Searching evidences of new physics in the light of the $\mu\nu$SSM

Pradipta Ghosh

IFT, UAM

Physics Challenges in the face of LHC-14
Madrid, September 25, 2014

Together.....

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

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

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

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

★ **At last a new scalar** PLB 716(2012) 1, 30

★ $\mu\ (ATLAS) = 1.30^{+0.18}_{-0.17}$,

$\mu\ (CMS) = 1.00^{+0.13}_{-0.13}$

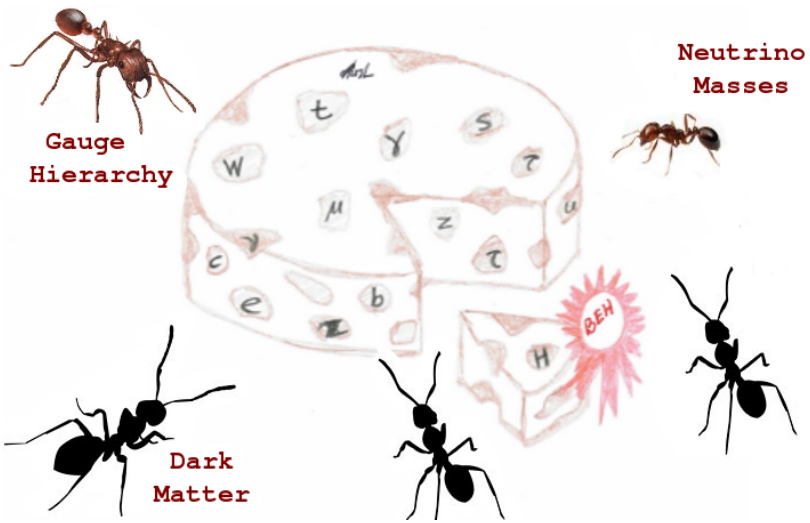
ATLAS-CONF-2014-009, CMS-PAS-HIG-14-009

★ $m_{\rm Higgs}\ (ATLAS) = 125.36^{+0.41}_{-0.41}$,

$m_{\rm Higgs}\ (CMS) = 125.03^{+0.29}_{-0.31}$

PRD 90 (2014) 052004, CMS-PAS-HIG-14-009

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



★ $\Gamma_H < 22$ MeV PLB 736 (2014) 64

★ $Br(\mathrm{H} \to X_{\mathrm{BSM}} X_{\mathrm{BSM}}) < 0.41$ (ATLAS), <0.58 (CMS)

ATLAS-CONF-2014-009, EPJ. C74 (2014) 2980

★ Large window for $\mu(\mathrm{H} \to b\bar{b})$

★ **An extension beyond the SM is still necessary**

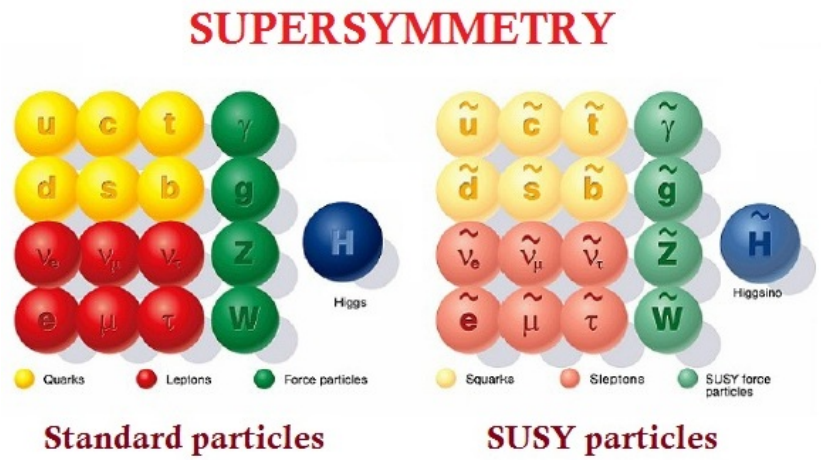
Beyond the SM with supersymmetry....

★ **Need two Higgs doublets...**

★ **Higgs mass is protected with super-partners**

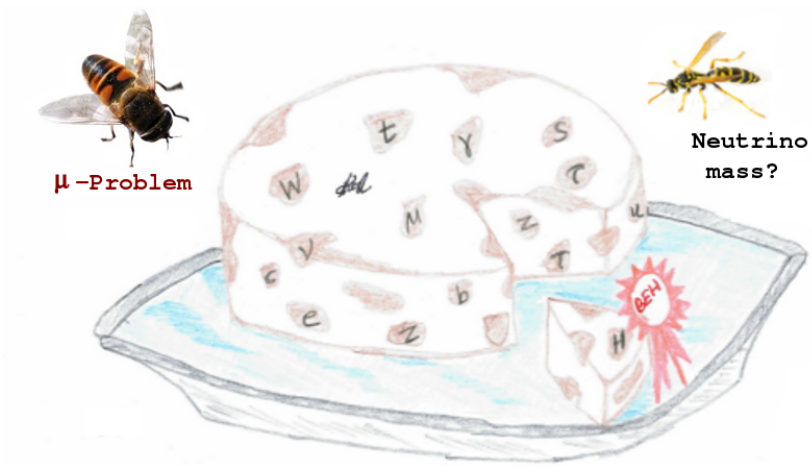
★ **The lightest supersymmetric particle as cold dark matter candidate**

★.....



Not the end of story....

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



★ μ determine EW-scale higgsino masses.. enters into EWSB $\Rightarrow$
μ must be around EW scale

★ μ belongs to superpotential.. respects SUSY $\Rightarrow$ μ can be as high as $M_{\rm Planck}$
So why the scale of $\mu \ll M_{\rm Planck}$ $\Rightarrow$
μ-problem Kim, Nilles, PLB 138 (1984) 150

★ m_ν $\Rightarrow$ extra fields or broken R_p

★ bilinear $\not{R}_P$, MSSM $+ \epsilon^i \hat{L}_i^a \hat{H}_u^b$
ϵ-problem... Loop corrections are essential..

★ trilinear $\not{R}_P$, MSSM $+ \frac{1}{2}\lambda_{ijk}\hat{L}_i^a\hat{L}_j^b\hat{e}_k^c$
and/or $\lambda'_{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{d}_k^c$ Loop generated m_ν...,
Many parameters, Less predictive....

Need an economic way to accommodate everything together...

Introducing $\mu\nu$SSM

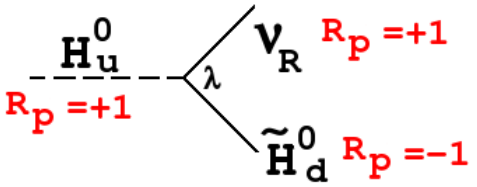
$$W = W^{\rm MSSM} - \epsilon_{ab}\mu \hat{H}_d^a \hat{H}_u^b + \epsilon_{ab}\Big(\underbrace{\overbrace{Y_{\nu_{ij}} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c}^{m_{D_{ij}} = Y_{\nu_{ij}} \langle H_u^0 \rangle}}_{\epsilon^i_{\rm eff} = Y_{\nu_{ij}} \langle \tilde{\nu}_j^c \rangle} - \underbrace{\overbrace{\lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b}^{\not{R}_p \text{ with } \Delta L=1}}_{\mu_{\rm eff} = \lambda_i \langle \tilde{\nu}_i^c \rangle}\Big) + \underbrace{\overbrace{\frac{1}{3}\kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c}^{\not{R}_p \text{ with } \Delta L=3}}_{m_{\nu^c_{ij}} = 2\ \kappa_{ijk} \langle \tilde{\nu}_k^c \rangle}$$

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

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

VEVs after EWSB: $\langle H_d^0 \rangle = v_d\,, \quad \langle H_u^0 \rangle = v_u, \quad \langle \tilde{\nu}_i \rangle = \nu_i\,, \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c$

μ-problem is solved with $\not{R}_P$ term $\Rightarrow$



$$m_\nu \sim \frac{(Y_\nu v_u)^2}{m_{\nu^c}}$$

10^{-6} Same as Y_e; 10^2 GeV; 10^3 GeV

$$m_\nu \sim \frac{(g_{1,2}\nu_i)^2}{M_{1,2}}$$

$\mathcal{O}(1)$; 10^{-4} GeV; 10^3 GeV

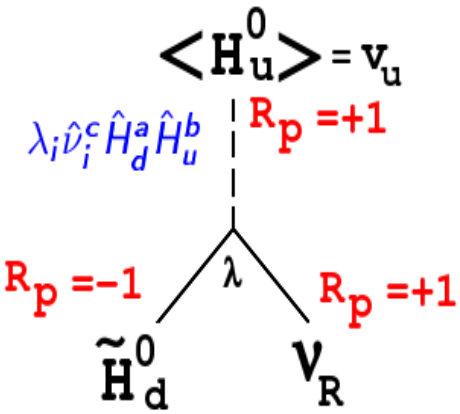
$m_\nu \sim 10^{-11}$ GeV $= 0.01$ eV

EW-scale seesaw

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

Particle spectrum of the $\mu\nu$SSM

$\not{R}_P$ + new superfields $\Rightarrow$ enhanced mass spectrum



- ★ h^0, H^0 + 3 $\tilde{\nu}_i^c$ + 3 $\tilde{\nu}_L^i$ $\Longrightarrow$ 8 CP-even states h_α
- ★ A^0+ 3 $\tilde{\nu}_i^c$ + 3 $\tilde{\nu}_L^i$ $\Longrightarrow$ 7 CP-odd states P_α
- ★ $H^\pm$ + 3 $\tilde{e}_L^i$ + 3 $\tilde{e}_R^i$ $\Longrightarrow$ 7 charged states $S_\alpha^\pm$
- ★ $\widetilde{H}_{u,d}^0$, $\widetilde{W}_3^0$, $\widetilde{B}^0$ + 3 ν_{R_i} + 3 ν_{L_i} $\Longrightarrow$ 10 neutralinos $\widetilde{\chi}_\alpha^0$
- ★ $\widetilde{H}_{u,d}^\pm$, $\widetilde{W}^\pm$ + 3 $e_{L,R}^i$ $\Longrightarrow$ 5 charginos $\widetilde{\chi}_\alpha^\pm$

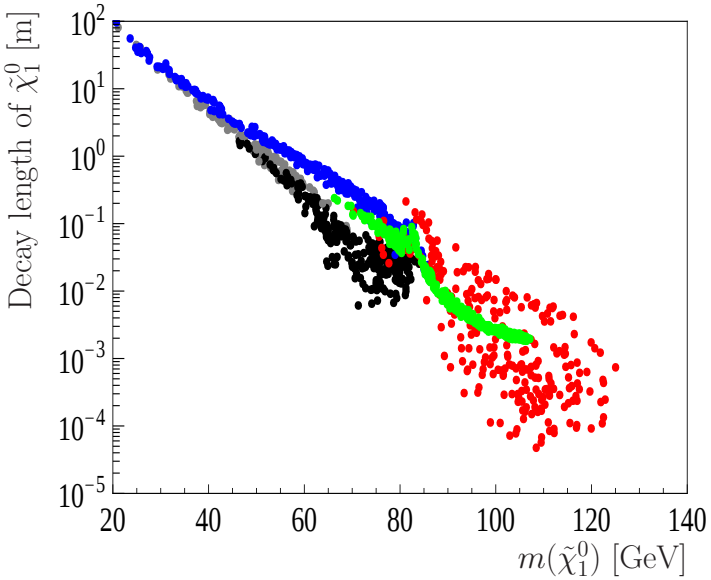
$\widetilde{\chi}_{1,2,3}^0 \equiv \nu_{L_i}$ and $\widetilde{\chi}_{1,2,3}^\pm \equiv e,\ \mu,\ \tau$

Lightest neutralino $\widetilde{\chi}_4^0$ and Lightest chargino $\widetilde{\chi}_4^\pm$

Novel signals with the $\mu\nu$SSM..... The proposal ...

- **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 $m_{\chi^0} < 40$ GeV... $l_{DL} \gtrsim 10$ m**
- **$d_{\rm ATLAS} \sim 25$ m $\Longrightarrow$ light $\widetilde{\chi}^0$ ($\lesssim 40$ GeV)...**

$\not{R}_P$ is an impostor to $R_p C$



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

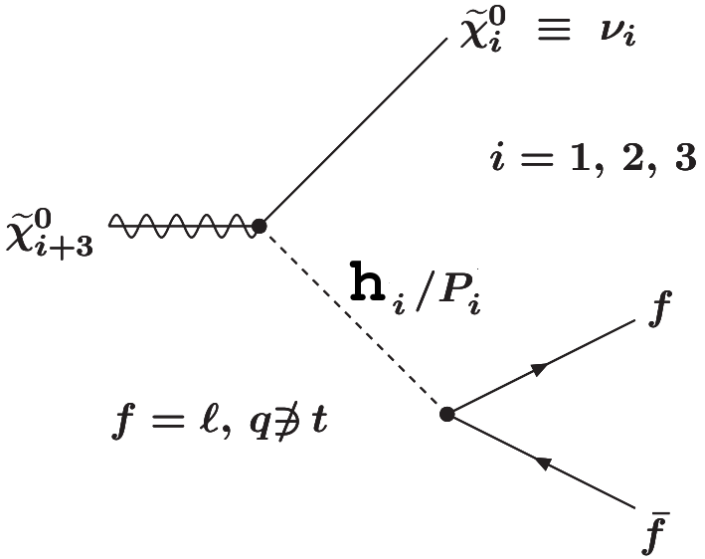
Figure. Decay length of the lightest neutralino $\tilde{\chi}^0_1$ in m as a function of its mass $m(\tilde{\chi}^0_1)$ in GeV. Note that the different colors stand for SPS1a' (real singlino, $|\mathcal{N}_{45}|^2 > 0.5$) (gray), SPS1a' (mixture state) (black), SPS3 (real singlino) (blue), SPS3 (mixture state) (red) and SPS4 (mixture state) (green).

Novel signals with the $\mu\nu$SSM..... The proposal ...

★ **A light $\widetilde{\chi}^0$ through $\widetilde{\chi}^0 \to h_i/P_i + \nu_L^i$ 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 (2013) 015009



PG *et al.* to appear in arXiv

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 (2013) 015009

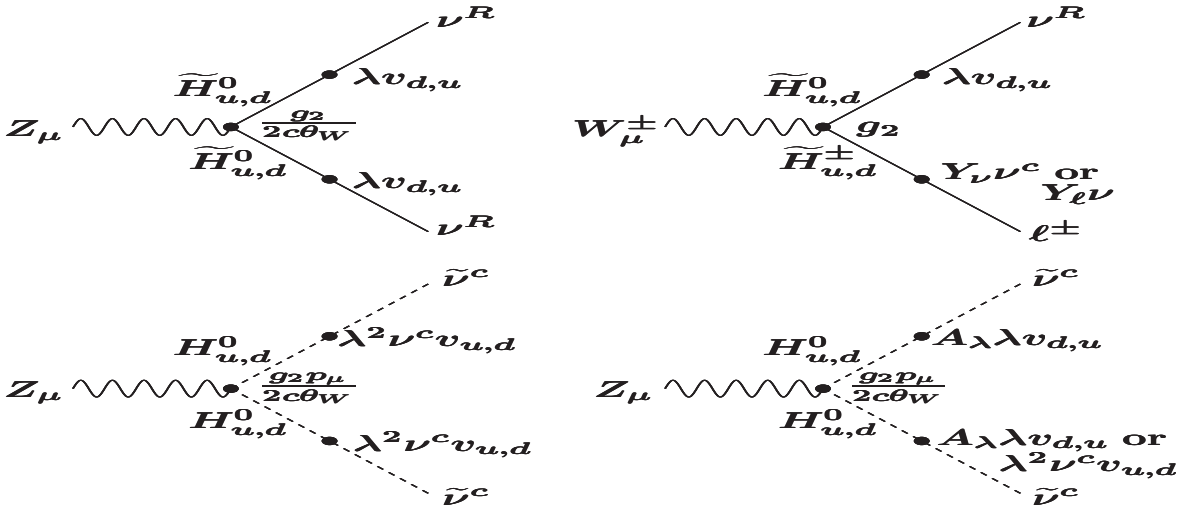
Setting up the convention... the signals

- **Small** κ, A_κ, λ_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 with $2m_\tau \lesssim m_{S^0_i,\, P^0_i} \lesssim M_Z/2$

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

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

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

- **Br($W^{\pm} \to x_D y_D + \not{E}_T + \ell_P^{\pm}$) $\sim \mathcal{O}(10^{-13})$ 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($B_s^0 \to \mu^+\mu^-$) $\sim \mathcal{O}(10^{-10})$

sensitive to η.... work in progress..

Probing new Z decays....

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

★ **Br($Z \to 2x_D 2y_D + \not{E}_T$) or Br($Z \to 2x_P 2y_P + \not{E}_T$) $\lesssim \mathcal{O}(10^{-5})$.... $x, y = \ell, \tau, q, \gamma$**

$Z \to 4b$ with $Br \approx 10^{-5}$, $\mathrm{E_{CM}} = 8$ TeV, $\mathcal{L} = 20.3$ fb^{-1}
1% detection efficiency $\mathrm{N_{event}} = 52$ events

The same with SM $\Rightarrow \mathrm{N_{event}} = 1853 \pm 669$ events

Similarly $Z \to 4\ell$ from $Z \to 4\tau$ (i.e. with $\tau \to \ell\nu_L\bar{\nu}_L$) with $Br \approx 10^{-5}$ at parton level
$\mathrm{N_{event}} \approx 77$ events while from the SM $\mathrm{N_{event}} \approx 2161^{+463}_{-411}$

Lost within the errors of the SM.... ☹ without proper detection

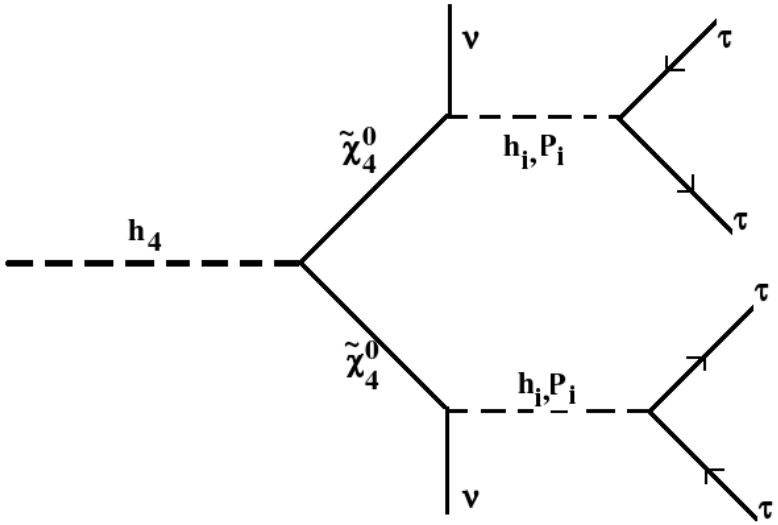
★ **Detection is possible at the LHC... novel future with LC-GigaZ and TLEP-TeraZ modes**

★ **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 (2014) 164

Experimental attention is needed to constrain $2m_\tau \lesssim m_{S_i^0, P_i^0} \lesssim M_Z/2$ region

The signals...contd.. back with Higgs



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

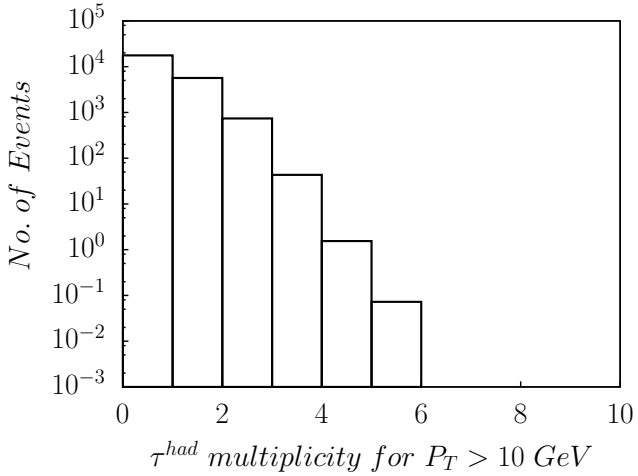
$$gg \longrightarrow h_4 \longrightarrow \tilde{\chi}_4^0 \tilde{\chi}_4^0 \longrightarrow 2h_i/P_i + 2\nu \longrightarrow 2\tau_D^+ 2\tau_D^- 2\nu$$

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}

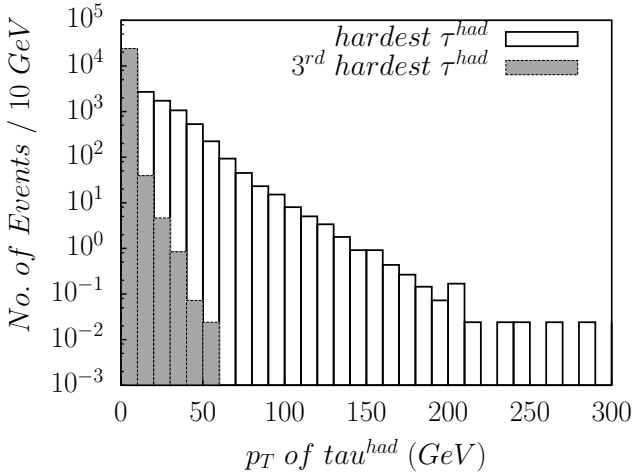
$\tau_{\rm had}$ **multiplicity**



- e, μs are from leptonic τ decay.. although $h_i/P_i \to \mu^+\mu^-$ is possible
- $4e, 4\mu$s from $\tau \sim 1.5\%$ 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

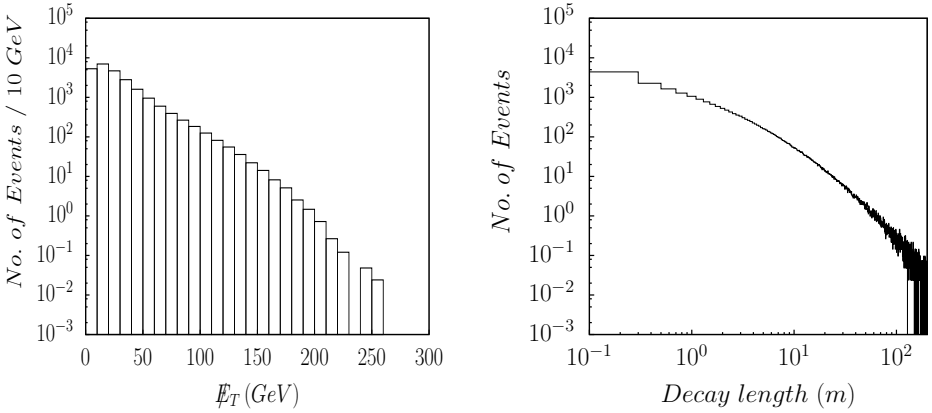
$p_{\rm T}^{\tau_{\rm had}}$ **distribution for 1st and 3rd leading** $\tau_{\rm had}$



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

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

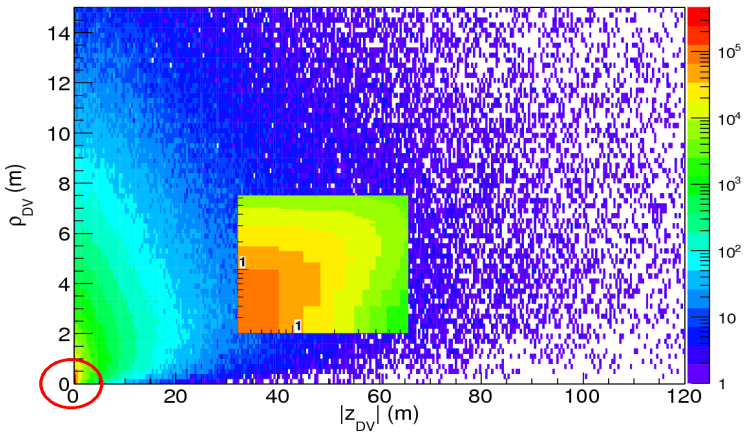
$\not{E}_T$ and DL distribution



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

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

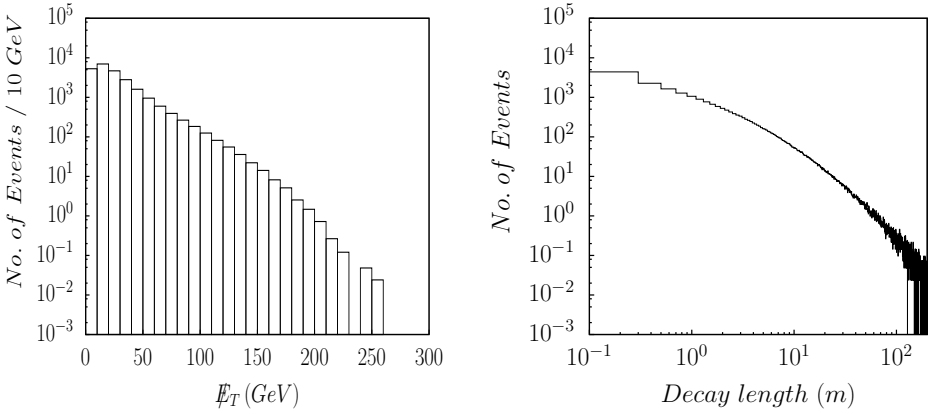
- A large fraction of DVs appear within $|z_{\rm DV}| \lesssim 2.5$ m and $\rho_{\rm DV} \lesssim 1$ m, i.e, in the range of inner tracker



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

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

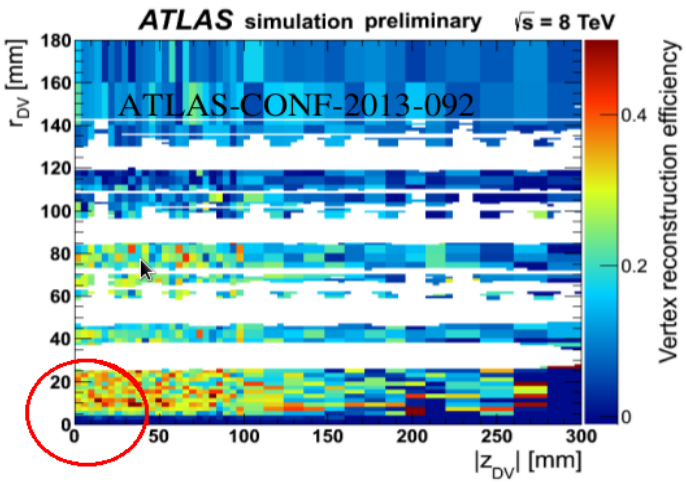
$\not{E}_T$ and DL distribution



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

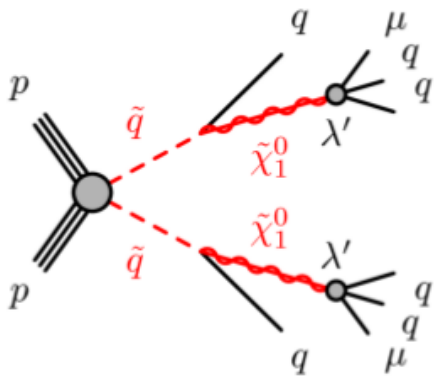
$|z_{\rm DV}|$ vs $\rho_{\rm DV}$

- 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

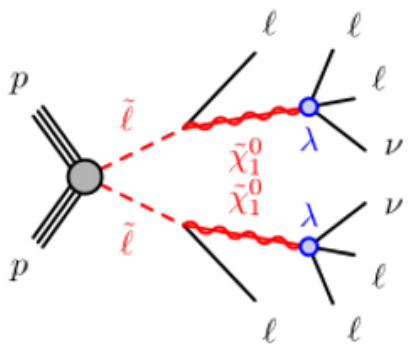


ATLAS-CONF-2013-092

Squark and Slepton pair production... in the $\mu\nu$SSM



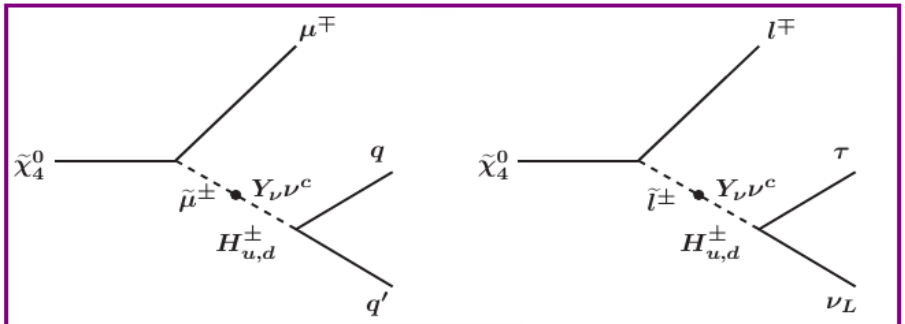
ATLAS-CONF-2013-092



PRD 90 (2014) 052001

★ **No longer required light h_i, P_i and $\widetilde{\chi}^0_{i+3}$ $\Rightarrow$ moderate to large values of λ, κ and A_κ parameters remain feasible**

Also possible with the $\mu\nu$SSM, following similar $\widetilde{q}$, $\widetilde{\ell}$ decay



PG, Kpatcha, López-Fogliani, Mitsou, Muñoz, Ruiz de Austri
Work in progress

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

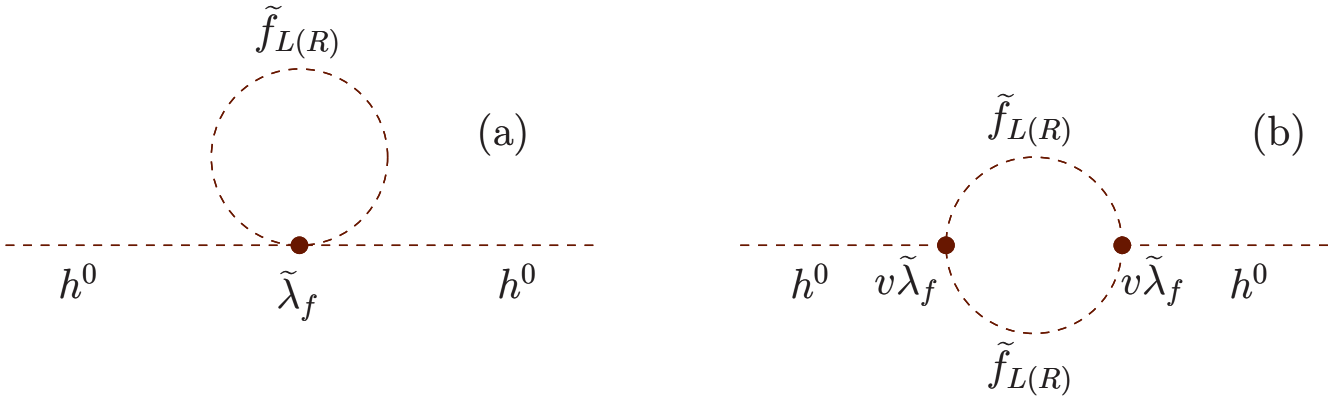
★ Displaced and/or soft objects at the LHC $\Rightarrow$ lesser backgrounds.. new signs are well envisaged but with sophisticated collider analyses of soft and/or displaced objects

★ Unique SUSY signatures $(\widetilde{l}, \widetilde{g})$ 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

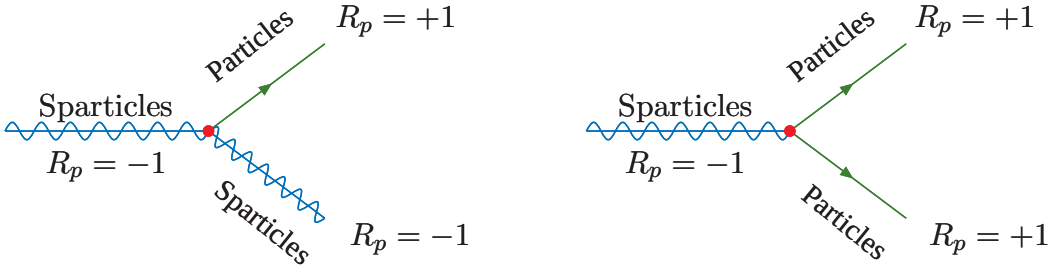


New one-loop radiative corrections to Higgs boson in SUSY

- **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** $\not{R}_P$

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

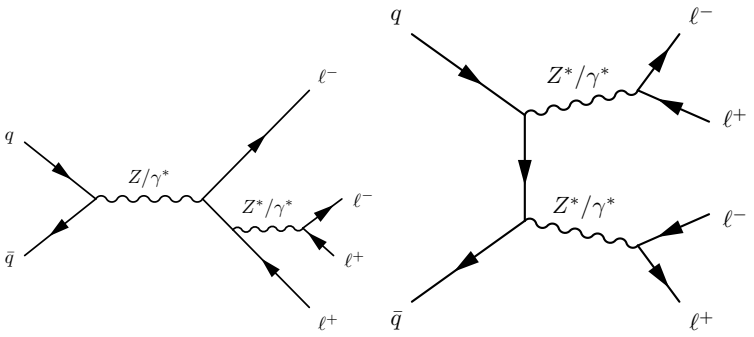
$$-\epsilon_{ab}(\underbrace{\epsilon^i\hat{L}_i^a\hat{H}_u^b}_{\Delta L=1,\Delta B=0} + \overbrace{\frac{1}{2}\lambda^{ijk}\hat{L}_i^a\hat{L}_j^b\hat{e}_k^c}^{\Delta L=1,\Delta B=0} + \underbrace{\lambda'^{ijk}\hat{L}_i^a\hat{Q}_j^b\hat{d}_k^c}^{\Delta L=1\Delta B=0,}) + \overbrace{\lambda''^{ijk}\hat{u}_i^c\hat{d}_j^c\hat{d}_k^c}^{\Delta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

The soft terms

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

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} = & (m^2_{\widetilde{Q}})_{ij}\widetilde{Q}^{a^*}_i\widetilde{Q}^a_j + (m^2_{\widetilde{u}^c})_{ij}\widetilde{u}^{c^*}_i\widetilde{u}^c_j + (m^2_{\widetilde{d}^c})_{ij}\widetilde{d}^{c^*}_i\widetilde{d}^c_j + (m^2_{\widetilde{L}})_{ij}\widetilde{L}^{a^*}_i\widetilde{L}^a_j \\
& + (m^2_{\widetilde{e}^c})_{ij}\widetilde{e}^{c^*}_i\widetilde{e}^c_j + m^2_{H_d}H^{a^*}_d H^a_d + m^2_{H_u}H^{a^*}_u H^a_u \quad + (m^2_{\widetilde{\nu}^c})_{ij}\widetilde{\nu}^{c^*}_i\widetilde{\nu}^c_j \\
& + \epsilon_{ab}\left[(A_u Y_u)_{ij}H^b_u\widetilde{Q}^a_i\widetilde{u}^c_j + (A_d Y_d)_{ij}H^a_d\widetilde{Q}^b_i\widetilde{d}^c_j + (A_e Y_e)_{ij}H^a_d\widetilde{L}^b_i\widetilde{e}^c_j + \textbf{H.c.}\right] \\
& + \left[\epsilon_{ab}(A_\nu Y_\nu)_{ij}H^b_u\widetilde{L}^a_i\widetilde{\nu}^c_j - \epsilon_{ab}(A_\lambda\lambda)_i\widetilde{\nu}^c_i H^a_d H^b_u + \tfrac{1}{3}(A_\kappa\kappa)_{ijk}\widetilde{\nu}^c_i\widetilde{\nu}^c_j\widetilde{\nu}^c_k \ + \textbf{H.c.}\right] \\
& \tfrac{1}{2}\left[M_1\widetilde{B}\widetilde{B} + M_2\widetilde{W}\widetilde{W} + M_3\widetilde{g}\widetilde{g} + \textbf{H.c.}\right]
\end{aligned}
$$

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



$\mathrm{Br}(Z \longrightarrow 4\ell) \lesssim 4.2^{+0.9}_{-0.8} \times 10^{-6}$

$\mathrm{Br}(Z \longrightarrow 4b) \lesssim 3.6^{+1.3}_{-1.3} \times 10^{-4}$

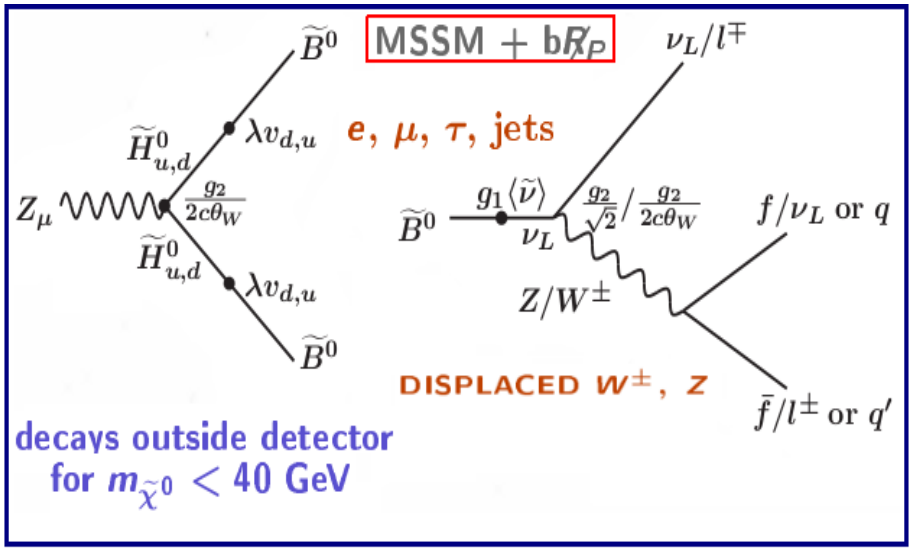
PDG, PRD 86 (2012) 010001

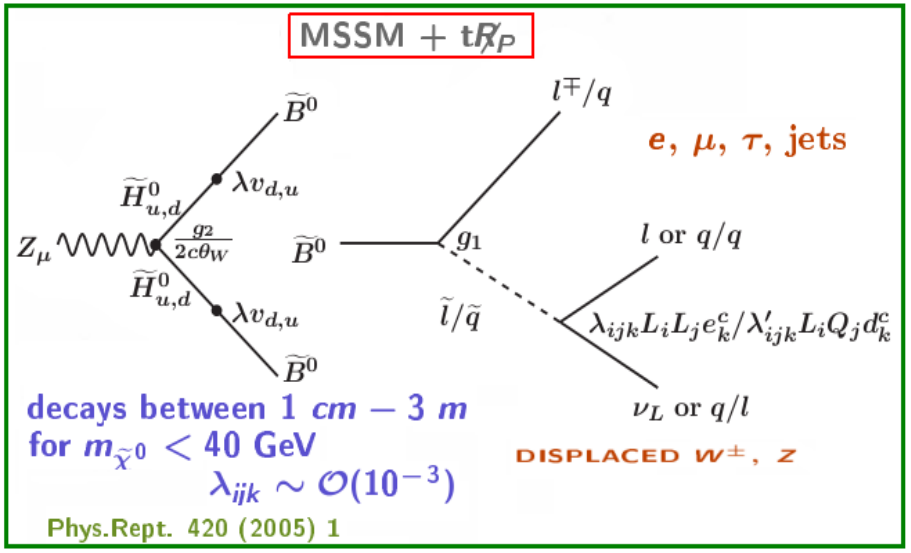
Latest LHC reporting... only e, μ

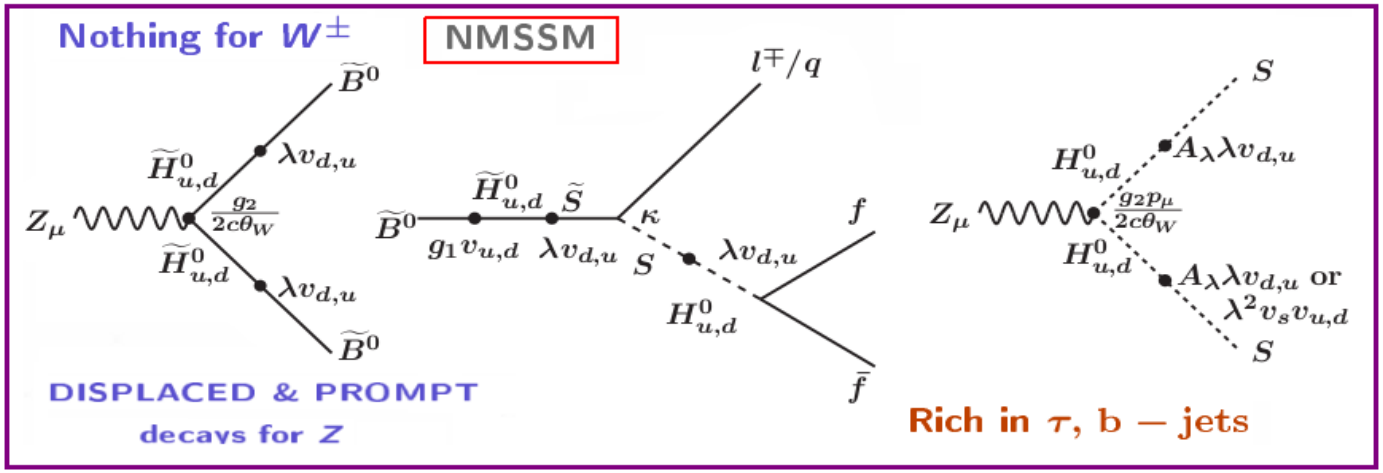
$\mathrm{Br}(Z \longrightarrow 4\ell) = 3.2^{+0.28}_{-0.28} \times 10^{-6}$

PRL 112 (2014) 231806

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







- NMSSM + $3\hat{\nu}^c$.. **DISPLACED & PROMPT Z decays, DISPLACED $W^{\pm}$ decays....**

Kitano, Oda, PRD 61 (2000) 113001

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]

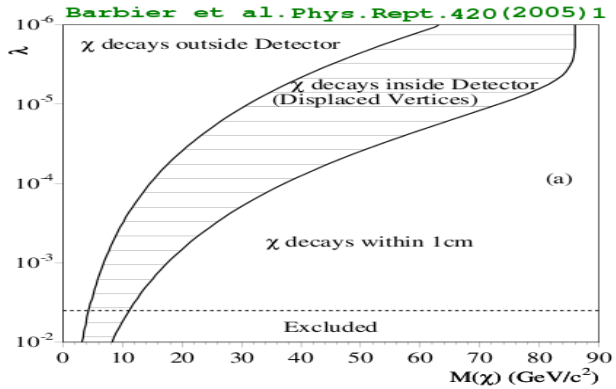
To kill the backgrounds.....Higgs

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

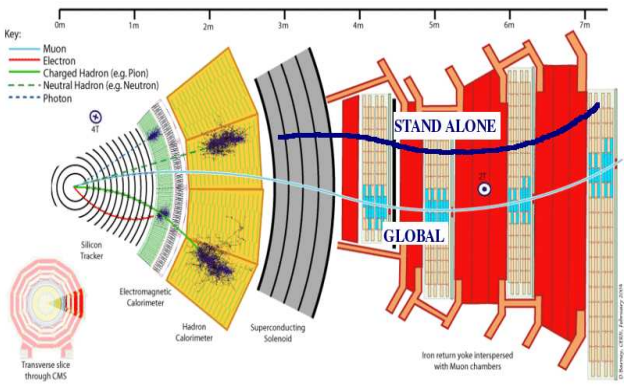
Irreducible impostor NMSSM $+ 3\nu^c$..
Kitano, Oda, PRD 61, 113001 (2000)

- **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 $h/P \to \ell^+\ell^-$ $\Rightarrow$ 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)

- **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 (2012) 199



Stand-alone muons...



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

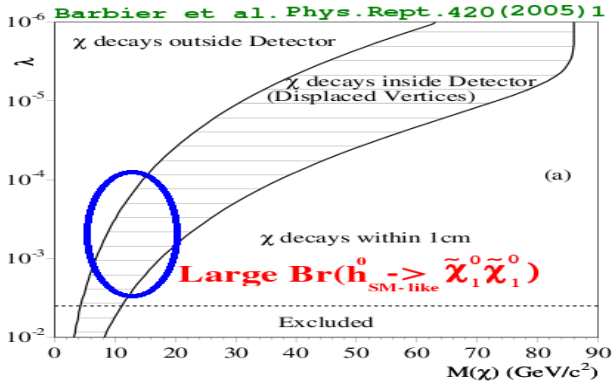
To kill the backgrounds.....Higgs

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

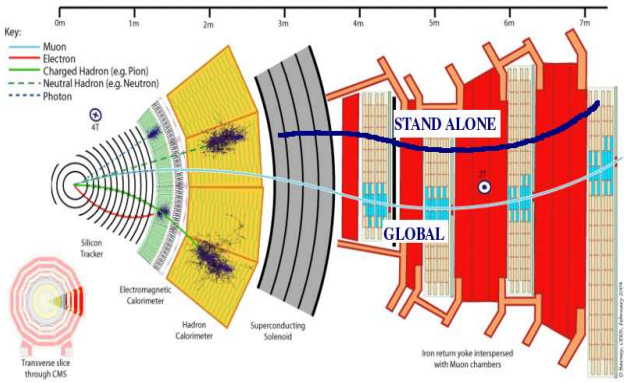
Irreducible impostor NMSSM $+ 3\nu^c$..
Kitano, Oda, PRD 61, 113001 (2000)

- **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 $h/P \to \ell^+\ell^-$ $\Rightarrow$ 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)

- **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 (2012) 199



Stand-alone muons...

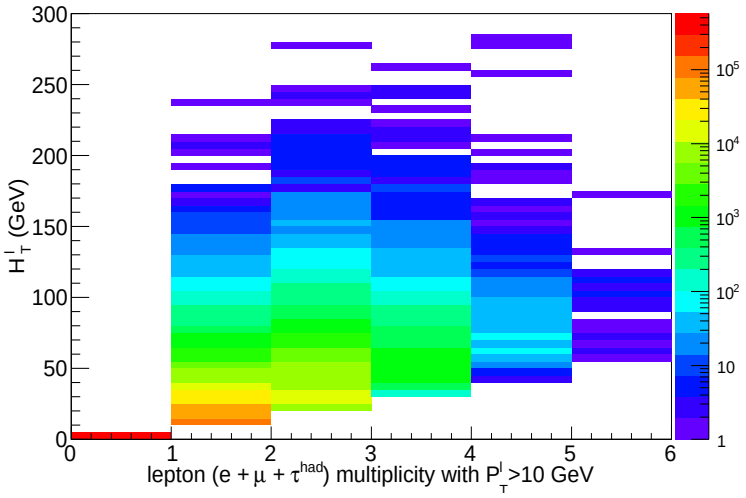


Bandyopadhyay, PG, Roy, PRD84, 115022 (2011)

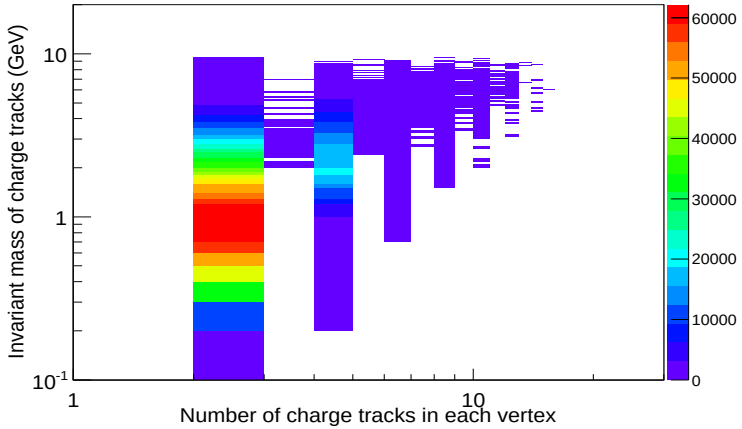
Probing DVs

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

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



Charge track mass vs n_{trk}



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

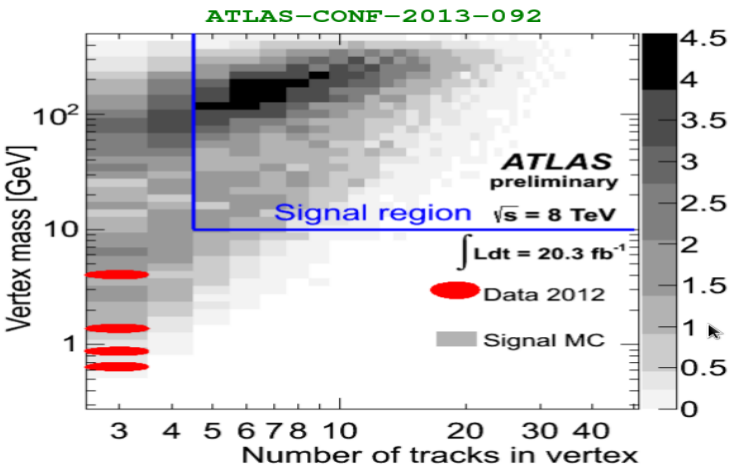
- A very useful event selection criteria

☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... ATLAS-CONF-2013-092

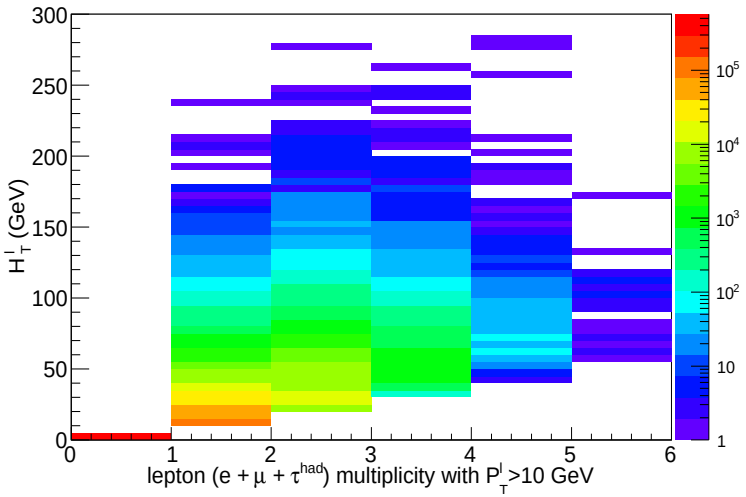
- Room for development... sensitivity to low vertex mass
- Life is better with jets

Probing DVs

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



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



- A very useful event selection criteria

☹ Sensitive for $n_{trk} > 4$ and vertex mass > 10 GeV... ATLAS-CONF-2013-092

- Room for development... sensitivity to low vertex mass
- Life is better with jets