Minimal Dirac Fermionic Dark Matter

Jae Ho HEO

University of Illinois at Chicago

PHENO 07

INTRODUCTION

We will assume that a spin ½ Dirac fermion is WIMP with a mass roughly near the electroweak scale (10~1000 GeV) and electro-magnetic dipole couplings. We don’t assume other new particles at that scale.

OUTLINE

- **Theoretical Description (Lagrangian)** :

  The effective Lagrangian with dimension 5 dipole operator.

- **Annihilation process** :

  WIMP may annihilate into SM particles via dipoles

- **Relic abundnace** :

  Strength of dipoles induced present WIMP Relic abundance

- **Direct dark matter detect** : CDMS, DAMA, GENIUS
- **Indirect dark matter detect** : neutrino telescopes
- **Collider** : WIMP production at ILC,LHC
- **Conclusion**

THEORETICAL DESCRIPTION

The effective Lagrangian with dimension 5 dipole operator,

$$\mathcal{L}_{eff} = \tfrac{1}{2}\mathcal{D}\ \bar{\psi}\sigma^{\mu\nu}\psi(B_{\mu\nu}+\tilde{B}_{\mu\nu})+\mathrm{H.C.}$$

$\mathcal{D} = |\mathcal{D}|e^{i\phi}$: complex coefficient dipole with CP phase ϕ

Rotate w.r.t Weinberg angle : $B_{\mu\nu} = \cos\theta_w F_{\mu\nu} - \sin\theta_w Z_{\mu\nu}$

$$\mathcal{L}_{eff} = \tfrac{1}{2}\ \bar{\psi}\sigma^{\mu\nu}(\mu + d\gamma^5)\psi\ (F_{\mu\nu} - \tan\theta_w Z_{\mu\nu})$$

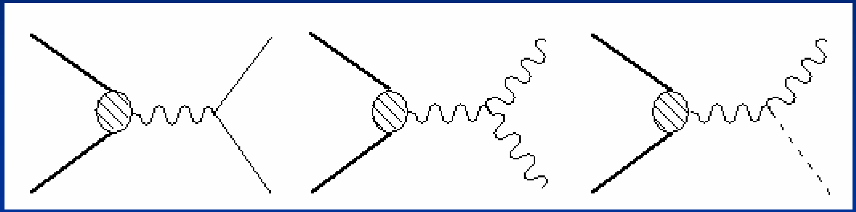
$$\mu = 2|\mathcal{D}|\cos\phi,\ d = 2|\mathcal{D}|\ \sin\phi\ ;\ d = \mu\ \tan\phi$$

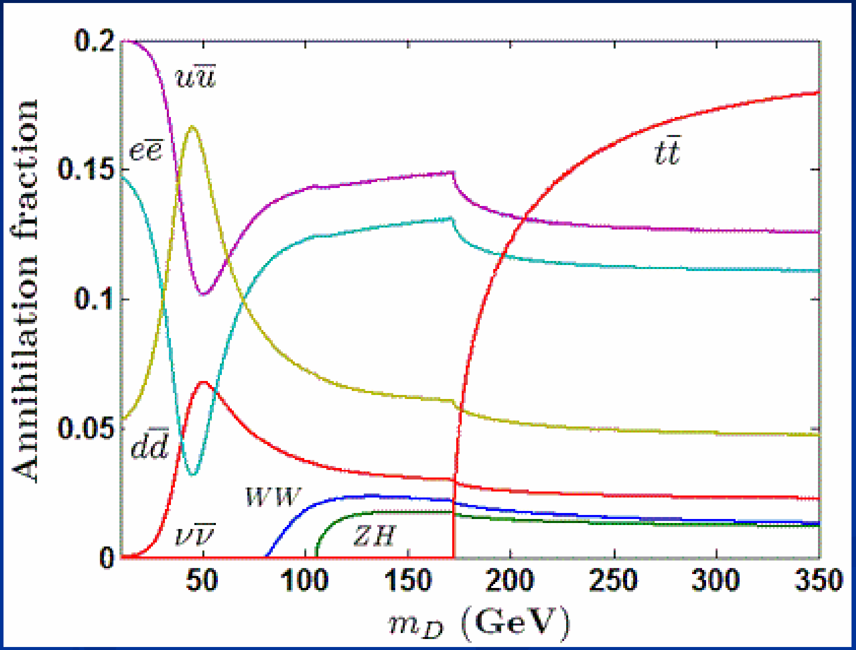
electron dipole experiment.
B. C. Regan, PRL, 88, 071805, 2002

CP is a good symmetry ($\phi \sim 0$), but the possibility of EDM ($\tan\phi < 2.4 \times 10^{-3}$)

ANNIHILATION PROCESS

γ,Z-mediated *s*-channel processes.





Annihilation fraction : fermionic annihilation products dominate, particularly hadronic annihilation. γ–Z interference plays important role for W-boson channel.

No mass and helicity suppression

Threshold suppression

Cross sections

$$\sigma_f = \sum_f \frac{N_C \alpha \beta_f [\mu^2 (s + 8m_D^2) + d^2 (s - 4m_D^2)]}{6\beta_D} [\frac{Q_f^2 \, (s + 2m_f^2)}{s^2} + \frac{s(c_V^2 + c_A^2) + m_f^2 (2c_V^2 - 4c_A^2)}{4c_W^4 [(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2]} - \frac{Q_f c_V (s - m_Z^2)(s + 2m_f^2)}{2c_W^2 s [(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2]}]$$

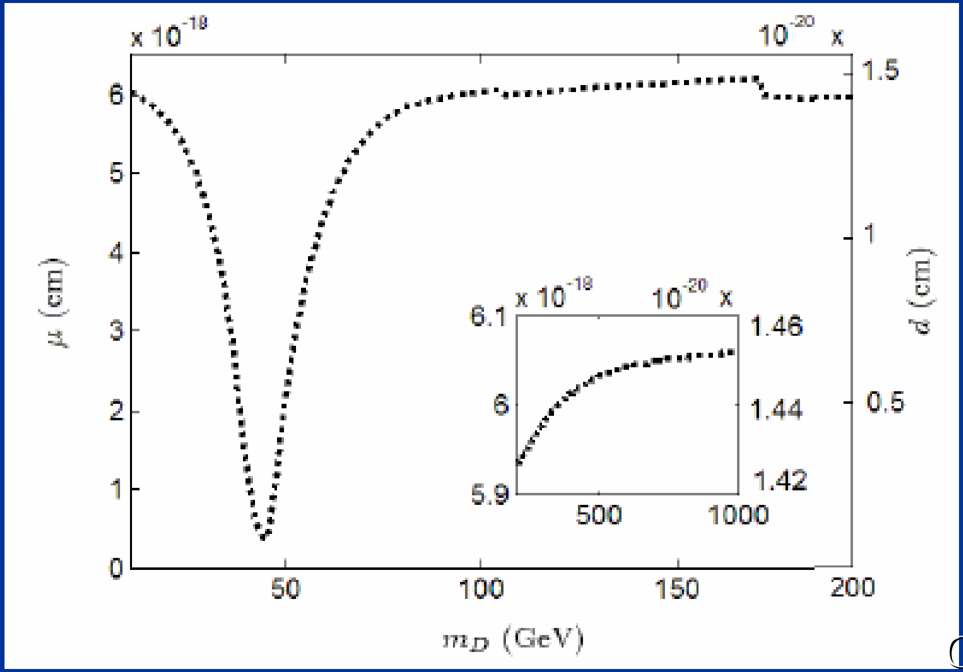
$$\sigma_W = \frac{\alpha \beta_W^3 [\mu^2 (s + 8m_D^2) + d^2 (s - 4m_D^2)]}{48\beta_D} [\frac{1}{s} + \frac{s}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} - \frac{2(s - m_Z^2)}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}] \frac{s^2 + 20 s m_W^2 + 12 m_W^4}{m_W^4}$$

$$\sigma_{ZH} = \frac{\alpha E_2 \beta_Z [\mu^2 (s + 8m_D^2) + d^2 (s - 4m_D^2)]}{4c_W^2 m_W^2 \sqrt{s} \beta_D} \frac{m_Z^4}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} (1 + \frac{E_2^2 \beta_Z^2}{3m_Z^2}), \quad \text{where} \quad E_2 \beta_Z = \frac{1}{2\sqrt{s}} ((s - m_H^2 + m_Z^2)^2 - 4 s m_Z^2)^{1/2}$$

RELIC ABUNDANCE

Thermal average for this annihilation

$$<\sigma\beta_D>=\frac{x}{8m_D^5K_2^2(x)}\int_{4m_D^2}^{\infty}ds\,\sigma(s)\beta_D^2s^{3/2}K_1\left(\frac{\sqrt{s}}{m_D}x\right)$$



This implies the new physics with

O(Λ)~3 TeV for MDM

O(Λ)~1 PeV for EDM

P.Gondolo NP B360, 124 (1991)

WMAP data

: $0.0946 < \Omega_{CDM}h^2 < 0.1286$ (at 2σ)

Relic density : Time evolution

Boltzmann equation

$$\frac{dn_D}{dt}+3Hn_D=-<\sigma\beta_D>[n_D^2-(n_D^{EQ})^2]$$

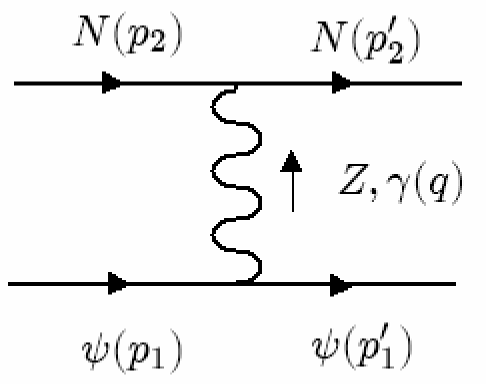
$$\Omega_Dh^2\simeq\frac{(1.07\times10^9)x_F}{\sqrt{g_*}m_{Pl}(GeV)<\sigma\beta_D>}$$

Constant inverse freeze out temperature : x_f~20

Constant annihilation rate : $<\sigma\beta_D>$ ~0.6pb

Direct Dark Matter Detect

Leading Feynman diagram (*t*-channel)



The events rate per unit target mass and unit time :

$$R = \frac{dN}{m_T dt} = \frac{\rho_D}{m_A m_D} \int_{\beta_{\min}}^{\beta_{\max}} \beta f(\beta) \sigma_{el} d^3\beta$$

Boltzman distribution

We have to calculate the elastic cross section, σ_{el}

MDM $\mathcal{L}_{eff} = \alpha_N \overline{\psi} \sigma^{\mu\nu} q_\nu \psi \overline{N} \gamma_\mu (1 - \epsilon \cancel{\gamma}^5) N$

EDM $\mathcal{L}_{eff} = \alpha_N \overline{\psi} \sigma^{\mu\nu} q_\nu \gamma^5 \psi \overline{N} \gamma_\mu (1 - \epsilon \cancel{\gamma}^5) N$

q is space-like vector,
time component is gone

$$\sigma_{el} = \frac{4}{\pi m_A^2 \beta^2} \int d|\vec{q}|^2 \alpha_\mu^2 |\vec{q}|^4$$

Extremely non-relativistic case
only consider time component

$$\sigma_{el} = \frac{1}{4\pi\beta^2} \int d|\vec{q}|^2 \alpha_d^2 |\vec{q}|^2$$

The couplings $\alpha_{\mu(d)}$ depend on the mediators (γ, *Z*) and atomic structure.

$Z\text{-boson} : \alpha_{\mu(d)} \sim \frac{[Z(1-4s_W^2)-(A-Z)]^2}{m_Z^2}$ mainly interact with neutron

$\gamma : \alpha_{\mu(d)} \simeq Z\alpha_p = \frac{Z\mu(d)e}{|\vec{q}|^2}$ Interact with proton

The contribution by Z-boson
Is very small at low energy
so neglect

MDM

$$\sigma_{el} = \frac{2Z^2\mu^2\alpha m_r^2}{m_A^2}$$

EDM

$$\sigma_{el} = \frac{Z^2 d^2 \alpha}{\beta^2}\log\left(\frac{|\overrightarrow{q}|^2_{\max}}{|\overrightarrow{q}|^2_{\min}}\right)$$

$$|\overrightarrow{q}|^2_{\max} = 4m_r^2\beta^2$$

$$|\overrightarrow{q}|^2_{\min} = 2m_A E_{R,\min}$$

$$R = \frac{\rho_D \sigma_{el}}{2m_D m_r^2}\frac{E_{R,\max}-E_{R,\min}}{2\beta_E}\left[\mathrm{erf}\left(\frac{\beta_{\min}+\beta_E}{\beta_0}\right) - \mathrm{erf}\left(\frac{\beta_{\min}-\beta_E}{\beta_0}\right)\right]$$

$$R = \frac{\rho_D \sigma_{el}}{m_A m_D}\frac{\beta^2 \log(E_{R,\max}/E_{R,\min})}{2\beta_E \log(|\overrightarrow{q}|^2_{\max}/|\overrightarrow{q}|^2_{\min})}\left[\mathrm{erf}\left(\frac{\beta_{\min}+\beta_E}{\beta_0}\right) - \mathrm{erf}\left(\frac{\beta_{\min}-\beta_E}{\beta_0}\right)\right]$$

TABLE I: Current and planned Dark Matter detectors. DAMA and CDMS is the most sensitive detectors and GENIUS is a future detector.

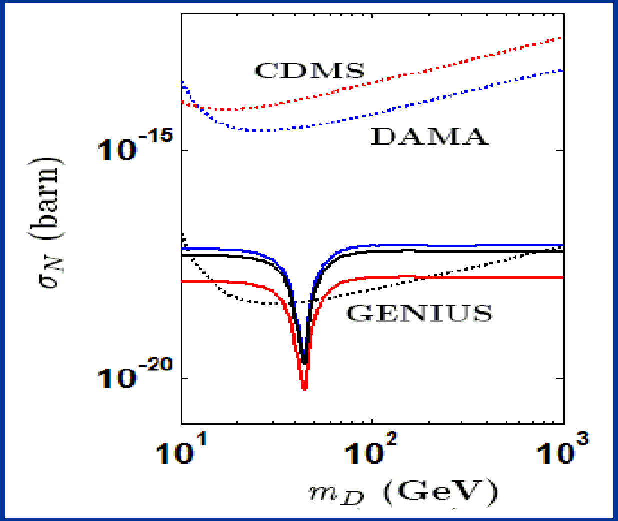
Experiment	Recoil energy range	Target	Mass(Kg)
DAMA	$2 \sim 20$KeV	NaI	250Kg
CDMS	$10 \sim 100$KeV	^{73}Ge	100Kg
GENIUS	$15 \sim 45$KeV	^{76}Ge	100Kg

current

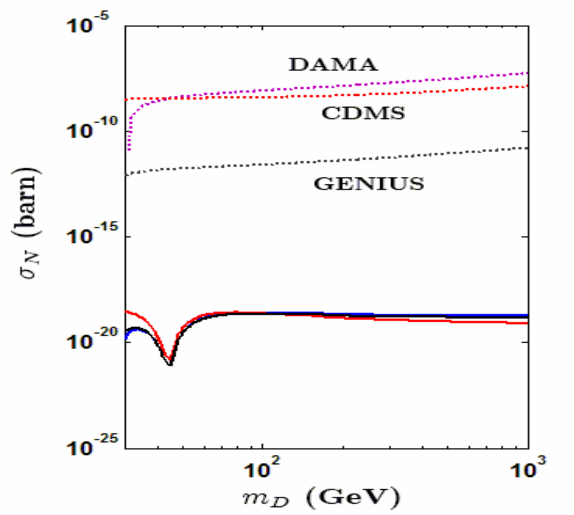
future

Cross section per nucleon

$$\sigma_N = \frac{m_r^2(P,D)}{A^2 m_r^2(A,D)}\sigma_{el}$$



Experimental sensitivity(R) :
DAMA : 1 event/kg/day
CDMS : 1 event/kg/day
GENIUS (Super CDMS)
: 1X10^{-4} event/kg/day



Both satisfy the present constraint

WIMP is in observation at GENIUS

Indirect Dark Matter Detect (neutrino telescopes)

WIMPs in the halo are trapped gravitationally

Maxwellian distribution, scattering kinematics, geometrical cross secion

Trapped WIMPs sink to the core of the Sun and Earth. They annihilate into ordinary particles. Because of absorption only neutrinos are capable of escaping to the surface.

Each annihilation decay two particles

These energetic neutrinos reach the terrestrial detectors.

Probability for a neutrino escaping the Sun

A small fraction of them are converted to muons through charged current interactions

Neutrino telescopes observe high energy muon neutrinos by identifying a muon track in detector.

General formulae for capture rate

$$C^{\odot} = (\frac{3}{2}\pi)^{1/2}(2GM_{\odot}R_{\odot})n_D f_\sigma f_E/\overline{v}$$

$$n_D = \frac{\rho_D}{m_D}$$
$$f_\sigma \sim Y_N\sigma_N$$
$$f_E \sim \frac{1}{m_D}$$

W. Press, ASP. J 296, 679, 1985

$$C^{\odot} = \frac{3.14 \times 10^{26}\,\mathrm{sec}^{-1}}{m_D^2}\sum_N \sigma_{N,36}Y_N m_N$$

$$\phi_{i\odot}^{\mathrm{ini}} = \frac{1}{2}\frac{C^{\odot}f_i}{4\pi \mathrm{R}_{ES}^2} = (559cm^{-2}\,\mathrm{sec}^{-1})\sum_N \frac{f_i\sigma_{N,36}Y_N m_N}{m_D^2}$$

$$\phi_{i\odot} \simeq (559cm^{-2}\,\mathrm{sec}^{-1})e^{-E_\nu/E_k}\sum_N \frac{f_i\sigma_{N,36}Y_N m_N}{m_D^2}$$

P. Cotty, PRD 66, 063504, 1985

$$\phi_{i\oplus} = \frac{1}{2}\frac{C^{\oplus}f_i}{4\pi \mathrm{R}_{\oplus}^2} = (0.05cm^{-2}\,\mathrm{sec}^{-1})\sum_N \frac{f_i\sigma_{N,36}Y_N m_N}{m_D^2}$$

$$\phi_\mu = P\phi_\nu \simeq 10^{-8}(\frac{E_\nu}{100GeV})^2\phi_\nu$$

K. Buner, PRL 73, 1067, 1994

$E_\nu \sim m_D$

Probability that a neutrino directed towords the detector produces a muon at the detector.

P. Cotty, PRD 66, 063504, 1985

$$\phi_\mu \simeq 3.3 \times 10^{-11} cm^{-2}\,\sec^{-1}\, e^{-m_D/E_K} \sigma_{N,36} \qquad E_K \simeq 130\text{ GeV for muon neutrino}$$

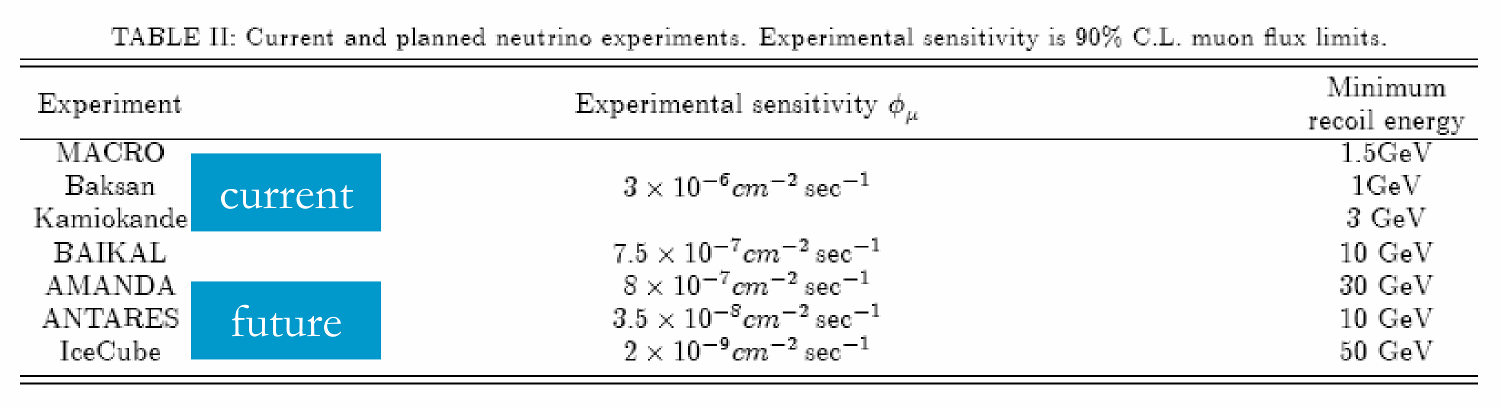
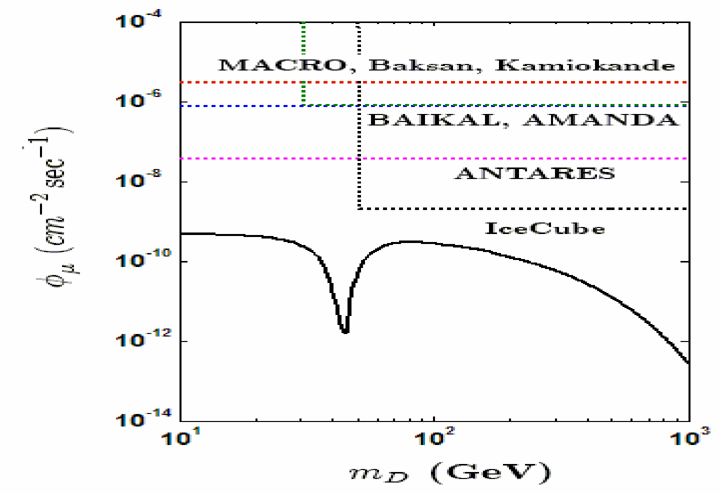
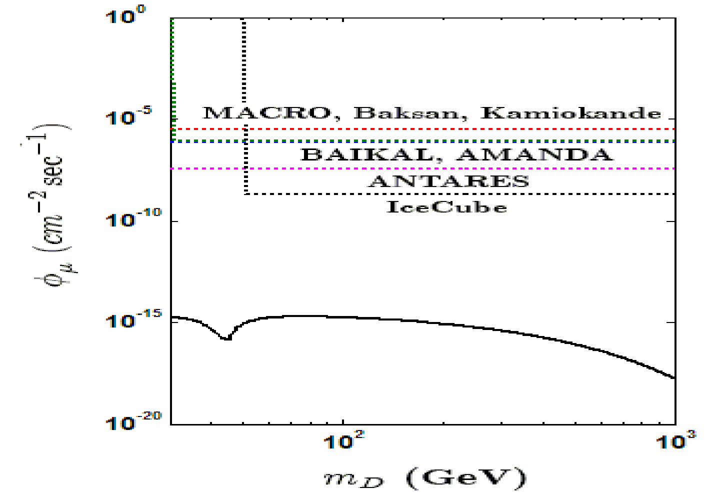


TABLE II: Current and planned neutrino experiments. Experimental sensitivity is 90% C.L. muon flux limits.

Experiment		Experimental sensitivity ϕ_μ	Minimum recoil energy
MACRO	current	$3 \times 10^{-6} cm^{-2} \sec^{-1}$	1.5GeV
Baksan			1GeV
Kamiokande			3 GeV
BAIKAL	future	$7.5 \times 10^{-7} cm^{-2} \sec^{-1}$	10 GeV
AMANDA		$8 \times 10^{-7} cm^{-2} \sec^{-1}$	30 GeV
ANTARES		$3.5 \times 10^{-8} cm^{-2} \sec^{-1}$	10 GeV
IceCube		$2 \times 10^{-9} cm^{-2} \sec^{-1}$	50 GeV



MDM



EDM

Both satisfy the present constraint

WIMP is not in observation in near future

Collider Experiments(ILC,LHC)

ILC : a hard-photon tagging

LHC : a hard photon, quark, gluon tagging

Kinematical cuts

$e^+e^- \rightarrow \psi\bar{\psi}\gamma$: ISR and ~~F~~SR

$q\bar{q} \rightarrow \psi\bar{\psi}\gamma,\ q\bar{q} \rightarrow \psi\bar{\psi}g,\ q(\bar{q})g \rightarrow \psi\bar{\psi}q(\bar{q})$

$$10^\circ < \theta_\gamma < 170^\circ(|\eta| < 2.4), \quad 10\ \text{GeV} \le E_T^\gamma \le \frac{s - 2m_D^2}{2\sqrt{s}}$$

$e^+e^- \rightarrow e^+e^-\gamma$ veto moller scattering events

A. Datta, PRD 59, 0550119 (1999)

$$\begin{array}{llll} \gamma : & 9^\circ < \theta_\gamma < 171^\circ & E_T \ge 47\ \text{GeV} & \not{E}_T \ge 42\ \text{GeV} \\ jet : & 3^\circ < \theta_{jet} < 177^\circ & E_T \ge 80\ \text{GeV} & \not{E}_T \ge 80\ \text{GeV} \end{array}$$

search for KK Graviton to isolate the tagged particles signal with a fixed cone of radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$

CDF col., hep-ex/0309051

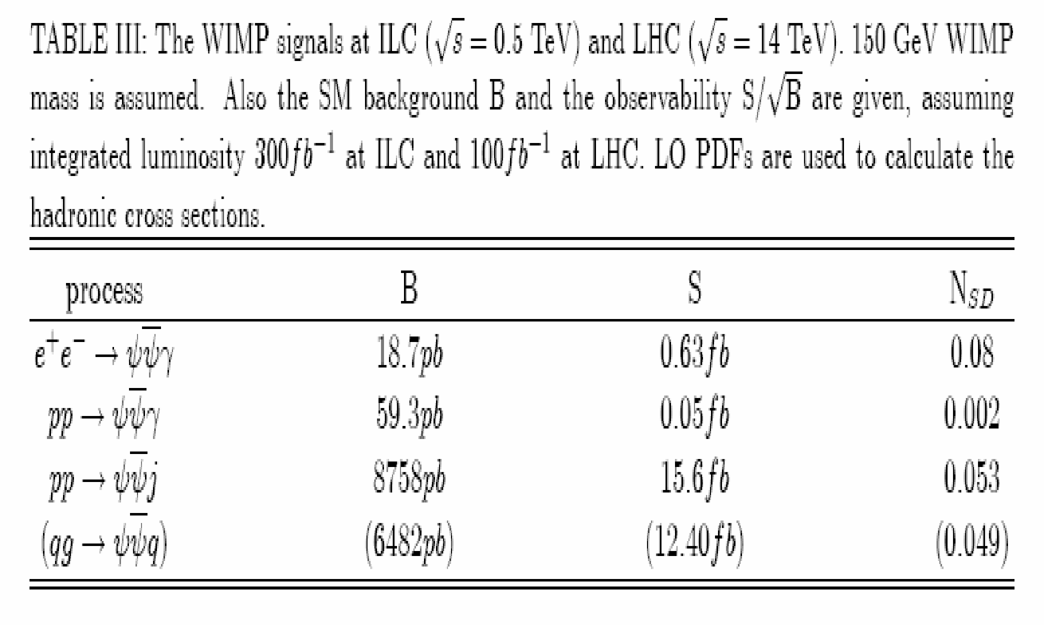


TABLE III: The WIMP signals at ILC ($\sqrt{s} = 0.5$ TeV) and LHC ($\sqrt{s} = 14$ TeV). 150 GeV WIMP mass is assumed. Also the SM background B and the observability $S/\sqrt{B}$ are given, assuming integrated luminosity $300 fb^{-1}$ at ILC and $100 fb^{-1}$ at LHC. LO PDFs are used to calculate the hadronic cross sections.

process	B	S	N_{SD}
$e^+e^- \rightarrow \psi\bar{\psi}\gamma$	18.7pb	0.63fb	0.08
$pp \rightarrow \psi\bar{\psi}\gamma$	59.3pb	0.05fb	0.002
$pp \rightarrow \psi\bar{\psi}j$	8758pb	15.6fb	0.053
$(qg \rightarrow \psi\bar{\psi}q)$	(6482pb)	(12.40fb)	(0.049)

S, B is the number of events for the signal and background (=σL). The main background is

ILC $e^+e^- \rightarrow \nu\bar{\nu}\gamma$

LHC $pp \rightarrow \nu\bar{\nu}\gamma(j)$

N_{SD}=5 : observability limit

Far from the observation at ILC, LHC

CONCLUSION

- A spin ½ Dirac fermion which has EM dipoles assumed WIMP and satisfy all experimental and observational constraints.
- This implies that spin ½ Dirac fermion may be WIMP.
- It can be observed with clear signals at on-going experiments in near future(GENIUS).