-jets + Missing p_T search
(conventional SUSY search)

$m_{gluino} > 1.8$ TeV or $m_{wino} > 600$GeV
$m_{gluino} > 1$TeV or $m_{wino} > 800$GeV
[@95%CL: ATLAS-CONF-2015-062 13TeV, 3.2fb^{-1}]

For ***gluino→tt+wino*** or ***bb+wino***, the constraints get a little more stringent.



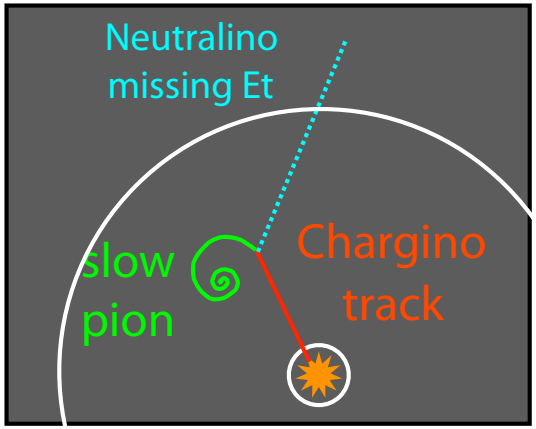
✔ Prospects ?

M_{gluino} ~ 2.3 TeV (14TeV,300fb^{-1})
M_{gluino} ~ 2.7 TeV (14TeV,3000fb^{-1})
M_{gluino} ~5.8 TeV (33TeV, 3000fb^{-1})

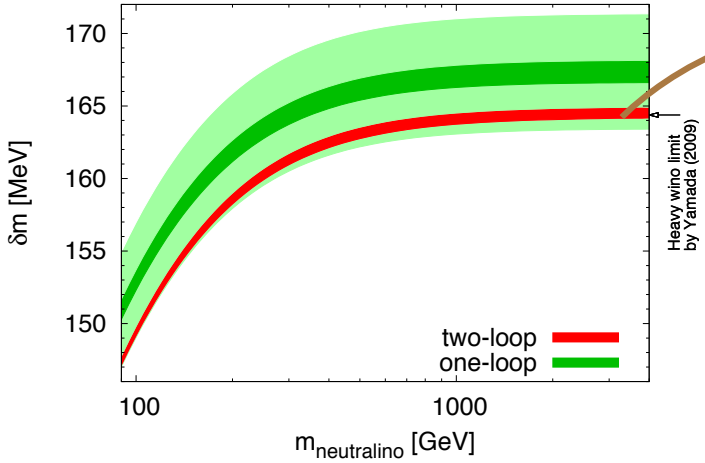
[arXiv:1310.0077]

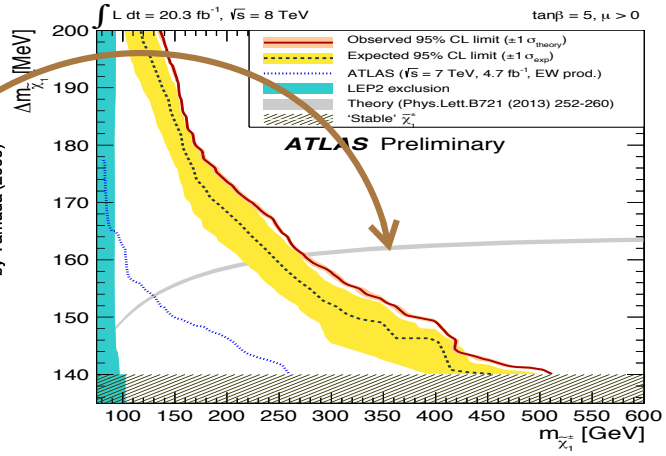
High Scale SUSY at 100TeV - PeV

✔ Direct Wino Production



['12 Ibe,Mastumoto,Sato]





✔ Main decay mode : $\chi^{\pm} \rightarrow \chi^{0} + \pi^{\pm}$: $\tau_{wino} = O(10^{-10})$ sec.

✔ Limits (disappearing track search):

$m_{wino} > 130GeV$ ($7TeV\&5fb^{-1}$) using TRT	[arxiv:1210.2852]
$m_{wino} > 270GeV$ ($8TeV\&20fb^{-1}$) using SCT & TRT	[arXiv:1310.3675]

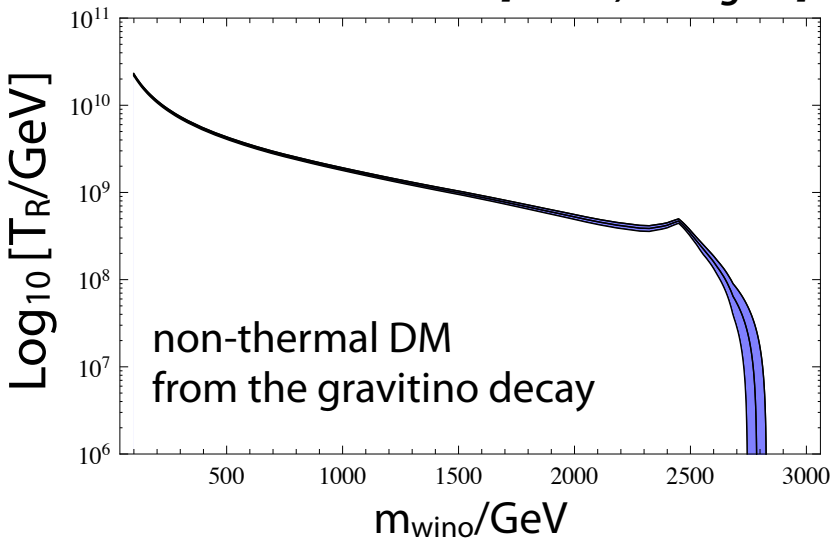
→Prospects: $M_{wino} \sim 500GeV$ ($14TeV, 300fb^{-1}$)
$M_{wino} \sim 650GeV$ ($14TeV, 3000fb^{-1}$)
$M_{wino} \sim 3TeV$ ($100TeV, 3000fb^{-1}$)

[1407.7058, Cirelli, Sala, Taoso]

High Scale SUSY at 100TeV - PeV

✔ Wino dark matter is very successful !

['11 MI, Yanagida]



Thermal Wino dark matter

$M_{wino} \sim 2.8\mathrm{TeV}$

['07 Hisano, Matsumoto, Nagai, Saito, Senarmi]

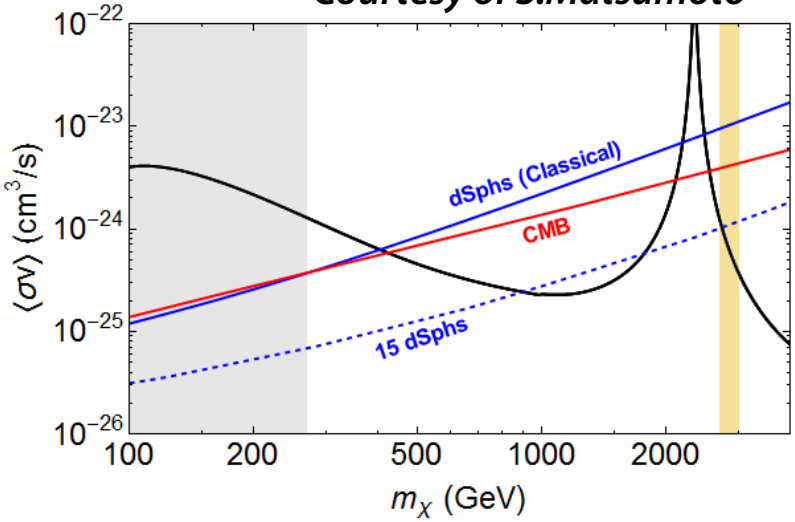
Non-thermal Wino dark matter from gravitino decay

$M_{wino} < 1\text{-}1.5\ \mathrm{TeV}$

for successful leptogenesis ($T_R > 10^9\mathrm{GeV}$).

✔ Indirect search by gamma-ray from dwarf Spheroidal galaxies are promising !

Courtesy of S.Matsumoto



Fermi-LAT 6 years data excluded the wino dark matter in

$M_{wino} < 400\ \mathrm{GeV}$ ***(classical dSphs)***

[For recent J-factor estimation '16 Hayashi, Ichikawa, Matsumoto, MI, Ishigaki, Sugai]

R-invariant Gauge Mediation

R-invariant Gauge Mediation Model *['97 Izawa, Nomura, Tobe, Yanagida]*

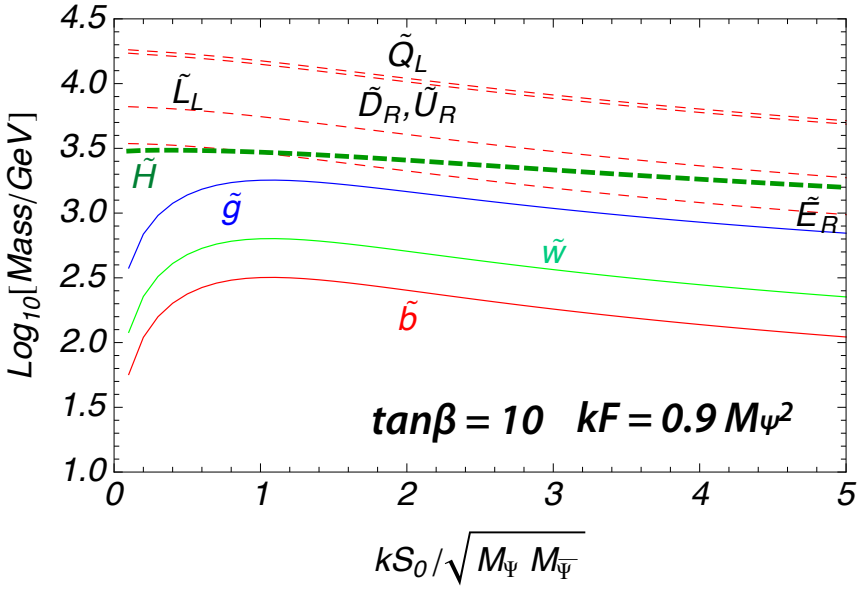
$$W = W_{\rm SUSY} + kS\Psi_i\bar{\Psi}_i + M_\Psi \Psi_i \bar{\Psi}'_i + M_{\bar{\Psi}}\bar{\Psi}_i\Psi'_i$$
$$W_{\rm SUSY} \simeq \Lambda^2 S$$

(***S*** : SUSY breaking field, ***Ψ*** : Messengers)

→ ***The SUSY vacuum in this model is stable !***

✔ MSSM Spectrum : $M_{sfermion} >> M_{gaugino}$

['15 Chiang, Harigaya,Ibe,Yanagida]



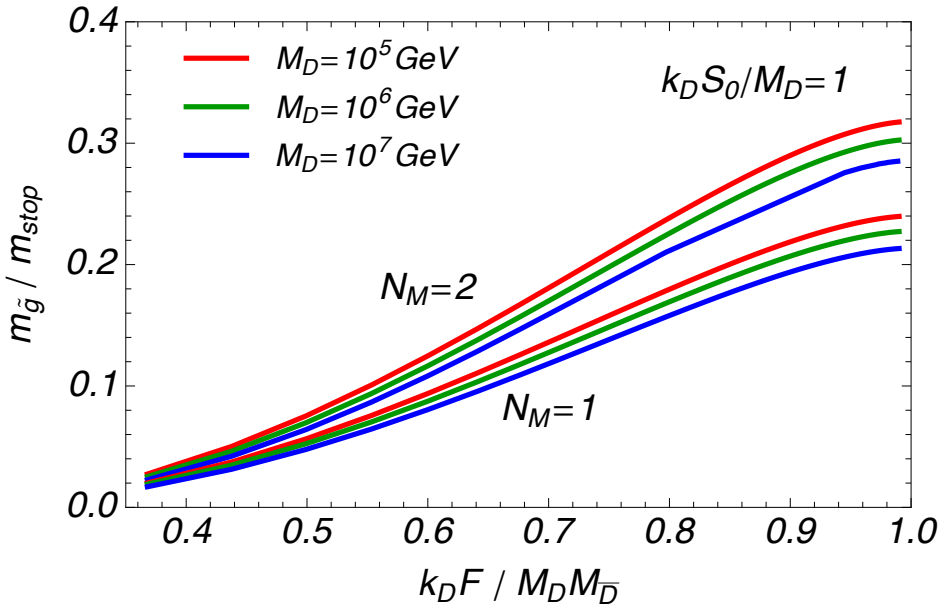
(Relative Size of spontaneous R-breaking)

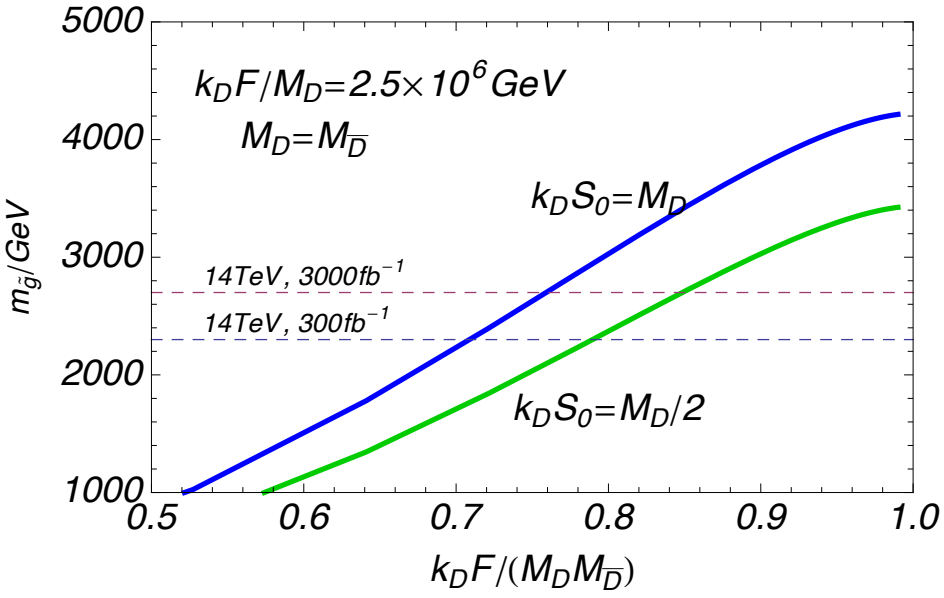
$$M_a \sim \frac{g_a^2}{16\pi}\frac{kF}{M_{\rm mess}} \times \mathcal{O}\left(\frac{k^2F^2}{M_{\rm mess}^4}\right) \times (0.1-0.3)\ ,$$
$$m_{\rm scalar} \sim \frac{g_a^2}{16\pi}\frac{kF}{M_{\rm mess}}\ ,$$

[This is due to ***d/dS(det[M_{Mess}]) = 0*** in ***R***-invariant models and hence generic!]

R-invariant Gauge Mediation

✔ Upper limit on the gluino mass ! *['15 Chiang, Harigaya,Ibe,Yanagida]*





✔ The gaugino are lighter than the sfermions!

✔ $M_{gluino}/M_{stop} < 0.2 - 0.3$

✔ To reproduce ***125GeV*** Higgs boson mass, $M_{stop} <$ ***20TeV*** (susyHD)
(large ***tanβ*** is predicted due to a small ***B-term***)

→ Gluino mass is bounded from above.

✔ NLSP = Stable Bino or Meta-stable Bino decaying into photon + gravitino

light Gravitino Mass region (m3/2 < O(10)eV)

- light stable gravitino is very attractive from Cosmology

- Recently, a severe upper limits are put from the CMB lensing and Cosmic Shear observations *['16 Osato, Sekiguchi, Shirasaki, Kamada, Yoshida]*

$$m_{3/2} < 4.7\ \mathrm{eV} \quad \rightarrow \quad \sqrt{F} \sim 65\ \mathrm{TeV} \times \left(\frac{m_{3/2}}{1\ \mathrm{eV}}\right)^{1/2}$$

Stringent constraints on the SUSY masses in GMSB !

- lighter gravitino might be preferred if we think of the naturalness problem from Cosmological Constant.

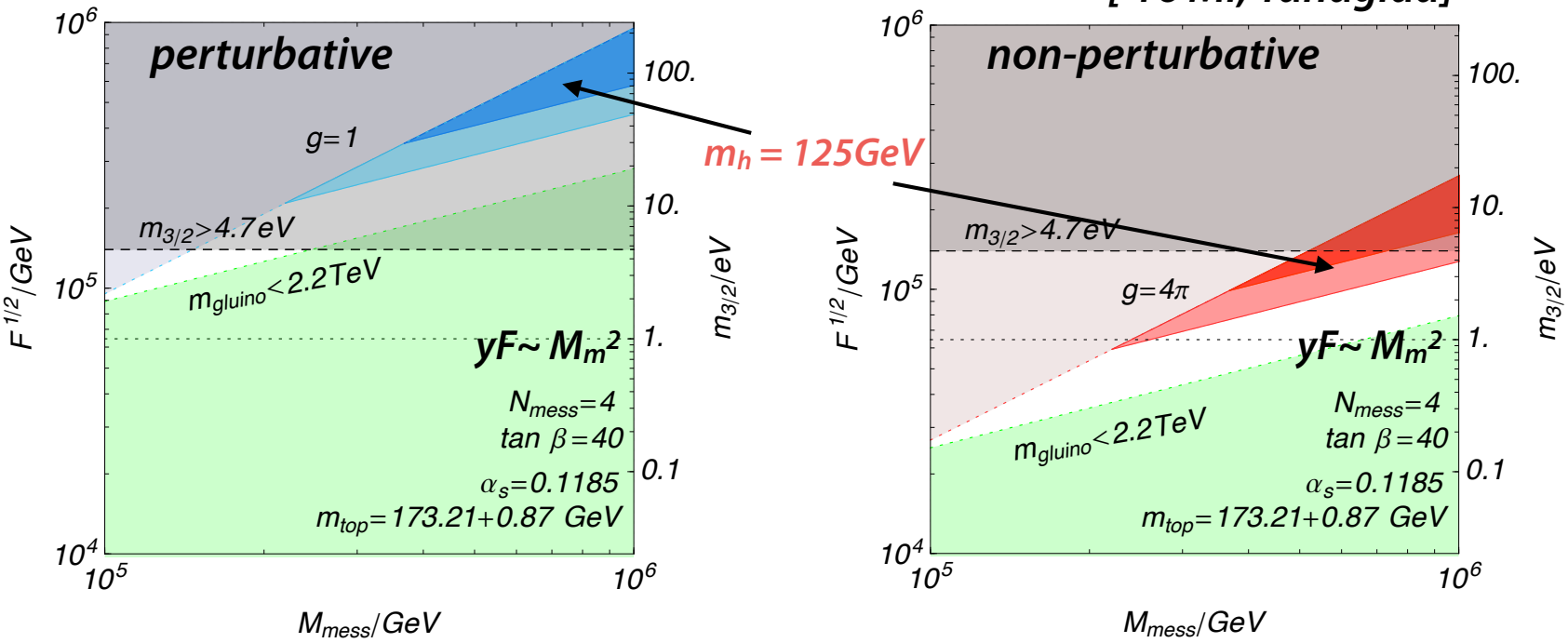
$$CC = F^2 - 3\, m_{3/2}^2\, M_{PL}^2$$

→ Closing this window is conceptually very important !

light Gravitino Mass region (m3/2 < O(10)eV)

$$W = yZ\Psi\bar{\Psi} + M_m\Psi\bar{\Psi} \ .$$

['16 MI, Yanagida]



- Most parameter regions have been excluded by the LHC searches (stau NLSP) for perturbative models (***y < O(1)***).
- For non-perturbative models with ***y = O(4π)***, there is an allowed parameter region.
- Future LHC and the cosmological observation (21cm observations) play important roles!

Summary

- The Standard Model is in very good shape...
  (Higgs can be fit by the simple elementary doublet.)

- The Higgs boson mass at ***125GeV*** disfavors very natural and simple SUSY models.

- In view of ***125GeV*** Higgs boson mass, the null SUSY results so far are not very surprising/discouraging.

- Although naturalness arguments become arguable than before, still SUSY is the most attractive model beyond the Standard Model.

  [SUSY can be consistent with the SM Yukawa intereactions. SUSY can be consistent with cosmology including inflation and baryogengesis such as leptogenesis.]

We still have a lot of chances to see ***TeV*** SUSY at the LHC !

Summary

- ***Natural SUSY models***

  Model building is more complicated than before…
  Parameter regions are getting smaller by direct searches.

  → Please let me know if you find good (and less complicated) models !

- ***TeV SUSY***

  We just need to wait for further results from the LHC !

  (Once it is discovered, it requires some extension to the MSSM.)

- ***High scale SUSY (in particular Pure Gravity Mediation Model)***

  This class of models is not only the simplest interpretation but also motivated by cosmological consistencies.

  Naturalness requires more scrutiny…

  Not only searchable at the LHC, the model can be tested via indirect searches of dark matter and precision measurements.

[Orthogonal to the above classification, models which account for the muon ***g-2*** are also important.]

Back Up Slides

R-invariant Gauge Mediation

- Gravitino mass (for ***125 GeV*** Higgs) :

$$m_{3/2} \simeq 10\,\mathrm{keV} \times \left(\frac{0.1}{k}\right)\left(\frac{(kF)^{1/2}}{2\times 10^6\,\mathrm{GeV}}\right)^2$$

- Bino decay length :

$$c\tau_{\tilde{B}} \simeq 0.6\,\mathrm{m} \times \left(\frac{500\,\mathrm{GeV}}{M_1}\right)^5 \left(\frac{m_{3/2}}{10\,\mathrm{keV}}\right)^2$$

- Gravitino thermalization temperature :

$$T_D \sim \max\left[M_{\tilde{g}}, 160\,\mathrm{GeV}\left(\frac{g_*(T_D)}{100}\right)^{1/2}\left(\frac{m_{3/2}}{10\,\mathrm{keV}}\right)^2\left(\frac{2\,\mathrm{TeV}}{M_3}\right)^2\right]$$

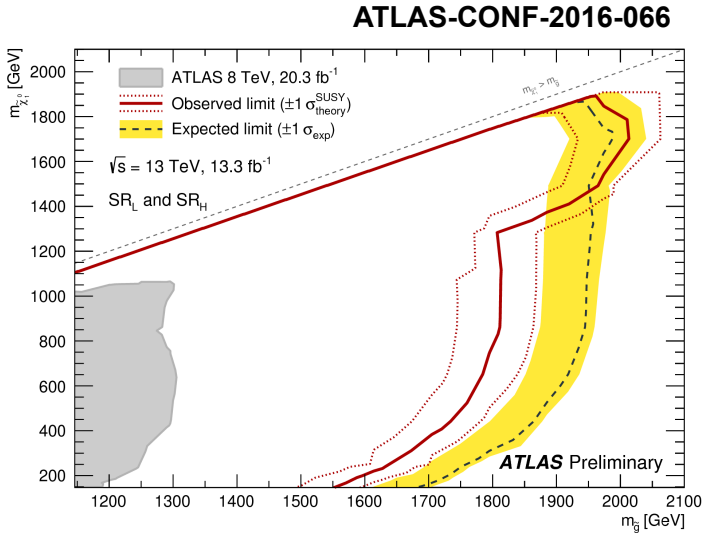
- Gravitino thermal dark matter density :

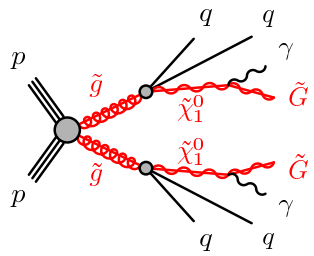
$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{100}{g_*(T_D)}\right)\left(\frac{m_{3/2}}{100\ \mathrm{eV}}\right)$$

We need entropy production ! (slightly warm dark matter)

Supersymmetry in the TeV ranges

- ✔ missing p_T search (the gravitino LSP with $m_{3/2} << O(1)keV$)
  - ✔ neutralino NLSP (missing p_T + photons)



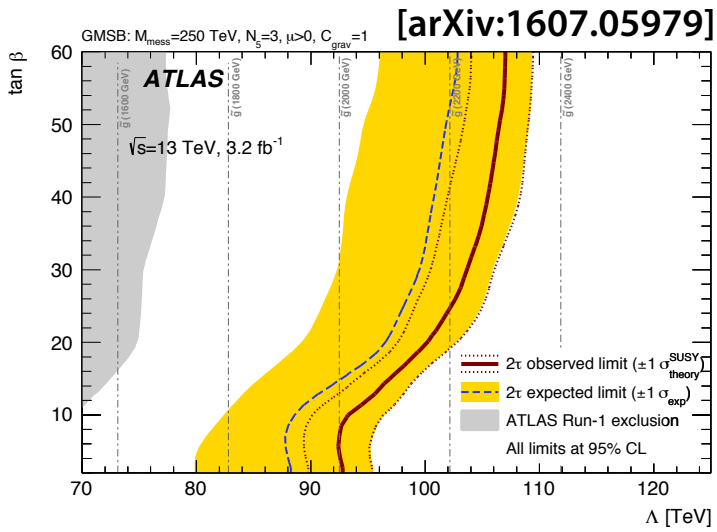


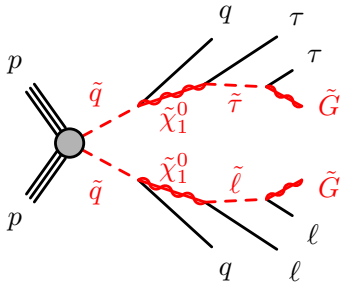
via gluino production

M_{gluino} >1.6 - 1.8 TeV

(M_{squark} >> TeV)

  - ✔ stau NLSP (missing p_T + tau)





via gluino,squark production

M_{gluino} >2 - 2.3 TeV

(GMSB : $N_m = 3$)

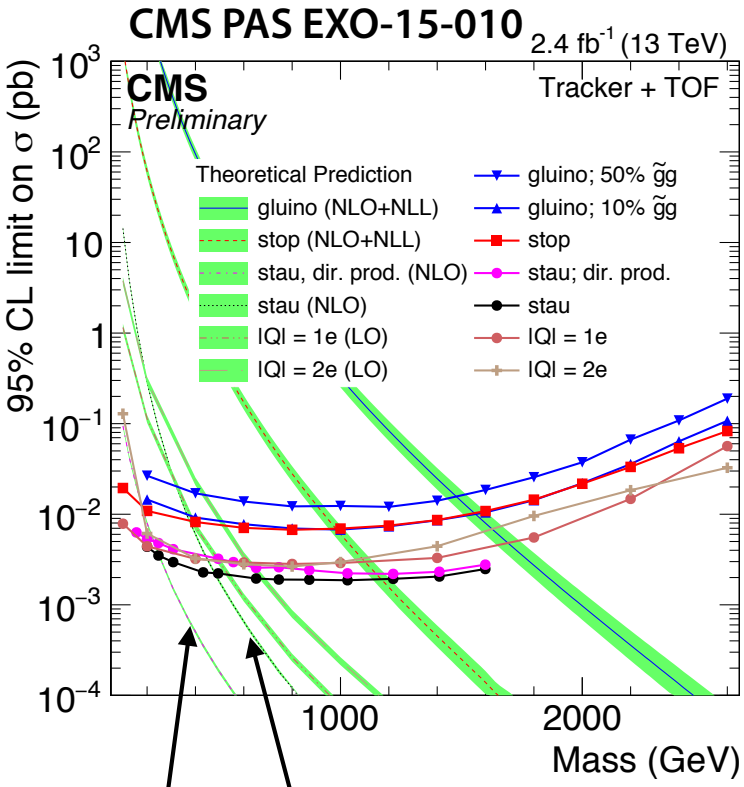
via gluino production

M_{gluino} >1.5 - 1.6 TeV

(M_{squark} >> TeV)

Supersymmetry in the TeV ranges

✔ stable stau search (***GMSB*** with $m_{3/2} > O(100)keV$)



via gluino production
(assuming GMSB with $N_m = 3$)

via direct (Drell-Yan) production
(assuming GMSB with $N_m = 3$)

via gluino,squark production

$M_{stau} > 480$ GeV

($GMSB\ N_m = 3,\ M_{gluino} > 3.3TeV$)

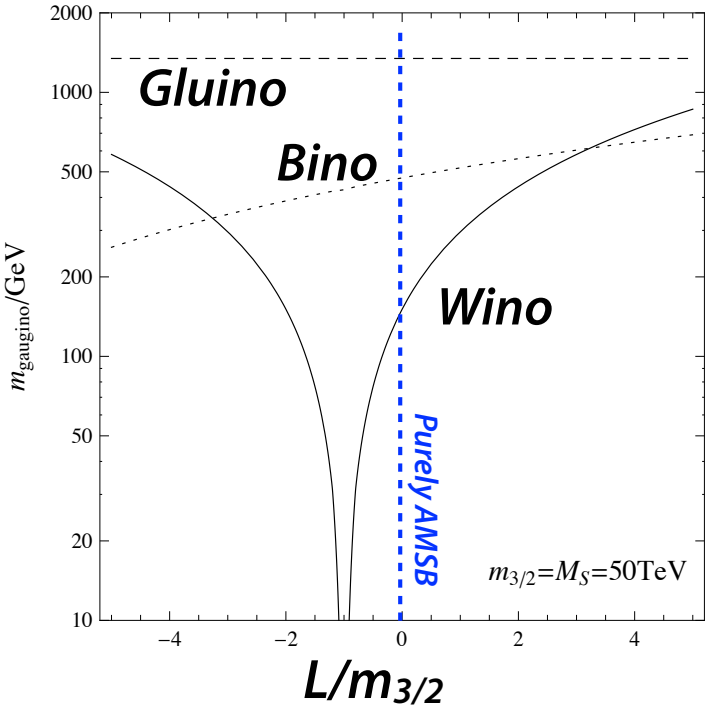
via Drell-Yan production

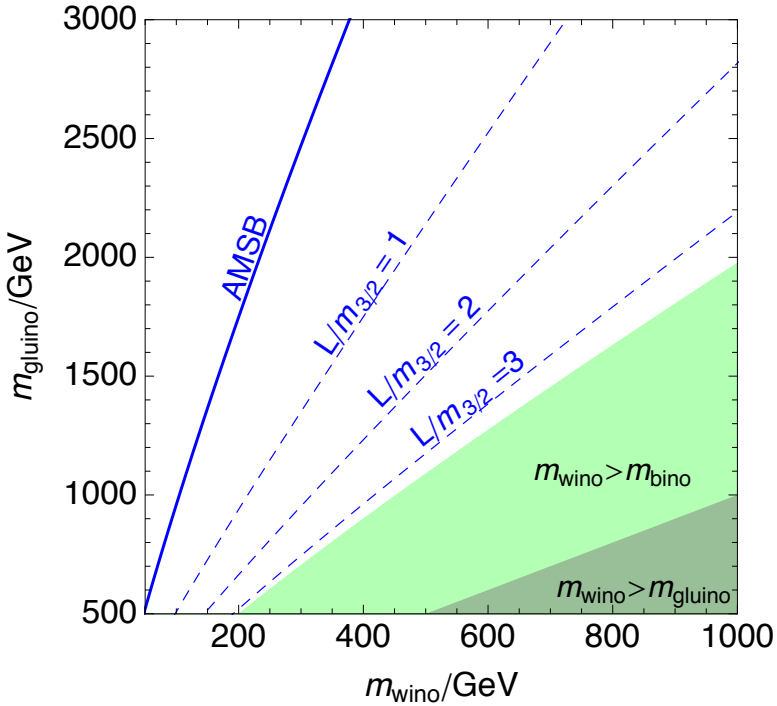
$M_{stau} > 340$ GeV (Run1)

($M_{gluino,squark} >> TeV$)

High Scale SUSY at 100TeV - PeV

✔ Gaugino Masses = Loop-suppressed (AMSB + Heavy Higgs Mediation)





['12, MI, Matsumoto,Yanagida ($\mu_H=O(M_{susy})$)]

$m_{gluino} = 2.5\times10^{-2} m_{3/2}$

$m_{wino} = 3.0\times10^{-3} (m_{3/2} + L)$

$m_{bino} = 9.6\times10^{-3} (m_{3/2} + L/11)$

for $m_{3/2}=O(100)$TeV.

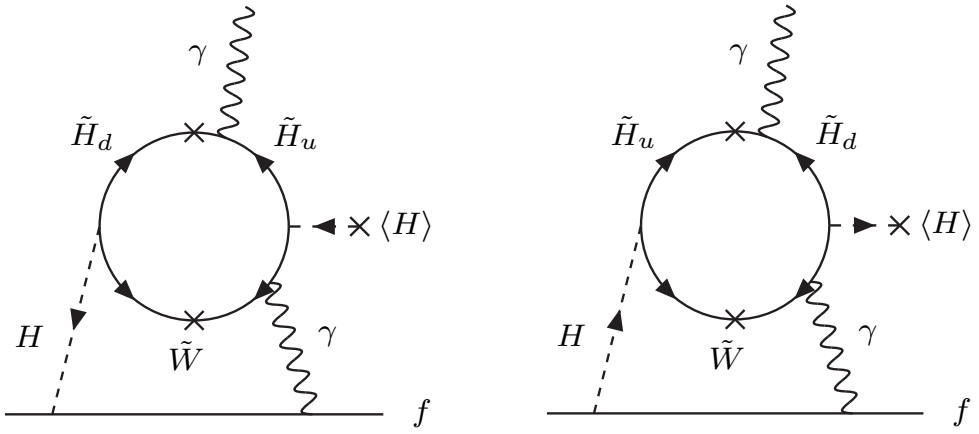
✔ The wino is the LSP in the most parameter space.

✔ The gluino can be lighter than the prediction in AMSB for $L/m_{3/2} = O(1)$.

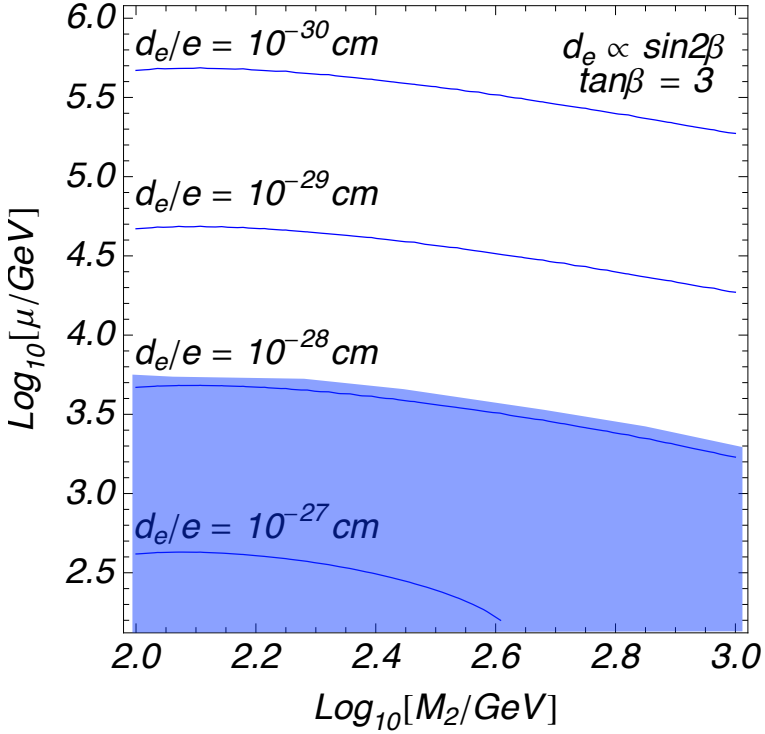
$L = O(m_{3/2})$: Higgsino mediation effect

High Scale SUSY at 100TeV - PeV

For detailed analyses
[`15 Hisano, Kobayashi,Kuramoto, Kuwahara]



['04 Arkani-hamed,Dimopoulos,Giudice, Rommanio]



Physical CP-violation is suppressed by $O(m_{3/2})$.

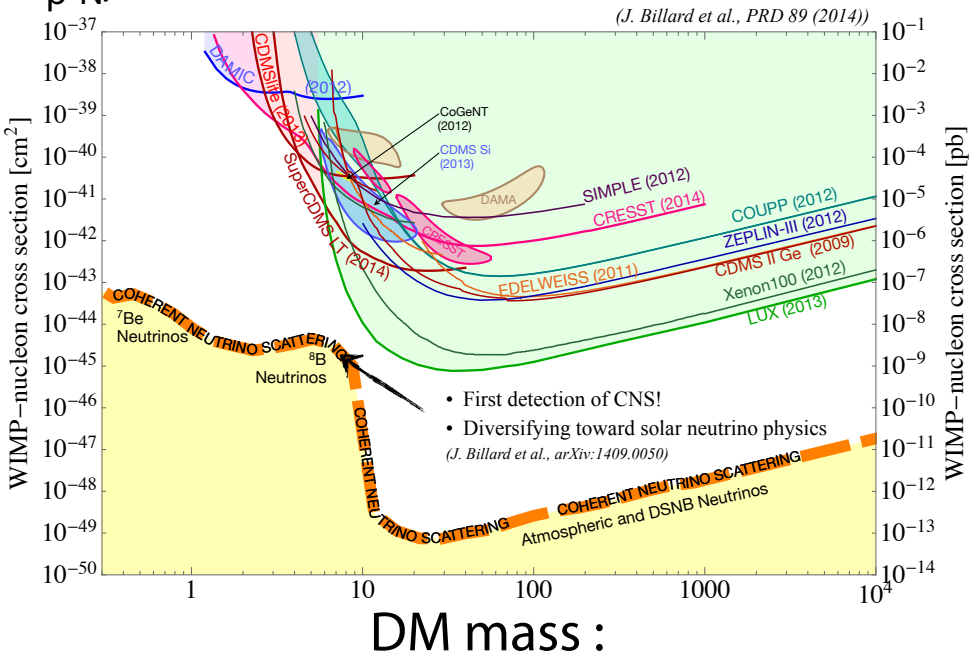
- ✔ EDM via one-loop slepton diagrams is suppressed by $m_{slepton}^{-2}$.
- ✔ EDM are dominated by two-loop diagrams in which the light Higgs boson is circulating (suppressed by $\mu_H^{-1}\sin 2\beta$)

The current limits $d_e/e < 8.7 \times 10^{-29}$cm is reaching to μ_H of $O(10^4)$ TeV !

[1310.7534 ACME : ThO]

High Scale SUSY at 100TeV - PeV

Wino Dark Matter Search (direct detections, $\chi N \rightarrow \chi N$)



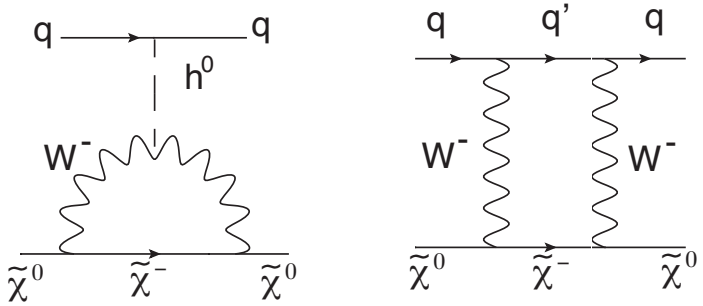
Coupling to H and Z are highly suppressed for $\mu_H = O(10\text{-}100)$ **TeV** at the tree-level.

Wino-Nucleon @ higher loop level

$\sigma_{p\text{-}N} = (10^{-47})cm^2$

(much smaller than the current reach...)

['10 Hisano, Ishiwata, Nagata]



One-loop diagrams which contribute to the Wino-nucleon scatterings.

['10 Hisano, Ishiwata, Nagata]

✔ Darwin (multi-ton Argon/Xe detector) will reach down to $10^{-47}cm^2$ for WIMP mass below 300GeV.

✔ The irreducible background from atmospher neutrinos at about $10^{-48}cm^2$. [arxiv:1003.5530]

Strongly coupled Gauge Mediation

Cascade SUSY breaking

$$K = |Z|^2 + |S|^2 + \frac{\kappa}{\Lambda^2}|Z|^2|S|^2 + \cdots \qquad F_Z \sim \frac{\Lambda^2}{4\pi}$$

$$m_S^2 \simeq -\frac{\kappa}{\Lambda^2} \times F_Z^2 \sim -\Lambda^2$$

$$V \sim m_S^2|S|^2 + \frac{k^2}{\Lambda^{2n-6}}|S|^{2n-2}$$

$$\langle S \rangle \sim \frac{\Lambda}{4\pi} \ , \quad \langle F_S \rangle \sim \frac{\Lambda^2}{4\pi} \ .$$

Messenger Coupling

$$W \simeq \frac{k}{\Lambda^{n-3}} S^n + \frac{\lambda}{\Lambda^{n-3}} S^{n-2} \Psi \bar{\Psi} \ \cdots$$

$$M_m \sim \Lambda, \qquad F_m \sim \Lambda^2 \sim 4\pi F_Z$$