CDM and Exotic Z′:
leptophilic vs. leptophobic

P. Ko (KIAS)

based on JCAP (2009) with S. Baek;
and works in preparation with
Y. Omura and P. Gondolo

Contents

- Leptophilic Z' : motivated by PAMELA
- Leptophobic Z' (DAMA and/or CoGeNT) in MSSM with gauged U(1)B and U(1)L (with both leptophobic and leptophilic Z's)

A Leptophilic Model Motivated by PAMELA

Based on Baek and Ko, arXiv:0811.1646;

JCAP 0910.011 (2009)

$U(1)_{L_\mu - L\tau}$ model

- Anomaly free subgroup of SM : one of

$$B - L \; , L_e - L_\mu \; , L_\mu - L_\tau \; , L_e - L_\tau$$

- Least constrained one : $L_\mu - L_\tau$
- Foot, He, Volkas, et al. in late 80's
- Baek, Deshpande, Ko, He : muon g-2
- PAMELA positron excess and collider signature (Baek and Ko)

$$\mathcal{L}_{\rm Model} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm New}$$

$$\mathcal{L}_{\rm New} = -\frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \overline{\psi_D}iD\cdot\gamma\psi_D - M_{\psi_D}\overline{\psi_D}\psi_D + D_\mu\phi^* D^\mu\phi$$
$$-\lambda_\phi(\phi^*\phi)^2 - \mu_\phi^2\phi^*\phi - \lambda_{H\phi}\phi^*\phi H^\dagger H.$$

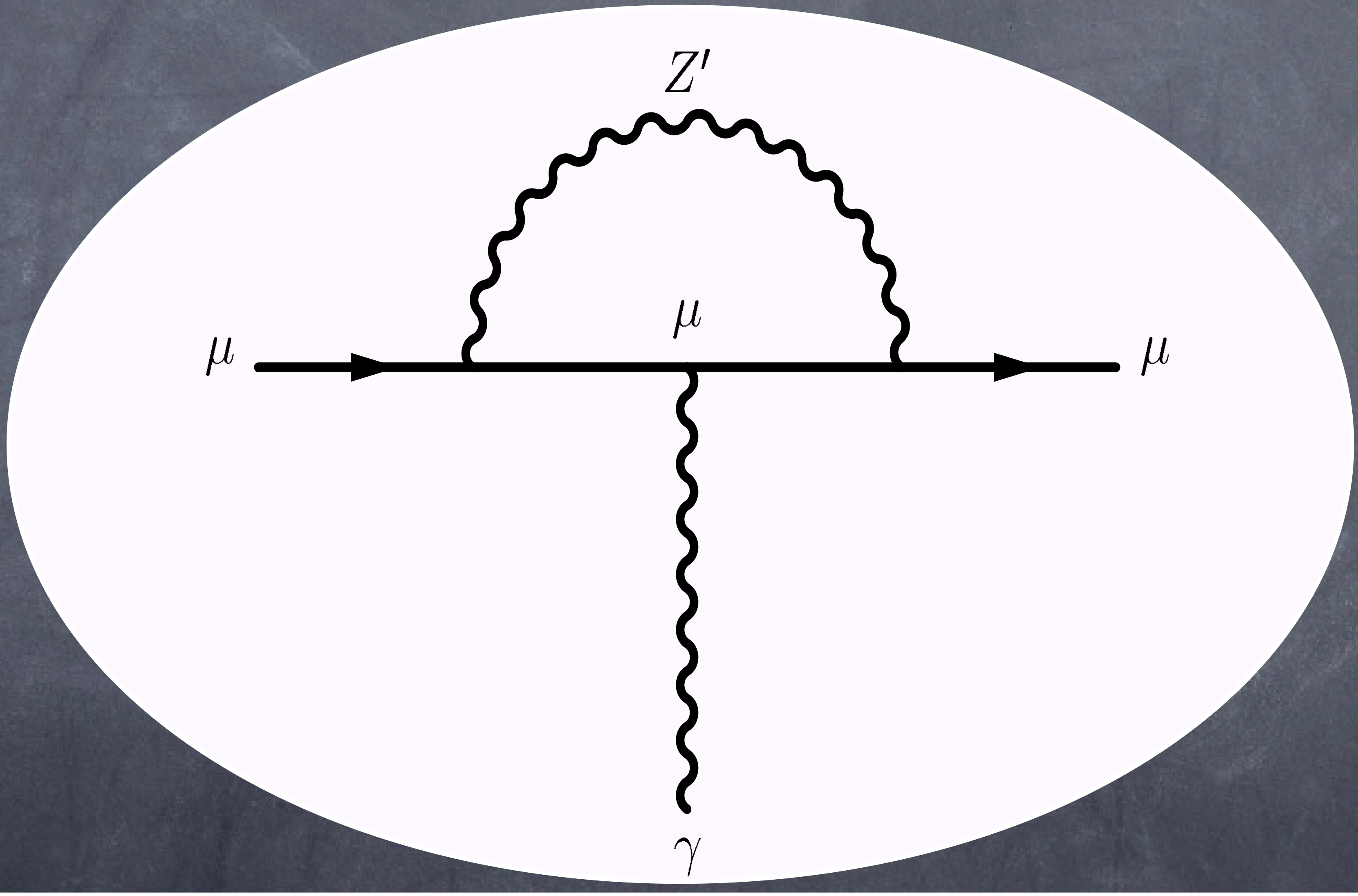
Here we ignored kinetic mixing for simplicity

$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{e}{s_W c_S}(I_3 - s_W^2 Q)Z_\mu + ig' Y' Z'_\mu$$

We will study the following observables:
Muon g-2, Leptophilc DM, Collider Signature

Muon (g-2)

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (302 \pm 88) \times 10^{-11}.$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi}\frac{2m_\mu^2}{3M_{Z'}^2}$$

Prediction for muon (g-2)

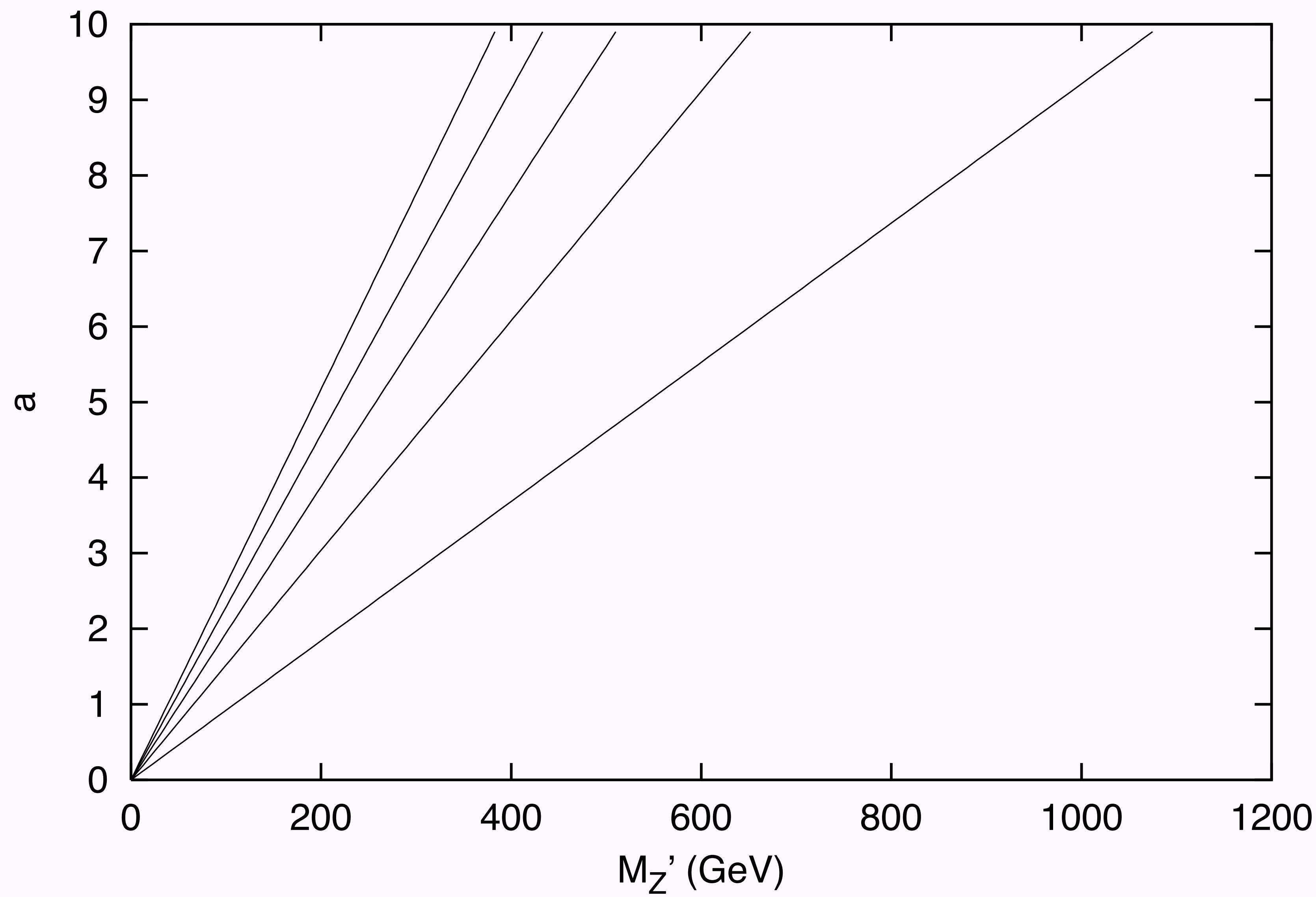


FIG. 2. Δa_μ on the a vs. $m_{Z'}$ plane in case b). The lines from left to right are for Δa_μ away from its central value at $+2\sigma, +1\sigma, 0, -1\sigma$ and -2σ, respectively.

Collider Signatures

$$Z^{'} \to \mu^+\mu^-, \tau^+\tau^-, \nu_\alpha\bar{\nu}_\alpha \text{ (with } \alpha = \mu \text{ or } \tau), \ \psi_D\overline{\psi}_D \ ,$$

$$\Gamma(Z^{'} \to \mu^+\mu^-) = \Gamma(Z^{'} \to \tau^+\tau^-) = 2\Gamma(Z^{'} \to \nu_\mu\bar{\nu}_\mu) = 2\Gamma(Z^{'} \to \nu_\tau\bar{\nu}_\tau) = \Gamma(Z^{'} \to \psi_D\bar{\psi}_D)$$

$$\Gamma_{\rm tot}(Z^{'}) = \frac{\alpha^{'}}{3}\, M_{Z'} \times 4(3) \approx \frac{4(\text{or } 3)}{3}\ \text{GeV} \left(\frac{\alpha^{'}}{10^{-2}}\right) \left(\frac{M_{Z'}}{100\text{GeV}}\right)$$

The dominant mechanisms of $Z^{'}$ productions at available colliders are

$$\begin{aligned} q\bar{q} \text{ (or } e^+e^-) &\to \gamma^*, Z^* \to \mu^+\mu^- Z^{'}, \tau^+\tau^- Z^{'} \\ &\to Z^* \to \nu_\mu\bar{\nu}_\mu Z^{'}, \nu_\tau\nu_\tau Z^{'} \end{aligned}$$

There are also vector boson fusion processes such as

$$\begin{aligned} W^+W^- &\to \nu_\mu\bar{\nu}_\mu Z^{'} \ \ (\text{or } \mu^+\mu^-\text{Z}^{'}), \quad \text{etc.} \\ Z^0Z^0 &\to \nu_\mu\bar{\nu}_\mu Z^{'} \ \ (\text{or } \mu^+\mu^-\text{Z}^{'}), \quad \text{etc.} \\ W^+Z^0 &\to \nu_\mu\bar{\mu} Z^{'} \ \ (\text{or } \mu^+\mu^-\text{Z}^{'}), \quad \text{etc.} \end{aligned}$$

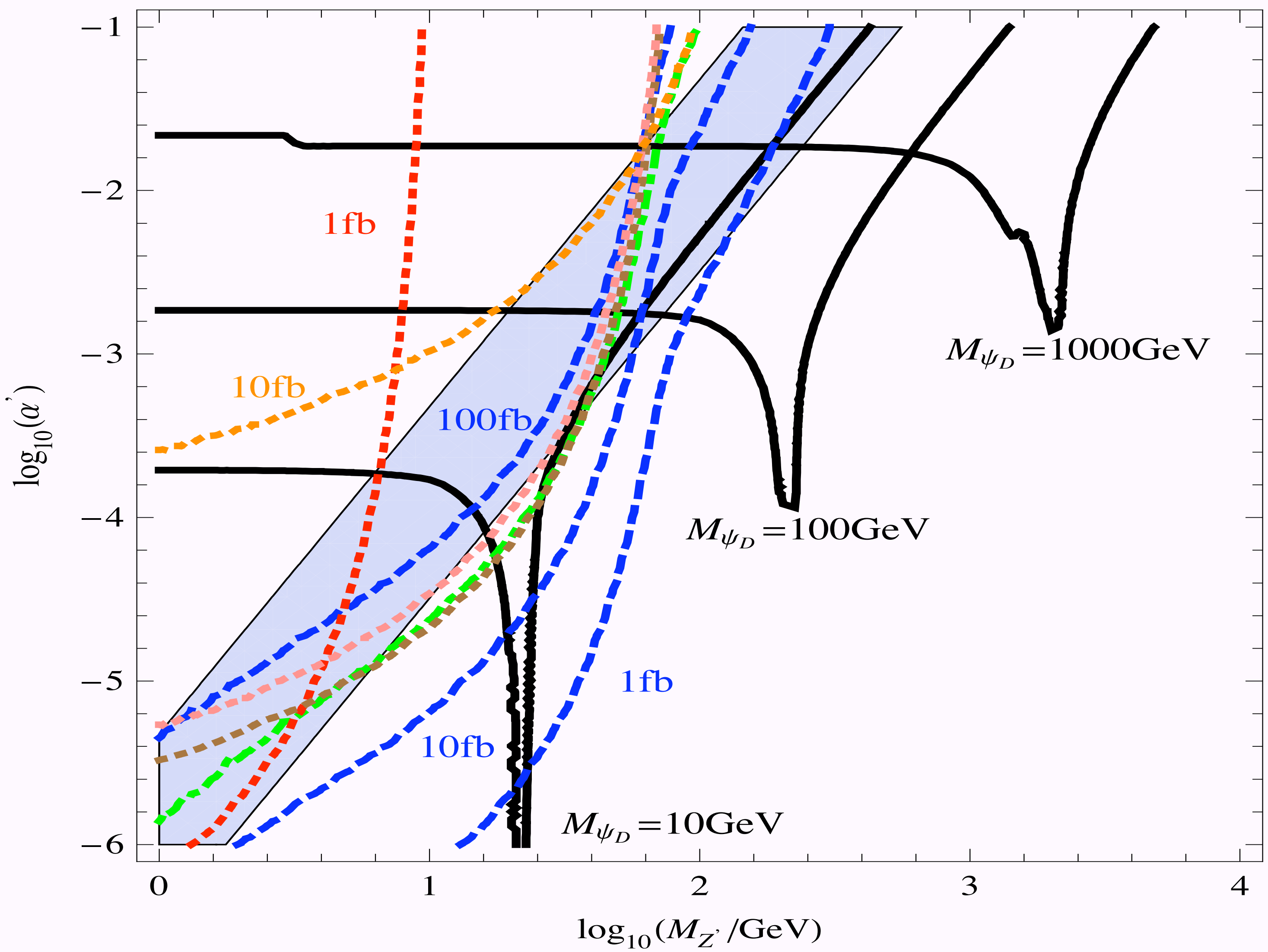


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5 $\times 10^{-6}$ GeV, brown dotted) in the $(\log_{10}\alpha', \log_{10} M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88) \times 10^{-11}$ within 3 σ.

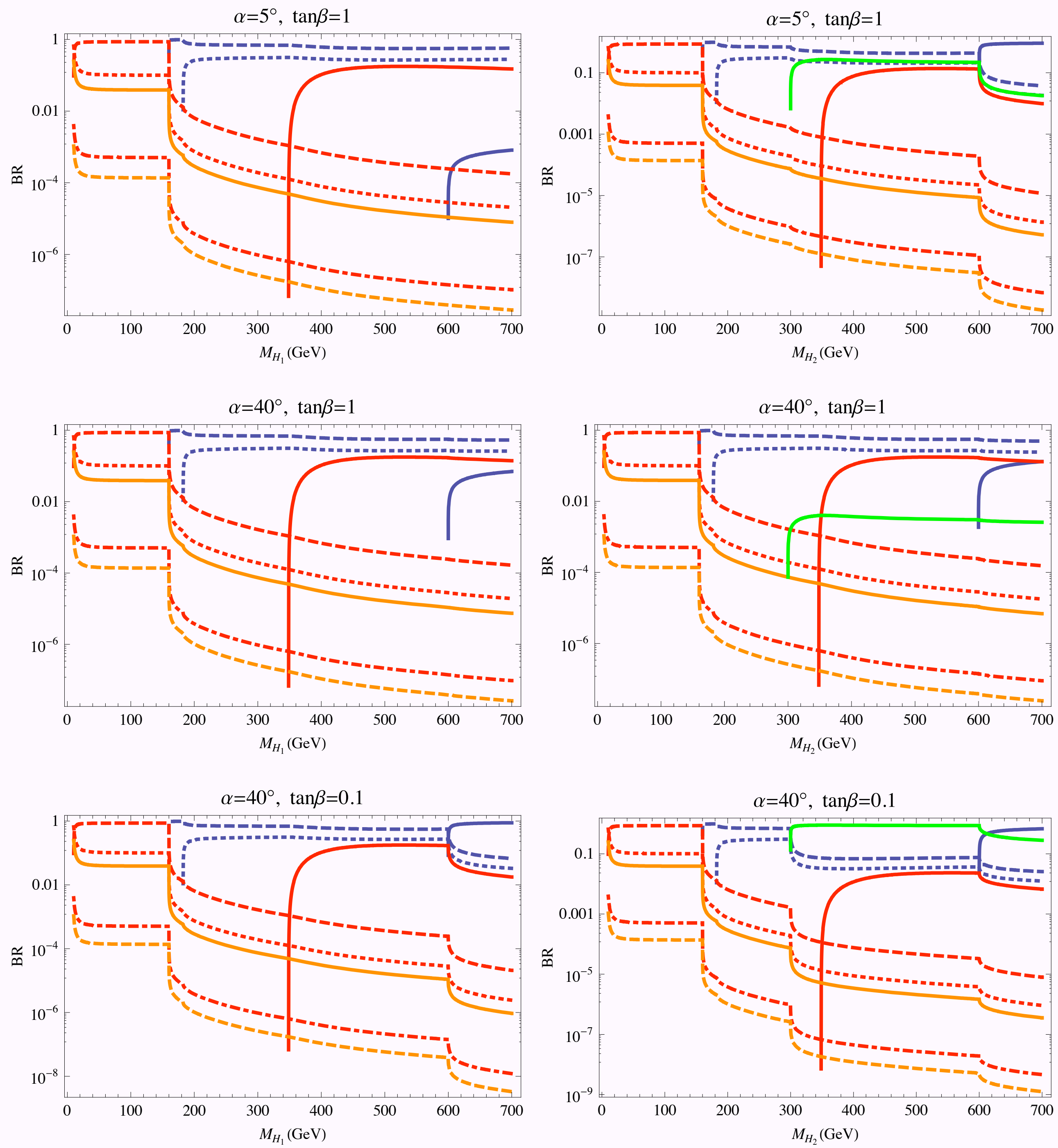


Figure 2: In the left (right) column are shown the branching ratios of the lighter (heavier) Higgs $H_{1(2)}$ into two particles in the final states: $t\bar{t}$ (solid in red), $b\bar{b}$ (dashed red), $c\bar{c}$ (dotted red), $s\bar{s}$ (dot-dashed red), $\tau\bar{\tau}$ (solid orange), $\mu\bar{\mu}$ (dashed orange), WW (dashed blue), ZZ (dotted blue) and $Z^{'}Z^{'}$ (solid blue) for difference values of the mixing angle α and $\tan\beta$. We fixed $M_{Z'} = 300$ GeV. We also fixed $M_{H_2} = 700$ GeV ($M_{H_1} = 150$ GeV) for the plots of the left (right) column.

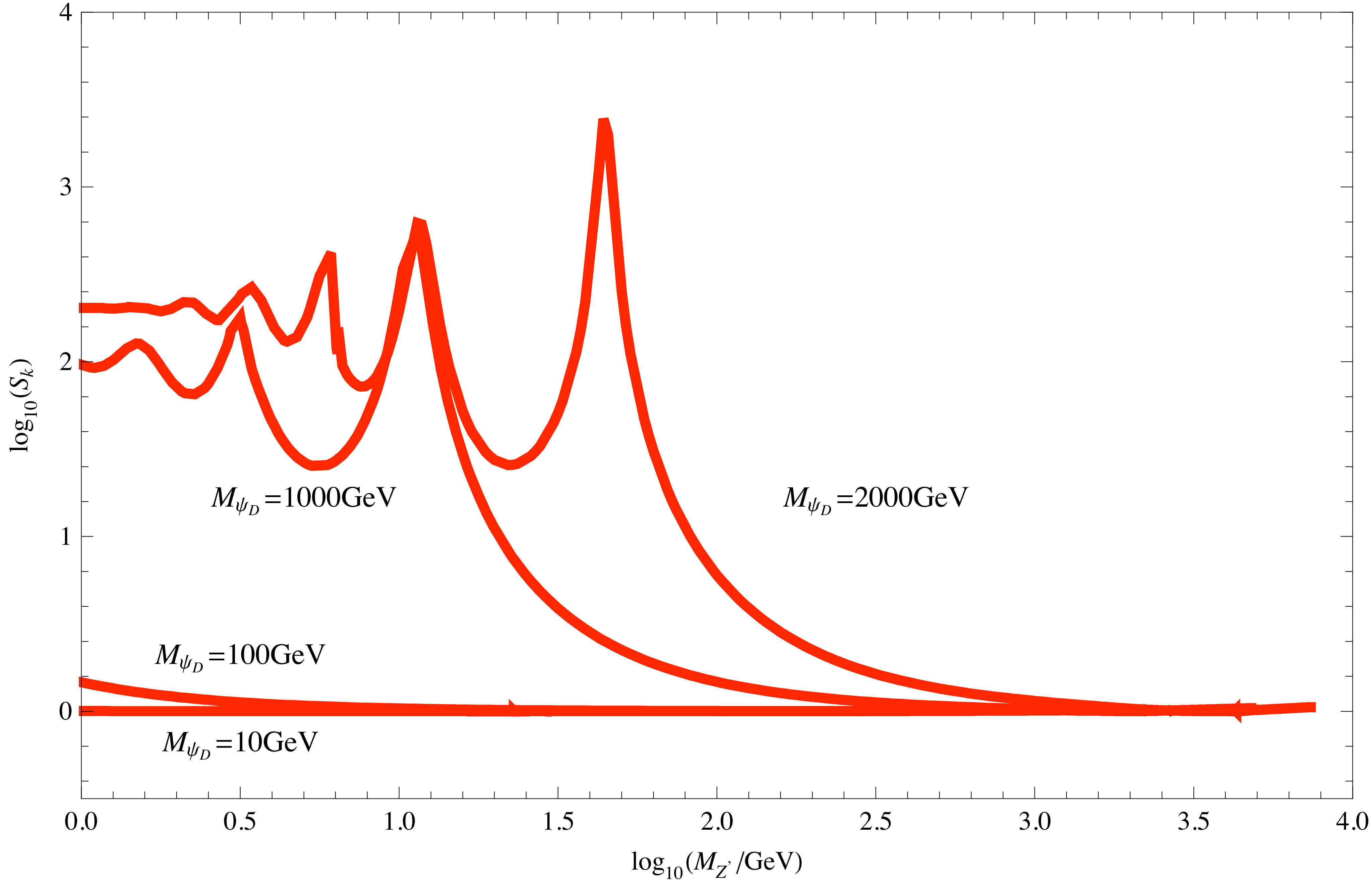
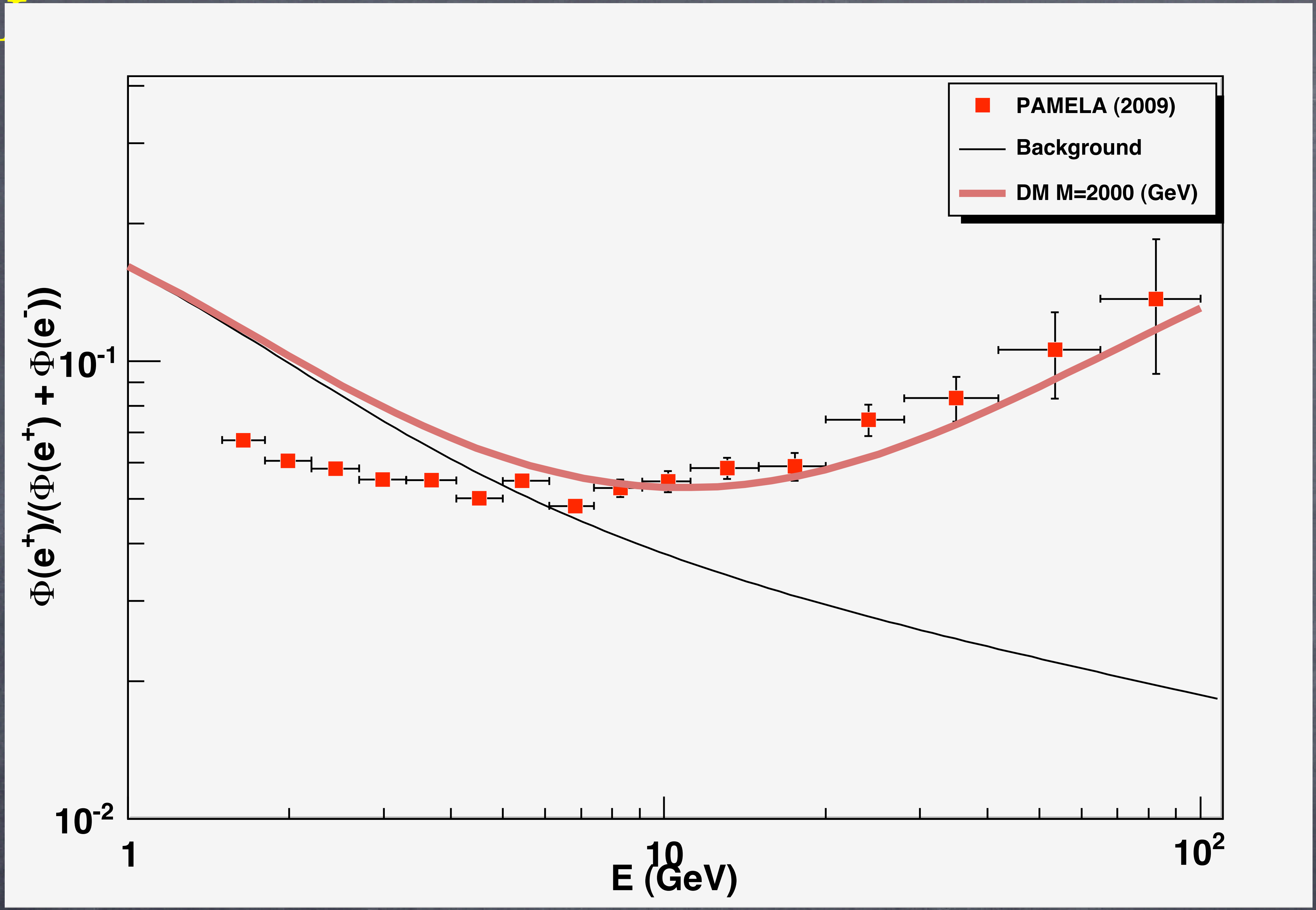
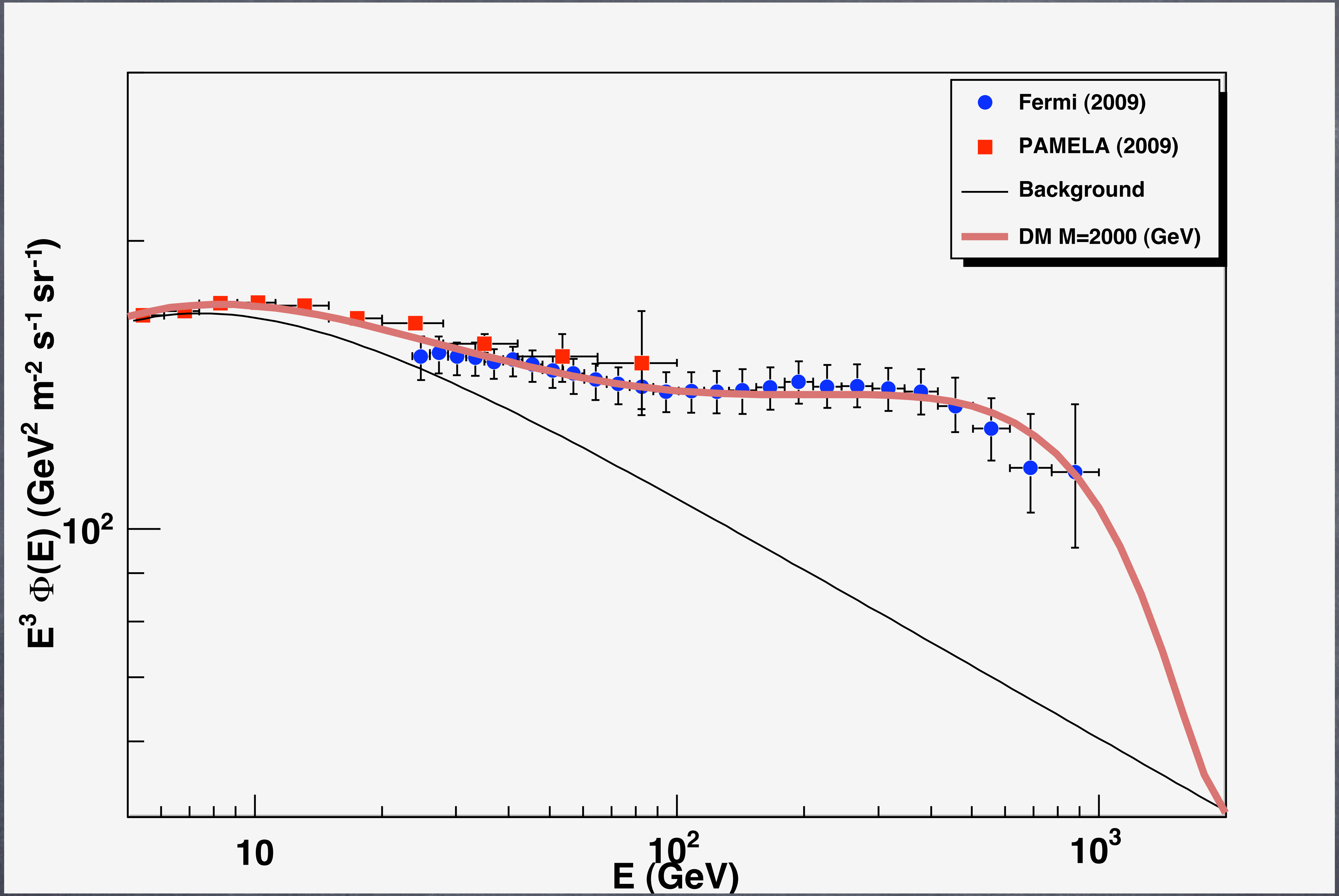


Figure: Sommerfeld enhancement factor along the constant relic density lines. $v = 200$ km/s.

$L_\mu - L$

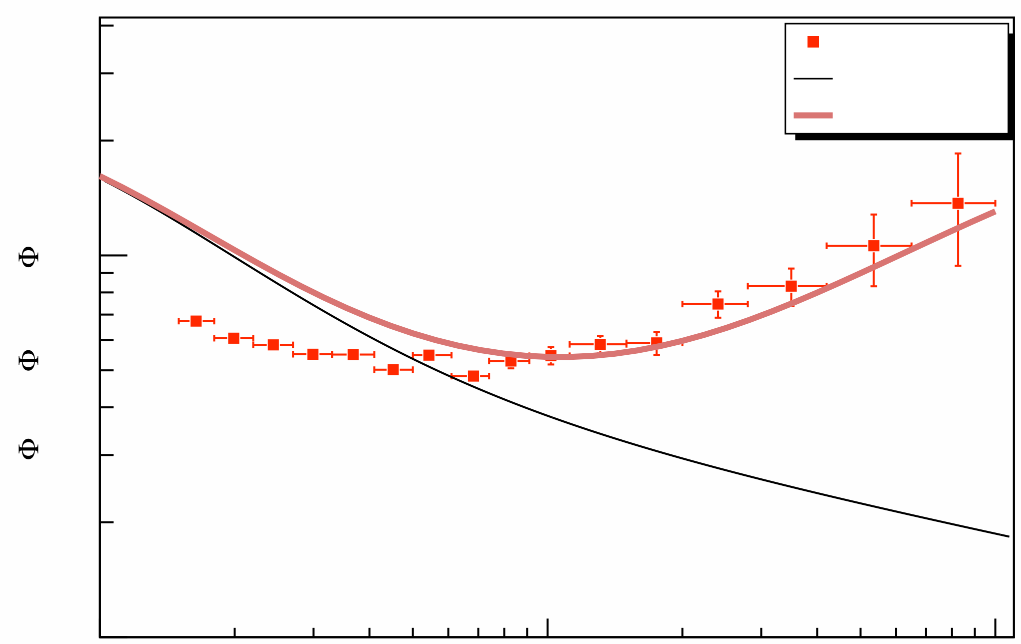


PAMELA positron ratio to (electro + positron)



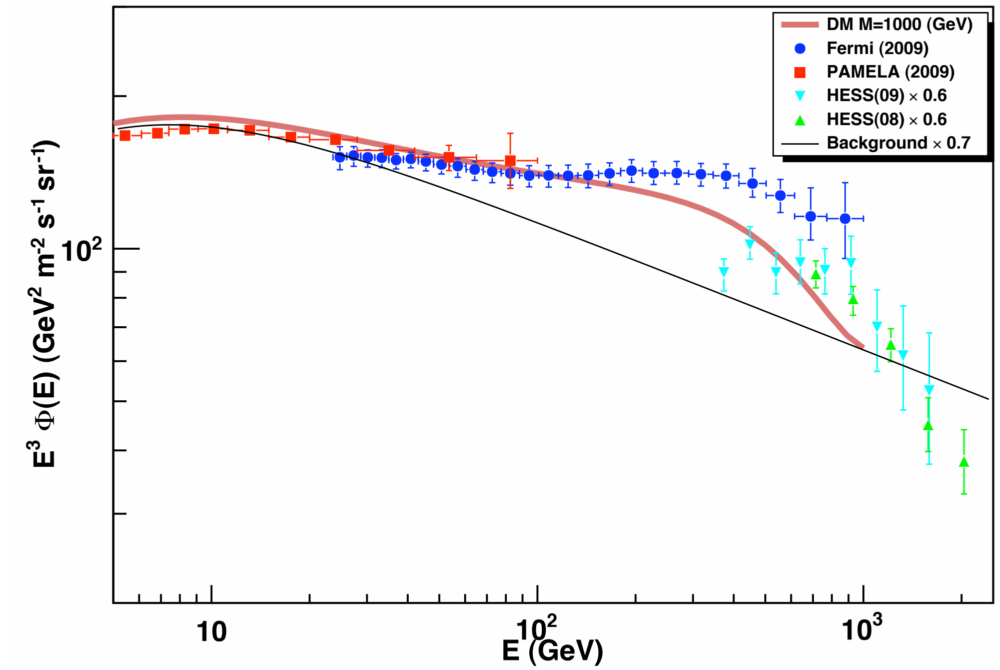
PAMELA + FERMI with bkgd x 0.67 and large boost factor ~O(5000)

Fit to PAMELA data



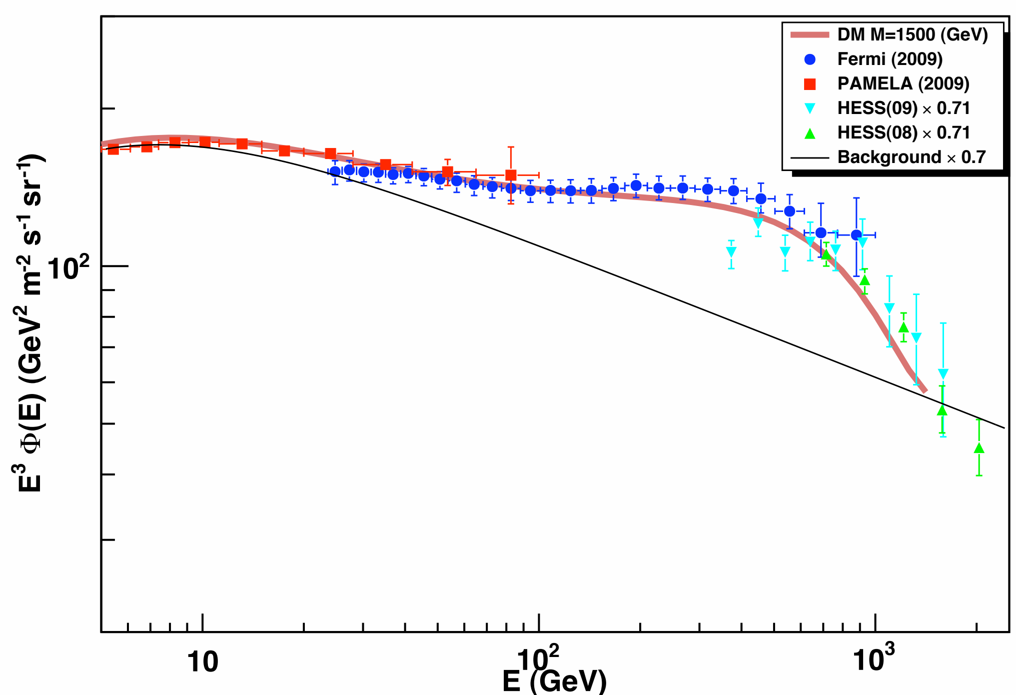
Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=1574, $\chi^2_{\rm min}/dof = 201/50$.



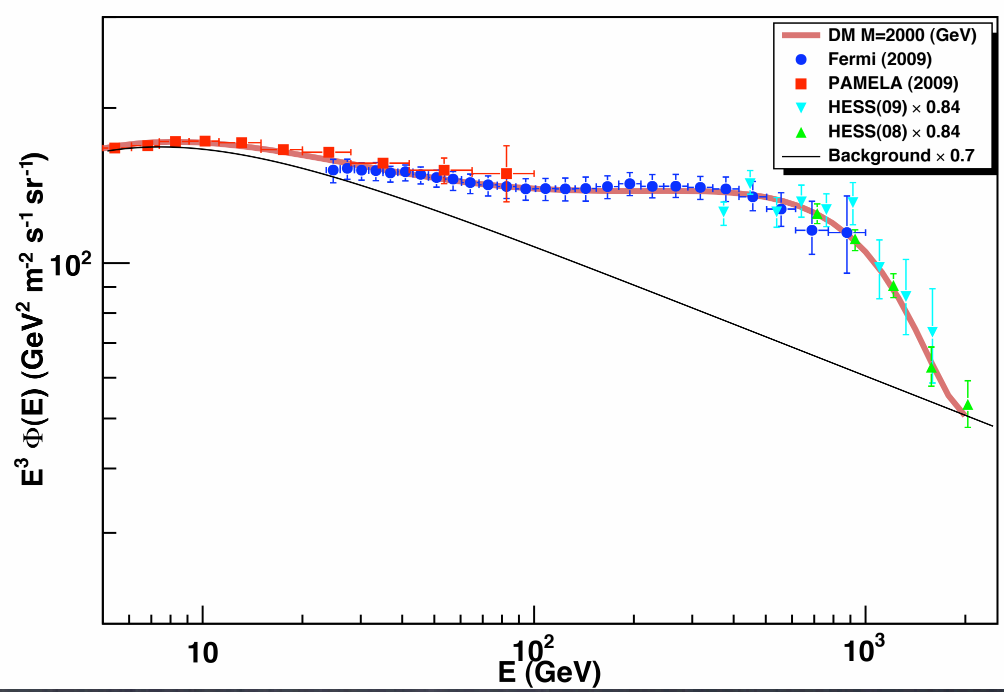
Fit to PAMELA, Fermi LAT, and HESS data

NFW MED, BF=3044, $\chi^2_{\rm min}/dof = 104/50$.

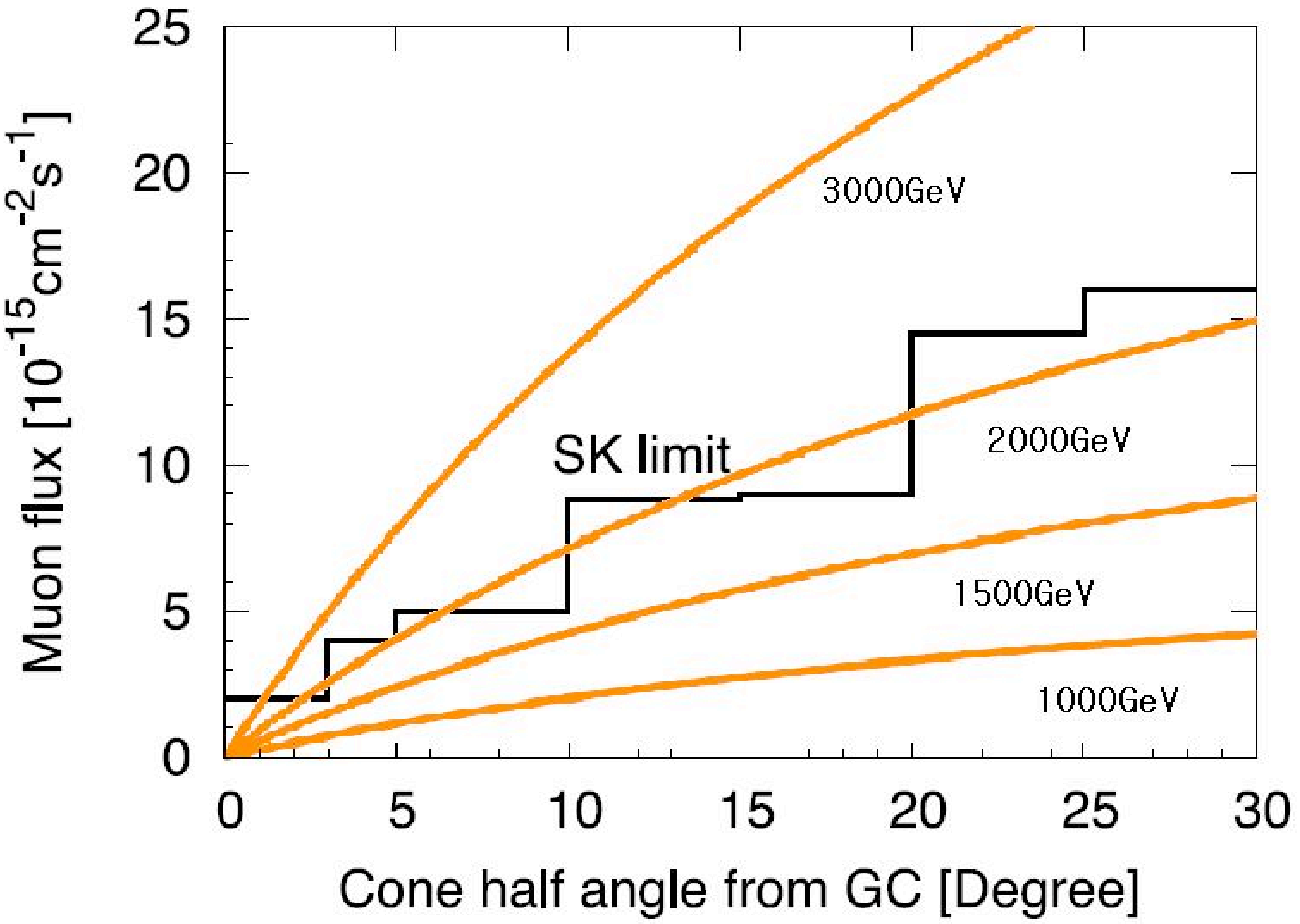


Fit to PAMELA, Fermi LAT, and HESS data

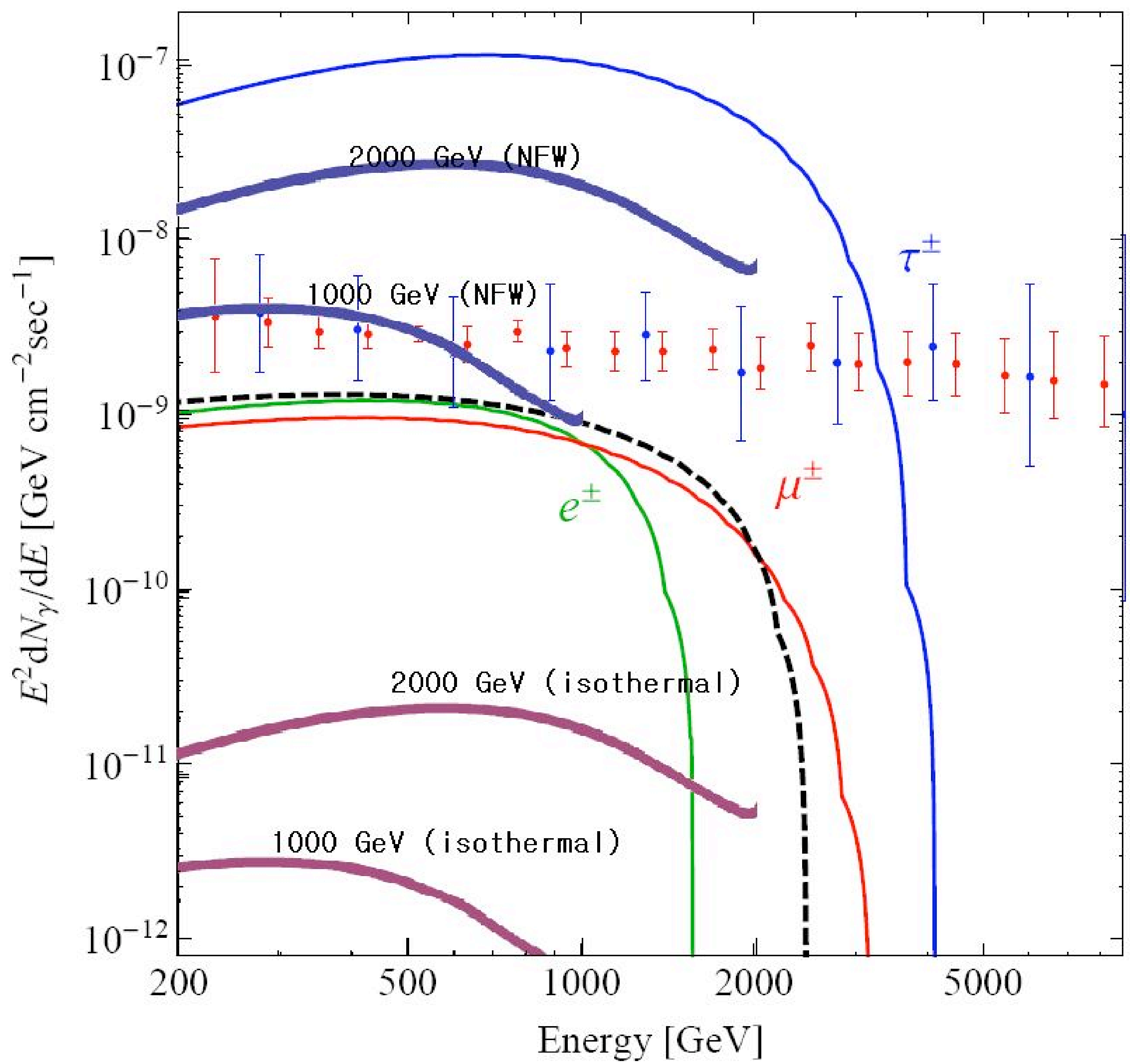
NFW MED, BF=5198, $\chi^2_{\rm min}/dof = 53/50$.



SK neutrino constraint



The gamma-ray from the GC (HESS)



HESS, PRL(2006)

Conclusions

- DM from leptophilic $U(1)_{L_\mu - L_\tau}$ model can be an explanation of positron/electron excess in PAMELA, Fermi LAT and HESS CR experiments.
  - the fit to the data is excellent when $M_{\rm DM} = 2000$ GeV
  - the required BF can be obtained from the Sommerfeld enhancement
  - $M_{\rm DM} = 2000$ GeV is only marginally allowed. $M_{\rm DM} > 2000$ GeV is ruled out by SK muon flux.
  - NFW density profile is disfavored by the HESS gamma-ray data. The isothermal profile is consistent with the data.
- LHC can cover the large parameter space of $U(1)_{L_\mu - L_\tau}$ model through multi muon/tau events.
- The Higgs searches can be non-standard.

Leptophobic Z' motivated by DAMA/CoGeNT: a part of SUSY U(1)B x U(1)L

works in preparation with
Omura and Gondolo

Contents

1. Introduction

- We discuss supersymmetric model with $U(1)_B$ and $U(1)_L$ gauge symmetries.
- Baryon symmetry and Lepton symmetry forbid the operator to cause proton decay. However, they must be broken to realize Baryon asymmetry.

- Our scenario is …

  The both symmetries are broken around TeV scale.

  (We do not discuss U(1)L sector in this talk.)

- *T.R. Dulaney*, *P. F. Perez*, and *M.B. Wise* suggested the non-SUSY model with $U(1)_B \times U(1)_L$. (1002.1754;1005.0617[hep-ph])

  They discussed how to realize Baryon asymmetry, and found that **the extension of $U(1)_B$ symmetry naturally gives a cold dark matter (CDM) candidate**.

- In the experiments concerned with DM, there are many signals which we can expect to relate to DM physics. The direct searches (*DAMA, CoGeNT etc.*) suggest light DM, and the indirect (*PAMELA etc.*) heavy DM.

- The extension of MSSM to $U(1)_B$ and $U(1)_L$, we discuss here, provides several DM candidates. Our model provides DM physics and experiments with interesting observations.

Furthermore, this model suggests a lot of interesting aspects, such as higgs physics, flavor physics and so on.

In this talk, I introduce DM candidates and focus on ~7GeV CDM, discussed in 1007.1005 [hep-ph] by Hooper, Collar, Hall and McKinsey .
Then we discuss several experimental constraints.

2. $U(1)_B \times U(1)_L$ Model

In MSSM, Baryon symmetry and Lepton symmetry are good symmetries at classical level.

$$U(1)_B : Q^i \to e^{\frac{ig_B}{3}} Q^i, U^i \to e^{\frac{-ig_B}{3}} U^i$$

$$U(1)_L : L^i \to e^{ig_L} L^i, E^i \to e^{-ig_L} E^i$$

However, these symmetries are anomalous,

$$SU(2)^2 U(1)_B = \frac{3}{2}, \quad U(1)_Y^2 U(1)_B = -\frac{3}{2}$$

$$SU(2)^2 U(1)_L = \frac{3}{2}, \quad U(1)_Y^2 U(1)_L = -\frac{3}{2}$$

where right-handed neutrino, N_i, are added.

Extra chiral superfields must be added to built gauged B and L model.

field contents

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_B \times U(1)_L$$

Field	Charges	Fields	Charges
Q^i	$(3, 2, 1/6; 1/3, 0)$	Q'	$(\bar{3}, 2, -1/6; -1, 0)$
U^i	$(\bar{3}, 1, -2/3; -1/3, 0)$	U'	$(3, 1, 2/3; 1, 0)$
D^i	$(\bar{3}, 1, +1/3; -1/3, 0)$	D'	$(3, 1, -1/3; 1, 0)$
L^i	$(1, 2, -1/2; 0, 1)$	L'	$(1, 2, 1/2; 0, -3)$
E^i	$(1, 1, 1; 0, -1)$	E'	$(1, 1, -1; 0, 3)$
N^i	$(1, 1, 0; 0, -1)$	N'	$(1, 1, 0; 0, 3)$
H_u	$(1, 2, 1/2; 0, 0)$	H_d	$(1, 2, -1/2; 0, 0)$
X_B	$(1, 1, 0; 2/3, 0)$	$\overline{X_B}$	$(1, 1, 0; -2/3, 0)$
S_L	$(1, 1, 0; 0, 2)$	$\overline{S_L}$	$(1, 1, 0; 0, -2)$
S_B	$(1, 1, 0; n_B, 0)$	$\overline{S_B}$	$(1, 1, 0; -n_B, 0)$
X_L	$(1, 1, 0; n_L, 0)$	$\overline{X_L}$	$(1, 1, 0; -n_L, 0)$

Extra Quarks (chirality is opposite.)

They break U(1)L and U(1)B.

$n_B \neq \pm\frac{2}{3}, n_L \neq \pm 2$ to forbid couplings between SM particles and $S_B(\bar{S}_B), X_L(\bar{X}_L)$.

Superpotential for extra superfields

The difference is only chirality.
Extra quark and lepton mass terms are

Quark sector: $Y_u^{'}Q^{'}U^{'}H_d + Y_d^{'}Q^{'}D^{'}H_u$

Lepton sector: $Y_l^{'}L^{'}E^{'}H_u + Y_\nu^{'}L^{'}N^{'}H_d$

In order to avoid stable charged particles and generate neutrino masses, the couplings between extra B and L symmetric superfields and MSSM fields are given by

$$\lambda_{Qi}X_B Q^{'}Q^i + \lambda_{Ui}\overline{X_B}U^{'}U^i + \lambda_{Di}\overline{X_B}D^{'}D^i$$

$$\lambda_{Ei}\overline{S_L}E^{'}E_i + \lambda_i S_L L^{'}L_i + \lambda_{ij}N^i N^j S_L + \lambda_{Ni}N_i\overline{S_L}N^{'}$$

Assumptions to avoid large FCNC are

$$\langle X_B\rangle = \langle \overline{X}_B\rangle = 0$$

$$\langle S_L\rangle, \langle \overline{S}_L\rangle \neq 0, \quad \lambda_{Ei}, \lambda_i \approx 0$$

3. CDM in the $U(1)_B \times U(1)_L$ Model

The symmetries of cold dark matter (CDM)

1) The B and L charges of S_B and S_L are $n_B=2k/3$ $(k=2,3,\dots)$ and $n_L=2k$ $(k=2,3,\dots)$,

$U(1)_B$ breaking: $\langle S_B \rangle, \langle \bar{S}_B \rangle \neq 0 \longrightarrow Z_2^B$

$U(1)_L$ breaking: $\langle S_L \rangle, \langle \bar{S}_L \rangle \neq 0 \longrightarrow Z_2^L$

} **R-parity** $(-1)^{3B+L+2j}$

R-parity even: q, X_B, S_B, S_L

odd: $\tilde{q}, \tilde{X}_B, \tilde{S}_B, \tilde{S}_L$

2) Global $U(1)$ symmetries can be assigned, because of

$$\langle X_B \rangle = \langle \bar{X}_B \rangle = 0, \langle X_L \rangle = \langle \bar{X}_L \rangle = 0.$$

$U(1)_{XB}$: $X_B \to e^{i\alpha} X_B,\ Q' \to e^{-i\alpha} Q',\ U' \to e^{-i\alpha} U'$

$U(1)_{XL}$: $X_L \to e^{i\alpha} X_L,\ \bar{X}_L \to e^{-i\alpha} \bar{X}_L$

five candidates for DM

$$(\lambda_B, \tilde{S}_B, \overline{\tilde{S}_B}) \Longrightarrow \chi^1_B$$

$$(\lambda_L, \tilde{S}_L, \overline{\tilde{S}_L}) \Longrightarrow \chi^1_L$$

$$(\widetilde{B}, \widetilde{W}^3, \widetilde{H}_u, \widetilde{H}_d) \Longrightarrow \hat{\chi}^0_1$$

χ^0_1 **(Lightest component)**

There is mixing at one-loop.

$$(X_B, \overline{X}_B^*) \Longrightarrow X'_B$$ **(Lightest complex scalar)**

$$(\widetilde{X}_B, \widetilde{\overline{X}}_B^+) \Longrightarrow \widetilde{X}_B$$ **((U(1)XB charged) dirac fermion)**

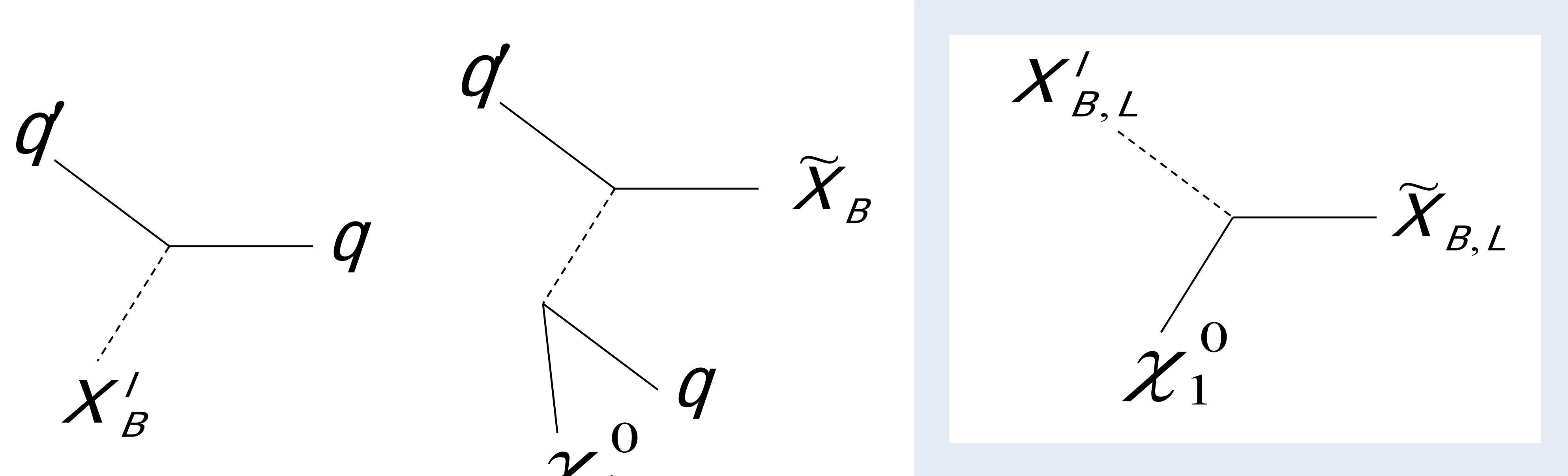
$$(X_L, \overline{X}_L^*) \Longrightarrow X'_L$$ **(Lightest complex scalar)**

$$(\widetilde{X}_L, \widetilde{\overline{X}}_L^+) \Longrightarrow \widetilde{X}_L$$ **((U(1)XL charged) dirac fermion)**

- 3 particles of them can be stable, because of 3 global symmetries, *U(1)XB*, *U(1)XL*, and *R-parity*.

2010년 9월 23일 목요일

- ***Important vertex***



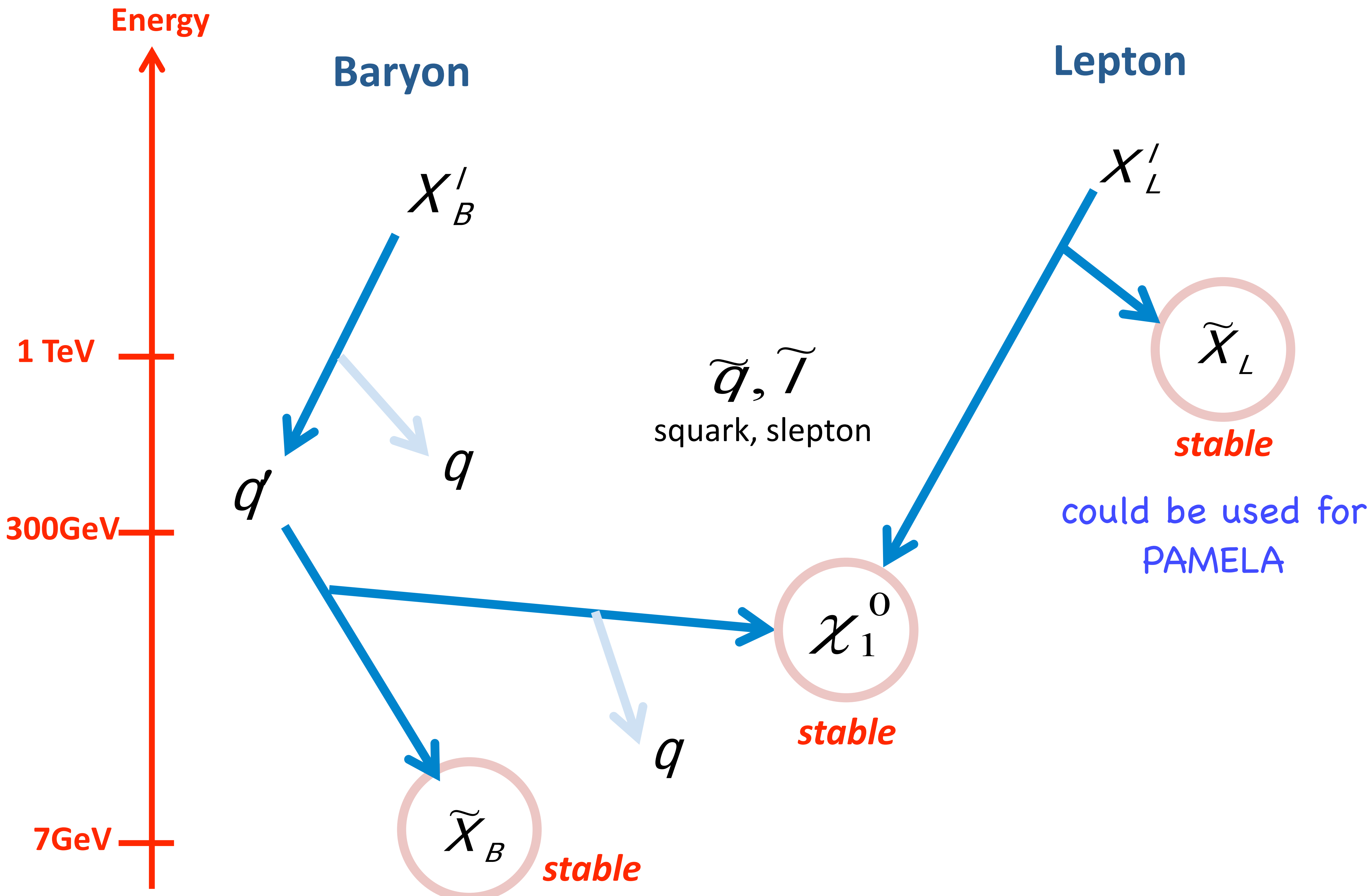
2 of 5 decay to 2 CDM.

- ➢ *q'* limits the masses of CDM.
- ➢ *q'* is charged under U(1)XB, so at least one of X'_B and $\tilde{X}_B$ must be smaller than *q'*.
- ➢ R-parity of *q'* is even, so it cannot decay to only $\tilde{X}_B$ and quarks.

<u>I introduce the scenario that $\tilde{X}_B$ is the lightest.</u>

We assume that SUSY particles, such as squarks and sleptons, are very heavy, around 1 TeV.

Example



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4. ~ 7 GeV Dark Matter

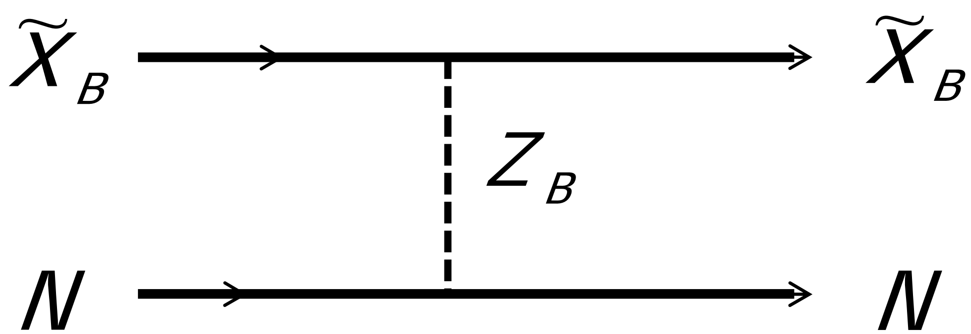
- D. Hooper, J.I. Collar, J. Hall and D. McKinsey (1007.1005 [hep-ph]) suggest

$$m_{DM} \cong 7\,GeV, \quad \sigma_{SI} \cong 2\times 10^{-40}\,cm^2.$$

- *Direct detection vs Relic density* due to vector current coupling

Direct detection

U(1)B charged particles scatters with Nuclei through *ZB* boson (*squark'*),



$$\sigma_{SI} = BQ_X^2 Q_N^2 \frac{\mu_X^2}{\pi}\left(\frac{g_B}{M_{Z_B}}\right)^4 \Longleftrightarrow \left(\frac{g_B}{M_{Z_B}}\right)^4 = \frac{\sigma_{SI}\pi}{\mu_X^2 Q_X^2 Q_N^2 B}$$

Roughly, $\frac{M_{Z_B}}{g_B} \sim O(TeV)$. It must explain relic density, $\Omega h^2_{CDM} \cong 0.11.$

Relic density

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma v \rangle \left(n_X^2 - n_{eq}^2 \right)$$

As well known, the Boltzmann equation is approximatelly estimated as

$$\Omega h^2 \cong 0.1 \times \left(\frac{1\,pb}{\langle \sigma v \rangle} \right).$$

Annihilation cross section of $\widetilde{X}_B$ through Z_B boson is

$$\sigma v \cong \frac{A_{an}(m_{DM}, M_{Z_B}) Q_X^2}{\pi} \left(\frac{g_B}{M_{Z_B}} \right)^4 \left(m_{DM}^2 \sum_q Q_q^2 + \cdots \right)$$

S-wave

Boson case is p-wave, no S-wave.

Direct scattering leads

$$\Omega h^2 \cong O(10) \times \left(\frac{B Q_N^2}{A_{an} \sum Q_q^2} \right)$$

for $m_{DM} \cong 7\,GeV$.

$B = 1$, for dirac fermion and boson

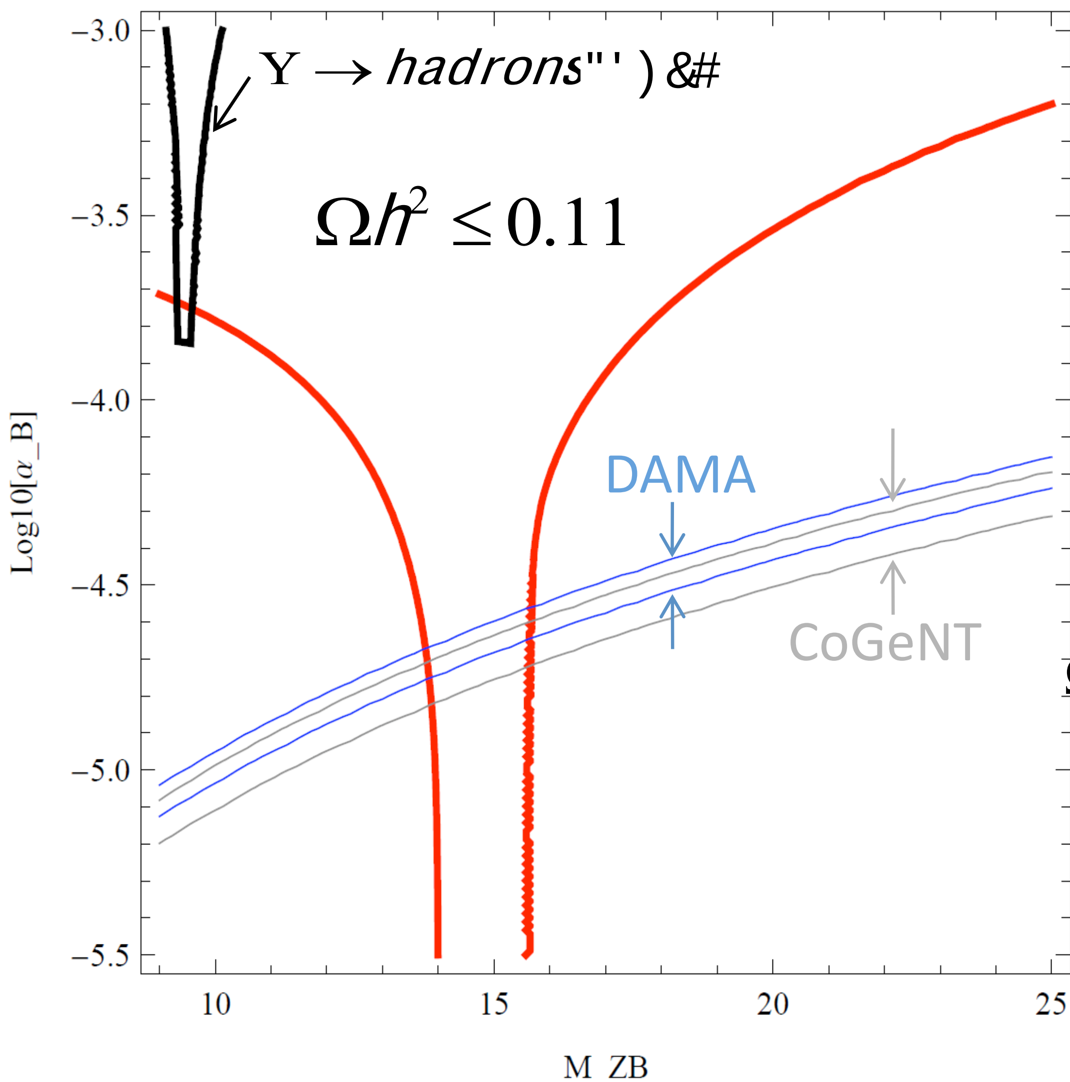
$A_{an}(m_{DM}, M_{Z_B})$ must be large to explain the relic density, around 0.11.

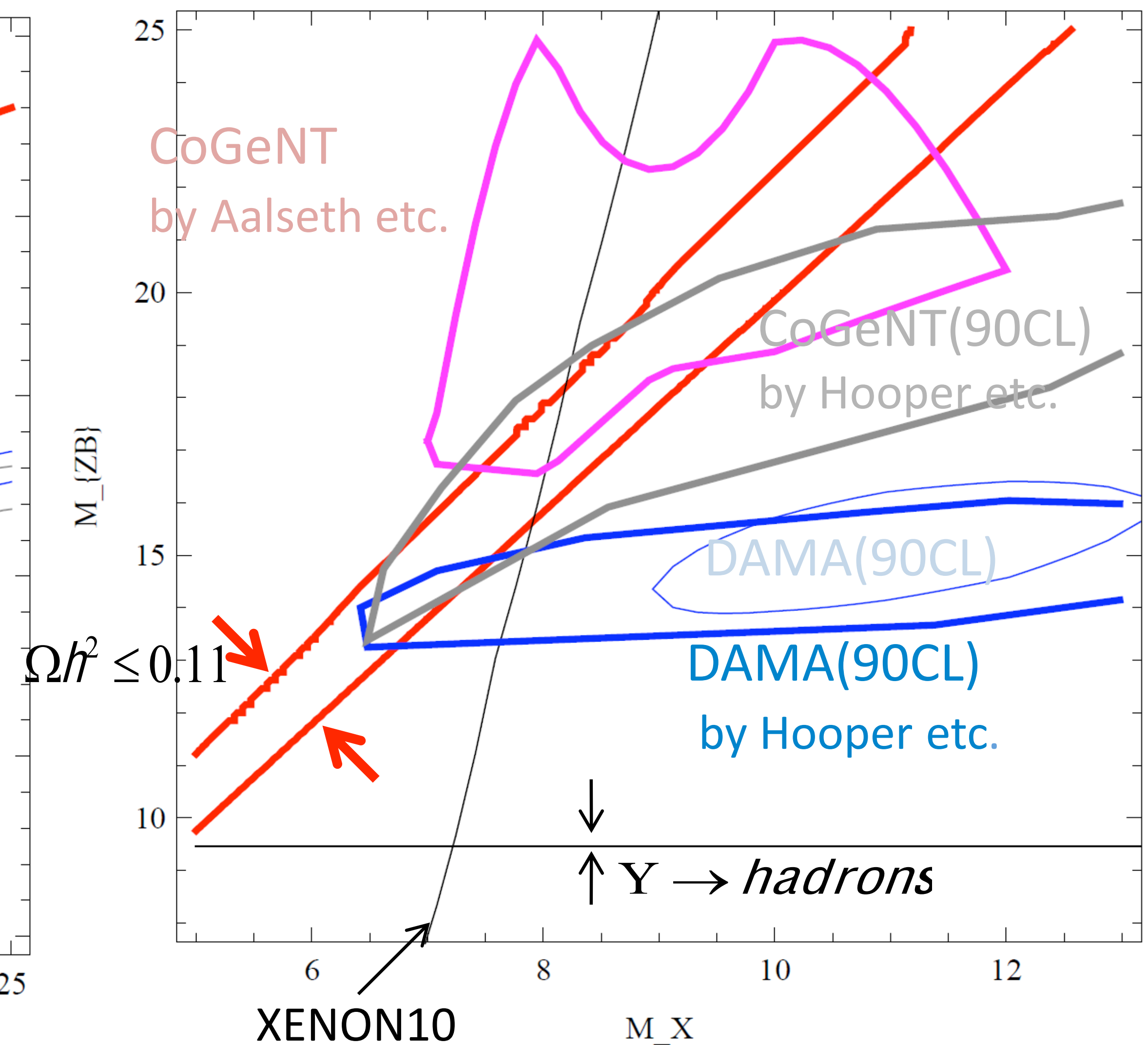
We use resonance enhancement.

2010년 9월 23일 목요일

$ *(! (% =7 GeV)

% vs ! ($\alpha_B \sim 2\times10^{-5}$)





$$A_{an}(m_{DM}, M_{Z_B}) = \frac{M_{Z_B}^4}{\left(M_{Z_B}^2 - m_X^2\right)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2} \geq O(10)$$

Very small mass and coupling are required,

$$\alpha_B \sim 2\times10^{-5}, M_{Z_B} \sim 2m_X.$$

5. Constraints

- Constraints on very light Z_B boson mass have been discussed.
- For example, the hadoronic decay width of Z boson require $\alpha_B < 0.2$. Upsiron decay to hadrons gives the strongest constraint.

(PRL74,3122(1995) by C.D.Carone and H. Murayama, PLB443, 352(1998) by A.Aranda and C.D.Carone.)

Our model has enough small *U(1)*$_B$ gauge coupling.

- On the other hand, kinematic mixing must be enough small to avoid conflicts with experiments. $Tr(BY) \neq 0$
- Other stable particles also contribute to the relic density. There are a lot of arguments about heavy DM and scalar DM,

Scalar DM with yukawa:PLB670,37(2008) by J.L.Feng, J.Kumar, L.E.Strigari

MSSM DM: PR267,195(1996), by G.Jungman, M.Kamionkowski, K.Griest, etc.

- Our model predicts very light scalar.

$\left(S_B, \bar{S}_B\right)$, which correspond to Higgs, give this lightest scalar.

$$m_{S1}^2 \leq M_{Z_B}^2 \cos^2 2\beta_B + \alpha_B M_{Z_B}^2 \cos^2 2\beta_B f\left(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2\right)$$

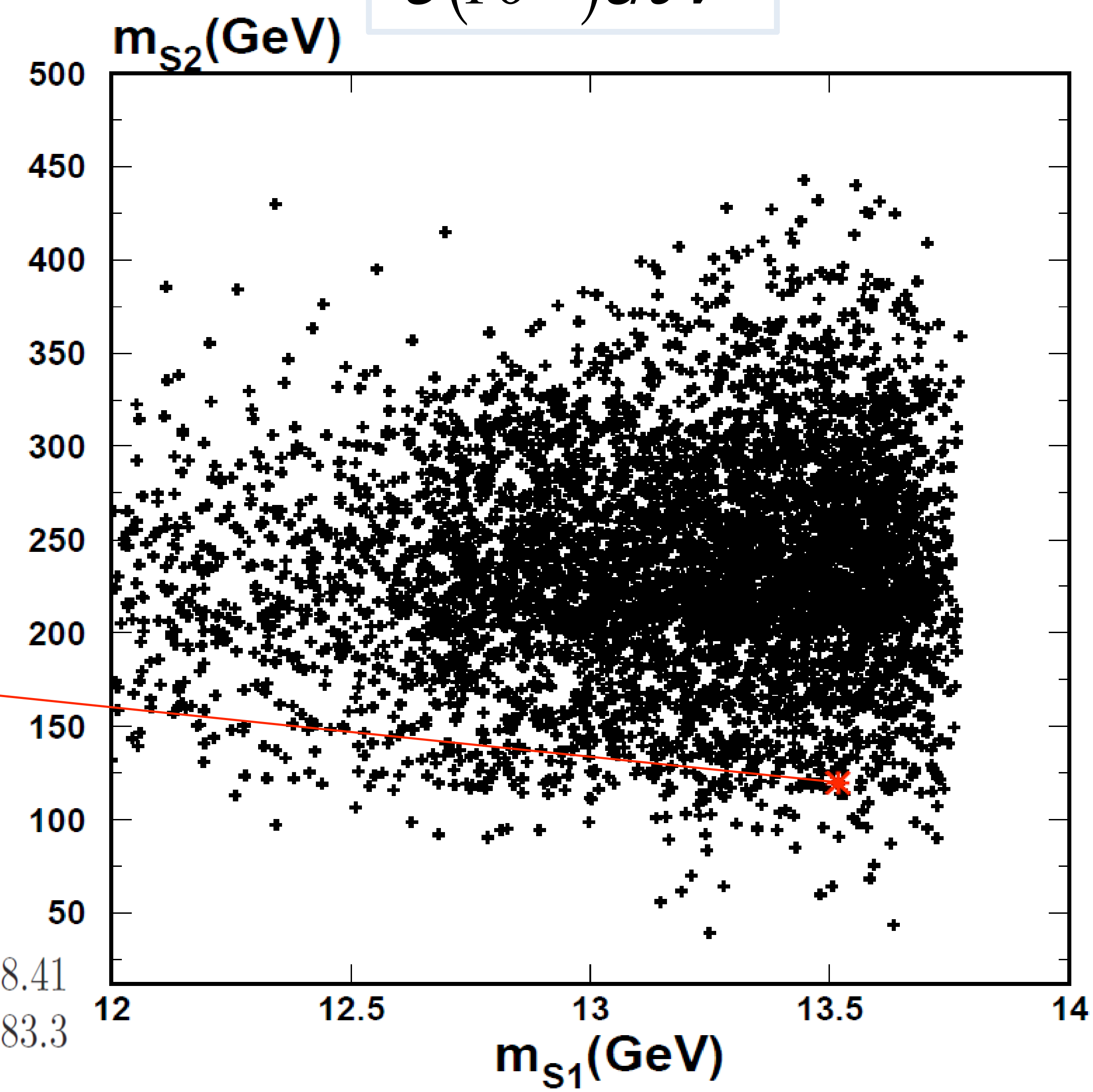
$O\left(10^{-3}\right) GeV^2$

- They do not couple with SM particles at tree level.
- The one-loop corrections are also strongly suppressed by small *U(1)B* coupling.

ex)

S_i	m_{S_i} GeV	$C^2_{S_i ZZ}$
S_1	13.5	0.506×10^{-7}
S_2	119.7	0.931×10^{-1}
S_3	283.3	0.100×10^{-6}
S_4	396.4	0.203
S_5	398.1	0.70257
S_6	495.8	0.114×10^{-2}

TABLE: $\sum_{i=1}^{6} C^2_{S_i ZZ} = 1$, $m_{t'} = 309.7$ GeV, $m_{b'} = 368.41$ GeV, $m_{\tau'} = 499.7$ GeV, $m_{P_H} = 297.0$ GeV, $m_{P_B} = 283.3$ GeV, $m_{P_L} = 401.1$ GeV.



6. Summary

- We discussed supersymmetric model with $U(1)_B \times U(1)_L$ gauge symmetries.
- This model provides a lot of interesting topics, such as Flavor physics, Higgs physics, dark matter, and so on. I introduced DM physics related to direct detections.
- There are several candidates for CDM and several scenarios. In any cases, 3 stable particles appear.
- In order to explain ~7GeV CDM of CoGeNT/DAMA, we considered very light Z_B mass and the resonance effect. $U(1)_B$ gauge coupling is also very small,

$$\alpha_B \sim 2\times10^{-5}, M_{Z_B} \sim 2m_{DM}.$$

- I introduced several constraints, especially the predicted light scalar.

Conclusion

- I presented two models with exotic Z's (leptophilic and leptophobic) which are motivated by (in)direct detection of CDM
- These Z's are not easy to detect: not strongly constrained so far
- Leptophilic Z' in the 1st model could be in the reach of the LHC
- Leptophobic Z' (for DAMA/CoGeNT) is more difficult to detect because of low mass and small coupling