RWTH AACHEN UNIVERSITY

Role of electroweak corrections in Dark Matter indirect detection.

Leila Ali Cavasonza

in collaboration with

Michael Krämer, Mathieu Pellen

Desy Theory Workshop

Hamburg - September 25th, 2014

DFG

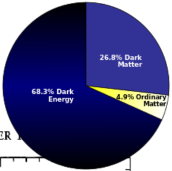
NASA

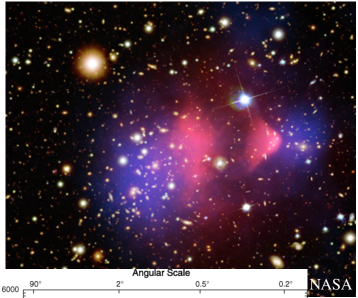
Outline of the talk

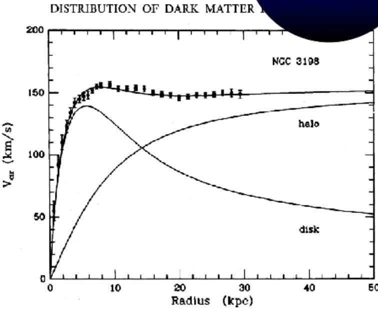
1. Dark Matter: a short introduction;
2. Dark Matter indirect detection - theoretical predictions;
3. Inclusion of electroweak corrections;
4. The splitting fuctions approximation;
5. Results.

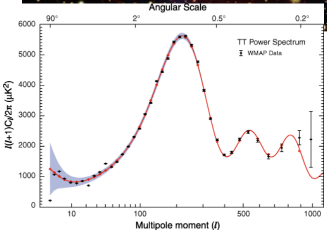
Search for new physics - Dark Matter

Big challenge in particle and astroparticle physics:
exploration of nature of DARK MATTER









Evidences of the existence of Dark Matter:
strongest phenomenological
hints for BSM physics.

DM properties

Properties

According to the observations DM should be

- cold (non relativistic);
- massive (local density = 0.3 GeV/cm^3);
- weakly interacting (not observed);
- small self interaction cross-section (Bullet cluster);

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- cold (non relativistic);
- massive (local density = 0.3 GeV/cm^3);
- weakly interacting (not observed);
- small self interaction cross-section (Bullet cluster);

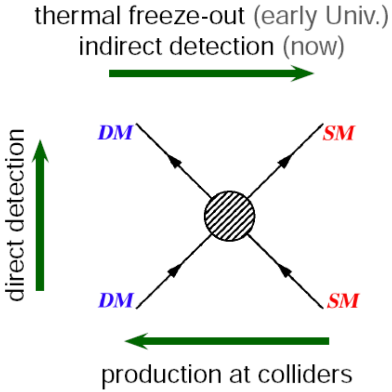
N.B. There are more exotic scenarios, but we stick to this one..

Search for new physics - Dark Matter

Huge experimental effort in DM searches.

In principle there are three ways of discovering Dark Matter:

- **production** at colliders (LHC);
- **direct** detection;
- ***indirect* detection.**

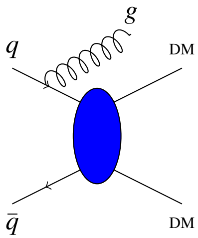


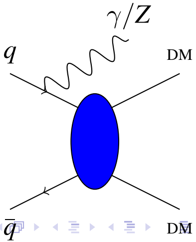
Huge experimental effort in DM searches.

In principle there are three ways of discovering Dark Matter:

- **production** at colliders (LHC)

  - final state: DM + DM + jet,
    mono - jet searches, signature: jet + MET;
  - final state: DM + DM + γ,
    mono - photon searches, signature: γ + MET;
  - final state: DM + DM + Z($\rightarrow\ l\,\bar{l}$),
    mono - Z searches, signature: $l\bar{l}$ + MET;
  - ...





Search for new physics - Dark Matter

Huge experimental effort in DM searches.

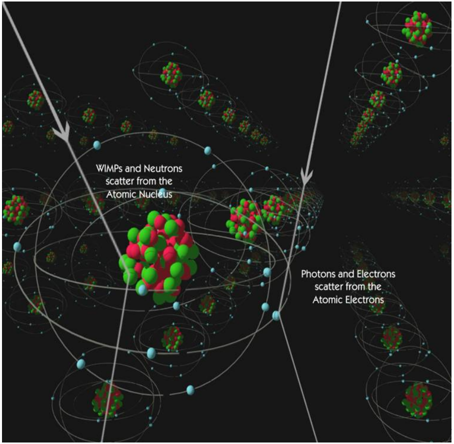
In principle there are three ways of discovering Dark Matter:

- **direct** detection

  dark matter interacts with ordinary matter: (in)elastic scattering on nucleus or elastic scattering on electron.

  Recoil energy is measured with various techniques, (scintillators, noble liquids, bolometers).

  Many experiments: Xenon, CDMS, LUX…



Search for new physics - Dark Matter

Huge experimental effort in DM searches.

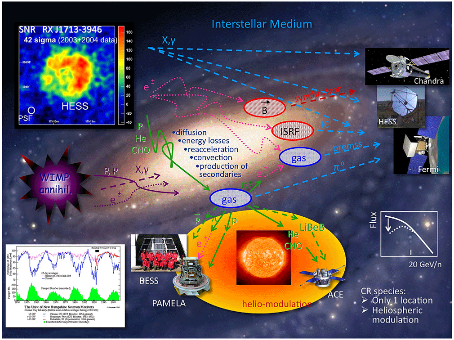
In principle there are three ways of discovering Dark Matter:

- ***indirect* detection**

  dark matter annihilates into SM particles
  (γ, ν, charged cosmic rays)

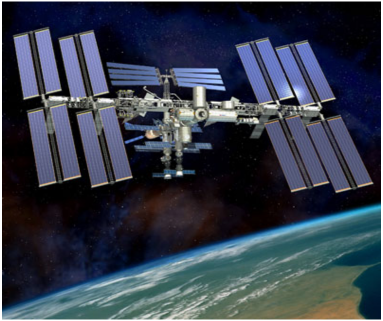
  various experiments to detect DM annihilation products: AMS-02, PAMELA, Fermi, IceCUBE etc…

  They see anomalies…

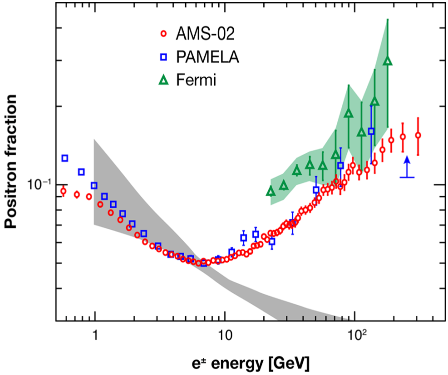


[Moskalenko, Strong, Reimer]

AMS: the Alpha Magnetic Spectrometer Experiment



AMS detector on the International Space Station (ISS)

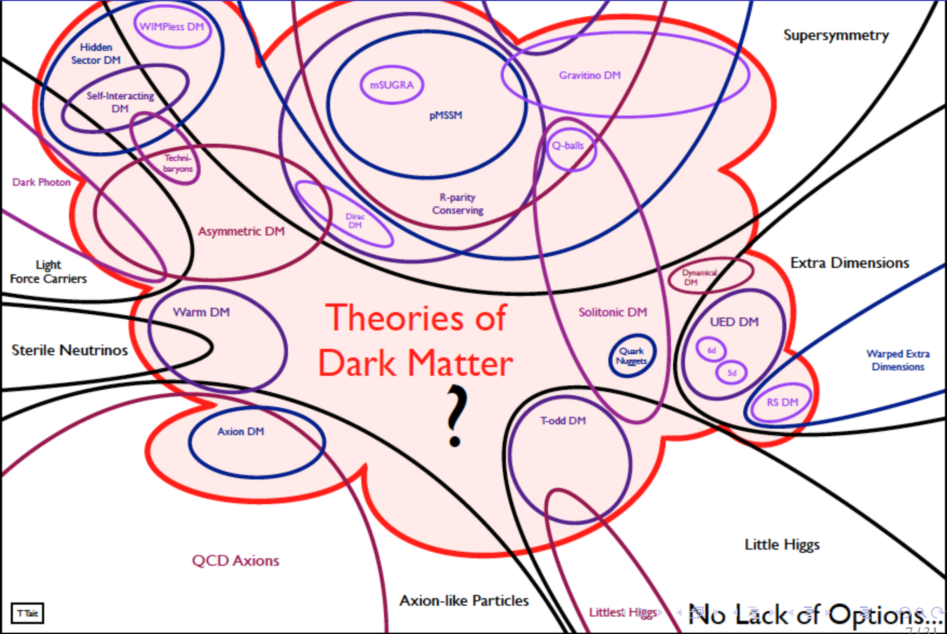


First results for the positron fraction

Search for antimatter,

high precision measurements of composition and fluxes of cosmic rays, ...

From a theoretical perspective. . . many possibilities...



No Lack of Options...

From a theoretical perspective

Candidates:

- byproduct of a more comprehensive model (e.g. SUSY, UED)
- ad hoc models (e.g. Minimalistic Models, New Dark Forces, . . .)

To explain AMS data **Dark Matter** must be

- multi TeV mass particle;
- leptophilic;
- large annihilation cross section in light final states.

No detection of possible DM candidate at LHC (so far):
exclusion of certain regions of the parameter space/certain models.

AMS:
detection of dark matter or exclusion of some other regions of the parameter space/models.

Theoretical predictions

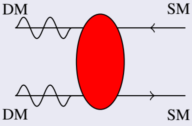
AMS: measures the fluxes of secondary antimatter particles produced (maybe) by DM annihilation.

THEORETICAL PREDICTION FOR FLUXES

FLUX AT PRODUCTION $\Leftrightarrow$ primary flux

(DM + DM annihilation is parametrized by the cross section $\langle \sigma v \rangle = a + bv^2 + \mathcal{O}(v^4)$)

(`FeynArt` + `FormCalc`, `MadGraph`)



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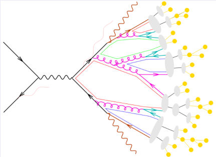
PARTON SHOWER AND HADRONIZATION

(`Pythia` 8)



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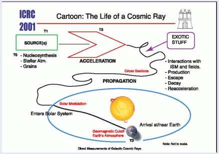
PROPAGATION THROUGH THE GALAXY

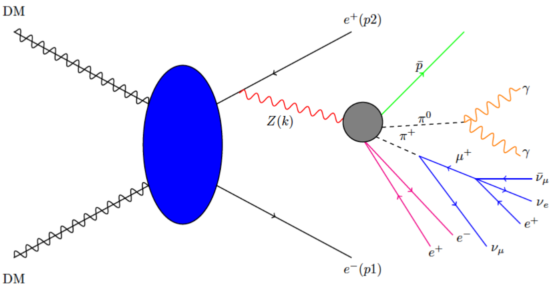
$\Leftrightarrow$ secondary flux

(`Galprop` or Green functions)



Theoretical predictions - EW corrections

Importance of inclusion of electroweak emission
for calculation of energy spectra.



At the $\sim$ TeV scale EW corrections can be extremely relevant:

the DM mass M is much larger than the EW scale
$\Rightarrow$ the emission is enhanced by factors $\ln M^2/M_W^2$ (Sudakov logs)

Decay and hadronization of EW bosons
$\Rightarrow$ all stable SM particles in the final state, independently from initial state.

Theoretical predictions - EW corrections:

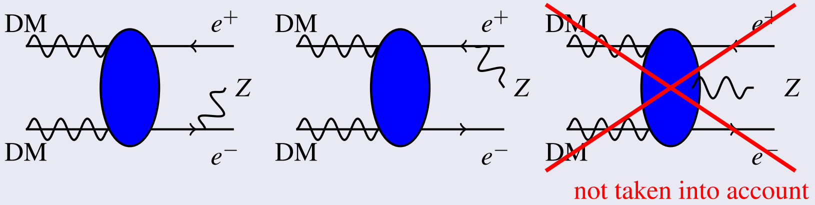
EW corrections from the DM initial state are *model dependent*.

EW corrections from the SM final state are *model independent*.

We restrict ourselves to this second subset of EW corrections.

To include EW corrections:
partonic splitting functions for massive partons (W and Z bosons)

- model independent approximation;
- capture log-enhanced behaviour of the amplitude;
- obey DGLAP-like evolution equations.



Generalized partonic splitting functions

1009.0224 [Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano]

$$\frac{dN_{I\to f}}{d\ln x}(M,x) = \sum_J \int_x^1 dz\, D^{EW}_{I\to J}(z)\, \frac{dN^{MC}_{J\to f}}{d\ln x}(zM, \frac{x}{z}),$$

with

$$D^{EW}_{I\to J}(z) = \delta_{IJ}\delta(1-z) + \frac{\alpha_2}{2\pi}\int_{M_W^2}^{s} \frac{d\mu^2}{\mu^2} P^{EW}_{I\to J}(z,\mu^2),$$

where

- I is the generic pair of SM particles produced via DM DM annihilation (e.g. $e^+e^-, \nu\bar{\nu}, \ldots$);
- $\frac{dN_{I\to f}}{d\ln x}$ is the energy spectrum of the stable SM particle f and $x = E_f/\sqrt{s}$;
- $D^{EW}_{I\to J}(z)$ is the $I \to J$ parton distribution;
- $P^{EW}_{I\to J}$ is the generalized splitting function;

Check the quality of the approximation

Check the quality of the approximation in two simple concrete cases: compare full $2 \to 3$ calculation against fragmentation functions result.

SUSY case

DM candidate: pure bino neutralino χ
$\chi\,\chi \to e^+\,e^-\,Z,$

χ is a Majorana fermion.

UED case

DM candidate: first KK photon $B^{(1)}$
$B^{(1)}\,B^{(1)} \to e^+\,e^-\,Z,$

$B^{(1)}$ is a vector boson.

Comparisons:

- energy spectrum of the Z boson;
- fluxes of stable SM particles before propagation through the Galaxy;
- fluxes of stable SM particles after propagation through the Galaxy.

Comparison - Z energy distribution

First check: shape of the Z energy distribution.

$$\frac{dN}{dE_Z} = \frac{d\langle\sigma_{(\chi\ \chi\to e^+\ e^-\ Z)}v\rangle}{dE_Z}\frac{1}{\langle\sigma_{(\chi\ \chi\to e^+\ e^-\ Z)}v\rangle}$$

With the fragmentation functions approximation:

$$\frac{d\sigma_{(\chi\chi\to e^+e^-Z)}}{dx} = 2\left(\sigma_{(\chi\chi\to e_L^+ e_L^-)}D_{e_L\to e_L} + \sigma_{(\chi\chi\to e_R^+ e_R^-)}D_{e_R\to e_R}\right)$$

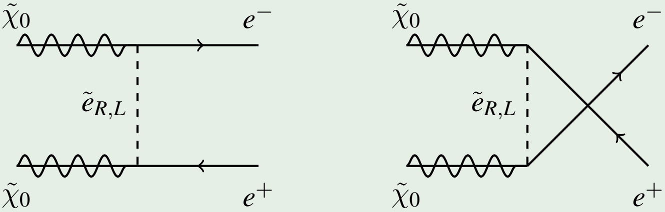
$$D_{e_{L,R}\to e_{L,R}} = \frac{\alpha_2}{2\pi\cos^2\theta_w}g_f^2 P_{e_{L,R}\to e_{L,R}}, \quad \text{with} \quad g_f = T_3^f - \sin^2\theta_w Q_f$$

$$P_{e_{L,R}\to e_{L,R}} = \frac{1+x^2}{1-x}L(1-x)$$

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

$$x = \frac{E_z}{M_\chi} \qquad s \simeq 4M_\chi^2$$

Concrete case 1: bino annihilation - Majorana DM



Contributions to $\chi\ \chi \to e^+\ e^-$

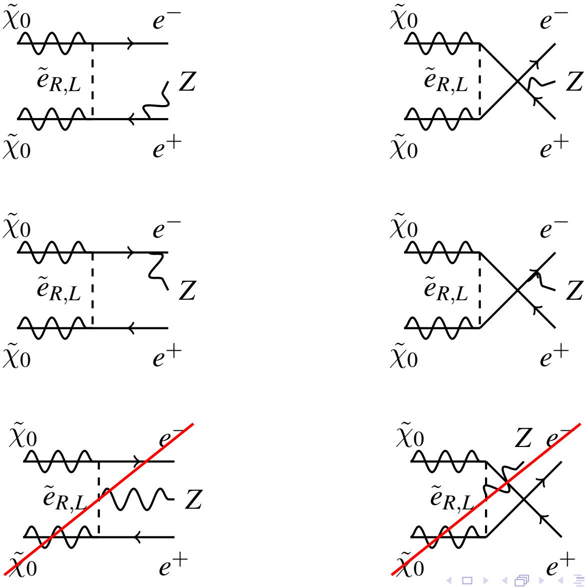
(Very simple model: $M_\chi = M_{\tilde{e}_{L,R}}$ and no neutralinos and sleptons mixing)

Add EW correction: Z boson emission

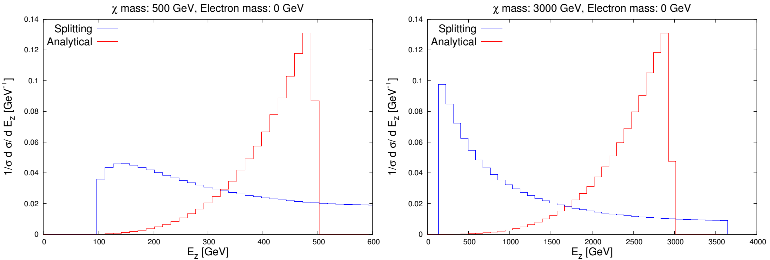
Fragmentation functions approach reproduce only the log-enhanced behaviour of the cross section$\Rightarrow$

exact calculation to check the quality of the approximation

Concrete case: $\chi\ \chi \to e^+\ e^-\ Z$



Comparison: Z energy distribution



. . . they don't match at all. . .

$$\langle \sigma v \rangle_{v \to 0} = \frac{e^4 m_e^2 \sqrt{m_\chi^2 - m_e^2}}{\pi m_\chi^2 (2m_\chi^2 - m_e^2)} \propto m_e^2$$

Cross-section is **helicity suppressed** ($\sigma = 0$ if $m_e = 0$)

(0805.3423 [Bell, Dent, Jacques, Weiler])

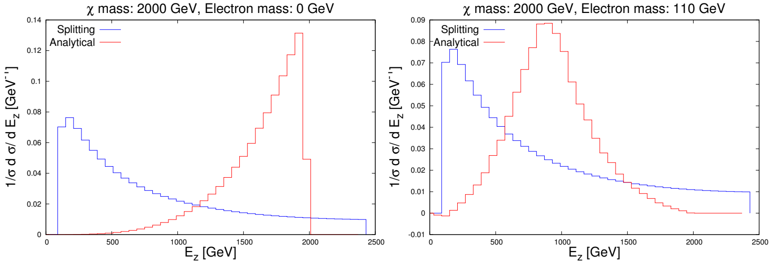
Z boson emission lifts the cross-section,
but for soft Z bosons the suppressed behaviour is recovered!

APPROXIMATION CANNOT WORK IN THIS CASE.

Comparison - what happens?

Massive fermions in the final state ⇒ no helicity suppression. . . BUT
fragmentation functions expected not to be a good approximation:
to switch off the helicity suppression $m_{fermion} \sim 50 - 100$ GeV.

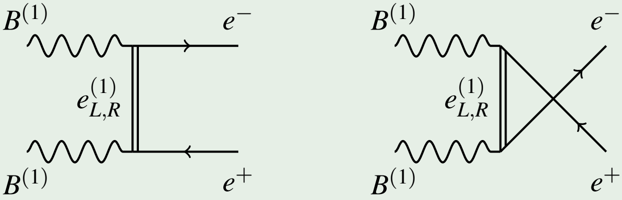
$P_{F \to F+V}$ describes the splitting of a **massless** fermion
whereas we have $m_{fermion} \sim m_{boson}$



Take home message

The fragmentation functions do not reproduce the amplitude for processes with Majorana fermions in the initial state!

Concrete case 2: KK photon annihilation - vector DM



Contributions to $B^{(1)}B^{(1)} \to e^+ \, e^-$

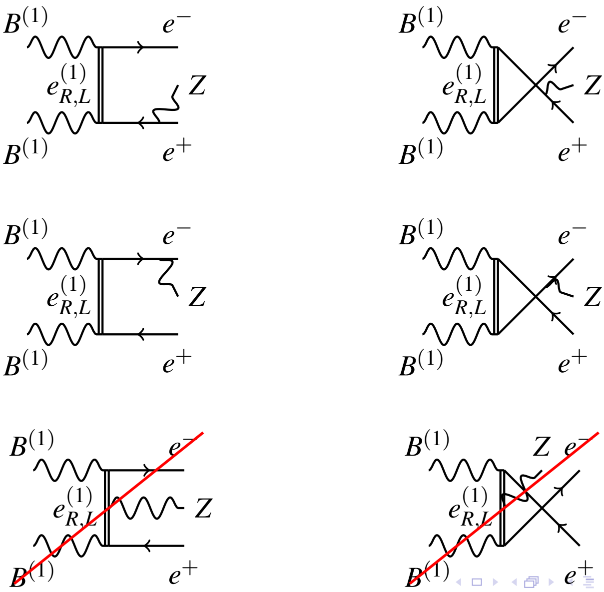
$$\sigma = \frac{\alpha^2\pi^2}{\cos^4\theta_w} \frac{\left(Y_L^4 + Y_R^4\right)}{72\pi s^2 \beta^2} \left(10\left(2M_{\rm DM}^2 + s\right) \operatorname{arctanh}(\beta) - 7s\beta\right)$$

Very simple model: $M_{B^{(1)}} = M_{e^{(1)}_{L,R}}$ and no mixing;

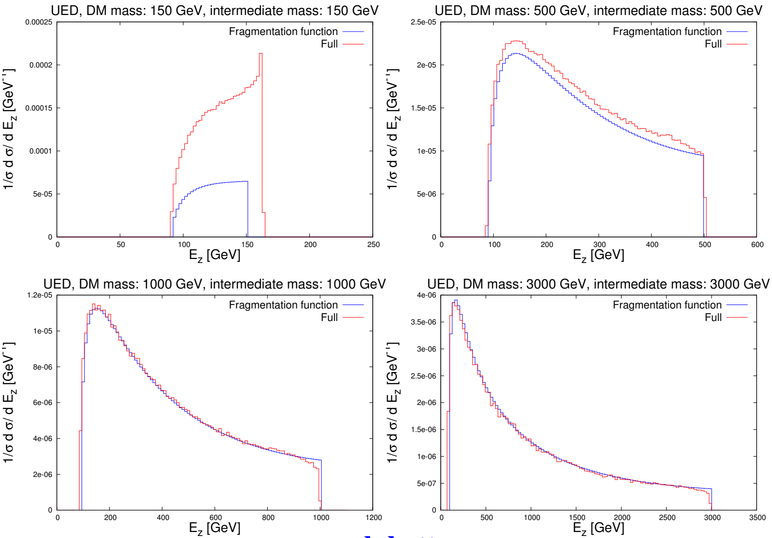
DM candidate is a **vector boson**;

No suppression mechanism, the approximation is expected to work.

Concrete case: $B^{(1)}\ B^{(1)} \to e^+\ e^-\ Z$



Comparison 2



…much better…

As expected the approximation improves with larger DM masses

$\Leftrightarrow$ the logs are more and more dominant.

Computation of the secondary flux

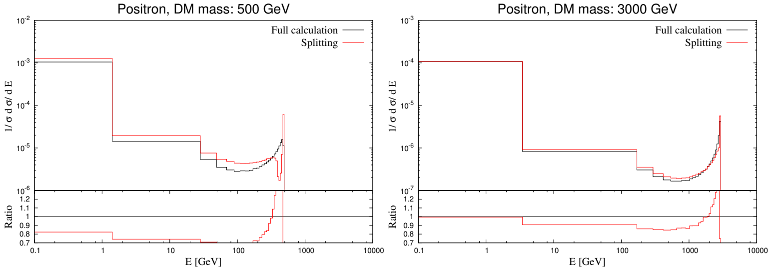
Steps to compute the flux of stable SM particles measured at Earth:

- **parton shower and hadronization with `Pythia` 8 $\Rightarrow$ stable SM particles flux at production point;**
- **choose DM profile and parametrization of astrophysical effects;**
- **Green function formalism to propagate e^+ and $\bar{p}$ through the Galaxy $\Rightarrow$ stable SM particles flux at detection point.**

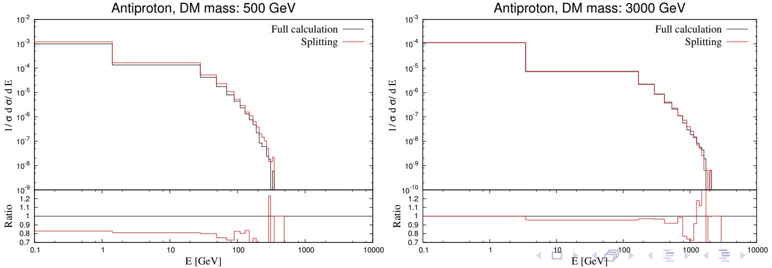
NASA

Results after `Pythia`

Positron before propagation:



Antiproton before propagation:



Propagation through the Galaxy

Positrons

$$\frac{d\Phi_{e^\pm}}{dE}(\epsilon, r_\odot) = \frac{1}{4\pi}\frac{v_{e^\pm}}{b_T(\epsilon)}\frac{1}{2}\left(\frac{\rho_\odot}{M_{DM}}\right)^2 \langle\sigma v\rangle \int_\epsilon^{M_{DM}} d\epsilon_s \frac{dN_{e^\pm}}{dE}(\epsilon_s)\mathcal{I}\left(\lambda_D(\epsilon, \epsilon_s)\right)$$

Antiprotons

$$\frac{d\Phi_{\bar{p}}}{dK}(\epsilon, r_\odot) = \frac{1}{2}\frac{v_p}{4\pi}\left(\frac{\rho_\odot}{M_{DM}}\right)^2 R(K)\langle\sigma v\rangle\frac{dN_{\bar{p}}}{dK}$$

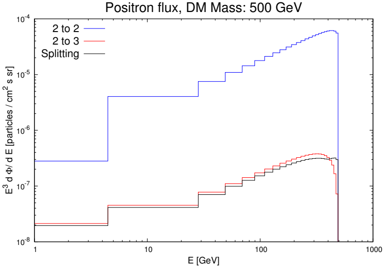
in both cases

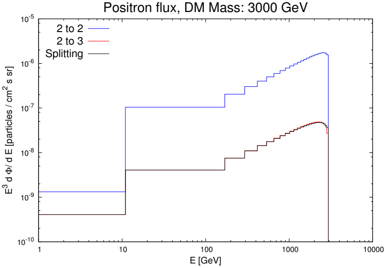
$$\frac{dN_{e^\pm,\bar{p}}}{dE} = \frac{1}{\langle\sigma v\rangle_{\text{DM DM}\to\text{I}}}\frac{d\langle\sigma v\rangle_{\text{DM DM}\to\text{I}} \times BR_{\text{I}\to e^\pm,\bar{p}}}{dE}$$

with ϵ the energy, $I = \{e^+, e^-, Z\}$ and $v_{e^\pm}$ is the velocity of the electron.

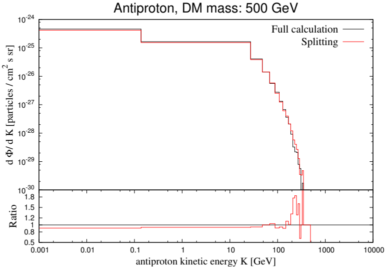
Results after propagation

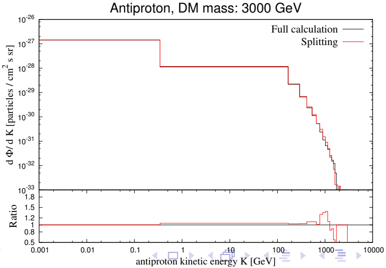
Positron after propagation:





Antiproton after propagation:





Conclusions and outlook

Conclusions

The splitting function approximation

- works well for models without helicity suppression;
- gives reliable results for spectra at the production point, with simpler calculations;
- gives reliable results for fluxes after evolution and propagation.

Next steps

- study the behaviour with non-degenerated masses;
- apply to "still-alive" models;
- compare to data to obtain limits on the cross-section.

Thank you!


WE'VE BEEN STUDYING MATTER FOR A COUPLE HUNDRED YEARS...
...AND WE HAVE A FINE UNDERSTANDING OF CHEMICALS, ETC...
AND ALL OF A SUDDEN WE DISCOVER THAT ALL THAT WORK WE'VE BEEN DOING,
IS ONLY ON A TINY FRACTION OF WHAT THE UNIVERSE IS MADE OUT OF!
IT'S LIKE YOU'VE BEEN STUDYING AN ELEPHANT'S TAIL FOR TWO HUNDRED YEARS AND YOU DISCOVER...
IT'S ONLY THE TAIL!
JORGE CHAM © 2011

Backup - Sudakov parametrization for massive bosons

Implementation of the splitting function approach:
Sudakov parametrisation

- Initial state: $S^\mu = (2E, 0, 0, 0)$, where $E = M_{\rm DM}/\sqrt{1-v_{\rm cm}^2}$;
- Momentum of the electron that radiates the Z boson

$$p_1 = \left(E\left(x + \frac{k_t^2}{4E^2 x}\right), -k_t, 0, E\left(x - \frac{k_t^2}{4E^2 x}\right)\right), \text{ with } k_t \ll 1, x = E_Z/\sqrt{s};$$

- Four-momentum of the emitted Z boson:

$$k_Z = \left(E\left((1-x) + \frac{k_t^2+m_Z^2}{4E^2(1-x)}\right), k_t, 0, E\left((1-x) - \frac{k_t^2+m_Z^2}{4E^2(1-x)}\right)\right).$$

- Four-momentum of the electron which does not radiate

$$p_2 = \left(E\left(1 - R(k_t,x)\right), 0, 0, -E\left(1 - R(k_t,x)\right)\right),$$

with $R(x,k_t) = \frac{k_t^2}{4E^2 x} + \frac{k_t^2+m_Z^2}{4E^2(1-x)}$.

Perfect conservation of four-momentum ensured.

Backup - Analytical calculation for $2 \to 3$ in UED

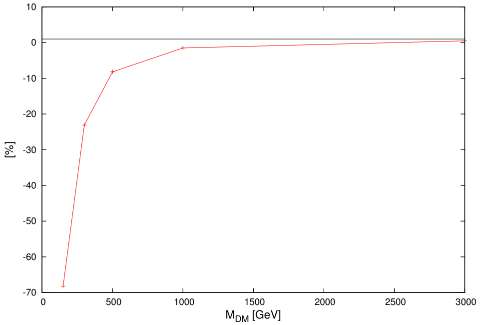
Differential cross-section integrated over angles: $v d\sigma = \frac{|\mathcal{M}|^2}{256\pi^3} dx_1 dx_2$,
x_1 and x_2 parametrise the phase space:
$k^0 = (1 - x_2)\sqrt{s}/2 \quad , p_1^0 = x_1\sqrt{s}/2 \quad , p_2^0 = (1 - x_1 + x_2)\sqrt{s}/2$,

Integration of the phase space for x_1: $x_- \leq x_1 \leq x_+$,
$x_\pm = \frac{1+x_2}{2} \pm \sqrt{\frac{(1-x_2)^2}{4} - \frac{m_Z^2}{s}}$, and for x_2: $\quad -\frac{m_Z^2}{s} \leq x_2 \leq 1 - 2\frac{m_Z}{\sqrt{s}}$.

Expansion in v, integration over x_1, terms vanishing for $m_Z \to 0$ neglected:
$\frac{d\langle\sigma v\rangle}{dx_2} = \frac{\alpha}{2304\, M_{\rm DM}^2 \pi^2} \frac{(1-2\sin^2\theta_w)^2}{\sin^2\theta_w \cos^2\theta_w} |g_L|^4 F(x_2)$, with $g_L = Y_L g_1$ and
$F(x_2) = \frac{1+x_2^2}{1-x_2^2} \log\left(\frac{\bar{x}_+}{\bar{x}_-}\right) + \frac{3(1-x_2)}{4(1+x_2)^2}\left(5 + 8x_2 + 5x_2^2\right) + \frac{(1+4x_2+9x_2^2+4x_2^3+x_2^4)}{(1+x_2)^3} \log(x_2)$,
$\bar{x}_\pm = 1 - x_2 \pm \sqrt{(1-x_2)^2 - m_Z^2/M_{\rm DM}^2}$.
Expanding Born cross section in v, only lowest order contribution:
$\langle\sigma v\rangle_{\rm Born} = \frac{|g_L|^4}{576 M_{\rm DM}^2 \pi}$.

We can recast it in the form: $\frac{d\langle\sigma v\rangle}{dx_2} = 2\langle\sigma v\rangle_{\rm Born} \frac{\alpha}{2\pi} \frac{g_f^2}{\sin^2\theta_w \cos^2\theta_w} F(x_2)$.

Backup - discrepancy



Mass [GeV]	$2 \to 2$ [pb]	$2 \to 3$ [pb]	splitting [pb]	discrepancy [%]
150	2.642	4.583×10^{-3}	1.459×10^{-3}	68.2
300	0.6604	2.078×10^{-3}	1.597×10^{-3}	23.1
500	0.2378	1.202×10^{-3}	1.104×10^{-3}	8.1
1000	5.944×10^{-2}	5.362×10^{-4}	5.282×10^{-4}	1.5
3000	6.605×10^{-3}	1.221×10^{-4}	1.227×10^{-4}	0.5

Table: $\langle \sigma v \rangle$ for the annihilation into electron and positron ($2 \to 2$) and with the radiation of a Z boson ($2 \to 3$) in UED with different set of masses for the KK resonances.