Phys. Lett. B 855 (2024) 138774

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

A new purpose for the W-boson mass measurement: Searching for New Physics in lepton+ MET

Kaustubh Agashe [a], Sagar Airen [a], Roberto Franceschini [b], Doojin Kim [c], Ashutosh V. Kotwal [d], Lorenzo Ricci [a], Deepak Sathyan [a,*]

[a] Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742, USA
[b] Università degli Studi and INFN Roma Tre, Via della Vasca Navale 84, I-00146, Rome, Italy
[c] Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
[d] Department of Physics, Duke University, Durham, NC 27708, USA

ARTICLE INFO

Editor: G.F. Giudice

ABSTRACT

We show that the m_W measurement is a *direct* probe of New Physics (NP) contributing to $\ell+MET$, independently from *indirect* tests via the electroweak fit. Such NP modifies the kinematic distributions used to extract m_W, necessitating a simultaneous fit to m_W and NP. This effect can in principle bias the m_W measurement, but only to a limited extent for our considered models. Given that, we demonstrate that the agreement at high-precision with SM-predicted shapes results in bounds competitive to, if not exceeding, existing ones for two examples: anomalous W decay involving a $L_\mu - L_\tau$ gauge boson and $\tilde{\nu}_l\tilde{l}$ production in the MSSM.

1. Introduction

The mass of the W boson plays a crucial role in our understanding of nature. The discrepancy between the recent and most precise measurement by CDF [1] and the SM prediction might already be a hint of new physics (NP) beyond the Standard Model (BSM). Theoretical explanations commonly invoke new contributions to the electroweak (EW) fit [2] in order to shift the value of the SM prediction (see for instance [3,4]) and explain the anomaly. Yet, the more recent re-measurement by ATLAS [5,6] adds to the puzzle, confirming the SM-predicted value and the previous measurements by LHCb, DØ and LEP [7–9]. Whether in the future the CDF anomaly will be confirmed cannot be foreseen. The only fact that we have today is the striking precision of 10^{-4} of these measurements and of the corresponding theory SM predictions. This precision might even improve in the near future due to an ongoing intense experimental [5,10] and theoretical effort (see e.g. Refs. [11–17] for recent works).

The m_W experimental value is extracted from the simultaneous fit of different measured kinematic distributions (see below) in leptonic decays of singly-produced W-bosons to the SM predictions. Both ATLAS and CDF find perfect agreement with their best-fit SM distributions.

We show in this *letter* that the data used for the m_W measurement can simultaneously be a powerful direct probe for any NP that contributes to the same final state. The key observation is that NP produces kinematic distributions that are sufficiently different with respect to those in the SM. Hence, the same analysis can be used for the extraction of both m_W and NP parameters. The correct procedure thus requires a global fit, which might in principle shift the measurement of m_W, with NP providing new nuisance parameters.

This paradigm is general, having already been attempted in [18–24] for the top quark, in the context of NP copiously produced via strong interactions. Fainter signals of NP charged only under the electroweak interaction are more challenging. Yet we will show how the extraordinary precision of the m_W measurement can put competitive bounds on motivated new physics scenarios, and in some cases to *exceed* present bounds, e.g. those for long-sought SUSY sleptons. This strategy is in addition to the classic test based on EW fit of the SM to which we are accustomed since LEP [25].

In this *letter*, we focus solely on the m_W measurement. More precisely, in Sec. 2, we classify the possible NP that can contaminate the measured sample. Then we focus on two concrete, well-known BSM scenarios (see Fig. 1): (1) $L_\mu - L_\tau$ leptophilic Z' and (2) MSSM slepton-

* Corresponding author.
E-mail addresses: kagashe@umd.edu (K. Agashe), sairen@umd.edu (S. Airen), roberto.franceschini@uniroma3.it (R. Franceschini), doojin.kim@tamu.edu (D. Kim), ashutosh.kotwal@duke.edu (A.V. Kotwal), lricci@umd.edu (L. Ricci), dsathyan@umd.edu (D. Sathyan).

https://doi.org/10.1016/j.physletb.2024.138774
Received 25 January 2024; Received in revised form 20 May 2024; Accepted 2 June 2024
Available online 5 June 2024

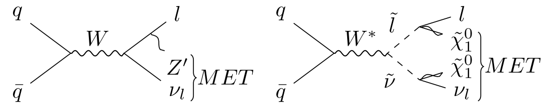


Fig. 1. NP contributions to the W-boson mass sample in the $\ell + MET$ channel. Left: invisibly-decaying $L_\mu - L_\tau$ Z'-boson. Right: slepton-sneutrino production in the MSSM.

sneutrino production, respectively. For each scenario, we show in Fig. 2 the sensitivity projections of our analysis compared to the strongest present constraints. Our results highlight the ability of precision measurements of m_W to probe NP. In Secs. 3 and 4 we describe for each scenario the methodology employed to obtain the main result, and we further explore the effect of the global fit on the determination of m_W.

2. Invisible New Physics behind the semi-invisible W-boson

The W-boson mass measurement is special. The remarkable precision, reached by hadron colliders, relies only on the partially visible leptonic decays. The masses of other heavy SM bosons are instead extracted from fully visible and clean final states (e.g., $h \to \gamma\gamma$, $Z \to \ell^+\ell^-$), hence resonance reconstruction is possible in a narrow region. For hadronic W-boson decays, resonance reconstruction is plagued by the challenges of QCD observables. The semi-invisible final state of leptonic W-decays, namely $\ell + MET$, is cleaner, but it presents a good hideout for invisible NP.

Given that the W-boson decay cannot be fully reconstructed, the measurement of the m_W is a result of the fit to the lepton p_T^ℓ and the transverse mass m_T distributions.[1] Hence, any BSM that contributes to the same final state, modifying these kinematic distributions, can affect the m_W measurement. Such NP can be classified in three possibilities:

(A) anomalous W-boson decay,
(B) anomalous W-boson production,
(C) $\ell + MET$ not from an on-shell W-boson, $\ell = (e, \mu)$.

The first (second) possibility includes all BSM models that modify the W-boson decay (production), yet resulting in $\ell + MET$. Option (C) collects all BSM models that can produce an $\ell + MET$ final state, without the involvement of any on-shell W-boson. This category includes the production of new particles, decaying into $\ell + MET$, and new interactions among quark/gluons and leptons.[2]

Here we explore two simple, yet relevant, case studies that cover options (A) and (C). In Sec. 3, we focus on anomalous W-boson decay in the invisibly-decaying $L_\mu - L_\tau$ gauge boson scenario (Fig. 1 left). This represents a proof-of-principle of our idea, highlighting the relevant points with rather simple phenomenology. Nevertheless, we find that the m_W measurement represents a competitive probe for this model. We point the interested reader to Fig. 2a (left panel) to see the expected bounds from our strategy in comparison to the present limits. In Sec. 4 we focus on category (C), using $\tilde{\nu}\tilde{\ell}$ production in SUSY as an example. This production mechanism is not currently investigated at the LHC. Our results from the work described in Sec. 4 are shown in Fig. 2b and clearly indicate that the m_W measurement can cover unexplored parameter space of slepton searches.

In a follow-up paper [31], we will study additional examples of category (A) and an illustration of category (B): a Z'-boson gauging baryon number (see [32] and references therein). Overall, our two papers thus represent a *comprehensive* study of probing NP giving $\ell + MET$ using m_W analysis. Ref. [33] studied a specific example of category (B) only. Moreover, in the following, we describe a more general approach than Ref. [33] for the associated analyses.

3. A proof-of-principle: $L_\mu - L_\tau$ gauge boson

The first model that we consider is the $L_\mu - L_\tau$ Z' [34]:

$$\mathcal{L}_{\rm int} = g_{Z'} Z'_\rho J^\rho_{\mu-\tau} + g_D Z'_\rho J^\rho_D , \quad (1)$$

where $g_{Z'}$ and g_D are the couplings of Z'-boson to SM and dark-sector states, respectively. The $U(1)_{L_\mu - L_\tau}$ current reads

$$J^\rho_{\mu-\tau} = (\bar{\nu}_\mu \gamma^\rho \nu_\mu + \bar{\mu}\gamma^\rho \mu - \bar{\nu}_\tau \gamma^\rho \nu_\tau - \bar{\tau}\gamma^\rho \tau). \quad (2)$$

The term $Z'_\rho J^\rho_D$ describes the interaction of the Z'-boson with some invisible, unspecified dark-sector states. The key assumptions, that $g_D \gg g_{Z'}$ and the dark sector contains states sufficiently lighter than $m_{Z'}$, guarantee that the Z'-boson decays predominantly invisibly.

This model has been extensively studied as a possible portal to dark matter or as an extension to SM. The 2-dimensional parameter space $(g_{Z'}, m_{Z'})$ is tested by a variety of searches, from K-/B-factories, $g-2$, and especially by neutrino beam-dump experiments such as the Chicago-Columbia-Fermilab-Rochester (CCFR) experiment [43] which has been shown to provide strong bounds on this type of model [26,35].[3] In this model belonging to category (A), the W-boson has a 3-body decay into $\mu\, \nu_\mu\, Z'$ (Fig. 1 left), modifying the kinematic distributions of $\ell + MET$ final state.[4]

We obtain the kinematic distributions through a Monte Carlo (MC) simulation via MadGraph5_aMC@NLOv3.42 [37] + PYTHIA8.212 [38] + Delphesv3.4 [39] (ATLAS card). We employed LHAPDF [40], PDF ID:244800 [41]. The 3-body decay (versus 2-body) softens the p_T and m_T distributions, as seen in Fig. 3 for a benchmark value of $(m_{Z'}, g_{Z'}) = (10\ \text{GeV}, 0.12)$.[5]

As shown in Fig. 3, for $g_{Z'} \sim \mathcal{O}(0.1)$, the expected S/B ratio is $\mathcal{O}(10^{-3})$. Sensitivity to these effects strongly relies on the various sources of uncertainties, which is exactly the main target for the experimental collaborations that reached percent [1] and even sub-percent uncertainties [5,6], aimed at measuring m_W. In all of our results, we show variations on the systematic uncertainties, taking as baseline the reported uncertainty, e.g., in Fig. 25 of Ref. [6]: the uncertainty on m_T is estimated to reach few 0.1% around the peak region at about 80 GeV. Also backgrounds are extensively studied and they are only a few% in the region of interest. In this *letter* we will not attempt a complete study of the various sources of uncertainties in the presence of NP. We just comment on the possible effect of our NP hypothesis on the sample of $Z \to \ell\ell$ events which are heavily used for detector calibration [1,6] and for tuning the boson production model on data [15]. Thus a contamination of NP in the $Z \to \ell\ell$ sample might affect the calibration of the MCs, "calibrating away" signs of NP [42]. However, by isolating pure Z-boson events with appropriate kinematic cuts, such as those imposed by ATLAS [6]: $80 < m_{\ell\ell}/\text{GeV} < 100$, the possible contamination of NP in the calibration sample is limited to $\mathcal{O}(10^{-4})$, still for $g_{Z'} \sim \mathcal{O}(0.1)$.

We estimate the sensitivity and the impact of our NP hypothesis on the m_W measurement through a binned χ^2 analysis for the p_T^ℓ and m_T distributions. Our analysis is aligned as much as possible with the ATLAS measurement [5,6], only slightly extending the fit range aiming at maximal sensitivity (see Table 1). We then construct the following χ^2:

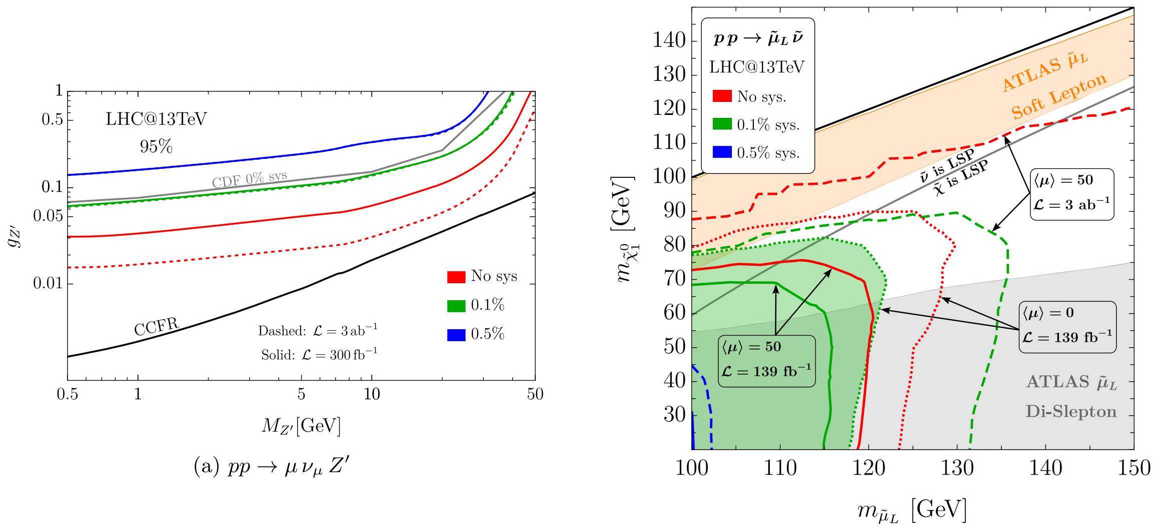
[1] CDF also fits the missing transverse momentum $p_T^{\rm miss}$ distribution.

[2] Examples of this are dim-6 quark-lepton four fermion operators that mediate $qq \to \ell\, \nu_\ell$ processes. The latter is usually very well constrained by high-energy measurements [28–30].

[3] Additional constraints arise when $m_{Z'}$ is of Stuckenberg origin [36].

[4] Additional signal events come from $\tau \to Z' \mu\, \nu_\mu\, \nu_\tau$. For simplicity we don't include them in our analysis.

[5] NP also modifies W-boson total decay width. This effect is expected to be negligible given the projected bound on the NP parameters. Therefore we fix the width to its SM value. The effect of the width on the m_W determination within the SM is only a few MeV. [5,15].



(a) $pp \to \mu\,\nu_\mu\,Z'$

(b) $pp \to \tilde{\mu}\,\tilde{\nu}_\mu$

Fig. 2. LHC 95% CL projected sensitivity to (a) $L_\mu - L_\tau$ and (b) MSSM slepton-sneutrino production from our proposal. All of our projections include detector simulations. Pileup ($\langle\mu\rangle = 50$), simulated through the dedicated DELPHES ATLAS card, is included unless indicated otherwise. Panel (a): present bounds (solid black line) are obtained from the Chicago-Columbia-Fermilab-Rochester (CCFR) experiment [26]. Our results are the **blue, green, red lines**, for 0.5%, 0.1% and 0% systematics, for $\mathcal{L} = 139\,\text{fb}^{-1}$ (solid) and $\mathcal{L} = 3\,\text{ab}^{-1}$ (dashed). Panel (b): present bounds (gray and orange shaded areas) from the ATLAS experiment are adapted from Ref. [27]. Our results are the **green shaded area**, for the present $\mathcal{L} = 139\,\text{fb}^{-1}$ integrated luminosity and 0.1% systematics. We also present results under several different pile-up and integrated luminosity options in colors and dashed or dotted lines, as indicated in the plot.

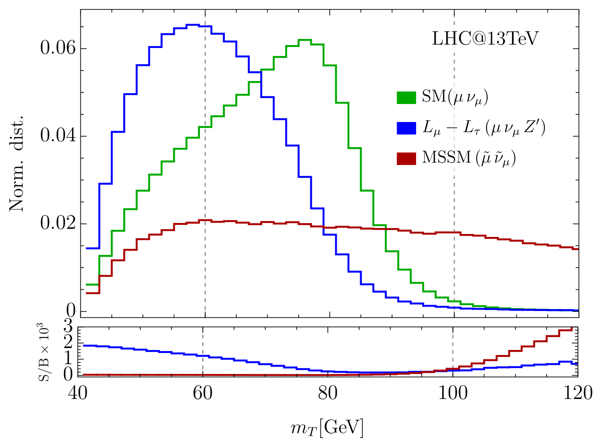


Fig. 3. (top) Normalized transverse mass distributions for $\mu + MET$ at the LHC for the SM **(green)**, and for pure BSM in two scenarios to show the shapes of the BSM events. **Blue** line: $m_{Z'} = 10\,\text{GeV}$, $g_{Z'} = 0.12$. **Red** line: $m_{\tilde{\mu}} = 115\,\text{GeV}$, $m_{\tilde{\nu}} = 83\,\text{GeV}$, $m_{\tilde{\chi}^0_1} = 70\,\text{GeV}$. (bottom) Signal-over-Background ratios for the BSM signals over SM background are shown in the lower panel. The dashed gray lines indicate the ATLAS fitting range for the measurement of m_W.

$$\chi^2(\Delta_{m_W}, \theta_{\text{NP}}) = \sum_{i=1}^{N_{\text{Bins}}} \frac{\left(N^i_{ev}(\Delta_{m_W}, \theta_{\text{NP}}) - \overline{N}^i_{ev}\right)^2}{\sigma^2_{stat} + \sigma^2_{sys}}\,, \tag{3}$$

where $N^i_{ev}(\Delta_{m_W}, \theta_{\text{NP}})$ is the expected number of events in the bin i as function of m_W, through the combination $\Delta_{m_W} = m_W - \overline{m}_W$ and the NP parameters, collectively labeled by θ_{NP}. The value $\overline{m}_W$ denotes the fixed value of the W boson mass that we have used to generate our samples,[6] thus it represents the true value realized in Nature. We centered our χ^2 at $\theta_{\text{NP}} = 0$ and $\Delta_{m_W} = 0$ because we are assuming data to realize the SM expectation for the W-boson mass $\overline{m}_W$. We stress that we are testing the New Physics hypothesis with no prior on $\overline{m}_W$, as both θ_{NP} and m_W are floated.

On the contrary, the authors of [33] *fixed* m_W in the hypothesis to the EW fit prediction. The simultaneous fit to m_W and NP that we perform here is thus a more general test of NP and has the added value to be independent of the EW fit results and the assumptions therein.

The qualitatively new aspect of Δ_{m_W} being a floated parameter in Eq. (3) implies that with the same analysis we extract m_W and test NP. The 2-dimensional fit in the $(\Delta_{m_W}, \theta_{\text{NP}})$ is reported in Fig. 4 for $m_{Z'} = 10$ GeV. By assuming 0.5% per-bin uncorrelated systematics and including the effect of pileup through DELPHES, the ATLAS measured uncertainty is roughly reproduced.[7] Pileup has an impact on the m_T distribution and on the resulting m_W sensitivity. The p_T^ℓ distribution, on the contrary, is largely insensitive to pileup, hence we use it to draw more firm conclusions on features of our 2D-fit.

The systematics on the kinematic distributions shown in [5] are below 0.5%. Therefore, we also consider per-bin systematics of 0.1%. The expected sensitivity to m_W (at zero $g_{Z'}$) is slightly stronger than the current ATLAS 7 TeV $\mathcal{L} = 4.6\ \text{fb}^{-1}$ measurement [5]. This is mainly because we are not including any source of correlated systematics, and we are assuming much larger statistics from a 13 TeV run with $\mathcal{L} = 300\ \text{fb}^{-1}$.

The distortion of the p_T^ℓ exclusion line (blue) at large values of $g_{Z'}$ implies a preference towards positive Δ_{m_W}. This suggests that NP might in principle impact the sensitivity to m_W, possibly producing a shift in the extracted value and/or affecting the estimate of the associated uncertainty on m_W. Yet, the effect shown in Fig. 4 is limited to only ~ 10 MeV. However, a quantitative assessment of this effect requires the inclusion of the proper experimental setup and is beyond the scope of this *letter*. The sensitivity to $g_{Z'}$ at $\Delta_{m_W} = 0$ is only marginally affected by pileup, showing the robustness of the sensitivity to NP.

For completeness, we report in the supplemental material an analogous study for CDF [1]. In this case, the effect of the NP in the m_W determination is less pronounced, due to a sharper Jacobian peak related to the better control of the hadronic activity at CDF which anchors the m_W fit more robustly.

[6] Namely, for our simulation we used $\overline{m}_W = 80.419$ GeV. This value is close to the measured W-boson mass, and it is the default value in the SM model file we employed in MADGRAPH5_AMC@NLOv3.42.

[7] The average number of pileup events per bunch crossing is $\langle\mu\rangle = 50$.

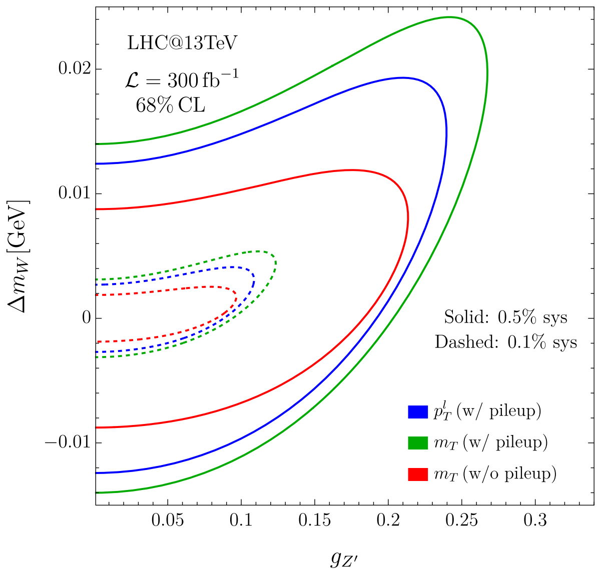


Fig. 4. 68% CL projected sensitivity to $L_\mu - L_\tau$ at LHC (ATLAS) ($m_{Z'} = 10\,\text{GeV}$) in the plane of coupling of the new boson $g_{Z'}$ and the shift from the true value of the W boson mass.

We now turn to the test of the NP hypothesis. Assuming no prior knowledge on $\overline{m}_W$, the correct procedure to put bounds on NP is to marginalize on Δm_W for each value of the NP parameters. This is shown in Fig. 2a for LHC ($\mathcal{L} = 300\text{ fb}^{-1}$) sensitivity projection. Prior knowledge on $\overline{m}_W$ (either from other measurements or from theory predictions) might impact the sensitivity to NP, as shown in Fig. 4.

For this analysis, positively and negatively charged-muon events are added together, and χ^2 for p_T^ℓ and m_T are combined without correlation. Here, the sensitivity projections for CDF are also reported. The reach for $m_{Z'} \simeq 10$ GeV is competitive with the best probe for this model from a dedicated experiment (CCFR) [26,43]. Yet, it is remarkable that for a 10 GeV Z'-boson, the m_W measurement has the power to probe couplings $\sim few \times 0.01$, provided sufficient control of the systematics. Interestingly, less constrained models such as the "neutrinophilic scalar" of [44] or the "Dirac neutrino portal" [45] fall in category (A). For the neutrinophilic scalar, we expect the m_W measurement to be the best probe [31].

4. MSSM: slepton-sneutrino production

We now turn to the minimal supersymmetric standard model (MSSM) [46], which offers a simple irreducible "background" for the m_W measurement: "left-handed" $SU(2)_L$ doublet slepton-sneutrino production, with subsequent decay into lepton plus only invisible particles (see Fig. 1 right),

$$pp \to \tilde{\ell}(\to \ell\, \tilde{\chi}_1^0)\, \tilde{\nu}_\ell\,. \tag{4}$$

In this scenario, both the sneutrino and neutralino are invisible, and either one could be the lightest stable particle (LSP).[8] For simplicity, we assume that the other superpartners, including $SU(2)_L$ singlet – or right-handed sleptons – are heavy, thus having negligible cross-sections at the LHC.

Sleptons lighter than 100 GeV are excluded by LEP [47–51]. Sleptons heavier than the LEP bound have negligible cross-section at the Tevatron so we do not consider CDF in this section. LHC searches for di-sleptons [27,52] are sensitive to sleptons above the LEP bounds but suffer when the sleptons and $\tilde{\chi}^0$ are similar in mass. In particular, when the mass gap $m_{\tilde{\ell}} - m_{\tilde{\chi}_0} \sim m_W$, the lepton p_T resembles that of the lepton from SM W-boson decay. This compressed region of parameter space is dominated by SM events and requires a dedicated analysis. In [53,54] it has been proposed to use precision measurements to disentangle WW events from di-slepton production. Yet, there is still some uncovered gap in the parameter space in the experimental results (see our summary of present constraints in Fig. 2b). Addressing this shortcoming of the present searches by filling this gap is a main result of this *letter*.

The phenomenology of the process in eq. (4) belongs to category (C), since no on-shell W-boson is produced (see Fig. 1). As shown in Fig. 3, NP produces a rather flat and extended m_T distribution with a rising S/B ratio at "high-m_T", since the process is not initiated by the decay of a resonance. The contamination in the Z-boson sample due to $pp \to \bar{\tilde{\ell}}\tilde{\ell} \to \bar{\ell}\ell\,\tilde{\chi}_0\tilde{\chi}_0$ is limited to $\mathcal{O}(10^{-5})$.

For this model, we follow the same procedure as in Sec. 3 of marginalizing on Δ_{m_W} for varying NP parameters. For each point on the $m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$ plane, m_W is varied as an input in the template, and the minimum χ^2 is obtained from the fit. The m_W determination is largely governed by the peak positions of p_T^ℓ and m_T spectra. Therefore, the rather flat kinematic distributions of NP contributions make a milder impact on the m_W measurement than what is shown in Fig. 4. Sensitivity projections are reported in Fig. 2b as functions of $(m_{\tilde{\ell}}, m_{\tilde{\chi}_0})$. The sneutrino mass is fixed at the lowest allowed value in the MSSM, assuming the large $\tan\beta$ limit [46].

Two sets of expected sensitivities are reported in Fig. 2b, corresponding to the inclusion or not of pileup. In both cases, the fitting range (see Table 1) is chosen to cover part of the unexplored parameter space. Extending the range to "high-m_T", still keeping sufficient control of the systematics, might improve the sensitivity, as shown in Fig. 3. However, far from the "m_W" region, systematics becomes more challenging. This is caused, for instance, by the limited Z-boson sample available for calibrations, or by the increasing backgrounds. The study of systematics outside of the range presently used for each kinematic distribution employed in the m_W measurement can only be carried out by the experimental collaborations. Here we are pointing out the huge gain in sensitivity to NP that can be obtained by enlarging the fitting range. Ideally ATLAS and CMS experiments will find the best range of each kinematic variable for which the experiment can keep systematics under control so as to maximize the sensitivity to NP.

A major result of ours is that the same analysis used for the m_W measurement, with only a slightly extended fitting range, can put new bounds and potentially discover new physics in an unexplored parameter space of MSSM.

Table 1
Kinematic range considered for our fit. $\vec{u}_T$ is the hadronic recoil vector. The range with $*$ is considered when we include no pileup effects. We construct bins of 2 GeV for m_T and 1 GeV for p_T^ℓ [5].

	ATLAS [5,6] (μ)	$\tilde{\ell}_\mu \tilde{\nu}_\mu$	$L_\mu - L_\tau$
p_T^ℓ (GeV)	> 30 (analysis) > 18 (trigger)	> 30	> 20
p_T^{miss}	> 30	> 30	> 20
m_T (GeV)	> 60	> 60	> 40
$\lvert\vec{u}_T\rvert$ (GeV)	< 30	< 30	< 30
m_T range (GeV)	[60, 100]	[60, 120]* [60, 140]	[40, 100]
p_T^ℓ range (GeV)	[30, 50]	[30, 60]* [30, 70]	[20, 50]

5. Conclusion

In summary, NP resulting in $\ell + MET$ is an irreducible "background" for the m_W measurement. We demonstrate, using two examples of such NP, that a fit to this data can simultaneously extract m_W

[8] When the lightest neutralino $\tilde{\chi}_1^0$ is the LSP, $\tilde{\ell} \to \ell\,\tilde{\chi}_1^0$, and $\tilde{\nu} \to \nu\,\tilde{\chi}_1^0$, as illustrated in Fig. 1, produces the $\ell + MET$ final state. If the sneutrino is the LSP (not shown), then $\tilde{\chi}_1^0 \to \bar{\tilde{\nu}}\,\nu$ also maintains the $\ell + MET$ final state.

and bound NP, with the extracted value of m_W being possibly different than that determined assuming only SM contribution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors would like to thank Alberto Belloni, Javier Montejo Berlingen, Cecile Sarah Caillol, Rafael Lopes de Sa, Valentina Dutta, Sarah Eno, Tao Han, Philip Harris, Bodhitha Jayatilaka, Jakub Kremer, Gustavo Marques-Tavares, Mario Masciovecchio, Patrick Meade, Federico Meloni, Pier Francesco Monni, Alessandro Vicini and Felix Yu for discussions. The work of K. A., S. A., L. R. and D. S. is supported by NSF Grant No. PHY-2210361 and by the Maryland Center for Fundamental Physics. The work of D. K. is supported by the DOE Grant No. DE-SC0010813. The work of A. V. K. is supported by the DOE Grant No. DE-SC0010007. The work of RF is supported in part by the European Union - Next Generation EU through the MUR PRIN2022 Grant n.202289JEW4.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2024.138774.

References

[1] T. Aaltonen, et al., CDF, Science 376 (2022) 170.
[2] J. de Blas, M. Pierini, L. Reina, L. Silvestrini, Phys. Rev. Lett. 129 (2022) 271801, arXiv:2204.04204 [hep-ph].
[3] A. Strumia, J. High Energy Phys. 08 (2022) 248, arXiv:2204.04191 [hep-ph].
[4] P. Asadi, C. Cesarotti, K. Fraser, S. Homiller, A. Parikh, arXiv:2204.05283 [hep-ph], 2022.
[5] Improved W boson Mass Measurement using 7 TeV Proton-Proton Collisions with the ATLAS Detector, Tech. Rep., CERN, Geneva, 2023.
[6] M. Aaboud, et al., ATLAS, Eur. Phys. J. C 78 (2018) 110, arXiv:1701.07240 [hep-ex], Erratum: Eur. Phys. J. C 78 (2018) 898.
[7] R. Aaij, et al., LHCb, J. High Energy Phys. 01 (2022) 036, arXiv:2109.01113 [hep-ex].
[8] V.M. Abazov, et al., D0, Phys. Rev. Lett. 108 (2012) 151804, arXiv:1203.0293 [hep-ex].
[9] S. Schael, et al., ALEPH, Eur. Phys. J. C 47 (2006) 309, arXiv:hep-ex/0605011.
[10] E. Manca, Precision measurements of W detected at CMS, 2021, presented 27 Jan 2022.
[11] J. Campbell, T. Neumann, arXiv:2308.15382 [hep-ph], 2023.
[12] S. Camarda, L. Cieri, G. Ferrera, Phys. Lett. B 845 (2023) 138125, arXiv:2303.12781 [hep-ph].
[13] A. Autieri, L. Cieri, G. Ferrera, G.F.R. Sborlini, J. High Energy Phys. 07 (2023) 104, arXiv:2302.05403 [hep-ph].
[14] L. Rottoli, P. Torrielli, A. Vicini, arXiv:2301.04059 [hep-ph], 2023.
[15] J. Isaacson, Y. Fu, C.P. Yuan, arXiv:2205.02788 [hep-ph], 2022.
[16] X. Chen, T. Gehrmann, N. Glover, A. Huss, P.F. Monni, E. Re, L. Rottoli, P. Torrielli, in: 56th Rencontres de Moriond on QCD and High Energy Interactions, 2022, arXiv:2206.11059 [hep-ph].
[17] X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss, P.F. Monni, E. Re, L. Rottoli, P. Torrielli, Phys. Rev. Lett. 128 (2022) 252001, arXiv:2203.01565 [hep-ph].
[18] Z. Han, A. Katz, D. Krohn, M. Reece, J. High Energy Phys. 08 (2012) 083, arXiv:1205.5808 [hep-ph].
[19] M. Czakon, A. Mitov, M. Papucci, J.T. Ruderman, A. Weiler, Phys. Rev. Lett. 113 (2014) 201803, arXiv:1407.1043 [hep-ph].
[20] T. Eifert, B. Nachman, Phys. Lett. B 743 (2015) 218, arXiv:1410.7025 [hep-ph].
[21] T. Cohen, S. Majewski, B. Ostdiek, P. Zheng, J. High Energy Phys. 06 (2020) 019, arXiv:1909.09670 [hep-ph].
[22] R. Franceschini, in: 3rd Large Hadron Collider Physics Conference, 2015, pp. 420–425, arXiv:1601.02684 [hep-ph].
[23] Emanuele Bagnaschi, Gennaro Corcella, Roberto Franceschini, Dibyashree Sengupta, The rise and fall of light stops in the LHC top quark sample, arXiv:2312.09794 [hep-ph], 2023, CERN-TH-2023-241.
[24] R. Franceschini, arXiv:2301.04407 [hep-ph], 2023.
[25] The LEP Electroweak Working Group, Tech. Rep.
[26] W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, Phys. Rev. Lett. 113 (2014) 091801, arXiv:1406.2332 [hep-ph].
[27] G. Aad, et al., ATLAS, J. High Energy Phys. 06 (2023) 031, arXiv:2209.13935 [hep-ex].
[28] M. Farina, G. Panico, D. Pappadopulo, J.T. Ruderman, R. Torre, A. Wulzer, Phys. Lett. B 772 (2017) 210, arXiv:1609.08157 [hep-ph].
[29] R. Torre, L. Ricci, A. Wulzer, J. High Energy Phys. 02 (2021) 144, arXiv:2008.12978 [hep-ph].
[30] G. Panico, L. Ricci, A. Wulzer, J. High Energy Phys. 07 (2021) 086, arXiv:2103.10532 [hep-ph].
[31] K. Agashe, S. Airen, R. Franceschini, D. Kim, A.V. Kotwal, L. Ricci, D. Sathyan, arXiv:2404.17574 [hep-ph].
[32] B.A. Dobrescu, F. Yu, arXiv:2112.05392 [hep-ph], 2021.
[33] T. Bandyopadhyay, A. Budhraja, S. Mukherjee, T.S. Roy, arXiv:2212.02534 [hep-ph], 2022.
[34] X.-G. He, G.C. Joshi, H. Lew, R.R. Volkas, Phys. Rev. D 44 (1991) 2118.
[35] G. Krnjaic, G. Marques-Tavares, D. Redigolo, K. Tobioka, Phys. Rev. Lett. 124 (2020) 041802, arXiv:1902.07715 [hep-ph].
[36] M. Ekhterachian, A. Hook, S. Kumar, Y. Tsai, Phys. Rev. D 104 (2021) 035034, arXiv:2103.13396 [hep-ph].
[37] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].
[38] C. Bierlich, et al., https://doi.org/10.21468/SciPostPhysCodeb.8, arXiv:2203.11601 [hep-ph], 2022.
[39] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi, DELPHES 3, J. High Energy Phys. 02 (2014) 057, arXiv:1307.6346 [hep-ex].
[40] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, G. Watt, Eur. Phys. J. C 75 (2015), https://doi.org/10.1140/epjc/s10052-015-3318-8.
[41] R.D. Ball, V. Bertone, S. Carrazza, L.D. Debbio, S. Forte, A. Guffanti, N.P. Hartland, J. Rojo, Nucl. Phys. B 877 (2013) 290.
[42] E. Hammou, Z. Kassabov, M. Madigan, M.L. Mangano, L. Mantani, J. Moore, M.M. Alvarado, M. Ubiali, arXiv:2307.10370 [hep-ph], 2023.
[43] S.R. Mishra, et al., CCFR, Phys. Rev. Lett. 66 (1991) 3117.
[44] A. de Gouvêa, P.B. Dev, B. Dutta, T. Ghosh, T. Han, Y. Zhang, J. High Energy Phys. 2020 (2020), https://doi.org/10.1007/jhep07(2020)142.
[45] B. Batell, T. Han, D. McKeen, B. Shams Es Haghi, Phys. Rev. D 97 (2018) 075016, arXiv:1709.07001 [hep-ph].
[46] S.P. Martin, Adv. Ser. Dir. High Energy Phys. 18 (1998) 1, arXiv:hep-ph/9709356.
[47] A. Heister, et al., ALEPH, Phys. Lett. B 526 (2002) 206, arXiv:hep-ex/0112011.
[48] A. Heister, et al., ALEPH, Phys. Lett. B 583 (2004) 247.
[49] J. Abdallah, et al., DELPHI, Eur. Phys. J. C 31 (2003) 421, arXiv:hep-ex/0311019.
[50] P. Achard, et al., L3, Phys. Lett. B 580 (2004) 37, arXiv:hep-ex/0310007.
[51] G. Abbiendi, et al., OPAL, Eur. Phys. J. C 32 (2004) 453, arXiv:hep-ex/0309014.
[52] Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $sqrts = 13$ TeV, Tech. Rep., CERN, Geneva, 2023.
[53] D. Curtin, P. Jaiswal, P. Meade, Phys. Rev. D 87 (2013) 031701, arXiv:1206.6888 [hep-ph].
[54] D. Curtin, P. Jaiswal, P. Meade, P.-J. Tien, J. High Energy Phys. 08 (2013) 068, arXiv:1304.7011 [hep-ph].