Dynamical R-parity breaking: from Cosmology to early LHC

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Portorož 2011

Based on arxiv: 1010.3968 and 1011.2214

OUTLINE

- Motivation
- Light sterile neutrino(s) & Scale- TeV
- New R-parity breaking interactions
- LHC signatures

MSSM and R-parity

- A fundamental question of Supersymmetry: is R-parity good symmetry or not?
- Conserved R-p implies stable LSP.
- MSSM with R-p implies massless neutrino, or needs higher dimensional operators $\Delta L = 2$.
- MSSM as a complete theory must break R-p.
- Gravitino: still possible DM, strong correlations between indirect detection and neutrino mass.

(Bajc, Enkhbat, Ghosh, Senjanovic, YZ 1002.3631)

Origin of R-parity violation

- Take the issue of R-parity breaking seriously.
- Study common predictions of supersymmetric theories with spontaneous R-parity breaking.

Breaking R-parity means: $\mathrm{R-parity} \propto (-1)^{B-L}$

- Break lepton number: Neutrino physics
- Tie the R-p breaking scale to soft mass scale: LHC

Gauging the B-L

- Spontaneously Break R-parity? MSSM $\widetilde{\nu}$: No way. Also break B-L global symmetry, Goldstone particle (Majoron) -- ruled out by LEP.

(Aulakh, Mohapatra, 82')

- Use a SM singlet -- explicit breaking $\mu_i L_i H_u$ plus a light J -- no prediction on the scale.

- Gauging B-L -- possible TeV scale realizations:

$$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

The minimal model

- Three RH neutrinos for anomaly cancelation. $U(1)_{B-L}$
- Break B-L: minimal scenario - use RH sneutrino

$$V \sim g_{BL}^4 \widetilde{\nu}^{c4} - M_{SUSY}^2 \widetilde{\nu}^{c2}$$

- $\langle \widetilde{\nu}^c \rangle \approx M_{SUSY}/g_{BL}^2$ also break R-parity - SM singlet.

(Mohapatra, 86', Barger, et al 0812.3661)

- $M_{Z'} \approx M_{SUSY}/g_{BL}$ scale tied to M_{SUSY}
- If low-energy SUSY, theoretical upper bound:

$$M_{Z'} \sim \text{TeV}$$

- Tree level, only one massive RH neutrino, "eaten" by $\widetilde{Z}'$, two others are light.

$$\begin{bmatrix} 0 & M_{Z'} \\ M_{Z'} & m_{1/2} \end{bmatrix} \sim \text{TeV}$$

- Loop corrections safe - if $Y_\nu = 0$ break B-L only in one "flavor".
- HD operators: $\frac{N_1^{c\dagger} N_1^{c\dagger} N_a^c N_b^c}{M^2} \left(\frac{H_u H_d}{M^2}\right)^p \left(\frac{H_u^\dagger H_d^\dagger}{M^2}\right)^q$ $M \gtrsim 10 M_{BL}$
- Upper bound on N_a mass <= MeV.
- Decaying slowly, lifetime ~ universe.
- Must be eV in order not to dominate the universe.

(Ghosh, Senjanovic, YZ 1010.3968)

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$$\begin{bmatrix} 0 & M_{Z'} \\ M_{Z'} & m_{1/2} \end{bmatrix} \sim \text{TeV} \begin{bmatrix} m_{\nu_1} & 0 & 0 & m_D^1 & m_D^2 \\ 0 & m_{\nu_2} & 0 & m_D^3 & m_D^4 \\ 0 & 0 & 0 & m_D^5 & m_D^6 \\ m_D^1 & m_D^3 & m_D^5 & 0 & 0 \\ m_D^2 & m_D^4 & m_D^6 & 0 & 0 \end{bmatrix} \sim \text{eV}$$

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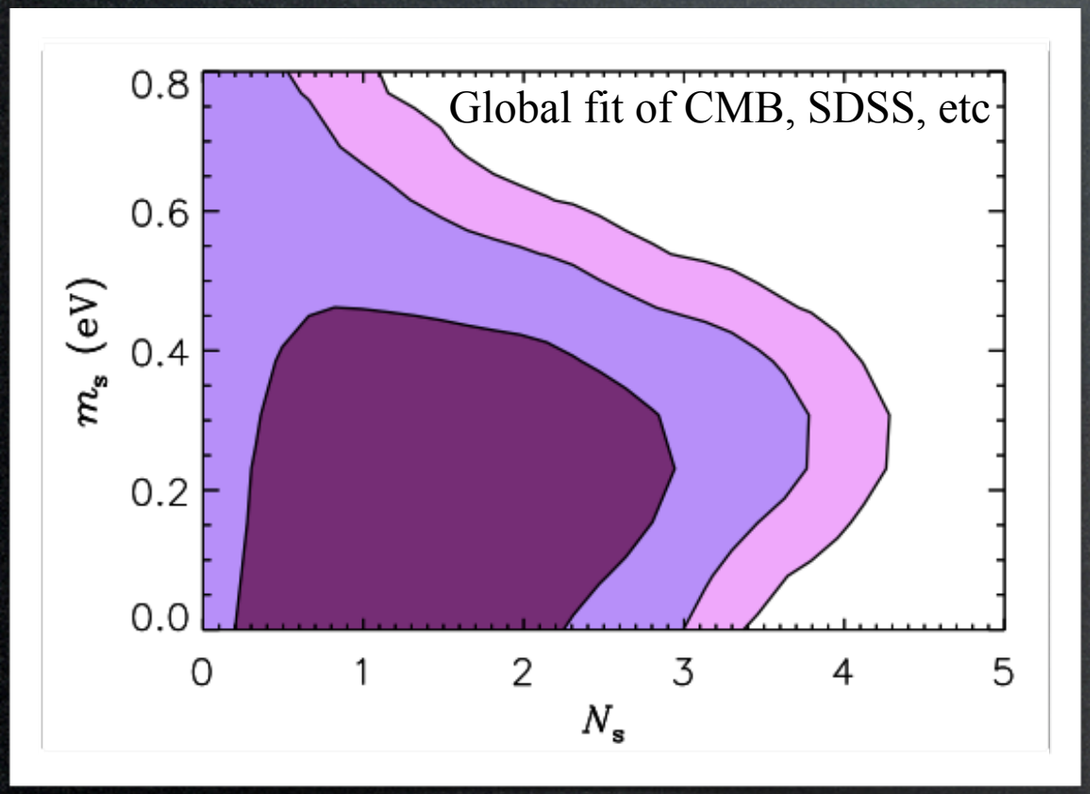
Cosmology prefers more neutrinos

- WMAP: $N_{\rm eff} \approx 4.34^{+0.86}_{-0.88}$ LSS: $N_{\rm eff} \approx 4.78^{+1.86}_{-1.79}$
- BBN: ${}^4He, D$ abundances also prefer $N_{\rm eff} > 3.046$

(Hamann, et al 1006.5276)

- A natural candidate: light RH neutrinos (3+2) -- thermalized through t-channel Z': $N_i e \to N_i e$



Phenomenological upper bound:

$$M_{Z'} \lesssim 10\text{TeV}$$

R-parity in left-right theories

- Miminal version: $U(1)_Y \times U(1)_{\rm B-L} \to SU(2)_R \times U(1)_{\rm B-L}$

$$V \sim g_{BL}^4 (\widetilde{L}^\dagger \widetilde{L} - \widetilde{L}^{\dagger c} \widetilde{L}^c)^2 + \widetilde{L}^\dagger m_{\widetilde{l}}^2 \widetilde{L} - \widetilde{L}^{\dagger c} m_{\widetilde{l}^c}^2 \widetilde{L}^c$$

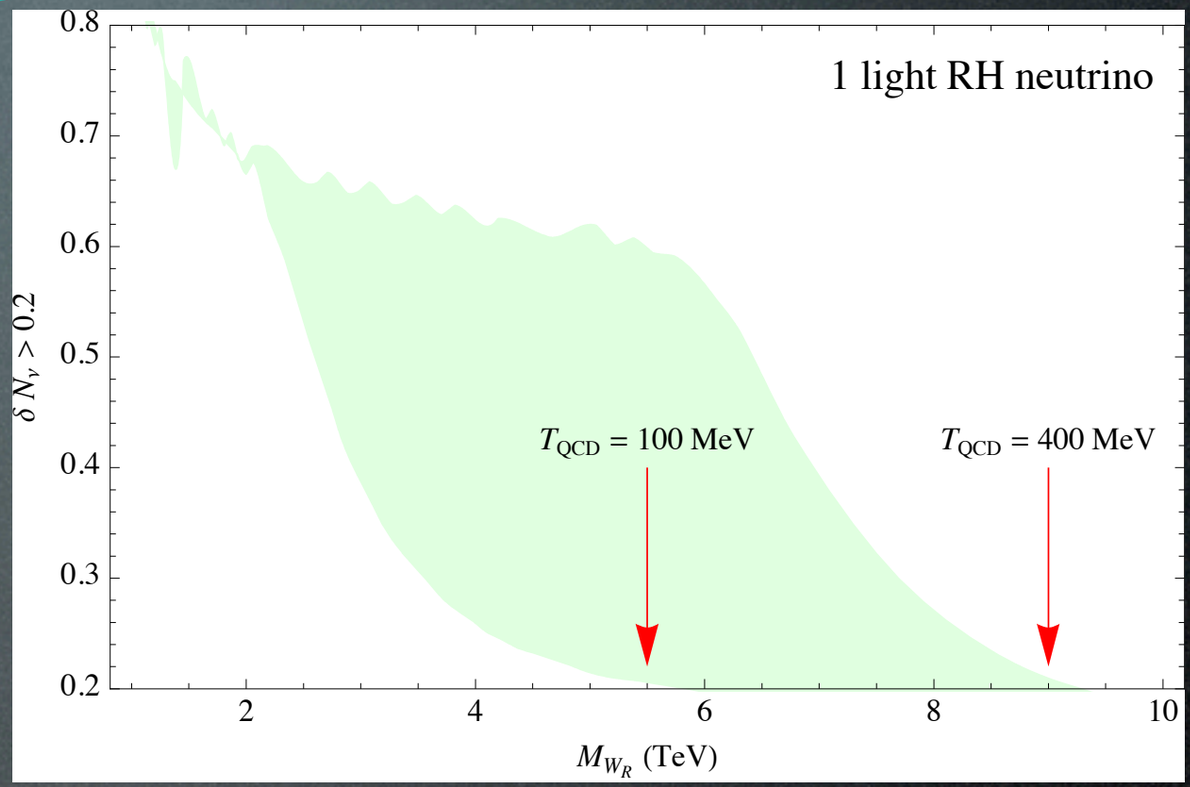
(Fileviez Perez, Spinner 0811.3424)

- Asymmetric soft masses -- "parity" symmetry broken at high scale.
- R-p breaking scale: $M_{W_R} \approx M_{\rm SUSY}/g_R$
- Seesaw version, add Higgs triplets $\Delta, \overline{\Delta}, \Delta^c, \overline{\Delta^c}$.
- $\langle \Delta^c \rangle$ could lift one light RH neutrino mass

Setting the scale

More predictive:

$$M_{W_R} \lesssim 5 - 9\,\mathrm{TeV}$$



- 3+1 scenario:
- Lifting one RH neutrino mass with $\langle \Delta^c \rangle$: even better fit to cosmological observations.
- More predictive: Scale & bring new signatures from the heavy neutrino to LHC.

(Chen, Ghosh, Mohapatra, YZ 1011.2214)

Seesaw version of susylr

- SUSY limit, tree-level: no symmetry breaking.

$$W \sim \mu_\Delta \mathrm{Tr}(\Delta\overline{\Delta}) + \mu_\Delta \mathrm{Tr}(\Delta^c\overline{\Delta^c}) + f L \Delta^c L$$

- Not D-flat direction: $\langle \Delta^c \rangle = \begin{bmatrix} 0 & 0 \\ v_R & 0 \end{bmatrix}$ $\langle \overline{\Delta^c} \rangle = \begin{bmatrix} 0 & \bar{v}_R \\ 0 & 0 \end{bmatrix}$

(Kuchimanchi, Mohapatra, 93')

- HD operators: R-parity conserved by the vev.

(Aulakh, Melfo, Senjanovic, 97')

- Including soft terms: R-parity violating direction.

$$V = \text{soft masses} + \left[-2|A_f|v_R - 2|f|\mu_\Delta \bar{v}_R\right] \langle \widetilde{\nu}_e^c \rangle^2 + \mathrm{F, D} - \text{terms}$$

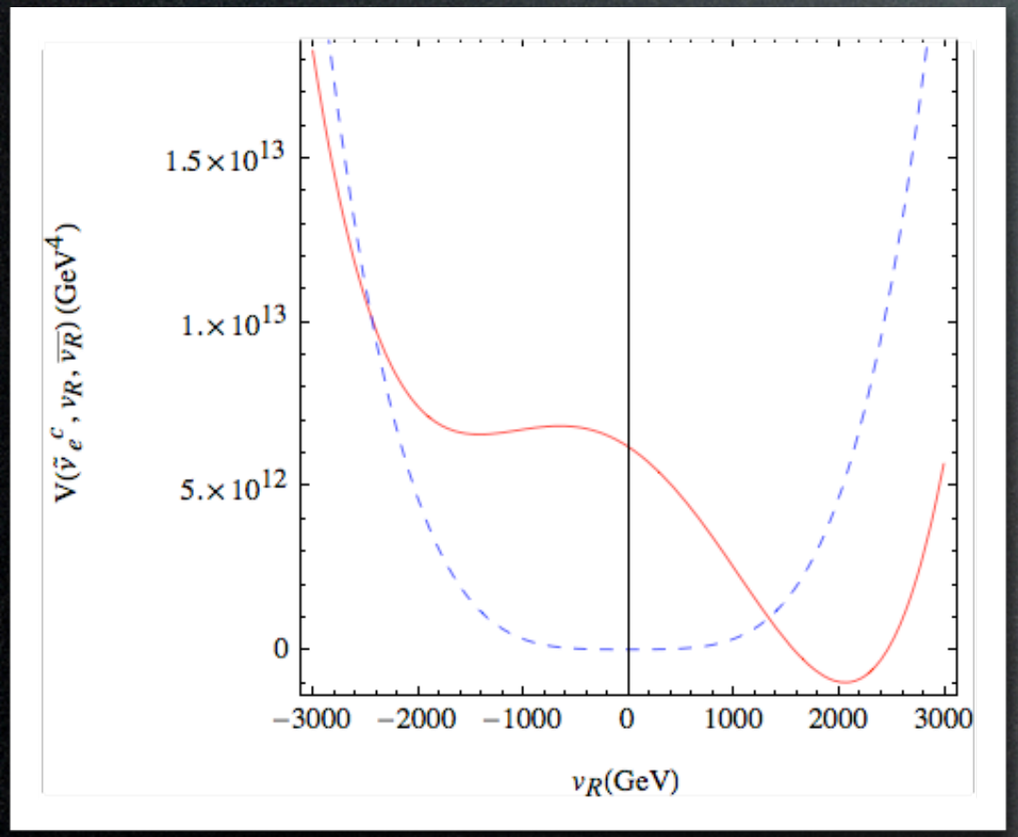
- If $\langle \Delta^c \rangle$ nonzero, develop tachyonic mass for $\widetilde{\nu}_e^c$

(Ji, Mohapatra, Nussinov, YZ, 0808.1904)

Dynamical R-parity breaking

- Deeper vacuum in R-parity breaking direction.
- Amount of R-pV of the same scale as gauge symmetry breaking: $\langle \widetilde{\nu}_e^c \rangle \sim v_R \sim \bar{v}_R$.
- Still nearly D-flat: $\langle \widetilde{\nu}_e^c \rangle^2 - 2v_R^2 + 2\bar{v}_R^2 \approx 0$.

(Chen, Ghosh, Mohapatra, YZ 1011.2214)



Scale again tied to $M_{\rm SUSY}$

$$M_{W_R} \approx g M_{\rm SUSY}/f^2$$

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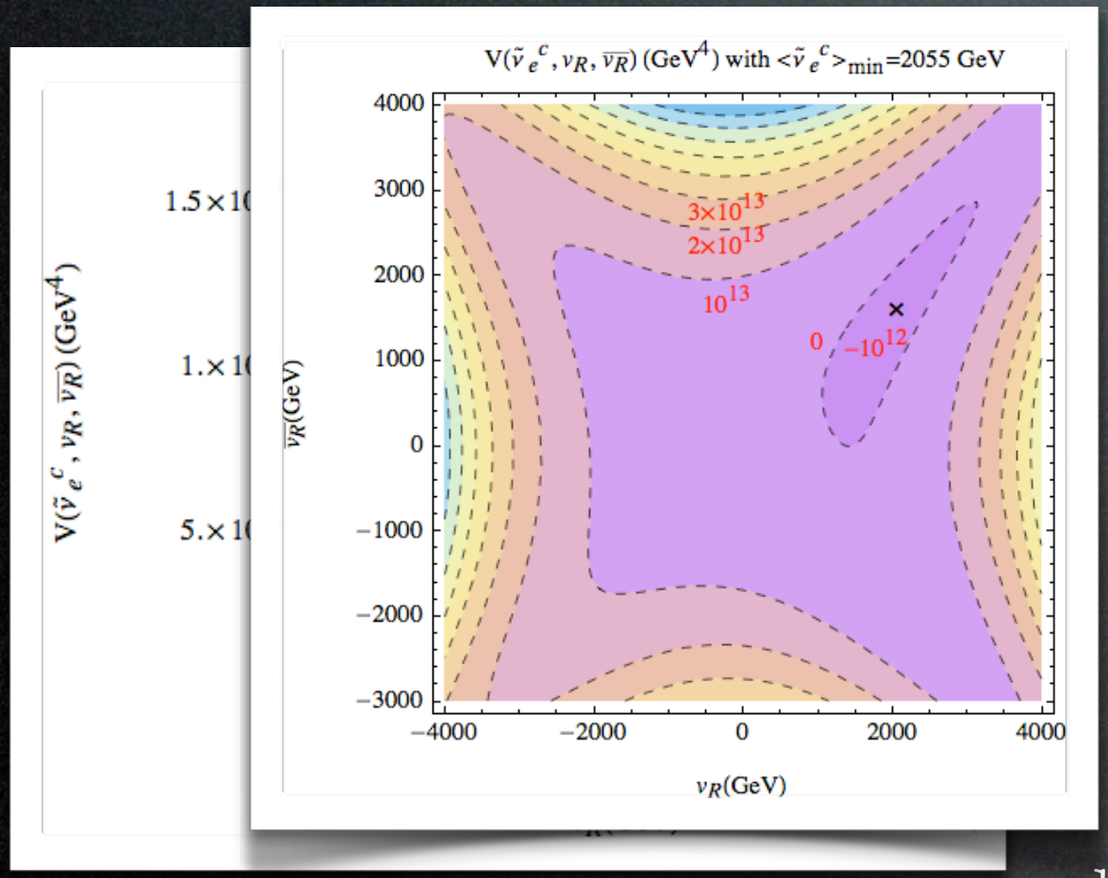

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Generic R-parity breaking

- Generate usual MSSM R-pV terms, but small.. and?
- MSSM: no large lepton-gaugino mixings.

$$\begin{array}{c} \\ e^c \\ \widetilde{W}^+ \end{array}\begin{array}{c} \begin{array}{cc} e & \widetilde{W}^- \end{array} \\ \begin{bmatrix} m_e & 0 \\ g\langle\widetilde{\nu}\rangle & m_{1/2} \end{bmatrix} \end{array} \quad \overset{SU(2)_L}{\longleftrightarrow} \quad \begin{array}{c} \\ \nu \\ \widetilde{Z} \end{array}\begin{array}{c} \begin{array}{cc} \nu & \widetilde{Z} \end{array} \\ \begin{bmatrix} 0 & g_Z\langle\widetilde{\nu}\rangle \\ g_Z\langle\widetilde{\nu}\rangle & m_{1/2} \end{bmatrix} \end{array}$$

- SUSYLR: large mixings possible.

$$\begin{array}{c} \\ e^c \\ \widetilde{W}_R^+ \end{array}\begin{array}{c} \begin{array}{cc} e & \widetilde{W}_R^- \end{array} \\ \begin{bmatrix} m_e & g_R\langle\widetilde{\nu}^c\rangle \\ 0 & m_{1/2} \end{bmatrix} \end{array} \quad \overset{SU(2)_R}{\longleftrightarrow} \quad \begin{array}{c} \\ \nu^c \\ \widetilde{Z}' \end{array}\begin{array}{c} \begin{array}{cc} \nu^c & \widetilde{Z}' \end{array} \\ \begin{bmatrix} 0 & g'_Z\langle\widetilde{\nu}^c\rangle \\ g'_Z\langle\widetilde{\nu}^c\rangle & m_{1/2} \end{bmatrix} \end{array}$$

- Physical electron $\hat{e}^c = \theta_{ee} e^c + \theta_{eW} \widetilde{W}_R^+$

Chirality preserving

$$\hat{\nu}^c = \theta_{NN} \nu^c + \theta_{NZ} \widetilde{Z}', \quad \theta_{eW}, \theta_{NZ} \sim O(1)$$

Large RPV interactions

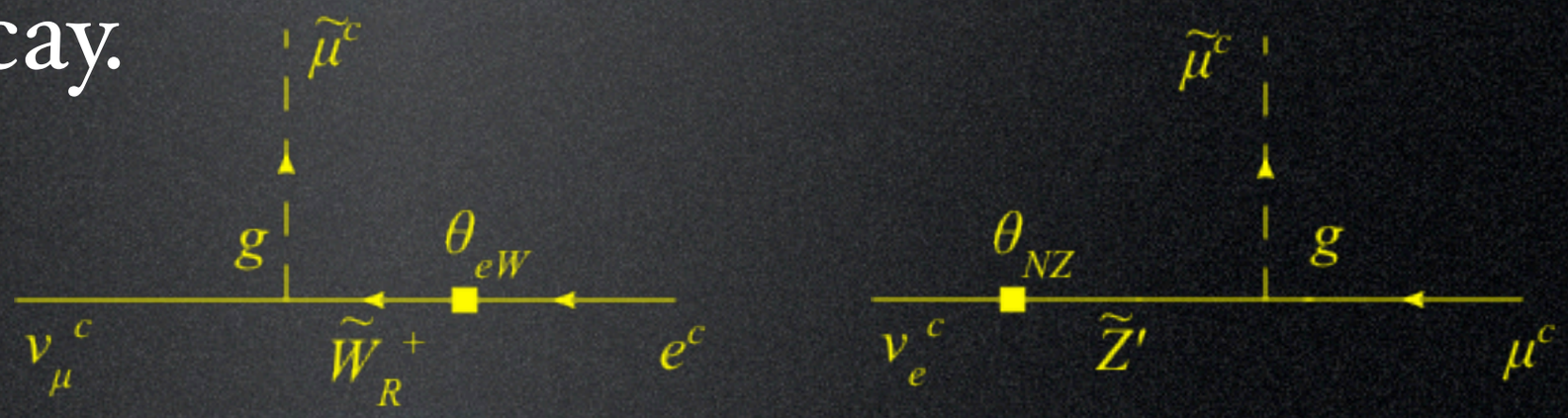
(Chen, Ghosh, Mohapatra, YZ 1011.2214)

- Integrate out extra heavy gauginos.

$$\sqrt{2}g\theta_{eW}\left[\hat{e}^c\nu_\ell^c\tilde{\ell}^{c\dagger}+\hat{e}^c u^c\tilde{d}^{c\dagger}\right]+\sqrt{2}g_{Z'}\theta_{NZ}\left[\hat{\nu}_e^c\ell^c\tilde{\ell}^{c\dagger}+\hat{\nu}^c q^c\tilde{q}^{c\dagger}\right]+\text{h.c.}$$

$(\ell=\mu,\tau)$

- As alrge as gauge coupling.
- No susy counterparts -- susy breaking terms as trigger of R-p violation.
- Facilitate single production of smuon/stau from $\nu_{e,\mu}^c$ decay.

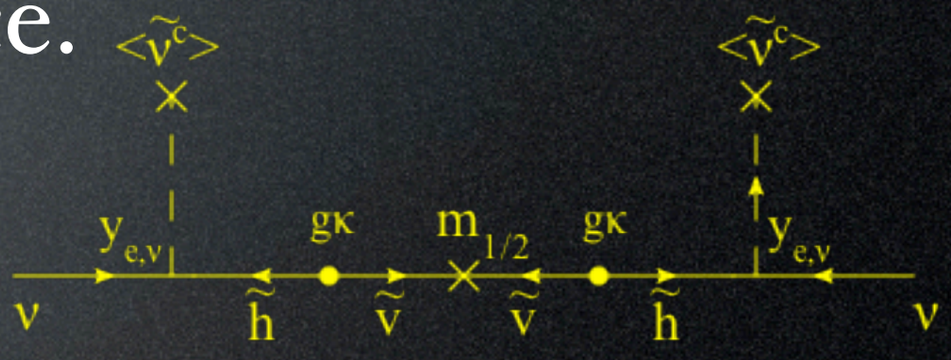


Flavor alignment of R-p V

- Neutrino Mass: Yukawa couplings in LR

$$W = Y_\ell L \Phi_1 L^c + Y_\nu L \Phi_2 L^c, \;\; \langle \Phi_1 \rangle = \begin{bmatrix} v_1 & 0 \\ 0 & 0 \end{bmatrix}, \;\; \langle \Phi_2 \rangle = \begin{bmatrix} 0 & 0 \\ 0 & v_2 \end{bmatrix}$$

- $\langle \widetilde{\nu}^c_\ell \rangle$ induces large LNV: LHu unless only couples to $Y_e \sim 10^{-6}$ -- a natural choice.

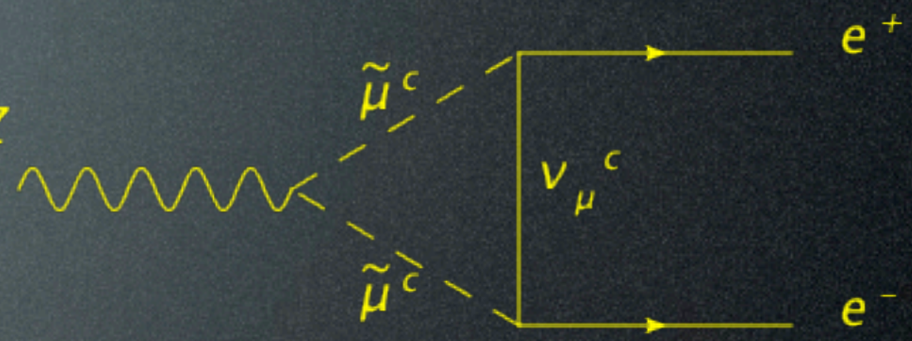


- Lepton flavor violation: safe only if R-pV in single (electron) flavor.
- Only suffer the usual SUSY flavor problem.

pre-LHC constraints

- LEP: loop correction Z to ee.

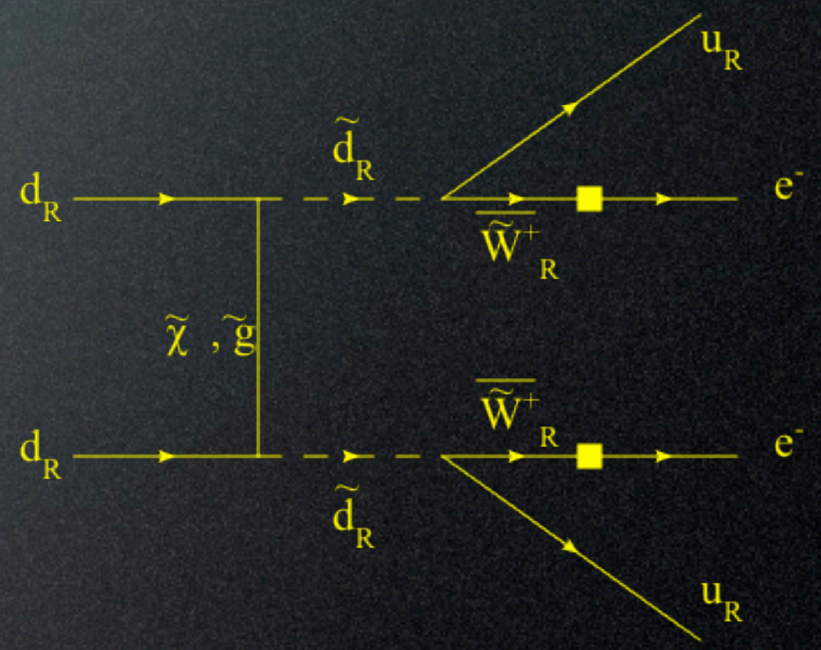
$$g\theta_{eW} \lesssim 0.5 \left(\frac{m_{\tilde{\mu}^c,\tilde{d}^c}}{100\mathrm{GeV}}\right)$$



(Barbier, et al 04')

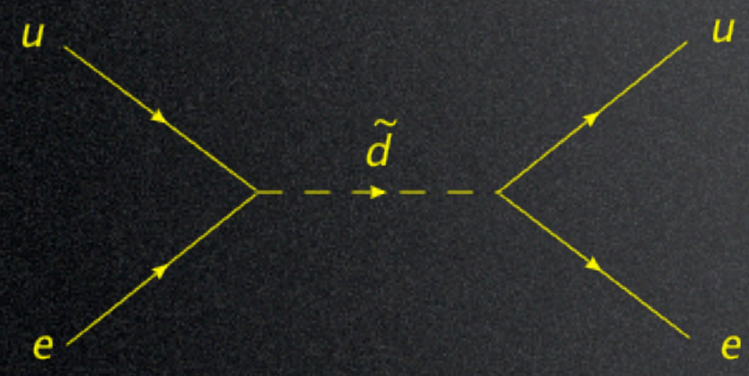
- neutrino-less double beta decay.

$$g\theta_{eW} \lesssim 0.39 \times 10^{-3} \left(\frac{m_{\tilde{d}^c}}{100\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{100\mathrm{GeV}}\right)^{1/2}$$



(Hirsch, et al 95')

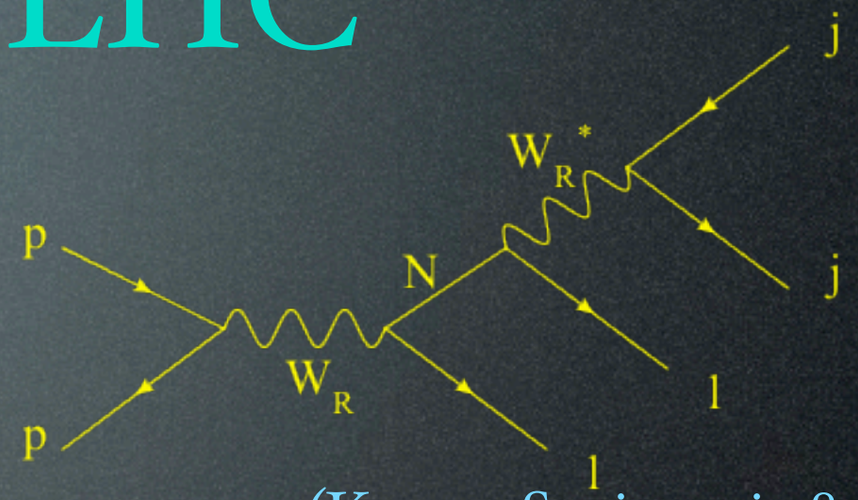
- Hera single production.



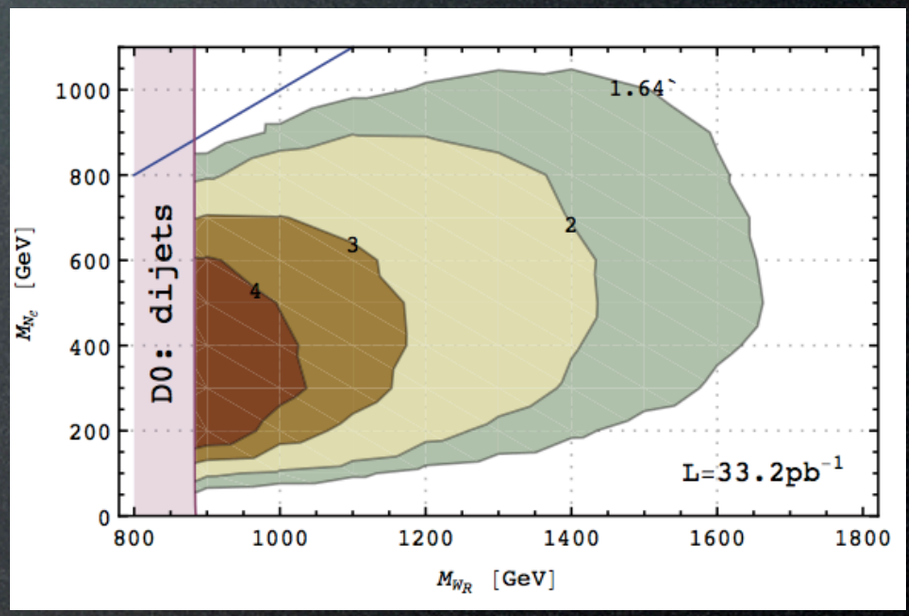
$$m_{\tilde{\mu}^c} \gtrsim 100\,\mathrm{GeV}$$

$$m_{\tilde{q}}, m_{\tilde{g}} \gtrsim 1\,\mathrm{TeV}$$

Signature at LHC



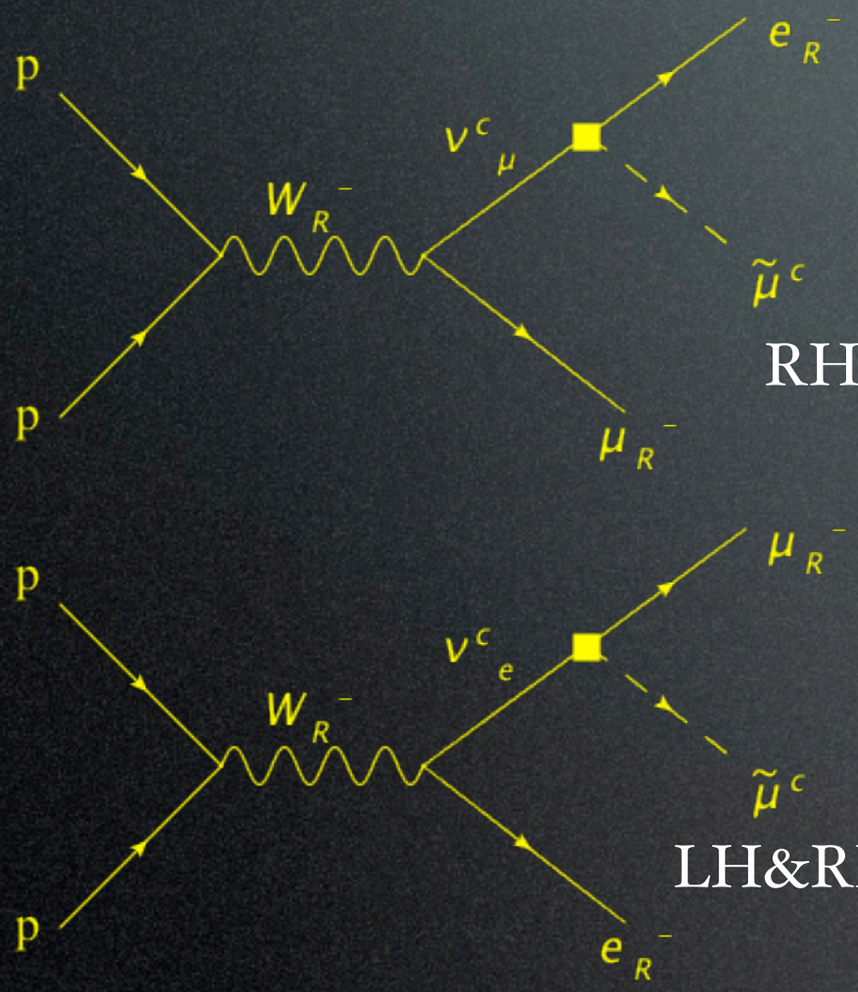
(Keung, Senjanovic 83')



(Nemevsek, Nesti, Senjanovic, YZ 1010.3968)
See also Fabrizio Nesti' talk

Signature at LHC

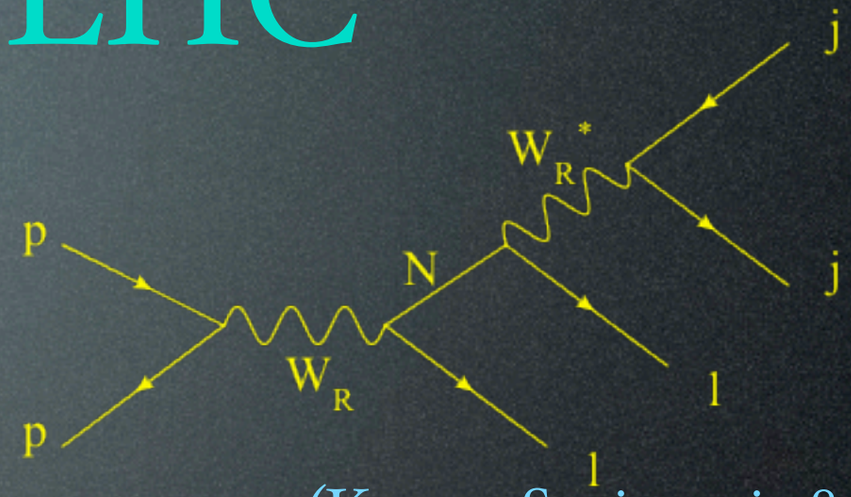
$$pp \to e\mu\tilde{\mu}$$



RH slepton

LH&RH slepton

(Ghosh, Senjanovic, YZ 1010.3968)
(Chen, Ghosh, Mohapatra, YZ 1011.2214)



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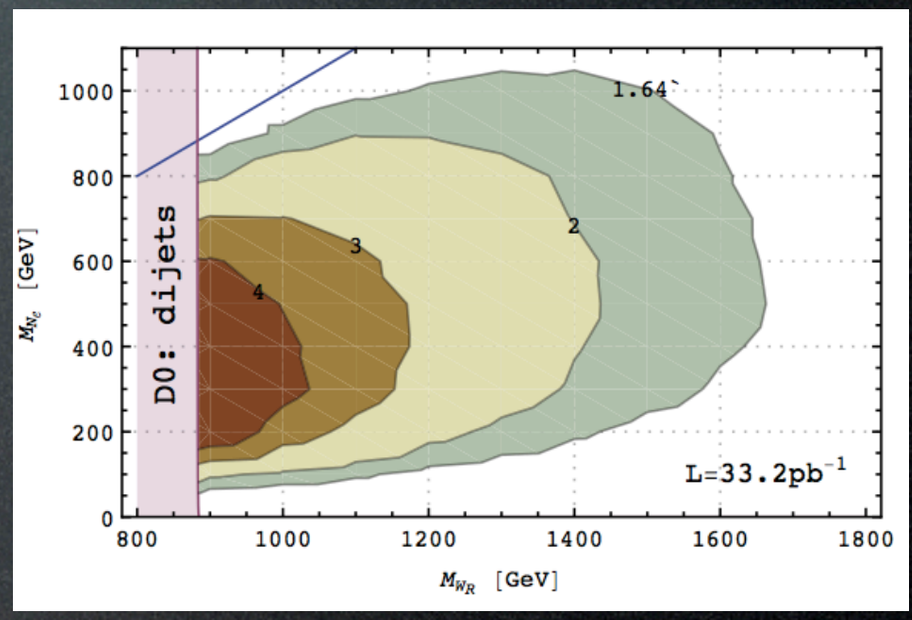

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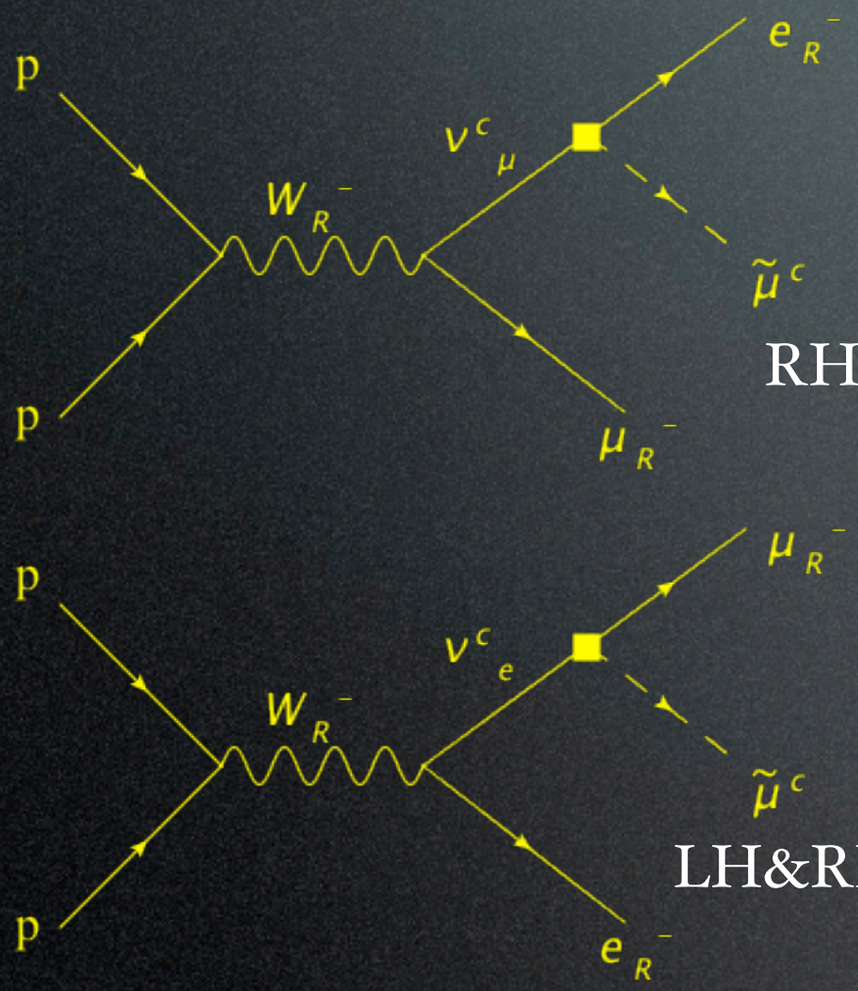

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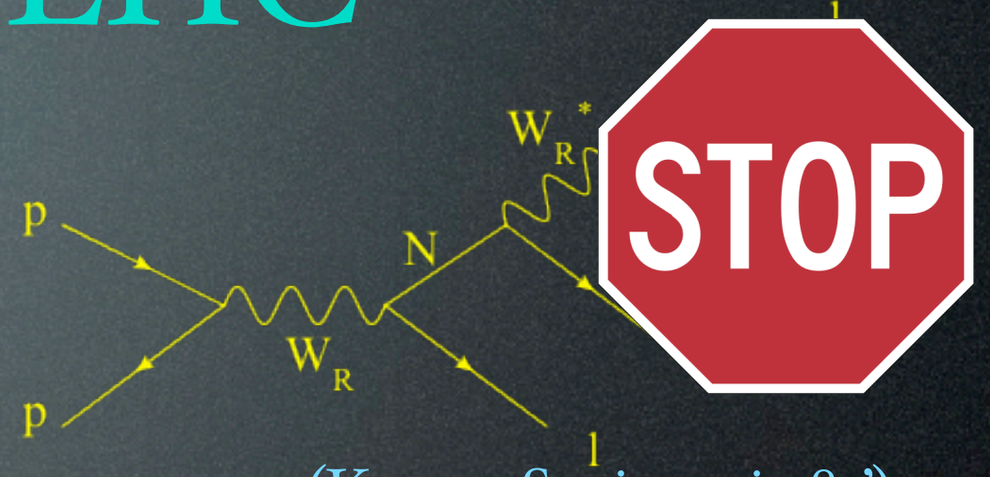

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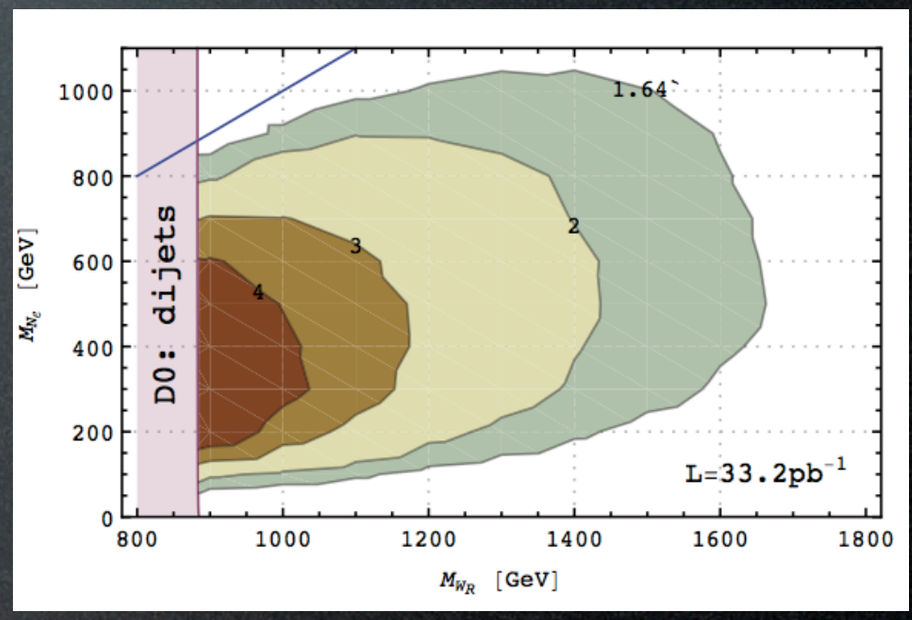

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Signature at LHC

- Single production of slepton

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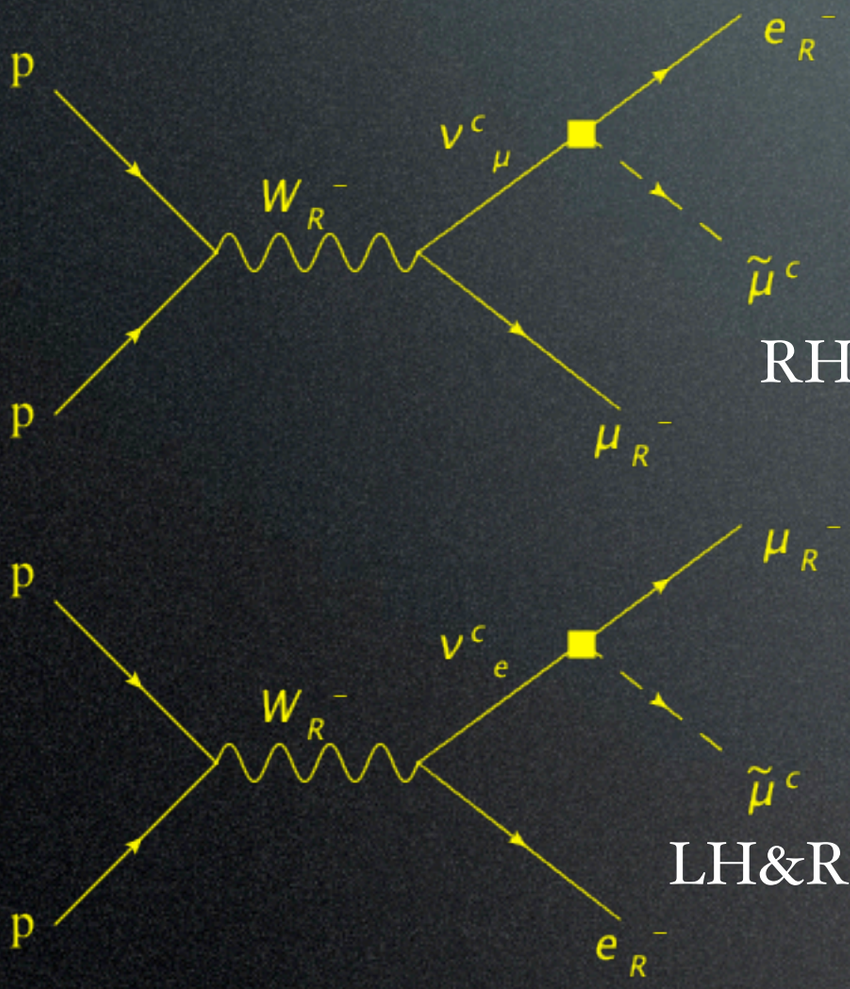

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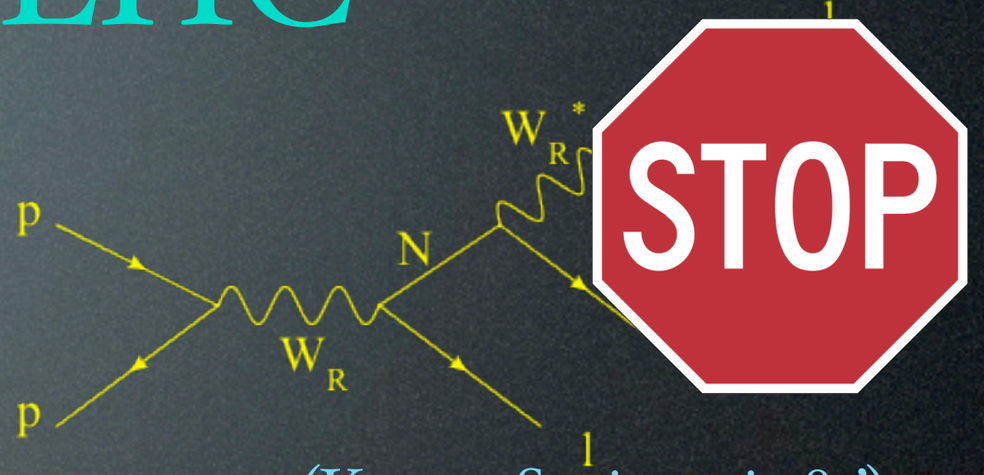

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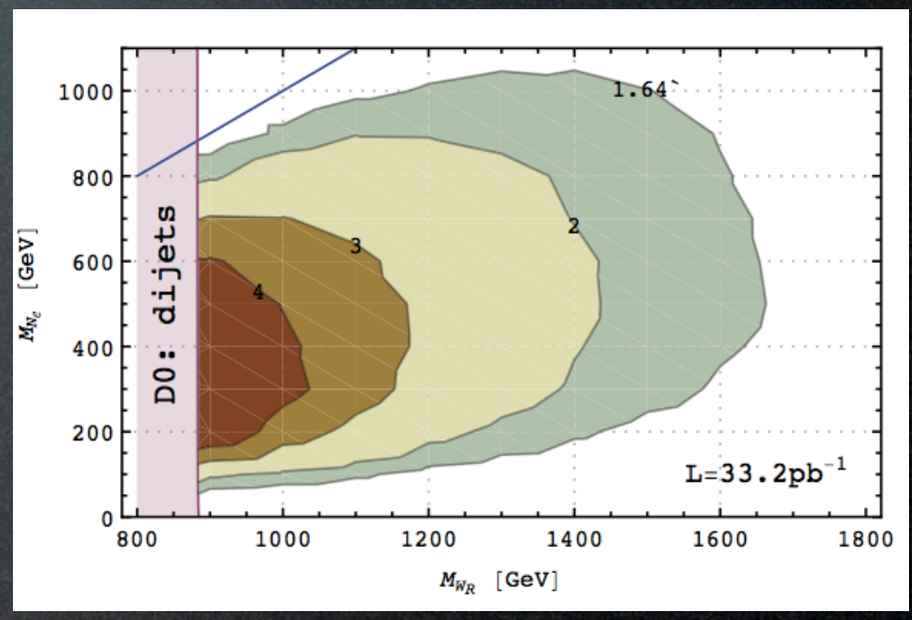

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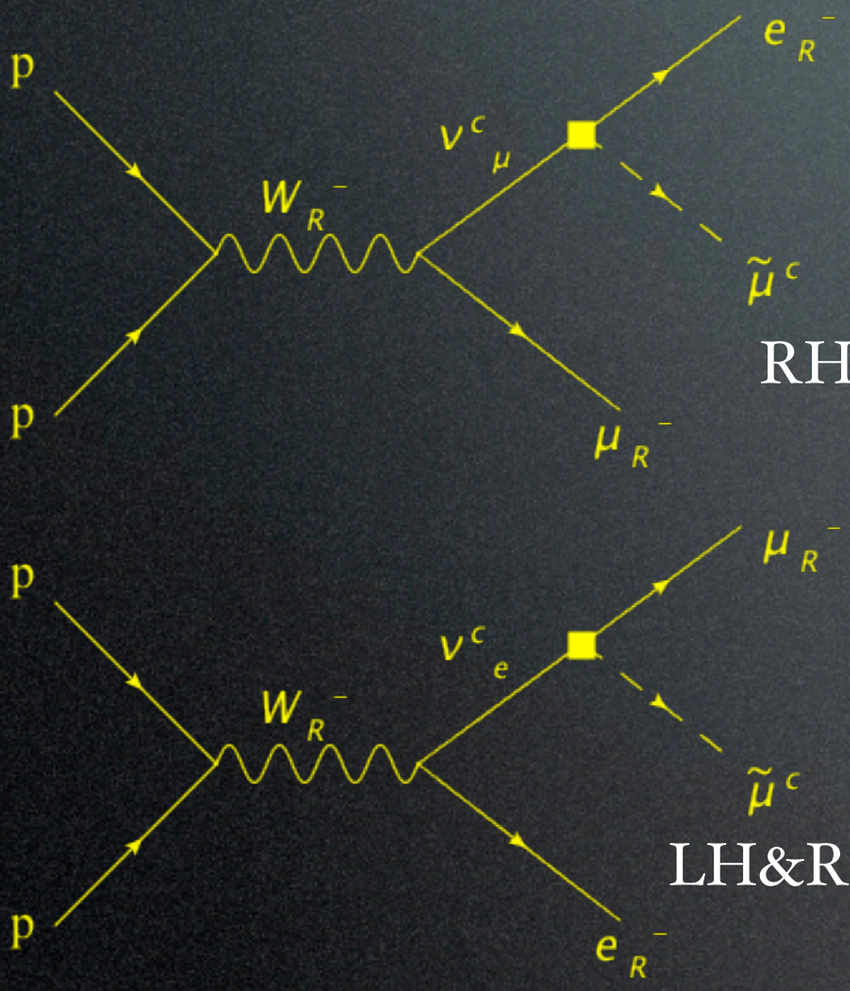

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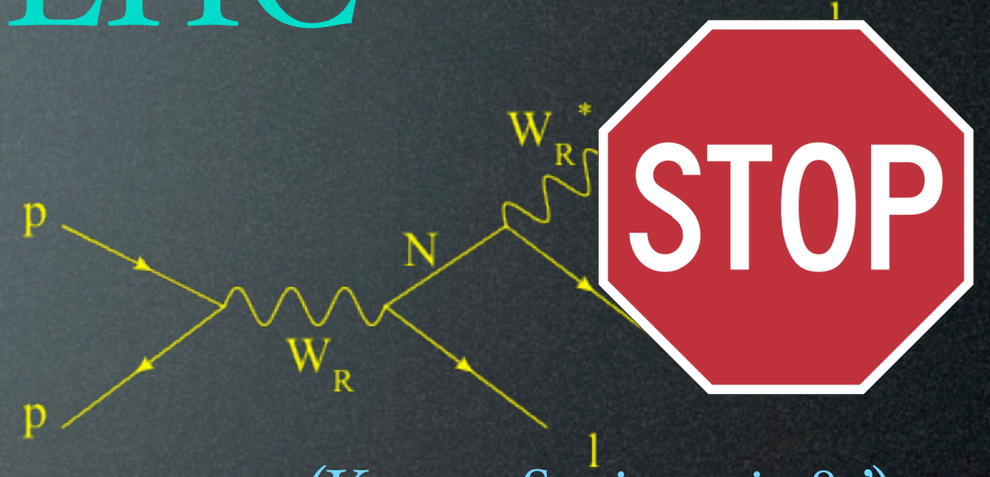

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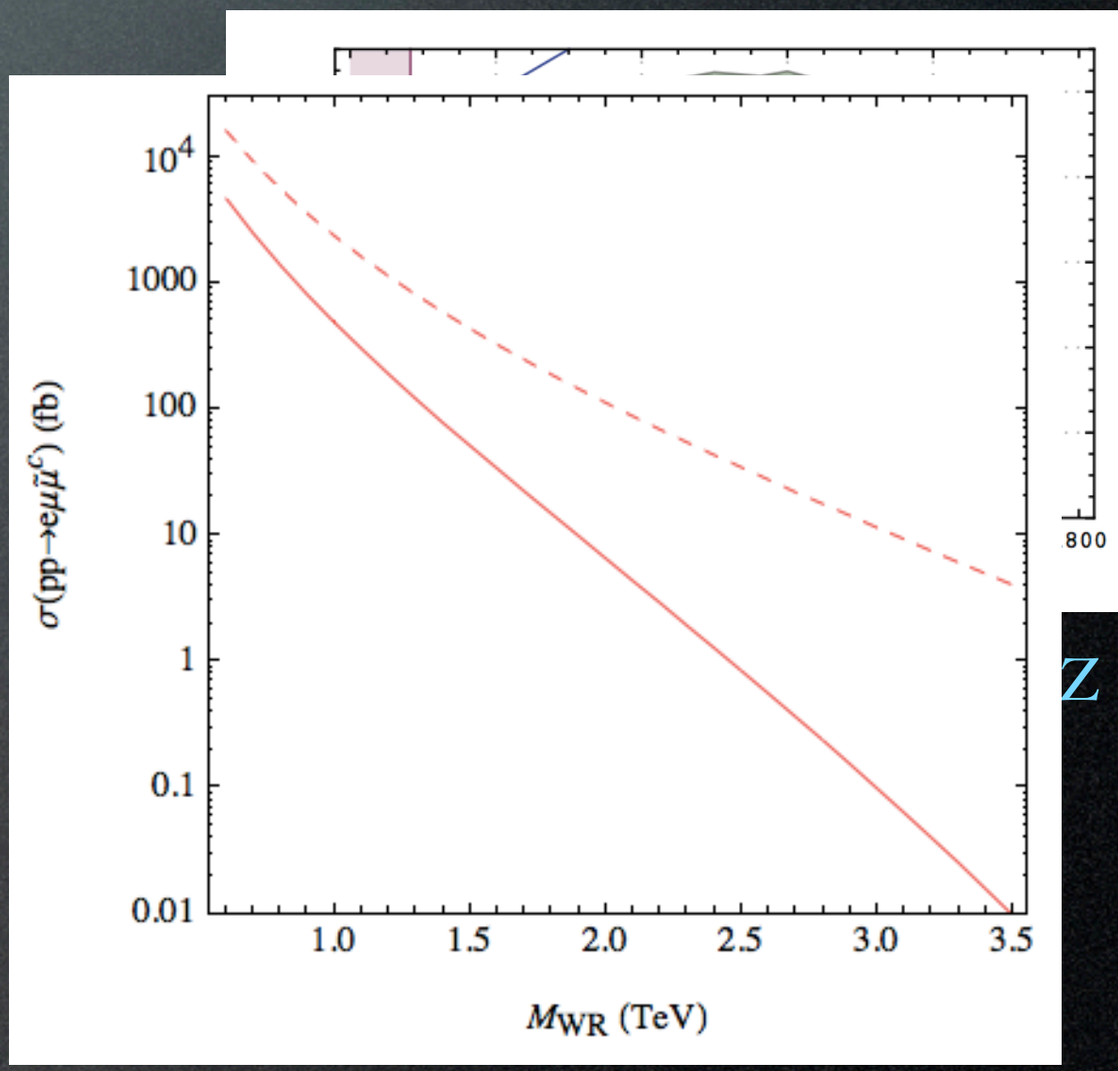
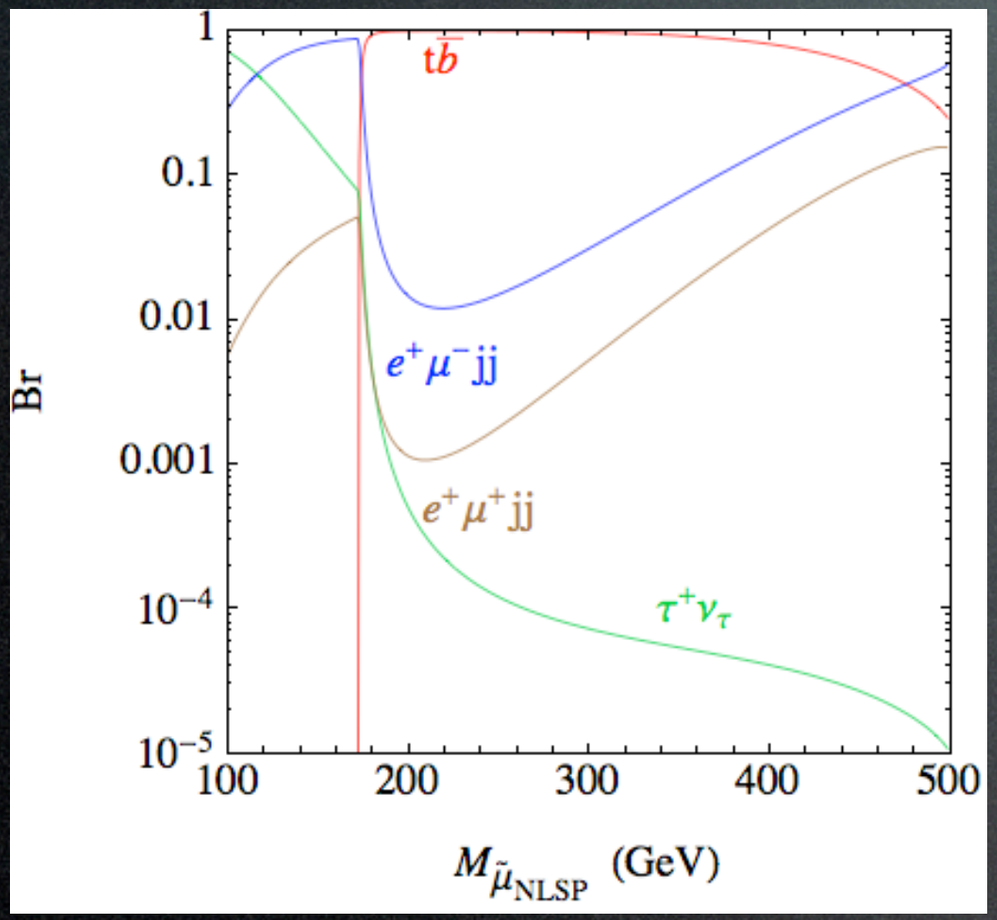


Z

Slepton LSP decays

Large smuon mixing $\tilde{\mu}_{\rm LSP} = \alpha\tilde{\mu}_L + \beta\tilde{\mu}_R, \quad \alpha, \beta \sim O(1)$



decays through:

$$\lambda' \bar{t} b \tilde{\mu}^c, \quad \lambda' \approx y_t y_\nu \langle \tilde{\nu}_e^c \rangle / \mu$$

Signatures:

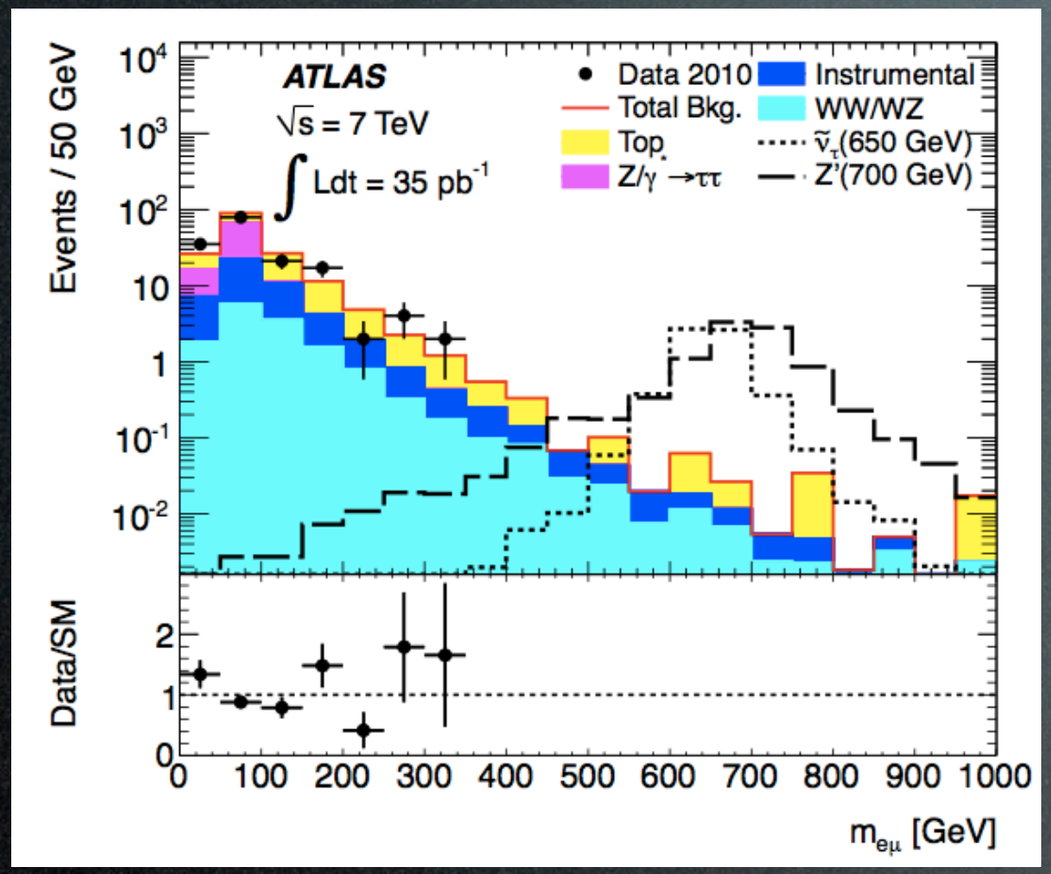
$$pp \to e^+\mu^- \bar{t}b, e^+\mu^+ t\bar{b}$$

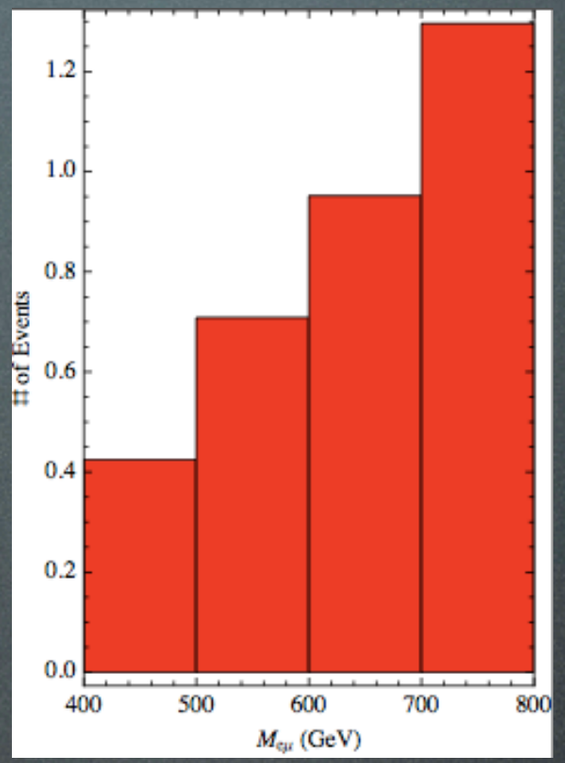
$$\to e\mu + jets$$

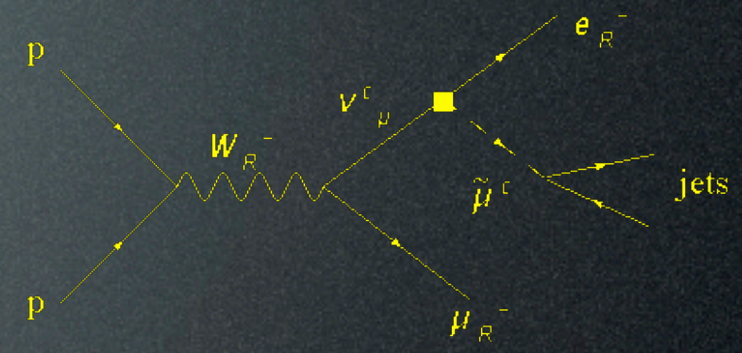
Opposite sign e mu data now available from ATLAS !

(ATLAS collaboration, 1103,5559)

Early LHC limits on dR-p scale



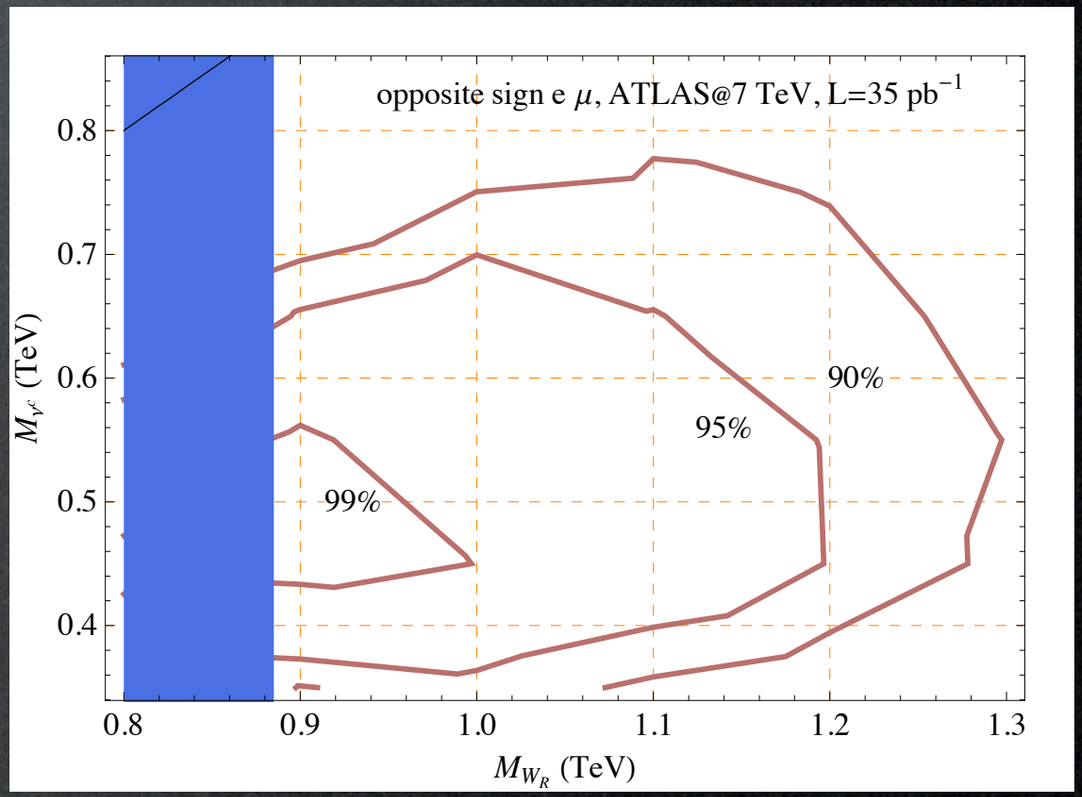




Events in high invariant mass region > 400 GeV

(YZ, to appear 2011)

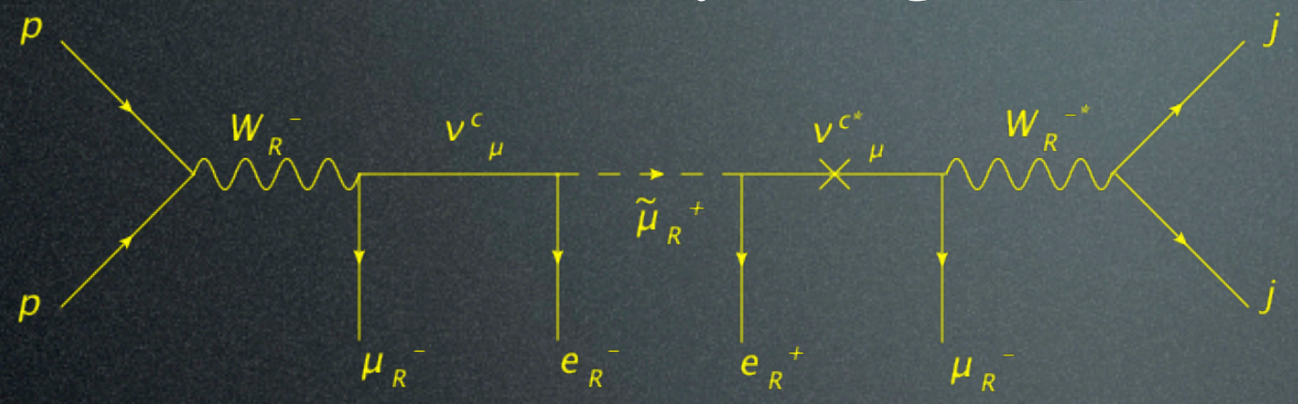
- ATLAS, 7 TeV, 35/pb
- Limit: $M_{W_R} > 1.2\,\mathrm{TeV}@95\%\mathrm{C.L.}$
- Can reach 2-3 TeV for $L \sim \mathrm{fb}^{-1}$



Mainly RH smuon LSP

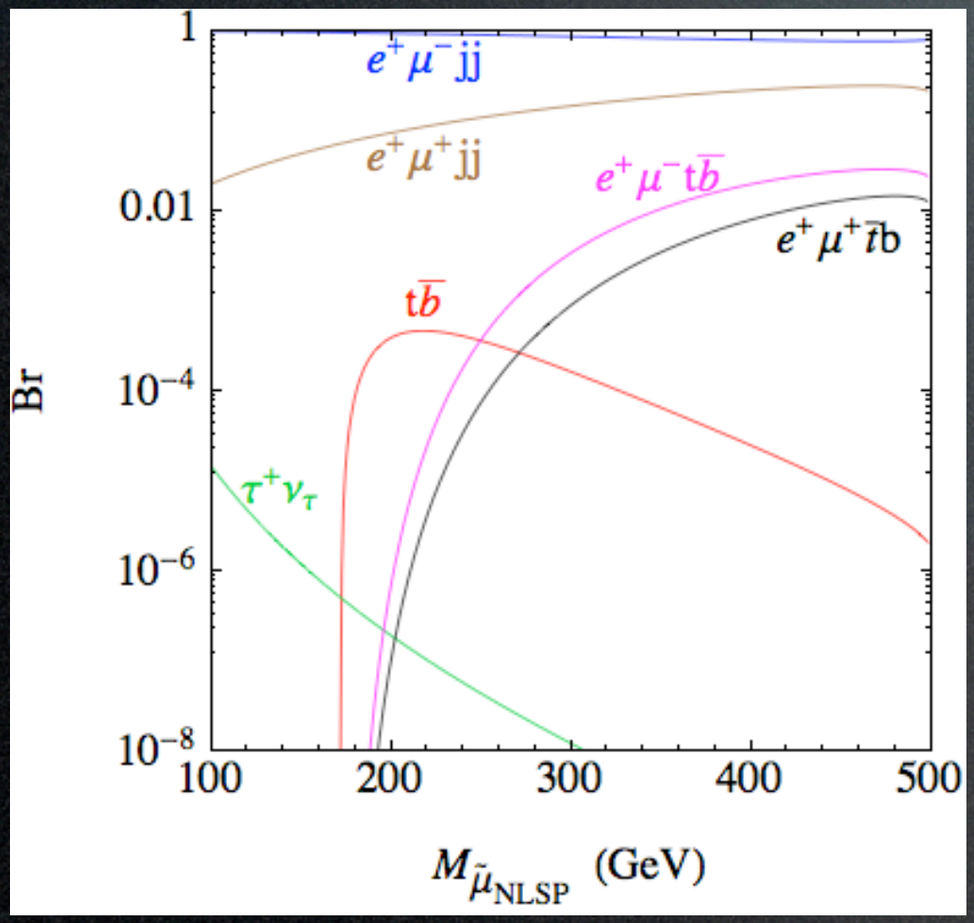
$$\widetilde{\mu}_{\rm NLSP} \approx \widetilde{\mu}^c$$

- dominantly single-produced if:



$$M_{\nu^c_e} > M_{W_R}$$

$$M_{\nu^c_\mu} < M_{W_R}$$



Signatures:

$$pp \to e^\pm e^\mp \mu^\pm \mu^\pm jj$$

- Multi-lepton final states.
- lepton number violating, no $\not{E}_T$.
- All heavy states reconstructable.

Almost background free

Conclusions

We study a class of susy models with R-parity broken spontaneously with extra gauge symmetries.

- Interesting predictions on neutrino mass.
- Cosmology implies the scale could be near TeV.
- A new class of R-parity breaking interactions.
- Distinct signatures at the LHC.

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Thanks! Hvala!