宇宙の進化と素粒子模型

平成25年度宇宙線研究所共同利用研究成果発表会 宇宙線研究所理論グループ 伊部昌宏

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Coupling Unification and Dark Matter in a small extension of the Standard Model

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The mass of the Higgs is around **125GeV**!



Both the ATLAS and the CMS discovered a new boson with mass around 125-126 GeV compatible with the SM Higgs boson!

[ATLAS:Phys.Lett.B716(2012)1, CMS:Phys.Lett.B716(2012)30]



How about New Physics @ Collider Experiments?

No signals so far ... (ex. Supersymmetry)

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

	Model	e, μ, τ, γ	Jets	$E_{\rm T}^{\rm miss}$	∫£ dt[fb	Mass limit		Reference
Inclusive Searches	$ \begin{array}{l} MSUGRA/CMSSM \\ MSUGRA/CMSSM \\ MSUGRA/CMSSM \\ \tilde{q}\bar{q}, \tilde{q} \rightarrow q \tilde{k}_{1}^{0} \\ \tilde{g}\bar{k}, \tilde{g} \rightarrow q \bar{q} \tilde{k}_{1}^{0} \\ \tilde{g}\bar{k}, \tilde{g} \rightarrow q \bar{q} \tilde{k}_{1}^{0} \\ \tilde{g}\bar{k}, \tilde{g} \rightarrow q q \tilde{k}_{1}^{0} \\ \tilde{g}\bar{k}, \tilde{g} \rightarrow q q \tilde{k}_{1}^{0} \\ \tilde{g}\bar{k}, \tilde{g} \rightarrow q q \tilde{k}_{1}^{0} \\ GMSB (\tilde{\ell} NLSP) \\ GMSB (\tilde{\ell} NLSP) \\ GGM (bino NLSP) \\ GGM (bino NLSP) \\ GGM (higgsino-bino NLSP) \\ GGM (higgsino NLSP) \\ GGM (higgsino NLSP) \\ Gravitino LSP \end{array} $	$\begin{array}{c} 0 \\ 1 \ e, \mu \\ 0 \\ 0 \\ 1 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 1 \ 2 \ r + 0 \ - 1 \ \ell \\ 2 \ \gamma \\ 1 \ e, \mu + \gamma \\ \gamma \\ 2 \ e, \mu (Z) \\ 0 \end{array}$	2-6 jets 3-6 jets 7-10 jets 2-6 jets 3-6 jets 0-3 jets 2-4 jets 0-2 jets 1 b 0-3 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	\$\vec{x}\vec{x}\$ 1.2 \$\vec{x}\$ 1.1 Tr \$\vec{y}\$ 850 GeV \$\vec{x}\$ 1.1 Tr \$\vec{y}\$ 850 GeV \$\vec{x}\$ 1.1 Tr \$\vec{x}\$ 1.1 Tr \$\vec{x}\$ 1.1 Tr \$\vec{x}\$ 1.2 Tr \$\vec{x}\$ 1.2 Tr \$\vec{x}\$ 1.2 Tr \$\vec{x}\$ 1.2 Tr \$\vec{x}\$ 619 GeV \$\vec{x}\$ 619 GeV \$\vec{x}\$ 690 GeV \$\vec{x}\$ 690 GeV \$\vec{x}\$ 645 GeV	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	1405.7875 ATLAS-CONF-2013-062 1308.1841 1405.7875 ATLAS-CONF-2013-062 ATLAS-CONF-2013-062 ATLAS-CONF-2013-089 1208.4688 1407.0603 ATLAS-CONF-2014-001 ATLAS-CONF-2012-144 1211.1167 ATLAS-CONF-2012-152 ATLAS-CONF-2012-152
3 rd gen. § med.	$\tilde{g} \rightarrow b \tilde{b} \tilde{\chi}_{1}^{0}$ $\tilde{g} \rightarrow t \tilde{\chi}_{1}^{0}$ $\tilde{g} \rightarrow t \tilde{\chi}_{1}^{0}$ $\tilde{g} \rightarrow b \tilde{t} \tilde{\chi}_{1}^{+}$	0 0 0-1 e,µ 0-1 e,µ	3 b 7-10 jets 3 b 3 b	Yes Yes Yes Yes	20.1 20.3 20.1 20.1	ž 1.2 ž 1.1 To ž 1.1 To ž 1.1 To ž 1.1 To	5 TeV m(k ⁰ ₁)<400 GeV ■V m(k ⁰ ₁)<350 GeV	1407.0600 1308.1841 1407.0600 1407.0600
3 rd gen. squarks direct production	$ \begin{array}{c} \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{b}_{1}\tilde{b}_{1}, \tilde{b}_{1} \rightarrow t\tilde{\chi}_{1}^{\pm} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{light}), \tilde{r}_{1} \rightarrow b\tilde{\chi}_{1}^{\pm} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{light}), \tilde{r}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{medium}), \tilde{r}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{medium}), \tilde{r}_{1} \rightarrow b\tilde{\chi}_{1}^{0} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{heavy}), \tilde{r}_{1} \rightarrow t\tilde{\chi}_{1}^{0} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{heavy})_{0} \\ \tilde{r}_{1} \rightarrow t\tilde{\chi}_{1}^{0} \\ \tilde{r}_{1}\tilde{r}_{1}(\text{netural GMSB}) \\ \tilde{r}_{2}\tilde{r}_{2}, \tilde{r}_{2} \rightarrow \tilde{r}_{1} + Z \end{array} $	$\begin{array}{c} 0 \\ 2 e, \mu (\text{SS}) \\ 1 \cdot 2 e, \mu \\ 2 e, \mu \\ 2 e, \mu \\ 0 \\ 1 e, \mu \\ 0 \\ 1 e, \mu \\ 0 \\ 3 e, \mu (Z) \end{array}$	2 b 0-3 b 1-2 b 0-2 jets 2 jets 2 b 1 b 2 b 1 b 2 b 1 b 1 b 1 b 1 b 1 b	Yes Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.1 20.3 4.7 20.3 20.3 20.1 20 20.1 20.3 20.3 20.3 20.3	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} m(\tilde{k}_{1}^{0}){<}90\text{GeV} \\ m(\tilde{k}_{1}^{-}){=}2m(\tilde{k}_{1}^{0}) \\ m(\tilde{k}_{1}^{0}){=}55\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}55\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}1\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}1\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}0\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}0\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}0\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}0\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}150\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}150\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}200\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}150\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}200\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}150\text{GeV} \\ m(\tilde{k}_{1}^{0}){=}200\text{GeV} \\ \end{array}$	1308.2631 1404.2500 1208.4305, 1209.2102 1403.4853 1403.4853 1308.2631 1407.0583 1405.1122 1407.0608 1403.5222 1403.5222
EW direct	$ \begin{array}{c} \tilde{\ell}_{1_{\mathbf{LR}}} \tilde{\ell}_{\mathbf{LR}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell} \nu (\ell \tilde{\nu}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau} \nu (\tau \tilde{\nu}) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell (\tilde{\nu} \nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell (\tilde{\nu} \nu) \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{2}^{0} Z \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{1}^{+} \tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} h \tilde{\chi}_{1}^{0} \\ \tilde{\chi}_{2}^{+} \tilde{\chi}_{3}^{0}, \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{R} \ell \end{array} $	2 e,μ 2 e,μ 2 τ 3 e,μ 2-3 e,μ 1 e,μ 4 e,μ	0 - 0 2 <i>b</i> 0	Yes Yes Yes Yes Yes Yes Yes	20.3 20.3 20.3 20.3 20.3 20.3 20.3 20.3	$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{split} m(\tilde{k}_{1}^{0}) &= 0 \text{ GeV} \\ m(\tilde{k}_{1}^{0}) &= 0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu}) &= 0.5(m(\tilde{k}_{1}^{+}) + m(\tilde{k}_{1}^{0})) \\ m(\tilde{k}_{1}^{0}) &= 0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu}) &= 0.5(m(\tilde{k}_{1}^{+}) + m(\tilde{k}_{1}^{0})) \\ m(\tilde{k}_{1}^{+}) &= m(\tilde{k}_{2}^{0}), m(\tilde{k}_{1}^{0}) &= 0, \text{ min}(\tilde{k}_{1}^{+}) + m(\tilde{k}_{1}^{0})) \\ m(\tilde{k}_{1}^{+}) &= m(\tilde{k}_{2}^{0}), m(\tilde{k}_{1}^{0}) &= 0, \text{ sleptons decoupled} \\ m(\tilde{k}_{1}^{0}) &= m(\tilde{k}_{2}^{0}), m(\tilde{k}_{1}^{0}) &= 0, \text{ sleptons decoupled} \\ m(\tilde{k}_{2}^{0}) &= m(\tilde{k}_{3}^{0}), m(\tilde{k}_{1}^{0}) &= 0, m(\tilde{\ell}, \tilde{\nu}) &= 0.5(m(\tilde{k}_{2}^{0}) + m(\tilde{k}_{1}^{0})) \end{split}$	1403.5294 1403.5294 1407.0350 1402.7029 1403.5294, 1402.7029 ATLAS-CONF-2013-093 1405.5086
Long-lived particles	Direct $\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}$ prod., long-lived $\tilde{\chi}_{1}^{\pm}$ Stable, stopped \tilde{g} R-hadron GMSB, stable $\tilde{r}, \tilde{\chi}_{1}^{0} \rightarrow \tilde{r}(\tilde{c}, \tilde{\mu}) + \tau(c, g)$ GMSB, $\tilde{\chi}_{1}^{0} \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_{1}^{0}$ $\tilde{q}\tilde{q}, \tilde{\chi}_{1}^{0} \rightarrow qq\mu$ (RPV)	Disapp. trk 0 μ) 1-2 μ 2 γ 1 μ, displ. vtx	1 jet 1-5 jets - -	Yes Yes - Yes -	20.3 27.9 15.9 4.7 20.3	x̂1 270 GeV x̂ 832 GeV x̂1 475 GeV x̂1 230 GeV ŷ 1.0 TeV	$\begin{array}{l} m(\tilde{k}_1^{\pi})\text{-}m(\tilde{k}_1^{0}) {=} 160 \text{ MeV}, \ r(\tilde{k}_1^{\pi}) {=} 0.2 \text{ ns} \\ m(\tilde{k}_1^{0}) {=} 100 \text{ GeV}, \ 10 \ \mu {\rm s} {<} r(\tilde{g}) {<} 1000 \text{ s} \\ 10 {<} {\rm tan} \beta {<} 50 \\ 0.4 {<} r(\tilde{k}_1^{0}) {<} 2 \text{ ns} \\ 1.5 {<} cr {<} 156 \text{ mm}, \ {\rm BR}(\mu) {=} 1, \ m(\tilde{k}_1^{0}) {=} 108 \text{ GeV} \end{array}$	ATLAS-CONF-2013-069 1310.6584 ATLAS-CONF-2013-058 1304.6310 ATLAS-CONF-2013-092
RPV	$ \begin{array}{l} LFV pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e + \mu \\ LFV pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau \\ Bilinear RPV CMSSM \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow ee\tilde{v}_{\mu}, e\mu \tilde{v}_{e} \\ \tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \tau \tau \tilde{v}_{e}, e\tau \tilde{v}_{\tau} \\ \tilde{g} \rightarrow qqq \\ \tilde{g} \rightarrow \tilde{I}_{1}t, \tilde{I}_{1} \rightarrow bs \end{array} $	$\begin{array}{c} 2 \ e, \mu \\ 1 \ e, \mu + \tau \\ 2 \ e, \mu \ (\text{SS}) \\ 4 \ e, \mu \\ 3 \ e, \mu + \tau \\ 0 \\ 2 \ e, \mu \ (\text{SS}) \end{array}$	0-3 b 6-7 jets 0-3 b	- Yes Yes Yes - Yes	4.6 4.6 20.3 20.3 20.3 20.3 20.3	\bar{p}_{e} 1.1 Te \bar{q}, \bar{g} 1.1 Te \bar{q}, \bar{g} 1 $\bar{\chi}_{1}^{\pm}$ 750 GeV $\bar{\chi}_{1}^{\pm}$ 450 GeV \bar{g} 916 GeV \bar{g} 850 GeV	1.61 TeV $\lambda'_{311} = 0.10, \lambda_{132} = 0.05$ V $\lambda'_{311} = 0.10, \lambda_{10233} = 0.05$ 35 TeV $m(\tilde{q}) = m(\tilde{g}), c\tau_{LSF} < 1 \text{ mm}$ $m(\tilde{k}_1^0) > 0.2 \times m(\tilde{k}_1^0), \lambda_{121} \neq 0$ $m(\tilde{k}_1^0) > 0.2 \times m(\tilde{k}_1^0), \lambda_{133} \neq 0$ BR(t) = BR(b) = BR(c) = 0% BR(c) = 0%	1212.1272 1212.1272 1404.2500 1405.5086 1405.5086 ATLAS-CONF-2013-091 1404.250
Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$ Scalar gluon pair, sgluon $\rightarrow d\bar{t}$ WIMP interaction (D5, Dirac χ)	0 2 e, μ (SS) 0	4 jets 2 b mono-jet	Yes Yes	4.6 14.3 10.5	sgluon 100-287 GeV sgluon 350-800 GeV M* scale 704 GeV	incl. limit from 1110.2693 m(g)<80 GeV, limit of <687 GeV for D8	1210.4826 ATLAS-CONF-2013-051 ATLAS-CONF-2012-147
	full data	artial data	full of	data		10-1	1 Mass scale [TeV]	

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

ATLAS Preliminary

 $\sqrt{s} = 7, 8 \text{ TeV}$

Other Indications ?

CMB B-mode detection by the BICEP2 $\rightarrow r \sim 0.2$?



If this is correct, it indicates the energy scale during inflation ! $V \sim (2 \times 10^{16} \text{ GeV})^4 (0.2/r)$

This result also suggests a very special type of inflation Chaotic Inflation !

Other Indications ?

CMB B-mode detection by the BICEP2 $\rightarrow r \sim 0.2$?



We were inspired a lot and our group produced more than 30 papers in 10 months !

Other Indications ?

CMB B-mode detection by the BICEP2 \rightarrow *r* ~ 0.2 ?



Planck experiments showed that the foreground contribution seems larger than expected...

→ We need to wait for the results of the joint analysis...

Guiding Principles for Beyond the Standard Model?

Ground Unification

- Standard Model = Unified theory of electromagnetic and weak interaction.
- Three gauge coupling constants unify at high energy rather well.

Dark Matter

- Rotational curve of the galaxies
- Gravitational Lensing
- CMB, Large Scale Structure

Very Good Example = Supersymmetry



Better Unification & LSP dark matter

Guiding Principles for Beyond the Standard Model?

However, to achieve unification and dark matter, we do not need a gorgeous symmetry

For unification (with long enough proton lifetime):
 We need colored and SU(2) charged matter to bend the running of coupling.



The running of a_1^{-1} only bends downwards

Long lifetime of proton requires to bend both SU(2) and SU(3) running.

Guiding Principles for Beyond the Standard Model?

However, to achieve unification and dark matter, we do not need a gorgeous symmetry

For unification (with long enough proton lifetime):

 We need colored and SU(2) charged matter to bend the running of coupling.

For dark matter

We need a stable neutral particle.

What is the minimal choice ?

Majora adjoint fermions !

[SU(2) triplet (e.g. Z, W-boson), SU(3) octet (e.g. gluon)]

We can predict mass ranges from better unification !



In this range, the couplings unify as good as in the MSSM!

Triplet : 10² - 10⁴ *GeV*

Octet: 10⁷⁻⁸ x Triplet Mass

The model predicts a rather low GUT scale !

Triplet Mass : 10² - 10⁴ GeV !



 ✓ Triplet Fermion includes Neutral Component
 → Good Dark Matter Candidate !

If it is produced thermally \rightarrow Triplet Mass = 3TeV !

Can the lighter triplet be a good DM candidate ?

Majorana Fermion Extension

The triplet Dark Matter can be provided by the decay of the Octet Fermion !

Late time decay of Octet \rightarrow Triplet + a quark pair !



The non-thermal triplet abundance is independent of the octet fermion abundance.

Prediction on the Proton Decay



Most Parameter space has been excluded by the SK ! With the HK, this model can be fully tested !

Majorana Fermion Extension

 10^{-1}

 10^{-2}

 10^{-4}

 10^{-12}

10-13

Enectali Figueroa-Feliciano

Astroparticle Physics / June 2014



 10^{-35}

 10^{-38}

10⁻⁴³ 10⁻⁴⁴

10⁻⁴⁵ 10⁻⁴⁶ 10⁻⁴⁷

 10^{-48}

 10^{-49}

10-39 10-10

WIMP-nucleon cross

LHC triplet search : lower limit 270GeV Future LHC could reach to 500GeV

Direct Detection : $\sigma \sim 10^{-47} \text{ cm}^2$

challenging but not impossible!





Summary

After the success of the Standard Model (i.e. the unified theory of the electromagnetic and weak interaction), it is worthy to reappraise the longstanding idea, the Grand Unification.

In particular, it is one of the good strategy to start from the minimal possibilities.

The Majorana extension is one of the minimal possibilities.

Can be tested via the proton decay, the LHC search, the Dark Matter direct and indirect searches !