Searching for the Light Higgsino at Future e-p Collider and QCD Axion in the MSSM

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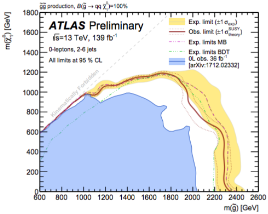
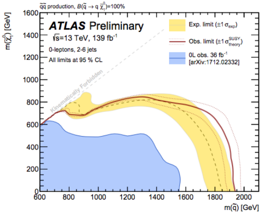
LHC Constraint

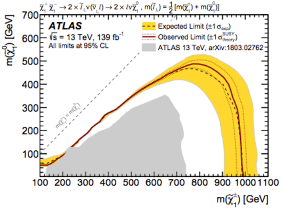
LHC with $\sqrt{s} = 13$ TeV has put stringent lower bounds on the supersymmetric particles, and excluded a large parameter space for the low-energy SUSY model.

- colored SUSY particles have been excluded to $\mathcal{O}(2.0 - 2.4\ \text{TeV})$ via jets or leptons plus $\not{E}_T$. (ATLAS-CONF-2019-040)
- electroweak SUSY particles, such as chargino, have been excluded to $\mathcal{O}(1\ \text{TeV})$ via multilepton plus $\not{E}_T$.(1908.08215)

Tagging leptons in the final states is crucial to suppress large backgrounds at the LHC.



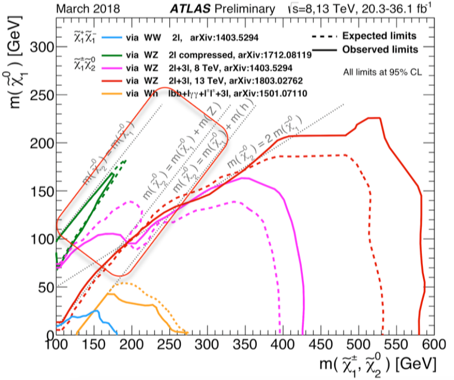




Search Corner: Light Higgsino

One well-known exception is the light Higgsino, which have a nearly degenerate spectrum and relatively small production rate.(FCCWeek BSM@FCC-eh Monica)

- In the limit of $\mu \ll M_1, M_2$ the low-energy charginos/neutralinos are all Higgsino-like and nearly degenerate.
- For example: $\mu = 100$ GeV, $M_1 = 2$ TeV, $M_2 = 2$ TeV, $A_t = 3$ TeV, and all of the other SUSY particles are set to 3 TeV, then $\tilde{\chi}_1^{\pm} \approx 102.6$ GeV, $\tilde{\chi}_2^0 \approx 104$ GeV, $\tilde{\chi}_1^0 \approx 101$ GeV.
- Invisible Higgsinos $\tilde{\chi}_1^0$: extremely soft leptons, not long-lived ($\tau_{\tilde{\chi}_1^{\pm}} \sim 10^{-14}$s)



In this case, we reckon leptons from $\tilde{\chi}_1^{\pm} \to W^{\pm *}\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z^*\tilde{\chi}_1^0$ are too soft to be detected.

Without the hard leptons, the general searches for such invisible Higgsinos at the LHC can be categorized into three subchannels:

- cascade decay of colored SUSY particles: gluino/squarks are heavy $\sim \mathcal{O}(\text{TeV})$, small rate.(1004.4902...)
- direct pair production: well-studied, additional object required (monojet, mono-γ/Z plus $\not{E}_T$), no kinematic features. (1310.4274,1409.7058...)
- weak boson fusion production: $2j + Z/W$ backgrounds, small rate, well kinematic features(1502.05044,1801.05432...)

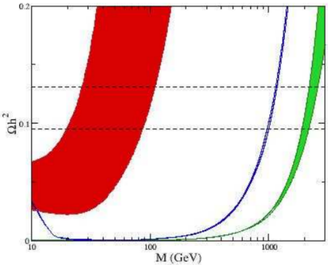
Moving to e-p collider to search such light Higgsinos: WBF process

- no color exchange ⇒ smaller QCD backgrounds
- dominant WBF production ⇒ larger production rate
- well kinematic features ⇒ forward/backward jet or electron tagging

Dark Matter Constraint

On the other hand, besides the direct limit at the colliders, the light Higgsino also receives constraints from dark matter direct detection experiments.

- relic density (blue band) ×
  - the correct relic density ⇔ Higgsino-like DM ∼ 1 TeV.
  - $\Omega_{\tilde{H}} h^2 \sim 0.1 \times (\frac{\mu}{1\,\text{TeV}})$, $\mu \sim 100$ GeV $\sim \mathcal{O}(1)\%$
    (Arkani-Hamed, Delgado, Giudice, 2006)
  - the light Higgsino only consists of a small portion of the dark matter and requires additional components.



- direct detection √
  - Evading this bound by the small portion and decoupling.
  - For example: $\mu = 120$ GeV, $M_1 = M_2 = 2$ TeV, $A_t = 4.5$ TeV, $m_{t_L} = m_{t_R} \sim 3$ TeV, the $\sigma_{SI} = 5 \times 10^{-48}$ cm^2 (the strongest exclusion limit is for 30 GeV WIMPs, at 4.7×10^{-47}cm^2 from XENON1T Experiment). (PRL.121(2018)no.11,111302)

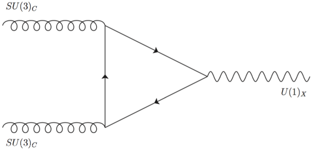
What is the other Dark Matter in the MSSM with the light Higgsino?

QCD axion in the MSSM automatically

In fact, if we introduced a new global $U(1)_{PQ}$ symmetry, QCD axion could be existed in the MSSM automatically.(Phys. Lett. 104B, 199 (1981))
the MSSM is a kind of 2HDM $\Rightarrow$ μ term $\sim \mu H_u H_d \Rightarrow$ under the new global $U(1)_X$ symmetry, the charge h_u, h_d of the two Higgs doublets H_u, H_d can not cancel each other

$$h_u + h_d \neq 0$$

- the bare μ term is forbidden.
- assuming $U(1)_X$ to be flavor independent.
- imposing the Yukawa couplings condition.



$$A_{SU(3)_C^2 \times U(1)_X} = -\frac{3}{2}(h_u + h_d) \neq 0$$

QCD anomaly $\Rightarrow U(1)_X \sim U(1)_{PQ} \Rightarrow$ pseudo-Goldstone boson – axion

To allow the electroweak symmetry breaking and the existence of the light Higgsinos, $\mu \sim$ EW scale $\sim \mathcal{O}(100$ GeV$)$.
In this case, we introduce a SM singlet S and a new physics scale $M_{PQ} \sim 10^{10} - 10^{12}$ GeV. After the PQ symmetry is broken, S develops a VEV and μ arise via

$$W \supset S^2 H_u H_d / M_{PI} \Longrightarrow \mu \sim <S^2>/M_{PI} \approx M_{PQ}^2/M_{PI} \sim \mathcal{O}(100\,\text{GeV}),$$

which is consistent with the DFSZ axion model. (Phys. Lett. B 138, 150 (1984))

- QCD axion can be existed in the MSSM after introducing a new global PQ symmetry.
- QCD axion can be identified as another well-studied cold dark matter.
- PQ symmetry spontaneous breaking can induce a μ in EW scale.

$$\Updownarrow$$

Light Higgsinos Search

Search Strategy at e-p Colliders

- LHeC: $E_e = 60 - 140$ GeV, $E_p = 7$ TeV; FCC-eh: $E_e = 60$ GeV, $E_p = 50$ TeV.
- simulation package: MadGraph5, Pythia and Delphes.
- signal production: WBF processes (well kinematic feature, forward/backward partons, production rate...)

$$e^- p \to e^- j \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp},\ e^- j \tilde{\chi}_1^{\pm} \tilde{\chi}_{1,2}^{0},\ e^- j \tilde{\chi}_{1,2}^{0} \tilde{\chi}_{1,2}^{0}.$$

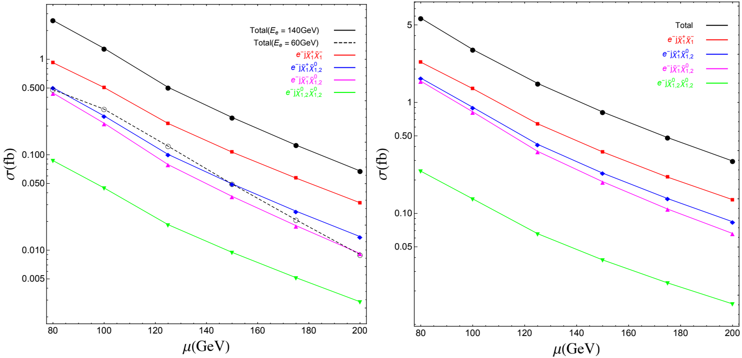


Figure 1: The cross sections of the signals at the LHeC and FCC-eh.

Backgrounds and Selection Cuts

- main irreducible backgrounds: $e^- p \to e^- j \nu_e \bar{\nu}_e$, $e^- p \to e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$
- main reducible backgrounds: $e^- p \to e^- j \tau^+ \nu_\tau$, $e^- p \to e^- j \tau^- \bar{\nu}_\tau$.
  - the τ fakes a hard jet in the detector
  - the products from hadronic τ decays are too soft to be tagged, and thus contribute to the $\not{E}_T$ (similar to the irreducible background)
  - $e^- p \to \nu_e j \tau^+ \nu_\tau, e^- p \to \nu_e j \tau^- \bar{\nu}_\tau$ might mimic the signal since there is one electron from leptonic τ decays. But the final electron has totally different kinematic distribution, we could suppress them to an insignificant order and they will not be considered in the following.

ep collider	$e^- j \tau^+ \nu_\tau$	$e^- j \tau^- \bar{\nu}_\tau$	$e^- j \nu_e \bar{\nu}_e$	$e^- j \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}$
LHeC with $E_e = 60$ GeV	163.8	146.8	115.5	32.82
LHeC with $E_e = 140$ GeV	330.2	302.0	243.6	58.11
FCC-eh	546.5	567.0	446.6	100.7

Table 1: The production cross section (fb) of all backgrounds at different $e - p$ colliders setup respectively.

machine	LHeC@140(FCC-eh)
basic cuts	$p_T^j > 20$ GeV, $p_T^\ell > 5$ GeV, $\lvert\eta_{\ell j}\rvert < 5$, $\Delta R > 0.4$
central jets veto	$p_T^{j_i} > 3.0(3.0)$ GeV, $\lvert\eta_{j_i}\rvert < 2.0(3.0)$ $(i \geq 2; i \in \mathbb{N})$
hard extra leptons(e, μ) veto	$p_T^{e_m} > 5.0(5.0)$ GeV, $p_T^{\mu_k} > 5.0(5.0)$ GeV $(m \geq 2, k \geq 1; m, k \in \mathbb{N})$
τ-jet veto	vetoing any events with τ-jet
missing transverse energy cut	$\not{E}_T > 30(70)$ GeV
transverse momentum cut	$p_T^{e_1} < 30(25)$ GeV
pseudorapidity cuts	$\eta_{e_1} > 1.0(0.0)$, $\eta_{j_1} < -2.0(-3.0)$
invariant mass cut	$M(e_1, j_1) > 400(400)$ GeV
inelasticity variable cut	$y > 0.3(0.15)$

Table 2: Cut-flow of the signal and background events at LHeC(140 GeV) and FCC-eh.

$y = \frac{k_P\cdot(k_e - p_e)}{k_P\cdot k_e}$. k_P is the 4-momenta of the initial proton, k_e is the 4-momenta of the initial electron, p_e is the 4-momenta of the out-going electron. After these cuts, the signal can be comparable to the backgrounds.

Kinematic differential distributions

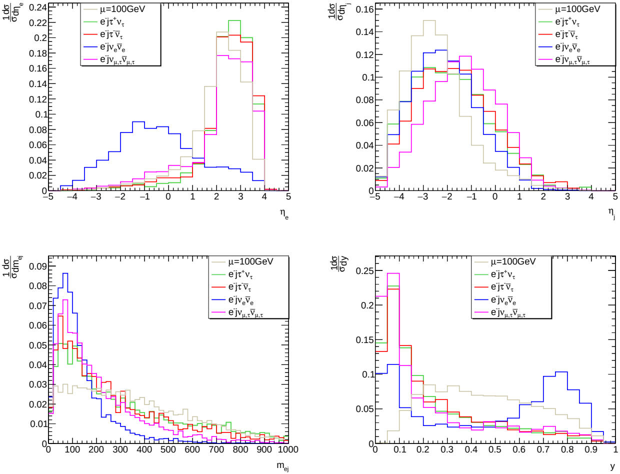


Figure 2: The normalised pseudo-rapidity η_{e_1} (top left), η_{j_1} (top right) distributions and the invariant mass $M(e_1, j_1)$ (bottom left) after veto criteria cuts i-ii when $E_e = 140$ GeV. The normalised inelasticity variable y (bottom right) distributions after veto criteria cuts i-iii when $E_e = 140$ GeV.

Results

We calculate the signal significance Z through the formula:

$$Z = \frac{S}{\sqrt{S+B}}$$

where S represents the number of signal events, $B = \Sigma_i B_i$ denotes the overall background ($i = e^- j\tau^+\nu_\tau, e^- j\tau^-\bar{\nu}_\tau, e^- j\nu_e\bar{\nu}_e$, $e^- j\nu_{\mu.\tau}\bar{\nu}_{\mu,\tau}$). The significance can reach up to 2σ nearby $\mu = 145$ GeV with $\mathcal{L} = 3$ ab^{-1} at the FCC-eh compared to $\mu = 95$ GeV at the 140 GeV LHeC.

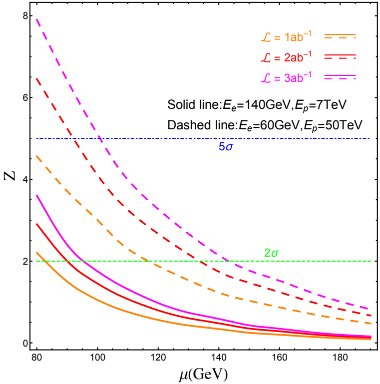


Figure 3: The significance Z varying with the Higgsino mass μ at the LHeC@140 GeV and FCC-eh respectively.

Conclusion

- Though current LHC data has excluded a large parameter space for low-energy SUSY, light Higgsinos is still existed in the corner of the collider search.
- A μ term automatically arises after PQ symmetry breaking, which provides QCD axion as an additional component of the cold dark for relic density.
- Search for the light Higgsino at the future e-p colliders provides a complementary constraint from mono or multi jets plus $\not{E}_T$ at the hadron collder.

Thanks!