The spin 0 window to New Physics

Rocío del Rey Bajo

UAM-IFT Madrid

Based on

Non-linear Higgs portal with a dynamical Higgs (1511.01099)

ALPs at colliders with a dynamical Higgs (to appear soon)

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

(Pseudo)scalars are interesting to study

The nature of Dark Matter
is unknown

↓

May be a singlet scalar

$$S$$

Studied in the Higgs portal [*].

The strong CP problem

Why is the
QCD theta parameter
small?

↓

A dynamical solution:

$$a$$

the axion [**]

[*] Silveira, Zee Phys.Lett.B161 136 // Patt, Wilczek hep-ph/0605188 (& many more…)
[**] Peccei, Quinn PRL 38 (1977) 1440-1443

Specially those we already know...

Electroweak hierarchy problem

Why is the Higgs light?

↓

GB origin for the **Higgs** ?

eg.Composite Higgs models

General approach

with effective Lagrangians

Nature of h particle

The Higgs may not behave as an exact SU(2) doublet at low energies.

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

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 at low energies.

treated independently

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

eg. using chiral Lagrangians

In effective Lagrangians:
we use a polynomial expansion

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

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

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

Dimensionless matrix of the GBs ($W^{\pm}_L$ and Z_L)

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

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

Appelquist, Bernard (1980) // Longhitano (1981)

Nature of h particle

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

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

Less assumptions about origin of h(x)
$\Rightarrow$ **U** and *h(x)* independent
$\Rightarrow$ ***More operators + decorrelations***

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

Appelquist, Bernard (1980) // Longhitano (1981)

Non-linear effective Lagrangian:

Effective Theory approach: $$\mathcal{L} = \mathcal{L}_0^{a,S} + \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{A}_i$$

Building blocks:

- ✓ Physical Higgs: $\mathcal{F}(h)$
- ✓ Gauge bosons:

in unitary gauge:

$$\left.\begin{aligned} \mathbf{T} &= \mathbf{U}\sigma^3\mathbf{U}^\dagger \\ \mathbf{V}_\mu &= (D_\mu \mathbf{U})\mathbf{U}^\dagger \end{aligned}\right\} \quad \begin{aligned} \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) &\longrightarrow igZ_\mu \\ \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu) &\longrightarrow (gv)^2(Z_\mu Z_\nu + W^+_{\{\mu}W^-_{\nu\}}) \end{aligned}$$

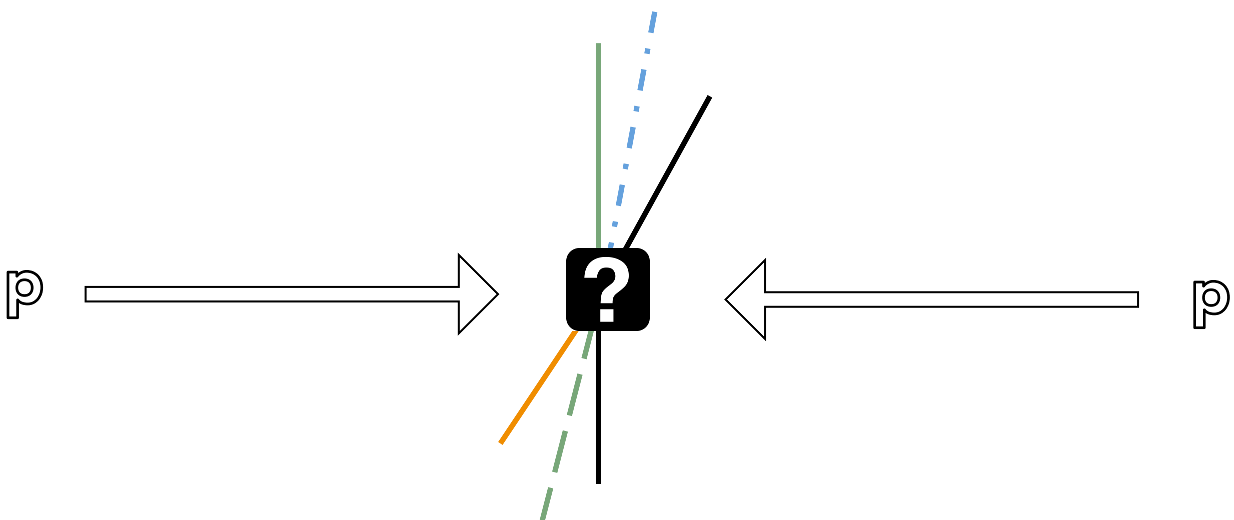
Non-linear effective Lagrangian:

✓ New

- scalar $S \xrightarrow{Z_2 \text{ for stability}} S^2$

OR

- pseudoscalar $a \xrightarrow{\text{Goldstone Boson}} \dfrac{\partial_\mu a}{f_a}$



mono-h

mono-W

mono-Z

Non-linear effective Lagrangian:

✓ New

scalar $\quad S \xrightarrow{Z_2 \text{ for stability}} S^2$

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pseudoscalar $\quad a \xrightarrow{\text{Goldstone Boson}} \dfrac{\partial_\mu a}{f_a}$

mono-h

mono-W

mono-Z

Scalar Dark Matter: leading order CP-even

Brivio et al. 1511.01099

S

$$\mathcal{L}_S = \underbrace{\frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2} S^2 - \lambda_S S^2 \left(2vh + bh^2\right)}_{\text{Standard Higgs portal (b=1)}} + \sum_{i=1}^{5} d_i \mathbf{O}_i(h)$$

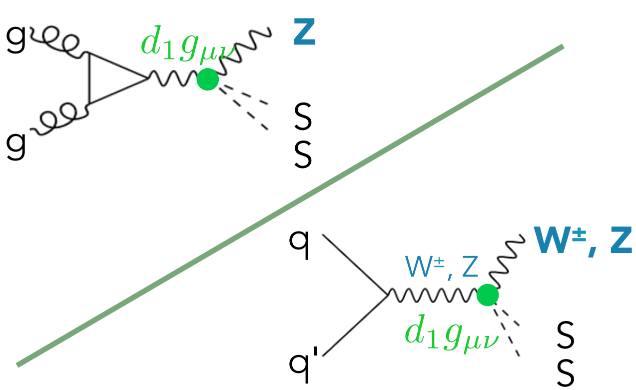
$$\mathbf{O}_1 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) S^2 \mathcal{F}_1(h) \qquad \mathbf{O}_2 = S^2 \Box \mathcal{F}_2(h) \qquad \mathbf{O}_3 = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) S^2 \mathcal{F}_3(h)$$

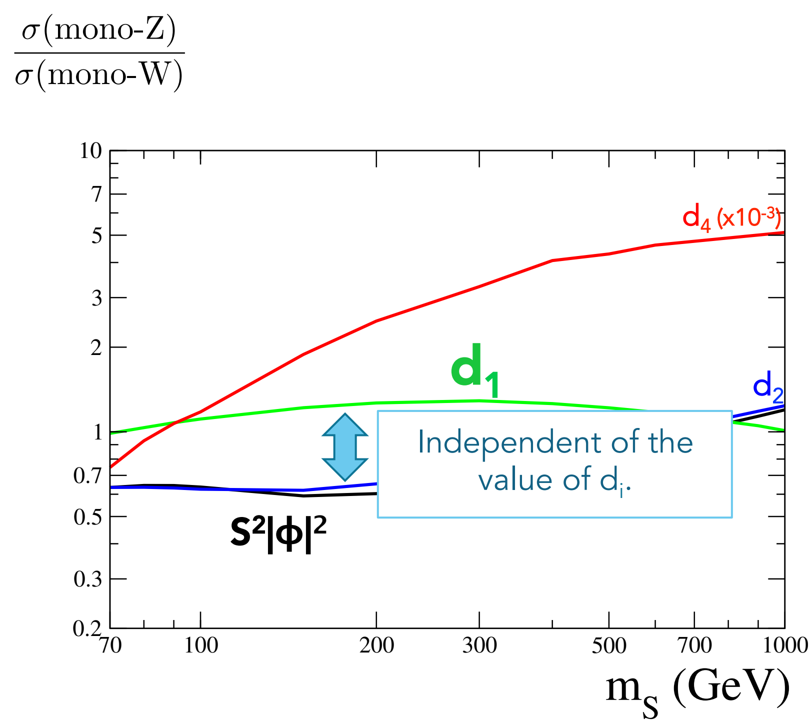
mono-Z vs. mono-W

S

$$\mathcal{O}_i = \mathrm{Tr}\left(\mathbf{V}^{\mu}\mathbf{V}_{\mu}\right) S^2 \mathcal{F}_1(h) \longrightarrow$$

New leading order
$S^2W^+W^-$ and **S^2Z^2** couplings!





One operator at a time:

$\sigma(\text{mono-X}) \sim d_i^2, \lambda_S^2$

mono-Z vs. mono-W

S

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

New leading order
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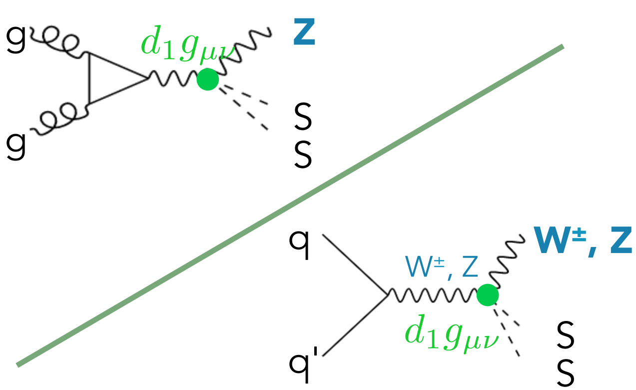

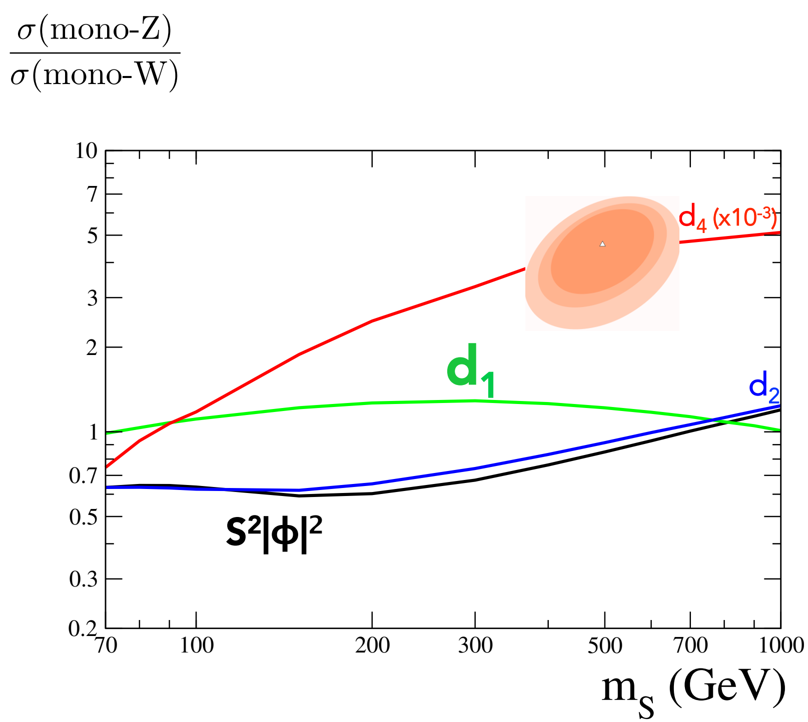

Strategy to disentangle from $S^2|\phi|^2$:

Say we were to measure:

- the ratio mono-Z/mono-W
- m_S from p_T (E_T^{miss}) distributions

+ More signals in DM relic density, Γ(h->inv.) and direct detection.

Brivio et al. 1511.01099

Non-linear effective Lagrangian:

✓ New

scalar S $\xrightarrow{Z_2 \text{ for stability}}$ S^2

OR

pseudoscalar a $\xrightarrow{\text{Goldstone Boson}}$ $\dfrac{\partial_\mu a}{f_a}$

Axion-Like Particle

ALP

Brivio et al. (To appear soon!)

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D} i f^2 \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\mathcal{F}_{2D}(h) \qquad + \sum_i c_i \mathcal{A}_i$$

+ NLO:

$$\mathcal{A}_{\tilde{X}} = -X_{\mu\nu}\tilde{X}^{\mu\nu}\frac{a}{f_a} \text{ for } X = B,\, W,\, G$$

$$\mathcal{A}_1(h) = \frac{i}{4\pi}\tilde{B}_{\mu\nu}\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_1(h)$$

$$\mathcal{A}_2(h) = \frac{i}{4\pi}\mathrm{Tr}[\tilde{W}_{\mu\nu}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_2(h)$$

$$\mathcal{A}_3(h) = \frac{1}{4\pi}B_{\mu\nu}\partial^\mu \frac{a}{f_a}\partial^\nu\,\mathcal{F}_3(h)$$

$$\mathcal{A}_4(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}_\nu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_4(h)$$

$$\mathcal{A}_5(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{V}_\mu\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\nu]\partial_\nu \frac{a}{f_a}\,\mathcal{F}_5(h)$$

$$\mathcal{A}_6(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}[W_{\mu\nu},\mathbf{V}^\mu]]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_6(h)$$

$$\mathcal{A}_7(h) = \frac{i}{4\pi}\mathrm{Tr}[\mathbf{T}\tilde{W}_{\mu\nu}]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_7(h)$$

$$\mathcal{A}_8(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[[\mathbf{V}_\nu,\mathbf{T}]\mathcal{D}_\mu\mathbf{V}^\mu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_8(h)$$

$$\mathcal{A}_9(h) = \frac{i}{(4\pi)^2}\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}^\mu]\mathrm{Tr}[\mathbf{T}\mathbf{V}_\nu]\partial^\nu \frac{a}{f_a}\,\mathcal{F}_9(h)$$

$$\mathcal{A}_{10}(h) = \frac{1}{4\pi}\mathrm{Tr}[\mathbf{T}W_{\mu\nu}]\partial^\mu \frac{a}{f_a}\partial^\nu\,\mathcal{F}_{10}(h)$$

$$\mathcal{A}_{11}(h) = \frac{i}{(4\pi)^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\Box\frac{a}{f_a}\partial^\mu\,\mathcal{F}_{11}(h)$$

$$\mathcal{A}_{12}(h) = \frac{i}{16\pi^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu\partial^\nu \frac{a}{f_a}\partial_\nu\,\mathcal{F}_{12}(h)$$

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$$\mathcal{A}_{14}(h) = \frac{i}{16\pi^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu \frac{a}{f_a}\partial^\mu\partial^\nu\,\mathcal{F}_{14}(h)$$

$$\mathcal{A}_{15}(h) = \frac{i}{16\pi^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\partial_\nu\,\mathcal{F}_{15}(h)\partial^\nu\,\mathcal{F}'_{15}$$

$$\mathcal{A}_{16}(h) = \frac{i}{16\pi^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial_\nu \frac{a}{f_a}\partial^\mu\,\mathcal{F}_{16}(h)\partial^\nu\,\mathcal{F}'_{16}$$

$$\mathcal{A}_{17}(h) = \frac{i}{16\pi^2}\,\mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{\Box a}{f_a}\,\mathcal{F}_{17}(h)\,.$$

Momentum tails: mono-h

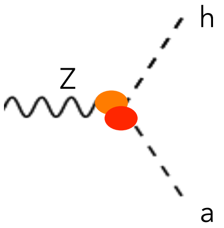
Brivio et al. (To appear soon!)

ALP

Goldstone boson => derivative couplings

$$\mathcal{A}_3 = \frac{1}{4\pi} B_{\mu\nu} \partial^\mu \frac{a}{f_a} \partial^\nu \mathcal{F}_3(h)$$

$$\mathcal{A}_{2D} = i f^2 \mathrm{Tr}\left(\mathbf{TV}_\mu\right) \partial^\mu \frac{a}{f_a} \mathcal{F}_{2D}(h)$$



$$v^2 c_{2D} p_a + c_3 p_Z^2 p_a$$

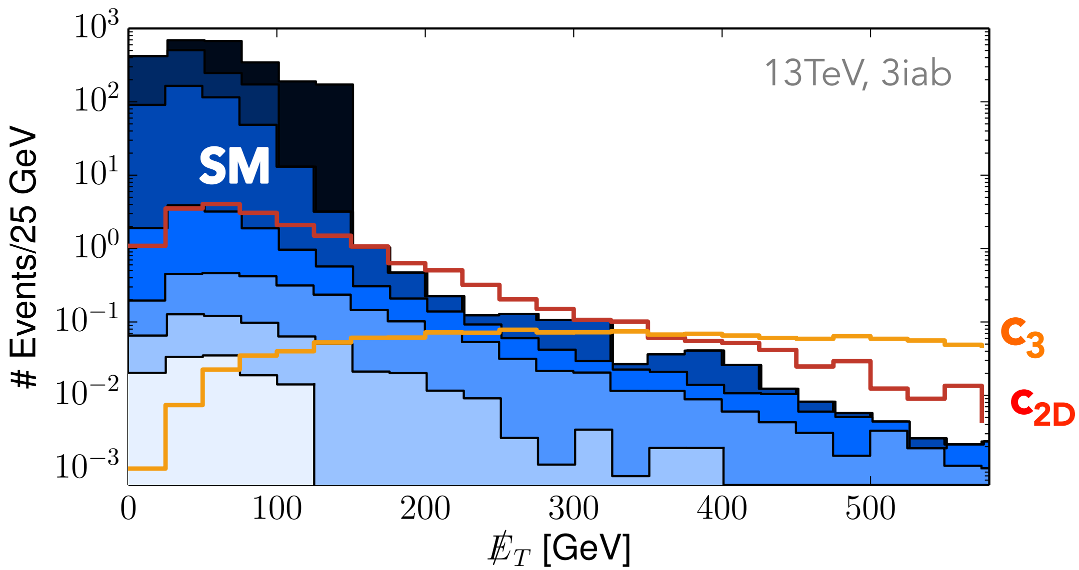
New at leading order!!

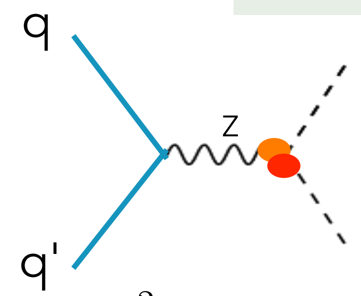
Momentum tails: mono-h

Brivio et al. (To appear soon!)

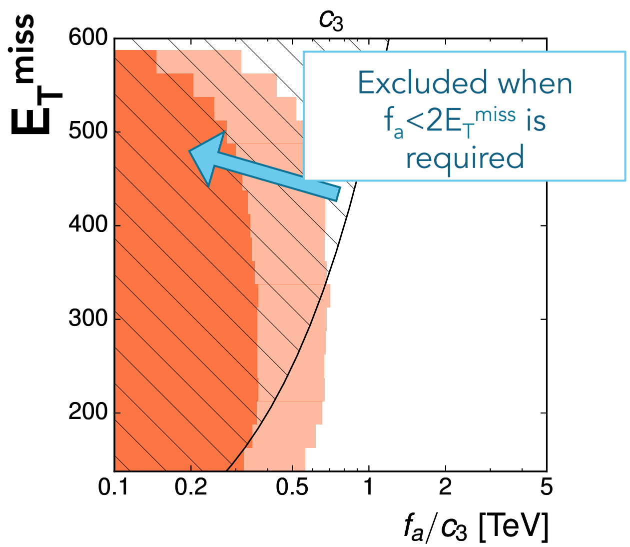
ALP

Mono-Higgs: pp -> h + missing energy





$$v^2 c_{2D} p_a + c_3 p_Z^2 p_a$$



When contrasted with validity of EFT:

2σ/5σ will be testable for f_a/c_3~**700/300** GeV

BGs from Les Houches 2015: Physics at TeV colliders [arXiv:1605.02684]

Conclusions

The Higgs discovery opened the door to fundamental scalars motivated by SM unknowns.

Effective Lagrangians allow to study EWSB scenarios with a GB origin for the Higgs in a model independent way.

Adding a (pseudo)scalar gives rise to very rich phenomenology:

New couplings at renormalisable level

$\Rightarrow$ In particular GB: mono-h @ LO Harder momentum tails!

Independence of operators

$\Rightarrow$ Independence of signals: mono-Z & mono-W

in different proportion Their ratio may be a smoking gun!

Thank you for your attention!

Backup Slides

CP even leading order bases

2 different bases:

Brivio et al. 1511.01099

S

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S^2}{2}S^2 - \lambda_S S^2\left(2vh + bh^2\right) + \sum_{i=1}^{5} d_i \mathbf{O}_i(h)$$

$$\mathbf{O}_1 = \mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) S^2 \mathcal{F}_1(h) \qquad \mathbf{O}_2 = S^2 \Box \mathcal{F}_2(h) \qquad \mathbf{O}_3 = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) S^2 \mathcal{F}_3(h)$$

+ CP odd: $\mathbf{O}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)(\partial^\mu S^2)\mathcal{F}_4(h)$ $\quad \mathbf{O}_5 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) S^2 \partial^\mu \mathcal{F}_5(h)$

ALP

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + c_{2D} i f^2 \mathrm{Tr}[\mathbf{T}\mathbf{V}_\mu]\partial^\mu \frac{a}{f_a}\mathcal{F}_{2D}(h) \quad + \sum_i c_i \mathcal{A}_i$$

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Brivio et al. (To appear soon!)

SM portals to dark sectors

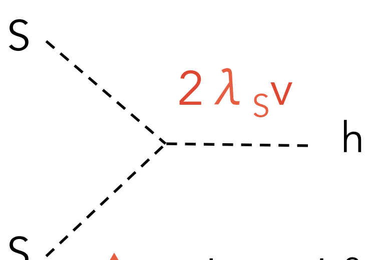
Silveira, Zee Phys.Lett.B161 136
Patt, Wilczek hep-ph/0605188
and many more…

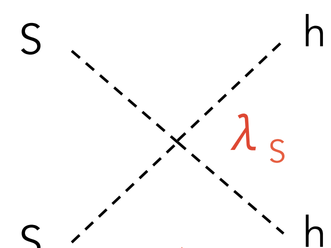
Standard portal to DM

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

doublet structure

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





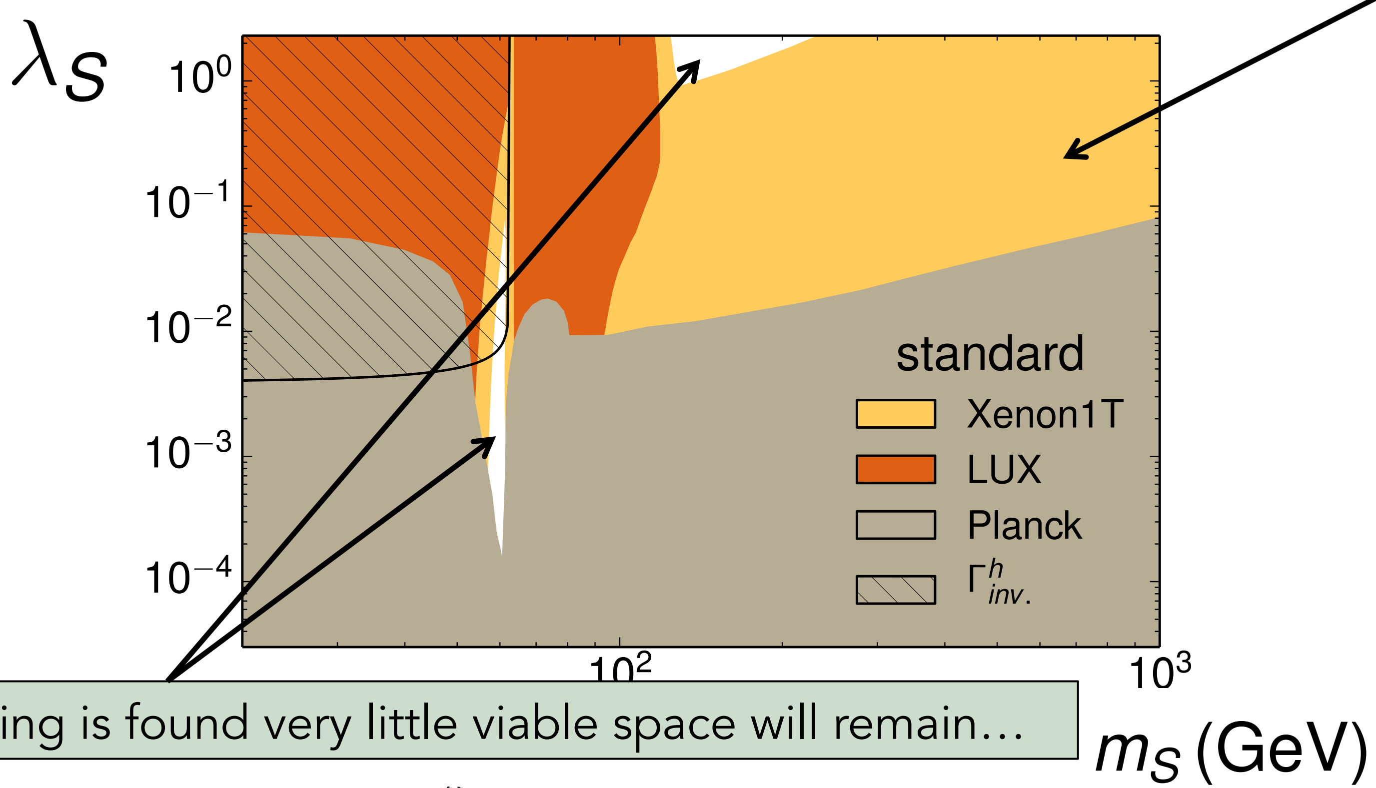
h vs. h^2 couplings correlated

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

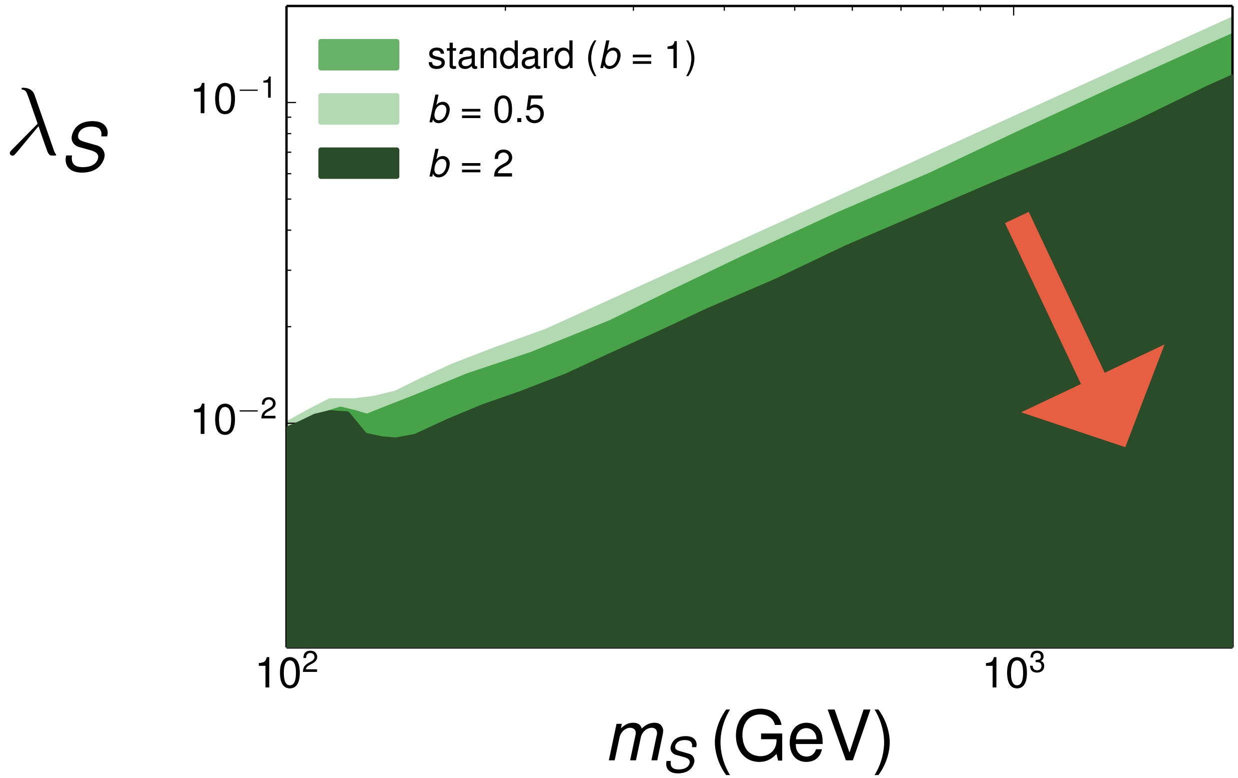
Direct detection (LUX)

Γ(h→*inv.*)

Projected reach of Xenon1T

Non-linear H portal to DM

Brivio et al. 1511.01099

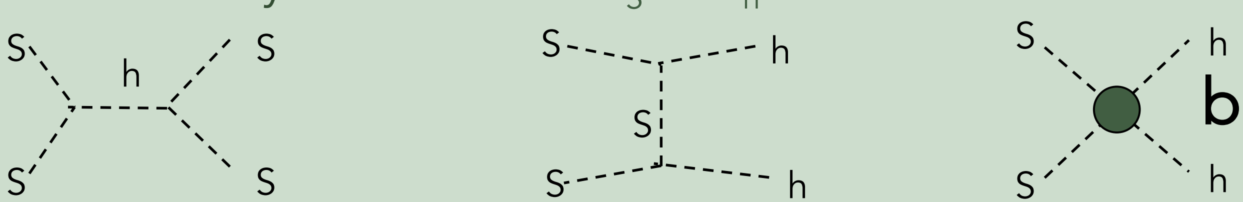


Excluded by relic density

$\Omega_S \leq \Omega_{DM} \simeq 0.12$

… but there's more to it!

Main DM decay channels for $m_S > m_h$



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:

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

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

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

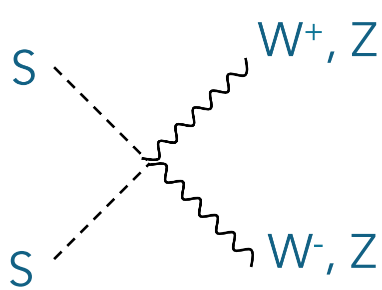
$$\mathcal{A}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\partial^\mu S^2 \mathcal{F}_4(h)$$

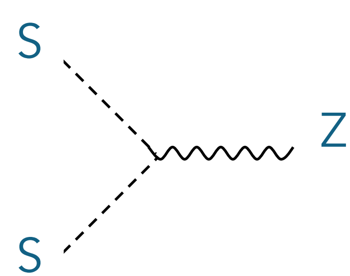
$$\mathcal{A}_5 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) S^2 \partial^\mu \mathcal{F}_5(h)$$

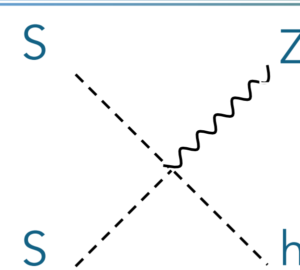
$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger$	$\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu) \longrightarrow ig\, Z_\mu$
$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger$	$\mathrm{Tr}(\mathbf{V}_\mu \mathbf{V}_\nu) \longrightarrow (gv)^2\,(Z_\mu Z_\nu + W_\mu^+ W_\nu^-)$

New couplings!

phenomenological consequences?



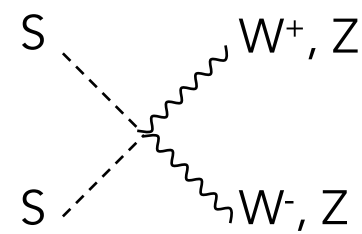


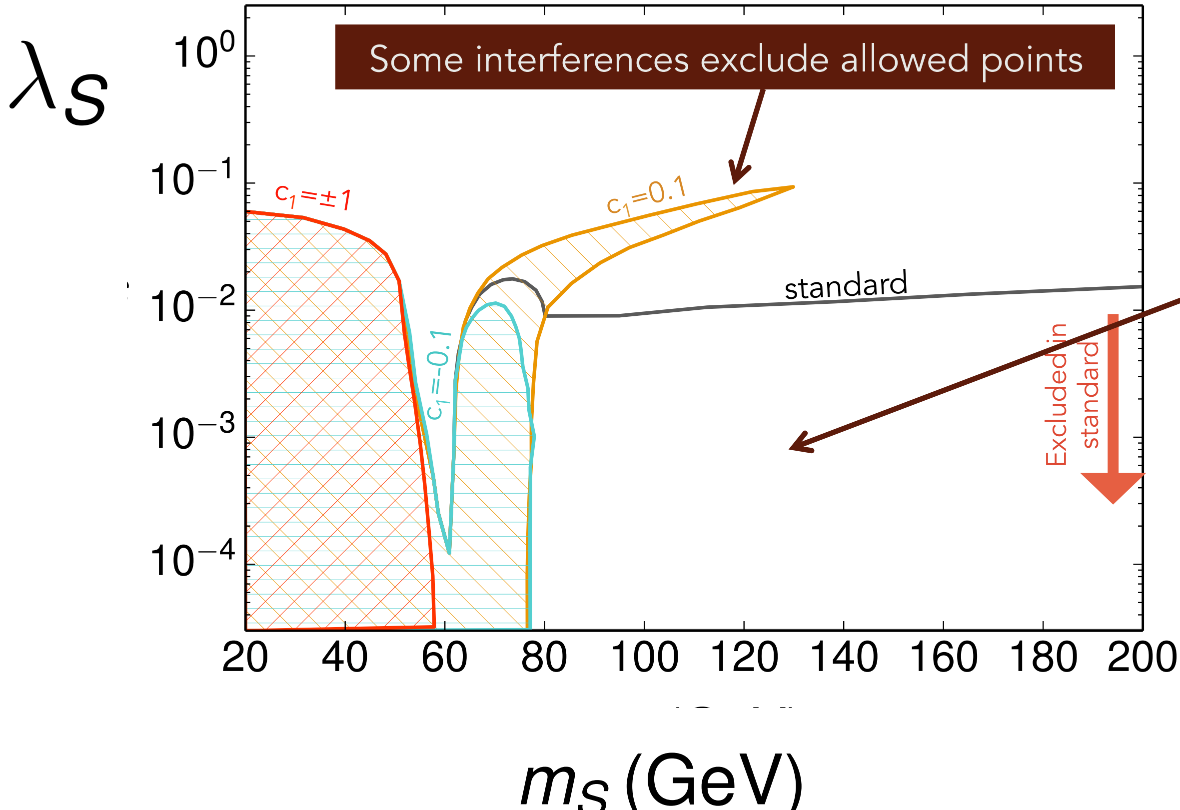


Impact on relic density

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

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





More decay channels
$\Rightarrow$ Lower Ω_S
$\Rightarrow$ Larger allowed region

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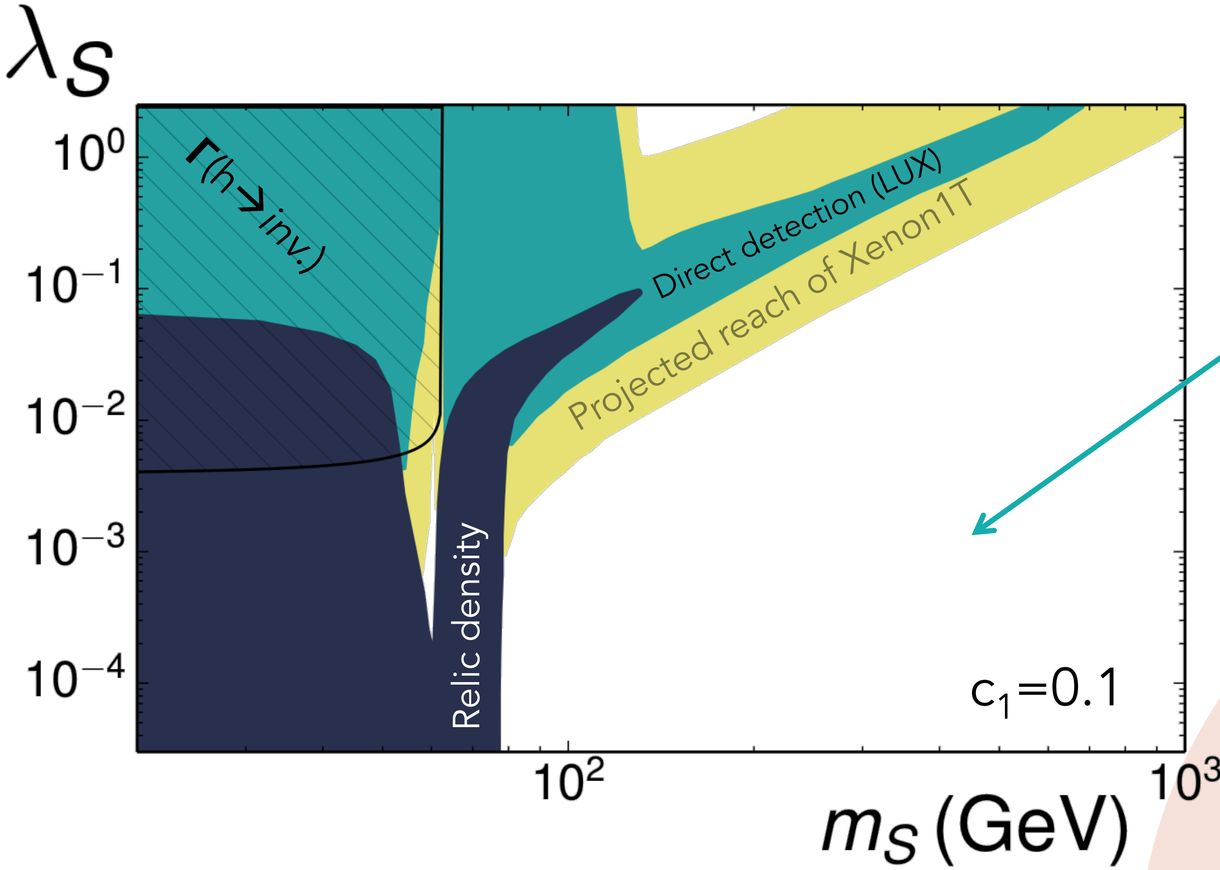
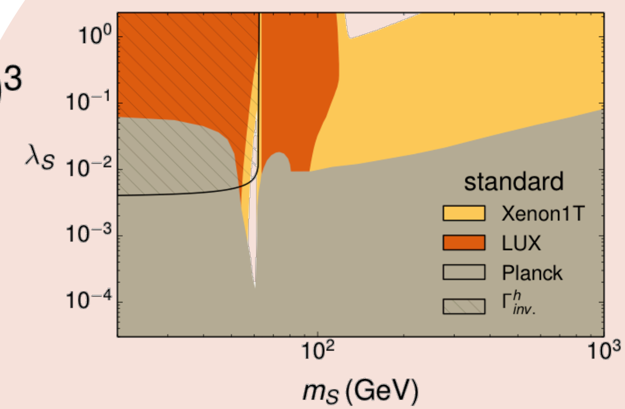
Non-Linear portal: Summary



The portal is wide open!

…to be compared with:

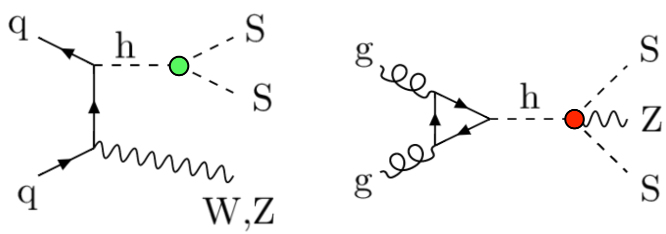


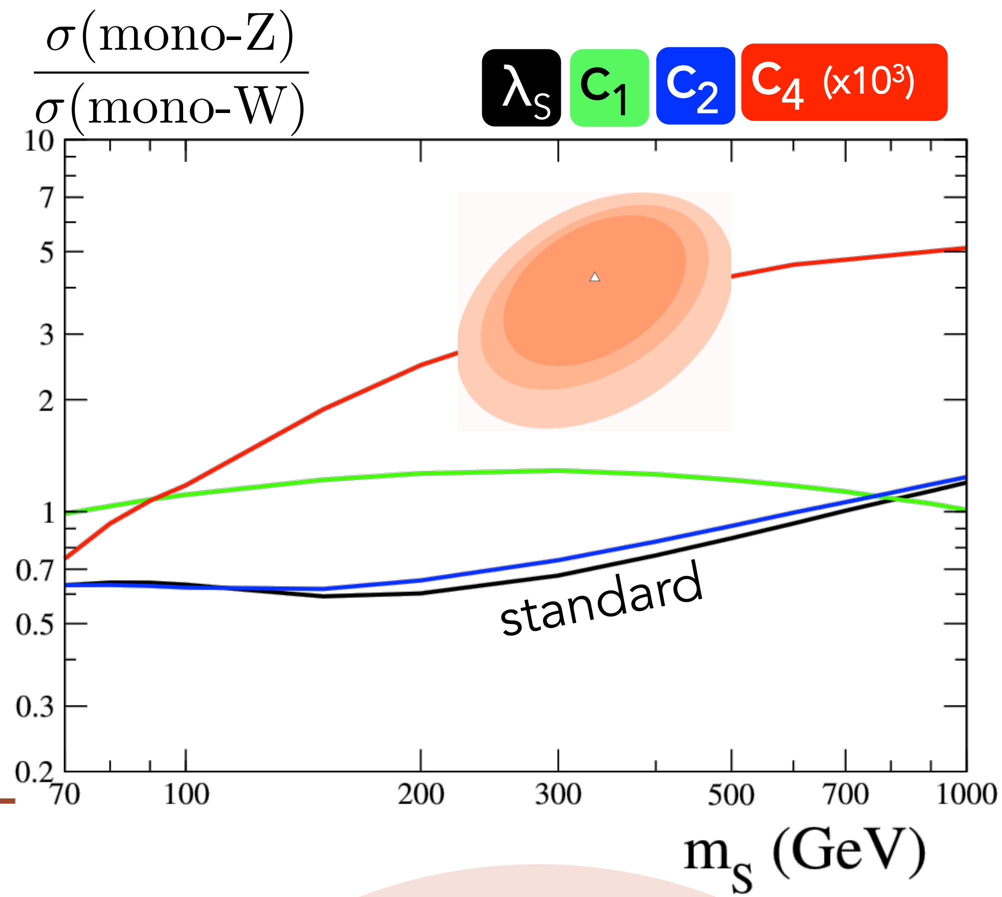
Standard portal

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

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

$\Rightarrow$ 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!

Complete Lagrangian

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

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

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

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

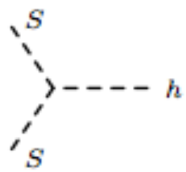
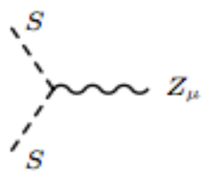
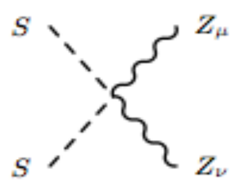
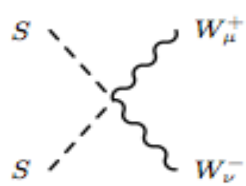
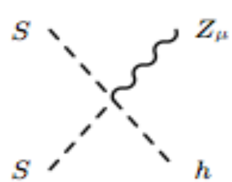
$$\mathcal{A}_2 = S^2\Box\mathcal{F}_2(h)$$

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

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

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

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		b	c_1	c_2	c_3	c_4	c_5
		Parameters contributing					
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

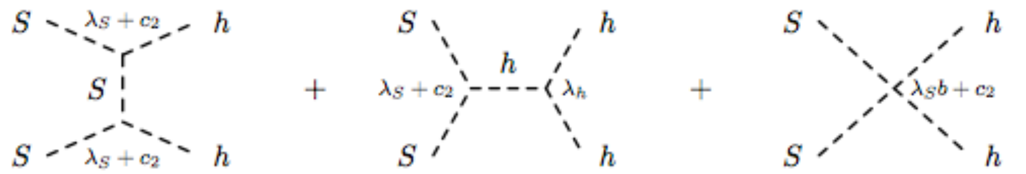
- relevant for $m_S \lesssim m_h/2$
- BR(h->inv.) ≤ 0.23

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

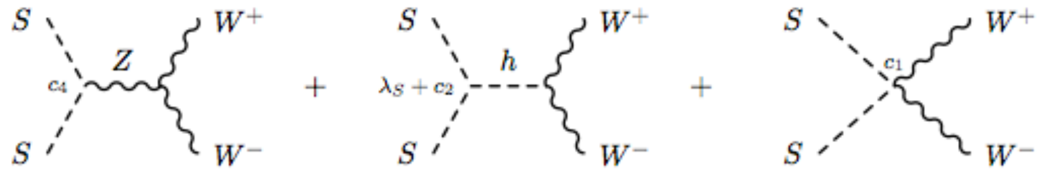
Thermal relic density

- 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 $\boldsymbol{\alpha_s}$**(SS** $\longrightarrow$ **XX)**

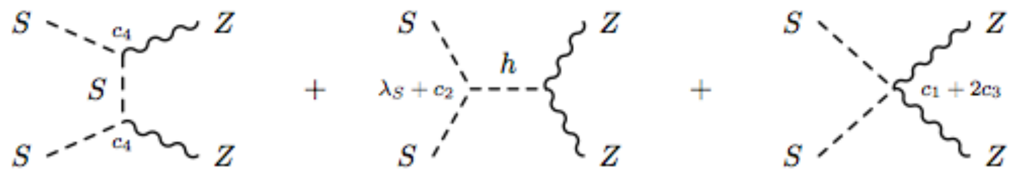
Decay diagrams



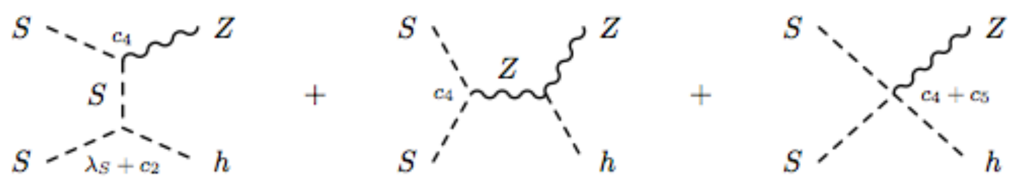
(a) Dark Matter annihilation to Higgs bosons.



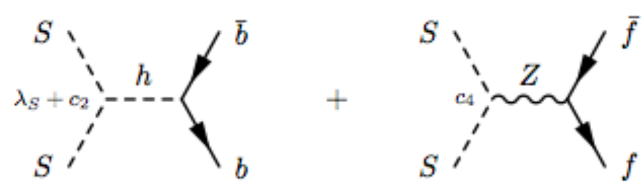
(b) Dark Matter annihilation to W bosons.



(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:

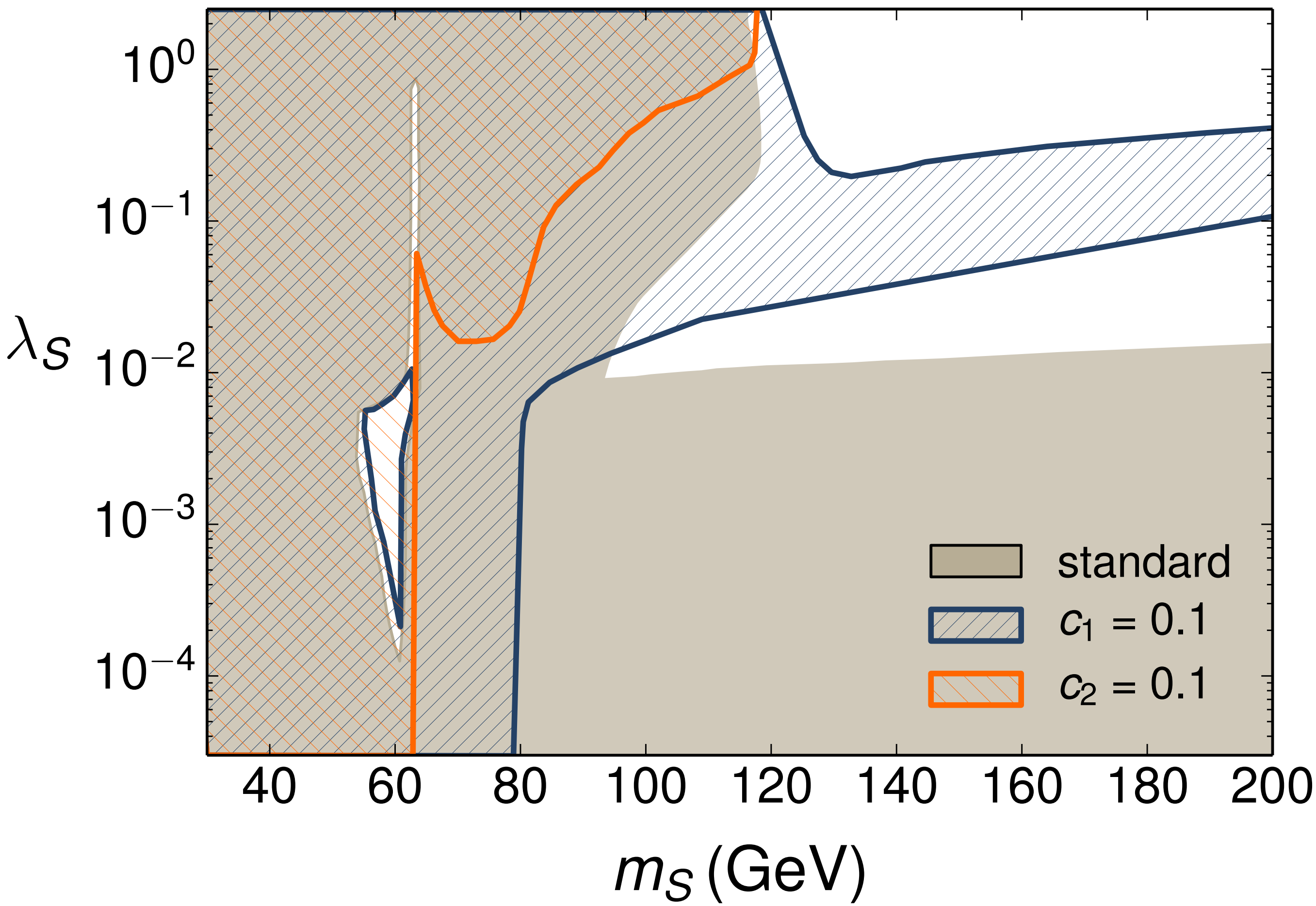
$$\overline{\psi}_L \mathbf{U} \psi_R S^2 \mathcal{F}(h) \qquad \text{and} \qquad \overline{\psi}_{L,R} \gamma_\mu \psi_{L,R}\, \partial^\mu S^2\, \mathcal{F}(h)$$

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

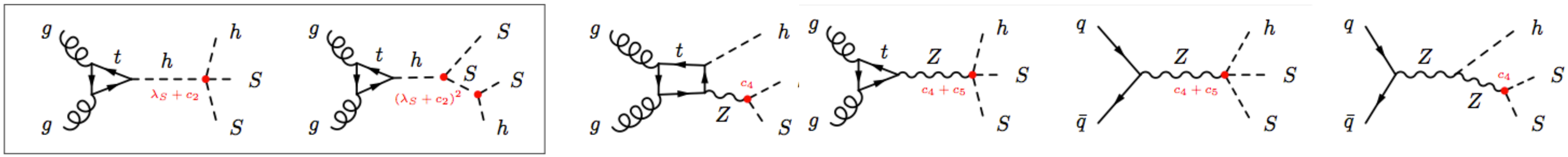
$$\mathcal{A}_4 = i\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\partial^\mu \mathcal{F}(h) \longrightarrow 4 \sum_{i=L,R} \overline{\psi}_i \mathcal{Y}_i \gamma_\mu \psi_i \partial^\mu S^2$$

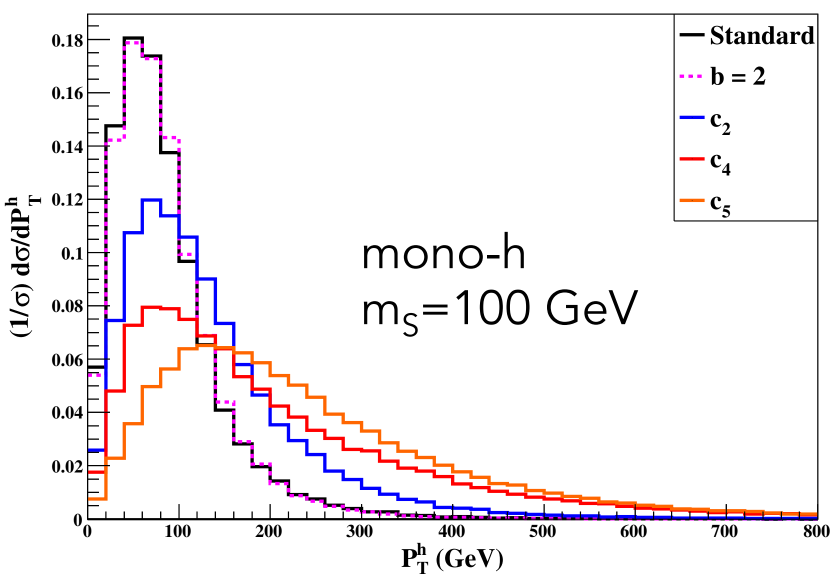
$$\mathcal{A}_2 = S^2 \Box \mathcal{F}(h) \longrightarrow \mathcal{A}_1 + S^2(\overline{\psi}_L \mathbf{U}\mathbf{Y} \psi_R + \mathrm{h.c.})$$

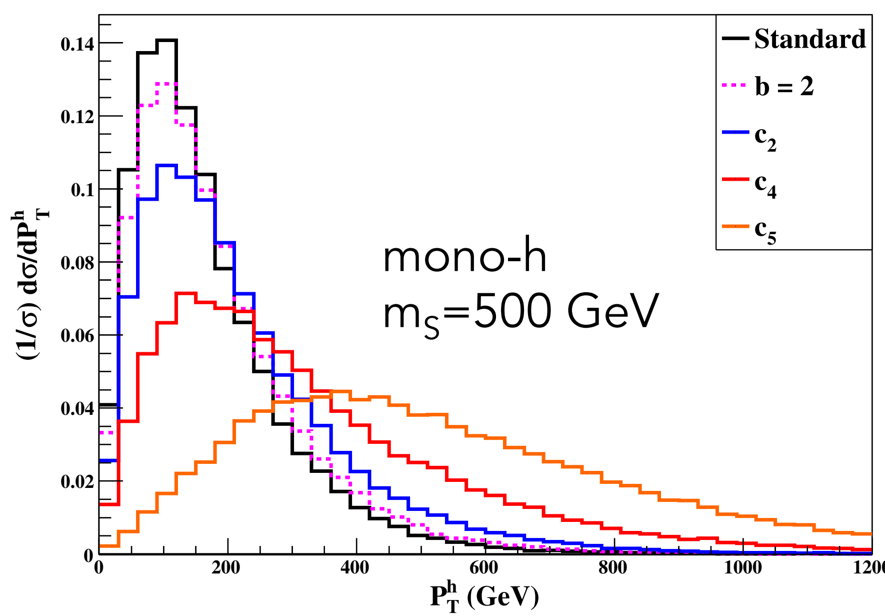
Summary plot (standard vs. non-linear)



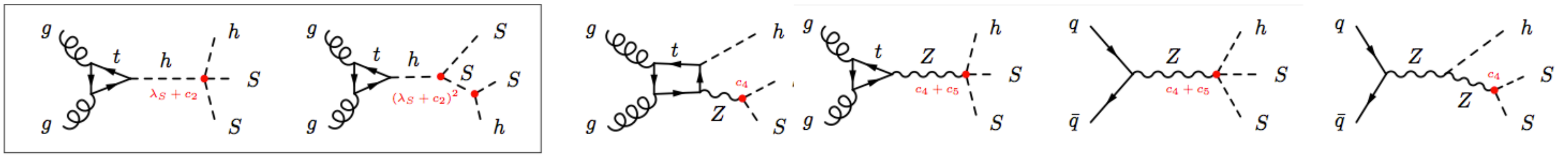
Collider signals: mono-h differential distributions

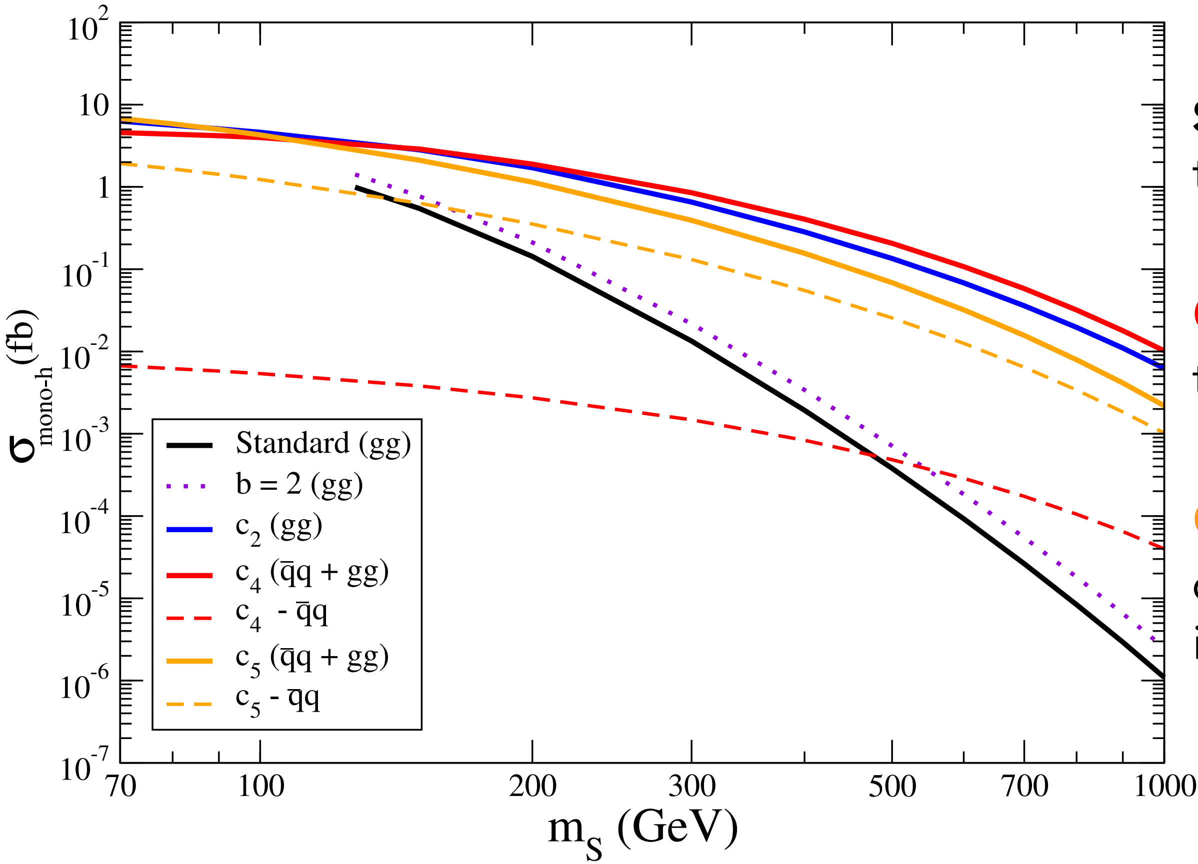






Collider signals: mono-h





standard: drops fast due to gluon pdf

c_2: large enhancement due to momentum dependence

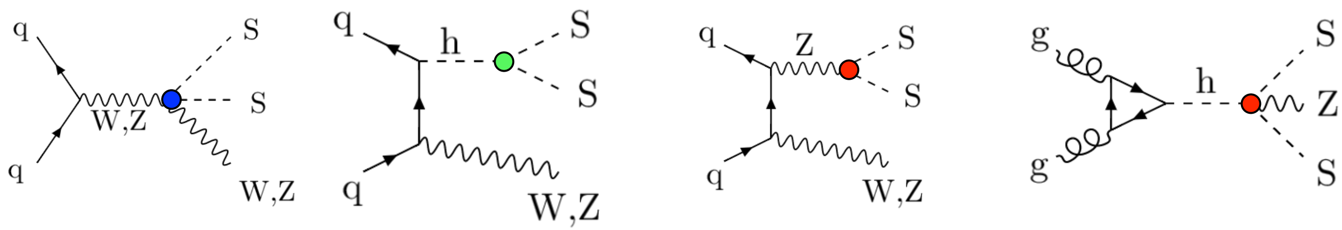
c_5: momentum dependence & q-qbar initiation

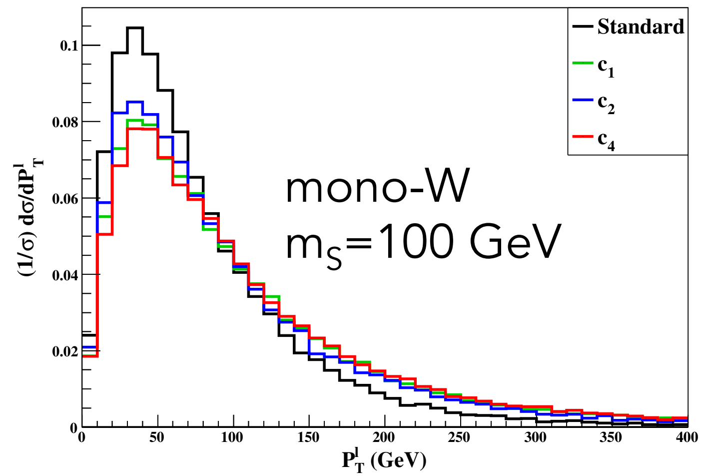
- Calculated for or c_i=2
- Scale as c_i^2

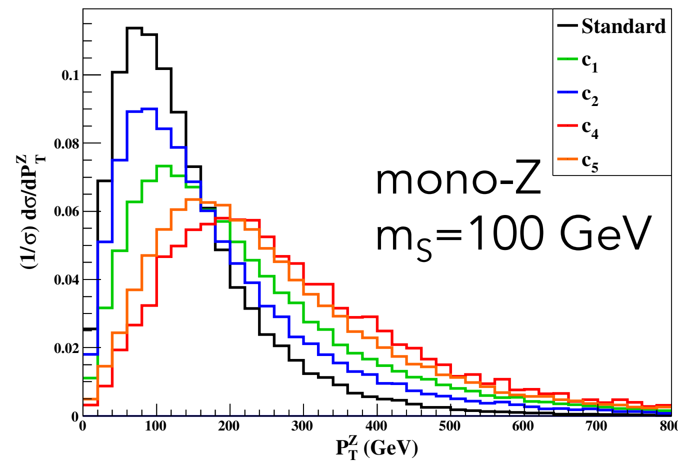
Collider signals: mono-V differential distributions

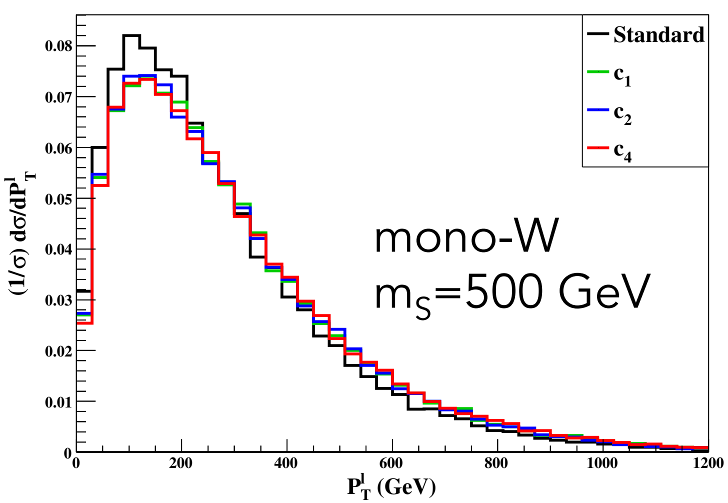
λ_S c_1 c_2 c_4 (x10^3)

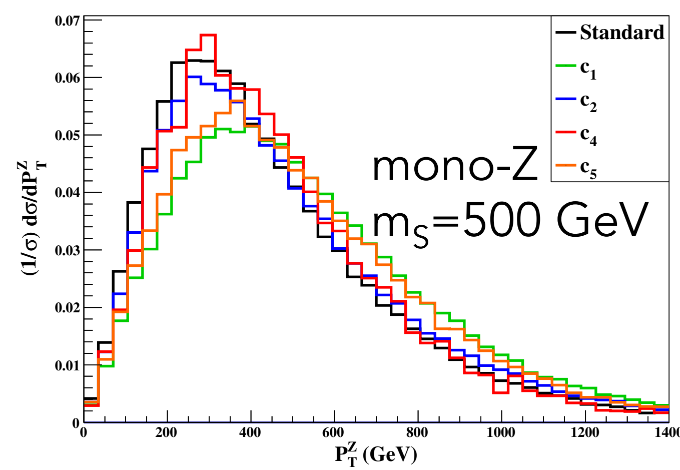
example diagrams mono-Z and mono-W:







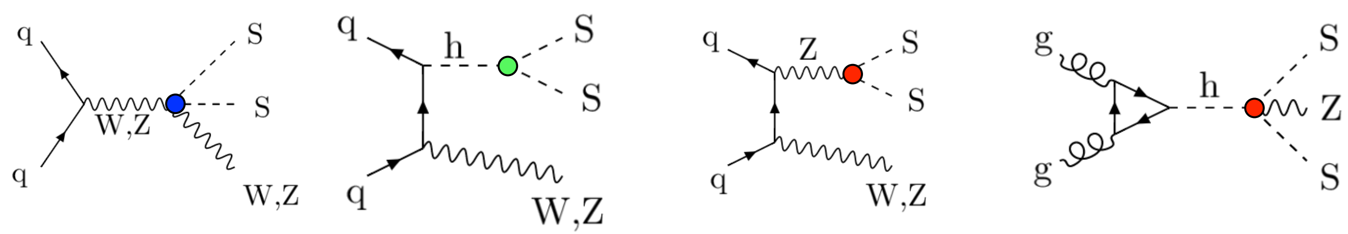


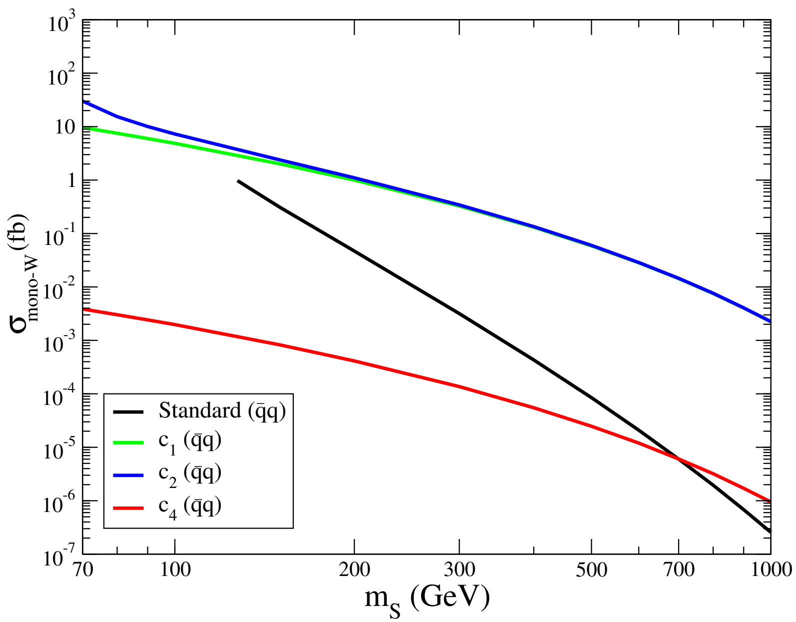


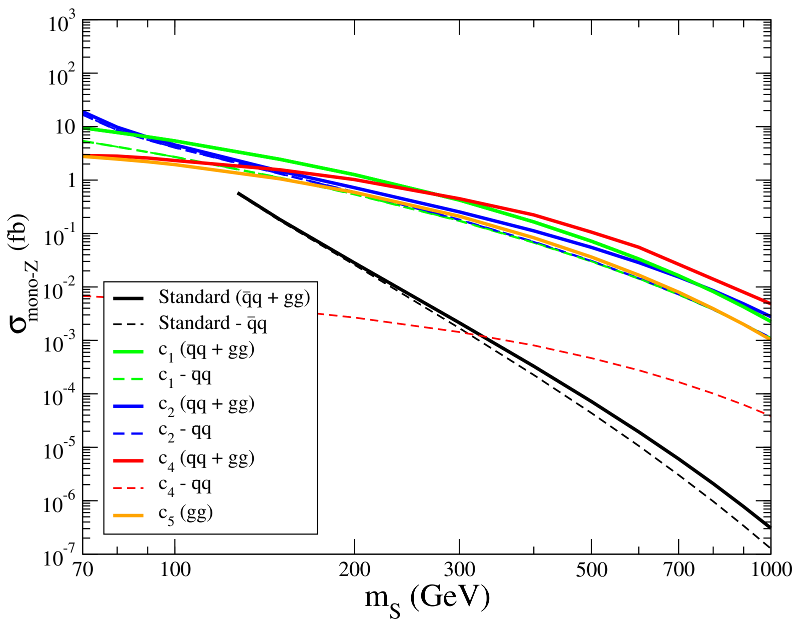
Collider signals: mono-V m_S scan

λ_S C_1 C_2 C_4 (x10^3)

example diagrams mono-Z and mono-W:



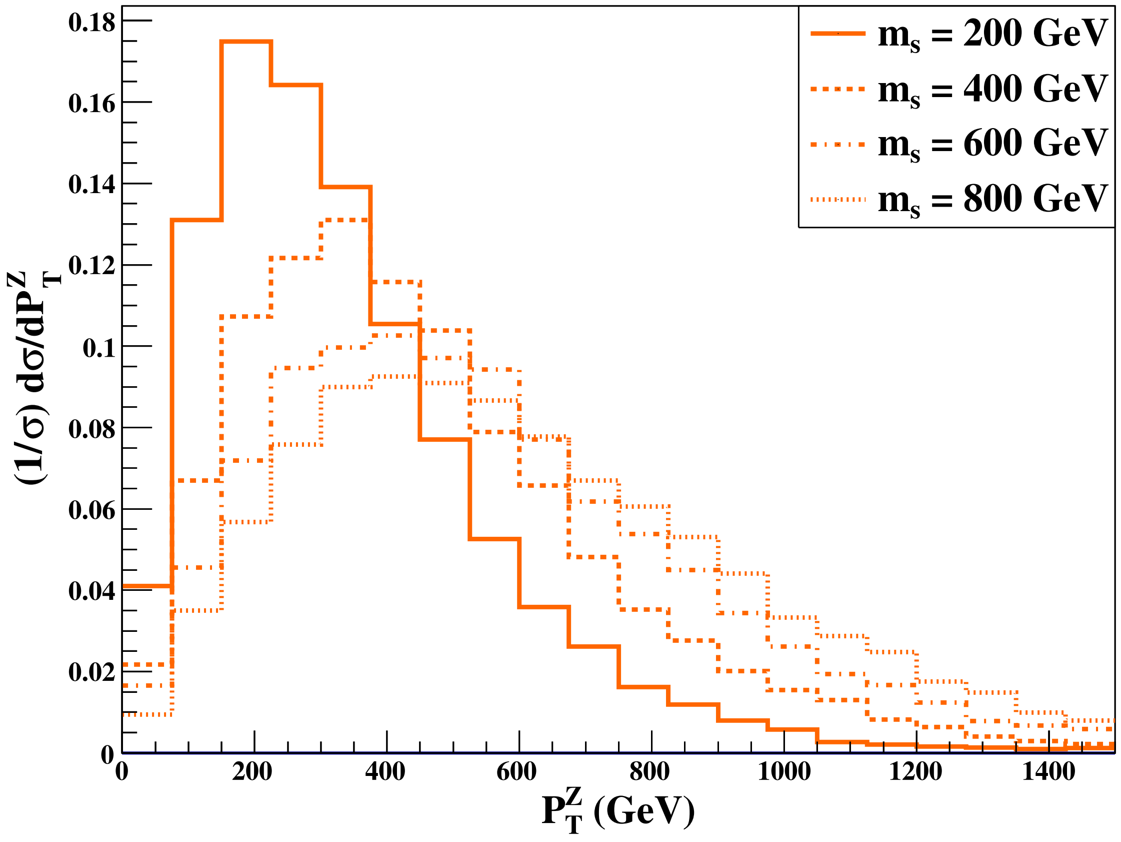




- Calculated for or c_i=2
- Scale as c_i^2

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:

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