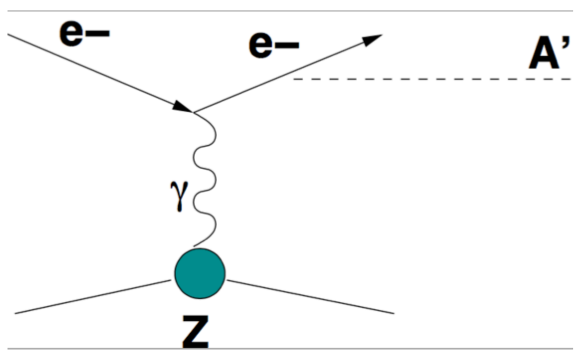
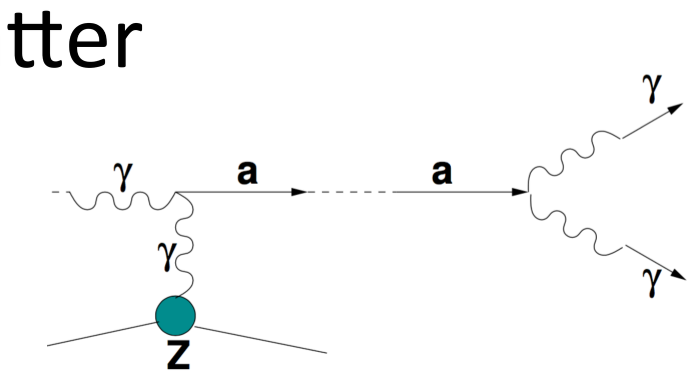
Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments





We present the package for the simulation of DM (Dark Matter) particles in fixed target experiments. We chose the Geant4 toolkit framework as a standard for compatibility with particle tracing programs used in many DM search experiments. The package includes the codes for the simulation of the processes of DM particles production via a number of processes, such as electron and muon bremsstrahlung off nuclei. The total cross sections of bremsstrahlung processes are calculated numerically at exact tree level (ETL).

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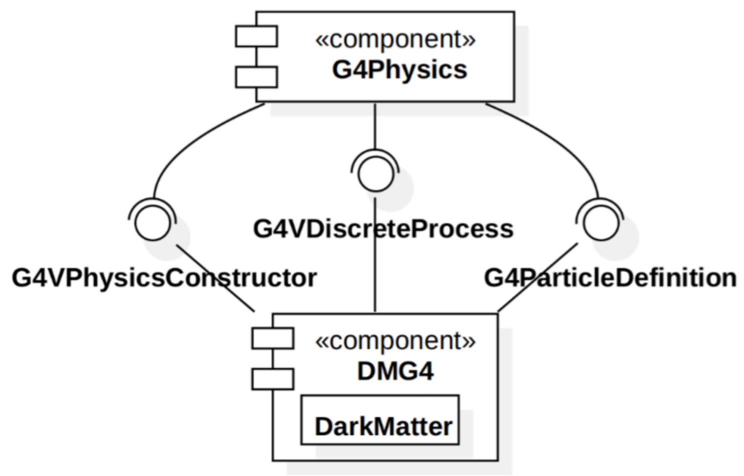


Name	PDG ID	emitted by	spin	parity	stable?	decay
DMParticleAPrime	5500022	e^+, e^-	1	1	true	-
DMParticleXBoson	5500122	e^+, e^-	1	1	false	e^+e^-
DMParticleScalar	5400022	e^+, e^-	0	1	true	-
DMParticleXScalar	5400122	e^+, e^-	0	1	false	e^+e^-
DMParticlePseudoScalar	5410022	e^+, e^-	0	-1	true	-
DMParticleXPseudoScalar	5410122	e^+, e^-	0	-1	false	e^+e^-
DMParticleAxial	5510022	e^+, e^-	1	-1	true	-
DMParticleZPrime	5500023	μ	1	1	true	-
DMParticleALP	5300122	γ	0	-1	false	$\gamma\gamma$

DM particles defined in the package DMG4

Processes of DM production:

- **Bremsstrahlung-like** of the type **p N → p N X**, where **p** is a projectile (can be e^-, e^+, μ^-, μ^+), and **X** is a DM particle. Classes Dark* (DarkPhotons etc.).
- **Primakoff** photon conversion **γ N → a N**, where **a** is an axion-like particle (ALP). Class ALP.
- **Resonant in-flight positron annihilation** on atomic electrons **e⁺ e⁻ → X → χ χ**, where **χ** is a dark matter mediator decay product. Classes *Annihilation.

DM mediator mass

Mixing ε (coupling)

Decay to SM particles to be handled?

Threshold

BiasSigma Factor

Class derived from DarkMatter:

- DarkPhotons
- DarkScalars
- DarkPseudoScalars
- DarkAxials
- DarkZ
- ALP
- DarkPhotonsAnnihilation
- DarkScalarsAnnihilation
- DarkPseudoScalarsAnnihilation
- DarkAxialsAnnihilation

Annihilation only

$R = M_\chi/M_{DM}$

α_{DM}

Procedure:

Take DMG4 package (currently at the link below) http://mkirsano.web.cern.ch/mkirsano/DMG4.tar.gz

Compile it against Geant4 installation used in your experiment simulation program (README) (cmake)

Configure your physics in the method of the factory class *DarkMatterPhysics* *DarkMatterPhysicsConfigure* : choose one class and instantiate it (DarkPhotons, DarkZ, ALP etc.). You have to choose also a few more parameters here.

Change the main program of your simulation application to add DMG4 physics as specified in the DMG4 examples and compile it.

What is inside (see the main reference below):

Vector DM mediator full Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{SM} - \frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \sum_\psi e\epsilon_V V_\mu \bar\psi\gamma^\mu\psi + g_V^D V_\mu \bar\chi\gamma^\mu\chi + \bar\chi(i\gamma^\mu\partial_\mu - m_\chi)\chi$$

Scalar DM mediator full Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \sum_\psi e\epsilon_S S\bar\psi\psi + g_S^D S\bar\chi\chi + \bar\chi(i\gamma^\mu\partial_\mu - m_\chi)\chi$$

… pseudoscalar, axial

ALP model full Lagrangian:

$$\mathcal{L}_{int} \supset -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde F^{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2$$

Improved Weizseker-Williams (IWW) approach for **electron** beams:

Vector mediator cross section:

$$\left(\frac{d\sigma^X}{dx\,d\cos\theta}\right)_{IWW} = 2\epsilon_X^2\alpha^3|\mathbf{k}|E_0(1-x)\frac{\chi}{\tilde u^2}|\mathcal{A}^X|^2$$

$$|\mathcal{A}^V|^2 = 2\frac{2-2x+x^2}{1-x} + 4(m_V^2+2m_l^2)\frac{\tilde u x + m_V^2(1-x) + m_l^2 x^2}{\tilde u^2}$$

…

Vector mediator annihilation cross section (ETL):

$$\sigma_{e^+e^-} = \frac{4\pi\alpha_{EM}\alpha_D\varepsilon^2}{\sqrt{s}}q\frac{\mathcal{K}}{(s-m_X^2)^2+\Gamma_X^2 m_X^2}$$, K= $\left(s - \frac{4}{3}q^2\right)$

…

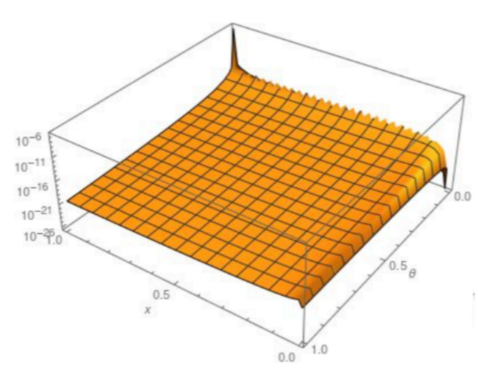
New development: Weizseker-Williams (**WW**) approach for **muon** beams. More sophisticated (formulas too big to be shown here), but much closer to ETL, no need of K-factors. Quite recently: analytic integration of dσ/dxdcosθ over θ, possibility of more exact and faster sampling.

K-factors

IWW approximations for **electrons** gives reasonable results for the differential cross section ds/dx, but overestimates the total cross section by factors up to ~3 (bigger factors for heavy DM mediators). We use K-factors $K = \sigma_{ETL}/\sigma_{IWW}$

They are derived by comparing with cross sections calculated at Exact Tree Level (ETL) and tabulated. Cross sections calculated with IWW at runtime are corrected by these K-factors.

Sampling is usually done by simple Von Neuman method. However, for electron beams a more sophisticated sampler was designed.



For heavy DM sharply peaked: direct Von Neuman suboptimal. Modified method using inverse function: the cross section too complicated to invert. Solution: simpler majorant function M, then sample x using $M^{-1}(u(x_{min}, x_{max}))$

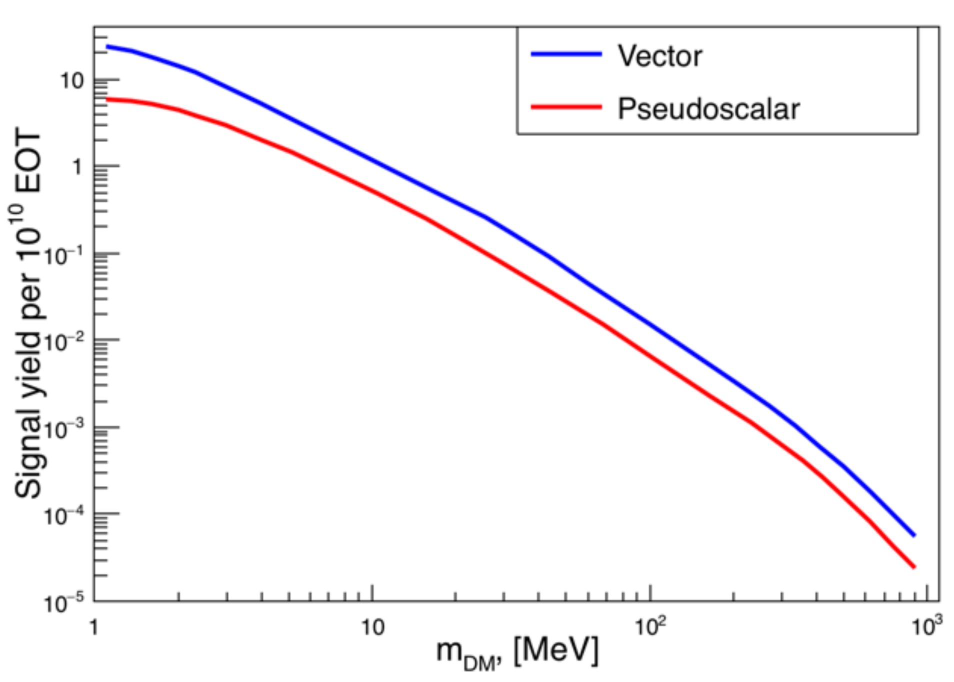
```
mj1x[x_] := 1 / (2 E0² (-ma² (-1 + x) + me² x))
```

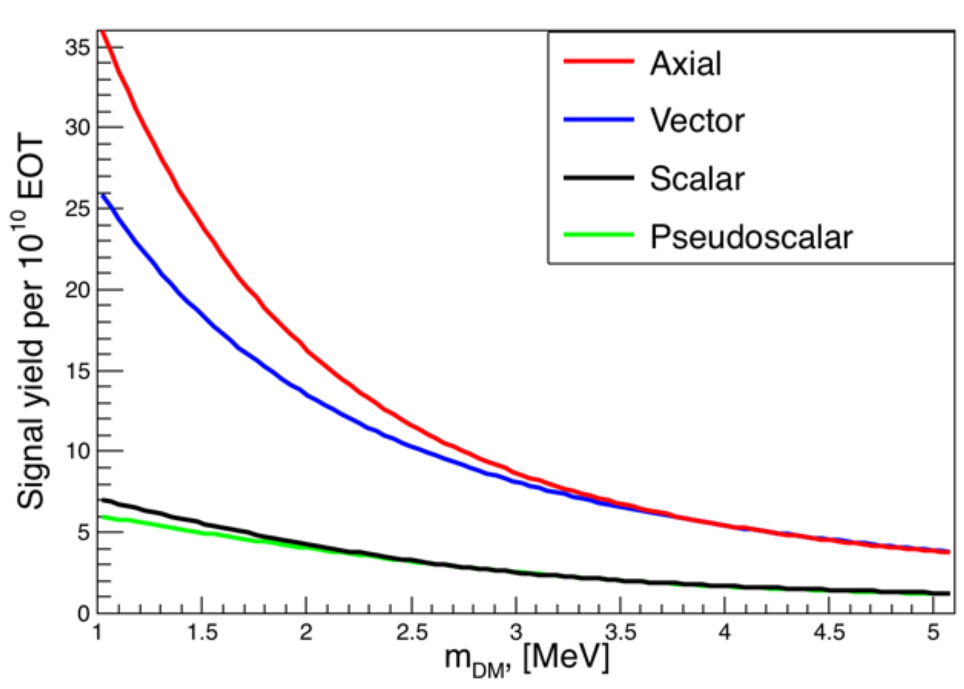
After that sample θ

```
mj1[x_, θ_] := θ x³ / (E0² θ² x² + ma² (1 - x) + me² x²)²
```

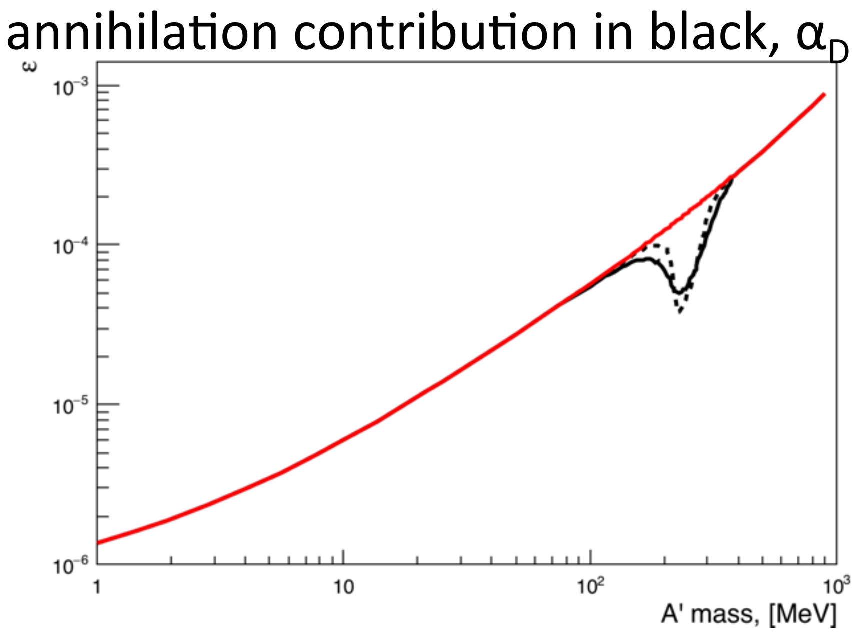
Sufficiently exact and faster by several orders of magnitude

Performance, results

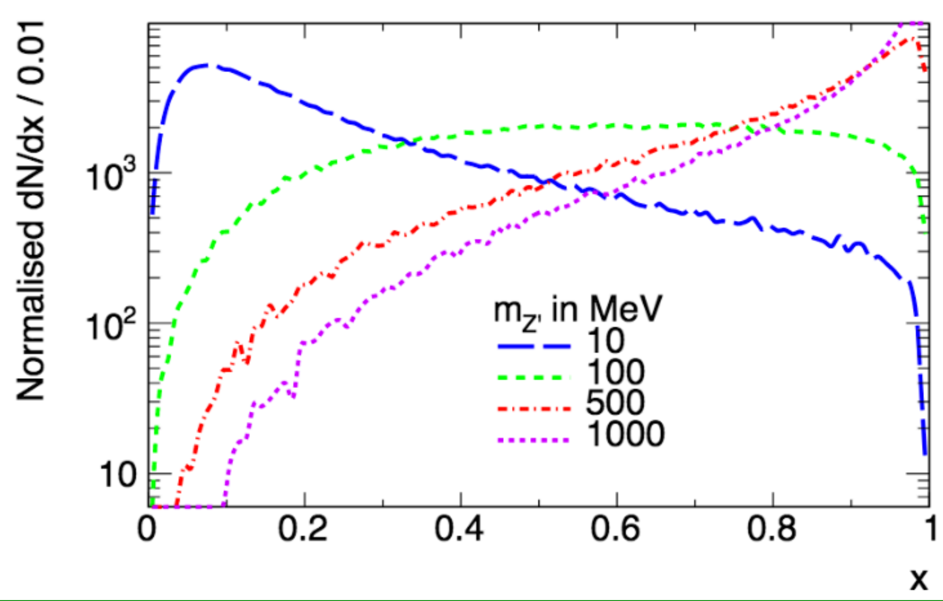




Sensitivity to vector DM, 5×10^{12} EOT, with annihilation contribution in black, α_D 0.1, 0.5:



Z' energy spectra, muon beam 160 GeV:



Plans:

- Semivisible decay modes (cascade decays)
- WW approximation for electrons
- More examples and tests, more possibilities
- New processes: coherent μ – τ conversion on nuclei etc.
- Process inverse to gamma – ALP conversion
- Processes for incident hadrons?

Summary:

- Fully Geant4 compatible package for the DM simulation in fixed target experiment is created
- Processes for lepton beams and γ, different mediator types, cross sections calculated at ETL

Main reference:

A. Celentano et al. Comput. Phys. Commun, 269, 108129 (2021) arXiv:2101.12192 [hep-ph]

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