Supersymmetry and Dark Matter: Interplay of Collider and Non-Collider Searches

Satoshi Shirai

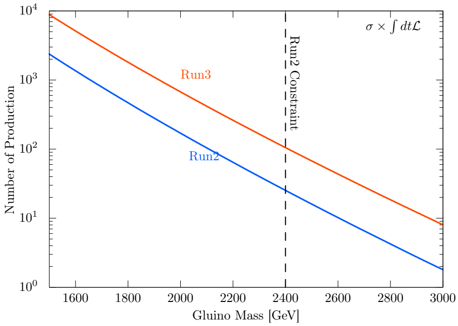
Kavli IPMU

2025-Dec-26

Outline

Run3 opportunities: two frontiers — and where the leverage is largest

- **Mass frontier:** more $\mathcal{L}$ + modest $\sqrt{s}$ gain
  - solid, steady extension of classic high-mass programs (gluino/squark, heavy resonances, ...)
- **Signature frontier:** acceptance- and reconstruction-limited searches
  - **Compressed spectra** $\Rightarrow$ soft leptons/jets, ISR-tag strategies
  - **Long-lived particles** $\Rightarrow$ disappearing tracks, displaced/tracklet signatures
- **Why emphasize this today:**
  - DM-motivated neutralinos are frequently **near-degenerate and/or long-lived**
  - Run3 gains can be **disproportionately large** compared to pure yield scaling
- **Main message:** keep pushing the mass frontier, but **expand coverage** by investing in signature frontier.



Yield scaling example
$N_{\text{prod}} = \sigma \times \mathcal{L}$; Run2 ~2.4 TeV → Run3 rough target ~2.8 TeV.

Why SUSY+DM points to the "signature frontier"

- In the MSSM electroweakino sector, the interaction eigenstates are:
  - **Bino** $\tilde{B}$ ($U(1)_Y$ gaugino), **Wino** $\tilde{W}^{0,\pm}$ ($SU(2)_L$ triplet), **Higgsinos** $\tilde{H}_{u,d}$ ($SU(2)_L$ doublets).
- The DM candidate is typically the lightest neutralino,

$$\tilde{\chi}_1^0 \simeq N_{11}\tilde{B} + N_{12}\tilde{W}^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0,$$

  i.e. a **mixture** of these components.
- Direct detection increasingly disfavors **large gaugino–Higgsino mixing** (via Higgs/Z couplings) $\Rightarrow$ viable regions often lie close to the **Bino-/Wino-/Higgsino-like limits**.
- Those limits naturally imply:
  - **compressed neutralino–chargino spectra** (small Δm) $\Rightarrow$ soft objects
  - **(possibly) long lifetimes** $\Rightarrow$ disappearing tracks / displaced decays
- Goal: identify motivated corners where Run3/HL-LHC can make **disproportionate gains**.

What I would like to see searched

- **Disappearing tracks: Wino-/Higgsino-like electroweakinos** with tiny $\Delta m(\tilde{\chi}^{\pm} - \tilde{\chi}^{0})$.
- **Compressed electroweakinos (EWinos):** use a hard **ISR jet** to recoil the system $\Rightarrow$ trigger + access **soft leptons/jets** + E_T^{miss}.
- **Displaced / LLP signatures:** small mass splittings and/or suppressed couplings (often in **coannihilation-motivated** regions) $\Rightarrow$ soft displaced tracks/vertices.
- Emphasis today: **physics motivation and complementarity**

Three complementary approaches to DM (one interaction, four probes)

Relic abundance

freeze-out: $\Omega_\chi h^2 \leftrightarrow \langle \sigma v \rangle$

- thermal history
- coannihilation / resonances

Direct detection (DD)

$\chi N \to \chi N$ in the lab

- Higgs/Z couplings
- nuclear responses

DM annihilation

$\chi\chi \to \mathrm{SM}\,\mathrm{SM}$

Indirect detection (ID)

$\chi\chi \to \mathrm{SM}\,\mathrm{SM}$ today

- γ rays / CR / ν
- halo-profile systematics

Colliders

$pp \to \chi\chi + X$

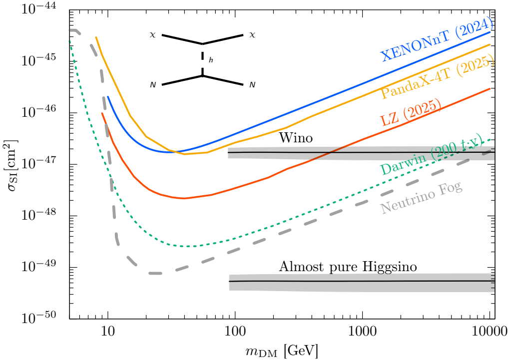
- production
- no cosmological/astrophysical assumptions

Direct detection: Higgs coupling and the mixing squeeze

- Leading experiments strongly constrain **spin-independent** scattering over a wide mass range.
- For neutralino WIMPs, SI scattering is often dominated by **Higgs-mediated** $\chi N \to \chi N$.
- **Order-of-magnitude message (generic):**

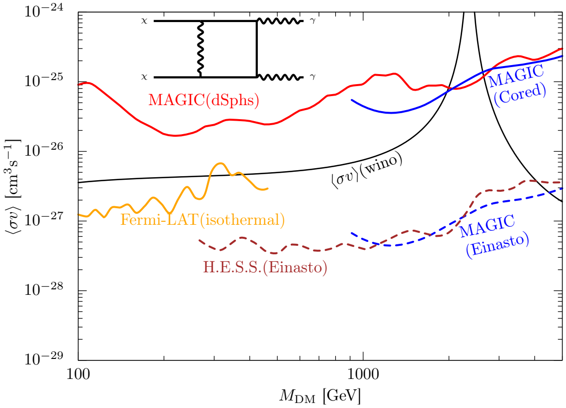
$$\sigma_{\rm SI} \sim \mathcal{O}(10^{-43}\,{\rm cm}^2) \times (\text{gaugino–higgsino mixing})^2 \;\Rightarrow\; \text{large mixing is strongly constrained.}$$

- Loop-induced SI scattering provides a well-defined target for (almost) pure **Wino** DM.



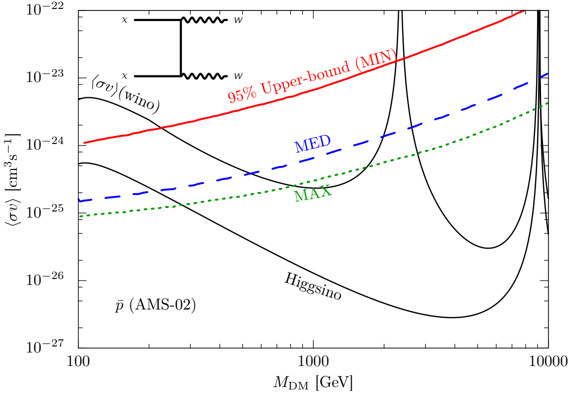
Indirect detection: strong reach, strong astrophysical systematics

- Line gamma-ray searches can be strong, but constraints depend strongly on the DM density profile.
- A single model (e.g. Wino DM) can move from "strongly constrained" to "still viable" depending on halo assumptions.
- Takeaway: state assumptions explicitly when translating ID limits into particle-physics conclusions.



Antiprotons / CR constraints

- Antiproton limits can be powerful for large $\langle \sigma v \rangle$ candidates (e.g. Wino-like DM).
- Dominant uncertainties: CR propagation, solar modulation, production cross sections.
- Use as complementary information; avoid over-interpreting "exclusion".



Interim summary: what DD/ID tell us (and what they do not)

- **Direct detection (DD):** strong constraints on **spin-independent** scattering ⇒ **large gaugino–Higgsino mixing is squeezed** (with model-dependent blind spots).
- **Indirect detection (ID):** powerful for candidates with large annihilation rates (e.g. **Wino-like**) but **astrophysical systematics** (halo profile, J-factors, propagation) can dominate interpretations.
- **Net result (working targets for 2026):** neutralino WIMP scenarios often cluster near **Bino-/Wino-/Higgsino-like limits**, frequently implying **compressed spectra and/or long lifetimes**.
- **Implication for Run3/HL-LHC:** the highest ROI (at least to me) is the **signature frontier**: **disappearing tracks, soft-object searches, displaced/LLP signatures**.

Electroweakinos in one slide: composition and limiting cases

- Gauge interaction eigenstates:
  - **Bino** $\tilde{B}$ ($U(1)_Y$), **Wino** $\tilde{W}^{0,\pm}$ ($SU(2)_L$ triplet), **Higgsinos** $\tilde{H}_{u,d}$ ($SU(2)_L$ doublets)
- After EWSB they mix ⇒ mass eigenstates (EWinos):
  - neutralinos $\tilde{\chi}_i^0$ (4), charginos $\tilde{\chi}_i^\pm$ (2)
- Collider intuition:
  - Wino/Higgsino-like ⇒ nearby chargino ⇒ Δm & lifetime matter
  - Bino-like ⇒ often needs coannihilation to get the relic density

The (M_1, M_2, μ) map

- Controls the EWino spectrum:

$$M_1,\ M_2,\ \mu$$

- Limiting cases:
  - **Bino-like:** $M_1 \ll M_2, |\mu|$
  - **Wino-like:** $M_2 \ll M_1, |\mu|$
  - **Higgsino-like:** $|\mu| \ll M_1, M_2$
- These corners are where DD/ID/collider complementarity is often sharpest.

Working assumptions

- Focus on **R-parity conserving** SUSY where the LSP is a **neutralino WIMP** (minimal SUSY WIMP setup).
- Use a simplified viewpoint: **"DM multiplet + nearest partner(s)"** are light, while other superpartners may be heavy.
  - Purpose: a clear map between **relic mechanism** and **collider signatures** (compressed spectra / LLPs).
- **Heavy sfermions** as a motivated (not mandatory) prior:
  - alleviates SUSY flavor/CP constraints; compatible with (mini-)Split SUSY
  - can help accommodate $m_h \simeq 125$ GeV with heavy stops
  - can alleviate the **gravitino problem** in some cosmologies
- From a model-building viewpoint, such spectra can be justified in specific setups (e.g. an **R-symmetry**).

(A) Bino-like DM: why a partner is needed

- Pure **Bino** has suppressed annihilation ⇒ typically overabundant.
- A clean mechanism: **coannihilation** with a near-degenerate partner.
  - Rule of thumb: requires $\Delta m/m \sim \mathcal{O}(1\text{–}10\%)$.
  - Classic example: slepton/stau coannihilation in mSUGRA-like scenarios.
- In these corners, DD/ID can be weak ⇒ **colliders can be decisive** (compressed spectra, possibly LLPs).

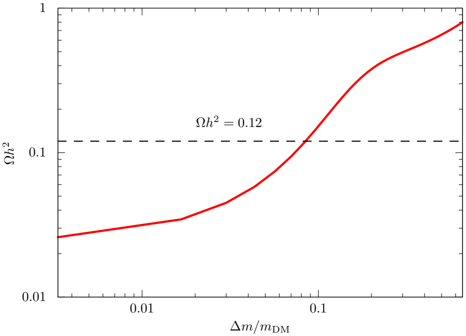
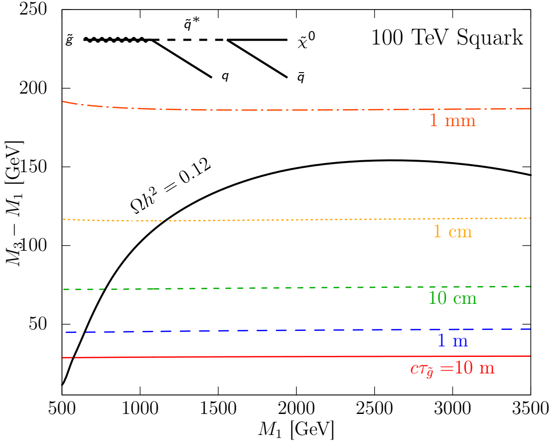


Illustration: relic abundance is highly sensitive to the mass difference Δm.

Example: Bino–gluino coannihilation

- Relic abundance sets a relation between $m_{\tilde{B}}$ and $\Delta m(\tilde{g} - \tilde{B})$.
- The same parameter region can imply **long-lived gluinos** (macroscopic lifetimes).
- Message: motivates **compressed** and **LLP/R-hadron/Displaced-vertex**-type searches.



(B) Wino DM: a motivated target: AMSB and (non-)thermal production

- **Well-motivated framework:** in anomaly-mediated SUSY breaking (AMSB), the **Wino** is naturally the lightest electroweakino $\Rightarrow$ a minimal neutralino DM candidate.
- Thermal relic target: $m_{\tilde{W}} \sim 3\ \mathrm{TeV}$.
- **Non-thermal abundance is plausible:** late decays of heavy fields (notably the **gravitino**) can populate Winos after freeze-out.
  - High reheating temperature T_R motivated by **thermal leptogenesis** (via heavy right-handed neutrinos) also enhances gravitino production, which can significantly affect the final Wino abundance.
- Large $\langle \sigma v \rangle$ $\Rightarrow$ potentially strong ID constraints/signals.
- It links a concrete SUSY spectrum (AMSB) to early-Universe physics (leptogenesis/T_R) and leads to sharp experimental targets (ID + disappearing tracks).
- I will revisit the detailed phenomenology later in a worked-example "hint $\to$ collider" demo.

Wino fingerprint at colliders: disappearing tracks (and soft pions)

- For a (nearly) pure **Wino** ($SU(2)_L$ triplet), the charged–neutral splitting is essentially fixed:

$$\Delta m \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \simeq 160\ \mathrm{MeV} \quad \text{(loop prediction; higher-order effects are small)}$$

- This directly sets the key collider observables:
  - $\tilde{\chi}_1^\pm$ is **long-lived on detector scales** $\Rightarrow$ a **disappearing track / tracklet** in the inner tracker (typically with ISR + $E_T^{\rm miss}$).
  - $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \pi^\pm$ with a **very soft** pion.
- **Bonus handle (ambitious):** reconstructing the soft $\pi^\pm$
  - provides sensitivity to Δm (spectroscopy) — a **critical test of the EW quantum numbers**
  - and may help with background rejection if it can be done reliably

(C) Higgsino DM: thermal target and why splittings are the observable

- **Thermal target:** a nearly pure Higgsino gives the observed relic density for

$$m_{\tilde{H}} \sim 1 \text{ TeV} .$$

- Higgsino-like LSP: $|\mu| \ll M_1, M_2 \quad \Rightarrow$ a quasi-degenerate multiplet ($\tilde{\chi}^0_{1,2}$ and $\tilde{\chi}^\pm_1$), often close to a **pseudo-Dirac** limit.
- Mass splittings are set by loops and by mixing with **Bino/Wino**:

$$\Delta m(\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1), \quad \Delta m(\tilde{\chi}^0_2 - \tilde{\chi}^0_1).$$

- DD constraints mixing/splitting ⇒ collider signatures often involve **soft** objects and sometimes **displaced** tracks.
- If $\Delta m(\tilde{\chi}^\pm_1 - \tilde{\chi}^0_1)$ is very small, the chargino can be long-lived ⇒ **(short) disappearing tracks / tracklets** also become an important handle.

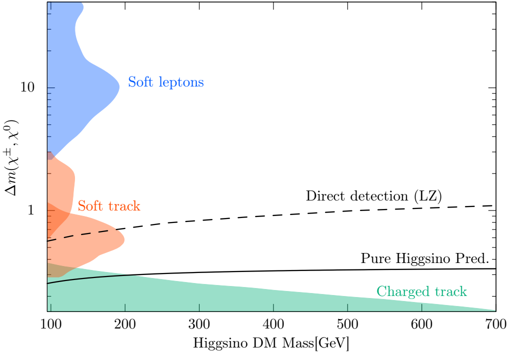
Higgsino: mass vs splitting ⇒ collider strategy

- The $(m_{\tilde{H}}, \Delta m)$ plane summarizes DD pressure and collider gaps.
- **Mass split and DD:**

$$(\Delta m)_{\rm tree} \simeq 0.5\ {\rm GeV} \left(\frac{\sigma_{\rm SI}}{10^{-47}\ {\rm cm}^2}\right)^{1/2}$$

(tree-level contribution; loops add on top)

- **Collider handles by Δm:**
  - $\Delta m \sim \mathcal{O}(1-10)\,{\rm GeV}$: **soft dileptons**
  - $\Delta m \sim \mathcal{O}(100)\,{\rm MeV}$: **soft pion / track-based** observables
  - very small Δm or suppressed couplings: **displaced** soft tracks/vertices



Mini-summary: DM constraints $\Rightarrow$ collider targets

- DD/ID already shape the viable neutralino DM space:
  - DD squeezes large gaugino–higgsino mixing $\Rightarrow$ near-pure corners
  - ID can be powerful (especially for Wino-like DM), but astrophysical systematics matter
- Colliders provide **spectroscopy** that non-collider searches cannot:

$$\text{multiplet structure, } \Delta m,\ c\tau \ \Rightarrow\ \text{EW quantum numbers}$$

- **Practical implication (signature frontier):** motivated targets often require **ISR+soft objects** and **non-standard tracks** (disappearing / displaced / tracklets).
- Next: a worked example ("hint" $\rightarrow$ search plan) using a recent MW-halo continuum excess claim.

If we see a hint: mapping to collider targets

- A DD hint gives $(m_\chi, \sigma_{\rm SI/SD}), \Delta m \Rightarrow$ implies mixing/couplings.
- An ID hint gives $(m_\chi, \langle \sigma v \rangle)$ and modes $\Rightarrow$ points to annihilation-dominant candidates (often Wino/Higgsino-like).
- Collider goal: identify the multiplet structure and the spectrum:
  - charged partner? mass splittings? lifetime $(c\tau)$?
  - coannihilation partner(s) and decay topology?

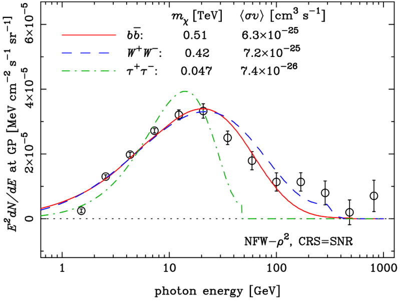
Demo: a reported MW-halo continuum excess (JCAP 11 (2025) 080)

- A recent **analysis/press release** reports a continuum bump in the **Milky Way halo** (**excluding** the Galactic Center).
- If interpreted as DM annihilation, the preferred region is roughly

$$m_\chi \sim 0.5\text{–}0.8\ \mathrm{TeV}, \qquad \langle \sigma v \rangle \sim \mathcal{O}(10^{-25})\ \mathrm{cm}^3\,\mathrm{s}^{-1}$$

  (analysis- and astrophysics-dependent).
- Here I use it only as a **worked example** of the **“hint $\to$ search plan”** decision tree.

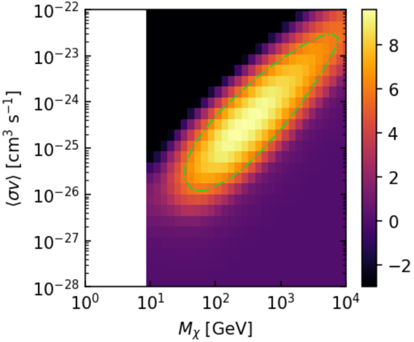
(Context: press release / headline)



(Reported spectrum / fit region)

Other indications? Dwarfs and isotropic component

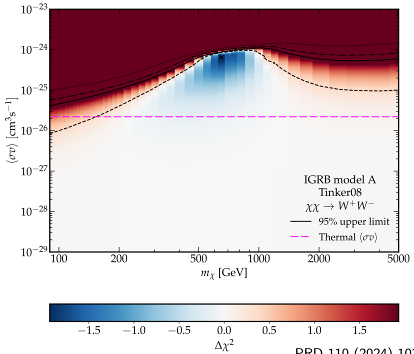
- Some analyses report **mild** preferences in a similar mass range:
  - a subset of dwarfs show excess-like features
  - isotropic gamma-ray component: weak preference (analysis-dependent)
- Not statistically compelling individually; useful as **cross-check targets**.



Based on PRD 109 (2024) 063024

(Dwarf gamma rays (Reticulum 2))

$TS \equiv 2\,\Delta \ln \mathcal{L} = 2\,(\ln \mathcal{L}_{\rm DM} - \ln \mathcal{L}_{\rm no\,DM})$

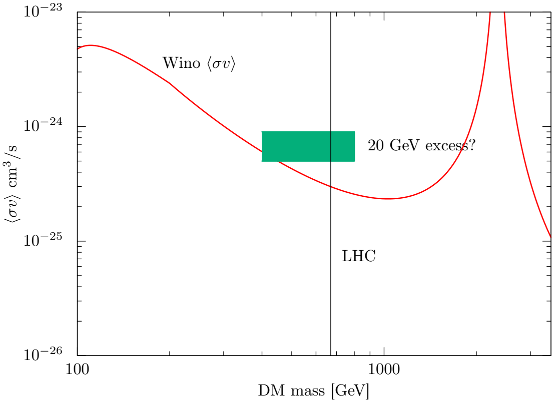


PRD 110 (2024) 103032

(Isotropic gamma-ray component)

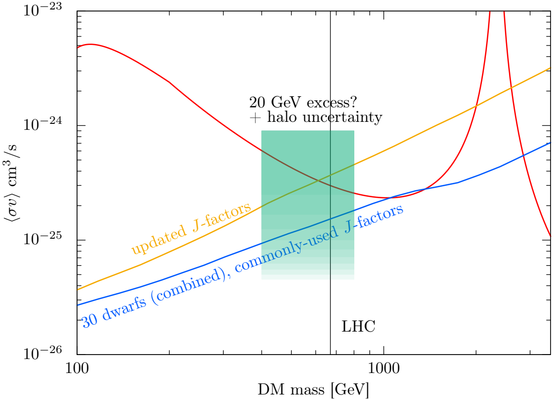
Can Wino DM explain it? Focus on $\chi\chi \to W^+W^-$

- A natural candidate: **Wino-like DM** with dominant annihilation to W^+W^- with non-thermal production.
- Key question: does the predicted $\langle\sigma v\rangle$ match the required region from the MW-halo fit?
- In many fits, the Wino prediction is **low by a factor of** ~ 2–3 in the **flux-equivalent normalization** (analysis/halo dependent).
- This shortfall can be phrased as requiring an astrophysical enhancement of order a **few** (e.g. substructure boost), which is not excluded a priori.



Dwarfs: “tension” depends on J-factors

- It is often stated that the MW-halo interpretation is excluded by **combined dwarf** constraints.
- However, the resulting limit depends strongly on the adopted ***J*-factor determinations** (stellar-kinematics systematics, priors, and uncertainty treatment).
- Takeaway for this demo: best viewed as **tension under conventional assumptions**, not a model-independent no-go.



Same gamma-ray data, different J-factor sets ⇒ different limits.
Blue: PRD 109 (2024) 063024; Orange: MNRAS 544 (2025) 2946

Other constraints (brief): DD and early-Universe bounds

- **Direct detection:** Wino SI scattering is loop-suppressed; current bounds **push toward** $m_\chi \gtrsim \mathcal{O}(\text{few} \times 100\ \mathrm{GeV})$ (depending on the local DM density and theory uncertainties).
- **CMB/BBN:** energy/particle injection (CMB and BBN) can constrain parts of parameter space.
- Bottom line: the Wino interpretation is not obviously a no-go, but it is **assumption-sensitive**.

Action plan: probing a sub-TeV Wino target (signature frontier)

Illustrative case study: conclusions depend on astrophysical assumptions.

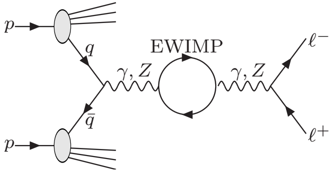
- If this ROI points to a **sub-TeV** Wino-like DM candidate, the next steps are complementary:
  - **LHC/HL-LHC:** disappearing tracks (measure $c\tau$, test the $SU(2)_L$ triplet nature)
  - **CTA:** improved MW-halo sensitivity; spectrum and morphology tests
  - **Dwarfs/IGRB:** unified analyses with explicit J-factor/background systematics
  - **DD:** wait for the next sensitivity step and improved systematics
- Even if the excess disappears, this exercise identifies a **well-defined experimental target**.

Summary

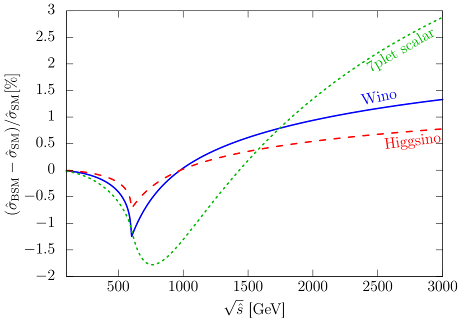
- **Run3/HL-LHC opportunity:** beyond steady progress at the mass frontier, SUSY+DM gives especially strong motivation for the **signature frontier**.
- **Non-collider constraints shape the target space:** DD squeezes large neutralino mixing; ID is powerful but astrophysics-limited $\Rightarrow$ viable SUSY WIMPs often live in **near-pure Bino/Wino/Higgsino corners**.
- **Collider implications:** those corners naturally imply **compressed spectra and/or long lifetimes** $\Rightarrow$ high ROI in **ISR + soft objects** and **exotic tracks** (disappearing / displaced / tracklets).
- **If a hint appears in the sky:** colliders provide a **DM fingerprint**: measure Δm and $c\tau$ to determine EW quantum numbers and test consistency with DD/ID.
- **Looking ahead:** as statistics grow, the impact of **systematic uncertainties** will be important, and **precision SM measurements** become an increasingly powerful tool for **indirect BSM searches**.

Precision Drell–Yan as an indirect EWino probe (loop effects)

- Instead of producing DM directly, one can probe new EW states via **loop corrections** to SM "standard candles" (e.g. Drell–Yan $pp \to \ell^+\ell^-$).
- Key advantage: the signal depends mainly on the **gauge quantum numbers** of the particles in the loop — largely independent of decay modes.
- The expected deviations are typically at the **percent level** $\Rightarrow$ requires very large $\mathcal{L}$ and excellent control of **systematics**.
- Naive statistics-only reach suggests sensitivity to $\mathcal{O}(500\ \mathrm{GeV})$ Wino/Higgsino masses, but the program is **systematics-limited**.
- It would be great to see more dedicated experimental work in this direction.



Loop effects in DY (schematic)



Example impact on $m_{\ell\ell}$ distribution