Searching evidences of new physics in the light of extended supersymmetric models

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SUSY2014

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Together..........

PG, Daniel E. López-Fogliani, Vasiliki A. Mitsou,
Carlos Muñoz and Roberto Ruiz de Austri

⋆ arXiv:1403.3675 [hep-ph] ⋆
Hunting physics beyond the standard model with unusual $W^{\pm}$ and Z decay

⋆ Phys. Rev. D 88, 015009 (2013), arXiv:1211.3177 [hep-ph] ⋆
Probing the μ-from-ν supersymmetric standard model with displaced multileptons from the decay of a Higgs boson at the LHC

PG, David G. Cerdeño, Chan Beom Park

⋆ JHEP 1306 (2013) 031, arXiv:1301.1325 [hep-ph] ⋆
Probing the two light Higgs scenario in the NMSSM with a low-mass pseudoscalar

The Standard Model, The LHC and us .....

- **No excess confirmed over the SM predictions**

- **And..... A scalar at the LHC..** PLB716 (2012) 1,30 **appears to be 0^+.. with mass about 125 GeV..** $\mu = 1.30 \pm 0.12\ (\text{stat})^{+0.14}_{-0.11}\ (\text{sys})$.. ATLAS-CONF-2014-009, PLB726 (2013) 120, 1312.5353...

Is this the one.... ?

⋆ $\Gamma_{\text{Higgs}} < 4.2 \times \Gamma^{\text{SM}}_{\text{Higgs}}$.... CMS-PAS-HIG-14-002 ⋆ **Br (Higgs → invisible) < 0.58@ 95 % C.L. ....** 1404.1344 [hep-ex]...

⋆ **Apparent excess in $\gamma\gamma$ still for ATLAS..** (1.57).. ATLAS-CONF-2014-009.. **Not in the CMS...** (0.78).. HIG-13-001 ⋆ **Need precise measurement of $b\bar{b}$..**

Hope survives....

⋆ **LHC@14 TeV... $\mathcal{L} \sim 3000\ fb^{-1}$** ⋆ **Golden future... ILC.. CLIC.. TLEP**

But... Neutrino mass..?, Dark Matter..? ....

New Physics is much needed..... Supersymmetry.. Scalar mass in protected..

However, a class of issues to be addressed... e.g... μ-problem.. massive neutrinos.. ⟶ a handful of models... larger parameter set.. less predictive.. ...

Is there an economic way...... ?

Introducing $\mu\nu$SSM López-Fogliani, Muñoz

NMSSM

$\lambda \hat{S} \hat{H}_d^a \hat{H}_u^b \Longrightarrow \mu_{eff} = \lambda v_s$

MSSM + $\epsilon^i \hat{L}_i^a \hat{H}_u^b$ and/or
$\frac{1}{2}\lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{e}_k^c$ and/or $\lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{d}_k^c$ or
MSSM + RH-neutralinos or ....

NMSSM

~~$\lambda \hat{S} \hat{H}_d^a \hat{H}_u^b$~~

ϵ-problem... Loop corrections are essential.. Many parameters.. Less predictive....

Introducing $\mu\nu$SSM López-Fogliani, Muñoz

It is... $\overbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u}^{R_p\!\!\!/ \text{ with } \Delta L=1}$

★ Natural entry of $Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j$

$$W = \underbrace{\epsilon_{ab}(Y^{ij}_u \hat{H}^b_u \hat{Q}^a_i \hat{u}^c_j + Y^{ij}_d \hat{H}^a_d \hat{Q}^b_i \hat{d}^c_j + Y^{ij}_e \hat{H}^a_d \hat{L}^b_i \hat{e}^c_j)}_{W^{MSSM} - \epsilon_{ab}\mu \hat{H}^a_d \hat{H}^b_u} +$$

$$\epsilon_{ab}\ (\underbrace{Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j}_{\epsilon^i_{eff} = Y^{ij}_\nu \langle \tilde{\nu}^c_j \rangle} - \overbrace{\underbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u)}_{\mu_{eff} = \lambda^i \langle \tilde{\nu}^c_i \rangle}}^{R_p\!\!\!/ \text{ with } \Delta L=1} + \overbrace{\underbrace{\frac{1}{3}\kappa^{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k}_{m_{\nu^c_{ij}} = 2\ \kappa^{ijk} \langle \tilde{\nu}^c_k \rangle}}^{R_p\!\!\!/ \text{ with } \Delta L=3}$$

López-Fogliani, Muñoz, PRL 97, 041801 (2006)

$Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j$ is the seed of $R_p\!\!\!\!/$.... with $Y_\nu \to 0$.... $\hat{\nu}^c \Leftrightarrow \hat{S}$... $\Rightarrow$ ~~$R_p\!\!\!\!/$~~

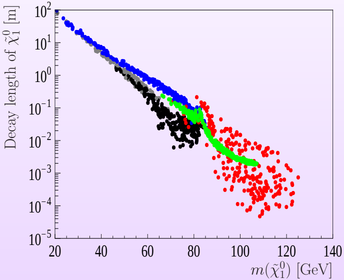
TeV scale seesaw with right-handed neutrino + $R_p\!\!\!\!/ \implies m_\nu \neq 0$

PG, Roy *JHEP* 04 (2009) 069; Fidalgo, López-Fogliani, Muñoz and Ruiz de Austri *JHEP* 08 (2009) 105; PG, Dey, Mukhopadhyaya and Roy *JHEP* 05 (2010) 087

Significance of Lepton number (L) is lost

- MSSM + $R_p\!\!\!\!/$ + 3 $\hat{\nu}^c_i \implies$ 8(7) CP-even(odd) states $h_\alpha(P_\alpha)$ / 10 neutralinos $\tilde{\chi}^0_\alpha$ / 7 charged states $S^\pm_\alpha$ / 5 charginos $\tilde{\chi}^\pm_\alpha$

- **Low mass ($\lesssim m_W$) unstable LSP ($\widetilde{\chi}^0$) decays mainly through $\ell^\pm W^{\mp *}$, νZ^* while $l_{DL} \sim 1/m^4_{\chi^0}$...**
- **When $m_{\chi^0} < 20$ GeV... $l_{DL} > 100$ m**
- **$d_{\rm ATLAS} \sim 25$ m $\Longrightarrow$ light $\widetilde{\chi}^0$ ($\lesssim 40$ GeV)... $R\!\!\!/_P$ is an impostor to $R_p C$**



Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 0905, 120

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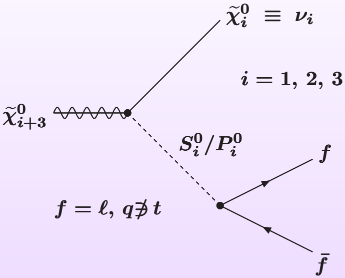


PG *et al.* to appear in arXiv

A light $\widetilde{\chi}^0$ through $\widetilde{\chi}^0 \to h_i/P_i + \nu^i_L$ can yield mesoscopic DV ($1\ cm \lesssim l_{DL} \lesssim 3\ m$)

Light h_i, P_i are possible in the $\mu\nu$SSM... A very light $\widetilde{\chi}^0$ ($\lesssim 20$ GeV) is detectable!..

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

How about $Z \to \widetilde{\chi}^0\widetilde{\chi}^0$, h_iP_j, $W^\pm \to \widetilde{\chi}^0\widetilde{\chi}^\pm_{1,2,3}$ at colliders....?

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

And finally Higgs$\to \widetilde{\chi}^0\widetilde{\chi}^0$ at the LHC and further...

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

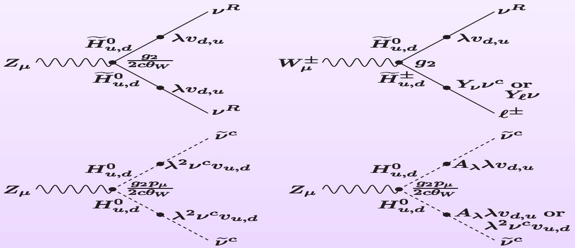
Setting up the convention... the signals

- **Small** κ, A_κ, $\lambda_i \Longrightarrow$ **light singlet-like** $h_i,\ P_i,\ \widetilde{\chi}^0_{i+3}$ $(i = 1, 2, 3)$

  Formulas are coming.... PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, to appear in arXiv

- h_4 **is the lightest doublet-like Higgs while** $\widetilde{\chi}^0_4$ **is the lightest neutralino**

  Fidalgo, López-Fogliani, Muñoz, Ruiz de Austri JHEP 1110, 020 (2011)



Prompt + Displaced yet detectable multi-leptons/jets/photons at the LHC

$$Z \longrightarrow \widetilde{\chi}^0_4 \widetilde{\chi}^0_4 \longrightarrow 2h_i/P_i + 2\nu \longrightarrow 2\ell^+_D \ell^-_D\ /2q_D\bar{q}_D + 2\nu$$

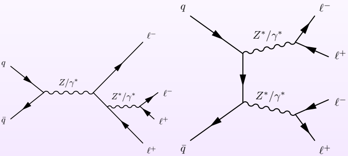
$$Z \longrightarrow h_i P_j \longrightarrow 2\ell^+_P \ell^-_P\ ,\ \ell^+_P \ell^-_P\ q_P \bar{q}_P \ldots \text{etc..}$$

$$W^\pm \longrightarrow \widetilde{\chi}^0_4 \widetilde{\chi}^\pm_{1,2,3} \longrightarrow \ell^+_D \ell^-_D\ /q_D \bar{q}_D + \nu + \ell^\pm_P$$

τ **or** b**-jet rich signals**

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

The $W^\pm$ and Z decays... a broader perspective



SM-Br($Z \to 4\ell,\ 4b$) $\lesssim 4.2^{+0.9}_{-0.8} \times 10^{-6}, 3.6^{+1.3}_{-1.3} \times 10^{-4}$
PDG, PRD 86, 010001 (2012)

Latest LHC reporting... only e, μ
CERN-CMS-NOTE-2006-057; JHEP 12, 034 (2012);
ATLAS-CONF-2013-055; PRL 112, 231806 (2014)

e, μ, τ, jets....

∗ MSSM + b$\not{R}_P$.. decays outside detector for $m_{\tilde{\chi}^0} < 20$ GeV... DISPLACED $W^\pm$, Z

∗ MSSM + t$\not{R}_P$.. decays between 1 cm − 3 m for $m_{\tilde{\chi}^0} < 20$ GeV with $\lambda_{ijk} \sim \mathcal{O}(10^{-3})$...
hep-ph/0406039 DISPLACED $W^\pm$, Z.. often with slightly altered topology..e.g., $2\ell_P 2\ell_D + \not{E}_T$

Rich in τ, b − jets....

∗ NMSSM.. DISPLACED decays for $Z \to$ bino-like NLSP pair $\to$ 2 LSP + 2 $h/P \to 2\ell^+\ell^-/q\bar{q} + \not{E}_T$
PROMPT Z decays {SM backgrounds}... $Z \to h + P \to 2\ell^+\ell^-/q\bar{q}$.. Nothing for $W^\pm$

∗ NMSSM + $3\hat{\nu}^c$.. DISPLACED & PROMPT decays for $Z \to 2\ell^+\ell^-/q\bar{q}$.... $\not{R}_P$ and R_pC.. DISPLACED decays for $W^\pm$ ..... Kitano, Oda, PRD 61, 113001 (2000)

∗ The $\mu\nu$SSM.. *minimal extension* beyond the MSSM $\Longrightarrow$ distinctive collider signatures + correct neutrino physics
PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

Probing new $W^{\pm}$ and Z decays....

Challenges... $\tau/\mathrm{b}-\mathrm{jet}$ rich signal.... Detection of soft, collimated and often displaced objects.... Need better statistics... better detection

* Br($Z \longrightarrow 2x_D 2y_D + \not{E}_T$) or Br($Z \longrightarrow 2x_P 2y_P + \not{E}_T$) $\sim \mathcal{O}(10^{-5})$ or less.. $x, y = \ell,\ q,\ \gamma$
* May remain hidden within SM process..for $x = b$... Br($Z \longrightarrow b\bar{b}b\bar{b}$) $\lesssim 3.6^{+1.3}_{-1.3} \times 10^{-4}$
* e.g. 2ℓ and 4ℓ mass peaks may get lost in the SM continuum.. see PRL 112, 231806 (2014)
* Detectable at the LHC... novel future.. GigaZ (linear collider) and TeraZ (TLEP) mode
* 2×10^9 (GigaZ).. 7×10^{11} (TeraZ) Z events/year $\Longrightarrow$ sensitive to much lower Br

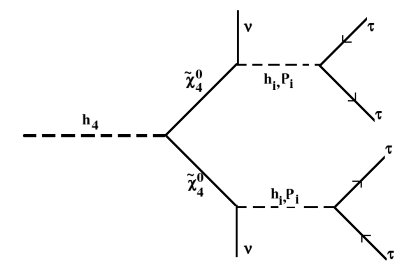
hep-ph/0102083; hep-ex/0106057; JHEP 01, 164 (2014)

* Br($W^{\pm} \longrightarrow x_D y_D + \not{E}_T + \ell_P^{\pm}$) $\sim \mathcal{O}(10^{-14})$ or less..
* Difficult at the LHC... also in future.. MegaW (linear collider) and OkuW (TLEP) mode
* 2×10^6 (MegaW).. 7×10^8 (OkuW) $W^{\pm}$ events/year $\Longrightarrow$ need much lower sensitivity.. ☹

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, arXiv:1403.3675 [hep-ph]

Hope... techniques from flavour observables... ☺

LHCb Br($B_s^0 \longrightarrow \mu^+\mu^-$) $\sim \mathcal{O}(10^{-10})$ sensitive to η.... work in progress..



Masses	Values in GeV
m_{h_4}	125.7
$m_{P_1}, m_{P_2}, m_{P_3}$	3.6, 3.8, 5.5
$m_{h_1}, m_{h_2}, m_{h_3}$	7.5, 8.0, 19.6
$m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_5^0}, m_{\tilde{\chi}_6^0}$	9.6, 11.5, 11.9

Displaced yet detectable multi-leptons/jets/photons at the LHC

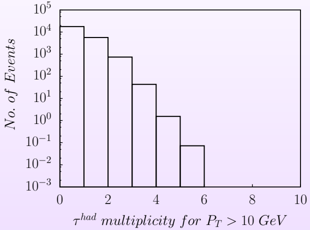
$$gg \longrightarrow h_4 \longrightarrow \tilde{\chi}_4^0 \tilde{\chi}_4^0 \longrightarrow 2h_i/P_i + 2\nu \longrightarrow 2\tau_D^+ 2\tau_D^- 2\nu$$

Prompt multi-leptons/jets/photons or mixed states are also possible from Higgs to Higgs cascades... $h_4 \longrightarrow h_i h_j, P_i P_j$... like the NMSSM

Cerdeño, PG, Park, JHEP 1306 (2013) 031

τ multiplicity... @8 TeV @20 fb^{-1}

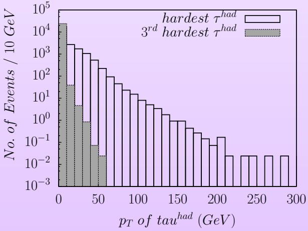
$\tau_{\rm had}$ **multiplicity**



- e, μs are from leptonic τ decay.. although $h_i/P_i \to \mu^+\mu^-$ is possible
- $4e, 4\mu$s from $\tau \sim 0.1\%$ while $4\tau^{\rm had} \sim 18\%$
- Highly collimated QCD jets faking $\tau^{\rm had}$..... $\Longrightarrow$ $n^{\tau^{\rm had}} > 4$... disappears with higher $p_{\rm T}^{\tau^{\rm had}}$ cut

- $\tau^{\rm had}$'s are clearly the best bet... next one is of course μ...... careful about PLB 726 (2013) 564

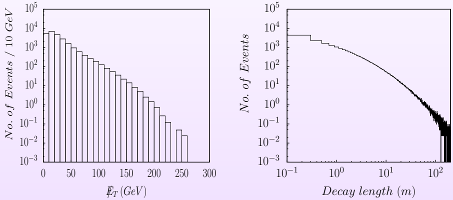
$p_{\rm T}^{\tau_{\rm had}}$ **distribution for** 1^{st} **and** 3^{rd} **leading** $\tau_{\rm had}$



PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

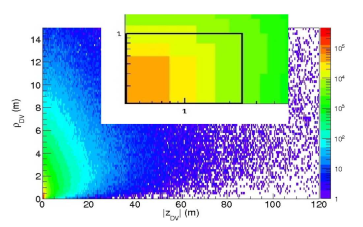
$\not{E}_T$, DL.......

$\not{E}_T$ and DL distribution



- **Moderately high $MET \Leftarrow\ \gtrsim 6$ neutrinos from $\widetilde{\chi}^0_4$ and τ decays...**
- **$c\tau_{\widetilde{\chi}^0_4} \approx 30$ cm.... large number of events appear inside charge tracker**

$|z_{\rm DV}|$ vs $\rho_{\rm DV}$

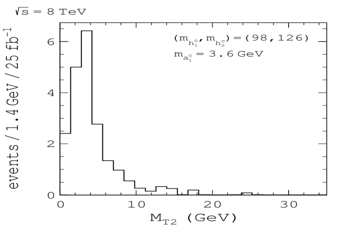


- **A large fraction of DVs appear within $|z_{\rm DV}| \lesssim 2.5$ m and $\rho_{\rm DV} \lesssim 1$ m, i.e, in the range of inner tracker**

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

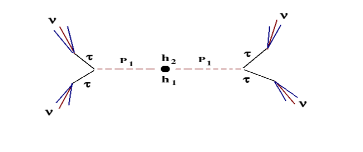
98+126 GeV Higgses with light P_1 @ NMSSM

M_{T2} distribution



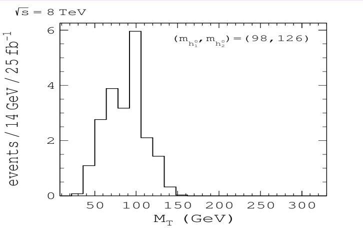
- **Signals $h_2, h_1 \to P_1 P_1 \to 2\tau^+ 2\tau^-$**
- **τ rich signal... better detection efficiency than $2m_\tau \lesssim m_{P_1} \lesssim 2m_b$**
- **Also considered $2m_{h_1} \lesssim m_{h_2}$... experimentally more challenging.. softer τs from $h_1 \to P_1 P_1$ decays**

Need small $\Delta_{\ell^+\ell^-}$



- **Good estimation of the mass scale...**

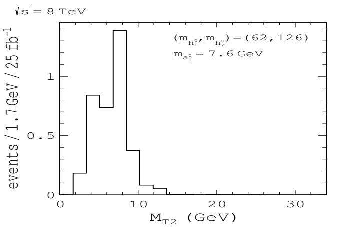
M_T distribution



Cerdeño, PG, Park, JHEP 1306 (2013) 031

$2m_{h_1} \lesssim 126{+}126$ GeV Higgses with light P_1 @ NMSSM

$\mathrm{M_{T2}}$ distribution



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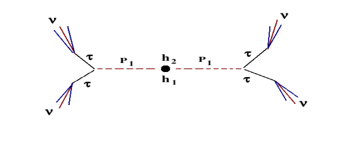

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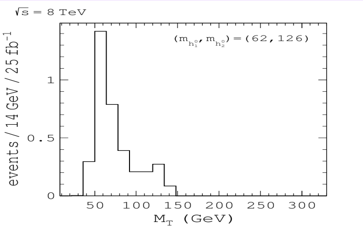
$\mathrm{M_T}$ distribution



Cerdeño, PG, Park, JHEP 1306 (2013) 031

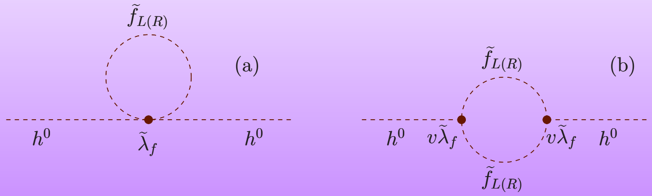
Summary and conclusion...... and beyond

- Light singlet-sector can produce novel and/or indirect (decays of heavier SM particles) evidence of new physics $\Longrightarrow$ need experimental attention
- $\mu\nu$SSM.... least extension beyond the MSSM to solve the μ-problem and reproduce correct neutrino physics
- Novel signals are well expected with enriched mass spectrum and broken R_p
- Displaced and/or soft objects at the LHC $\Rightarrow$ lesser backgrounds.. new signs are well envisaged but with sophisticated collider analyses of soft and/or displaced objects
- Unique SUSY signatures are also possible

With new data and up-gradation to 14 TeV and beyond...... more phenomenological wonder with $\mu\nu$SSM are awaiting.....

Dreaming the future..

Loop corrections in SUSY

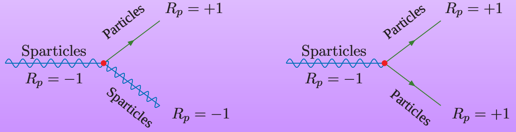


New one-loop radiative corrections to Higgs boson in SUSY

- **Certain restrictions on masses and couplings of new states $\Longrightarrow$ radiative correction vanishes**
- **Symmetry between states of different spin quantum numbers $\Longrightarrow$ Higgs (scalar) mass is protected**

R-Parity

- R_p, a discrete symmetry $\Longrightarrow$ prevents too fast proton decay through sparticle mediated process
- $R_p = (-1)^{L+3B+2S}$ with $L(B)$ as lepton(baryon) and S as spin



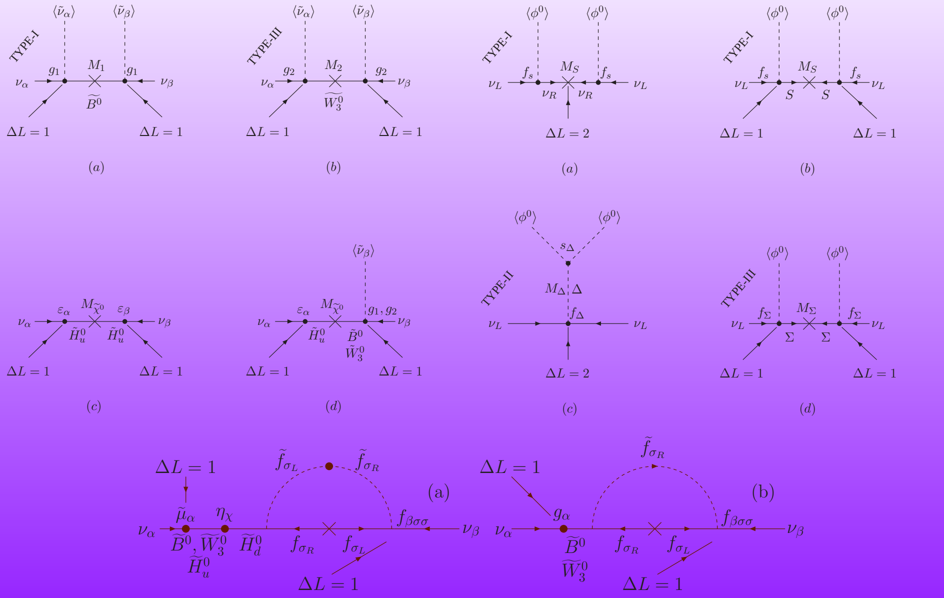
R_p conserved $\qquad$ R_p violated

- R_p conservation $\Longrightarrow$ stable Lightest Supersymmetric Particle (LSP)
- Most general MSSM superpotential with bilinear and trilinear $\not{R}_P$

$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c - \mu\hat{H}_d^a\hat{H}_u^b)$$

$$-\epsilon_{ab}(\underbrace{\epsilon^i\hat{L}_i^a\hat{H}_u^b}_{\Delta L=1,\Delta B=0} + \overbrace{\frac{1}{2}\lambda^{ijk}\hat{L}_i^a\hat{L}_j^b\hat{e}_k^c}^{\Delta L=1,\Delta B=0} + \underbrace{\lambda'^{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{d}_k^c)}^{\Delta L=1\Delta B=0,} + \overbrace{\lambda''^{ijk}\hat{u}_i^c\hat{d}_j^c\hat{d}_k^c}^{\Delta L=0,\Delta B=1}$$

$m_\nu \neq 0$



TYPE-I
TYPE-III
TYPE-I
TYPE-I
(a)
(b)
(a)
(b)
TYPE-II
TYPE-III
(c)
(d)
(c)
(d)
$\Delta L = 1$
$\Delta L = 2$
(a)
(b)

μ-problem

- **MSSM superpotential**

$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c) - \underline{\epsilon_{ab}\mu\hat{H}_d^a\hat{H}_u^b}$$

- **Since μ ϵ superpotential $\longrightarrow$ μ respects supersymmetry (SUSY)**
- **μ appears in the EWSB, generates TeV-scale higgsino masses**
- **SUSY respecting $\mu \sim$ SUSY breaking TeV-scale soft terms $\Longrightarrow$ μ-problem**

J. E. Kim and H. P. Nilles, Phys. Lett. B 138, 150 (1984)

- **Alternatively,**

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu^2|.$$

The soft terms

- **The Lagrangian $\mathcal{L}_{\text{soft}}$, containing the soft-supersymmetry-breaking terms is given by**

$$-\mathcal{L}_{\text{soft}} = (m^2_{\tilde{Q}})^{ij}\tilde{Q}^{a^*}_i\tilde{Q}^a_j + (m^2_{\tilde{u}^c})^{ij}\tilde{u}^{c^*}_i\tilde{u}^c_j + (m^2_{\tilde{d}^c})^{ij}\tilde{d}^{c^*}_i\tilde{d}^c_j + (m^2_{\tilde{L}})^{ij}\tilde{L}^{a^*}_i\tilde{L}^a_j$$

$$+ (m^2_{\tilde{e}^c})^{ij}\tilde{e}^{c^*}_i\tilde{e}^c_j + m^2_{H_d}H^{a^*}_d H^a_d + m^2_{H_u}H^{a^*}_u H^a_u + (m^2_{\tilde{\nu}^c})^{ij}\tilde{\nu}^{c^*}_i\tilde{\nu}^c_j$$

$$+ \epsilon_{ab}\left[(A_uY_u)^{ij}H^b_u\tilde{Q}^a_i\tilde{u}^c_j + (A_dY_d)^{ij}H^a_d\tilde{Q}^b_i\tilde{d}^c_j + (A_eY_e)^{ij}H^a_d\tilde{L}^b_i\tilde{e}^c_j + \mathbf{H.c.}\right]$$

$$+ \left[\epsilon_{ab}(A_\nu Y_\nu)^{ij}H^b_u\tilde{L}^a_i\tilde{\nu}^c_j - \epsilon_{ab}(A_\lambda\lambda)^i\tilde{\nu}^c_i H^a_d H^b_u + \frac{1}{3}(A_\kappa\kappa)^{ijk}\tilde{\nu}^c_i\tilde{\nu}^c_j\tilde{\nu}^c_k + \mathbf{H.c.}\right]$$

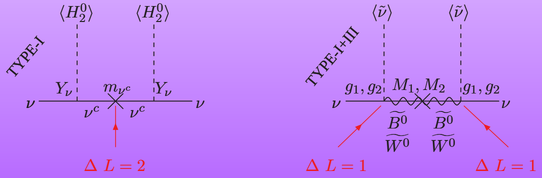
- **The neutral fields develop non zero VEVs while minimizing the neutral scalar potential,**

$$\langle H^0_d\rangle = v_d\,,\quad \langle H^0_u\rangle = v_u\,,\quad \langle\tilde{\nu}_i\rangle = \nu_i\,,\quad \langle\tilde{\nu}^c_i\rangle = \nu^c_i\,.$$

Neutrino mass generation in $\mu\nu$SSM

"TeV - scale" Type I + Type III seesaw, even with flavour diagonal neutrino Yukawa couplings $\Longrightarrow$ tree level masses for all three neutrinos

PG and Roy, JHEP 04, 069 (2009)



$m_\nu \sim \frac{Y_\nu^2 \langle H_u^0 \rangle^2}{m_{\nu^c}}$ **TYPE-I**

$m_\nu \sim \frac{g^2 \langle \tilde{\nu} \rangle^2}{m_{\chi^0}}, \quad m_{\chi^0} = M_1, M_2$ **TYPE-I+III**

- Approximate analytical expression for entries of M^{tree}_{seesaw} matrix

$$(M^{tree}_{seesaw})_{ij} \approx \frac{a_i a_j}{6\kappa\nu^c}(1-3\delta ij) - \frac{1}{2M_{eff}}\left[c_i c_j + \frac{(a_i c_j + a_j c_i)}{3\lambda tan\beta} + \frac{a_i a_j}{9\lambda^2 tan^2\beta}\right]$$

PG and Roy, JHEP 04, 069 (2009)

where $$M_{eff} = \left[1 - \frac{v^2}{2M(\kappa{\nu^c}^2 + \lambda v_d v_u)\mu}\left(\kappa{\nu^c}^2 \sin 2\beta + \frac{\lambda v^2}{2}\right)\right], \frac{1}{M} = \frac{g_1^2}{M_1} + \frac{g_2^2}{M_2}$$

$$v^2 = v_d^2 + v_u^2,\ tan\beta = \frac{v_u}{v_d},\ a_i = Y_\nu^{ii} v_u,\ c_i = \nu_i,\ i = e, \mu, \tau$$

- In the limit $\nu^c \to \infty$ and $v \to 0$, equation one reduces to

$$(M^{tree}_{seesaw})_{ij} \approx -\frac{c_i c_j}{2M} \Longrightarrow \text{Gaugino seesaw or Type - III seesaw}$$

- In the limit $M \to \infty$, same equation reduces to

$$(M^{tree}_{seesaw})_{ij} \approx \frac{a_i a_j}{6\kappa\nu^c}(1-3\delta ij) \Longrightarrow \text{Ordinary seesaw or Type - I seesaw.}$$

To kill the backgrounds......Higgs

Mesoscopic displaced vertex....
Displaced charge tracks....

Irreducible impostor NMSSM + $3\nu^c$..
Kitano, Oda, PRD 61, 113001 (2000)

- **All SM (e.g. ZZ^*)/SUSY backgrounds** ($e.g.\ h_1 \to P_1 P_1 \to 2\ell^+ 2\ell^-$@NMSSM), **with prompt ℓ are effaced ... also long-lived b/c meson decays**
- **NMSSM with $10^{-3} \lesssim \lambda \lesssim 10^{-2}$... light NLSP $\to$ LSP + h/P, with $h/P \to \ell^+\ell^-$ $\Rrightarrow$ a possible impostor..** Ellwanger, Hugonie, Eur. Phys. J. C 5, 723 (1998); Eur. Phys. J. C 13, 681 (2000)
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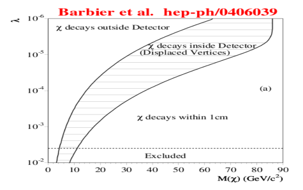
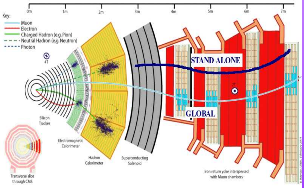
- **Options.. e.g. MSSM $+\frac{1}{2}\lambda^{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k$.. difficult with, LEP (and LHC) results... but not impossible**
Dreiner, Kim, Lebedev, PLB 715, 199 (2012)



Stand-alone muons...



Bandyopadhyay, PG, Roy, PRD84, 115022 (2011)

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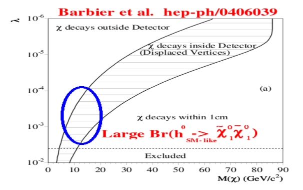

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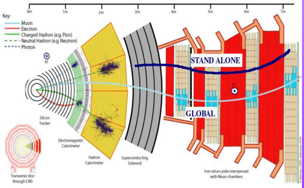
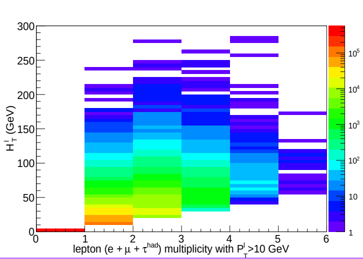


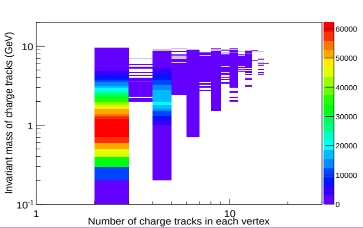
Bandyopadhyay, PG, Roy, PRD84, 115022 (2011)

- H_T^ℓ is moderately high for larger lepton multiplicity
- $H_T^\ell + \not{E}_T$ can be used as a differentiator

H_T^ℓ $(\equiv \sum p_T^\ell)$ distribution



Charge track mass vs n_{trk}



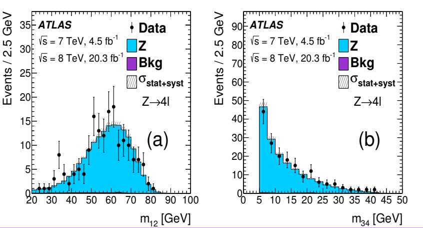
$n_{trk}^{vertex}|_{max} = 12$, **four 3-prong τ decay**

- A very useful event selection criteria
- ☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... G. Aad *et al.* [ATLAS] 2013
- Room for development... sensitivity to low vertex mass
- Life is better with jets

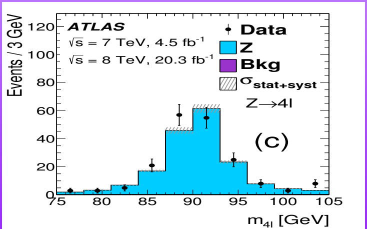
$Z \longrightarrow 4\ell$, $\ell = e, \mu$ in ATLAS

- $E_{\rm CM} = 8$ TeV, $\mathcal{L} = 20.3\ {\rm fb}^{-1}$, Br$(Z \longrightarrow 4b) \sim 10^{-5} \Longrightarrow \sigma(pp \longrightarrow Z \longrightarrow 4b) \times \mathcal{L} \approx 5150$ events.. without any kinematical cuts
- In the SM ≈ 185400 events with Br$(Z \longrightarrow 4b) \sim 3.6 \times 10^{-4}$!!!!!!

2ℓ m_{inv} distributions



4ℓ m_{inv} distribution



- Poor detection efficiency for low $p_{\rm T}$ τs compared to e, μ....