SUSY2013@ICTP, Trieste, Italy (2013 August 27)

Compact Supersymmetry++

Kohsaku Tobioka

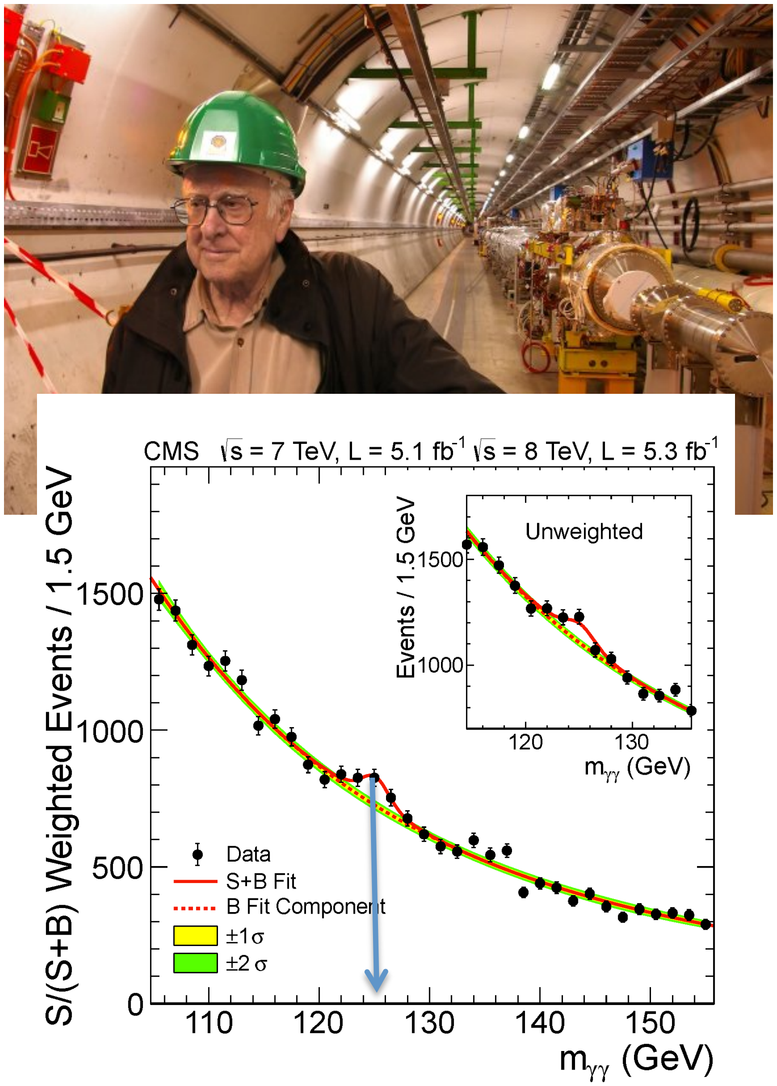
Kavli IPMU, Univ. of Tokyo

Murayama, Nomura, Shirai, KT (arXiv:1206.4993)
Murayama, Nojiri, KT (arXiv:1107.3369)

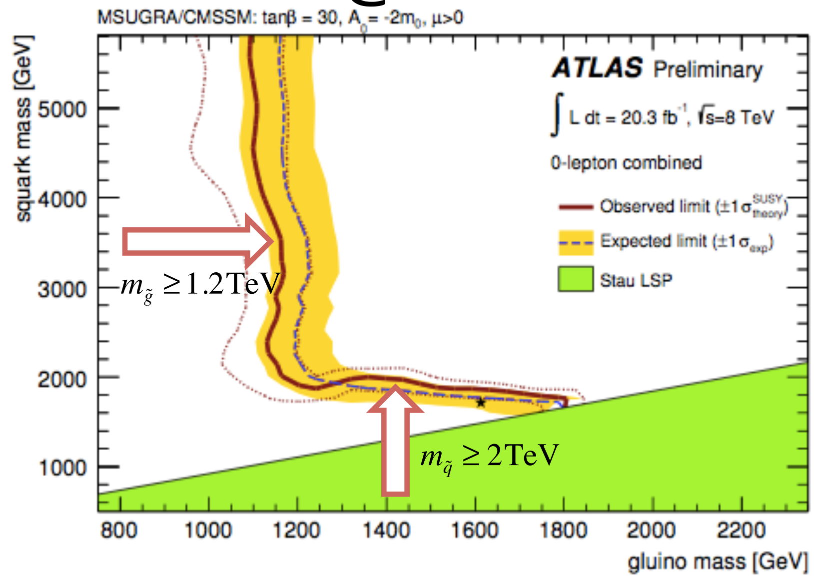
東京大学 THE UNIVERSITY OF TOKYO

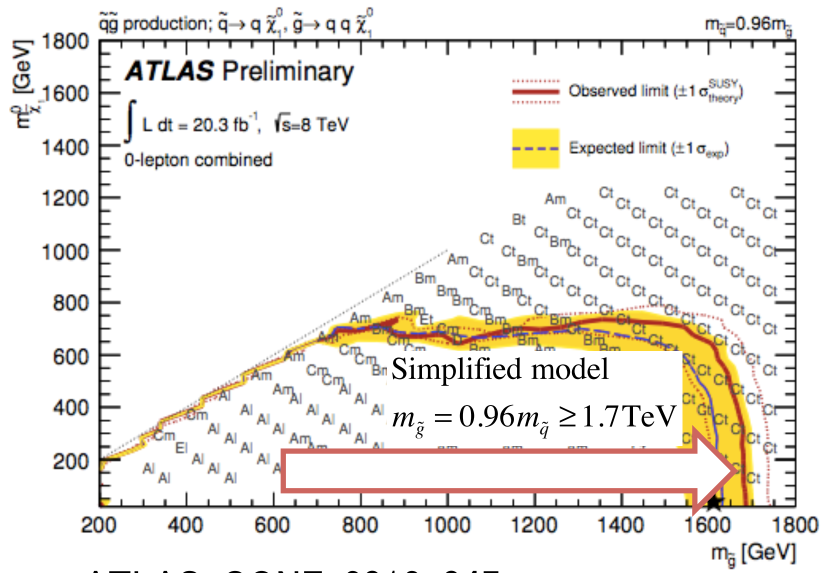
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Discovery of 125GeV Higgs and E_{Tmiss} exclusion of MSSM @LHC



arXiv:1207.7235 (CMS)





ATLAS−CONF−2013−047

Implications for MSSM

1. Higgs mass is relatively heavy compared with m_Z
   =>Radiative corrections

Large At term:
Stop L-R mixing

Heavy
Sparticles

2. E_{Tmiss} Search excludes squark/gluino mass up to TeV

Compressed
spectrum

RPV

Exist in TeV range

Beyond MSSM:
Change Higgs mass
and/or
LHC limit

Implications for MSSM

1. Higgs mass is relatively heavy compared with m_Z
   => Radiative corrections

Large At term:
Stop L-R mixing

Heavy
Sparticles

2. E_{Tmiss} Search excludes squark/gluino mass up to TeV

Compressed
spectrum

RPV

Exist in TeV range

Beyond MSSM:
Change Higgs mass
and/or
LHC limit

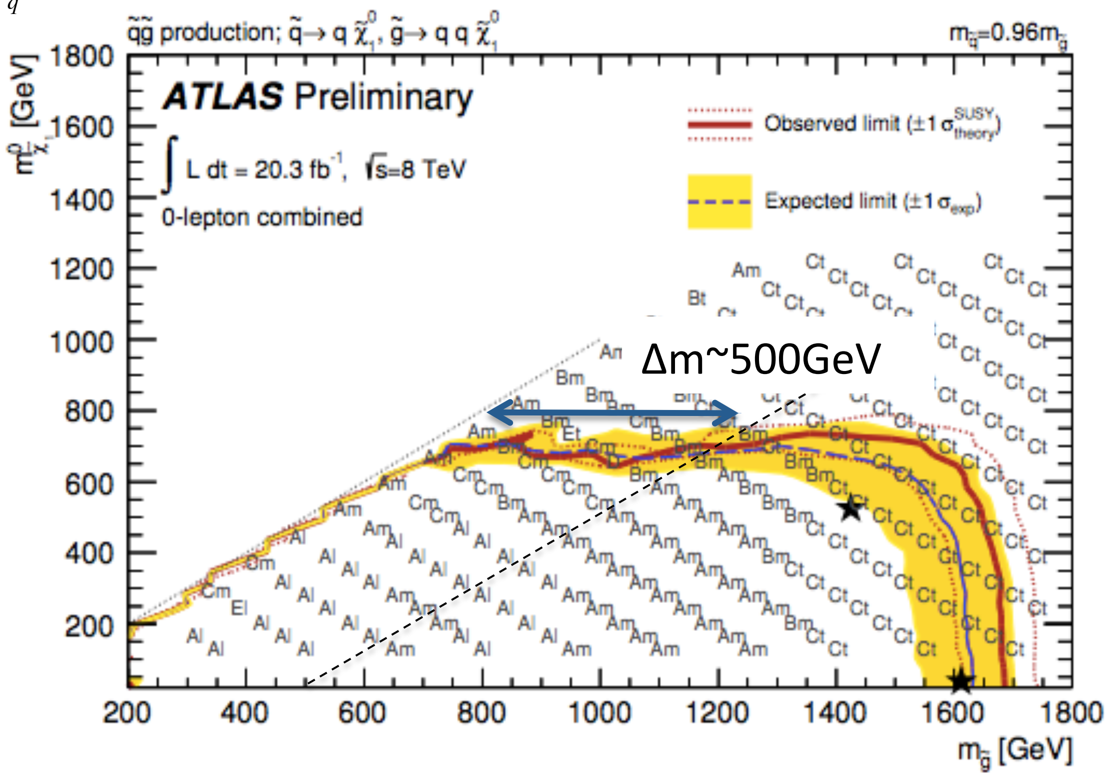
This talk

Compressed spectrum leads very different limit

Simplified model

$m_{\tilde{g}} = 0.96 m_{\tilde{q}}$

ATLAS-CONF-2013-047



•Beyond m_{LSP}~700GeV, gluino/squark mass is not constrained, because missing energy is much smaller due to the compression

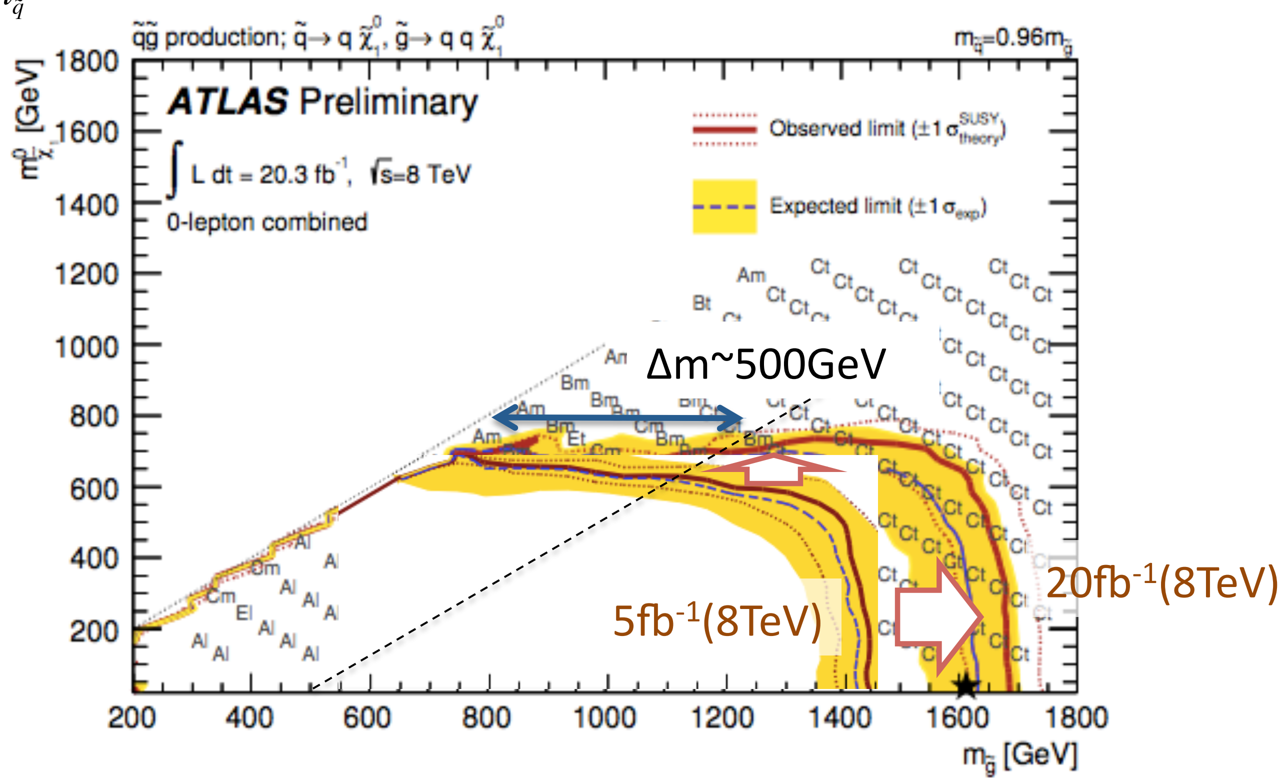
•Increasing data (by factor of 4) doesn't improve the limit

Compressed spectrum leads very different limit

Simplified model

$m_{\tilde{g}} = 0.96 m_{\tilde{q}}$

ATLAS-CONF-2013-047



•Beyond m_{LSP}~700GeV, gluino/squark mass is not constrained, because missing energy is much smaller due to the compression

•Increasing data (by factor of 4) doesn't improve the limit

•Compressed Spectrum

Mostly based on Phenomenological studies

[arXiv:1105.4304, 1206.6767, 1207.1613, 1207.6289, 1208.0949, 1308.1526..]

Is there any theoretical motivation? …

•Compressed Spectrum

• Large A term

Higgs mass is enhanced when $|A_t| \sim \sqrt{6} * m_{stop}$

But too much A term, $|A_t| > 3m_{stop}$, leads instability

Not easy from model building point of view,
e.g. GMSB…
[arXiv:1302.2642,1206.4086, 1107.3006, 1112.3068..]

•Compressed Spectrum

• Large A term

SUSY breaking from Extra Dimension

“Scherk-Schwarz mechanism”

=Radion Mediation

Scherk-Schwarz mechanism

y: 5th dimensional coordinate /R: radius of extra dimension [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)

- ☐ Non-trivial boundary condition on SU(2)$_R$ space breaks supersymmetry =Scherk-Schwarz mechanism
  - Non-trivial B.C.

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

Continuous twist parameter, α<<1

Scherk-Schwarz mechanism

y: 5th dimensional coordinate /R: radius of extra dimension [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)

- Non-trivial boundary condition on SU(2)$_R$ space breaks supersymmetry =Scherk-Schwarz mechanism

•Non-trivial B.C.

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

Continuous twist parameter, α<<1

•Resulting KK decomposition

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

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

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

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 $\phi^{(c)}, \psi^{(c)}$

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 $\phi^{(c)}, \psi^{(c)}$

Inversion [y ⟶ -y](Orbifold)

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

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

Translation [y ⟶ y+2πR] (SS mechanism)

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

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

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

same for gravitinos

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

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

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) …]

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) …]

◆Gauge sector

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

◆Matter sector

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

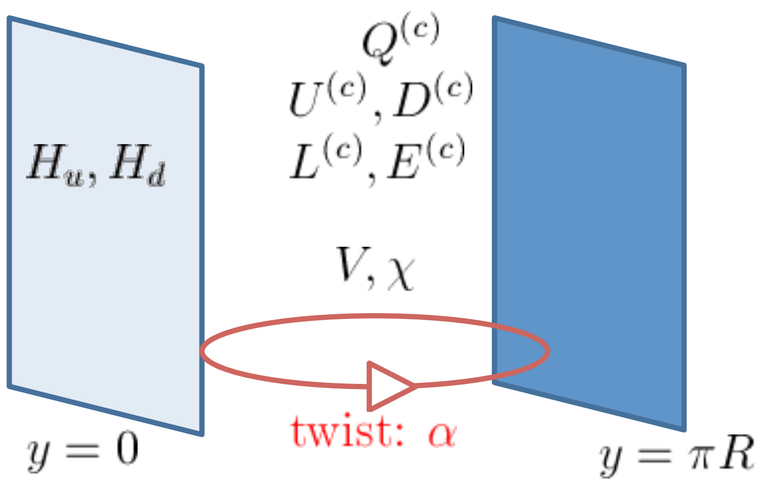
<u>Radion vev:</u> $\langle T \rangle = R + F_T\theta^2 \Rightarrow R - 2\alpha\theta^2$ $\boxed{F_T = -2\alpha}$

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

Compact Supersymmetry model

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

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



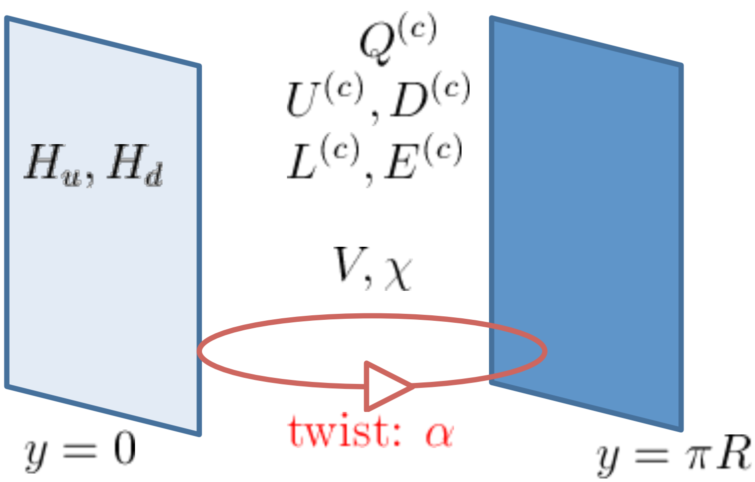
Compact Supersymmetry model

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

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

Large A term is generated by the field redefinition

$$\Phi^{(c)} \to \left(1 + \frac{\alpha}{R}\theta^2\right)\Phi^{(c)} \qquad y_U^{ij} \underline{Q_i U_j} H_u \to \left(1 + \underline{\frac{2\alpha}{R}}\theta^2\right) y_U^{ij} \underline{Q_i U_j} H_u$$



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

Higgs mass can be larger!

Compact Supersymmetry model

- Take α<<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,

$$M_{1/2} = \frac{\alpha}{R}, \quad m^2_{\tilde{Q},\tilde{U},\tilde{D},\tilde{L},\tilde{E}} = \left(\frac{\alpha}{R}\right)^2, \quad m^2_{H_u,H_d} = 0,$$
$$A_0 = -\frac{2\alpha}{R}, \quad \mu \neq 0, \quad B = 0,$$

Compact Supersymmetry model

- Take α<<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,

$$M_{1/2} = \frac{\alpha}{R}, \quad m^2_{\tilde{Q},\tilde{U},\tilde{D},\tilde{L},\tilde{E}} = \left(\frac{\alpha}{R}\right)^2, \quad m^2_{H_u,H_d} = 0,$$
$$A_0 = -\frac{2\alpha}{R}, \quad \mu \neq 0, \quad B = 0,$$

- 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

$$\delta m^2_{H_u} = \left(-\frac{33y_t^2}{8\pi^2} + \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\right)\left(\frac{\alpha}{R}\right)^2,$$
$$\delta m^2_{H_d} = \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\left(\frac{\alpha}{R}\right)^2,$$
$$\delta B = \left(\frac{9y_t^2}{8\pi^2} - \frac{3(g_2^2+g_1^2/5)}{8\pi^2}\right)\frac{\alpha}{R},$$

Only three parameters!

- No physical phase
- Geometry is universal

Compact Supersymmetry model

- Take α<<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,

$$M_{1/2} = \frac{\alpha}{R}, \quad m^2_{\tilde{Q},\tilde{U},\tilde{D},\tilde{L},\tilde{E}} = \left(\frac{\alpha}{R}\right)^2, \quad m^2_{H_u,H_d} = 0,$$
$$A_0 = -\frac{2\alpha}{R}, \quad \mu \neq 0, \quad B = 0,$$

- 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

$$\delta m^2_{H_u} = \left(-\frac{33y_t^2}{8\pi^2} + \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\right)\left(\frac{\alpha}{R}\right)^2,$$
$$\delta m^2_{H_d} = \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\left(\frac{\alpha}{R}\right)^2,$$
$$\delta B = \left(\frac{9y_t^2}{8\pi^2} - \frac{3(g_2^2+g_1^2/5)}{8\pi^2}\right)\frac{\alpha}{R},$$

Only three parameters!

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

•No physical phase
•Geometry is universal

Compact Supersymmetry model

- Take α<<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,

$$M_{1/2} = \frac{\alpha}{R}, \quad m^2_{\tilde{Q},\tilde{U},\tilde{D},\tilde{L},\tilde{E}} = \left(\frac{\alpha}{R}\right)^2, \quad m^2_{H_u,H_d} = 0,$$
$$A_0 = -\frac{2\alpha}{R}, \quad \mu \neq 0, \quad B = 0,$$

- 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

$$\delta m^2_{H_u} = \left(-\frac{33y_t^2}{8\pi^2} + \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\right)\left(\frac{\alpha}{R}\right)^2,$$
$$\delta m^2_{H_d} = \frac{9(g_2^2+g_1^2/5)}{16\pi^2}\left(\frac{\alpha}{R}\right)^2,$$
$$\delta B = \left(\frac{9y_t^2}{8\pi^2} - \frac{3(g_2^2+g_1^2/5)}{8\pi^2}\right)\frac{\alpha}{R},$$

Only three parameters!

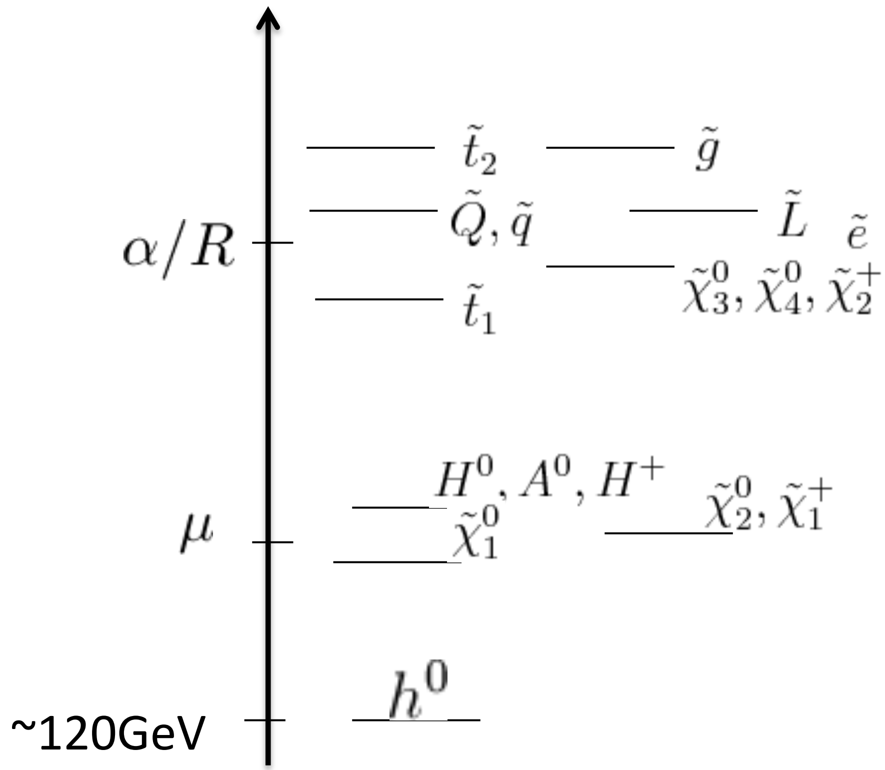
$$\frac{1}{R}, \quad \frac{\alpha}{R}, \quad \mu.$$

- No physical phase
- Geometry is universal

✓ CP
✓ Flavor

Spectrum

- 2 scales: μ and α/R
- More compressed as μ→α/R, i.e. larger 1/R (Q_0)



Higgsino like LSP

$\sim \mu$

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

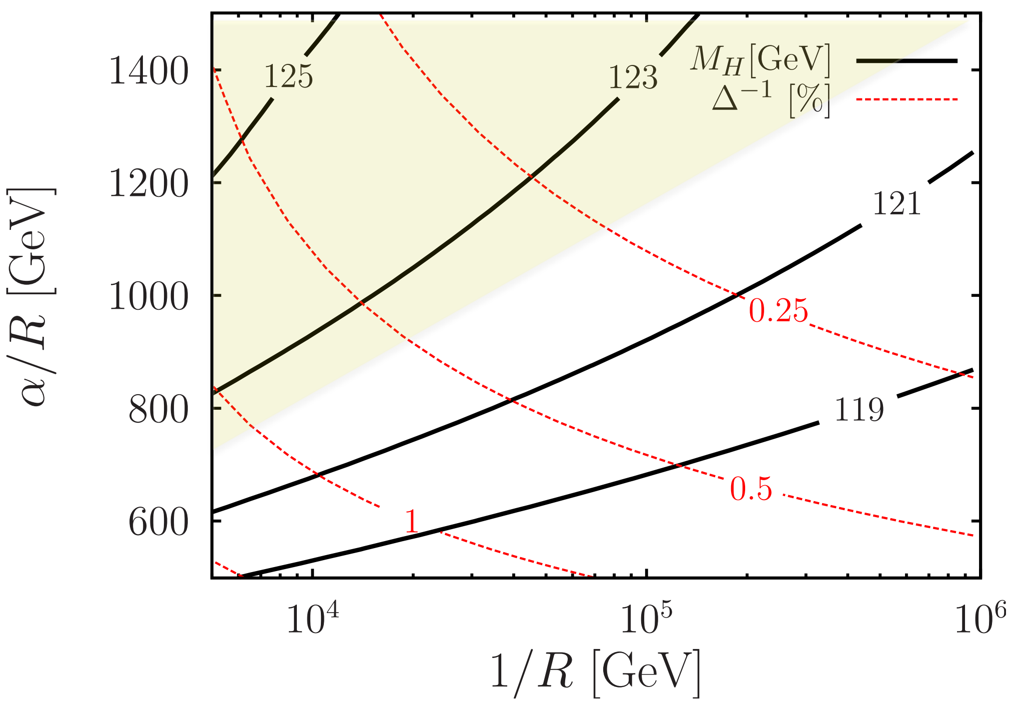
$$\Delta m^2_{H_u} \sim \frac{3y_t^2}{8\pi^2}(m^2_{Q_3} + m^2_{u_3} + |A_0|^2)\Delta \ln\left(\frac{Q}{Q_0}\right)$$

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

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

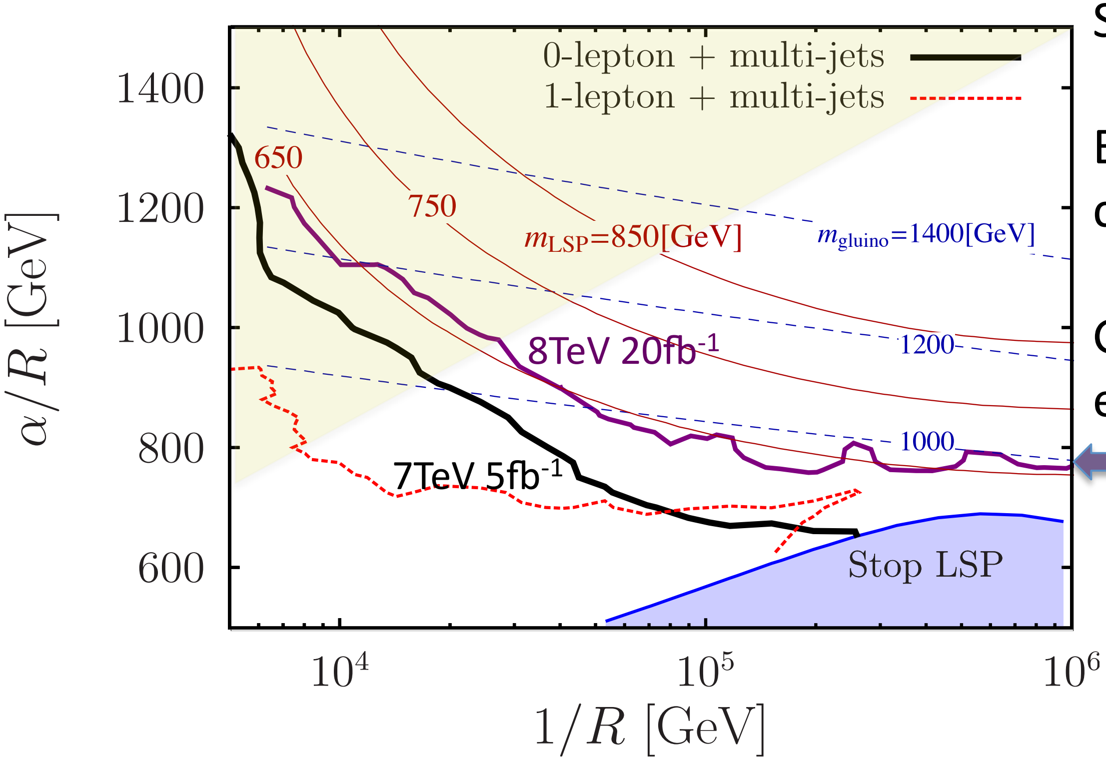
$$\Delta m_t = \pm 0.9 \text{ GeV}$$

$$\Rightarrow \Delta M_H \approx \pm 1 \text{ GeV}$$

- Fine tuning of sub-% level mainly from μ

→ better than CMSSM

Collider limit



Still very mild

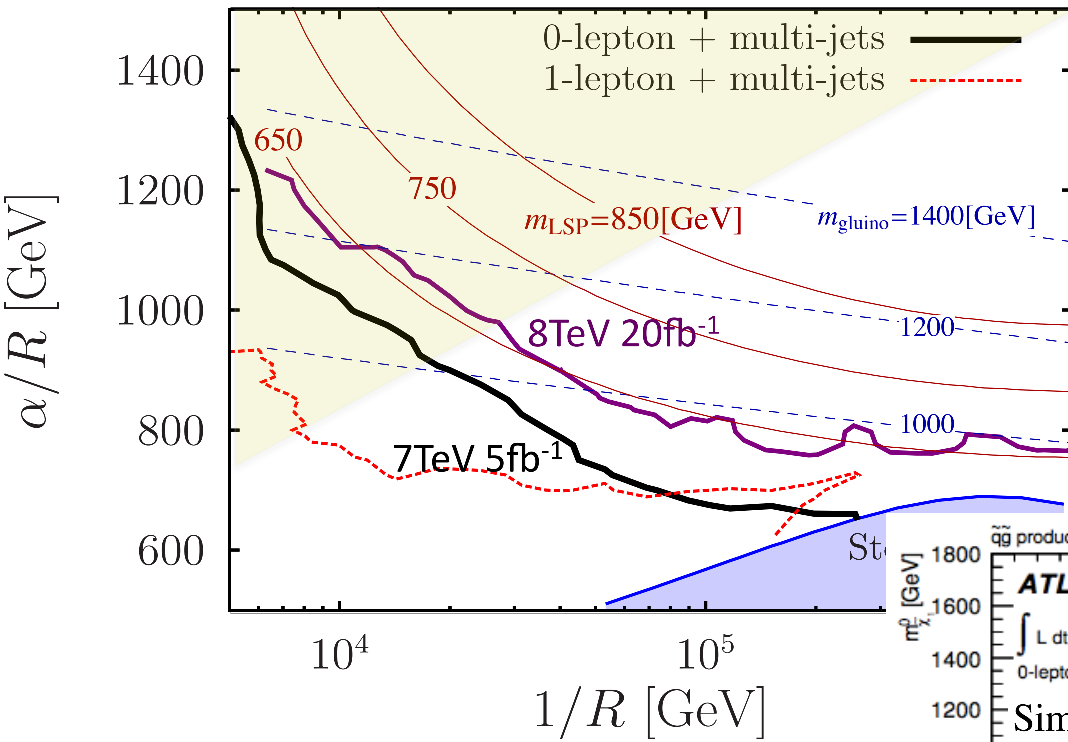
Excluded line(puple) corresponds to LSP~ 650GeV

Gluino~1200GeV is alive explaining mh=125GeV

0-lepton+multi-jets (Preliminary)

•Limit does not change much
5fb^{-1}(7TeV)⇒20fb^{-1}(8TeV)
•Need improvement

Collider limit

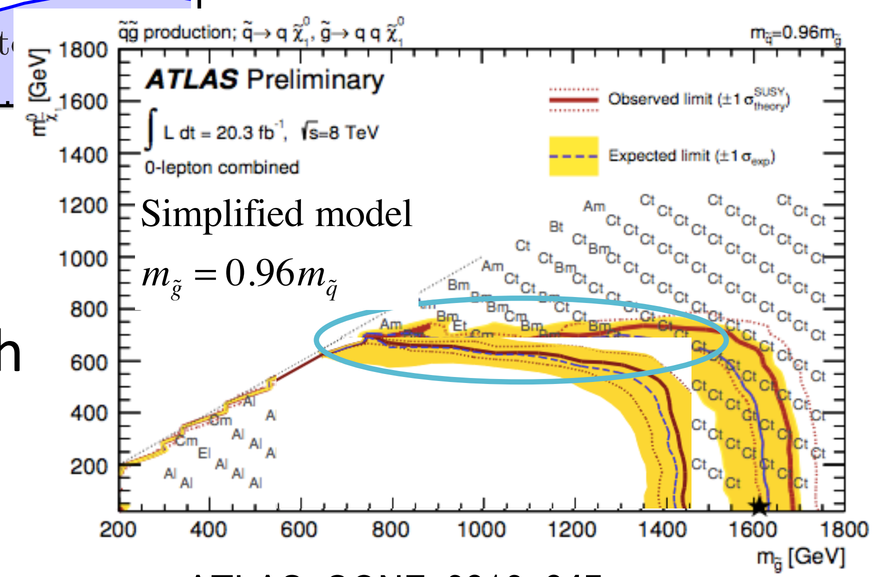


Still very mild

Excluded line(puple) corresponds to LSP~ 650GeV

Gluino~1200GeV is alive explaining mh=125GeV

0-lepton+multi-jets (Preliminary)



ATLAS−CONF−2013−047

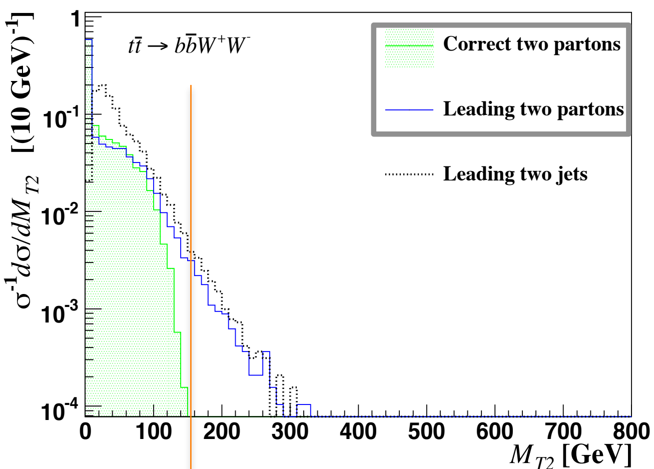
- Limit does not change much 5fb^{-1}(7TeV)⇒20fb^{-1}(8TeV)
- Need improvement

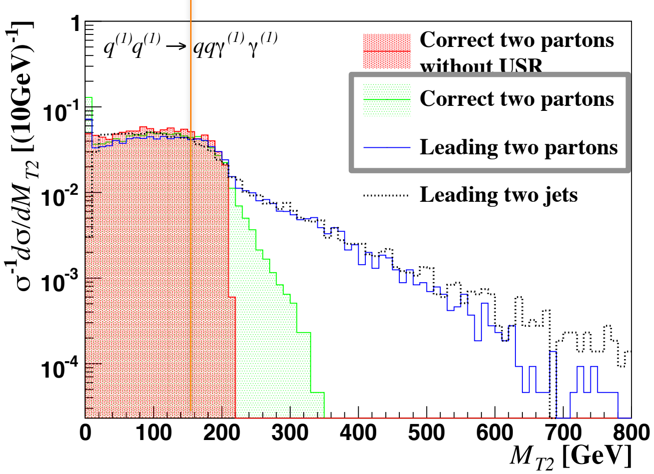
Possible improvement by M_{T2}

$$M_{T2} \equiv \min_{\mathbf{p}_T^{inv(1)}+\mathbf{p}_T^{inv(2)}=\mathbf{p}_T^{miss}} \left[\max\left\{M_T^{(1)},\ M_T^{(2)}\right\}\right]$$

$$M_T^{(i)} = \sqrt{m_{vis(i)}^2 + m_{inv(i)}^2 + 2\left(E_T^{vis(i)}E_T^{inv(i)} - \mathbf{p}_T^{vis(i)}\cdot\mathbf{p}_T^{inv(i)}\right)}$$

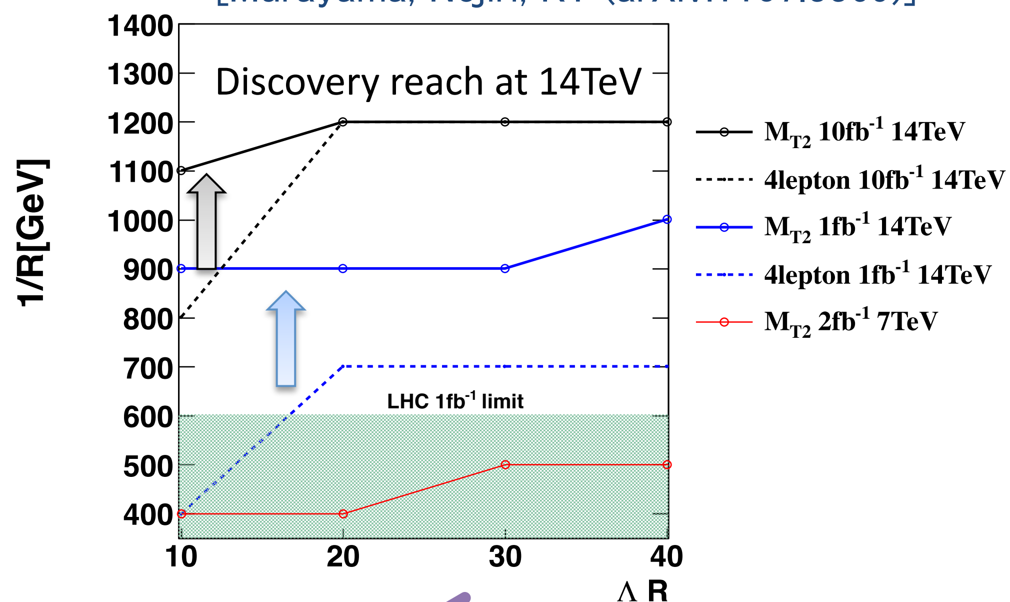
For BSM scenario with compressed spectra M_{T2} is useful
main background ttbar can be removed systematically while keeping the signal





Application to MUED (~compressed SUSY)

[Murayama, Nojiri, KT (arXiv:1107.3369)]



More compressed

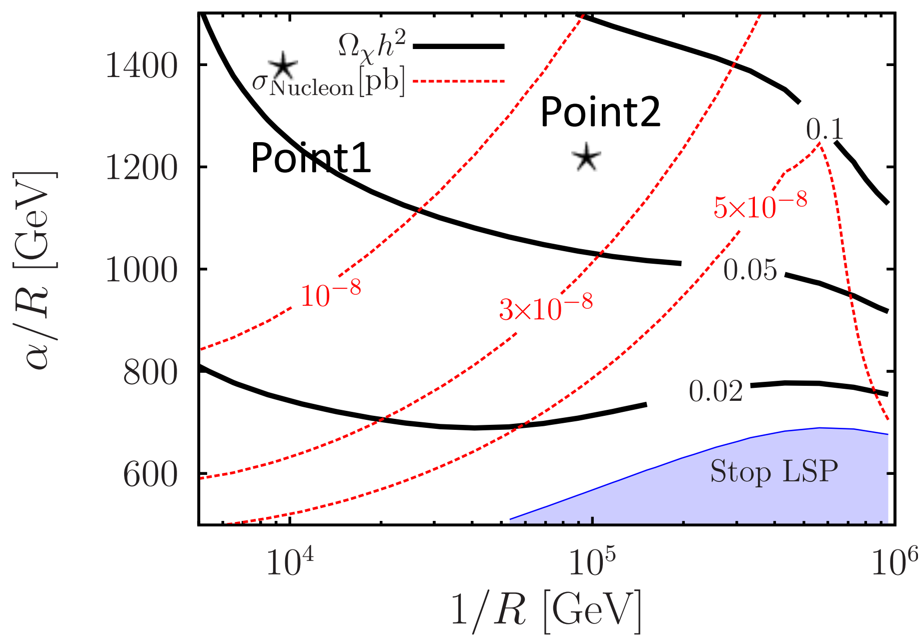
MUED discovery reach is improved by 300~500GeV
=>Possible to improve SUSY search as well

Dark Matter Nature

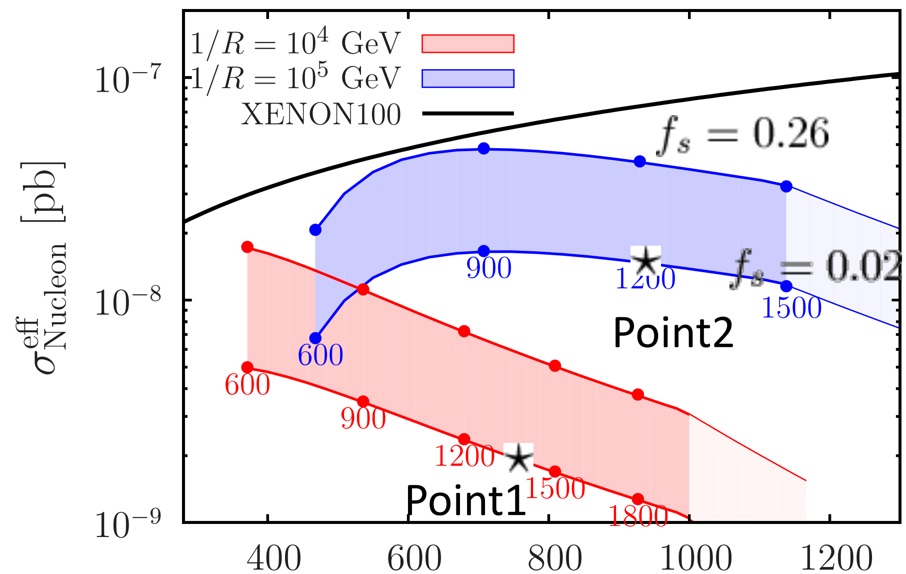
☐ Thermal relic of LSP is not enough for observed DM density unless LSP ≳TeV $\Omega_{DM}h^2 \simeq 0.1$

•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

Conclusion

- Compact Supersymmetry: model with SUSY breaking from Extra Dimension

- Compressed spectrum & large A term are realized. Only 3 parameters (No Flavor & No CP problem), sub-% tuning

- Collider limit is mild. It is not much improved by increasing data/energy. MT2 is useful to search for the signal

- Higgsino-like LSP, sub-dominant component of DM. Consistent with Direct detection result

Grazie!

Backup

Mu problem in NMSSM extension

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

Singlet Hypermultiplet in the bulk

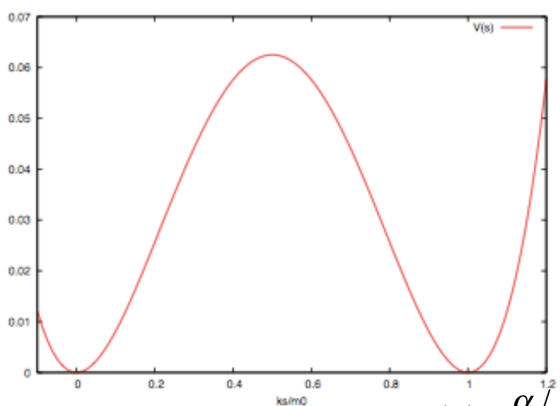
$$W_{NMSSM} = (\lambda S H_u H_d + \frac{1}{3}\kappa S^3)\ \delta(y)$$

- Again, soft parameters are automatically determined

•No CP violation source

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

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



$\langle S \rangle = \frac{\alpha / R}{\kappa}$

Figure 1: Potential $V(s)$

•Double well potential at ~1/R

$$V(S) = S^2 (\kappa S - \alpha / R)^2, \quad \langle S \rangle = \frac{\alpha / R}{\kappa}$$

$$\mu_{eff} = \lambda \langle S \rangle = \frac{\lambda}{\kappa} \frac{\alpha}{R} \sim O(1) \frac{\alpha}{R}$$

μ term is generated, ~α/R , -> compressed

• Relatively free λ, κ realize Higgs mass

Compact Supersymmetry model

Brane-localized kinetic terms and cutoff

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

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

- Assume the tree level contributions are same size of radiative ones

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

Compact Supersymmetry model

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

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

- 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

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

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