Exploring Dark Matter through Electroweak emissions

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[1506.XXXX] → To appear soon!

In collaboration with:
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University of Zaragoza, Spain

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Institut für Theoretische Teilchenphysik und Kosmologie | RWTH AACHEN UNIVERSITY

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Outlook

1. Introduction
2. The Dark Matter Signal
3. Background function
4. Upper limits
5. Conclusion

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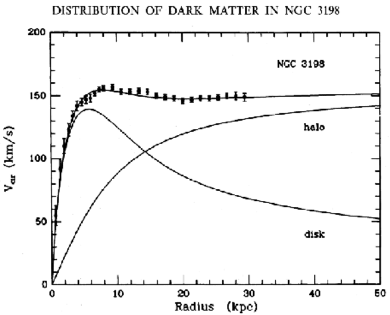
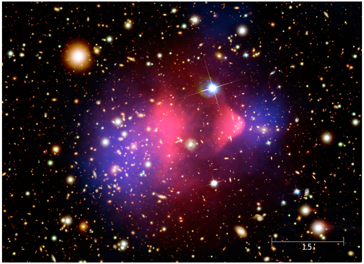
Standard
Model

Evidences for Dark Matter



[Rubin, Ford, Kent]



[Clowe, Gonzalez, Markevitch, astro-ph/0312273]

And more: CMB, weak lensing, large scale structure ...
→ Weakly Interacting Massive Particles (WIMPs)

Anomalies

Anomalies but no conclusive signal:

- Gamma ray line from the center of the galaxy
- Positron excess by AMS-02, PAMELA and Fermi

$\rightarrow$ Could it be dark matter?

- If yes, what is the Dark Matter model
- If not, set limits on parameters

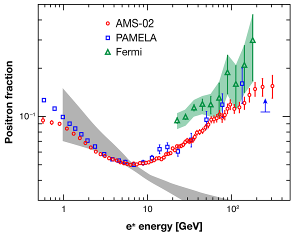
Anomalies

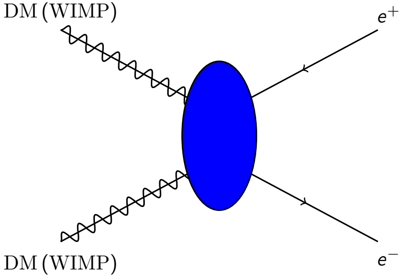
Anomalies but no conclusive signal:

- DAMA anomaly (?)
- Gamma ray line from the center of the galaxy
- **Positron excess by AMS-02, PAMELA and Fermi**

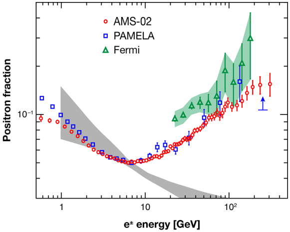
$\rightarrow$ Could it be Dark Matter?

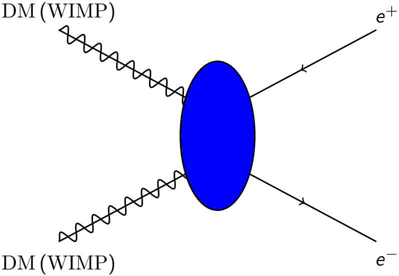
- If yes, what is Dark Matter model
- **If not, set limits on parameters**





$\rightarrow$ Leptophilic scenarios

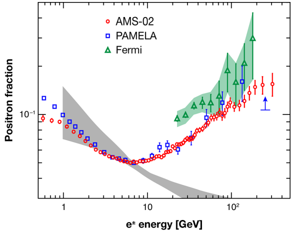


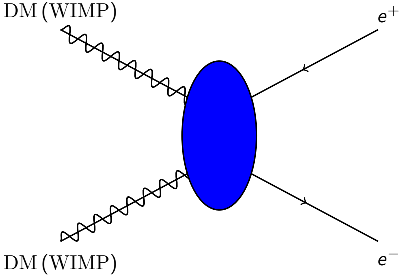


→ Leptophilic scenarios

→ Unexpected Dark matter scenario

→ Astrophysics, Pulsar(s) (?)

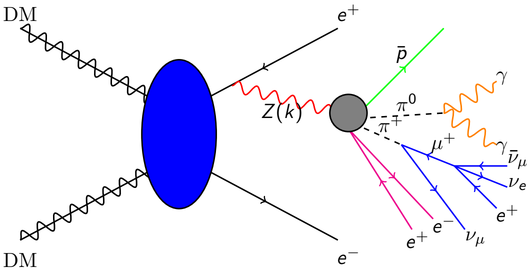


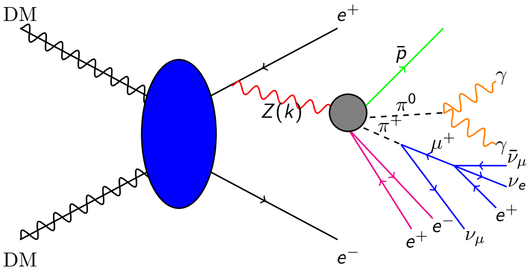


→ Leptophilic scenarios

→ Unexpected Dark matter scenario
→ Astrophysics, Pulsar(s) (?)

→ Dark Matter is only a sub-dominant contribution


DM
DM
e^+
e^-
$\bar{p}$
γ
γ
$Z(k)$
π^0
π^+
μ^+
$\bar{\nu}_\mu$
ν_e
e^+
e^-
e^+
ν_μ



→ Electroweak emissions are important

→ Correlation between fluxes *e.g.* with antiprotons

- Need to compute these emissions
- Need to take into account decay and emissions
- Need to take into account propagation scenarios

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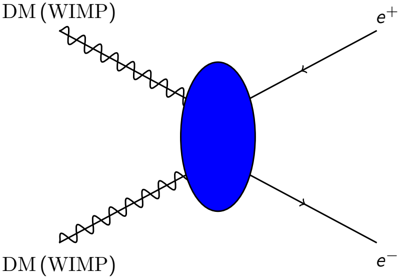
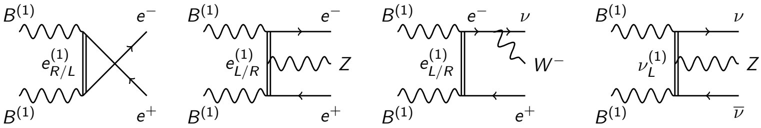


- The kinematic fixes the energy of the final $e^{\pm}$
- Only the cross section depends on the model (important remark for upper limits)

$\rightarrow$ **The** $2 \rightarrow 2$ **Dark Matter signal is completely model independent**

Universal Extra Dimension model → Vector Dark Matter

[Servant, Tait, hep-ph/0206071], [Cheng, Feng, Matchev, hep-ph/0207125]



→ Importance of the EW emissions:

- Complementarity between different fluxes
- Low energy part of the spectrum enhanced (extremely relevant for experiment)

→ **For large Dark Matter mass,**
the $2 \to 3$ **Dark Matter signal is completely model independent**

[Ciafaloni et al., 1009.0224], [Ali Cavasonza, MP, Krämer, 1409.8226]

Propagation (example of positrons)

- In-house Monte Carlo (Events / Cross section)
- Pythia (Parton Shower) [Sjostrand, Mrenna, Skands, 0710.3820]
- Propagation (Dark matter halo / Astrophysics) [Cirelli et al., 1012.4515]

$$\frac{d\Phi_{e^\pm}}{dE}(\epsilon, r_\odot) =$$

$$\frac{1}{4\pi}\frac{v_{e^\pm}}{b_T(\epsilon)}\frac{1}{2}\left(\frac{\rho_\odot}{M_{\rm DM}}\right)^2 \langle\sigma v_{\rm cm}\rangle_{\rm DM\ DM\to I}\int_\epsilon^{M_{\rm DM}} d\epsilon_s \frac{dN_{e^\pm}}{dE}(\epsilon_s)\mathcal{I}\left(\lambda_D(\epsilon,\epsilon_s)\right)$$

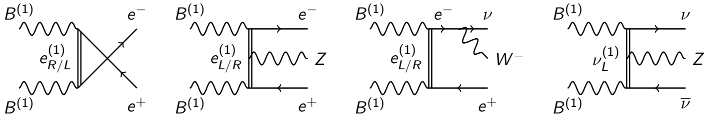
with

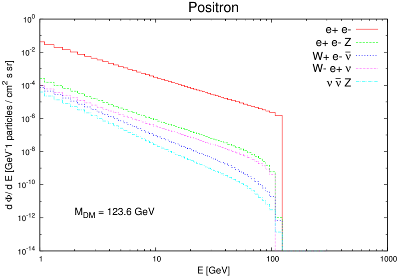
$$\frac{dN_{e^\pm}}{dE} = \frac{1}{\langle\sigma v_{\rm cm}\rangle_{\rm DM\ DM\to I}}\frac{d\langle\sigma v_{\rm cm}\rangle_{\rm DM\ DM\to I}\times BR_{I\to e^\pm}}{dE}$$

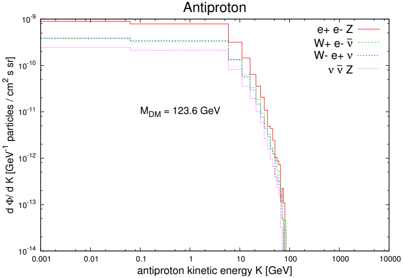
and

$$I \in \{e^+e^-, e^+e^-Z\}$$

All massive gauge bosons contributions







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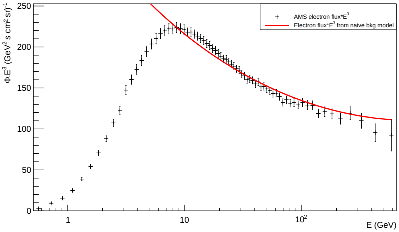
Fitting the data

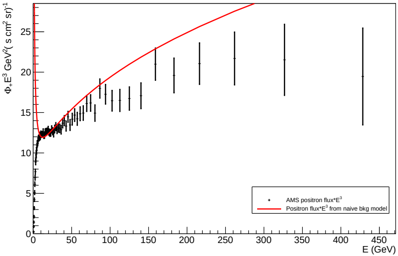
→ Electron and positron flux fitted with standard background function:

$$\Phi_{e^\pm} = C_{e^\pm} E^{-\gamma_{e^\pm}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

[AMS collaboration, Phys. Rev. Lett. 110, 14, 141103 (2013)]

→ Used by [Bergstrom, Bringmann, Cholis, Hooper, Weniger, 1306.3983]





- Use most recent AMS-02 data
  [AMS collaboration, Phys.Rev.Lett. 113 (2014)]

→ New background function:

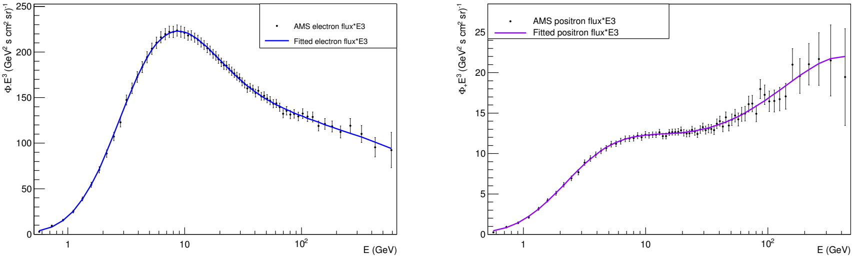
[S. Schael "The e^- Spectrum and e^+ Spectrum from AMS", Talk at CERN, 15 April 2015 (2015)]

$$\Phi_{e^\pm} = \frac{E^2}{\widehat{E}^2}\left[C_{e^\pm}\widehat{E}^{\gamma_{e^\pm}} + C_S\widehat{E}^{\gamma_S}\exp\left(-\widehat{E}/E_S\right)\right]$$

- Describes smoothly the model over the whole energy range
  → even for low energy (*e.g.* solar modulation)
- Significance scan → No significance deviation
- Toy Monte Carlo experiments

Fitting the data

→ Electron and positron fluxes
fitted (perfectly) with new background function:



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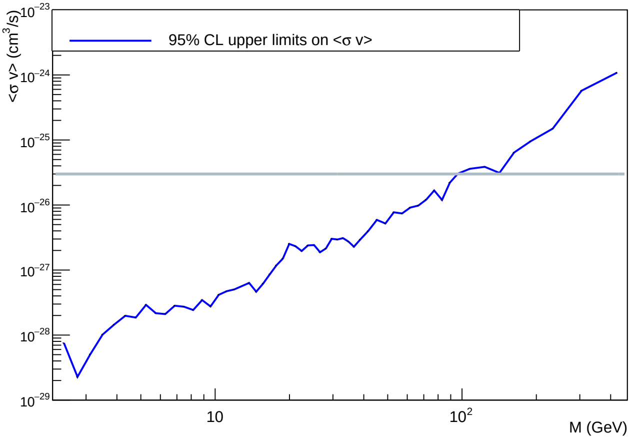
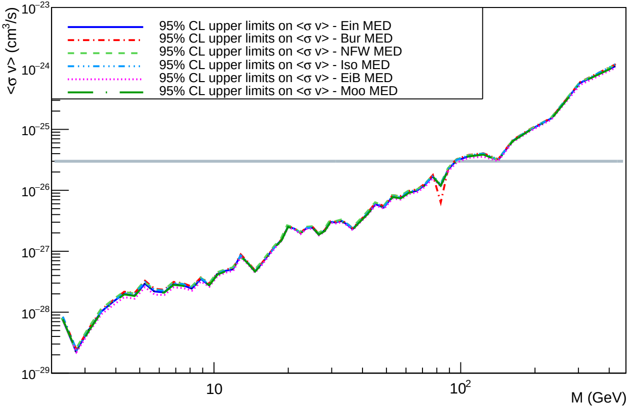


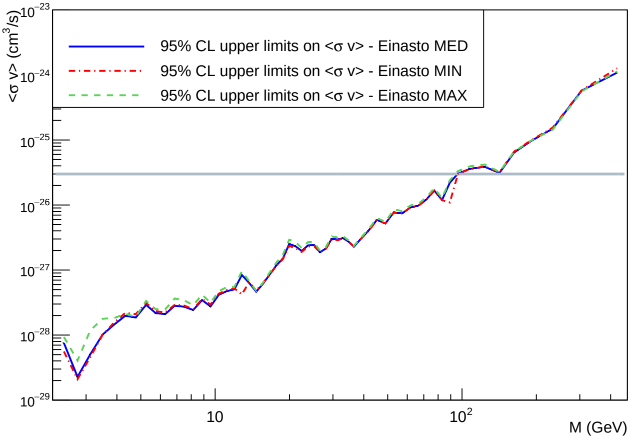
→ Upper limits over the whole energy range

Dark Matter halo model



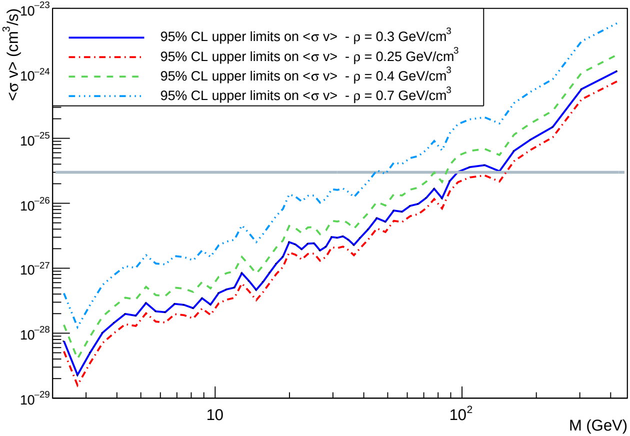
→ Relative influence

Propagation model



→ Noticeable influence for low energy part

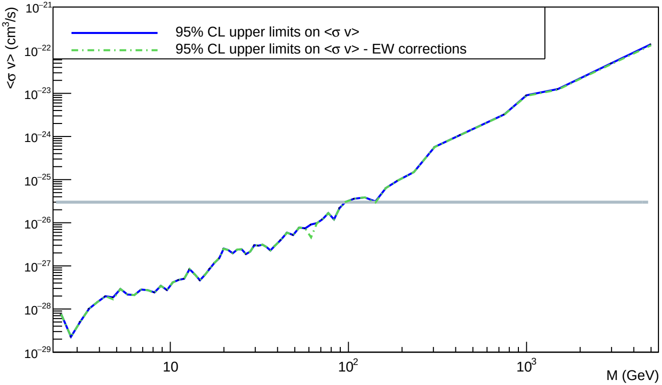
Dark Matter density at Earth



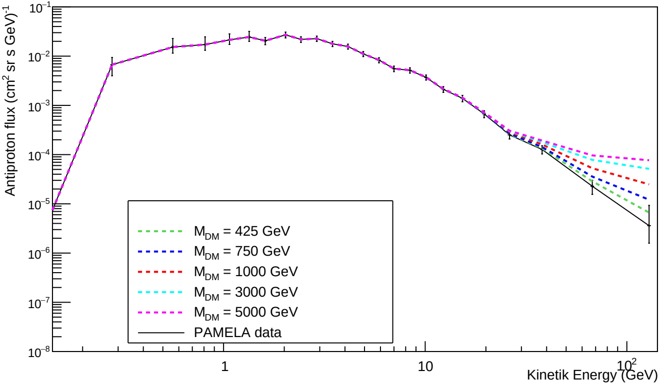
→ Scales as ρ^2

Including Electroweak Contributions

→ Modest impact on exclusion limit



→ Assuming a Dark Matter signal at the exclusion limit in $e^{\pm}$ flux



→ Interesting complementarity between different fluxes

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  - Computation including all massive gauge bosons
  - ... decay them and account for further radiations
  - Flux predictions for positrons and antiprotons

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  - Robust upper limits on the annihilation cross section
  - $2 \to 2$ model independent limits
  - $2 \to 3$ model independent limits for high mass

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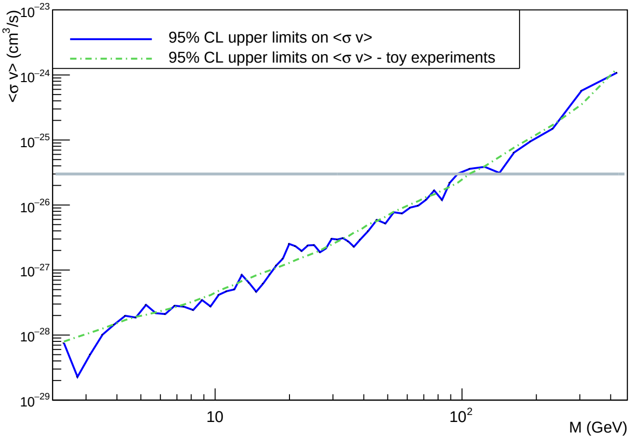
Complementarity between different anti-particles fluxes

$\to$ Dark Matter is around the corner ...

Back-up slides

BACK-UP

Toy Monte Carlo experiment



→ Consistent with derived upper limits from real data

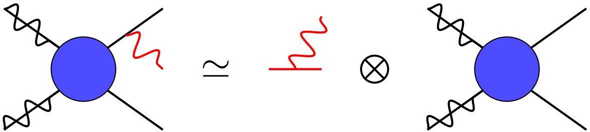
Back up
Fragmentation function for Z boson

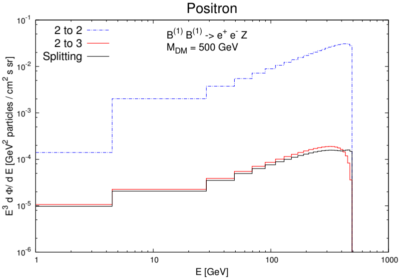
$$D_{F\to V} = \frac{\alpha_2}{2\pi\cos^2\theta_w} g_f^2 P_{F\to V}$$

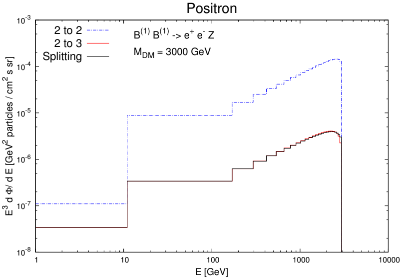
$$P_{F\to V} = \frac{1+(1-x)^2}{x} L(x) \text{ with } x = 2E_f/\sqrt{s}$$

$$L(x) = \ln\frac{sx^2}{4m_Z^2} + 2\ln\left(1+\sqrt{1-\frac{4m_Z^2}{sx^2}}\right)$$

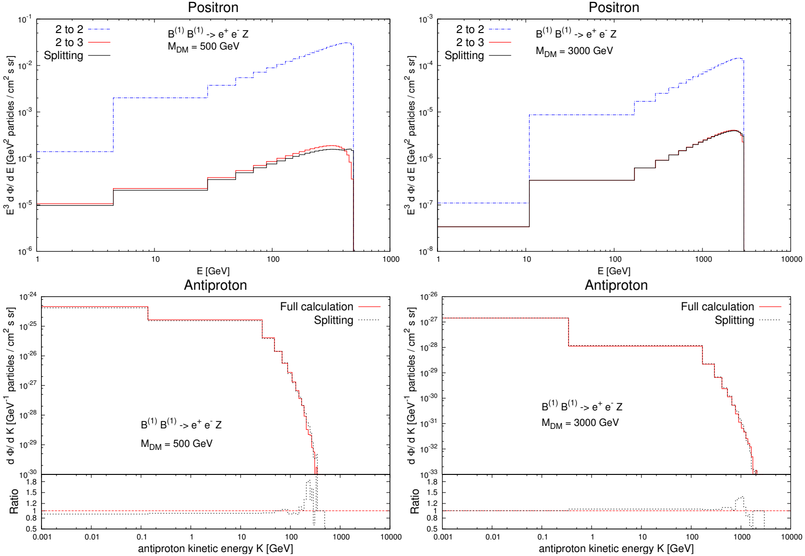
$$s = 4m_D M^2 + v^2 ...$$







[Ali Cavasonza, MP, Krämer, 1409.8226]



[Ali Cavasonza, MP, Krämer, 1409.8226]

$$F(x_2) = \left(A \ln\left(\frac{\overline{x}_+}{\overline{x}_-}\right) + B + C \ln\left(\frac{\overline{x}_+ - 2}{\overline{x}_- - 2}\right) \right)$$

$$\begin{aligned}
A &= -\frac{1}{8M_{\mathrm{DM}}^6}\frac{1}{x_2(x_2-1)}\Big(m_Z^6 + M_{\mathrm{DM}}^2 m_Z^4(4+5x_2) \\
&\quad + 4M_{\mathrm{DM}}^4 m_Z^2(1+3x_2+2x_2^2) + 8M_{\mathrm{DM}}^6(x_2+x_2^3)\Big), \\
B &= -\sqrt{(1-x_2)^2 - \frac{m_Z^2}{M_{\mathrm{DM}}^2}} + \frac{1}{16M_{\mathrm{DM}}^6}\frac{1}{(1+x_2)^2}\sqrt{(1-x_2)^2 - \frac{m_Z^2}{M_{\mathrm{DM}}^2}}\frac{1}{x_2 + \frac{m_Z^2}{4M_{\mathrm{DM}}^2}}\Big(2m_Z^6 \\
&\quad + 2M_{\mathrm{DM}}^2 m_Z^4(2+9x_2) + 12M_{\mathrm{DM}}^6 x_2(5+8x_2+5x_2^2) + 5M_{\mathrm{DM}}^4 m_Z^2(3+8x_2+11x_2^2)\Big), \\
C &= \frac{1}{8M_{\mathrm{DM}}^6}\Big(M_{\mathrm{DM}}^2 m_Z^4(4+9x_2-4x_2^2+5x_2^3) + 8M_{\mathrm{DM}}^6 x_2(1+4x_2+9x_2^2+4x_2^3+x_2^4) \\
&\quad + m_Z^6(1+x_2^2) + M_{\mathrm{DM}}^4 m_Z^2(4+25x_2+36x_2^2-7x_2^3+8x_2^4)\Big)\frac{1}{x_2(1+x_2)^3}
\end{aligned}$$

$$\frac{d\langle\sigma v\rangle}{dx_2} = 2\langle\sigma v\rangle_{\mathrm{Born}}\frac{\alpha}{2\pi}\frac{g_f^2}{\sin^2\theta_w\cos^2\theta_w}F(x_2)$$

For $m_Z \to 0$

$$A \ln\left(\frac{\overline{x}_+}{\overline{x}_-}\right) \to \frac{1+x_2^2}{1-x_2}\left(\ln\left((1-x_2)^2\frac{M_{\mathrm{DM}}^2}{m_Z^2}\right) + 2\ln(2)\right)$$

Back up

cross section comparison

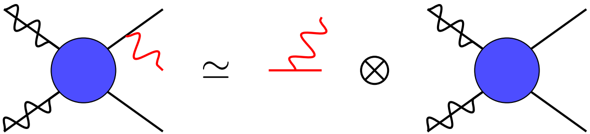
M_{DM}	$\langle\sigma v\rangle_{B^{(1)}B^{(1)}\to e^+e^-}$	$\langle\sigma v\rangle_{B^{(1)}B^{(1)}\to e^+e^-Z}$	$\langle\sigma v\rangle_{B^{(1)}B^{(1)}\to e^+e^-Z}\|_{\mathrm{ff}}$
150	2.642	4.583×10^{-3}	1.459×10^{-3}
300	0.6604	2.078×10^{-3}	1.597×10^{-3}
500	0.2378	1.202×10^{-3}	1.104×10^{-3}
1000	5.944×10^{-2}	5.362×10^{-4}	5.282×10^{-4}
3000	6.605×10^{-3}	1.221×10^{-4}	1.227×10^{-4}

in [GeV] and [pb]

Electroweak Emissions

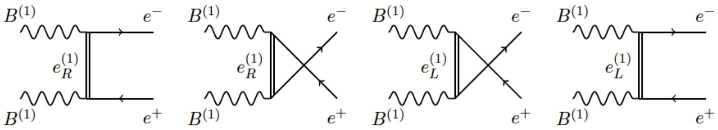
- When the hard scale (the DM mass) is much larger than the gauge boson mass
- *Log* enhanced contributions from singular internal propagator
- They becomes model independent for high mass

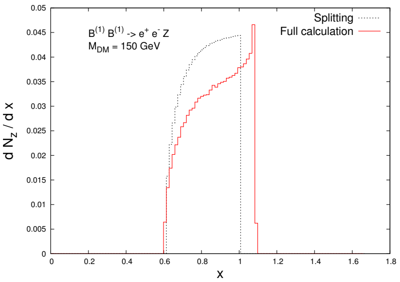
  [Ciafaloni et al., 1009.0224], [Ali Cavasonza, MP, Krämer, 1409.8226]

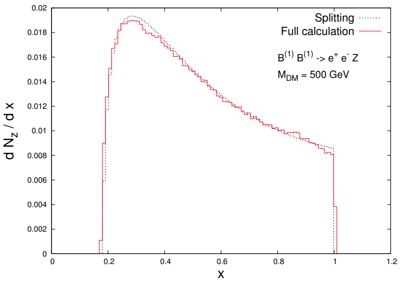


→ **For large Dark Matter mass,**
the $2 \rightarrow 3$ **Dark Matter signal is completely model independent**

Working example: Universal Extra Dimension



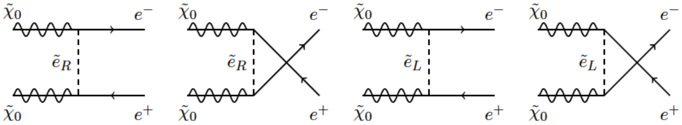


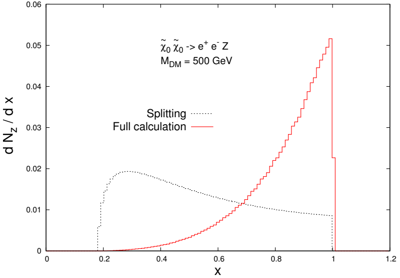


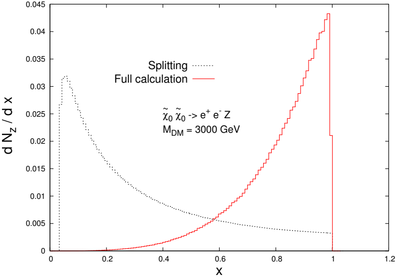
[Ali Cavasonza, MP, Krämer, 1409.8226]

$\longrightarrow$ Perfectly working for $m_{DM} > 500$ GeV

Counter example: Supersymmetry







[Ali Cavasonza, MP, Krämer, 1409.8226]

→ Helicity suppression [Ciafaloni et al., 1104.2996]