Dark matter with jets and photons in DSM-EFT

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Summary and Conclusions

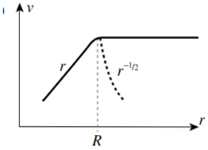
Motivation

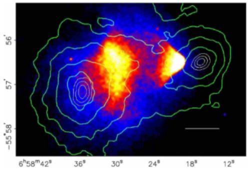
The gravitational effects are the primary observable manifestations of dark matter:

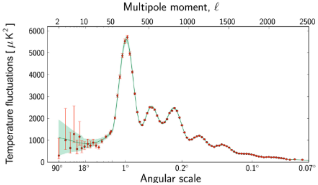
Scales of galaxies, galaxy clusters, and cosmological scales.

The Standard Model fails to account for dark matter in the universe.

Evidence confirms the existence of dark matter.[a]

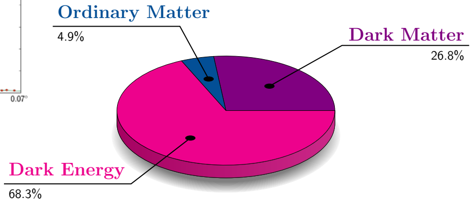






Dark Matter:

- DM observable effects are gravitational
- Stability on a cosmological scale
- Longer life than the age of the universe
- Neutral. No electromagnetic interaction



85% of the total matter is non-baryonic.

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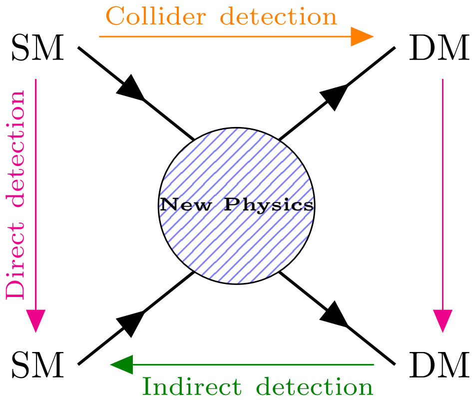
[a] H. Babcock (1939)[10.5479/ADS/bib/1939LicOB.19.41B]
V. C. Rubin et al. (1970 and 1978) [Astrophys. J. 159 (1970) 379, Astrophys, J. 225 (1978) L.107-L.111]
F. Zwicky [Helvetica Physica Acta, Vol. 6, p. 110-127, 1933]
CHANDRA & CLOWE ET AL. (2006)
Planck 2018 results-vi. Cosmological parameters, Astronomy & Astrophysics 641 (2020) A6

The Standard Model successfully describes the known elementary particles and their interactions; however, it does not contain a viable candidate for dark matter.

Can DM be detected via interactions with SM particles?

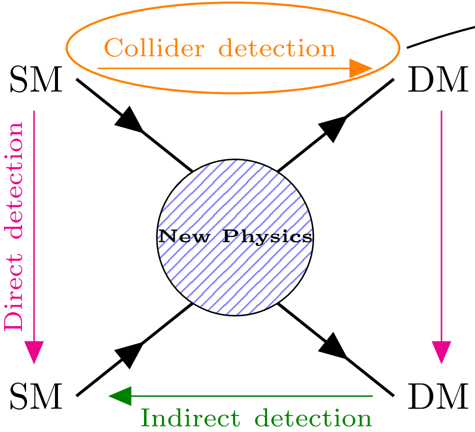


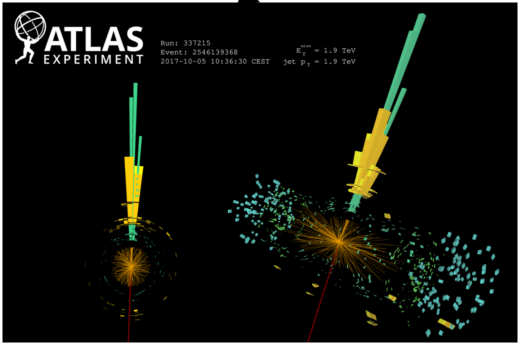
Direct detection: Look for nuclear recoils from elastic DM–nucleus scattering in underground detectors.

Indirect detection: Search for SM particles (γ, e^+/e^-, ν) from DM annihilation or decay in astrophysical environments.

Collider detection: Production of DM in proton–proton collisions, inferred from missing transverse energy (MET).

Can DM be detected via interactions with SM particles?





Dark Matter Signature: Mono-jet Event An Experimental signature featuring a high-momentum jet (1.9 TeV) accompanied by substantial missing transverse energy (MET). This energy deficit suggests the generation of non-detectable, invisible particles. [ATLAS-PHOTO-2020-020 (2020)].

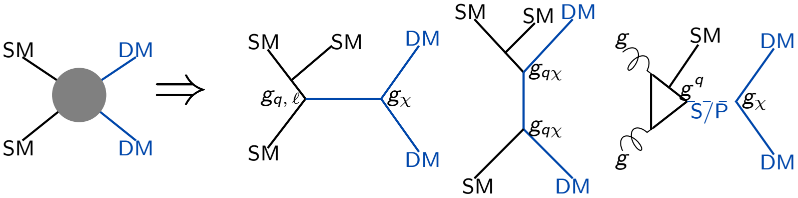
Missing Transverse Energy (MET): $\sum \vec{p}_{T,i} + \vec{E}_T^{\text{miss}} = 0 \Rightarrow \vec{E}_T^{\text{miss}} = - \sum_{\text{observable}} \vec{p}_{T,i}$

Motivation

Dark Matter (DM) searches at the LHC

A jet is the visible signature of a quark or gluon that hadronizes, producing a collimated stream of particles.

- **Mono-X searches (MET+X)**



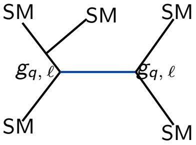
⇛ DM is produced in pairs and escapes the detector ⇒ large MET.

⇛ One visible SM particle ($X = g, \gamma, q, Z, W, h$) recoils against the invisible system.

⇛ Mono-X searches probe the mediator structure predicted in EFT and simplified models.

⇛ Conventional mono-X searches have already placed strong limits on WIMP-like scenarios, motivating the exploration of less conventional regimes such as t-channel mediators and long-lived particles (LLPs).

- **Visible searches**



Resonance searches (dijets, dileptons, ...)

Mediator searches in obvious final states

- $\gamma + \text{jets} + E_T^{\text{miss}}$ searches-Run 2 (ATLAS Collaboration, JHEP 07 (2023) 021, arXiv:2206.06012)

Model

Effective Field Theory: SMEFT

SMEFT

Wilson coefficients

Effective SM fields operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{nd} \frac{C_i^{(d)} \mathcal{O}_i^{(d)}}{\Lambda^{d-4}}, \quad d > 4$$

Scale of new physics

Why EFT?

- Model-independent approach
- Systematic way to include new physics
- Connects UV theories to experiments

Dark SMEFT (DSMEFT)

- Extends SMEFT with dark sector
- Systematic DM-SM interactions
- Gauge invariant framework
- **Framework used in this analysis**

Model

DSM-EFT

DSMEFT model: effective extension of SMEFT

- The models we employ **DSMEFT**[1] is an extension of SMEFT that includes dark fields and systematically describes SM–DM interactions.

Effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_1^{\mu\nu}X_{1\mu\nu} + \frac{M_{X_1}^2}{2}X_1^{\mu}X_{1\mu} - \frac{1}{4}X_2^{\mu\nu}X_{2\mu\nu} + \frac{M_{X_2}^2}{2}X_2^{\mu}X_{2\mu} + C_{BX^2}\,B_{\mu}{}^{\nu}X_{1\nu}{}^{\alpha}X_{2\alpha}{}^{\mu} + C_{\tilde{B}X^2}\,\tilde{B}_{\mu}{}^{\nu}X_{1\nu}{}^{\alpha}X_{2\alpha}{}^{\mu}.$$

- Invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Operators $\mathcal{Q}_i^{(d)}$ may involve SM and DM fields: $\mathcal{Q}_{BX^2} = B_{\mu}^{\nu}X_{1\,\nu\alpha}X_2^{\alpha\mu}$, $\quad \mathcal{Q}_{\tilde{B}X^2} = \tilde{B}_{\mu}^{\nu}X_{1\,\nu\alpha}X_2^{\alpha\mu}$.
- New-physics scale: $C_{BX^2} = C_{\tilde{B}X^2} \simeq 1/\Lambda^2$, with $\Lambda \gtrsim 1$ TeV
- $\mathbb{Z}_2$ symmetry: $X_\mu \to -X_\mu$. This symmetry **forbids kinetic mixing** of the type $\epsilon_a B_{\mu\nu}X_a^{\mu\nu}$
- Two singlet dark vector bosons: X_1^{μ}, X_2^{μ} are required due to the antisymmetric structure.
- The lighter field X_1: Stable DM candidate and X_2: Heavier, unstable

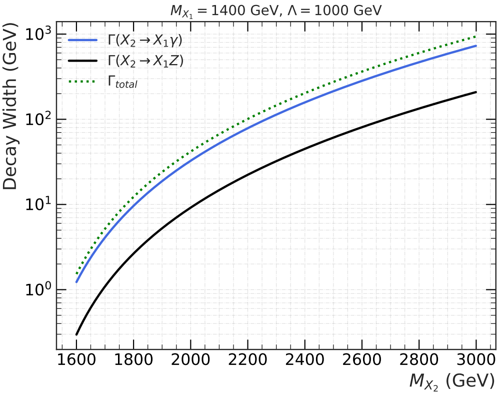
[1] ArXiv:2202.06968

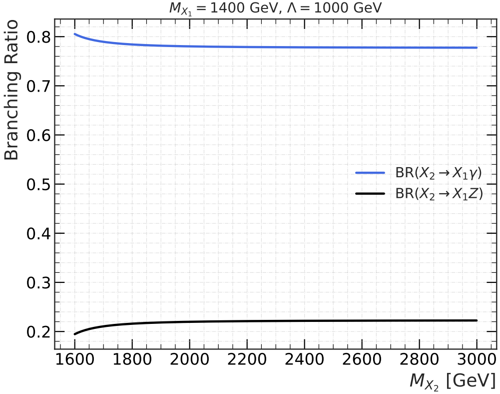
Decays: $X_2 \to X_1\gamma, \quad X_2 \to X_1 Z.$

Leading partial width:

$$\Gamma(X_2 \to X_1\gamma) = \frac{\cos^2\theta_W}{96\pi}\left(C^2_{BX^2} + C^2_{\tilde{B}X^2}\right) M^5_{X_2}(1+\varrho)(1-\varrho)^3,$$

where $\varrho = (M_{X_1}/M_{X_2})^2$.





$X_2 \to X_1\gamma$ mode dominates $(\mathrm{BR} \sim 80\%)$.

Phenomenology of the DSMEFT

DSMEFT at LHC ($\gamma + jet + E_{\mathrm{T}}^{\mathrm{miss}}$)

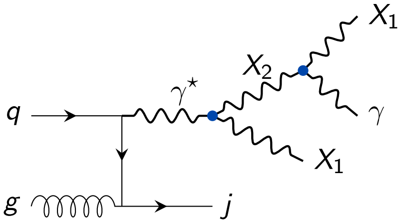
Experimental signature in ATLAS: $pp \to j + \gamma + E_T^{miss}$

Signal Process:

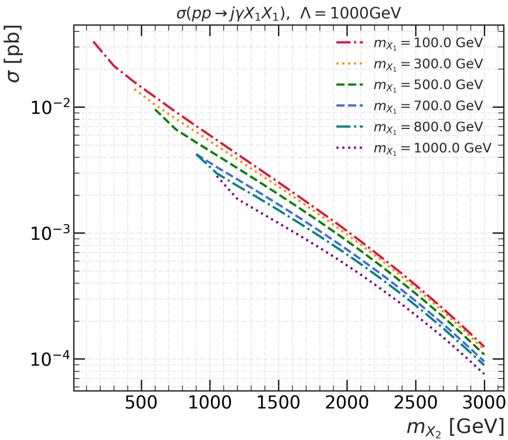
$pp \to j\,\gamma^* \to X_2 X_1, \quad X_2 \to X_1\gamma.$

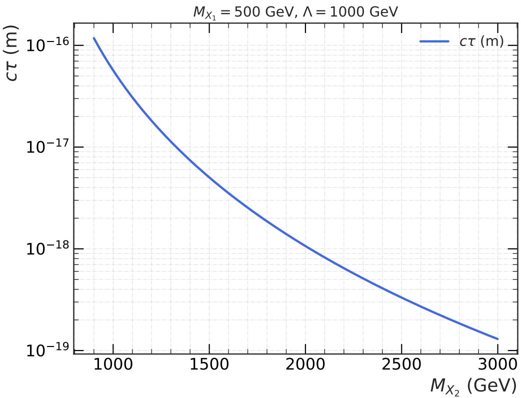
- Hadronic jet + isolated photon + missing transverse energy (E_T^{miss}).
- E_T^{miss} arises from invisible X_1 (DM).

Dominant backgrounds: $Z(\nu\bar{\nu}) + \gamma + jet$, $W(\ell\nu) + \gamma + jet$, and $t\bar{t}\gamma$.



Feynman diagram for the quark-gluon interaction in the t-channel, producing a virtual γ, which decays into boson vectors X_1 and X_2.





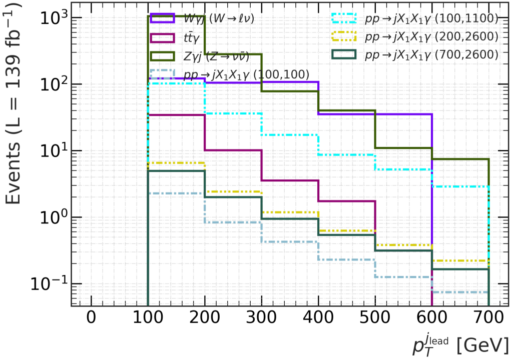
- $X_2 \to X_1\gamma$ ($\mathrm{BR} \sim 80 - 70\%$).
- Lifetime and total width of X_2 — decay times $\sim 10^{-18}$–10^{-16} s.

  $\Rightarrow$ prompt decays inside the detector $\to$ visible photon.

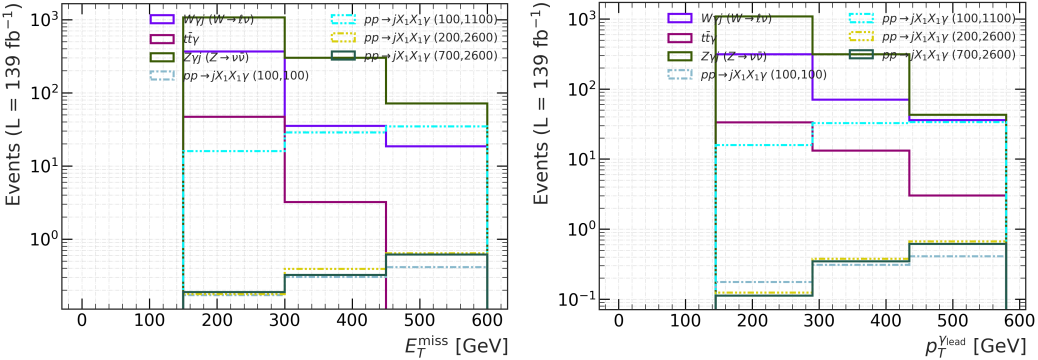
Event selection and kinematic cuts

Selection criteria

- Leading photon: $p_T^\gamma > 150$ GeV, $|\eta_\gamma| < 2.37$.
- Leading jet: $p_T^j > 100$ GeV, $|\eta_j| < 2.5$.
- Missing transverse energy: $E_T^{\text{miss}} > 150$ GeV.
- Lepton veto (electrons, muons) and b-tagged jets veto.
- Angular separations: $|\Delta\phi(j, E_T^{\text{miss}})| > 0.4$, $|\Delta\phi(\gamma, E_T^{\text{miss}})| > 0.4$.

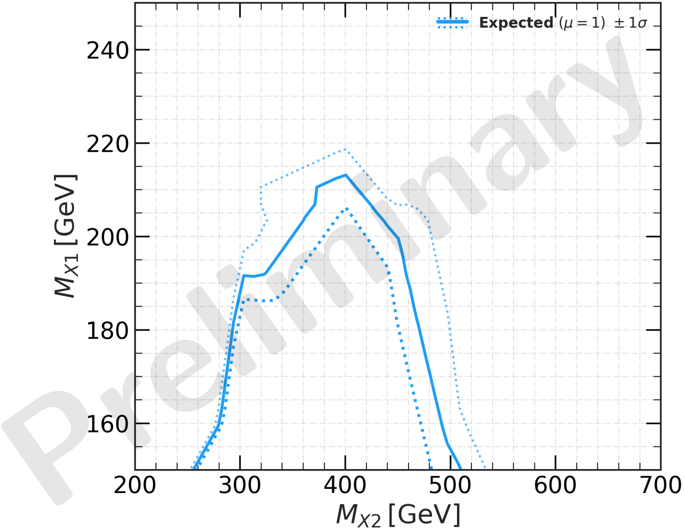


Event selection and kinematic cuts



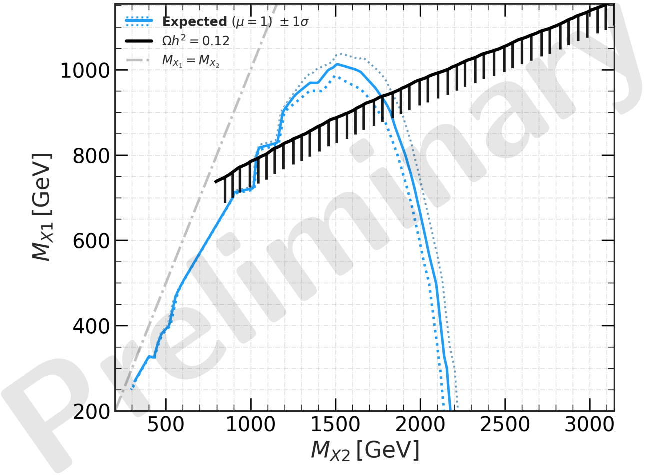
The p_T^γ and E_T^{miss} distributions are strongly correlated for the signal. In our topology, the invisible system recoils mainly against the photon and jet, but E_T^{miss} is typically of the same order as p_T^γ. The photon kinematics, therefore, dominate the MET spectrum.

Collider sensitivity to DSMEFT at LHC ($\gamma + jet + E_{\mathrm{T}}^{\mathrm{miss}}$)



- Expected 95% C.L. exclusion contour from the $j+\gamma+E_T^{\mathrm{miss}}$ analysis (ATLAS Run 3) with $\sqrt{s} = 13.6\ TeV$ and $\mathcal{L} = 139\mathrm{fb}^{-1}$
- Inside the blue curve: parameter points excluded by the collider search.

Signal regions and combined constraints



Signal regions (MET bins)

- SR1: $150 \leq E_T^{miss} < 300$ GeV
- SR2: $300 \leq E_T^{miss} < 450$ GeV
- SR3: $E_T^{miss} \geq 450$ GeV

Interpretation

⇛ SR3 is the most sensitive region for heavy X_2.

⇛ The overlap of the blue exclusion and the black band marks regions where ATLAS can directly test cosmologically motivated parameter space.

Outlook: Analysis with Lorenzetti Showers

MadGraph5_aMC@NLO
Generates LHE parton-level events

→

Pythia8
Performs parton showering & hadronization
Outputs HepMC

→

HepMC → EVT.root Conversion
Maps particle data: pdg_id, energy, momentum, vertex

↓

Propagation (Geant4)
Simulates energy deposits in calorimeter cells
Output: `HIT.root`

↓

Digitization
Models ADC response, Crosstalk, Pileup
Output: `ESD.root`

↓

Reconstruction
Computes shower variables & E_T^{miss}
Output: `AOD.root`

↓

BSM / ML Analysis
Physics or Machine Learning analysis

Why Lorenzetti?

- In this work, the DSMEFT analysis is based on a fast simulation chain: MadGraph5 + Pythia8 + Delphes.
- To get closer to an **ATLAS-like** description of calorimeter showers and reconstructed objects, we plan to use the **Lorenzetti** ML-based shower framework. [10.1016/j.cpc.2023.108671]

Work in progress

⇛ Compare event yields and kinematic distributions with the Delphes setup to assess the robustness of the DSMEFT constraints in the $j + \gamma + E_T^{\text{miss}}$ channel.

Conclusions

Summary and Conclusions

Summary and Conclusions

- DSM-EFT with dark vector bosons leads to a characteristic $j + \gamma + E_T^{\text{miss}}$ signature at the LHC.
- The **freeze-out** scenario provides cosmologically viable parameters that could be accessible to constrain at the LHC, if we have a DM excess tail.
- The p_T^γ and E_T^{miss} distributions are strongly correlated for the signal.
- CLs analyses indicate that LHC Run 3 could exclude regions up to $M_{X_2} \sim 0.5$ or 2.2 TeV, depending on the signal regions.
- Next steps: compare the results with the Lorenzetti shower framework (machine learning-based) to obtain a more realistic detector response.

Thank you so much for your attention!

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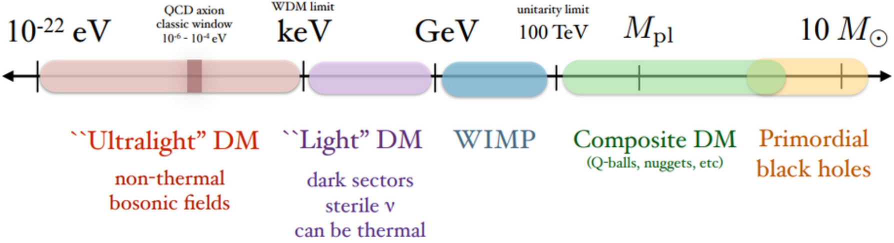
QUESTIONS & COMMENTS

Acknowledgement:

Backup slides

Mass scale of dark matter

(not to scale)



T. Lin,1904.07915

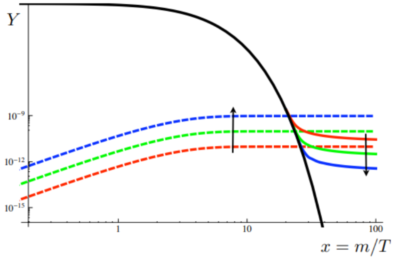
Phenomenology of the DSMEFT

- Evolution of the commoving DM abundance:

$$Y = \frac{n}{s}, \qquad x = \frac{m}{T}.$$

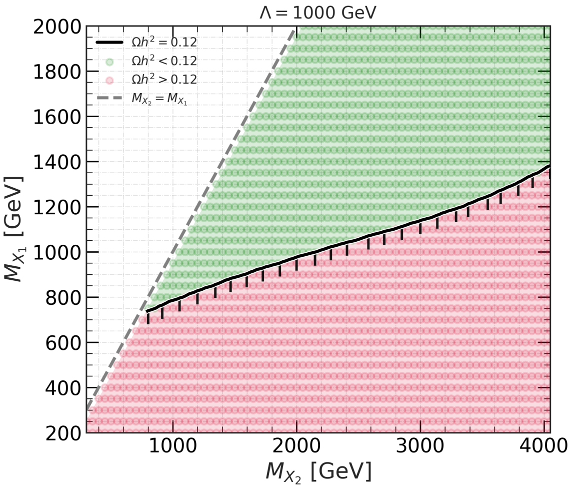
- **Freeze-out**
  - DM initially in thermal equilibrium with the plasma ($Y \simeq Y_{\mathrm{eq}}$).
  - When $\Gamma_{\mathrm{ann}} < H$, annihilations become inefficient and Y **freezes out** at a constant value.
- **Freeze-in**
  - DM never thermalises ($Y \ll Y_{\mathrm{eq}}$ at all times).
  - Produced gradually through very feeble interactions (decays/scatterings of SM particles).
  - Y slowly increases and saturates when production shuts off.
- The final plateau of each curve gives the **relic density**.

Dark Matter Production



Comparison between freeze-out and freeze-in mechanisms [ArXiv: 0911.1120]

Freeze-Out scenario in the DSMEFT

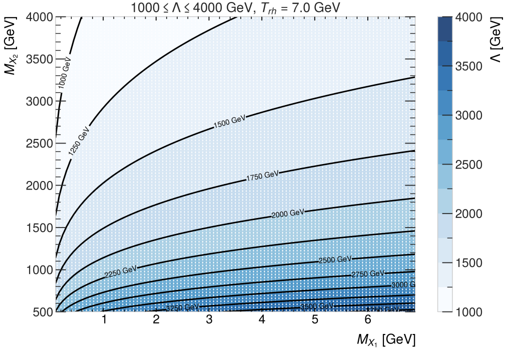


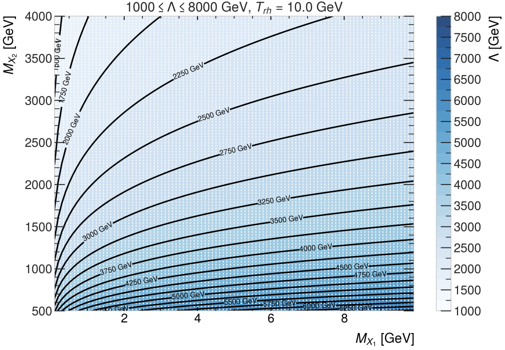
- Relic density computed in DSMEFT using MadDM.
- **Left:** relic density in the (M_{X_1}, M_{X_2}) plane for $\Lambda = 1$ TeV.
- Green region: $\Omega h^2 < 0.12 \Rightarrow$ allowed.
  Pink region: $\Omega h^2 > 0.12 \Rightarrow$ excluded (overproduced DM).
  Black line exact observed relic.
- Increasing $\Lambda \Rightarrow$ requires heavier masses to reproduce the observed Ωh^2.

In DSMEFT, the regime is set by the effective coupling C/Λ^2:
small $\Lambda \Rightarrow$ freeze-out,
large $\Lambda \Rightarrow$ freeze-in.

Freeze-In scenario in the DSMEFT

New-physics scale relation: $\dfrac{\Lambda}{T_{\rm rh}} \simeq 700 \left(\dfrac{M_{X_1}}{1\ \mathrm{GeV}}\right)^{1/8} \left(\dfrac{T_{\rm rh}}{100\ \mathrm{GeV}}\right)^{3/8} \times \left(\dfrac{1\ \mathrm{TeV}}{M_{X_2}}\right)^{1/2} \left(\dfrac{100}{g_*}\right)^{3/16}$.



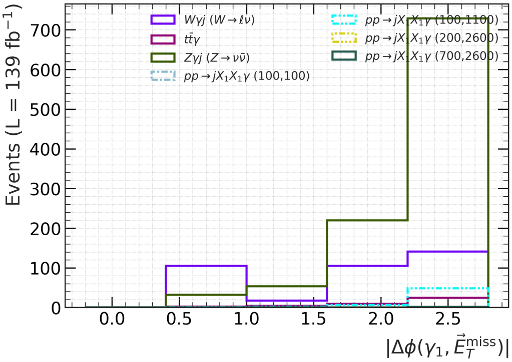


- DSMEFT predicts the relic density through freeze-in production of X_1.
- The reheating temperature $T_{\rm rh} << M_{X_2}$ ensures out-of-equilibrium decays.
- Each contour corresponds to the value of Λ hat reproduces the observed Ωh^2
- Larger M_{X_1} and $T_{\rm rh}$ require larger $\Lambda \Rightarrow$ weaker interactions (in collider)

Signal regions and cuts

	SR1	SR2	SR3
Photon p_T^{γ}	> 150 GeV	> 150 GeV	> 150 GeV
Jet p_T^{j}	> 100 GeV	> 100 GeV	> 100 GeV
E_T^{miss}	> 150 GeV	> 350 GeV	> 450 GeV
N_{γ}	≥ 1	≥ 1	≥ 1
N_{jets}	≥ 1	≥ 1	≥ 1
Lepton veto	yes	yes	yes
b-jet veto	yes	yes	yes
$\Delta\phi(j, E_T^{\text{miss}})$	> 0.4	> 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{\text{miss}})$	> 0.4	> 0.4	> 0.4

SR1: moderate MET; SR2: intermediate MET; SR3: very high MET.



Events (L = 139 fb^{-1})
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
$|\Delta\phi(\gamma_1, \vec{E}_T^{\mathrm{miss}})|$
$W\gamma j$ $(W \to \ell\nu)$
$t\bar{t}\gamma$
$Z\gamma j$ $(Z \to \nu\bar{\nu})$
$pp \to jX_1X_1\gamma$ (100,100)
$pp \to jX_1X_1\gamma$ (100,1100)
$pp \to jX_1X_1\gamma$ (200,2600)
$pp \to jX_1X_1\gamma$ (700,2600)