Dark Matter searches with Photons at the LHC

Subhojit Roy

Argonne National Laboratory

Based on JHEP04(2024)106
(arXiv:2401.08917)

In collaboration with Carlos Wagner

SUSY 2024

June 11, 2024

Outline

- The nature of the DM stands out as a prominent challenge in theoretical particle physics and cosmology.

  We focus to the electroweakino sector of NMSSM.

- Singlino-dominated Dark Matter

  Dark Matter spin-independent direct detection blind spot

  singlino-higgsino and singlino-bino co-annihilation scenarios

- Focus to relatively unexplored parameter space of NMSSM

  Radiative decay of the higgsino-like states

  Electroweakino searches involving photons at the LHC

Z_3-symmetric NMSSM

- Z_3-symmetric NMSSM superpotential: $\mathcal{W} = \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u.\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$

- Compared with MSSM,
  NMSSM has extra two singlet-like scalars and one additional neutralino, known as singlino

- The symmetric neutralino mass matrix has got a dimensionality of 5×5 and, in the basis $\psi^0 = \{\widetilde{B},\ \widetilde{W}^0,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0,\ \widetilde{S}\}$, is given by

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_S \end{pmatrix}$$

$M_1,\ M_2 \rightarrow$ soft SUSY breaking masses for the $U(1)_Y$ and the $SU(2)_L$ gauginos, i.e., the bino and the wino, respectively.

$m_{\widetilde{S}} = 2\kappa v_S = 2\frac{\kappa}{\lambda}\mu_{\text{eff}} \rightarrow$ singlino mass term.

- Charginos $(\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)$=mass eigenstates of $(\widetilde{W}^\pm, \widetilde{H}_{u/d}^\pm)$

$$\begin{pmatrix} M_2 & \sqrt{2}m_W c_\beta \\ \sqrt{2}m_W s_\beta & \mu \end{pmatrix}$$

In order to comply with the observed relic abundance, we focus to the co-annihilation mechanism of singlino-dominated DM.

For co-annihilation to function, the mass gap between the DM and other weakly interacting particles must be minimal relatively small
==> compressed scenario at the LHC

Possibly $\tilde{S}$ -like LSP admixtures with $\tilde{B}$ and $\tilde{H}$

==> 'well-tempered' singlino-like LSP

sensitive to DM Direct detection experiments

Singlino-dominated DM direct detection blind spot (spin-independent)

[Singlino-dominated neutralino is tempered by the bino-like and higgsino-like states]

→ (3x3) CP-even Higgs diagonalizing matrix

$$g_{h_i\chi_1^0\chi_1^0} = \sqrt{2}\lambda(S_{i1}N_{14} + S_{i2}N_{13})N_{15} + \sqrt{2}\lambda S_{i3}(N_{13}N_{14} - \frac{\kappa}{\lambda}N_{15}^2)$$

$$+ \quad (g_1 N_{11} - g_2 N_{12})(S_{i1}N_{13} - S_{i2}N_{14}).$$

Coupling blind spot: $g_{h_{SM}\chi_1^0\chi_1^0} \sim 0 \Longrightarrow \left(m_{\chi_1^0} + \frac{g_1^2 v^2}{M_1 - m_{\chi_1^0}}\right)\frac{1}{\mu_{\rm eff}\sin 2\beta} \simeq 1$

Blind spot favorable criteria:

→ $\kappa < 0 (> 0)$, when M_1 and $\mu_{\rm eff}$ carry same (different) sign

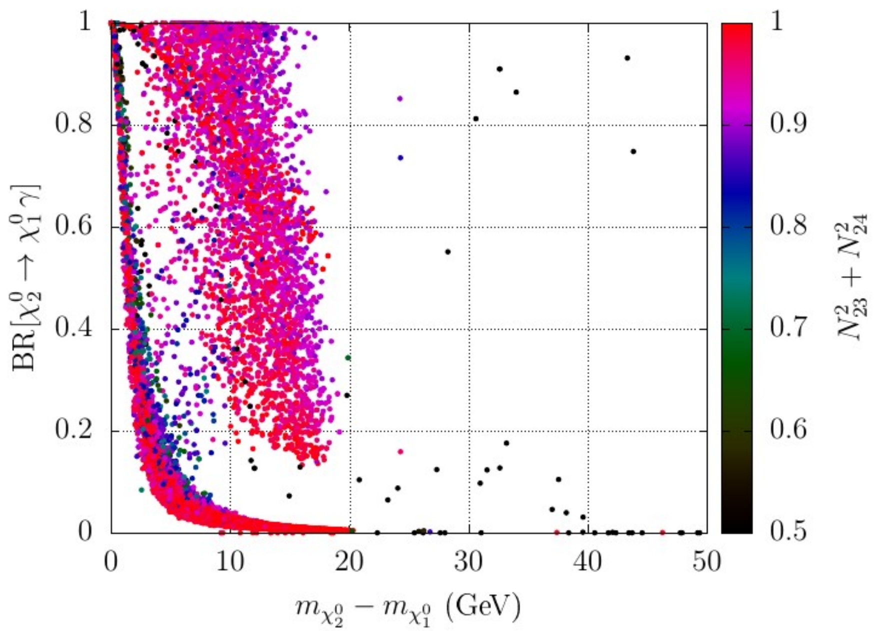
κ	$\mu_{\rm eff}$	M_1
$-$	$+$	$+$
	$-$	$-$
$+$	$+$	$-$
	$-$	$+$

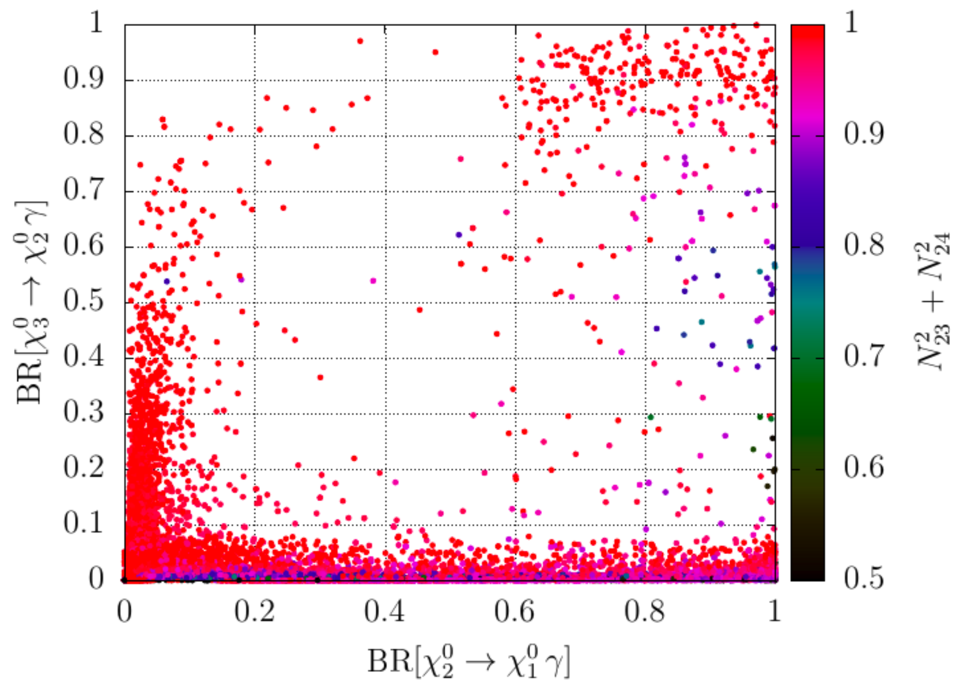
→ This new region $\kappa < 0$ may have significant implication for explaining the discrepancy of the anomalous muon magnetic moment (a_μ)

A positive contribution from the Bino-smuon loop to a_μ if M_1 and $\mu_{\rm eff}$ have the same relative sign

→ Influence the decay patterns of neutralinos

Neutralino radiative decay





When a two-body decay mode is kinematically closed, the possibility arises for the radiative one-loop branching ratio to be higher compared to the three-body tree-level decay branching ratio.

Mass splitting parameter, $$\varepsilon \equiv \frac{m_{\chi_2^0}}{m_{\chi_2^0}} - 1$$

Tree-level decays are suppressed as $\Gamma(\chi_2^0 \to \chi_1^0 + f\bar{f}) \propto \varepsilon^5,$

while the radiative decays are suppressed as $\Gamma(\chi_2^0 \to \chi_1^0 + \gamma) \propto \varepsilon^3$

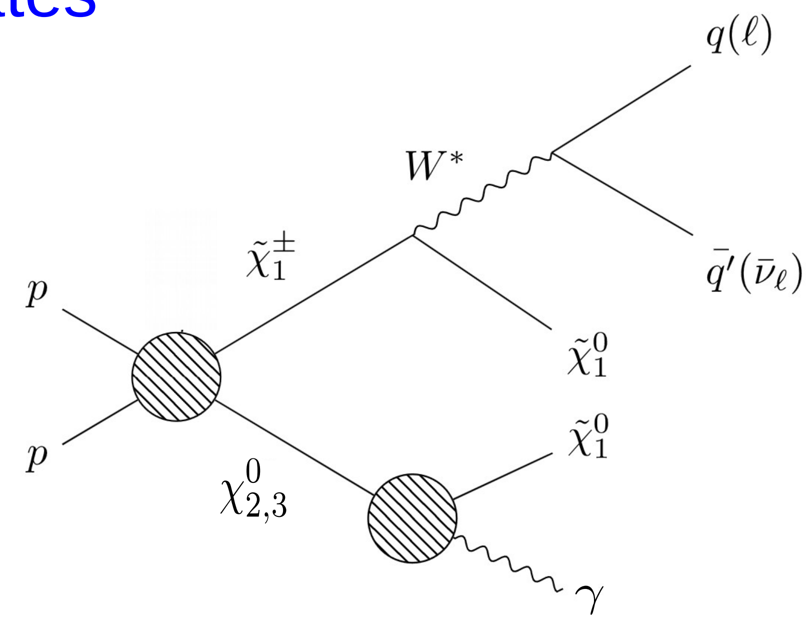
hep-ph/9609212

Therefore, radiative decays play an important role in the compressed region.

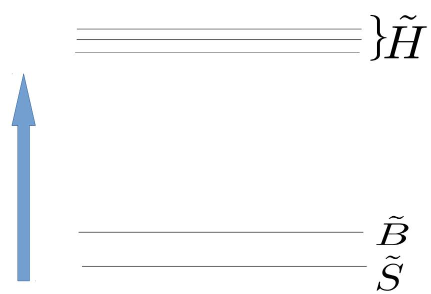
Decay chains of Higgsino-like states

Singlino-higgsino coannihilation scenario:

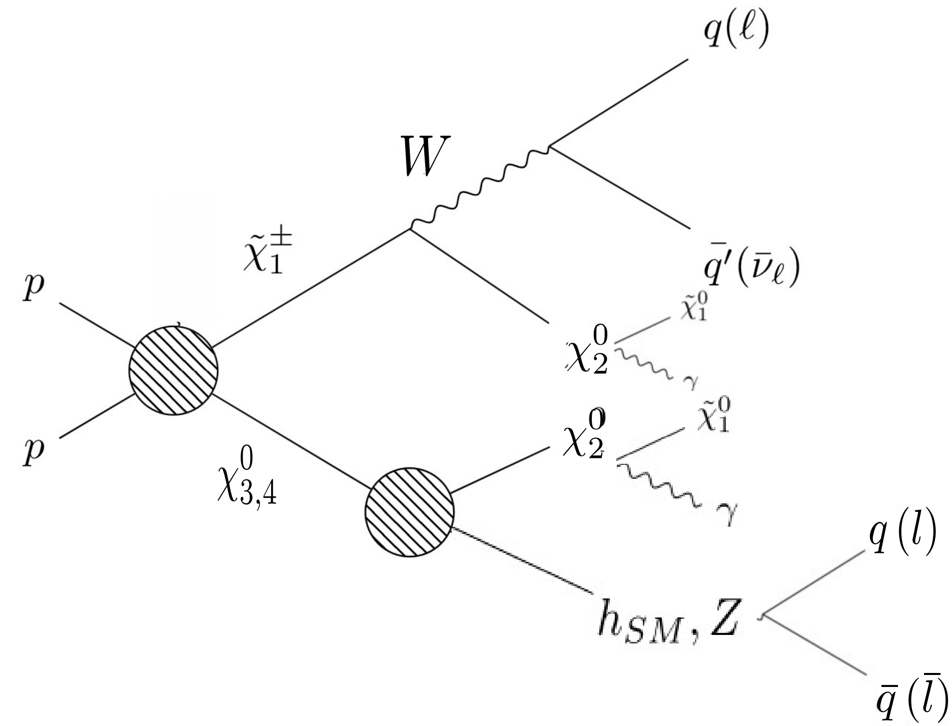
Level diagrams of neutralino hierarchies
with higgsino-like NLSP



Singlino-bino coannihilation scenario:



Level diagrams of neutralino hierarchies
with Bino-like NLSP



$$pp \to \chi^0_{3,4}(\widetilde{H})\chi^\pm_1(\widetilde{H}) \to h_{\rm SM}/Z + W^\pm + \chi^0_2(\tilde{B})\,[\chi^0_2 \to \gamma\,\chi^0_1(\tilde{S})] \Rightarrow 3\ell + \geq 1\gamma + \not{E}_T \text{ or } 1\ell + 2b + \geq 1\gamma + \not{E}_T$$

Singlino-bino co-annihilation excluded scenario

λ	κ	$\tan\beta$	$\mu_{\rm eff}$ (GeV)	M_1 (GeV)	$m_{\chi_1^0}, m_{\chi_2^0}$ (GeV)	$m_{\chi_{3,4}^0}$ (GeV)	$m_{h_S}, m_{h_{\rm SM}}, m_{a_S}$ (GeV)
0.0964	0.0062	10.06	−418.5	66.4	−55.5, 66.0	$\sim$ 433	49, 125, 50

$\mathrm{BR}(\chi_2^0 \to \chi_1^0\gamma)$	$\mathrm{BR}(\chi_3^0 \to \chi_2^0 h_{\rm SM}/Z)$	$\mathrm{BR}(\chi_4^0 \to \chi_2^0 h_{\rm SM}/Z)$
0.995	0.87	0.86

$\sigma_{pp\to\chi^0_{2,3,4}\chi_1^\pm}$ (pb)	0.0418
CheckMATE result	Excluded
r-value	2.87
Analysis ID	atlas_2004_10894
Signal region ID	Cat12

Excluded by the ATLAS analysis (arXiv:2004.10894) for the search of chargino-neutralinos by studying the di-photon decay channel of the on-shell h_{SM} coming from the decay of heavier neutralino.

Although not dedicated to co-annihilation, this ATLAS analysis gains sensitivity to singlino-bino coannihilation through signal region overlap, featuring final states with leptons, jets, photons, and missing energy.

Due to large mass gap between M_1 and $\mu_{\rm eff}$, bino-like NLSP emerges with a boost.

→ The tail of the $m_{\gamma\gamma}$ of two photons from the process $pp \to \chi_1^\pm \chi_{3,4}^0$ broadens relatively and lies around the mass window of $h_{\rm SM}$, which is considered in the selection cuts of this ATLAS analysis.

Singlino-bino co-annihilation allowed scenario

BP1

λ	κ	$\tan\beta$	$\mu_{\rm eff}$ (GeV)	M_1 (GeV)	$m_{\chi_1^0}$, $m_{\chi_2^0}$ (GeV)	$m_{\chi_{3,4}^0}$, $m_{\chi_1^\pm}$ (GeV)	m_{h_S}, $m_{h_{\rm SM}}$, m_{a_S} (GeV)
0.0964	0.0038	7	-700	66	-56.8, 65.8	$\sim$715	50, 125, 171

BR($\chi_2^0 \to \chi_1^0 \gamma$)	BR($\chi_3^0 \to \chi_2^0 h_{\rm SM}/Z$)	BR($\chi_4^0 \to \chi_2^0 h_{\rm SM}/Z$)	BR($\chi_1^\pm \to \chi_2^0 W^\pm$)
0.88	0.88	0.87	0.87

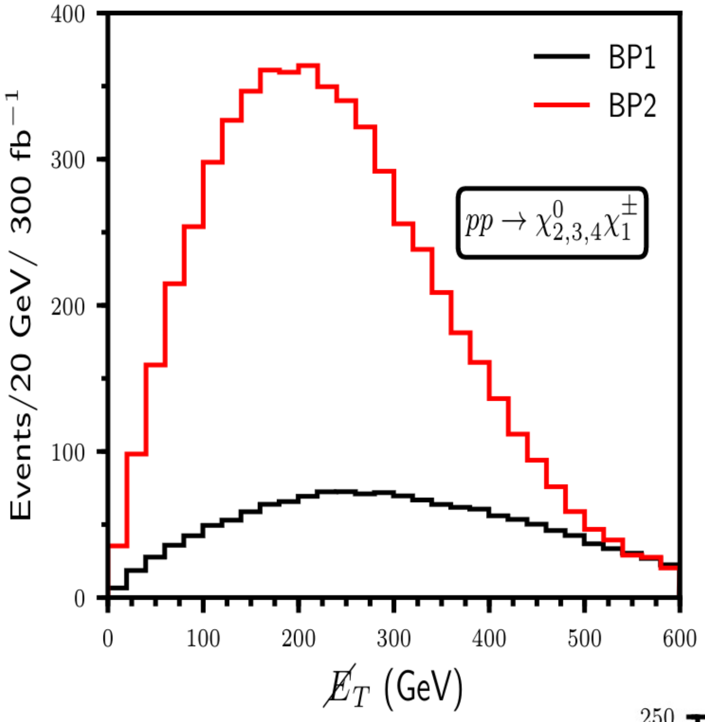
BP2

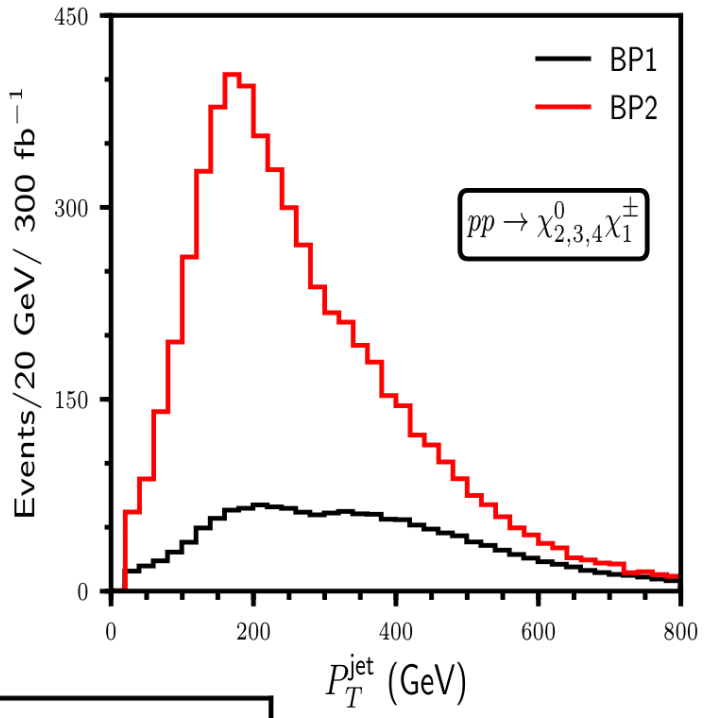
λ	κ	$\tan\beta$	$\mu_{\rm eff}$ (GeV)	M_1 (GeV)	$m_{\chi_1^0}$, $m_{\chi_2^0}$ (GeV)	$m_{\chi_{3,4}^0}$, $m_{\chi_1^\pm}$ (GeV)	m_{h_S}, $m_{h_{\rm SM}}$, m_{a_S} (GeV)
0.2086	0.0118	6	-525	-91.6	-67.7, -92.2	$\sim$540	70, 125, 64

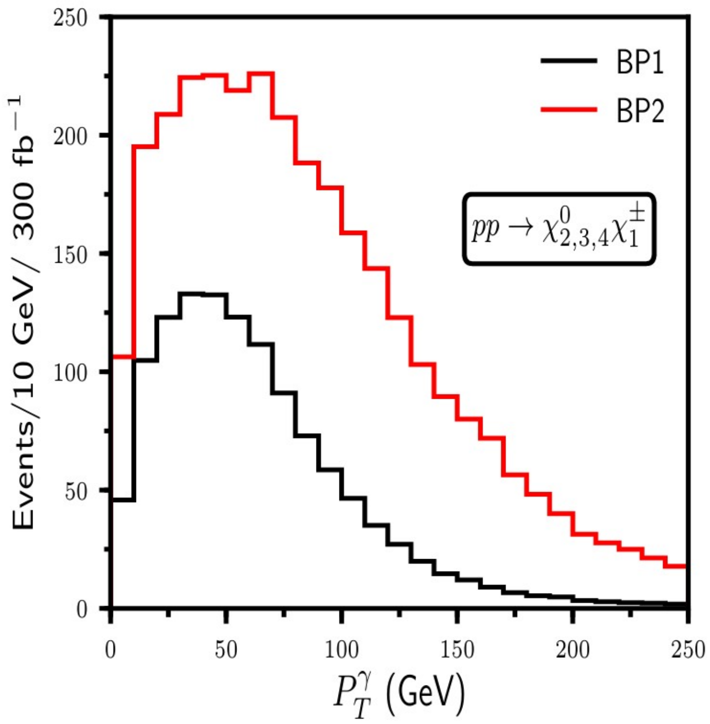
BR($\chi_2^0 \to \chi_1^0 \gamma$)	BR($\chi_3^0 \to \chi_2^0 h_{\rm SM}/Z$)	BR($\chi_4^0 \to \chi_2^0 h_{\rm SM}/Z$)	BR($\chi_1^\pm \to \chi_2^0 W^\pm$)
0.72	0.58	0.57	0.57

	BP1	BP2
$\sigma_{pp \to \chi_{2,3,4}^0 \chi_1^\pm}$ (pb)	0.00425	0.01577
CheckMATE result	Allowed	Allowed
r-value	0.68	0.61
Analysis ID	atlas_2004_10894	atlas_2004_10894
Signal region ID	Cat12	Cat12

Differential event distributions







Singlino-Higgsino coannihilation scenario

λ	κ	$\tan\beta$	$\mu_{\rm eff}$ (GeV)	M_1 (GeV)	$m_{\chi_1^0}$ (GeV)	$m_{\chi^0_{2,3}}$, $m_{\chi_1^\pm}$ (GeV)	$m_{\chi_4^0}$ (GeV)	m_{h_S}, $m_{h_{\rm SM}}$, m_{a_S} (GeV)
0.067	0.0316	6	-307	509.2	-296	~ 312	~ 510	202, 125, 36

BP3

$\text{BR}(\chi_2^0 \to \chi_1^0\gamma)$	$\text{BR}(\chi_3^0 \to \chi_2^0\gamma)$	$\text{BR}(\chi_1^\pm \to \chi_2^0 f\bar{f})$
0.63	0.86	0.57

λ	κ	$\tan\beta$	$\mu_{\rm eff}$ (GeV)	M_1 (GeV)	$m_{\chi_1^0}$ (GeV)	$m_{\chi^0_{2,3}}$, $m_{\chi_1^\pm}$ (GeV)	$m_{\chi_4^0}$ (GeV)	m_{h_S}, $m_{h_{\rm SM}}$, m_{a_S} (GeV)
0.018	-0.0083	8.8	-198	-350	-188	~ 200	~ -355	178, 125, 83

BP4

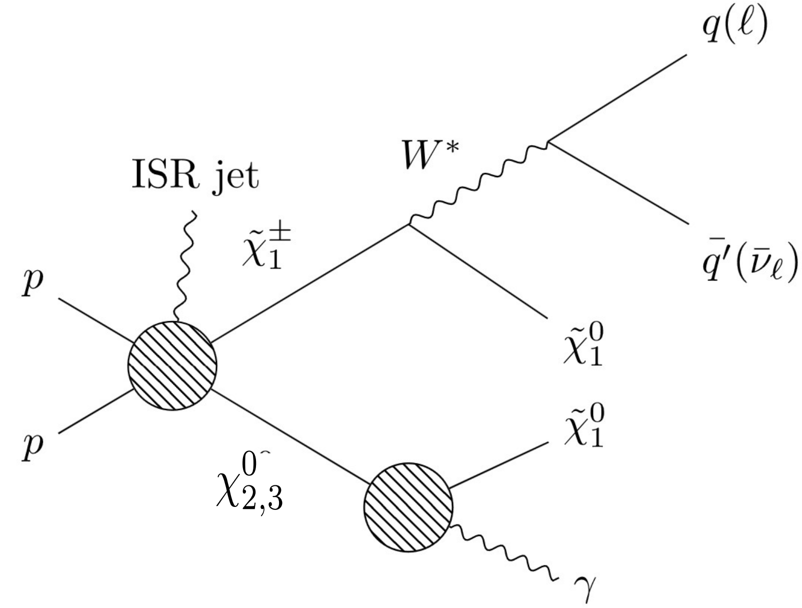
$\text{BR}(\chi_2^0 \to \chi_1^0\gamma)$	$\text{BR}(\chi_3^0 \to \chi_2^0\gamma)$	$\text{BR}(\chi_1^\pm \to \chi_2^0 f\bar{f})$
0.73	0.92	0.80

	BP3	BP4
$\sigma_{pp\to\chi^0_{2,3,4}\chi_1^\pm}$ (pb)	0.140	0.743
CheckMATE result	Allowed	Allowed
r-value	0.07	0.12
Analysis ID	atlas_conf_2017_060	atlas_conf_2020_048
Signal region ID	EM7	EM09

Singlino-Higgsino coannihilation scenario with a hard ISR

$$pp \to \chi_1^{\pm}\chi_{2,3}^{0}$$

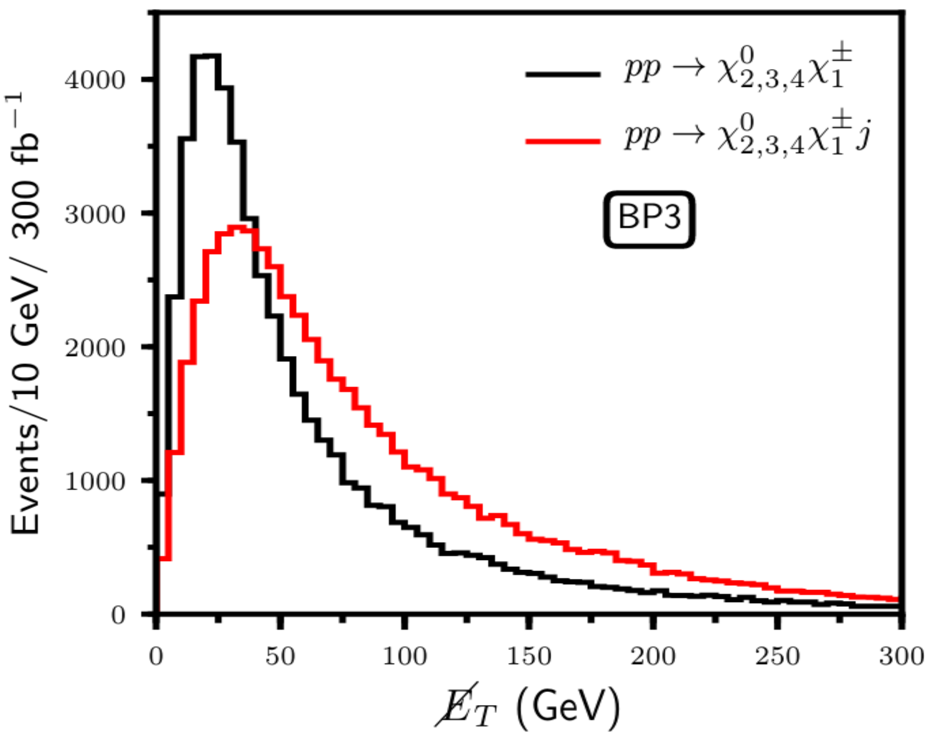
$\chi_1^{\pm}$ and $\chi_{2,3}^{0}$ would primarily be produced at the LHC with equal and opposite P_T

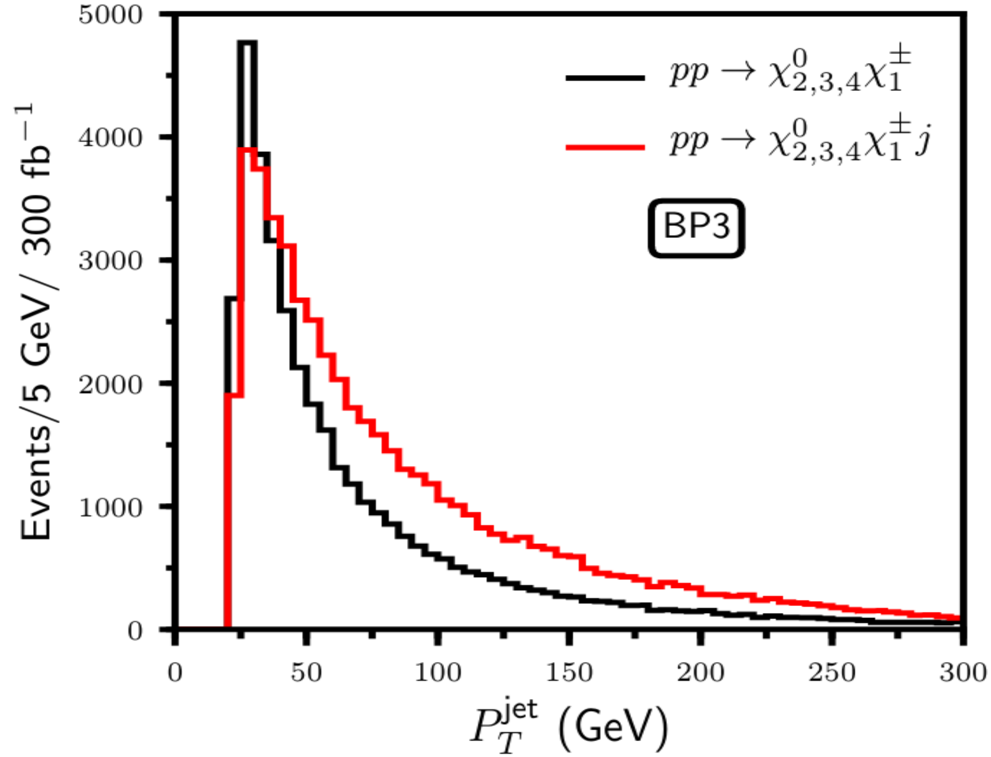


In the presence of the ISR jet, $(\chi_1^{\pm}\chi_{2,3}^{0})$ system recoils against the ISR jet in the transverse plane.

Due to the small mass difference between the LSP and the higgsino-like states, a significant portion of the P_T of the higgsino-like $\chi_1^{\pm}$ and $\chi_{2,3}^{0}$ is transferred to the LSP, contributing to event $\not{E}_T$ that approximately balances with P_T of the ISR jet.

Differential event distributions





Peak of $\not{E}_T$ distribution occurs at a relatively higher value for the process involving the ISR jet.

Additionally, a broad high $\not{E}_T$ tail is observed for events containing one ISR jet.

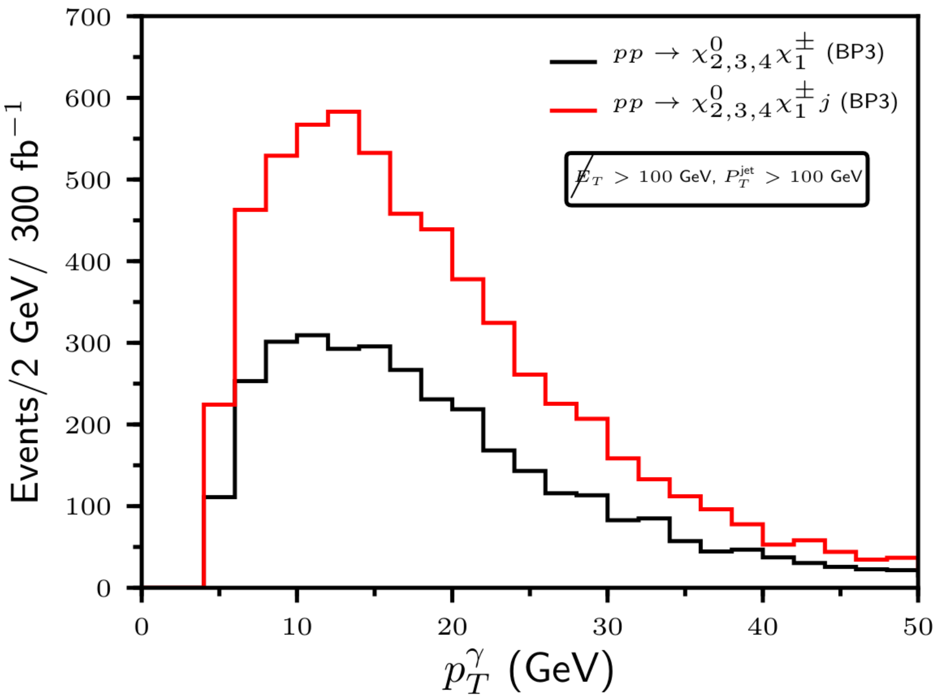
This characteristic allows for more aggressive selection cuts on $\not{E}_T$ in the analysis, effectively rejecting a significant amount of the SM backgrounds at a moderate cost in losing signal events.

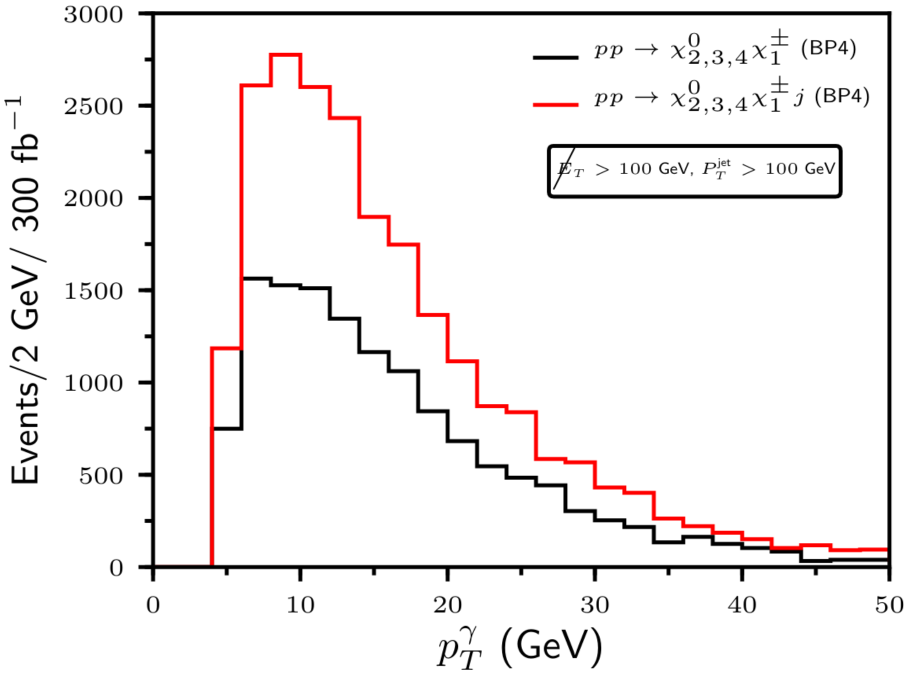
Similar broader high P_T tail of the leading jet is also observed in events containing one ISR jet.

Correlation between $P_T^{\rm jet}$ and $\not{E}_T$ in events with one ISR jet,

→ imposing a stringent cut on $\not{E}_T > 100\,\mathrm{GeV}$ ensures that most signal events have substantially larger $P_T^{\rm jet} \gtrsim 100\,\mathrm{GeV}$

Differential event distributions





The presence of a single ISR jet in the events under those specified cuts $\not{E}_T$, $P_T^{\rm jet} > 100\,{\rm GeV}$ leads to a notable increase in the number of events at the peak of the distribution and a broadening of the high P_T^γ tail.

A substantial drop in the cross-section of the process in the absence of any ISR jet under such cuts.

Distribution exhibits a peak at a slightly higher P_T^γ when the ISR jet is considered

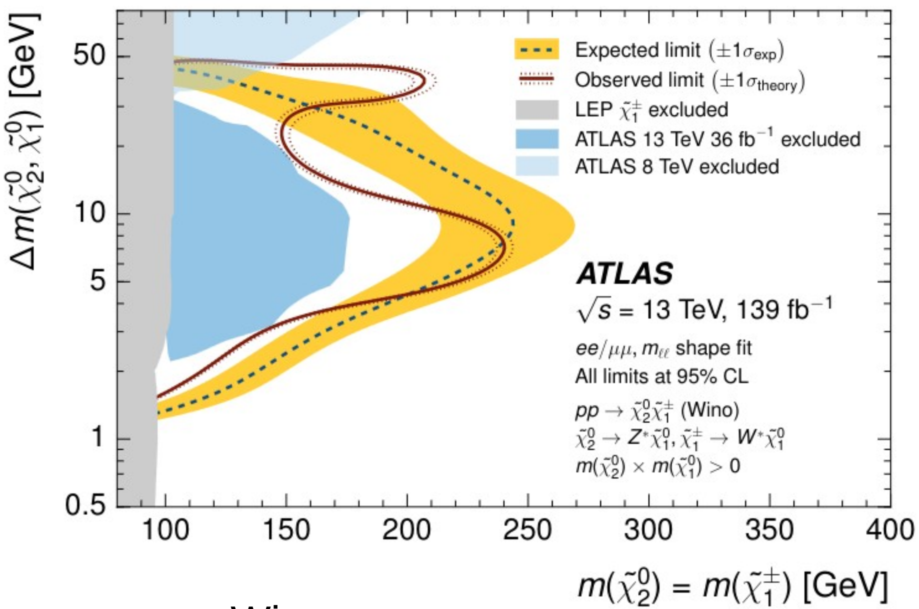
→ suggesting an overall transverse boost for the photon

This can be understood from the fact that if the decaying photon from $\chi^0_{2,3}$ originated in the same direction in which $\chi^0_{2,3}$ are produced and boosted due to large P_T of the ISR jet in the event.

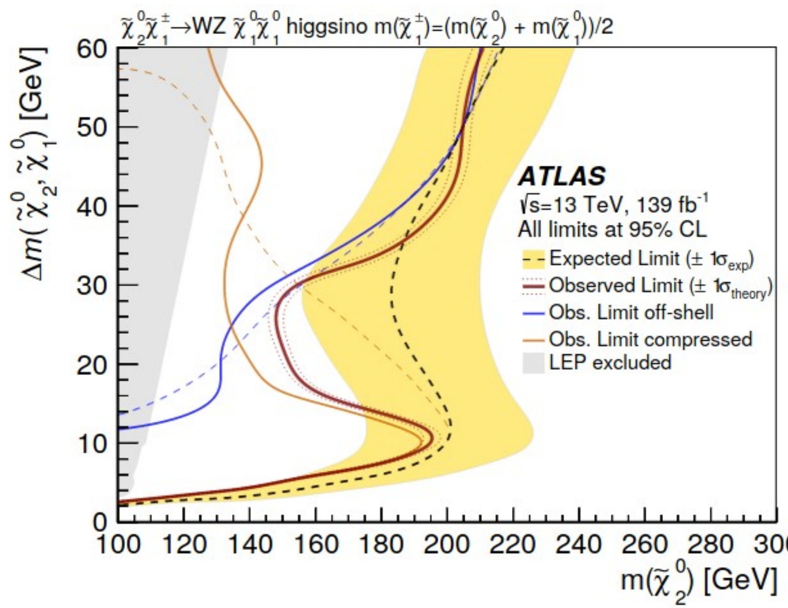
ATLAS and CMS reported mild excesses in electroweakino searches

arXiv:1911.12606

arXiv:2106.01676



Wino



Higgsinos

Observed mild excess ($\sim 2\sigma$) in the (soft lepton analysis) $3l + \not{E}_T$ and $2l + \not{E}_T$ scenario for $m_{\chi^\pm, \chi_2^0} \sim$ 200 GeV and Δm ~20 GeV.

Light singlino-Higgsino region of NMSSM ⟶ Agin et al. arXiv:2404.12423, Ellwanger et al. arXiv:2404.19338

Recently, a paper by Agin et al. (arXiv:2311.17149) claims that the current monojet searches (arXiv: 2102.10874, 2107.13021) show excesses in a region that partially overlaps with that favored by the soft-lepton analyses.

It may be feasible to explain these excesses in the soft lepton channels within the context of the singlino-higgsino co-annihilation scenarios discussed in our work.

Such a co-annihilation scenario can also indicate another possible detection channel involving photons.

A dedicated analysis can be done using the exiting Run 2 data of LHC

Conclusion

- A new blind spot condition $\kappa < 0$ for singlino-dominated dark matter resulting from bino and higgsino tempering.

- This blind spot condition demads same relative sign between M_1 and $\mu_{\rm eff}$, which generates a positive contribution from the Bino-smuon loop to a_μ .

- Higgsino-like states prefer radiative decay

- The compressed scenario is emerging as a promising WIMP-DM candidate, being explored through combined LHC and direct detection efforts.

- Here, we suggest a new radiative decay search for higgsino-like neutralinos in the singlino-higgsino coannihilation scenario, complementing current multilepton searches.

- For the singlino-higgsino scenario, consider a hard ISR jet with $pp \to \chi_1^\pm \chi_{2,3}^0$ process

  Select signal region with a hard mono-jet with significant missing energy and at least one photon.

- For the case of singlino-bino scenario, photons can become relatively hard due large mass difference between higgsino-like states and bino-like NLSP.

  This scenario could leads to $3\ell + \geq 1\gamma + \not{E}_T$ or $1\ell + 2b + \geq 1\gamma + \not{E}_T$ final states at the LHC.

Thank you