PLANCK 2011 – Lisbon

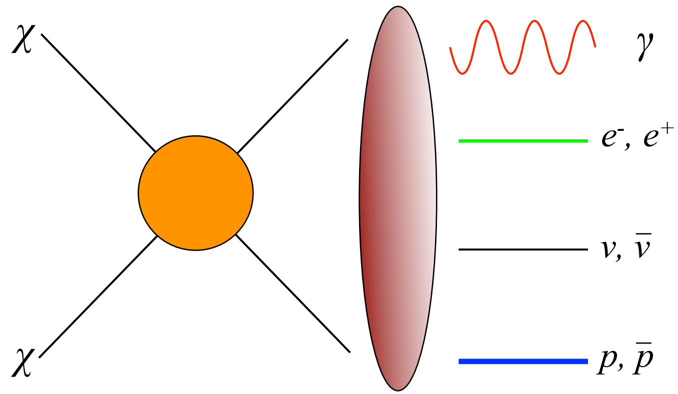
Electroweak lights from DM annihilations

ANDREA DE SIMONE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Based on:
Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano
arXiv:1104.2996 (to appear on JCAP)

Introduction



Radiation of EW gauge bosons is a SM effect and can have a big impact on final fluxes in 3 situations:

1. when looking at low-energy tails of the spectra, mostly populated by decay products of extra gauge bosons;

2. when some species are absent without EW corrections (e.g. $\bar{p}$ from $\chi\chi \to \ell^+\ell^-$);

3. *(this talk)* when $\sigma(2 \to 2)$ is suppressed, so $\sigma(2 \to 3)$ can even dominate.

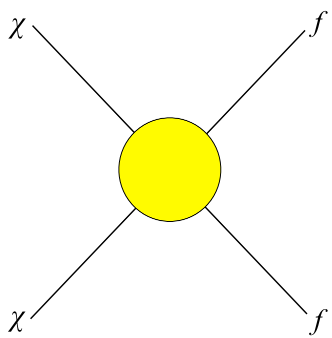
Annihilations of Majorana fermions

$$v\sigma_{\rm ann} \;=\; a \;+\; b\,v^2 + \mathcal{O}(v^4)$$

↑ s-wave ↑ p-wave

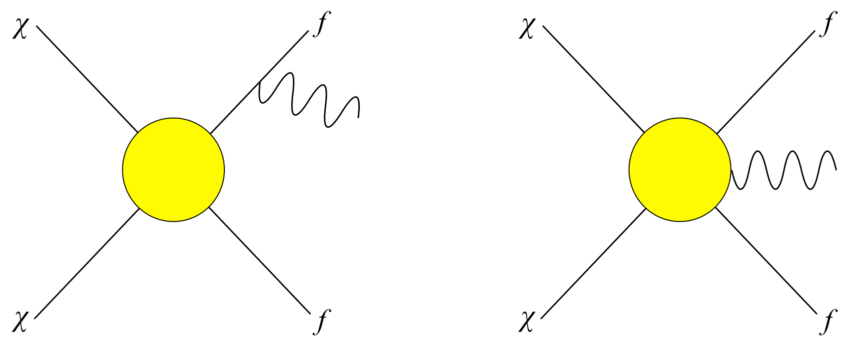
(today $v \sim 10^{-3}$)

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



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

radiation
$\Longrightarrow$



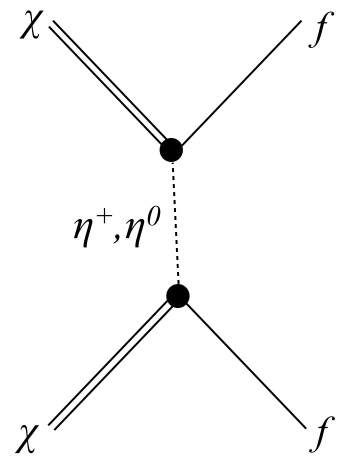
there is an s-wave!

The Model

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

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

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

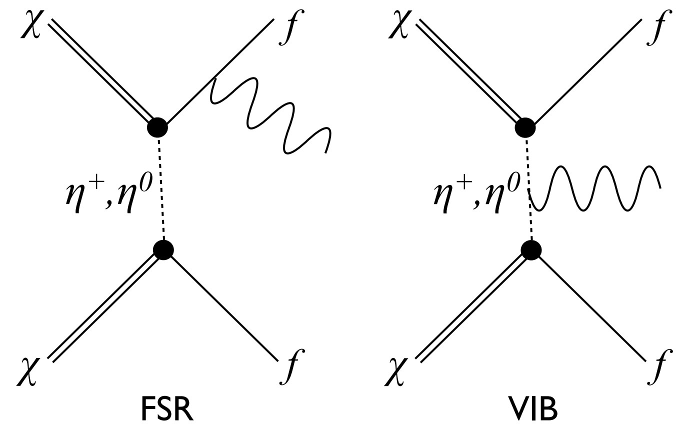


Mass parameters: M_χ, M_S

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

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

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:

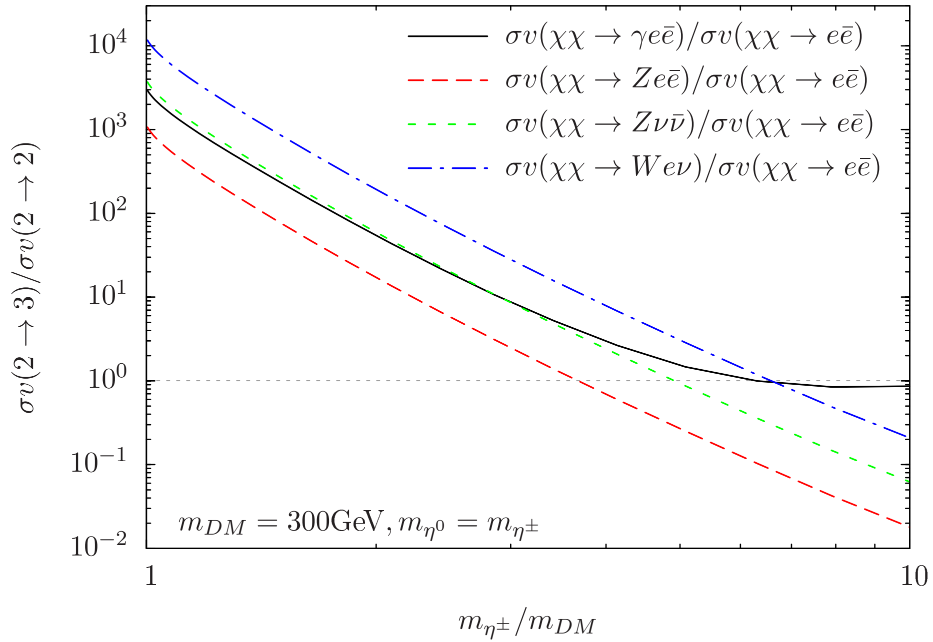
$$v\sigma(2\to 2) \quad\sim\quad \frac{1}{M_\chi^2}\frac{v^2}{r^2}$$

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

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

$$r \lesssim \sqrt{\frac{\alpha_W}{4\pi}}\frac{1}{v} \sim \mathcal{O}(10)$$

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



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

Effective Field Theory

Integrate out the heavy scalar S:

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

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

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

- The s-wave appears due to $\mathcal{O}_8$.
  $\mathcal{O}_8$ can be more important than $\mathcal{O}_6$ despite larger dimensionality.

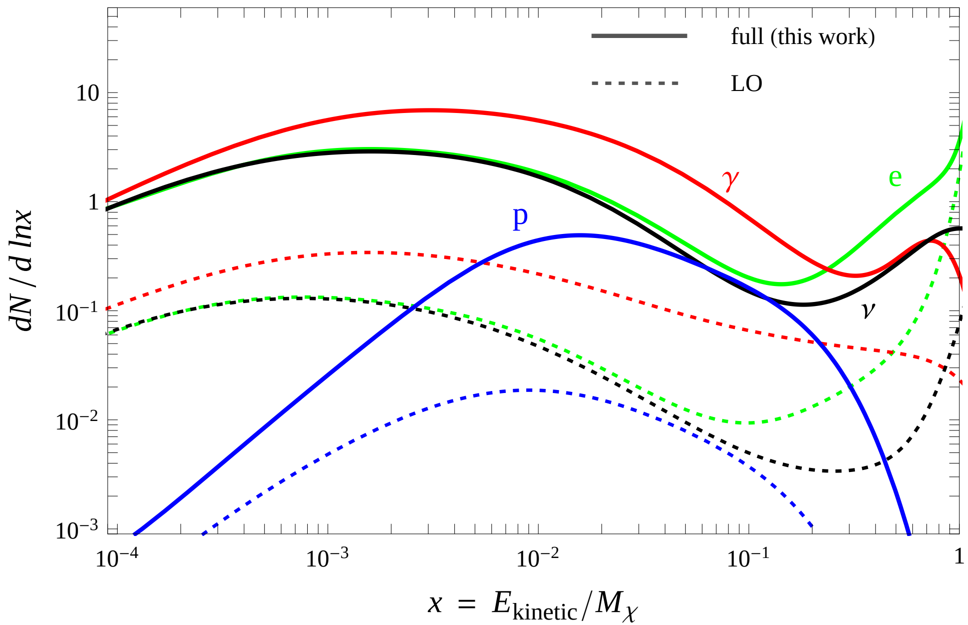
- Warning: in this case, naive dimensional analysis fails to assess the relative importance of operators in the expansion.

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 8.1`: 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 energy spectra at interaction point for each species
- propagation in the galactic halo

Energy spectra at the interaction point

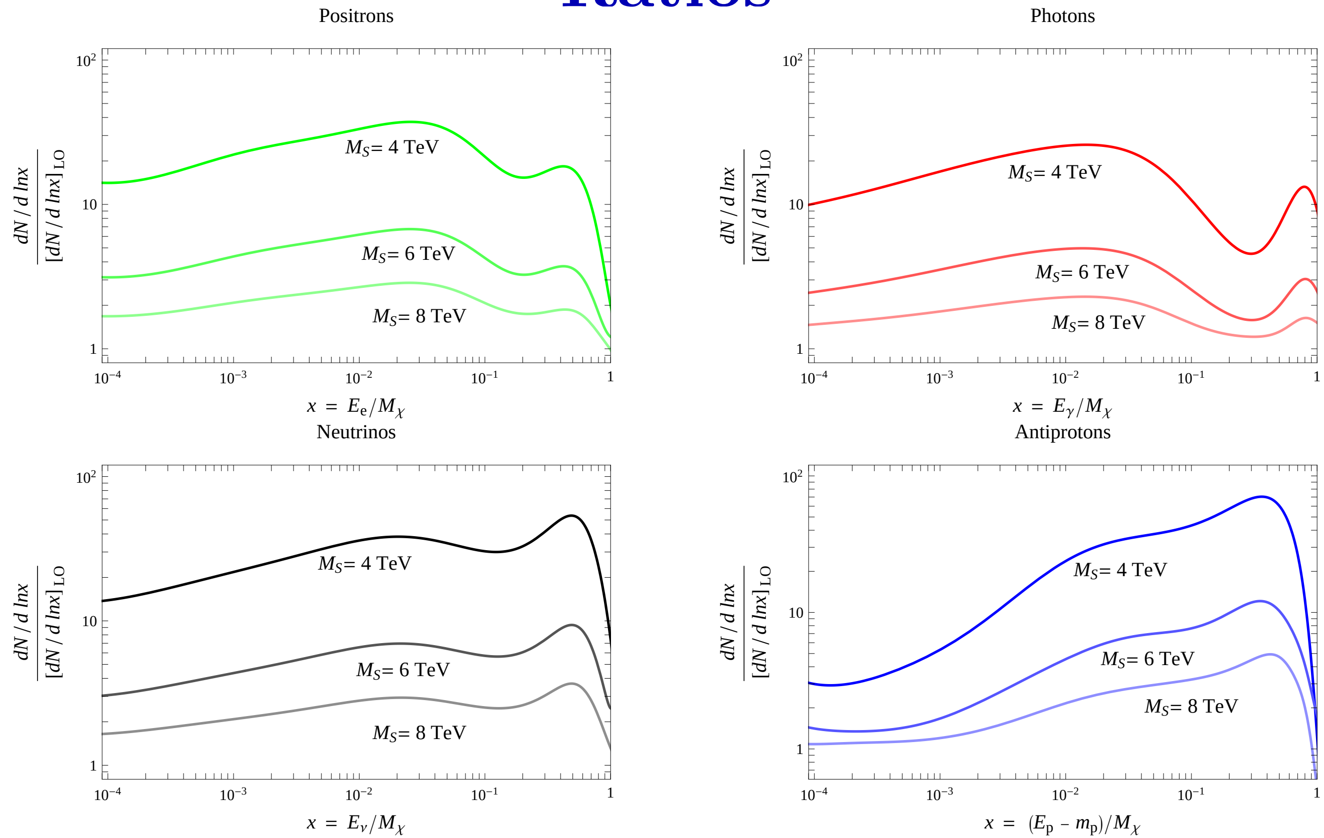


$$M_S = 4 \text{ TeV}$$
$$M_\chi = 1 \text{ TeV}$$

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

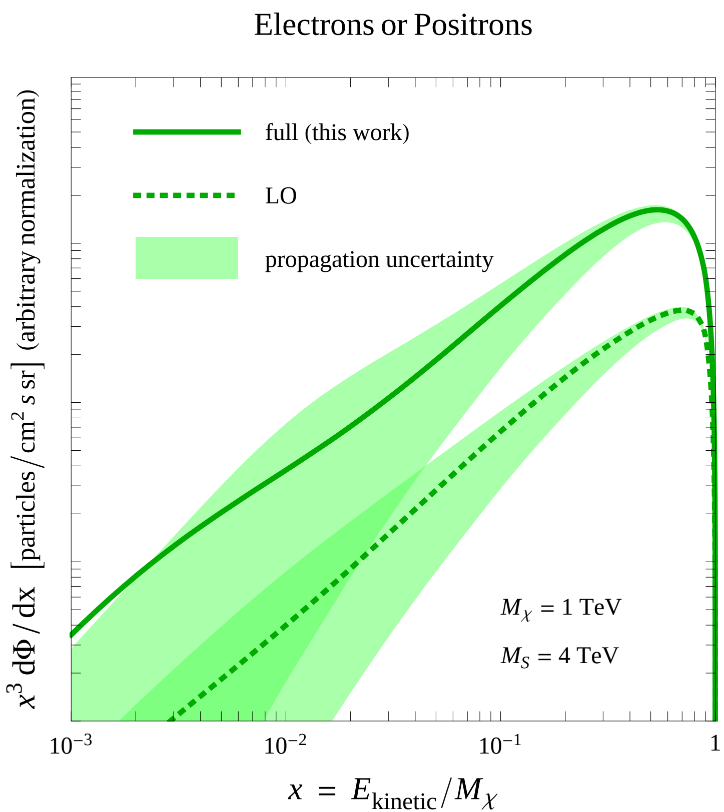
- ∗ “LO” means adding EW radiation at the lowest order, keeping only the $\mathcal{O}(1/r)$ in the amplitude (p-wave).
- ∗ Bump of primary hard photons due to s-wave annihilation $\chi\chi \to e^+e^-\gamma$.
- ∗ Large low-energy tails due to showering and hadronization of W, Z.

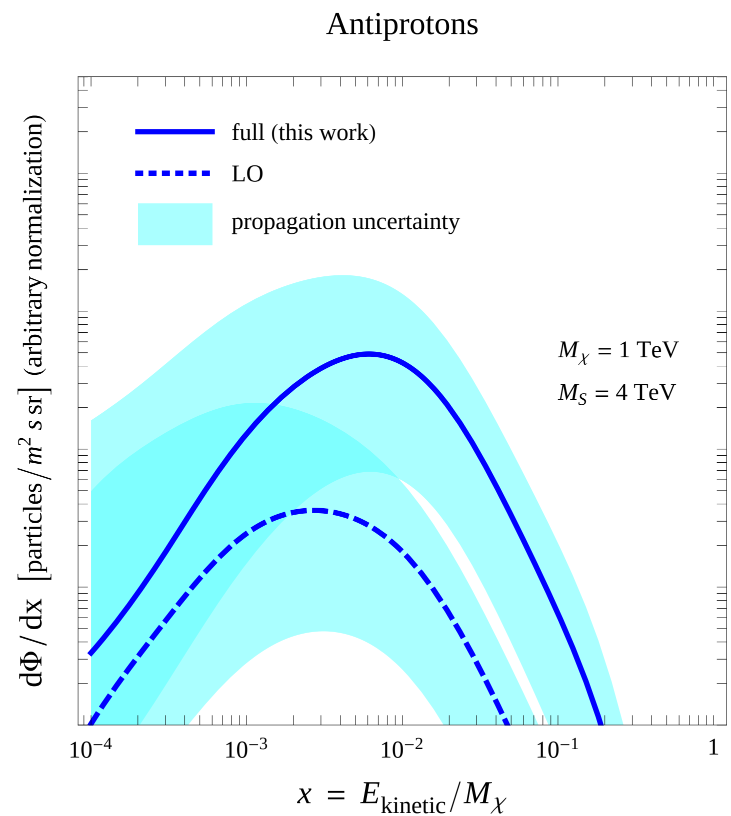
Ratios



- $dN/dE/[dN/dE]_{\rm LO} \sim \mathcal{O}(10 - 100)$
- Of course, much larger enhancement wrt not including EW corrections.

Propagated fluxes





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

Conclusions

- Majorana DM annihilates through s-wave once EW radiation is included.
- Care when using EFT: the naive dim analysis can be misleading. This effect is missed by $\mathcal{O}_6$.
- 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.
- EW corrections are a SM effect (no exotics!).
  Reliable calculations of fluxes for DM ID should take them into account.