Collider Signals of Dark Higgs in Gauge-Higgs Unification

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Introduction

Two big issues in particle physics

Electro-Weak Symmetry Breaking

Higgs mechanism: Not seen yet.

Hierarchy problem: SUSY, PNGB, GHU, ...

Dark Matter

WMAP: $\Omega_{\mathrm{CDM}} h^2 = 0.1131 \pm 0.0034$

Rotation curves of galaxies: DM in galactic halo.

Both problems may be solved at once.

Stable Higgs as Dark Matter (Dark Higgs scenario)

Questions on the dark Higgs scenario

How is it realized?

a gauge-Higgs unification model

Does it explain the relic abundance?

a constraint on Higgs mass

How do we confirm it?

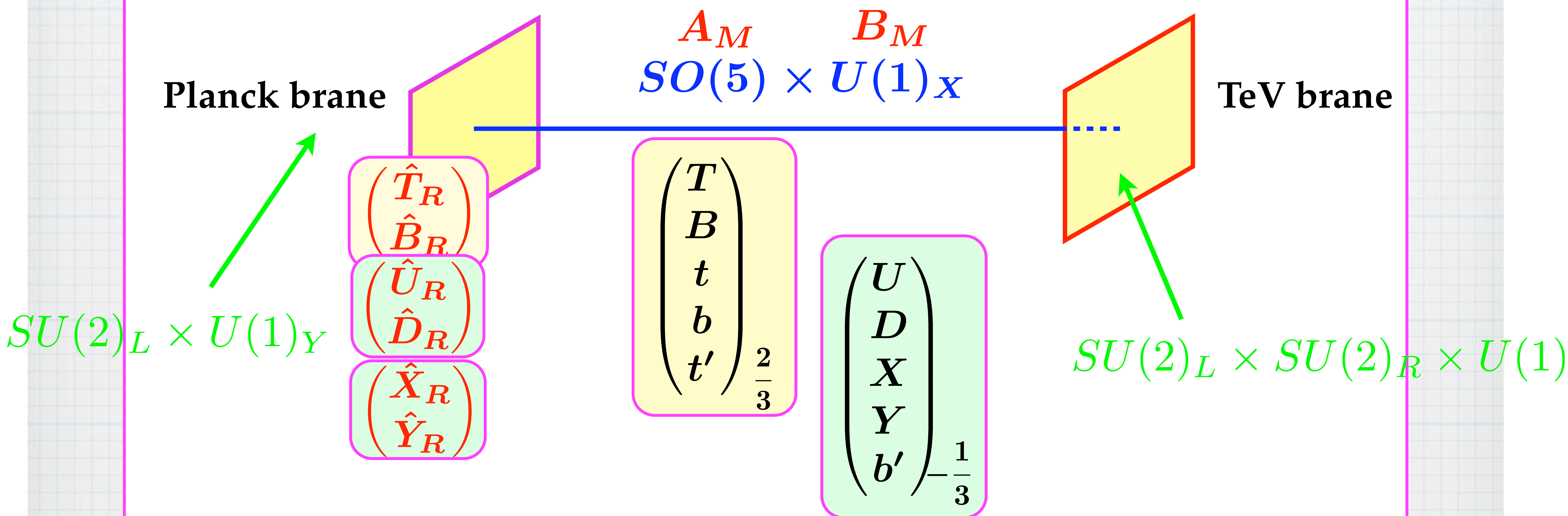
collider phenomenology

Model

Hosotani, Oda, Ohnuma, Sakamura, PRD78,096002(2008).

SO(5)xU(1) Model on RS

YH, Oda, Ohnuma, Sakamura 2008
(YH, Noda, Uekusa 2009)



At low energies γ , W , Z $\begin{pmatrix} t_L \\ b_L \end{pmatrix}$ t'_R b'_R $\cdots$
H

Y. Hosotani, 物理学会, 12 September 2009 - 2

Symmetry of the Higgs sector

EWSB by Hosotani mechanism

4D Higgs field: Wilson line (AB) phase, $\hat{\theta}_H(x)$

→ Periodicity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + 2\pi)$

Bulk fermions: vectors (and/or tensors) of SO(5), no spinors.

→ Reduction of period: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(\hat{\theta}_H + \pi)$

Mirror reflection symmetry

$y \to -y\,,\ A_y \to -A_y\,,\ \Psi \to \gamma_5 \Psi$

→ Parity: $\mathcal{L}(\hat{\theta}_H) = \mathcal{L}(-\hat{\theta}_H)$

Effective Lagrangian at the Weak Scale

$$\mathcal{L}_{\rm eff} = -V_{\rm eff}(\hat{\theta}_H) - \sum_f m_f(\hat{\theta}_H)\bar{f}f$$
$$+m_W^2(\hat{\theta}_H)W^{+\mu}W_\mu^- + \frac{1}{2}m_Z^2(\hat{\theta}_H)Z^\mu Z\mu$$

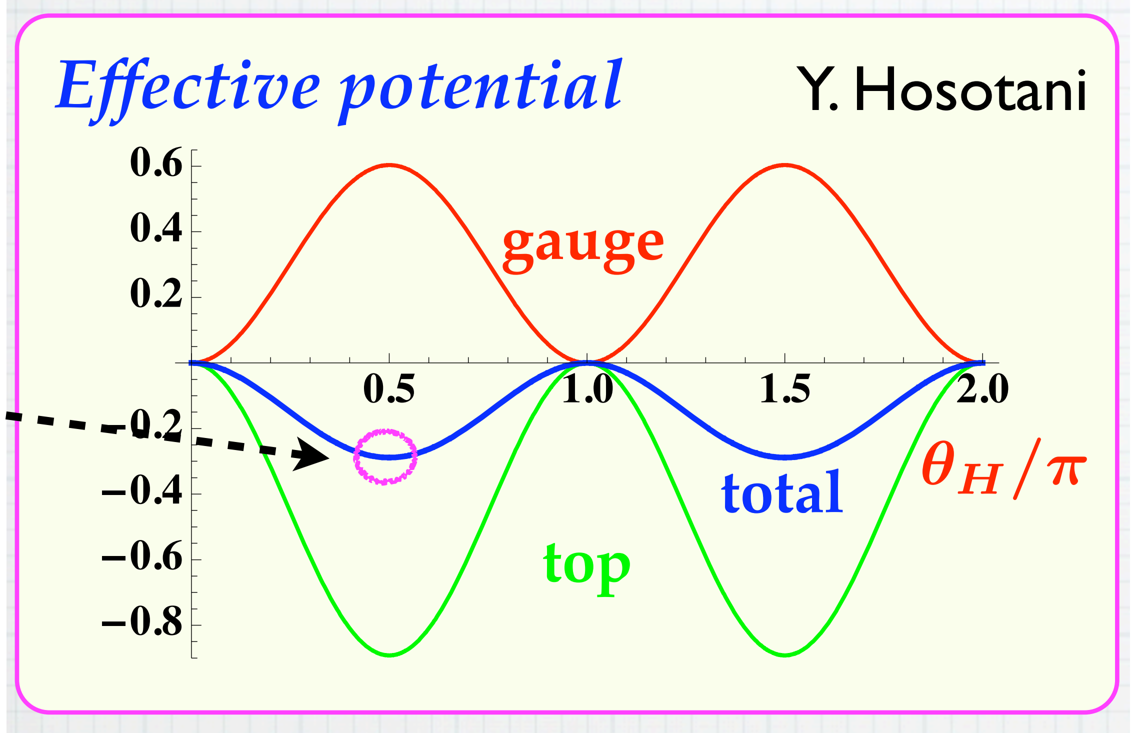
Symmetry implication:

$$V_{\rm eff}(\hat{\theta}_H+\pi) = V_{\rm eff}(\hat{\theta}_H) = V_{\rm eff}(-\hat{\theta}_H)\,,$$
$$m_{W,Z}^2(\hat{\theta}_H+\pi) = m_{W,Z}^2(\hat{\theta}_H) = m_{W,Z}^2(-\hat{\theta}_H)\,,$$
$$m_f(\hat{\theta}_H+\pi) = -m_f(\hat{\theta}_H) = m_f(-\hat{\theta}_H)\,.$$

EWSB

Vacuum: Minimize $V_{\rm eff}(\theta_H)$

$\theta_H = \pi/2\,.$



Physical Higgs:

$$\hat\theta_H(x) = \frac{\pi}{2} + \frac{H(x)}{f_H}\,.$$

$$f_H = 246\,{\rm GeV}\,(\Leftarrow m_W = g f_H/2)$$

A new dynamical parity, H-parity,

$$\frac{\pi}{2} + \frac{H}{f_H} \xrightarrow[\hat\theta \to -\hat\theta]{} -\frac{\pi}{2} - \frac{H}{f_H} \xrightarrow[\hat\theta \to \hat\theta + \pi]{} \frac{\pi}{2} - \frac{H}{f_H}$$

$$H(x) \to -H(x)\,.$$

Effective Interactions

Integrating out KK modes,

$$m_W(\hat{\theta}_H) \sim \cos\theta_W m_Z(\hat{\theta}_H) \sim \frac{1}{2} g f_H \sin\hat{\theta}_H \ ,$$

$$m_a^F(\hat{\theta}_H) \sim \lambda_a \sin\hat{\theta}_H \ ,$$

$$\mathcal{L}_{\rm int} = -\frac{m_W^2}{f_H^2} H^2 W^{+\mu} W_\mu^- - \frac{m_Z^2}{2 f_H^2} H^2 Z^\mu Z_\mu + \sum_f \frac{m_f}{2 f_H^2} H^2 \bar{f} f + \cdots \ .$$

No odd powers of H .

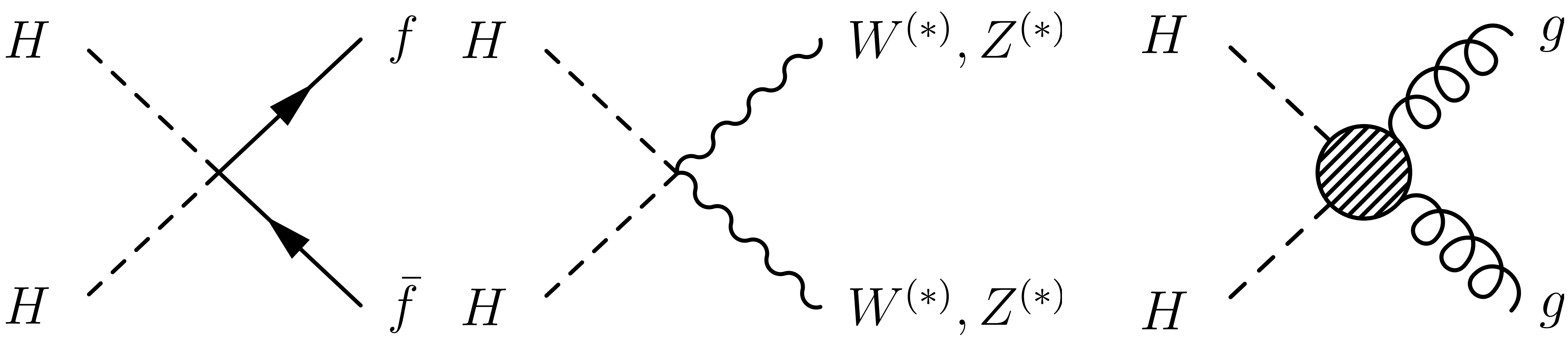
Higgs is STABLE!

A good candidate for WIMP DM.

Dark Higgs

Relic Abundance

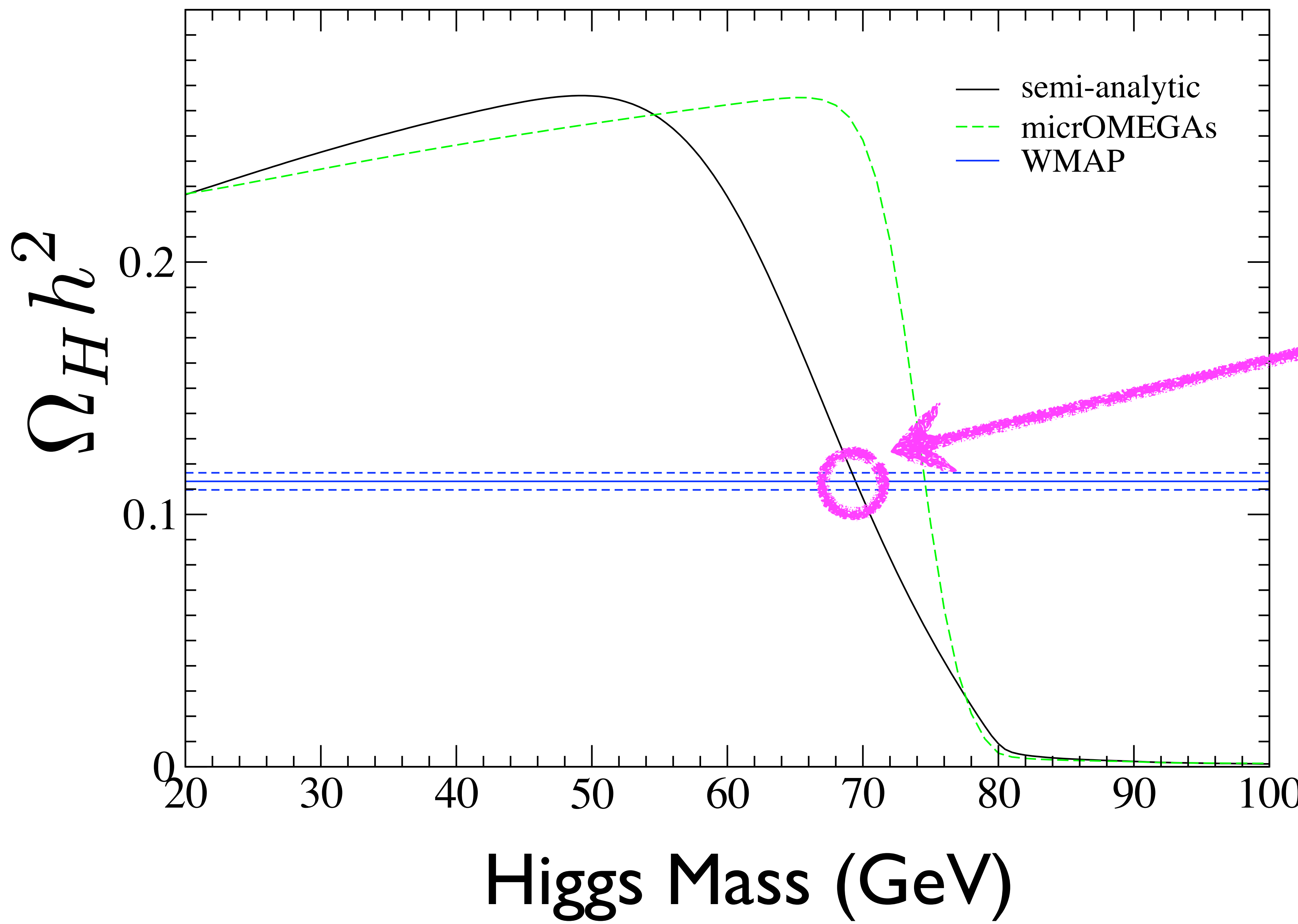
Annihilation processes:



Semi-analytic formula, e.g. Kolb and Turner

micrOMEGAs 2.2 by G. Belanger et al.

Relic Abundance

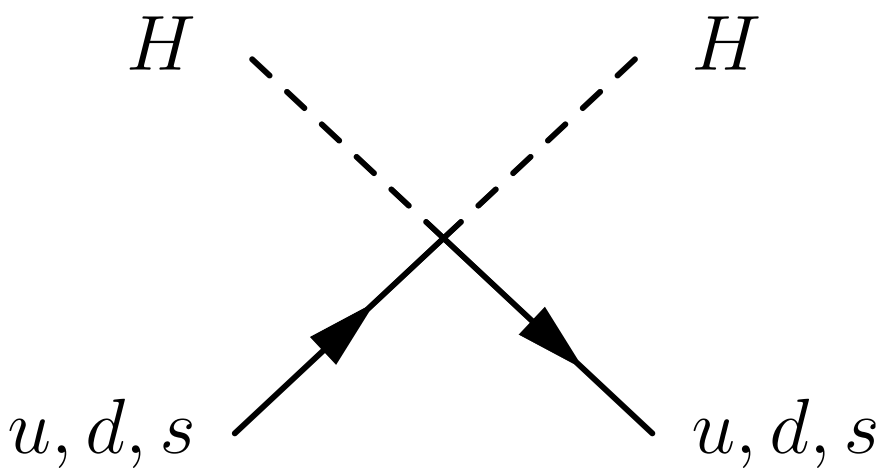


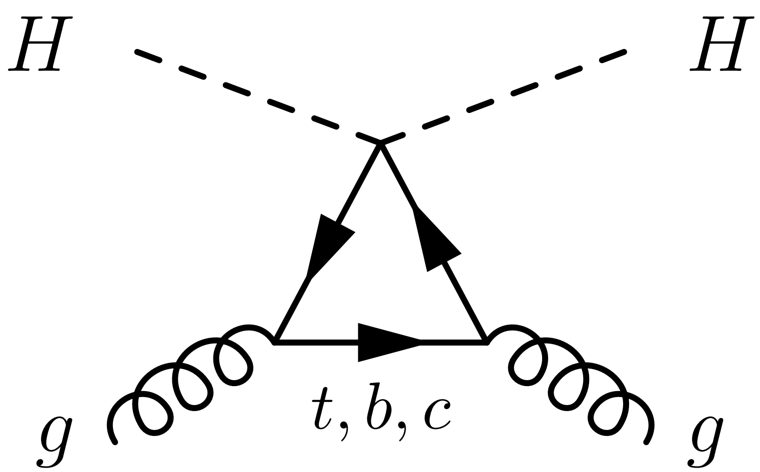
$m_H \sim 70\,\mathrm{GeV}$ favored.

$T_f \sim 3\,\mathrm{GeV}$

$10^{-27}\mathrm{cm}^3/\mathrm{s}$	$b\bar{b}$	$W^{(*)}W^{(*)}$	$Z^{(*)}Z^{(*)}$
$\sigma v\|_{v\to 0}$	7.3	11	1.5

Direct Detection $HN \to HN$





$$\mathcal{L}_{\rm eff} \simeq \frac{H^2}{2f_H^2}\left[\sum_{q=u,d,s} m_q \bar{q} q - \frac{\alpha_s}{4\pi} G^a_{\mu\nu} G^{a\,\mu\nu}\right]$$

$$\longrightarrow \quad \mathcal{L}_{HN} \simeq \frac{2+7f_N}{9}\,\frac{m_N}{2f_H^2}\,H^2 \bar{N} N$$

$$f_N = \sum_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle / m_N \simeq 0.1 \sim 0.3$$

Spin-Independent Cross Section

CDMS II

arXiv:0912.3592

Local DM density

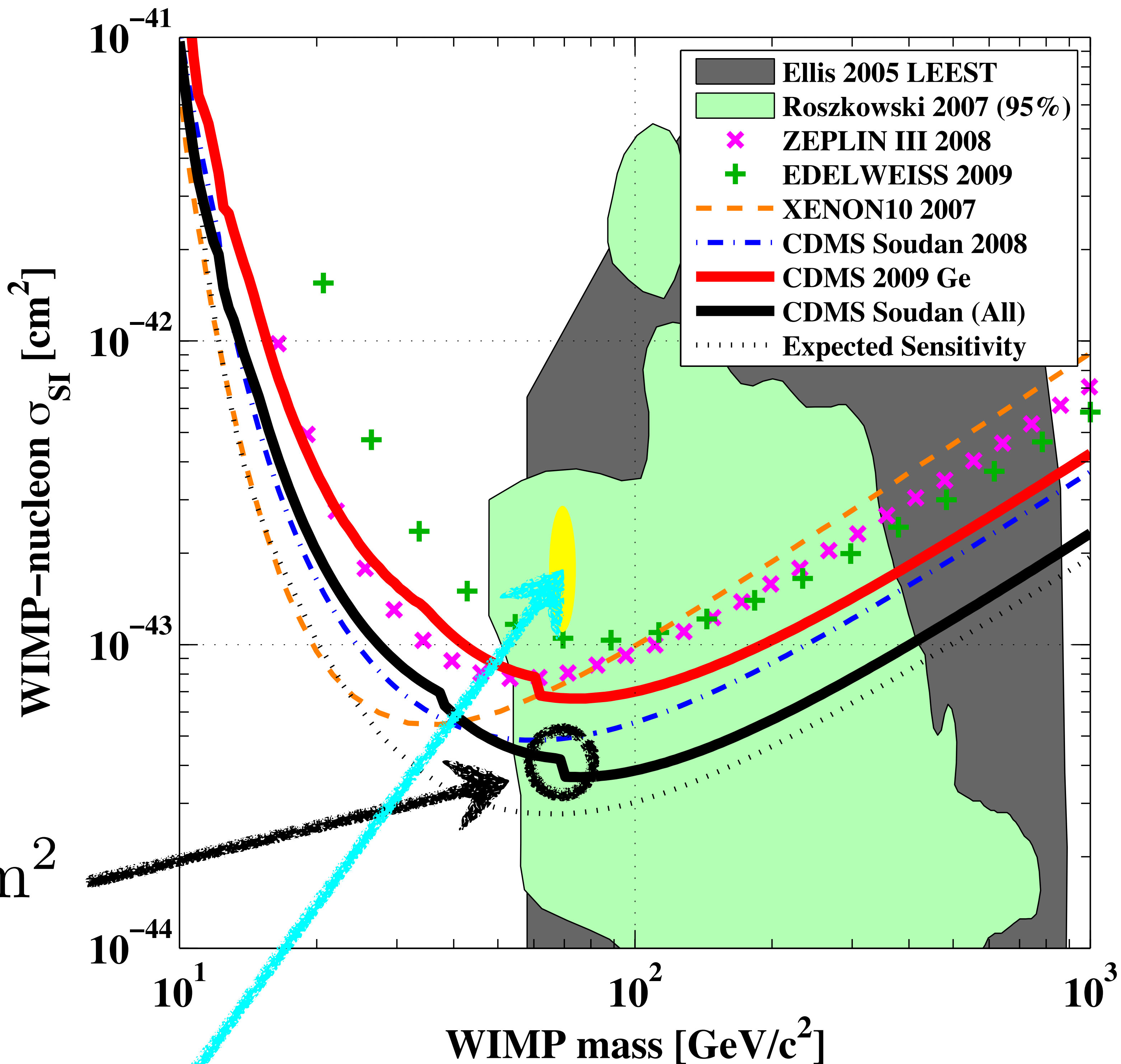
$\rho_0 = 0.3\,\mathrm{GeV/cm^3}$

assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

Exp. bound:

$\sigma_{\mathrm{SI}} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$



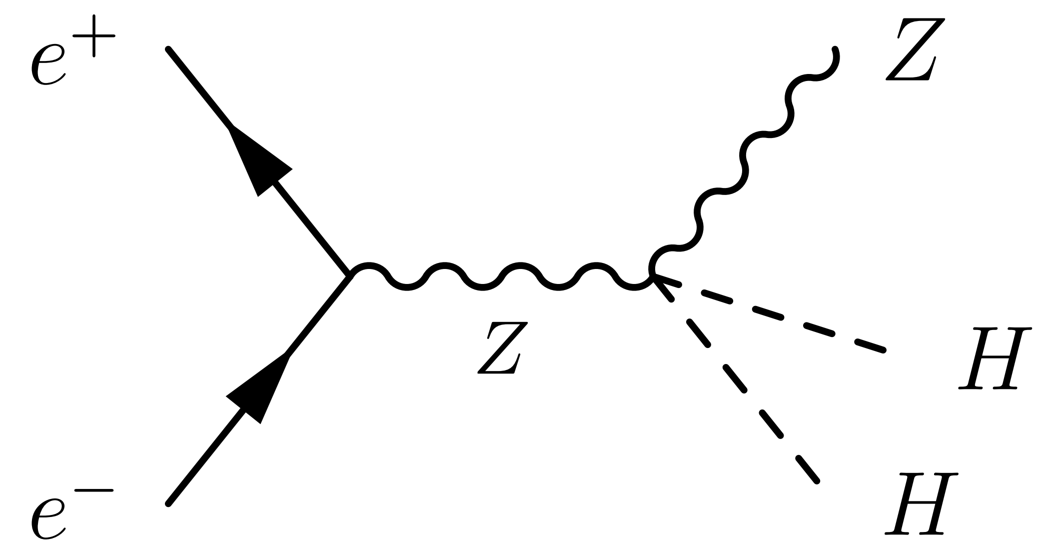
Dark Higgs

Prediction: $\sigma_{\mathrm{SI}} \simeq (1.2 - 2.7) \times 10^{-43}\,\mathrm{cm}^2$

Collider Signals

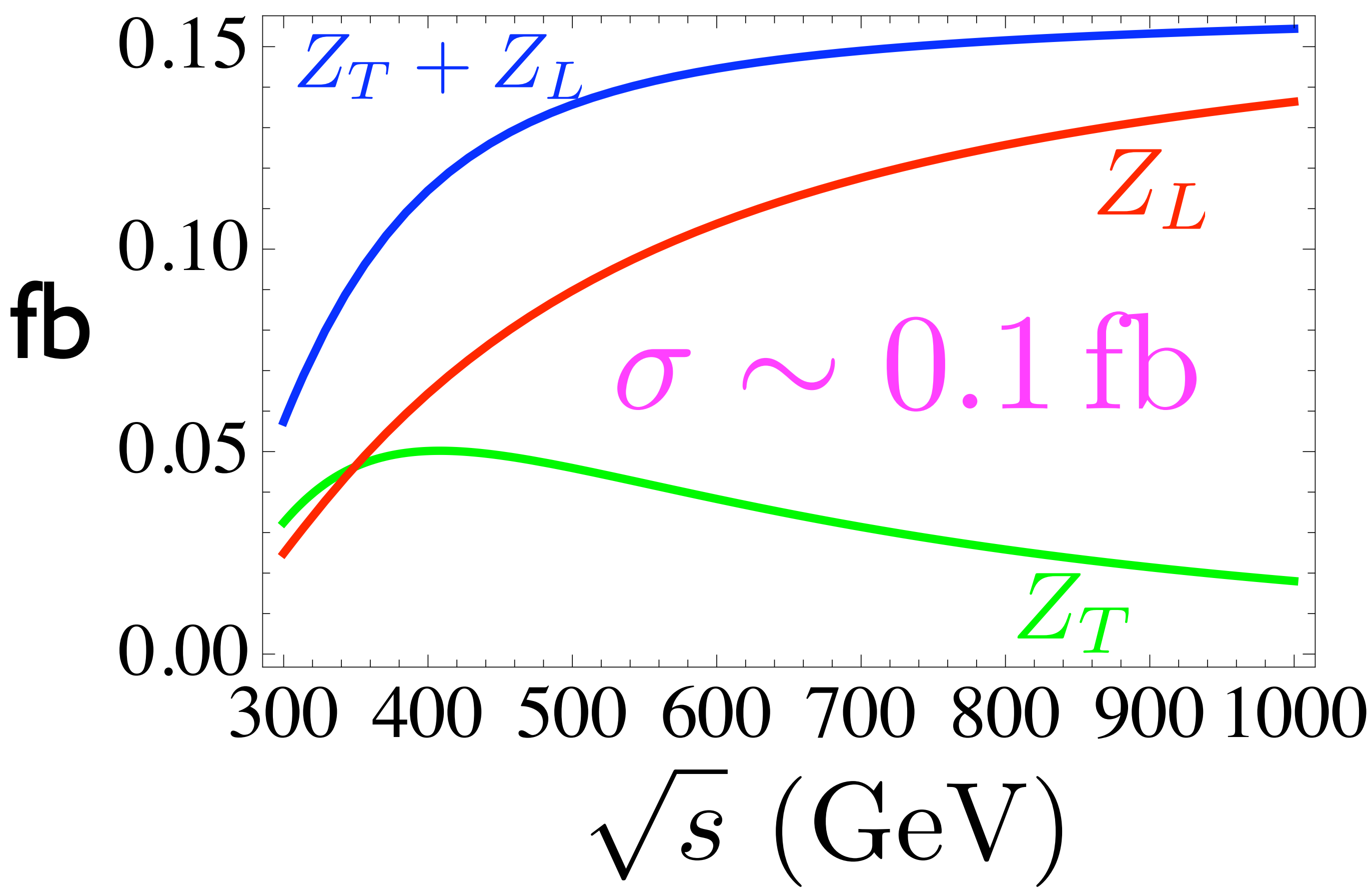
Linear Collider

Signal: $e^+e^- \to ZHH$



H's are missing.

total cross section for $m_H = 70\,\mathrm{GeV}$

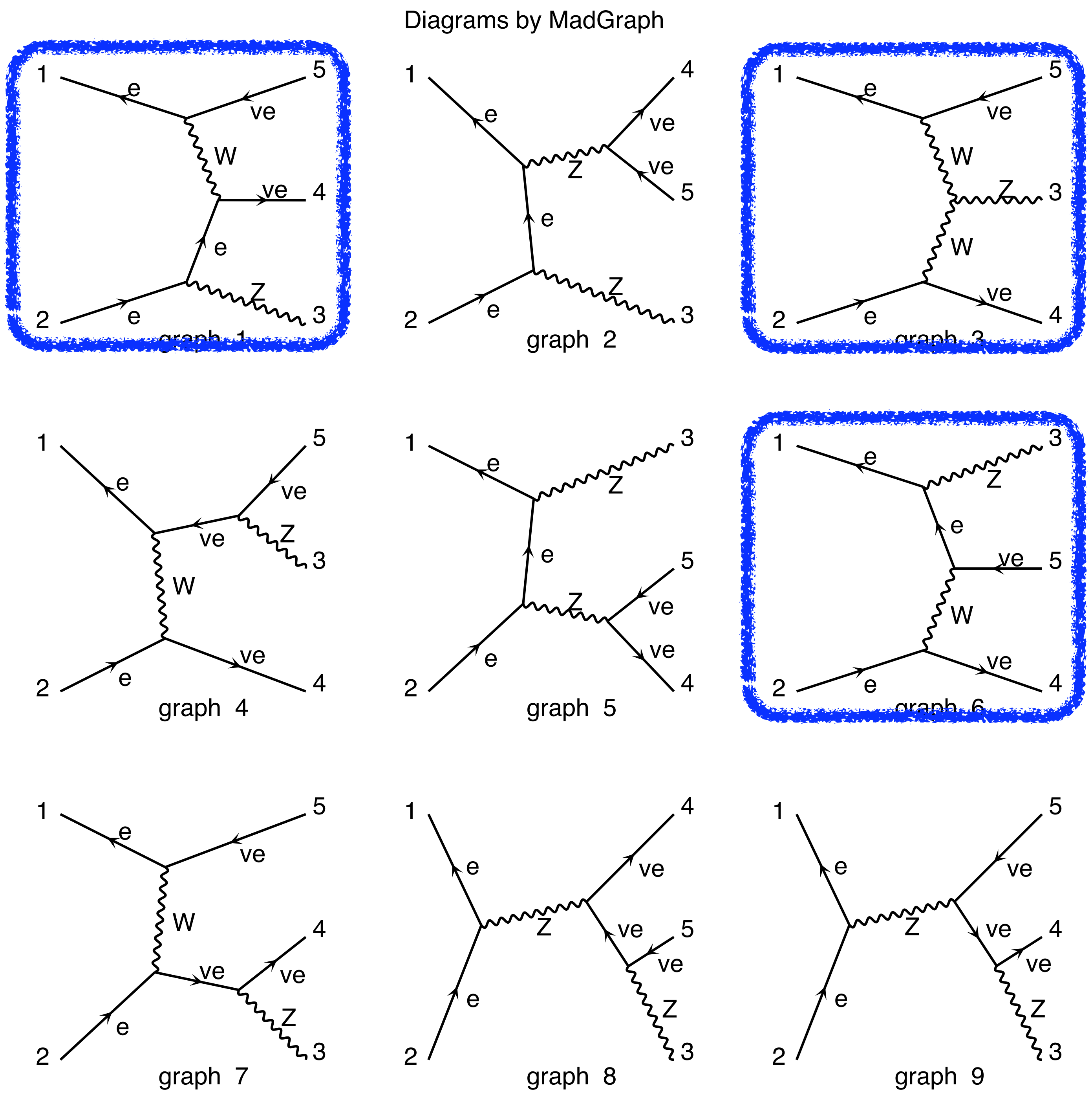


Z_L violates the unitarity unless $s/m_{\mathrm{KK}}^2 \ll 1$.

$m_{\mathrm{KK}} \sim 1.5\,\mathrm{TeV}$

$\sqrt{s} = 500\,\mathrm{GeV}$ in the following.

LC background $e^+e^- \to Z\nu\bar{\nu}$



BG cross section with $M_{\text{miss}} \geq 120\,\text{GeV}$

$\sigma_{\text{BG}} \simeq 311\,\text{fb}$

Need polarizations!

beams and Z

LC with polarizations

Ideal case: $e_L^+ e_R^- \to Z_L H H \,,\; Z_L \nu\bar{\nu}$

$\sigma_{\rm signal} \simeq 0.12\,{\rm fb}$ vs $\sigma_{\rm BG} \simeq 0.42\,{\rm fb}$

$|\cos\theta| < 0.6$ is applied.

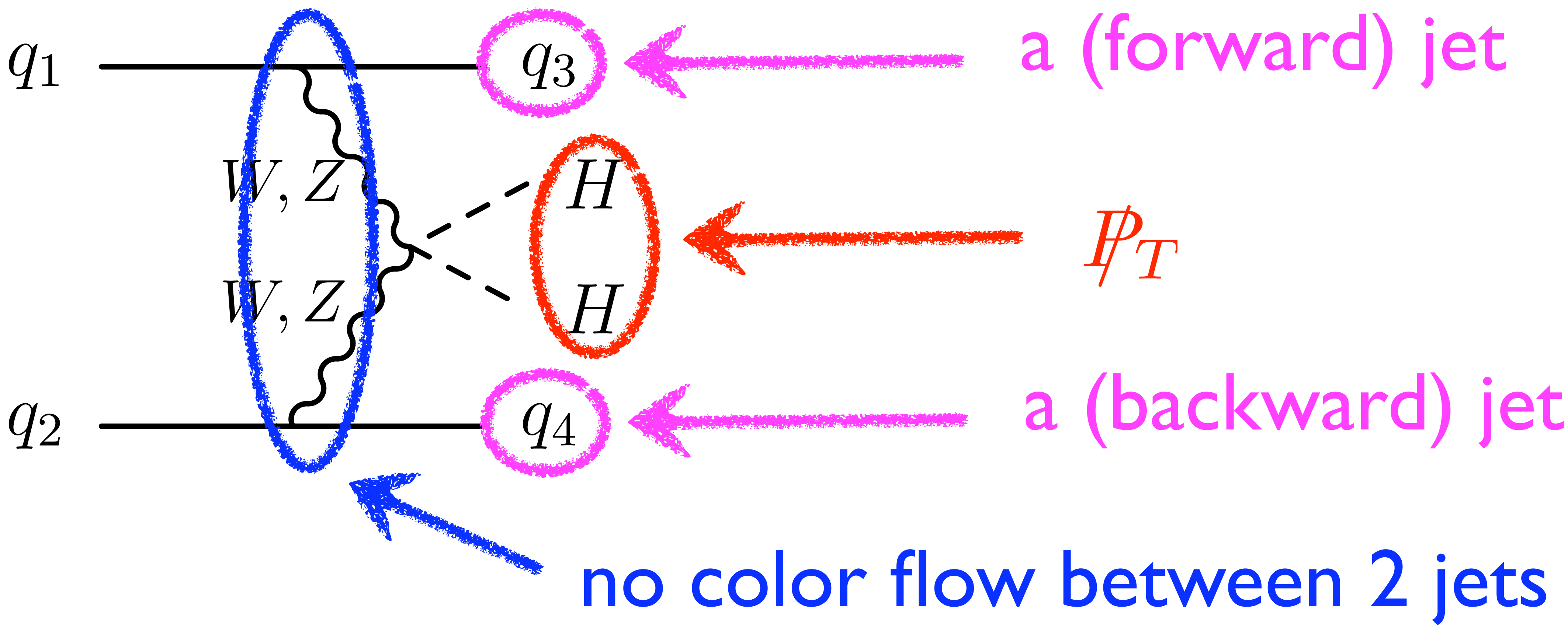
Significance: $\mathcal{S} \equiv \dfrac{N_{\rm signal}}{\sqrt{N_{\rm signal} + N_{\rm BG}}}$

$$\mathcal{S} = 1.4\sqrt{L/100\,{\rm fb}^{-1}}$$

A few (or more) ${\rm ab}^{-1}$ is required!

LHC

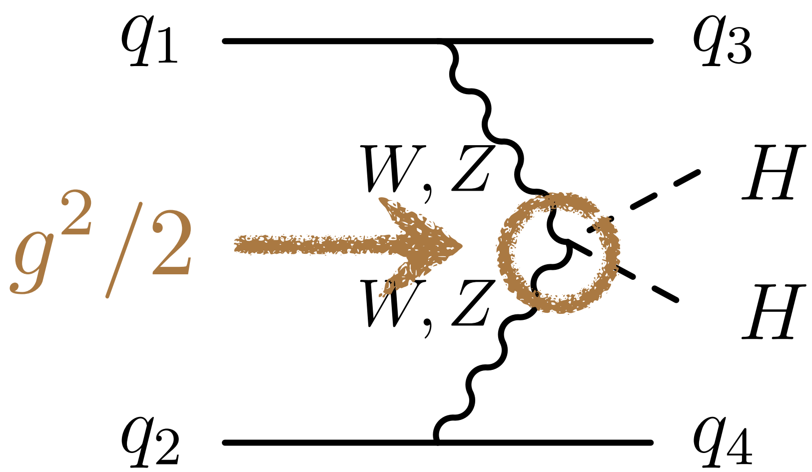
Signal: Weak boson fusion

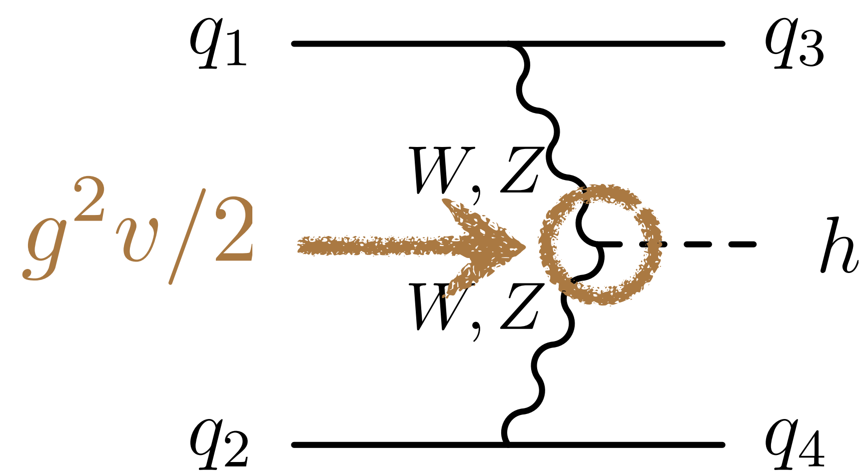


Background: Wjj, Zjj, jjj

→ Similar as invisible Higgs search

Signal Cross Section at LHC





$$\frac{d\sigma_{HH}}{dm^2_{HH}} = \frac{\bar{\beta}_f}{32\pi^2 v^2} \sigma_h |_{m_h^2 = m^2_{HH}}$$

in the SM or alike

$$\sigma_{HH} \sim 1.5\,\mathrm{fb}$$

$$\sigma_{BG} \simeq 167\,\mathrm{fb}$$

$$\mathcal{S} \sim 1.2\sqrt{L/100\,\mathrm{fb}^{-1}}$$

Éboli, Zeppenfeld

$p_T^j > 40$ GeV, $\quad |\eta_j| < 5.0,$

$|\eta_{j1} - \eta_{j2}| > 4.4, \quad \eta_{j1} \cdot \eta_{j2} < 0,$

$\not{p}_T > 100$ GeV.

$M_{jj} > 1200$ GeV, $\quad \phi_{jj} < 1.$

Summary

- Stable Higgs is a viable candidate of dark matter.

  Dark Higgs scenario

- $m_H \sim 70\,\mathrm{GeV}$ is predicted.

- Direct detection is likely.

  Exp. limits depend on the local DM density, ρ_0 .

  $$\rho_0 \simeq 0.04 \sim 0.6\,\mathrm{GeV/cm^3}$$

- We need a few ab^{-1} or more.

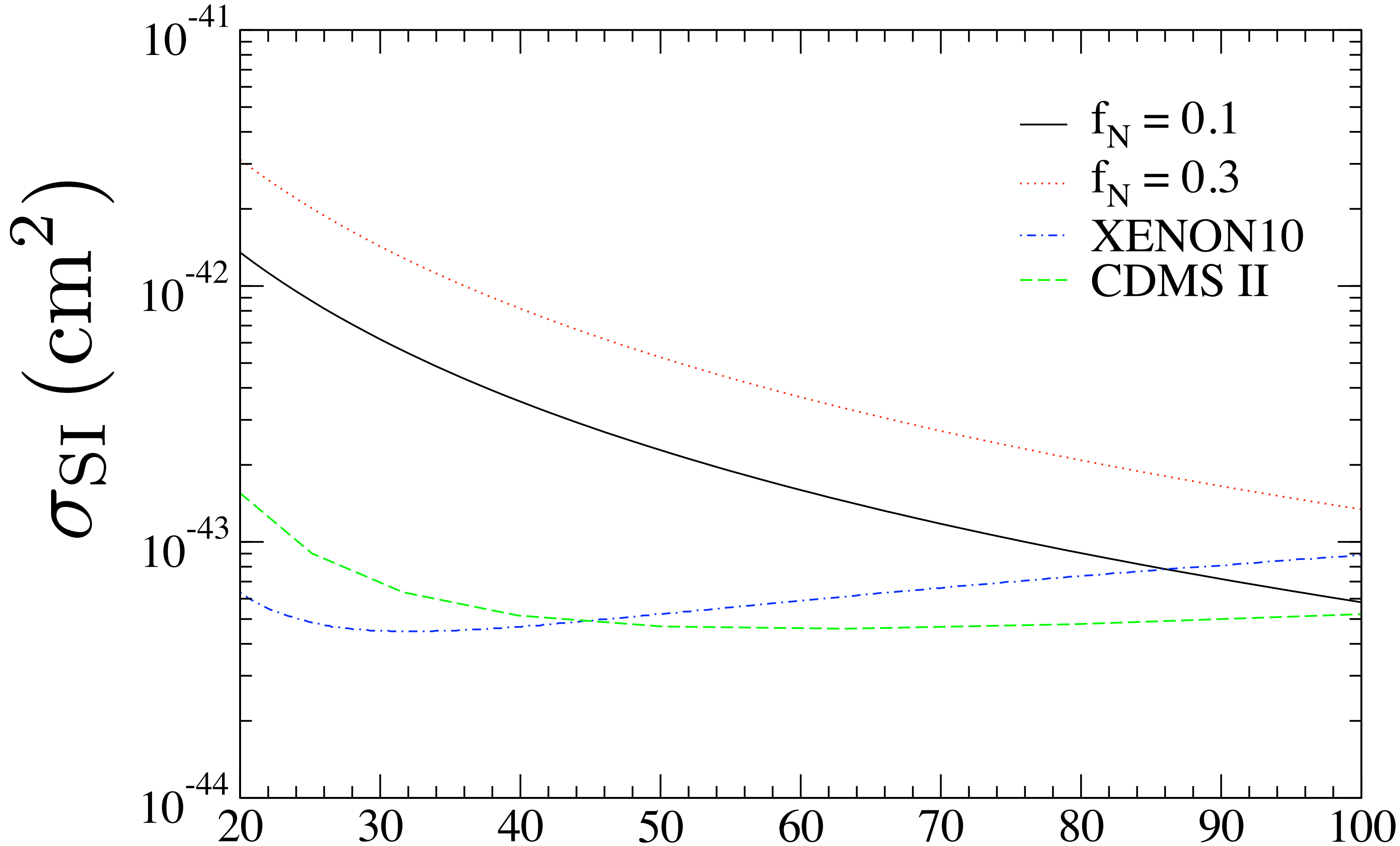
  both for LHC and LC.

- Signals in KK mode production should be studied.

  $m_{\mathrm{KK}} \sim 1.5\,\mathrm{TeV}$ Higher energy colliders?

Backup Slides

Spin-Independent Cross Section



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assumed in exps.

For $m_H = 70\,\mathrm{GeV}$

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Exp. bound: $\sigma_{\mathrm{SI}} \lesssim 3.8 \times 10^{-44}\,\mathrm{cm}^2$

Uncertainties in the direct detection

Local density of CDM (not measured)

$\rho_0 = 0.3\,\mathrm{GeV}/\mathrm{cm}^3$

assumed in the experiments.

$\rho_0 = 0.2 \sim 0.6\,\mathrm{GeV}/\mathrm{cm}^3$

reasonable for smooth halo.

$\rho_0 \sim 0.04\,\mathrm{GeV}/\mathrm{cm}^3$ (Kamionkowski and Koushiappas)

possible for non-smooth halo.

Effective Higgs coupling $HH\bar{f}f$

may be altered in more general models.

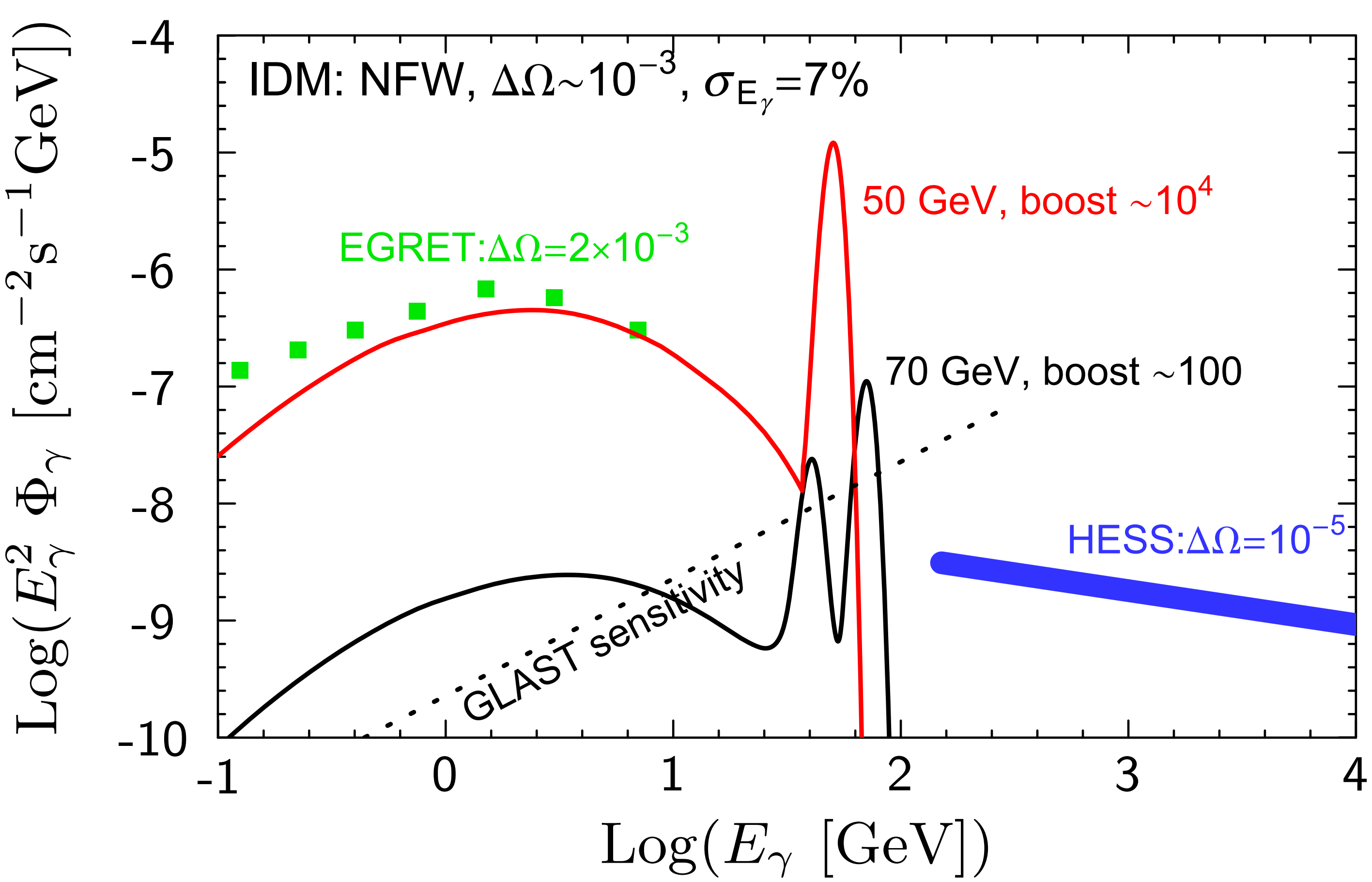
Astrophysical Signals

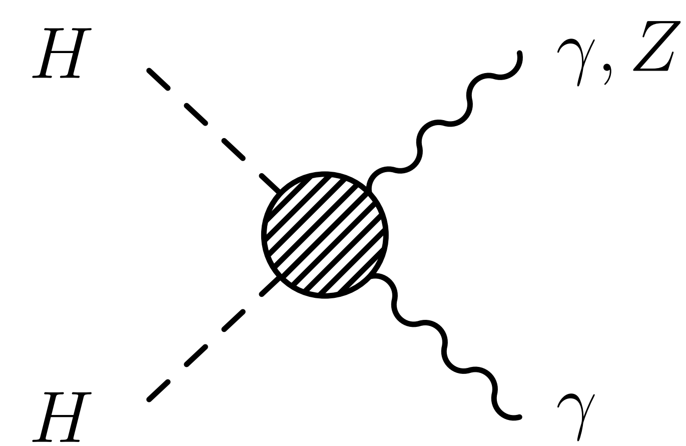
$HH \to \gamma\gamma,\ \gamma Z$ in the Galactic halo.

Two (nearly) monochromatic gamma lines.

$$E_\gamma = m_H (\simeq 70\mathrm{GeV})\,, m_H - m_Z^2/(4m_H)(\simeq 40\mathrm{GeV})$$

$$\sigma_{\gamma\gamma(\gamma Z)}\, v|_{v\to 0} \simeq 4.3(5.4) \times 10^{-29}\mathrm{cm}^3/\mathrm{s}$$





cf. Inert Doublet Model

← Gustafsson et al.