UNIVERSITY OF FERRARA

Master Degree Thesis in Physics (11/03/2011)

Signatures of a Fourth Lepton Family in Cosmic Rays

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Motivation

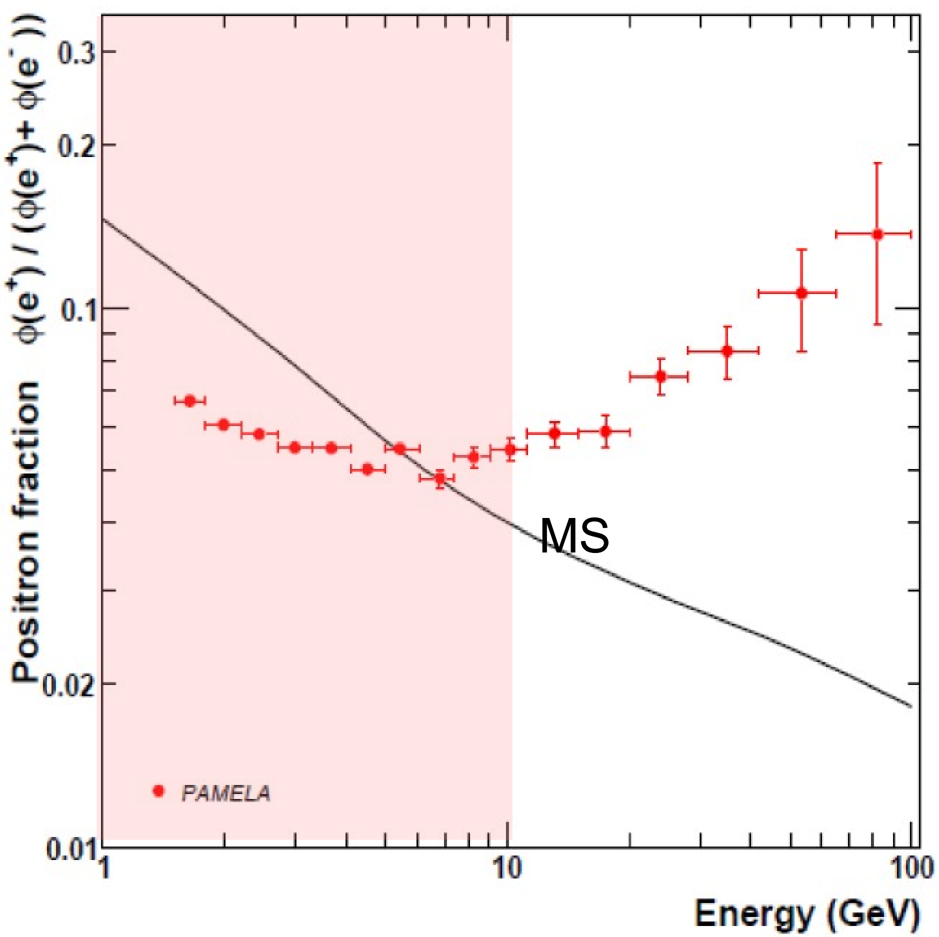
Recently PAMELA satellite (2006) and Fermi LAT telescope (2008) found a very interesting result:

an excess of e^+ and e^- in the CRs above 10GeV

we tried to explain this excess by making the exciting hypothesis that this excess is generated from the decay of a dark matter candidate: a TeV scale neutrino.

PAMELA and Fermi LAT Experiments

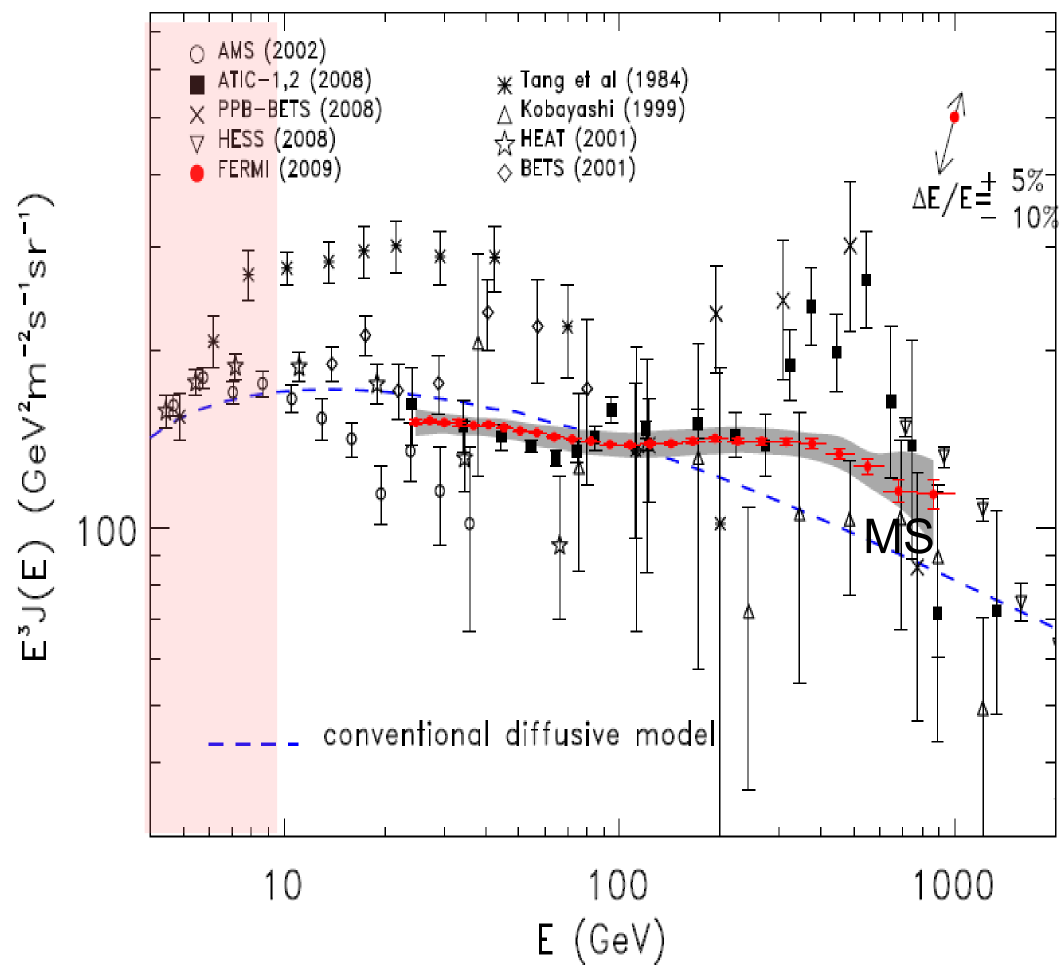
PAMELA



The solid line is the theoretical background model of Moskalenko & Strong (MS).

[O. Adriani et al. [PAMELA Collaboration], Nature 458 (2009) 607 [arXiv:0810.4995 [astro-ph]].]

Fermi LAT

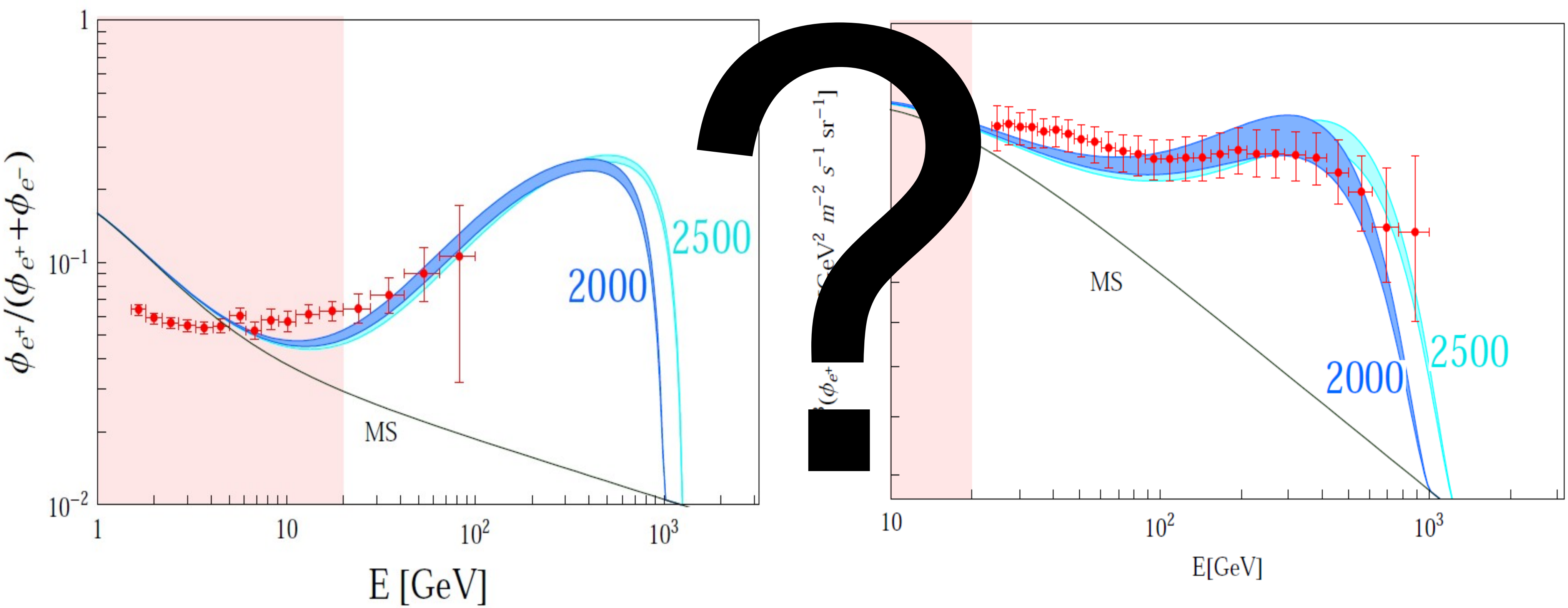


The dashed line is the theoretical background model of Moskalenko & Strong (MS).

[A. A. Abdo et al. [The Fermi LAT Collaboration], Phys. Rev. Lett. 102 (2009) 181101 [arXiv:0905.0025 [astro-ph.HE]].]

Are we able to find a dark matter candidate fitting PAMELA and Fermi LAT excesses?

PAMELA **Fermi**



Propagation of e^+ and e^- in our galaxy (1)

After being produced in the MilkyWay halo, e^+ and e^- propagate through the Galaxy and its diffusive halo before reaching the Earth.

This propagation is described by a transport equation.

$$0 = \frac{\partial}{\partial t} f_{e^\pm}(E, \boldsymbol{r}) = K(E)\,\nabla^2 f_{e^\pm}(E, \boldsymbol{r}) + \frac{\partial}{\partial E}\left[\, b(E)\, f_{e^\pm}(E, \boldsymbol{r}) \,\right] + Q_{e^\pm}(E, \boldsymbol{r})$$

where $f_{e^\pm}(E, \boldsymbol{r})$: number density of e^+ and e^- per unit energy

$b(E)$: rate of energy loss

$K(E)$: diffusion coefficient

$Q_{e^\pm}(E, \boldsymbol{r})$: source term

Propagation of e^+ and e^- in our galaxy (2)

If dark matter decays into e^+ and e^- at a sufficiently large rate, these could be observed as an anomalous contribution to the high energy cosmic ray fluxes.

Here the source term becomes

$$Q_{e^\pm}(E, \boldsymbol{r}) = \frac{\rho(\boldsymbol{r})}{m\,\tau}\,\frac{dN_{e^\pm}}{dE}$$

where $\rho(\boldsymbol{r})$: dark matter distribution density

τ : lifetime of dark matter particles

m : mass of dark matter particles

$\frac{dN}{dE}$: number of decays of dark matter particles per unit energy

Propagation of e$^+$ and e$^-$ in our galaxy (3)

The solution of the transport equation in the Solar System, can be formally expressed by the convolution

$$f_{e^\pm}(E) = \int_0^{E\mathrm{max} = m} dE' \, G_{e^\pm}(E, E') \, Q_{e^\pm}(E', \boldsymbol{r})$$

The flux of e$^+$ and e$^-$ in the Solar System from dark matter decay is given by

$$\phi_{e^\pm}(E) = \frac{c}{4\pi} f_{e^\pm}(E)$$

[see e.g., Y. Z. Fan, B. Zhang and J. Chang, e+ and e- Excesses in the Cosmic Ray Spectrum and Possible Interpretations, arXiv:1008.4646v1 [astro-ph.HE]]

A possible candidate for dark matter

Fourth Lepton Family (1)

We add a 4th-family of leptons for which we introduce the ζ flavor

$$L_\zeta = \begin{pmatrix} \nu_\zeta \\ \zeta \end{pmatrix}_L , \qquad \zeta_R , \qquad \nu_{\zeta R}$$

with quantum numbers *SU(2)xU(1)* given by

$$L_\zeta = (2, -1/2), \qquad \zeta_R = (1, -1), \qquad \nu_{\zeta_R} = (1, 0) .$$

We keep our scenario as general as possible, but we stress that it would arise naturally in Minimal Walking Technicolor models.

[M. T. Frandsen, I. Masina and F. Sannino, Fourth lepton family is natural in technicolor, Physical Review D 81-035010, arXiv:0905.1331v1]

Fourth Lepton Family (3)

We consider the possibility that these new neutral leptons mix with one SM neutrino of flavor ℓ, (ν_ℓ).

$$\mathcal{L}^{\rm mix}_{\ell\zeta} = -\frac{1}{2}\left(\overline{\nu_{\ell L}} \quad \overline{\nu_{\zeta L}} \quad \overline{(\nu_{\zeta R})^c} \right) \begin{pmatrix} 0 & 0 & m' \\ 0 & 0 & m_D \\ m' & m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_{\ell L})^c \\ (\nu_{\zeta L})^c \\ \nu_{\zeta R} \end{pmatrix} + h.c$$

interaction eigenstates:

$$\begin{pmatrix} \nu_{\ell_L} \\ \nu_{\zeta_L} \\ (\nu_{\zeta_R})^c \end{pmatrix} = \begin{pmatrix} c' & ics' & ss' \\ -s' & icc' & sc' \\ 0 & -is & c \end{pmatrix} \begin{pmatrix} \eta'_{0L} \\ \eta'_{1L} \\ \eta'_{2L} \end{pmatrix}$$

mass :eigenstates

with $s = \sin\theta, c = \cos\theta, s' = \sin\theta', c' = \cos\theta'$ and $\tan\theta' = \frac{m'}{m_D}$, $\tan 2\theta = \frac{2m_D}{m_R}$

we expect that $\theta' \ll 1$ and $\theta \sim O(1)$

Fourth Lepton Family (4)

We assume that η'_1 , η'_2 and $\zeta^\pm$ are produced in the BigBang and that η'_2 and $\zeta^\pm$ are heavy enough in comparison to η'_1 , so that they have already decayed into η'_1 via E.W. interaction.

Thus, the remaining heavy lepton η'_1 constitutes (at least part of) dark matter.

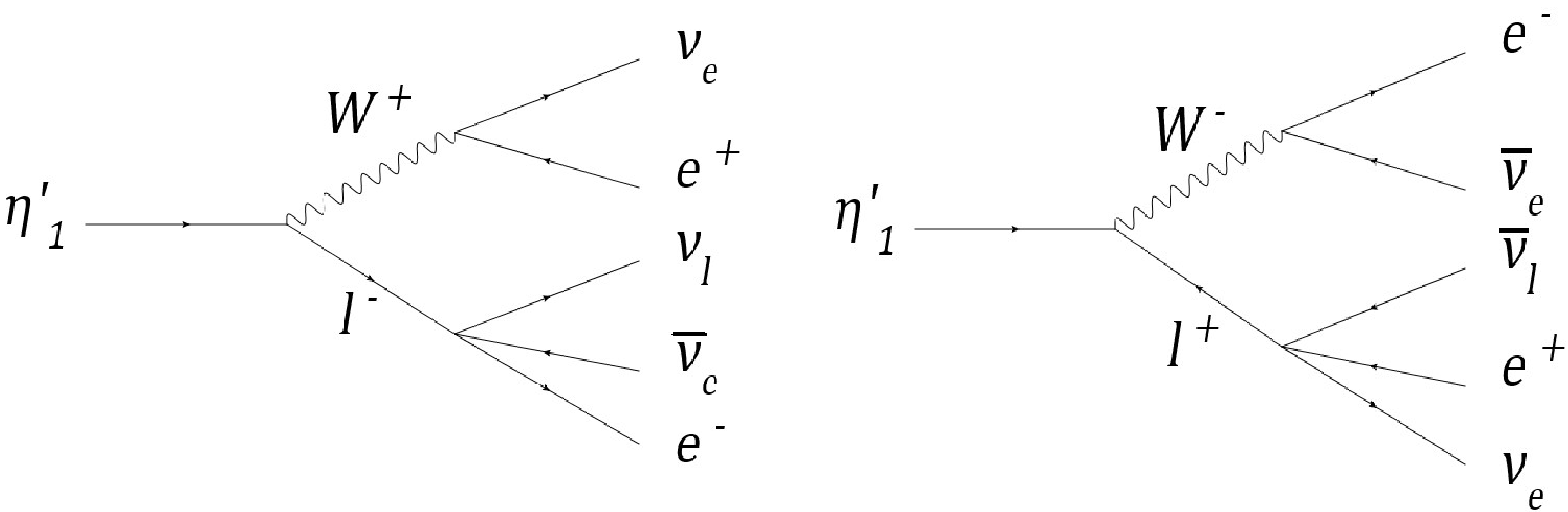
[see e.g., W. Keung and P. Schwaller, Long Lived Fourth Generation and the Higgs, arXiv:1103.3765v2 [hep-ph]]

The charged current vertex $V_{\ell W \eta_1'}$ is

$$V^{CC}_{\ell W \eta'_1} = \frac{ig\cos\theta\sin\theta'}{\sqrt{2}} W^-_\mu \, \overline{\ell}_L \, \gamma^\mu \, \eta'_{1L} + h.c$$

Decay processes of interest (1)

Our goal is to calculate the number of e+ and e- per unit energy, indicated by *dN/dE* , in the decay chains:

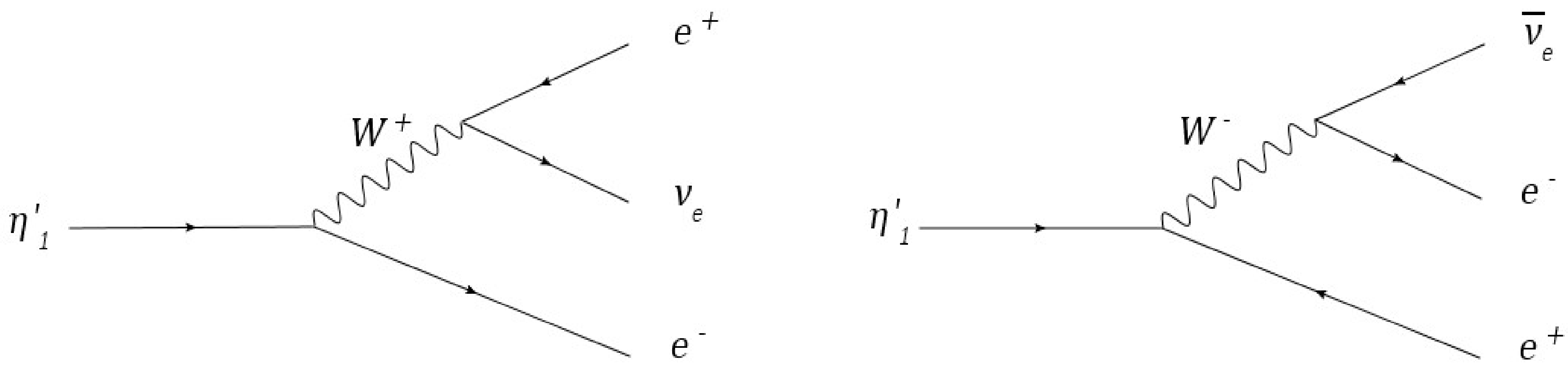


Note that *dN/dE* of a process is always equal to the one of its charge conjugated process.

Studying the first decay we get: $E_\ell \simeq \frac{m_{\eta'_1}}{2}, \qquad E_W \simeq \frac{m_{\eta'_1}}{2}$

Decay processes of interest (2)

- 1° Decay chain: direct *e* and *W* decays



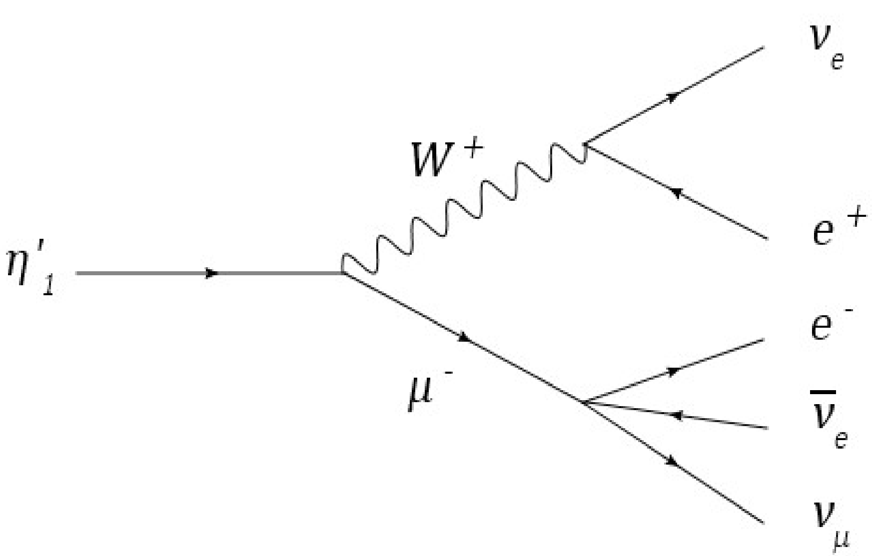
The total number of final e^+ (or e^-) is

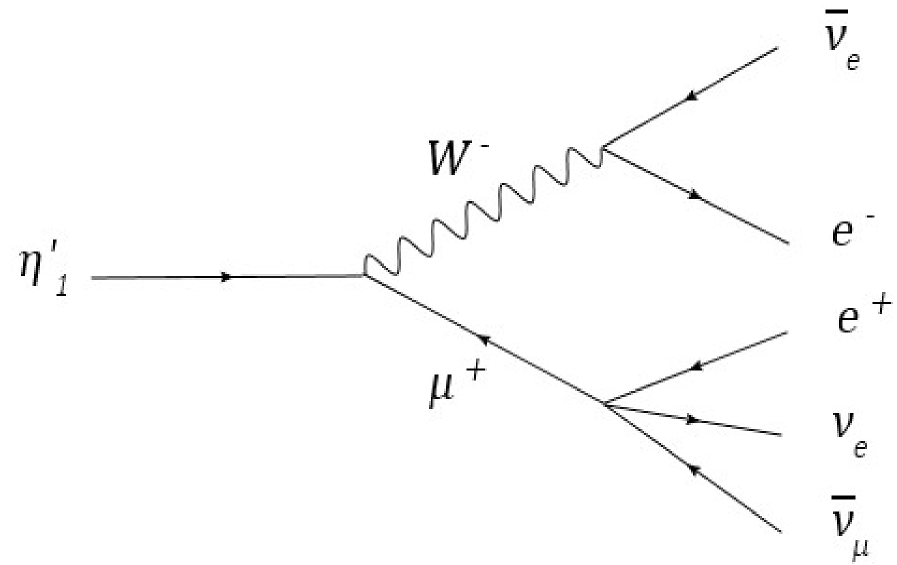
$$\frac{dN^{tot}}{dE_e} = \frac{dN^{(\eta')}}{dE_e} + \frac{dN^{(W)}}{dE_e} = \delta\left(E_e - \widetilde{E}_e\right) + \frac{BR_W(e\nu_e)}{m_{\eta'_1}/2}$$

where $$\widetilde{E}_e = \frac{m_{\eta'_1}}{2}\left(1 - \frac{M_W^2}{m_{\eta'_1}^2}\right)$$

Decay processes of interest (3)

- 2° Decay chain: *W* and *μ* decays



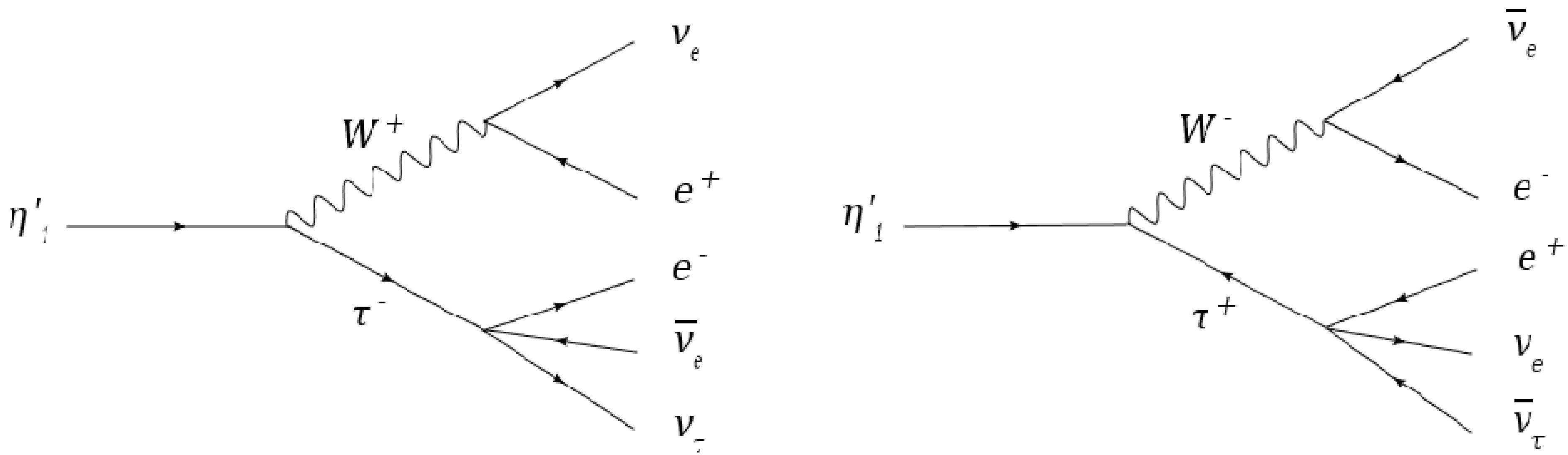


The total number of final e^+ (or e^-) is

$$\frac{dN^{tot}}{dE_e} = \frac{dN^{(\mu)}}{dE_e} + \frac{dN^{(W)}}{dE_e} = \frac{BR_\mu(e\nu_e\nu_\mu)}{3E_e}\left(5 - 9\frac{E_e^2}{E_\mu^2} + 4\frac{E_e^3}{E_\mu^3}\right) + \frac{BR_W(e\nu_e)}{m_{\eta'_1}/2}$$

Decay processes of interest (4)

- 3° Decay chain: W and τ decays



The total number of final e^+ (or e^-) is

$$\frac{dN^{tot}}{dE_e} = \frac{dN^{(\tau)}}{dE_e} + \frac{dN^{(W)}}{dE_e} = \frac{BR_\tau(e\nu_e\nu_\tau)}{3E_e}\left(5 - 9\frac{E_e^2}{E_\tau^2} + 4\frac{E_e^3}{E_\tau^3}\right) + \frac{BR_W(e\nu_e)}{m_{\eta_1'}/2}$$

Flux of e^+ (or e^-) produced by dN/dE (1)

To obtain the flux of e^+ (or e^-) is first necessary to find $f_{e^\pm}(E)$ which, for a decay chain, is given by

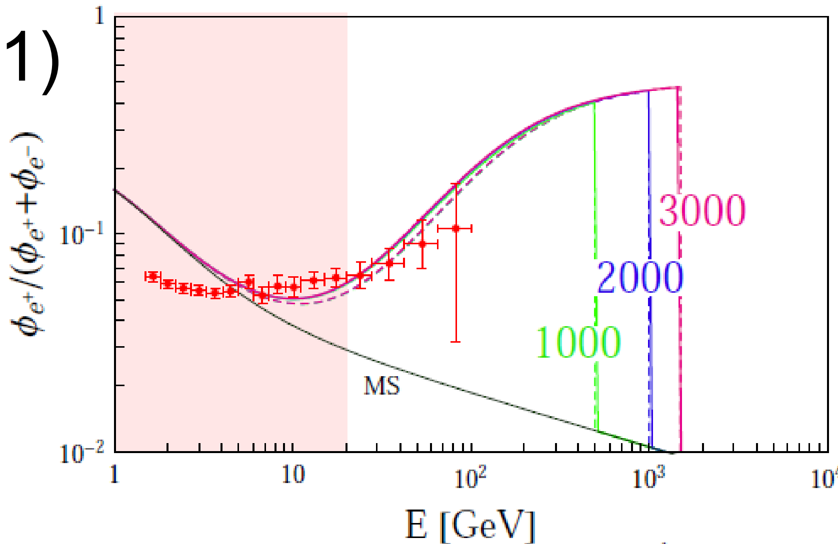
$$f_{e^\pm}(E) = \frac{\rho(r)}{m\tau} \int_0^{Emax} dE' \, G_{e^\pm}(E,E') \sum_i \frac{dN^i_{e^\pm}(E')}{dE'}$$

Below we display the fluxes of e^+ (or e^-) produced by the decay chains combined with known astrophysical sources Moskalenko-Strong (computation made by my tutor).

Our results-PAMELA data

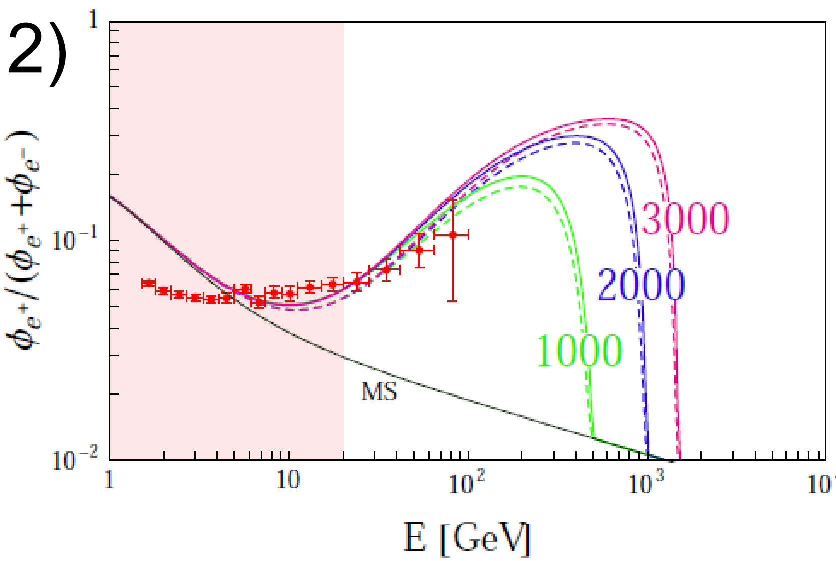
cs′ fitted to
25 GeV bin

1)

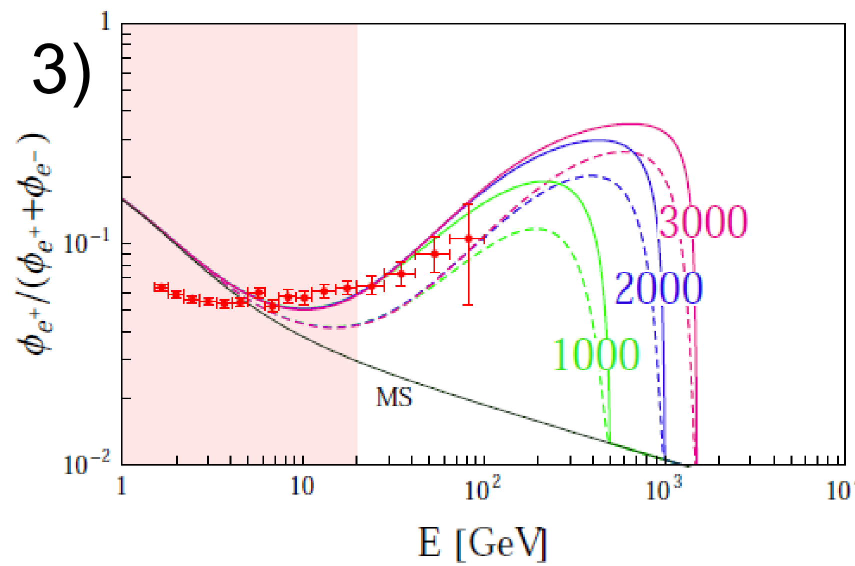


direct *e* and *W* decays

2)



3)



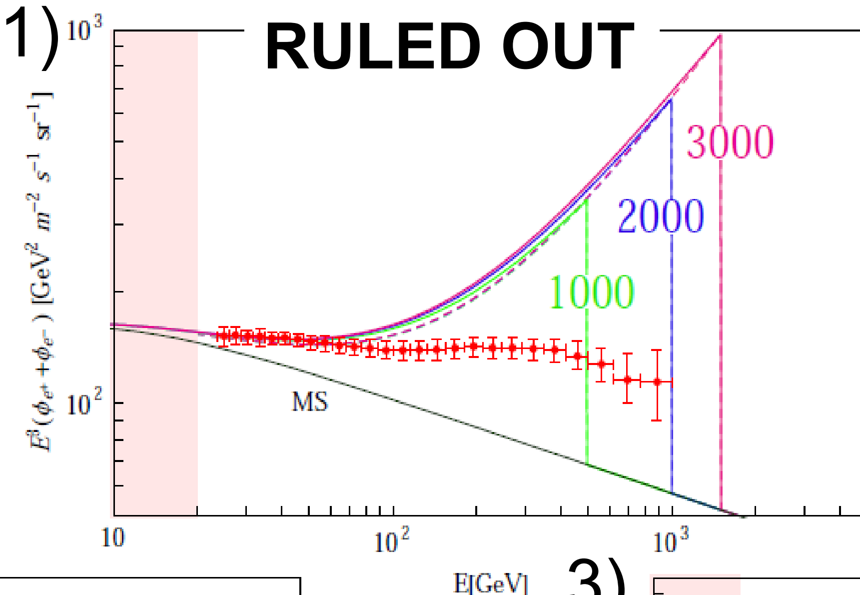
μ and *W* decays

τ and *W* decays

Our results-Fermi LAT data

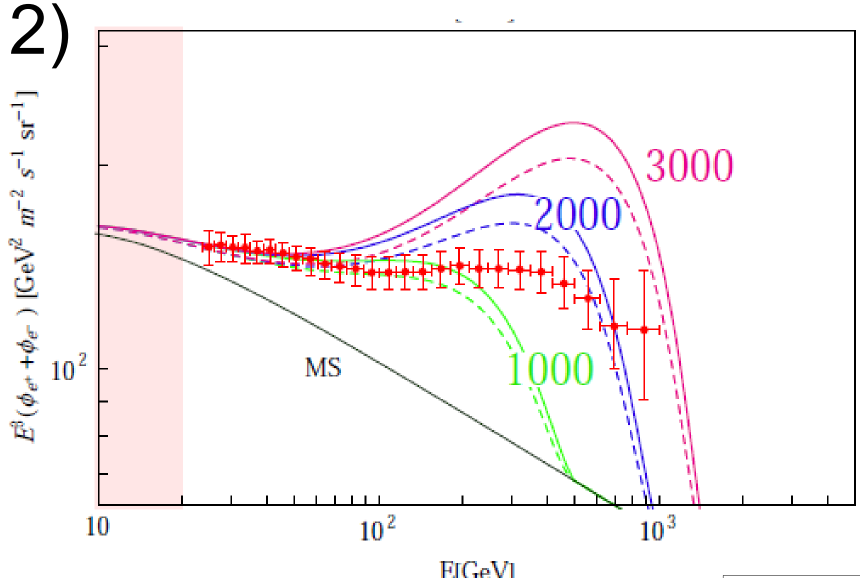
cs' as before

1)

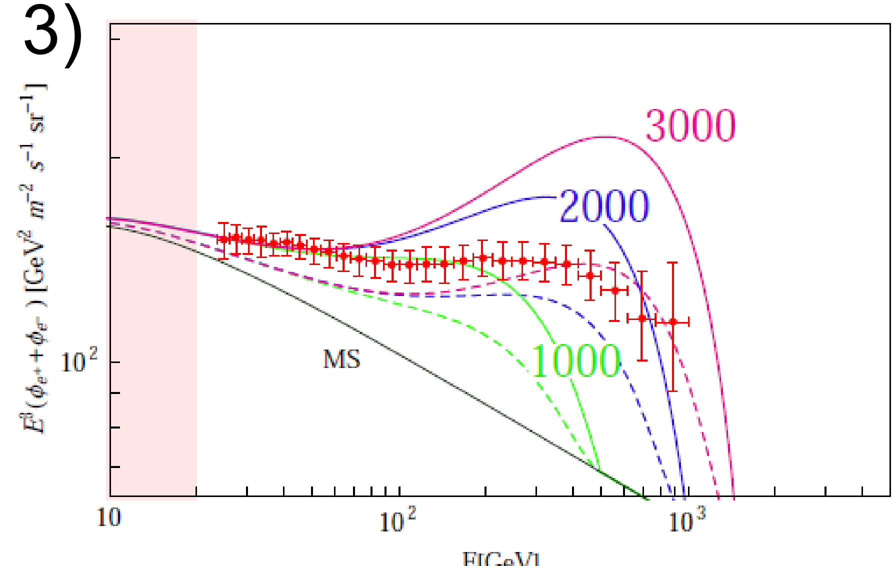


direct *e* and *W* decay

2)



3)

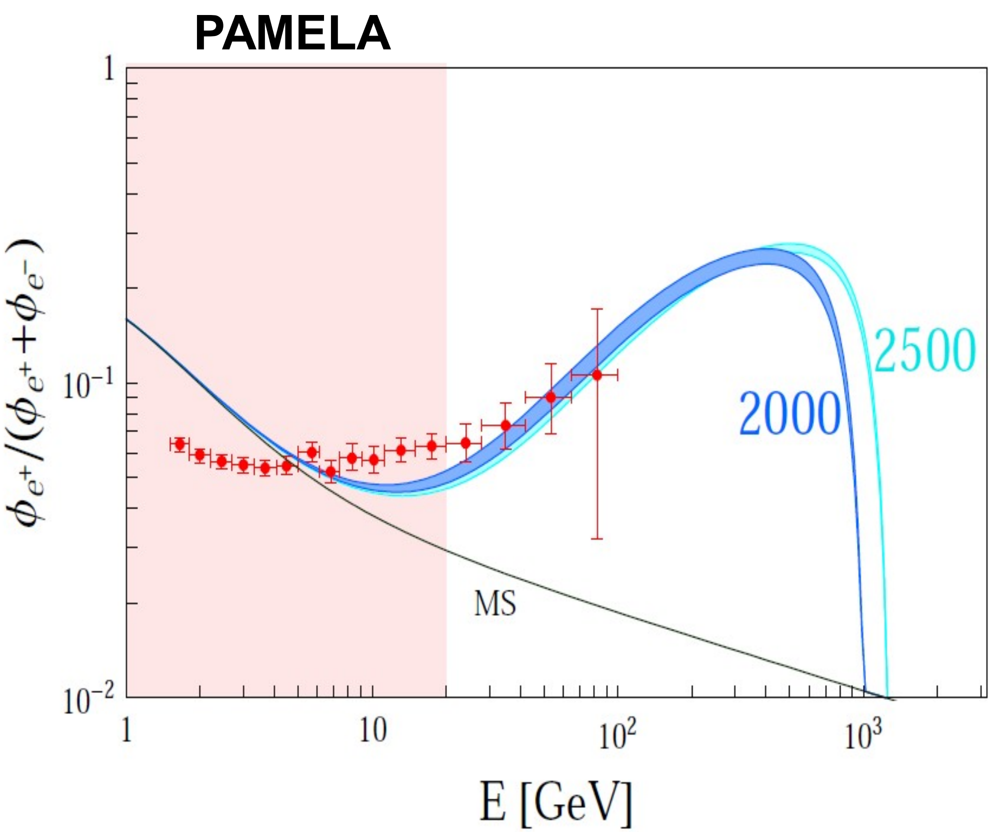


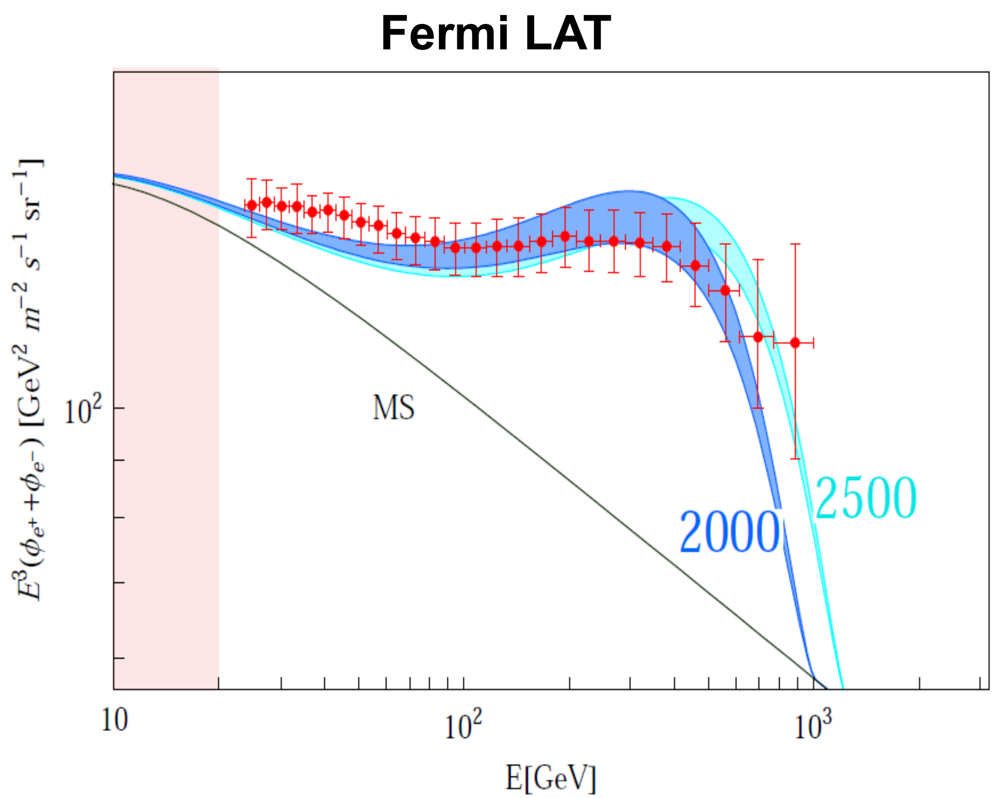
μ and *W* decays

$m_{\eta'1} \sim$ 2000 GeV

τ and *W* decays

Our best fit for μ and W decays





$m_{\eta'1} = 2000\ GeV,\ 10^{-27.15} \leq \cos\theta \sin\theta' \leq 10^{-27.10}$

$m_{\eta'1} = 2500\ GeV,\ 10^{-27.27} \leq \cos\theta \sin\theta' \leq 10^{-27.24}$

$m_{\eta'1} = 2000\ GeV,\ 10^{-27.15} \leq \cos\theta \sin\theta' \leq 10^{-27.10}$

$m_{\eta'1} = 2500\ GeV,\ 10^{-27.27} \leq \cos\theta \sin\theta' \leq 10^{-27.24}$

We analitically confirmed the numerical result of Ibarra, Tran and Weniger.

[A. Ibarra, D. Tran and C. Weniger, arXiv:0906.1571v3[Hep-ph]]

Conclusions

A) The decay chains in better agreement with experimental data are

1. $\eta'_1 \to W^-\mu^+$ with $W^- \to e^-\overline{\nu}_e$ and $\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$
2. $\eta'_1 \to W^-\tau^+$ with $W^- \to e^-\overline{\nu}_e$ and $\tau^+ \to \overline{\nu}_\tau e^+ \nu_e$

and their corresponding charge conjugated processes.

B) To fit our results with the experimental data, we found information about the mass $m_{\eta'1}$, the couplings $\sin\theta' \cos\theta$ of μ and τ and the hierarchy of interaction: $cs'_e \ll cs'_{\mu,\tau} \sim O(10^{-27})$

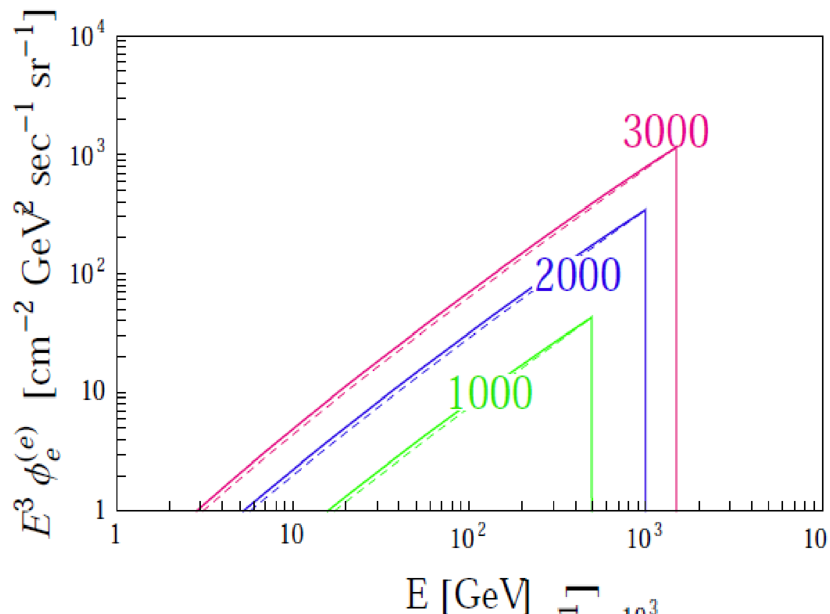
C) We stress that our achievement could be confirmed or rejected by AMS-02 experiment, which will investigate the fluxes of e^- and e^+ at higher energies and with greater sensitivity than the experiments made so far.

THE END

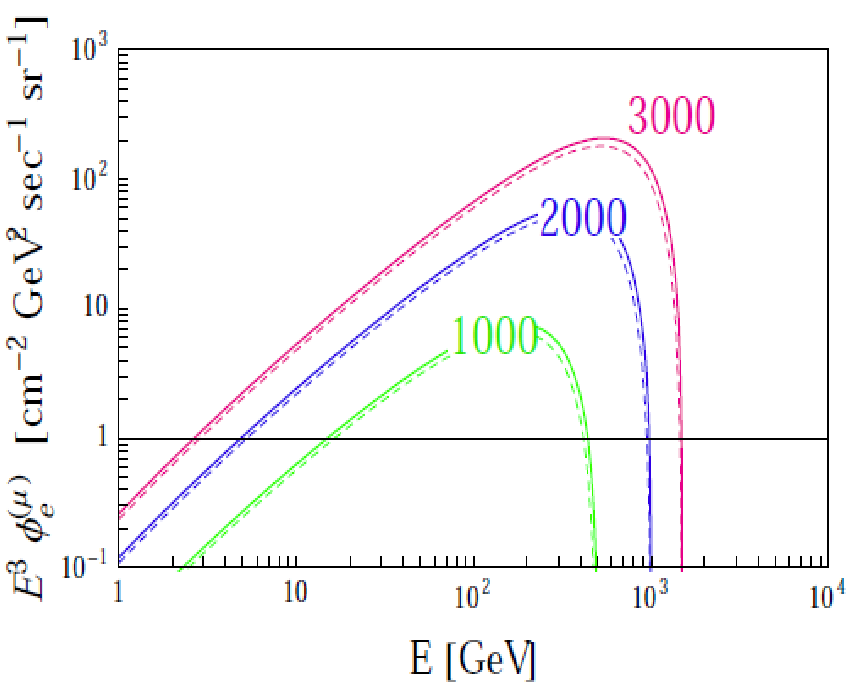
Thanks

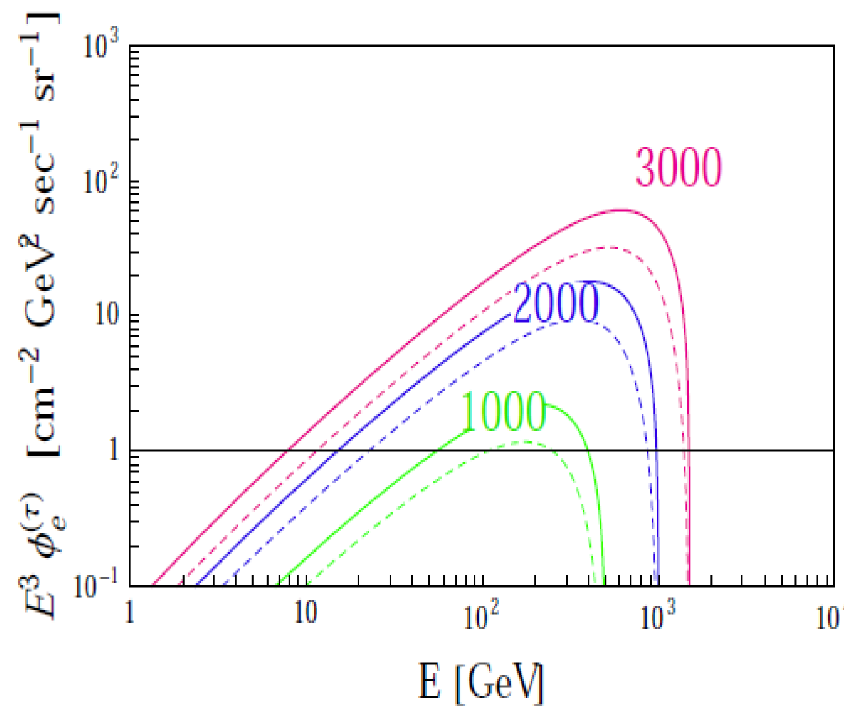
Flux of total e^+ (or e^-) multiplied by E^3

cancellata



cs' = 10^{-25}





Decay processes of interest (2) cancellare

- Decay of ℓ with: $\ell = \mu$

  we have the decays: $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$, $\mu^- \to e^- \overline{\nu}_e \nu_\mu$

$$\frac{dN^{(\mu)}}{dE_e} = \frac{BR_\mu(e\nu_e\nu_\mu)}{3E_e}\left(5 - 9\frac{E_e^2}{E_\mu^2} + 4\frac{E_e^3}{E_\mu^3}\right)$$

- Decay of ℓ with: $\ell = \tau$

  we have the decays: $\tau^+ \to e^+ \nu_e \overline{\nu}_\tau$, $\tau^- \to e^- \overline{\nu}_e \nu_\tau$

$$\frac{dN^{(\tau)}}{dE_e} = \frac{BR_\tau(e\nu_e\nu_\tau)}{3E_e}\left(5 - 9\frac{E_e^2}{E_\tau^2} + 4\frac{E_e^3}{E_\tau^3}\right)$$

Decay Channel	$BR=\Gamma_{channel}/\Gamma_{tot}$
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	0.9860
$\tau^+ \to e^+ \nu_e \overline{\nu}_\tau$	0.1735

Decay processes of interest (3 cancellare)

- Decay of *W*

we have the decays: $W^+ \to e^+ \nu_e\,,\qquad W^- \to e^- \overline{\nu}_e$

The energy spectrum of outgoing electrons and positrons is flat. In fact, we get

$$\frac{dN^{(W)}}{dE_e} = \frac{BR_W(e\nu_e)}{m_{\eta_1'}/2}$$

with $BR_W(e\nu_e) = 0.1079$, $E_{e\,min} \leq E_e \leq E_{e\,max}$

and $E_{e\,min} = \dfrac{E_W - p_W}{2}\,,\qquad E_{e\,max} = \dfrac{E_W + p_W}{2}.$

Fourth Lepton Family (2) CANCELLARE

The ζ-charged lepton, $\zeta = \zeta_L + \zeta_R$, have a Dirac mass term while ν-neutral Weyl fermions $\nu_{\zeta L}$, $\nu_{\zeta R}$ have a Majorana-Dirac mass term:

$$\mathcal{L}_\zeta^{\rm mass} = -m_\zeta \, \overline{\zeta_L} \, \zeta_R - \frac{1}{2} \begin{pmatrix} \overline{\nu_{\zeta L}} & \overline{(\nu_{\zeta R})^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} (\nu_{\zeta L})^c \\ \nu_{\zeta R} \end{pmatrix} + h.c$$

The mass eigenstates of φ and ω corrispond to two Majorana neutrinos, called η'_1 and η'_2. We expect that these masses are large enough (TeV-scale) to avoid conflict with the experimental limits.

The ζ-neutrino interaction eigenstates will be an admixture of the two Majorana eigenstates η'_1 and η'_2

$$\begin{pmatrix} \nu_{\zeta L} \\ (\nu_{\zeta R})^c \end{pmatrix} = \begin{pmatrix} i\cos\theta & \sin\theta \\ -i\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \eta'_{1L} \\ \eta'_{2L} \end{pmatrix}$$

with

$$\tan 2\theta = \frac{2m_D}{m_R - m_L}$$