Supersymmetry after Higgs discovery

DBD16 Workshop : 11/8/2016

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What have we learned from LHC results ?

- ✔ Higgs exists

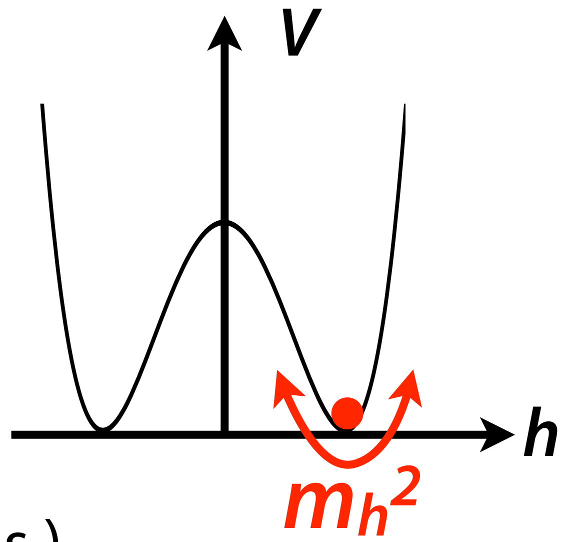
- ✔ Higgs is more like an elementary scalar

  Higgs can be fit by the simplest implementation

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

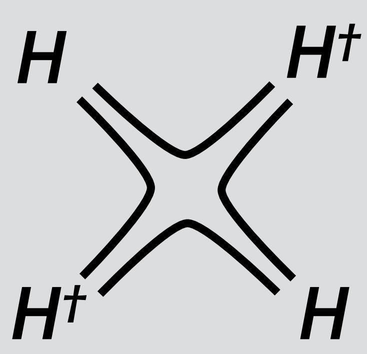
$$m_{higgs} = \lambda^{1/2} v \; [v = 174.1\text{GeV}]$$

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



(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.

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

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

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

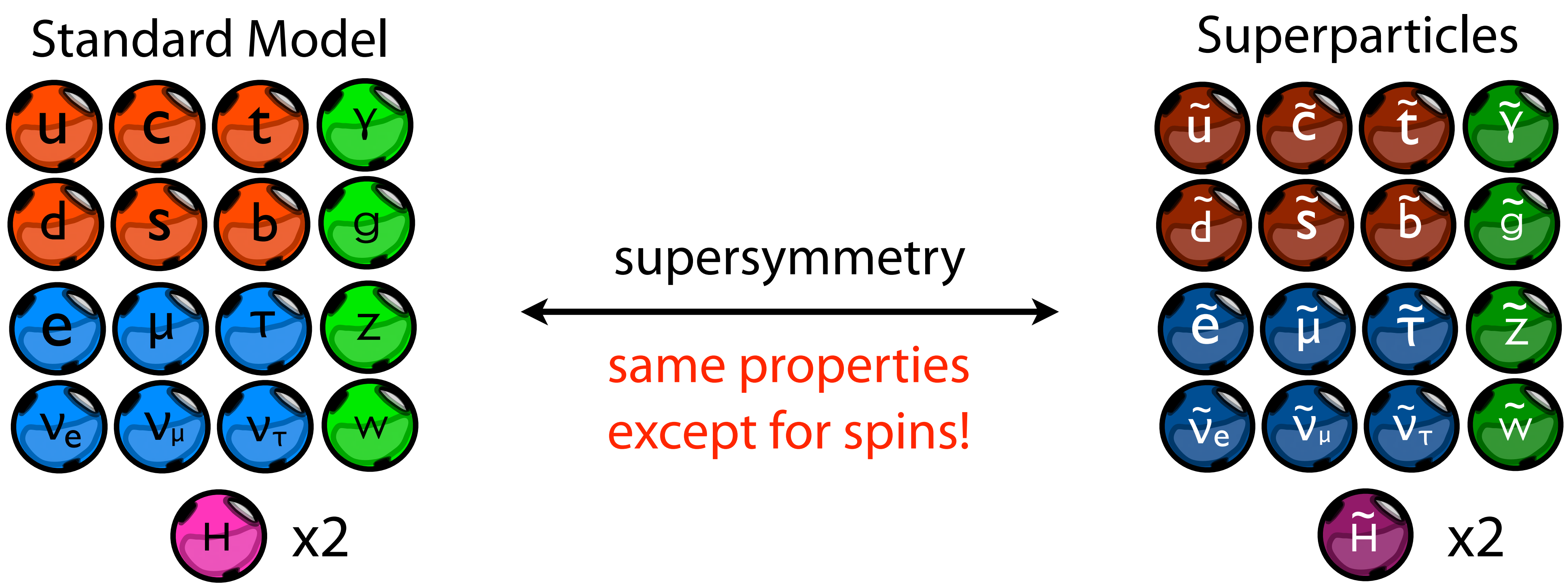
If M_W << M_{PL} is explainable, there should be new physics close to M_W which renders the SM being UV insensitive.

→ 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 !

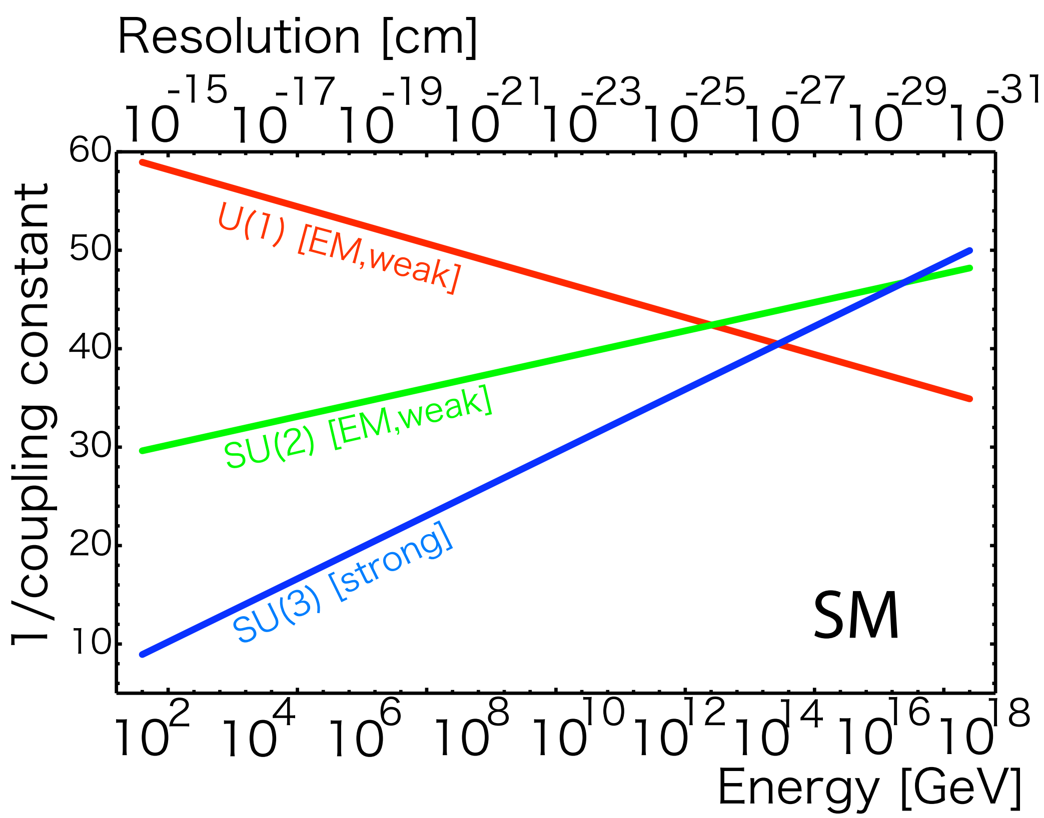
Higgs mass term = Higgsino mass term
Higgsino mass term can be protected by chiral symmetries!
Hierarchy problem is solved if SUSY breaking is around M_W.

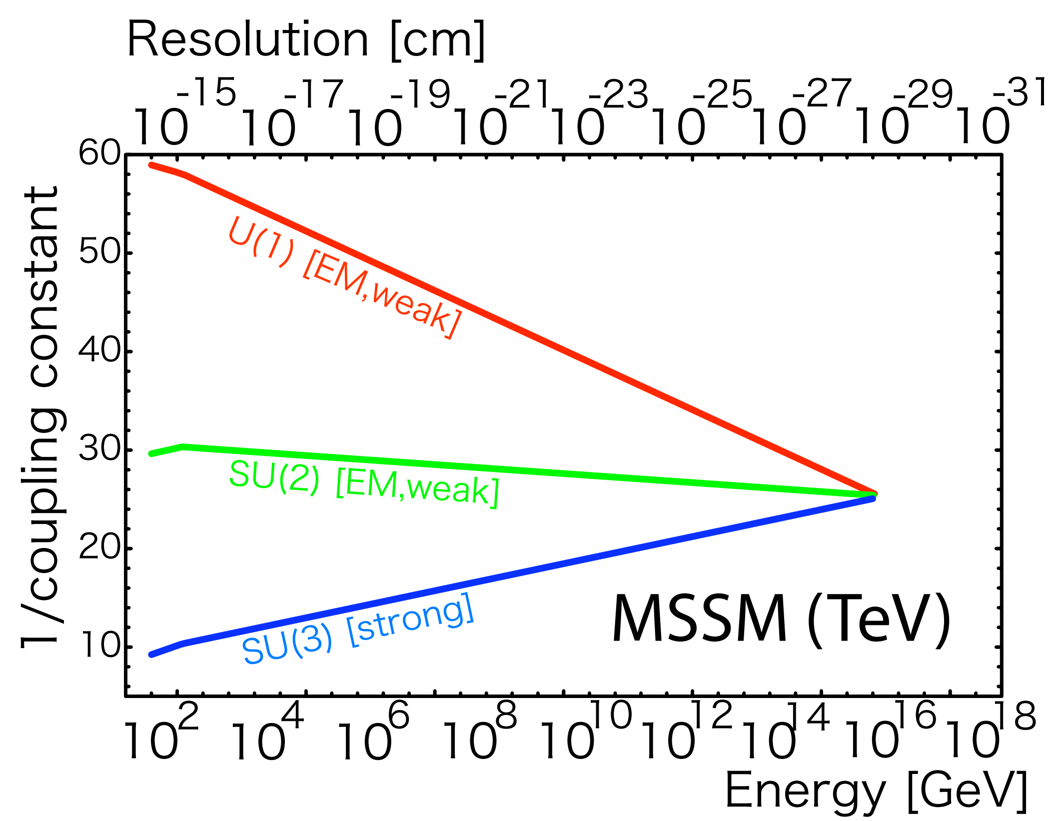
['79 Maiani, '81 Witten, '81 Kaul]

Supersymmetric Standard Model

✔ Big Bonus !

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





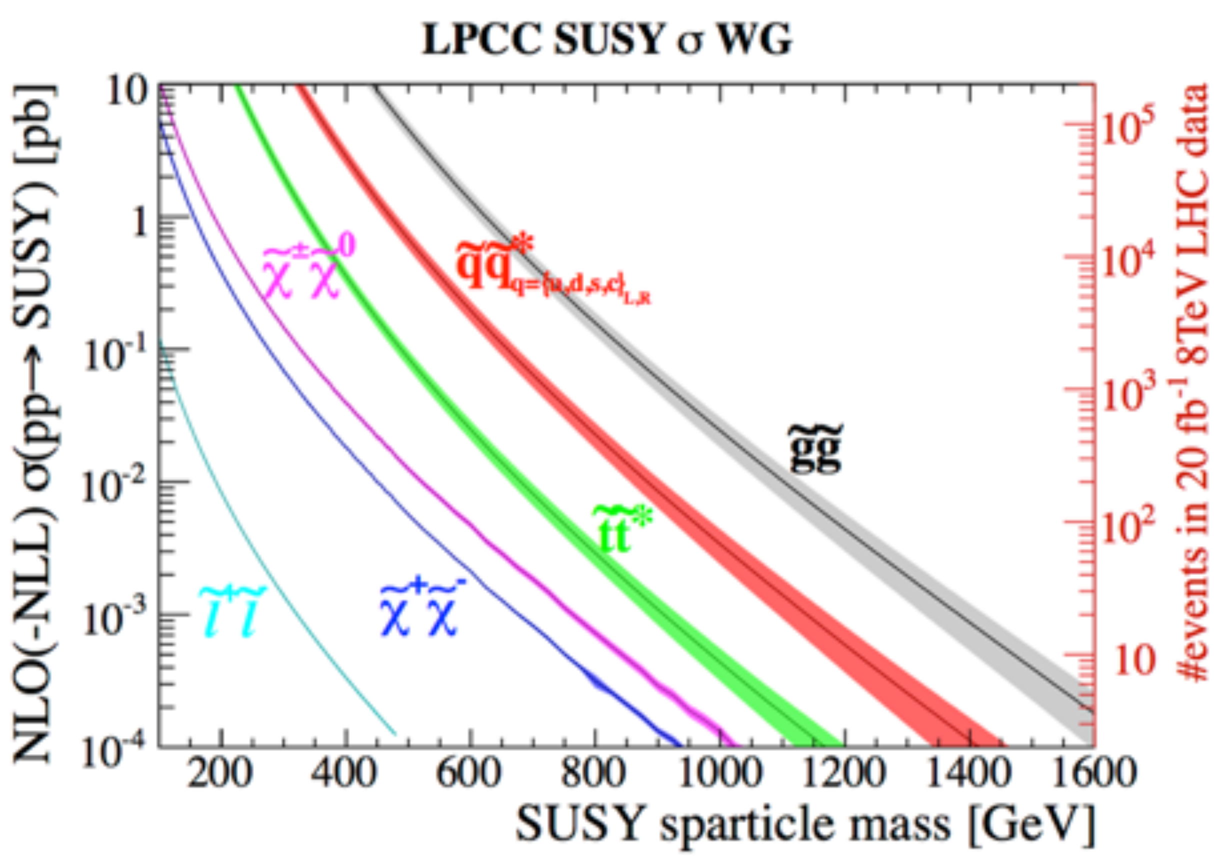
Supersymmetric standard model is perfectly consistent with GUT !

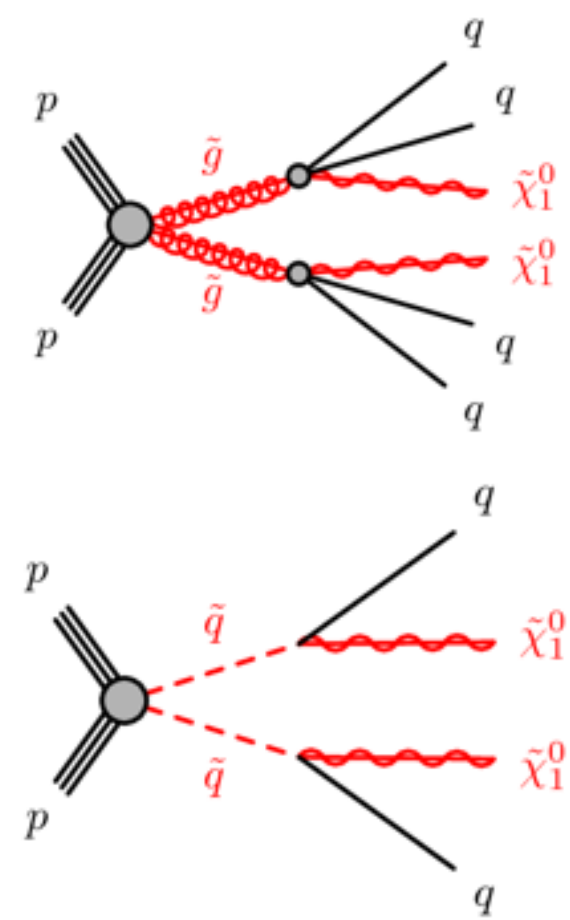
Supersymmetric Standard Model

✔ 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 ?

<u>The Higgs boson ~ 125GeV requires multi-TeV SUSY ?</u>

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 ?

<u>The Higgs boson ~ 125GeV requires multi-TeV SUSY ?</u>

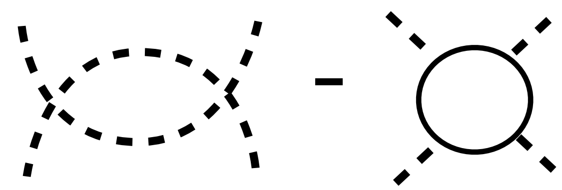
The radiative corrections to the Higgs boson mass logarithmically depend on the stop masses.

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

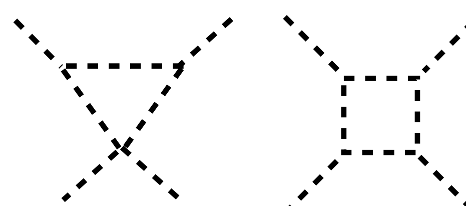
Tree-level quartic term:

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

One-loop log enhanced:



One-loop finite:



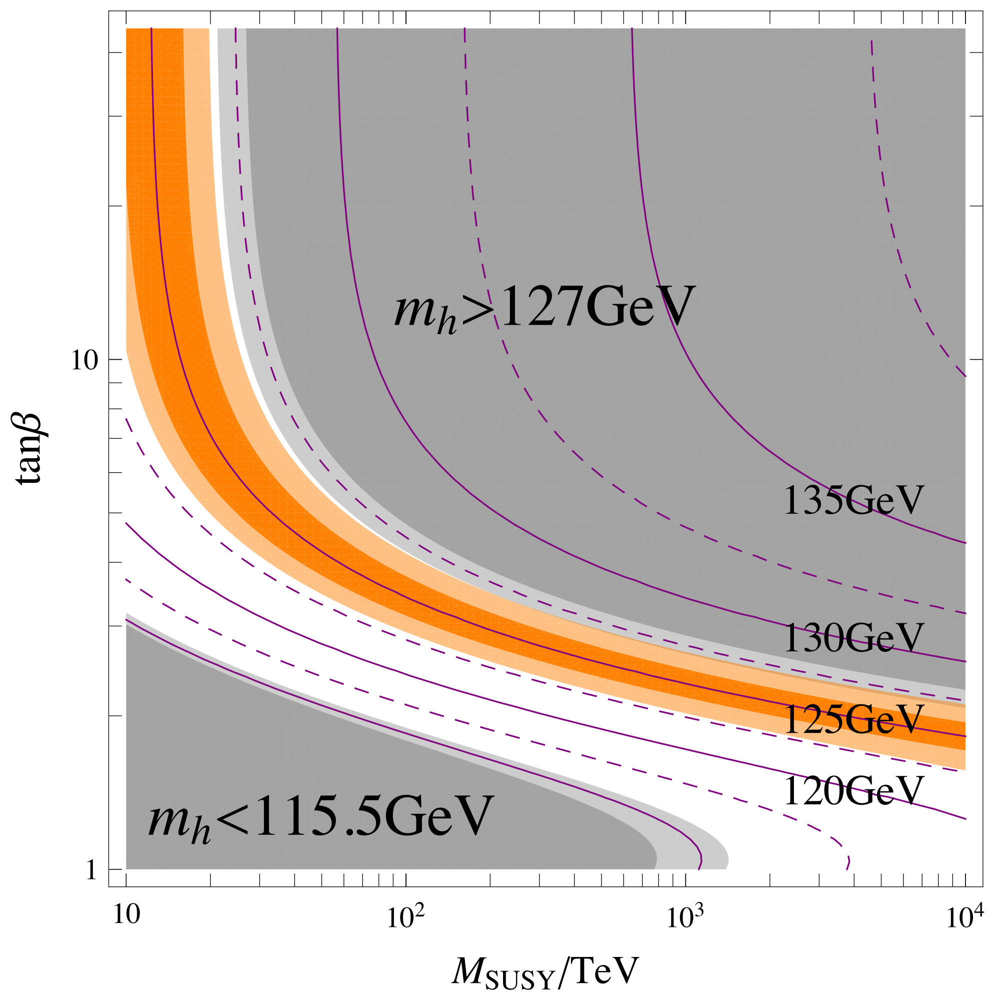
['91 Okada, Yamaguchi, Yanagida, '91 Haber, Hempfling, '91 Ellis, Ridolfi, Zwirner]

The Higgs boson mass larger than m_Z can be obtained for larger SUSY breaking effects!

Big Blow ?

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

The simplest interpretation: m_H ***~ 125 GeV*** suggests that the sfermion (stop) masses are above ***O(10-1000)TeV*** !



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

m_H ~ 125 GeV with O(1)TeV SUSY?

- A large ***stop A-term*** (trilinear coupling)
- ***Singlet*** extension (NMSSM)
- Extra vector-like matter
- ***U(1)*** extension

Model building becomes complicated though.

Direct SUSY search at the LHC.

- Proton stability
- Baryon asymmetry of the universe

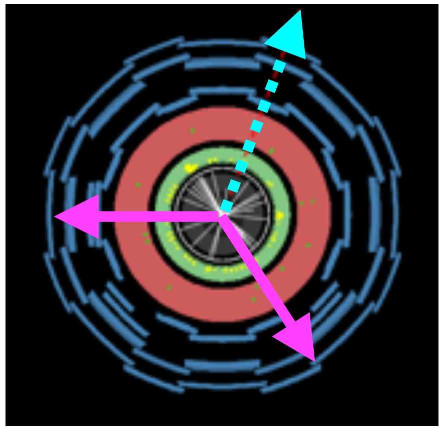
We assume ***R***-parity (or ***B-L*** parity)

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

The lightest superparticle (LSP) is ***stable*** (at least inside detectors).

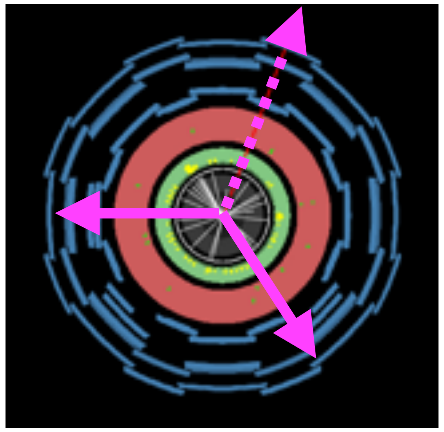
- The neutral LSP (neutralino, gravitino):

  We look for missing transverse momentum



- The charged LSP (charged stau) :

  We look for heavy charged track.



✔ Direct SUSY search at the LHC.

squark mass	SUSY spectrum	Higgs	EW Naturalness	GUT	10 years from now?
≫ PeV	DM ?? wino<3TeV Higgsino <2TeV	m_{Higgs} ≫125GeV	We need to rethink…	Unification is OK as long as $M_{gaugino}$ < O(TeV)	Stopping Gluinos ?
10TeV-PeV	One-loop suppressed Gaugino mass	m_{Higgs} ~125GeV in the MSSM	We need to rethink…	Unification is OK as long as $M_{gaugino}$ < O(TeV)	Gaugino searches. DM Cosmic ray ? EDM
TeV	Getting excluded by the LHC…	Large A-term NMSSM Other extensions	sub% Tuning (low scale mediation is preferred ?)	Unification is OK	The LHC will discover the SUSY (M_{SUSY} < 3TeV) ! Or merged into high-scale SUSY…
Light Stop& Higgsino	Stop <TeV DM : Higgsino	Enhancement is required!	Better than O(1)% if M_{gulino} < TeV	Most models have tensions with the GUT…	Searchable! Gluino/Stop search will be discovered !
Compressed Spectrum	Loophole in the LHC searches!	Enhancement is required!	Can be better than the simple TeV scenarios	GUT relation in the gaugino masses are not favored (exception: Mirage Mediation)	Searchable! ISR jet ? ISR photon ? soft lepton ?

Unnatural | Natural

This table is an extended version of
http://www2.yukawa.kyoto-u.ac.jp/~fumihiro.takayama/YITP_ws2012March_BSM/talks/SUSY_sub.pdf

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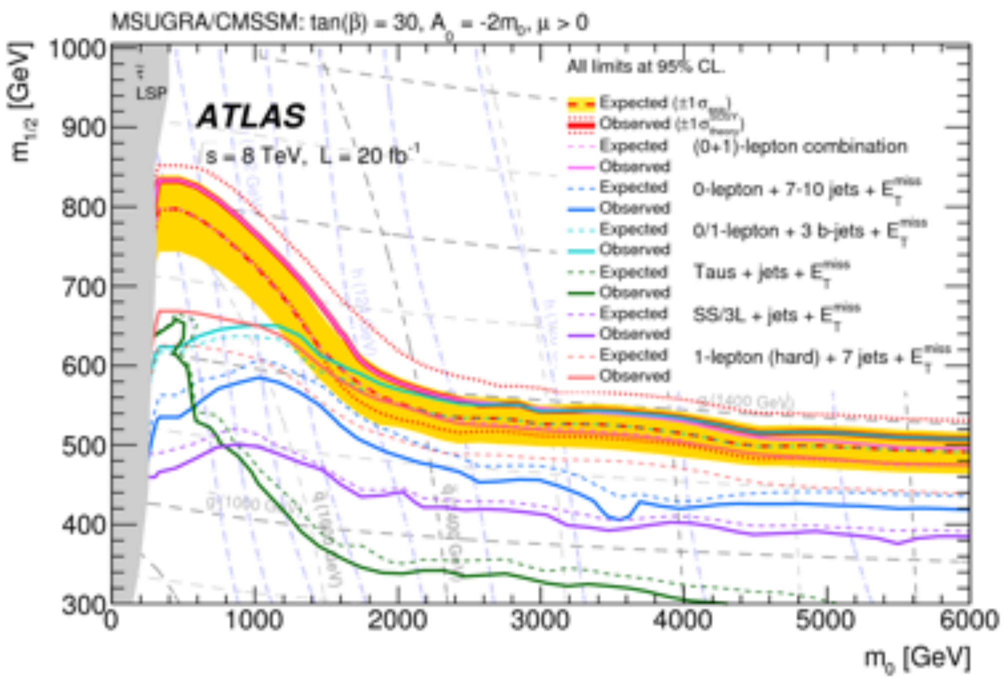
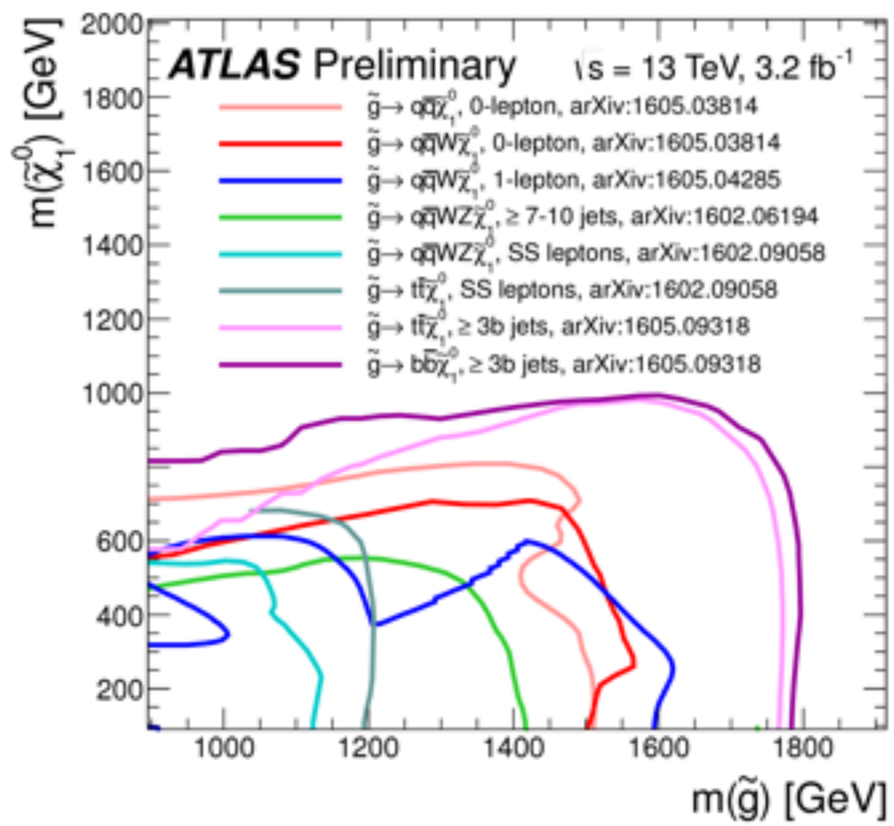
Supersymmetry in the TeV ranges

✔ missing p_T search (the neutralino LSP)

[ATLAS:1507.05525, 8TeV]



[ATLAS Summary, 13TeV]



✔ Current limit from p_T^{miss} search :

$M_{gluino} \sim M_{squark} > 1.8$ *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*$^{-1}$*)*]

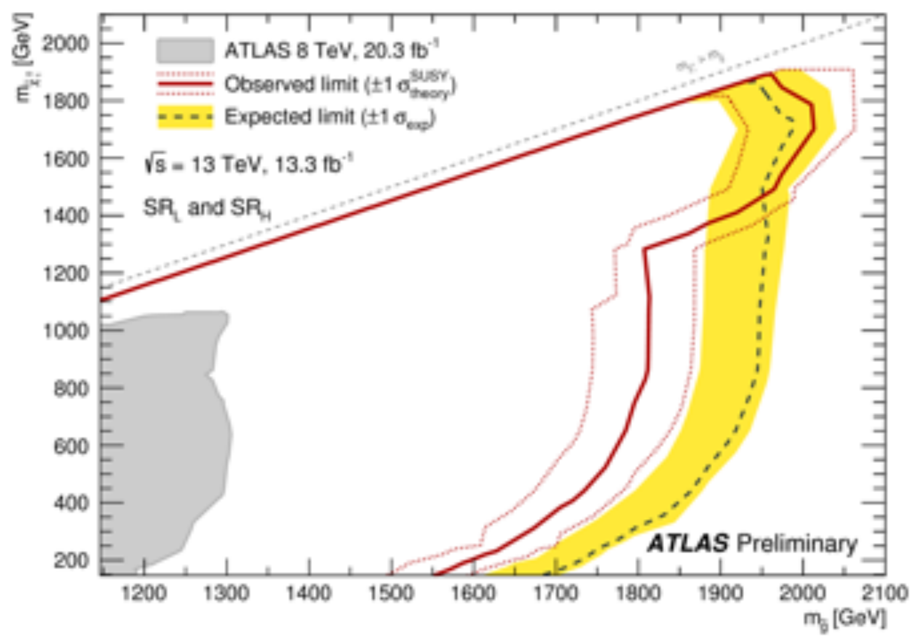
[arXiv:1310.0077]

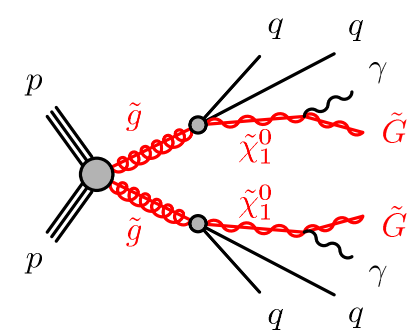
Supersymmetry in the TeV ranges

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

✔ neutralino NLSP (missing p_T + photons)

ATLAS-CONF-2016-066





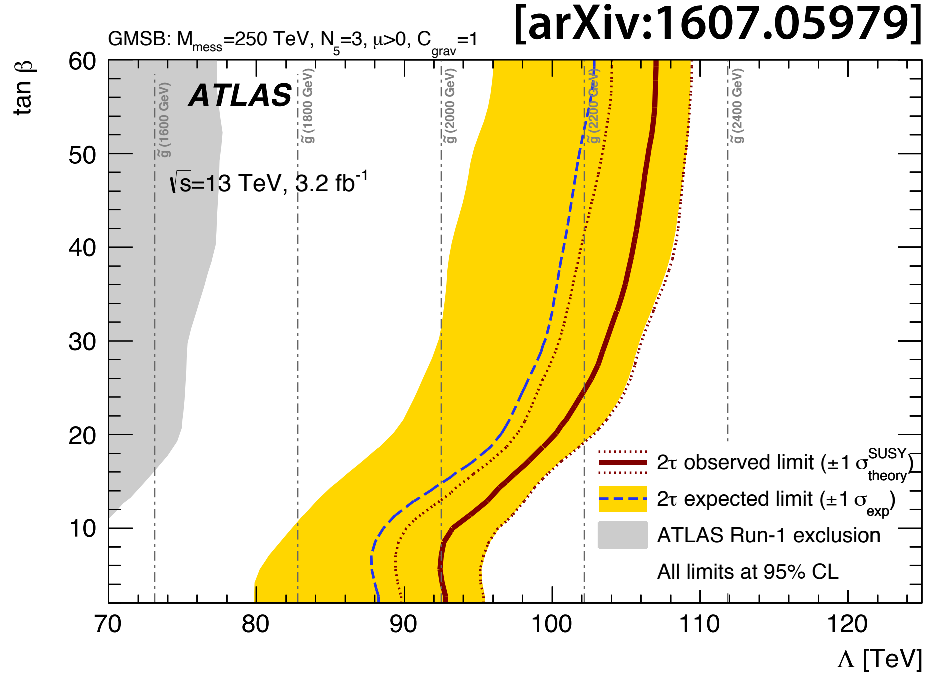
via gluino production

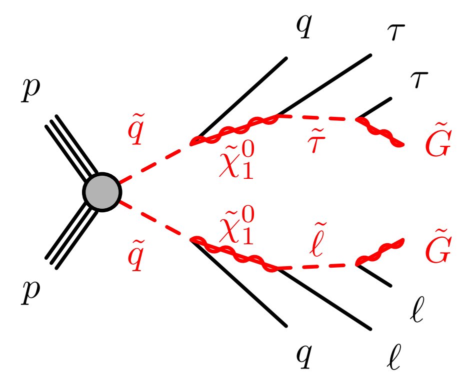
M_{gluino} >1.6 - 1.8 TeV

(M_{squark} >> TeV)

✔ stau NLSP (missing p_T + tau)

[arXiv:1607.05979]





via gluino,squark production

M_{gluino} >2 - 2.3 TeV

(GMSB : $N_m = 3$)

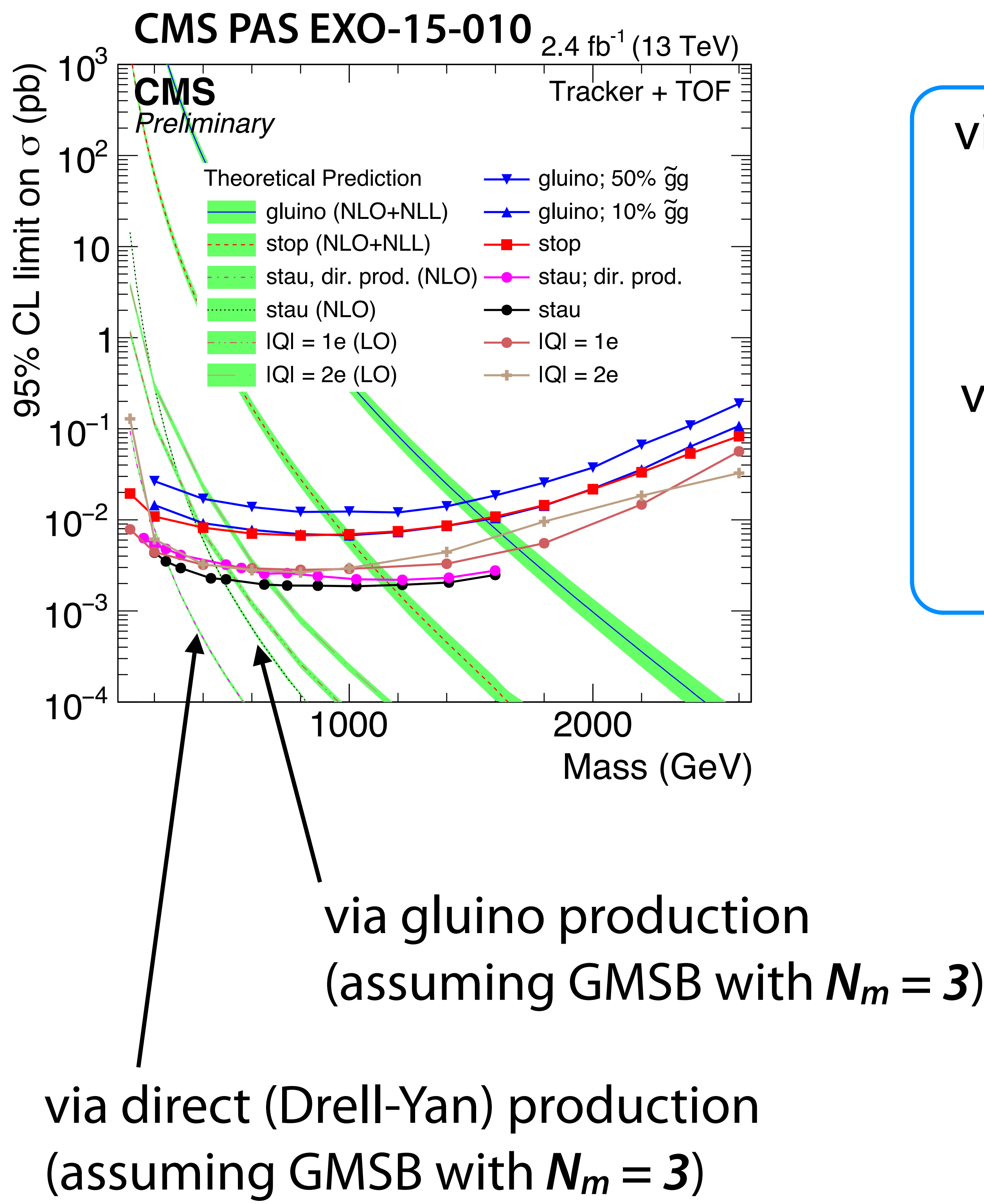
via gluino production

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,squark production

$M_{stau} > 480$ GeV

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

via Drell-Yan production

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

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

✔ Direct SUSY searches at the LHC.

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Supersymmetry with light stop and light Higgsino

Why light stop/ light Higgsino ?

- Higgs mass terms in the MSSM

$$V = (m_{Hu}^2 + |\mu_H|^2)\,|H_u|^2 + (m_{Hd}^2 + |\mu_H|^2)\,|H_d|^2 + B\mu_H\, H_u H_d + h.c.$$

μ_H : Higgsino mass

$m_{Hu}^2, m_{Hd}^2, B\mu_H$: soft SUSY breaking Higgs mass

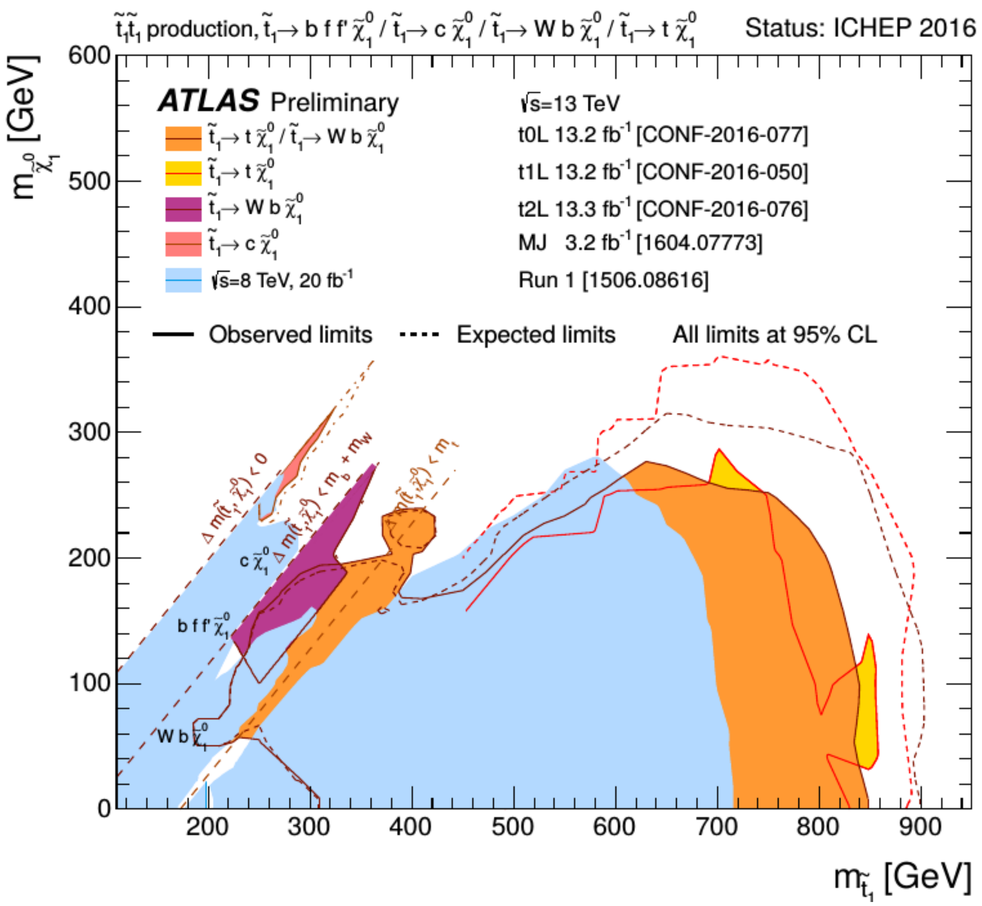
- Soft SUSY breaking mass receives large contributions from the stop mass

$$\Delta m_{H_u}^2 = -\frac{12 y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log\left(\frac{M_{\rm med}}{m_{\tilde{t}}}\right)$$

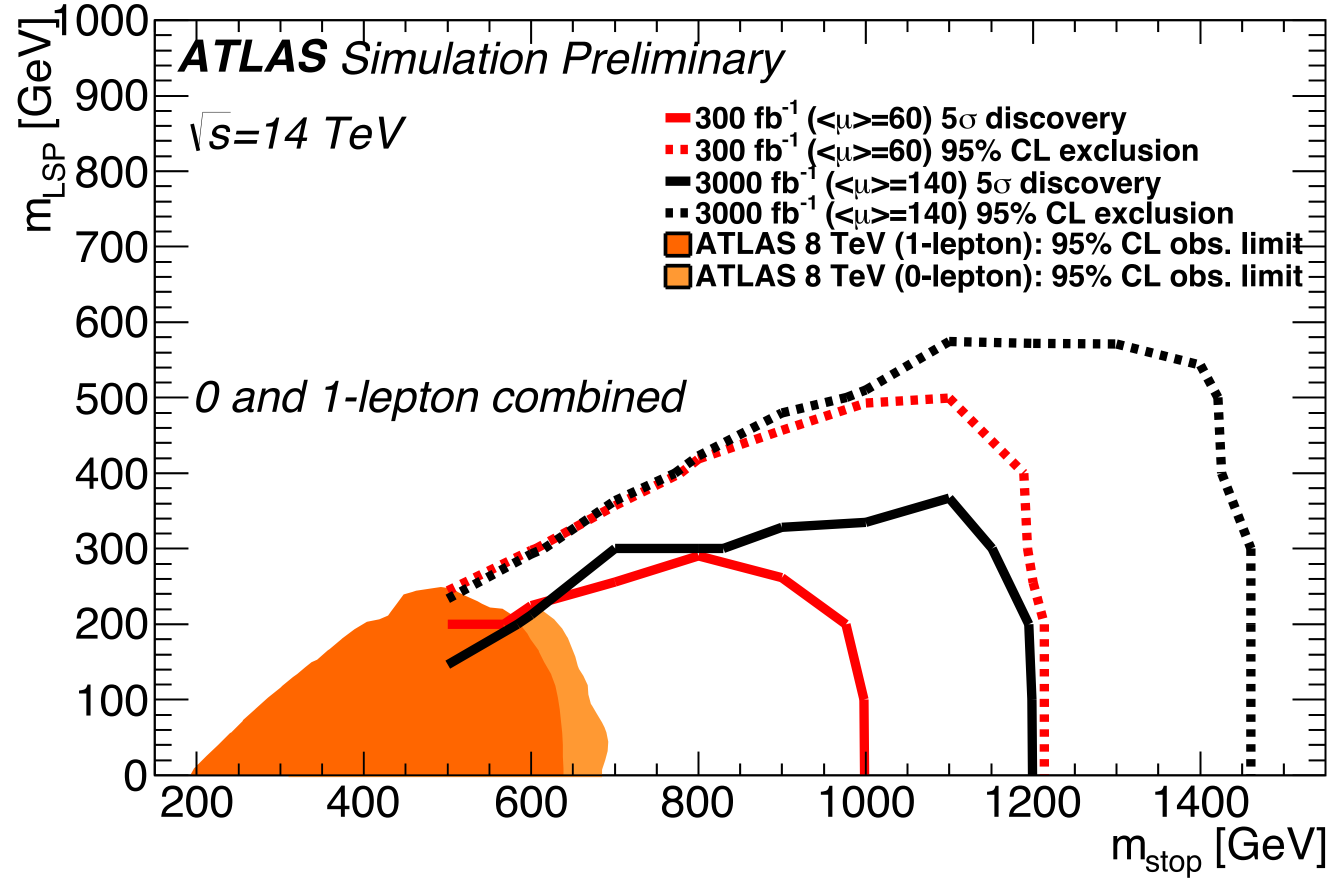
→ m_{stop} , μ_H ~ M_{weak} *is favorable for naturalness*

[Model building with consistent Higgs boson mass is very difficult though…]

Supersymmetry with light stop and light Higgsino



[ATL-PHYS-PUB-2013-011]



✔ Current limit :

> ***M_{stop} < 800 GeV*** has been excluded
> (when stop → top + χ^0 mode is open)

✔ Prospect :

Discovery could be possible for ***M_{stop} = 1 - 1.2 TeV (14TeV)***.

Direct SUSY searches at the LHC.

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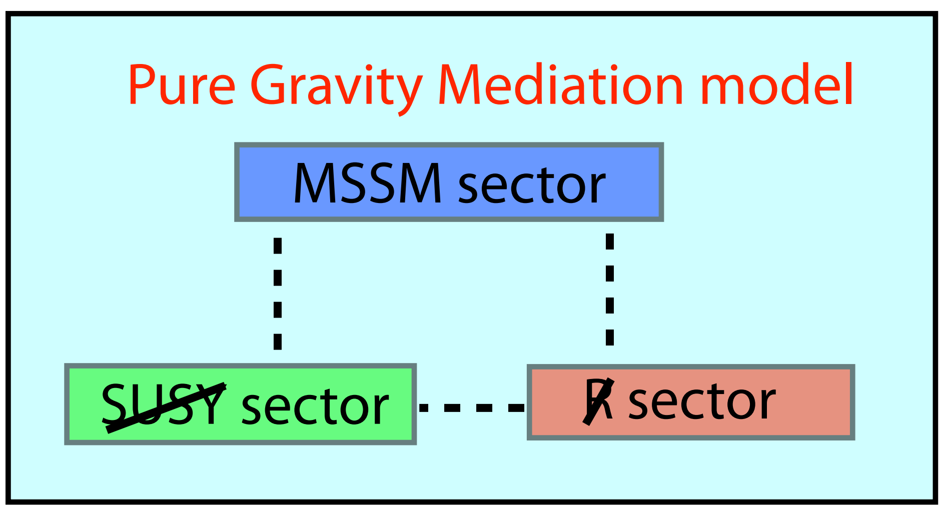
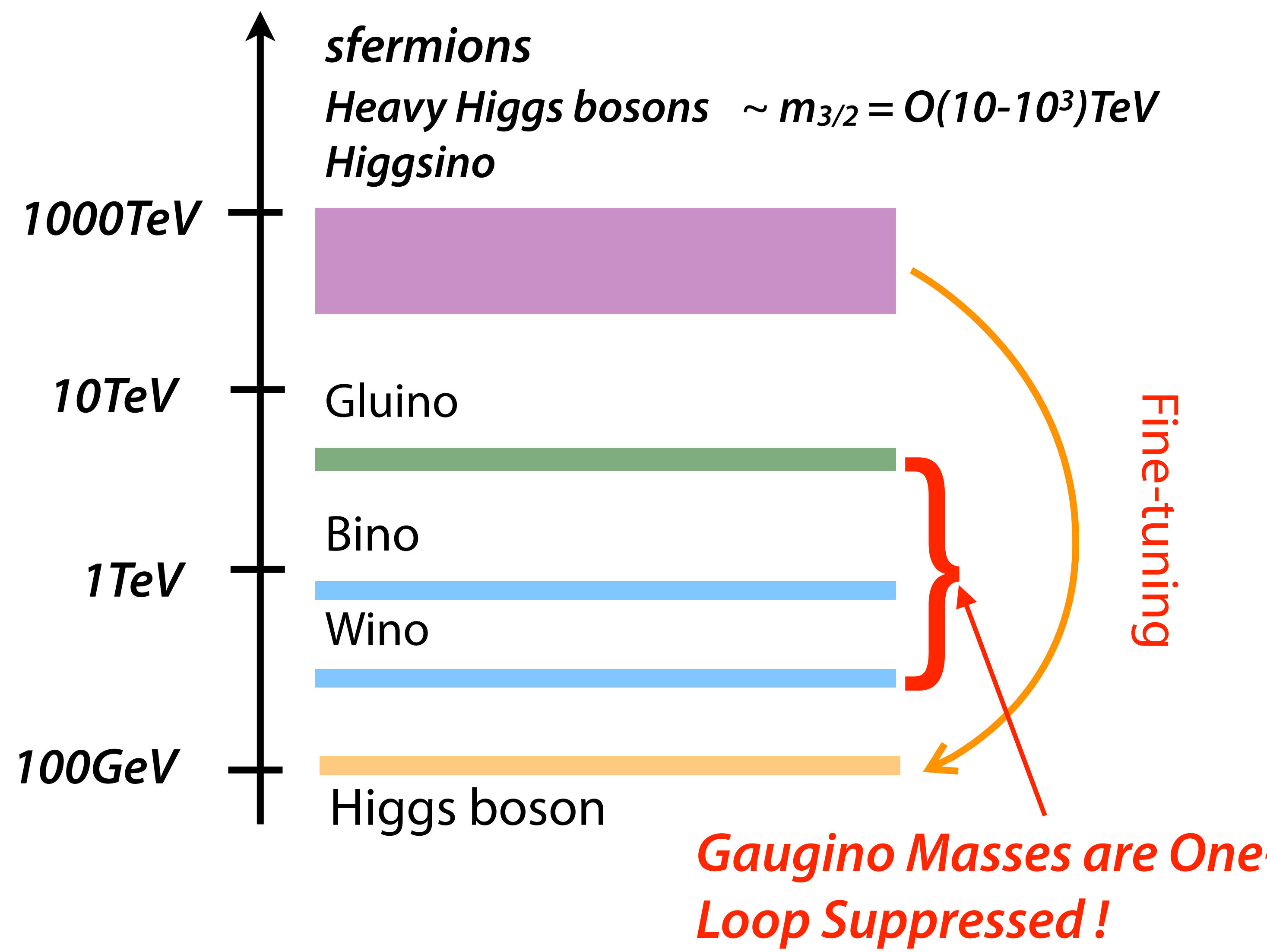
<u>*High Scale SUSY at 10TeV - PeV*</u>

- ✓ The simplest interpretation: ***m_H ~ 125 GeV*** suggests that the sfermion (stop) masses are above ***O(10-1000)TeV*** !
- ✓ Model building is ridiculously simple !
- ✓ Consistent with cosmology (good DM candidate, no Polonyi problem)
- ✓ ***Gaugino Masses in the TeV range can be naturally obtained.***
- ✓ Fine-tuning problem between ***O(10-1000)TeV*** and ***O(100)GeV…***



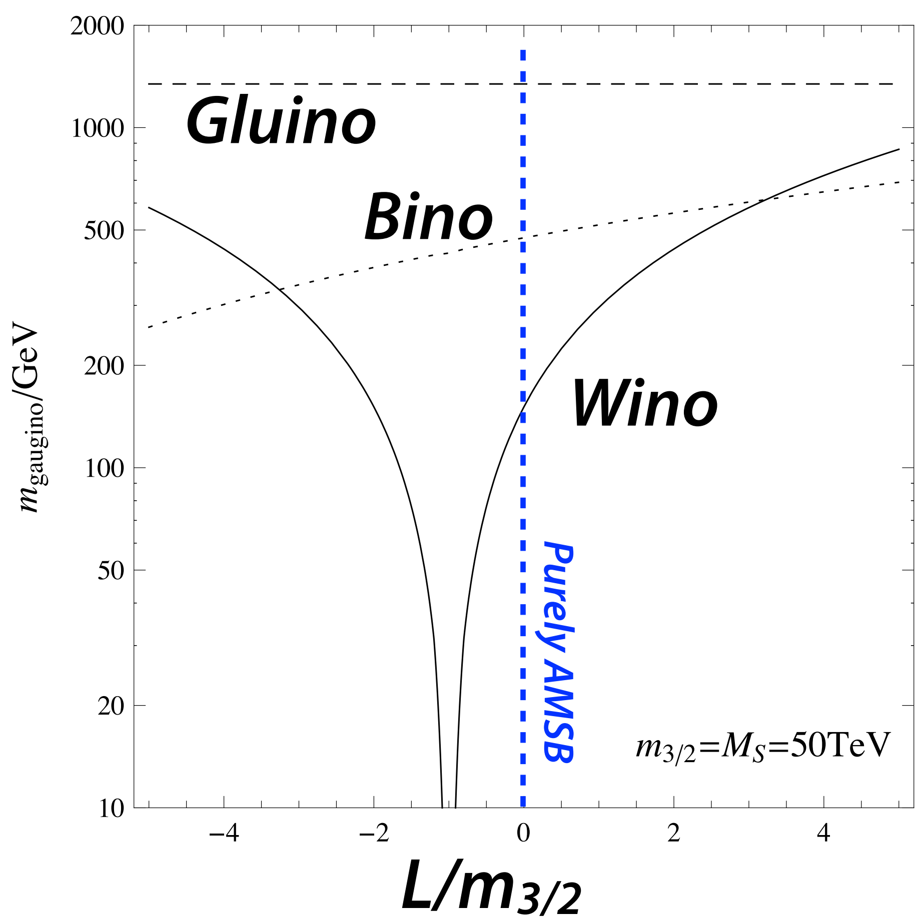
They are connected by generic Planck suppressed operators with each other.

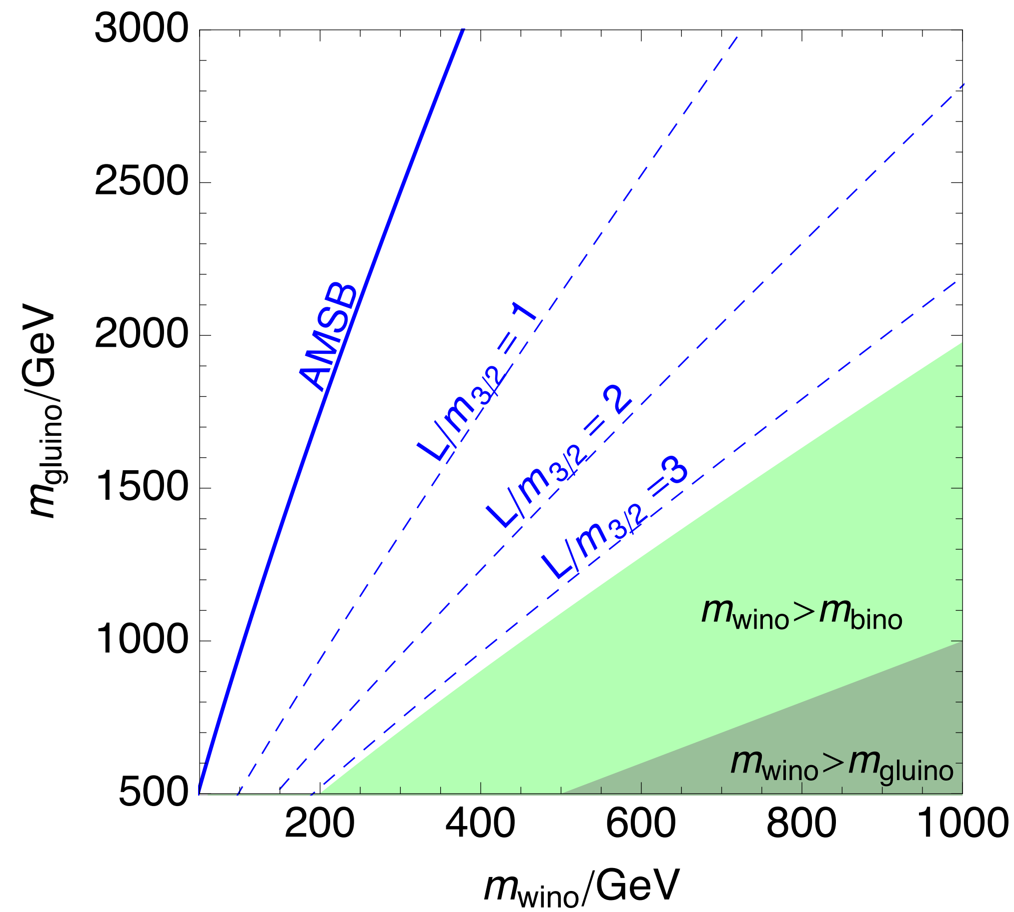
['04 Wells, 06'MI,Moroi,Yanagida,12 MI, Yanagida, '12 Arkani-hamed, Gupta, Kaplan, Weiner, Zorawski…]



High Scale SUSY at 10TeV - 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.

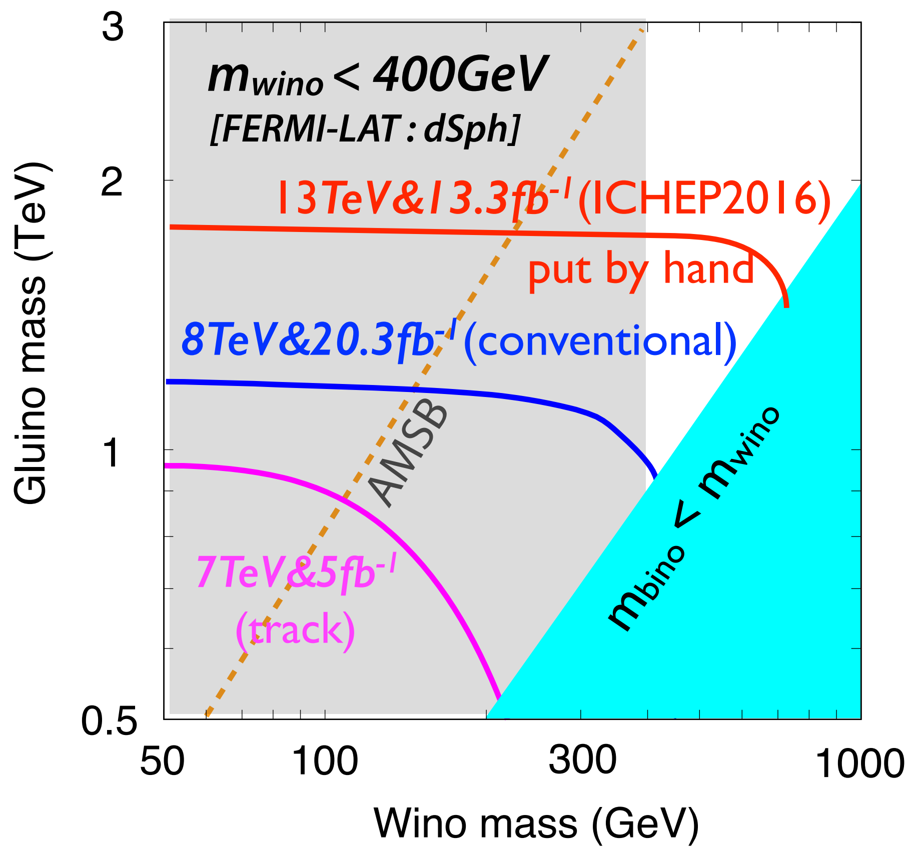
$L = O(m_{3/2})$: Higgsino mediation effect

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

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

High Scale SUSY at 10TeV - PeV

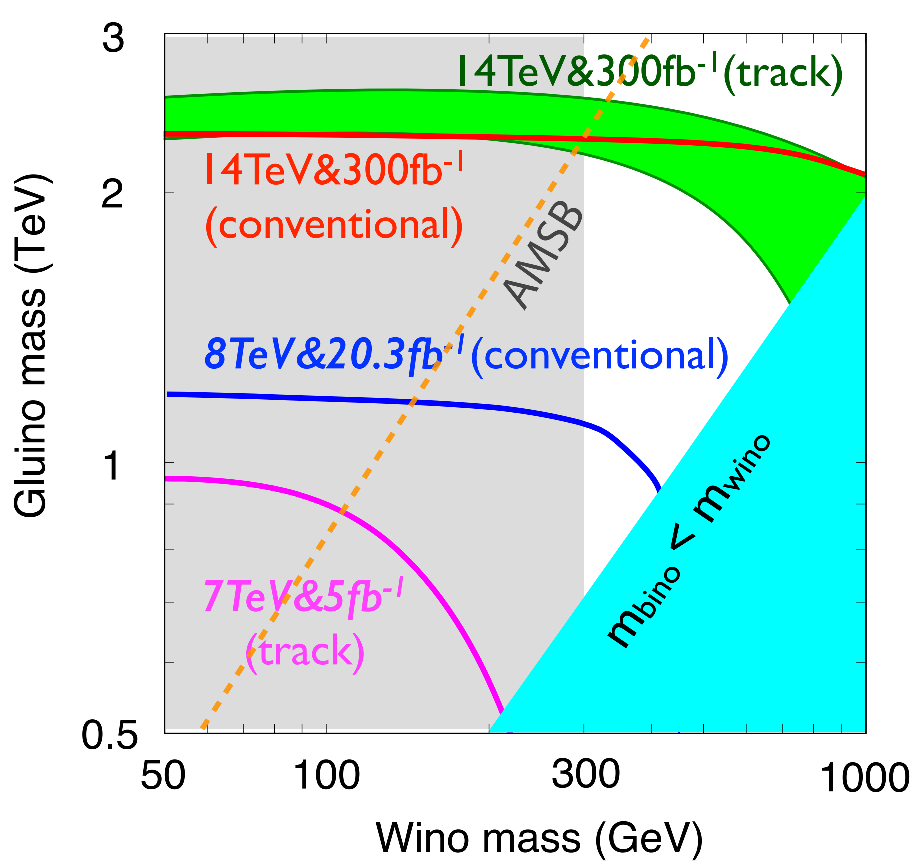
Current limits via gluino production



- ✔ 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 ?

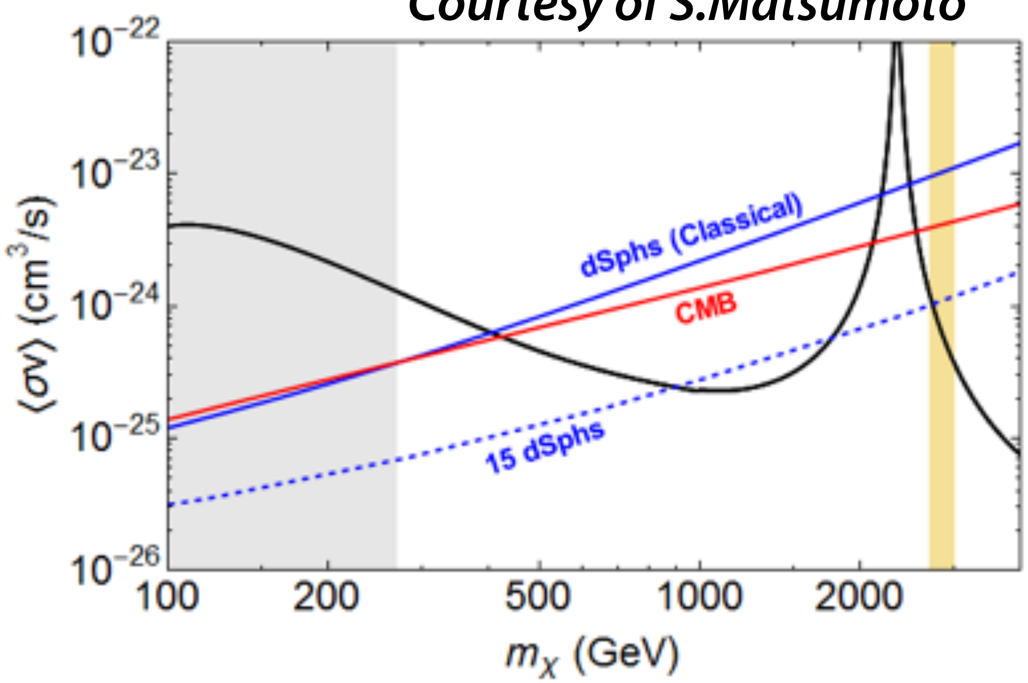
$M_{gluino} \sim 2.3$ TeV (14TeV,300fb^{-1})
$M_{gluino} \sim 2.7$ TeV (14TeV,3000fb^{-1})
$M_{gluino} \sim 5.8$ TeV (33TeV, 3000fb^{-1})

[arXiv:1310.0077]

High Scale SUSY at 10TeV - PeV

- ✓ ***DM is Pure Wino Dark Matter !***
- ✓ Indirect search by gamma-ray from dwarf Spheroidal galaxies are promising !

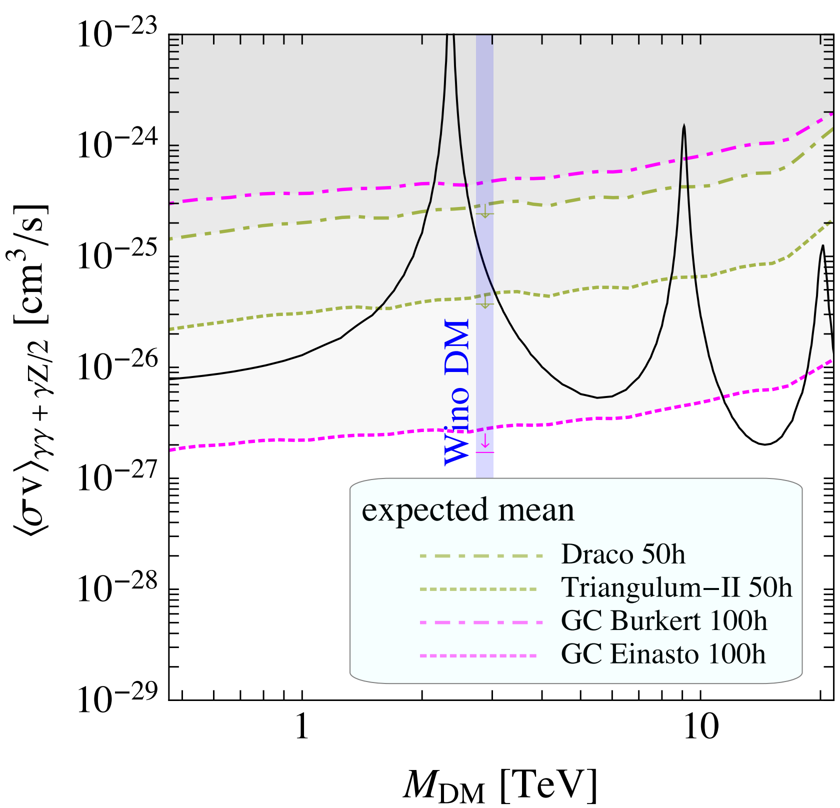
Courtesy of S.Matsumoto



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

$m_{triplet}$ < 400 GeV (classical dSphs)

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



- ✓ Future prospect at CTA

Dwarf looks better target than the galactic center by taking the DM profile of the galactic center into account!

['16 Lefranca, Moulina, Panci, Sala, Silk]

✔ Direct SUSY searches at the LHC.

squark mass	SUSY spectrum	Higgs	EW Naturalness	GUT	10 years from now?
≫ PeV	DM ?? wino<3TeV Higgsino <2TeV	m_{Higgs} ≫125GeV	We need to rethink…	Unification is OK as long as $M_{gaugino}$ < O(TeV)	Stopping Gluinos ?
10TeV-PeV	One-loop suppressed Gaugino mass	m_{Higgs} ~125GeV in the MSSM	We need to rethink…	Unification is OK as long as $M_{gaugino}$ < O(TeV)	Gaugino searches. DM Cosmic ray ? EDM
TeV	Getting excluded by the LHC…	Large A-term NMSSM Other extensions	sub% Tuning (low scale mediation is preferred ?)	Unification is OK	The LHC will discover the SUSY (M_{SUSY} < 3TeV) ! Or merged into high-scale SUSY…
Light Stop& Higgsino	Stop <TeV DM : Higgsino	Enhancement is required!	Better than O(1)% if M_{gulino} < TeV	Most models have tensions with the GUT…	Searchable! Gluino/Stop search will be discovered !
Compressed Spectrum	Loophole in the LHC searches!	Enhancement is required!	Can be better than the simple TeV scenarios	GUT relation in the gaugino masses are not favored (exception: Mirage Mediation)	Searchable! ISR jet ? ISR photon ? soft lepton ?

Unnatural | Natural

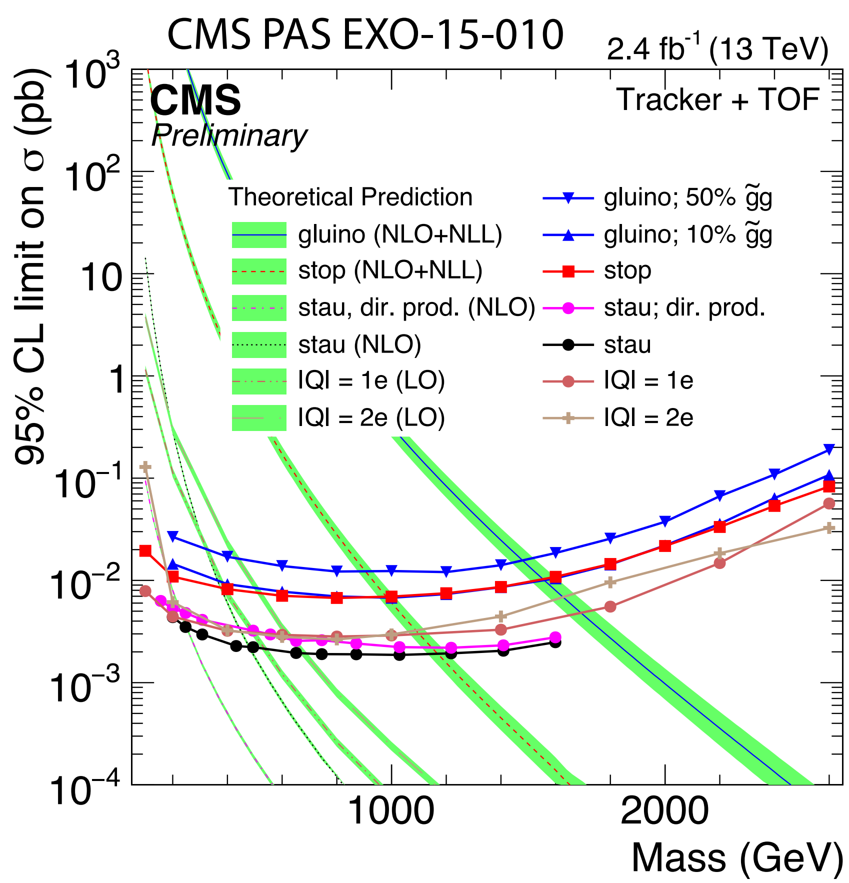
This table is an extended version of
http://www2.yukawa.kyoto-u.ac.jp/~fumihiro.takayama/YITP_ws2012March_BSM/talks/SUSY_sub.pdf

Split Supersymmetry : Squark Mass ≫ PeV

['04 Arkani-Hamed, Dimopoulos, Giudice, Romanino]

MSSM fermions = O(TeV) ≪ MSSM scalars

- ✔ Bino, Wino, Higgsinos are good candidate for dark matter
- ✔ Coupling Unification is OK
- ✔ Severe fine-tuning problem…
- ✔ Higgs mass tends to be larger than ***125GeV*** .
- ✔ Gaugino Masses are generically ***10^{-2} x MSSM scalars***…



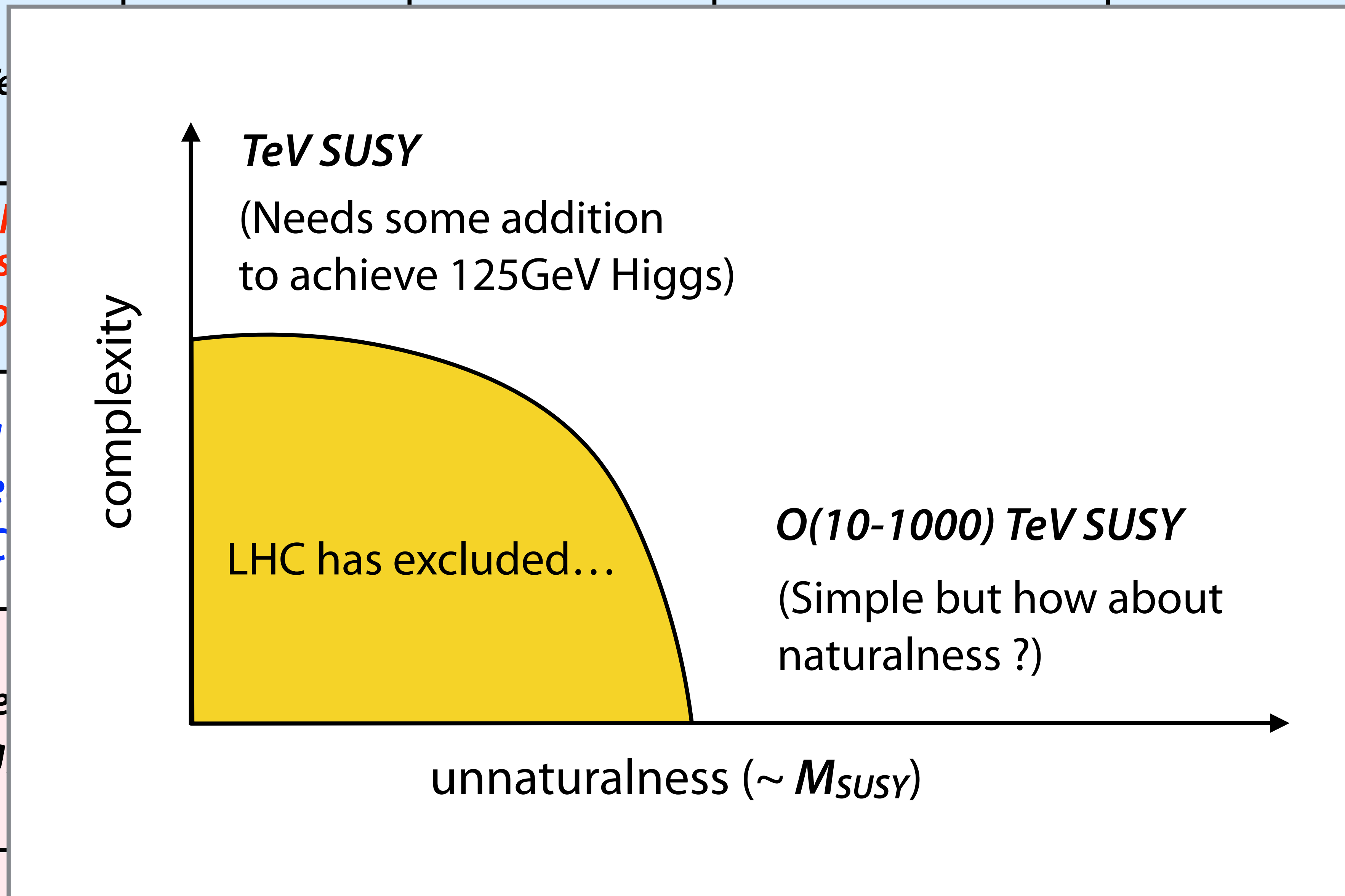
Gluino may have a long lifetime !

$$\tau_{gluino} = 5 \times 10^{-9}\, sec \times (TeV / m_{gluino})^5 \times (m_{squark} / 10^4\, TeV)^4$$

Current limit from heavy charged track search :
M_{gluino} > 1.4-1.6 TeV.

✓ Direct SUSY searches at the LHC.

squark mass	SUSY spectrum	Higgs	EW Naturalness	GUT	10 years from now?
≫ PeV	DM ?? wino<3Te Higgsino				inos ?
10TeV-PeV	One-loo suppress Gaugino				ches. y ?
TeV	Getting exclude the LHC				iscover the 3TeV) ! o high-scale
Light Stop& Higgsino	Stop <Te DM : Hig				search will d !
Compressed Spectrum	Loophole in the LHC searches!	Enhancement is required!	Can be better than the simple TeV scenarios	gaugino masses are not favored (exception: Mirage Mediation)	Searchable! ISR jet ? ISR photon ? soft lepton ?



Unnatural | Natural

This table is an extended version of
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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 !

Other channels such as DM searches are getting more important !

<u>Although we have no strong hints at this point, we must keep seeking/thinking beyond the Standard Model !</u>

picture from http://www.vecteezy.com

Don't give up, we don't know how near we are with new physics!

Back Up Slides

✔ Neutralino Dark Matter

Neutralino mixing mass

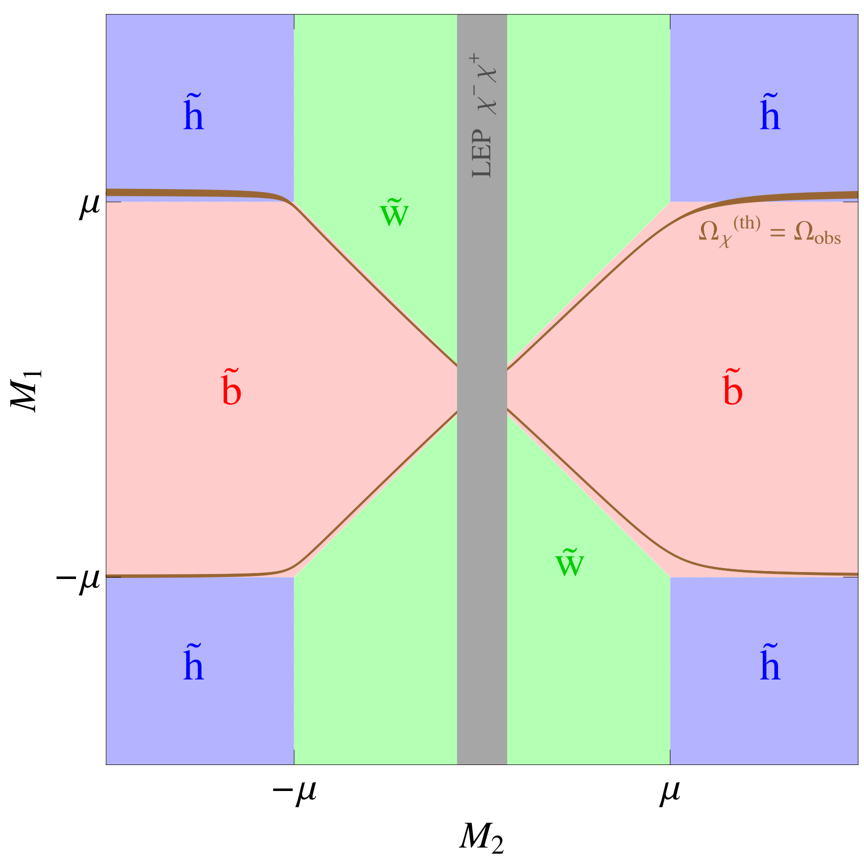
$$M_\chi = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v\cos\beta & \frac{1}{2}g'v\sin\beta \\ 0 & M_2 & \frac{1}{2}gv\cos\beta & -\frac{1}{2}gv\sin\beta \\ -\frac{1}{2}g'v\cos\beta & \frac{1}{2}gv\cos\beta & 0 & -\mu \\ \frac{1}{2}g'v\sin\beta & -\frac{1}{2}g'v\cos\beta & -\mu & 0. \end{pmatrix}$$

bino
wino
Higgino1
Higgino2

→ ***lightest Neutralino is DM !***

Main component of the LSP

bino / wino / Higgsino DM



['12 Cheung, Hall, Pinner, Ruderman]

Thermal Relic Dark Matter

Pure Bino LSP : too small cross section to be WIMP

Pure Wino LSP : WIMP cross section at M_{wino} ~ 3TeV

Pure Higgsino LSP : WIMP cross section at $M_{Higgsino}$ ~ 1TeV

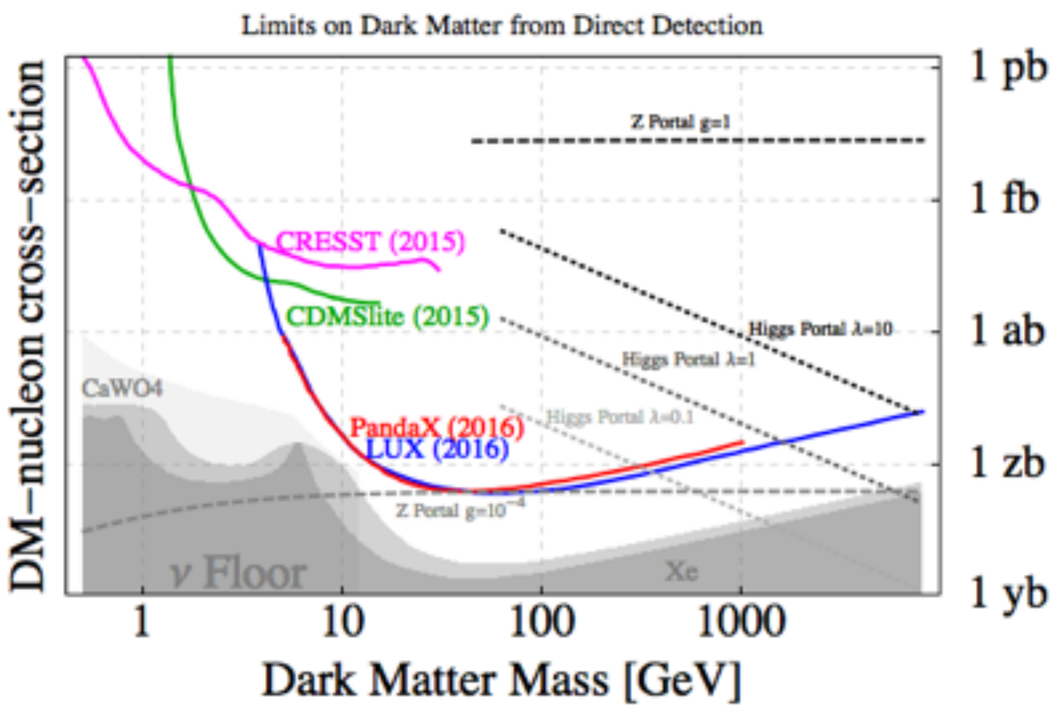
For WIMP with M_χ < TeV, we need appropriate mixing !

→ couplings to Higgs and Z tend to be unsuppressed

→ Direct detection cross sections are rather unsuppressed.

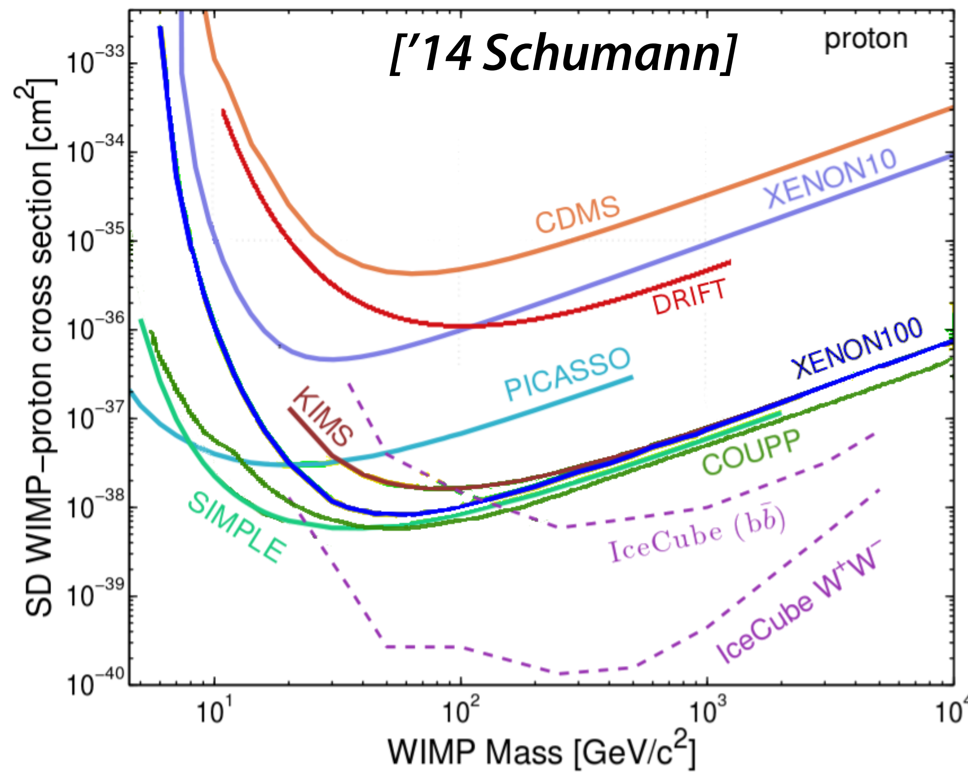
Neutralino Dark Matter

Spin Independent (zb = 10^{-45}cm^2)



http://resonaances.blogspot.jp/2016/09/weekend-plot-update-on-wimps.html

Spin dependent



Neutralino DM interaction with Nucleus

$$\mathcal{L}_{\rm int} = \frac{c_{h\chi\chi}}{2}\, h(\chi\chi + \chi^\dagger\chi^\dagger) \rightarrow \mathcal{L}_{\rm int} \propto {\rm DM}^2 \times \bar\psi_n\psi_n \rightarrow \sigma_{\rm SI} = 8\times 10^{-45}\ {\rm cm}^2 \left(\frac{c_{h\chi\chi}}{0.1}\right)^2$$

$$\mathcal{L}_{\rm int} = c_{Z\chi\chi}\, \chi^\dagger\bar\sigma^\mu\chi Z_\mu \rightarrow \mathcal{L}_{\rm int} \propto ({\rm DM}^2)_\mu \times \bar\psi_n\gamma_5\gamma^\mu\psi_n \rightarrow \sigma_{\rm SD} = 3\times 10^{-39}\ {\rm cm}^2 \left(\frac{c_{Z\chi\chi}}{0.1}\right)^2$$

Bino/Higgsino DM

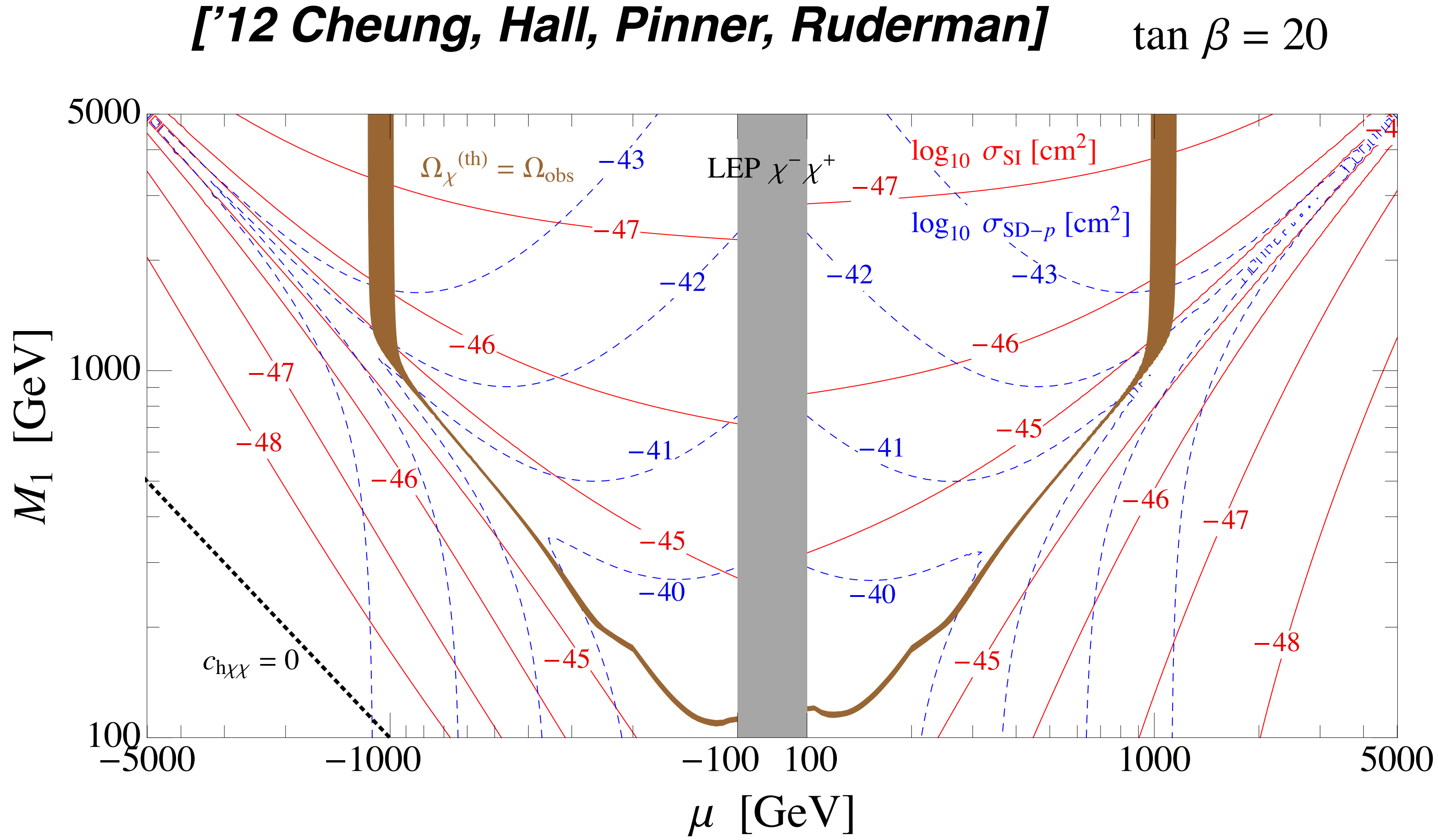
$$c_{h\chi\chi}, c_{Z\chi\chi} \propto \frac{(\sin\beta \pm \cos\beta)\sin\theta_W}{\sqrt{2}} \left(\frac{M_Z}{\Delta M}\right),$$

Bino/Wino DM

$$c_{h\chi\chi}, c_{Z\chi\chi} \propto \frac{\sin 2\beta \sin 2\theta_W}{2} \left(\frac{M_Z^2}{\mu(M_2 - M_1)}\right)$$

Neutralino Dark Matter

['12 Cheung, Hall, Pinner, Ruderman]



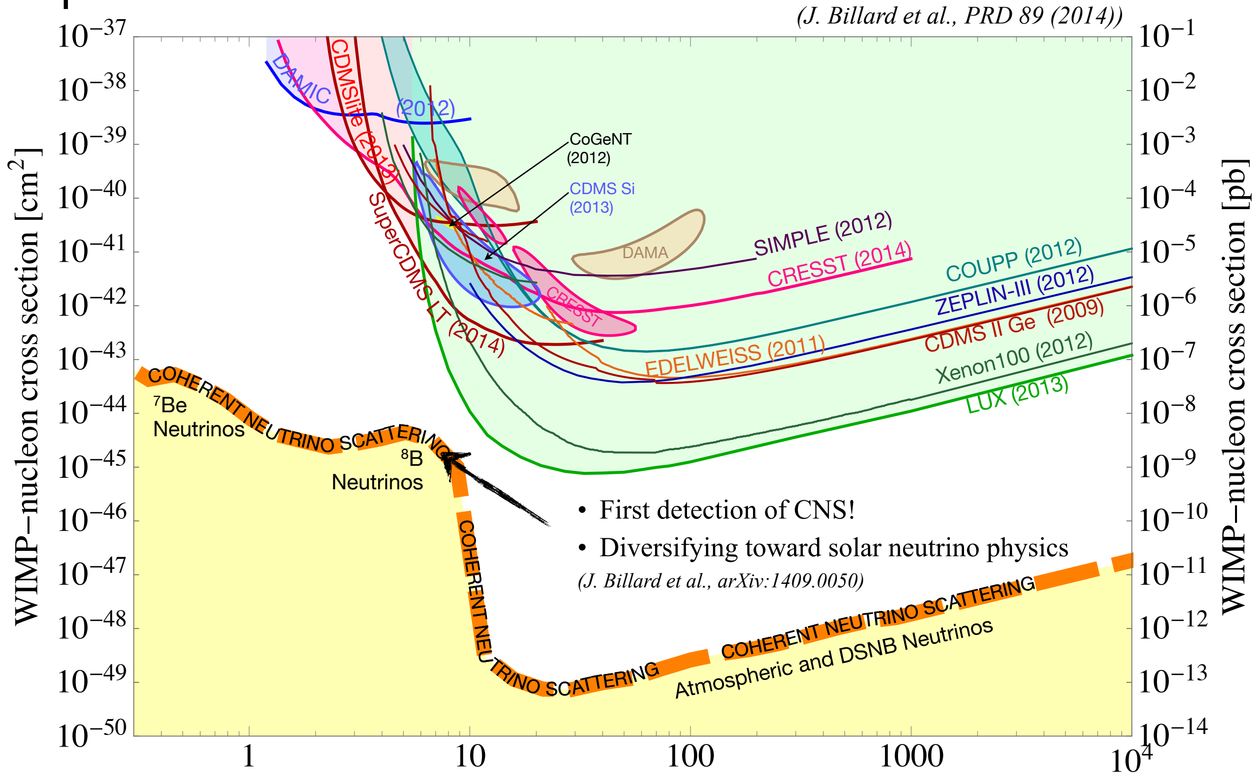
On the brown lines, the dark matter abundance is consistent with observation !

- Direct detection searches give complemental information to the LHC searches and the indirect searches (***<σv> ~ 10^{-9}GeV^{-2}***).

✔ *Pure Wino Dark Matter*

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

$\sigma_{p\text{-}N}/cm^2$



DM mass :

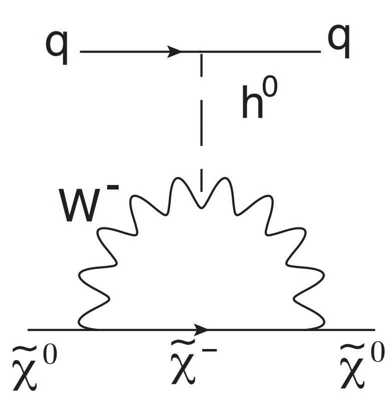
Coupling to H and Z are highly suppressed for μ_H=*O(10-100) TeV* at the tree-level.

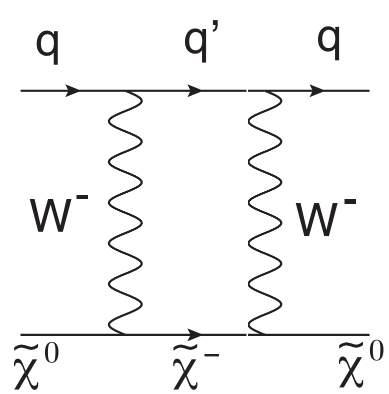
Wino-Nucleon @ higher loop level

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

(much smaller than the current reach...)

['10 Hisano, Ishiwata, Nagata]





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

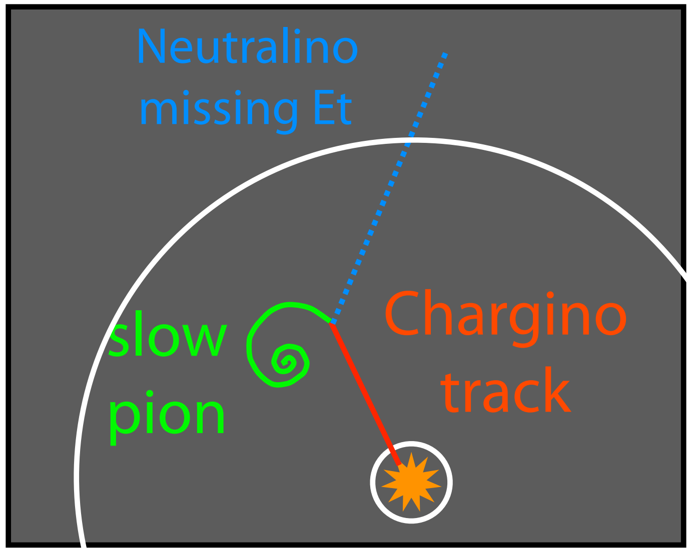
['10 Hisano, Ishiwata, Nagata]

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

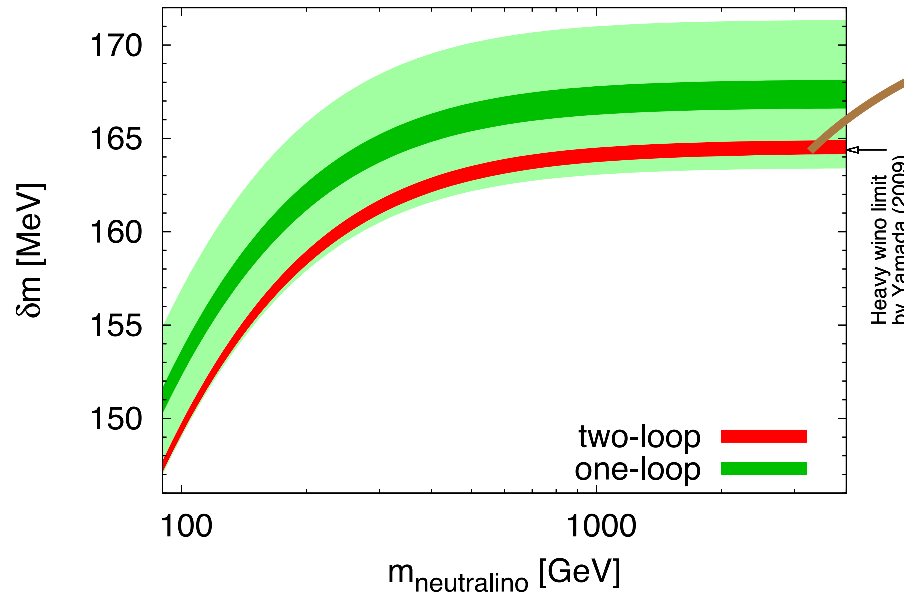
✔ The irreducible background from atmospheric neutrinos at about $10^{-48}cm^2$. [arxiv:1003.5530]

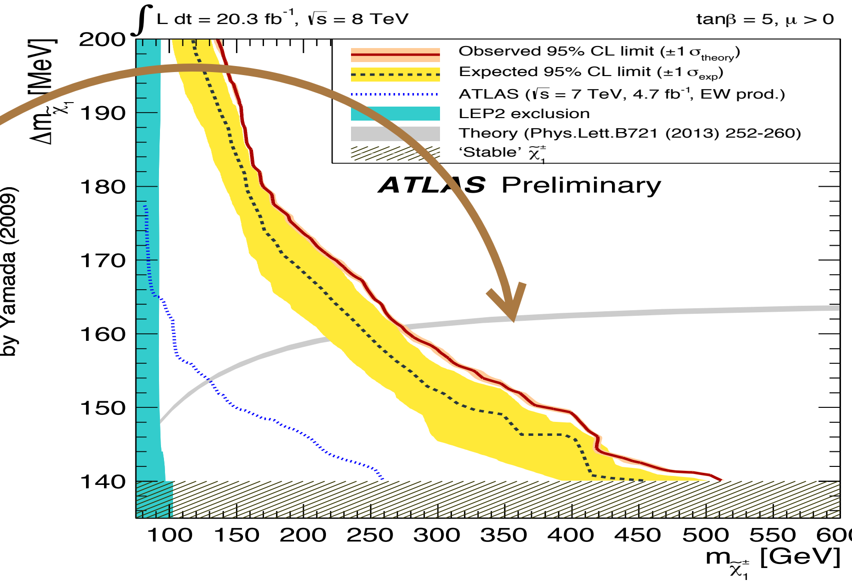
High Scale SUSY at 10TeV - PeV

✔ 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):

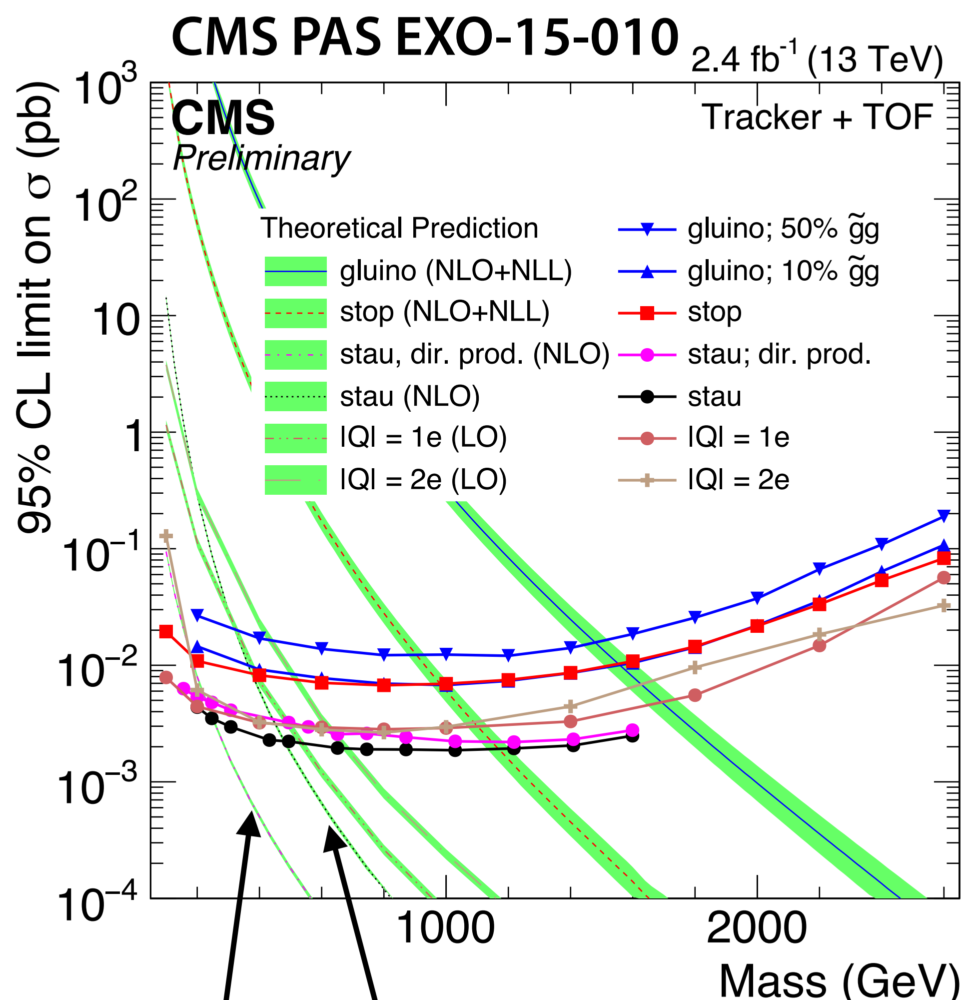
$m_{wino} > 130GeV$ ($7TeV\&5fb^{-1}$) using TRT	[arxiv:1210.2852]
$m_{wino} > 270GeV$ ($8TeV\&20fb^{-1}$) using SCT & TRT	[arXiv:1310.3675]

→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]

Supersymmetry in the TeV ranges

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



via gluino,squark production

$M_{stau} > 480$ GeV

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

via Drell-Yan production

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

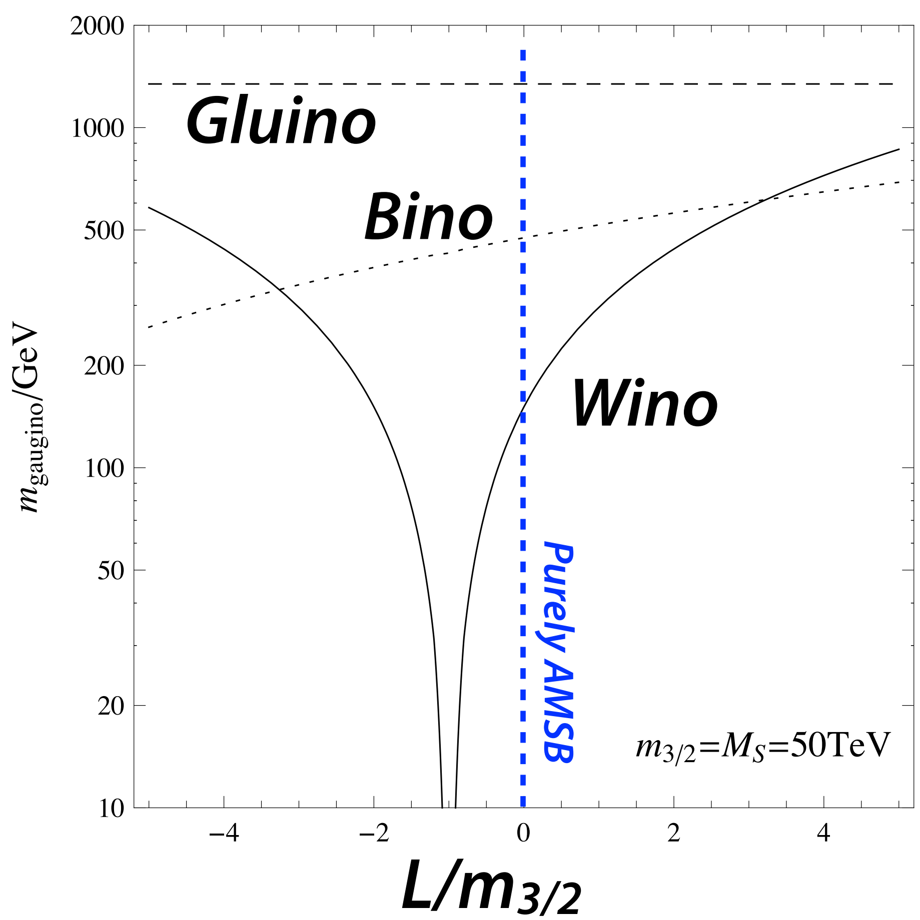
($M_{gluino,squark} >>$ TeV)

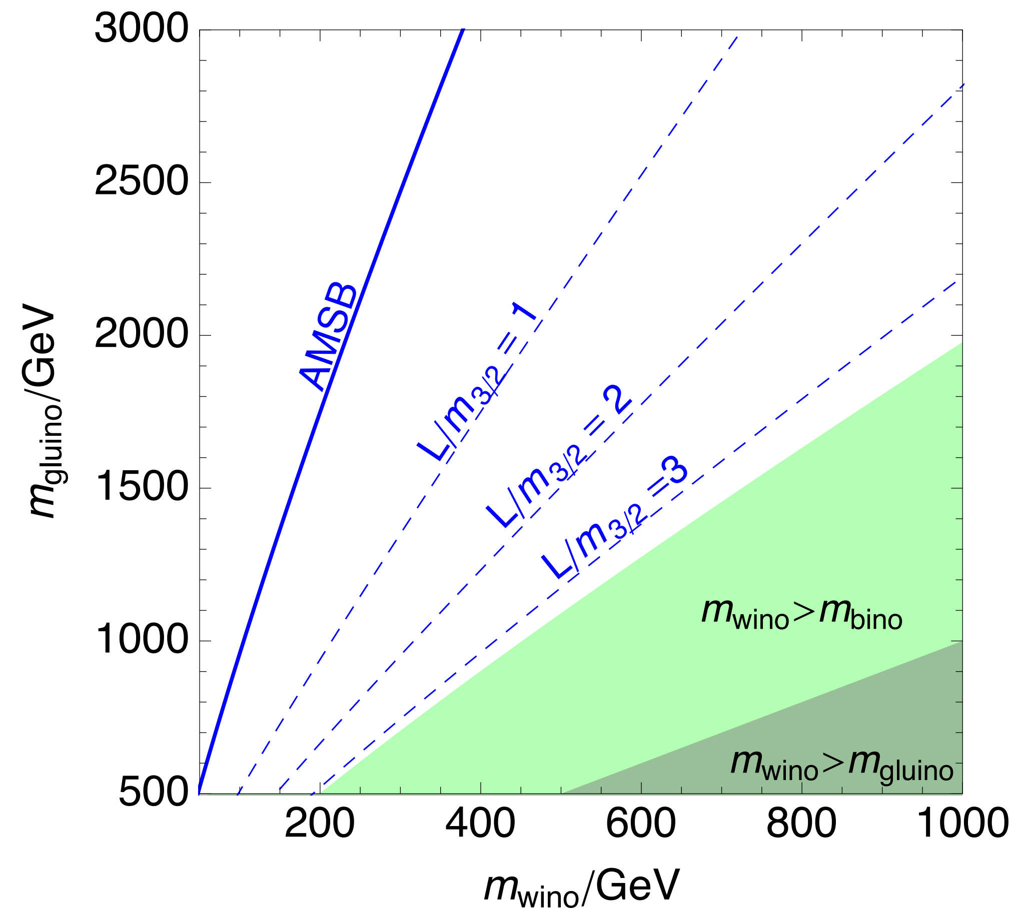
via gluino production
(assuming GMSB with $N_m = 3$)

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

High Scale SUSY at 100TeV - PeV

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





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

$m_{gluino}=2.5\text{x}10^{-2}m_{3/2}$
$m_{wino}=3.0\text{x}10^{-3}(m_{3/2}+L)$
$m_{bino}=9.6\text{x}10^{-3}(m_{3/2}+L/11)$
for $m_{3/2}=O(100)\text{TeV}$.

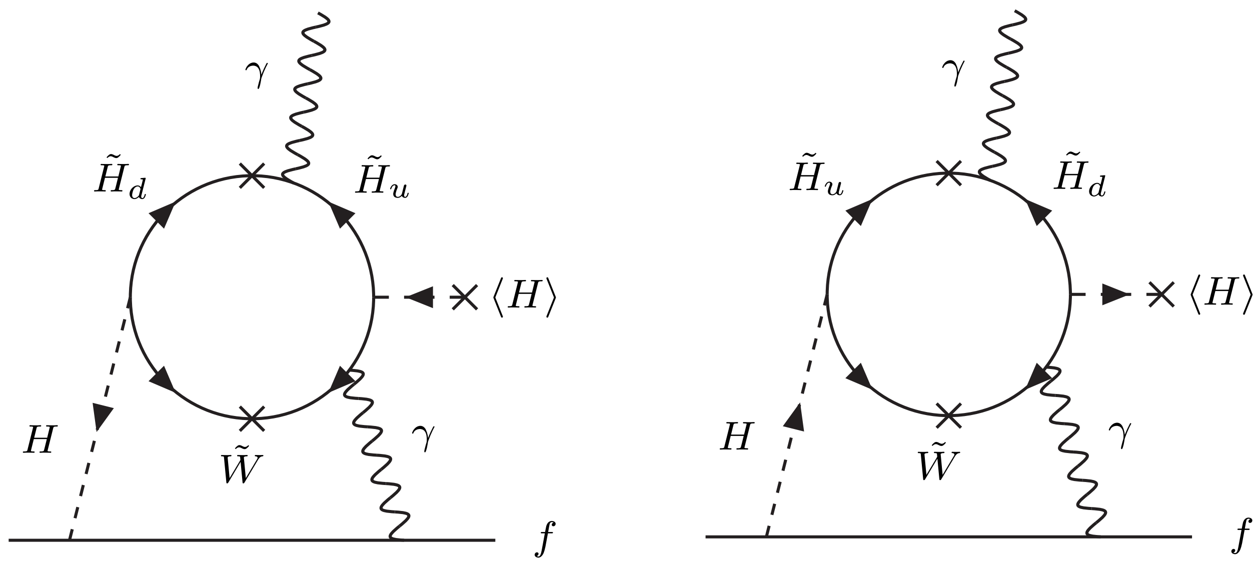
$L=O(m_{3/2})$: Higgsino mediation effect

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

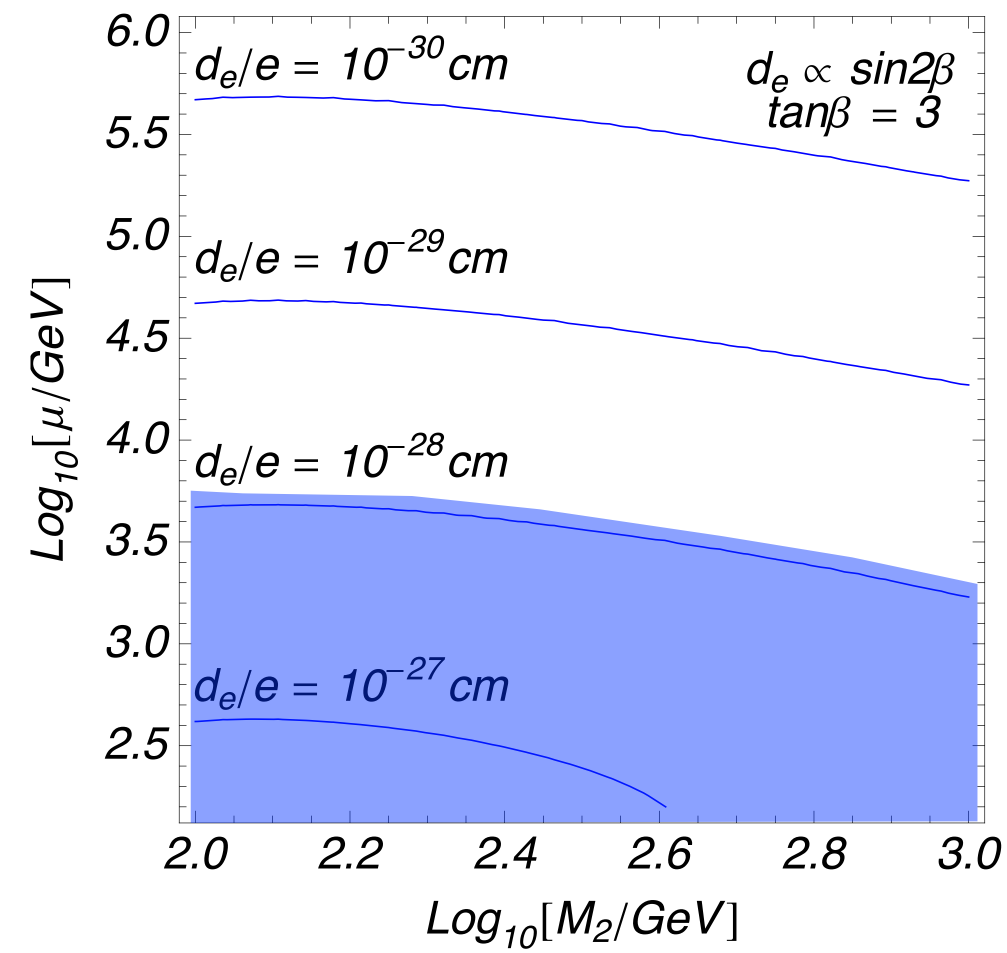
✔ The gluino can be lighter than the prediction in AMSB for $L/m_{3/2}=O(1)$.

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 $\mu_H^{-1} \sin 2\beta$)

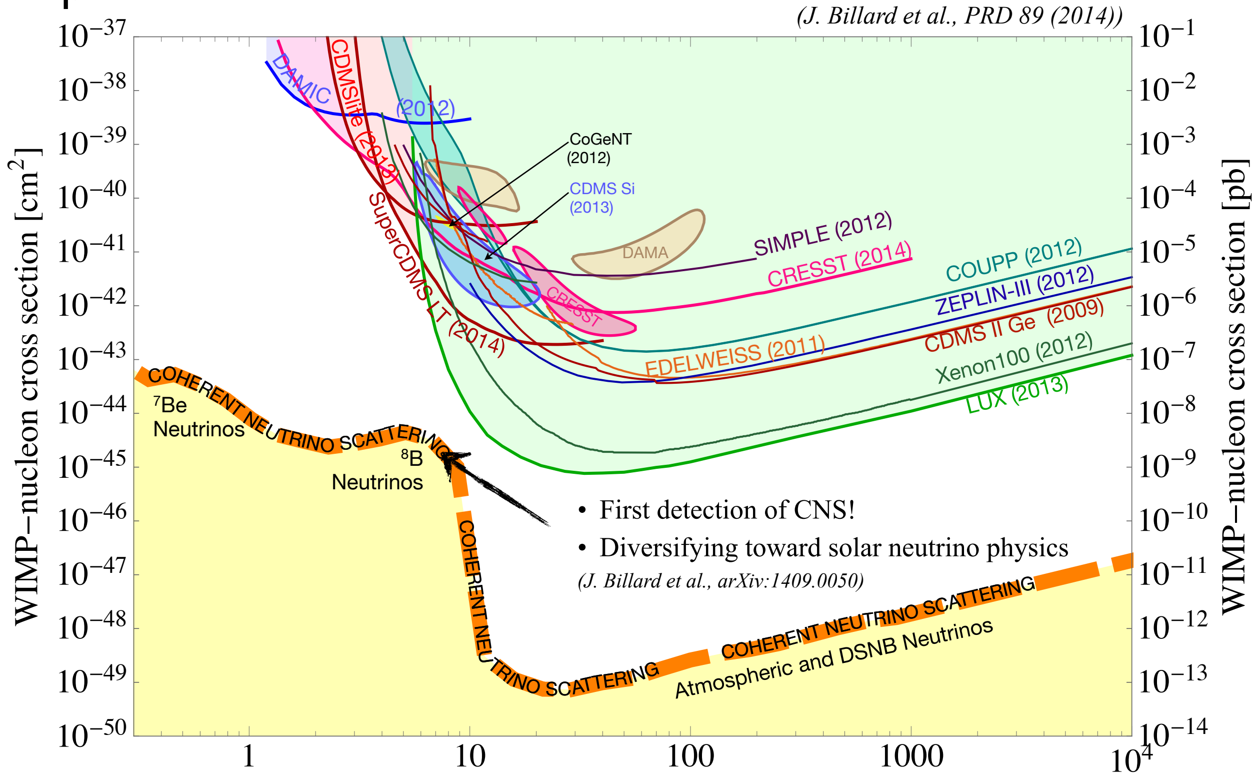
The current limits $d_e/e < 8.7 \times 10^{-29}$cm is reaching to μ_H of $O(10^4)$ TeV !

[1310.7534 ACME : ThO]

High Scale SUSY at 100TeV - PeV

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

$\sigma_{p\text{-}N}/\mathrm{cm}^2$



DM mass :

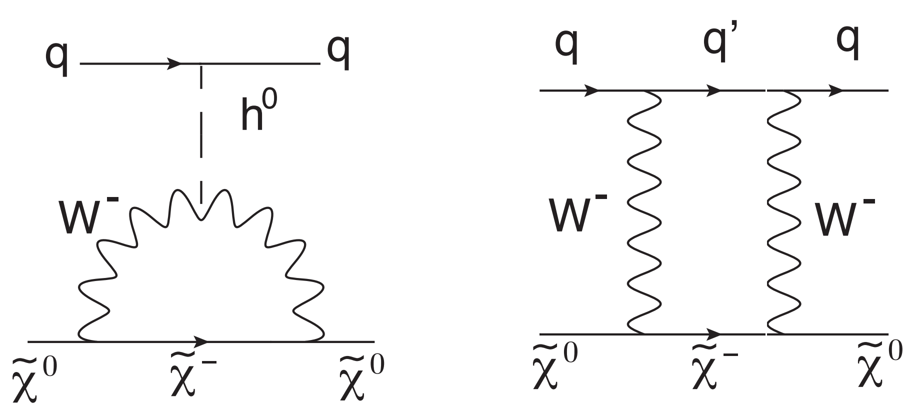
Coupling to H and Z are highly suppressed for μ_H=*O(10-100) TeV* at the tree-level.

Wino-Nucleon @ higher loop level

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

(much smaller than the current reach...)

['10 Hisano, Ishiwata, Nagata]



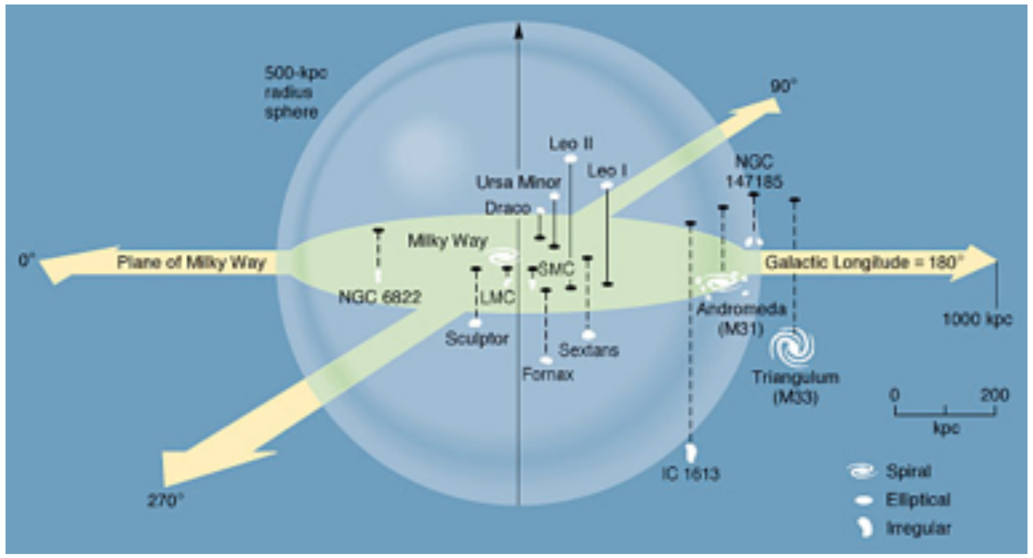
One-loop diagrams which contribute to the Wino-nucleon scatterings.

['10 Hisano, Ishiwata, Nagata]

- Darwin (multi-ton Argon/Xe detector) will reach down to $10^{-47}\mathrm{cm}^2$ for WIMP mass below 300GeV.
- The irreducible background from atmospher neutrinos at about $10^{-48}\mathrm{cm}^2$. [arxiv:1003.5530]

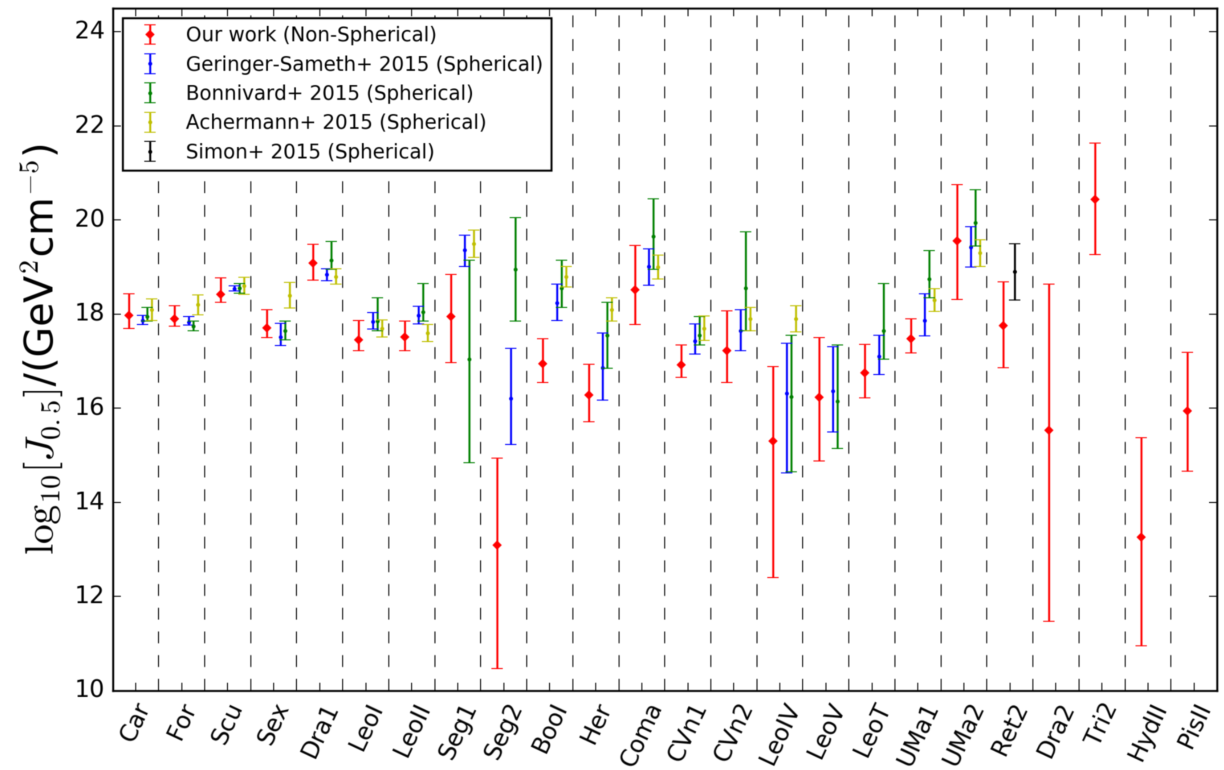
✔ Indirect WIMP Detection (see more arXiv:1511.08787)

✔ Dwarf Spheroidal Galaxies !



http://astronomy.nmsu.edu/tharriso/ast110/class24.html

['16 Hayashi, Ishikawa, Matsumoto, MI, Ishigaki, Sugai]



Object	$N_{\rm sample}$	RA(J2000) [hh:mm:ss]	DEC(J2000) [dd:mm:ss]	M_V	$D_\odot$ [kpc]	b_* [pc]	q' (axial ratio)	Ref.[a]
Classical dwarfs								
Carina	776	06:41:36.7	−50:57:58	-9.1 ± 0.5	106 ± 6	250 ± 39	0.67 ± 0.05	1,6
Fornax	2523	02:39:59.3	−34:26:57	-13.4 ± 0.3	147 ± 12	710 ± 77	0.70 ± 0.01	1,6
Sculptor	1360	01:00:09.4	−33:42:33	-11.1 ± 0.5	86 ± 6	283 ± 45	0.68 ± 0.03	1,6
Sextans	445	10:13:03.0	−01:36:53	-9.3 ± 0.5	86 ± 4	695 ± 44	0.65 ± 0.05	1,6
Draco	468	17:20:12.4	+57:54:55	-8.8 ± 0.3	76 ± 6	221 ± 19	0.69 ± 0.02	1,7
Leo I	328	10:08:28.1	+12:18:23	-12.0 ± 0.3	254 ± 15	251 ± 27	0.79 ± 0.03	1,8
Leo II	200	11:13:28.8	+22:09:06	-9.8 ± 0.3	233 ± 14	176 ± 42	0.87 ± 0.05	1,9
Ultra faint dwarfs								
Segue 1	73	10:07:04.0	+16:04:55	-1.5 ± 0.8	32 ± 6	29^{+8}_{-5}	0.53 ± 0.10	1,10
Segue 2	24	02:19:16.0	+20:10:31	-2.5 ± 0.3	35 ± 2	35 ± 3	0.85 ± 0.13	1,11
Boötes I	37	14:00:06.0	+14:30:00	-6.3 ± 0.2	66 ± 2	242 ± 21	0.61 ± 0.06	1,12
Hercules	18	16:31:02.0	+12:47:30	-6.6 ± 0.4	132 ± 12	330^{+75}_{-52}	0.32 ± 0.08	1,13
Coma Berenices	59	12:26:59.0	+23:54:15	-3.7 ± 0.6	44 ± 4	64 ± 7	0.62 ± 0.14	1,14
Canes Venatici I	214	13:28:03.5	+33:33:21	-7.9 ± 0.5	224^{+22}_{-20}	554 ± 63	0.61 ± 0.03	1,14
Canes Venatici II	25	12:57:10.0	+34:19:15	-4.8 ± 0.6	151^{+15}_{-13}	132 ± 16	0.48 ± 0.11	1,14
Leo IV	18	11:32:57.0	−00:32:00	-5.1 ± 0.6	158^{+15}_{-14}	152 ± 17	0.51 ± 0.11	1,14
Leo V	5	11:31:09.6	+02:13:12	-5.2 ± 0.4	178 ± 10	135 ± 32	0.50 ± 0.15	1,15
Leo T	19	09:34:53.4	+17:03:05	-7.1 ± 0.3	417^{+20}_{-19}	170 ± 15	~ 1.00	1,14
Ursa Major I	39	10:34:52.8	+51:55:12	-5.6 ± 0.6	106^{+9}_{-8}	308 ± 32	0.20 ± 0.04	1,14
Ursa Major II	20	08:51:30.0	+63:07:48	-3.8 ± 0.6	32^{+5}_{-4}	127 ± 21	0.37 ± 0.05	1,14
Reticulum II	25	03:35:42.1	−54:02:57	-2.7 ± 0.1	32 ± 3	32^{+2}_{-1}	0.41 ± 0.03	2,16
Draco II	9	15:52:47.6	+64:33:55	-2.9 ± 0.8	20 ± 3	19^{+8}_{-6}	$0.76^{+0.27}_{-0.24}$	3,17
Triangulum II	13	02:13:17.4	+36:10:42	-1.8 ± 0.5	30 ± 2	34^{+9}_{-8}	$0.79^{+0.17}_{-0.21}$	4,18
Hydra II	13	12:21:42.1	−31:59:07	-4.8 ± 0.3	134 ± 10	68 ± 11	$0.99^{+0.01}_{-0.19}$	5,19
Pisces II	7	22:58:31.0	+05:57:09	-5.0 ± 0.5	~ 180	~ 60	0.60 ± 0.10	1,19

DM profile can be estimated from motions of stars.

We observe gamma ray flux from entire dwarf galaxies .

→ less sensitive to the structure of the core region!

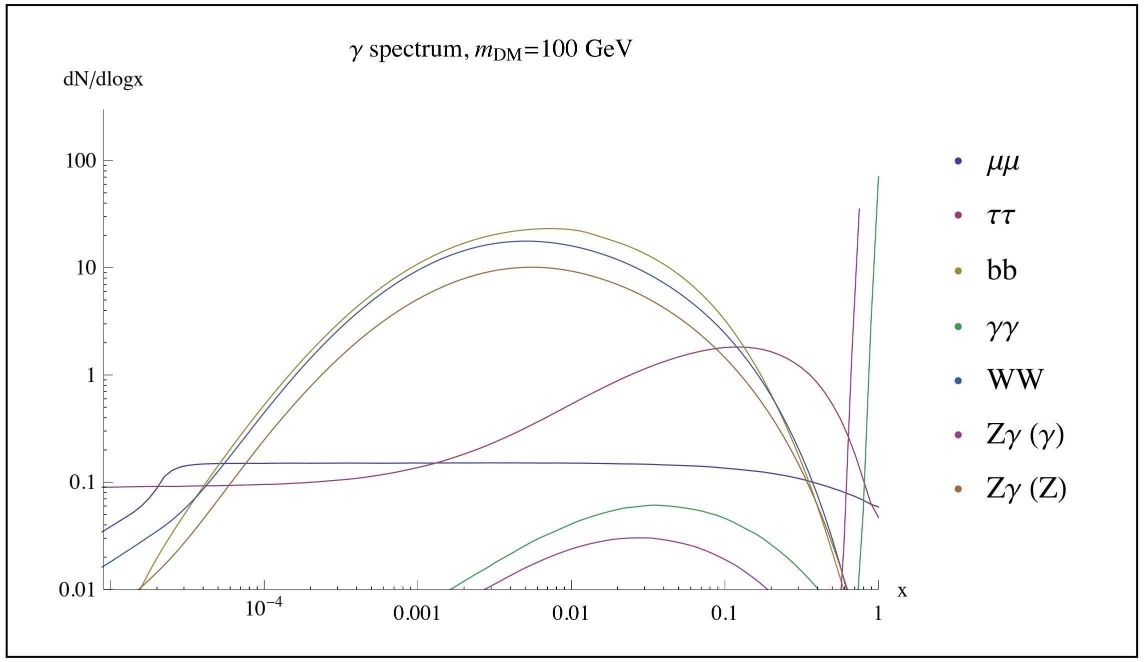
Less active, and hence, less background gamma ray.

Indirect WIMP Detection (see more arXiv:1511.08787)

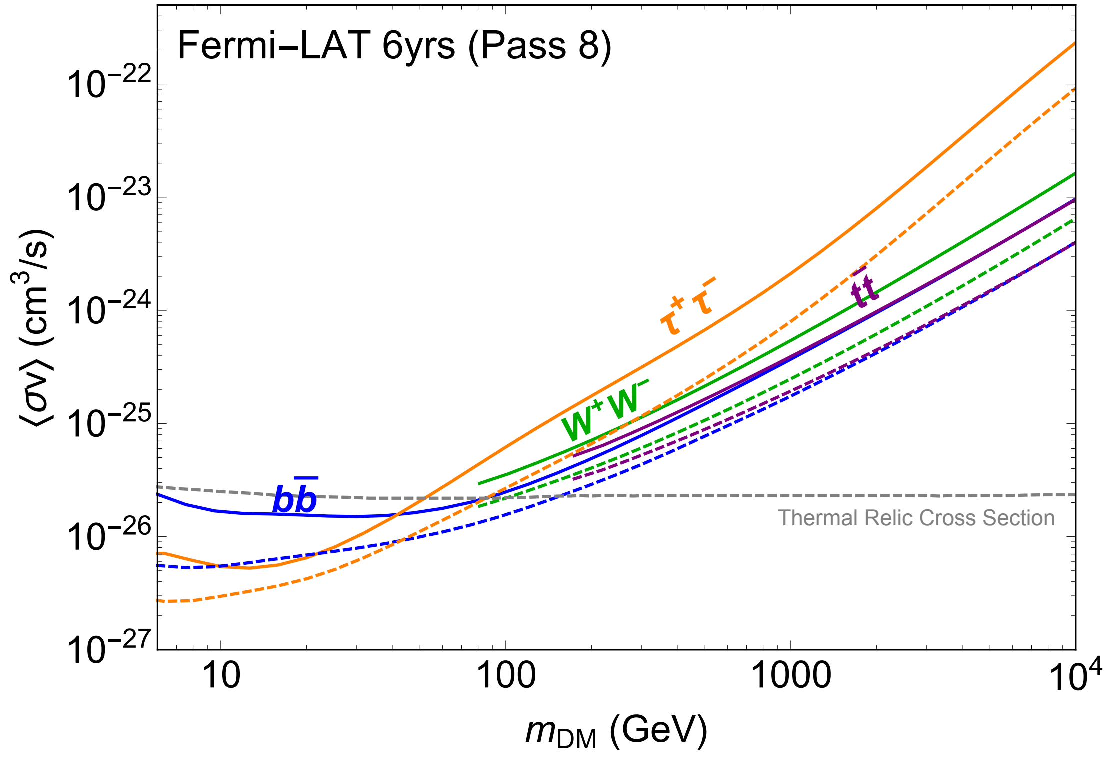
Constraints on continuous spectrum from dwarf Spheroidal Galaxy

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2{m_\chi}^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s}\rho^2_{\rm DM}(l,\Omega)dld\Omega$$

['15 Carpenter, Colburn, Goodman]



['16 Hayashi, Ishikawa, Matsumoto, MI, Ishigaki, Sugai]

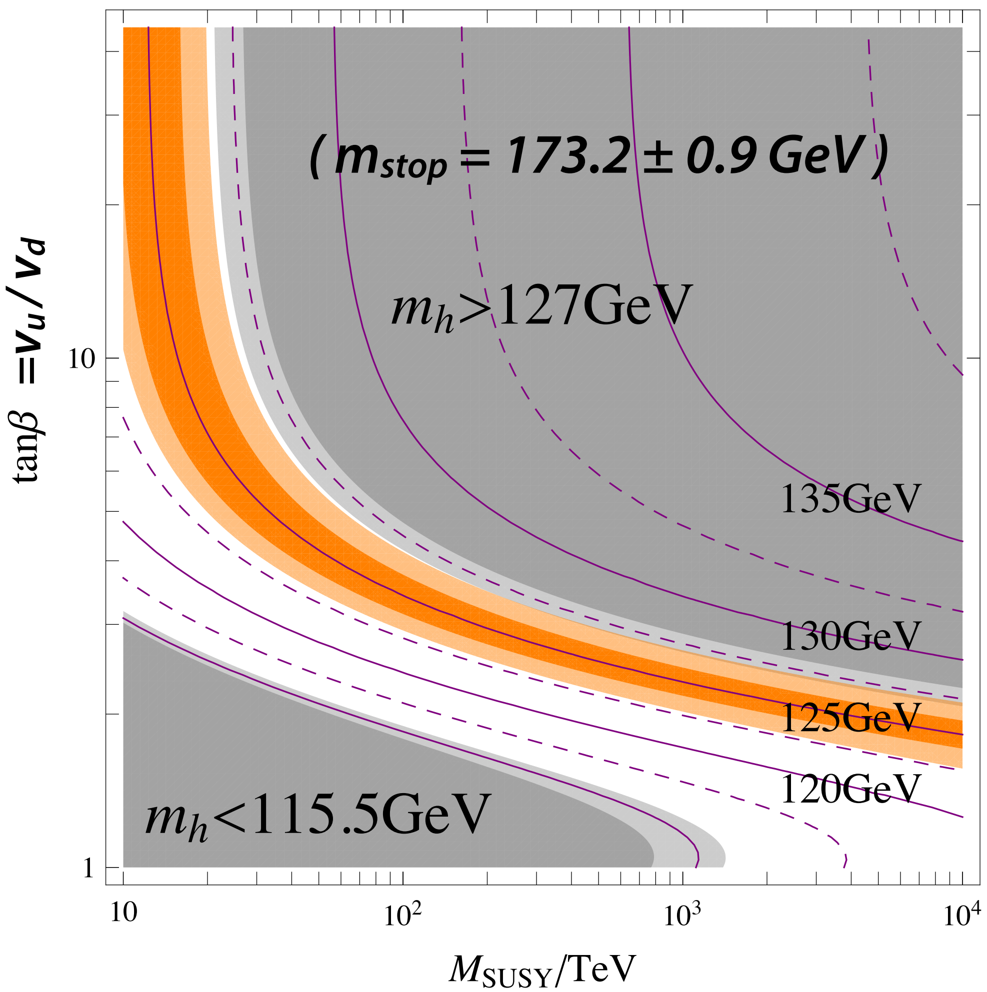


WIMP cross section has been excluded for m_{DM} < 100GeV annihilating into bb!

Big Blow to supersymmetry?

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

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

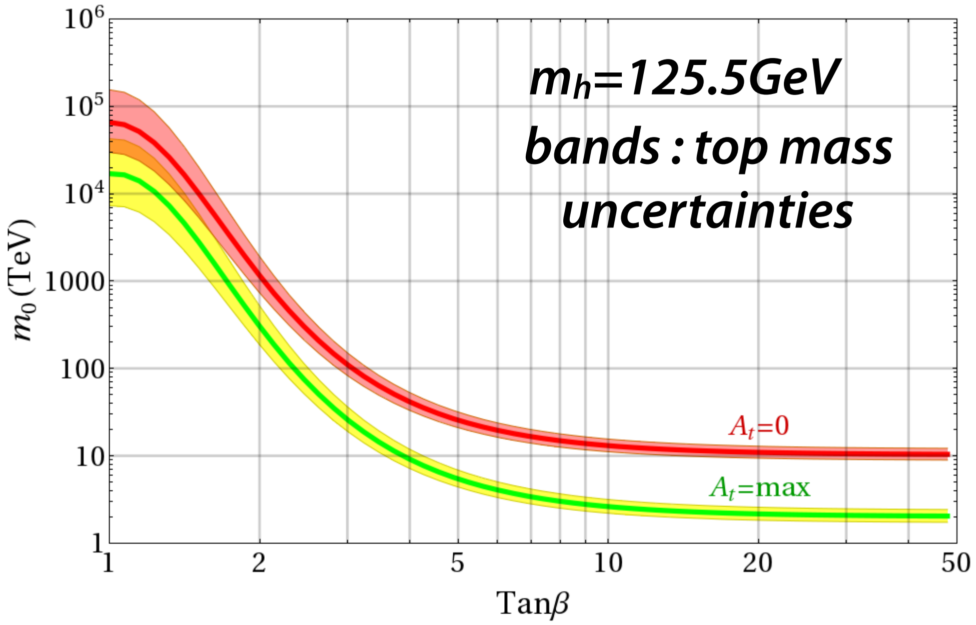


['12, MI, Matsumoto,Yanagida (μ_H=O(M_{susy}))]

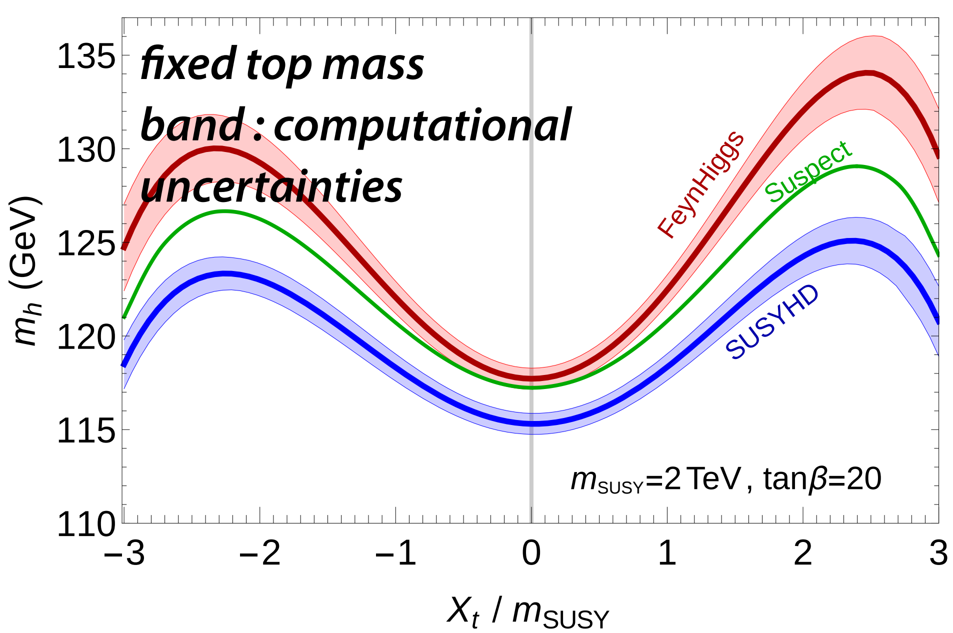
Big Blow to supersymmetry?

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, $\boldsymbol{m_{squark}}$ > ***TeV*** is required

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

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

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

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…

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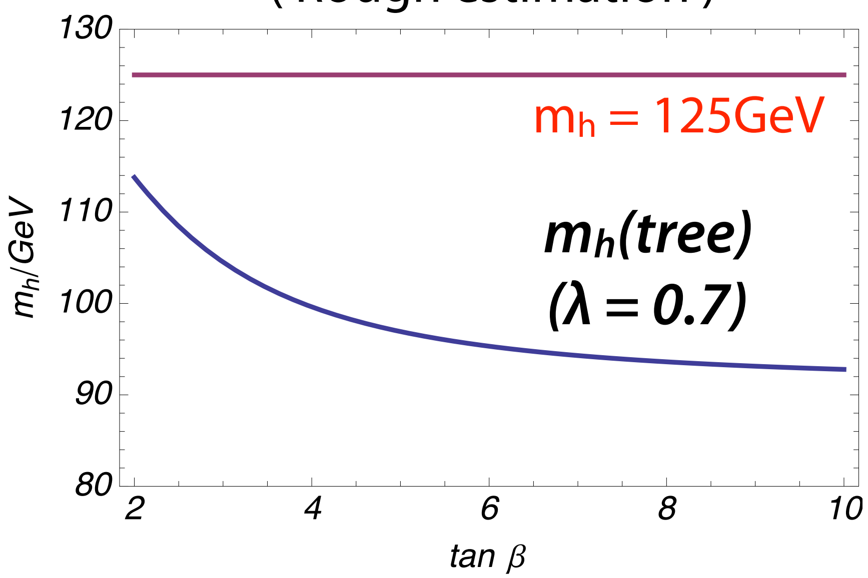
✔ Singlet Extension (NMSSM) *[see '10 Maniatis for review]*

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.

($\lambda < 0.7$ from perturbativity)

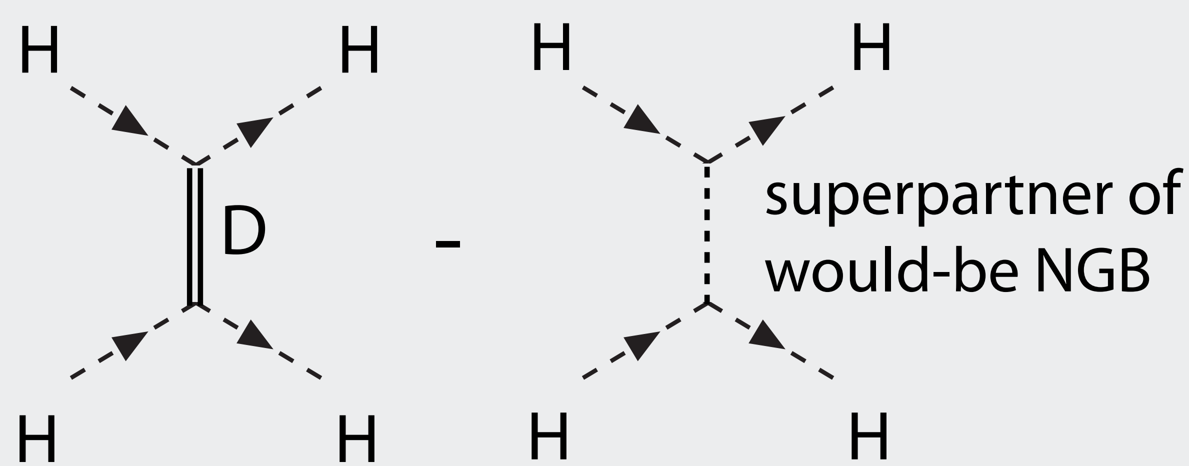
[For the scenarios where the lightest Higgs is not the observed one see ***'13 Christensen, Han, Liu, Su***] .

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



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

$M_{Z'}$: 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.