Displaced multi-leptons at the LHC - probing a 125 GeV new boson in $\mu\nu$SSM

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IOP, Bhubaneswar
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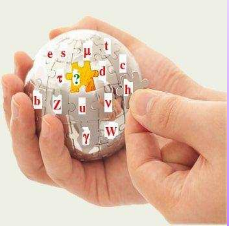
Together..........

PG, Daniel E. López-Fogliani, Vasiliki A. Mitsou,
Carlos Muñoz and Roberto Ruiz de Austri
Phys. Rev. D 88, 015009 (2013)
PRD 88, 015009 (2013)

Life after 13/12/2011.....

At last a scalar ☺



Phys. Lett. **B716** (2012) 1 [ATLAS]
Phys. Lett. **B716** (2012) 30 [CMS]

Is this the one?....

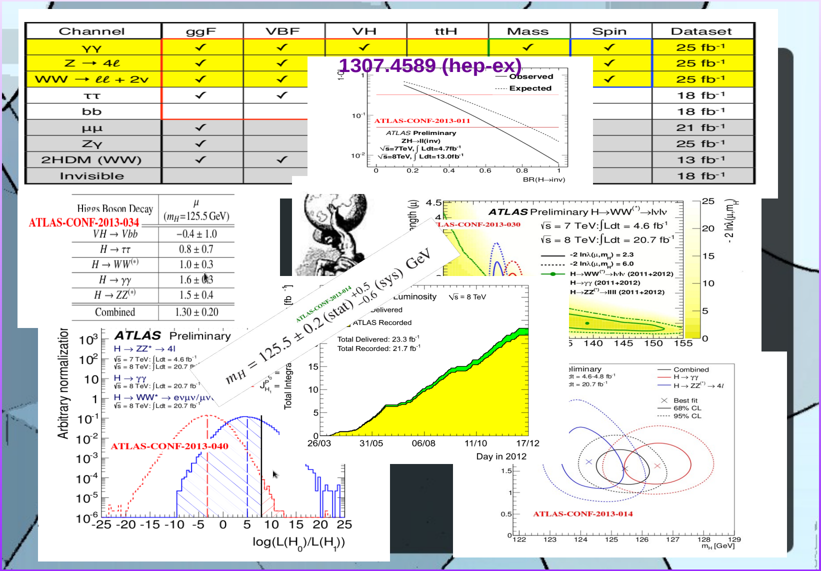
• 2^+ (gg) excluded at 99.9% confidence C.L. (channel $\gamma\gamma, WW^*, ZZ^*$), $0^-, 1^+(1^-)$ excluded at $\gtrsim 97.8\%(94\%)$ C.L. from ZZ^*... ATLAS-CONF-2013-040,013 CMS-PAS-HIG-13-005... ▸ 15-04-2013

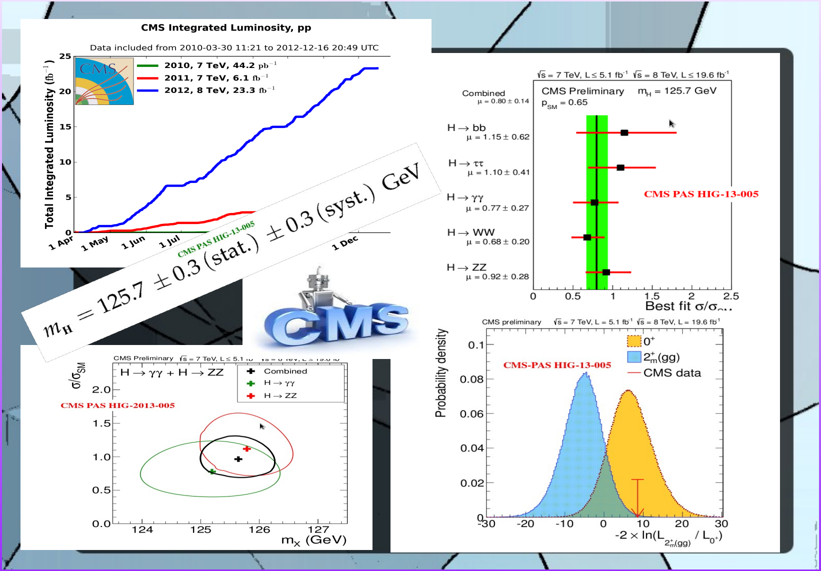
• Combined signal strength $\mu = 1.30(0.80) \pm 0.20(0.14)$ agrees with the SM at 2σ ATLAS-CONF-2013-034,CMS PAS-HG-13-005

• $m_{scalar} = 125.2 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV, $m_{scalar} = 125.7 \pm 0.3$ (stat) ± 0.3 (syst) GeV ATLAS-CONF-2013-014, CMS PAS-HG-13-005

• Apparent excess in $\gamma\gamma$ for ggF and even for VBF..ATLAS-CONF-2013-034
• Need precise measurement of $b\bar{b}$..$\sim 56\% - 58\%$ for 125-126 GeV Higgs like scalar
• Neutrino mass..?, Dark Matter..? Flavour violation..? g_i unification..?

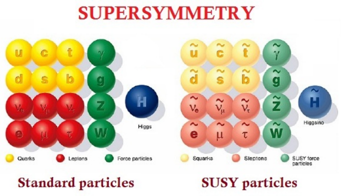
Hope survives... ☺


Channel | ggF | VBF | VH | ttH | Mass | Spin | Dataset
γγ ✓ ✓ ✓ ✓ ✓ 25 fb-1
Z → 4ℓ ✓ ✓ ✓ 25 fb-1
WW → ℓℓ + 2ν ✓ ✓ ✓ 25 fb-1
ττ ✓ ✓ 18 fb-1
bb 18 fb-1
μμ ✓ 21 fb-1
Zγ ✓ 25 fb-1
2HDM (WW) ✓ ✓ 13 fb-1
Invisible 18 fb-1
1307.4589 (hep-ex)
Observed
Expected
ATLAS-CONF-2013-011
ATLAS Preliminary
ZH→ll(inv)
BR(H→inv)
Higgs Boson Decay
μ (m_H=125.5 GeV)
ATLAS-CONF-2013-034
VH → Vbb −0.4 ± 1.0
H → ττ 0.8 ± 0.7
H → WW(*) 1.0 ± 0.3
H → γγ 1.6 ± 0.3
H → ZZ(*) 1.5 ± 0.4
Combined 1.30 ± 0.20
ATLAS Preliminary H→WW(*)→lνlν
ATLAS-CONF-2013-030
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
H→γγ (2011+2012)
H→ZZ(*)→llll (2011+2012)
ATLAS-CONF-2013-014
$m_H = 125.5 \pm 0.2\,(stat)\,^{+0.5}_{-0.6}\,(sys)$ GeV
ATLAS Preliminary
H → ZZ* → 4l
H → γγ
H → WW* → eνμν
Arbitrary normalization
ATLAS-CONF-2013-040
log(L(H0)/L(H1))
Luminosity √s = 8 TeV
Delivered
ATLAS Recorded
Total Delivered: 23.3 fb-1
Total Recorded: 21.7 fb-1
Total Integrated
Day in 2012
Combined
Best fit
68% CL
95% CL
ATLAS-CONF-2013-014
mH [GeV]


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
Total Integrated Luminosity (fb⁻¹)
1 Apr
1 May
1 Jun
1 Jul
1 Dec
CMS PAS HIG-13-005
$m_H = 125.7 \pm 0.3\,(\text{stat.}) \pm 0.3\,(\text{syst.})$ GeV
CMS
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
CMS Preliminary m_H = 125.7 GeV
p_{SM} = 0.65
Combined μ = 0.80 ± 0.14
H → bb μ = 1.15 ± 0.62
H → ττ μ = 1.10 ± 0.41
H → γγ μ = 0.77 ± 0.27
H → WW μ = 0.68 ± 0.20
H → ZZ μ = 0.92 ± 0.28
CMS PAS HIG-13-005
Best fit σ/σ
CMS Preliminary
H → γγ + H → ZZ
Combined
H → γγ
H → ZZ
CMS PAS HIG-2013-005
σ/σ_SM
m_X (GeV)
CMS preliminary √s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 19.6 fb⁻¹
0⁺
2⁺_m(gg)
CMS data
CMS-PAS HIG-13-005
Probability density
-2 × ln(L_{2⁺_m(gg)} / L_{0⁺})

Beyond the SM with SUSY

Need two Higgs doublets..
H_u, H_d



• Cure to gauge hierarchy problem of the SM with superpartners....
• Stable lightest SUSY particle $\Longrightarrow$ DM candidate
• Enhanced FV $\Longrightarrow$ stringent constraint
• gauge coupling unification

• Fast proton decay through sparticles mediated processes
• Impose R-parity (R_p) $\Longrightarrow$ stable LSP
• $m_\nu = 0$ unless ~~R-parity~~ or extra superfields
• μ-problem with bilinear $\epsilon_{ab}\mu \hat{H}_d^a \hat{H}_u^b$

Kim and Nilles, Phys. Lett. B 138, 150 (1984)

Waking up with the idea.....

• Replace $\mu\hat{H}_d^a\hat{H}_u^b$ by $\lambda\hat{S}\hat{H}_d^a\hat{H}_u^b$.. after EWSB, $\mu_{eff} = \lambda\langle\widetilde{S}\rangle$...
$\hat{S}$, a SM gauge singlet superfield... $\Longrightarrow$ NMSSM... **Extra tree level contribution to** $m_{lightest}^{Higgs} \propto 3.62\ m_Z^2\ |\lambda|^2 \sin^2 2\beta$.. Drees 1989, Ellis, Gunion, Haber, Roszkowski, Zwirner, 1989

• However, m_ν still zero.. unless $\not{R}_P$ or extra superfields added..

• Simplest is b$\not{R}_P$, i.e. through $\epsilon_i\hat{L}_i\hat{H}_u$ ..

• One $m_\nu \neq 0$ at the tree level.. need one more at least for three flavour global data Forero, Tortola, Valle, Phys. Rev. D 86, 073012 (2012); Schwetz, Tortola, Valle, New. J. Phys. 10, 113011 (2008)

• Loop corrections are essential......

• Suffers from ϵ-problem Nilles and Polonsky, Nucl. Phys. B 484, 33 (1997)

• Next possibility is t$\not{R}_P$, free from any naturalness problems

• Neutrino masses appear through loop calculations

• Large number of parameters $\Longrightarrow$ less predictive

• Critically challenged with LFV..... Dreiner, Nickel, Staub, Vicente, Phys. Rev. D 86, 015003 (2012)

• **Why not the gauge singlet right-handed neutrinos, ν^c ??**

- $\cancel{\lambda \hat{S} \hat{H}^a_d \hat{H}^b_u}$ ... 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 $Y^{ij}_\nu \hat{H}^b_2 \hat{L}^a_i \hat{\nu}^c_j$

$$W = \underbrace{\epsilon_{ab}(Y^{ij}_u \hat{H}^b_u \hat{Q}^a_i \hat{u}^c_j + Y^{ij}_d \hat{H}^a_d \hat{Q}^b_i \hat{d}^c_j + Y^{ij}_e \hat{H}^a_d \hat{L}^b_i \hat{e}^c_j)}_{W^{MSSM} - \epsilon_{ab}\mu \hat{H}^a_d \hat{H}^b_u} + \epsilon_{ab}\left(\underbrace{Y^{ij}_\nu \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j}_{\epsilon^i_{eff} = Y^{ij}_\nu \langle \tilde{\nu}^c_j \rangle} - \overbrace{\underbrace{\lambda^i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u}_{\mu_{eff} = \lambda^i \langle \tilde{\nu}^c_i \rangle}}^{R_p \text{ with } \Delta L = 1}\right) + \overbrace{\underbrace{\frac{1}{3}\kappa^{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k}_{m_{\nu^c_{ij}} = 2\,\kappa^{ijk} \langle \tilde{\nu}^c_k \rangle}}^{R_p \text{ with } \Delta L = 3}$$

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

Escudero, López-Fogliani, Muñoz, Ruiz de Austri *JHEP* 12 (2008) 099

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

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

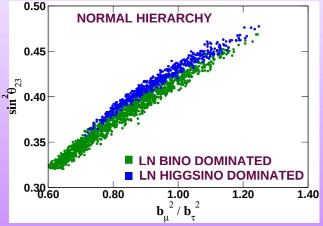
$Y_\nu \propto \langle \tilde{\nu}_i \rangle$, with TeV scale seesaw $Y_\nu \sim 10^{-6}$

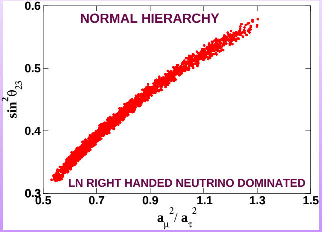
Similar R_p in $\mathcal{L}_{soft} \implies \langle \tilde{\nu}_i \rangle = \nu_i\,, \quad \langle \tilde{\nu}^c_i \rangle = \nu^c_i \neq 0$ sneutrino VEVs

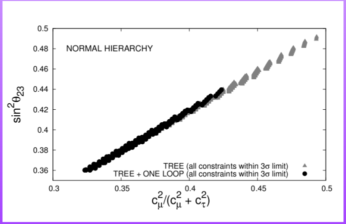
Three $\hat{\nu}^c$, natural from family symmetry, even with $Y^{ii}_\nu \implies$

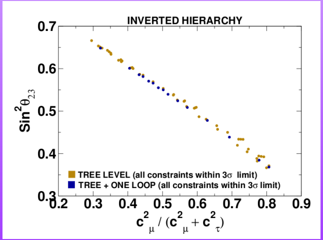
correct neutrino physics at the tree level PG, Roy *JHEP* 04 (2009) 069

The neutrinos in $\mu\nu$SSM





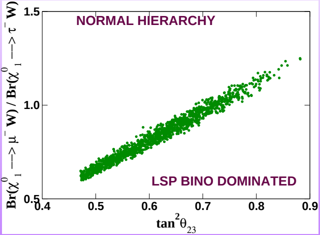


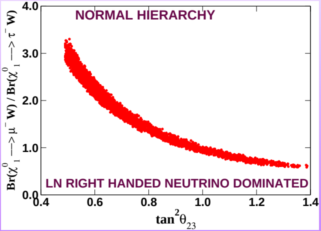


$$a_i = Y_\nu^{ii} v_u,\ b_i = a_i \cot\beta + 3\lambda c_i,\ c_i = \nu_i$$

PG, S. Roy, JHEP 04, 069 (2009), PG, Dey, Mukhopadhyaya and Roy, *JHEP* 05 (2010) 087

Goliath meets David.....





PG, S. Roy, JHEP 04, 069 (2009), A. Bartl, M. Hirsch, A. Vicente, S. Liebler, W. Porod, JHEP 05, 120 (2009)

Correlations between neutrino mixing angles and LSP decay

B. Mukhopadhyaya, S. Roy, F. Vissani, Phys. Lett. B 443, 191 (1998)
S.Y. Choi, E. J. Chun, S. K. Kang, J. S. Lee, Phys. Rev. D 60, 075002 (1999)
J.C. Romao, M.A. Diaz, M. Hirsch, W. Porod, J.W.F Valle, Phys. Rev. D 61, 071703 (2000)

The Spectrum

Significance of Lepton number (L) is lost

- 2 from MSSM + 3 $\widetilde{\nu}_i^c$ + 3 $\widetilde{\nu}_L^i$ $\Longrightarrow$ 8 CP-even states h_α
- 1 from MSSM + 3 $\widetilde{\nu}_i^c$ + 3 $\widetilde{\nu}_L^i$ $\Longrightarrow$ 7 CP-odd states P_α
- 1 from MSSM + 3 $\widetilde{e}_L^i$ + 3 $\widetilde{e}_R^i$ $\Longrightarrow$ 7 charged states $S_\alpha^\pm$
- 4 from MSSM + 3 ν_i^c + 3 ν_L^i $\Longrightarrow$ 10 neutral fermions $\widetilde{\chi}_\alpha^0$
- 2 from MSSM + 3 $e_{L,R}^i$ $\Longrightarrow$ 5 charged fermions $\widetilde{\chi}_\alpha^\pm$

With small $Y_\nu \sim 10^{-6}$ (and ν_i) ... $\widetilde{\nu}_L^i, e_{L,R}^i, \widetilde{e}_{L,R}^i$ are practically decoupled

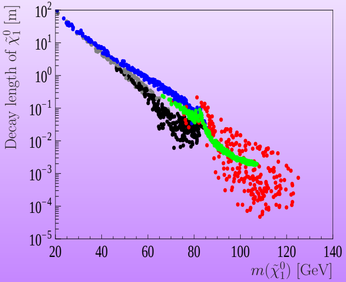
Although decoupled, ν_L^i owe their mass to $Y_\nu, \nu_i ... \in R\!\!\!/_P$ and TeV seesaw

λ and A_λ $\Longrightarrow$ key ingredient for singlet-doublet admixing

At the limit $\lambda \to 0$, $\widetilde{\nu}_i^c$ decoupled from the doublets...

Escudero, López-Fogliani, Muñoz, Ruiz de Austri, *JHEP* 12 (2008) 099
Ellis, Gunion, Haber, Roszkowski, Zwirner, Phys. Rev. D 39, 844 (1989)

- Low mass ($\lesssim m_W$) unstable LSP ($\widetilde{\chi}^0$) decays mainly through $\ell^\pm W^{\mp *}$, νZ^* while $l_{DL} \sim 1/m^4_{\chi^0}\cdots$
- When $m_{\chi^0} < 20$ GeV... $l_{DL} > 100$ m
- $d_{\rm ATLAS} \sim 25$ m $\Longrightarrow$ light $\widetilde{\chi}^0$ ($\lesssim 40$ GeV)... $\not R_P$ is an impostor to $R_p C$
- Pronounced for $m_{\widetilde{\chi}^0} \lesssim 20$ GeV



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

Any new two body decays for $\widetilde{\chi}^0$?

In $\mu\nu$SSM three singlet like lighter h_i, P_i are possible..

A light $\widetilde{\chi}^0$ through $\widetilde{\chi}^0 \to h_i/P_i + \nu^i_L$ can yield mesoscopic DV

$(1\ cm \lesssim l_{DL} \lesssim 3\ m)$

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

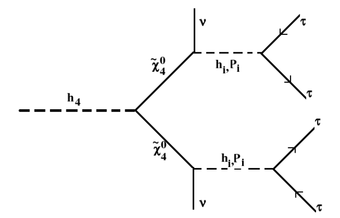
PG, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri, PRD 88, 015009 (2013)

How about Higgs$\to \widetilde{\chi}^0\widetilde{\chi}^0$ at the LHC....?

An unique signal........setting up the convention

- With small λ_i small doublet-singlet mixing $\Longrightarrow h_i,\ P_i,\ \widetilde{\chi}^0_{i+3}\ (i = 1, 2, 3)$ are with leading $\widetilde{\nu}^c_i$ composition
- $\widetilde{\chi}^0_i$ are practically left-chiral neutrinos
- 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)



- **Displaced yet detectable multi-leptons at the LHC**
- $2m_\tau \lesssim m_{h_i, P_i} \lesssim 2m_b$**...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}

With $m_{h_4} \sim 125$ GeV and higher $p_{\mathrm{T}}^{\mathrm{jet}}$ trigger $\Longrightarrow$ jets are not the best bet at the first place, though $h_i, P_i \to b\bar{b}$ is more general

Our signal..... $gg \to h_4 \to \widetilde{\chi}^0_4 \widetilde{\chi}^0_4 \to 2h_i/P_i + 2\nu \to 2\tau^+ 2\tau^- 2\nu$

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

- Correlations among χ_4^0 decay and neutrino mixing angle $\Longrightarrow n_\mu > n_e$

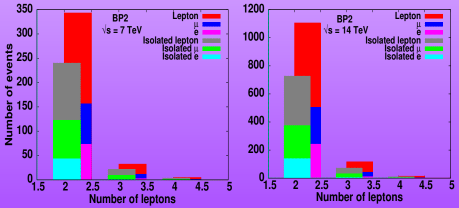
PG, S. Roy, JHEP **04**, 069 (2009)

- **These correlations are absent in usual trilinear $\not R_P$ models...**

Choi, Chun, Kang, Lee Phys. Rev. D **60**, 075002 (1999)

- The correlations survives even with isolation $(\ell\ell, \ell jet)$ cuts

P. Bandyopadhyay, PG and S. Roy, Phys. Rev. **D84**, 115022 (2011)



- An unique feature and test of the $\mu\nu$SSM...

☹ In the current analysis leptons are from h_i/P_i decays... correlations lost

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

An unique signal.......Looking for the spectrum

A generic idea....

- $\widetilde{\chi}^0 \to h/P + \nu$ **with** $m_{\widetilde{\chi}^0} \lesssim 20$ **GeV** $\Rightarrow$ **we need lighter** m_{h_i}/m_{P_i}
- **Light** $m_{h,P} \Leftarrow$ **small** λ**... we fixed** $\lambda_i = 0.11$

Ellis *et al.* Phys. Rev. D 39, 844 (1989)

- **Small** $\lambda \;\Rightarrow \nu^c \sim 1$ **TeV** $\Leftarrow$ **lighter** $\widetilde{\chi}^{\pm}$ **mass..**$\rightsquigarrow \mu(\sim 3\lambda\nu^c) \gtrsim 100$ **GeV... we fixed** $\nu_i^c = 780$ **GeV**

- **With** $2m_\tau \lesssim |m_{\widetilde{\chi}^0}\ (2\kappa\nu^c)| \lesssim 20$ **GeV and** $\nu_i^c \sim 1$ **TeV** $\Rightarrow 10^{-3} \lesssim |\kappa| \lesssim 10^{-2}$**.. we took** $\kappa_{111} = -0.0073$, $\kappa_{222} = -0.0075$, $\kappa_{333} = -0.0077$
- **Small** $\lambda \Rightarrow m_P^2 \sim -3m_{\widetilde{\chi}^0} A_\kappa/2$**... So** $2m_\tau \lesssim m_P \lesssim 2m_b \Rightarrow 0.4 \lesssim |A_\kappa(\mathrm{GeV})| \lesssim 30$
- $m_h^2 \sim m_{\widetilde{\chi}^0}^2 + m_{\widetilde{\chi}^0} A_\kappa/2$ **in the same limit.. we fixed** $A_\kappa = 5$ **GeV**

Escudero, López-Fogliani, Muñoz, Ruiz de Austri, JHEP 0812, 099 (2008); Ellis *et al.* Phys. Rev. D 39, 844 (1989)

- $\tan\beta = 3.7$ **and** $A_\lambda = 990$ **GeV, can be varied without drastic alteration to the proposed signal... e.g.** $980 \lesssim A_\lambda \lesssim 1040$ **GeV for fixed** $\tan\beta, \nu^c, \lambda, \kappa, A_\kappa$
- **Gaugino unification at GUT scale and** $M_2 = 500$ **GeV...... singlet like** $\widetilde{\chi}^0$ **with** $|2\kappa\nu^c| << |\mu|, |M_{\mathrm{gaugino}}|$
- $m_{\tilde{e}^c} = m_{\tilde{u}^c} = m_{\tilde{d}^c} = m_{\tilde{Q}} = 1$ **TeV,** $A_e = A_d = -A_\nu = 1$ **TeV and** $A_u = 2.4$ **TeV.**

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

Looking for the spectrum......contd...

- **Large A_u and $m_{\widetilde{u}^c}, m_{\widetilde{Q}} \Rightarrow m_{h_4} \sim 125$ GeV for smaller λ**

☹**With smaller λ.... an extra piece of contribution to tree level m_{h_4} is irrelevant...even with small** tanβ

Drees, Int. J. Mod. Phys. A 4, 3635 (1989)

- **Y_ν, ν are constrained to reproduce correct neutrino data**
- **Variation in $Y_\nu, \nu \Rightarrow$ change in absolute m_ν... change in $\Gamma_{\widetilde{\chi}^0_4}$... altered l_{DL}**
- **Flavour information of the signal is practically independent of Y_ν, ν since leptons are from h/P decay.... missing correlation with neutrino mixing angles** ☹

Bandyopadhyay, PG, Roy, Phys. Rev. D 84, 115022 (2011)

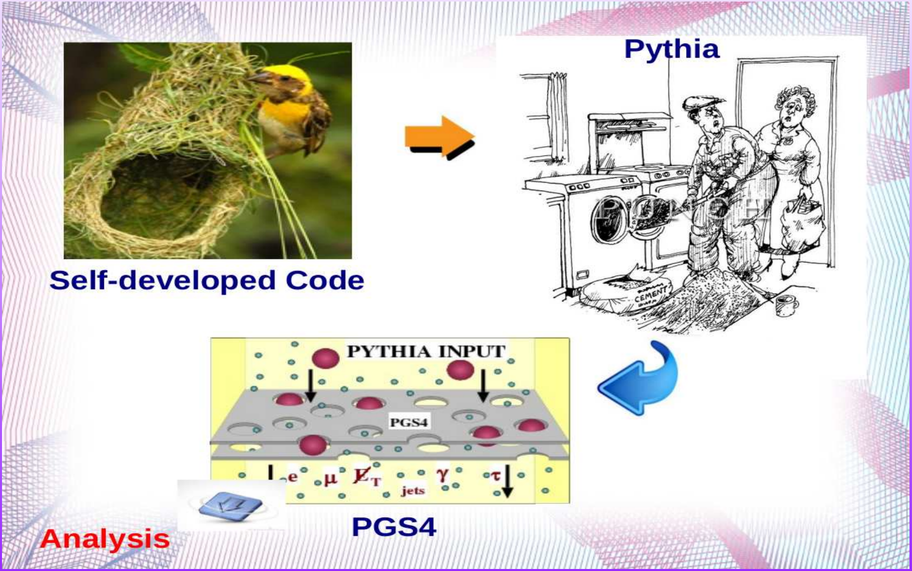
- **$\kappa > 0$ yields mainly $h_4 \to \widetilde{\chi}^0_6 \widetilde{\chi}^0_6$... followed by $\widetilde{\chi}^0_6 \to \widetilde{\chi}^0_{4,5} \mu^+ \mu^-$... hardly detectable soft μ... with small $\Delta m_{\widetilde{\chi}^0_{ij}}$.. $\Leftarrow \Delta\kappa_{ab} \to 0$... . thus ~~$\kappa > 0$~~**

Br($h_4 \to \widetilde{\chi}^0_4 \widetilde{\chi}^0_4$) $\approx 6\%$ at chosen benchmark... while $\widetilde{\chi}^0_4 \to \tau^+ \tau^- \nu \approx 99\%$

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

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

Following the footsteps.....



To kill the backgrounds......

Mesoscopic displaced vertex....

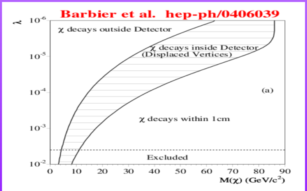
• All SM (e.g. ZZ^*)/SUSY backgrounds ($e.g.$ $h_1 \to P_1 P_1 \to 2\ell^+ 2\ell^-$@NMSSM), with prompt ℓ are effaced ... also long-lived b/c meson decays

• 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)

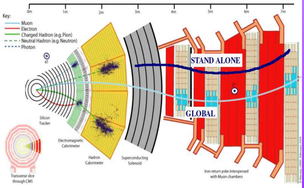
• NLSP $\to$ LSP + h/P, never produces mesoscopic decay length.... Eur. Phys. J. C 13, 681 (2000)

Displaced charge tracks....

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



Stand-alone muons...



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

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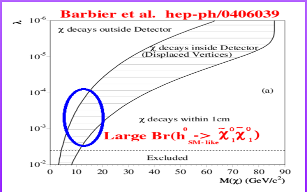
• NMSSM with $10^{-3} \lesssim \lambda \lesssim 10^{-2}$... light NLSP $\to$ LSP + h/P, with $h/P \to \ell^+\ell^-$ $\Rrightarrow$ a possible impostor.. Ellwanger, Hugonie, Eur. Phys. J. C 5, 723 (1998); Eur. Phys. J. C 13, 681 (2000)

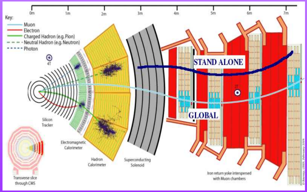
• NLSP $\to$ LSP + h/P, never produces mesoscopic decay length.... Eur. Phys. J. C 13, 681 (2000)

Displaced charge tracks....

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

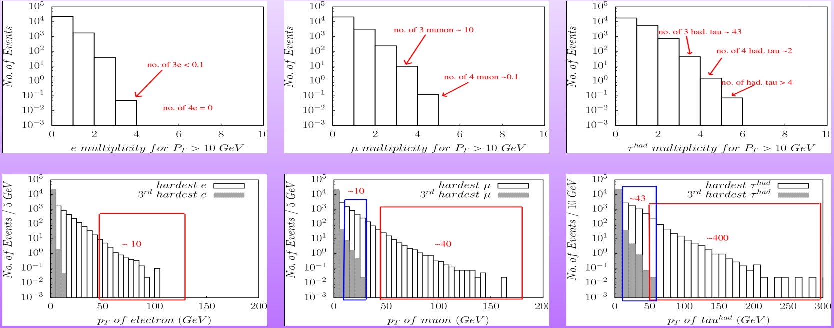


Stand-alone muons...



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

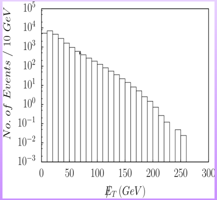
Lepton multiplicity... @8 TeV @20 fb^{-1}

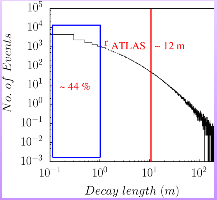


- e, μs are from leptonic τ decay.. although $h_i/P_i \to \mu^+\mu^-$ is possible
- $4e, 4\mu$s from $\tau \sim 0.1\%$ while $4\tau^{\rm had} \sim 18\%$
- Highly collimated QCD jets faking $\tau^{\rm had}$..... $\Longrightarrow$ $n^{\tau^{\rm had}} > 4$... disappears with higher $p_{\rm T}^{\tau^{\rm had}}$ cut
- $\tau^{\rm had}$'s are clearly the best bet... next one is of course μ

$\not{E}_T$, DL, $H_{\rm T}^{\ell}$

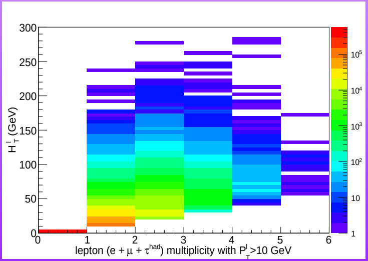
$\not{E}_T$ and DL distribution





- Moderately high MET $\Leftarrow$ $\gtrsim 6$ neutrinos 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

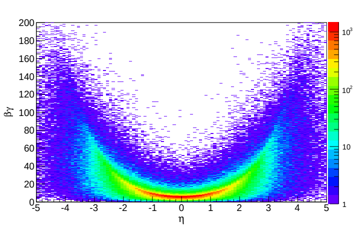
$H_{\rm T}^{\ell}$ ($\equiv \sum p_{\rm T}^{\ell}$) distribution



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

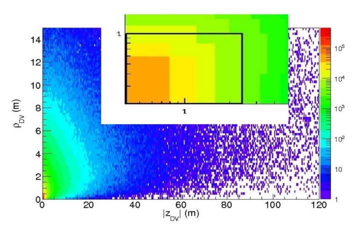
$\widetilde{\chi}_4^0$ decay kinematics

$\beta\gamma$ vs η



- Low momentum in the central region, single h_4 at the LHC
- High boost leads to collimated tracks ... hard to disentangle from PV

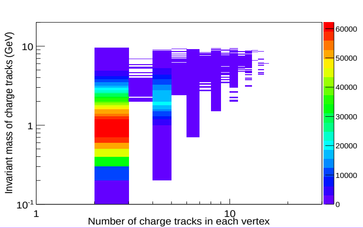
$|z_{\rm DV}|$ vs $\rho_{\rm DV}$



- 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
- It is possible to track this signal...☺

Probing DVs

Charge track mass vs n_{trk}



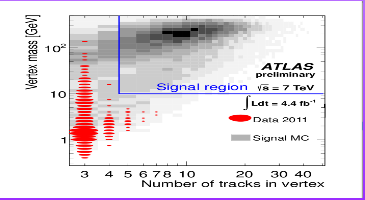
$n_{trk}^{vertex}|_{max} = 12$, four 3-prong τ decay

With large track multiplicity similar analysis with jets seem promising.. ...they are usually softer ☹

- A very useful event selection criteria

☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... G. Aad *et al.* [ATLAS], Phys. Lett. B 719, 280 (2013)

- Room for development... sensitivity to low vertex mass



ATLAS-CONF-2012-113

Summary and conclusion...... and beyond

• $\mu\nu$SSM.... solves μ-problem and reproduce correct neutrino physics

• Novel signals are well expected with enriched mass spectrum and broken R_p

• Displaced objects at the LHC $\Rightarrow$ lesser backgrounds.. new signs are well envisaged

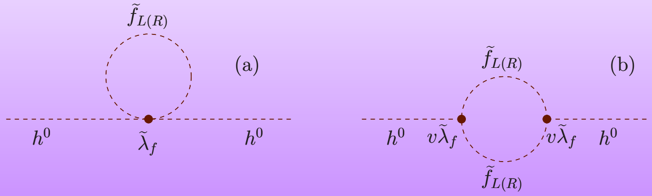
• Sophisticated analysis of displaced objects are expected in near future

• 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..

Loop corrections in SUSY

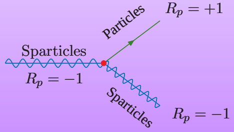


New one-loop radiative corrections to Higgs boson in SUSY

- 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



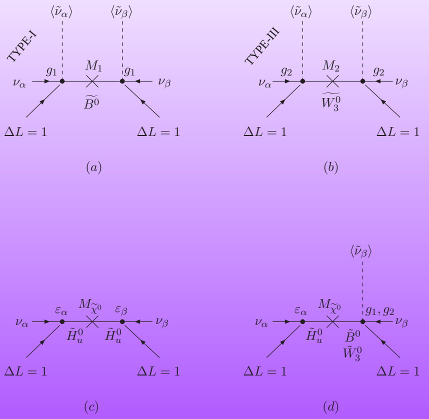
R_p **conserved** R_p **violated**

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

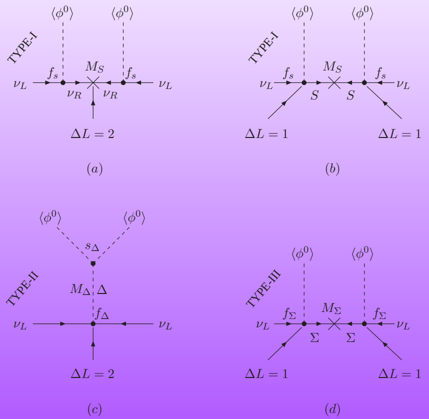
$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c - \mu\hat{H}_d^a\hat{H}_u^b)$$

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

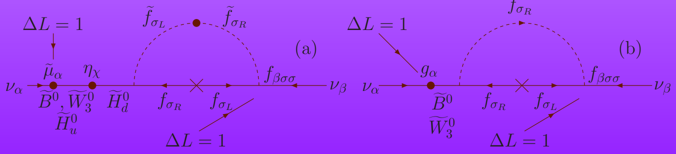
$m_\nu \neq 0$



TYPE-I
$\langle\tilde{\nu}_\alpha\rangle$ $\langle\tilde{\nu}_\beta\rangle$
g_1 M_1 g_1
ν_α ν_β
$\widetilde{B}^0$
$\Delta L = 1$ $\Delta L = 1$
(a)
TYPE-III
$\langle\tilde{\nu}_\alpha\rangle$ $\langle\tilde{\nu}_\beta\rangle$
g_2 M_2 g_2
ν_α ν_β
$\widetilde{W}^0_3$
$\Delta L = 1$ $\Delta L = 1$
(b)
ε_α $M_{\widetilde{\chi}^0}$ ε_β
ν_α ν_β
$\tilde{H}^0_u$ $\tilde{H}^0_u$
$\Delta L = 1$ $\Delta L = 1$
(c)
$\langle\tilde{\nu}_\beta\rangle$
ε_α $M_{\widetilde{\chi}^0}$ g_1, g_2
ν_α ν_β
$\tilde{H}^0_u$ $\tilde{B}^0$ $\tilde{W}^0_3$
$\Delta L = 1$ $\Delta L = 1$
(d)



TYPE-I
$\langle\phi^0\rangle$ $\langle\phi^0\rangle$
f_s M_S f_s
ν_L ν_R ν_R ν_L
$\Delta L = 2$
(a)
TYPE-I
$\langle\phi^0\rangle$ $\langle\phi^0\rangle$
f_s M_S f_s
ν_L S S ν_L
$\Delta L = 1$ $\Delta L = 1$
(b)
TYPE-II
$\langle\phi^0\rangle$ $\langle\phi^0\rangle$
s_Δ
M_Δ Δ
f_Δ
ν_L ν_L
$\Delta L = 2$
(c)
TYPE-III
$\langle\phi^0\rangle$ $\langle\phi^0\rangle$
f_Σ M_Σ f_Σ
ν_L Σ Σ ν_L
$\Delta L = 1$ $\Delta L = 1$
(d)



$\Delta L = 1$
$\widetilde{f}_{\sigma_L}$ $\widetilde{f}_{\sigma_R}$
(a)
$\tilde{\mu}_\alpha$ η_χ $f_{\beta\sigma\sigma}$
ν_α ν_β
$\widetilde{B}^0, \widetilde{W}^0_3$ $\widetilde{H}^0_d$ f_{σ_R} f_{σ_L}
$\widetilde{H}^0_u$
$\Delta L = 1$
$\Delta L = 1$
$\widetilde{f}_{\sigma_R}$
(b)
g_α $f_{\beta\sigma\sigma}$
ν_α ν_β
$\widetilde{B}^0$ f_{σ_R} f_{σ_L}
$\widetilde{W}^0_3$
$\Delta L = 1$

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 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

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

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

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

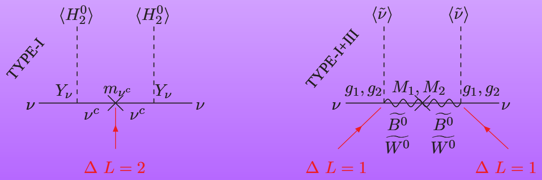
$$+ \left[\epsilon_{ab}(A_\nu Y_\nu)^{ij} H^b_u \tilde{L}^a_i \tilde{\nu}^c_j - \epsilon_{ab}(A_\lambda \lambda)^i \tilde{\nu}^c_i H^a_d H^b_u + \frac{1}{3}(A_\kappa \kappa)^{ijk}\tilde{\nu}^c_i\tilde{\nu}^c_j\tilde{\nu}^c_k + \text{H.c.}\right]$$

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

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

"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)



$m_\nu \sim \frac{Y_\nu^2 \langle H_2^0\rangle^2}{m_{\nu^c}}$ 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

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