素粒子物理学の進展、基礎物理学研究所、2012年7月

Compact Supersymmetry

飛岡　幸作
Kavli IPMU, 東京大学

arXiv:1206.4993[hep-ph]

Collaboration with
Hitoshi Murayama, Yasunori Nomura and Satoshi Shirai

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Table of my talk

1. Introduction
   I. Current Situation
   II. Weaker constraint by LHC on Compressed Scenario

2. Compact Supersymmetry model
   I. Scherk-Schwarz mechanism ~ Radion Mediation
   II. Model setup
   III. Phenomenology

3. Summary

Current Situation

1. Higgs like particle is discovered around 125 GeV

Implication to Supersymmetry

Tightly constraints MSSM, need to boost the Higgs mass by radiative corrections:

- High scale of M_{SUSY} (Split) and/or
- Large A term

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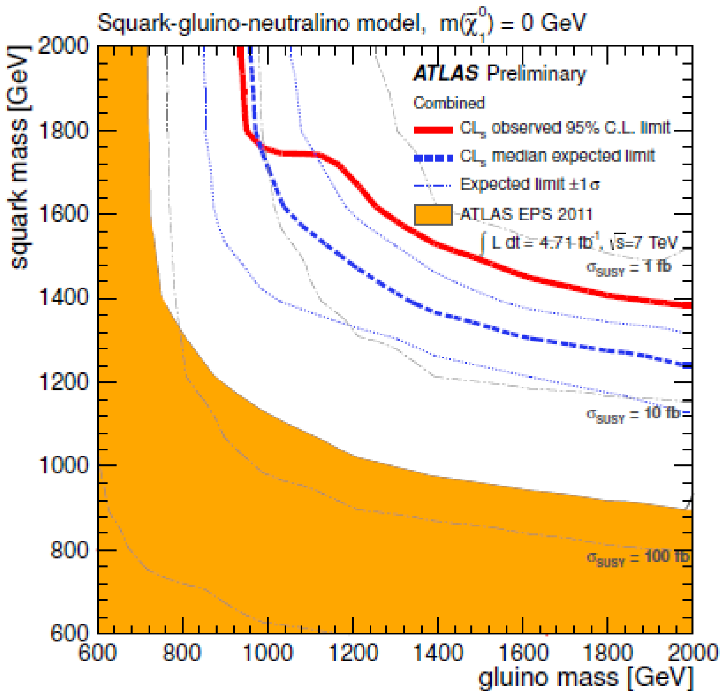
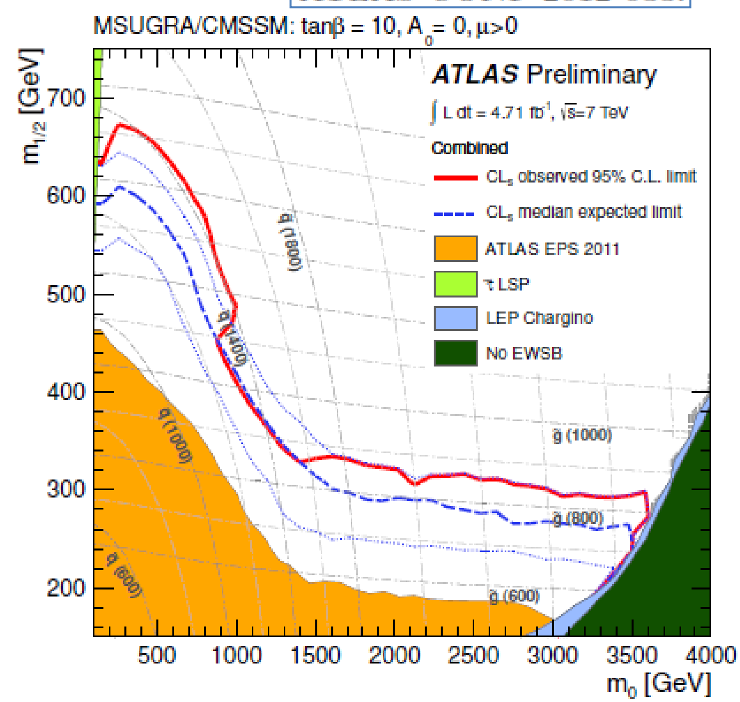
Measure M_{SUSY}
arXiv:1207.3608
Sato, Shirai, Tobioka

Current Situation

2. No signal of Beyond Standard Model with Missing Energy

ATLAS-CONF-2012-033.





$M_{gluino}=M_{squark}$>1.4TeV for 5fb^-1
(>1TeV for 1fb^-1)

Current Situation

2. No signal of Beyond Standard Model with Missing Energy

Implication to Supersymmetry

- Split -> Small cross section
- R-parity violation
- Compressed Spectrum -> Small q-value (this talk)

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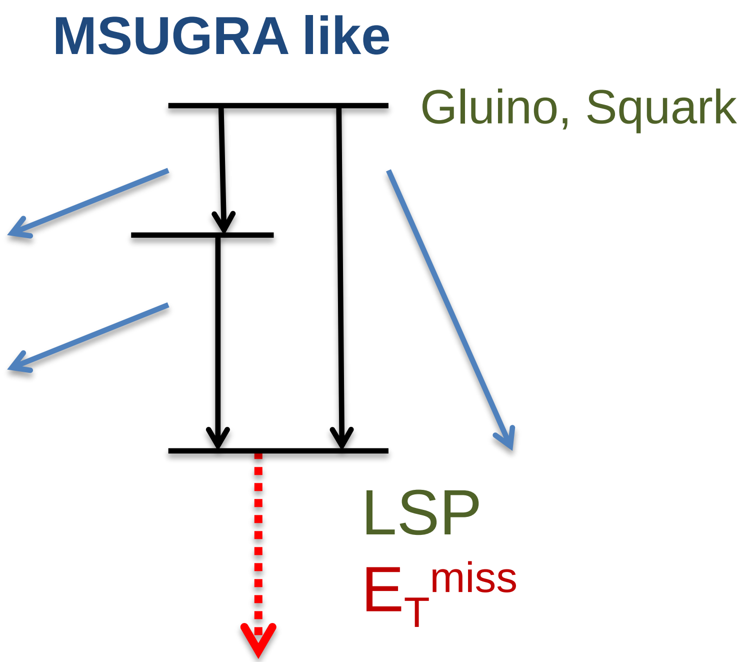
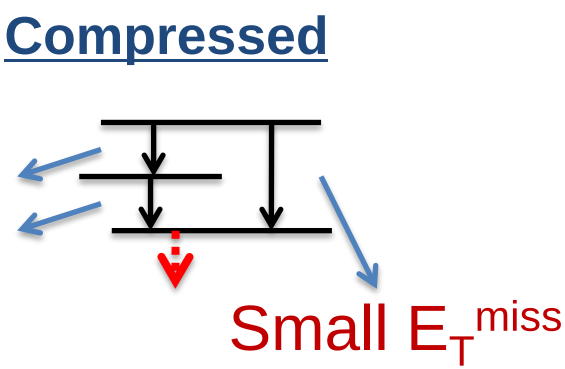
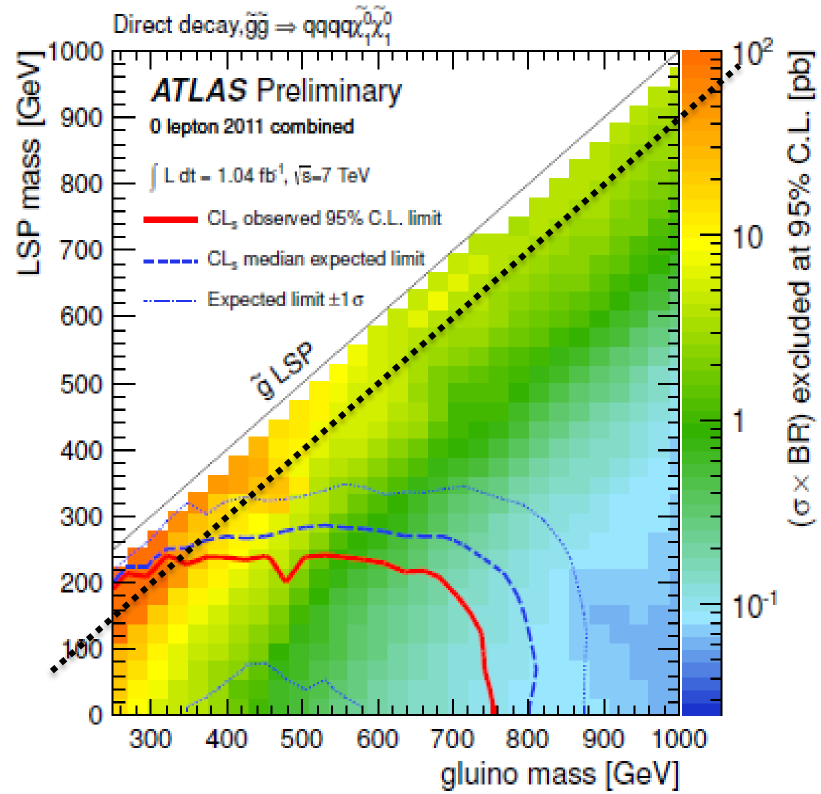




Difficult to extract the signal from the background (ttbar, W+jets)

Weaker constraint by LHC in Compressed scenario

Experimentalist's Analysis
ATLAS-CONF-2011-155



- Gluino+LSP model
  M_{gluino}~350GeV

- Squark+LSP model
  M_{squark}~250GeV
  (Δm >100GeV)

- Gluino+Squark+LSP model
  $M_{gluino}=M_{squark}$~400GeV
  (Δm =5GeV!)

Actually much weaker constraint, 400 GeV <<1TeV

Weaker constraint by LHC in Compressed scenario

Theorist's Analysis
LeCompte, S. P. Martin [arXiv:1111.6897]

Phenomenological model + ATLAS Multijet search

$M_{gluino} \simeq M_{squark}$~650GeV when Δm ≥ 100GeV

$$M_1 = \left(\frac{1+5c}{6}\right) M_{\tilde{g}}$$

$$M_2 = \left(\frac{1+2c}{3}\right) M_{\tilde{g}}$$

Recent analysis
H. K. Dreiner et al. [arXiv: 1207.1613]

Phenomenological model + Monojet/Various CMS analyses

$M_{gluino} \simeq M_{squark}$~650GeV when Δm ≥ 1GeV !

Still much weaker constraint, 650 GeV <<1TeV

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Mostly based on Phenomenological models,
Scherk-Schwarz SUSY breaking generates universal soft masses

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Scherk-Schwarz mechanism

[Scherk and Schwarz (1979)]

- 5D Minimal SUSY (corresponding to $\mathcal{N}$=2 in 4D)
- Geometry: S^1/Z_2 (chiral for zero mode, $\mathcal{N}$=1 in 4D)

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- Non-trivial boundary condition on $SU(2)_R$ space

breaks supersymmetry =Scherk-Schwarz mechanism

Non-trivial B.C.

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} (x_\mu, y + 2\pi R) = e^{-2\pi i \alpha \sigma_2} \begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} (x_\mu, y)$$

y: 5th dimensional coordinate
R: radius of extra dimension

Continuous twist parameter (α)
We take α<<1

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Resulting KK decomposition

$$\begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix} (x_\mu, y) = \sum_{n=0}^{\infty} e^{-i\alpha\sigma_2 y/R} \begin{pmatrix} \lambda_1^{(n)}(x_\mu)\cos[ny/R] \\ \lambda_2^{(n)}(x_\mu)\sin[ny/R] \end{pmatrix}$$

$$\supset \begin{pmatrix} \lambda_1^{(0)}(x_\mu)\cos[\alpha y/R] \\ \lambda_1^{(0)}(x_\mu)\sin[\alpha y/R] \end{pmatrix}$$

5D derivative generates (soft) masses in 4D

$$m_n = \begin{cases} \alpha/R & \text{zero mode} \\ (\alpha \pm n)/R & \text{non-zero modes} \end{cases}$$

Field Properties in 5th dimension

Fields: $V, \ \chi, \ \Phi, \ \Phi^c$

Higgs localized at y=0: $H_u(x), H_d(x)$

V :Vector superfield A_μ, λ_1

χ : Adjoint chiral superfield $\lambda_2, \ A_5, \ \Sigma$

$\Phi^{(c)}$: Hypermultiplet of matter fields $\phi^{(c)}, \psi^{(c)}$

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Inversion

$$\begin{pmatrix} V(x,-y) \\ \chi(x,-y) \end{pmatrix} = \begin{pmatrix} V(x,y) \\ -\chi(x,y) \end{pmatrix}$$

$$\begin{pmatrix} \Phi(x,-y) \\ \Phi^c(x,-y) \end{pmatrix} = \begin{pmatrix} \Phi(x,y) \\ -\Phi^c(x,y) \end{pmatrix}$$

Translation (SS mechanism)

For $SU(2)_R$ doublets, common twist

$$\begin{pmatrix} \lambda_1(x,y+2\pi R) \\ \lambda_2(x,y+2\pi R) \end{pmatrix} = e^{-2\pi\alpha\sigma_2} \begin{pmatrix} \lambda_1(x,y) \\ \lambda_2(x,y) \end{pmatrix}$$

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same for gravitinos

For others, $X(x,y+2\pi R) = X(x,y)$

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same for gravitinos

For others, $X(x,y+2\pi R) = X(x,y)$

$$m_{1/2,\text{squark,slepton}} = \frac{\alpha}{R}$$

Common soft mass

Radion Mediation ~ SS mechanism

Radion mediation: SUSY breaking by the Radion superfield vev

$$T = R + iB_5 + \theta\Psi_R^5 + \theta^2 F_T$$

~Dynamical realization of Scherk-Schwarz mechanism

[D.Marti and A.Pomarol(2001), D.Kaplan and N. Weiner(2001)]

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◆Gauge sector

$$S_5 = \int dx^4 dy \left[\frac{1}{4g_5^2} \int d^2\theta \left(\frac{T}{R}\right) W^\alpha W_\alpha + \text{h.c.} + \frac{1}{g_5^2} \int d^4\theta \frac{2R}{T+T^\dagger} \left(\partial_5 V - \frac{\chi + \chi^\dagger}{\sqrt{2}} \right)^2 \right]$$

◆Matter sector

$$S_5 = \int dx^4 dy \left[\frac{1}{4g_5^2} \int d^4\theta \, \frac{T+T^\dagger}{2R} \left(\Phi^\dagger e^{-V} \Phi + \Phi^c e^V \Phi^{c\dagger} \right) + \int d^2\theta \; \Phi^c \left(\partial_5 - \frac{\chi}{\sqrt{2}} \right) \Phi + \text{h.c.} \right]$$

Radion vev: $< T >= R + F_T \theta^2$ $\qquad \frac{F_T}{2} = -\alpha$

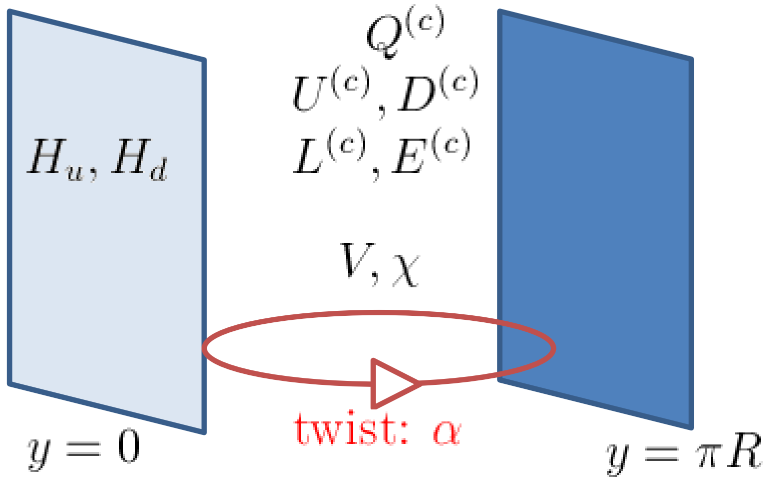
Canonically normalize: $\Phi^{(c)} \to \left(1 - \frac{F_T}{2R}\theta^2\right) \Phi^{(c)}, \; \chi \to \left(1 + \frac{F_T}{2R}\theta^2\right) \chi$

Actually this theory is identified as SSSB

Compact Supersymmetry model

Higgs fields and Yukawa interactions are localized on the brane at y=0

$$\mathcal{L}_{\text{brane}} = \delta(y) \int d^2\theta \big(y_U^{ij} Q_i U_j H_u + y_D^{ij} Q_i D_j H_d + y_E^{ij} L_i E_j H_d + \mu H_u H_d \big).$$



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Large A term is generated by the field redefinition

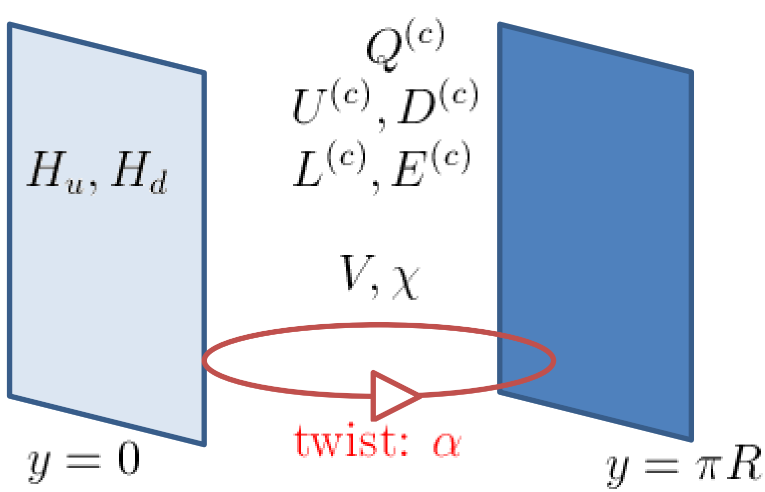
$$\Phi^{(c)} \to \left(1 - \frac{F_T}{2R}\theta^2\right) \Phi^{(c)} ,$$

$$y_U^{ij} Q_i U_j H_u \to (1 - \frac{F_T}{R}\theta^2) y_U^{ij} Q_i U_j H_u$$

$$= (1 + \frac{2\alpha}{R}\theta^2) y_U^{ij} Q_i U_j H_u$$

$$\frac{F_T}{2} = -\alpha$$

$$A_0 = -\frac{2\alpha}{R}$$



Compact Supersymmetry model

- Take alpha<<1
- KK states(~n/R) are decoupled ->MSSM at low energy
- Compact parameter set rather than CMSSM:

At tree level and at scale ~1/R,

$$M_{1/2} = \frac{\alpha}{R}, \quad m^2_{\tilde{Q},\tilde{U},\tilde{D},\tilde{L},\tilde{E}} = \left(\frac{\alpha}{R}\right)^2, \quad m^2_{H_u,H_d} = 0,$$
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- Radiative corrections from at and above 1/R are under control because of symmetries of higher dimensions
- Calculated threshold corrections to the Higgs mass parameters

$$\delta m^2_{H_u} = \left(-\frac{33y_t^2}{8\pi^2} + \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\right)\left(\frac{\alpha}{R}\right)^2,$$
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Only three parameters!

$$\frac{1}{R}, \quad \frac{\alpha}{R}, \quad \mu.$$

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Only three parameters!

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- No physical phase
- Geometry is universal

✓CP
✓Flavor

Brane-localized kinetic terms and cutoff

- Radiative corrections from above 1/R generates boundary kinetic terms from dimensional analysis

$$\frac{\delta M_{1/2}}{M_{1/2}}, \frac{\delta m^2_{\tilde{f}}}{m^2_{\tilde{f}}}, \frac{\delta A_0}{A_0} \approx O\left(\frac{1}{16\pi^2}\ln(\Lambda R)\right).$$

- Assume the tree level contributions are same size of radiative ones $\sim \frac{y_t^2}{16\pi^2}\mathcal{O}(1)$

Effective theory with tree level estimation of soft parameters is valid for $\Lambda R \ll 16\pi^2$

Power of $\mathcal{N}$=2

- S^1/Z_2 orbifolding makes zero modes chiral, but higher KK modes consists $\mathcal{N}$=2 multiplets
- No wavefunction renormalization of hypermultiplet in $\mathcal{N}$=2 SUSY

$$S_5 = \int dx^4 dy \left[\frac{1}{4g_5^2} \int d^4\theta \boxed{\frac{T+T^\dagger}{2R}} \left(\Phi^\dagger e^{-V} \Phi + \Phi^c e^V \Phi^{c\dagger} \right) + \int d^2\theta \; \Phi^c \left(\partial_5 - \frac{\chi}{\sqrt{2}} \right) \Phi + \text{h.c.} \right]$$

- Even log divergences are cancelled out for each KK mode (n>0)
- Only MSSM(n=0) particles give log divergences

Gravitino mass

- Obviously the SU(2)R doublets should have same soft mass from their 5d derivatives

- SUSY breaking is from Radion

•GR action

$$M_{pl}^2 \mathcal{R} \to M_{pl}^2 \left(\frac{T + T^\dagger}{R} \right)^2$$

$$\left(g_{55} \to \frac{T + T^\dagger}{R} \right)$$

•Gravitino mass

Radion should be canonically normalized

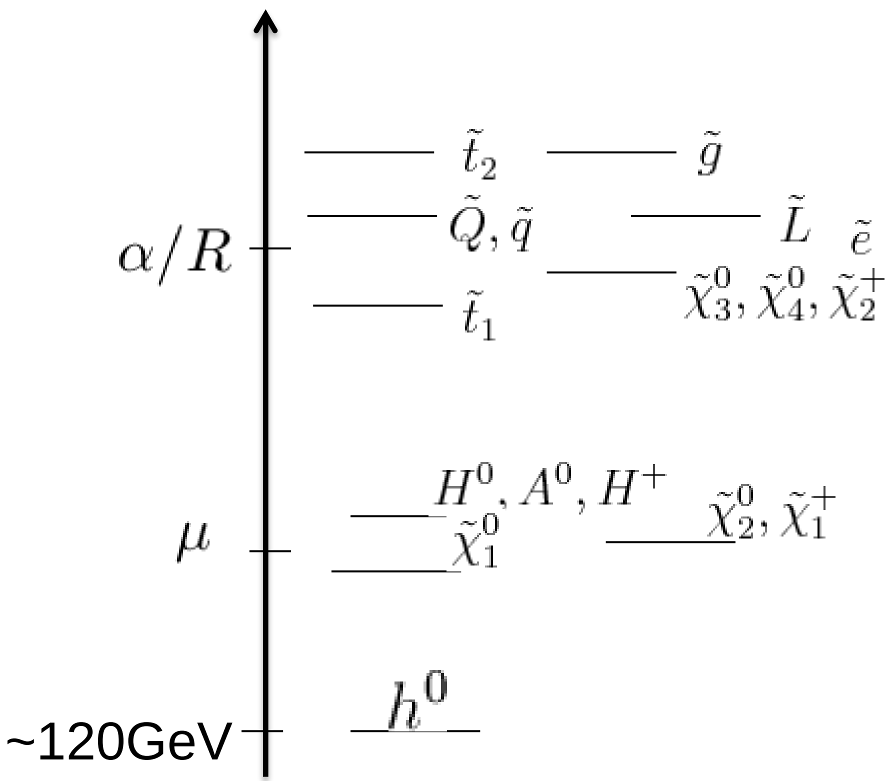
$$M_{3/2} \sim \frac{< \mathcal{F} >}{M_{pl}} \sim \frac{(F_T/R) M_{pl}}{M_{pl}}$$

$$M_{1/2,\ \mathrm{squark,\ slepton}} = M_{3/2} = \frac{\alpha}{R}$$

Spectrum

Point1: $\alpha/R = 1400$ GeV, $1/R = 10^4$ GeV

Point2: $\alpha/R = 800$ GeV, $1/R = 10^5$ GeV



Particle	Point1	Point2	Particle	Point1	Point2
$\tilde{g}$	1494	949	–	–	–
$\tilde{u}_L$	1467	939	$\tilde{u}_R$	1459	925
$\tilde{d}_L$	1469	942	$\tilde{d}_R$	1458	924
$\tilde{b}_2$	1460	924	$\tilde{b}_1$	1430	875
$\tilde{t}_2$	1557	988	$\tilde{t}_1$	1267	681
$\tilde{\nu}$	1411	822	$\tilde{\nu}_\tau$	1410	822
$\tilde{e}_L$	1413	826	$\tilde{e}_R$	1406	812
$\tilde{\tau}_2$	1417	823	$\tilde{\tau}_1$	1402	809
$\tilde{\chi}_1^0$	767	630	$\tilde{\chi}_2^0$	777	671
$\tilde{\chi}_3^0$	1384	755	$\tilde{\chi}_4^0$	1410	821
$\tilde{\chi}_1^\pm$	771	642	$\tilde{\chi}_2^\pm$	1409	817
h^0	125	120	H^0	819	718
A^0	819	717	$H^\pm$	822	722

Higgsino like LSP

$\sim \mu$

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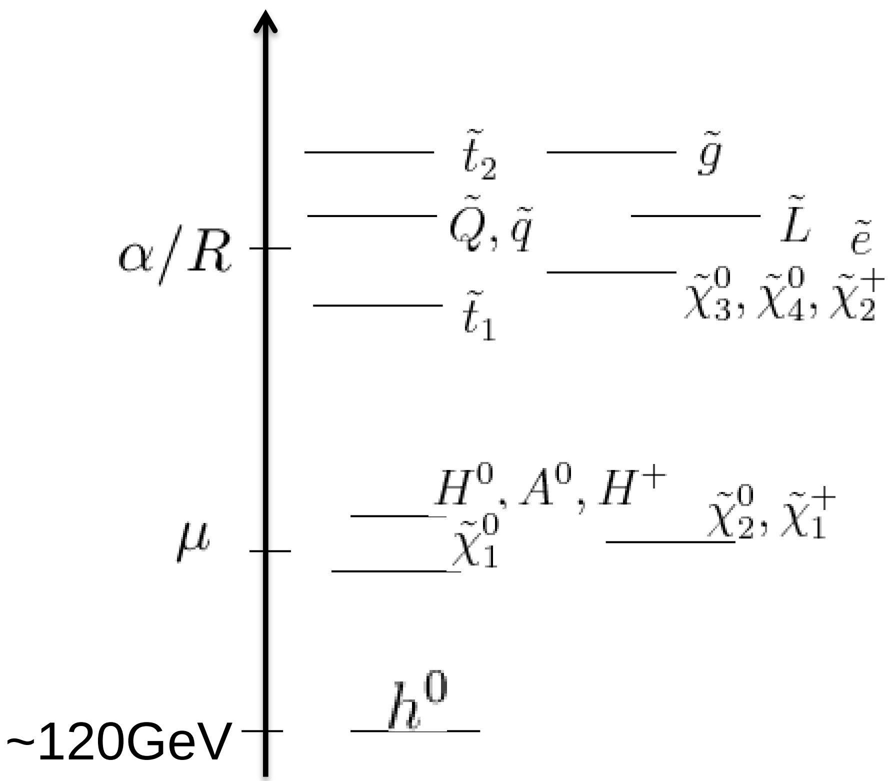

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Spectra are available!
http://www-theory.lbl.gov/~shirai/compactSUSY.php

Spectrum and LHC constraint

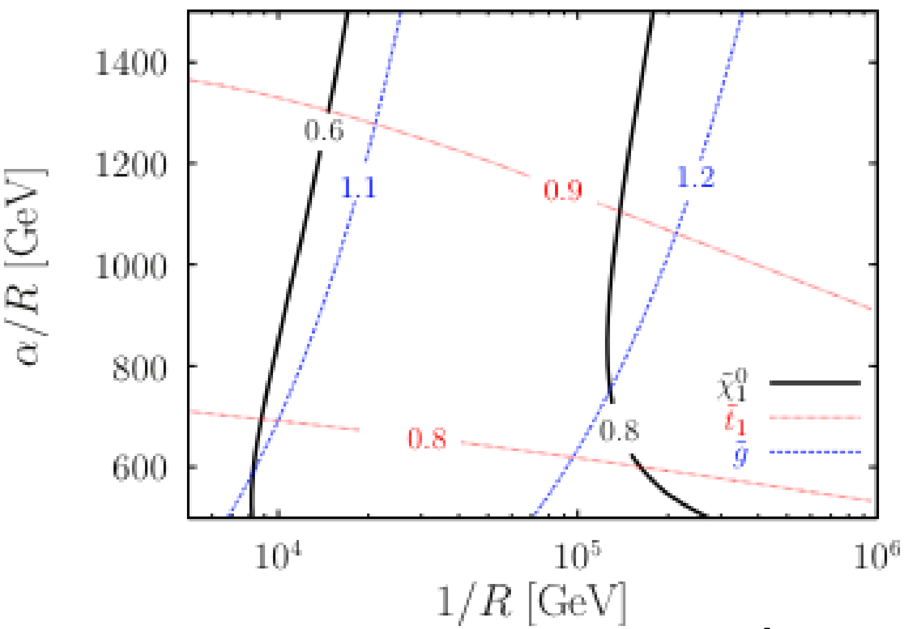
- More compressed as $\mu \to \alpha/R$, i.e. larger 1/R (Q_0)

$$m_{H_u}^2 + |\mu|^2 \simeq m_z^2 \cos 2\beta/2 \quad \text{(EWSB)}$$

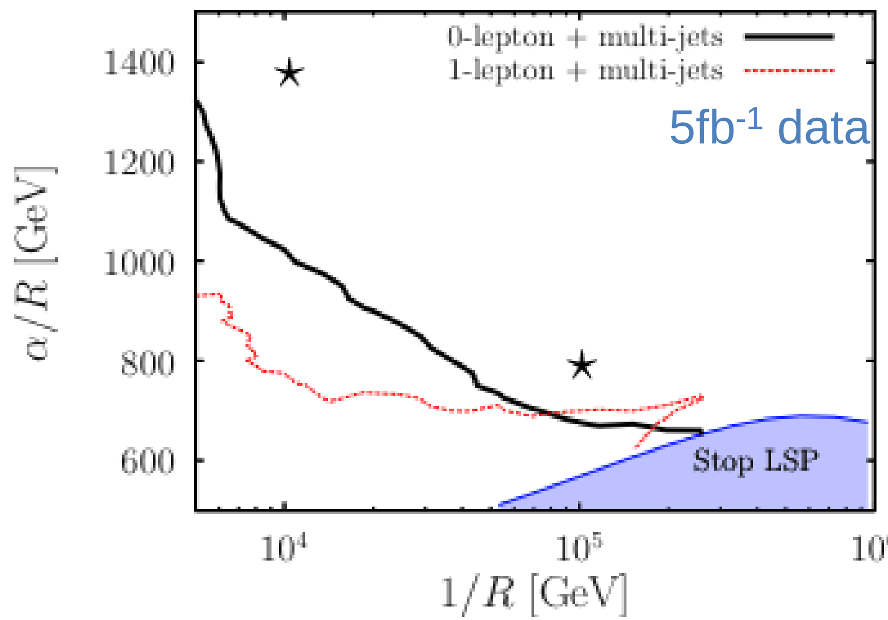
$$\delta m_{H_u}^2 = \left(-\frac{33y_t^2}{8\pi^2} + \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\right)\left(\frac{\alpha}{R}\right)^2$$

$$\Delta m_{H_u}^2 \sim \frac{3y_t^2}{8\pi^2}(m_{Q_3}^2 + m_{u_3}^2 + |A_0|^2)\Delta \ln\left(\frac{Q}{Q_0}\right)$$

•Mass in unit of α/R



•Collider bound



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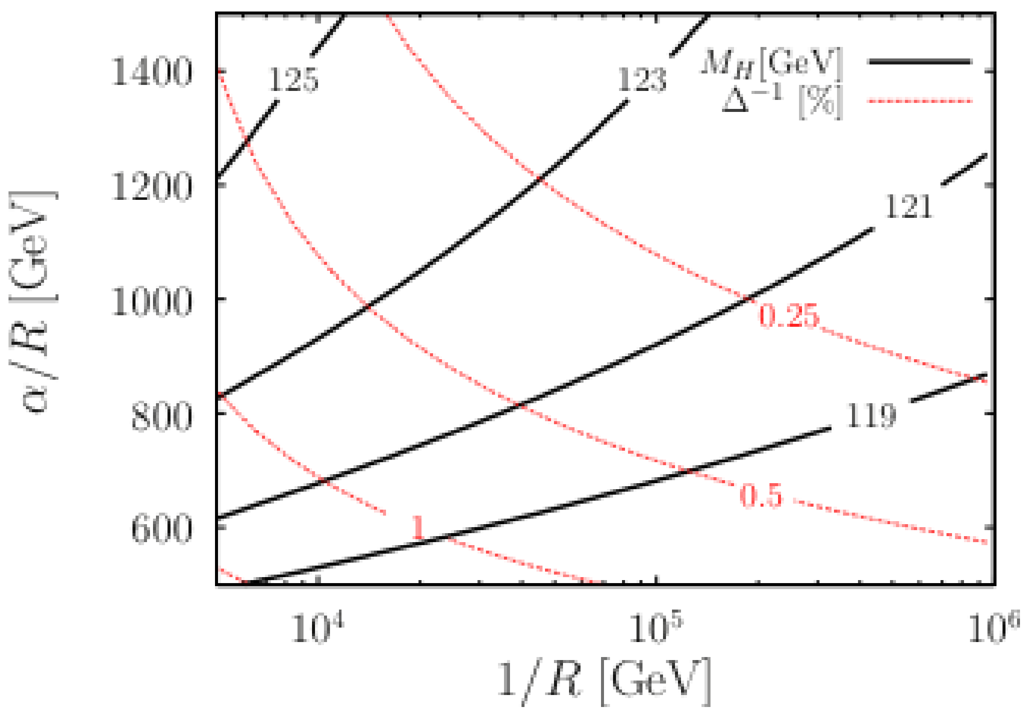
Spectra are available!
http://www-theory.lbl.gov/~shirai/compactSUSY.php

Higgs mass and tuning

$m_t = 173.2$ GeV



$$\Delta^{-1} \equiv \min_x |\partial \ln m_Z^2 / \partial \ln x|^{-1} \text{ with } x = \alpha, \mu, 1/R, y_t, g_3, \cdots$$

- Theoretical error of Higgs mass is not small

$$|\Delta M_H| \approx 2 - 3 \text{ GeV}$$

•Also deviation from top mass

$\Delta m_t = \pm 0.9$ GeV ⇨ $\Delta M_H \approx \pm 1$ GeV

- Fine tuning of sub-% level mainly from μ

➡ better than CMSSM

Spectra are available!
http://www-theory.lbl.gov/~shirai/compactSUSY.php

Possible NMSSM extension

Work in progress [Murayama, Nomura, Shirai, KT]

Singlet Hypermultiplet in the bulk

$$W_{NMSSM} = (\lambda S H_u H_d + \frac{1}{3}\kappa S^3)\ \delta(y)$$

- Again, soft parameters of singlet are automatically determined by SS mechanism

$$V_{soft}^{\mathrm{NMSSM}} = (a_\lambda S H_u H_d + \frac{1}{3} a_\kappa S^3 + \mathrm{h.c.}) + m_s |S|^2$$

where $$a_\lambda = -\frac{\alpha}{R},\ a_\kappa = -\frac{3\alpha}{R},\ m_s^2 = \left(\frac{\alpha}{R}\right)^2,$$

- No CP violation source
- Cubic term of S is important for vacuum

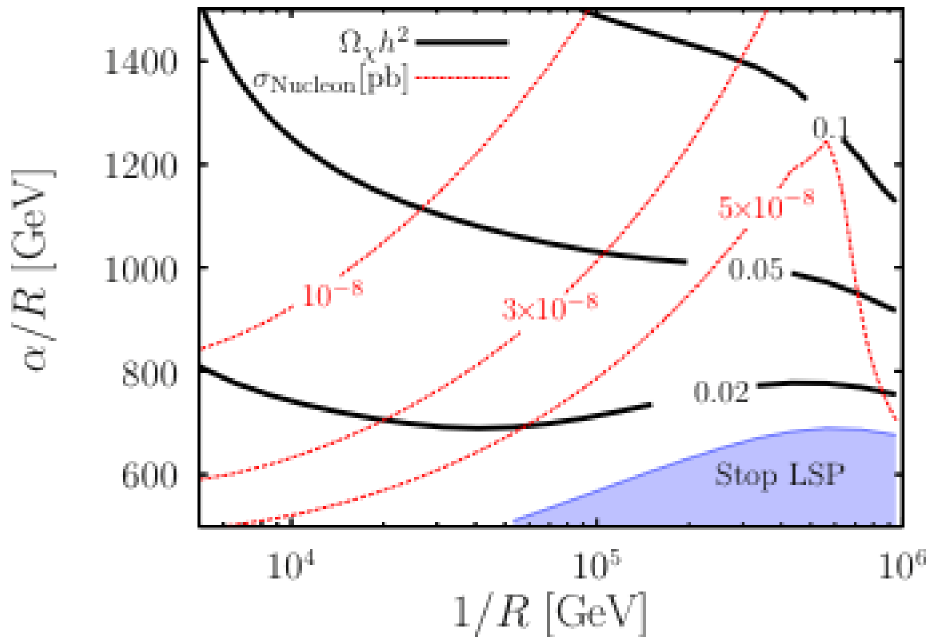
- Not necessarily consider the landau pole
  - Relatively free λ, κ realize various Higgs mass

Dark Matter Nature

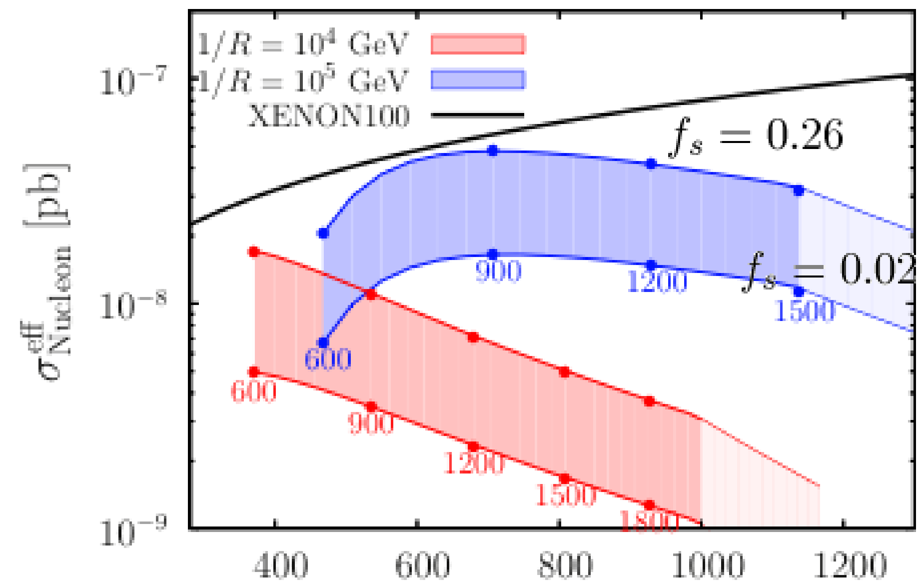
- Thermal relic of LSP is not enough for observed DM density unless LSP $\gtrsim$TeV

$$\Omega_{\rm DM} h^2 \simeq 0.1$$

- •Relic abundance
- •Spin-Indep. cross section with a nucleon



- •Effective DM-nucleon cross section



$$\sigma^{\rm eff}_{\rm Nucleon} \equiv \sigma_{\rm Nucleon} \frac{\min\{\Omega_\chi, \Omega_{\rm DM}\}}{\Omega_{\rm DM}}$$

- Direct detection of DM does not exclude this scenario, and the future update will be interesting

Summary

- ☐ Compressed scenario is rather difficult to test at the LHC
- ☐ This scenario is realized by Compact SUSY model

- ☐ This model has only 3 parameters (No Flavor and CP problem)
- ☐ Less fine-tuned than CMSSM, and alive in sub-TeV

- ☐ Large radiative corrections boost Higgs mass (up to 125GeV?)

- ☐ LSP is sub-dominant component of DM

Future work

- Higgs sector and DM in NMSSM
- Non-thermal production of DM
- Non-trivial radiative corrections from KK modes
- Correspondence of SS mechanism and Radion mediation

Thank you for your attention

ありがとうございました

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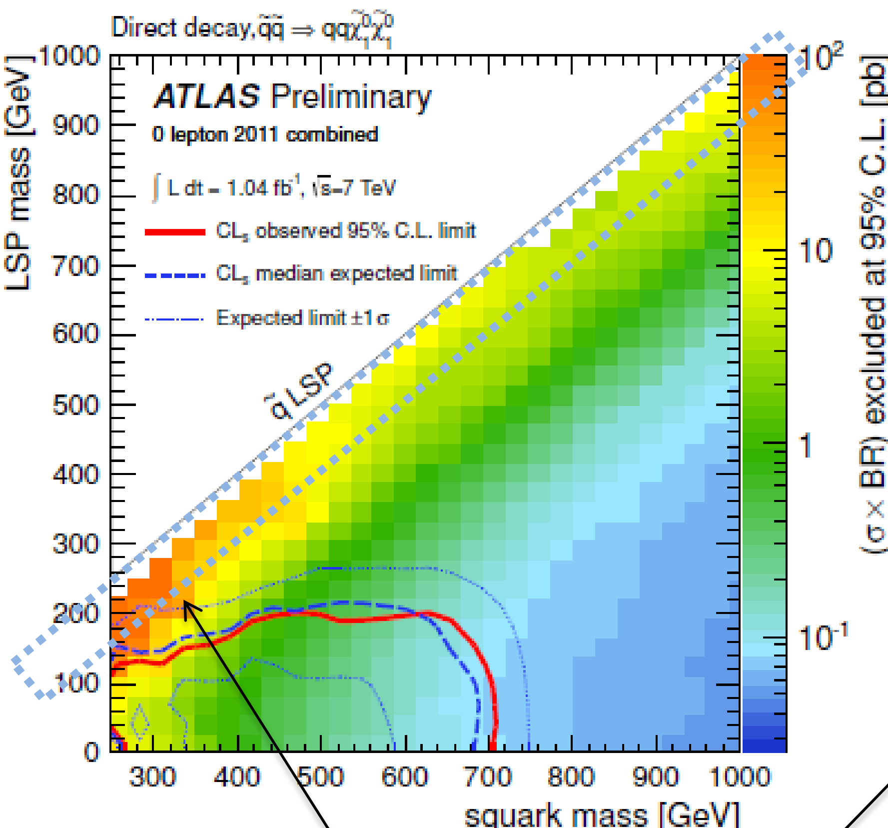
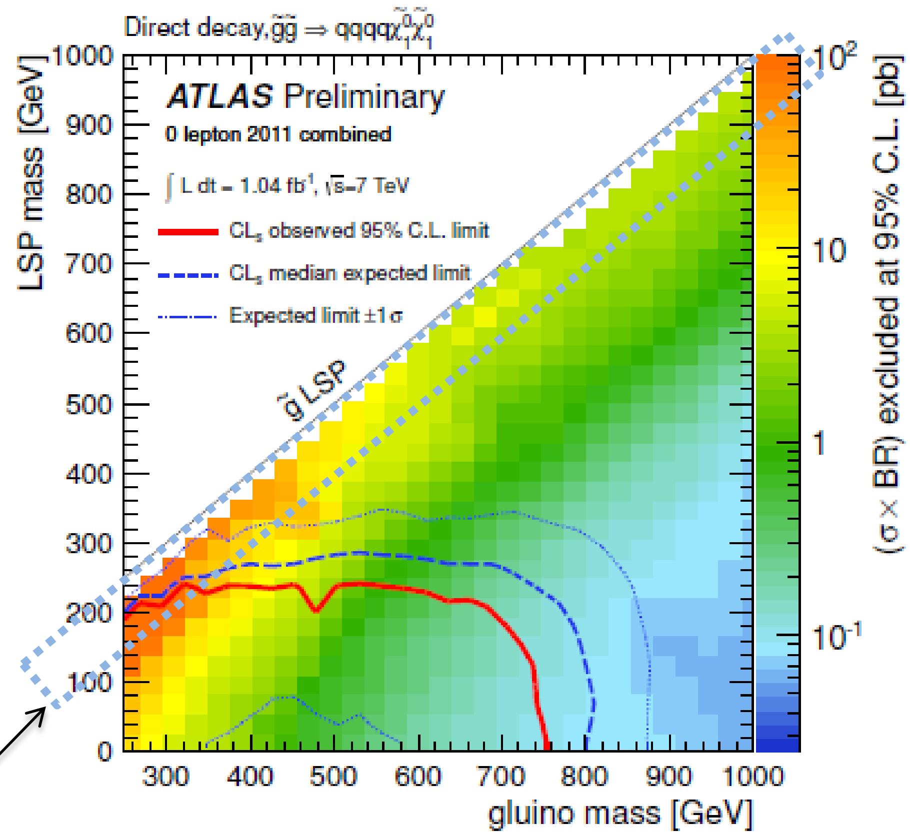
Squarks+LSP model



Gluino+LSP model



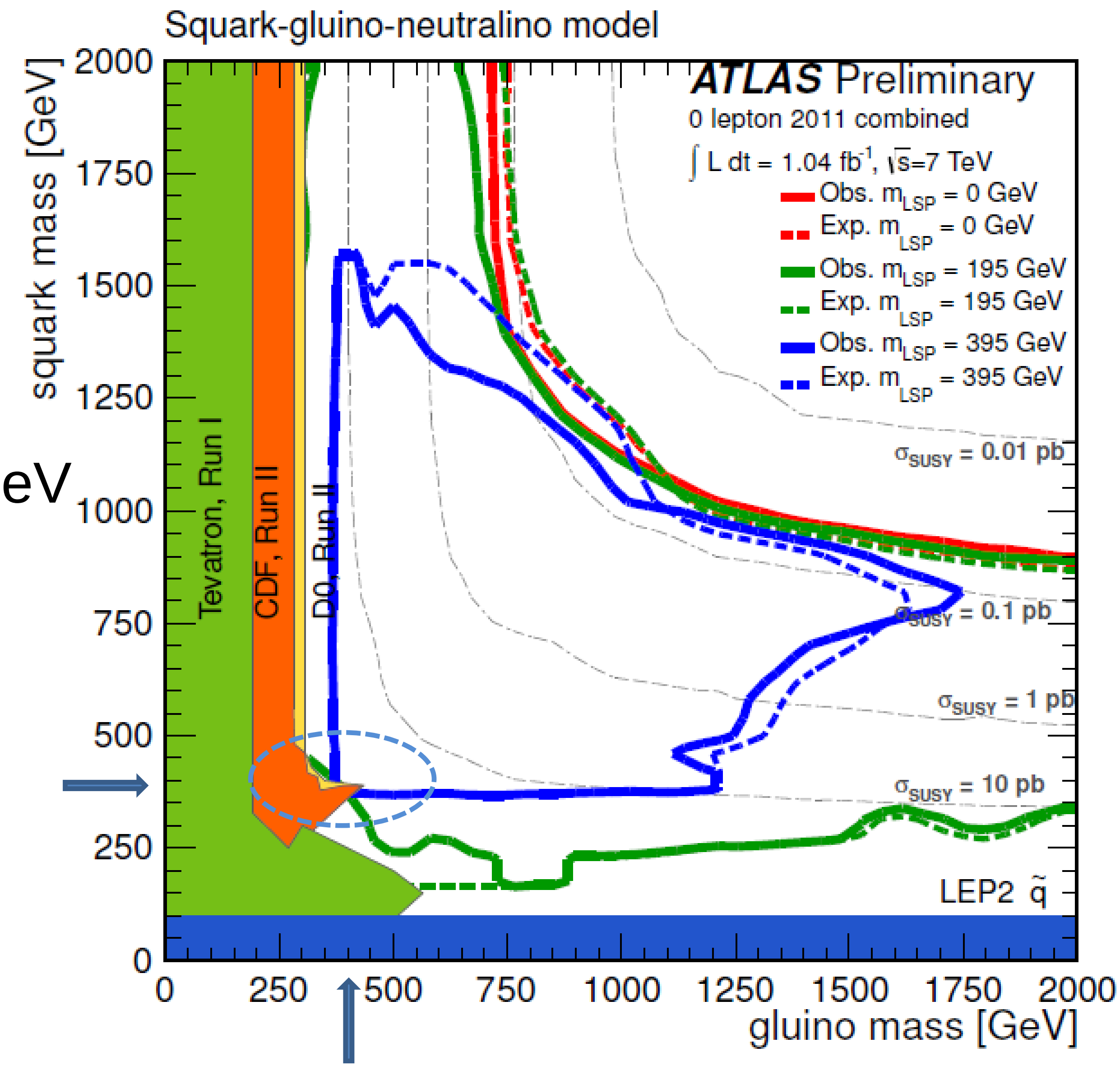
100 GeV splitting

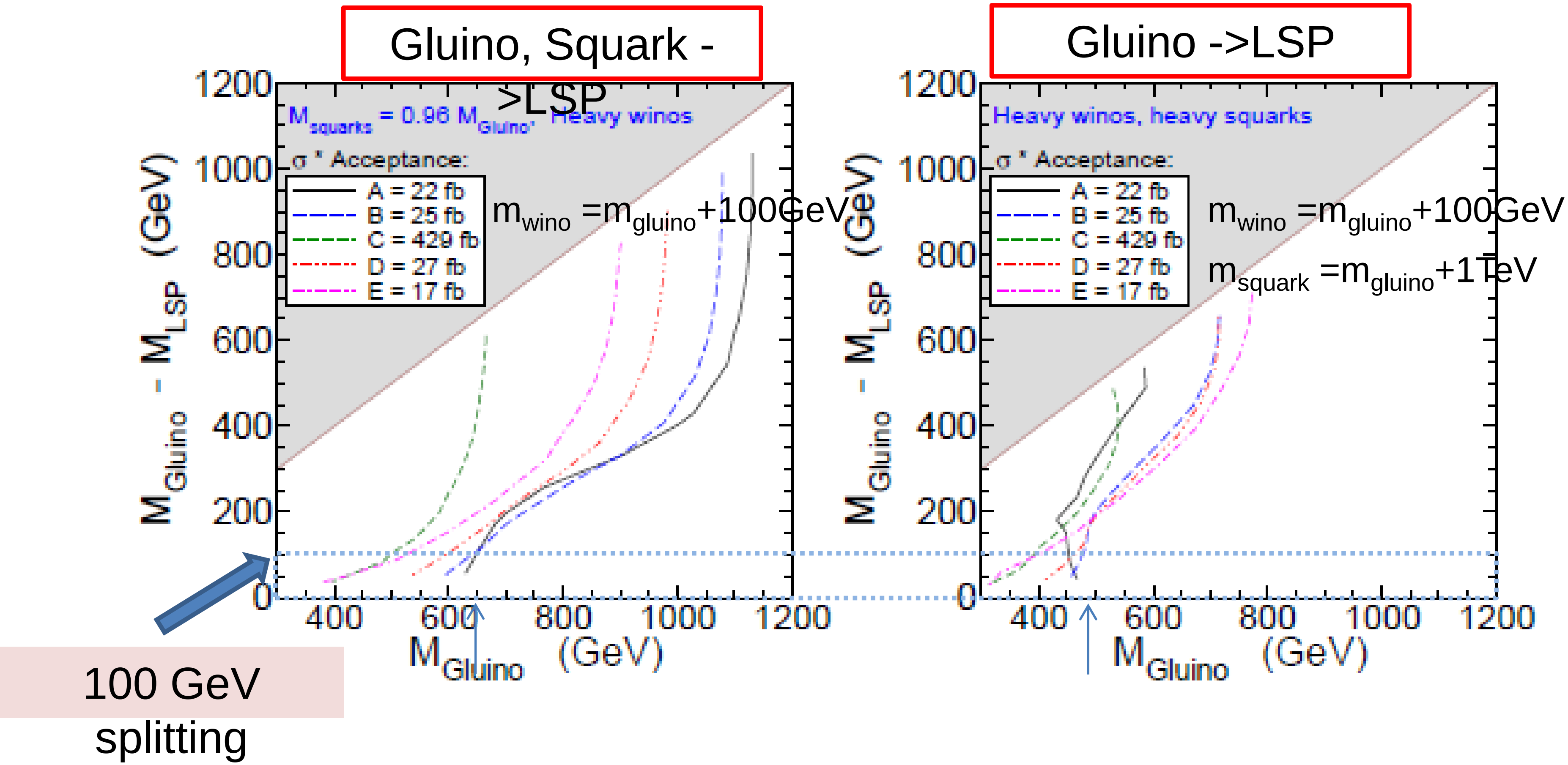
M_{squark}~250GeV, M_{gluino}~350GeV

Squarks+Gluino+LSP model

$M_{squark}=M_{gluino}$~400GeV

with >5GeV splitting!





$$M_1 = \left(\frac{1+5c}{6}\right) M_{\tilde{g}}, \qquad M_2 = \left(\frac{1+2c}{3}\right) M_{\tilde{g}}.$$