Non-linear scalar portal to Dark Matter

Based on hep-ph/1511.01099 (submitted to JHEP)

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SM portals to dark sectors

Three singlet combinations in SM with d ≤ 4 to which Dark Matter can couple:

Vector $B^{\mu\nu} X_{\mu\nu}$

Fermion $\bar{L}\Phi\,\Psi$

Scalar $\Phi^\dagger\Phi\, S^2$

$\Phi^\dagger\Phi\, S$

SM portals to dark sectors

Three singlet combinations in SM with d ≤ 4 to which Dark Matter can couple:

Scalar

$$\Phi^\dagger \Phi \, S^2$$

$$\xcancel{\Phi^\dagger \Phi \, S}$$

$$\text{Assuming } \mathbb{Z}_2 : \begin{cases} S \to -S \\ \text{SM} \to \text{SM} \quad \text{for DM stability} \end{cases}$$

SM portals to dark sectors

Silveira, Zee Phys.Lett.B161 136
Patt, Wilczek hep-ph/0605188
and many more…

Standard portal to DM

$$\lambda_S \, \Phi^\dagger \Phi S^2$$

SM portals to dark sectors

Silveira, Zee Phys.Lett.B161 136
Patt, Wilczek hep-ph/0605188
and many more…

Standard portal to DM

$$\lambda_S \underbrace{\Phi^\dagger \Phi}_{\text{doublet structure}} S^2$$

$$(v+h)^2 = v^2 + 2vh + h^2$$

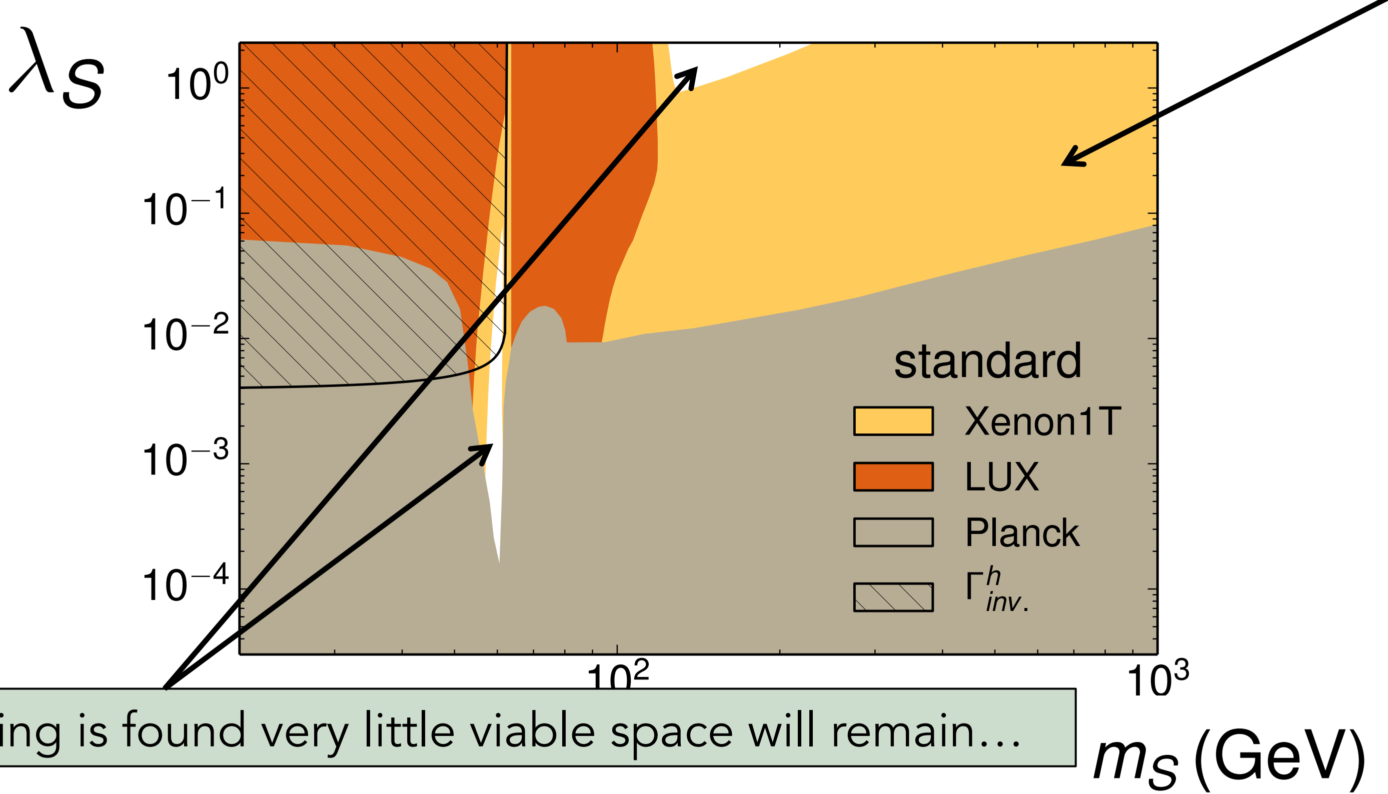
h vs. h^2 couplings correlated

direct impact on DM relic abundance

Standard Portal

It is usually thought that the portal is quite closed:

To be probed soon!



If nothing is found very little viable space will remain...

Constraints from

- ● Relic density
- ● Direct detection (LUX)
- ▨ Γ(h→*inv.*)
- ● Projected reach of Xenon1T

Nature of h particle

The Higgs may not behave as an exact SU(2) doublet

$$\Phi(x) = \frac{v + h(x)}{\sqrt{2}} e^{i\vec{\pi}\vec{\sigma}/v}$$

pNGB Higgs

Eg. In SO(5)/SO(4) breaking

$$\mathcal{F}_C(h) = \frac{4}{\xi} \sin^2 \frac{\varphi}{2f}$$

Grinstein, Trott (PRD 76 073002) // Contino et al. (JHEP 1005 089) // Azatov et al. (JHEP 1204 127)

Nature of h particle

The Higgs may not behave as an exact SU(2) doublet

$$\Phi(x) = \frac{v+h(x)}{\sqrt{2}} e^{i\vec{\pi}\vec{\sigma}/v}$$

In effective Lagrangians:
we use a polynomial expansion

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \ldots$$

with arbitrary coefficients ***a*** and ***b***

- ***h*** treated as a singlet
- SM is recovered for ***a***=***b***=1

Grinstein, Trott (PRD 76 073002) // Contino et al. (JHEP 1005 089) // Azatov et al. (JHEP 1204 127)

Non-linear H portal to DM

Brivio et al. 1511.01099

Linear vs. **Chiral**

$$\Phi^\dagger \Phi\, S^2 \longrightarrow \mathcal{F}(h) S^2$$

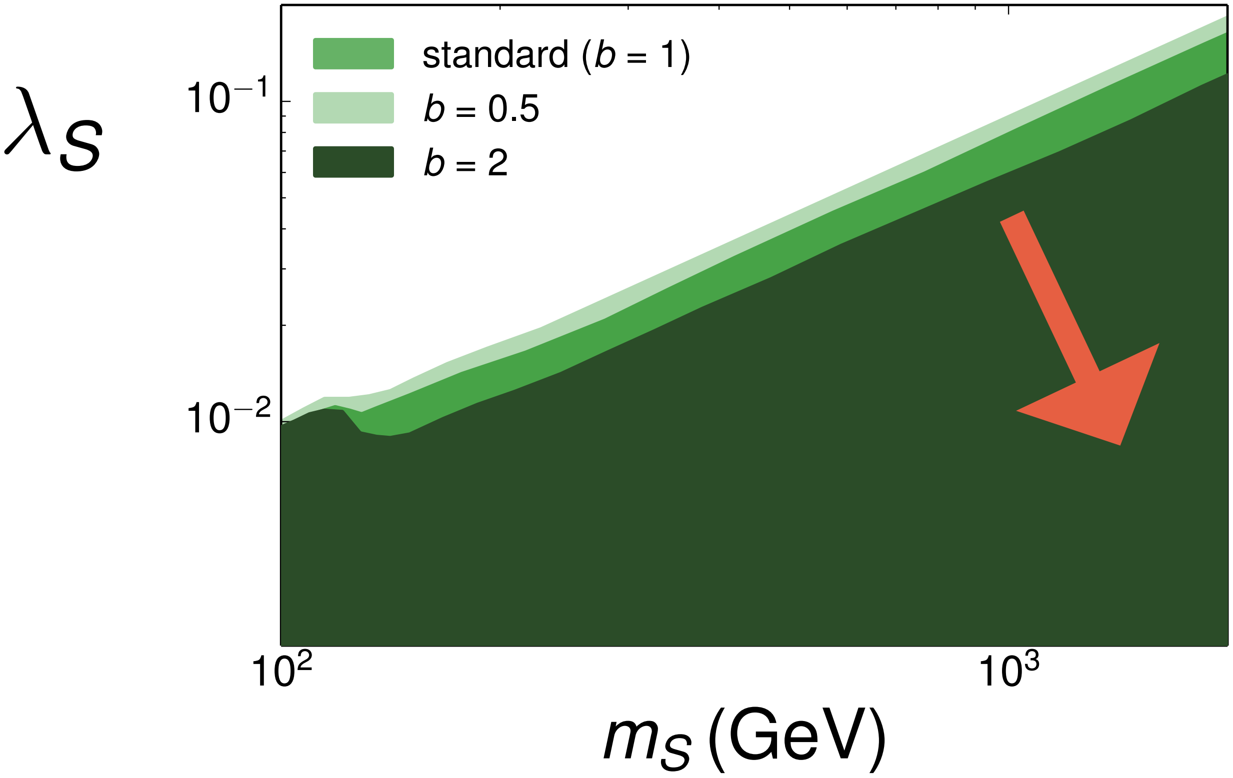
$$(2vh + h^2) S^2 \longrightarrow (2vh + \boxed{\mathbf{b}}\, h^2) S^2$$

fixed relative strength

new arbitrary coefficient!

Non-linear H portal to DM

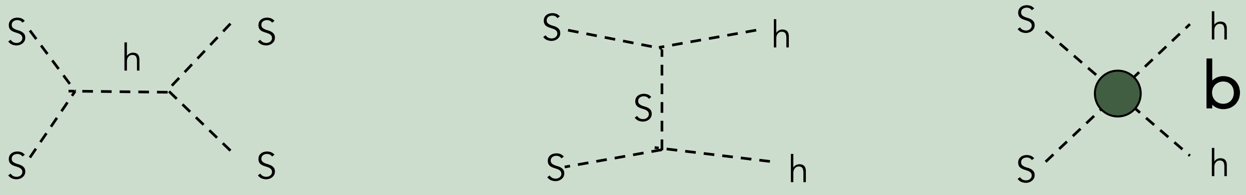
Brivio et al. 1511.01099



Excluded by relic density
$\Omega_S \leq \Omega_{DM} \simeq 0.12$

… but there's more to it!

Main DM decay channels for $m_S > m_h$



Nature of h particle

The Higgs may not behave as an exact SU(2) doublet

Appelquist, Bernard (1980)
Longhitano (1981)

treated independently

$$\Phi(x) = \frac{v + h(x)}{\sqrt{2}} e^{i\vec{\pi}\vec{\sigma}/v}$$

In effective Lagrangians:
we use a polynomial expansion

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \ldots$$

with arbitrary coefficients ***a*** and ***b***

eg. using chiral
Lagrangians

Dimensionless matrix of the GBs
($W^\pm_L$ and Z_L)

$$\mathbf{U}(x)$$

- *h* treated as a singlet
- SM is recovered for ***a***=***b***=1

Grinstein, Trott (PRD 76 073002)
Contino et al. (JHEP 1005 089)
Azatov et al. (JHEP 1204 127)

Less assumptions about origin of h(x)

⇒**U** and *h(x)* independent

⇒ ***More operators + decorrelations***

Non-linear Higgs Portal

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2} S^2 - \lambda_S S^2 (2vh + bh^2) + \sum_{i=1}^{5} c_i \mathcal{A}_i$$

Brivio et al. 1511.01099

New bosonic operators at LO:

$$\mathcal{A}_1 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) S^2 \mathcal{F}_1(h)$$

$$\mathcal{A}_2 = S^2 \Box \mathcal{F}_2(h)$$

$$\mathcal{A}_3 = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) S^2 \mathcal{F}_3(h)$$

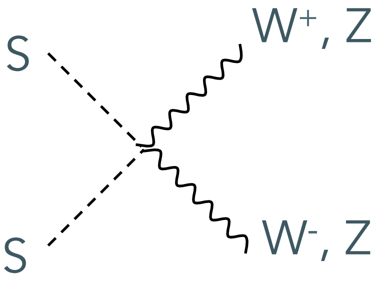
$$\mathcal{A}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\partial^\mu S^2 \mathcal{F}_4(h)$$

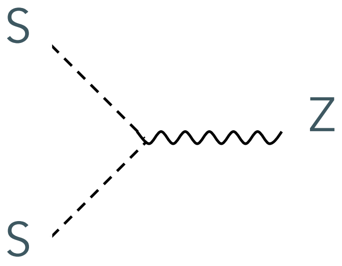
$$\mathcal{A}_5 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) S^2 \partial^\mu \mathcal{F}_5(h)$$

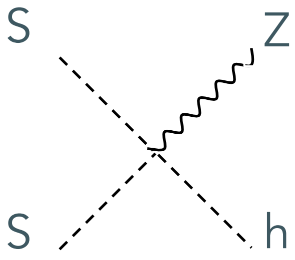
$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger$	$\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \longrightarrow ig\, Z_\mu$
$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger$	$\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \longrightarrow (gv)^2\,(Z_\mu Z_\nu + W_\mu^+ W_\nu^-)$

New couplings!

phenomenological consequences?



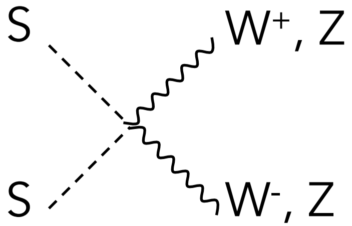


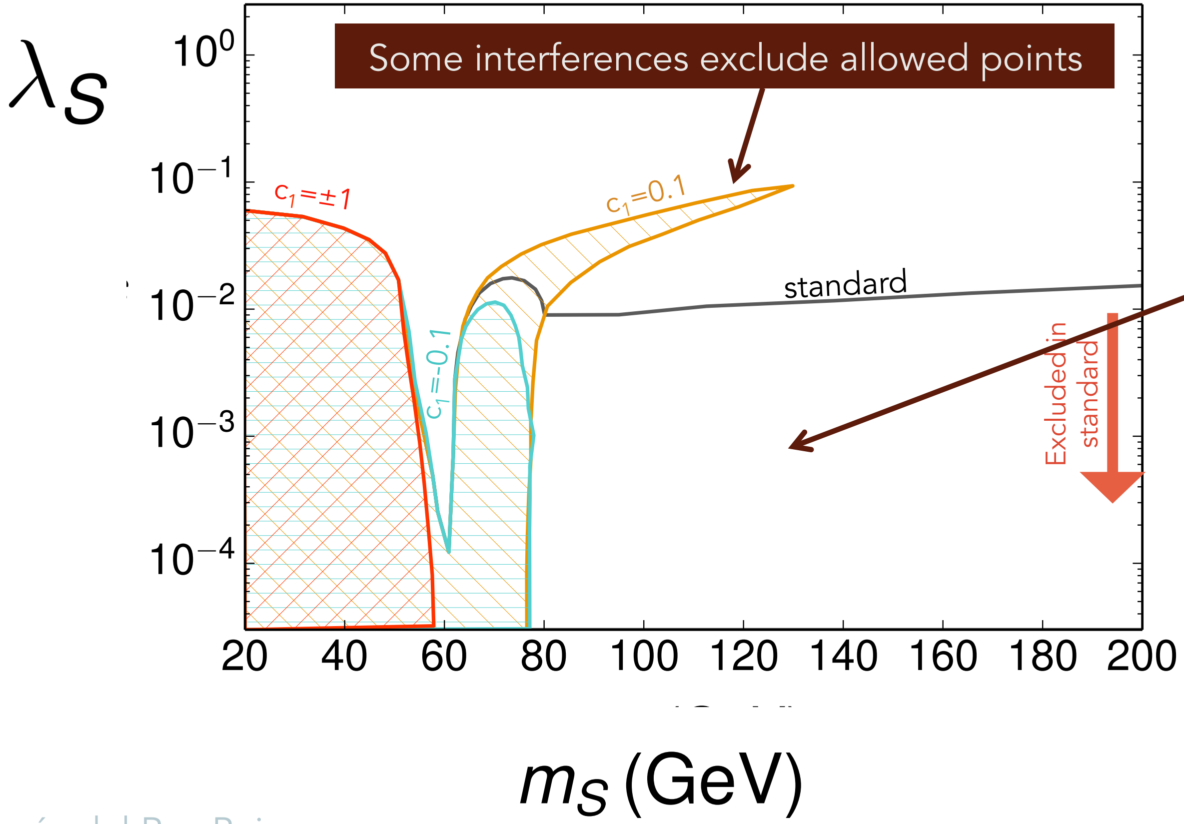


Impact on relic density

Ω_S mostly determined by s-wave contribution of DM annihilation: $\alpha_s(SS \longrightarrow XX)$

$$\begin{aligned}\mathcal{A}_1 =& \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) S^2 \mathcal{F}(h) \\ & \to (W_\mu W^\mu + Z_\mu Z^\mu) S^2\end{aligned}$$





Some interferences exclude allowed points

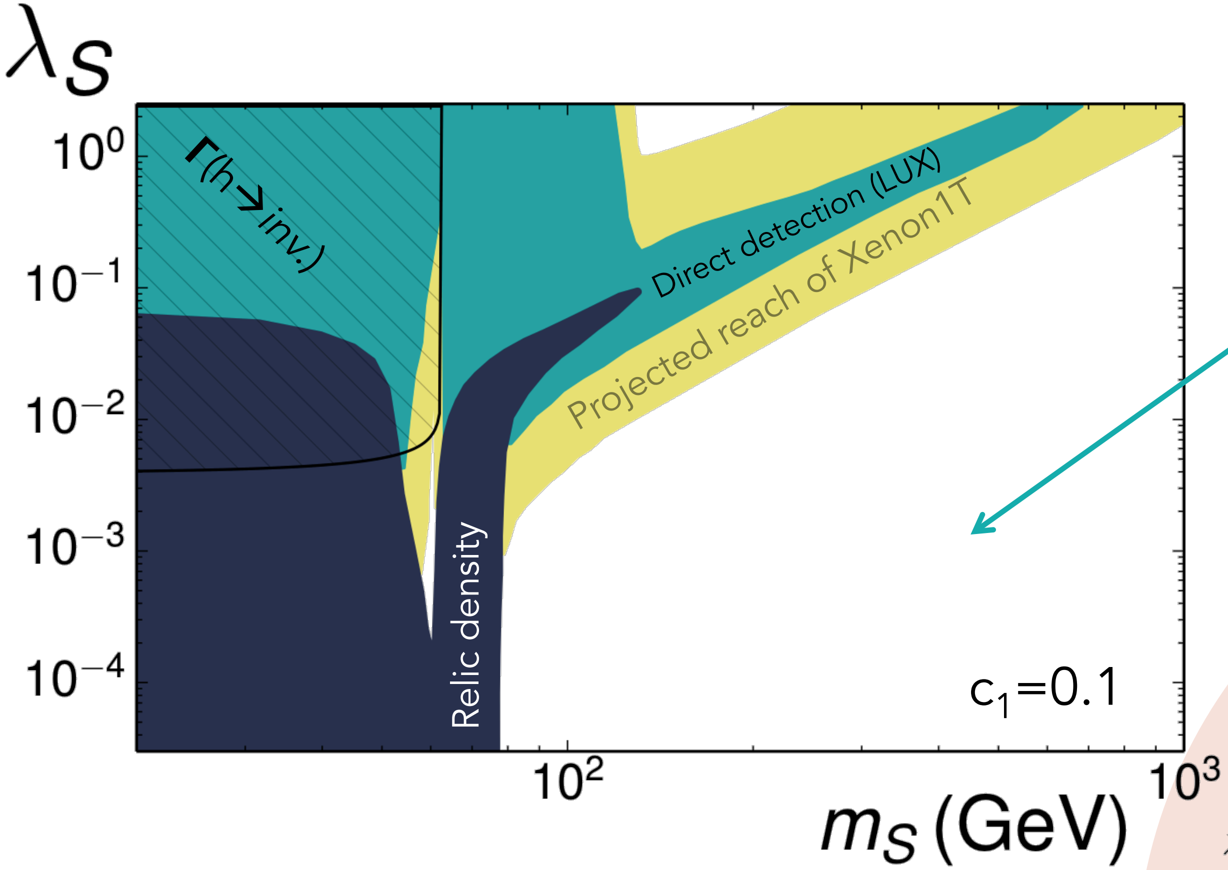
More decay channels

$\Rightarrow$ Lower Ω_S

$\Rightarrow$ Larger allowed region

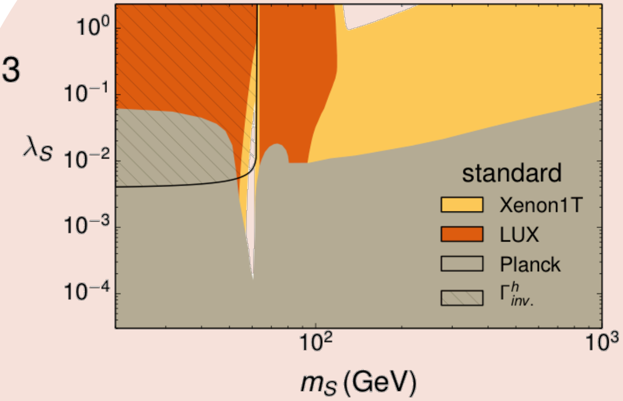
Brivio et al. 1511.01099

Non-Linear portal: Summary



The portal is wide open!

…to be compared with:

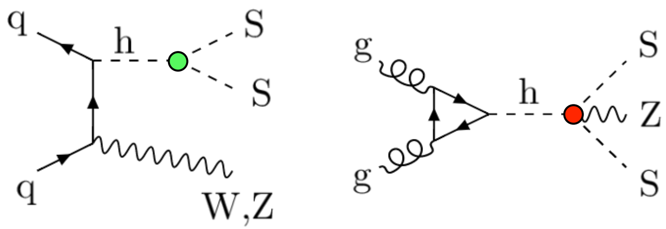


Standard portal

Planck Collab. 1502.01589 // Xenon100: PRL109 181301 (2012) // Xenon1T C. Sprin
Proc.Phys.148 93 // LUX: PRL112 091303 (2014) // h-inv: Atlas Collab. 1509.00672

@Colliders: mono-h, mono-Z & mono-W very promising!

for example: **Ratio(monoZ/monoW)**



one operator at a time

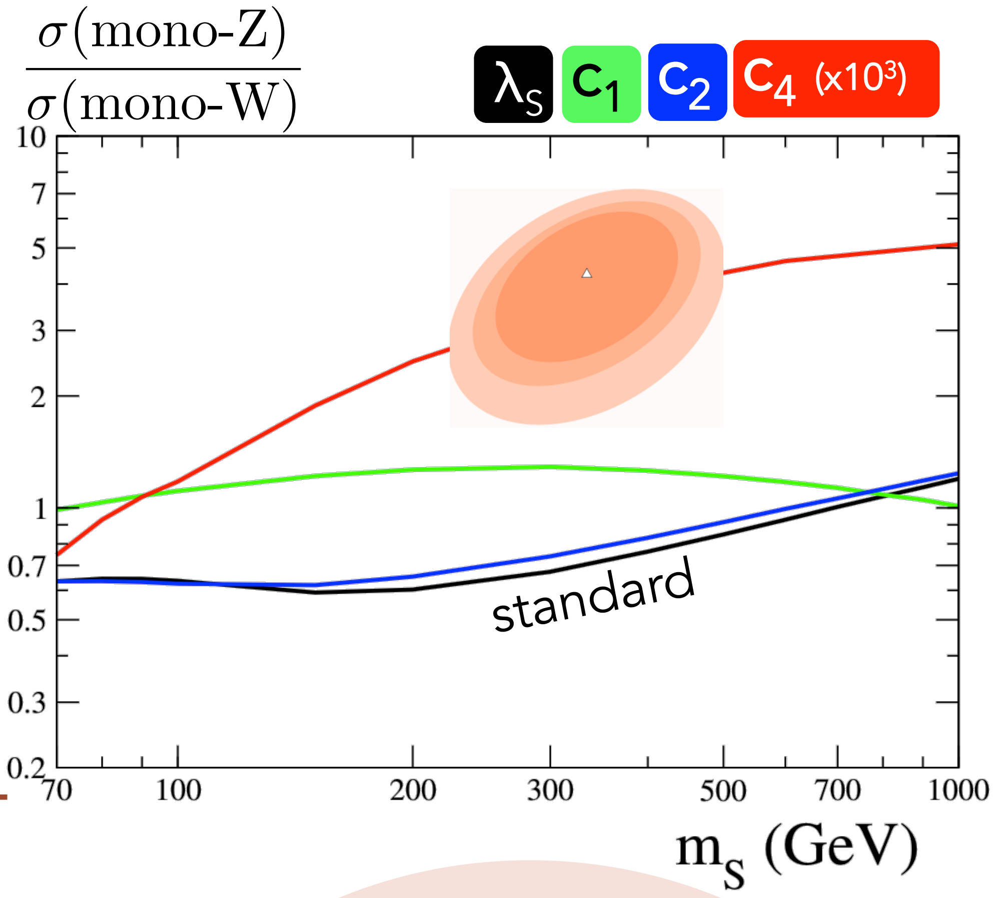
⇒ $\sigma(\text{mono-V}) \sim c_i^2,\ \lambda_S^2$

⇒ ratio is independent of the parameters

strategy to disentangle:

Say we were to measure:

- ✦ the ratio monoZ/monoW
- ✦ m_S from p_T ($\not{E}_T$) distributions



the standard portal may be excluded!

Conclusions

Scalar H portal has been studied in a model independent way using Effective Lagrangians.

It is wide open if EWSB is non-linearly realized.

(eg. Composite Higgs models)

Gives rise to very rich phenomenology:

Decorrelations **between S^2h vs. S^2h^2 couplings**

⇒ Impact on relic dentity & direct detection

New allowed regions!

New couplings at renormalisable level

⇒ Signals at colliders: h⇒ invisibles & monoX

Possible smoking gun!

Thank you for your attention!

Backup Slides

Complete Lagrangian

$$\mathscr{L} = \mathscr{L}_{EW} + \mathscr{L}_S\,,$$

$$\begin{aligned}
\mathscr{L}_{EW} =& -\frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu}\mathcal{F}_W(h) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h) + \frac{1}{2}\partial_\mu h\partial^\mu h \\
& - \frac{v^2}{4}\,\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C(h) + c_T\frac{v^2}{4}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h) - V(h) + \\
& + i\bar{Q}_L \not{D} Q_L + i\bar{Q}_R \not{D} Q_R + i\bar{L}_L \not{D} L_L + i\bar{L}_R \not{D} L_R + \\
& - \frac{v}{\sqrt{2}}\left(\bar{Q}_L\mathbf{U}\mathbf{Y}_Q Q_R + \text{ h.c.}\right)\mathcal{F}_Q(h) - \frac{v}{\sqrt{2}}\left(\bar{L}_L\mathbf{U}\mathbf{Y}_L L_R + \text{ h.c.}\right)\mathcal{F}_L(h)\,,
\end{aligned}$$

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{m_S^2}{2}S^2 - \lambda_S S^2(2vh + bh^2) + \sum_{i=1}^{5} c_i\mathcal{A}_i$$

$$\mathcal{A}_1 = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)S^2\mathcal{F}_1(h)$$

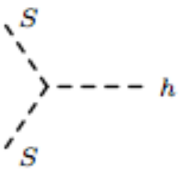
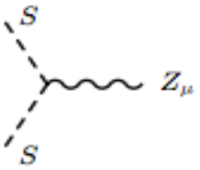
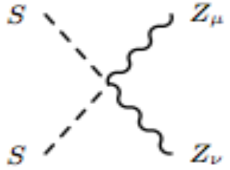
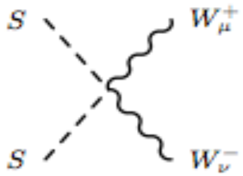
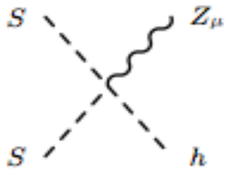
$$\mathcal{A}_2 = S^2\Box\mathcal{F}_2(h)$$

$$\mathcal{A}_3 = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)S^2\mathcal{F}_3(h)$$

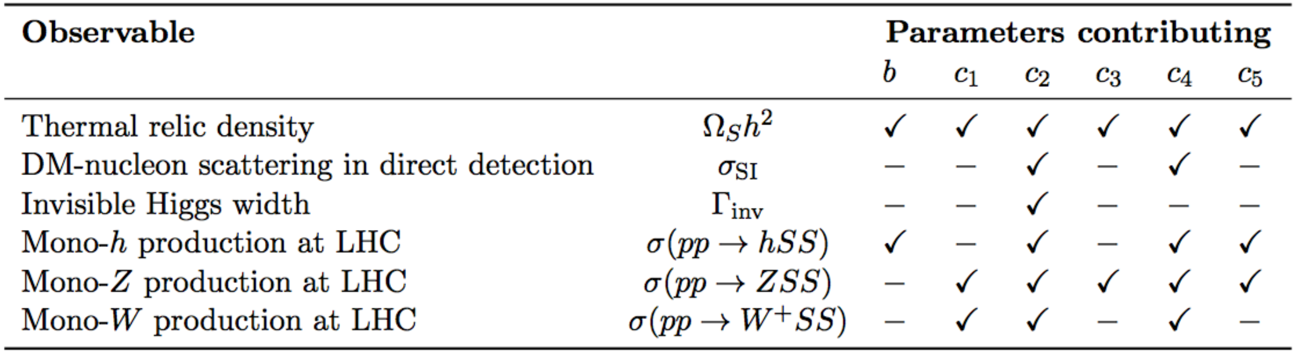
$$\mathcal{A}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\partial^\mu S^2\mathcal{F}_4(h)$$

$$\mathcal{A}_5 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)S^2\partial^\mu\mathcal{F}_5(h)$$

Feynman Rules

		Standard	**Non-linear**	**Linear $d \leq 6$**
(FR.1)		$-4i\lambda_S v$	$-4i\left(\lambda_S v + \frac{c_2 a_2 p_h^2}{v}\right)$	$-4i\left(\lambda_S v + \frac{2vc_2^L p_h^2}{\Lambda^2}\right)$
(FR.2)		–	$\frac{2gc_4}{c_\theta} p_Z^\mu$	$-\frac{4v^2 gc_4^L}{c_\theta \Lambda^2} p_Z^\mu$
(FR.3)		$-4i\lambda_S$	$-4i\left(\lambda_S b + \frac{c_2 b_2 (p_{h1} + p_{h2})^2}{v^2}\right)$	$-4i\left(\lambda_S + \frac{2c_2^L (p_{h1} + p_{h2})^2}{\Lambda^2}\right)$
(FR.4)		–	$-\frac{2ig^2(c_1 + 2c_3)}{c_\theta^2} g_{\mu\nu}$	$-\frac{8v^2 ig^2 c_1^L}{c_\theta^2 \Lambda^2} g_{\mu\nu}$
(FR.5)		–	$-2ig^2 c_1 g_{\mu\nu}$	$-8\frac{v^2}{\Lambda^2} ig^2 c_1^L g_{\mu\nu}$
(FR.6)		–	$\frac{4g}{vc_\theta}\left(c_4 a_4 (p_Z + p_h)^\mu - c_5 a_5 p_h^\mu\right)$	$-\frac{8vg}{\Lambda^2 c_\theta}\left(c_4^L (p_Z + p_h)^\mu\right)$

Summary of constraints



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	$\sigma_{\rm SI}$	–	–	✓	–	✓	–
Invisible Higgs width	$\Gamma_{\rm inv}$	–	–	✓	–	–	–
Mono-h production at LHC	$\sigma(pp \to hSS)$	✓	–	✓	–	✓	✓
Mono-Z production at LHC	$\sigma(pp \to ZSS)$	–	✓	✓	✓	✓	✓
Mono-W production at LHC	$\sigma(pp \to W^+SS)$	–	✓	✓	–	✓	–

Table 1: Non-linear Higgs portal parameters affecting each of the observables considered. The standard Higgs-DM portal $b = 1$ and all c_i=0.

Direct Detection -> Strongest bound from LUX (90% C.L.)

- spin-independent x-sec for S-nucleon scattering
- rescaling to corresponding density
- projected sensitivity of Xenon1T

$$\Omega_S h^2 \simeq \frac{2.09 \times 10^8\ \mathrm{GeV}^{-1}}{M_P \sqrt{g_{*s}(x_F)}(\alpha_s/x_F + 3\,\alpha_p/x_F^2)}$$

$$\sigma_{SI}(\Omega_S/\Omega_{SM}) \leq \sigma_{SI}^{exp}$$

Higgs Invisible Width -> Strongest bound from ATLAS

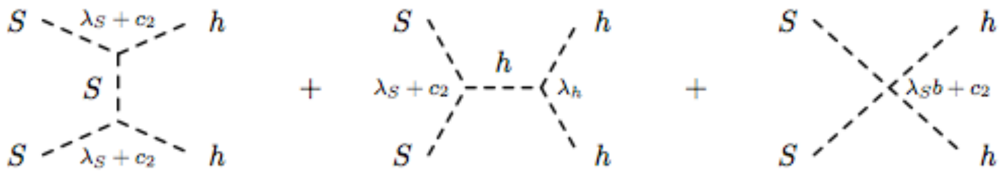
- relevant for $m_S \lesssim m_h/2$
- BR(h->inv.) ≤ 0.23

$$\Gamma_{\rm inv} = \frac{\lambda_S^2 v^2}{2\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}\left(1 + \frac{c_2 a_2 m_h^2}{\lambda_S v^2}\right)^2$$

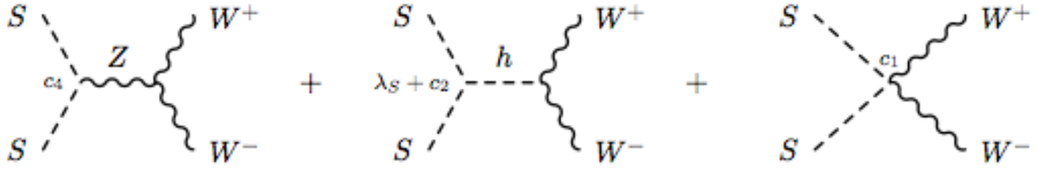
Thermal relic density

- Measured by Planck (fit to CMB data): $\Omega_{DM} h^2 \simeq 0.12$
- Conservatively we require $\Omega_S \leq \Omega_{DM}$
- Mostly determined by s-wave contribution to DM anihilation **α_s(SS $\longrightarrow$XX)**

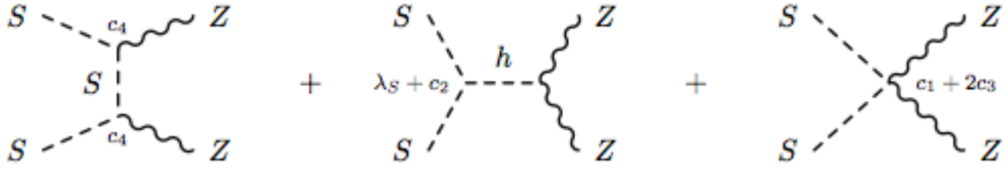
Decay diagrams



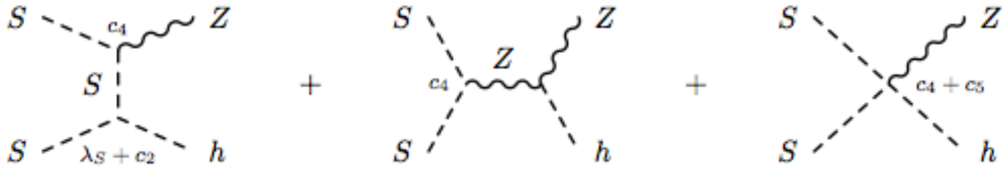
(a) Dark Matter annihilation to Higgs bosons.



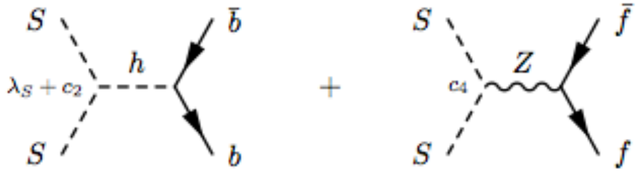
(b) Dark Matter annihilation to W bosons.



(c) Dark Matter annihilation to Z bosons.



(d) Dark Matter annihilation to Z and Higgs bosons.



(e) Dark Matter annihilation to $f\bar{f}$.

Fermionic operators

2 possible fermionic operators:

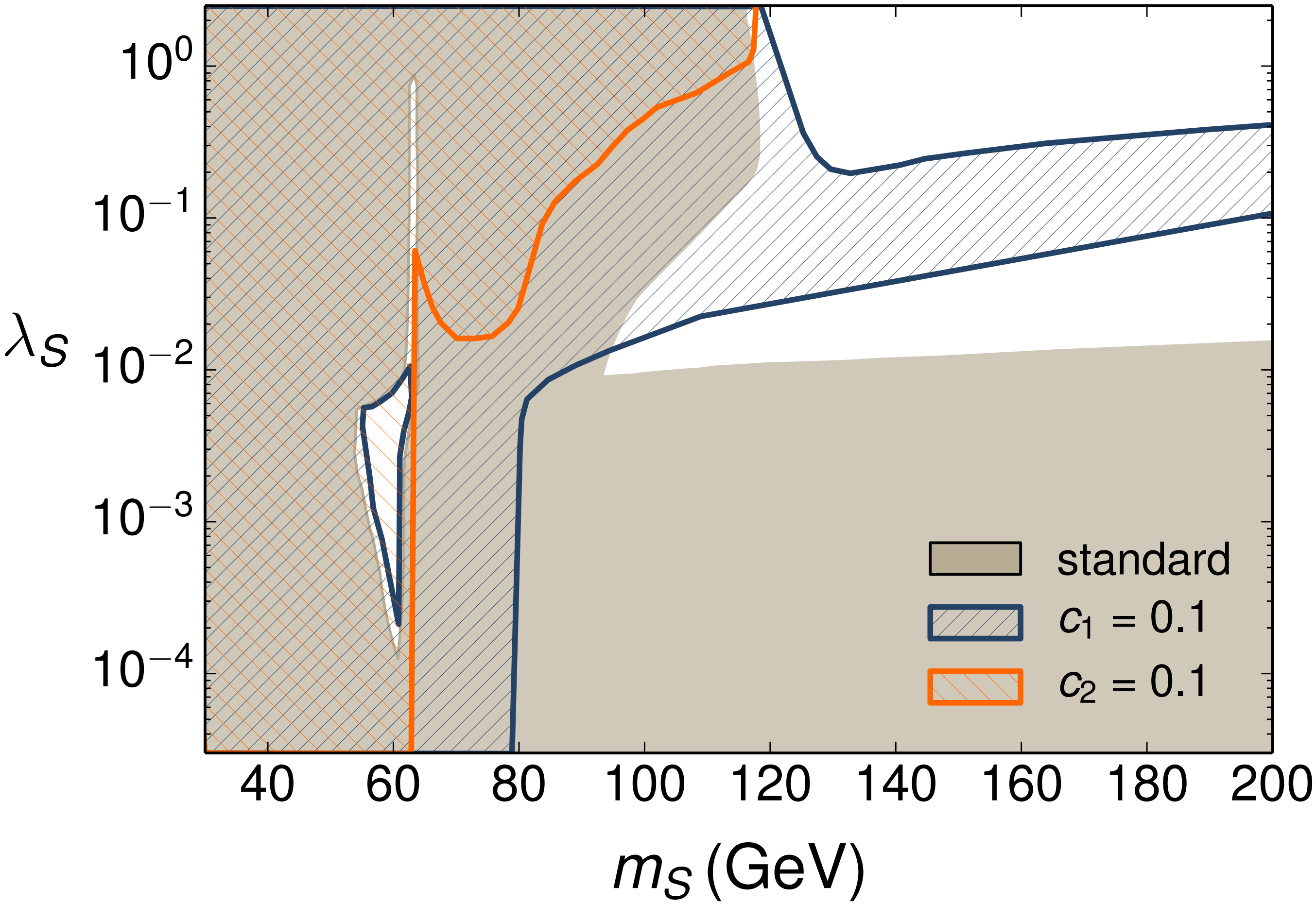
$\overline{\psi}_L \mathbf{U} \psi_R S^2 \mathcal{F}(h)$ and $\overline{\psi}_{L,R} \gamma_\mu \psi_{L,R}\, \partial^\mu S^2\, \mathcal{F}(h)$

Combinations of these operators are connected to the bosonic basis via EOMs

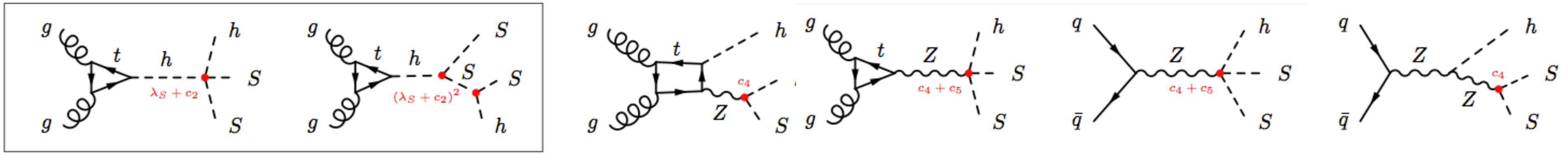
$$\mathcal{A}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\partial^\mu \mathcal{F}(h) \longrightarrow 4 \sum_{i=L,R} \overline{\psi}_i \mathcal{Y}_i \gamma_\mu \psi_i \partial^\mu S^2$$

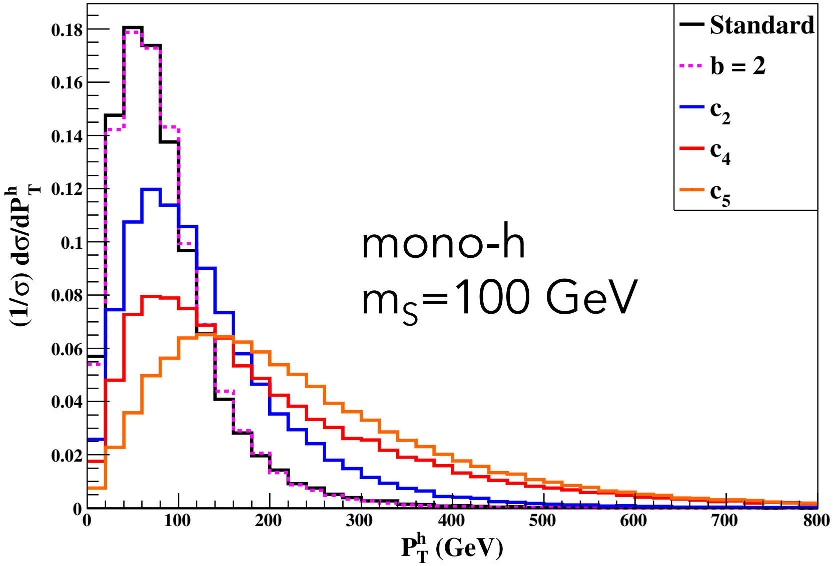
$$\mathcal{A}_2 = S^2 \Box \mathcal{F}(h) \longrightarrow \mathcal{A}_1 + S^2(\overline{\psi}_L \mathbf{U}\mathbf{Y}\psi_R + \mathrm{h.c.})$$

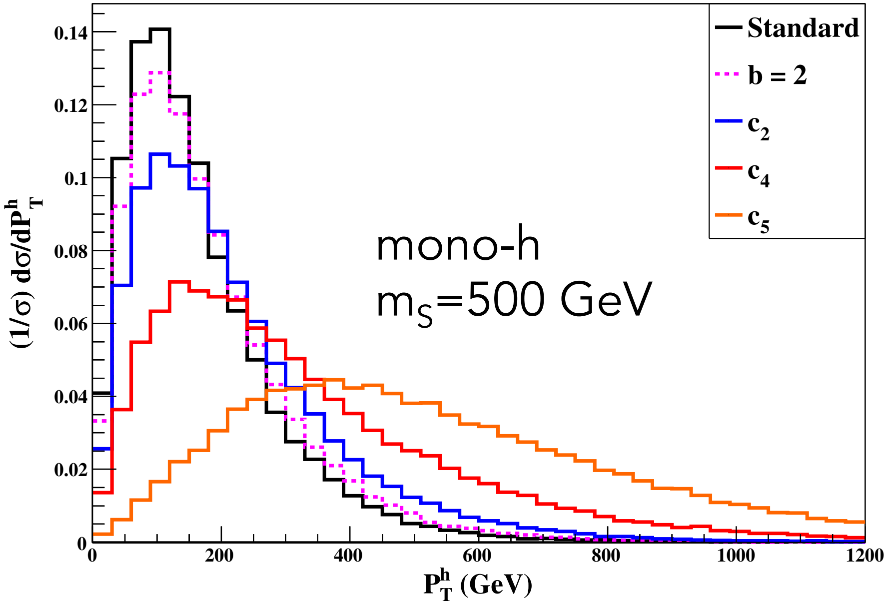
Summary plot (standard vs. non-linear)



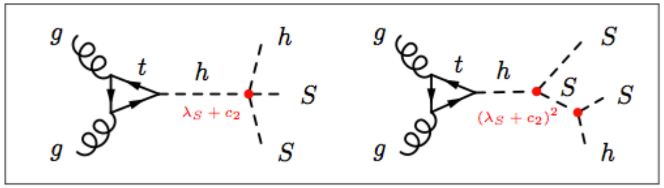
Collider signals: mono-h differential distributions

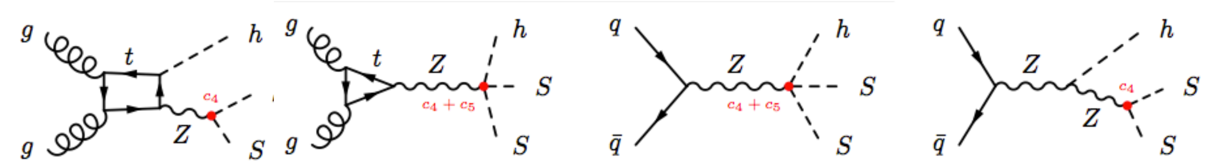


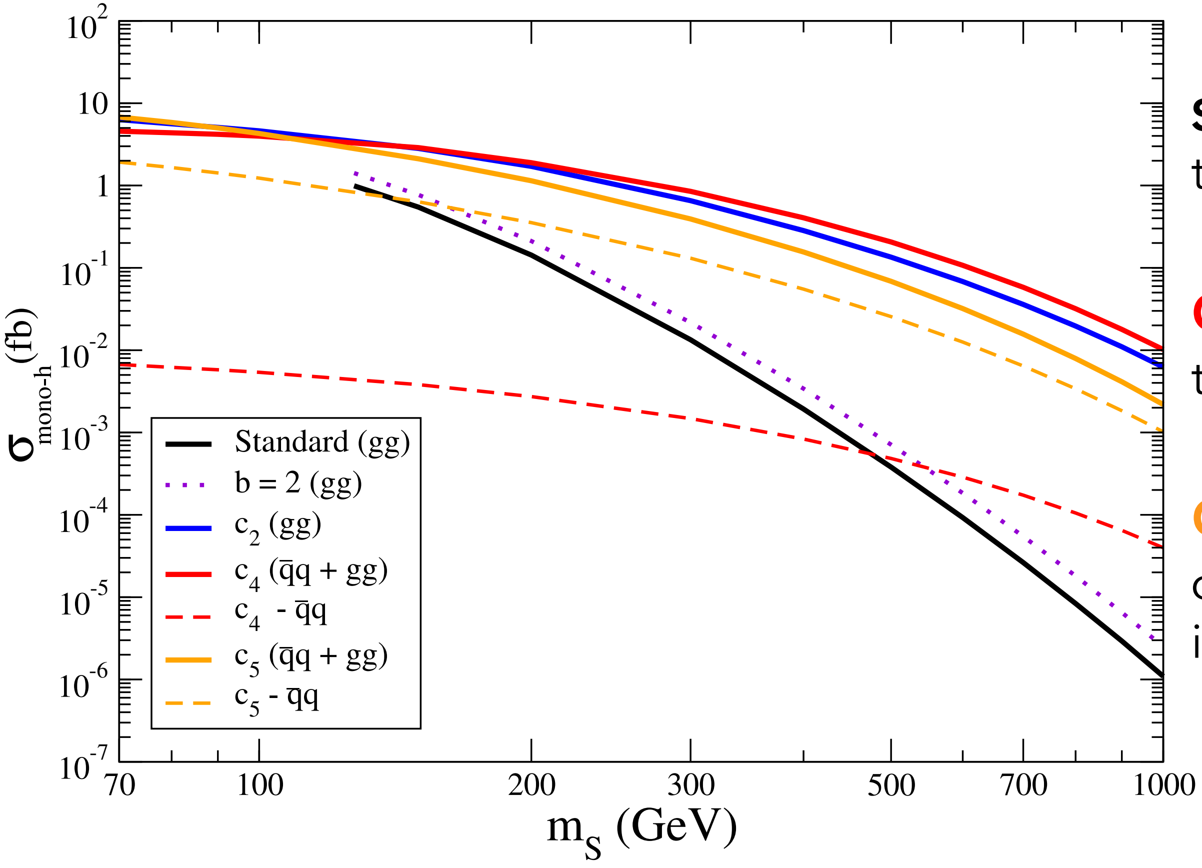




Collider signals: mono-h







standard: drops fast due to gluon pdf

c_2: large enhancement due to momentum dependence

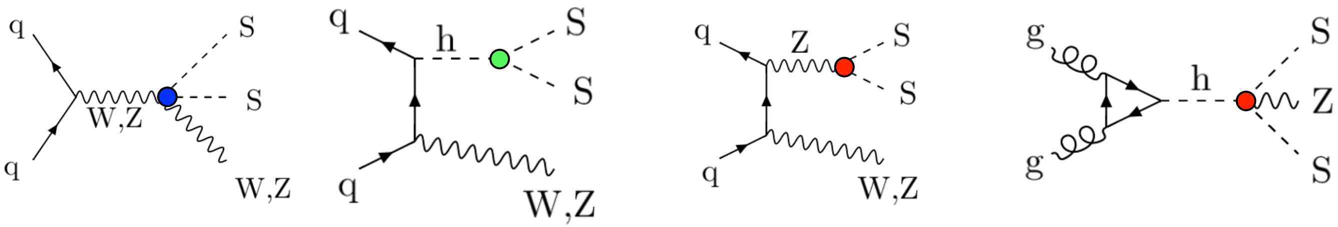
c_5: momentum dependence & q-qbar initiation

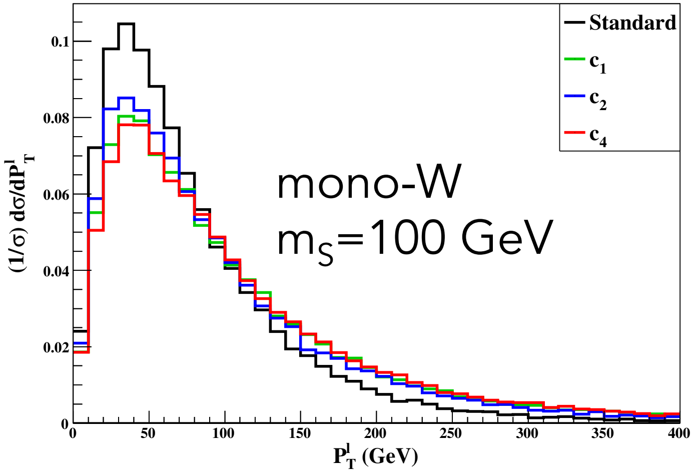
- Calculated for or c_i=2
- Scale as c_i^2

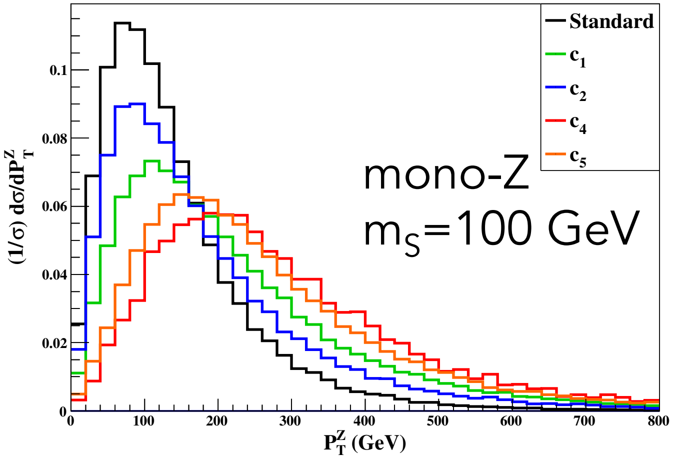
Collider signals: mono-V differential distributions

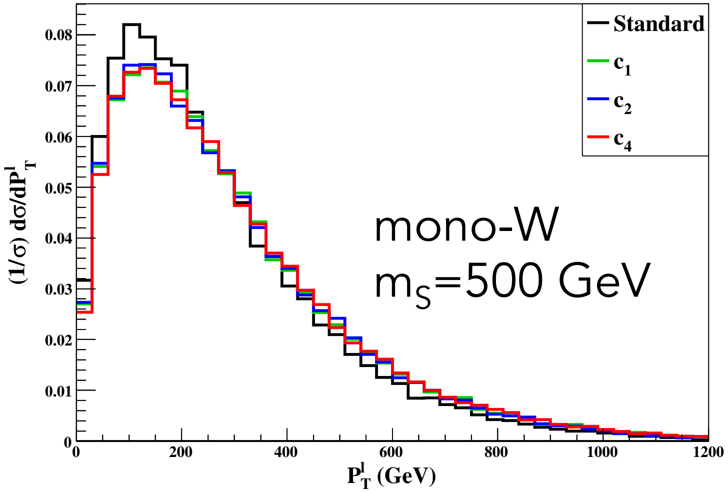
λ_S c_1 c_2 c_4 (x10^3)

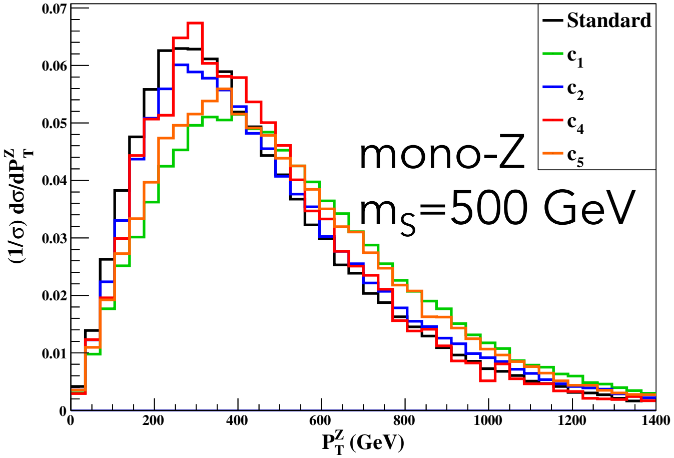
example diagrams mono-Z and mono-W:







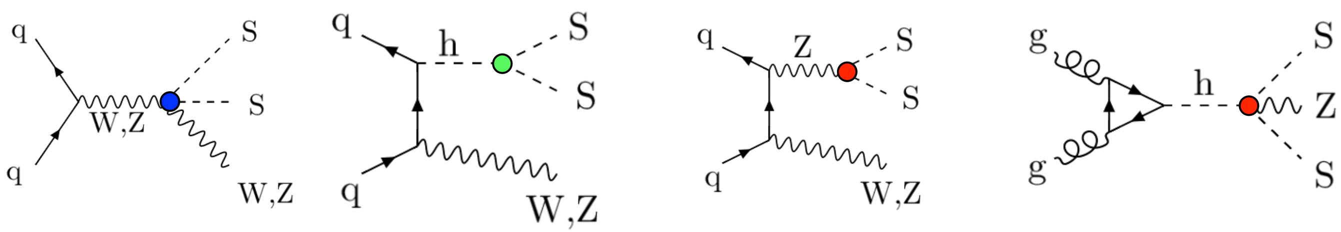


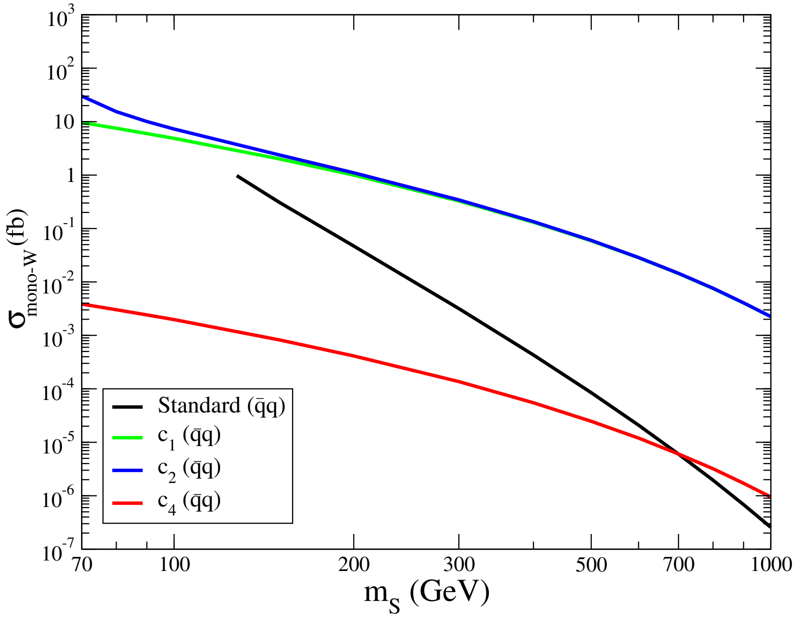


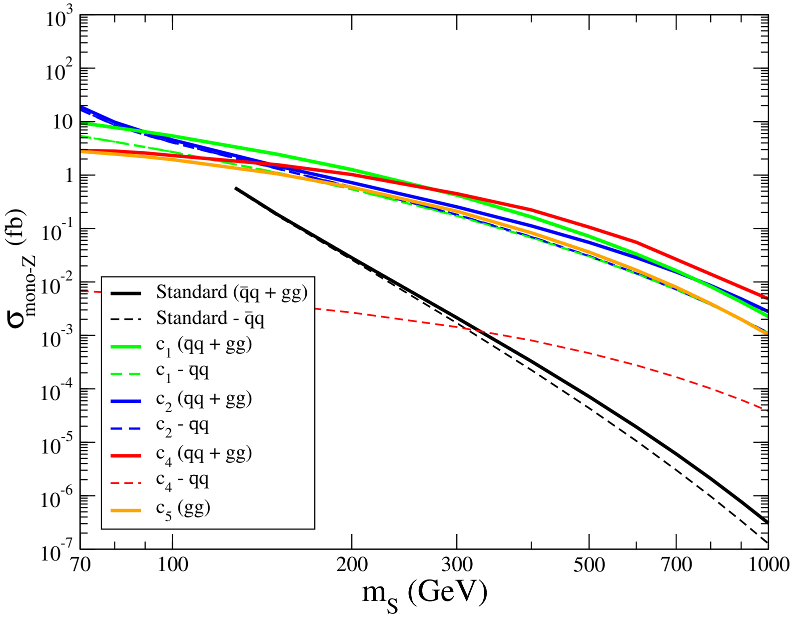
Collider signals: mono-V m_S scan

λ_S C_1 C_2 C_4 ($\times 10^3$)

example diagrams
mono-Z and mono-W:



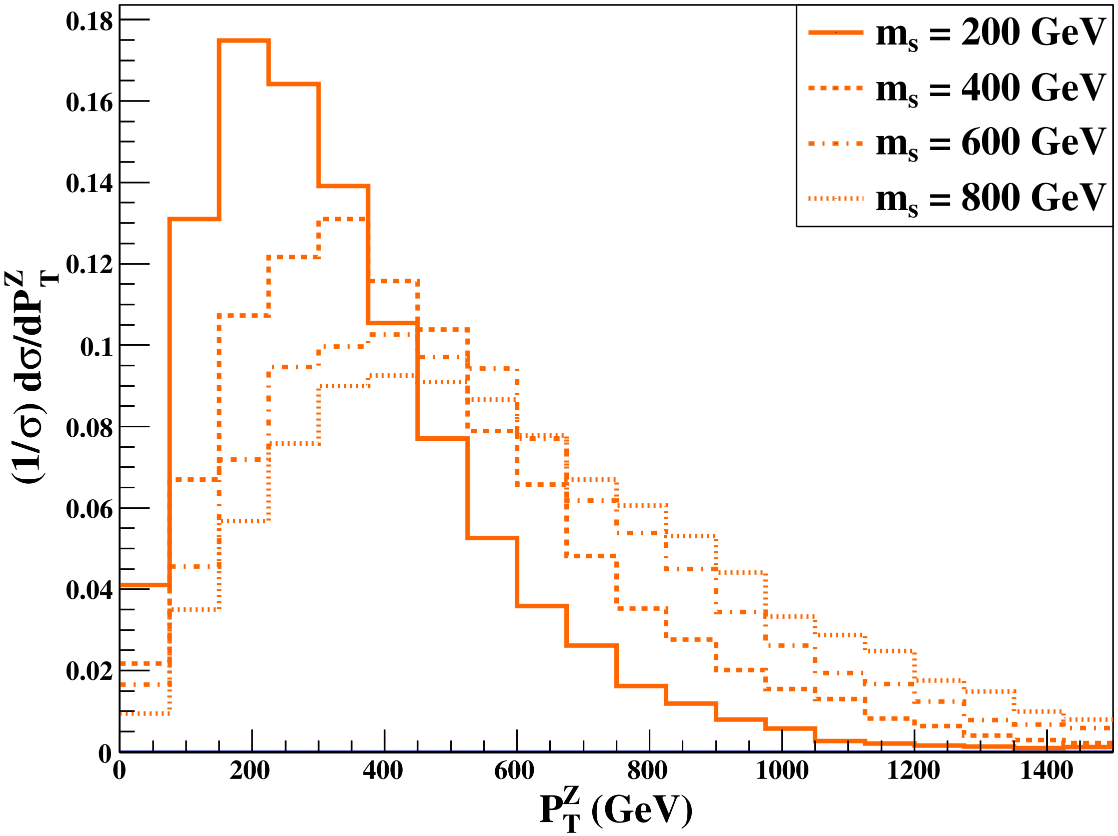




- Calculated for or c_i=2
- Scale as c_i^2

Collider signals: mono-Z differential distributions

Differential distributions for c_5 for different DM masses.



Linear siblings

$d=6$	$d=8$
$b \longrightarrow \mathcal{O}_b \equiv (\Phi^\dagger\Phi)^2 S^2$	$\mathcal{A}_3 \longrightarrow \mathcal{O}_3 \equiv (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi) S^2$
$\mathcal{A}_1 \longrightarrow \mathcal{O}_1 \equiv D_\mu \Phi^\dagger D^\mu \Phi \, S^2$	$\mathcal{A}_5 \longrightarrow \mathcal{O}_5 \equiv (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) D^\mu \left(\Phi^\dagger \Phi\right) S^2$
$\mathcal{A}_2 \longrightarrow \mathcal{O}_2 \equiv \Box \left(\Phi^\dagger \Phi\right) S^2$	
$\mathcal{A}_4 \longrightarrow \mathcal{O}_4 \equiv (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) D^\mu S^2$	

The linear could mimic, if:

$$c_i^L \frac{v^2}{\Lambda_{DM}^2} = c_i \qquad \text{for} \quad i = 1, 2, 4 \,, \qquad\qquad c_i^L \frac{v^4}{\Lambda_{DM}^4} = c_i \qquad \text{for} \quad i = 3, 5$$