The top window for dark matter

arXiv:1009.0618 [JHEP10(2010)081]

張敬民 (Kingman Cheung), 瀬名波栄問 (Eibun Senaha),
曾柏彥 (Po-Yan Tseng), 阮自強 (Tzu-Chiang Yuan) [Taiwan]

馬渡健太郎 (Kentarou Mawatari)

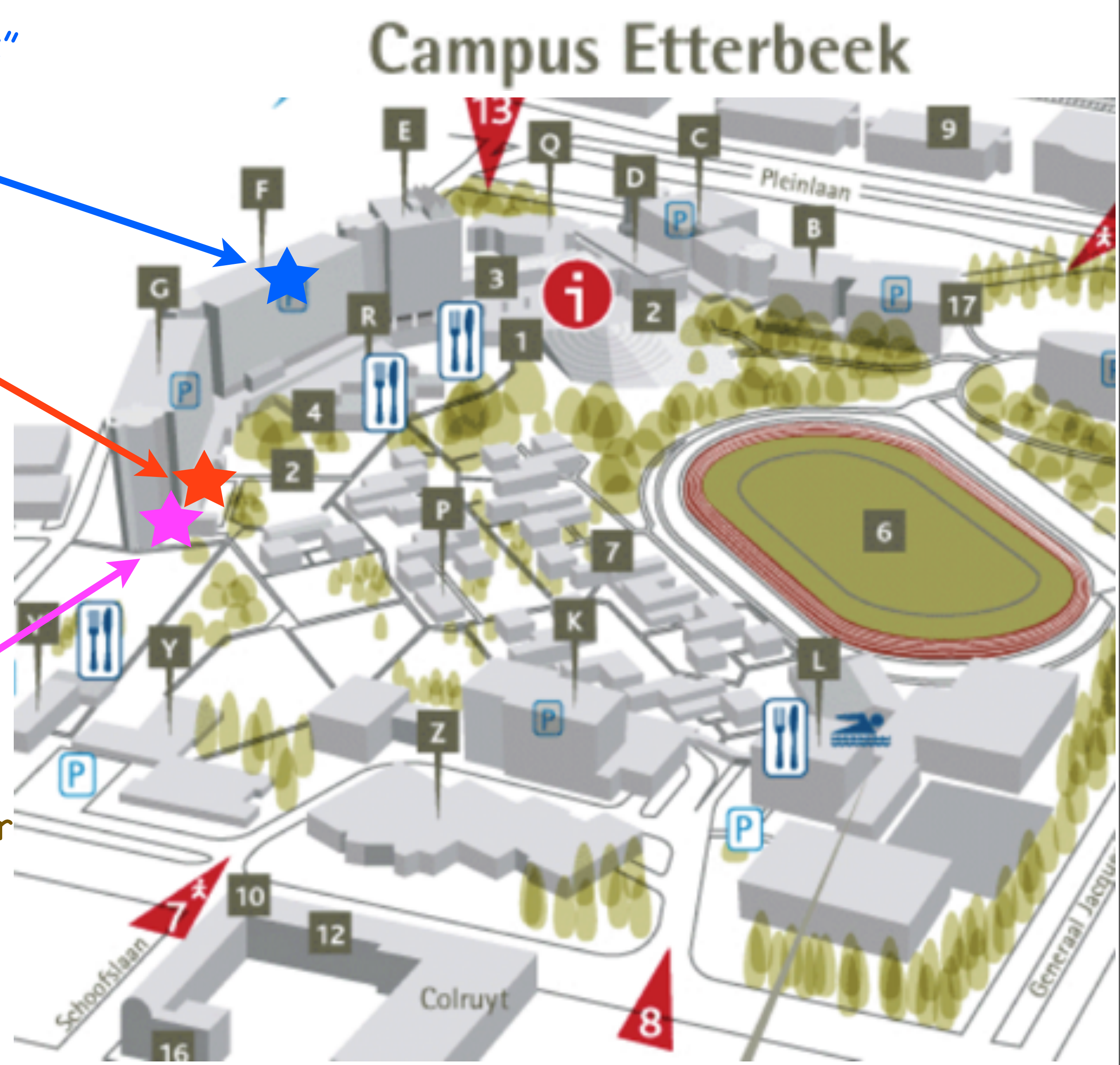
Vrije Universiteit Brussel

Theoretiche Natuurkunde (TENA)
Elementaire Deeltjes Fysica (ELEM)
Inter-univ. Institute for High Energies (IIHE)

Seminar @ ULB, 01/04/2011

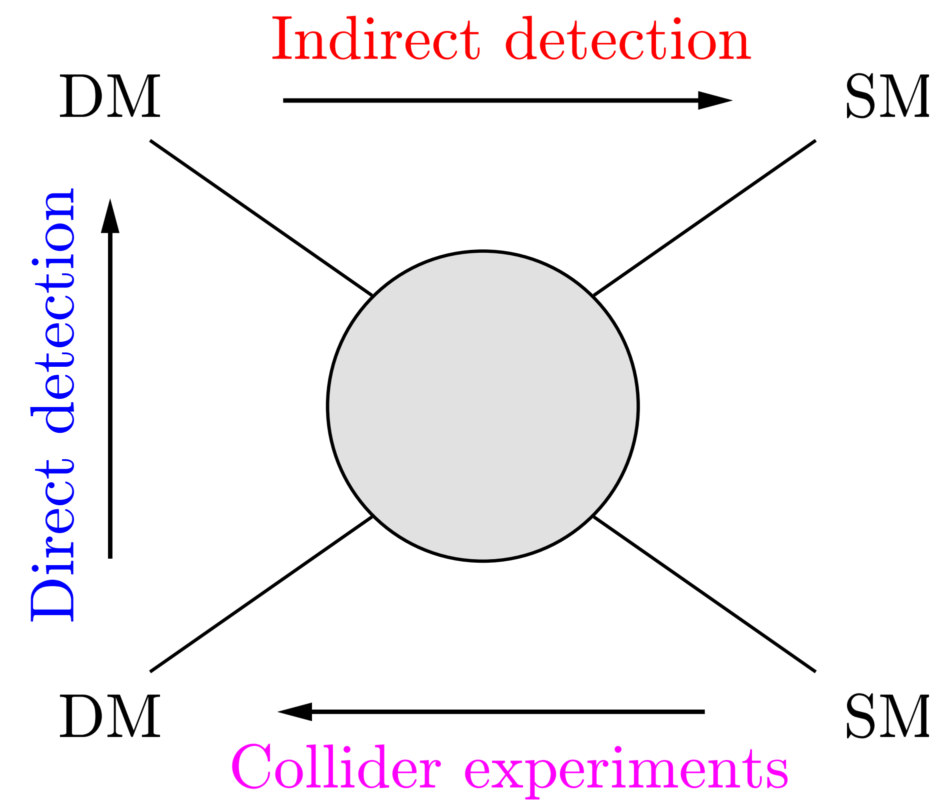
New phenomenology group at the VUB since 2010/Oct.

- A 5-year GOA (Geconcentreerde Onderzoeksactie) project on "Supersymmetric models and their signatures at the LHC"
  - Ben Craps, Alexander Sevrin, Alberto Mariotti (theory) - F. 9th floor
  - Catherine De Clercq, Jorgen D'Hondt (experiment) - G. 0th and 1st floor
  - Fabio Maltoni (pheno) - CP3/UCL
- The main goal of the project is
  - to establish a complete chain from fundamental theory to experiment.
  - to use this chain to study possible signatures of SUSY models at the LHC.
- The phenomenology members
  - Kentarou Mawatari (from U. Heidelberg) -Project leader
  - Phillip Grajek (from KEK, Japan) -PD
  - Bettina Oexl (from U. Tuebingen) -PhD
- Contact to
  - http://we.vub.ac.be/dntk/onderzoek/GOAindex.htm
  - pheno@vub.ac.be



Outline

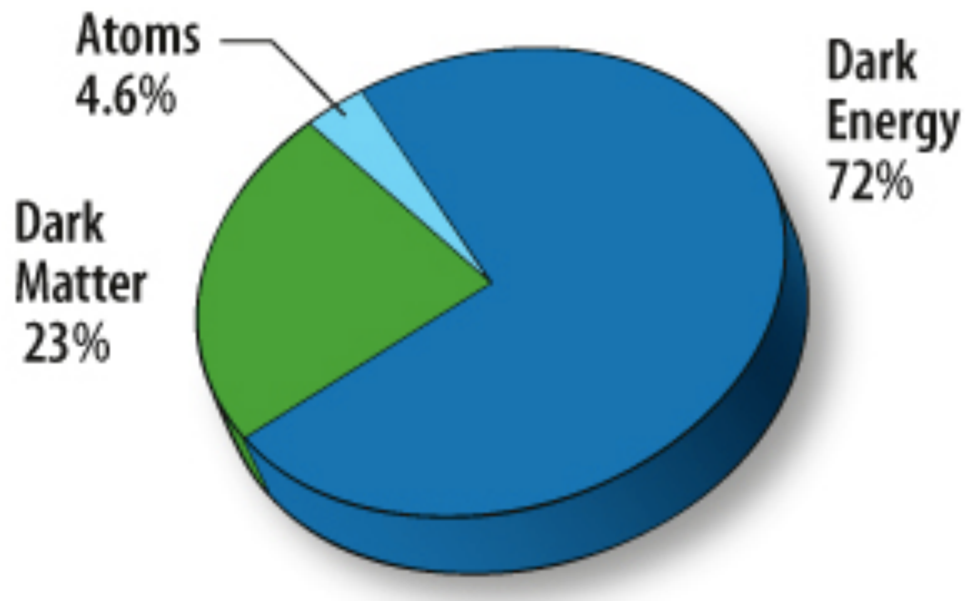
- Model - top-philic DM
  - Relic abundance
  - Indirect detection
  - Direct detection
  - Collider experiments
- Summary



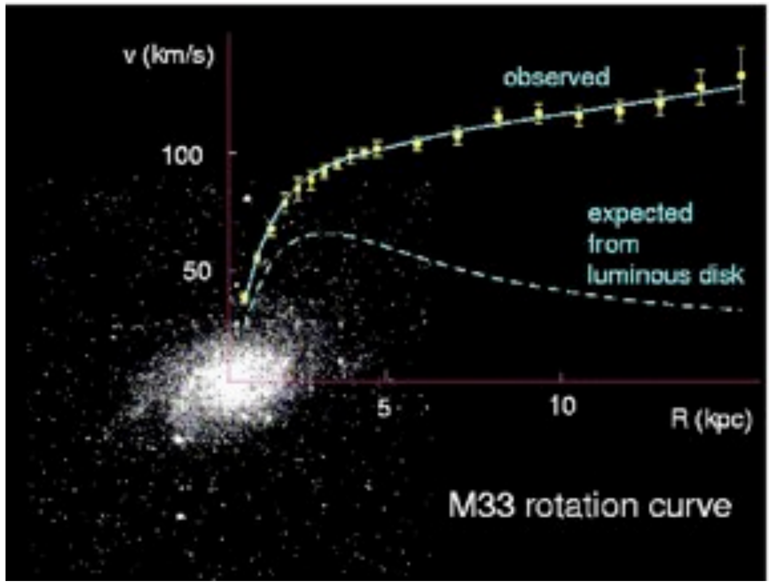
Motivation

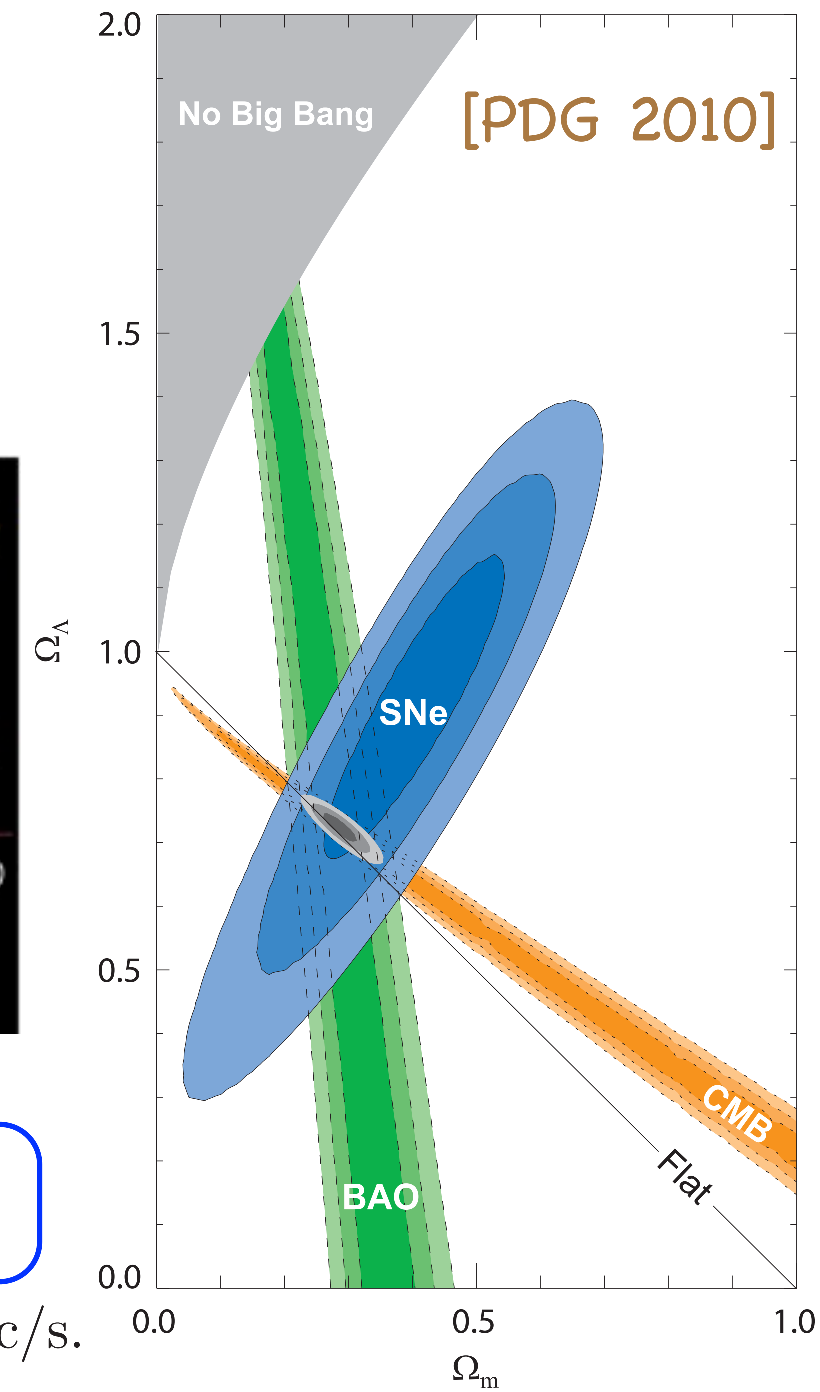
❑ Evidence for dark matter (DM)

CMB, BBN, BAO, rotation curves, etc.



NASA / WMAP Science Team





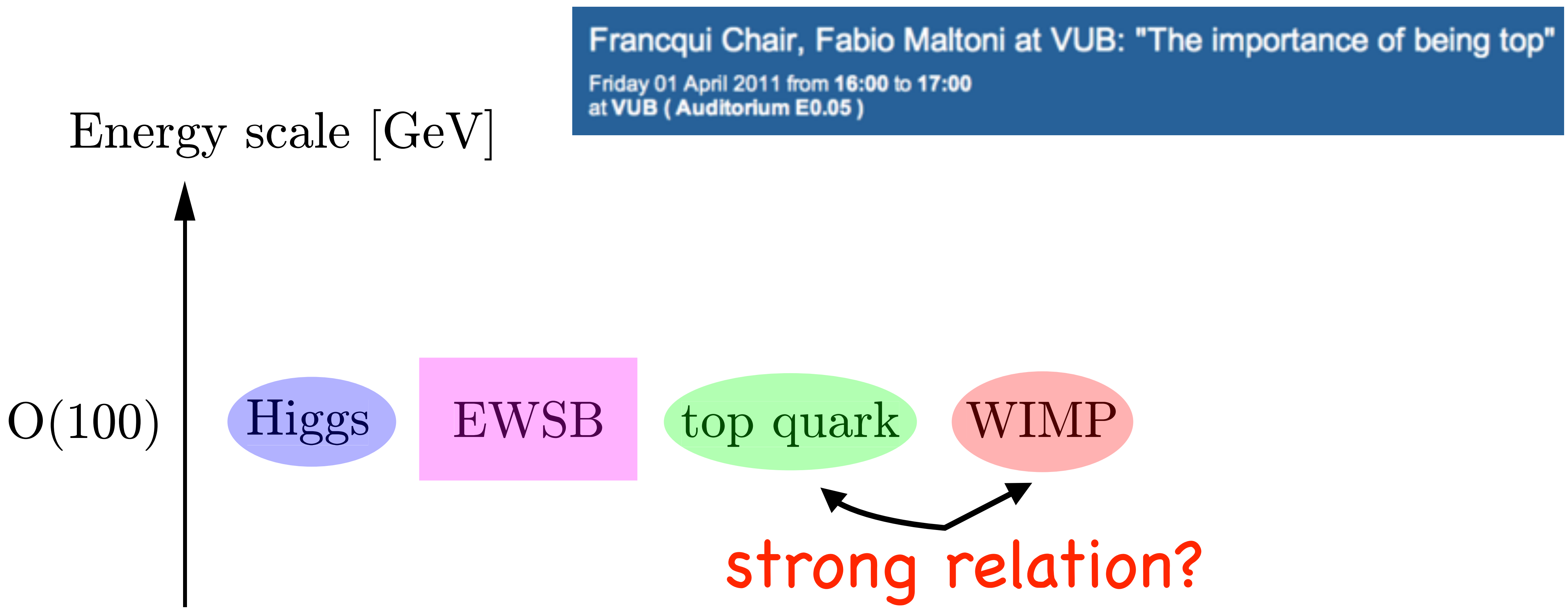
WMAP result: $\boxed{\Omega_{\mathrm{CDM}}\, h^2 = 0.1099 \ \pm 0.0062}$

where h is the Hubble constant in units of 100 km/Mpc/s.

❑ Though the gravitation nature of DM is established, we know almost nothing about the particle nature (mass, spin, quantum #, interaction) except electrically neutral.

What is the relevant energy scale of the DM?

- If DM is a WIMP, the relevant scale is the EW scale.
- Mass of top quark is also close to the EW scale.

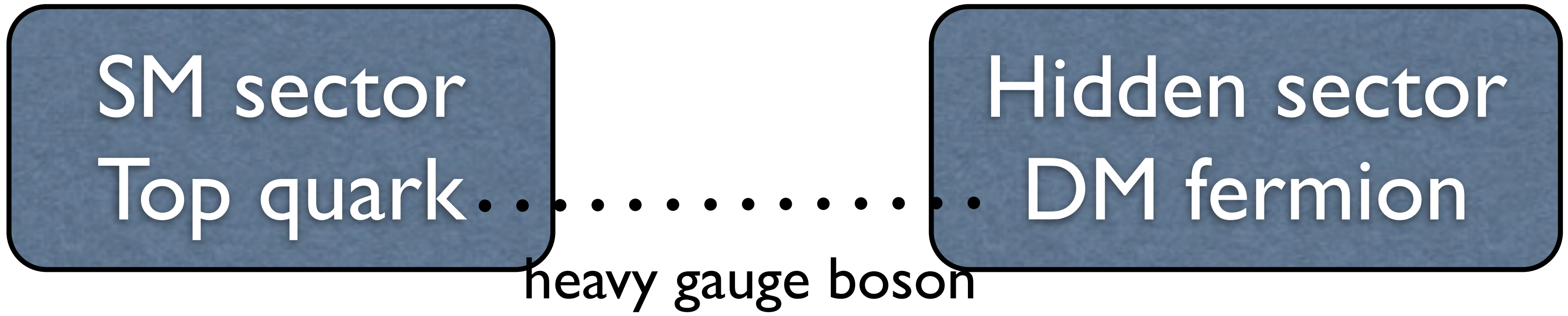


- Since top quark and DM have the common energy scale, there might be some relationship between them.

- The top quark might be the only window to probe DM.

  We consider DM which couples only to the top quark.

Model



❑ If the mass of the gauge boson is heavy enough, we can integrate it out, and below the heavy mass scale Λ the effective interaction Lagrangian is given by

$$\mathcal{L} = \frac{g_\chi^2}{\Lambda^2}\,(\overline{\chi}\Gamma\chi)\,\,(\bar{t}\Gamma t)$$

where $\Gamma = 1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5$, $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$ and $\sigma^{\mu\nu}\gamma_5$ for scalar, pseudoscalar, vector, axial-vector, tensor and axial-tensor respectively.

❑ A realization of such a DM can be found in the following references.

C.B. Jackson, G. Servant, G. Shaughnessy, T.M.P. Tait and M. Taoso, 0912.0004;
M. Battaglia and G. Servant, 1005.4632.

Joachim Kopp

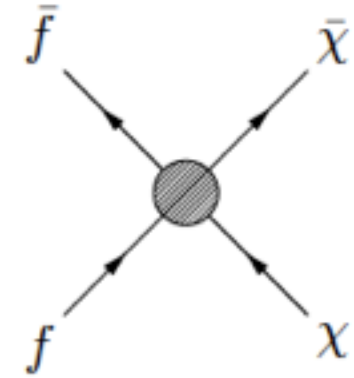
Moriond Electroweak Session, March 18th, 2011

Mono-jet and mono-photon signatures of dark matter

Assumption:
DM (χ) interactions described by effective field theory
Sample operators: (Λ = suppression scale)

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{f}f)}{\Lambda^2} \qquad \text{(scalar, } s\text{-channel)}$$

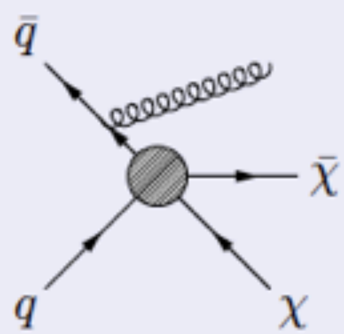
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{f}\gamma^\mu\gamma_5 f)}{\Lambda^2} \qquad \text{(axial vector, } s\text{-channel)}$$



Tevatron/LHC: Mono-jets

χ–q coupling probed in jet(s) + $\not{E}_T$

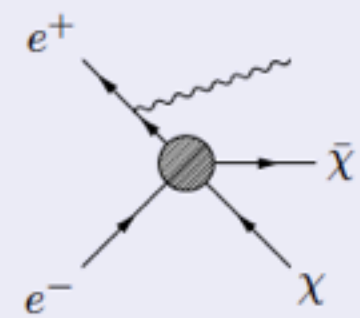
CDF (1.1 fb^{-1}): PRL 101 (2008) 181602
Goodman *et al.*, arXiv:1005.1286, arXiv:1008.1783
Fox Harnik Bai, arXiv:1005.3797



LEP: Mono-photons

χ–e coupling probed in photon + $\not{E}$

DELPHI (650 pb^{-1}): hep-ex/0406019, arXiv:0901.4486
Fox Harnik JK Tsai, arXiv:1103.0240

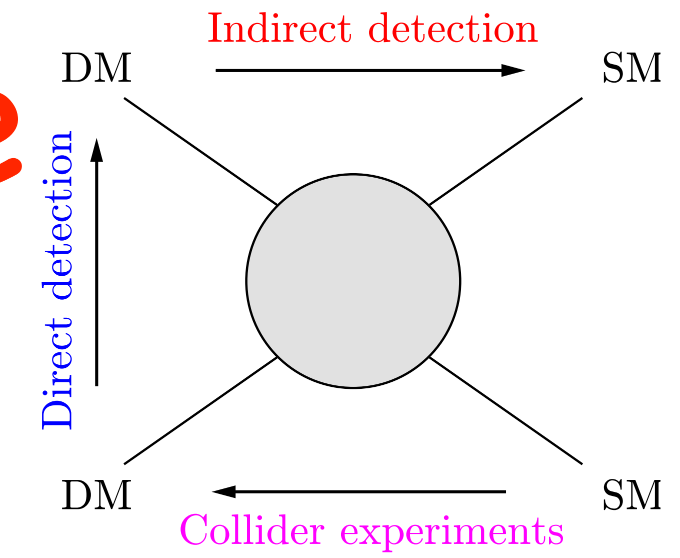


Check points

- DM relic abundance?
  Thermal production of DM in the early Universe is assumed.
- Direct detection?
  The cross section of direct detection would be consistent with the current limit since the top content within the nucleon is so small.
- Indirect detection?
  The annihilation of the DM in the Galactic Halo would give rise to positron and antiprotons that can be observed by antimatter search experiments.
- Collider experiments?
  pp > (t-pair)+(DM-pair) > (t-pair)+(large missing energy)

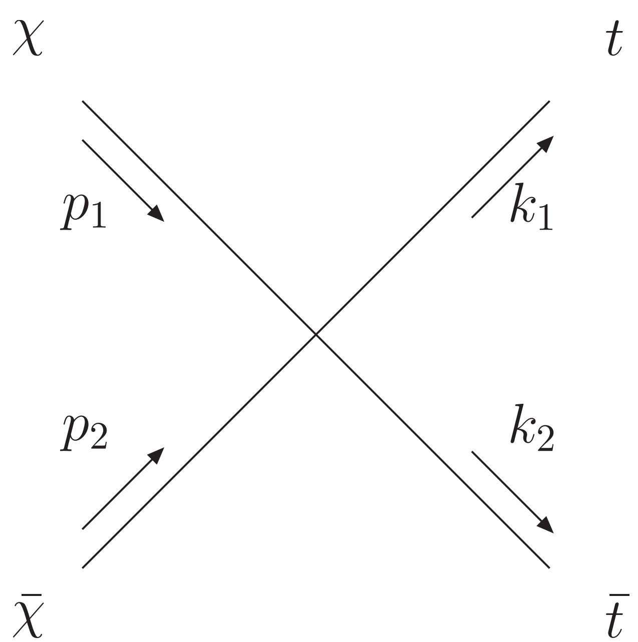
Relic abundance

Relic abundance



- The annihilation cross section

$$\chi(p_1)\,\overline{\chi}(p_2) \to t(k_1)\,\bar{t}(k_2)$$



vector type interaction: $\Gamma = \gamma^\mu$

$$(\sigma v)_V = \frac{N_C}{8\pi}\frac{g_\chi^4}{\Lambda^4}\beta_t s\left[1 + \frac{1}{3}\beta_t^2\beta_\chi^2 + \frac{4(m_t^2 + m_\chi^2)}{s}\right]$$

$$N_C = 3, \quad s = (p_1 + p_2)^2, \quad \beta_{t,\chi} = \sqrt{1 - 4m_{t,\chi}^2/s},$$
$$v = 2\beta_\chi$$

- Instead of solving the Boltzmann equation, we simply estimate the correct size of the annihilation cross section using

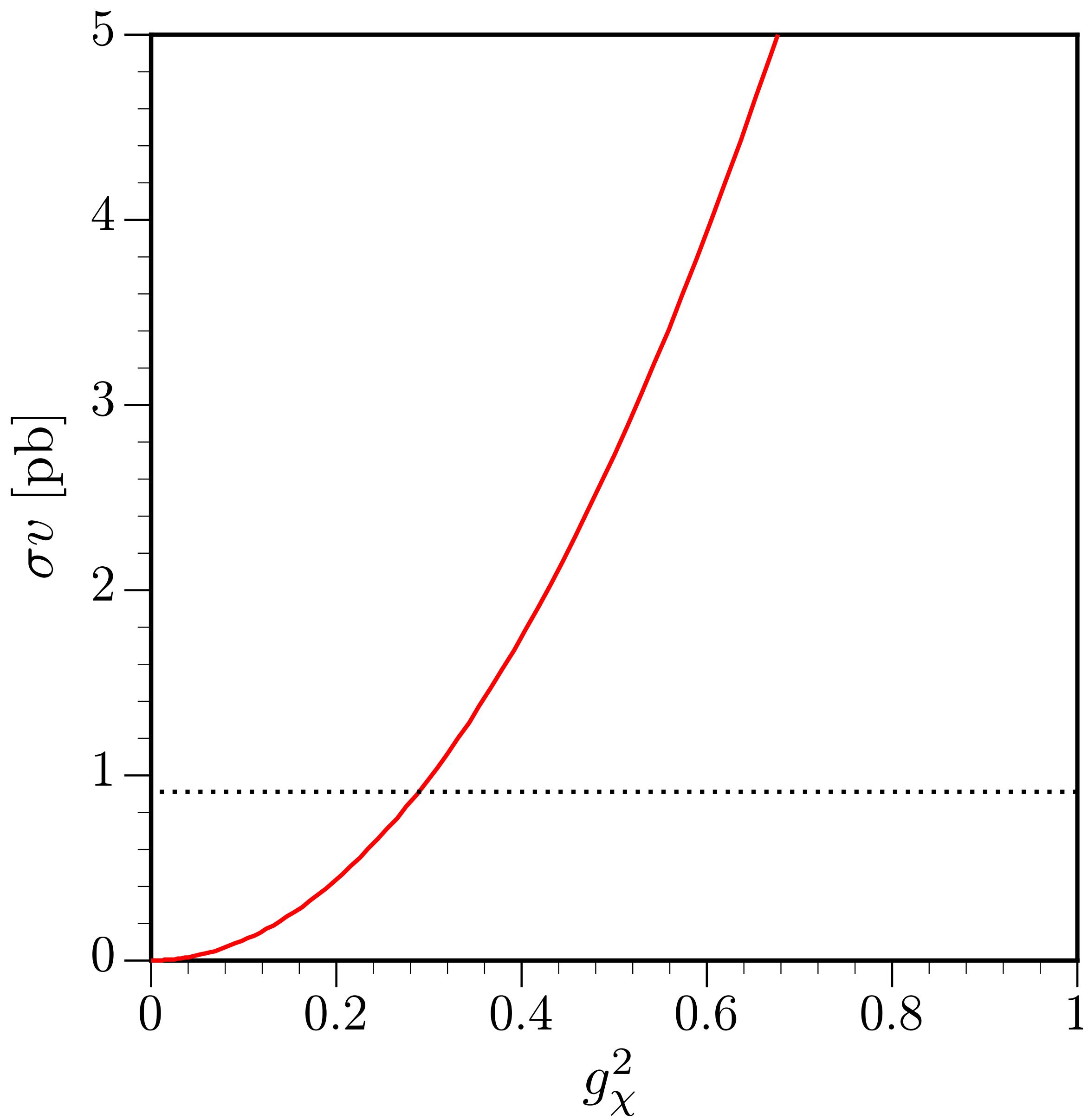
$$\Omega_\chi h^2 \simeq \frac{0.1\ \mathrm{pb}}{\langle \sigma v\rangle}$$

From $\Omega_{\mathrm{CDM}} h^2 = 0.1099 \pm 0.0062$, one gets $\boxed{\langle \sigma v\rangle \simeq 0.91\ \mathrm{pb.}}$

σv vs. g_χ^2

$$\Gamma = \gamma^\mu,\ m_\chi = 200 \text{ GeV},\ \Lambda = 1.0 \text{ TeV},\ v = 0.3$$

the velocity of the DM at around the freeze-out time

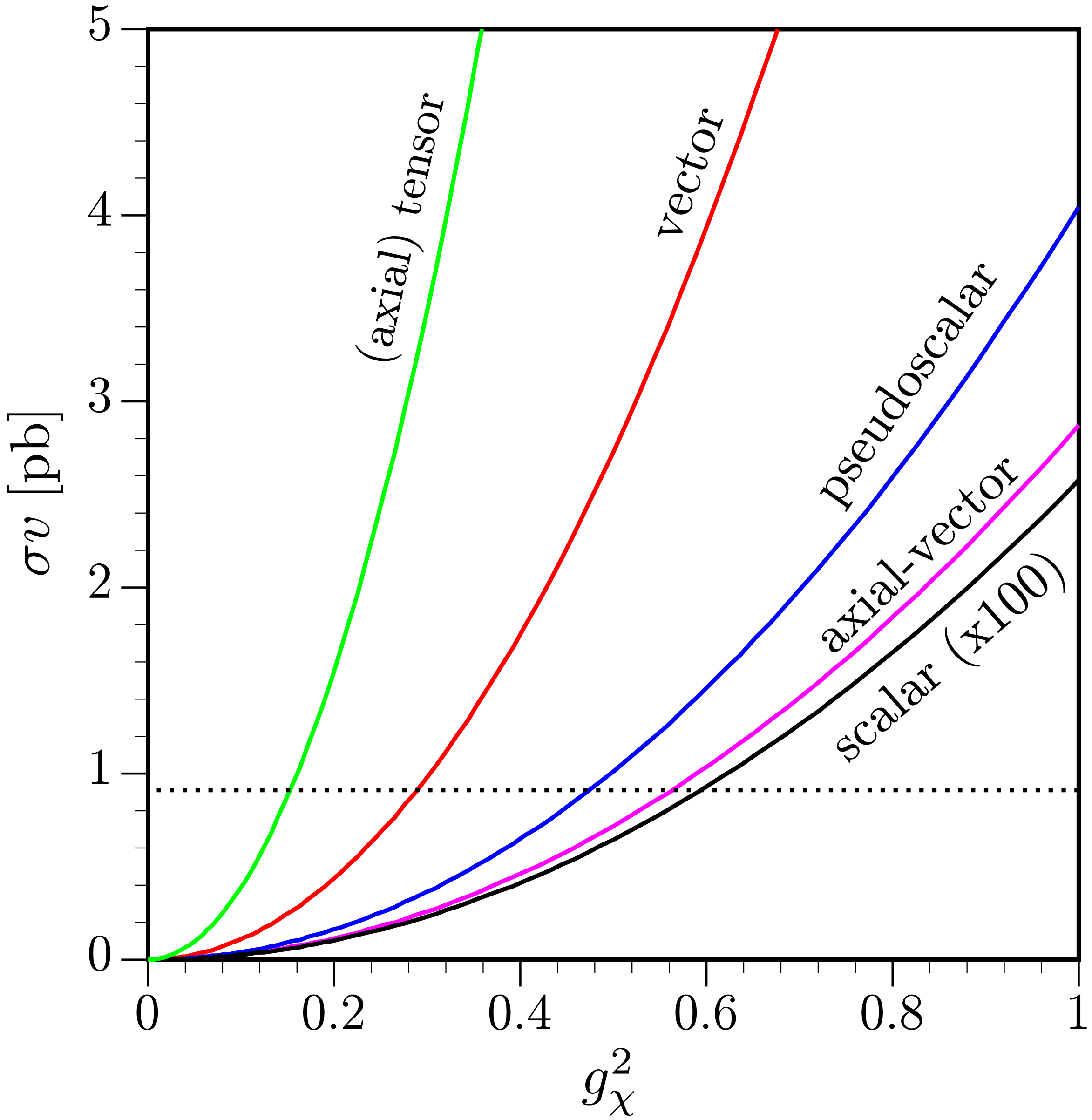


0.91 pb

$g_\chi^2 \simeq 0.3$ is consistent with the observed DM abundance.

σv vs. g_χ^2

scalar, pseudoscalar, axial-vector, (axial) tensor cases:



$$m_\chi = 200 \text{ GeV}, \ \Lambda = 1.0 \text{ TeV}, \ v = 0.3$$

$$(\sigma v)_S = \frac{N_C}{8\pi}\frac{g_\chi^4}{\Lambda^4}\beta_\chi^2\beta_t^3 s,$$

$$(\sigma v)_{PS} = \frac{N_C}{8\pi}\frac{g_\chi^4}{\Lambda^4}\beta_t s,$$

$$(\sigma v)_V = \frac{N_C}{8\pi}\frac{g_\chi^4}{\Lambda^4}\beta_t s\left[1 + \frac{1}{3}\beta_t^2\beta_\chi^2 + \frac{4(m_t^2+m_\chi^2)}{s}\right],$$

~1.4

$$(\sigma v)_{AV} = \frac{N_C}{8\pi}\frac{g_\chi^4}{\Lambda^4}\beta_t s\left[1 + \frac{1}{3}\beta_t^2\beta_\chi^2 - \frac{4(m_t^2+m_\chi^2)}{s} + \frac{32 m_t^2 m_\chi^2}{s^2}\right]$$

$$(\sigma v)_T = \frac{N_C}{\pi}\frac{g_\chi^4}{\Lambda^4}\beta_t s\left[\frac{1}{3}\beta_t^2\beta_\chi^2 + \frac{2(m_t^2+m_\chi^2)}{s} + \frac{8 m_t^2 m_\chi^2}{s^2}\right].$$

$\sim 2\times10^{-3}$ ~ 0.85 ~ 0.35

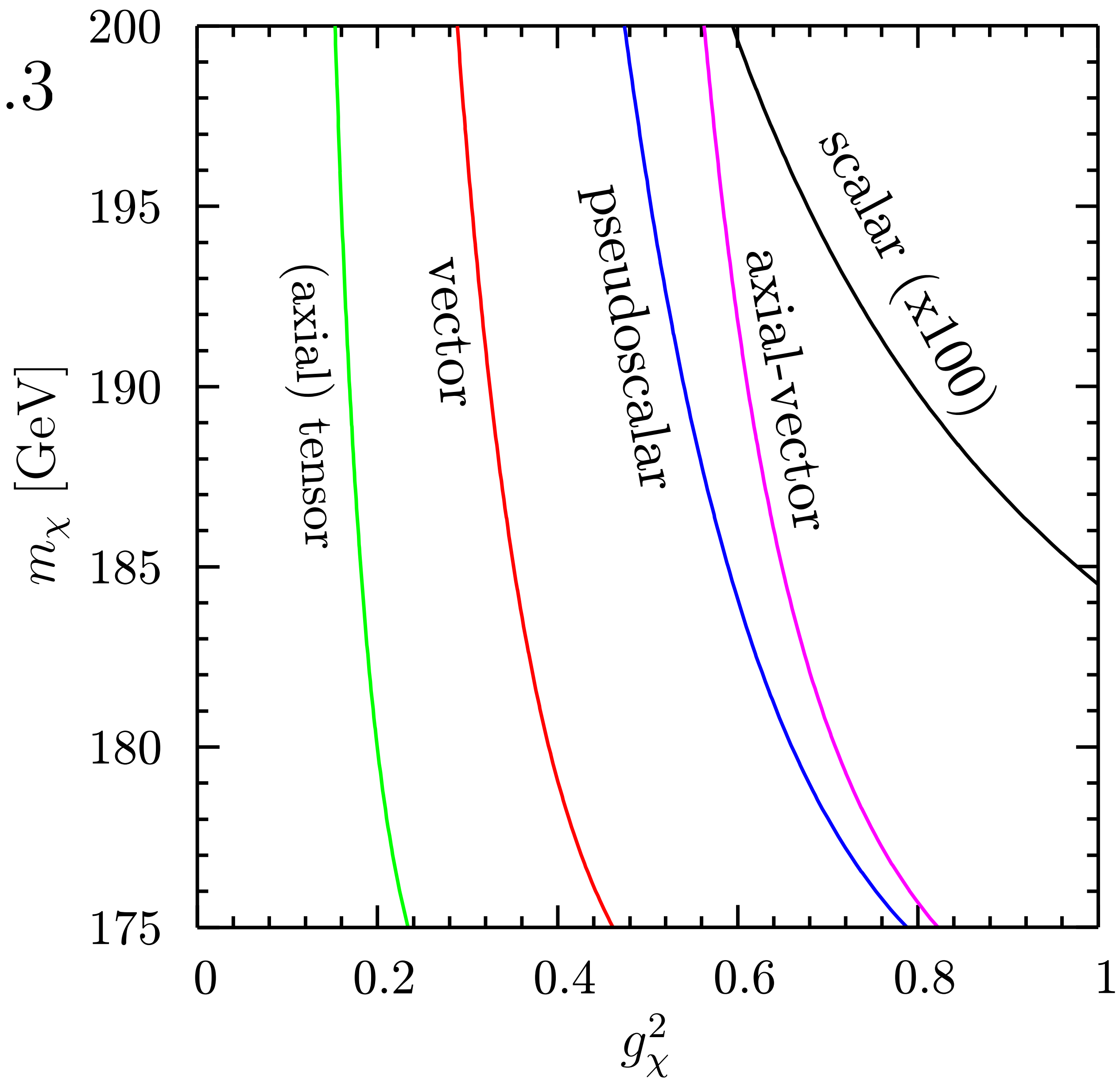
- Scalar-type interaction has a velocity suppression.
- $0.2 \lesssim g_\chi^2 \lesssim 0.6$ is found in other types of interactions.

m_χ vs. g_χ^2

Changing the DM mass, we find

contour plots of $\sigma v = 0.91$ pb

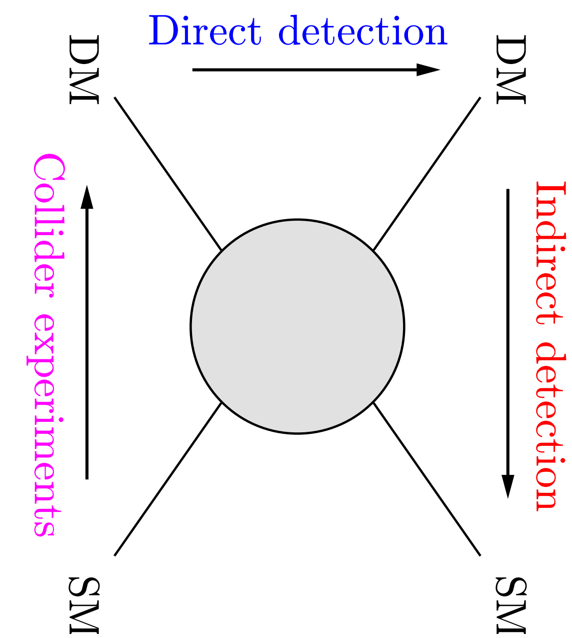
$\Lambda = 1.0$ TeV, $v = 0.3$



❑ Dependence of the DM mass is relatively mild.

Direct detection

Direct detection



Spin-independent (SI) cross sections can arise from the scalar- and vector-type interactions:

$$\mathcal{L} = \sum_{q=u,d,s,c,b,t} \{\alpha_q^S \, \overline{\chi}\chi \, \bar{q}q + \alpha_q^V \, \overline{\chi}\gamma^\mu\chi \, \bar{q}\gamma_\mu q\}$$

SI cross section between DM and nucleon:

$$\sigma_{\chi N}^{\rm SI} = \frac{4\mu_{\chi N}^2}{\pi}\left(\left|G_s^N\right|^2 + \frac{|b_N|^2}{256}\right) \quad \text{where } \mu_{\chi N} = m_\chi m_N/(m_\chi + m_N)$$

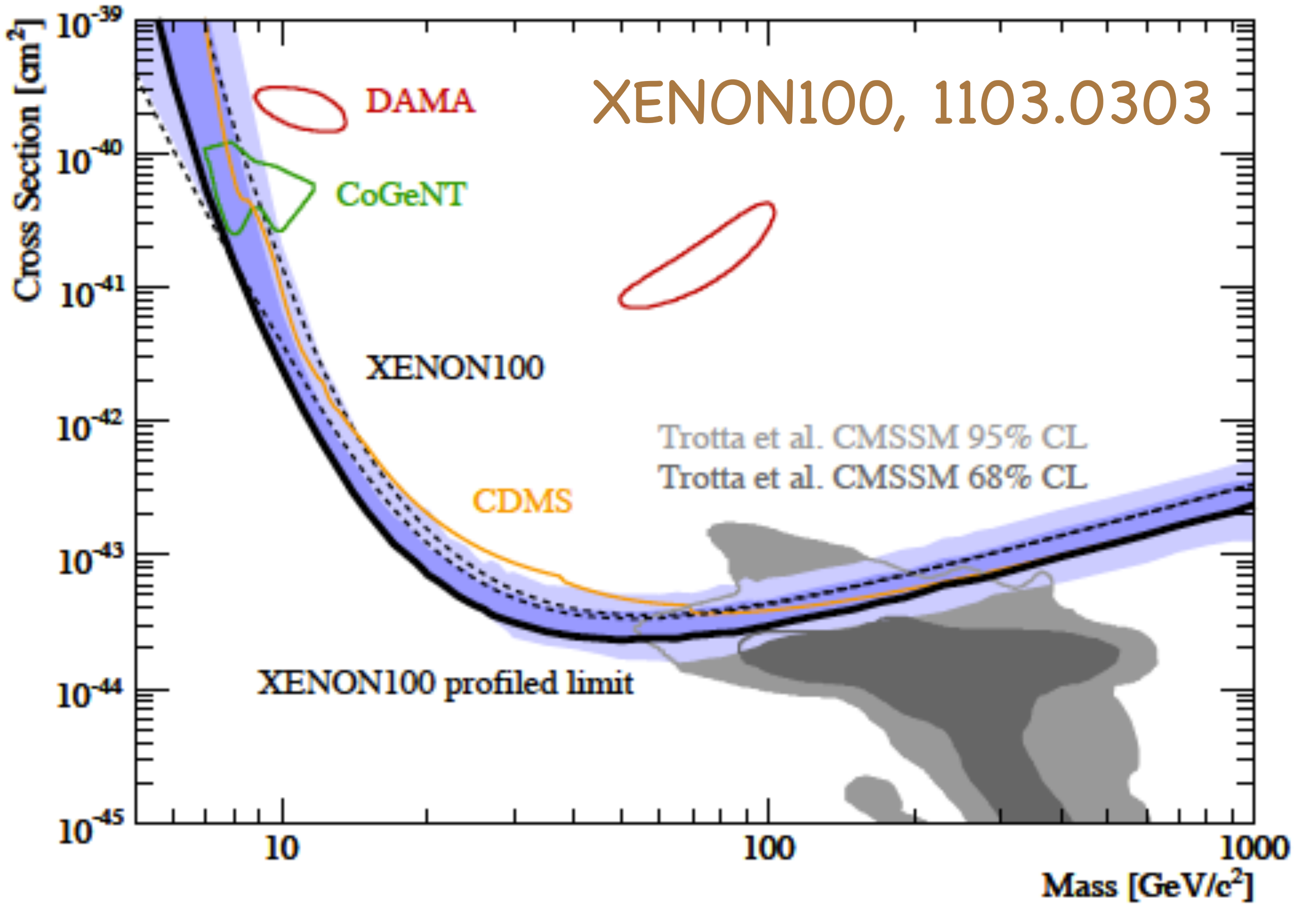
$$G_s^N = \sum_{q=u,d,s,c,b,t} \langle N|\bar{q}q|N\rangle \, \alpha_q^S = \langle N|\bar{t}t|N\rangle \left(\frac{g_\chi^2}{\Lambda^2}\right) \simeq \frac{f_{Tt}^N m_N}{m_t}\left(\frac{g_\chi^2}{\Lambda^2}\right)$$

The contribution to b_N come from valence quarks only.

$$\boxed{\sigma_{\chi N}^{\rm SI} \approx \frac{4\mu_{\chi N}^2}{\pi}\left(\frac{f_{Tt}^N m_N}{m_t}\right)^2 \left(\frac{g_\chi^2}{\Lambda^2}\right)^2}$$

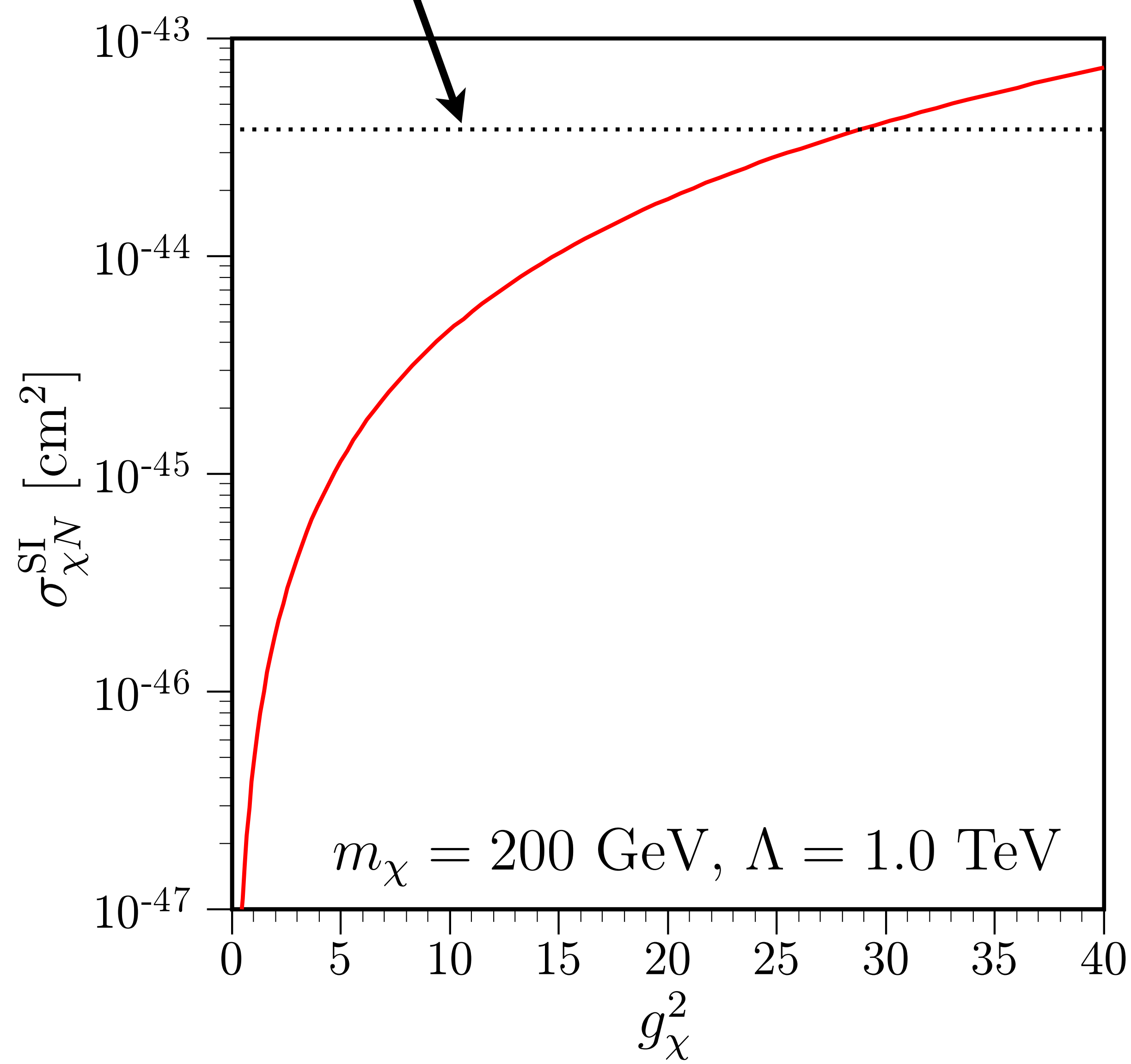
Note: the axial-vector interactions contributes to spin-dependent (SD) cross sections, but the constraint from SD cross sections is a few orders of magnitude weaker than that from SI cross sections.

$\sigma_{\chi N}^{\mathrm{SI}}$ vs. g_χ^2



CDMSII: $\sigma_{\chi N}^{\mathrm{SI}} < 3.8 \times 10^{-44}$ cm^2 for $m_\chi \approx 70$ GeV.

0912.3592

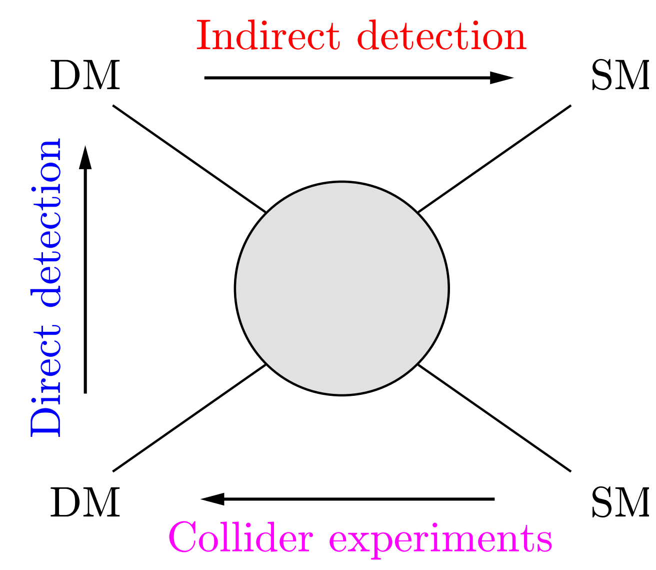


- $g_\chi^2 \lesssim 30$ is allowed, which is somewhat strong but still perturbative ($< (4\pi)^2$)

Indirect detection

Indirect detection

- We use the observed positron and antiproton spectra as constraints on the DM-top coupling.



Positron flux observed at the Earth:

$$\Phi_{e^+}(E) = \frac{v_{e^+}}{4\pi} f_{e^+}(E)$$

v_{e^+}: velocity of e^+, f_{e^+}: number density of e^+ per unit energy.

Diffusion equation

source term

$$\frac{\partial f}{\partial t} - K(E)\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

diffusion coefficient   energy-loss rate

$$K(E) = K_0 (E/\mathrm{GeV})^\delta, \quad b(E) = E^2/(\mathrm{GeV} \times \tau_E), \quad \tau_E = 10^{16}\mathrm{sec}.$$
$$K_0 = 0.006 - 0.08\ [\mathrm{kpc}^2/\mathrm{Myr}],\ \delta = 0.4 - 0.7,\ L = 1 - 15\ [\mathrm{kpc}].$$

* Antiproton Flux in Cosmic Ray Propagation Models with Anisotropic Diffusion
arXiv:1012.0587 (Phill Grajek, Kaoru Hagiwara)

Positron fraction

Source term by the annihilation of DM

$$Q_{\rm ann} = \frac{1}{4}\left(\frac{\rho_{\rm CDM}}{M_{\rm CDM}}\right)^2 \langle\sigma v\rangle_{\chi\bar{\chi}\to t\bar{t}}\,\frac{dN_{e^+}}{dE_{e^+}}$$

$\rho_{\rm CDM}$: energy density of the DM, $\frac{dN_{e^+}}{dE_{e^+}}$: energy spectrum of the positron

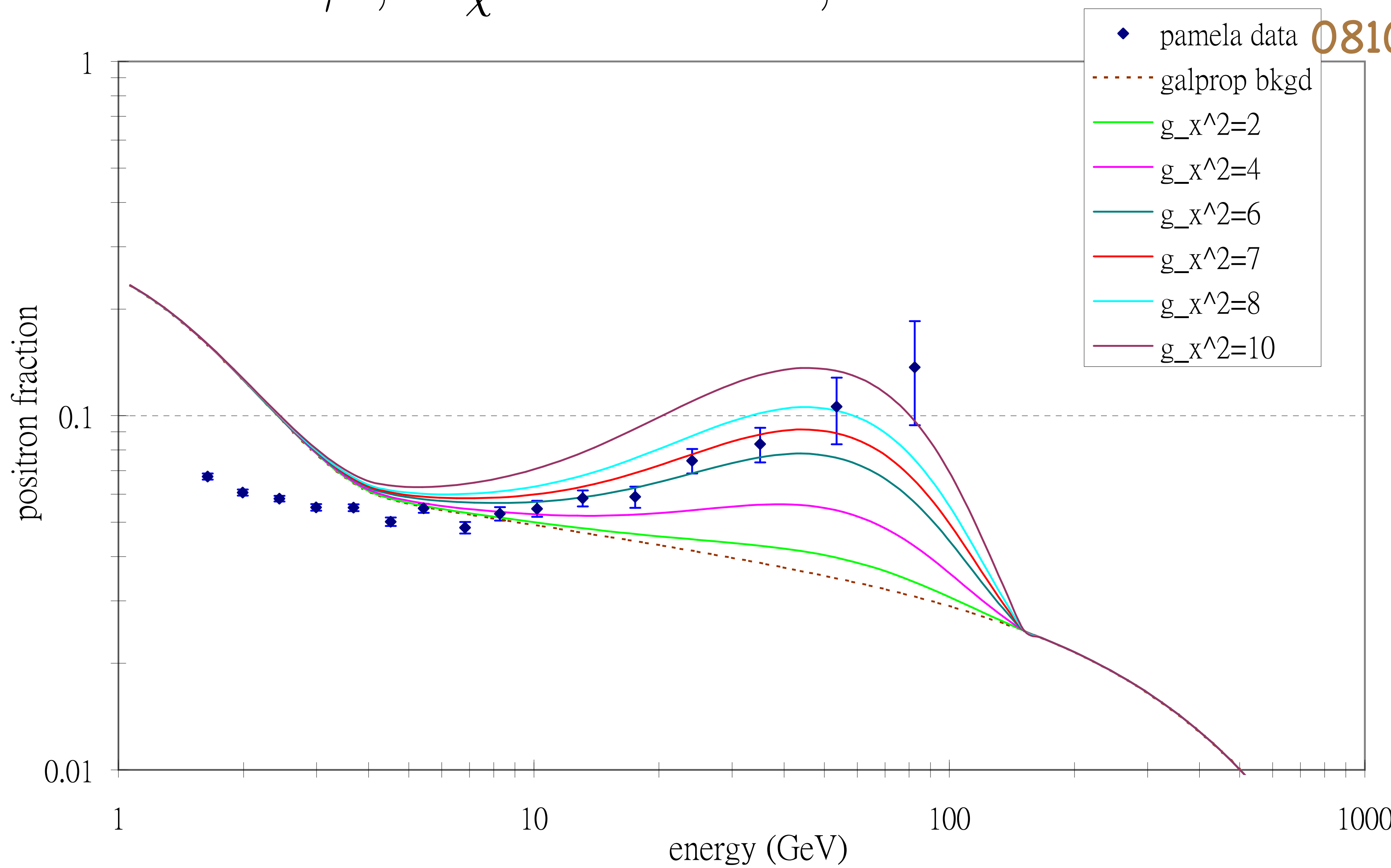
Let us consider the positron coming from the process.

$$\chi\bar{\chi} \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (be^+\nu_e) + X$$

- Most energetic positron comes from the W^+ decay.
- Public code "GALPROP" is used to solve the diffusion equation.

Positron fraction

$\Gamma = \gamma^\mu$, $m_\chi = 200$ GeV, $\Lambda = 1.0$ TeV



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$g_\chi^2 \lesssim 8$ is allowed by the positron fraction data

Antiproton fraction

Source term for the antiproton spectrum

$$Q_{\rm ann} = \eta \left(\frac{\rho_{\rm CDM}}{M_{\rm CDM}}\right)^2 \sum \langle \sigma v \rangle_{\bar{p}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

where $T_{\bar{p}}$ is the kinetic energy of the antiproton.

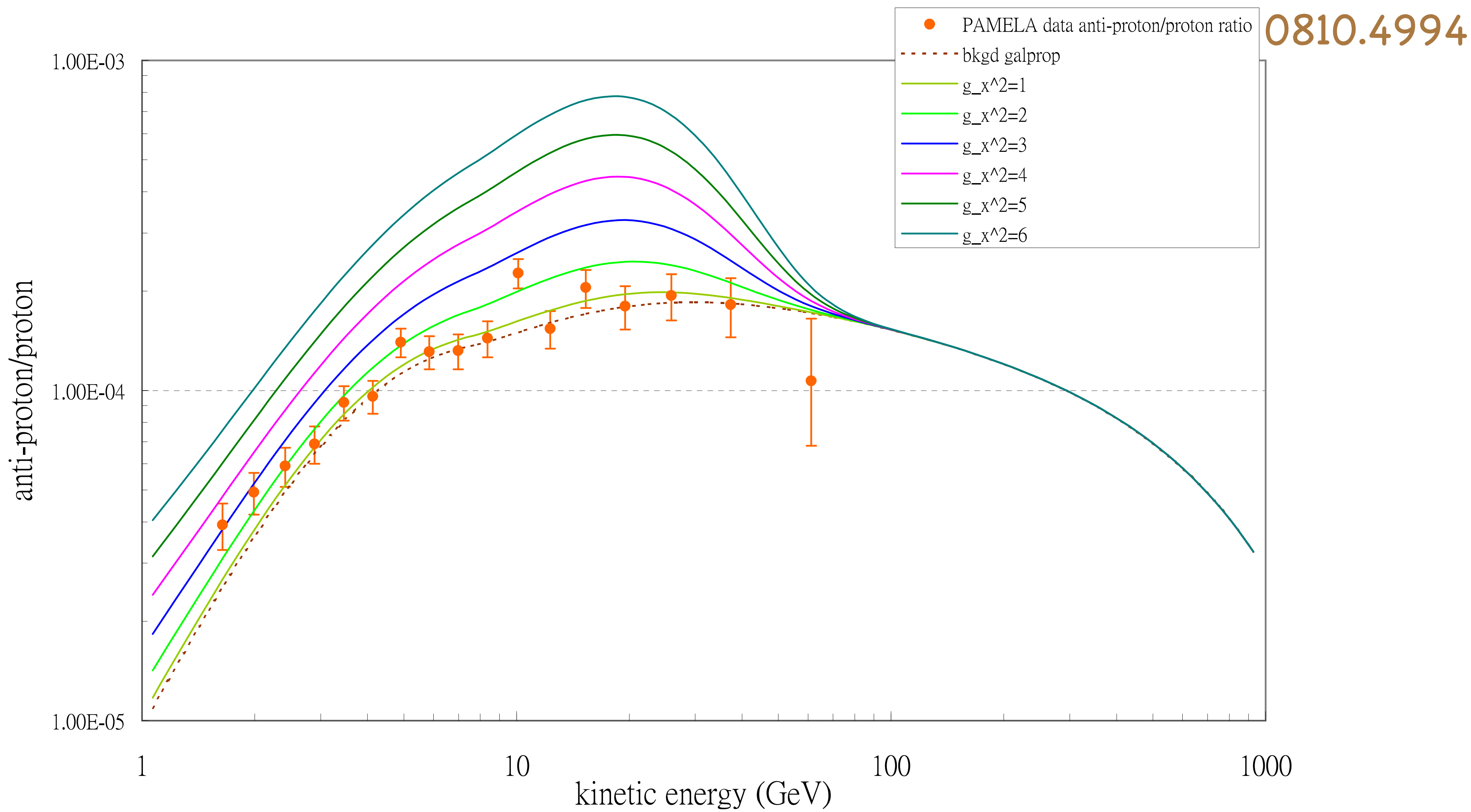
Antiproton mainly come from the process

$$\chi\bar{\chi} \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (bq\bar{q}')(\bar{b}q\bar{q}') \to \bar{p} + X$$

- $b, \bar{b}, q, \bar{q}'$ can fragment into $\bar{p}$.
- Public code [S.Albino et al,NPB725, 181 ('05)] is used to calculate the fragmentation function $D_{q\to h}$, where $h \ni p, \bar{p}, \pi$ etc.

Antiproton fraction

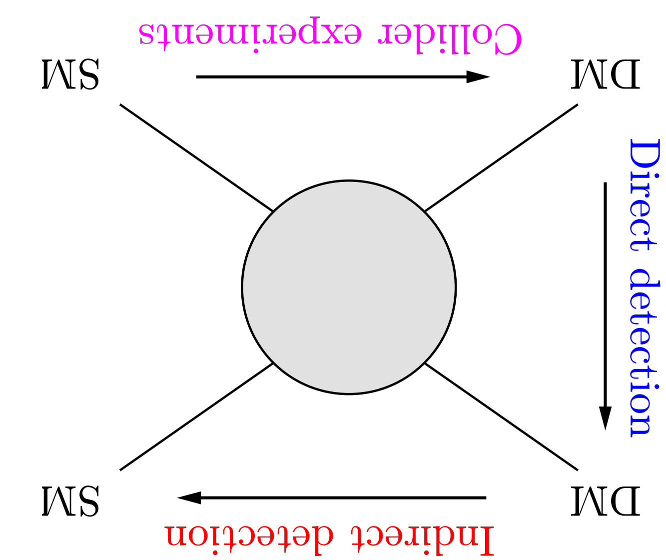
$$\Gamma = \gamma^\mu,\ m_\chi = 200\ \text{GeV},\ \Lambda = 1.0\ \text{TeV}$$



Constraint coming from the antiproton fraction is somewhat stronger than that of positron, $g_\chi^2 \lesssim 4-5$.

Collider experiments

Collider experiments



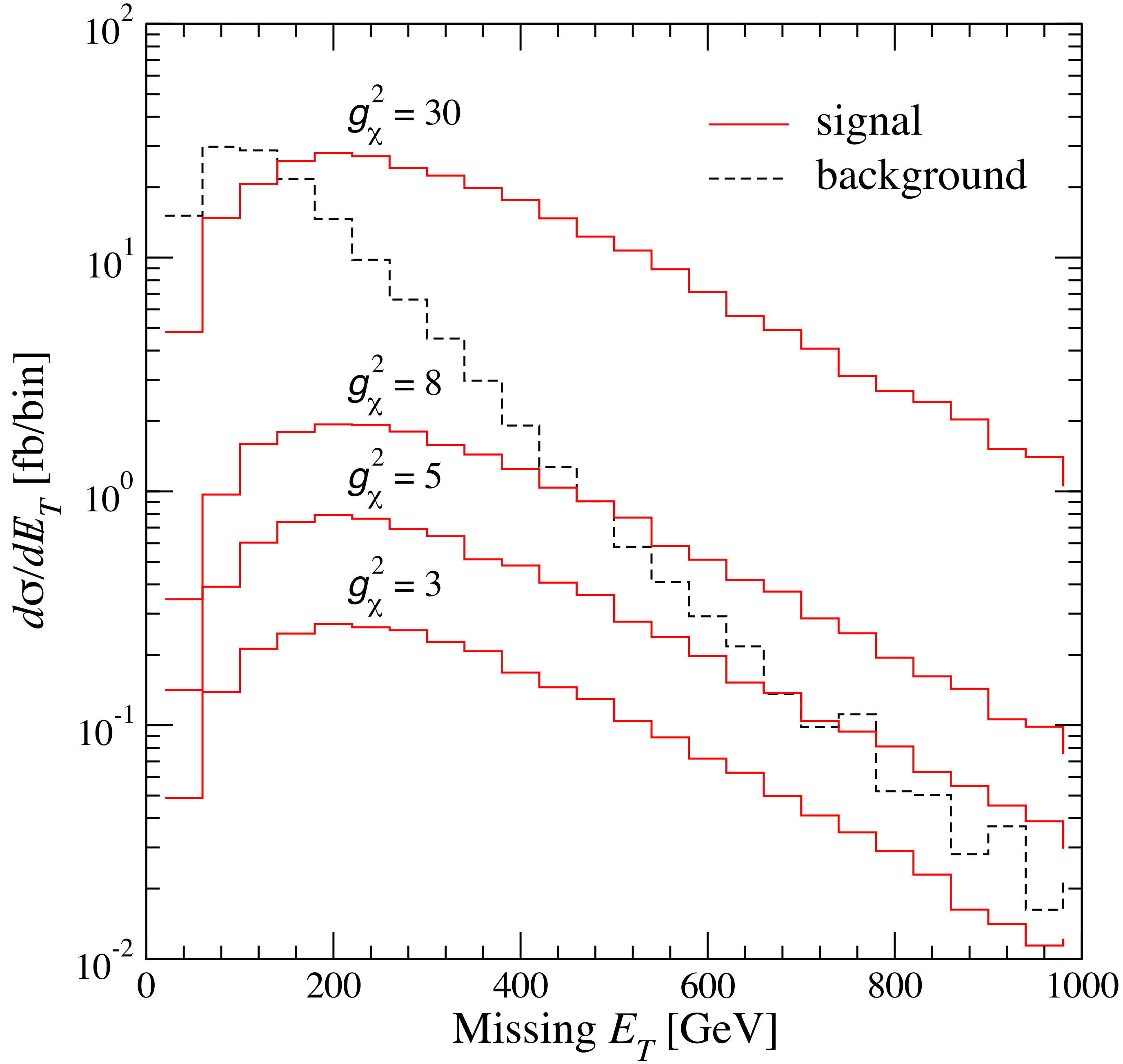
- Collider signatures of this model:
  pp > (t-pair)+(DM-pair) > (t-pair)+(large missing energy)

- Public code "MadGraph/MadEvent" is used to calculate the signal and background cross sections.
  The irreducible background process: $t\bar{t} + Z \to t\bar{t}\nu\bar{\nu}$

- We implemented the DM and its interaction into MG/ME.

Missing E_T

$\Gamma = \gamma^\mu,\ m_\chi = 200$ GeV, $\Lambda = 1.0$ TeV $\quad \sqrt{s} = 14$ TeV



- ❑ Signal has a harder missing E_T spectrum than the bkgd.
- ❑ $E_T \simeq 400$ GeV cuts can substantially reduce the bkgd.

Invariant mass

$$\Gamma = \gamma^\mu,\ m_\chi = 200\ \text{GeV},\ \Lambda = 1.0\ \text{TeV},\ g_\chi^2 = 5$$

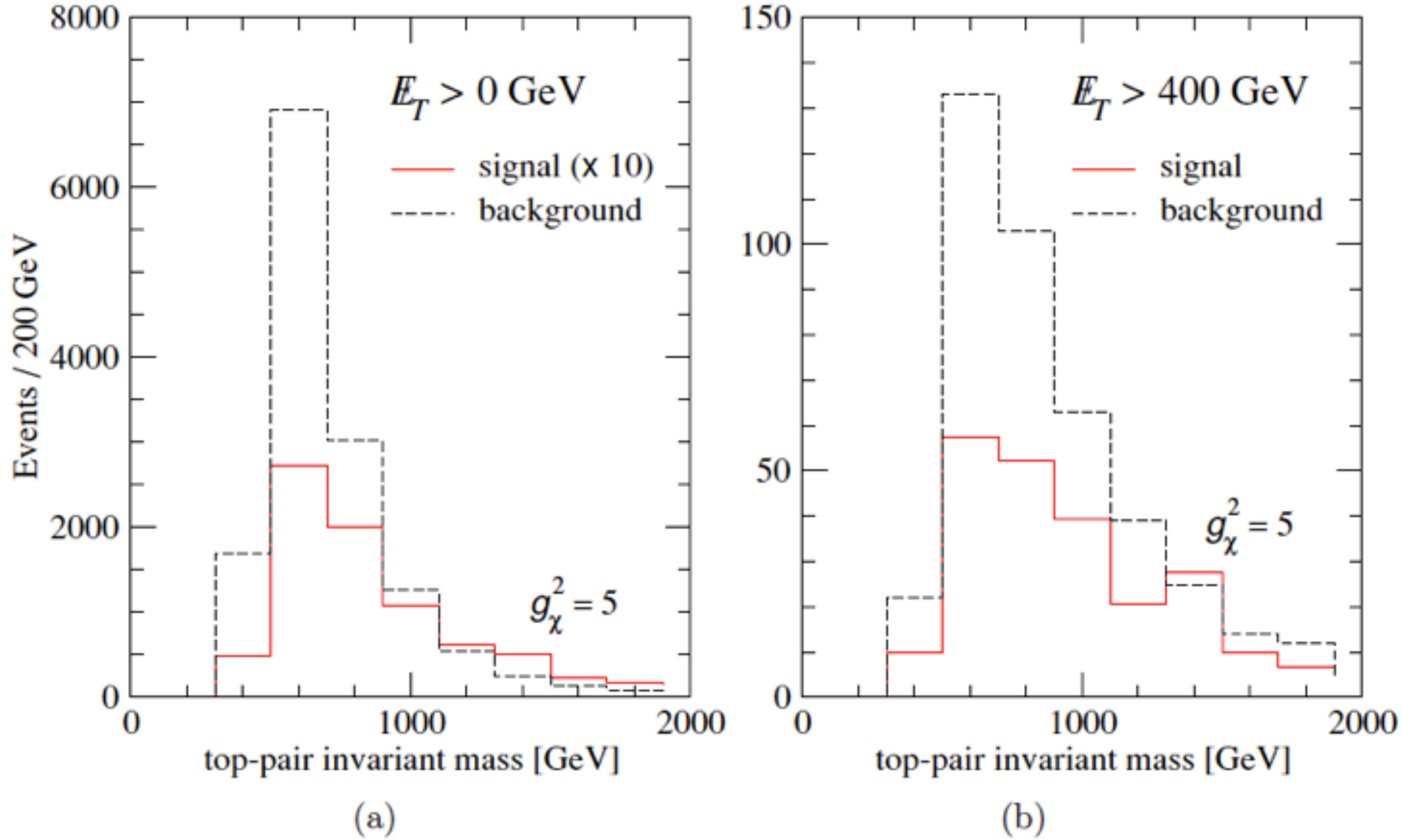


Figure 8. Event numbers for the invariant mass $t\bar{t}$ distributions for the signal $pp \to t\bar{t} + \chi\bar{\chi}$ and the background $pp \to t\bar{t}Z$ (a) before and (b) after applying the missing transverse momentum cut of 400 GeV. The assumed luminosity is 100 fb^{-1}, which corresponds to 240 signal events and 420 background events after the cut.

Cross sections

$\not{E}_T >$	$pp \to t\bar{t} + \chi\bar{\chi}$	$p \to t\bar{t}Z \to t\bar{t}\nu\bar{\nu}$	S/B	$S/\sqrt{B}$ (100 (30) fb^{-1})
0 GeV	8.2	140.3	0.06	6.9 (3.8)
300 GeV	3.6	10.7	0.34	11.0 (6.0)
400 GeV	2.4	4.2	0.57	11.8 (6.4)
500 GeV	1.5	1.9	0.78	10.6 (5.9)

Table 1. Cross sections in fb for the signal $pp \to t\bar{t} + \chi\bar{\chi}$ and the background $pp \to t\bar{t}Z \to t\bar{t} + \nu\bar{\nu}$ at the LHC. We used $g_\chi^2 = 5$ for illustration. The signal cross section scales as g_χ^4. The significance $S/\sqrt{B}$ is calculated with an integrated luminosity of 100 (30) fb^{-1}.

- $S/\sqrt{B}$ with $\mathcal{L} = 100$ fb^{-1} stays around 11 with a cut of 300-500 GeV.
- Since $S/\sqrt{B}$ scales as $\sqrt{\mathcal{L}}$, it is still as large as 6 with $\mathcal{L} = 30$ fb^{-1}.

❑ Other types of the interactions

	Signal cross section (fb)	S/B	$S/\sqrt{B}$
Vector	2.4	0.57	11.8 (6.4)
Axial-vector	1.9	0.45	9.3 (5.1)
Pseudoscalar	0.82	0.20	4.0 (2.2)
Scalar	0.55	0.13	2.7 (1.5)

Table 2. Cross sections in fb for the signal $pp \to t\bar{t} + \chi\bar{\chi}$ for vector, axial-vector, pseudoscalar, and scalar interactions at the LHC. We have imposed the $\not{E}_T > 400$ GeV cut. The S/B and $S/\sqrt{B}$ are shown. The background is from table I. The significance $S/\sqrt{B}$ is calculated with an integrated luminosity of 100 (30) fb^{-1}.

Summary

- We have considered the scenario in which DM can couple only to the top quark via 4-fermi interactions.
- If the DM is thermally produced, $g_\chi^2 \approx 0.3 - 0.6$
- Direct search experiments allows $g_\chi^2 \simeq 30$
- However, the PAMELA data can constrain $g_\chi^2 \lesssim 4 - 5$
- By using the appropriate missing E_T cut, the significance $S/\surd B$ can be improved, and this model is testable at the LHC. $\mathrm{w}/\ g_\chi^2 \simeq \mathcal{O}(1)$