Perspective of extended Higgs sectors in Super-Symmetric beyond Standard Model scenarios part-II

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Plan

- TMSSM: Triplino and singlino
- TNMSSM: Possible displaced vertex
- MSSM: Higgs sector CP-violation
- NMSSM: Spontaneous CP-violation

Neutralinos and charginos

- The extension of Higgs sector increases both neutralino and charging sectors

- Neutralios: $\tilde{B},\ \tilde{W}_3,\ \tilde{H}_u,\ \tilde{H}_d,\ \tilde{T}_0,\ \tilde{S}.$

Triplino & singlino

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_Y v_d & \frac{1}{2}g_Y v_u & 0 & 0 \\ 0 & M_2 & \frac{1}{2}g_L v_d & -\frac{1}{2}g_L v_u & 0 & 0 \\ -\frac{1}{2}g_Y v_d & \frac{1}{2}g_L v_d & 0 & \frac{1}{2}v_T\lambda_T - \frac{1}{\sqrt{2}}v_S\lambda_S & \frac{1}{2}v_u\lambda_T & -\frac{1}{\sqrt{2}}v_u\lambda_S \\ \frac{1}{2}g_Y v_u & -\frac{1}{2}g_L v_u & \frac{1}{2}v_T\lambda_T - \frac{1}{\sqrt{2}}v_S\lambda_S & 0 & \frac{1}{2}v_d\lambda_T & -\frac{1}{\sqrt{2}}v_d\lambda_S \\ 0 & 0 & \frac{1}{2}v_u\lambda_T & \frac{1}{2}v_d\lambda_T & \sqrt{2}v_S\lambda_{TS} & \sqrt{2}v_T\lambda_{TS} \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda_S & -\frac{1}{\sqrt{2}}v_d\lambda_S & \sqrt{2}v_T\lambda_{TS} & \sqrt{2}\kappa v_S. \end{pmatrix}$$

- Charginos: $\tilde{W}^+, \tilde{H}_u^+, \tilde{T}_2^+ (\tilde{W}^-, \tilde{H}_d^-, \tilde{T}_1^-)$

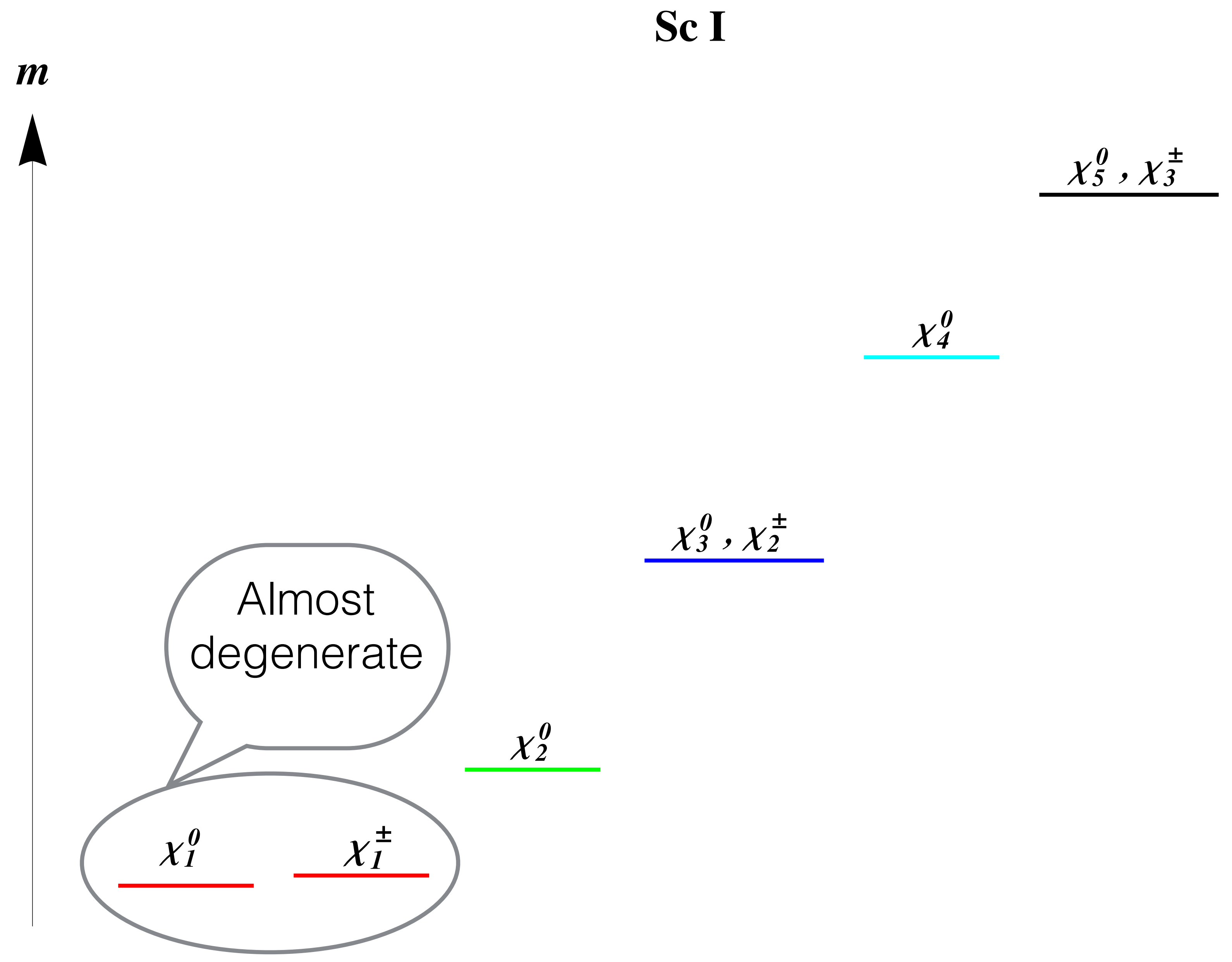
Triplino

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g_L v_u & -g_L v_T \\ \frac{1}{\sqrt{2}}g_L v_d & \frac{1}{\sqrt{2}}v_S\lambda_S + \frac{1}{2}v_T\lambda_T & \frac{1}{\sqrt{2}}v_u\lambda_T \\ g_L v_T & -\frac{1}{\sqrt{2}}v_d\lambda_T & \sqrt{2}v_S\lambda_{TS} \end{pmatrix}$$

Weakino spectrum

- Generic spectrum is very compressed

Benchmark Points	LSP mass (GeV)	NLSP mass (GeV)	NNLSP mass (GeV)	τ_{NLSP} (ns)	$c\tau_{NLSP}$ (cm)
BP1	542.30	542.50	864.70	0.79	23.61
BP2	561.12	561.54	651.82	0.022	0.646
BP3	530.75	530.94	771.40	1.21	36.15
BP4	498.38	498.53	722.40	3.27	97.76



- For a triplino-like LSP the NLSP is triplino-like chargino

- Very soft displaced charged leptons are produced

LHC Bounds from 3l , 2l signatures

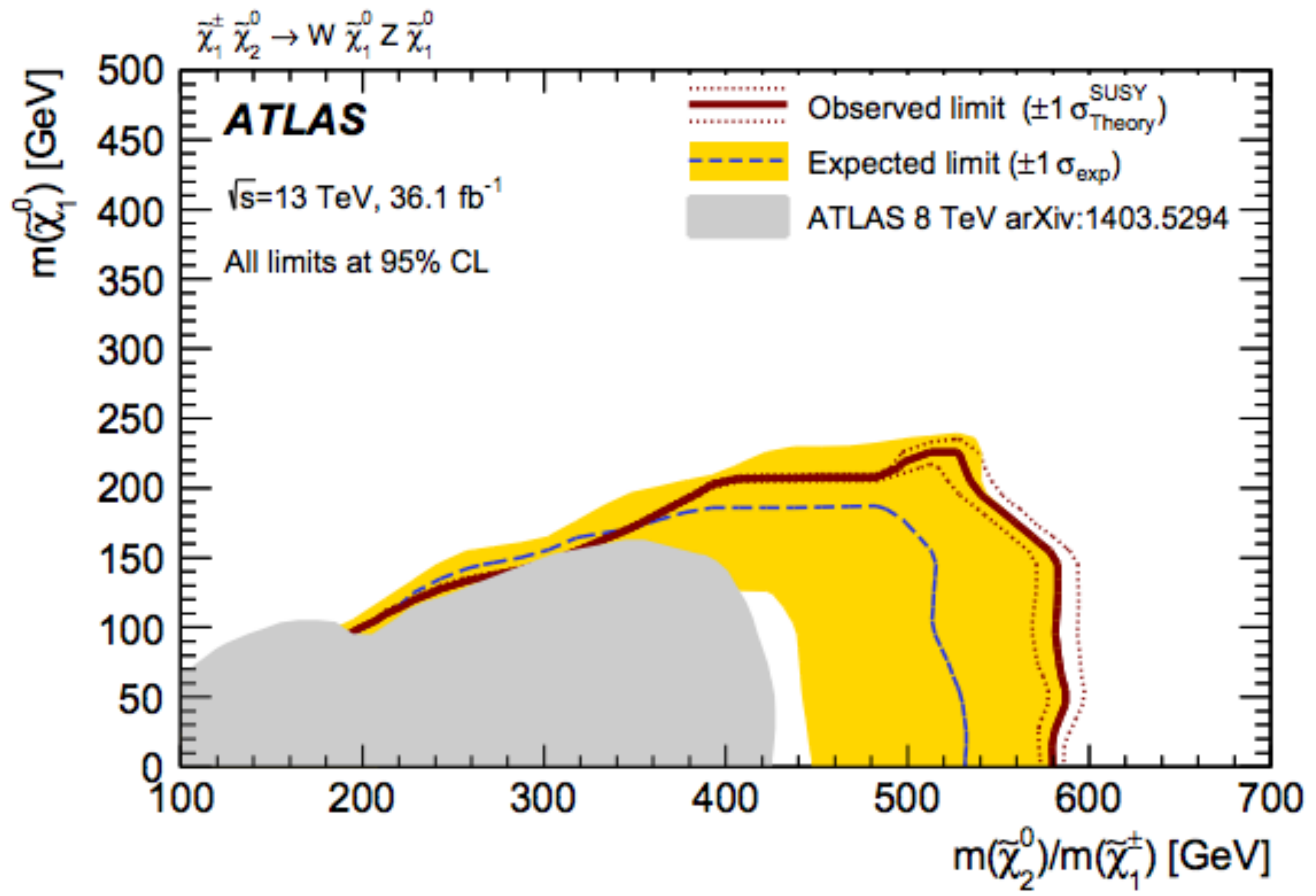
- ATLAS puts a bound at 36.1 1/fb of Ecm=13 TeV masses of NLPS < 580 GeV are ruled out for massless LSP

  arXiv:1803.02762 [hep-ex].

- The trigger used for these searches are with $p_T^\ell \geq 20 - 25\,\mathrm{GeV}$

- CMS also puts similar bounds

  JHEP03(2018)160



(d) 2ℓ+jets and 3ℓ channels: $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via W/Z

Triplinos with soft final states

- Triplino-type LSP decays to rather soft finalstates
- Often can be missed as they fall below the trigger cuts

- When the mass difference between chargino NLSP and LSP is O(150) MeV,

  $\tilde{\chi}_1^{\pm} \to \pi^{\pm} \tilde{\chi}_0$ mode is open and it becomes dominant

- Having very low momentum NLSP can just leaves a disappearing track in the detector

- The recoil by a hard ISR-jet or the boost of the final state particle can give some visibility to the finalstates.

Events with ISR jet

- Hard initial state radiation (ISR) can give the hard momentum recoil to the final state
- Without ISR jet as on shell particles are back to back and degenerate with LSP $\not{p}_T \simeq 0$
- The jets are leptons are also soft

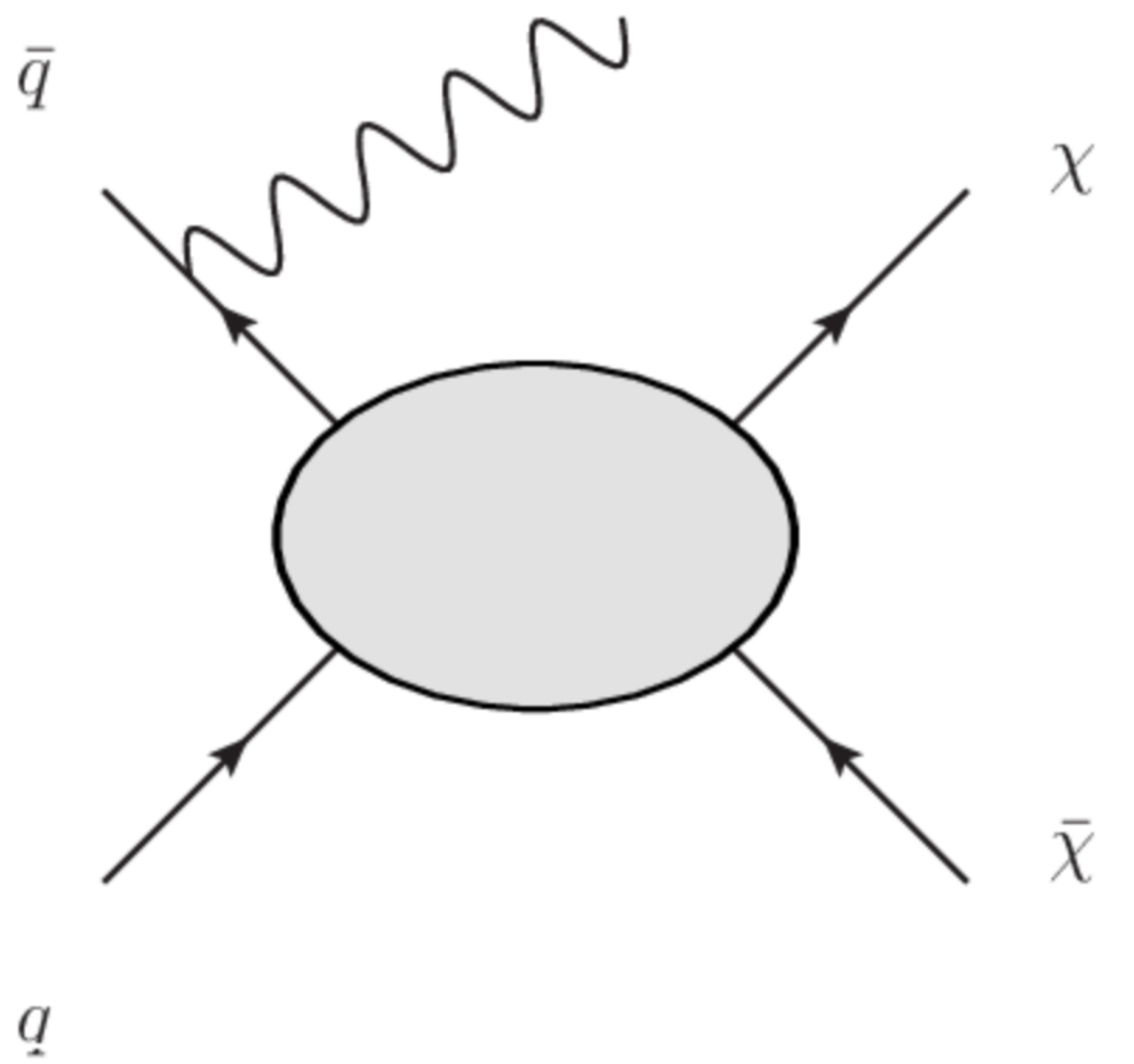
$$p_T^{\rm jets}, p_T^{\ell} \simeq 0$$

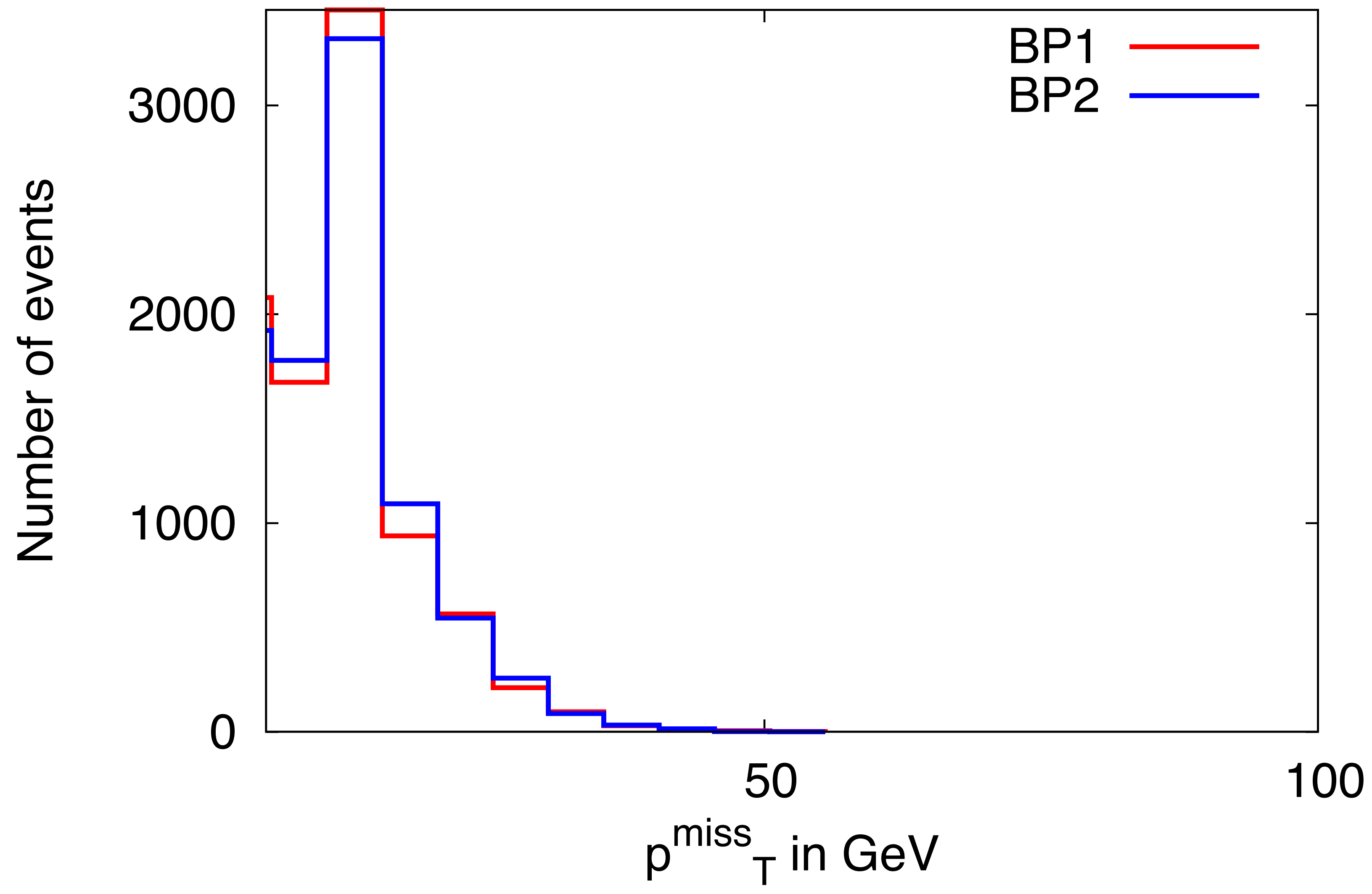
- But with a hard ISR jet,

$$\sum p_T^i = 0$$

$$p_T^{\rm ISR} + \underbrace{p_T^{\rm jets} + p_T^{\ell}} + \not{p}_T = 0$$

can be hard





Displaced Signature

- The displace decay can occur from 0.1 mm to 10 m

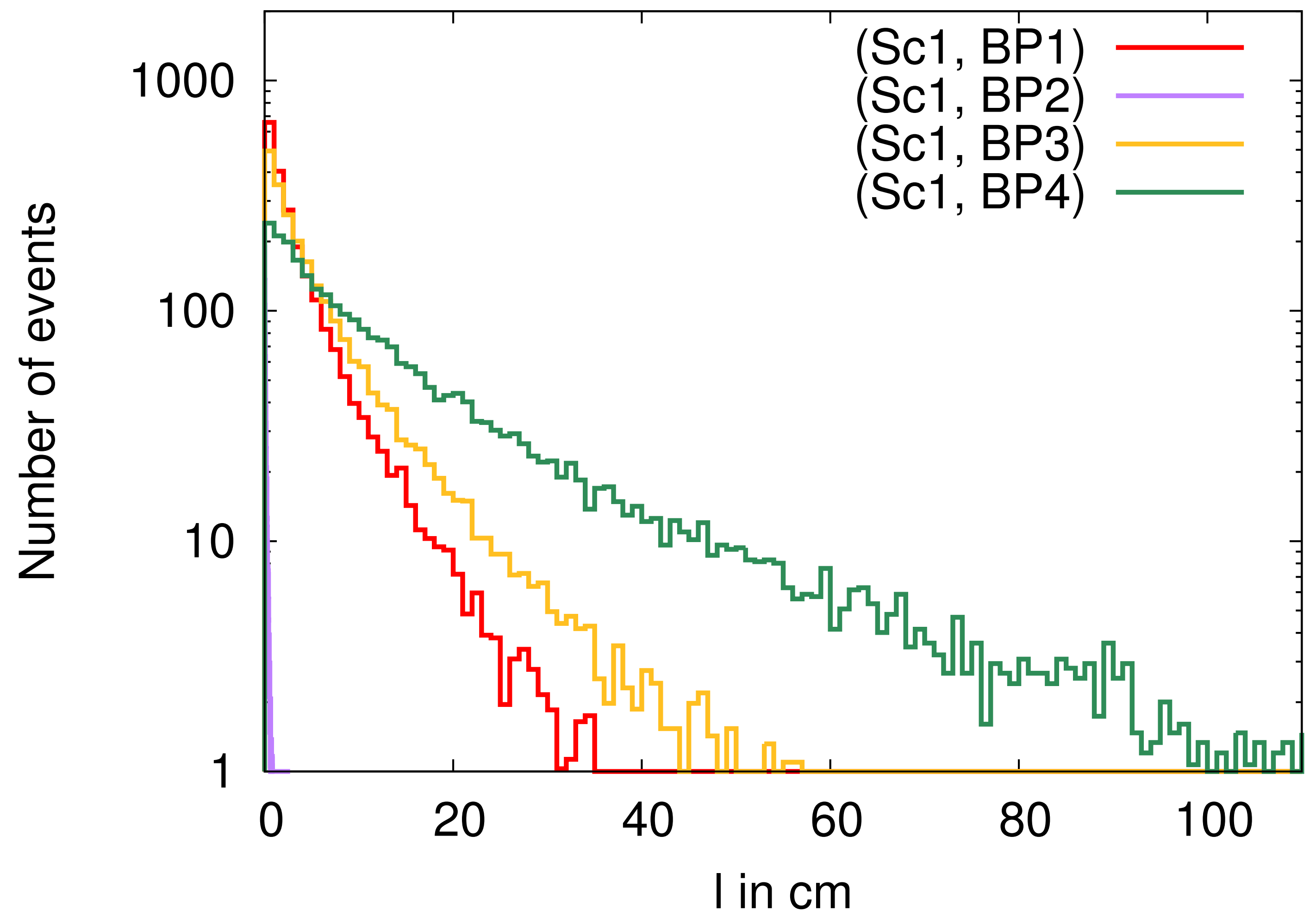
- Displaced charged tracks and decay signatures are Standard Model background free

- $\tilde{\chi}_1^{\pm} \to \ell^{\pm} \nu \tilde{\chi}_1^0$ can give rise to mono- or di-displaced charged leptonic signatures

- $\tilde{\chi}_1^{\pm} \to q q' \tilde{\chi}_1^0$ gives rise to displaced jets

- For neutralino NLSP we can get di-placed tri- and four-leptonic signatures via

$$\tilde{\chi}_2^0 \to \ell^+ \ell^- \tilde{\chi}_1^0$$



PB, K.Huitu, A.Sabanci, arXiv:1807:XXXXX

Prospect at the LHC

- Scenario 1: Triplino-type chargino NLSP- triplino LSP
- Scenario 2: Triplino-type neutralino NLSP - Bino LSP
- Scenario 3: Triplino-type chargino NLSP -Higgsino LSP
- Depending on scenarios and benchmark points these can probed at the LHC with very early data of 30-1000 1/fb with Ecm=14 TeV
- Soft lepton and jets can be produced from long lived particle
- Soft physics is important

PB, K.Huitu, A.Sabanci, Eur.Phys.J. C79 (2019) no.4, 345

CP-Violating Higgs sectors

CP-Violating MSSM

- CP-violation in nature is required to explain Baryogenesis
- δ_{CKM} is the only source of CP-violation in Standard Model
- In Minimal Supersymmetric extension of Standard Model(MSSM) is a good candidate as it can have many CP-phases through various soft terms and supersymmetric μ term.
- In the model considered here, Higgs sector CP-violation enters via loop effects

Possibilities of CP-violation in MSSM

The superpotential for the MSSM is

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d \,.$$

- Scalar potential

$$V = (|\mu|^2 + m^2_{H_u})|H_u^0|^2 + (|\mu|^2 + m^2_{H_d})|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

- Soft supersymmetry-breaking terms can introduce a large number of CP-violating phases not found in the Standard

- Minimization condition:

$$< H_u >= v_u, < v_d >= v_d e^{i\theta_1}, \quad b = |b| e^{i\theta_2}$$

$$Im\{bH_u H_d\} = 0 \implies \theta_1 + \theta_2 = 0$$

- No Higgs sector CP-violation at the tree-level

- In non-SUSY 2HDM we can have spontaneous CP-violation

Sources of CP violating phases in MSSM

- In the MSSM, CP-violating phases appear in the μ term of the superpotential,

$$W \supset \mu \hat{H}_u \cdot \hat{H}_d$$

- and in the soft-SUSY breaking terms as follows:

$$\begin{aligned}
-\mathcal{L}_{\rm soft} \supset\ & \\
& \frac{1}{2}\left(M_3\,\widetilde{g}\widetilde{g} + M_2\,\widetilde{W}\widetilde{W} + M_1\,\widetilde{B}\widetilde{B} + {\rm h.c.}\right) \\
& + \widetilde{Q}^\dagger\,\mathbf{M}^2_{\widetilde{\mathbf{Q}}}\,\widetilde{Q} + \widetilde{L}^\dagger\,\mathbf{M}^2_{\widetilde{\mathbf{L}}}\,\widetilde{L} + \widetilde{u}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{u}}}\,\widetilde{u}_R + \widetilde{d}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{d}}}\,\widetilde{d}_R + \widetilde{e}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{e}}}\,\widetilde{e}_R \\
& - m_1^2 H_d^* H_d - m_2^2 H_u^* H_u - \left(m_{12}^2 H_u H_d + {\rm h.c.}\right) \\
& + \left(\widetilde{u}_R^*\,\mathbf{A_u}\,\widetilde{Q} H_u - \widetilde{d}_R^*\,\mathbf{A_d}\,\widetilde{Q} H_d - \widetilde{e}_R^*\,\mathbf{A_e}\,\widetilde{L} H_d + {\rm h.c.}\right)
\end{aligned}$$

CP violating phases in MSSM

- Not all are independent.
- Physical observables depend on the two combinations:

$$\mathrm{Arg}(M_i \, \mu \, (m_{12}^2)^*) \,, \quad \mathrm{Arg}(A_f \, \mu \, (m_{12}^2)^*) \,,$$

  with $i = 1 - 3$ and $f = e, \mu, \tau; u, c, t, d, s, b$.
- Most relevant CP phases pertinent to the Higgs sector:

$$\Phi_i \equiv \mathrm{Arg}(M_i) \,; \quad \Phi_{A_{f_3}} \equiv \mathrm{Arg}(A_{f_3}) \,,$$

  with $f_3 = \tau, t, b$.

CP violating phases in MSSM

- CP violation in the Higgs potential of the MSSM leads to mixing terms between the CP-even and CP-odd Higgs fields.
  Pilaftsis, etal; 88,98
- In the weak basis (G^0, a, ϕ_1, ϕ_2), the neutral Higgs-boson mass matrix $\mathcal{M}_0^2$ may be cast into the form

$$\mathcal{M}_0^2 = \begin{pmatrix} \widehat{\mathcal{M}}_P^2 & \mathcal{M}_{PS}^2 \\ \mathcal{M}_{SP}^2 & \mathcal{M}_S^2 \end{pmatrix}$$

where,

$$\widehat{\mathcal{M}}_P^2 \Rightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \leftrightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \qquad \mathcal{M}_S^2 \Rightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \leftrightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\mathcal{M}_{PS}^2 = (\mathcal{M}_{SP}^2)^T \qquad \Rightarrow \begin{pmatrix} G^0 \\ a \end{pmatrix} \leftrightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

CP violating phases in MSSM

- Not all phases are independent.
- CP violation in the Higgs potential of the MSSM leads to mixing terms between the CP-even and CP-odd Higgs fields. Pilaftsis, etal; 88,98

$$\mathcal{M}_0^2 = \begin{pmatrix} \widehat{\mathcal{M}}_P^2 & \mathcal{M}_{PS}^2 \\ \mathcal{M}_{SP}^2 & \mathcal{M}_S^2 \end{pmatrix}$$

$$\Rightarrow M_{h_1} \leq M_{h_2} \leq M_{h_3} .$$

where these are not CP eigenstate.

- The mixing become significant when $(\mu A_t / M_{SUSY}^2)$ is large. and the lightest mass eigenstate becomes very light and also becomes mostly CP-odd and thus could have escaped detection at LEP. Carena,Pilaftsis, Ellis, Wagner

The CPX scenario

CPX Higgs

- A low lightest Higgs(h_1, $m_{h_1} \leq 60$ GeV)
- $Z - Z - h_1$ coupling goes down.

Associate Higgs Production

$$\begin{aligned} pp &\to \tilde{t}_1 \tilde{t}_1^* h_1 \\ \tilde{t}_1 &\to b\chi_1^+ \to bW^+\chi_1^0 \to b\ell^+\nu_\ell\chi_1^0 \\ h_1 &\to b\bar{b} \end{aligned}$$

- 4-b partons + dilepton + missing p_T can probe the 'hole' at LHC with $\mathcal{L}$=30fb^{-1}. P.B, AseshKrishna Datta, Amitava Datta, Biswarup Mukhopadhyaya; Phys. Rev. D 78, 015017 (2008)

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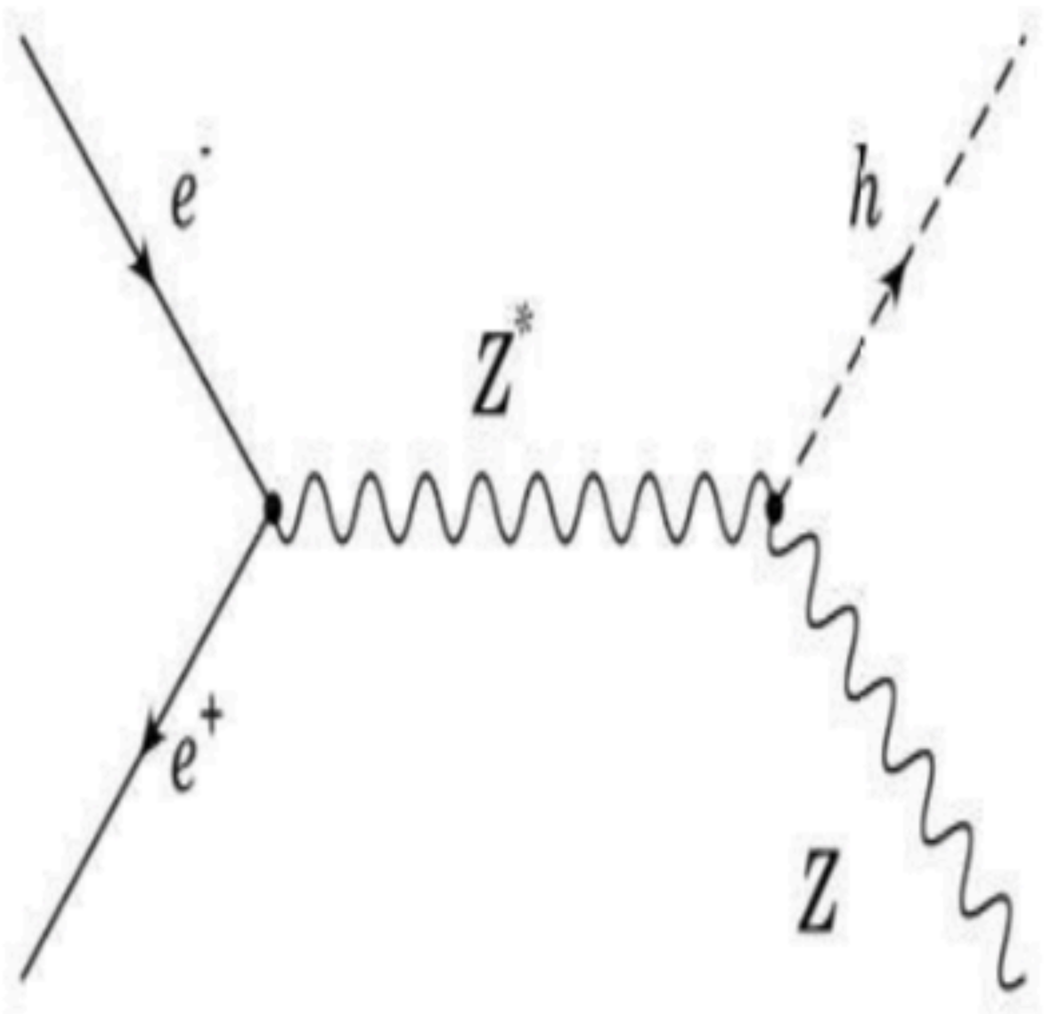

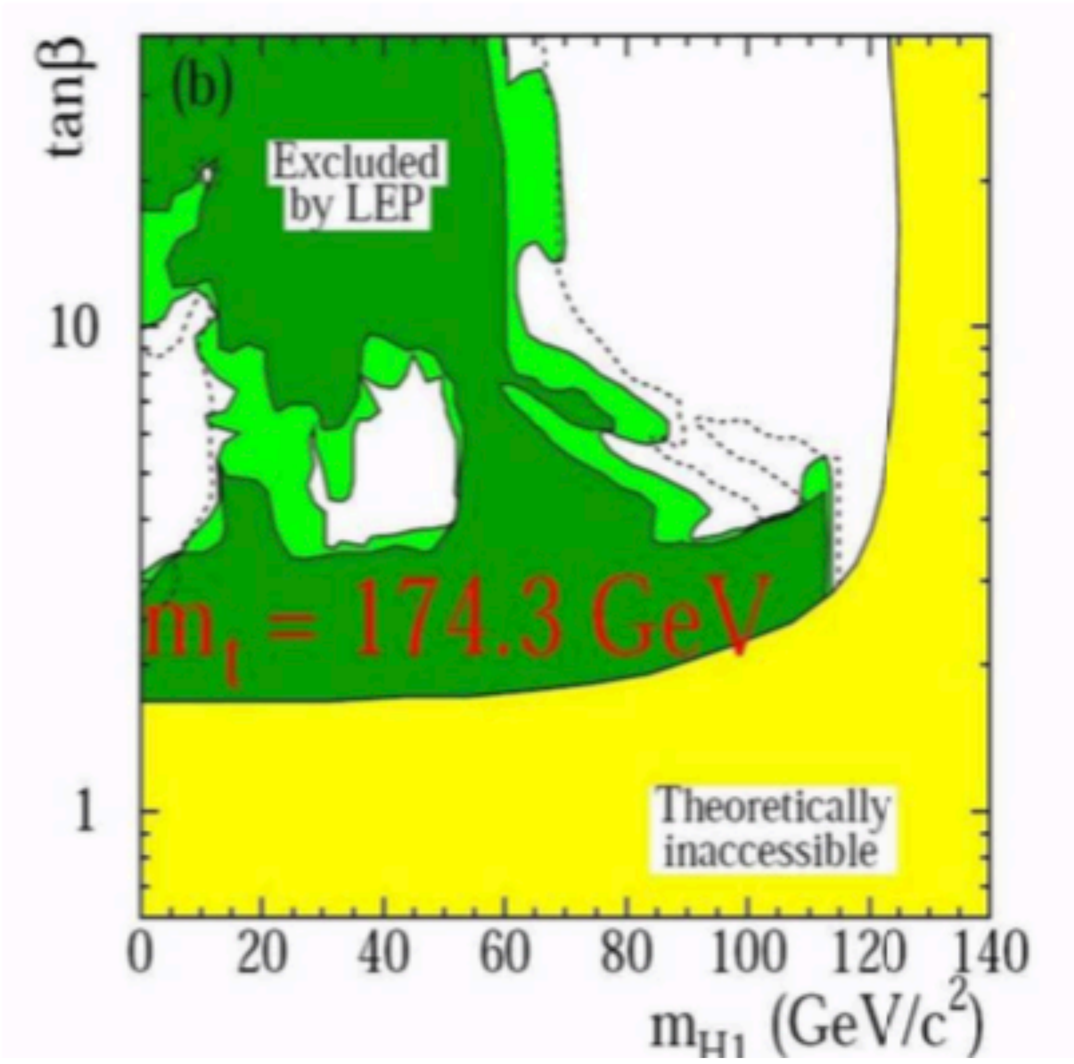

CP-violating Higgs production at the LHC

Higgs production in CPV-cascade decays

- Unlike MSSM, $H^{\pm} \to h_1 W^{\pm}$ mode is open here for light charged Higgs.
- Cascade decays of third generation squarks($\tilde{t_1}$ and $\tilde{b_1}$) and gluino($\tilde{g}$) could give signature at colliders.
- We produce at the LHC

$$pp \to \tilde{t_1}\tilde{t_1}^*,\ \tilde{b_1}\tilde{b_1}^*,\ \tilde{g}\tilde{g}$$

- Stop decays as:

$$\tilde{t_1} \to t\chi_1^0 / b\chi_1^+ \to bH^+ / W^- \chi_1^0$$

- Similarly, sbottom decays as:

$$\tilde{b_1} \to \tilde{t_1} H^-$$

- A multi-channel analysis shows that, 5σ significance can be achieve with an integrated luminosity of 5-10 fb^{-1}.
  P.Bandyopadhyay, JHEP08(2011)016

Two Higgses production

- Due to CP-mixing the heavier Higgses decay as: $h_{3,2} \to Z, h_1$.
- Unlike other processes Higgs pair production channels are clean
- We probe $pp \to h_1 h_{2,3}$ at the LHC.
  $\Rightarrow pp \to 4b + 2l$ signal topology.
  P.B, Katri Huitu; arXiv:1106.5108 [hep-ph]
- This scenario is getting more constrained with at least one Higgs around 125 GeV, flavour and EMD constraints.
  P.B, Katri Huitu; JHEP 1311 (2013) 058

Few comments

- One of Sakharov's condition: Departure from thermal equilibrium can be realized by the strong first order EWPT
- To have a first-order phase transition effective Higgs potential of the model should have several minima.
- Of special importance is the cubic term in effective potential

$$V_{eff}[\varphi, T] = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \ldots,$$

- In the Standard Model the cubic term, ET^3, is contributed only by the electroweak gauge bosons

$$v = 246\,\mathrm{GeV} \implies \mathrm{E} = \frac{2\mathrm{m_W^3} + \mathrm{m_Z^3}}{4\pi\mathrm{v^3}} \simeq 0.01$$

- Condition that the Higgs effective potential has two minima leads to the very small value for the Higgs self-coupling

$$\lambda \simeq 2E \simeq 0.02$$

- But $m_{h_{125}} = \sqrt{2\lambda}v = 125.5 \implies \lambda = 0.13$

- This means that within the Standard Model and MSSM the electroweak phase transition is a smooth crossover, i.e. of the second order
- For first order EWPT $m_{h_{SM}} \lesssim 73\,\mathrm{GeV}, \quad \mathrm{m_{h_{MSSM}}} \lesssim 53\,\mathrm{GeV}$

Conclusions

- So far we have observed one Higgs boson at 125 GeV
- More scalar is/are motivated from vacuum stability
- All standard and non-standard modes are yet to be explored
- Observation of Charged Higgs would be a direct proof of extended Higgs sector.
- Non-standard decay modes $h^\pm \to a_1 W^\pm$ and $h^\pm \to Z W^\pm$ are direct proofs of higher representations of Higgs sectors.
- Both SUSY and Non-SUSY Higgs extensions have their own merits
- Indirect searches can also give us some hints
- Electro-weak-ino sector has much more story to tell, so soft physics is important
- Finite temperature calculation along with CP-violation and Baryogenesis make such extensions very interesting


THANK
YOU!