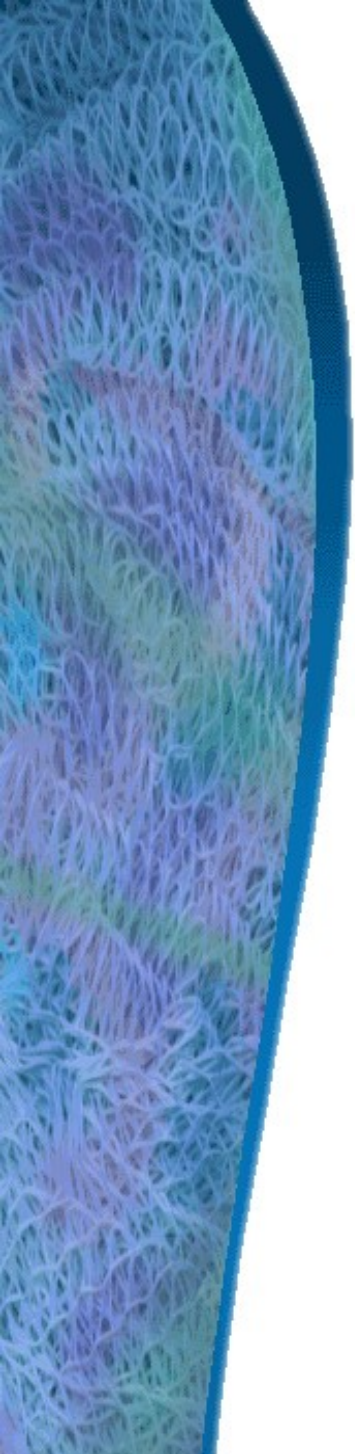




Dark Matter @ LHC: Scalar Portals at Play

Jose Miguel No, Sussex U.

Based on 1509.01110 (*PRL*), 1511.01099

*with I. Brivio, B. Gavela, L. Merlo,
K. Mimasu, R. del Rey, V. Sanz*

US

University of Sussex



SCALARS 2015
Warsaw 7th December 2015



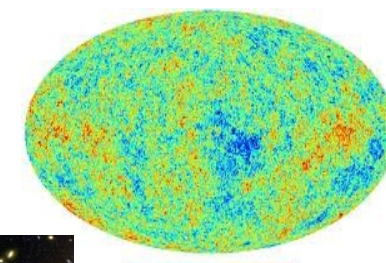
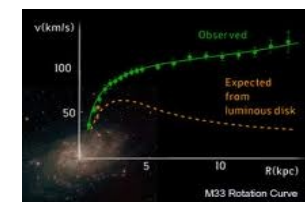
Dark Matter in a Nutshell



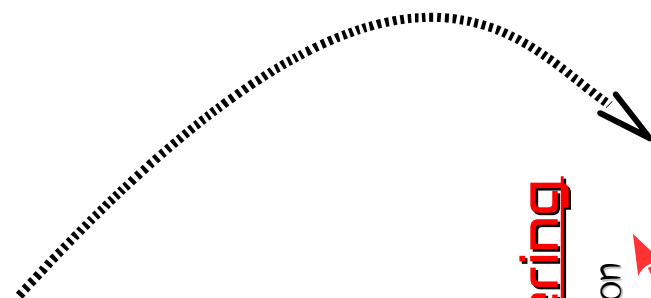
Abundant & Robust
Evidence of DM



Galaxy rotation curves
Gravitational lensing
Large scale structure
CMB
...



Probes of DM-SM
Interactions
(**WIMPs**)



DM Scattering

Direct Detection

DM Annihilation

Relic Density (Early Universe)
Indirect Detection (Now)

DM

SM

?

DM

SM

Colliders (LHC)

DM Production

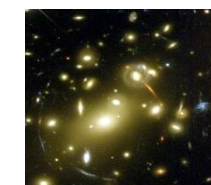
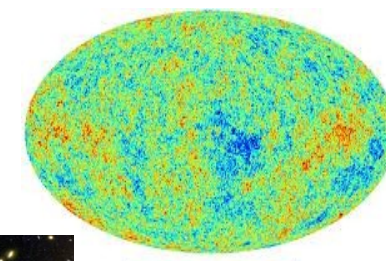
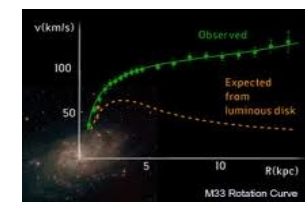
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DM Signatures @ LHC

Mono-X (X = jet, γ , W, Z, h...)

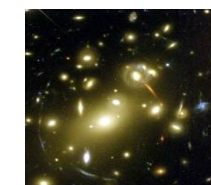
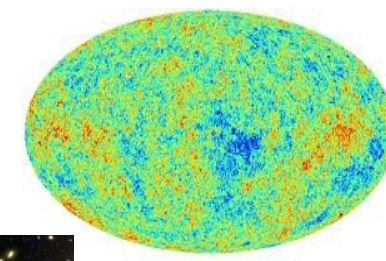
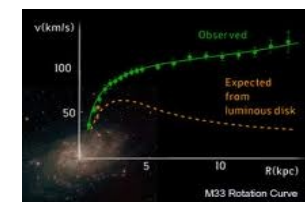
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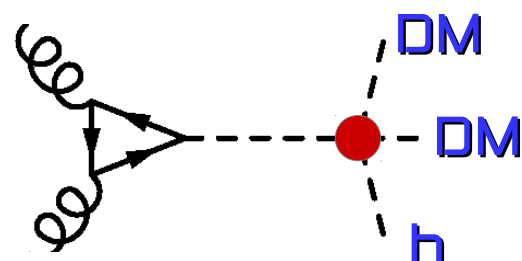
SM

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Mono-X (X = jet, γ , **W**, **Z**, **h**...)



Mono-Higgs (also W, Z) is not ISR
Direct Probe of DM-SM Interactions

Higgs Portals to Dark Matter

(Simple, yet well-motivated DM scenarios)

⇒ Higgs portal: $H^\dagger H \mathcal{O}_S$

B.Patt, F. Wilczek, hep-ph/0605188

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e.g. $\lambda_S S^2 H^\dagger H$ Singlet scalar
Higgs portal DM

Paradigm of Connection

Higgs Sector $\longleftrightarrow$ DM Sector



Via Higgs/EW Physics
we can learn about DM

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Via DM Physics we can learn
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Two beautiful realizations of this idea:

❶ Singlet Scalar DM: Linear (standard) VS Non-Linear Higgs Portal

(Linear VS Non-Linear EW Symmetry Breaking)

I. Brivio, B. Gavela, L. Merlo, K. Mimasu, J. M. No, R. del Rey, V. Sanz, arXiv:1511.01099

❷ Pseudo-Scalar Portal to DM (“Axion” Portal)

Y. Nomura, J. Thaler, Phys. Rev D79 (2009) 075008

(Resonant mono-X)

J. M. No, arXiv:1509.01110

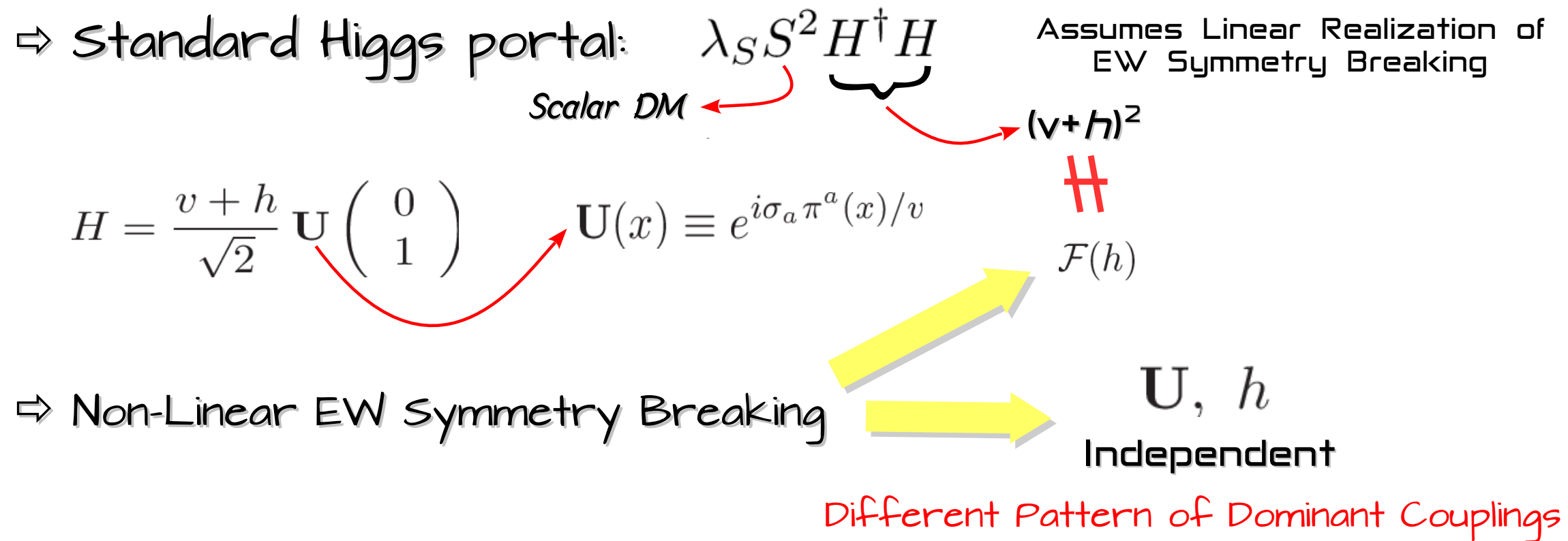
DM from Non-Linear Higgs Portals

⇒ Standard Higgs portal: $\lambda_S S^2 \underbrace{H^\dagger H}_{(v+h)^2}$ Assumes Linear Realization of EW Symmetry Breaking

Scalar DM ←

$$H = \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \mathbf{U}(x) \equiv e^{i\sigma_a \pi^a(x)/v}$$

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$\nparallel$
 $\mathcal{F}(h)$

⇒ Non-Linear EW Symmetry Breaking
+
Higgs portal DM

$\mathbf{U}, h$
Independent

Different Pattern of Dominant Couplings

I. Brivio, B. Gavela, L. Merlo, K. Mimasu, J. M. No, R. del Rey, V. Sanz, arXiv:1511.01099

① $\lambda_S S^2 \mathcal{F}(h)$ $\mathcal{F}(h) = v^2 \left(1 + 2\frac{h}{v} + b\frac{h^2}{v^2} + \dots \right)$ Decorrelation for $b \neq 1$

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Recall Belen Gavela's Talk

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$$\mathbf{T}(x) \equiv \mathbf{U}(x) \sigma_3 \mathbf{U}^\dagger(x), \quad \mathbf{V}_\mu(x) \equiv (\mathbf{D}_\mu \mathbf{U}(x)) \mathbf{U}^\dagger(x)$$

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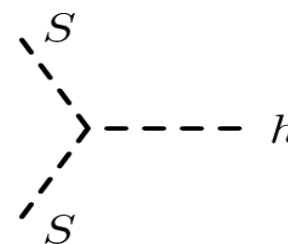
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Decorrelation for $b \neq$

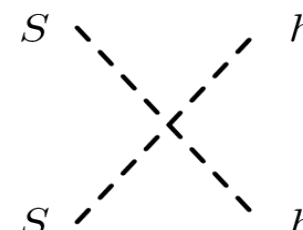
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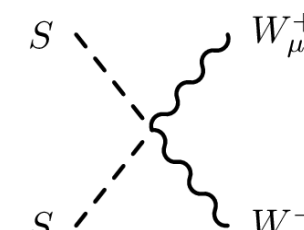
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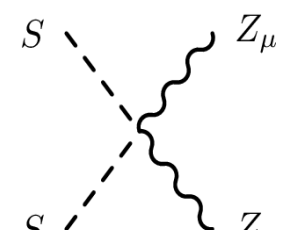
λ_S ❷



$\lambda_S b$ ❷



❶



❶ ❸

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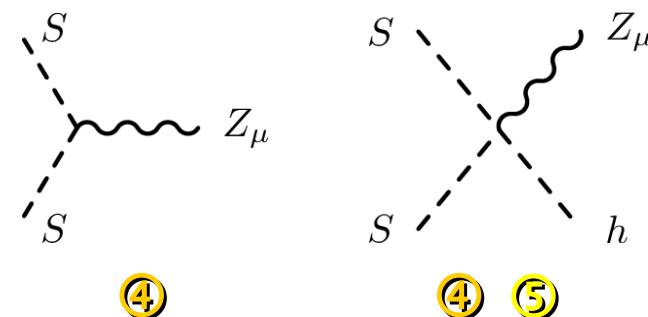
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Note we could consider Higher-Order Operators in a Linear EFT containing such interactions → LINEAR SIBLINGS

*I. Brivio, T. Corbett, O. Eboli, B. Gavela, J. Gonzalez-Fraile, M. Gonzalez-Garcia, L. Merlo, S. Rigolin, JHEP **1403** (2014) 043*

Gavela's Recall Belen Talk

DM from Non-Linear Higgs Portals

Phenomenology

Observable		Parameters contributing					
		b	c_1	c_2	c_3	c_4	c_5
Thermal relic density	$\Omega_S h^2$	✓	✓	✓	✓	✓	✓
DM-nucleon scattering in direct detection	σ_{SI}	—	—	✓	—	✓	—
Invisible Higgs width	Γ_{inv}	—	—	✓	—	—	—
Mono- h production at LHC	$\sigma(pp \rightarrow hSS)$	✓	—	✓	—	✓	✓
Mono- Z production at LHC	$\sigma(pp \rightarrow ZSS)$	—	✓	✓	✓	✓	✓
Mono- W production at LHC	$\sigma(pp \rightarrow W^+SS)$	—	✓	✓	—	✓	—

DM from Non-Linear Higgs Portals

LHC Phenomenology

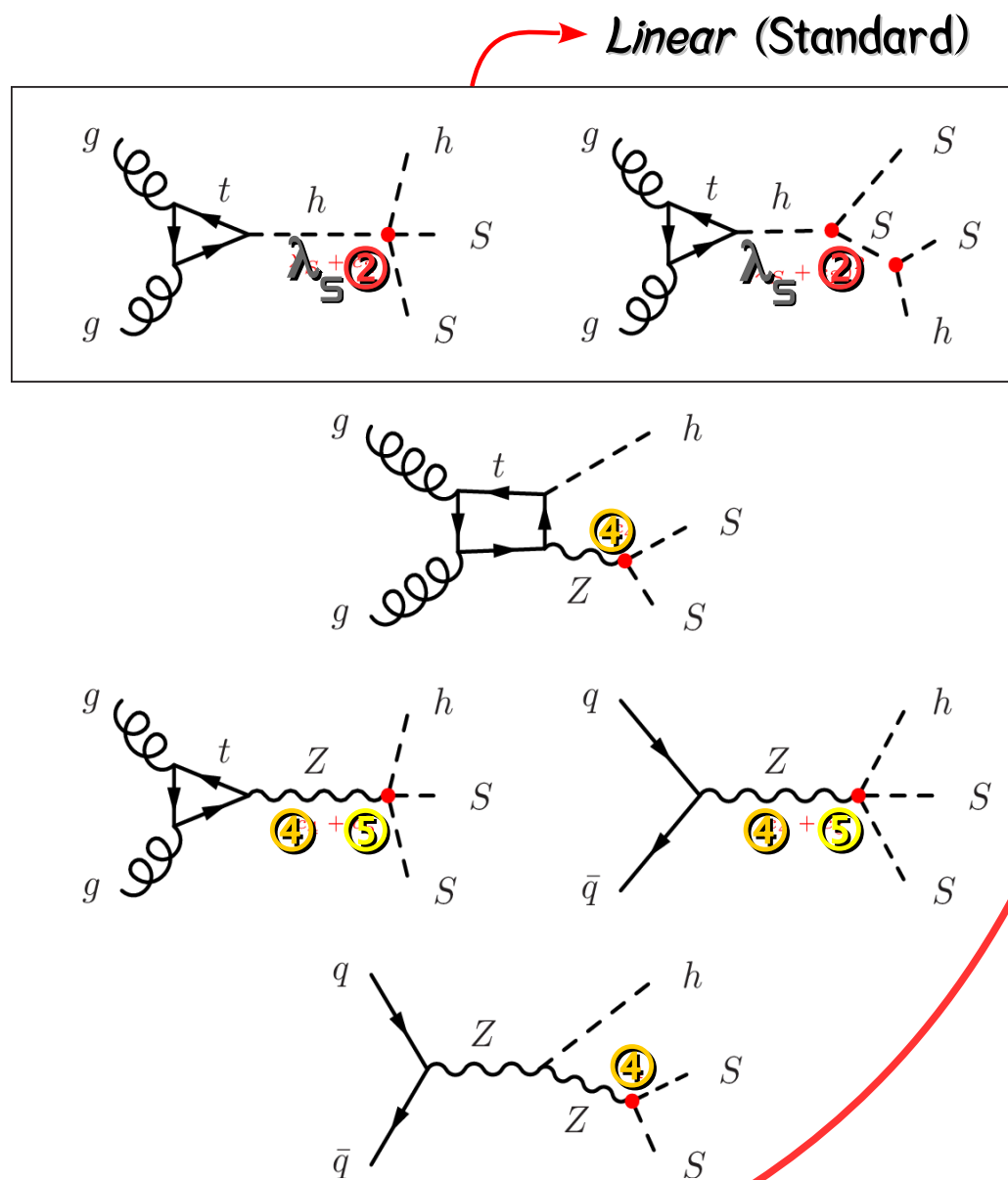
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Mono- Z production at LHC	$\sigma(pp \rightarrow ZSS)$	—	✓	✓	✓	✓	✓
Mono- W production at LHC	$\sigma(pp \rightarrow W^+SS)$	—	✓	✓	—	✓	—

We can exploit correlations
among different signatures

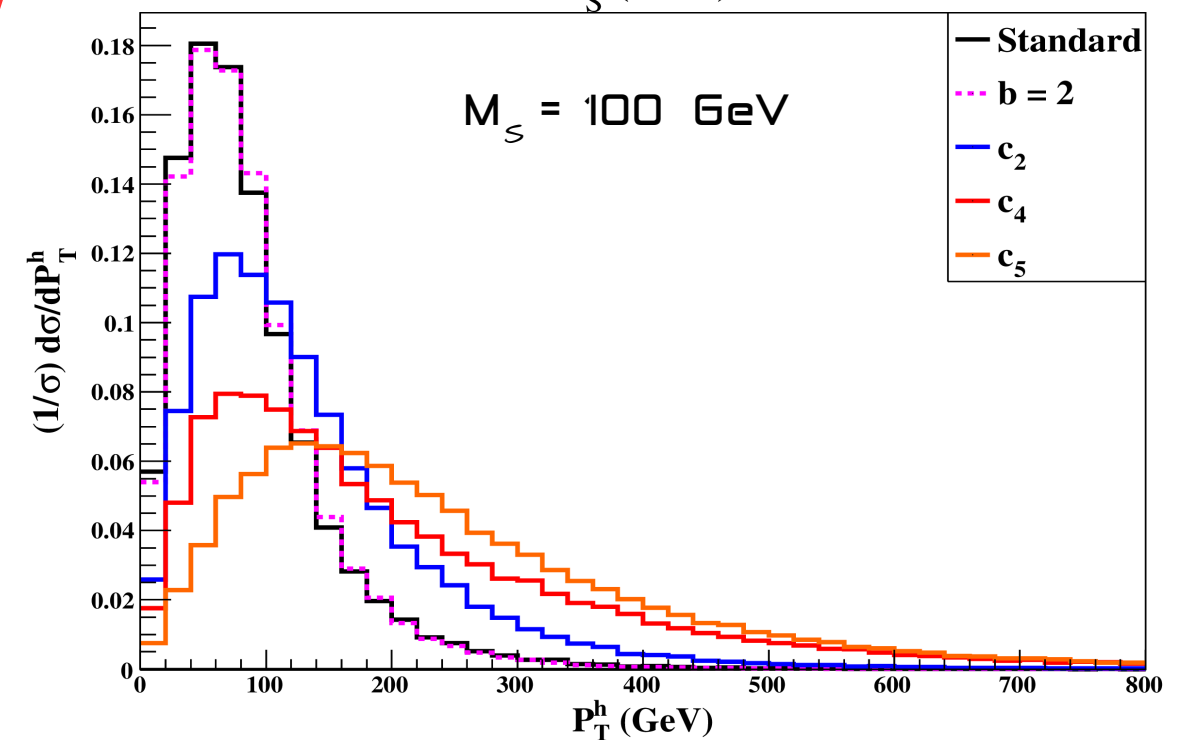
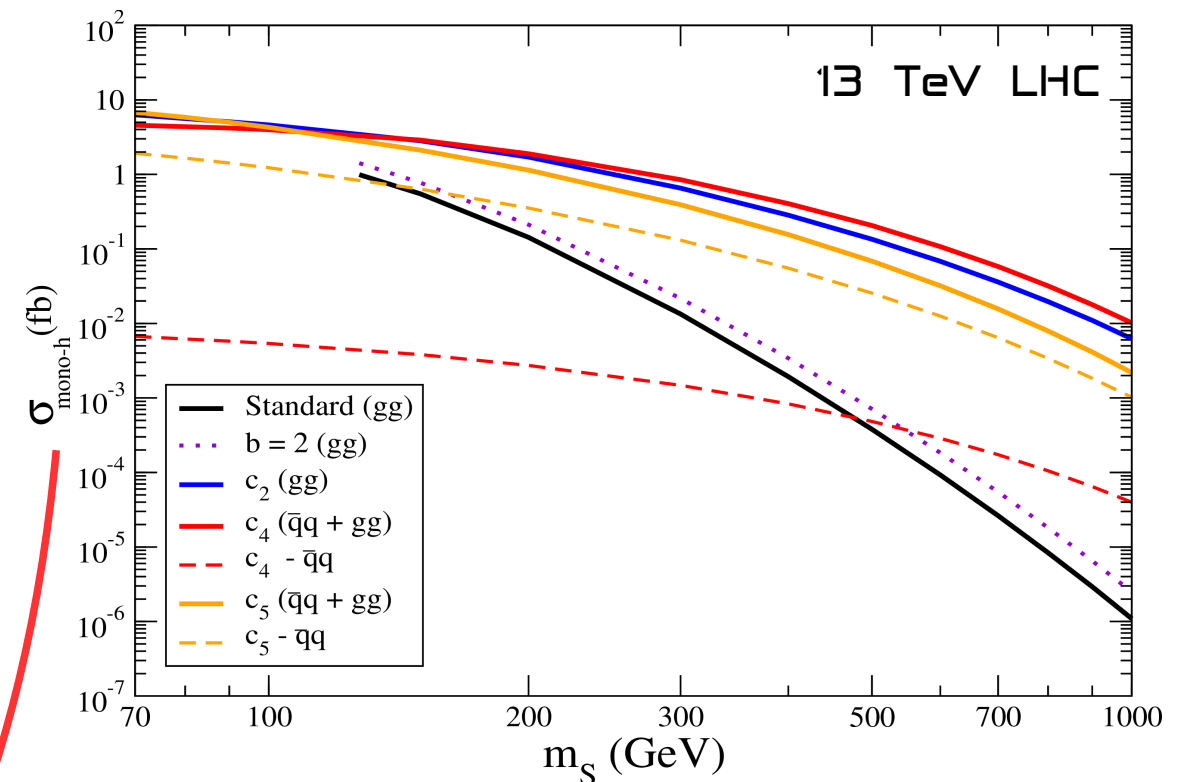
DM from Non-Linear Higgs Portals

LHC Phenomenology

Mono-Higgs:



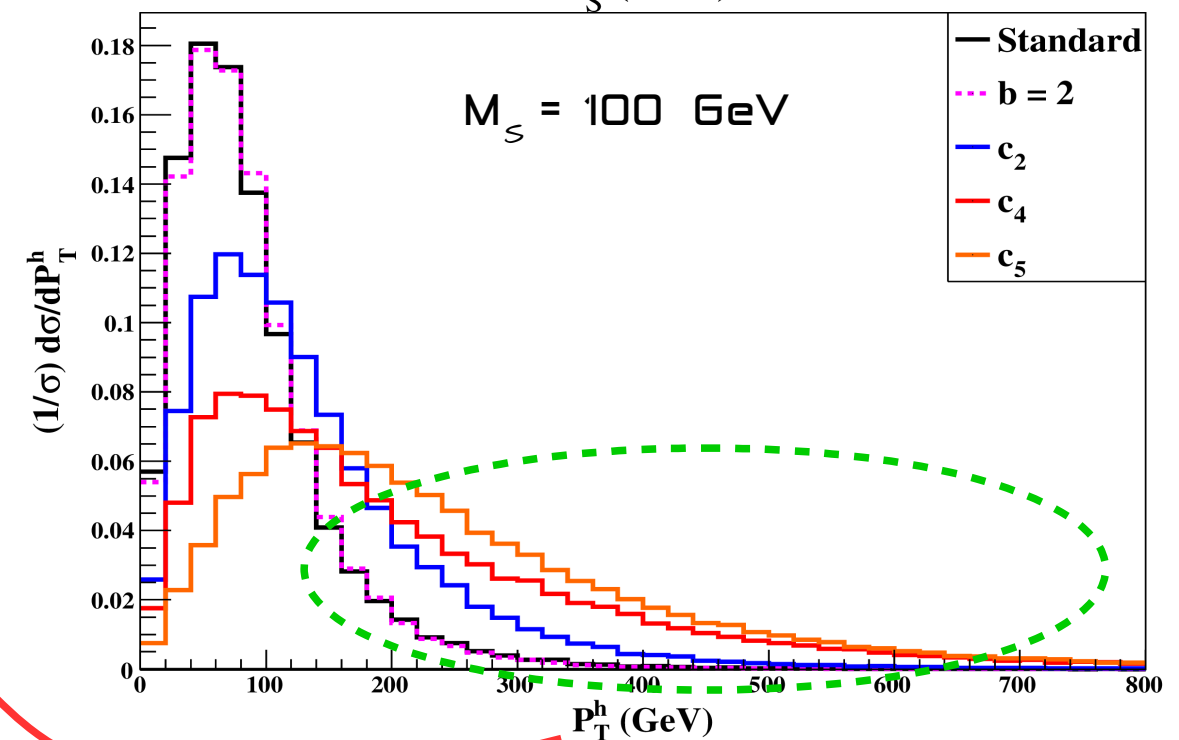
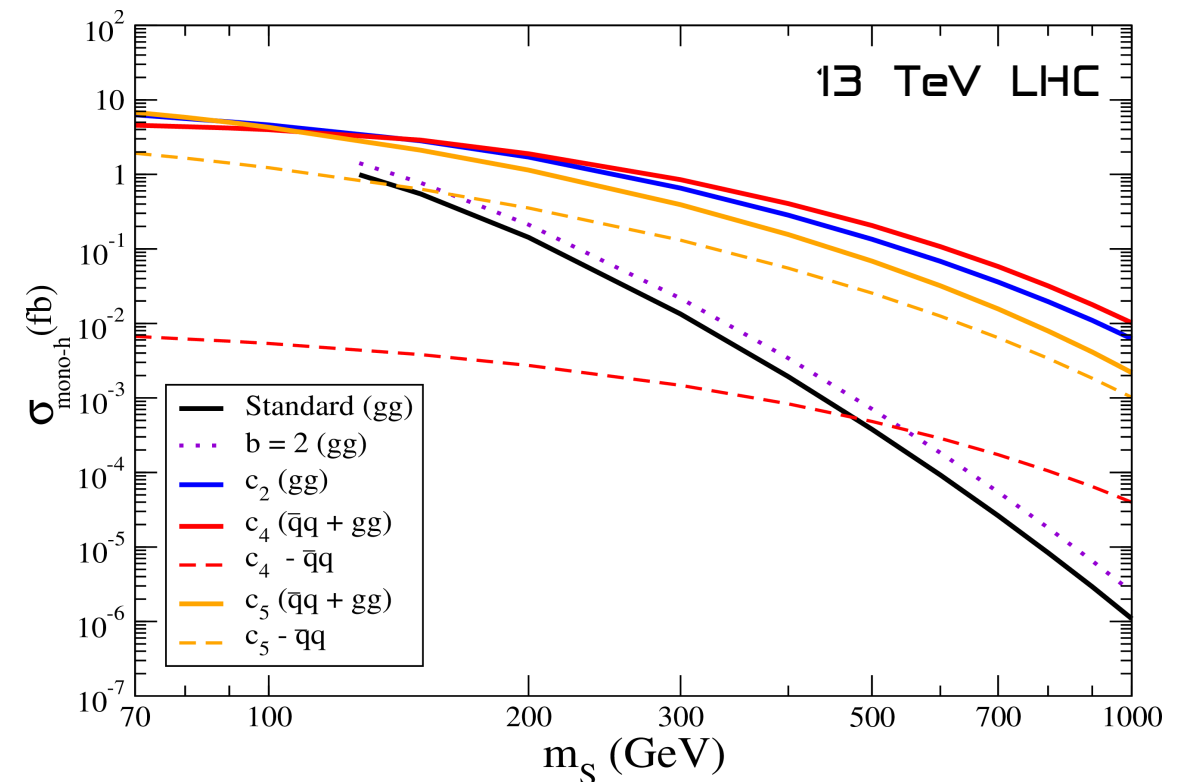
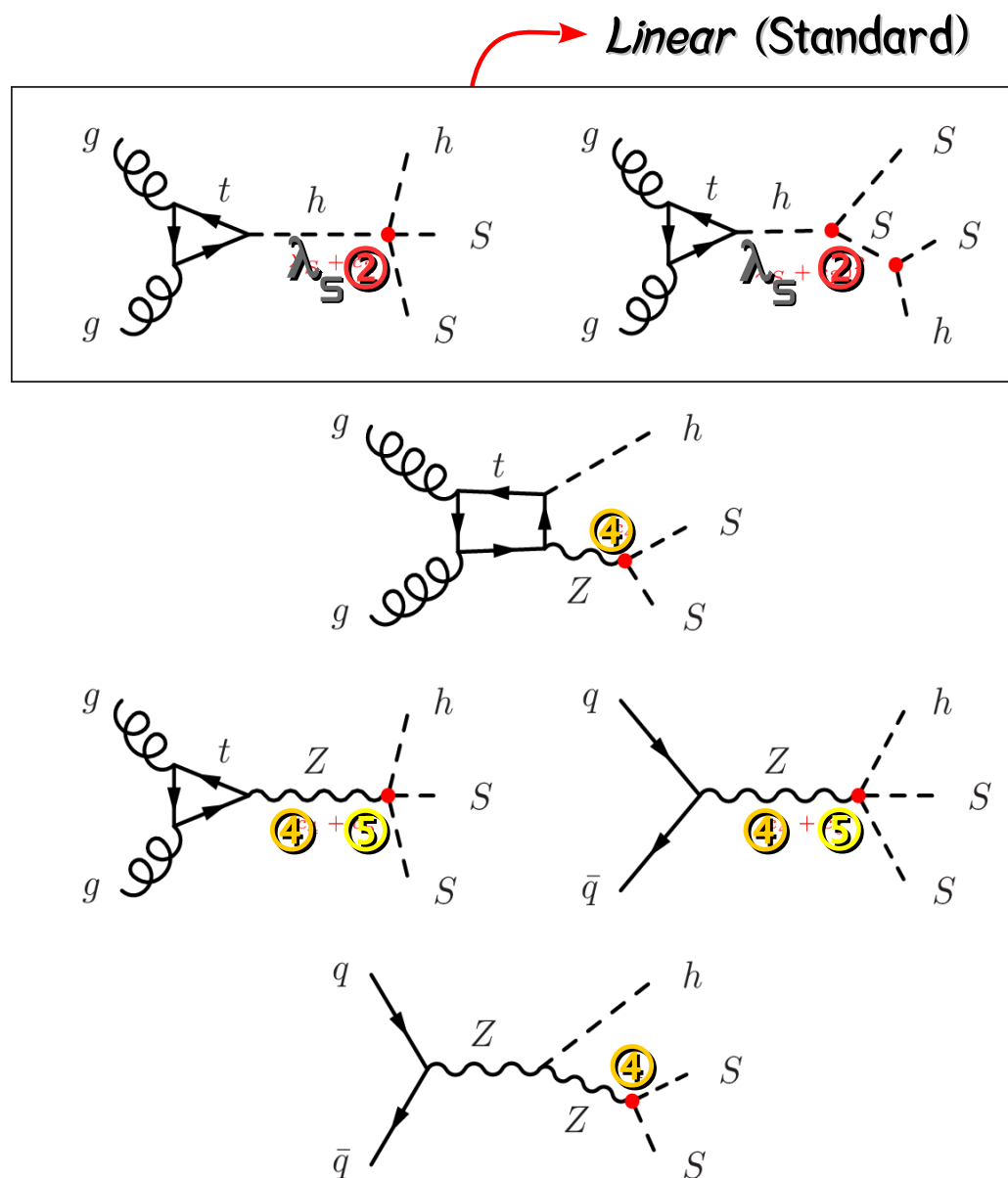
XS enhancement due to
qq-initiated + derivative vertices



DM from Non-Linear Higgs Portals

LHC Phenomenology

Mono-Higgs:



Much harder kinematical spectrum

DM from Non-Linear Higgs Portals

LHC Phenomenology

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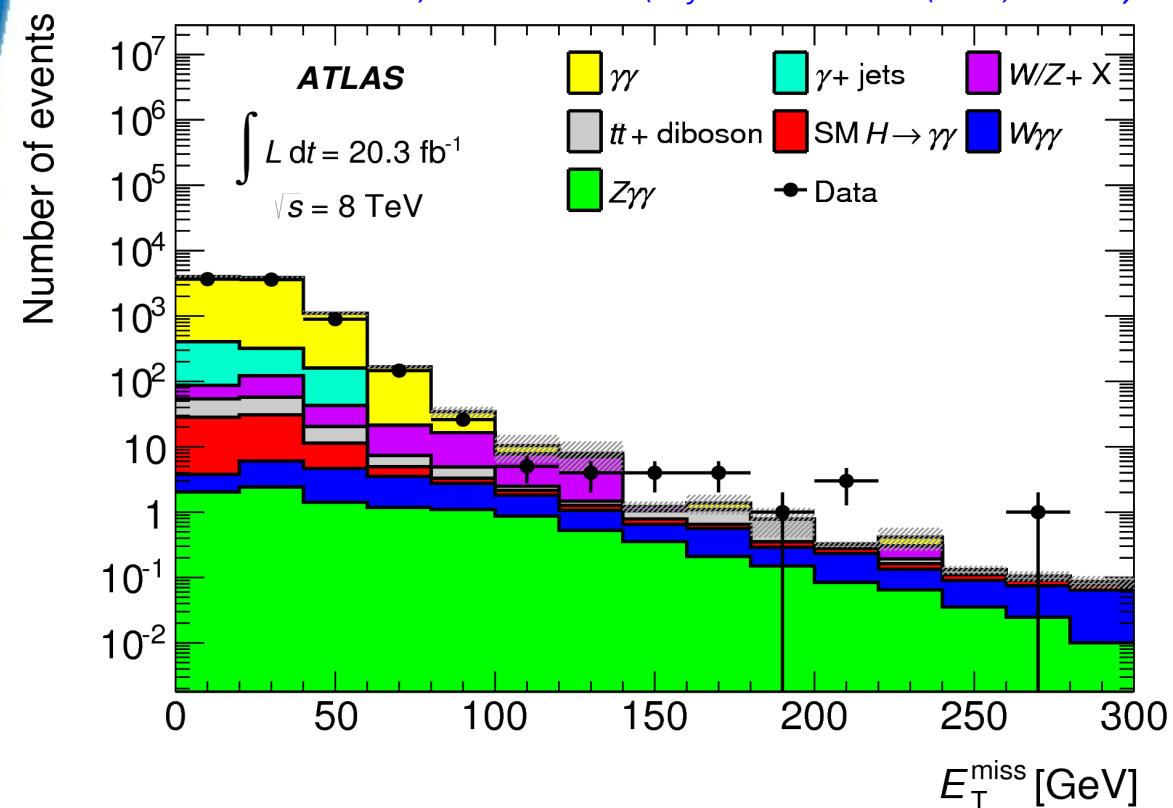
Promising in

$$\cancel{E}_T + h \quad (h \rightarrow b\bar{b})$$

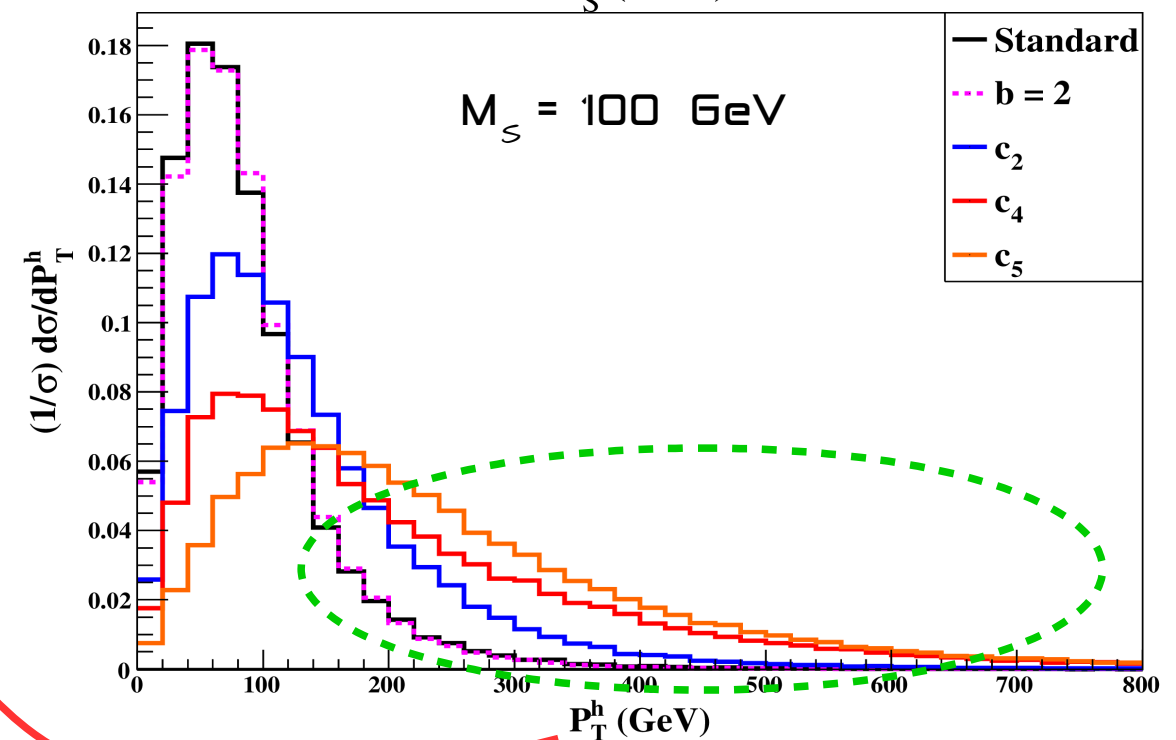
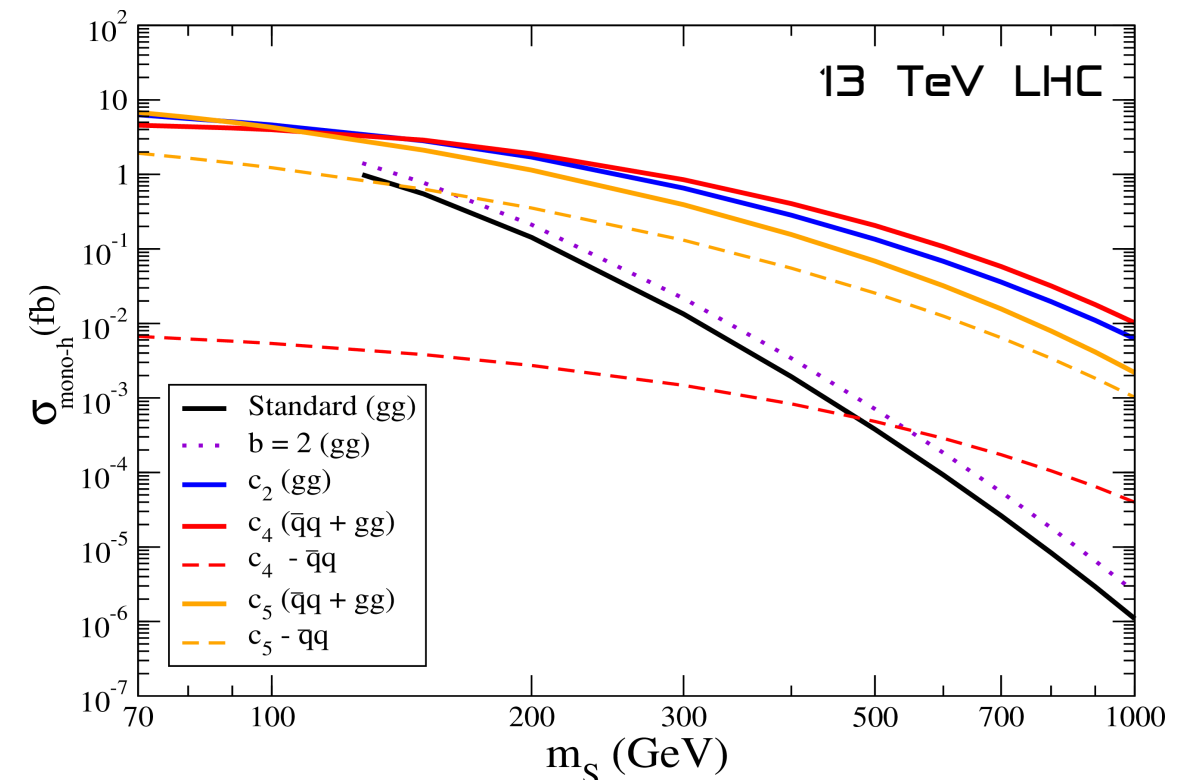
ATLAS Collaboration, 1510.06218

$$\cancel{E}_T + h \quad (h \rightarrow \gamma\gamma)$$

ATLAS Collaboration, 1506.01081 (Phys. Rev. Lett. 115 (2015) 131801)



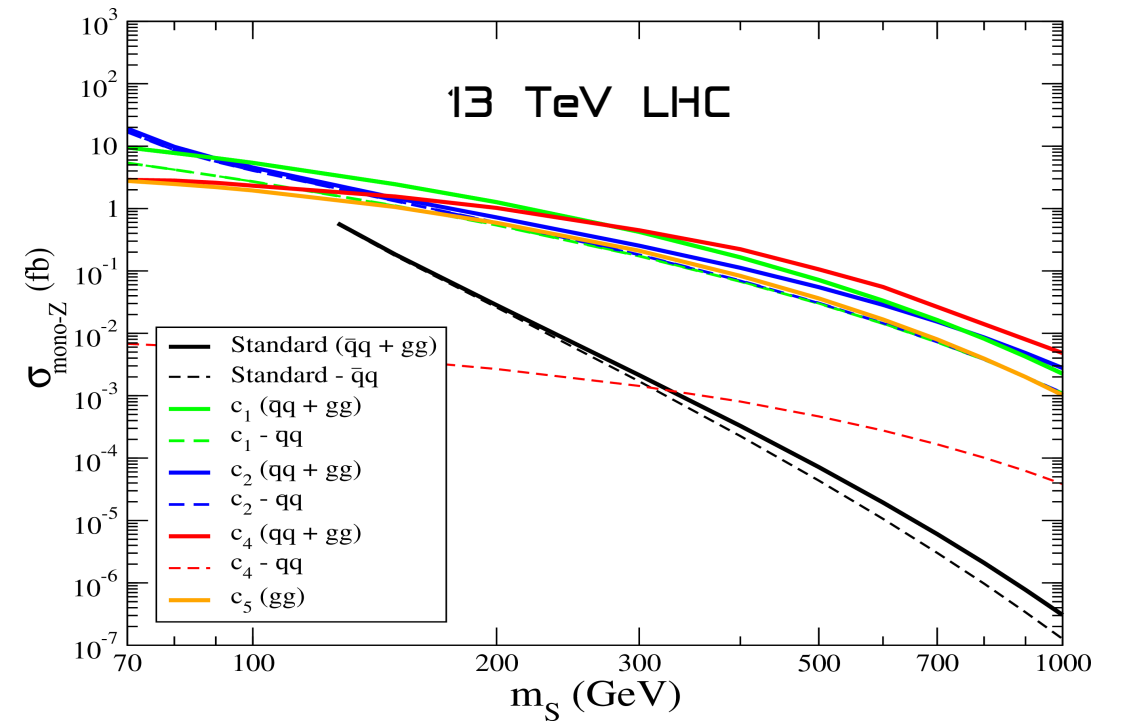
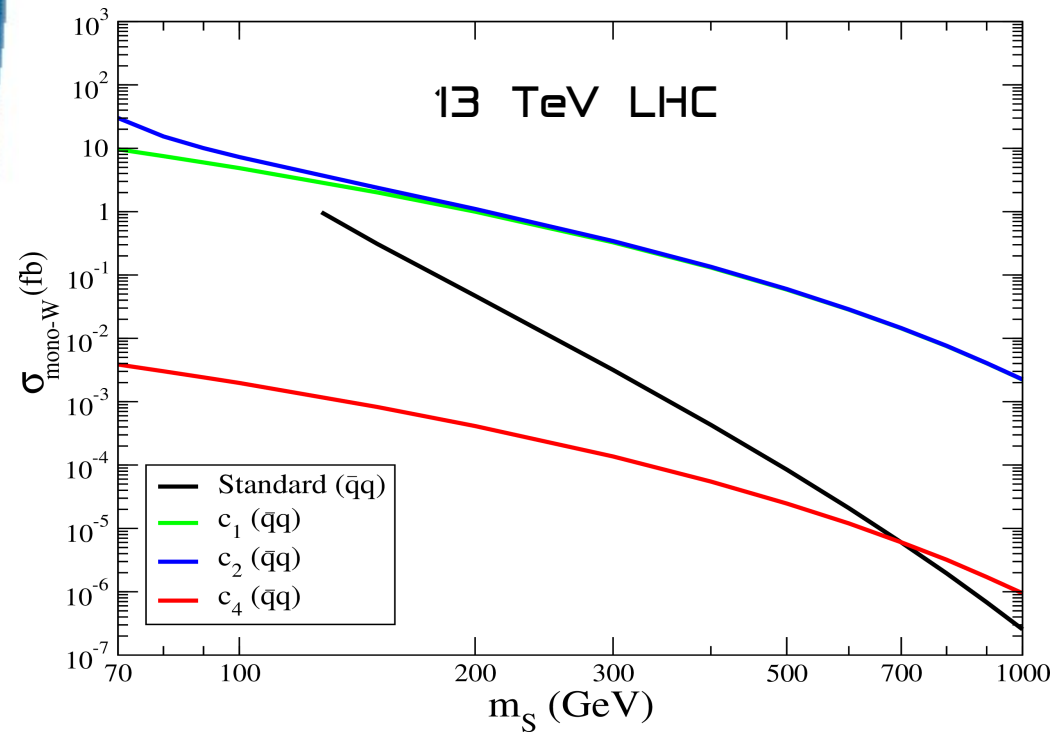
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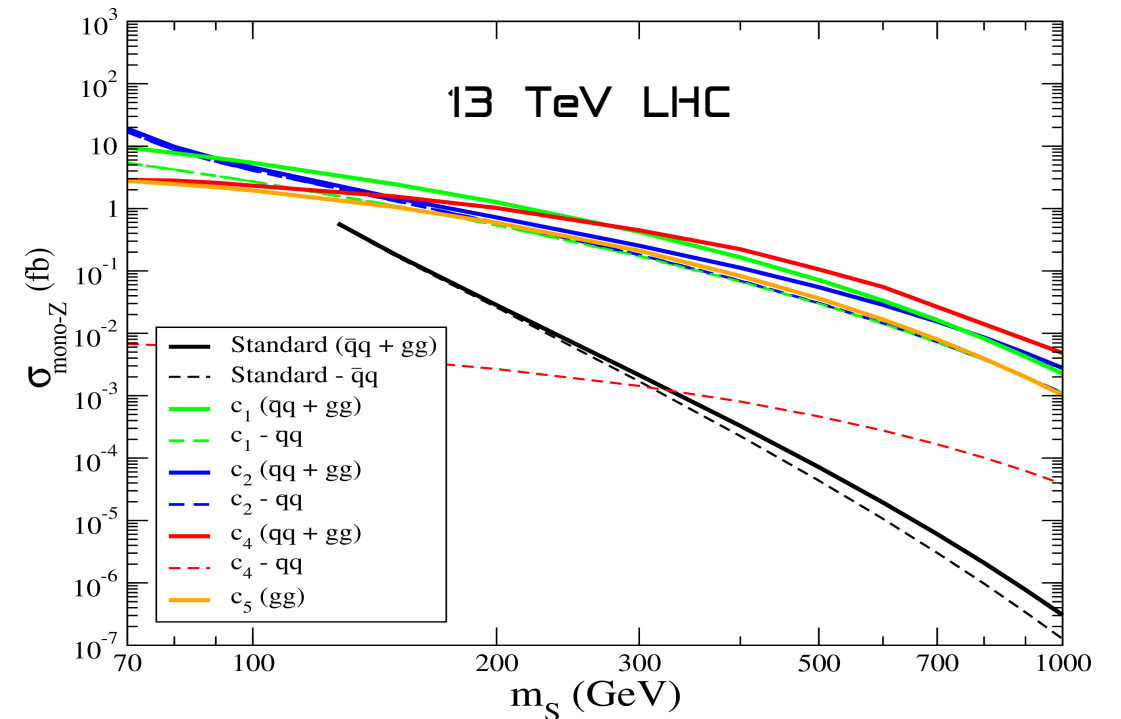
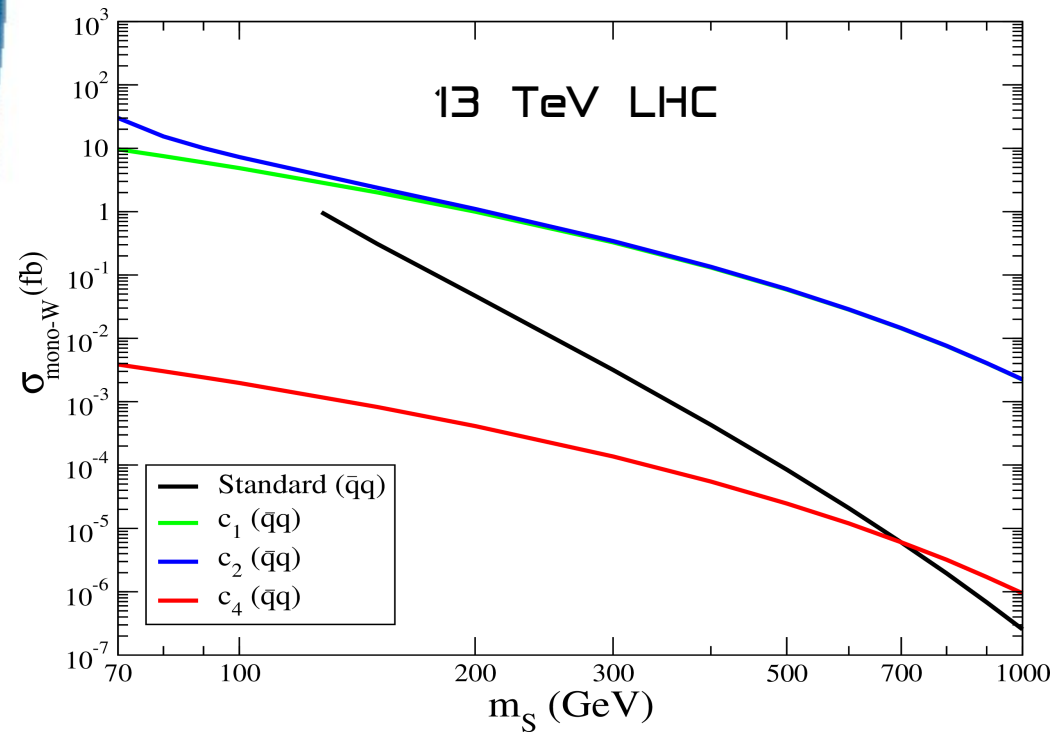
Mono-W,Z:



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LHC Phenomenology

Mono-W,Z:

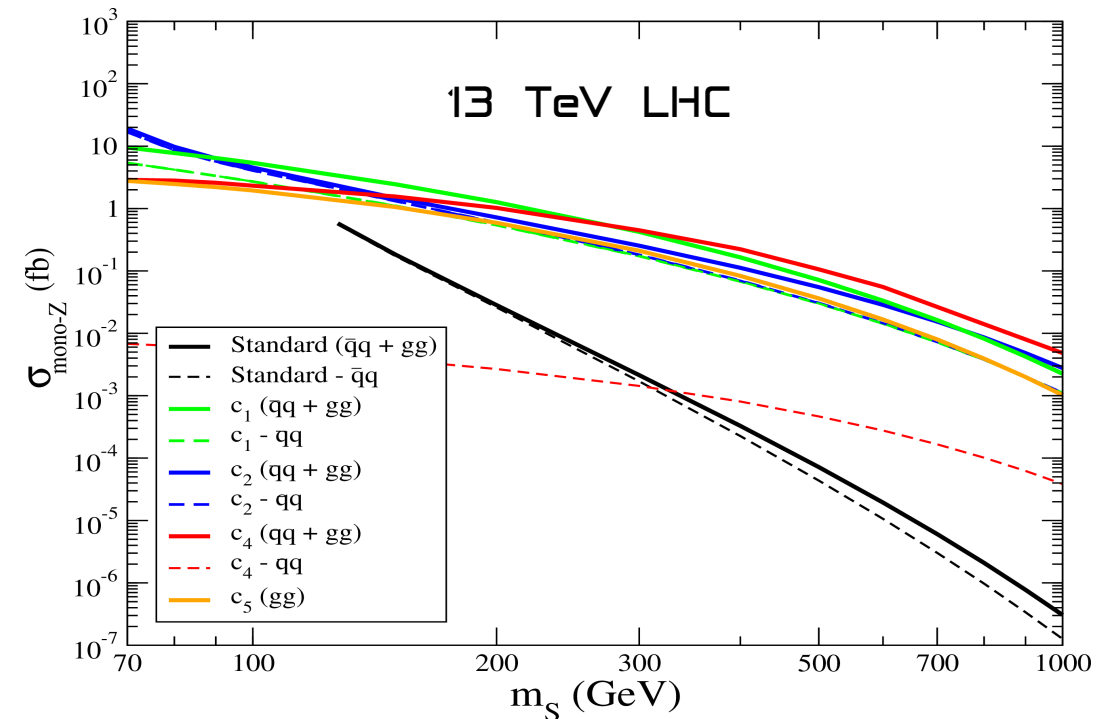
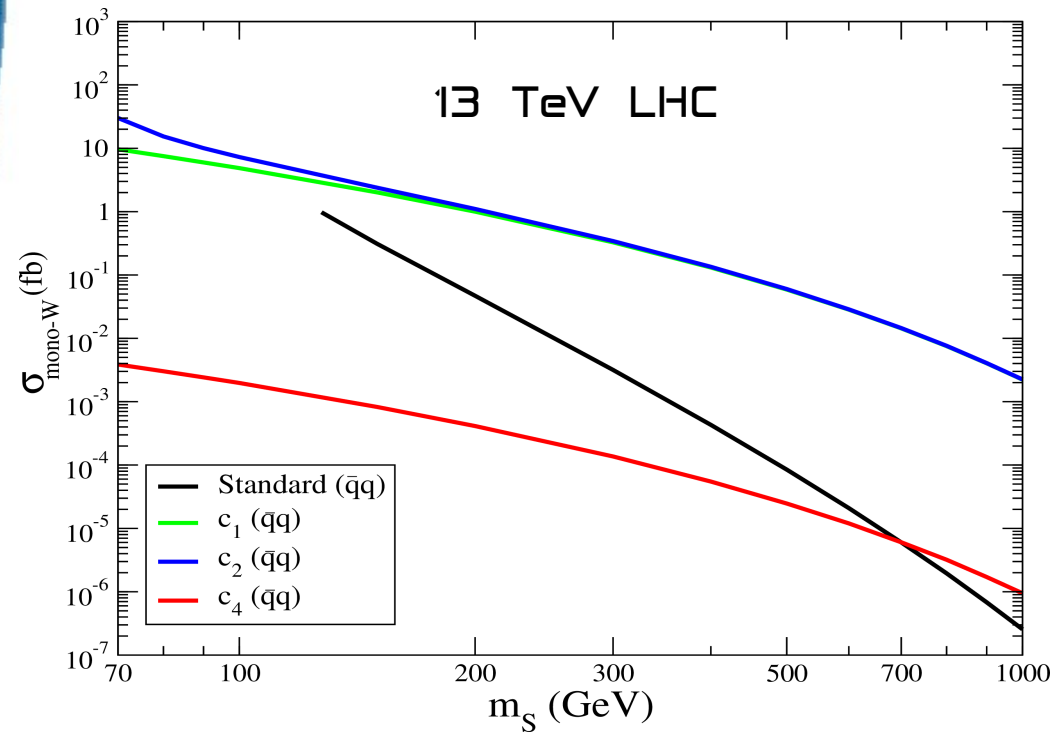


USE MonoW-MonoZ INTERPLAY as DISCRIMINATOR

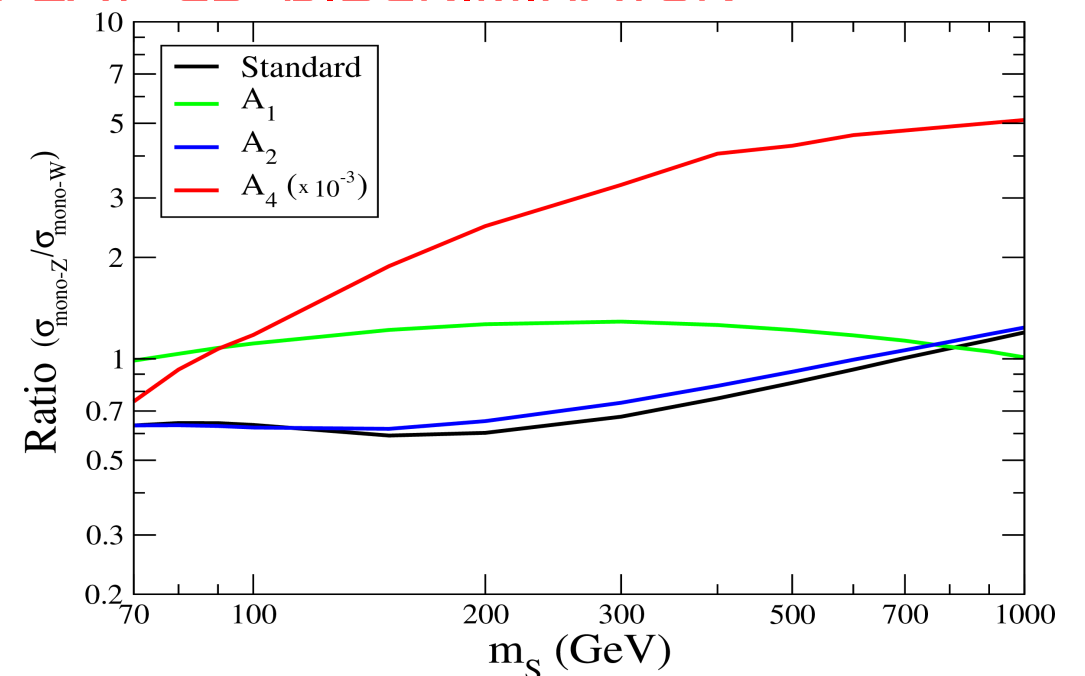
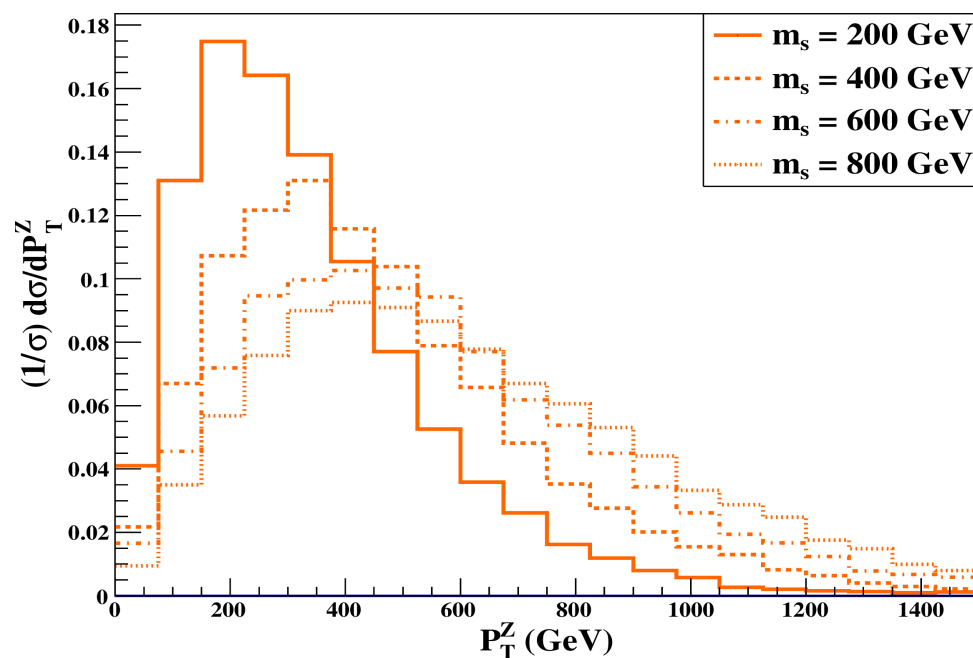
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Promising prospects for LHC13

DM through the “Axion” Portal

Y. Nomura, J. Thaler, Phys. Rev D **79** (2009) 075008

- ⇒ Assume DM couples to SM via pseudo-scalar mediator a_0 (as opposed to scalar)
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- ⇒ Then, need to extend the SM to couple (renormalizable) to a_0
2HDM (+ a_0 Portal) is the Minimal Setup

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Minimal Scenario (fermion DM ψ)

*S. Ipek, D. McKeen, A. Nelson, Phys. Rev D***90** (2014) 055021

$$\begin{aligned} V_{2\text{HDM}} = & \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.} \right] \\ & + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\ & + \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{h.c.} \right] \end{aligned} \quad \begin{aligned} V_{\text{dark}} = & \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi} \psi + y_\psi a_0 \bar{\psi} i \gamma^5 \psi \\ V_{\text{portal}} = & i \kappa a_0 H_1^\dagger H_2 + \text{h.c.} \end{aligned}$$

DM through the “Axion” Portal

Y. Nomura, J. Thaler, Phys. Rev D79 (2009) 075008

- ⇒ Assume DM couples to SM via pseudo-scalar mediator a_0 (as opposed to scalar)
Favoured e.g. by Direct Detection
- ⇒ Then, need to extend the SM to couple (renormalizable) to a_0
2HDM (+ a_0 Portal) is the Minimal Setup

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

$$V_{\text{dark}} = \frac{m_{a_0}^2}{2} a_0^2 + m_\psi \bar{\psi} \psi + y_\psi a_0 \bar{\psi} i \gamma^5 \psi$$

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

Physical States

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

$$V_{\text{dark}} \supset y_\psi (c_\theta a + s_\theta A) \bar{\psi} i \gamma^5 \psi$$

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

DM through the “Axion” Portal

Couplings $\begin{cases} a A h \\ a H_0 Z \end{cases} \sim S_{\beta-\alpha}$ Unsuppressed for SM-Like Higgs

If

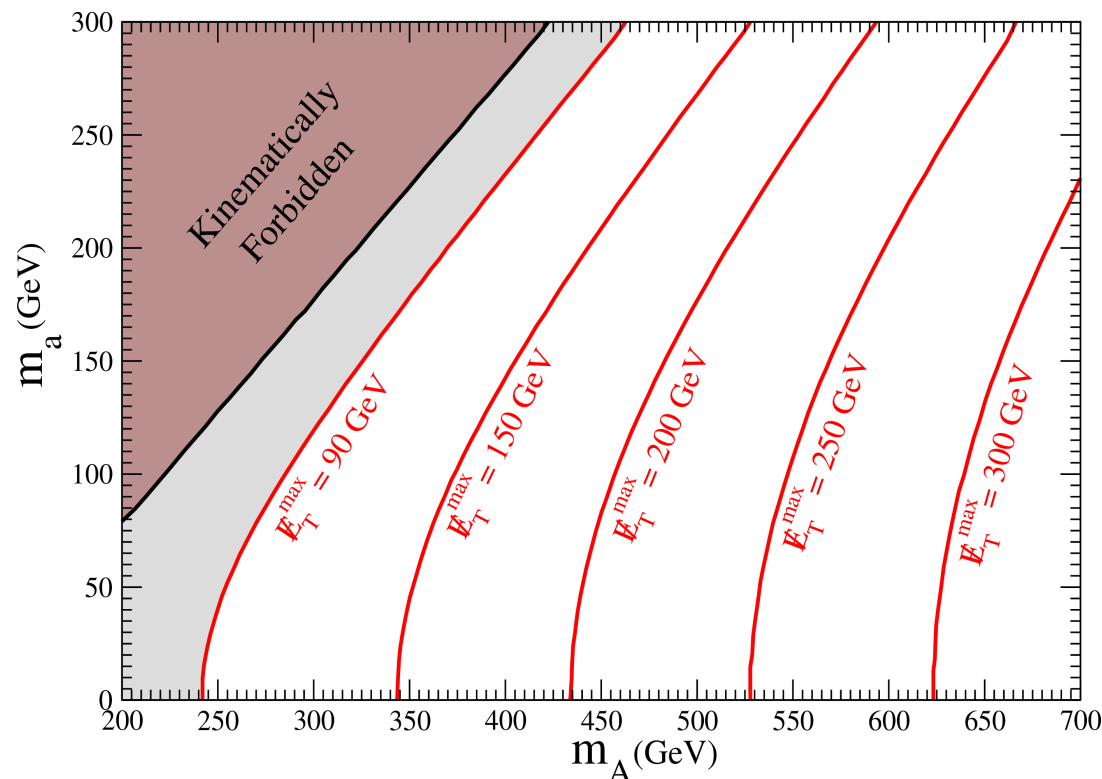
$\Rightarrow a$ decays mainly into the Hidden Sector (here, $a \rightarrow \psi\psi$)

$\Rightarrow m_A > m_a + m_h$ and/or $m_{H_0} > m_a + m_Z$

J. M. No, arXiv:1509.01110

Resonant mono- h / mono- Z

e.g. mono- h



Peak in the MET Spectrum!

$$E_T^{\max} = \frac{1}{2m_A} \sqrt{(m_A^2 - m_h^2 - m_a^2)^2 - 4m_h^2 m_a^2}$$

DM through the “Axion” Portal

Benchmarks

$$m_a = 80 \text{ GeV} \quad m_\psi = 30 \text{ GeV}$$

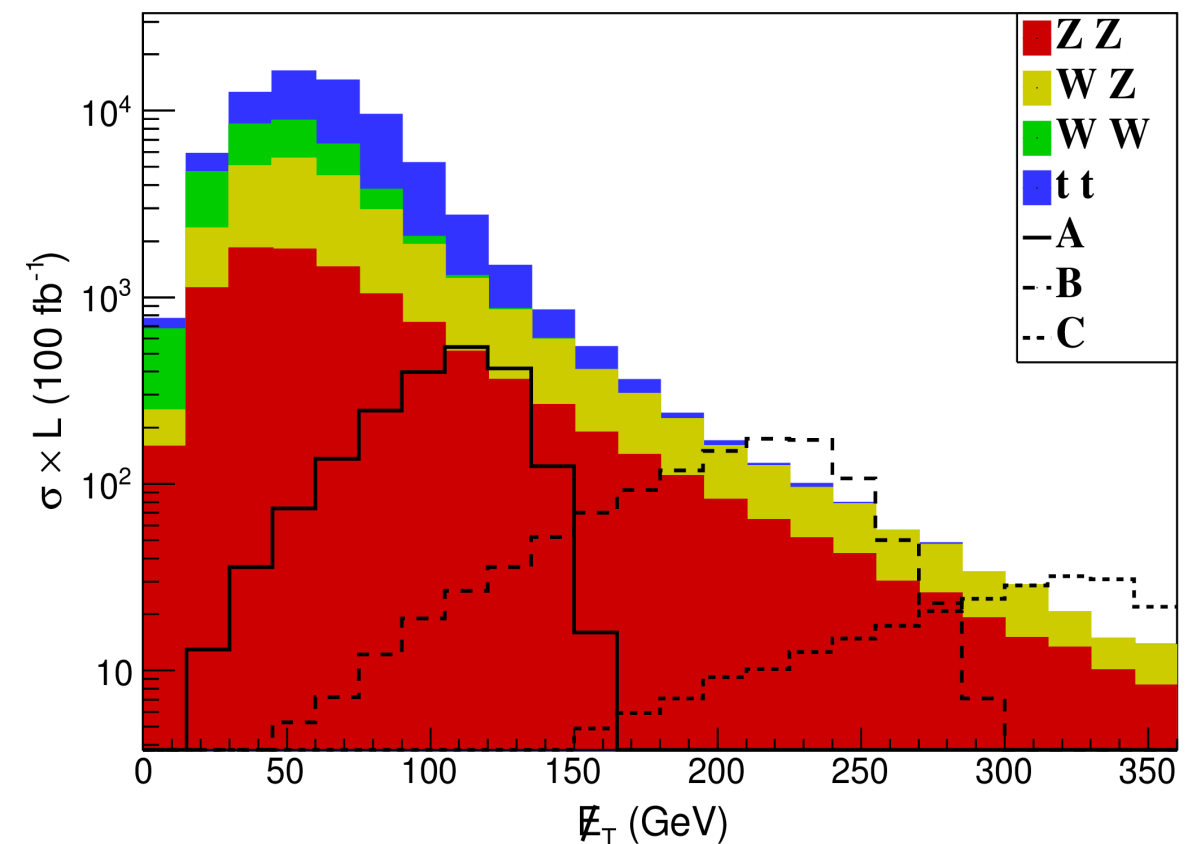
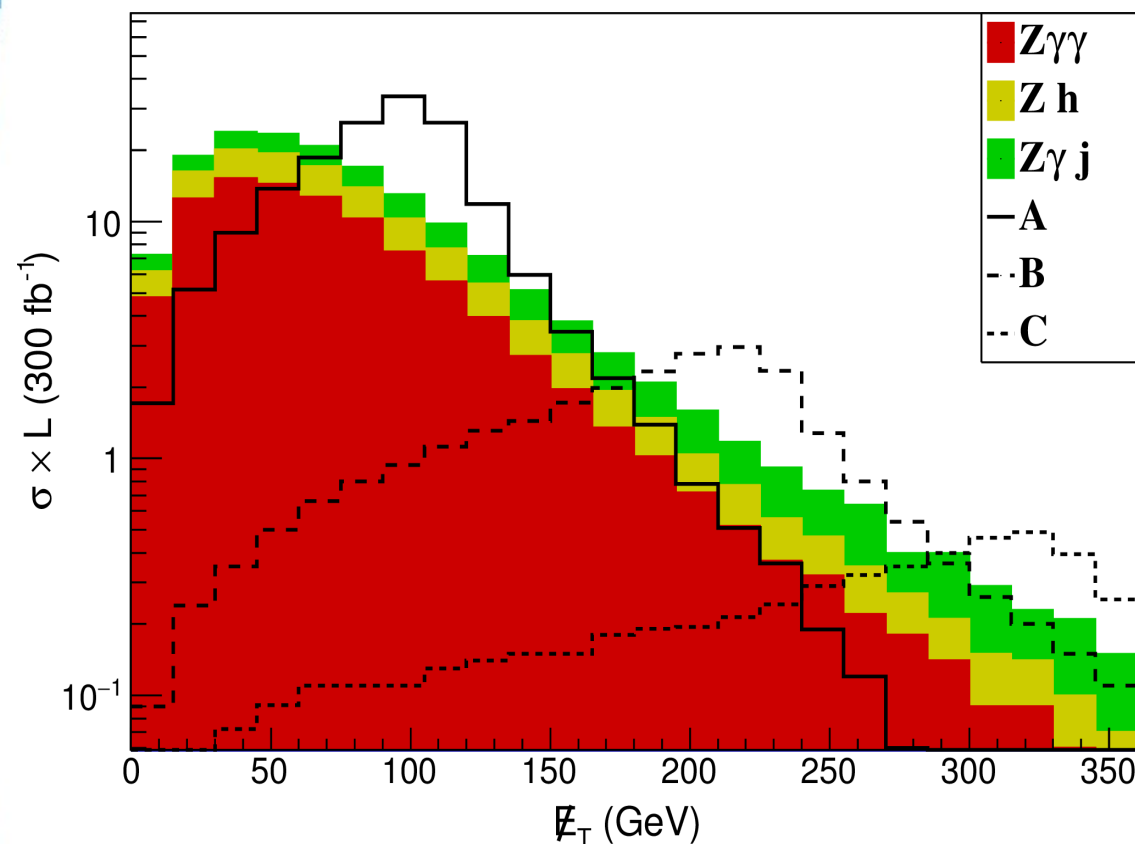
$$m_A = m_{H^0} = m_{H^\pm} = \begin{matrix} \text{A} & \text{B} & \text{C} \\ 300 \text{ GeV} & 500 \text{ GeV} & 700 \text{ GeV} \end{matrix}$$

mono- h

	A	B	C	Zh	$Z\gamma\gamma$	$Z\gamma j$
Event selection	249	56	16	51	517	157
$m_{\gamma\gamma} \in [120, 130] \text{ GeV}$	161	26	6	34	97	32
$\cancel{E}_T, P_T^{\gamma\gamma} > 80 \text{ GeV}$	105	24	5	13	32	12
$\cancel{E}_T, P_T^{\gamma\gamma} > 180 \text{ GeV}$	4	15	4	2	3	2
$\cancel{E}_T, P_T^{\gamma\gamma} > 280 \text{ GeV}$	< 0.1	2	3	0.4	0.5	0.5

mono- Z

	A	B	C	ZZ	WW	WZ	$t\bar{t}$
Event selection	2009	1130	282	10100	12670	16680	32060
$\cancel{E}_T > 90 \text{ GeV}$	1500	1105	279	2660	253	3530	5660
$\cancel{E}_T > 190 \text{ GeV}$	4.5	733	254	414	< 0.1	357	30
$\cancel{E}_T > 290 \text{ GeV}$	1.5	11	158	81	-	57	< 0.1



Conclusions

Higgs Portal to DM:
Simple yet very Attractive Paradigm

DM Signatures @ LHC & beyond could yield
key information on properties of EWSB Sector

- Linear vs Non - Linear Higgs Portal (Singlet Scalar DM)
- Pseudo-Scalar Portal to DM & 2HDM

Conclusions

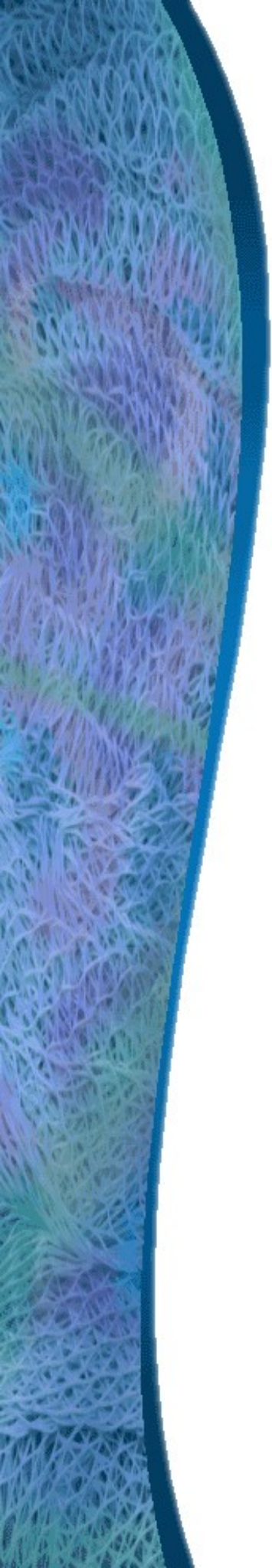
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Higgs Portals are fun!

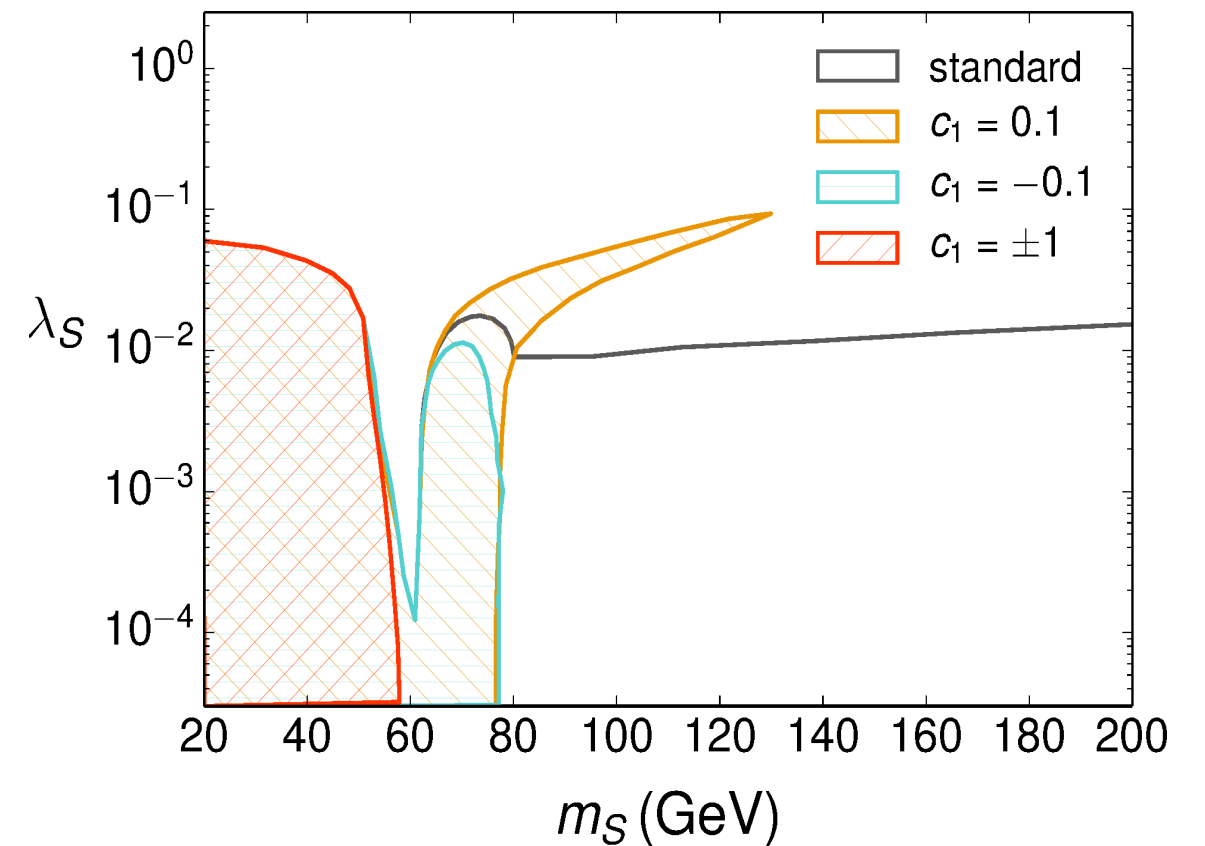
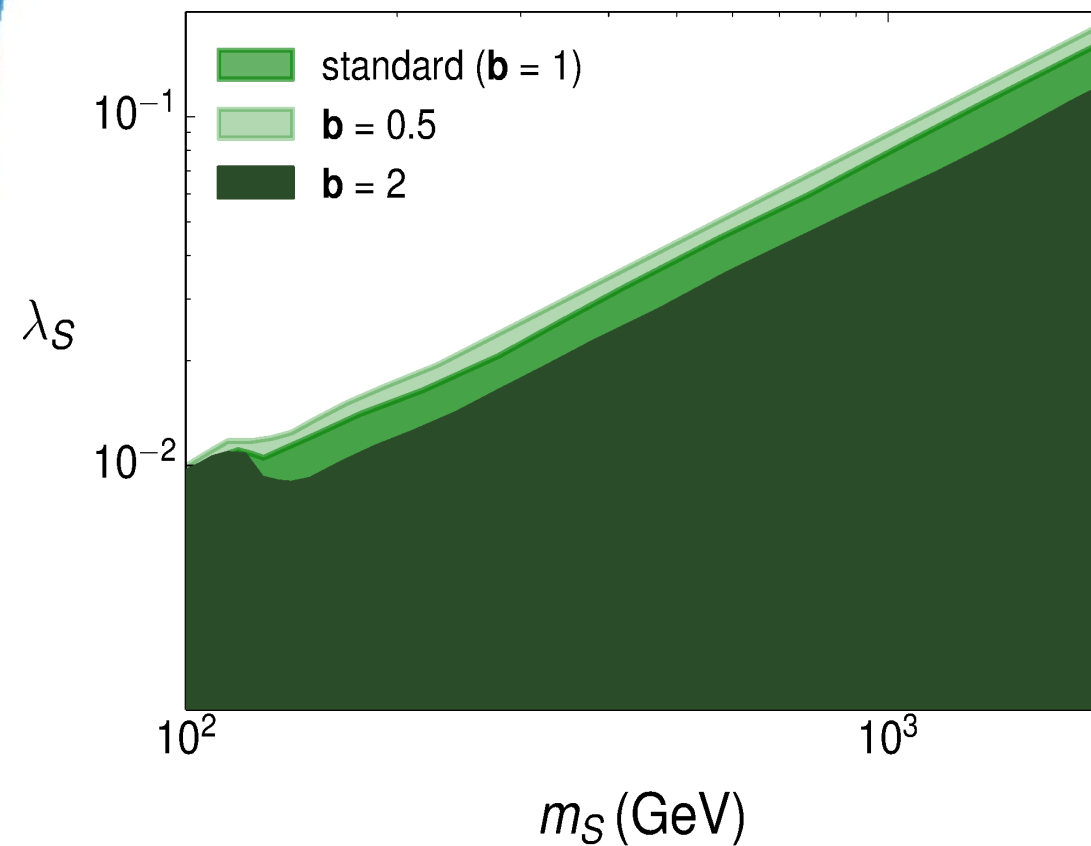




DM from Non-Linear Higgs Portals

Phenomenology

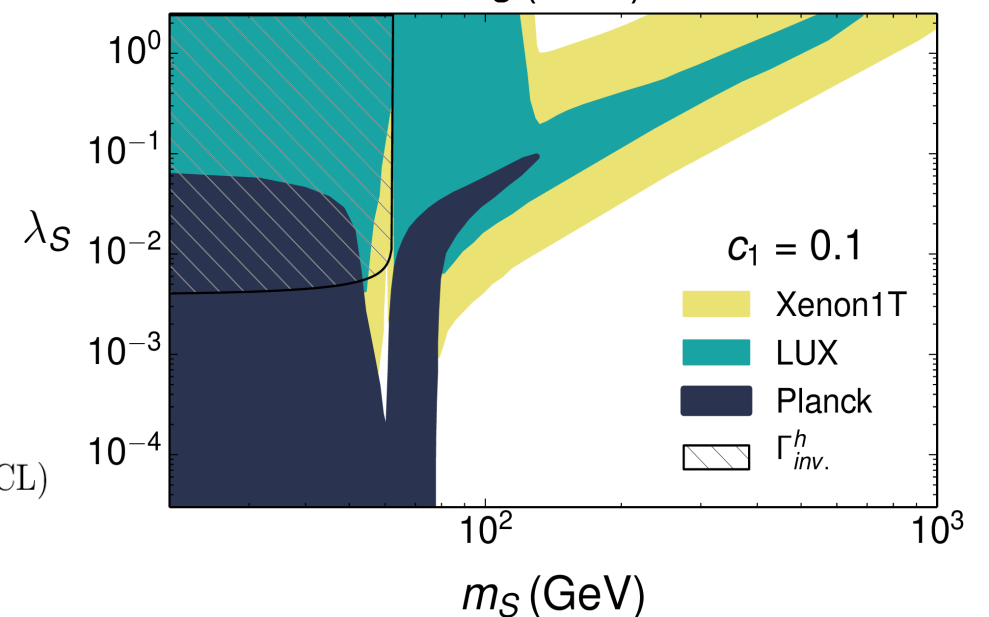
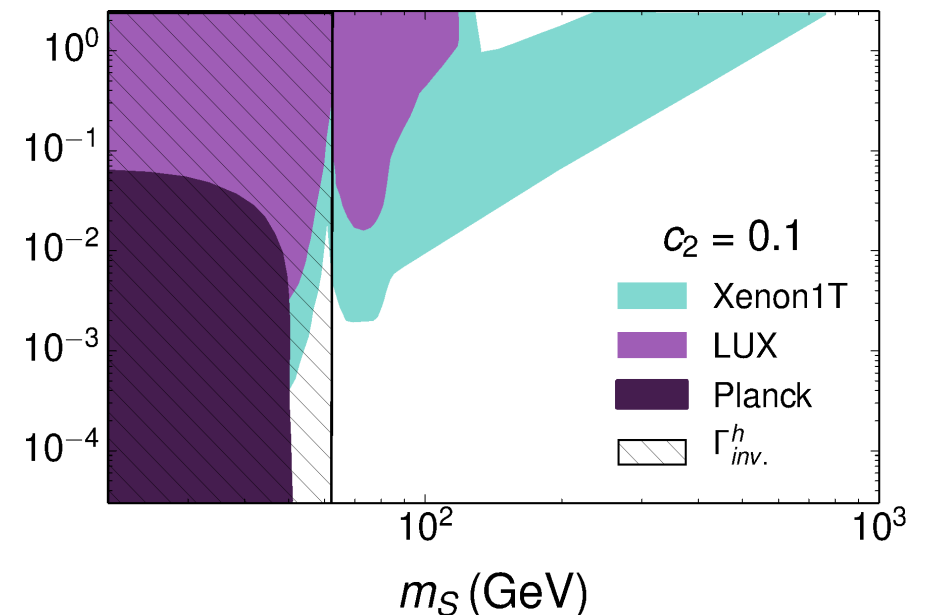
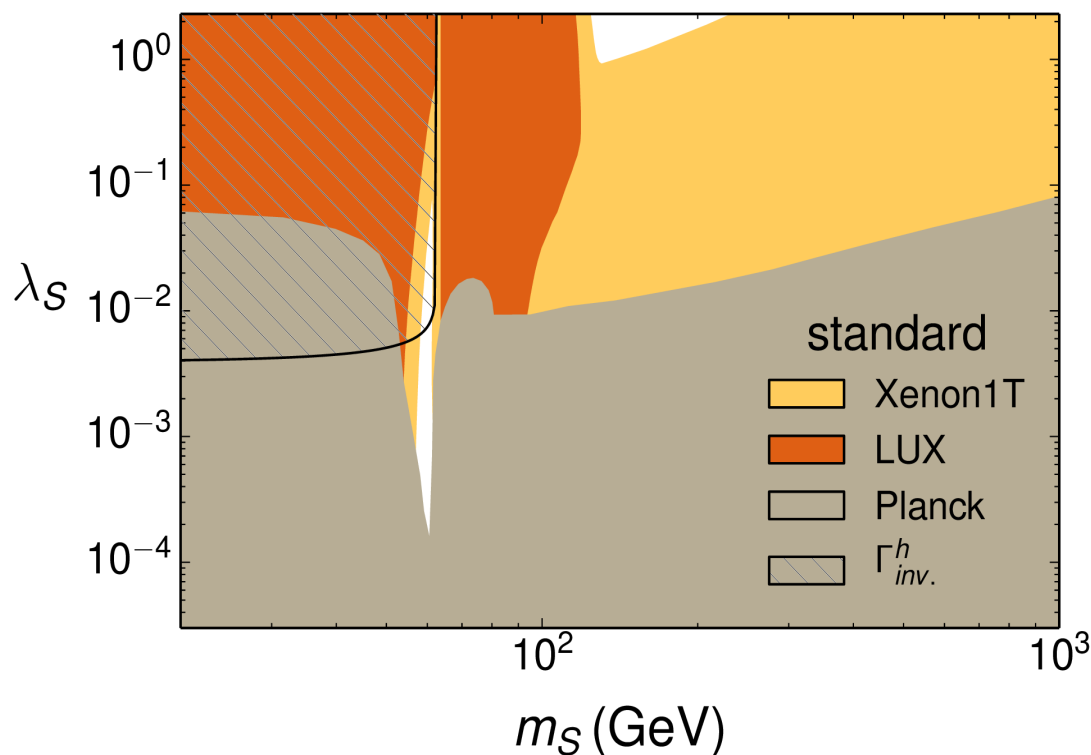
Observable		Parameters contributing					
		b	c_1	c_2	c_3	c_4	c_5
Thermal relic density	$\Omega_S h^2$	✓	✓	✓	✓	✓	✓
DM-nucleon scattering in direct detection	σ_{SI}	—	—	✓	—	✓	—
Invisible Higgs width	Γ_{inv}	—	—	✓	—	—	—
Mono- h production at LHC	$\sigma(pp \rightarrow hSS)$	✓	—	✓	—	✓	✓
Mono- Z production at LHC	$\sigma(pp \rightarrow ZSS)$	—	✓	✓	✓	✓	✓
Mono- W production at LHC	$\sigma(pp \rightarrow W^+SS)$	—	✓	✓	—	✓	—



DM from Non-Linear Higgs Portals

Phenomenology

Observable		Parameters contributing					
		b	c ₁	c ₂	c ₃	c ₄	c ₅
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Mono- Z production at LHC	$\sigma(pp \rightarrow ZSS)$	—	✓	✓	✓	✓	✓
Mono- W production at LHC	$\sigma(pp \rightarrow W^+SS)$	—	✓	✓	—	✓	—



$$\Gamma_{inv} = \frac{\lambda_S^2 v^2}{2\pi m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}} \left(1 + \frac{c_2 a_2 m_h^2}{\lambda_S v^2}\right)^2 \quad \text{BR}_{inv} = \frac{\Gamma_{inv}}{\Gamma_{inv} + \Gamma_{SM}} < 0.23 \quad (95\% \text{ CL})$$