A global view of the off-shell Higgs portal

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1910.04170 [SciPost] with Max Ruhdorfer and Andi Weiler + updates

This talk

- SM-singlet scalar ϕ coupled through a Higgs portal

$$\mathcal{L}_{\rm BSM} \supset -\frac{\lambda}{2}\,\phi^2 H^\dagger H \qquad \text{or} \qquad \mathcal{L}_{\rm BSM} \supset \frac{c_d}{2f^2}\,\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$$

- Assume ϕ is invisible on detector scales (stable or long-lived due to symmetry, or decays to invisible particles)

- Focus on $m_\phi > m_h/2 = 62.5\ \mathrm{GeV}$, where production goes through **off-shell** Higgs and the two portals give different kinematic distributions

- “Nightmare scenarios” for BSM physics. Well motivated, but generally difficult to test

[Ruhdorfer, Salvioni, Weiler 1910.04170]

BSM motivations/1

Renormalizable (or marginal) Higgs portal $\mathcal{L}_{\rm BSM} \supset -\frac{\lambda}{2}\phi^2 H^\dagger H$

- ϕ is DM (requires non-standard cosmology or extended models; minimal version ruled out by direct detection except above TeV or around Higgs resonance)

Huge literature. Recent review: [Arcadi, Djouadi, Raidal 1903.03616]

- ϕ is scalar top partner in neutral naturalness: SM singlet, but charged under hidden color. Effective coupling fixed to $\lambda = \sqrt{4N_c}\, y_t^2 \approx 3.4$

[Cheng, Li, Salvioni, Verhaaren 2018]
[Cohen, Craig, Giudice, McCullough 2018]

- Singlet assists a first-order electroweak phase transition. Large couplings are necessary

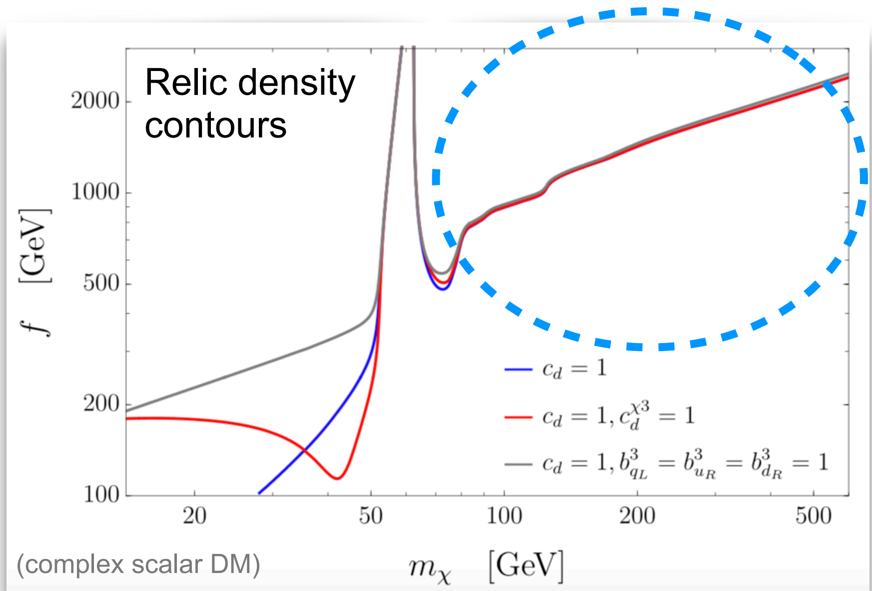
Again, huge literature. For collider tests e.g. [Curtin, Meade, Yu 2014]

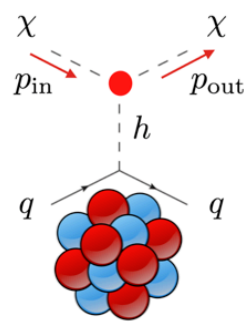
BSM motivations/2

Derivative Higgs portal $\mathcal{L}_{\rm BSM} \supset \frac{c_d}{2f^2}\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$

[Frigerio, Pomarol, Riva, Urbano 2012]

- ϕ is a pseudo-Goldstone WIMP. Operator mediates *s*-wave annihilation to SM, but DM - nucleus scattering is strongly suppressed by momentum transfer





$$\propto \frac{(p_{\rm in}-p_{\rm out})^2}{f^2} = \frac{q^2}{f^2} \sim \frac{m_\chi^2 v_{\rm DM}^2}{f^2} \sim 10^{-8}$$

$(v_{\rm DM} \sim 10^{-3})$

[Balkin, Ruhdorfer, Salvioni, Weiler 1809.09106]
[Ruhdorfer, Salvioni, Weiler 1910.04170]

- Colliders are crucial probe of this scenario

BSM motivations/2

Derivative Higgs portal $\mathcal{L}_{\rm BSM} \supset \frac{c_d}{2f^2}\,\partial_\mu(\phi^2)\partial^\mu(H^\dagger H)$

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e.g. $SO(6)/SO(5),\ SO(7)/SO(6),\ldots$

- Can arise in composite Higgs models with extended global symmetry patterns: both Higgs & DM as pNGBs with common decay constant f $\left(\frac{c_H}{c_d} \simeq 1\right)$

- Also realized by adding complex scalar to SM, with $U(1)$ broken by mass term

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |\partial_\mu S|^2 + \frac{\mu_S^2}{2}|S|^2 - \frac{\lambda_S}{2}|S|^4 - \lambda_{HS}|S|^2|H|^2 + \frac{\mu_S'^2}{4}(S^2 + {\rm h.c.})$$

integrate out radial mode ➡ identify ϕ with phase of S, and $\frac{c_d}{f^2} \simeq \frac{\lambda_{HS}}{\lambda_S v_S^2}$

$\left(\frac{c_H}{c_d} \simeq \frac{\lambda_{HS}}{\lambda_S}\right)$

[Barger et al. 2008, 2010]
[Gross, Lebedev, Toma 2017]

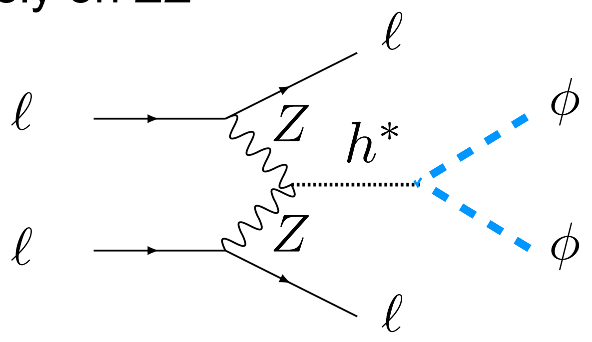
Invisible singlets at HELCs

- Focus on VBF, which dominates over Zh ass. prod. for $\sqrt{s} \gtrsim 1$ TeV
- *WW* fusion gives completely invisible final state, so rely on *ZZ*

$$\hat{\sigma}^{\text{deriv}}_{VV\to\phi\phi}(\hat{s}) = \frac{1}{32\pi}\frac{c_d^2\,\hat{s}}{f^4}\left(1-\frac{m_h^2}{\hat{s}}\right)^{-2}\left(1-\frac{4m_\phi^2}{\hat{s}}\right)^{1/2}$$

$$\hat{\sigma}^{\text{marg}}_{VV\to\phi\phi}(\hat{s}) = \frac{1}{32\pi}\frac{\lambda^2}{\hat{s}}\left(1-\frac{m_h^2}{\hat{s}}\right)^{-2}\left(1-\frac{4m_\phi^2}{\hat{s}}\right)^{1/2}$$

$(\hat{s} \gg m_V^2)$



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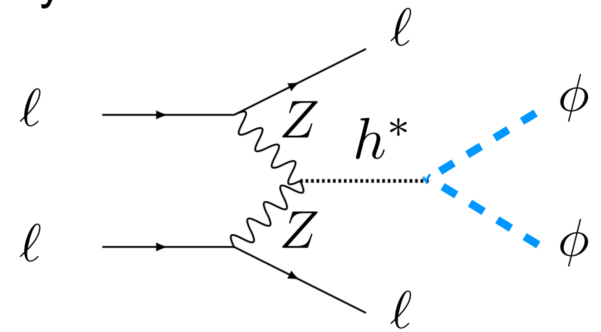
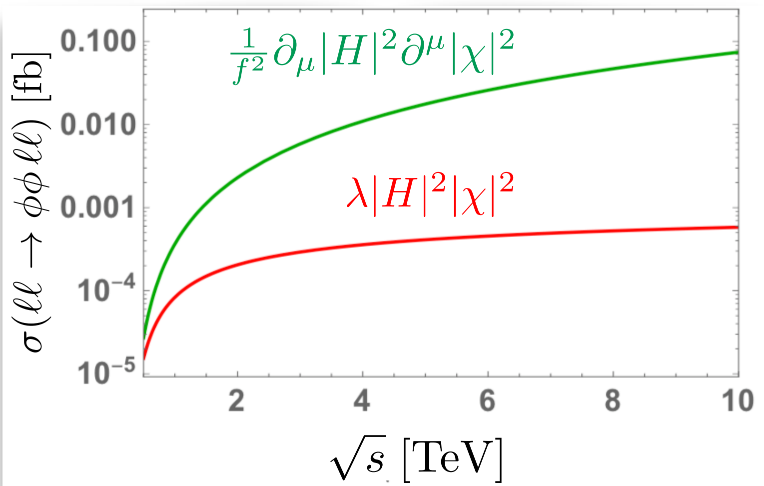


- After integration over parton luminosity

very different scaling with s and m_ϕ

[Buttazzo et al. 2018]
[Chacko, Cui, Hong 2013]
[Kanemura et al. 2011]

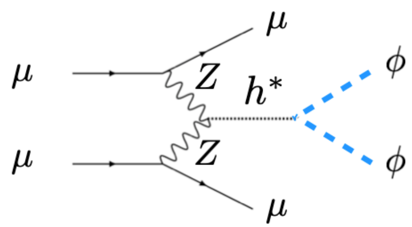


$\sigma \propto \frac{s}{f^4}$

$\sigma \propto \frac{\lambda^2}{m_\phi^2}\log(s/m_\phi^2)$

$(\hat{s} \gg m_h^2)$

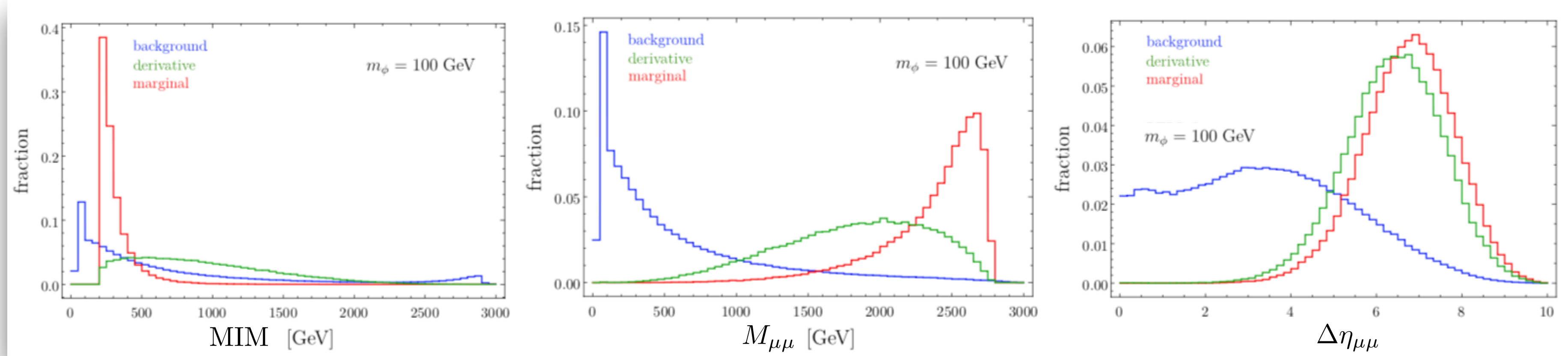
Invisible singlets at the muon collider



- Parton-level analysis with MG5_aMC@NLO

  Neglect ISR
- Dominant background is $\mu\mu \to \nu\bar{\nu}\,\mu\mu$
- Kinematic variables: $M_{\mu\mu},\ \mathrm{MIM},\ \Delta\eta_{\mu\mu},\ \not{E}_T$

$\sqrt{s} = 3\ \mathrm{TeV}$



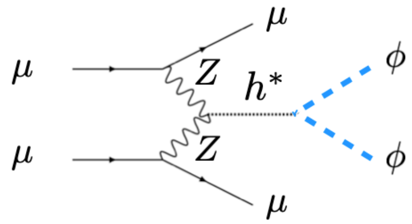
- Dimuon invariant mass cut less effective for derivative portal;

  compensate with tighter cut on MIM

$\mathrm{MIM} = (\not{p}_\mu \not{p}^\mu)^{1/2}$ $\qquad \not{p} = (\sqrt{s}, \vec{0}) - p_{e^-} - p_{e^+}$

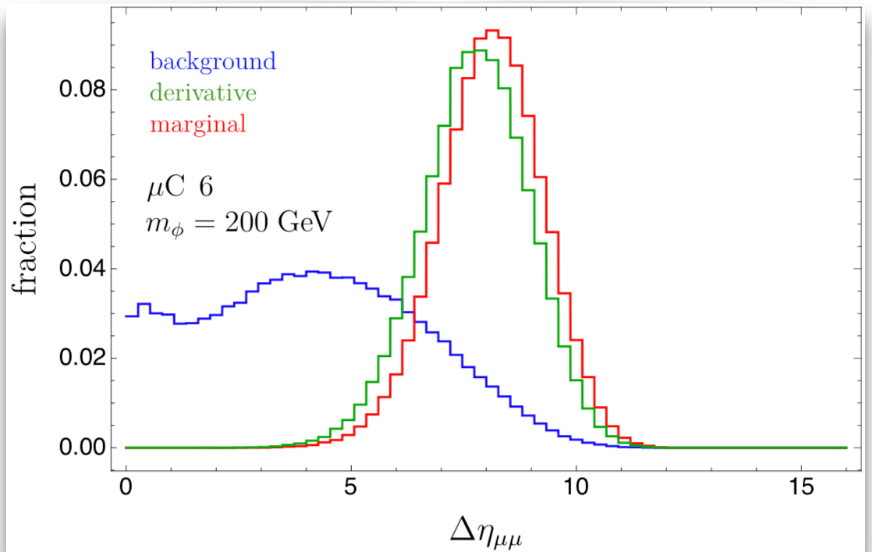
Invisible singlets at the muon collider/2

- Generation level: $p_T^\mu > 10\ \mathrm{GeV},\ \ |\eta_\mu| < 6,\ \ \Delta R_{\mu\mu} > 0.4$



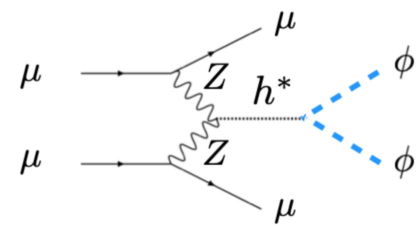
Muon Collider 6 TeV	signal, $m_\phi = 200$ GeV $f/c_d^{1/2} = 930$ GeV $[\lambda = 1]$	$\nu\bar{\nu}\mu^-\mu^+$ background
Generation cuts	0.028 [0.028]	1100
MIM > 1070 [400] GeV	0.021 [0.028]	386 [681]
$\Delta\eta_{\mu\mu} > 7$ [7]	0.015 [0.023]	0.658 [10.6]
$\not{E}_T > 80$ [60] GeV	0.009 [0.019]	0.124 [2.31]
$M_{\mu\mu} > 1700$ [4700] GeV	0.009 [0.013]	0.120 [0.234]

Table 4: Cross sections in fb. For 6 ab^{-1} we have $\mathcal{S} = 2.0\,[2.1]$ for the derivative [marginal] portal.

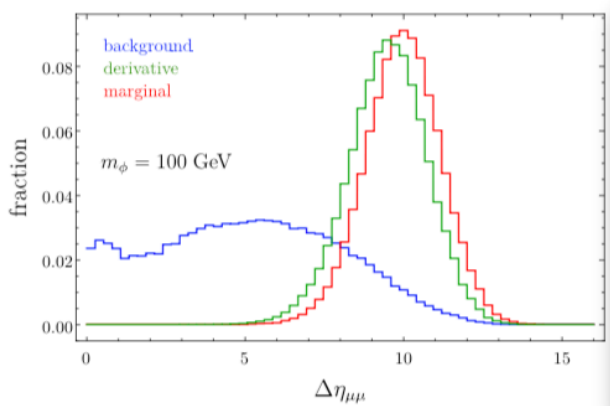


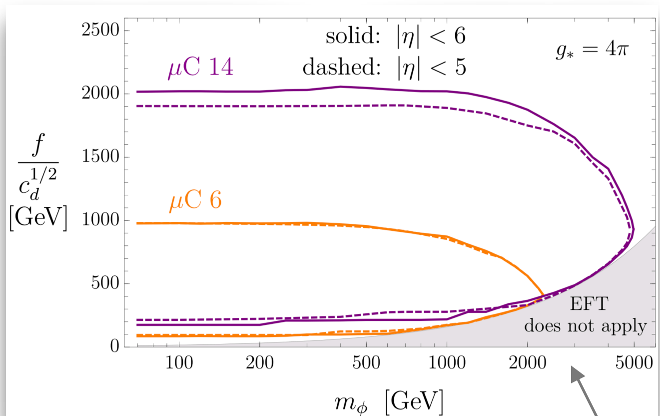
Invisible singlets at the muon collider/3

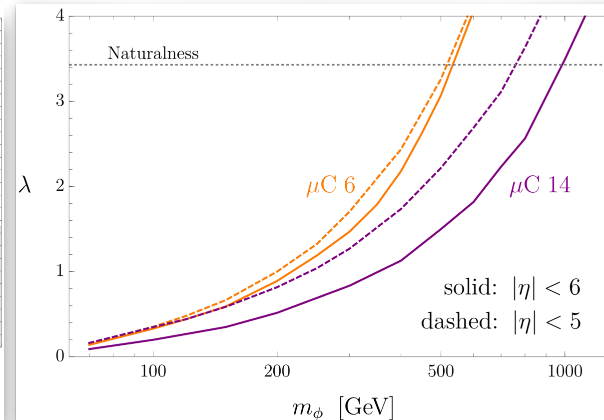
- At higher CoM energy, muons become *extremely* forward



$\sqrt{s} = 14$ TeV







θ	η
0°	∞
0.1°	7.04
0.5°	5.43
1°	4.74
2°	4.05
5°	3.13
10°	2.44

$|\eta_\mu| < 3$ would remove all signal

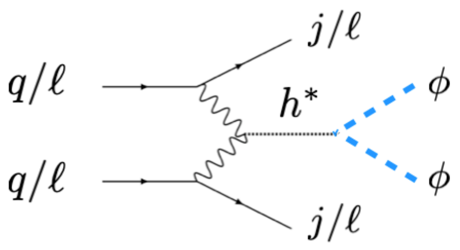
EFT consistency:

$$g_* f / c_d^{1/2} \gtrsim m(\phi\phi) > 2m_\phi$$

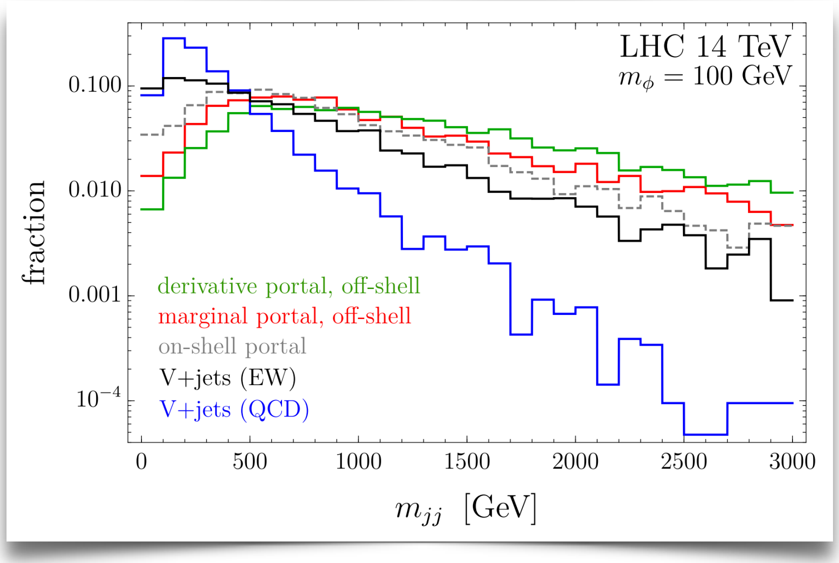
Extending coverage for muons at high $|\eta|$ is critical

Toward a global picture

- At hadron colliders, VBF was shown to be better than mono-jet and $t\bar{t}h$ (for renormalizable portal)



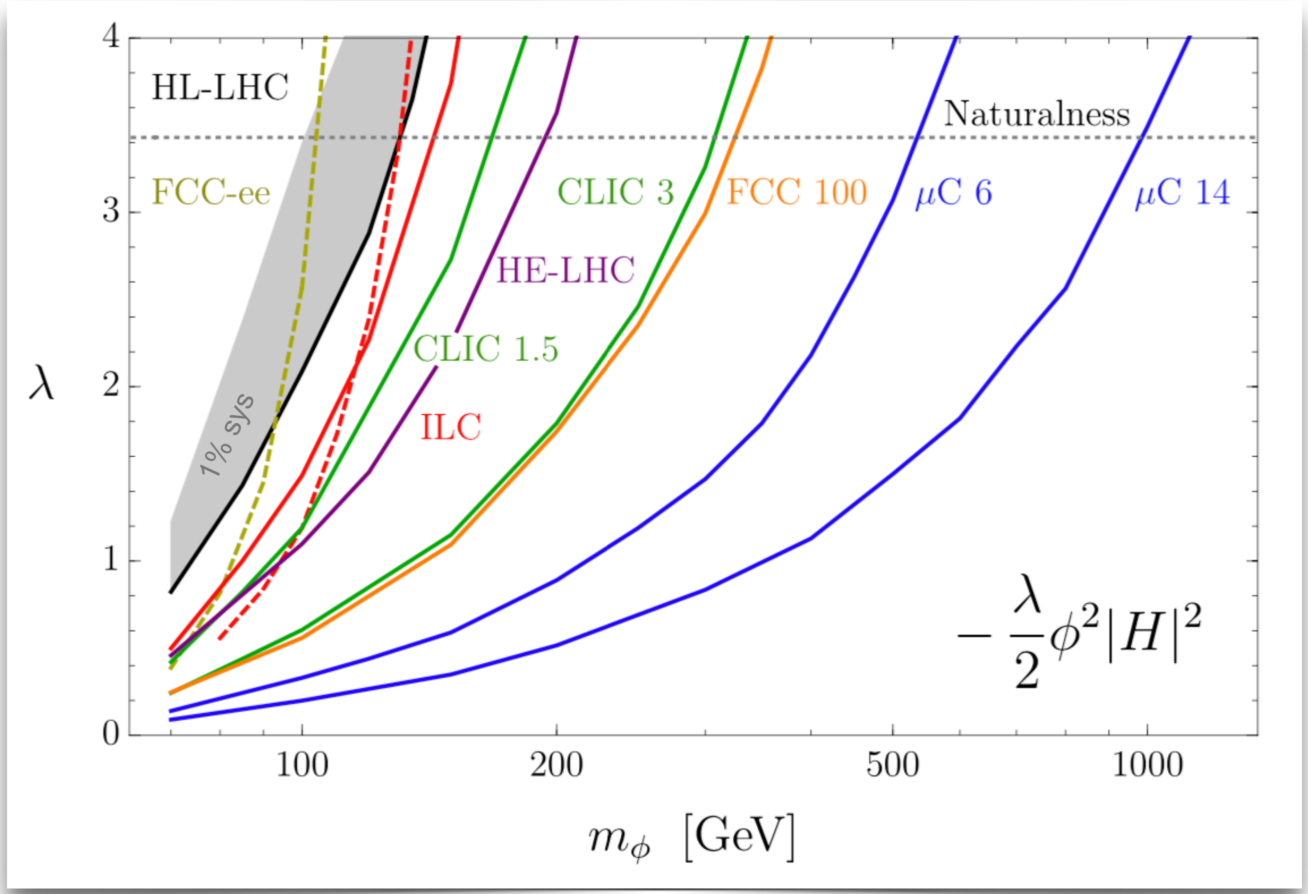
[Craig, Lou, McCullough, Thalapillil 2014]

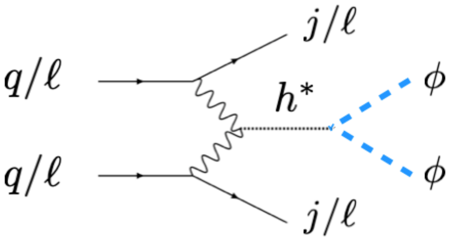


[Ruhdorfer, Salvioni, Weiler 1910.04170]

- Stronger sensitivity to derivative portal (compared to marginal portal), due to harder kinematic distributions. Better background suppression

Global picture: renormalizable portal



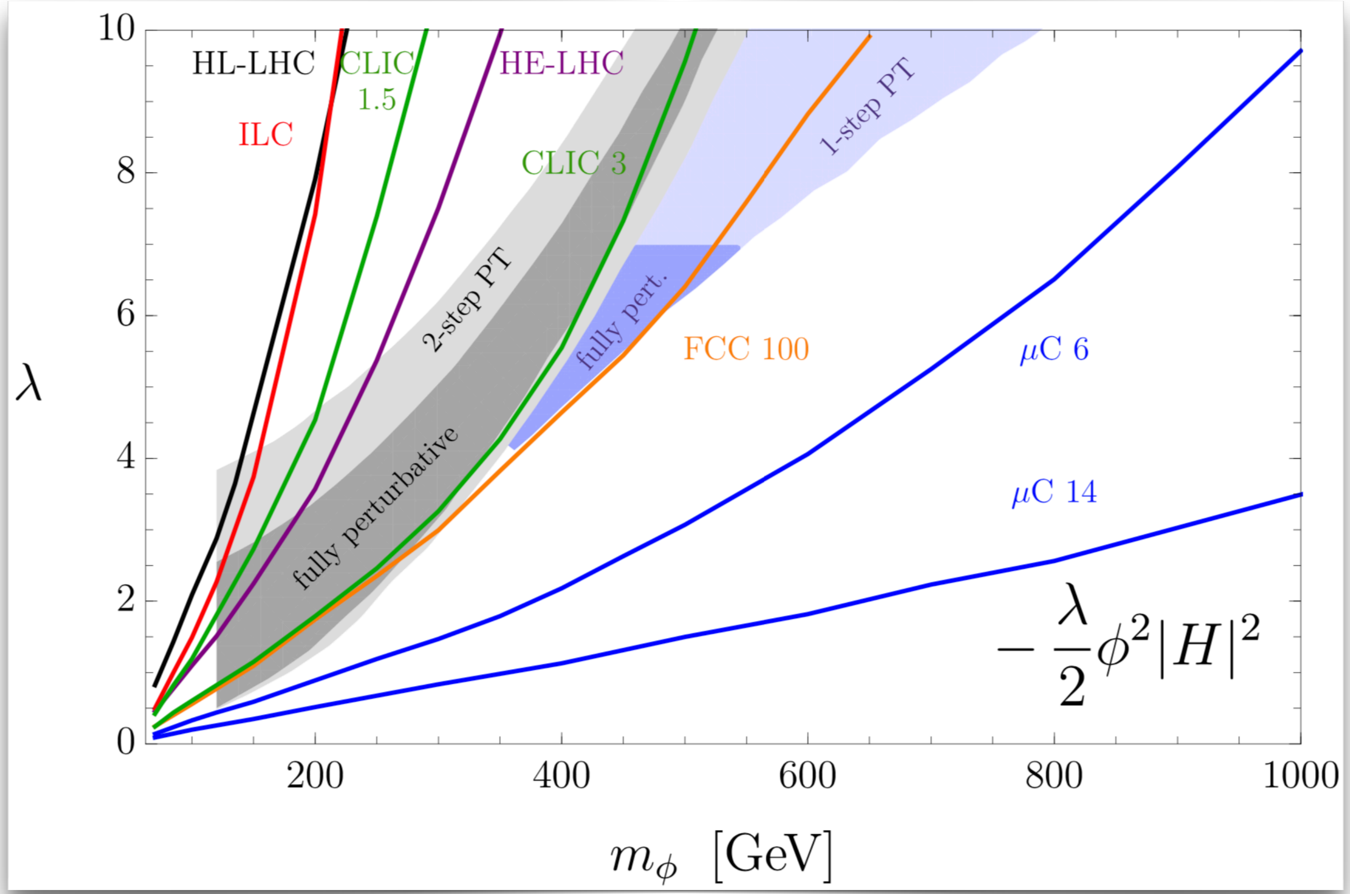


note FCC 100 ~ CLIC 3

Reach on scalar top partner masses:

	HL-LHC	CLIC 1.5	HE-LHC	CLIC 3	FCC 100	μC 6	μC 14
marginal, $\lambda = \sqrt{4N_c}\, y_t^2$: m_ϕ [GeV]	130	170	190	310	330	540	990

Singlet assisting electroweak phase transition



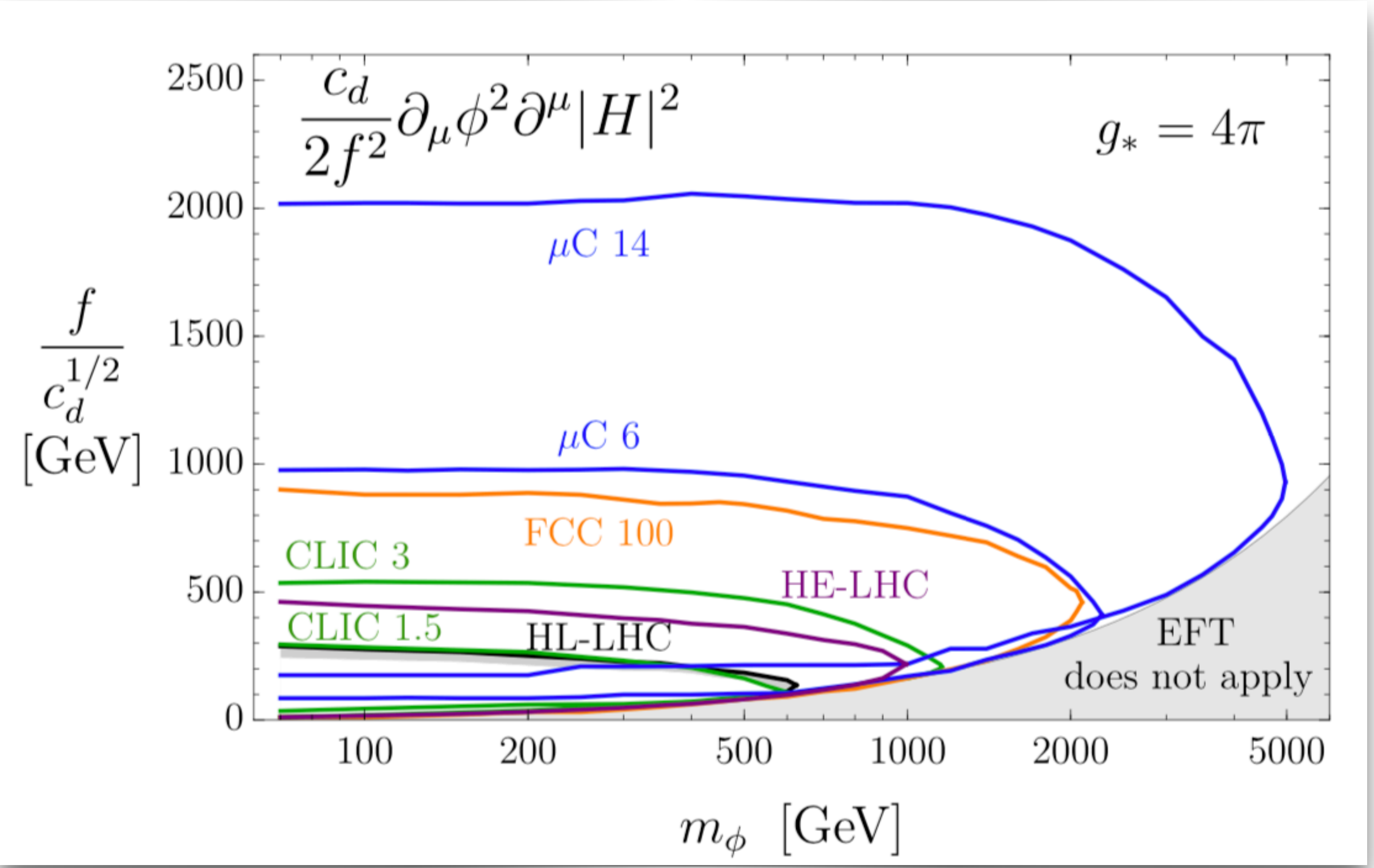
new

Regions with first order EW PT taken from [Buttazzo, Redigolo, Sala, Tesi 1807.04743]

(some analytical approximations, but region where EW baryogenesis can happen is within shaded areas)

[Curtin, Meade, Yu 2014]

Global picture: derivative portal



note FCC 100 ~ μC 6

Recall that DM relic density for $m_\phi > m_h/2$ requires $f/c_d^{1/2} \gtrsim 500$ GeV

Only FCC-hh and a muon collider would truly test pNGB DM

14 TeV μC would probe up to $m_\phi \sim 600$ GeV

Supplementary material

On-shell invisible Higgs decays

	LHC current [52] (mostly VBF)	HL-LHC VBF [53] [Zh] [54]	ILC 250 [44] (Zh)	FCC-ee 240 [44] (Zh)	FCC-hh [55] (inclusive)
BR($h \to$ inv)	0.19 *	0.035 [0.08]	$1.3 \cdot 10^{-3}$	$8 \cdot 10^{-4}$	$2.5 \cdot 10^{-4}$
$f/c_d^{1/2}$ [TeV]	1.0	1.7 [1.3]	3.8	4.3	5.8
λ [10^{-2}]	1.4	0.55 [0.86]	0.10	0.082	0.046

On-shell sensitivity is not affected by type of portal

* most recent bound: $\mathrm{BR}(\mathrm{Higgs} \to \mathrm{invisible}) < 13\%$

[ATLAS-CONF-2020-008]

Derivative vs marginal @ hadron colliders

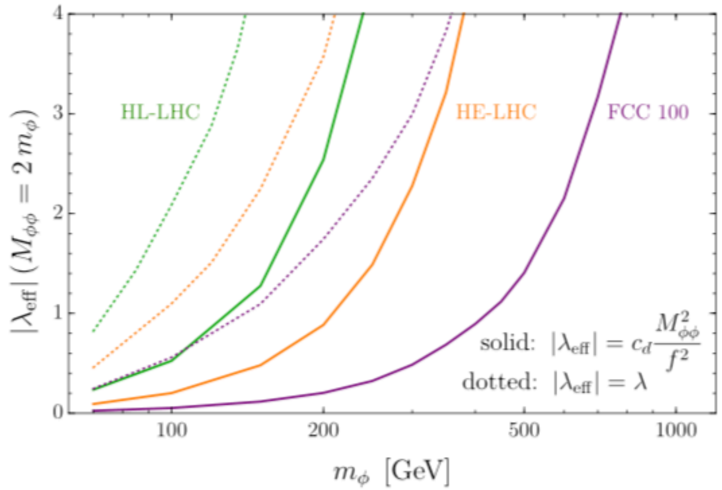


Figure 8: Hadron collider sensitivity on the effective coupling evaluated at the threshold $M_{\phi\phi} = 2m_\phi$, for the derivative and marginal portals, as obtained from our analysis. The figure quantifies the sensitivity gain that follows from the relative scaling $\propto \hat{s}^2$ in Eq. (12).

$$\hat{\sigma}^{\rm deriv}_{VV\to\phi\phi}(\hat{s}) = \frac{1}{32\pi}\frac{c_d^2\,\hat{s}}{f^4}\left(1-\frac{m_h^2}{\hat{s}}\right)^{-2}\left(1-\frac{4m_\phi^2}{\hat{s}}\right)^{1/2}$$

$$\hat{\sigma}^{\rm marg}_{VV\to\phi\phi}(\hat{s}) = \frac{1}{32\pi}\frac{\lambda^2}{\hat{s}}\left(1-\frac{m_h^2}{\hat{s}}\right)^{-2}\left(1-\frac{4m_\phi^2}{\hat{s}}\right)^{1/2}$$