Pseudoscalar Portal to Dark Matter: Beyond Simplified Models

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1611.04593 (with D. Goncalves & P. Machado), 1509.01110

LHC DM WG MEETING 15/12/16

Simplified Models for DM Searches

- **Simple enough** as sensible unit within (more) complicated model
- **Complete enough** to accurately capture relevant LHC physics

(expect them to be building blocks for UV complete DM theories)

Simplified Models for DM Searches

wish list

- **Simple enough** as sensible unit within (more) complicated model
- **Complete enough** to accurately capture relevant LHC physics

(expect them to be building blocks for UV complete DM theories)

Here focus on **Dirac Fermion DM + Spin-0 Mediator**

Scalar Mediator

$$\begin{aligned}\mathcal{L}_s &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu s)^2 - \frac{m_s^2}{2}s^2 \\ &- g_\chi\, s\, \bar{\chi}\chi - g_{\rm SM}\, s \sum_q \frac{y_q}{\sqrt{2}}\, \bar{q}q\end{aligned}$$

Pseudoscalar Mediator

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- i g_\chi\, a\, \bar{\chi}\gamma^5\chi - i g_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\, \bar{q}\gamma^5 q\end{aligned}$$

(Defined after EWSB)

For **PSEUDOSCALAR** Mediator, **LHC (much) More Sensitive** than DM Direct Detection

Strongly Suppressed
Spin Dependent @ Tree-level
Spin Independent @ One-loop

Simplified Models for DM Searches

Complete enough to accurately describe LHC physics ?

The Issue is $SU(2)_{\rm L} \times U(1)_{\rm Y}$ Gauge (non) Invariance

$$\begin{aligned}\mathcal{L}_a &= \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 \\ &- ig_\chi\, a\, \bar{\chi}\gamma^5\chi - ig_{\rm SM}\, a \sum_q \frac{y_q}{\sqrt{2}}\, \bar{q}\gamma^5 q\end{aligned}$$

ASSUME DM is SM GAUGE SINGLET

MEDIATOR NEEDS $SU(2)_{\rm L} \times U(1)_{\rm Y}$ CHARGE
to couple to SM fermions

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s-channel pseudoscalar portal:

Mixing between a and Scalar EW Multiplet

$\sin\theta$

New States
(Mediator EW Partners)

New States Only Decouple by Closing Portal: $\sin\theta \sim \dfrac{\lambda v^2}{M^2 - m_a^2}$

Simplified Models for DM Searches

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The Bottom Line:

- Imagine DM from EW Multiplet → DM Phenomenology neglecting other States in Multiplet likely to miss relevant physics
- Here, DM Simpl. Mod. face similar issue → Neglecting States in Mediator Multiplet Misses Relevant DM Physics

UV Complete Pseudoscalar Portal(s)

Consistently Complete the Pseudoscalar Portal DM Simplified Model

- H + S (+ DM)

  $s + ia$

  $$g_s(s+ia)\left|H\right|^2 + g_\chi \bar{\chi}(s+ia\gamma^5)\chi + h.c.$$

  a can Mix with SM Higgs if CP Violation

  ⇨ SI DM Direct Detection (scalar portal)

- 2HDM (+ DM)

  *Berlin, Gori, Lin, Wang, Phys. Rev **D92** (2015) 015005*

  $$V_{\rm 2HDM}(H_1, H_2) + g_\chi \bar{D}_{\chi_i} H_{1,2} \chi + h.c.$$

  SU(2) doublet(s)

  ⇨ Rich(er) DM Sector (+ DM feels SM Gauge Interactions)

  ⇨ $a,\ H_0,\ H^\pm$ (New Scalars)

  $$m_{H_0, H^\pm} - m_a \leq \mathcal{O}(\text{few}) \times v$$

  Stefania Gori's Talk

- 2HDM + S (+ DM)

  (a)

  Simplest Completion with DM EW Singlet and Pseudoscalar Mediator

  ⇨ $a,\ A,\ H_0,\ H^\pm$ (New Scalars)

Simplified Model Misses Key DM Physics

2HDM + S Completion
(a)

Simple Renormalizable Pseudoscalar Portal to DM

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

Visible Sector

$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.} \right] \\ &+ \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\ &+ \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{h.c.} \right] \end{aligned}$$

Dark Sector

$$V_{\rm Dark} = m_\chi \bar{\chi}\chi + \frac{1}{2}(\partial_\mu a_0)^2 + \frac{m_{a_0}^2}{2} a_0^2 + i g_\chi \, a_0 \, \bar{\chi}\gamma^5\chi$$

Portal

$$V_{\rm portal} = i\,\kappa\, a_0\, H_1^\dagger H_2 + \text{h.c.}$$

*Nomura, Thaler, Phys. Rev **D79** (2009) 075008*

$$H_j = \begin{pmatrix} \phi_j^+ \\ \frac{v_j + h_j + i\,\eta_j}{\sqrt{2}} \end{pmatrix} \qquad \begin{aligned} H^\pm &= -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm \qquad A_0 = -s_\beta \eta_1 + c_\beta \eta_2 \\ h &= -s_\alpha h_1 + c_\alpha h_2 \qquad H_0 = -c_\alpha h_1 - s_\alpha h_2 \end{aligned}$$

$h \to 125$ GeV Higgs

$$-\mathcal{L}_{\rm Yuk} = Y^u_{1,2} \bar{Q}_L q^u_R \tilde{H}_{1,2} + Y^d_{1,2} \bar{Q}_L q^d_R H_{1,2} + Y^\ell_{1,2} \bar{L}_L \ell_R H_{1,2} + h.c.$$

Assume Natural Flavour Conservation in $\mathcal{L}_{\rm Yuk}$

To Keep in Mind: 2 Scalar Doublets ⇨ New Constraints

EW Precision Observables

$m_{H^\pm} \simeq m_{H_0}$ or $m_{H^\pm} \simeq m_{A_0}$ (appr. custodial symmetry)

Higgs Signal Strengths

Flavour Physics

...

2HDM + S Completion

(a)

Simple Renormalizable Pseudoscalar Portal to DM

*Ipek, McKeen, Nelson, Phys. Rev **D90** (2014) 055021*

Seyda Ipek's Talk

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Portal

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Mixing

$$V_{\rm Dark} \supset i g_\chi \left(c_\theta a + s_\theta A \right) \bar{\chi}\gamma^5\chi$$

$$\begin{aligned} V_{\rm portal} &= \frac{\left(m_A^2 - m_a^2 \right) s_{2\theta}}{2\,v} \left(c_{\beta-\alpha}\, H_0 - s_{\beta-\alpha}\, h \right) \\ &\times \left[aA \left(s_\theta^2 - c_\theta^2 \right) + \left(a^2 - A^2 \right) s_\theta c_\theta \right] \end{aligned}$$

Physical States

$$A = c_\theta\, A_0 + s_\theta\, a_0 \quad , \quad a = c_\theta\, a_0 - s_\theta\, A_0$$

2HDM + $S_{(a)}$ Completion

NEW STATES $A \quad H^{\pm} \quad H_0$

multi-mediator scenario

Mass Splittings among $A \quad H^{\pm} \quad H_0$ bounded by 2HDM Unitarity

*Ginzburg, Ivanov, Phys. Rev **D72** (2005) 115010*

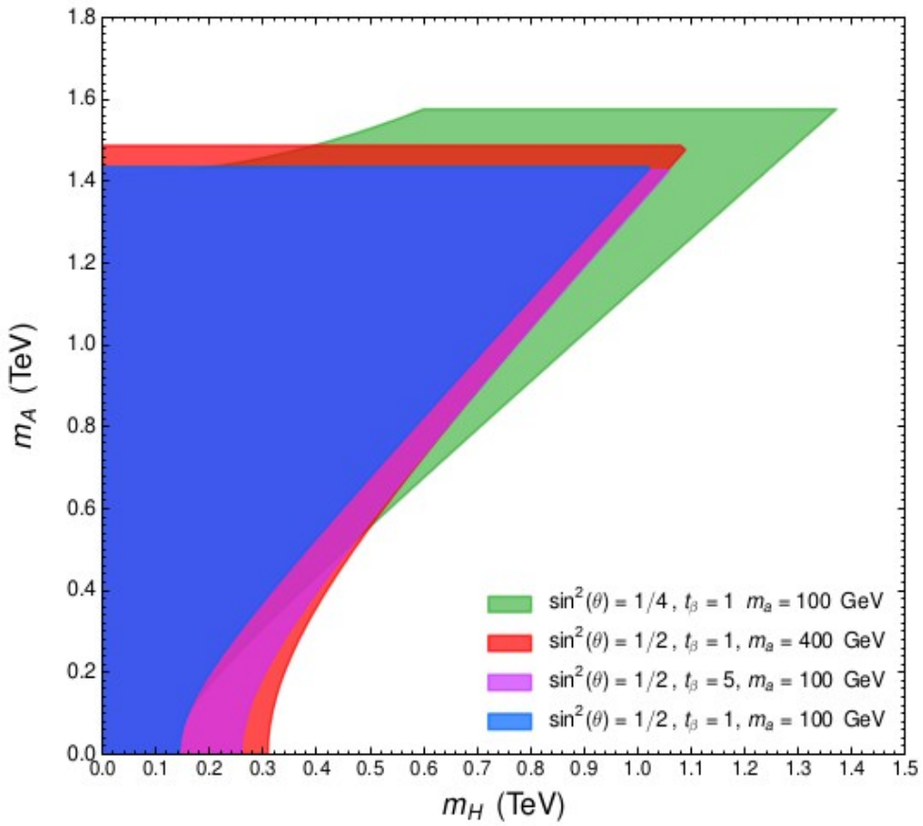
$$m_i - m_j \leq \mathcal{O}(\text{few}) \times v$$

1) $m_{A,H_0,H^{\pm}} \sim m_a$

2 mediators scenario (affects e.g. Relic Density)

$H^{\pm} \quad H_0$ phenomenology as in 2HDM

2) $m_{A,H_0,H^{\pm}} \gg m_a$



Goncalves, Machado, JMN, ArXiv:1611.04593

NEW STATES DO NOT (completely) DECOUPLE

(if $\sin\theta$ is kept fixed)

Assume $\quad [\, c_{\beta-\alpha} = 0 \qquad m_{H^{\pm}} = m_{H_0}\,]$

$$M^2 = \mu^2/(s_\beta c_\beta)$$

$$\Delta_a^2 \equiv m_A^2 - m_a^2 \qquad \Delta_H^2 = M^2 - m_{H^{\pm}}^2 + 2m_W^2 - m_h^2/2$$

$$\Lambda_{\pm} = \left[\frac{\Delta_H^2}{v^2} - \frac{\Delta_a^2\,(1 - c_{4\theta})}{8\,v^2} \pm \sqrt{\frac{\Delta_H^4}{v^4} + \frac{\Delta_a^4\,(1 - c_{4\theta})}{8\,v^4}} \right]$$

Pert. Unitarity ➔ $|\Lambda_{\pm}| \leq 8\pi$

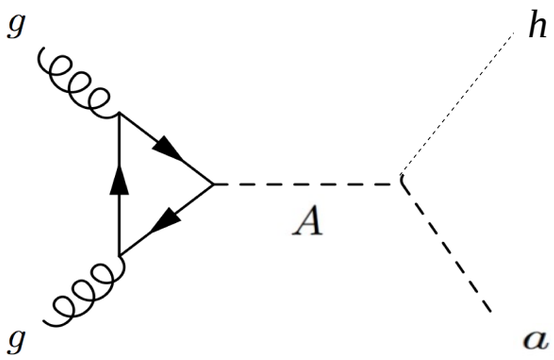
2HDM + S Completion

(a)

LHC SIGNATURES $m_{A,H_0,H^\pm} \gg m_a$

*JMN, Phys. Rev **D93** (2016) 031701*

$m_A > m_a + m_h$

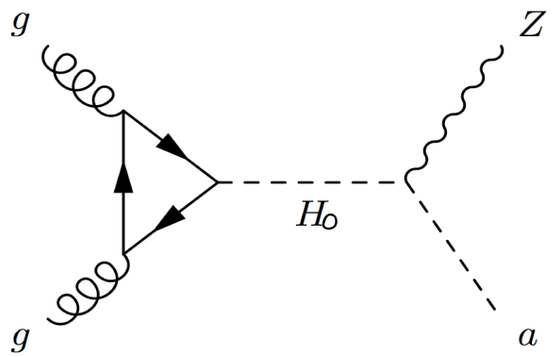


(Resonant) mono-h / mono-Z

(mono-W)

(Assume a Decays invisibly)

$m_{H_0} > m_a + m_Z$



$$\not{E}_T^{\max} \sim \frac{1}{2\,m_A}\sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4\,m_h^2\,m_a^2}$$

$$\not{E}_T^{\max} \sim \frac{1}{2\,m_{H_0}}\sqrt{(m_{H_0}^2 - m_Z^2 - m_a^2)^2 - 4\,m_Z^2\,m_a^2}$$

2HDM + S Completion

(a)

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*JMN, Phys. Rev **D93** (2016) 031701*

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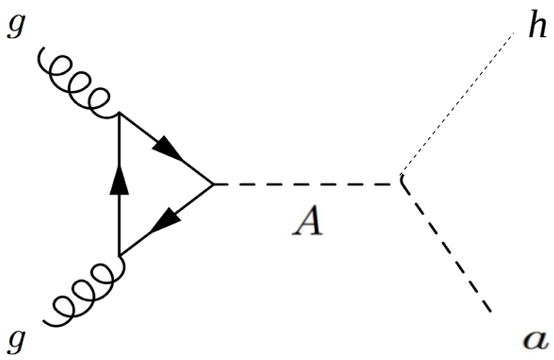

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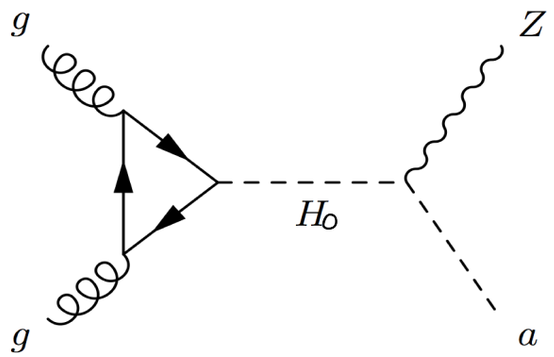

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Assumed Gluon Fusion production of $H_0\ A$ for 2HDM Type II & $t_\beta \gg 1$ ⇨ $\bar{b}b -$ associated

$$\bar{b}b + \not{E}_T + Z, h$$

Fairbairn, JMN, Tunney, work in progress

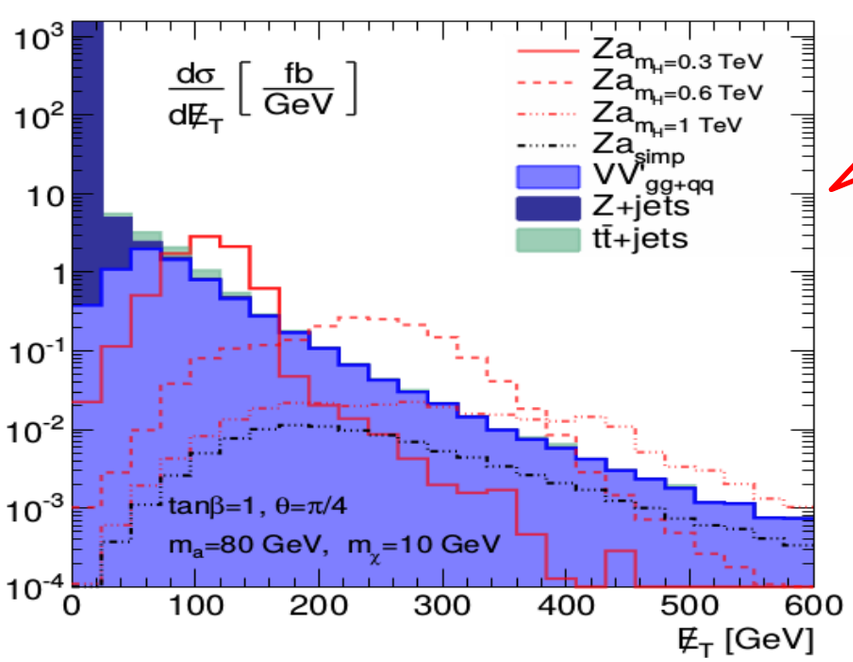
mono-h needs multi-mediator ~~2HDM~~ 2HDM + S

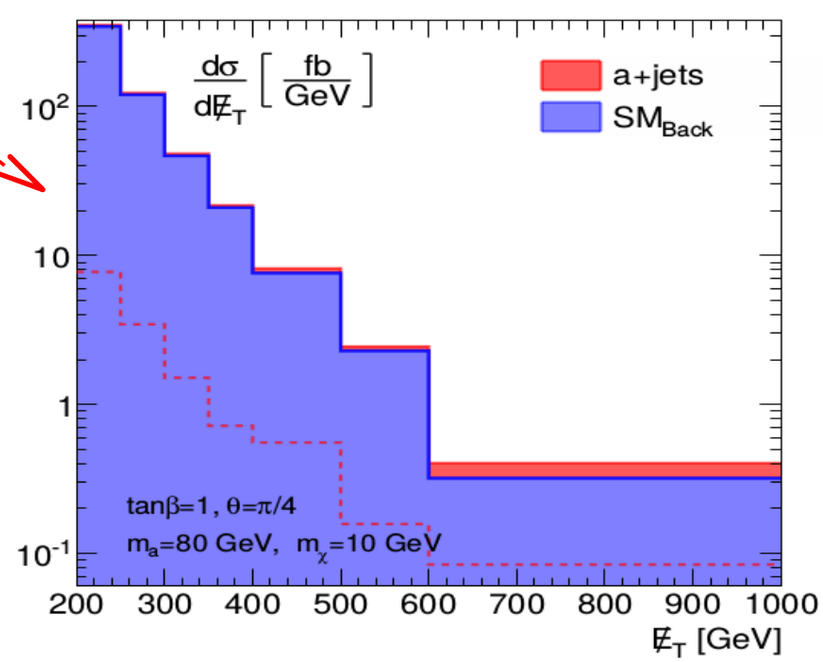
mono-Z is 2HDM generic 2HDM + S

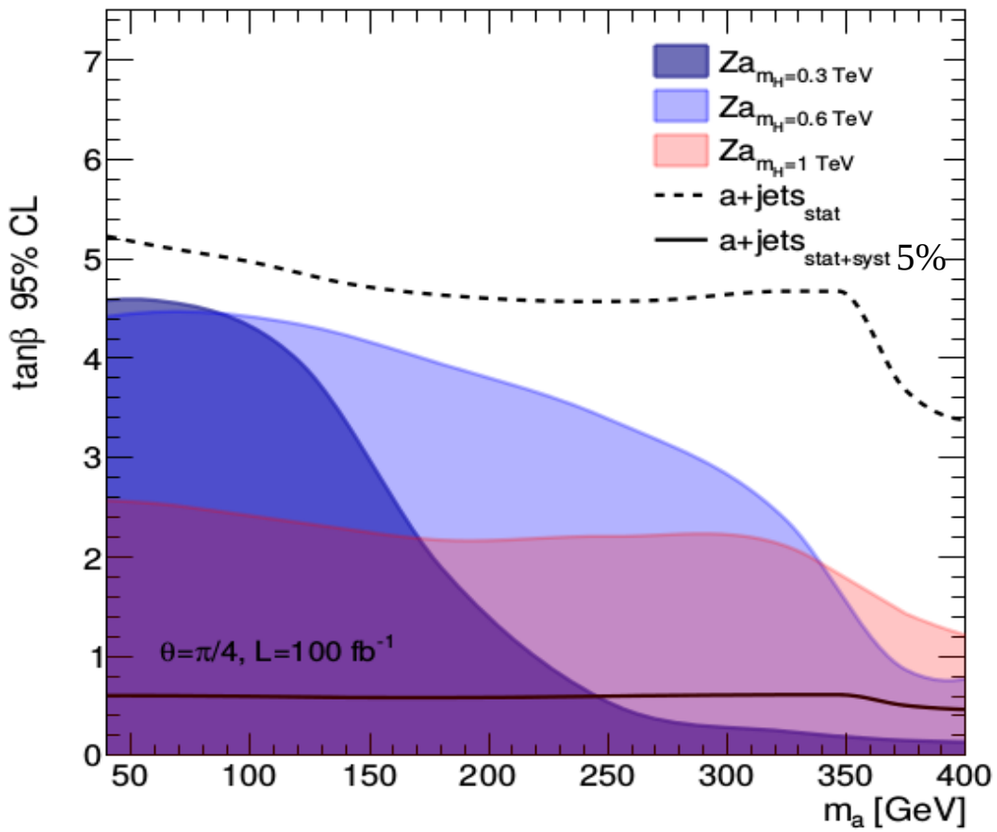
2HDM + S Completion

(a)

Compare $Z + \not{E}_T$ to Jets $+ \not{E}_T$ @ LHC



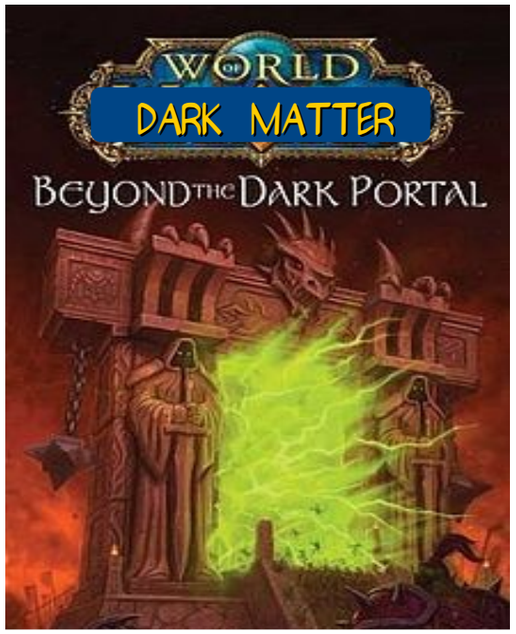




Sensitivity Comparison

Goncalves, Machado, JMN, ArXiv:1611.04593

Summary & Thoughts



- Pseudoscalar Portal to DM:

  Strong Case to Go Beyond Simplified Model

  → 2HDM + S (+ DM)

  → 2HDM (+ DM)

- Both 2HDM (+ DM), 2HDM + S (+ DM) Capture Scalar/Pseudoscalar Portal

- Resonant mono-Z Signature Generic in 2HDM (+ DM), 2HDM + S (+ DM) Scalar/Pseudoscalar Portal for $m_\phi \gg m_{\text{med}}$

- Consistent Completions Can Point to Reasonable Ranges of Couplings within Simplified Model → g_{SM}