PROCEEDINGS OF SCIENCE

Dark Matter and Baryogenesis via Conversion-Driven Freeze-Out

Jan Heisig

Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, D-52056 Aachen, Germany

E-mail: heisig@physik.rwth-aachen.de

We explore dark matter genesis beyond the WIMP paradigm, focusing on conversion-driven freeze-out – a mechanism that provides thermalization despite very weak dark matter couplings. While this scenario eludes conventional WIMP searches, it predicts distinctive signatures of long-lived particles at colliders, making it a key target for upcoming collider probes. We review realizations of this mechanism and demonstrate how conversion-driven freeze-out can additionally generate the baryon asymmetry, offering a unified explanation for the origins of both dark and visible matter.

Proceedings of the Corfu Summer Institute 2024 "School and Workshops on Elementary Particle Physics and Gravity" (CORFU2024) 12 - 26 May, and 25 August - 27 September, 2024
Corfu, Greece

https://pos.sissa.it/

PoS(CORFU2024)220

1. Introduction

The nature of dark matter (DM) remains one of the central open questions in fundamental physics. While the thermal freeze-out of weakly interacting massive particles (WIMPs) offers a theoretically appealing framework, its viability is increasingly challenged by null results from collider, direct and indirect detection experiments. This has motivated the exploration of alternative DM production mechanisms beyond the WIMP paradigm.

Conversion-driven freeze-out (or coscattering) [1, 2] presents a particularly intriguing alternative: Despite relying on very weak DM couplings that evade current experimental bounds, it still achieves thermalization in the early Universe. This distinguishes it from other scenarios with very weak couplings – such as freeze-in or superWIMP production – which lack thermalization and thus are sensitive to initial conditions.

A minimal and well-motivated realization involves t-channel mediator models, where DM (X) and a slightly heavier mediator (Y) are stabilized by a new Z_2 symmetry [3]. Both quark- and leptonphilic versions of this setup have been studied, consistently pointing toward viable DM scenarios with coupling strengths around 10^{-6} (see *e.g.* [1, 4–6]). In this regime, DM pair annihilation is negligible and freeze-out proceeds solely via conversion processes – (inverse) decays $Y \leftrightarrow Xi$ and scatterings $Yi \leftrightarrow Xj$, with i, j denoting SM particles [1]. Effectively, DM is diluted through these $Y \rightarrow X$ conversions, followed by efficient mediator annihilation into SM states.

Strikingly, this mechanism also provides a pathway to baryogenesis [7]. Due to the specific temperature dependence of the conversion rates, DM departs from equilibrium gradually, already during the semi-relativistic regime – before substantial dilution begins. This early out-of-equilibrium phase can generate a baryon asymmetry via CP-violating conversions. The same interactions then enable sufficient DM dilution to yield the correct DM relic abundance. This offers a unified explanation for both phenomena.

While conversion-driven DM freeze-out requires only two particles, successful baryogenesis demands at least one additional degree of freedom. One possibility is to promote X to a multiplet under a global symmetry, as in flavored DM scenarios [8]. The cogenesis framework of Ref. [7] realizes this idea with lepton-flavored DM, generating a lepton asymmetry that is converted into a baryon asymmetry via sphalerons [9], similar to thermal leptogenesis [10]. Quark-flavored variants yield qualitatively similar results, offering further opportunities for model-building.

Although the tiny DM coupling hinders direct detection of DM, the mediator's SM interactions remain testable. In particular, the mediator is typically long-lived, with decay lengths from millimeters to meters, making it a promising target for long-lived particle (LLP) searches at the LHC and future colliders [11].

In this contribution, we review the mechanism of conversion-driven freeze-out (Section 2), explore its link to baryogenesis (Section 3), and discuss collider signatures of the scenario (Section 4). We conclude in Section 5.

2. Conversion-drive freeze-out

To illustrate the mechanism of conversion-driven freeze-out, we consider a simple class of DM models featuring a t-channel mediator. These extend the Standard Model (SM) by a singlet DM

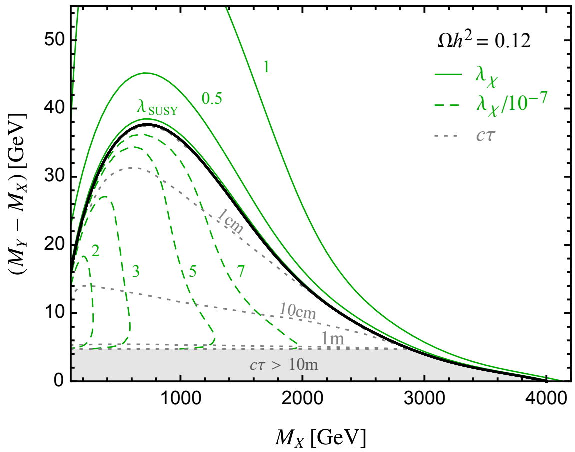

Figure 1: Cosmologically viable parameter space ($\Omega_X h^2 = 0.12$) in the bottom-philic t-channel mediator DM model. The thick black solid line marks the boundary between the WIMP regime (above) and the conversion-driven freeze-out regime (below). At this boundary, the required Yukawa coupling strength drops sharply by several orders of magnitude. Dashed gray lines indicate contours of constant proper decay length of the mediator. Figure adapted from [12].

candidate, X, and a mediator, Y, both stabilized by a new Z_2 symmetry. A minimal setup includes the renormalizable interaction:

$$\mathcal{L}_{X-Y-\rm SM} = -\lambda Y \bar{\psi} X + \text{h.c.}, \tag{1}$$

where ψ is a SM fermion – a quark or lepton. Here, we assume X to be a Majorana fermion and Y a complex scalar. Gauge invariance requires Y to carry the same quantum numbers as ψ. In addition, the scalar mediator can couple to the Higgs via

$$\mathcal{L}_{Y-\rm SM} = (D_\mu Y)^\dagger D^\mu Y - \lambda_H H^\dagger H Y^\dagger Y, \tag{2}$$

with D^μ the covariant derivative and H the SM Higgs doublet.

In the early Universe, three types of processes govern the evolution of the new physics particles' abundances: *(i)* Annihilation and coannihilation of the form $XX \to$ SM and $XY \to$ SM, with rates scaling as λ^4 and λ^2, respectively, *(ii)* pair-annihilation of the mediator, $YY \to$ SM, featuring a λ-independent part from the interactions in Eq. (2), and *(iii)* conversions between X and Y through (inverse) decays and scatterings, both scaling as λ^2.

In the regime of small Yukawa couplings λ, DM annihilations and coannihilations *(i)* become negligible, leaving mediator pair-annihilation *(ii)* as the dominant number-changing process of Z_2-odd states. Meanwhile, conversion processes *(iii)* can remain efficient, $\Gamma_{\rm con} \gg \mathcal{H}$, since – unlike annihilations – they are not exponentially Boltzmann-suppressed during freeze-out. This is because conversions typically involve only a single heavy particle in the initial state, allowing chemical equilibrium between X and Y to persist down to surprisingly small values of λ. However, when the coupling becomes very small, $\lambda \sim 10^{-6}$ [1], the conversion rate becomes comparable to the Hubble rate, $\Gamma_{\rm con} \sim \mathcal{H}$, initiating the chemical decoupling of X from Y and the SM bath. This defines the regime of conversion-driven freeze-out [1, 2].

This mechanism provides viable DM production with the correct relic density ($\Omega_X h^2 = 0.12$) in a broad class of models featuring a Z_2-odd mediator, such as t-channel mediator models. Figure 1 illustrates the viable parameter space for a minimal bottom-philic t-channel model ($\psi = b_R$), shown in terms of the DM mass and the mass splitting between Y and X. Conversion-driven freeze-out explains the measured relic density below the thick black line, *i.e.* for relatively small mass splittings (up to a few tens of GeV) and DM (and mediator) masses up to about 4 TeV [12]. Notably, due to the limited size of the mediator annihilation cross-section, the parameter space is fairly constrained toward large masses, placing the scenario well within the reach of future collider searches. See Section 4 for a discussion of the corresponding constraints.

Intriguingly, the small couplings required for conversion-driven freeze-out ($\lambda \sim 10^{-6}$) connect to other open questions in particle physics beyond the SM. For instance, in realizations of the mechanism within the scotogenic model, such small couplings naturally account for radiatively generated neutrino masses of the correct scale, while allowing for $\mathcal{O}(1)$ scalar couplings [13]. Moreover, the weak thermal coupling of DM to the SM bath opens a new window for baryogenesis [7], a possibility we explore in the next section.

3. Link to Baryogenesis

A defining feature of conversion-driven freeze-out is the semi-efficient nature of the conversion rate, $\Gamma_{\rm con}$. Due to its shallow temperature dependence, $\Gamma_{\rm con}$ remains close to the Hubble expansion rate over a prolonged period – from the relativistic into the non-relativistic regime – thus enabling thermalization, dilution, and eventually chemical decoupling of DM.

The left panel of Fig. 2 illustrates the resulting evolution of the mediator (blue) and DM (red) abundances, $\mathcal{Y}_Y$ and $\mathcal{Y}_X$, respectively, in the aforementioned minimal bottom-philic model. These curves are obtained by solving the coupled Boltzmann equations, accounting also for bound-state effects of the mediator [12]. The plot shows that DM departs from thermal equilibrium already when semi-relativistic, yet it remains sufficiently coupled to the mediator to undergo substantial dilution during the non-relativistic phase.

Interestingly, this early deviation from equilibrium can be leveraged to satisfy the third Sakharov condition required for baryogenesis [7]. Since the abundances are still sizeable during the semi-relativistic stage, the generated asymmetry can be significant. Of course, successful baryogenesis also demands C/CP violation and baryon number violation – the second and first Sakharov conditions, respectively.

Because of CPT invariance, the total decay rates of Y and $Y^\dagger$ are equal. Hence, for a single DM and mediator species, the decay $Y \to X\psi$ does not lead to a CP asymmetry. This motivates extending the particle content, for instance, by promoting X to a multiplet under a global symmetry, with mass eigenstates X_k coupling to SM fermions of flavor f through a matrix λ_{kf}, as in flavored DM scenarios [8]. In such setups, the partial decay widths of Y and $Y^\dagger$ into X_k can differ, giving rise to a nonzero CP asymmetry:

$$\epsilon_k = \frac{\Gamma_{Y\to X_k\psi} - \Gamma_{Y^\dagger\to X_k\bar{\psi}}}{\Gamma_{Y\to X_k\psi} + \Gamma_{Y^\dagger\to X_k\bar{\psi}}}\,, \tag{3}$$

where X is assumed to be self-conjugate.

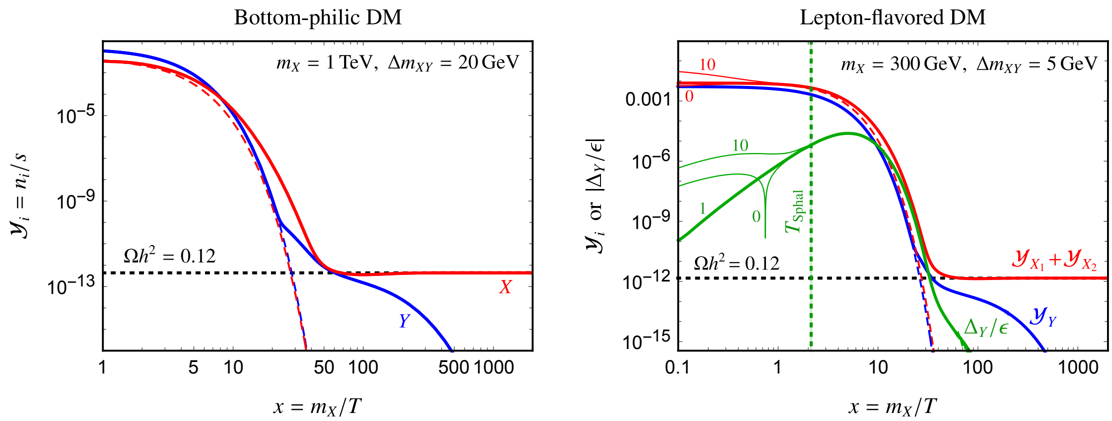

Figure 2: Evolution of the abundances, $\mathcal{Y}$, for DM (red) and the mediator (blue) as a function of $x = m_X/T$, for representative parameter points in the conversion-driven regime with $\Omega_X h^2 = 0.12$. Left: Bottom-philic minimal model, from [12]. Right: Lepton-flavored DM scenario that simultaneously accounts for the baryon asymmetry. The green curve shows the mediator asymmetry, Δ_Y, normalized to the CP asymmetry ϵ. Thick lines correspond to equilibrated initial conditions for the DM multiplet states; thin lines labeled '0' and '10' refer to initial DM abundances of 0 and 10 times the equilibrium value, respectively. The green dashed line marks the sphaleron decoupling temperature. Adapted from [7].

The presence of an CP asymmetry can induce an asymmetry in the mediator sector, $\Delta_Y = \mathcal{Y}_Y - \mathcal{Y}_{Y^\dagger}$. The right panel of Fig. 2 shows the resulting evolution of Δ_Y in a leptophilic realization, where $\psi_f = \ell_{\mathrm{R},f}$, with two DM flavors coupling to the first two SM generations. (The asymmetry is normalized by $\epsilon \equiv \epsilon_1$.) The asymmetry builds up during the semi-relativistic regime due to the departure from equilibrium of the DM flavors X_k. The source term is proportional to $\sum_k \epsilon_k \mathcal{Y}_k / \mathcal{Y}_k^{\text{eq}}$, requiring not only a deviation from equilibrium but also flavor-dependent abundances [7].

Importantly, the generated asymmetry is largely insensitive to initial conditions [7]. As demonstrated by the thin lines labeled '0' and '10', even vastly different initial DM abundances evolve toward the same out-of-equilibrium value, as previously observed in [1]. While the asymmetry itself may be somewhat more sensitive, it remains robust in the relevant semi-relativistic window, $m_X/T \gtrsim 2$. This distinguishes conversion-driven freeze-out from alternative cogenesis mechanisms relying on freeze-in.

Finally, regarding the first Sakharov condition, the scenario leverages baryon number violation of sphaleron processes in the SM for the generation of the baryon asymmetry: The conversion processes generate a lepton asymmetry in the SM sector, equal but of opposite sign to the mediator asymmetry. This lepton asymmetry is then partially converted into a baryon asymmetry by electroweak sphalerons, which are active until temperatures of about 130 GeV. Crucially, this decoupling occurs before the rapid depletion of the mediator (and its asymmetry) at $m_X/T \gtrsim 5$. Thus, conversion-driven freeze-out with DM masses in the few hundred GeV range provides an efficient and viable framework for simultaneous DM and baryon asymmetry generation.

In the resonant regime of quasi-degenerate DM multiplet states and for small mass splittings Δm_{XY}, the considered lepton-flavored model can account for both relic DM and the baryon asymmetry for m_X up to around 500 GeV [7]. This parameter space is accessible to future collider searches, as discussed in the next section.

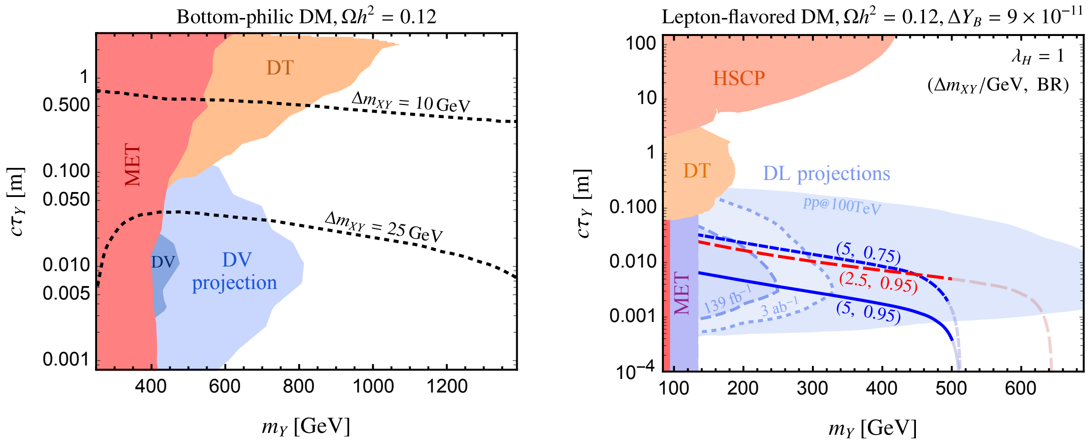

Figure 3: Collider bounds on parameter space in conversion-driven freeze-out scenarios. Left: Bottom-philic model [11]. Right: Lepton-flavored DM model simultaneously explaining the baryon asymmetry [7]. Colored regions show 95% CL exclusions from MET, DT, DV, and HSCP searches. Light blue areas indicate projected reach of future displaced object searches. Details in text and references.

4. Tests at colliders

In the scenarios outlined above, the mediator carries electric or color charge, resulting in a sizable production cross-section at colliders. A distinctive feature of conversion-driven freeze-out is the long lifetime of the mediator, leading to striking signatures of LLPs.

This fairly general feature of the mechanism can be understood from a simple estimate: For conversions to initiate chemical decoupling, their rate must be comparable to the Hubble rate, $\Gamma_{\rm con} \sim \mathcal{H}$. Since conversions involve both scatterings and decays, this implies $\Gamma_{\rm decay} \lesssim \mathcal{H}$, and hence a decay length of $c\tau_Y \gtrsim \mathcal{H}^{-1}$. For freeze-out temperatures relevant to $m_X \sim \mathcal{O}(100\,\mathrm{GeV})$, this corresponds to decay lengths around the centimeter scale. More precise estimates yield $c\tau_Y$ between millimeters and meters when $\Gamma_{\rm decay} \sim \Gamma_{\rm con}$ [1, 11] and longer if conversion is dominated by scatterings [4].

This broad range of lifetimes requires a variety of search strategies [11]. For very long lifetimes (meters and beyond), heavy stable charged particle (HSCP) searches utilizing anomalous ionization and time-of-flight are effective. In the intermediate range ($10\,\mathrm{cm} \lesssim c\tau_Y \lesssim 1\,\mathrm{m}$), disappearing track (DT) searches are promising. For shorter lifetimes, the mediator track may not be reconstructed, necessitating searches for displaced vertices (DV) or displaced leptons (DL). Standard missing energy (MET) searches may also be sensitive, although they do not specifically exploit the LLP nature and therefore have weaker reach.

The left panel of Fig. 3 shows current LHC constraints on the bottom-philic model from CMS disappearing track [14, 15], ATLAS displaced vertex [16], and CMS MET [17] searches. Notably, the DV search barely outperforms the MET search, despite its much lower background – revealing a gap in sensitivity to soft displaced objects. This limitation stems from current DV searches being tailored to hard decay products, as expected in scenarios like split supersymmetry, whereas conversion-driven freeze-out typically yields soft visible particles with energies of the order of the small mass splitting between the mediator and DM.

For example, the ATLAS DV search includes a cut on the invariant mass of the displaced jet that significantly suppresses signal efficiency. Lowering this threshold could enhance the reach substantially, as shown by the 'DV projection' region in Fig. 3 (left) [11]. Such improvements would be particularly effective in Run 3 and beyond, since LLP searches benefit more from increased statistics than MET-based analyses, which are already systematics-limited [11].

The right panel of Fig. 3 shows constraints on a lepton-flavored DM model that also accounts for the baryon asymmetry. The curves correspond to three benchmark scenarios with fixed mass splitting and mediator branching ratios. The viable region falls in the $c\tau$ range of a few millimeters to centimeters. MET searches [18, 19] currently provide the strongest bounds, though only up to mediator masses of about 140 GeV.

Similar to the quark-philic case, existing searches for displaced leptons have limited reach due to their focus on high-momentum signatures. A dedicated search targeting soft displaced leptons, in conjunction with MET, could significantly enhance sensitivity [7]. The projected reach of such a strategy at the LHC (for 139 fb^{-1} and 3 ab^{-1}) and at the FCC-hh is shown by the light blue regions in the right panel of Fig. 3.

5. Conclusions

Conversion-driven freeze-out provides a compelling framework for thermalized DM with very weak interactions, realized via a t-channel mediator nearly degenerate in mass with the DM particle. In the early Universe, chemical decoupling proceeds gradually and begins while DM is still relativistic, further enabling the generation of sizeable matter–antimatter asymmetries through CP-violating conversion processes.

This mechanism for baryogenesis exploits the fact that sphalerons act only on the SM asymmetries, while those in the dark sector – specifically of the mediator – remain unaffected. As a result, a net baryon asymmetry persists after sphaleron freeze-out. For lepton-flavored models, viable parameter space extends up to DM masses of $\sim$ 500 GeV and lies within reach of current and future colliders.

The small couplings required lead to mediator decay lengths of millimeters to meters, giving rise to characteristic LLP signatures. However, current LHC searches lack sensitivity to the soft displaced objects typical of this scenario, leaving a clear gap. Dedicated searches targeting such signatures are crucial to probing the lower lifetime frontier. Notably, future colliders offer the potential for full coverage of the viable parameter space.

References

[1] M. Garny, J. Heisig, B. Lülf and S. Vogl, *Coannihilation without chemical equilibrium*, *Phys. Rev. D* **96** (2017) 103521, [1705.09292].

[2] R. T. D'Agnolo, D. Pappadopulo and J. T. Ruderman, *Fourth Exception in the Calculation of Relic Abundances*, *Phys. Rev. Lett.* **119** (2017) 061102, [1705.08450].

[3] C. Arina et al., *t-channel dark matter at the LHC*, 2504.10597.

[4] M. Garny, J. Heisig, M. Hufnagel and B. Lülf, *Top-philic dark matter within and beyond the WIMP paradigm*, *Phys. Rev. D* **97** (2018) 075002, [1802.00814].

[5] S. Junius, L. Lopez-Honorez and A. Mariotti, *A feeble window on leptophilic dark matter*, *JHEP* **07** (2019) 136, [1904.07513].

[6] J. Herms and A. Ibarra, *Production and signatures of multi-flavour dark matter scenarios with t-channel mediators*, *JCAP* **10** (2021) 026, [2103.10392].

[7] J. Heisig, *Conversion-Driven Leptogenesis: A Testable Theory of Dark Matter and Baryogenesis at the Electroweak Scale*, *Phys. Rev. Lett.* **133** (2024) 191803, [2404.12428].

[8] P. Agrawal, S. Blanchet, Z. Chacko and C. Kilic, *Flavored Dark Matter, and Its Implications for Direct Detection and Colliders*, *Phys. Rev. D* **86** (2012) 055002, [1109.3516].

[9] V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, *On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe*, *Phys. Lett. B* **155** (1985) 36.

[10] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, *Phys. Lett. B* **174** (1986) 45–47.

[11] J. Heisig, A. Lessa and L. M. D. Ramos, *Probing conversion-driven freeze-out at the LHC*, *Phys. Rev. D* **110** (2024) 015031, [2404.16086].

[12] M. Garny and J. Heisig, *Bound-state effects on dark matter coannihilation: Pushing the boundaries of conversion-driven freeze-out*, *Phys. Rev. D* **105** (2022) 055004, [2112.01499].

[13] J. Heeck, J. Heisig and A. Thapa, *Dark matter and radiative neutrino masses in conversion-driven scotogenesis*, *Phys. Rev. D* **107** (2023) 015028, [2211.13013].

[14] CMS collaboration, CMS Collaboration, *Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **08** (2018) 016, [1804.07321].

[15] CMS collaboration, A. M. Sirunyan et al., *Search for disappearing tracks in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *Phys. Lett. B* **806** (2020) 135502, [2004.05153].

[16] ATLAS collaboration, ATLAS Collaboration, *Search for long-lived, massive particles in events with displaced vertices and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, *Phys. Rev. D* **97** (2018) 052012, [1710.04901].

[17] CMS collaboration, CMS Collaboration, *Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, *JHEP* **11** (2021) 153, [2107.13021].

[18] ATLAS collaboration, G. Aad et al., *Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector*, *Phys. Rev. D* **101** (2020) 052005, [1911.12606].

[19] CMS collaboration, A. Hayrapetyan et al., *Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at s=13 TeV*, *Phys. Rev. D* **109** (2024) 112001, [2402.01888].