R-parity breaking and baryon number violation in anomalous $U(1)_H$ models

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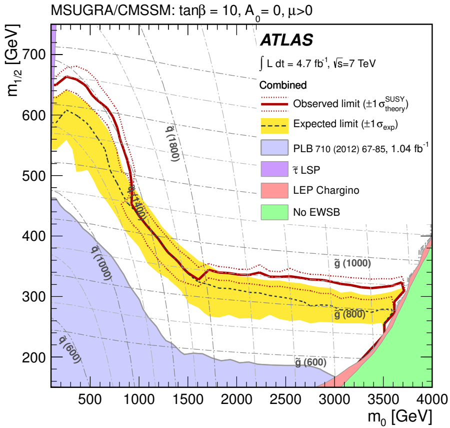
Outline

Motivation

- LHC searches for susy: $m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 1.4$TeV in cMSSM.
- Searches based on missing tranverse momentum carried by LSP, which is stable because R-parity conservation assumption.
- A high mass scale for $m_{\tilde{q}}$ represents a potential chink in the initial proposal of the MSSM as a possible solution to the hierarchy problem.



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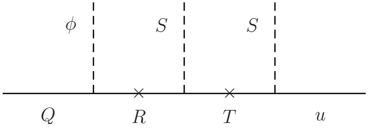
Motivation

- In $\not{R}_p$ scenarios such results have a lesser impact because the LSP can decay inside the detector, and the missing energy signal is degraded.
- $\not{R}_p$ with $\not{B}$ lead to the most difficult signal to be searched at hadron colliders.
- If lepton parity is imposed several issues arise. The size of R-parity breaking couplings must be precisely chosen by hand in order to avoid constraints from flavor physics observables.
- It it will be desirable to build a self-consistent supersymmetric framework with baryon number violation, where the operators and size of the their couplings can be generated.

Froggat-Nielsen mechanism

The approach to account for the fermion mass hierarchy is based on an hypothetical $U(1)_H$ symmetry which is spontaneously broken by vev of one flavon field S of horizontal charge $H[S] = -1$.

At high energies: $\mathcal{L} = \bar{Q}\phi_{(0)}R + \bar{R}S_{(-1)}T + \bar{T}S_{(-1)}u$



At low energies: $$\mathcal{L}_{eff} \sim \left(\frac{\langle S\rangle}{M_P}\right)^n \bar{Q}\phi u = \theta^n \bar{Q}\phi u,$$
$$n = n_Q + n_\phi + n_u.$$

Charged fermion masses hierarchy

$$m_u : m_c : m_t \simeq \theta^8 : \theta^4 : 1\,,$$
$$m_d : m_s : m_b \simeq \theta^4 : \theta^2 : 1\,,$$
$$m_e : m_\mu : m_\tau \simeq \theta^5 : \theta^2 : 1\,,$$
$$V_{us} \simeq \theta\,,\ \ V_{cb} \simeq \theta^2\,,$$
with $\theta \approx 0.22$.

SSM

The superpotential

$$W = h^u_{ij}\widehat{H}_u\widehat{Q}_i\widehat{u}_j + h^l_{ij}\widehat{H}_d\widehat{L}_j\widehat{l}_k + h^d_{ij}\widehat{H}_d\widehat{Q}_j\widehat{d}_k$$
$$+ \mu_0\widehat{H}_d\widehat{H}_u$$
$$+ \mu_i\widehat{L}_i\widehat{H}_u$$
$$+ \lambda_{ijk}\widehat{L}_i\widehat{L}_j\widehat{l}_k + \lambda'_{ijk}\widehat{L}_i\widehat{Q}_j\widehat{d}_k$$
$$+ \lambda''_{ijk}\widehat{u}_i\widehat{d}_j\widehat{d}_k,$$

- $W \Rightarrow \not{B}$ and $\not{L} \Rightarrow$ fast proton decay.
- To avoid it, it is imposed R-parity, obtaining the MSSM. μ_i, λ_{ijk}, λ'_{ijk} and λ''_{ijk} are forbidden.
- Because R_P conservation LSP is stable and DM candidate.
- However, either $\not{B}$ or $\not{L}$ can exist.

FN in SSM

Using a supersymmetric model extended by a anomalous $U(1)_H$ flavor symmetry, it is possible to obtain either $\not{L}$ or $\not{B}$, in addition to the fermion mass hierarchy.
The effective bilinear and trilinear $\not{R}_P$ terms are given by

$$\mu_\alpha \sim \begin{cases} M_P \theta^{n_\alpha} & n_\alpha \geq 0 \\ m_{3/2}\theta^{|n_\alpha|} & n_\alpha < 0 \\ 0 & n_\alpha \text{ fractional} \end{cases}$$

$$\lambda_T \sim \begin{cases} \theta^{n_\lambda} & n_\lambda \geq 0 \\ (m_{3/2}/M_P)\theta^{|n_\lambda|} & n_\lambda < 0 \\ 0 & n_\lambda \text{ fractional} \end{cases}$$

$$n_\alpha = L_\alpha + H_u, \qquad n_\lambda = L_i + L_j + \ell_k.$$

Constraints

In order to obtain a viable flavor model, the $U(1)_H$ charges must satisfy several phenomenological and theoretical constraints.

- 8 phenomenological constrains corresponding to six mass ratios for the charged fermions and two quarks mixing angles.
- Reproduce the third generation fermion masses

$$m_t \sim \langle \phi_u \rangle \Rightarrow \phi_u + u_3 + Q_3 = 0,$$
$$m_b \sim m_\tau \Rightarrow \phi_d + d_3 + Q_3 = \phi_d + \ell_3 + L_3 = x,$$

- 3 conditions from anomaly cancellation.

We are left with 4 parameters that we choose to be n_i and x (Mira2000).

- More additional constraints must be included.
  - Neutrino oscillation data (Dreiner2003)
  - Neutralino as decaying dark matter (Sierra2009).

R_p violating operators

$$H[\mu_i] = n_i$$

$$H\begin{pmatrix} \lambda_{121} & \lambda_{122} & \lambda_{123} \\ \lambda_{131} & \lambda_{132} & \lambda_{133} \\ \lambda_{231} & \lambda_{232} & \lambda_{233} \end{pmatrix} = \begin{pmatrix} 5+n_2 & 2+n_1 & n_1+n_2-n_3 \\ 5+n_3 & 2+n_1-n_2+n_3 & n_1 \\ 5-n_1+n_2+n_3 & 2+n_3 & n_2 \end{pmatrix} + (1+x)\mathbf{1}_3,$$

$$H\left(\lambda'_{ijk}\right) = \begin{pmatrix} 4 & 3 & 3 \\ 3 & 2 & 2 \\ 1 & 0 & 0 \end{pmatrix} + (1+n_i+x)\mathbf{1}_3,$$

$$H\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} = \begin{pmatrix} 6 & 3 & 1 \\ 6 & 3 & 1 \\ 5 & 2 & 0 \end{pmatrix} + n_{\lambda''}\mathbf{1}_3,$$

where $n_{\lambda''} = \frac{1}{3}(3x + n_1 + n_2 + n_3 - 1)$.

Choosing n_i charges

Once n_i are fractional it is obtained

- All λ'_{ijk} are forbidden.
- All λ_{ijk} with repeated indexes are also forbidden.

Several possibilities

- Choose the fractional n_i charges such that all the L and B violating terms in the superpotential also have fractional charges. R_p and P_6 discrete symmetries respectively, are obtained as remnants of a spontaneously broken $U(1)_H$.
- If $n_{1,2,3}$ not half-integers and $n_{\lambda''} = (n_1 + n_2 + n_3 - 1)/3$ integer, we have only trilinear B violating terms λ'' in the supersymmetric Lagrangian.

Baryon number violation

Once fixed n_i charges such that μ_i, λ_{ijk} and λ'_{ijk} are forbidden, we obtain

$$\begin{pmatrix} \lambda''_{112} & \lambda''_{212} & \lambda''_{312} \\ \lambda''_{113} & \lambda''_{213} & \lambda''_{313} \\ \lambda''_{123} & \lambda''_{223} & \lambda''_{323} \end{pmatrix} \sim \theta^{n_{\lambda''}} \begin{pmatrix} \theta^6 & \theta^3 & \theta \\ \theta^6 & \theta^3 & \theta \\ \theta^5 & \theta^2 & 1 \end{pmatrix}$$

The most important constraint on λ''_{ijk} are from neutron-antineutron oscillations and double nucleon decay, requiring $\lambda''_{112} \lesssim 10^{-8}$ and $\lambda''_{113} \lesssim 10^{-4}$ for $\tilde{m} \sim 200\,\mathrm{GeV}$.

$$\begin{aligned} &\lambda''_{112} \lesssim 10^{-8} \Rightarrow \lambda''_{112} \lesssim \theta^{12} \\ &\Rightarrow n_\lambda \geq 6,\; n_\lambda \leq -7 \\ &\Rightarrow \lambda''_{323} \lesssim \theta^4 \approx 10^{-4}. \end{aligned}$$

LSP decays with displaced vertices are expected.

Dimension-5 operators and proton decay

$$W_{D5} = \frac{(\kappa_1)_{ijkl}}{M_P}\widehat{Q}_i\widehat{Q}_j\widehat{Q}_k\widehat{L}_l + \frac{(\kappa_2)_{ijkl}}{M_P}\widehat{u}_i\widehat{u}_j\widehat{d}_k\widehat{e}_l + \frac{(\kappa_3)_{ijk}}{M_P}\widehat{Q}_i\widehat{Q}_j\widehat{Q}_k\widehat{H}_d$$
$$+ \frac{(\kappa_4)_{ijk}}{M_P}\widehat{Q}_i\widehat{H}_d\widehat{u}_j\widehat{e}_k + \frac{(\kappa_5)_{ij}}{M_P}\widehat{L}_i\widehat{H}_u\widehat{L}_j\widehat{H}_u + \frac{(\kappa_6)_i}{M_P}\widehat{L}_i\widehat{H}_u\widehat{H}_d\widehat{H}_d,$$
$$V_{5D} = \frac{(\kappa_7)_{ijk}}{M_P}\widehat{u}_i\widehat{d}^*_j\widehat{e}_k + \frac{(\kappa_8)_i}{M_P}\widehat{H}^*_u\widehat{H}_d\widehat{e}_i + \frac{(\kappa_9)_{ijk}}{M_P}\widehat{Q}_i\widehat{L}^*_j\widehat{u}_k + \frac{(\kappa_{10})_{ijk}}{M_P}\widehat{Q}_i\widehat{Q}_j\widehat{d}^*_k.$$

- $\kappa_{3,10}$ couplings induce $\not{B}$ processes and do not pose threat to the proton decay as long as there is no major $\not{L}$.
- $\kappa_{4,\ldots,9}$ couplings induce $\not{L}$ processes $\rightarrow$ must be suppressed enough.
- $QQQL$ and $UUDE$ operators violate both B and L, being the most dangerous for the stability of the proton as they require no other terms.

Dimension-5 operators and proton decay

The horizontal charges for those dimension-5 operators that violate only baryon number are given by

$$
\begin{aligned}
H\left[(\kappa_3)_{1jk}\widehat{Q}_1\widehat{Q}_j\widehat{Q}_k\widehat{H}_d\right] &= A_3 + (2x+4-n_{\lambda''})\mathbf{1_3}, \\
H\left[(\kappa_3)_{2jk}\widehat{Q}_2\widehat{Q}_j\widehat{Q}_k\widehat{H}_d\right] &= A_3 + (2x+3-n_{\lambda''})\mathbf{1_3}, \\
H\left[(\kappa_3)_{3jk}\widehat{Q}_3\widehat{Q}_j\widehat{Q}_k\widehat{H}_d\right] &= A_3 + (2x+1-n_{\lambda''})\mathbf{1_3}, \\
H\left[(\kappa_{10})_{ij1}\widehat{Q}_i\widehat{Q}_j\widehat{d}_1^*\right] &= A_3 + (x-n_{\lambda''})\mathbf{1_3}, \\
H\left[(\kappa_{10})_{ij2}\widehat{Q}_i\widehat{Q}_j\widehat{d}_2^*\right] &= A_3 + (x+1-n_{\lambda''})\mathbf{1_3}, \\
H\left[(\kappa_{10})_{ij2}\widehat{Q}_i\widehat{Q}_j\widehat{d}_3^*\right] &= H\left[(\kappa_{10})_{ij3}\widehat{Q}_i\widehat{Q}_j\widehat{d}_2^*\right].
\end{aligned}
$$

It follows that if the UDD operator is allowed by the horizontal symmetry, then the $QQQH_d$ and QQd^* are also allowed.

For the violating baryon and lepton number operators we have that

$$
\begin{aligned}
H\left[(\kappa_1)_{1jkl}\widehat{Q}_1\widehat{Q}_j\widehat{Q}_k\widehat{L}_l\right] =& A_1 + (5 + 2x + n_l - n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_1)_{2jkl}\widehat{Q}_2\widehat{Q}_j\widehat{Q}_k\widehat{L}_l\right] =& A_1 + (4 + 2x + n_l - n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_1)_{3jkl}\widehat{Q}_3\widehat{Q}_j\widehat{Q}_k\widehat{L}_l\right] =& A_1 + (2 + 2x + n_l - n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij11}\widehat{u}_i\widehat{u}_j\widehat{d}_1\widehat{e}_1\right] =& A_2 + (6 - n_1 + n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij21}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_1\right] =& A_2 + (5 - n_1 + n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij31}\widehat{u}_i\widehat{u}_j\widehat{d}_3\widehat{e}_1\right] =& H\left[(\kappa_2)_{ij21}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_1\right],\\
H\left[(\kappa_2)_{ij12}\widehat{u}_i\widehat{u}_j\widehat{d}_1\widehat{e}_2\right] =& A_2 + (3 - n_2 + n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij22}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_2\right] =& A_2 + (2 - n_2 + n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij32}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_2\right] =& H\left[(\kappa_2)_{ij22}\widehat{u}_i\widehat{u}_j\widehat{d}_3\widehat{e}_2\right]\\
H\left[(\kappa_2)_{ij13}\widehat{u}_i\widehat{u}_j\widehat{d}_1\widehat{e}_3\right] =& A_2 + (1 - n_3 + n_{\lambda''})\mathbf{1_3},\\
H\left[(\kappa_2)_{ij23}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_3\right] =& A_2 + (-n_3 + n_{\lambda''})\mathbf{1_3},\\
\left[(\kappa_2)_{ij33}\widehat{u}_i\widehat{u}_j\widehat{d}_2\widehat{e}_3\right] =& H\left[(\kappa_2)_{ij23}\widehat{u}_i\widehat{u}_j\widehat{d}_3\widehat{e}_3\right].
\end{aligned}
$$

Finally, for those couplings that violate only the lepton number we found

$$
\begin{aligned}
H\left[(\kappa_4)_{ij1}\widehat{Q}_i\widehat{H}_d\widehat{u}_j\widehat{e}_1\right] =& A_4+(5-n_1+x)\mathbf{1_3},\\
H\left[(\kappa_4)_{ij2}\widehat{Q}_i\widehat{H}_d\widehat{u}_j\widehat{e}_2\right] =& A_4+(2-n_2+x)\mathbf{1_3},\\
H\left[(\kappa_4)_{ij3}\widehat{Q}_i\widehat{H}_d\widehat{u}_j\widehat{e}_3\right] =& A_4+(-n_3+x)\mathbf{1_3},\\
H\left[(\kappa_5)_{ij}\widehat{L}_i\widehat{H}_u\widehat{L}_j\widehat{H}_u\right] =& \left(\begin{array}{ccc} 2n_1 & n_1+n_2 & n_1+n_3 \\ n_1+n_2 & 2n_2 & n_2+n_3 \\ n_1+n_3 & n_2+n_3 & 2n_3 \end{array}\right),\\
H\left[(\kappa_6)_{i}\widehat{L}_i\widehat{H}_u\widehat{H}_d\widehat{H}_u\right] =& -1+n_i,\\
H\left[(\kappa_7)_{ij1}\widehat{u}_i\widehat{d}^*_j\widehat{e}_1\right] =& A_7+(4-n_1)\mathbf{1_3},\\
H\left[(\kappa_7)_{ij2}\widehat{u}_i\widehat{d}^*_j\widehat{e}_2\right] =& A_7+(1-n_2)\mathbf{1_3},\\
H\left[(\kappa_7)_{ij3}\widehat{u}_i\widehat{d}^*_j\widehat{e}_3\right] =& A_7+(-1-n_3)\mathbf{1_3},\\
H\left[(\kappa_8)_{1}\widehat{H}^*_u\widehat{H}_d\widehat{e}_1\right] =& 5-n_1+x,\\
H\left[(\kappa_8)_{2}\widehat{H}^*_u\widehat{H}_d\widehat{e}_2\right] =& 2-n_2+x,\\
H\left[(\kappa_8)_{3}\widehat{H}^*_u\widehat{H}_d\widehat{e}_3\right] =& -n_3+x,\\
H\left[(\kappa_9)_{i1k}\widehat{Q}_i\widehat{L}^*_j\widehat{u}_k\right] =& A_9+(-n_j)\mathbf{1_3}.
\end{aligned}
$$

For n_i fractional all $\not{L}$ D-5 operators are also automatically forbidden by the $U(1)_H$.

Dark matter

- The proton decay mediated only by λ'' couplings occurs in scenarios with a gravitino lighter than proton (Choi:1996), leading to strong bounds on these couplings.
- By ensuring gravitino masses greater than 1 GeV in these scenarios there will be no contribution to the proton decay coming from gravitino.
- Because Planck mass suppression, a gravitino LSP can be also a dark matter canditate (Takayama:2000, Buchmuller:2007).
- For $\lambda'' \lesssim 10^{-5} \Rightarrow \tau_{\tilde{G}} \gtrsim 10^{26} s$ (Lola2008).

Neutrino masses

Dirac neutrinos

- LH_uLH_u is forbidden by $U(1)_H$ because n_i are not half-integers $\Rightarrow \cancel{m_L \nu_L \nu_L}$
- Introducing N_R: as n_i are non half-integers $\Rightarrow \cancel{M_N N_R N_R}$ if $L_i H_u N_j = n_i + N_j =$ integer.
- Dirac mass terms can only be generated in this scenario.

Majorana neutrinos

- By adding a new flavon S' with fractional H-charge Majorana neutrinos can be obtained.
- The H-charge of S' is such that it does not get coupled to L violating operators because the respective total H-charge are fractional (negative) and therefore forbidden (suppressed enough).
- The introduction of an additional flavon field do not spoil the proton stability via D5 operators.

Neutrino masses

The neutrino mass matrix is given by

$$M_\nu \sim m_{eff}\theta^n \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$

- A large θ_{13} supports models based on a anarchical texture (deGouvea2012, Altarelli2012).
- An inmediate consequence of the anarchy assumption is that the bilinear charges are equal and are set to $n_i = n_{\lambda''} - x + \frac{1}{3}$, being clearly non-integer numbers.
- Pseudo $\mu\tau$-anarchy or hierarchical textures are also possible.

Implications on collider searches

When R-parity conservation is assumed, the production of sparticles is in pairs and the LSP is stable.

R-parity violation allows for the single production of supersymmetric particle and decay of the LSP.

From $\not{B}$ terms, the LSP can decay directly or indirectly to quarks, and depending on whether $m_{LSP} > m_t$ or $m_{LSP} < m_t$, top quark can be present on the final states.

It is clear that λ''_{323} coupling dominates over the other couplings, and heavy quarks are to be present in the final states.

LSP can be any supersymmetric particle: neutralino, chargino, squark, slepton or gluino.

If $\tilde{G}$ is the real LSP $\Rightarrow \chi, \tilde{t} \to$ NLSP.

Stop LSP

- $\tilde{t}$ can decay directly into a two down quarks of different generations through the λ''_{3jk} coupling.
- Hence, final states with at least two b-jets are also expected, which could be observed at the LHC.

$$\frac{\mathrm{Br}(\tilde{t} \to bd)}{\mathrm{Br}(\tilde{t} \to bs)} \sim \frac{\mathrm{Br}(\tilde{t} \to sd)}{\mathrm{Br}(\tilde{t} \to bs)} \sim \theta^2 \approx 0.05.$$

- $\mathrm{Br}(\tilde{t} \to bd) \sim 0.9$.
- Plausible in natural SUSY.

- Through direct decays, the sbottom can decay into an up quark and a down quark, *i.e.* no *b*-jets).
- Approximately more than 99% of the decays involve a top quark, completely opposite to the case when $m_{\tilde{b}} < m_t$, where no top quarks are produced.
- $m^0_{\tilde{b}} > m_t$.

$$\frac{\mathrm{Br}(\tilde{b} \to td)}{\mathrm{Br}(\tilde{b} \to ts)} \sim \theta^2 \approx 0.05.$$

- $m_{\tilde{b}} < m_t$. In this point we have that $\tilde{b} \to cs$ is the dominant decay.

$$\frac{\mathrm{Br}(\tilde{b} \to cd)}{\mathrm{Br}(\tilde{b} \to cs)} \sim \theta^2 \approx 0.05.$$

Neutralino LSP

The lightest neutralino χ can decay to three quarks through virtual scalar exchange and the dominant decay mode will be $\chi \to tbs$. If the neutralino is lighter than top quark, then the dominant mode is $\chi \to cbs$. Therefore, horizontal symmetry allows for estimating relations between different ratios of branching ratios.

- $m_\chi > m_t$. Dominated by λ''_{323}, involving a top quark in the final state.

$$\frac{\mathrm{Br}(\chi \to tdb)}{\mathrm{Br}(\chi \to tsb)} \sim \frac{\mathrm{Br}(\chi \to tds)}{\mathrm{Br}(\chi \to tsb)} \sim \theta^2 \approx 0.05.$$

- $m_\chi < m_t$. Dominated by λ''_{223}.

$$\frac{\mathrm{Br}(\chi \to cdb)}{\mathrm{Br}(\chi \to csb)} \sim \frac{\mathrm{Br}(\chi \to cds)}{\mathrm{Br}(\chi \to csb)} \sim \theta^2 \approx 0.05.$$

In either case, neutralino decays are dominated by heavy flavors, and should contain displaced vertices.

Summary

- We have studied the question about if it is possible to obtain a framework with baryon number violation. By using a $U(1)_H$ horizontal gauge symmetry, we have found charge assignments that allow all λ'' couplings, being λ''_{3jk} the dominant ones.
- All $\not{B}$ terms satisfy current experimental bounds.
- Gravitino as a dark matter candidate.
- It is possible to obtain a neutrino matrix with a acceptable phenomenological texture with Majorana or Dirac neutrinos (with or without S').
- The ratio of branching ratios for the LSP have been analyzed. Hence, it is possible to infer the main decay channels of the LSP. Displaced vertices are expected.

H-charges

Set of H–charges allowing a $\not{B}$ self-consistent framework

x	0	0	1	0	1	2
$n_{\lambda''}$	8	9	9	10	10	10
n_i	$25/3$	$28/3$	$25/3$	$31/3$	$28/3$	$25/3$
N_R	$29/3$	$26/3$	$29/3$	$23/3$	$26/3$	$29/3$

x	1	1	1	2	2	2	3	3
$n_{\lambda''}$	5	6	7	6	7	8	8	9
n_i	$13/3$	$16/3$	$19/3$	$13/3$	$16/3$	$19/3$	$16/3$	$19/3$
S'	$-47/6$	$-53/6$	$-59/6$	$-47/6$	$-53/6$	$-59/6$	$-53/6$	$-59/6$