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Electroweak lights from DM annihilations

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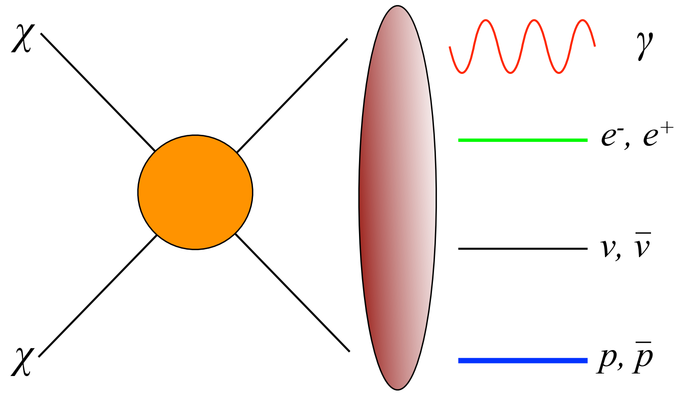
Based on:

Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano

arXiv:1104.2996, 1107.4453

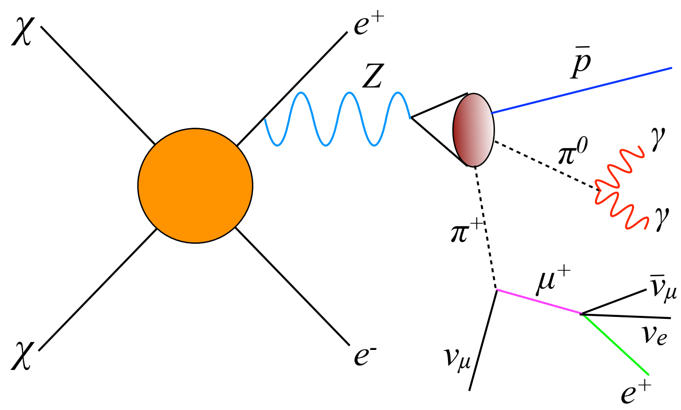
+ work in progress

ElectroWeak Bremsstrahlung



* Key observable for DM indirect detection: fluxes of stable particles from DM annihilation.

ElectroWeak Bremsstrahlung



* Key observable for DM indirect detection: fluxes of stable particles from DM annihilation.

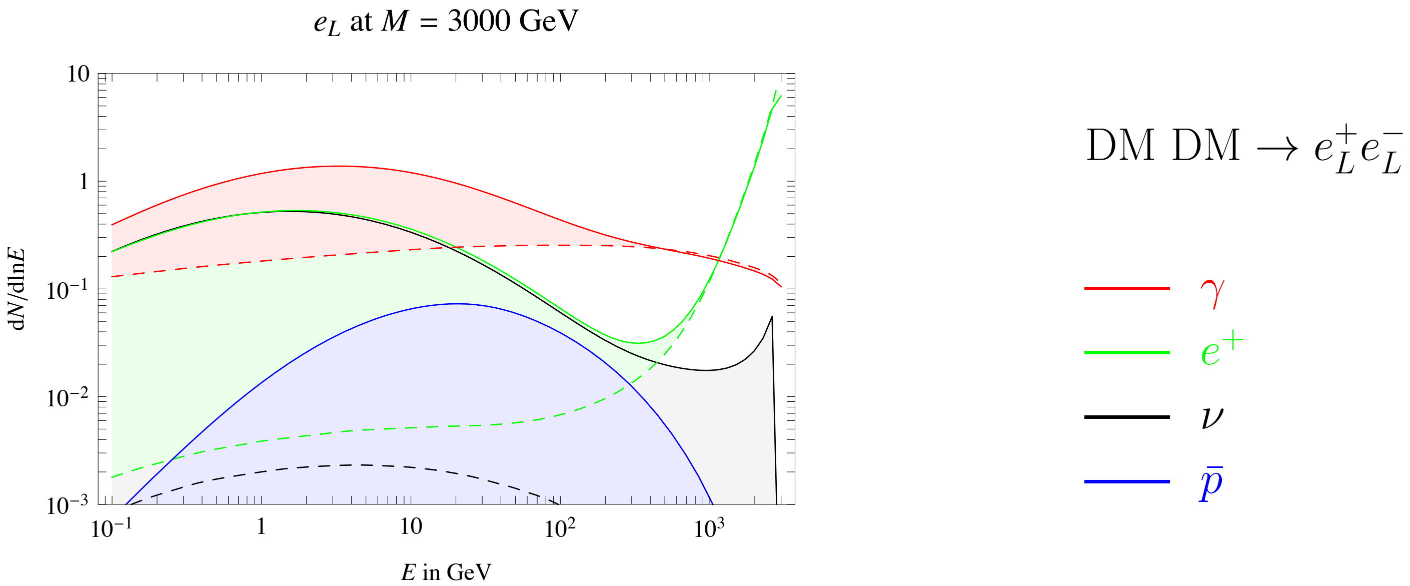
* The final state of the DM annihilation process can radiate $\gamma, Z, W^\pm$.
  It is a SM effect and can affect the final fluxes of stable particles importantly.

[Bergstrom (1989); Bringmann, Bergstrom, Edsjo (2008); Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano (2010)]

- EW interactions connect all SM particles $\rightsquigarrow$ all species will be present in the final spectrum.

- A few very energetic particles are converted into many soft particles.

ElectroWeak Bremsstrahlung



[Figure from: Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano (2010)]

EW corrections are particularly relevant in 3 situations:

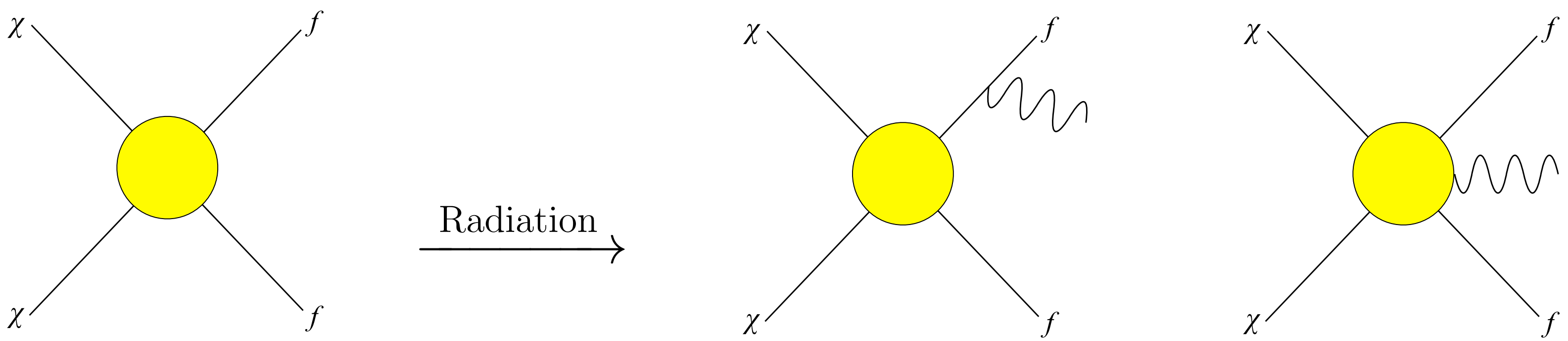
1. when the low-energy regions of the spectra, which are largely populated by the decay products of the emitted gauge bosons, are the ones contributing the most to the observed fluxes of stable particles;
2. when some species are absent without EW corrections (e.g. $\bar{p}$ from $\chi\chi \to \ell^+\ell^-$);
3. *(this talk)* when $\sigma(2 \to 3)$, with soft gauge boson emission, is comparable or even dominant with respect to $\sigma(2 \to 2)$.

Annihilations of Majorana fermions

$$v\sigma_{\rm ann} = \underset{\substack{\uparrow \\ s\text{-wave}}}{a} + \underset{\substack{\uparrow \\ p\text{-wave}}}{b\,v^2} + \mathcal{O}(v^4)$$

(today $v \sim 10^{-3}$)

For a Majorana fermion and SM singlet (e.g. Bino in SUSY)



only p-wave
($m_f \ll M_\chi$)

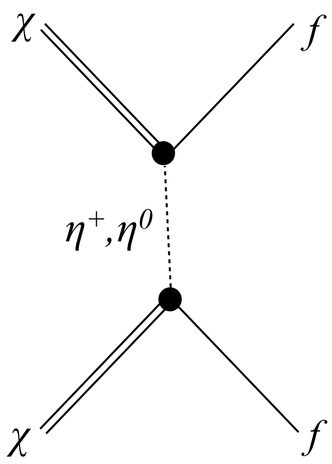
there is an s-wave!

The Model

The DM couples to the SM via a heavy scalar doublet: $S = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_\chi + \mathscr{L}_S + \mathscr{L}_{\rm int}$$

$$\begin{aligned}
\mathscr{L}_\chi &= \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - M_\chi)\chi\,, \\
\mathscr{L}_S &= (D_\mu S)^\dagger (D^\mu S) - M_S^2 S^\dagger S\,, \\
\mathscr{L}_{\rm int} &= y_L \bar{\chi}(L i\sigma_2 S) + {\rm h.c.} \\
&= y_L(\bar{\chi}P_L f_2 \eta^+ - \bar{\chi}P_L f_1 \eta^0) + {\rm h.c.}
\end{aligned}$$

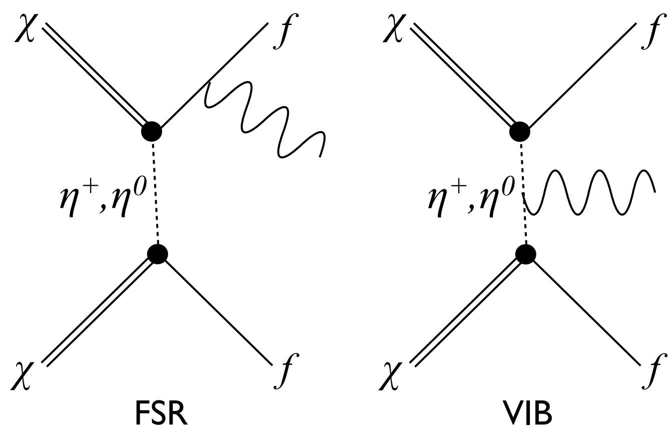


Mass parameters: M_χ, M_S

$$v\sigma \sim \frac{1}{M_\chi^2}\frac{v^2}{r^2}$$

$\rightsquigarrow M_\chi,\ r \equiv (M_S/M_\chi)^2 \geq 1$

Now add radiation of EW gauge bosons $\rightsquigarrow$



Schematically, the amplitude is

$$\mathcal{M} \sim \frac{1}{M_\chi}\mathcal{O}(v)\left[\mathcal{O}\left(\frac{1}{r}\right)\Big|_{\rm FSR} + \mathcal{O}\left(\frac{1}{r^2}\right)\Big|_{\rm FSR}\right] + \frac{1}{M_\chi}\left[\mathcal{O}\left(\frac{1}{r^2}\right)\Big|_{\rm VIB} + \mathcal{O}\left(\frac{1}{r^2}\right)\Big|_{\rm FSR}\right]$$

and the cross section

$$v\sigma(\chi\chi \to f\bar{f}Z) \sim \frac{\alpha_W}{M_\chi^2}\left[\mathcal{O}\left(\frac{v^2}{r^2}\right) + \mathcal{O}\left(\frac{v^2}{r^3}\right) + \mathcal{O}\left(\frac{1}{r^4}\right)\right]$$

Important lesson:

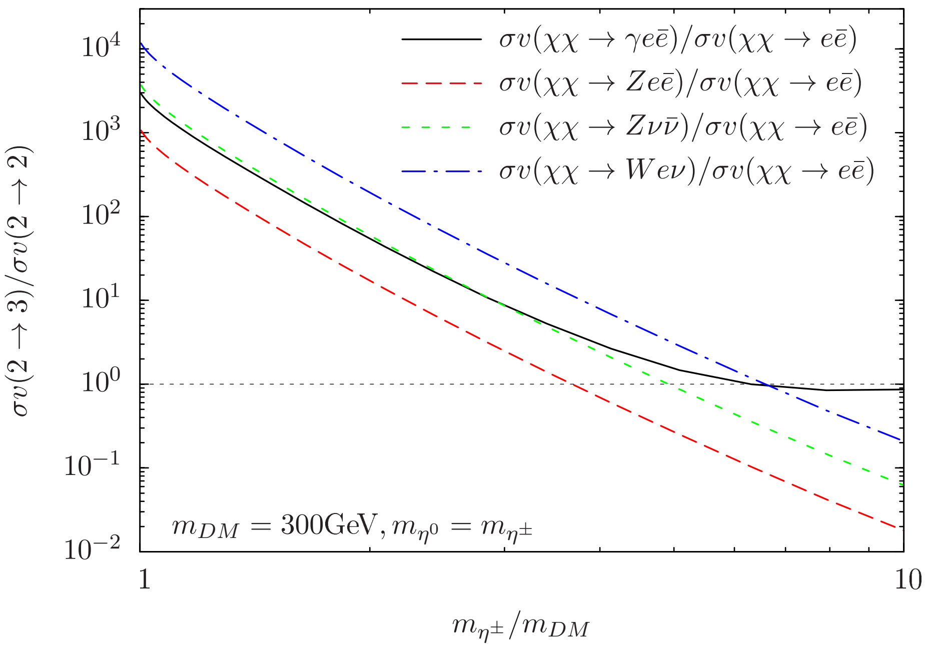
- limiting the expansion to $\mathcal{O}(1/r)$ in the amplitude keeps the annihilation in p-wave.
- at $\mathcal{O}(1/r^2)$, with VIB diagrams, the s-wave is opened.

When does the 3-body process dominate over the 2-body one?

Estimate:

$$v\sigma(2 \to 2) \sim \frac{1}{M_\chi^2}\frac{v^2}{r^2}$$

$$v\sigma(2 \to 3) \sim \frac{1}{M_\chi^2}\frac{\alpha_W}{4\pi}\frac{1}{r^4}$$



[Figure from: Garny, Ibarra, Vogl – 1105.5367]

$$\sigma(2 \to 3) \gtrsim \sigma(2 \to 2)$$

when

$$r \lesssim \sqrt{\frac{\alpha_W}{4\pi}}\frac{1}{v} \sim 50$$

$$(r \equiv M_S^2/M_\chi^2)$$

Effective Field Theory

Integrate out the heavy scalar S:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \mathscr{L}_\chi + \frac{1}{r}\frac{\mathcal{O}_6}{M_\chi^2} + \frac{1}{r^2}\frac{\mathcal{O}_8}{M_\chi^4} + \ldots$$

The lowest-dimensional operator gives a p-wave annihilation:

$$\mathcal{O}_6 = \frac{1}{2}|y_L|^2\,[\bar\chi\gamma_\mu\gamma_5\chi]\,\left[\bar L\gamma^\mu P_L L\right] \quad\Longrightarrow\quad v\sigma(\chi\chi\to f\bar f Z)\big|_{\mathcal{O}_6} \propto \frac{|y_L|^4}{M_\chi^2}\frac{v^2}{r^2}$$

- The s-wave appears due to $\mathcal{O}_8$.
  $\mathcal{O}_8$ can be more important than $\mathcal{O}_6$ despite larger dimensionality.
- Warning: in this case, naive dimensional analysis fails to assess the relative importance of operators in the expansion.
- Need to carry out a general operator expansion in v and $1/\Lambda$ (in progress).

More Quantitative Analysis

$$\chi\chi \to e^+e^-\,,\nu\bar{\nu}\,,e^+e^-\gamma\,,e^+e^-Z\,,\nu\bar{\nu}Z\,,e^\pm\nu W^\mp$$

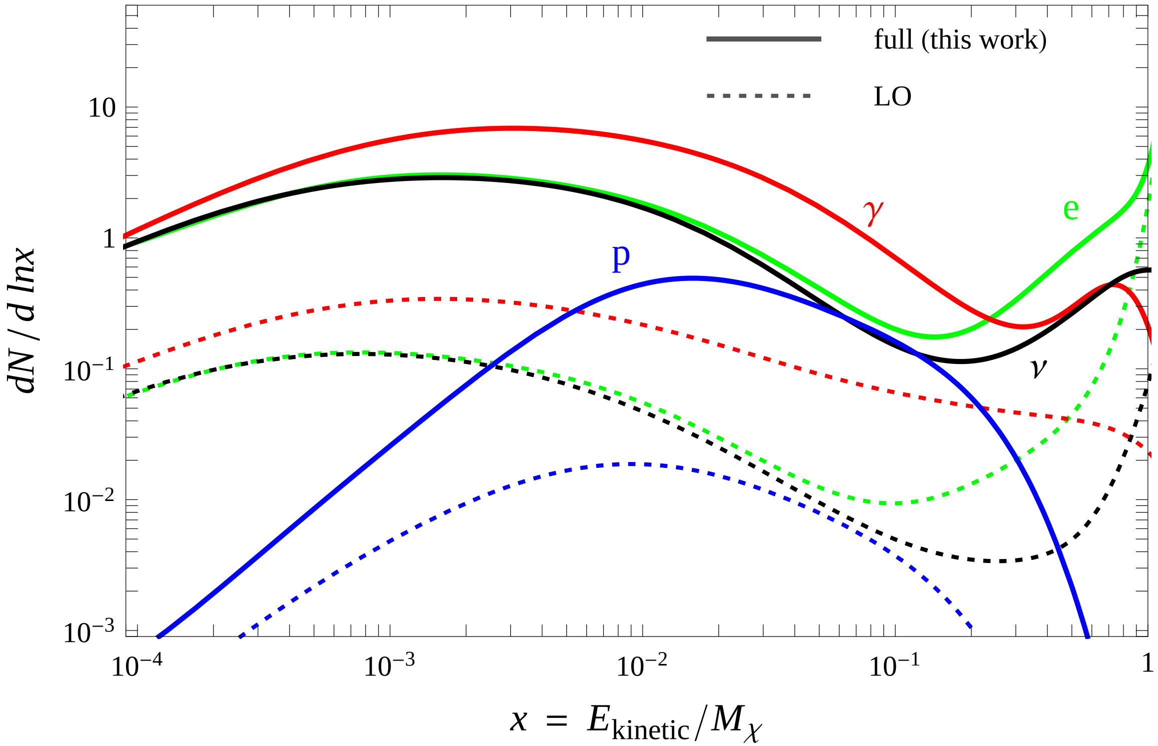
- `our MC`: generates primary annihilation events ($2 \to 3$) according to the $|\mathcal{M}|^2$ distribution;

- `PYTHIA 8`: for showering + hadronization + decay to final stable SM particles;
  (Technical remark: `PYTHIA 6` does not include $\gamma \to f\bar{f}$ branchings in the showering)

- extract primary energy spectra at interaction point for each species;

- cosmic-ray propagation in the galactic halo.

Energy spectra at the interaction point



$$M_S = 4 \text{ TeV}$$
$$M_\chi = 1 \text{ TeV}$$

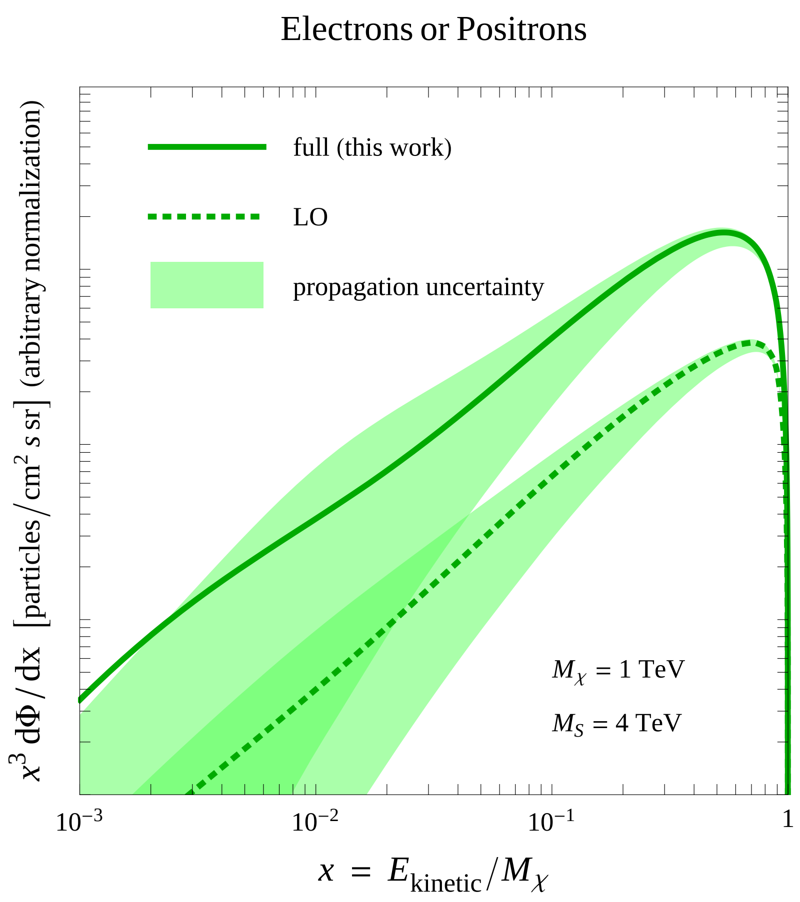
$$\frac{dN_f}{d\ln x} = \frac{1}{\sigma(2\to 2)} \frac{d\sigma(\chi\chi \to f + X)}{d\ln x}$$

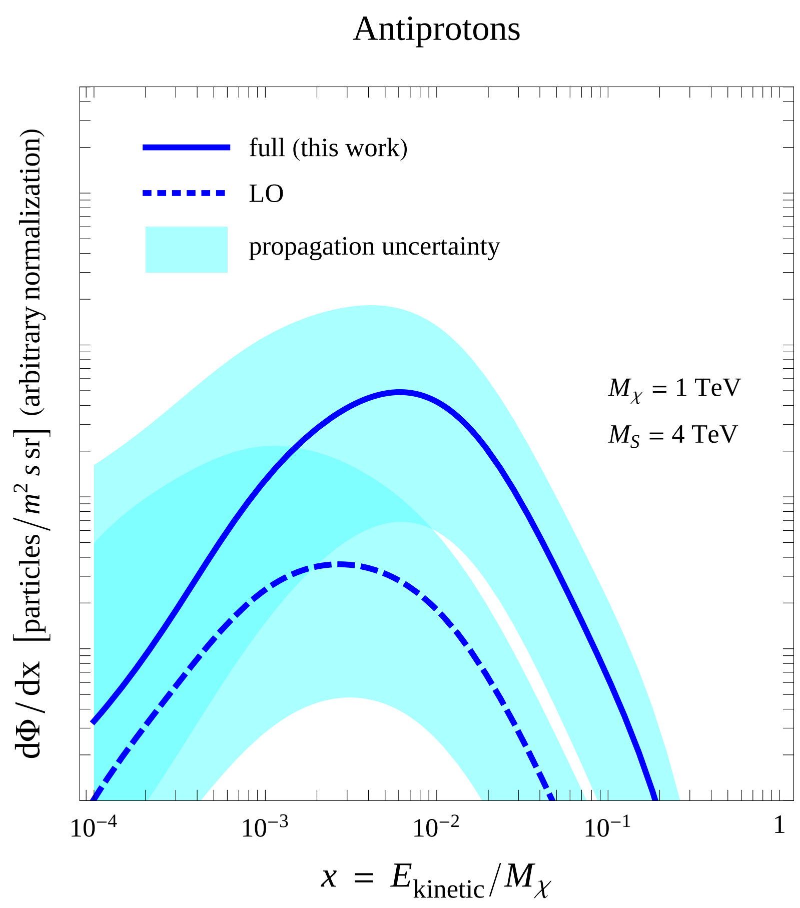
"LO" means adding EW radiation at the lowest order, keeping only the $\mathcal{O}(1/r)$ in the amplitude (p-wave).

* Bump of primary hard photons due to s-wave annihilation $\chi\chi \to e^+e^-\gamma$.
* Large low-energy tails due to showering and hadronization of W, Z.
* $dN/dE/[dN/dE]_{\rm LO} \sim \mathcal{O}(10-100)$.
  Of course, much larger enhancement wrt not including EW corrections.

Propagated fluxes

DM profile and propagation parameters are variated simultaneously.



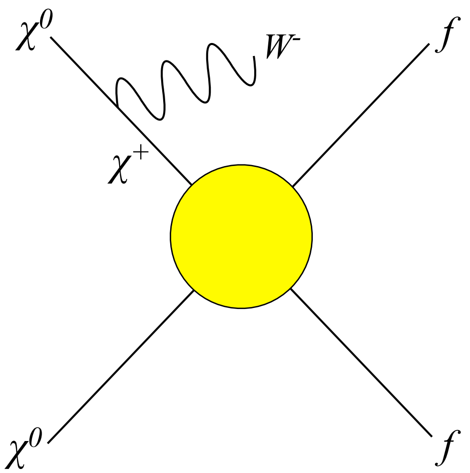


- Neutral particles (γ, ν) just go straight.
- Propagation does not spoil the effect.

Initial State Radiation

Let's abandon the hypothesis that DM is a gauge singlet...
Consider DM is the neutral Majorana component of a multiplet charged under $SU(2)_L \times U(1)_Y$, e.g. $SU(2)$-triplet with $Y=0$ (wino-like).

- ⋆ Dominant annihilation channel: $\chi^0\chi^0 \to W^+W^-$ ($v\sigma \sim g^4/M_\chi^2 \;\;\rightsquigarrow\;\; s$-wave).
- ⋆ The fermion channel with ISR is also in s-wave and can be competitive with W^+W^-.



$$v\sigma_{f\bar{f}}(\chi\chi \to f_i\bar{f}_i) \;\sim\; \frac{1}{M_\chi^2}\mathcal{O}\left(\frac{M_\chi^4}{\Lambda^4}\right)\,\mathcal{O}(v^2)\,,$$

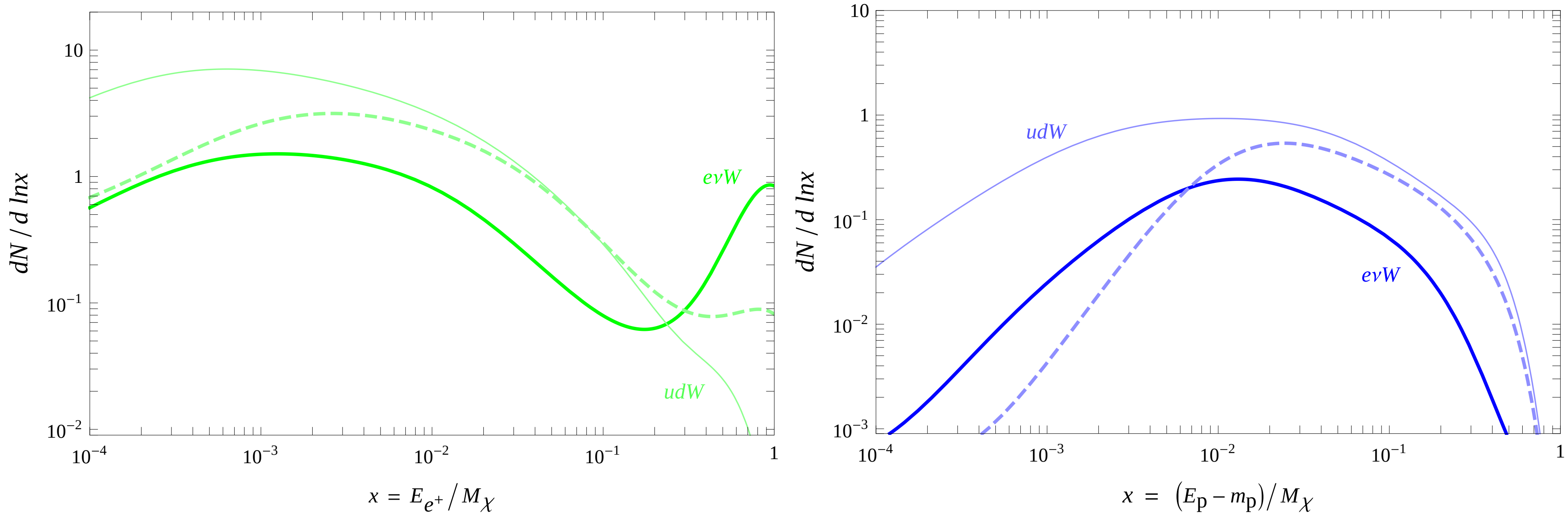
$$v\sigma_{\rm FSR}(\chi^0\chi^0 \to f_1\bar{f}_2W^-) \;\sim\; \frac{g^2}{M_\chi^2}\mathcal{O}\left(\frac{M_\chi^4}{\Lambda^4}\right)\,\mathcal{O}(v^2)\,,$$

$$v\sigma_{\rm ISR}(\chi^0\chi^0 \to f_1\bar{f}_2W^-) \;\sim\; \frac{g^2}{M_\chi^2}\mathcal{O}\left(\frac{M_\chi^4}{\Lambda^4}\right)\,\mathcal{O}(v^0)\,.$$

ISR lifts the helicity suppression already at the level of dim-6 operators.

Initial State Radiation

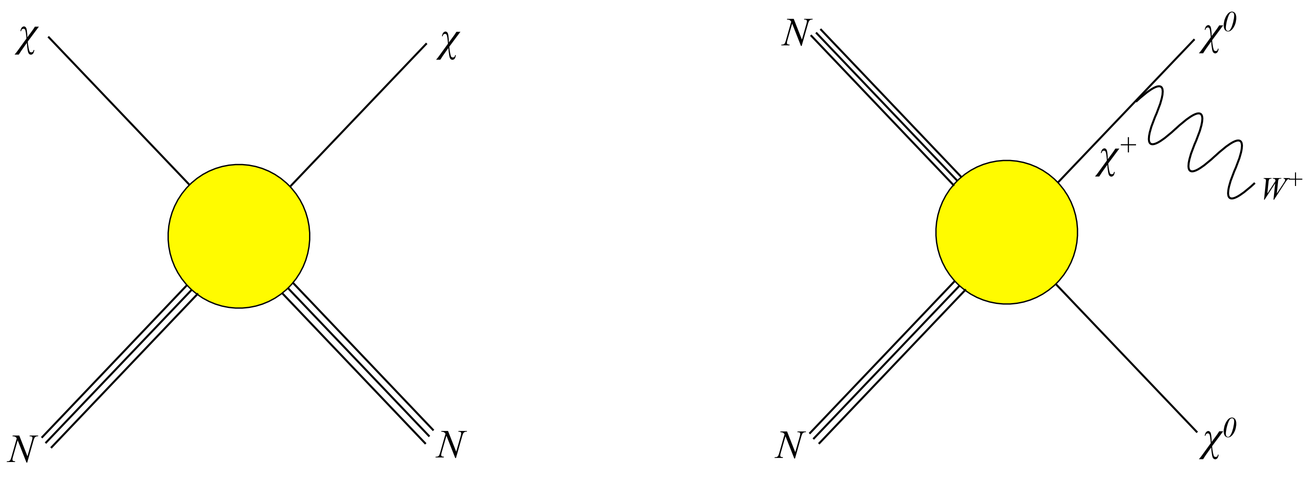
Comparison of $e^+, \bar{p}$ spectra from W^+W^- (dashed) and from ISR (solid).
Each contribution is normalized to 1 (proper channel-weighing is model-dependent).



Distinguishing features with respect to W^+W^-:

- abundant hard e^+ in the $e\nu W$ channel, due to primary positrons;
- abundant soft $\bar{p}$ in the udW channel, due to low-energy emitted W.

Collider-DD connection ?



Direct Detection Mono-W + $\not{E}_T$

* Data from mono-W searches at colliders can be used to constrain DM-quarks interactions.

* Results are complentary to and competitive with those from Direct Detection `(in progress)`.

See [Goodman et al (2010); Bai, Fox, Harnik (2010); Fox, Harnik, Kopp, Tsai (2011); Mambrini, Zaldivar (2011)] for mono-jet, mono-γ analyses.

Conclusions

- Majorana DM annihilates through s-wave once EW radiation is included.

- The resulting spectra get substantially enhanced by factors $\mathcal{O}(10 - 100)$ (with respect to p-wave only).
  Even more drastic effect with respect to the case without EW corrections.

- If DM belongs to a multiplet charged under EW interactions, ISR is possible and can play an important role.

- EW corrections are an important SM effect (no exotics!).
  Reliable calculations of fluxes for DM ID should take them into account.