

Dark Matter wants Linear Collider

Shigeki Matsumoto

IPMU INSTITUTE FOR THE PHYSICS AND
MATHEMATICS OF THE UNIVERSE

Collaboration with ILC physics group, Japan

<http://www-jlc.kek.jp/subg/physics/ilcphys/>

Collaborators

- 1. New Physics Search at LC**
- 2. DM detection at ILC (I)**
- 3. DM detection at ILC (II)**
- 4. Summary & Discussions**

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Collaboration with ILC physics

<http://www-jlc.kek.jp/sub>

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K. Fujii	(KEK),
T. Honda	(Tohoku Univ.)
R. S. Humdi	(Univ. of Hawaii)
H. Ito	(KEK)
S. Kanemura	(Univ. of Toyama)
T. Nabeshima	(Univ. of Toyama)
N. Okada	(Univ. of Alabama)
T. Saito	(Tohoku Univ.)
T. Suehara	(Univ. of Tokyo)
Y. Takubo	(Tohoku Univ.)
H. Yamamoto	(Tohoku Univ.)

Collaborators

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2. DM detection at ILC (I)
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New Physics search @ the ILC

The Standard Model (SM) is one of the most successful models describing physics below $O(100)$ GeV. There are, however, some problems that can not be explained in this framework.

~ Hierarchy Problem ~

$$m_h^2 = O(10^2 \text{ GeV})^2$$

Tree level
mass (m_0^2)

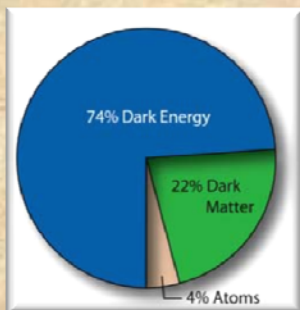
+

Quantum
Corrections

$$O(10^{-2})\Lambda^2$$

The cutoff scale Λ should be smaller than $O(1)$ TeV.

~ Dark Matter Problem ~

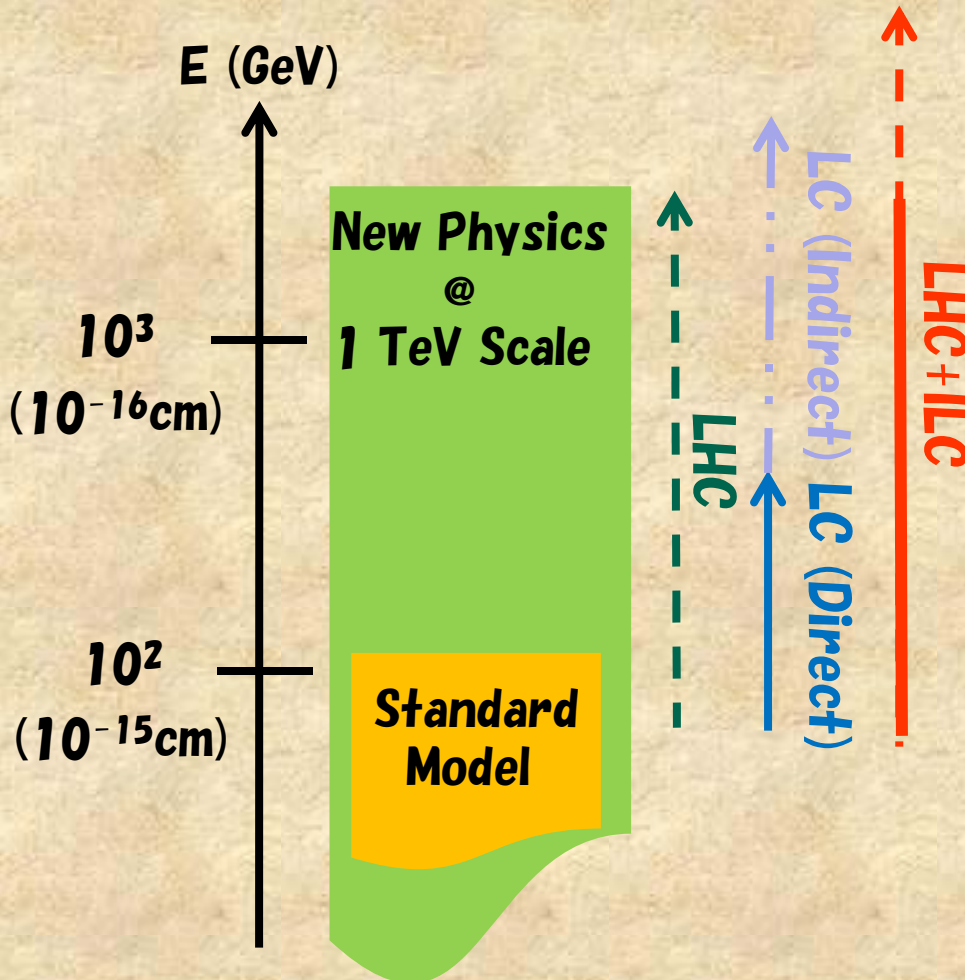


1. No candidate for dark matter in the SM.
2. WIMP seems to be natural for the DM.
Neutral & Stable particle with $O(1)$ TeV mass
→ Cold DM & Correct Relic Density of DM!

New particle (dark matter) will be at $O(1)$ TeV.

New Physics search @ the ILC

New Physics appears at the Tera-scale and it is expected to solve the problems and contains the SM as a low energy effective theory.



Physics at the LHC

- Discoveries of New particles up to $O(1)$ TeV.
- Investigating natures of colored new particles.

Physics at LC (Direct)

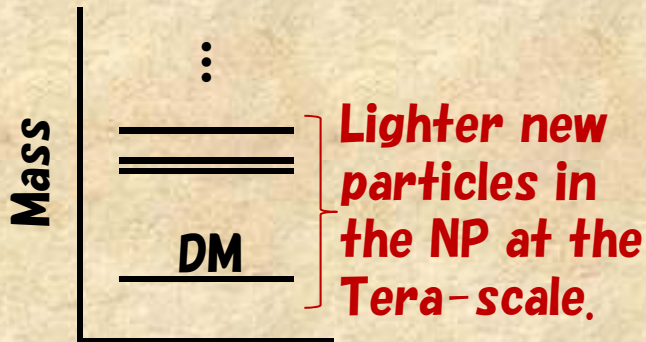
- Investigating natures of all particles up to $\sim s^{1/2}$.
- Investigating interactions among the new particles.

Physics at LC (Indirect)

- Investigating natures of heavy particles radiatively.
- Searching NP beyond TeV scale by precision measurs.

New Physics search @ the ILC

LHC & ILC have therefore complementary roles. One of important purposes at the LC experiments is to clarify new physics model (Lagrangian) at the Tera-scale in a model-independent way.



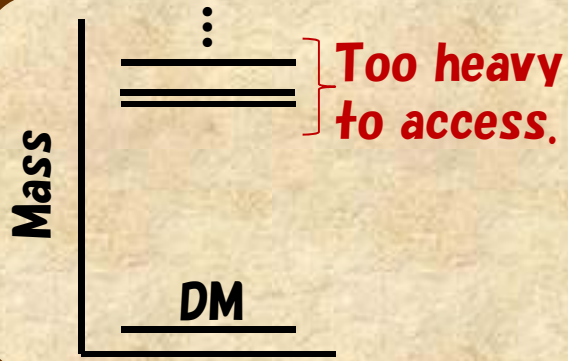
The natures of lighter particles are important because the dark matter is one of the particles.

- 1. Mass & Spin**
- 2. Gauge charges ($SU(2)_L \times U(1)_Y$)**
- 3. Interactions with the new particles.**
 - Vertex structures
 - Coupling constants



Once we know all about the dark matter, we can predict scattering and annihilation cross sections of the DM.
→ By comparing astrophysical observations, it (may) be possible to investigate the dark side of the universe.

Dark Matter detection at ILC (I)

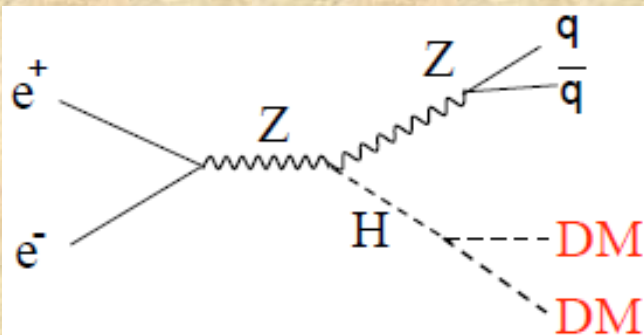


The case where all new particles (except the DM) are too heavy to access at the ILC. DM should be singlet to satisfy EWPO.

This case is almost nightmare scenario!

$$\begin{aligned}\mathcal{L}_S &= \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial\phi)^2 - \frac{M_S^2}{2}\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{d_S}{4!}\phi^4, \\ \mathcal{L}_F &= \mathcal{L}_{\text{SM}} + \frac{1}{2}\bar{\chi}(i\not{\partial} - M_F)\chi - \frac{c_F}{2\Lambda}|H|^2\bar{\chi}\chi - \frac{d_F}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}, \\ \mathcal{L}_V &= \mathcal{L}_{\text{SM}} - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{M_V^2}{2}V_\mu V^\mu + \frac{c_V}{2}|H|^2V_\mu V^\mu - \frac{d_V}{4!}(V_\mu V^\mu)^2,\end{aligned}$$

- Interactions as low dimensional as possible.
- Z_2 -symmetry for the stability of the DM
- DM interactions only thorough the Higgs



$(m_{\text{DM}} < m_H/2) \rightarrow$ Invisible decay width of H
 $(m_{\text{DM}} > m_H/2) \rightarrow$ Xsec. through off-shell H

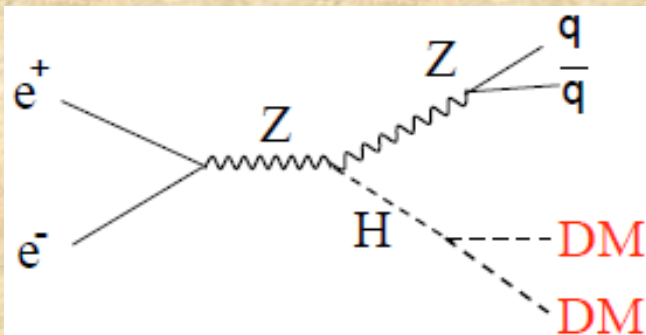
1. $\sqrt{s} = 300$ GeV.
2. Accumulating 2 ab^{-1} data
3. Using e^- polarization (80%)

Dark Matter detection at ILC (I)

	Spin	DM Field	Comments
Case S	0	$\phi(x)$	Neutral scalar
Case F	1/2	$\chi(x)$	Majorana fermion
Case V	1	$V_\mu(x)$	Neutral vector

$$\begin{aligned}\mathcal{L}_S &= \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial\phi)^2 - \frac{M_S^2}{2}\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{d_S}{4!}\phi^4, \\ \mathcal{L}_F &= \mathcal{L}_{\text{SM}} + \frac{1}{2}\bar{\chi}(i\not{\partial} - M_F)\chi - \frac{c_F}{2\Lambda}|H|^2\bar{\chi}\chi - \frac{d_F}{2\Lambda}\bar{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu}, \\ \mathcal{L}_V &= \mathcal{L}_{\text{SM}} - \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{M_V^2}{2}V_\mu V^\mu + \frac{c_V}{2}|H|^2V_\mu V^\mu - \frac{d_V}{4!}(V_\mu V^\mu)^2,\end{aligned}$$

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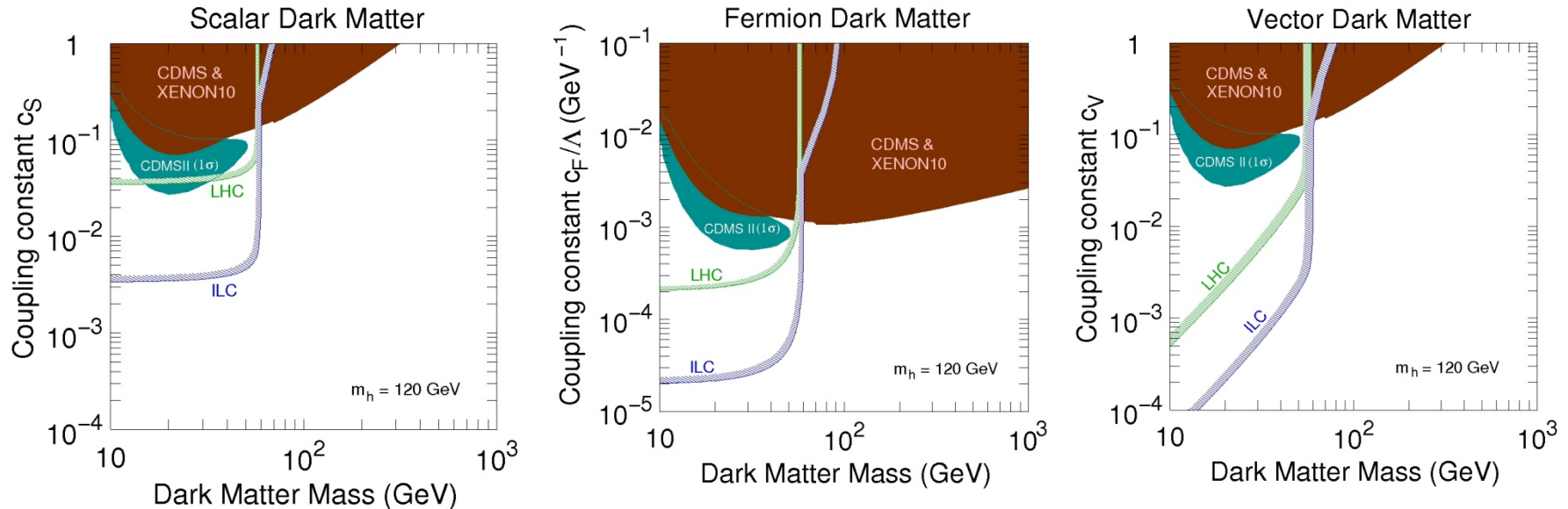


$(m_{\text{DM}} < m_H/2) \rightarrow$ Invisible decay width of H
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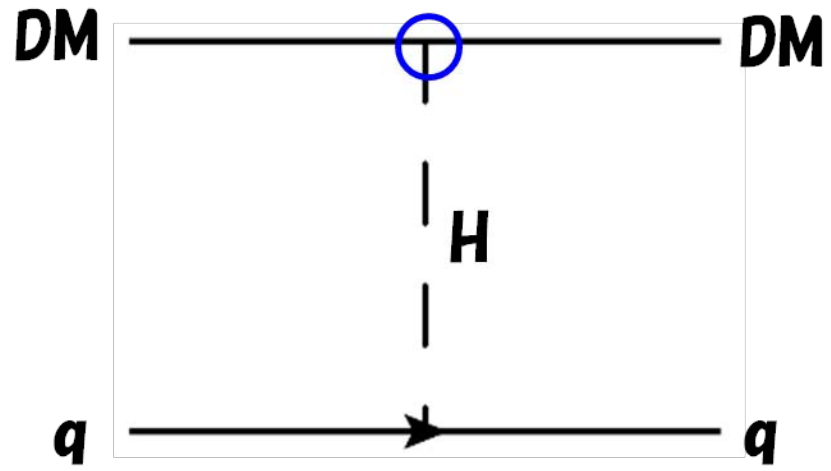
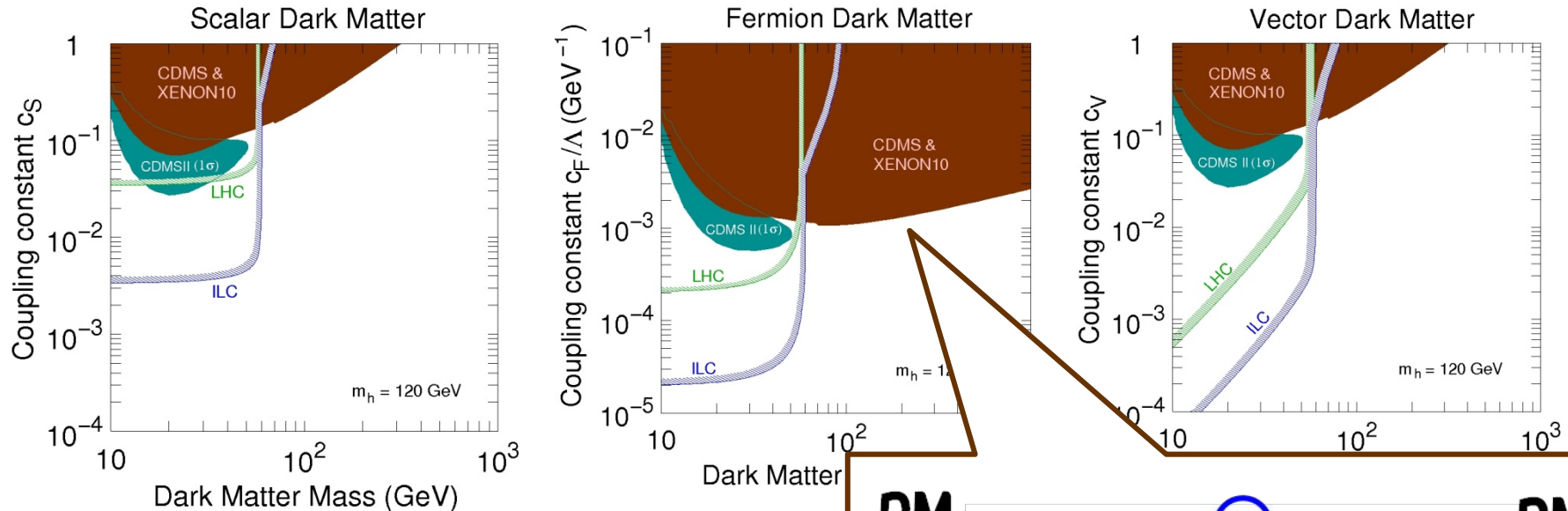
Sensitivity to detect the signal at the ILC (95% C.L.)



1. **Brown regions:** Excluded by CDMS & XENON experiment (2 σ).
2. **Dark green region:** Consistent with the CDMSII result (1 σ).
3. **Green line:** Sensitivity to detect the signal at the LHC (2 σ)
4. **Blue line:** Sensitivity to detect the signal at the ILC (2 σ)

Dark Matter detection at ILC (I)

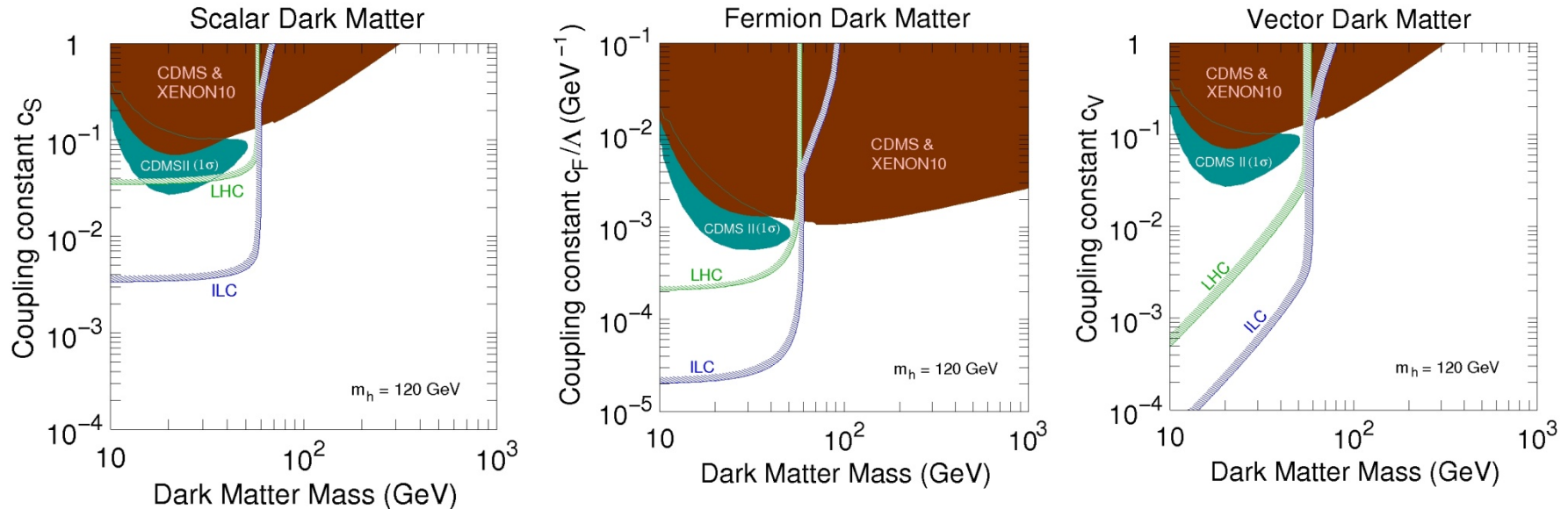
Sensitivity to detect the signal at the ILC (95% C.L.)



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Dark Matter detection at ILC (I)

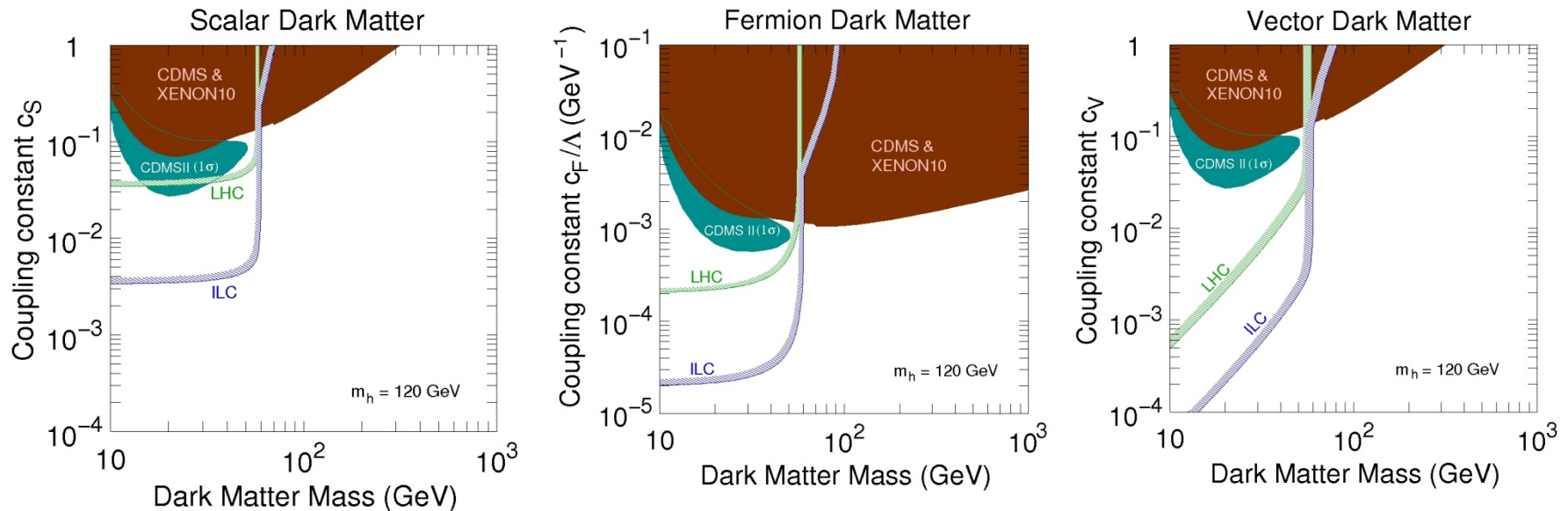
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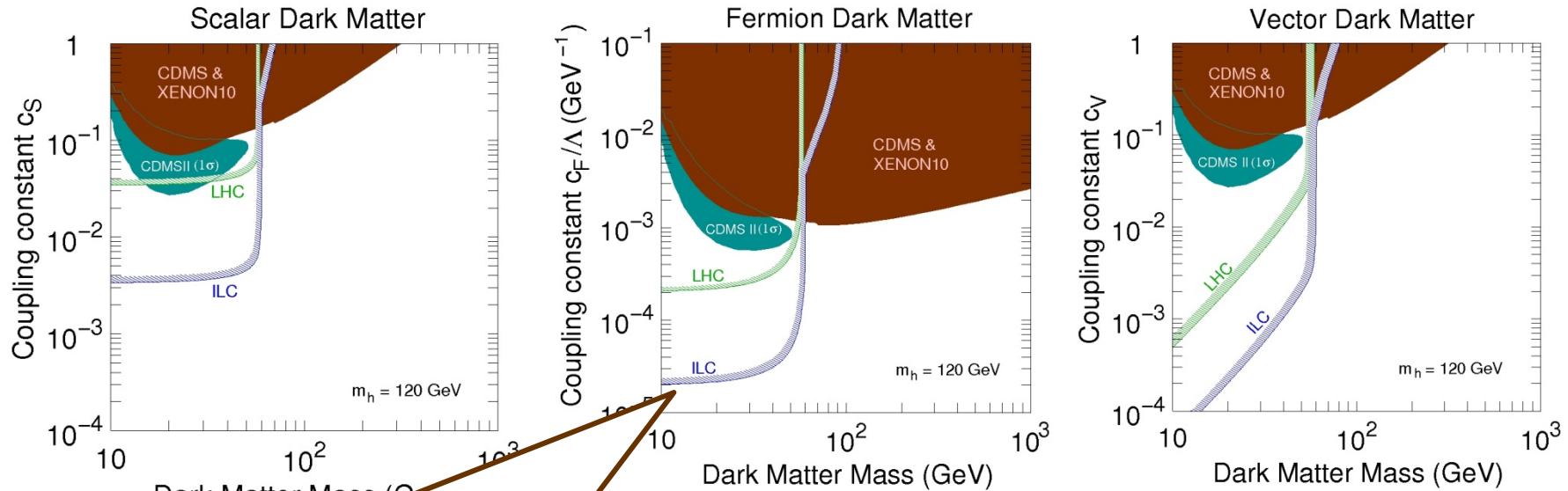
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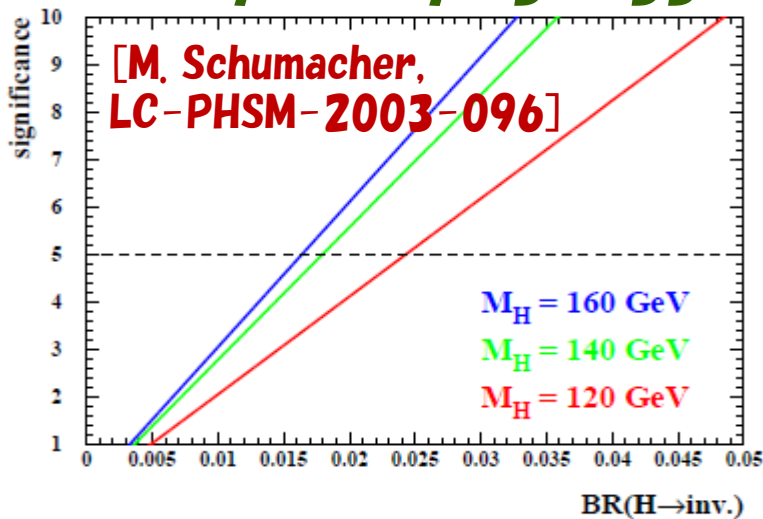
- When $m_{\text{DM}} < m_H/2$, the signal can be detected at the ILC (95%C.L.) even if the coupling between DM & H is small.
(OK when $\text{Br}(X \rightarrow \text{DM DM}) > 0.95\%$ at ILC, while $\text{Br} > 50\%$ at LHC.)**
- When $m_{\text{DM}} > m_H/2$, it is difficult to detect the signal even at the ILC when the coupling between DM & H not large.
(There may be other processes for efficient DM detections.)
(We should consider the processes from higher dimensional Ops.)**

Dark Matter detection at ILC (I)

Sensitivity to detect the signal at the ILC (95%C.L.)



Invisibly Decaying Higgs

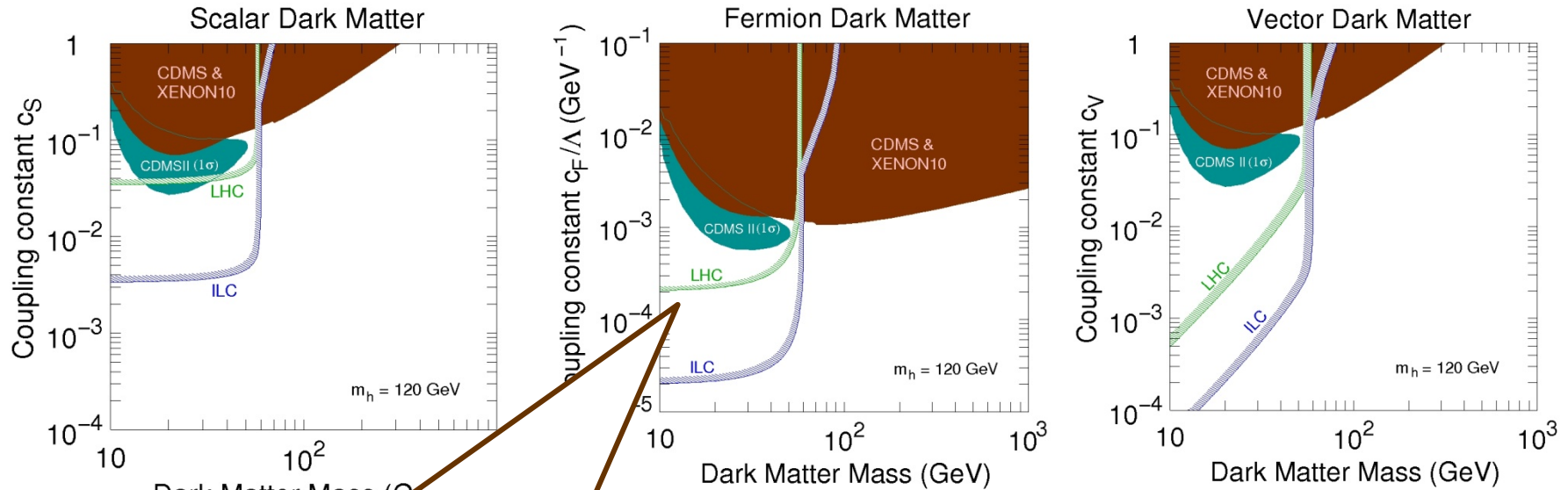


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coupling between DM & H is small.
95% at ILC, while $\text{Br} > 50\%$ at LHC.)

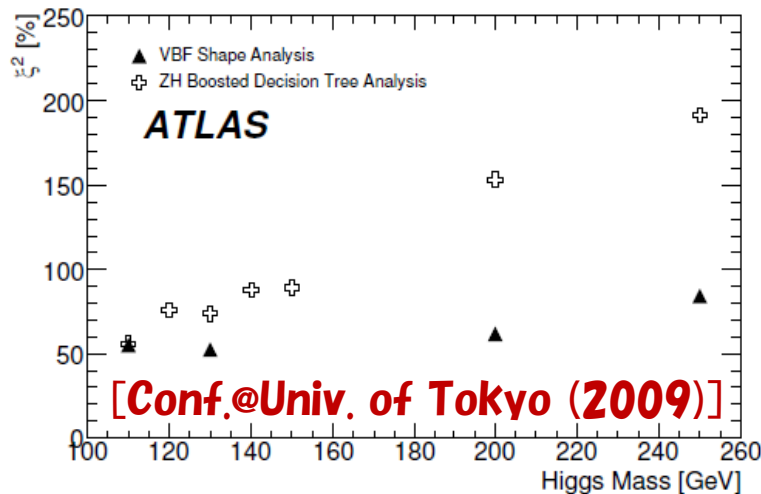
to detect the signal even at the ILC
coupling between DM & H not large.
challenges for efficient DM detections.)
challenges from higher dimensional Ops.)

Dark Matter detection at ILC (I)

Sensitivity to detect the signal at the ILC (95%C.L.)



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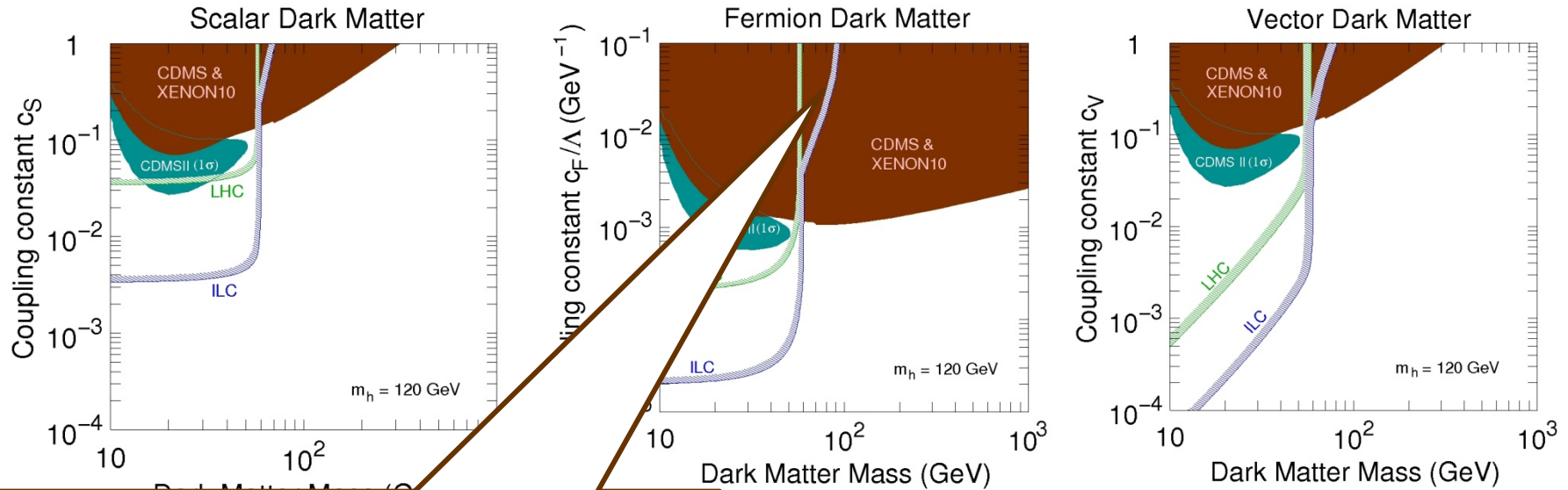


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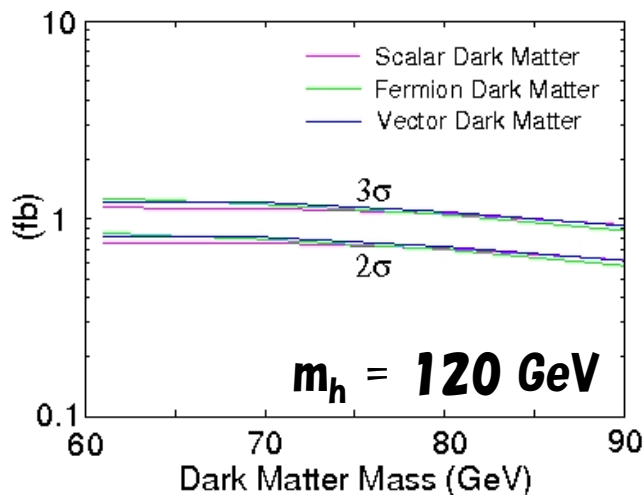
to detect the signal even at the ILC
 coupling between DM & H not large.
 (needs for efficient DM detections.)
 (needs from higher dimensional Ops.)

Dark Matter detection at ILC (I)

Sensitivity to detect the signal at the ILC (95%C.L.)



X-section for the observation

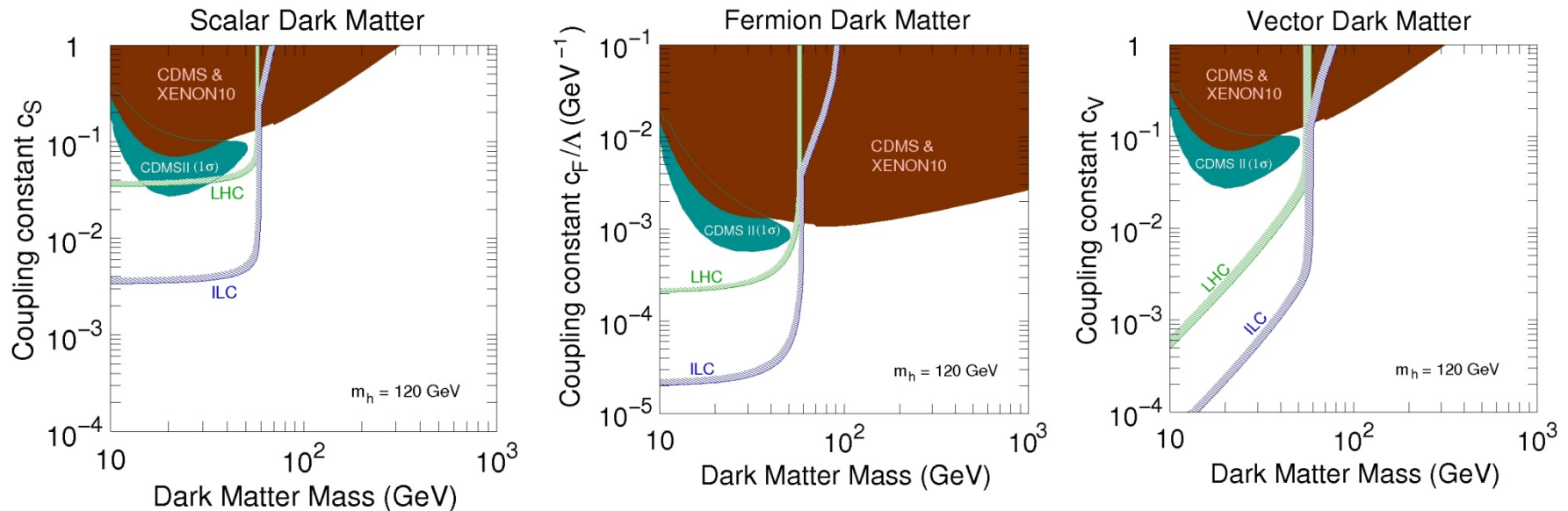


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 (cases for efficient DM detections.)
 (cases from higher dimensional Ops.)

Dark Matter detection at ILC (I)

Sensitivity to detect the signal at the ILC (95%C.L.)



When $m_{DM} < m_H/2$, the signal can be detected at the ILC (95%C.L.) even if the coupling between DM & H is small.

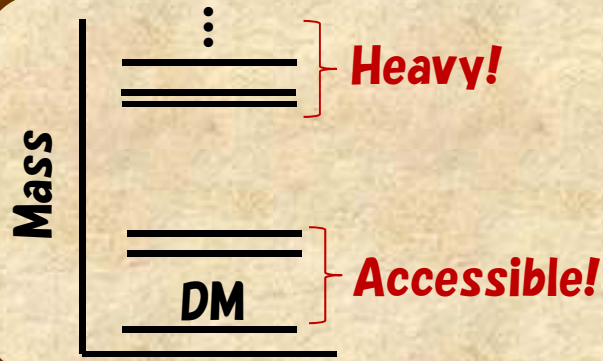
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(We should consider the processes from higher dimensional Ops.)

Dark Matter detection at ILC (II)



The case where several new particles, in addition to the dark matter, are light enough to access at the ILC.

Dark Matter detection may be possible using the production of new particles.

When new particles are non-singlet under $SU(2)_L$, there exist χ^+ having the $\chi^+ - \chi^0 - W$ interaction ($\chi^0 = DM$).

Particles	Spins	Representative Model
(χ_S^\pm, χ_S^0)	(0, 0)	Inert Higgs model
(χ_F^\pm, χ_F^0)	(1/2, 1/2)	Supersymmetric model
(χ_V^\pm, χ_V^0)	(1, 1)	Littlest Higgs model
(χ_V^\pm, χ_S^0)	(1, 0)	—
(χ_S^\pm, χ_V^0)	(0, 1)	—

Dark Matter detection at ILC (II)

Inert Higgs Model

$$\mathcal{L} = i [g_Z(1/2 - s_W^2)Z^\mu + eA^\mu] [(\partial_\mu \chi_S^+) \chi_S^- - (\partial_\mu \chi_S^-) \chi_S^+] \\ + (g/2) [- (\partial^\mu \chi_S^+) \chi_S^0 W_\mu^- + (\partial^\mu \chi_S^0) \chi_S^+ W_\mu^- + h.c.],$$

When new particles are in a triplet under $SU(2)_L$, there exist χ^+ having the $\chi^+ - \chi^0 - W$ interaction ($\chi^0 = DM$).

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(χ_V^\pm, χ_S^0)	(1, 0)	—
(χ_S^\pm, χ_V^0)	(0, 1)	—

Dark Matter detection at ILC (II)

Supersymmetric Model

$$\mathcal{L} = -g_Z \overline{\chi_F^-} \gamma^\mu (N_L P_L + N_R P_R) \chi_F^- Z_\mu - g \overline{\chi_F^-} \gamma^\mu (C_L P_L + C_R P_R) \chi_F^0 W_\mu^- + h.c.$$

When new particles are in a triplet under $SU(2)_L$, there exist χ^\pm having the $\chi^\pm - \chi^0 - W$ interaction ($\chi^0 = \text{DM}$).

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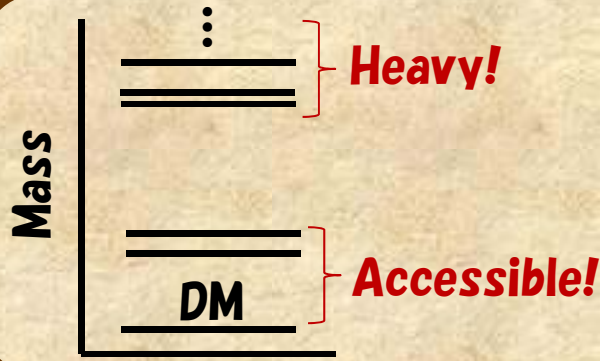
Little Higgs Model

$$\begin{aligned} \mathcal{L} = ig \bigg[& (c_W Z + s_W A)_\mu \chi_{V\nu}^+ (\partial^\mu \chi_V^{-\nu} - \partial^\nu \chi_V^{-\mu}) \\ & - (c_W Z + s_W A)_\mu \chi_{V\nu}^- (\partial^\mu \chi_V^{+\nu} - \partial^\nu \chi_V^{+\mu}) \\ & + \partial_\mu (c_W Z + s_W A)_\nu (\chi_V^{+\mu} \chi_V^{-\nu} - \chi_V^{-\mu} \chi_V^{+\nu}) \\ & + s_H W_\mu^+ \chi_{V\nu}^- (\partial^\mu \chi_V^{0\nu} - \partial^\nu \chi_V^{0\mu}) - s_H W_\mu^+ \chi_{V\nu}^0 (\partial^\mu \chi_V^{-\nu} - \partial^\nu \chi_V^{-\mu}) \\ & + s_H \partial_\mu W_\nu^+ (\chi_V^{0\nu} \chi_V^{-\mu} - \chi_V^{0\mu} \chi_V^{-\nu}) - s_H W_\mu^- \chi_{V\nu}^+ (\partial^\mu \chi_V^{0\nu} - \partial^\nu \chi_V^{0\mu}) \\ & + s_H W_\mu^- \chi_{V\nu}^0 (\partial^\mu \chi_V^{+\nu} - \partial^\nu \chi_V^{+\mu}) - s_H \partial_\mu W_\nu^- (\chi_V^{0\nu} \chi_V^{+\mu} - \chi_V^{0\mu} \chi_V^{+\nu}) \bigg] \end{aligned}$$

When new particles are non-trivial singlets under $SU(2)_L$, there exist χ^\pm having the $\chi^\pm - \chi^0 - W$ interaction ($\chi^0 = DM$).

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Dark Matter detection at ILC (II)



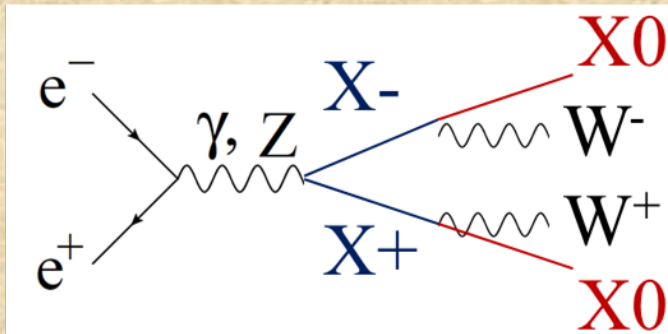
The case where several new particles, in addition to the dark matter, are light enough to access at the ILC.

Dark Matter detection may be possible using the production of new particles.

When new particles are non-singlet under $SU(2)_L$, there exist χ^+ having the $\chi^+ - \chi^0 - W$ interaction ($\chi^0 = \text{DM}$).

As a benchmark study, we discuss the discrimination of the models.

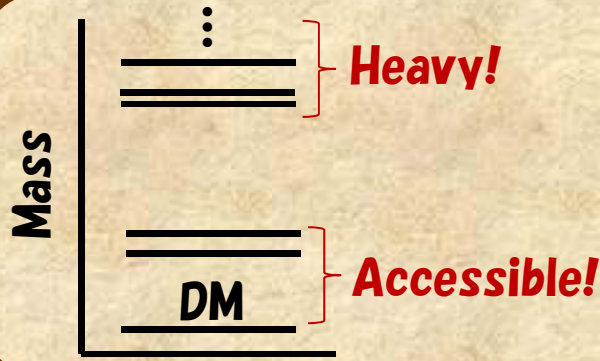
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500 fb ⁻¹	m_{χ^\pm} [GeV]	m_{χ^0} [GeV]	Cross section [fb]
$\sqrt{s} = 500$ [GeV]	232	44.0	40 & 200

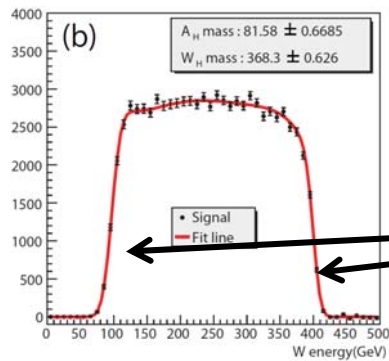
1. Energy distribution of W .
2. Threshold behavior of χ^\pm production.
3. Angular distribution of χ^\pm

Dark Matter detection at ILC (II)



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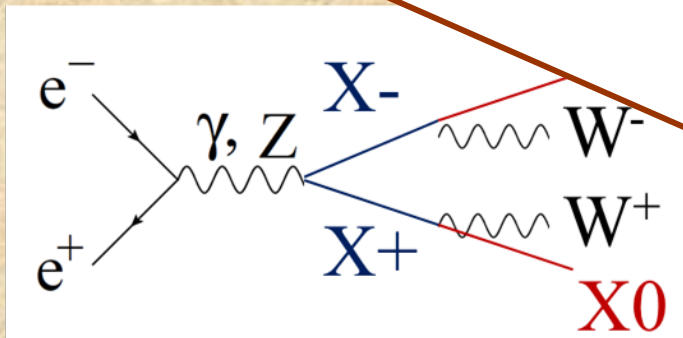
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W energy distribution

$$E_{\max} = \gamma_{\chi^\pm} E_W^* + \beta_{\chi^\pm} \gamma_{\chi^\pm} p_W^*,$$

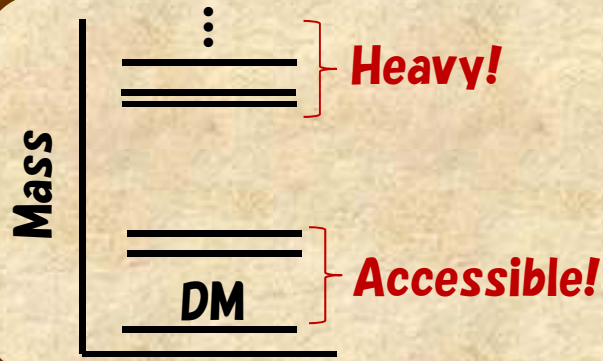
$$E_{\min} = \gamma_{\chi^\pm} E_W^* - \beta_{\chi^\pm} \gamma_{\chi^\pm} p_W^*,$$



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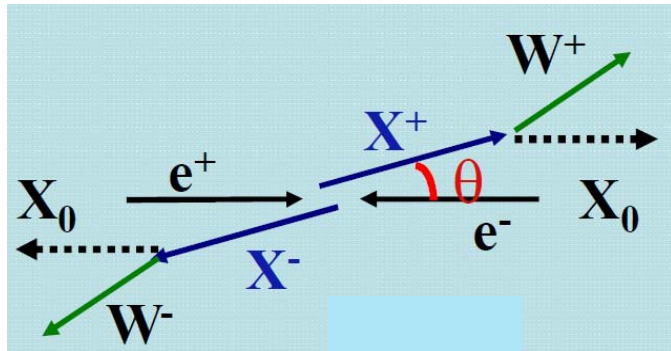
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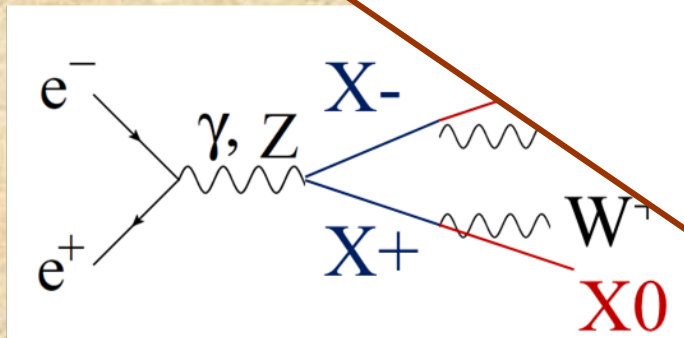
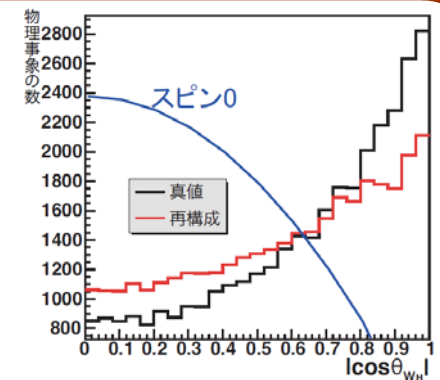


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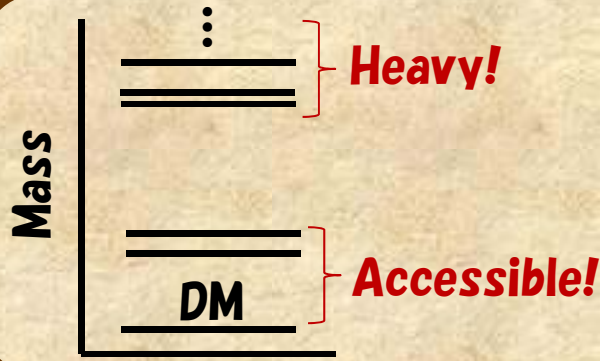
Angular distribution



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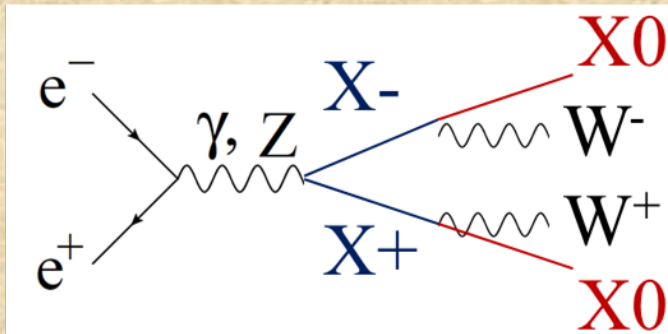
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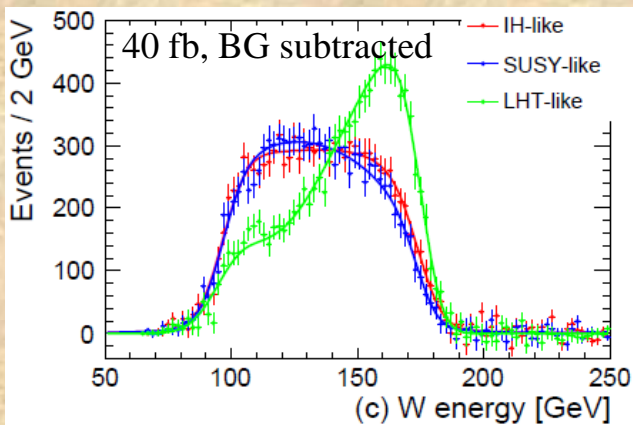
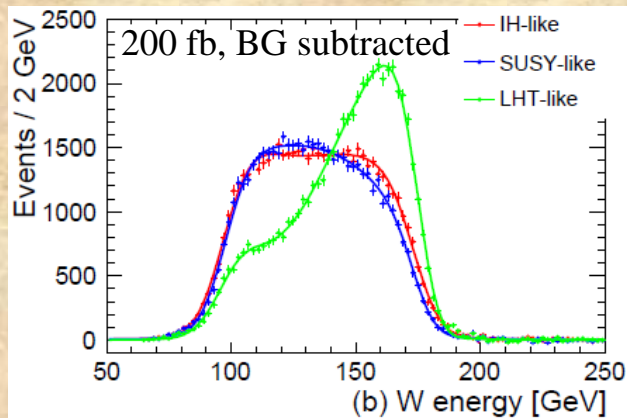


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3. Angular distribution of χ^\pm

Dark Matter detection at ILC (II)

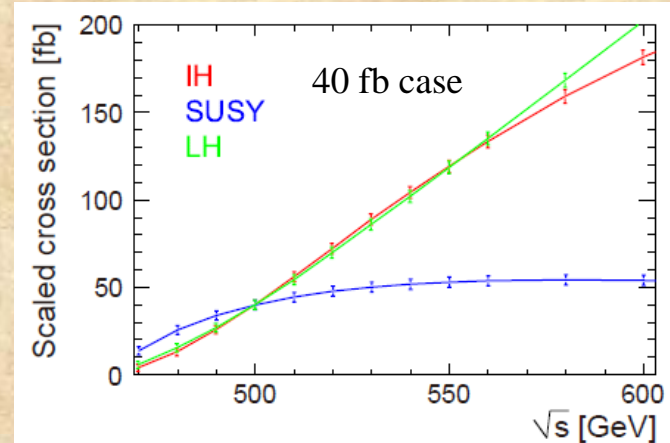
Energy distribution of W



Measurement Accuracy

($\sigma = 40 \text{ fb}$) **0.2 %** for χ^\pm
4.5 % for χ^0
 ($\sigma = 200 \text{ fb}$) **0.1 %** for χ^\pm
1.3 % for χ^0

Threshold behavior



Error bars are given by assuming 50 fb^{-1} data!

$$\sigma(s, n) = a(s - s_0)^n$$

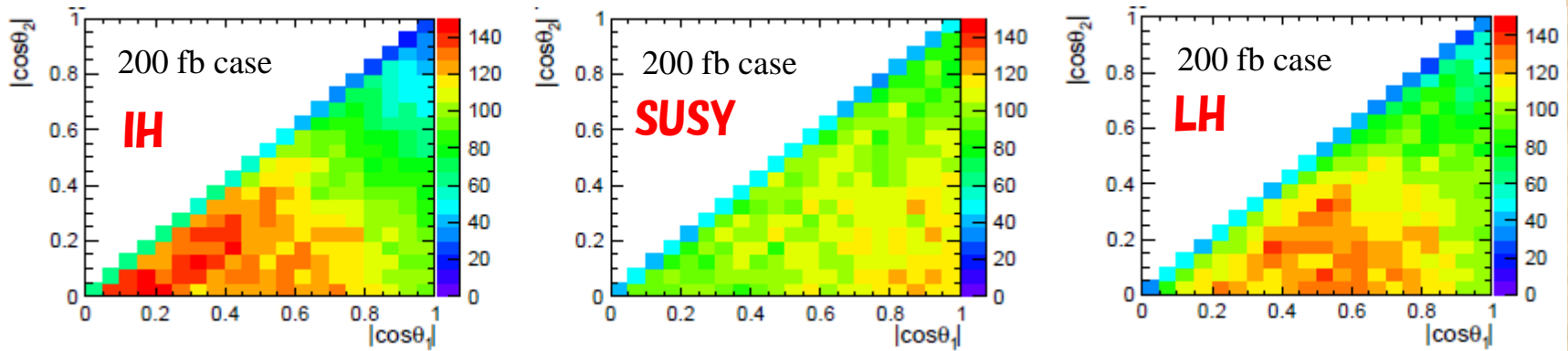
$n = 0.5$ for SUSY case,
 $n = 1.5$ for other cases.
 (General vector case is ...)

It is possible to discriminate the SUSY case from other cases (IH & LH cases)

Dark Matter detection at ILC (II)

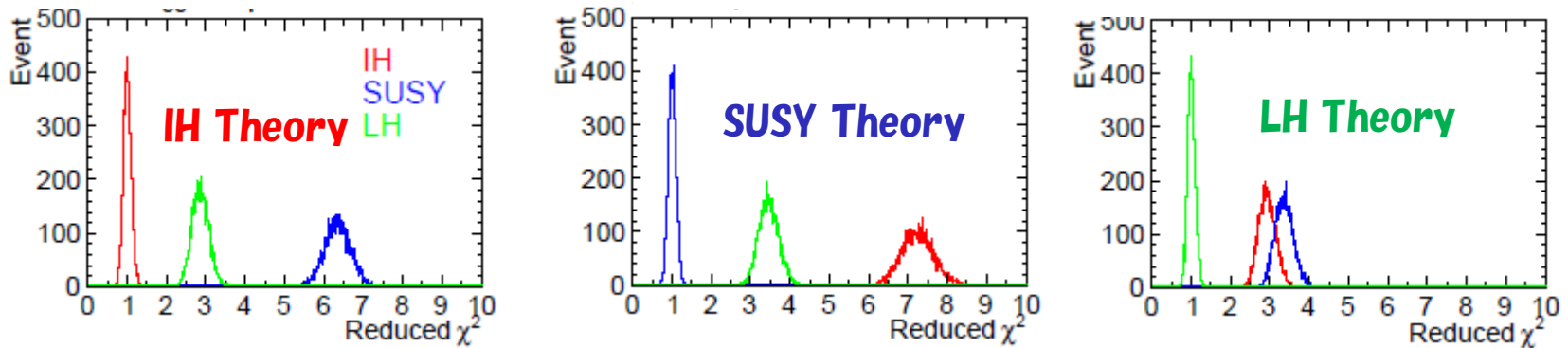
Angular distribution of reconstructed χ^\pm

~ Distributions of production angle ~



There are two-fold ambiguity to determine θ in the reconstruction of χ^\pm

~ Comparison between data & theory ~

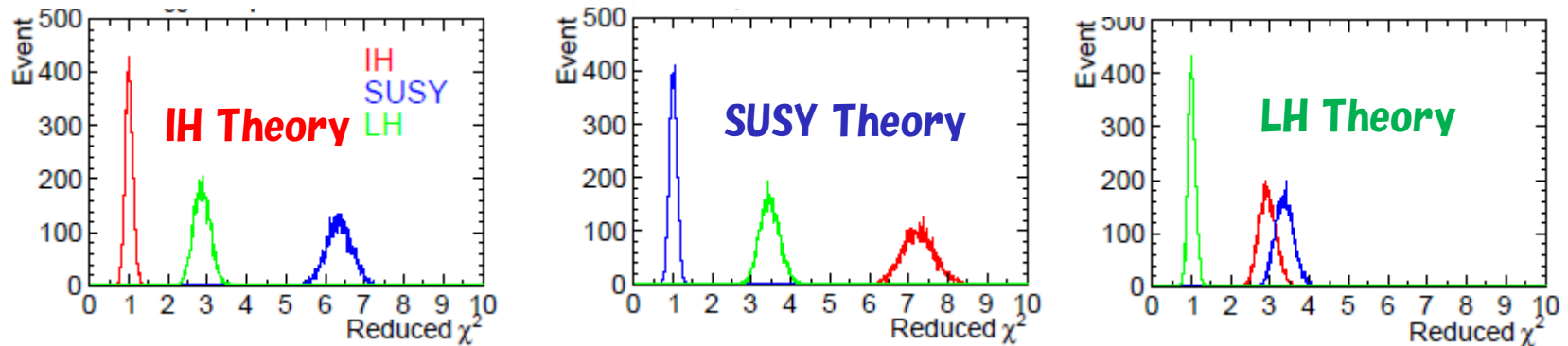


Comparisons between simulation results and theoretical predictions.

Dark Matter detection at ILC (II)

Angular distribution of reconstructed χ^\pm

~ Comparison between data & theory ~



Comparisons between simulation results and theoretical predictions.

~ Separation Power among three models ~

Cross sec.	Physics model	IH template	SUSY template	LHT template
40 fb	IH-like	-	7.7	2.5
	SUSY-like	8.6	-	3.5
	LHT-like	2.6	3.5	-
200 fb	IH-like	-	54	19
	SUSY-like	63	-	25
	LHT-like	19	24	-

Separation power $> 19\sigma$ is obtained with 200 fb signal cross section. In 40fb case, 2.5σ separation power is expected between IH & LHT.

Summary & Discussions

- **New Physics is expected to appear at the TeV scale, which will give solutions for hierarchy and dark matter problems. LHC will discover several New Physics signals, which give a clue to explore physics beyond the standard model.**
- **One of the important purposes of LC experiments is the determination of the Lagrangian at the TeV scale in a model-independent way. In particular, investigating the sector of new light particles including a dark matter candidate is important for not only particle physics but also astrophysics and cosmology.**
- **We have discussed the potential of the ILC to determine the nature of the dark matter (mass, spin, interactions, etc.)**
- **If the dark matter is the only particle which is accessible at the ILC, the higgs-dark matters coupling can be measured accurately when $m_{\text{DM}} < m_H/2$. In another case, the detection of the dark matter will be challenging. We should looking for other processes.**
- **If other new particles, in addition to the dark matter, are accessible at the ILC, it seems to be easy to investigate the nature of the new particles. Completely model-independent method for the investigation is now in progress.**