Inert Dark Matter in Type-II Seesaw

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collaborated with

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Two issues requiring beyond the Standard Model

- Astronomical evidence of dark matter
  - Unknown massive components in our Universe
  - Weakly Interacting Massive Particle (WIMP) is a candidate
  - How can we detect it?
- Neutrino mass
  - Non-zero but small masses
  - What is the origin of the masses?
  - What is the mass pattern of neutrinos?

It is interesting to construct a model accommodating these issues

The combination of Inert Higgs doublet and Type-II seesaw

★ Dark matter candidate from Inert Higgs Doublet

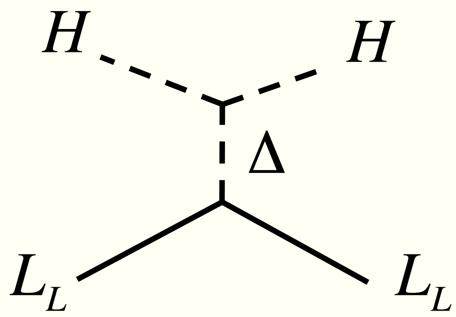
E. Ma, N.G. Deshpande (1977)

➡ Inert doublet : Z_2 odd new Higgs doublet

The lightest neutral component can be Dark Matter

★ Type-II seesaw

W.Konetschny, W.Kummer (1977)
T. P. Chen, L. F. Li (1980)
J. Schechter, J. W. F. Valle (1980)



❖Introduce triplet Higgs Δ

➡ ❖Triplet Higgs couple lepton doublet

❖Mass is generated through VEV of triplet

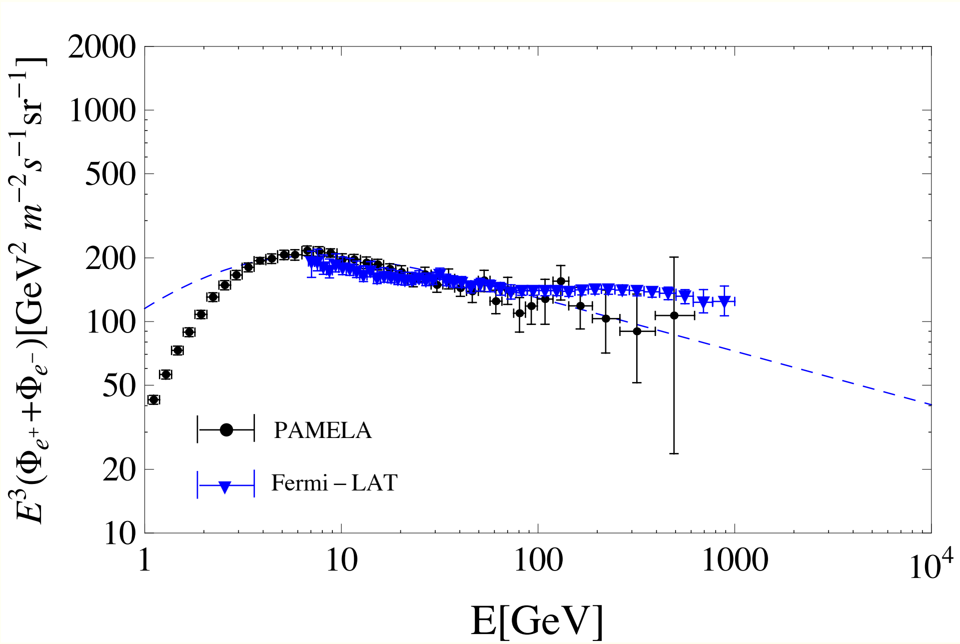
❖Accommodating DM and neutrino mass

❖New interactions appear from the combination

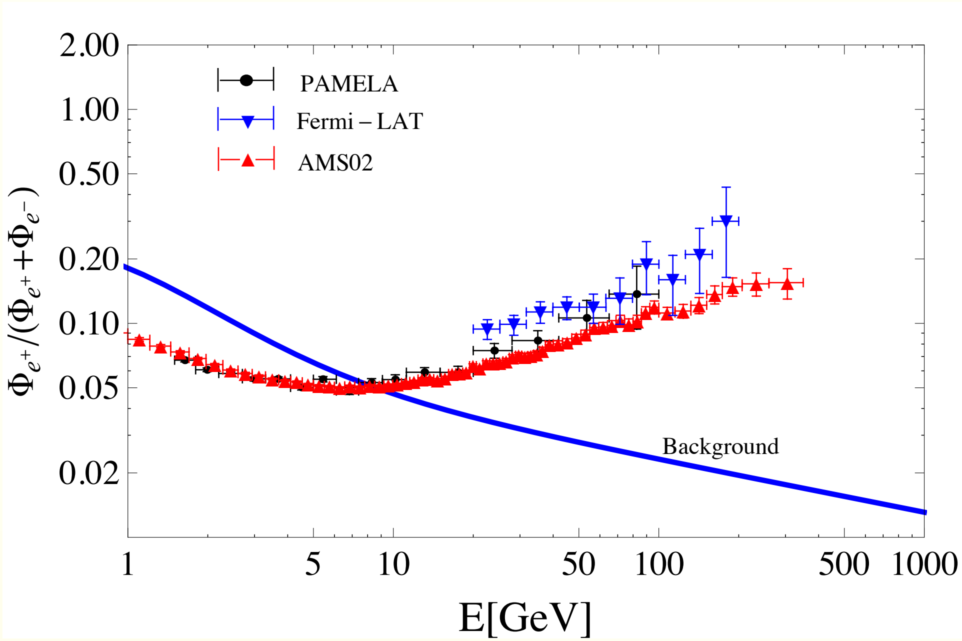
The benefit of the new interactions

- ❖Triplet Higgs boson couple to leptons but not to quarks
- ❖New interaction would explain the excess of positron flux

$$DM\ DM \rightarrow \Delta\ \Delta \rightarrow \ell\ell\ell\ell$$



PAMELA (2011) Fermi-LAT(2010)



AMS-02 (2013) PAMELA (2009) Fermi-LAT(2012)

The structure of our model

❖Symmetry ➡ $G_{SM} \times Z_2$

❖New particles [SU(2)(U(1)$_Y$)]

$\Phi : 2(1)$ *Inert Higgs doublet

$\Delta : 3(2)$ *Higgs triplet

$$\Phi = \begin{pmatrix} H^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ (v_\Delta + \delta^0 + i\eta^0)/\sqrt{2} & -\delta^+/\sqrt{2} \end{pmatrix}$$

❖New Lagrangian

$$\mathcal{L}_{NP} = (D_\mu\Phi)^\dagger D^\mu\Phi + (D_\mu\Delta)^\dagger D^\mu\Delta - \left[\frac{1}{2}L^T C(\mathbf{y} + \mathbf{y}^\mathbf{T}) i\sigma_2 \Delta P_L L + h.c.\right] - V(H,\Phi,\Delta)$$

$$\begin{aligned} V(H,\Phi,\Delta) &= \mu^2 H^\dagger H + \lambda_1 (H^\dagger H)^2 + m_\Phi^2 \Phi^\dagger\Phi + \lambda_2(\Phi^\dagger\Phi)^2 + \lambda_3 H^\dagger H \Phi^\dagger\Phi + \lambda_4 H^\dagger\Phi\Phi^\dagger H \\ &+ \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + h.c.\right] + m_\Delta^2 Tr\Delta^\dagger\Delta + \mu_1\left(H^T i\tau_2\Delta^\dagger H + h.c.\right) + \mu_2\left(\Phi^T i\tau_2 \Delta^\dagger\Phi\right) \\ &+ \lambda_6 H^\dagger H Tr\Delta^\dagger\Delta + \bar\lambda_6 \Phi^\dagger\Phi Tr\Delta^\dagger\Delta + \lambda_7 H^\dagger\Delta\Delta^\dagger H + \bar\lambda_7\Phi^\dagger\Delta\Delta^\dagger\Phi + \lambda_8 H^\dagger\Delta^\dagger\Delta H \\ &+ \bar\lambda_8\Phi^\dagger\Delta^\dagger\Delta\Phi + \lambda_9(Tr\Delta^\dagger\Delta)^2 + \lambda_{10} Tr(\Delta^\dagger\Delta)^2 . \end{aligned} \quad (17)$$

The structure of our model

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DM candidate

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SSB and mass of new particles

❖VEVs

$$< V > (v_0, v_\Delta) = \frac{\mu^2}{2} v_0^2 + \frac{\lambda_1}{4} v_0^2 + \frac{m_\Delta^2}{2} v_\Delta^2 + \frac{\lambda_6 + \lambda_7}{4} v_0^2 v_\Delta^2 + \frac{\lambda_9 + \lambda_{10}}{4} v_\Delta^4 - \frac{\mu_1}{\sqrt{2}} v_0^2 v_\Delta$$

➡

$$v_0 \approx \sqrt{\frac{-\mu^2}{\lambda_1}} \qquad v_\Delta \approx \frac{\mu_1 v_0^2}{\sqrt{2}(m_\Delta^2 + (\lambda_6 + \lambda_7) v_0^2 / 2)}$$

❖Masses of scalar bosons

$$m_S^2 = m_\Phi^2 + \lambda_L v_0^2 \qquad m_A^2 = m_S^2 - \lambda_5 v_0^2 \qquad m_{H^\pm}^2 = m_\Phi^2 + \lambda_3 v_0^2 / 2$$

$$m_{\delta^0}^2 \approx m_{\eta^0}^2 \approx m_\Delta^2 + \frac{\lambda_6 + \lambda_7}{2} v_0^2$$

$$\left(v_\Delta << v_0 \right)$$

$$m_{\delta^{++}}^2 \approx m_\Delta^2 + \frac{\lambda_6 + \lambda_8}{2} v_0^2 \qquad m_{\delta^+}^2 \approx \frac{1}{2}(m_{\delta^{++}}^2 + m_{\delta^0}^2)$$

Some constraints for triplet Higgs

❖ρ parameter

$$\rho \approx \frac{1+\frac{2v_\Delta^2}{v_H^2}}{1+\frac{4v_\Delta^2}{v_H^2}}$$

Current measurement $\rho = 1.0004^{+0.0003}_{-0.0004}$

(PDG 2012)

➡ $v_\Delta < 3.4\,GeV$

❖Experimental search for doubly charged Higgs

Doubly charged Higgs decays into

- ➢Two same sign leptons $v_\Delta << 10^{-4}\,GeV$
- ➢Two same sign W bosons $v_\Delta >> 10^{-4}\,GeV$

Mass bound from leptonic decay mode

➢Mass limits $m_{H\pm\pm}$ > 400 GeV for some benchmark points in HTM

CMS and ATLAS (2012)

Yukawa coupling and neutrino masses

❖Yukawa couplings

$$-L_Y = \frac{1}{2} h_{ij} \nu_i^T C P_L \nu_j \frac{v_\Delta + \delta^0 + i\eta^0}{\sqrt{2}} - h_{ij} \nu_i^T C P_L l_j \frac{\delta^+}{\sqrt{2}} - \frac{1}{2} h_{ij} l_i^T C P_L l_j + h.c.$$

❖Neutrino mass matrix

$$m_\nu^{ij} = v_\Delta h^{ij} / \sqrt{2} \quad \Rightarrow \quad h = \frac{\sqrt{2}}{v_\Delta} U^*_{PMNS} m_\nu^{diagonal} (U^*_{PMNS})^T$$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times {\rm diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$$

❖Small triplet VEV give small neutrino masses

❖The Yukawa coupling is restricted by neutrino experimental data

Pattern of neutrino mass spectrum

We consider three possible neutrino mass pattern

(1)Normal ordering (NO)

$$m_1 < m_2 < m_3 \qquad m_{2(3)} = \sqrt{m_1^2 + \Delta m_{21(31)}^2}$$

(2)Inverted ordering (IO)

$$m_3 < m_1 < m_2 \qquad m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}$$

(3)Quasi-degeneracy (QD)

$$m_1 \approx m_2 \approx m_3 \qquad m_\nu > 0.1eV$$

❖The leptonic decay branching ratio of δs depends on the pattern

Pattern of neutrino mass spectrum

The leptonic branching fraction of triplet Higgs bosons

Branching fraction of doubly charged Higgs [singly charged Higgs]

	$\ell_e\ell_e$	$\ell_e\ell_\mu$	$\ell_e\ell_\tau$	$\ell_\mu\ell_\mu$	$\ell_\mu\ell_\tau$	$\ell_\tau\ell_\tau$
NO	0.01 [0.02]	0.1 [0.06]	0[0]	0.3 [0.39]	0.29 [0.18]	0.28 [0.35]
IO	0.17 [0.23]	0.08 [0.06]	0.2 [0.14]	0.08 [0.11]	0.26 [0.17]	0.21[0.29]
QDI	0.39 [0.40]	0 [0]	0 [0]	0.29 [0.29]	0.02 [0]	0.30 [0.31]
QDII	0.21[0.28]	0.13[0.09]	0.24[0.16]	0.15[0.20]	0.13[0.09]	0.13[0.18]

*QDII is quasi-degeneracy case with non-zero Majorana phase

The branching fractions depends on neutrino mass pattern

Giving different spectrum of electron/positron flux

Numerical Analysis

❖The numerical calculation of relic density and cosmic-ray flux

➡ We apply micrOMEGAs package

(G. Belanger, F. Boudjema, A. Pukhov and A. Semenov)

- Positron and anti-proton flux from DM annihilation is calculated
- Navarro-Frenk-White (NFW) galactic halo DM density profile is used
- Propagation of charged particle and solar modulation effect

❖For cosmic-ray background we apply fitted functions

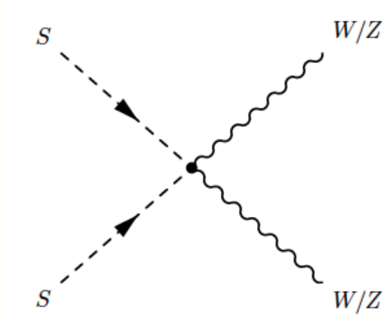
❖We apply boost factor (BF) in explaining positron excess

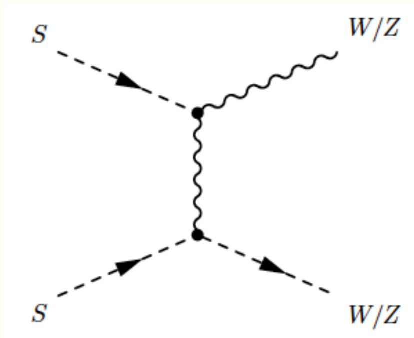
$$< \sigma v >_{boosted} = BF < \sigma v >_{original}$$

We also explore the constraint on BF from anti-proton flux

Constraints of boost factor from anti-proton flux

- Anti-proton flux is produced by SS → WW/ZZ





- Background and total flux

$$\log_{10}\Phi_{\bar{p}}^{bkg} = -1.64 + 0.07x - x^2 - 0.02x^3 + 0.028x^4 \quad (x = \log_{10} T/GeV)$$

M.Cirelli,R.Franceschini, A.Strumia (2008)

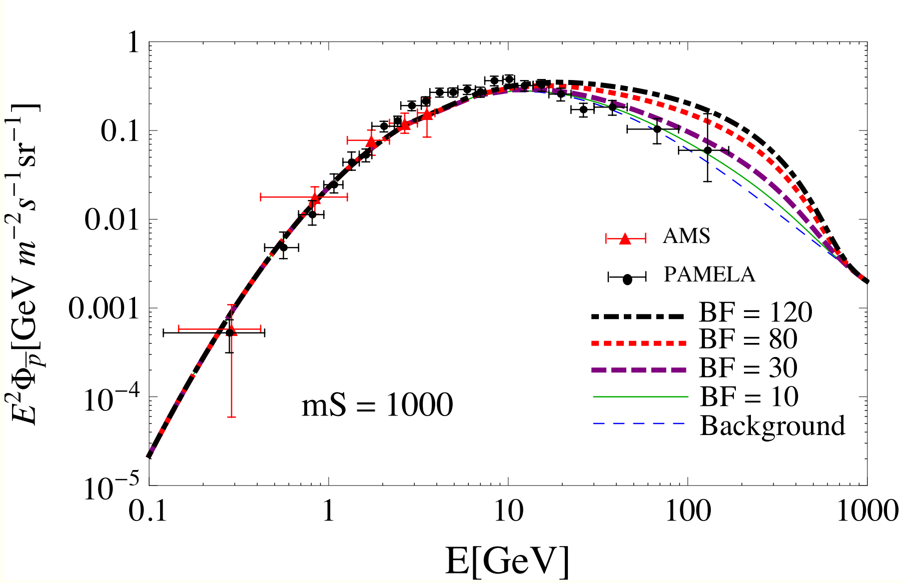
$$\Phi_{\bar{p}}^{Total} = \Phi_{\bar{p}}^{bkg} + \Phi_{\bar{p}}^{DM}$$

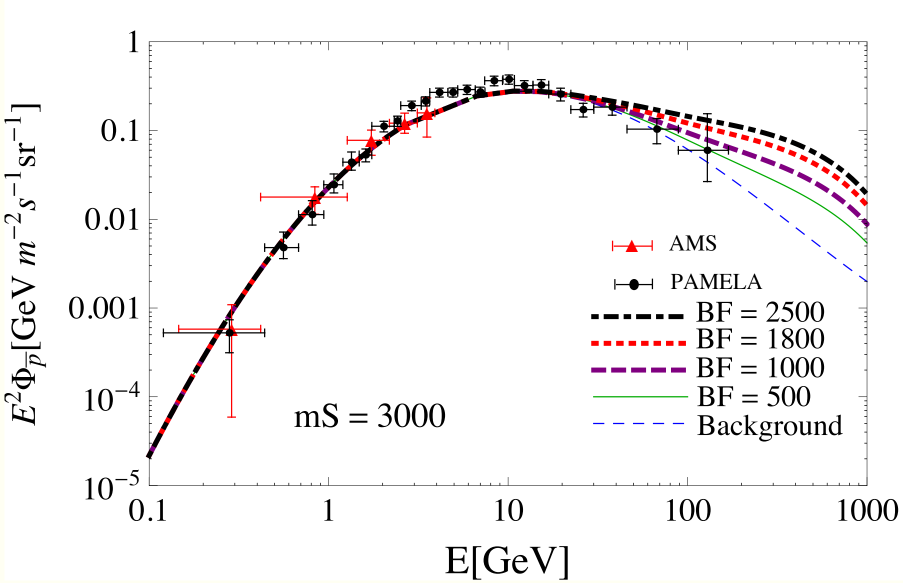
- Boost factor is constrained by anti-proton flux data

Compare with data from AMS(2002), PAMELA(2010)

Constraints of boost factor from anti-proton flux

❖Boost factor is constrained



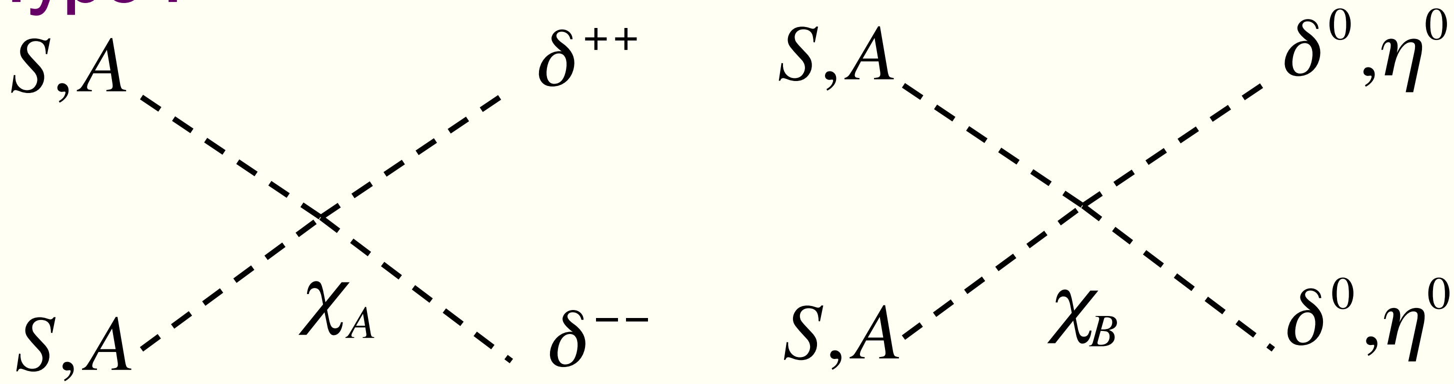


❖Roughly estimated limit of BF

m_S [GeV]	1000	2000	3000	4000
BF	$\lesssim 30$	$\lesssim 500$	$\lesssim 1800$	$\lesssim 4500$

(Co) Annihilation processes of our interest

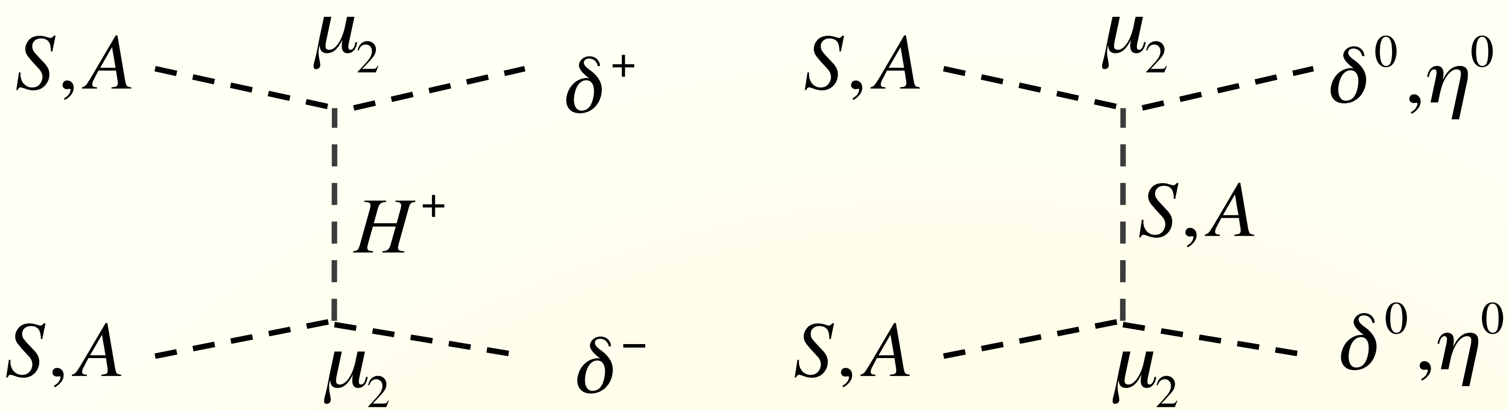
Type I



Etc.

Scenario I_a: $\chi_A >> \chi_B$ Scenario I_b: $\chi_A = \chi_B$ Scenario I_c: $\chi_A << \chi_B$

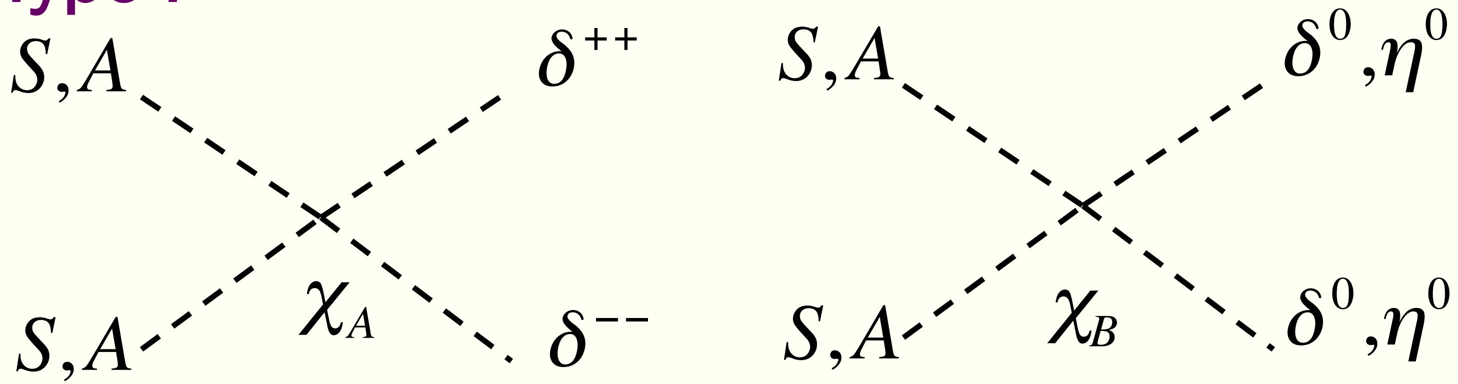
Type II



Etc.

(Co) Annihilation processes of our interest

Type I



Etc.

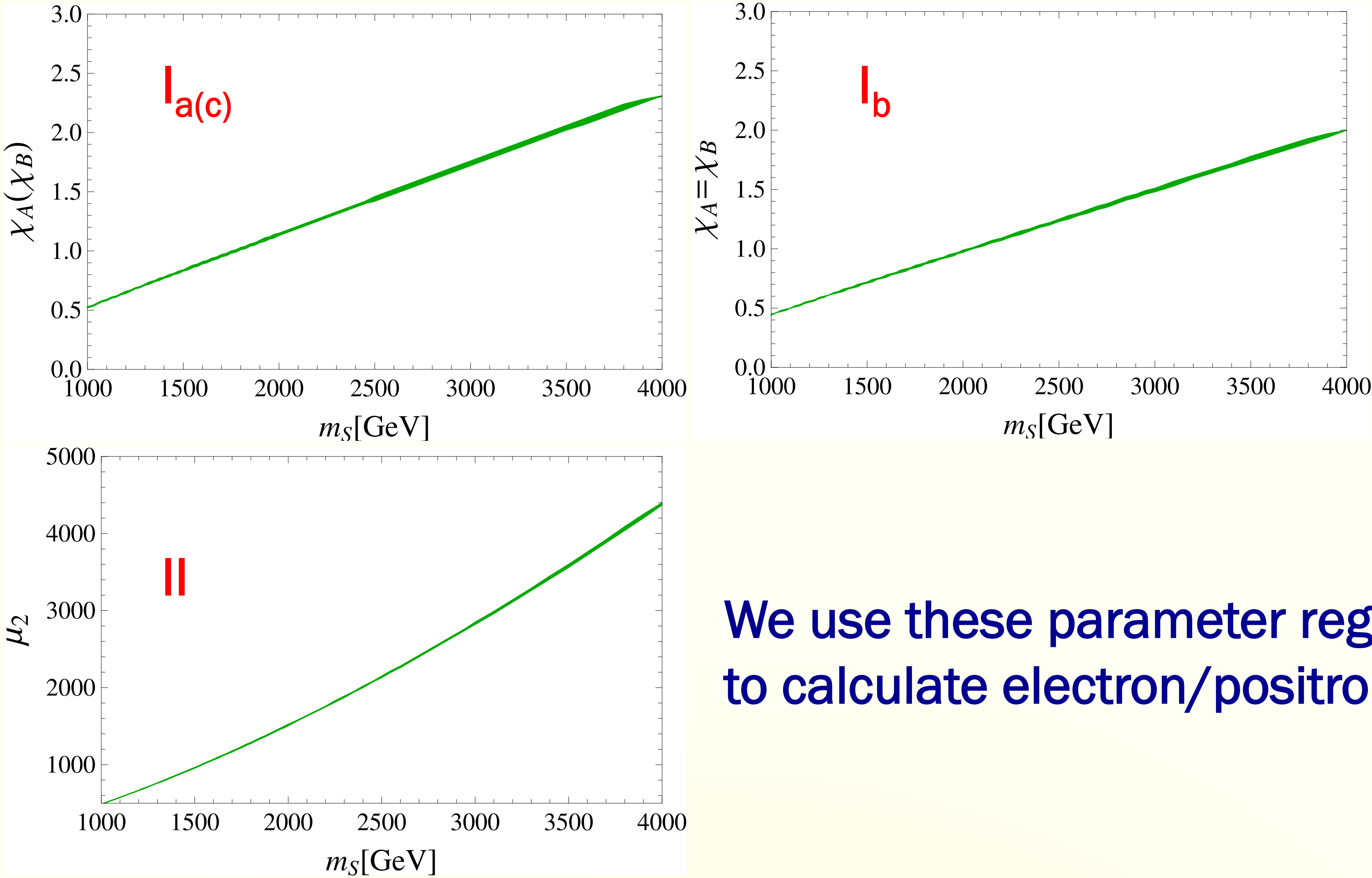
Scenario I : $\chi_A >> \chi_B$ Scenario I : $\chi_A = \chi_B$ Scenario I : $\chi_A << \chi_B$

Annihilation mode for Scenario-I and II

$\sigma(SS \to \delta_i\bar{\delta}_i)/\sum_i \sigma(SS \to \delta_i\bar{\delta}_i)$

channel	$\delta^{++}\delta^{--}$	$\delta^{+}\delta^{-}$	$\delta^{0}\delta^{0}$	$\eta^{0}\eta^{0}$
I_a	4/5	1/5	0	0
I_b	2/6	2/6	1/6	1/6
I_c	0	1/5	2/5	2/5
II	0	1/5	2/5	2/5

Results : Relic Density of DM



We use these parameter region to calculate electron/positron flux

❖ The parameter region giving observed relic density of 90% CL

$$0.1159 \leq \Omega h^2 \leq 0.1215$$

Planck(2013)

Positron/electron flux from DM annihilation

Positron/electron fluxes comes from

$$SS \to \delta^+\delta^-, \delta^{++}\delta^{--} \Rightarrow \delta^\pm \to l^\pm \nu, \delta^{\pm\pm} \to l^\pm l'^\pm$$

❖Background for primary and secondary fluxes

$$\Phi_{e^-}^{\rm prim}(E) = \kappa \frac{0.16E^{-1.1}}{1+11E^{0.9}+3.2E^{2.15}} \quad [{\rm GeV^{-1}cm^{-2}s^{-1}sr^{-1}}],$$

$$\Phi_{e^-}^{\rm sec}(E) = \frac{0.70E^{0.7}}{1+110E^{1.5}+600E^{2.9}+580E^{4.2}} \quad [{\rm GeV^{-1}cm^{-2}s^{-1}sr^{-1}}],$$

$$\Phi_{e^+}^{\rm sec}(E) = \frac{4.5E^{0.7}}{1+650E^{2.3}+1500E^{4.2}} \quad [{\rm GeV^{-1}cm^{-2}s^{-1}sr^{-1}}],$$

E.A.Baltz, J.Edsjo (1998)
E.A.Baltz, J.Edsjo, K.Freese,P.Gondolo (2002)

❖Total flux including DM originated flux and positron fraction

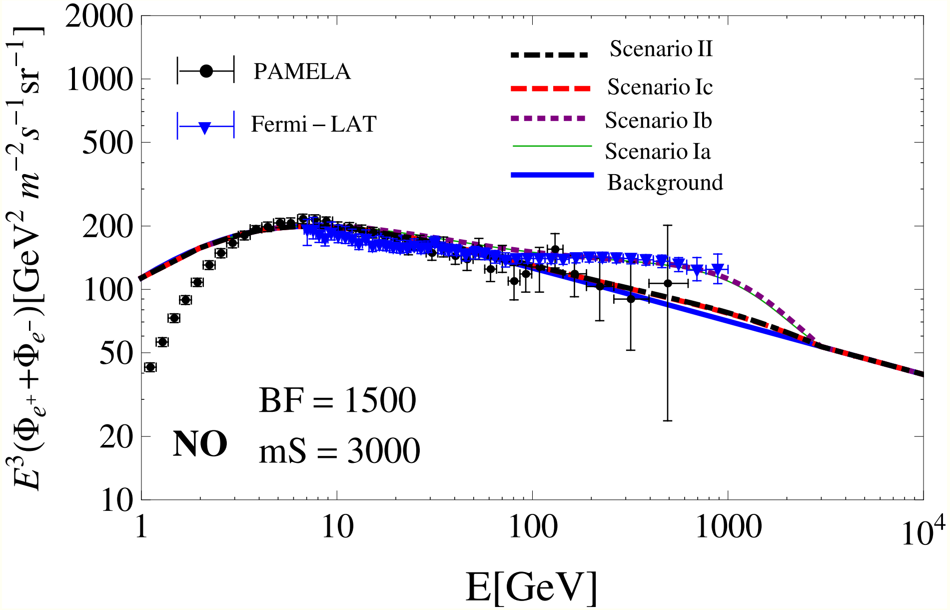
$$\Phi_{e^-} = \kappa\Phi_{e^-}^{\rm prim} + \Phi_{e^-}^{\rm sec} + \Phi_{e^-}^{\rm DM},$$

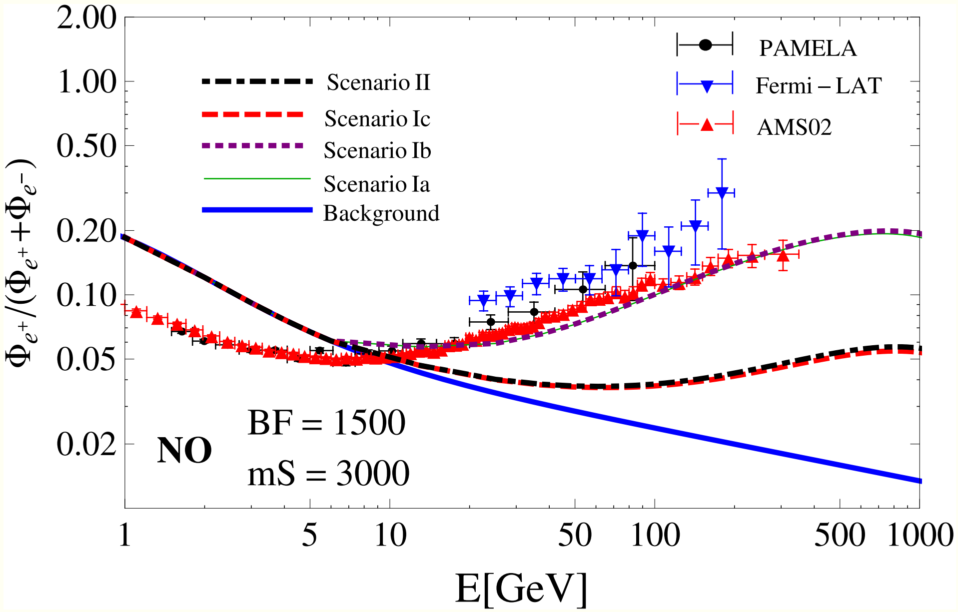
$$\Phi_{e^+} = \Phi_{e^+}^{\rm sec} + \Phi_{e^+}^{\rm DM}.$$

k corresponds to astrophysical uncertainty

k=0.78 is taken in our case

Results : Normal ordering case well fit the data

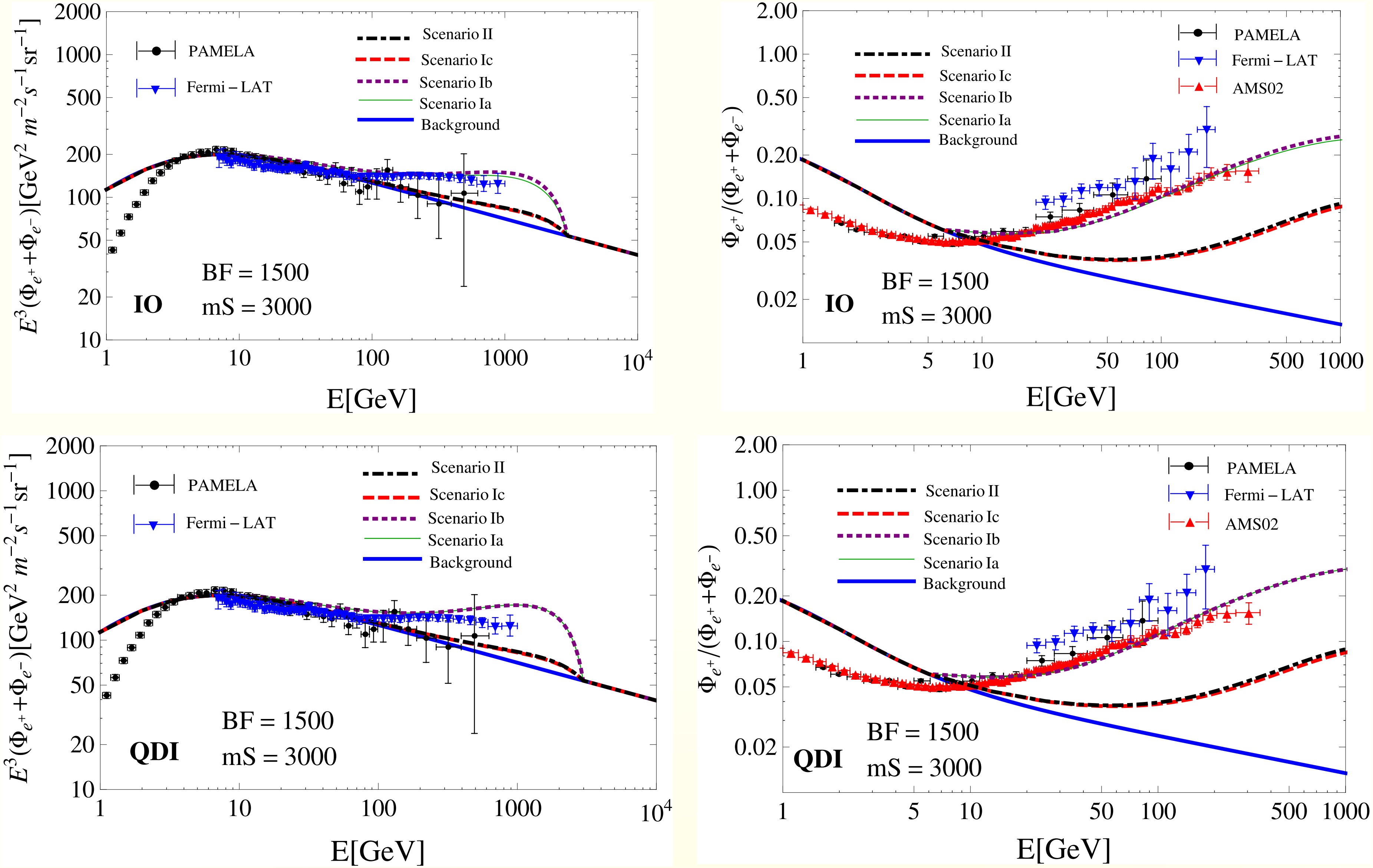




- ❖O(1000) BF is required to fit the data
- ❖Scenario I_c and II give too small positron flux
- ❖Larger DM mass require larger BF

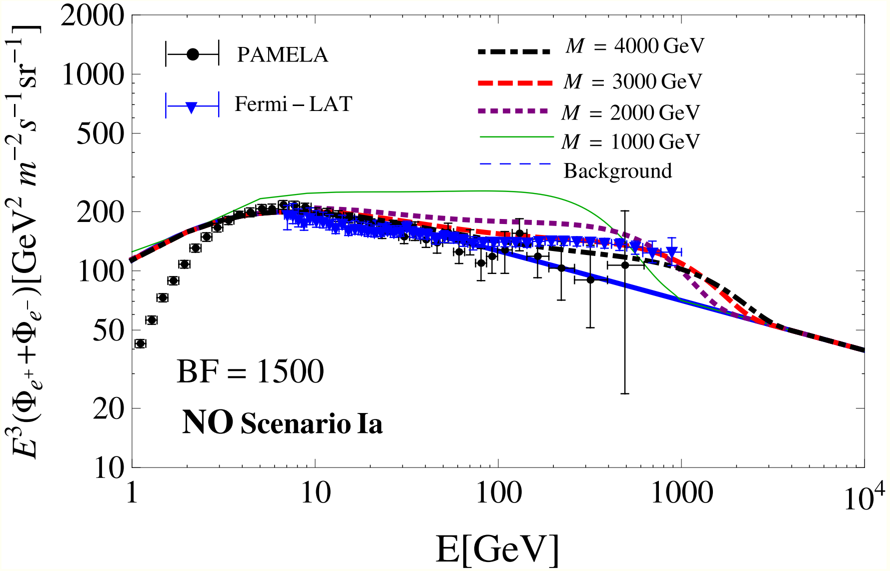
*BF=1500, mS=3000 GeV as a reference

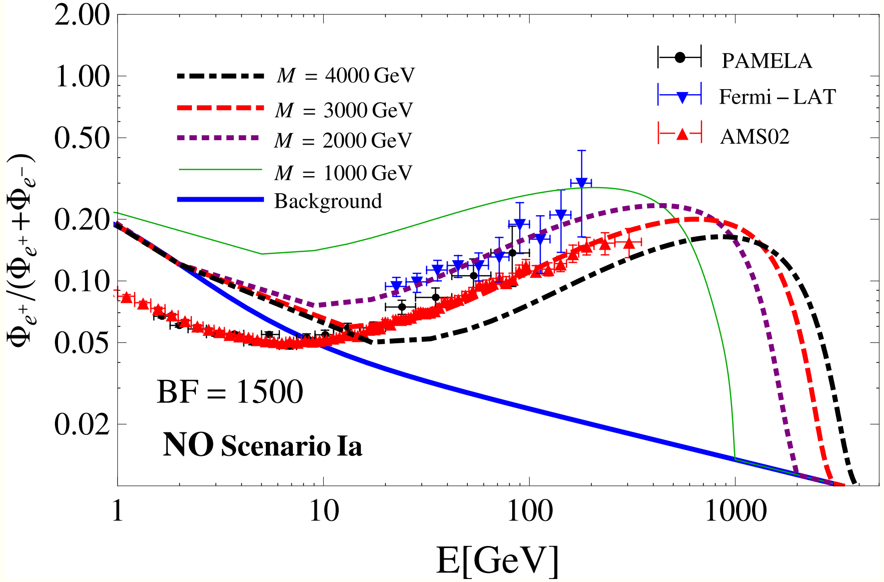
Results : Difference from neutrino mass pattern



*BF=1500, mS=3000 GeV as a reference

Results : Comparing different





❖ Roughly estimated BF to fit to the observed data

m_S	1000 GeV	2000 GeV	3000 GeV	4000 GeV
I_a	$BF > BF_{\max}$	(500, 500, 500, 500)	(1400, 1200, 900, 1100)	(2000, 1900, 1500, 1900)
I_b	$BF > BF_{\max}$	(500, 500, 500, 500)	(1400, 1200, 900, 1200)	(2000, 1900, 1500, 1800)
I_c	$BF > BF_{\max}$	$BF > BF_{\max}$	$BF > BF_{\max}$	$BF > BF_{\max}$
II	$BF > BF_{\max}$	$BF > BF_{\max}$	$BF > BF_{\max}$	$BF > BF_{\max}$

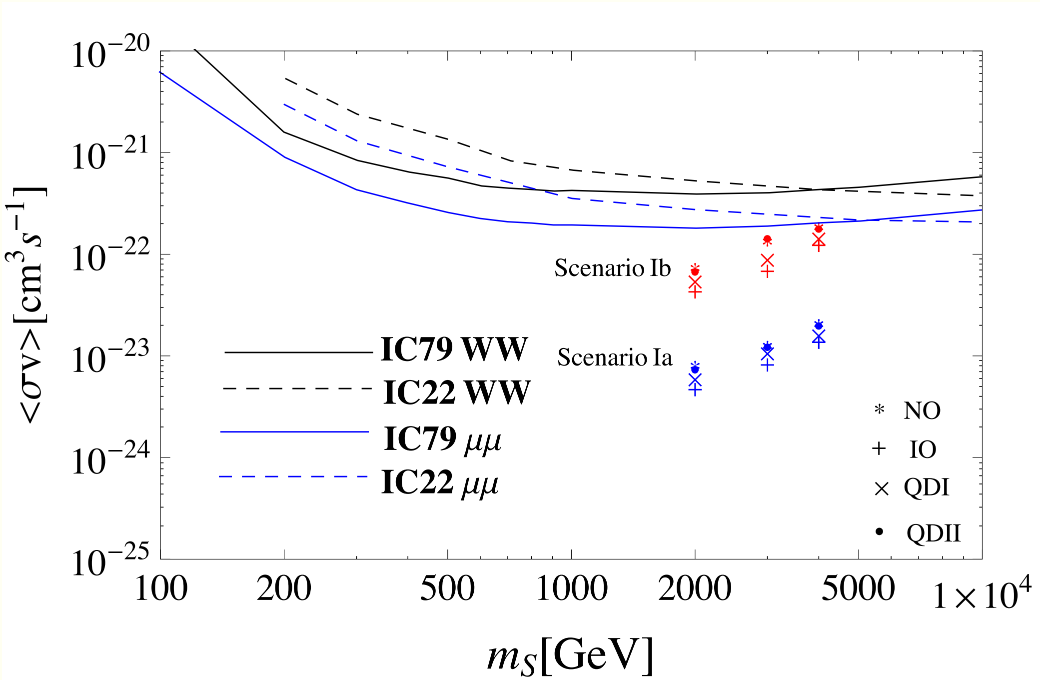
Results : Neutrino Flux from DM halo for scenario I_a, I_b

Neutrino flux is produced via $\delta^{\pm} \rightarrow l^{\pm}\nu, \delta^{0}, \eta^{0} \rightarrow \nu\nu$

We apply BF which is required to explain positron excess

<σv> to produce neutrino flux is calculated as

$$\langle\sigma v\rangle = \langle\sigma v\rangle_{SS\rightarrow\delta^+\delta^-} + 2\langle\sigma v\rangle_{SS\rightarrow\delta^0\delta^0} + 2\langle\sigma v\rangle_{SS\rightarrow\eta^0\eta^0}$$



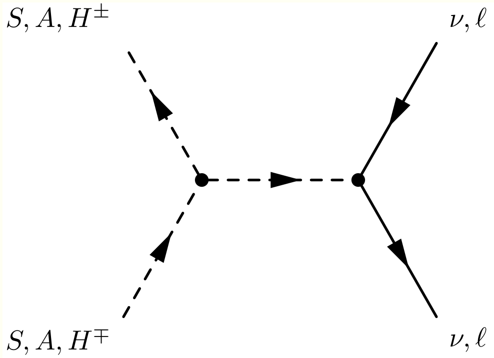
*<σv> for each cases

*Compared with IceCube limit (not direct comparison)

IceCube (2011, 2013)

Results : Neutrino Flux from S-channel process

Neutrino flux is produced via s-channel process



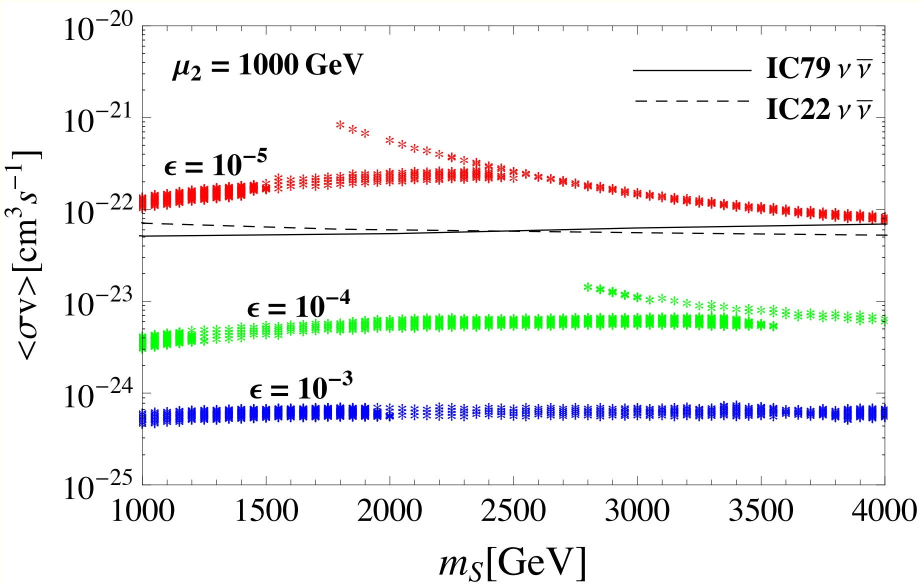
*$m_\delta \sim 2\, m_S$ give resonant effect

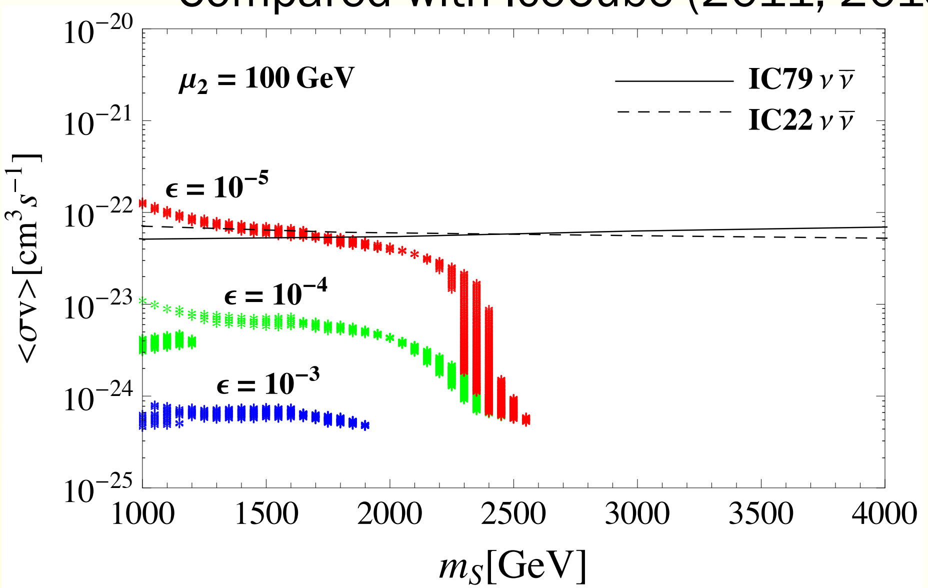
*It can give large neutrino flux

*We take $m_\delta = 2m_S(1-\varepsilon)$

$\langle\sigma v\rangle$ as a function of m_S and for each ε and μ_2

Compared with IceCube (2011, 2013)





Summary

- We constructed a model with inert Higgs doublet and triplet Higgs
  - DM candidate is neutral component of inert Higgs doublet
  - Stability of DM : Z_2 symmetry
  - Neutrino masses via Type-II seesaw mechanism

- We discussed phenomenology regarding DM
  - Possible explanation of excess of positron fraction with BF
  - BF is restricted by the anti-proton flux
  - The large neutrino flux is also expected in the model

Back up slides

The ongoing searches of doubly charged Higgs at LHC

The CMS search for $H^{\pm\pm}$

- Taking into account both $pp \to H^{\pm\pm}H^{\mp\mp}$ & $pp \to H^{\pm\pm}H^{\mp}$

  Signals

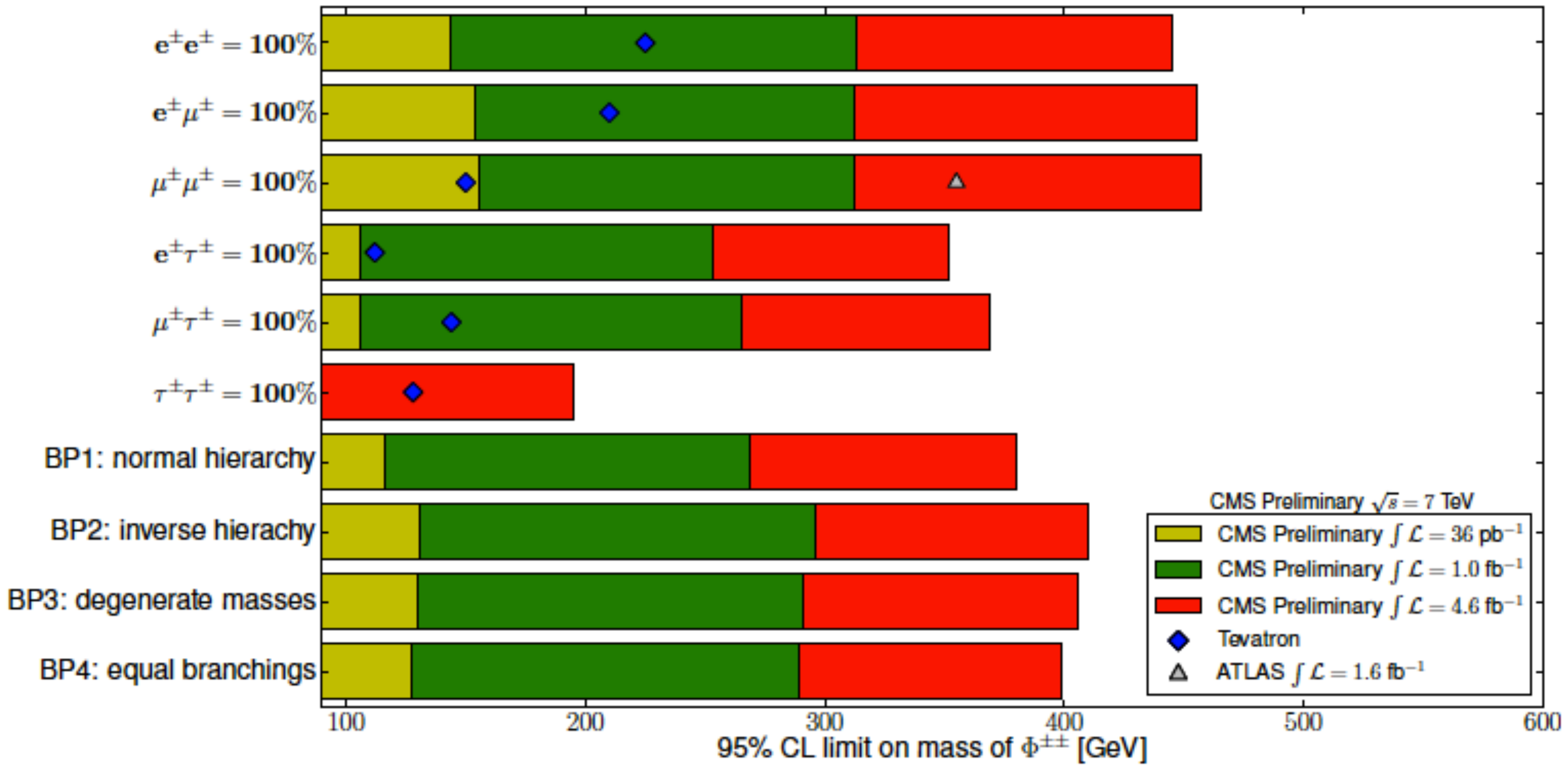
  (1) 4 lepton signature ($\ell^+\ell^+\ell^-\ell^-$)

  (2) 3 lepton signature ($\ell^\pm\ell^\pm\ell^\mp$)

- Define the four benchmark points for $Br(H^{\pm\pm} \to \ell^\pm\ell^\pm)$

Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	0.50	0	0	0.125	0.25	0.125
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

The CMS search for $H^{\pm\pm}$



➢Mass limits $m_{H\pm\pm}$ > 400 GeV for benchmark points in HTM

The ongoing searches of doubly charged Higgs at LHC

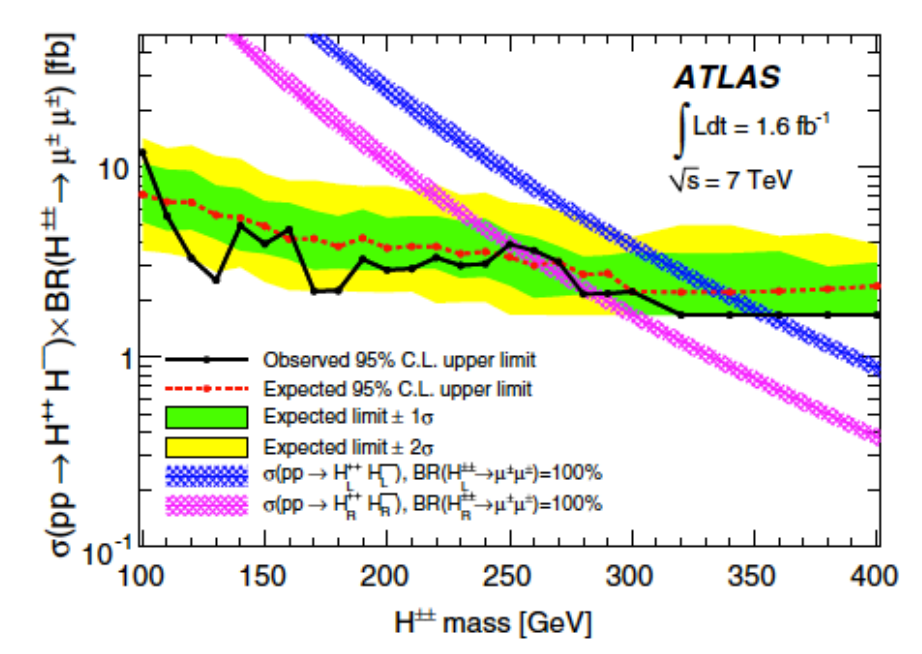
The ATLAS search for $H^{\pm\pm}$

- Taking into account only $pp \rightarrow H^{\pm\pm}H^{\mp\mp}$

Signals

Same sign charged $\mu^{\pm}\mu^{\pm}$

- Uses luminosity of 1.6 fb^{-1}



Results for mass limit

- For $BR(H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm})$=100%
- Mass limits $m_{H\pm\pm}$ > 355 GeV
- Looser limit than CMS

The doubly charged Higgs searches at Tevatron/LHC

➡ Generally assuming $H^{\pm\pm}$ decays to two leptons $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$

$$m_{H^{\pm\pm}} > 400\ GeV$$

It is the case of small triplet VEV ($<10^{-4}$ GeV)

The scenario with large triplet VEV is also important

➡ The $H^{\pm\pm}$ decays to two same sign W bosons

$$m_{H^{\pm\pm}} > m_Z/2 \quad \text{by LEP}$$

We focus on the WW signature of $H^{\pm\pm}$

Relevant couplings

Vertex	Coupling	Vertex	Coupling
SSh	$2\lambda_L v_0$	AAh	$(\lambda_3+\lambda_4-\lambda_5)v_0$
$SS(AA)\delta^0$	$\mp\sqrt{2}\mu_2$	$SA\eta^0$	$-\sqrt{2}\mu_2$
$SH^{\mp}\delta^{\pm}$	$-\mu_2$	$AH^{\mp}\delta^{\pm}$	$\pm i\mu_2$
H^+H^-h	$\lambda_3 v_0$	$H^{\pm}H^{\pm}\delta^{\mp\mp}$	$2\mu_2$
$\delta^+\delta^-h$	$(\lambda_6+(\lambda_7+\lambda_8)/2)v_0$	$\delta^{++}\delta^{--}h$	$(\lambda_6+\lambda_8)v_0$
$\delta^0\delta^0(\eta^0\eta^0)h$	$(\lambda_6+\lambda_7)v_0$	hhh	$6\lambda_1 v_0$
$SS(H^+H^-)hh$	$2\lambda_L(\lambda_3)$	$AAhh$	$\lambda_3+\lambda_4-\lambda_5$
$SS(AA)\delta^+\delta^-$	$\bar\lambda_6+(\bar\lambda_7+\bar\lambda_8)/2$	$(S^2,A^2)\delta^0\delta^0[\eta^0\eta^0]$	$\bar\lambda_6+\bar\lambda_7$
$SS(AA)\delta^{++}\delta^{--}$	$\bar\lambda_6+\bar\lambda_8$	$H^+H^-\delta^+\delta^-$	$\bar\lambda_6+(\bar\lambda_7+\bar\lambda_8)/2$
$H^+H^-\delta^{++}\delta^{--}$	$\bar\lambda_6+\bar\lambda_7$	$H^+H^-\delta^0\delta^0(\eta^0\eta^0)$	$\bar\lambda_6+\bar\lambda_8$
$SH^-\delta^-\delta^{++}(H^+\delta^+\delta^{--})$	$-(\bar\lambda_7-\bar\lambda_8)/2$	$AH^+\delta^+\delta^{--}(H^-\delta^-\delta^{++})$	$\pm i/2(\bar\lambda_7-\bar\lambda_8)$
$SH^{\mp}\delta^{\pm}\delta^0$	$(\bar\lambda_7-\bar\lambda_8)/(2\sqrt{2})$	$AH^{\mp}\delta^{\pm}\eta^0$	$(\bar\lambda_7-\bar\lambda_8)/(2\sqrt{2})$
$SH^{\pm}\delta^{\mp}\eta^0$	$\pm i/(2\sqrt{2})(\bar\lambda_7-\bar\lambda_8)$	$AH^{\mp}\delta^{\pm}\delta^0$	$\pm i/(2\sqrt{2})(\bar\lambda_7-\bar\lambda_8)$

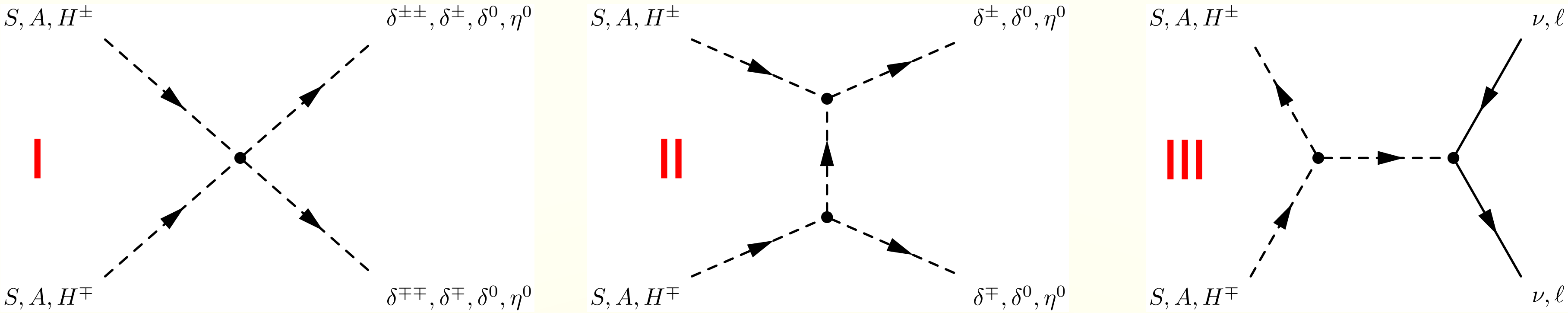
Parameter setting and main processes

❖Assumptions to suppress pure IHD interactions

$\lambda_L = 0$:Negligible interaction of ΦΦH

$m_A = m_{H^+} = m_S + 1\,GeV$:Suppress gauge interaction of Φ

❖The processes of our interest



❖The free parameters in our analysis

$\{m_S, \chi_A, \chi_B, \mu_2, h_{ij}\}$ $(m_\delta = 500\,GeV)$