

# Axino LSP Baryogenesis and Dark Matter

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Based on  
[JCAP05\(2015\)035 \(1412.5568\)](#) with Angelo Monteux

Aug. 27<sup>th</sup> 2015 at SUSY 2015

# Motivation of this work

**A** R-parity violating (RPV) SUSY (null result in missing energy search)

With sizable RPV couplings ( $>10^{-7}$ )

- 1) Baryon asymmetry generated above the EW scale is diluted.
- 2) Neutralino cannot be a dark matter, so new dark matter (DM) candidates are needed.

Is there any relation between genesis of baryon and DM ?

: Cogenesis of baryon asymmetry and DMs at low temperature

**B** The Nanopoulos-Weinberg theorem for baryogenesis

Non-LSP decays/annihilations are usually used to avoid the NW theorem.

Does baryogenesis via LSP decays generate too small asymmetry ?

: LSP baryogenesis

# Outline

Motivation

LSP Baryogenesis

- The Nanopoulos-Weinberg theorem

- Asymmetry in LSP baryogenesis

Axino LSP and baryogenesis in RPV SUSY

Dark Matter

- QCD axion

- Metastable Gravitino

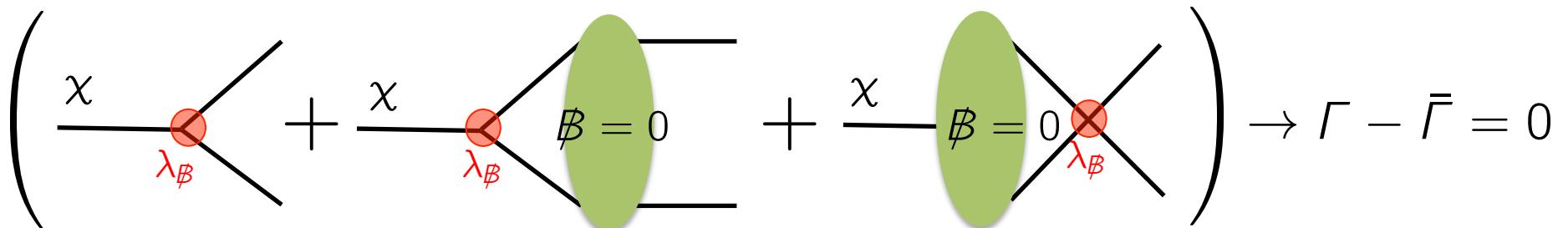
At the LHC

Conclusion

# The Nanopoulos-Weinberg Theorem (1)

For a particle  $\chi$ , which is stable when B (baryon) violating couplings are turned off, i.e.  $\Gamma(\chi \rightarrow \text{all}) = \mathcal{O}(\lambda_B^2)$ , Nanopolous, Weinberg 1979

$$\sum_{f_B} \Gamma(\chi \rightarrow f_B) - \sum_{\bar{f}_{-B}} \Gamma(\bar{\chi} \rightarrow \bar{f}_{-B}) = 0 \text{ at } \mathcal{O}(\lambda_B^2).$$



However B asymmetry can be generated at  $\mathcal{O}(\lambda_B^3)$  or  $\mathcal{O}(\lambda_B^4)$  from higher loop diagrams. This possibility is usually ignored.

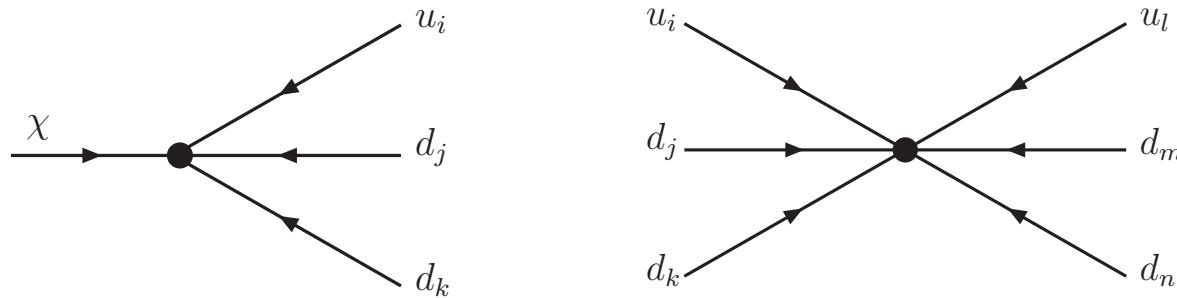
Common detours to generate B asymmetry at one loop level : Consider particles which can decay to new particles, which are not SM baryons/leptons. Generate (B-conserving) CP asymmetry first, followed by (B violating) decay of daughter particles.

# The Nanopoulos-Weinberg Theorem (2)

Here we consider generation of B asymmetry from decay of lightest new particles (LSPs in SUSY case).

Effective operators to generate asymmetry from LSP decays

$$\frac{1}{2}m_\chi\chi\chi + \frac{c_1}{\Lambda^2}(\chi q)(q\bar{q}) + \frac{c_2}{\Lambda^5}(q\bar{q})(q\bar{q})(q\bar{q}) + h.c.$$



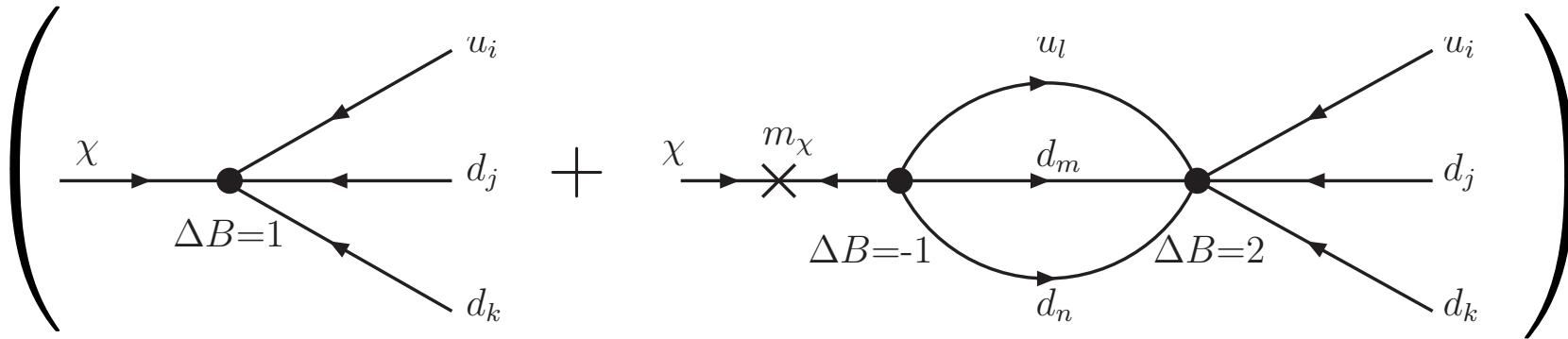
Monteux, CSS 2014

Dev Paratma, Mohapatra 2015; Davoudiasl, Zhang 2015

B-preserving terms like  $(\chi q)(\bar{\chi}\bar{q})$ ,  $(q\bar{q})(q\bar{q})$  do not contribute to the asymmetry.

# Asymmetry in LSP baryogenesis

Asymmetry is generated by interference between tree and two loop diagrams



$$\Gamma(\chi \rightarrow qqq) \sim \frac{1}{(8\pi)^3} \frac{|c_1|^2 m_\chi^5}{\Lambda^4}$$

$$\epsilon_B = \frac{\Gamma(\chi \rightarrow qqq) - \Gamma(\chi \rightarrow \bar{q}\bar{q}\bar{q})}{\Gamma(X \rightarrow \text{all})} \sim \frac{1}{(8\pi)^3} \frac{\text{Im}[c_1^{*2} c_2 m_\chi] |m_\chi|^2}{|c_1|^2 \Lambda^3}$$

$$\frac{n_B}{s} = \epsilon_B \left( \frac{n_\chi}{s} \right)_{t=1/\Gamma_\chi} = 0.8 \times 10^{-10} \quad \text{PLANK 2013}$$

 which depends on cosmological history of  $\chi$

A specific example : Axino LSP with RPV superpotentials,  $\lambda''_{ijk} U_i^c D_j^c D_k^c / 2$

Monteux, CSS 2014 (Dark matter is also naturally provided)

# Axino LSP and baryogenesis in RPV SUSY (1)

**Axino** is a fermionic superpartner of the QCD axion ( $a_{\text{QCD}}$ ).

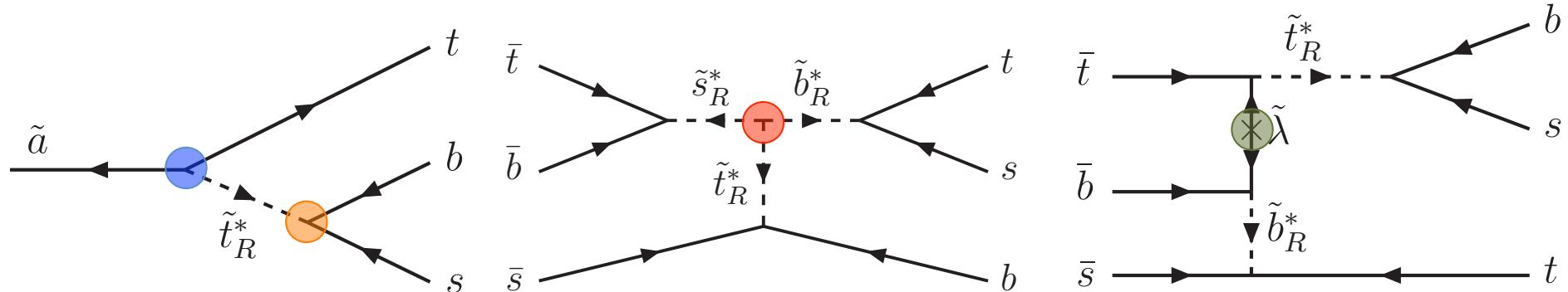
$$\mathcal{A} = \frac{1}{\sqrt{2}}(s + ia_{\text{QCD}}) + \sqrt{2}\theta \tilde{a} + \theta^2 F^A$$

Thermal production of axino by **out-of-equilibrium scattering** (e.g.  $gg \rightarrow \tilde{g}\tilde{a}$ )

$$\left(\frac{n_{\tilde{a}}}{s}\right)_{TP} = 10^{-3} g_s^6 \left(\frac{T_R}{10^{10} \text{ GeV}}\right) \left(\frac{10^{12} \text{ GeV}}{v_{\text{PQ}}}\right)^2 \left(\frac{c_s g_s^2}{v_{\text{PQ}}} \tilde{a} \sigma_{\mu\nu} \tilde{g}^a G^{a\mu\nu} \text{ with } v_{\text{PQ}} \gtrsim 10^9 \text{ GeV}\right)$$

Axino-three quark interactions from **axino-higgsino mixing** and **RPV terms**

Six quark interactions mediated by **squarks with A-term**, and **gauginos**



# Axino LSP and baryogenesis in RPV SUSY (2)

Axininos decay at  $T = T_D$

$$T_D \simeq 30 \text{ MeV} |\lambda''_{323}| \left( \frac{m_{\tilde{a}}}{\text{TeV}} \right)^{1/2} \left( \frac{m_{\tilde{a}}^2}{m_{\tilde{t}_R}^2} \right) \left( \frac{10^{12} \text{ GeV}}{v_{\text{PQ}}} \right)$$

The produced baryon asymmetry from A-term/gluino mediation

$$\epsilon_B[A] \sim \frac{|\lambda''_{323}|^4}{32\pi^3} \frac{m_t^2 m_{\tilde{a}}^2}{m_{\tilde{q}}^6} \text{Im}[m_{\tilde{a}} A''^*_{323}], \quad \epsilon_B[\tilde{g}] \sim \frac{|\lambda''_{323}|^2 g_s^2}{32\pi^3} \frac{m_t^2 m_{\tilde{a}}^2}{m_{\tilde{g}}^2 m_{\tilde{q}}^4} \text{Im}[m_{\tilde{a}} m_{\tilde{g}}^*]$$

gives the upper bound on squark/gluion masses  $< O(10 - 100 \text{ TeV})$

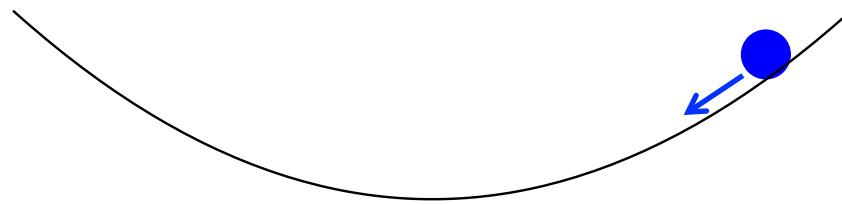
BP1 :	$m_{\tilde{q}} = 900 \text{ GeV}, m_{\tilde{g}} = 1.5 \text{ TeV},  \lambda''_{323}  = 1, \Phi = 1;$	$\epsilon = 3.4 \times 10^{-6};$
BP2 :	$m_{\tilde{q}} = 1 \text{ TeV}, m_{\tilde{g}} = 2 \text{ TeV},  \lambda''_{323}  = 0.5, \Phi = 0.2;$	$\epsilon = 5.9 \times 10^{-8};$
BP3 :	$m_{\tilde{q}} = 2 \text{ TeV}, m_{\tilde{g}} = 1 \text{ TeV},  \lambda''_{323}  = 1, \Phi = 1;$	$\epsilon = 1.5 \times 10^{-7}.$

Constraints from neutron EDM : same CP phases for the MSSM soft terms  
 KKbar mixing, n-n oscillation,  $\Delta m_K$  : the single coupling,  $\lambda''_{323}$ , dominance

# Dark Matter : QCD axion

Gravitino should be heavier than 50 TeV in order not to disturb the BBN

Coherent oscillation of QCD axion can be a cold dark matter



$$\Omega_a h^2 \simeq \theta_a^2 \left( \frac{v_{\text{PQ}}}{10^{12} \text{ GeV}} \right)^{7/6}$$

There is a bound on  $v_{\text{PQ}}$  from the correct value of baryon asymmetry

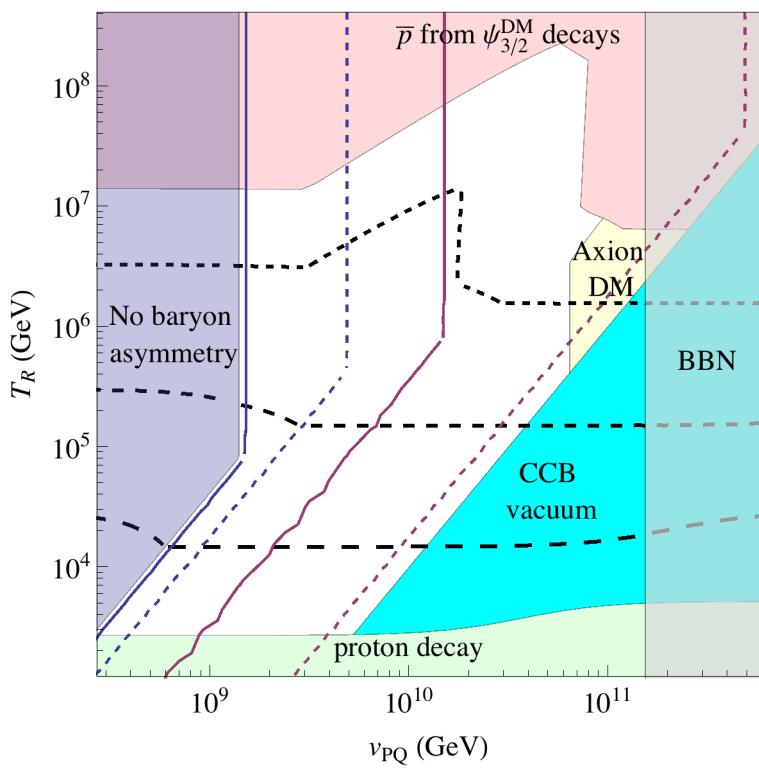
$$v_{\text{PQ}} = 10^{11} \text{ GeV} |\lambda''_{323}| \left( \frac{m_{\tilde{a}}}{0.5 \text{ GeV}} \right)^{3/2} \left( \frac{0.8 \times 10^{-10}}{n_B/s} \right)^{1/2} \left( \frac{\text{TeV}}{m_{\tilde{q}}} \right)^{5/2} \left( \frac{T_{\text{reh}}}{10^7 \text{ GeV}} \right)^{1/2}$$

For reasonable parameter spaces

$$10^{11} \text{ GeV} \lesssim v_{\text{PQ}} \lesssim 10^{12} \text{ GeV}$$

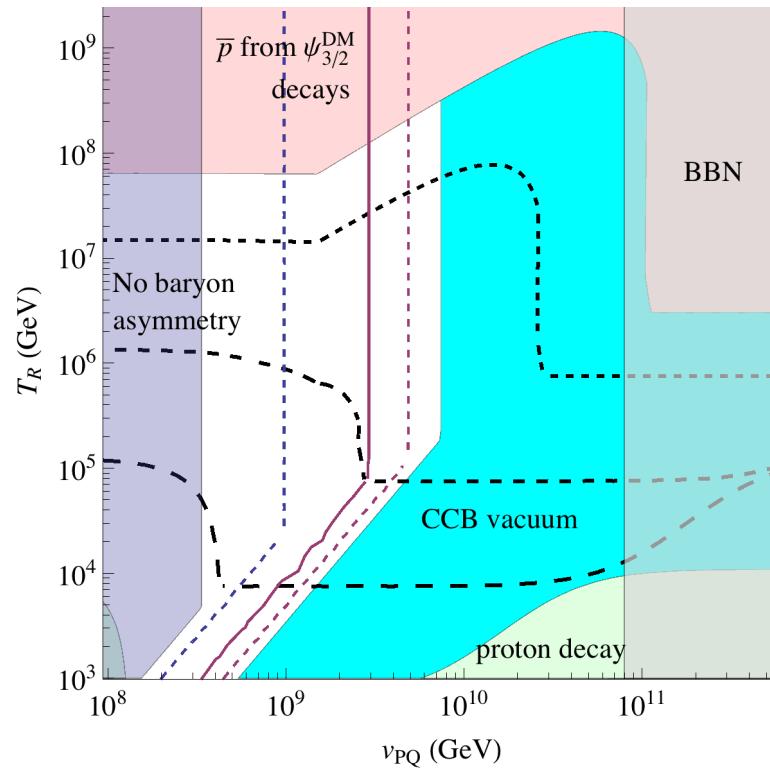
# Dark Matter : Light gravitino

The light gravitino (sub GeV) can be a metastable dark matter (without spoiling axino LSP baryogenesis idea) from thermal production ( $gg \rightarrow \tilde{g}\psi_{3/2}$ ) and direct decay of axino ( $\tilde{a} \rightarrow a\psi_{3/2}$ ).



$m_{3/2}$	$\lambda''_{323}=1$	$\lambda''_{323}=1$
---	$A''_{323} \approx X_t \approx m_{\tilde{q}}$	$A''_{323} \approx X_t \approx \sqrt{6} m_{\tilde{q}}$
---	$\Phi = 1$	$\Phi = 0.2$
---	$\Phi = 1$	$\Phi = 1$

**BP2**  
 $m\tilde{q} = 1 \text{ TeV}$ ,  
 $m\tilde{g} = 2 \text{ TeV}$

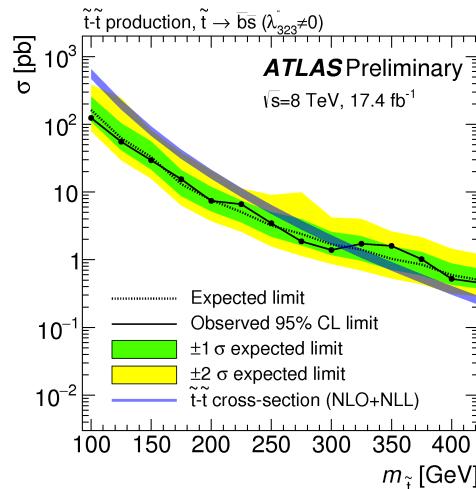
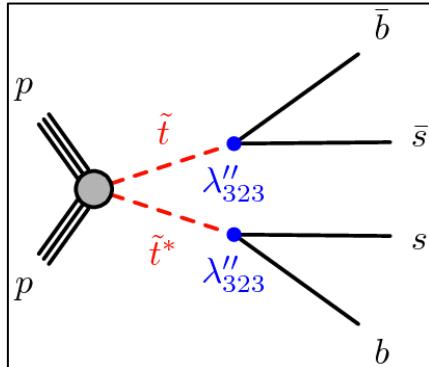


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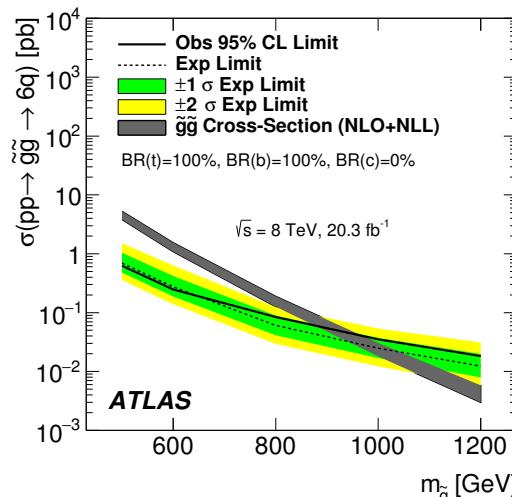
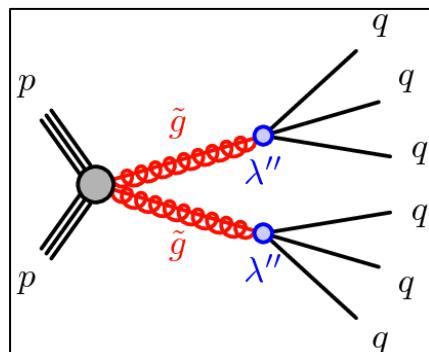
**BP3**  
 $m\tilde{q} = 2 \text{ TeV}$ ,  
 $m\tilde{g} = 1 \text{ TeV}$

# Implications at the LHC

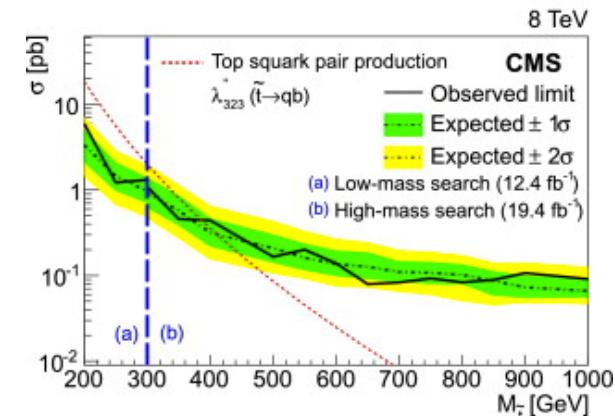
light squark/gluino masses with large RPV couplings : multijet searches



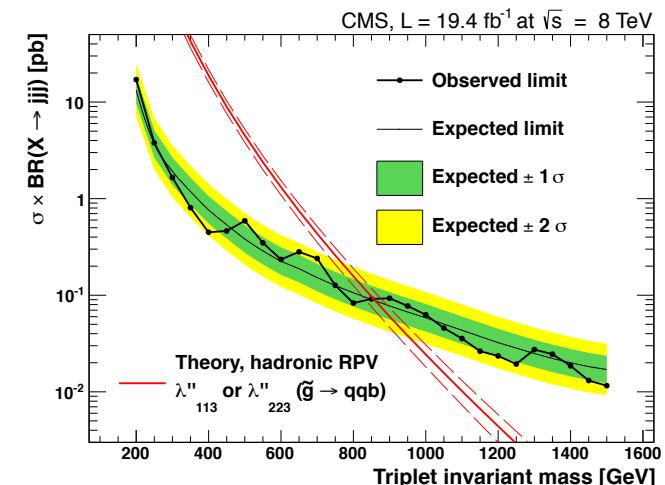
ATLAS-CONF-2015-026



Phys. Rev. D 91, 112016 (2015)



Phys.Lett. B747 (2015) 98-119



Phys.Lett. B730 (2014) 193-214

# Conclusion

If there are large B-violating couplings, all baryon asymmetry made at high temperature is diluted, and new baryon asymmetry should be generated at low temperature.

We proposed the idea that long lived LSP decays generate a sizable baryon asymmetry at two loop level.

Axino LSP in RPV SUSY gives a viable example to realize LSP baryogenesis with dark matter candidates: QCD axions, light gravitinos.

The large RPV coupling and relatively light squark/gluino masses are preferred. LHC searches for mulijet signal give implications on our baryogenesis model.