Displaced multileptons at the LHC – probing a 125 GeV new boson in $\mu\nu$SSM

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Together..........

PG, Daniel E. López-Fogliani, Vasiliki A. Mitsou,
Carlos Muñoz and Roberto Ruiz de Austri
Phys. Rev. D 88, 015009 (2013)
arXiv:1211.3177 [hep-ph]

- $\not{\lambda \hat{S} \hat{H}^a_d \hat{H}^b_u}$ ... It is $\underbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u}_{R\!\!\!/_p \text{ with } \Delta L=1}$
- Natural entry of $Y^{ij}_\nu \hat{H}^b_2 \hat{L}^a_i \hat{\nu}^c_j$

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

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

López-Fogliani, Muñoz, 2006; Escudero, López-Fogliani, Muñoz, Ruiz de Austri 2008

$Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j$, seed of $R\!\!\!/_P$.... with $Y_\nu \to 0$.... $\hat{\nu}^c \Leftrightarrow \hat{S}$... $\Rightarrow \not{R\!\!\!/_P}$

Similar $R\!\!\!/_P$ in $\mathcal{L}_{soft} \Longrightarrow$ $\langle \tilde{\nu}_i \rangle = \nu_i\,, \quad \langle \tilde{\nu}^c_i \rangle = \nu^c_i$

Neutrinos@$\mu\nu$SSM

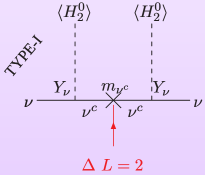
TeV scale seesaw with right-handed neutrino + $\not{R}_P \implies m_\nu \neq 0$

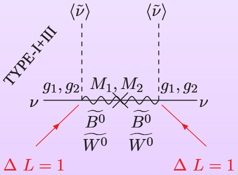
PG, Roy 2009; Fidalgo, López-Fogliani, Muñoz, Ruiz de Austri 2009; PG, Dey, Mukhopadhyaya, Roy 2010

Even with Y_ν^{ii} and $3\nu_i^c \implies m_{\nu_i} \neq 0, i \in 1, 2, 3$

correct neutrino physics at the tree level

"TeV - scale" Type I + Type III seesaw, $\implies m_\nu \neq 0$





$$m_\nu \sim \frac{Y_\nu^2 \langle H_2^0 \rangle^2}{m_{\nu^c}} \quad \text{TYPE-I}$$

$$m_\nu \sim \frac{g_i^2 \langle \tilde{\nu} \rangle^2}{m_{\tilde{\chi}^0}}, \quad m_{\tilde{\chi}^0} = M_{1,2} \quad \text{TYPE-I+III}$$

The Spectrum

Significance of Lepton number (L) is lost

- **MSSM + $R\!\!\!/_P$ + 3 $\hat{\nu}_i^c \Longrightarrow$ 8(7) CP-even(odd) states $h_\alpha(P_\alpha)$ / 10 neutralinos $\widetilde{\chi}_\alpha^0$ / 7 charged states $S_\alpha^\pm$ / 5 charginos $\widetilde{\chi}_\alpha^\pm$**

TeV scale seesaw with $\mathbf{Y}_\nu \sim 10^{-6}$.. $\widetilde{\nu}_L^i, e_{L,R}^i$ practically decoupled..

With small λ.. $H_u, H_d, \widetilde{\nu}_i^c$ decoupled..

κ, A_κ small... $h_{1,2,3}, P_{1,2,3}, \widetilde{\chi}_{4,5,6}^0$ singlet like

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
$m_{\widetilde{\chi}_4^0}, m_{\widetilde{\chi}_5^0}, m_{\widetilde{\chi}_6^0}$	9.6, 11.5, 11.9

h_4, lightest doublet-like Higgs, $\widetilde{\chi}_4^0$, lightest neutralino

$$\mathbf{m_{\tilde{\chi}^0} \lesssim m_W \ldots\ l_{DL} \sim 1/m^4_{\chi^0} \ldots}$$

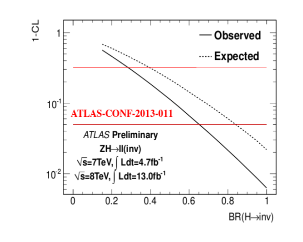
When $m_{\chi^0} < 20$ GeV... $l_{DL} > 100$ m...$\not{R}_P$ is an impostor to $R_p C$

Bartl, Hirsch, Vicente, Liebler, Porod, 2009

In the $\mu\nu$SSM

$$\tilde{\chi}^0 \rightarrow \mathbf{h_i/P_i} + \nu^i_L \Longrightarrow \text{mesoscopic DV } (1\text{ cm} \lesssim l_{DL} \lesssim 3\text{ m})$$

A very light $\tilde{\chi}^0$ ($\lesssim 20$ GeV) is detectable at the LHC!

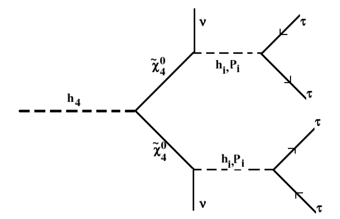


How about $h_4 \rightarrow \tilde{\chi}^0_4 \tilde{\chi}^0_4$ at the LHC....?

PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, 2013

An unique signal....$\mathbf{m_{h_{1,2,3}}}$, $\mathbf{m_{P_{1,2,3}}}$??

Jets are not the best bet though $h_i, P_i \longrightarrow b\bar{b}$ is more general



- $2m_\tau \lesssim m_{h_i,P_i} \lesssim 2m_b$...for clean final states
- τ's are the best... $n_{trk} = 3$ for hadronic τ decay.. (65% of time)

☹ τ detection efficiency varies with p_T^τ

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

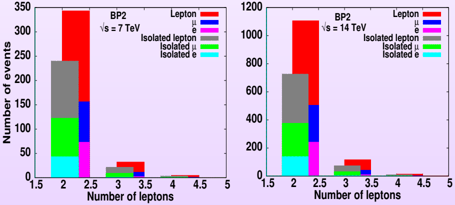
Displaced yet detectable multi-leptons at the LHC

A little price to pay...... correlation lost

- **Correlations among χ_4^0 decay and neutrino mixing angle**

$\Longrightarrow n_\mu > n_e$

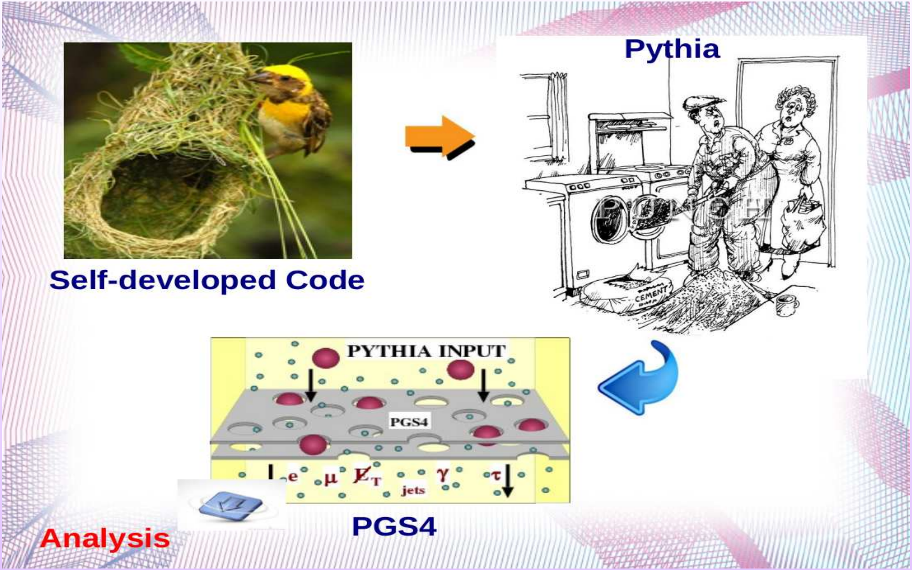
Bandyopadhyay, PG, Roy, 2011



☹ **In the current analysis $h_i/P_i \to \tau^+\tau^-$ decays... correlations lost**

☺ $\Rightarrow n_\ell$ **is practically independent of Y_ν, ν**

Following the footsteps.....



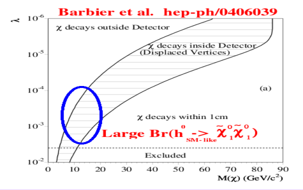
To kill the backgrounds......

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

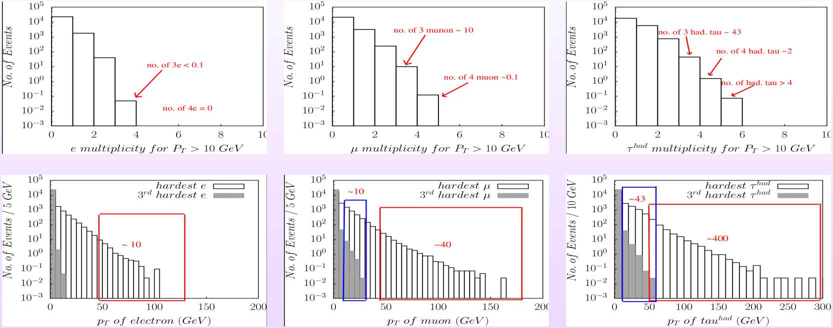
- **All SM (e.g. ZZ^*)/SUSY backgrounds (e.g. $h_1 \to P_1 P_1 \to 2\ell^+ 2\ell^-$@NMSSM), with prompt ℓ are effaced ...**
- **NMSSM with $10^{-3} \lesssim \lambda \lesssim 10^{-2}$... light NLSP $\to$ LSP + h/P, h/P $\to \ell^+\ell^- \Rrightarrow$ possible impostor..**
- **NLSP $\to$ LSP + h/P, $\not\Longleftrightarrow$ mesoscopic decay length....**

Ellwanger, Hugonie, 2000

- **Options.. e.g. MSSM $+\frac{1}{2}\lambda^{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k$.. hardly possible in reality... with LEP (and LHC) results...**



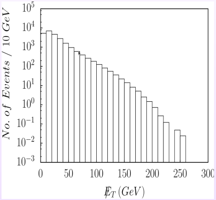
Lepton multiplicity... @8 TeV @20 fb^{-1}

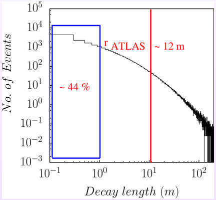


- **e, μs are from leptonic τ decay.. although $h_i/P_i \to \mu^+\mu^-$ is possible**
- **4e, 4μs from $\tau \sim 0.1\%$ while 4$\tau^{had} \sim 18\%$**
- **Highly collimated QCD jets faking τ^{had}..... $\Longrightarrow$ $n^{\tau^{had}} > 4$... disappears with higher $p_T^{\tau^{had}}$ cut**

$\not{E}_T$, DL, H_{T}^{ℓ}

$\not{E}_T$ and DL distribution

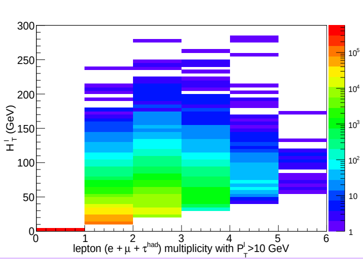




- Moderately high $MET \Leftarrow \quad \gtrsim 6\nu$ from $\widetilde{\chi}_4^0$ and τ decays...
- $c\tau_{\widetilde{\chi}_4^0} \approx 30$ cm.... large number of events appear inside charge tracker

H_{T}^{ℓ} $(\equiv \sum p_{\mathrm{T}}^{\ell})$ distribution

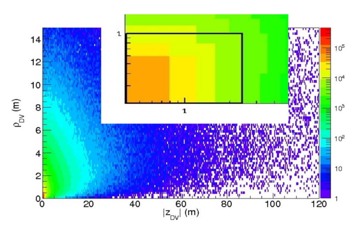
- H_{T}^{ℓ} is moderately high for larger lepton multiplicity
- $H_{\mathrm{T}}^{\ell} + \not{E}_T$ can be used as a differentiator



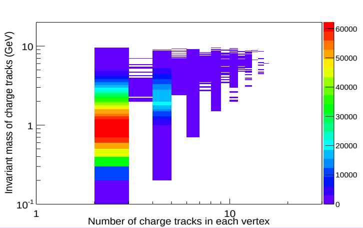
Probing DVs

- **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**
- **Tracking possible ☺**

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



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**

Summary and conclusion...... and beyond

★ $\mu\nu$**SSM.... solves** μ**-problem and reproduces correct neutrino physics**

★ **Novel signals are well expected with enriched mass spectrum.. and broken** R_p

★ **Collinear and Displaced objects at the LHC** $\Rightarrow$ **lesser backgrounds.. new signs are well envisaged**

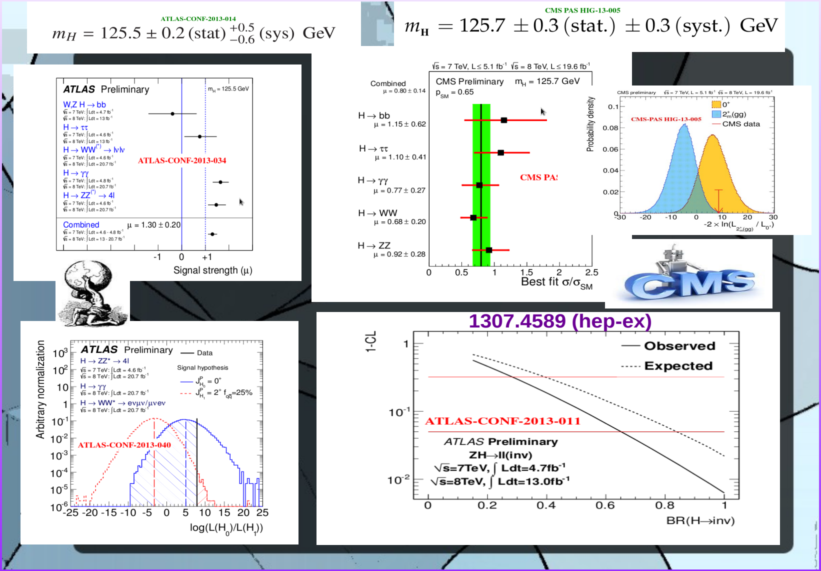
★ **Sophisticated analysis of collinear and displaced objects are expected in near future**

★ **Unique SUSY signatures are also possible**

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

Dreaming the future..

The Higgs boson?..



The soft terms

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

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

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

$$+ \epsilon_{ab} \left[(A_u Y_u)^{ij} H^b_u \tilde{Q}^a_i \tilde{u}^c_j + (A_d Y_d)^{ij} H^a_d \tilde{Q}^b_i \tilde{d}^c_j + (A_e Y_e)^{ij} H^a_d \tilde{L}^b_i \tilde{e}^c_j + \text{H.c.} \right]$$

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

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

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