Higgs Portal at 100 TeV

Fermilab

Dec 5th 2015

Matthew McCullough

Higgs Portal and DM

A "classic" extended Higgs sector:

- Higgs Portal (HP)

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$
$$+A_H\phi|H|^2 + \mu_\phi\phi + A_\phi\phi^3 + \phi\chi^2$$

- New scalar could be the DM itself (black only).
- Or the mediator to the DM (red and blue).

Straw Man for an EHS

A "classic" extended Higgs sector:

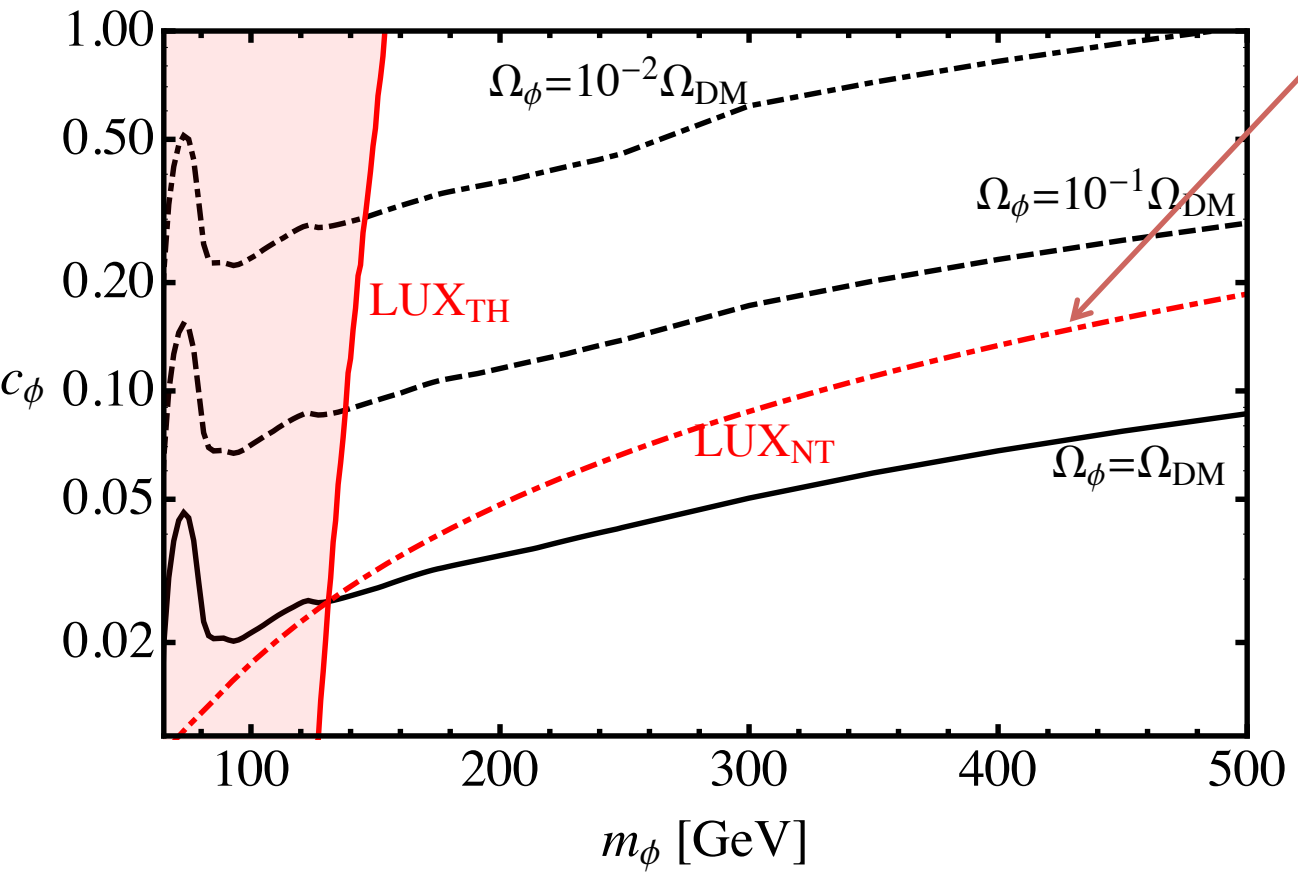
- Higgs Portal (HP)

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$
$$+A_H\phi|H|^2 + \mu_\phi\phi + A_\phi\phi^3 + \phi\chi^2$$

- New scalar could be the DM itself (black only).
  - This is the only renormalizable operator coupling singlet DM and Standard Model!

Higgs Portal

BSM Implications, Dark Matter:



What assumptions do we make here?

$$\rho \propto \frac{1}{c_\phi^2}$$

$$\sigma_{DD} \propto c_\phi^2$$

Coupling comparison
Cosmology-dependent!

Craig, Lou, MM, Thalapillil

Higgs Portal at 100 TeV

If the singlet is DM, i.e. only pair-produced, we have:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

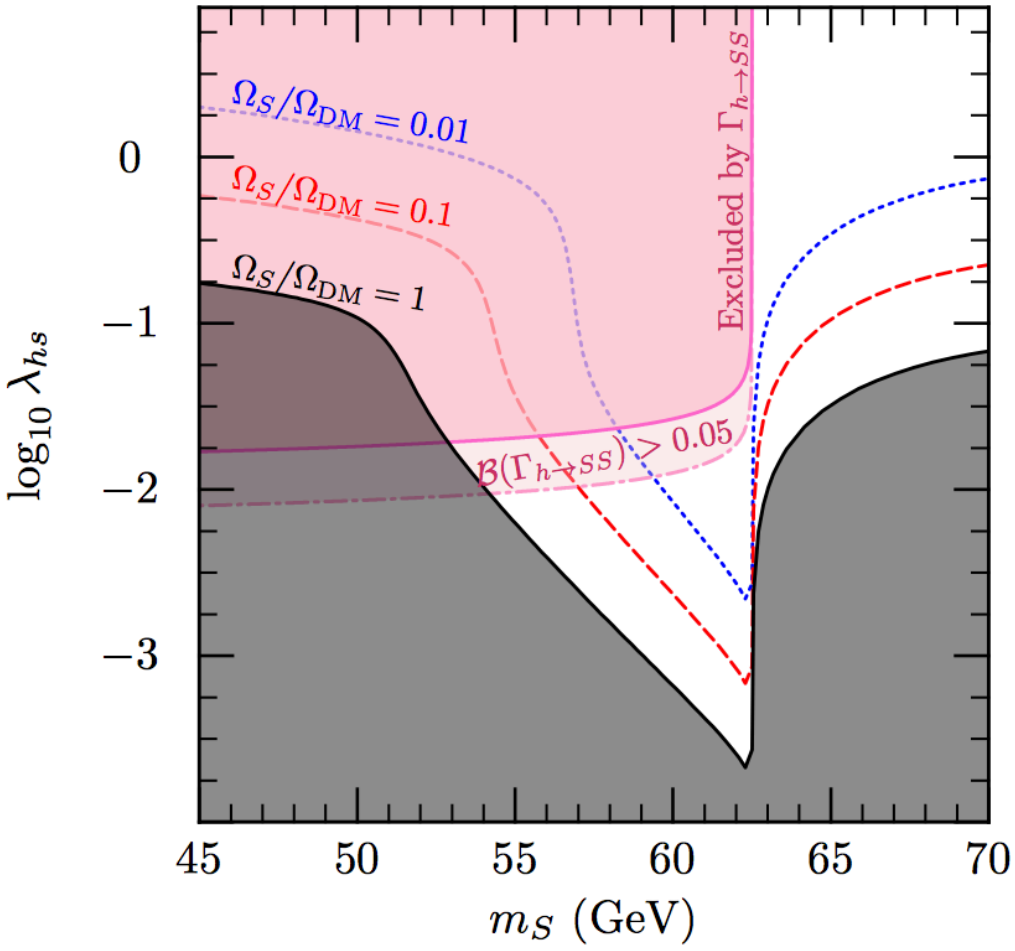
Usual limits on-shell: $h \to \phi\phi \Rightarrow \Gamma_{h\to\text{inv}} \neq 0$

Relevant if we have: $m_\phi < m_h/2 < 62\ \text{GeV}$

Can be constrained by global coupling fit, however MET+(di-)jet signatures also promising for direct search.

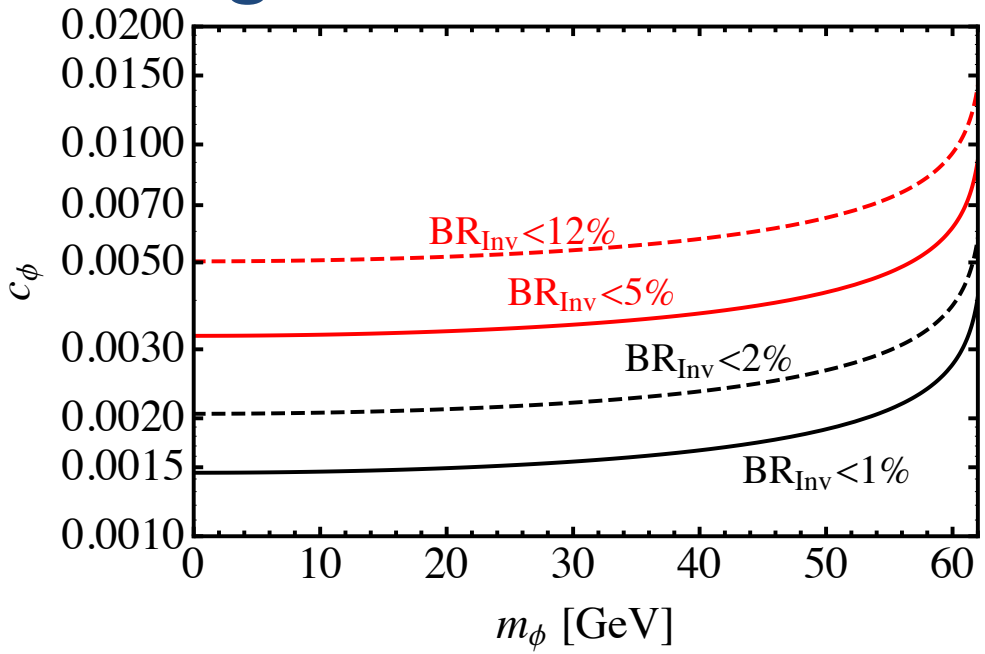
Higgs Portal at 100 TeV

Recent update from Cline, Scott, Kainulainen, Weniger:



Higgs Portal at 100 TeV

Coupling sensitivity possible with variety of invisible branching limits.

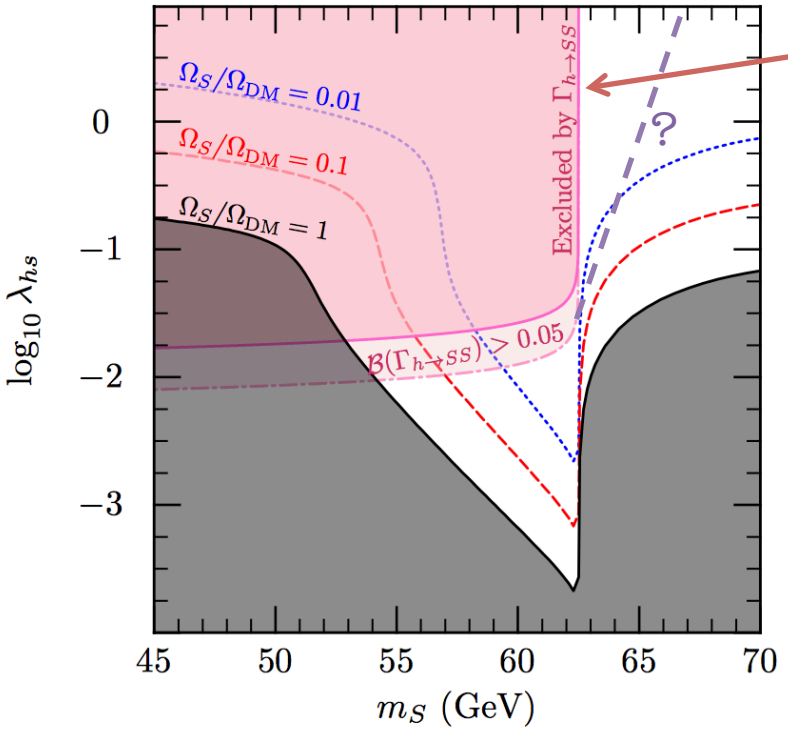


100 TeV capability depends on coupling precision.

What about $m_\phi > m_h/2$? This is the majority of parameter space. What can we do?

Higgs Portal at 100 TeV

Coupling sensitivity possible with variety of invisible branching limits.



Is this it?

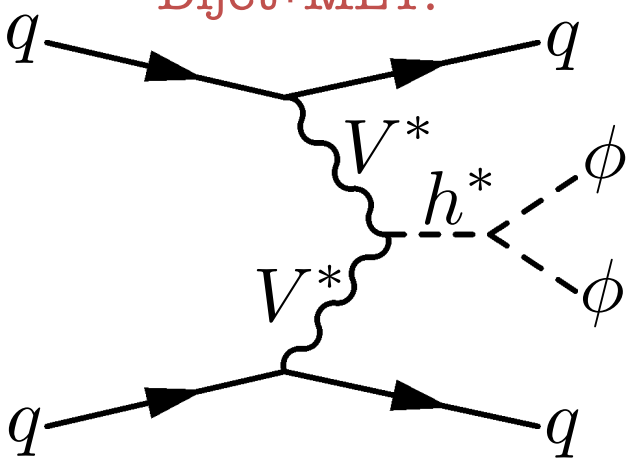
What about $m_\phi > m_h/2$? This is the majority of parameter space. What can we do?

Higgs Portal

Want more coverage! For $m_\phi > m_h/2$ must go off-shell...

VBF:

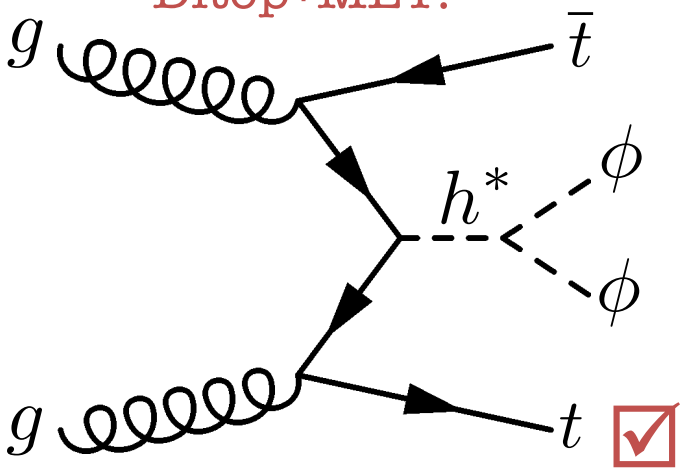
Dijet+MET:



☑

tth:

Ditop+MET:



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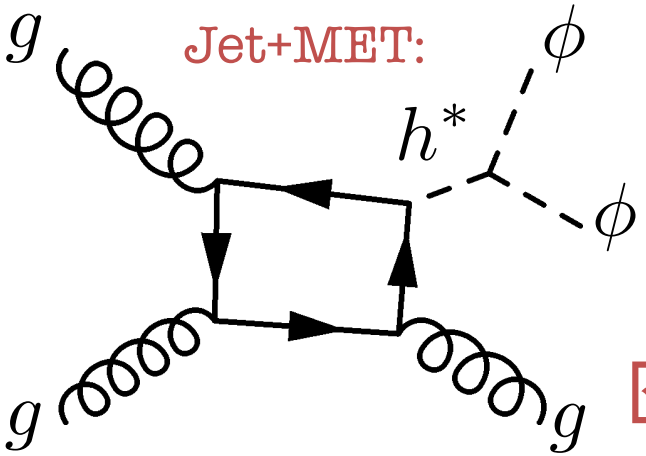
Gluon fusion:

Jet+MET:



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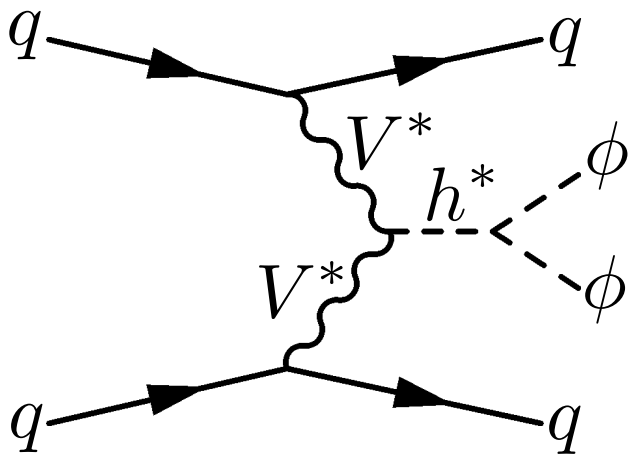
Note: Higgs EFT overestimates rate so full loop necessary.

Higgs Portal

VBF+MET

Backgrounds:

- Z+jets
- W+jets
- tt+jets



Cuts

- Two forward jets
- M_{jj} cut optimized for each mass.
- E_T cut also optimized

Craig, Lou, MM, Thalapillil

Higgs Portal

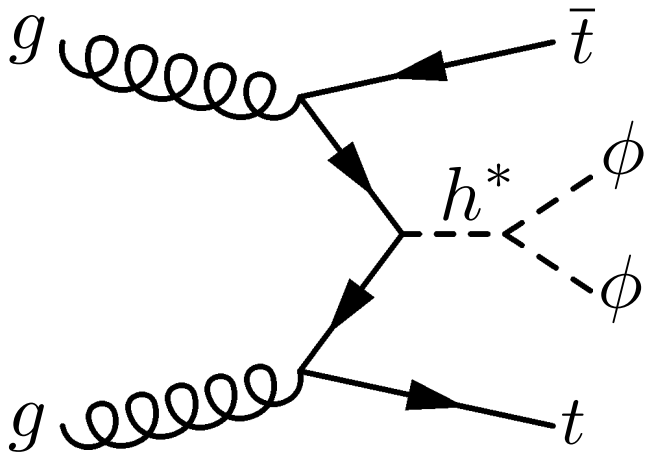
tt+MET

Backgrounds:

- W+jets
- tt+jets

Cuts

- An isolated lepton
- $N_{jet} > 4$
- $E_T > 300$ GeV



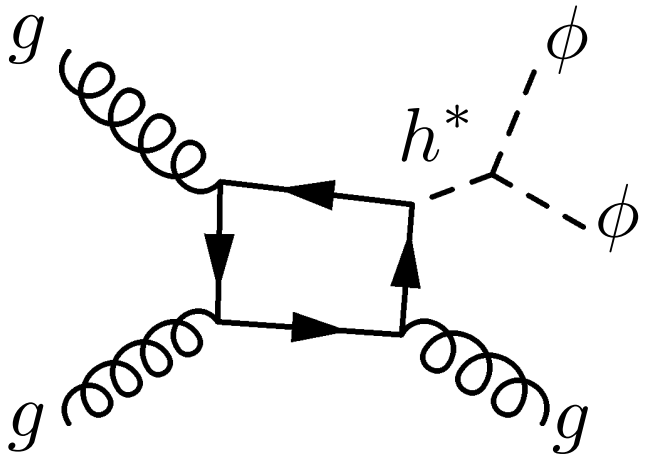
Craig, Lou, MM, Thalapillil

Higgs Portal

Jet+MET

Backgrounds:

- Z+jets
- W+jets
- tt+jets



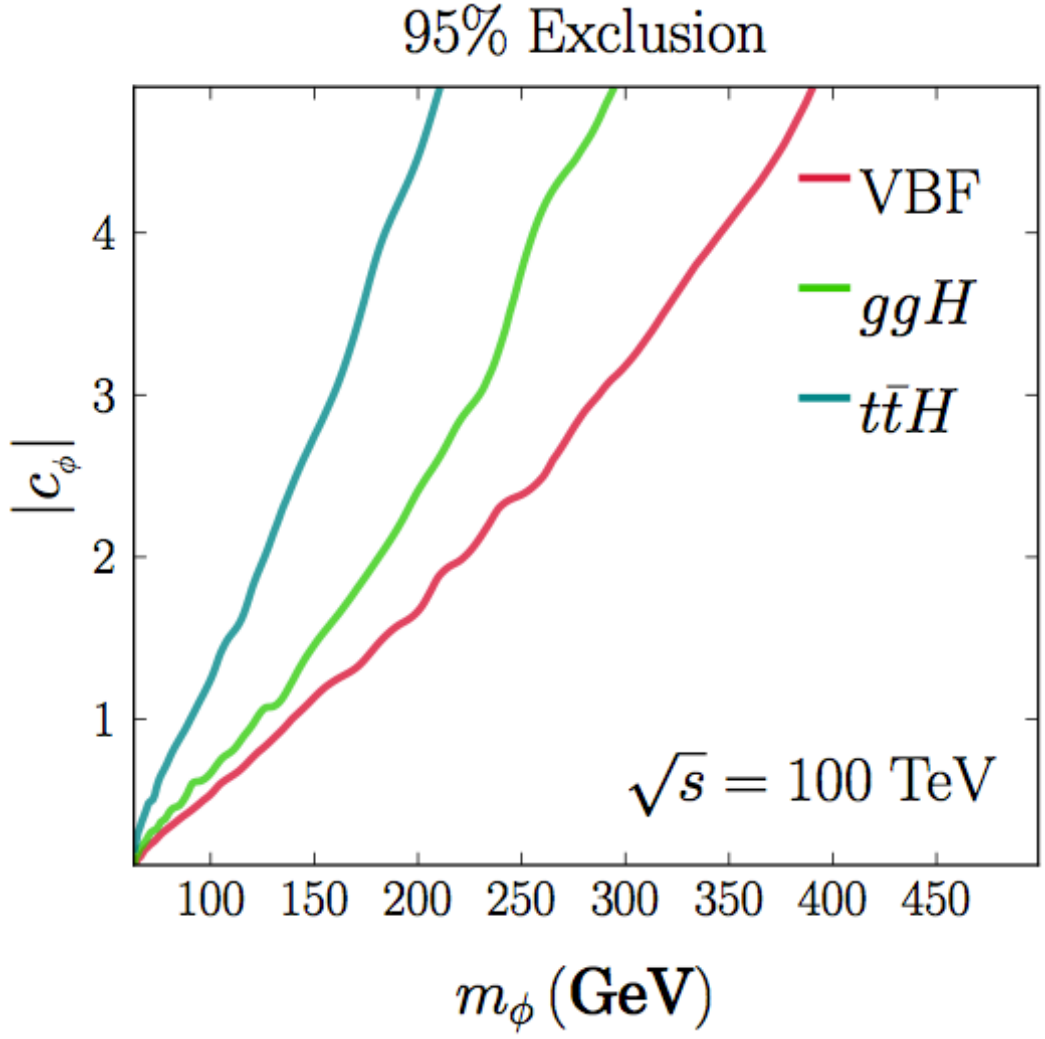
Cuts

- $P_{Tj1} > 110$ GeV
- $E_T > 300$ GeV

Loop in FormCalc, MadGraph HEFT events reweighted. (Nowadays: aMC@NLO)

Higgs Portal

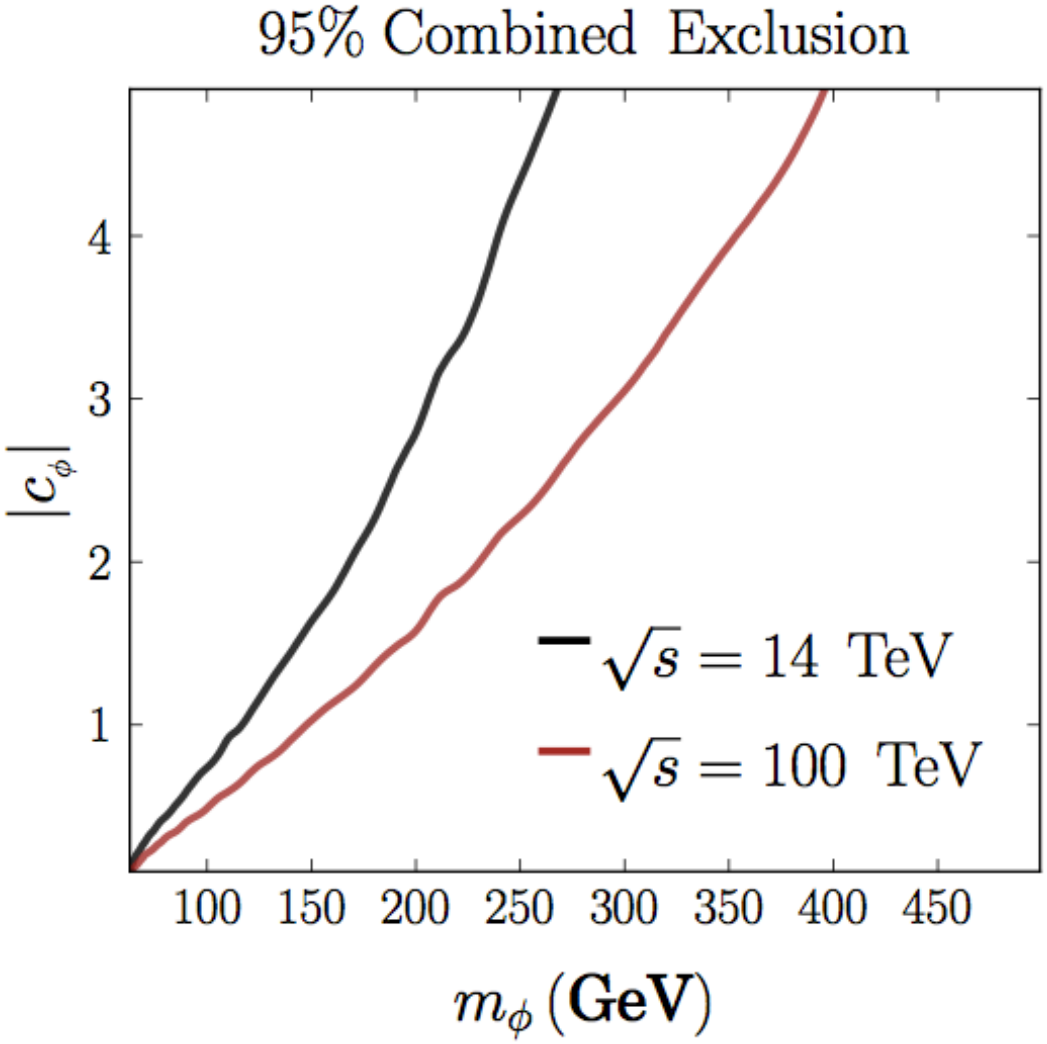
Different channels:



Craig, Lou, MM, Thalapillil

Higgs Portal

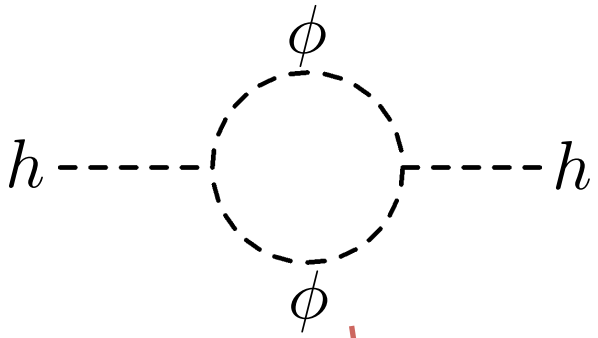
Different colliders:



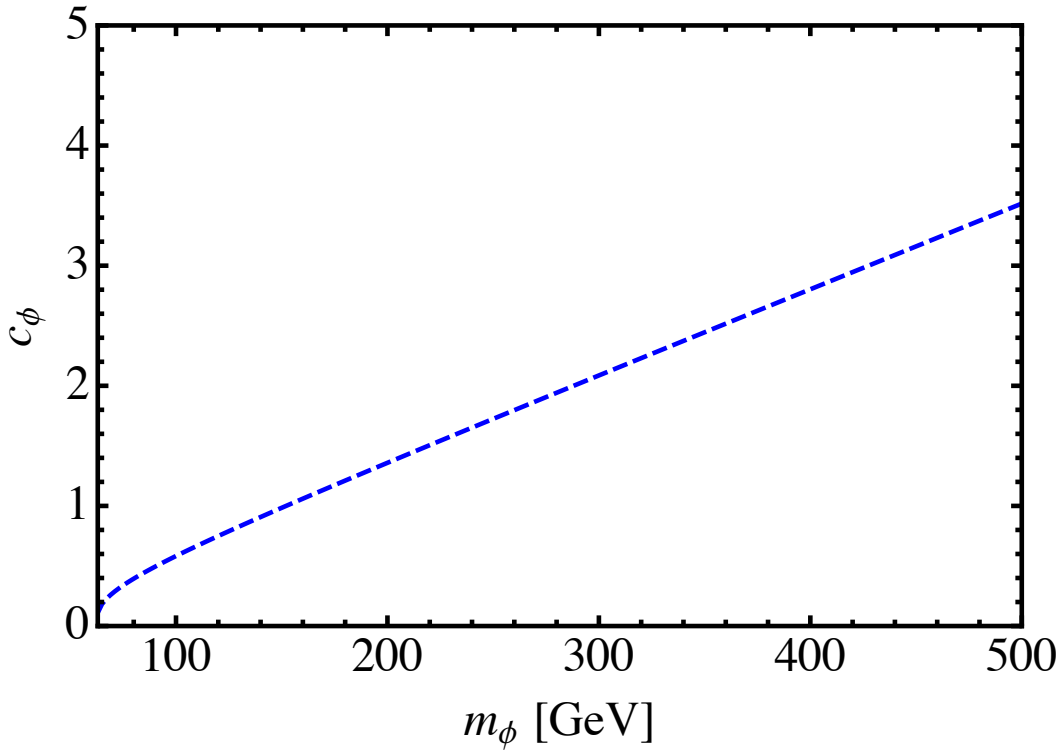
Craig, Lou, MM, Thalapillil

Higgs Portal

Indirect constraint from universal coupling shift at one-loop (FCC-ee):



$$\Delta\mathcal{L} \propto c_\phi^2 \frac{\left(\partial|H|^2\right)^2}{16\pi^2 m_\phi^2}$$

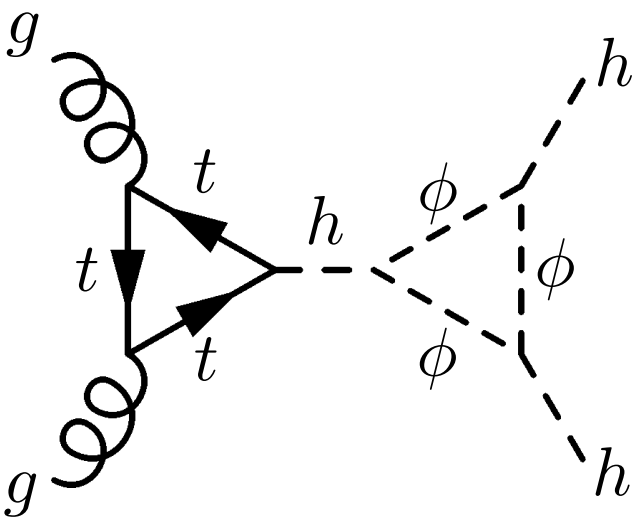


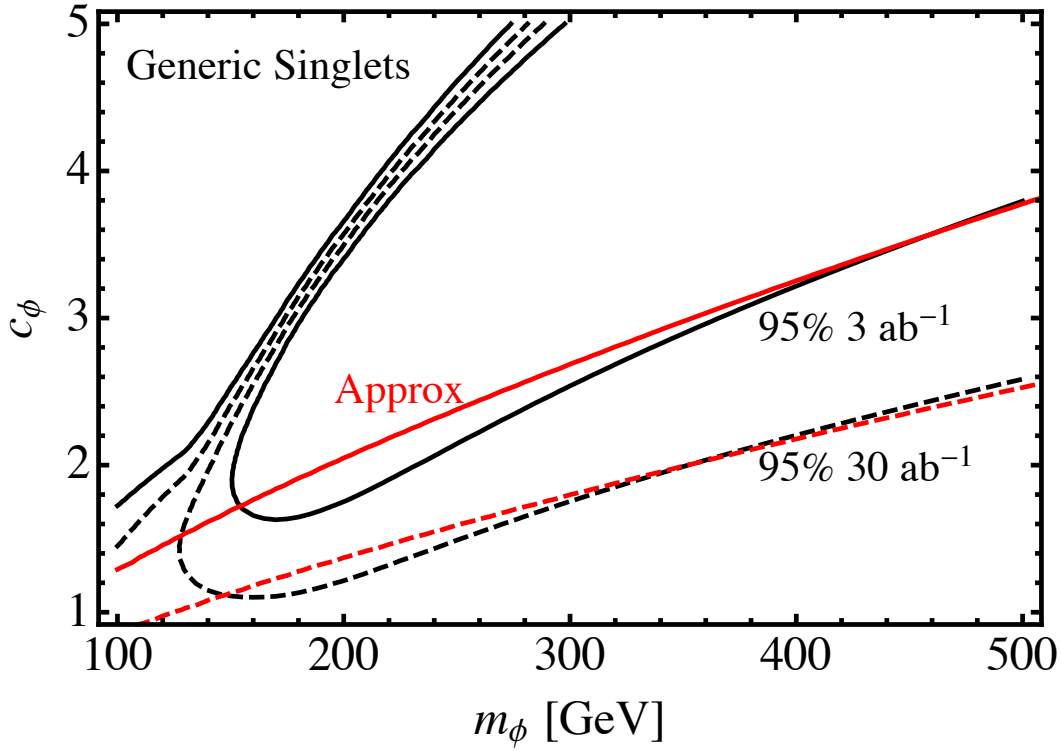
Complementary constraints.

Craig, Englert, MM

Higgs Portal

Indirect constraint from one-loop corrections to Higgs pair production.





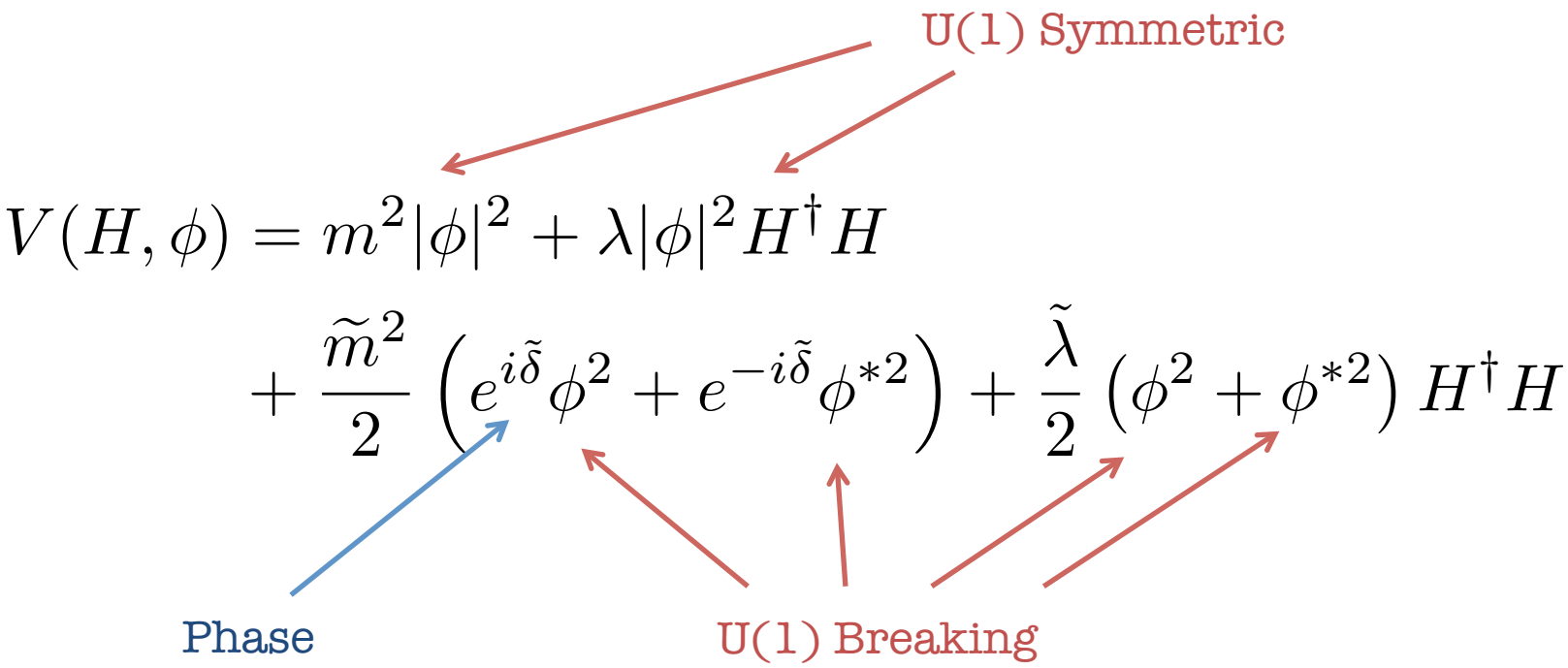
Complementary constraints.

100 TeV Reach pointed out by Curtin, Meade, Yu

Split Higgs Portal

Window into the dark sector could offer even more exotic possibilities.

Consider a complex scalar:



In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

Window into the dark sector could offer even more exotic possibilities.

Consider a complex scalar:

$$V(H,\phi) = m^2|\phi|^2 + \lambda|\phi|^2 H^\dagger H + \frac{\widetilde{m}^2}{2}\left(e^{i\tilde{\delta}}\phi^2 + e^{-i\tilde{\delta}}\phi^{*2}\right) + \frac{\tilde{\lambda}}{2}\left(\phi^2 + \phi^{*2}\right) H^\dagger H$$

Rich set of possibilities of this model, including some signatures I will discuss, emphasized in: Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy.

Split Higgs Portal

Window into the dark sector could offer even more exotic possibilities.

$\mathcal{Z}_2 \times \mathcal{Z}_2$ Symmetric

$\mathcal{Z}_2 \times \mathcal{Z}_2 \to \mathcal{Z}_2$

$$V(h, \phi_1, \phi_2) = vh\left(\kappa_{11}\phi_1^2 + \kappa_{22}\phi_2^2 + \kappa_{12}\phi_1\phi_2\right)$$

$$\kappa_{11,22} = \frac{1}{2}(\lambda \mp \tilde{\lambda}\cos 2\theta) \quad , \quad \kappa_{12} = \tilde{\lambda}\sin 2\theta$$

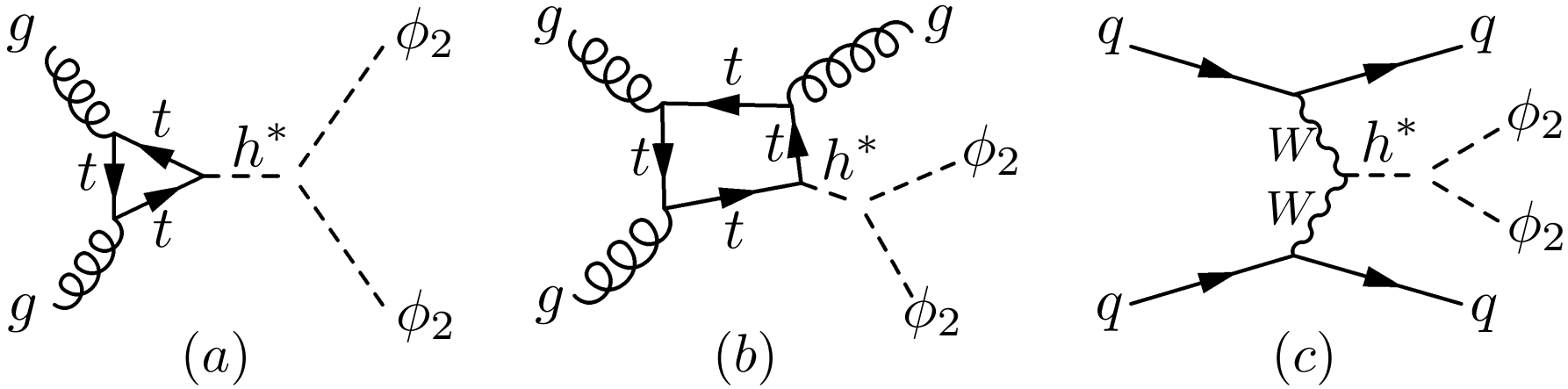
$$\tan 2\theta = \frac{\widetilde{m}^2 \sin\tilde{\delta}}{\widetilde{m}^2\cos\tilde{\delta} + \frac{1}{2}\tilde{\lambda}v^2}$$

Off-diagonal coupling determined by phase.

In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

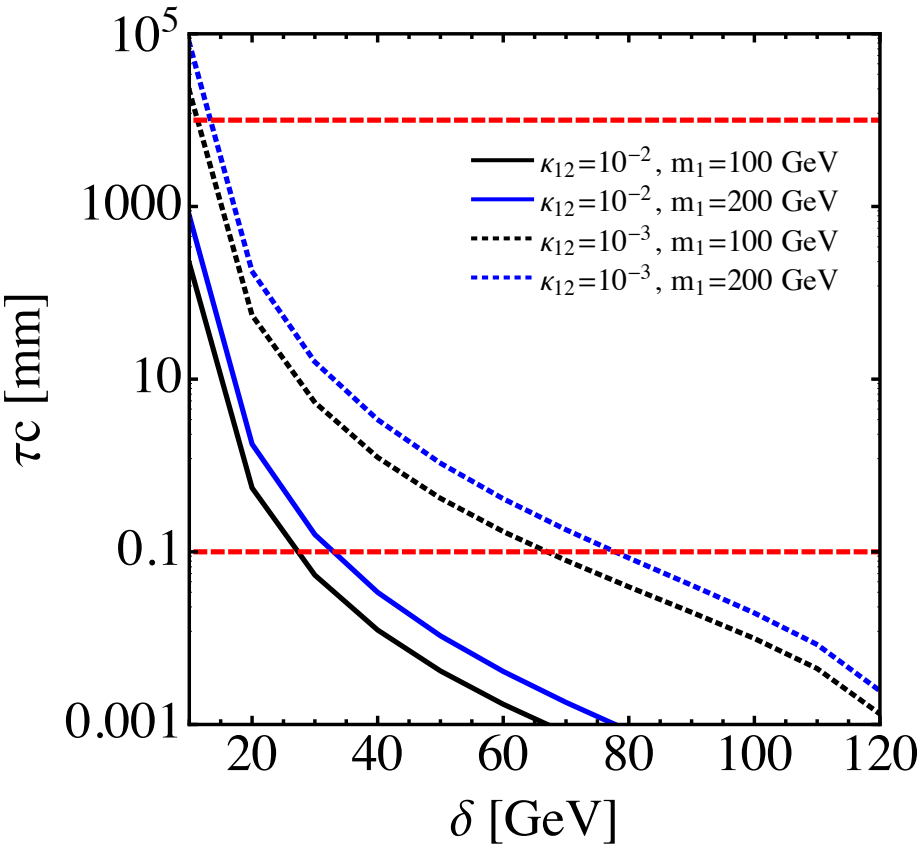
Production of heavier state through usual suspects:



In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

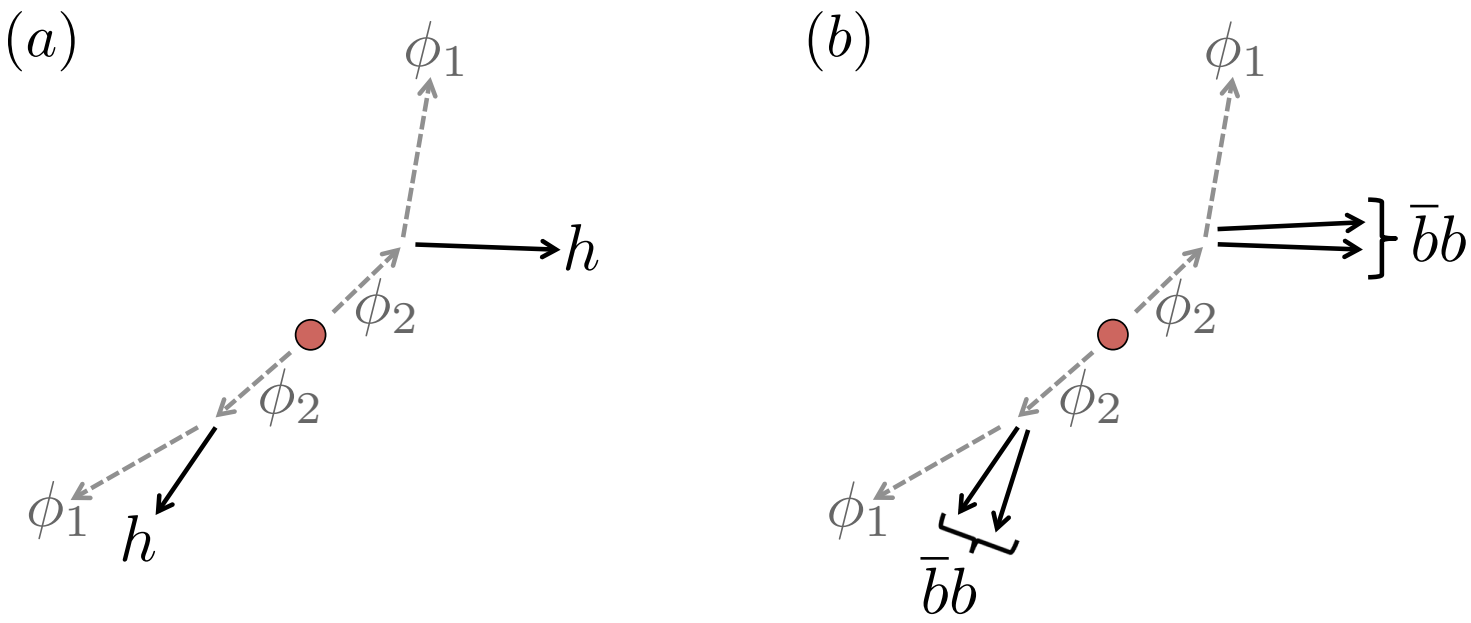
Variety of decay lengths possible, depending on mass splitting and coupling:



In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

Rich set of signatures:

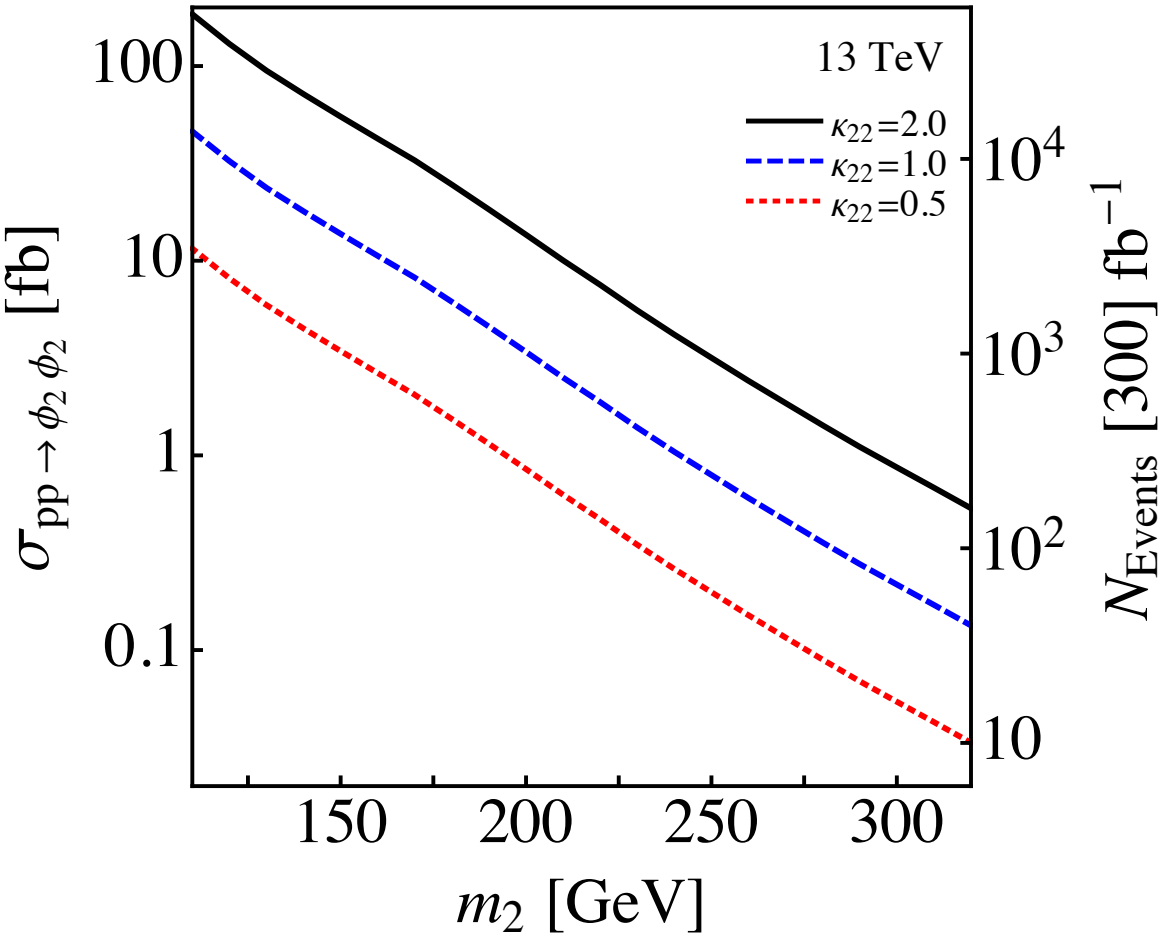


Pair of on- or off-shell Higgs pairs.
Missing energy.
Possibility of a pair of displaced vertices

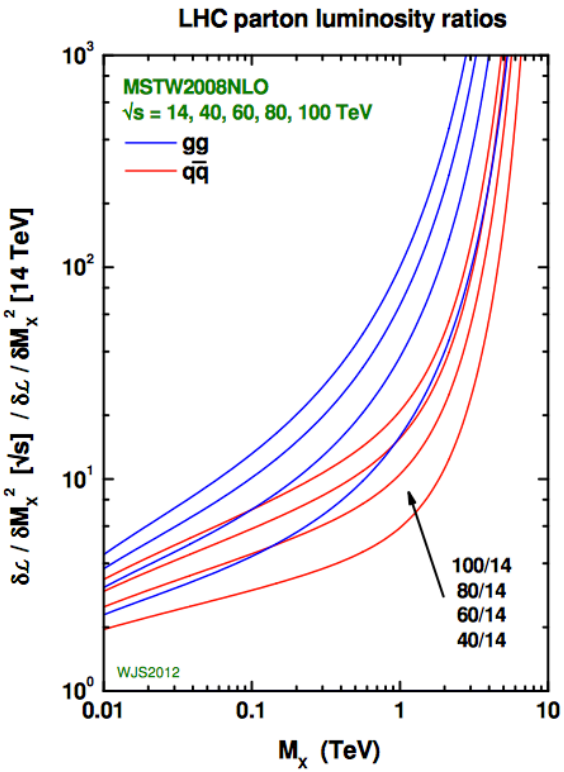
In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

Pair production



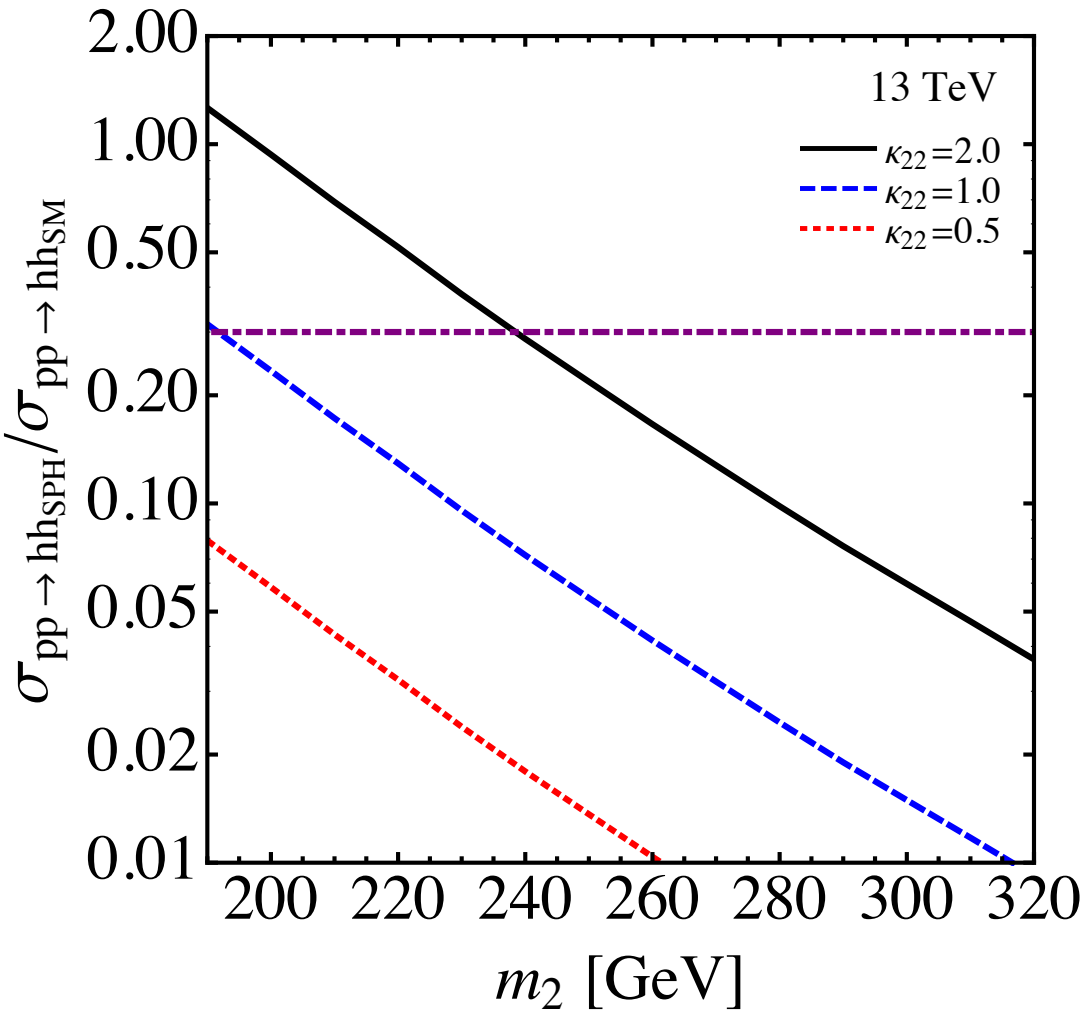
For 100 TeV look at this plot...



In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

Pair production



In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Higgs Portal

Signatures in more detail:

- Higgs pairs + MET.
  - Cross section can be similar to SM Di-Higgs.
  - MET significantly reduces SM backgrounds.
  - At 100 TeV cross section hugely increased.

- Displaced Higgs pairs + MET
  - Pair of displaced due to $\mathcal{Z}_2$ connected to DM.
  - At 100 TeV signal grows, background still small: can take advantage of cross section increase.

In preparation: Kang, MM, Scanlon, Schwaller, Papaefstathiou.

Split Displaced DM

- Pair of displaced-X + MET can arise in range of models:

$$\mathcal{L}_{\rm int} = \left[c_0\left(\xi_1\xi_1 + \xi_2\xi_2\right) + c_1\delta\left(\xi_1\xi_1 - \xi_2\xi_2\right) + c_2\epsilon\left(\xi_1\xi_2\right) + \text{h.c.}\right] \times \sum_i \frac{\mathcal{O}^d_{\rm SM}}{\Lambda^{d-1}}$$

- Possible to construct simplified models of displaced dark matter production at colliders.

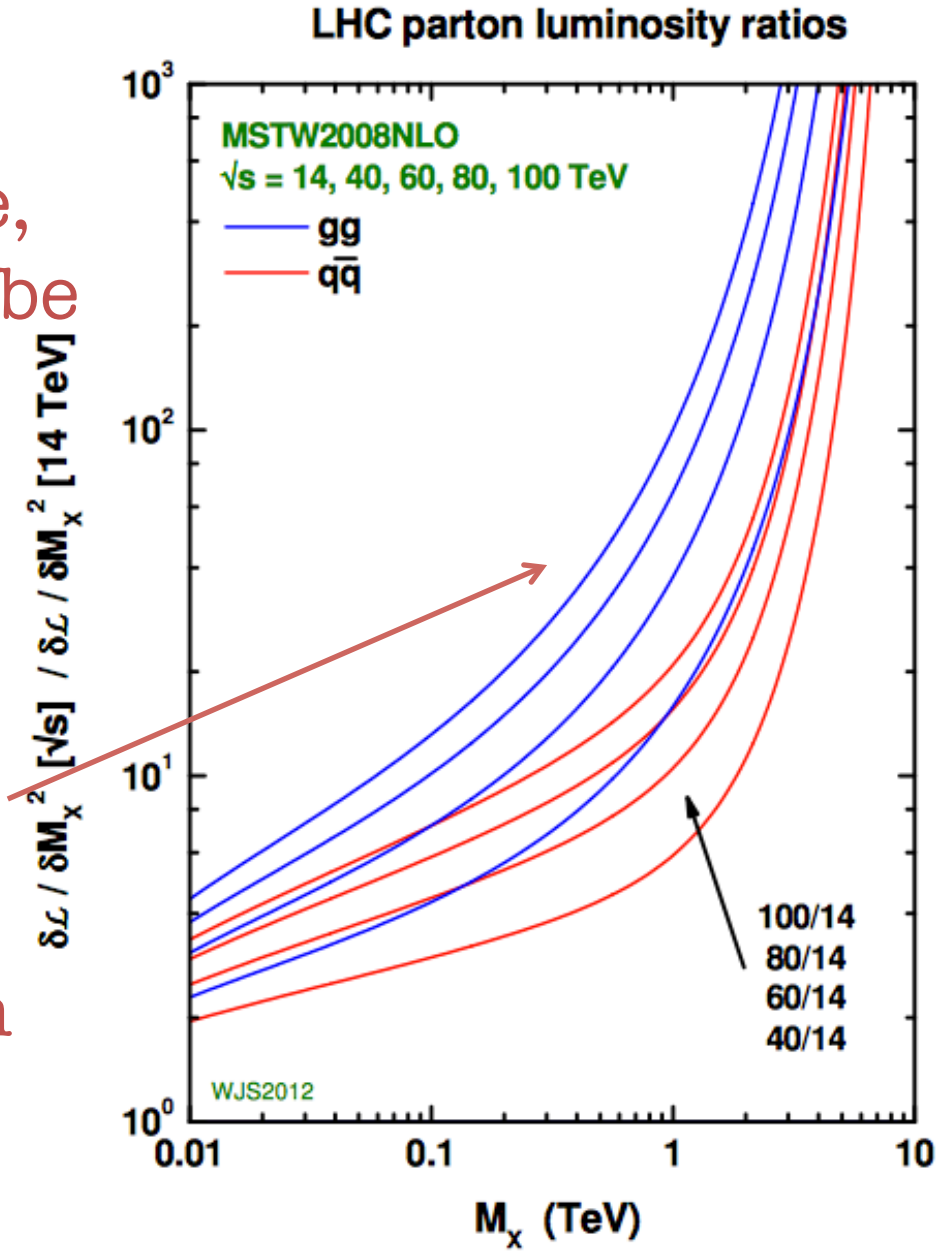
Decay Modes	Final States
$X_{\rm Sing}$	$\gamma,\ Z,\ h$
$X_{\rm EM}$	$\gamma\gamma,\ e^+e^-,\ \mu^+\mu^-$
$X_{\rm Had}$	$\tau^+\tau^-,\ \bar{q}q,\ gg$
$X_{\rm EW}$	$W^+W^-,\ ZZ,\ hh$
$X_{\rm 3rd}$	$\bar{b}b,\ \bar{t}t$
$X_{\rm Inv}$	$\bar{\nu}\nu$

- Probably an interesting signature to think about beyond the Higgs portal...

Personal comments on 100 TeV detector design...

Depending on signature, displaced searches can be low background, with limits set on a signal of a few events. (Multijets can be a big contrib...)

If backgrounds remain small, could take full advantage of the leap in cross section!



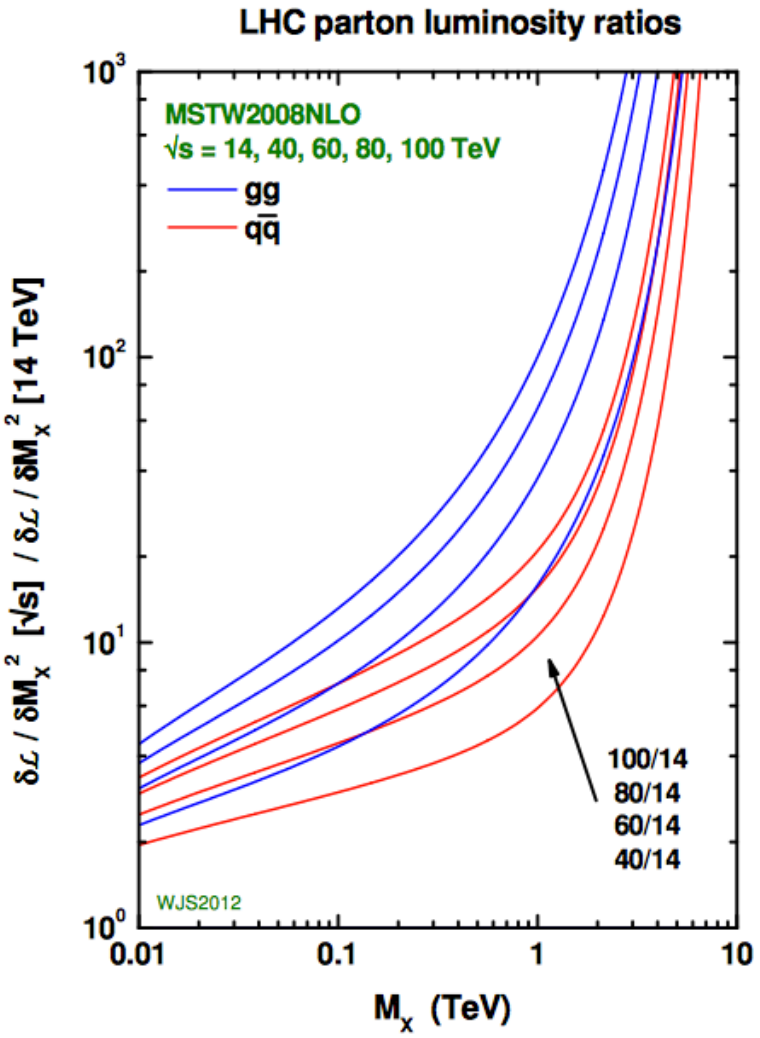
Personal comment on 100 TeV detector design...

Dedicated displaced triggers would be super!

For some displaced searches have to pay price of H_T, or MET first.

If possible, a dedicated displaced trigger would increase reach even further!

Disclaimer: I am a theorist...



Higgs Portal: Messenger

Most general renormalizable interactions with singlet scalar

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

$$+A_H\phi|H|^2 + \mu_\phi\phi + A_\phi\phi^3 + \phi\chi^2$$

Vacuum described by:

$$\phi \to v_\phi + \phi \qquad H \to \frac{1}{\sqrt{2}}\begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix}$$

And mass mixing: $V \supset m^2\phi h$

Final mass eigenstates are

$$h' = \cos(\theta)h + \sin(\theta)\phi$$

$$\phi' = \cos(\theta)\phi - \sin(\theta)h$$

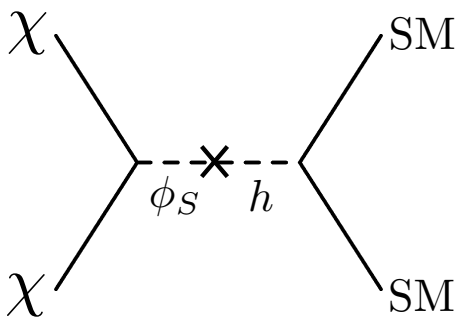
Higgs Portal: Messenger

Most general renormalizable interactions with singlet scalar

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

$$+A_H\phi|H|^2 + \mu_\phi\phi + A_\phi\phi^3 + \phi\chi^2$$

Now the Higgs portal is a messenger to the dark sector:



MET signatures covered in Oliver, James, Philip talks. Here focus on associated signatures.

Higgs Portal: Messenger

Higgs couplings suppressed by a factor $\cos(\theta)$ relative to SM.

Singlet inherits Higgs couplings by factor $\sin(\theta)$.

At LHC with 300 fb^{-1} (3000 fb^{-1}) we expect a precision from Higgs coupling measurements of

$$\cos(\theta) \gtrsim 0.94(0.98)$$

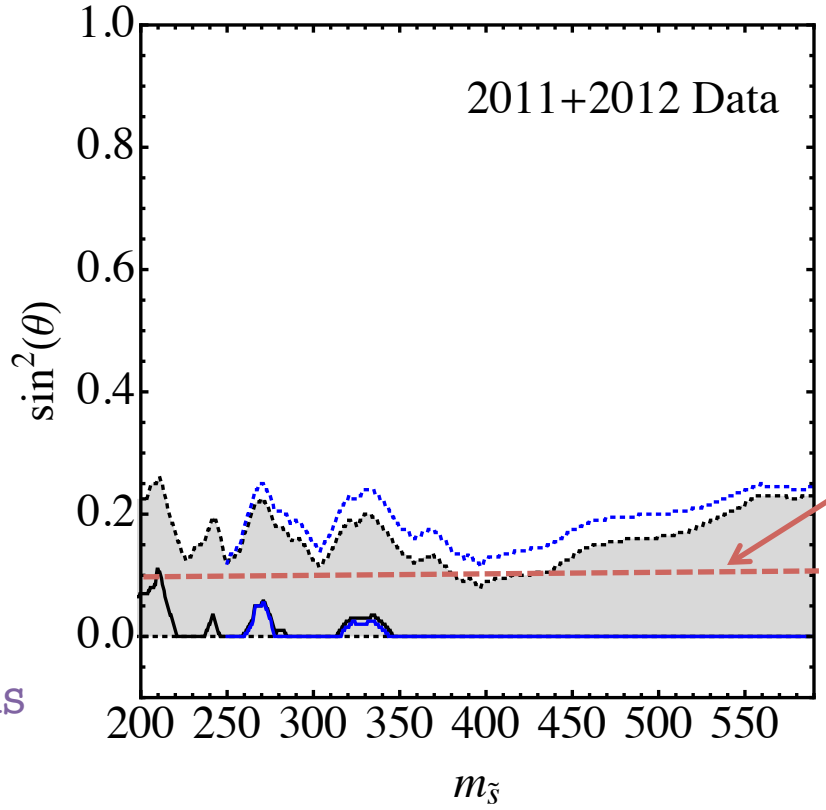
Thus coupling of Heavy Higgs can be

$$\sin(\theta) \lesssim 0.33(0.22)$$

Which is still pretty big!

Higgs Portal so far at 8 TeV

Stronger constraints may come from searching for the scalar directly (Bertolini, MM):

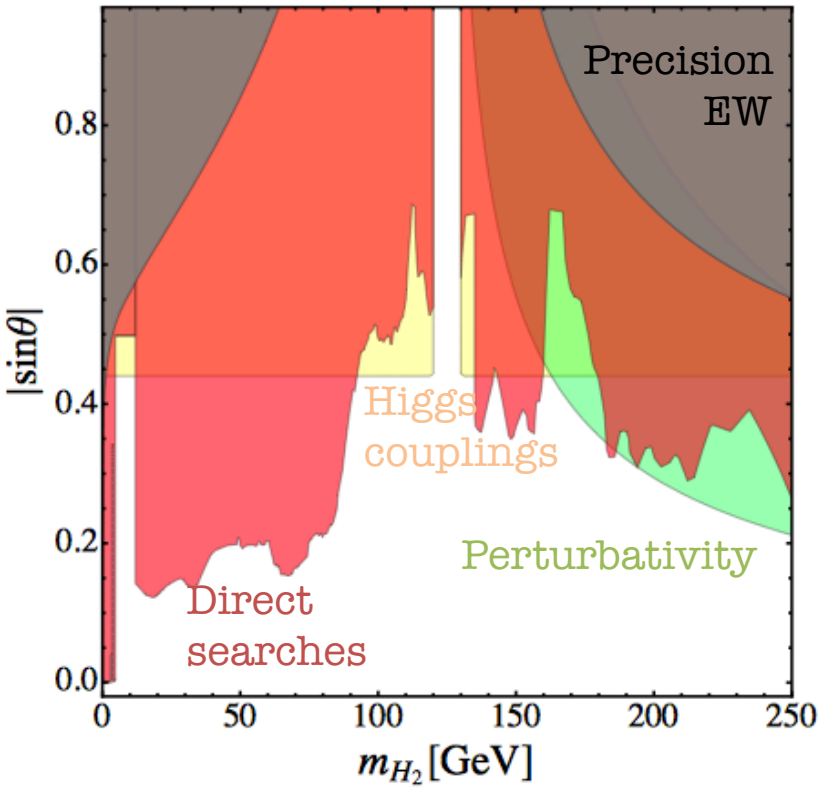


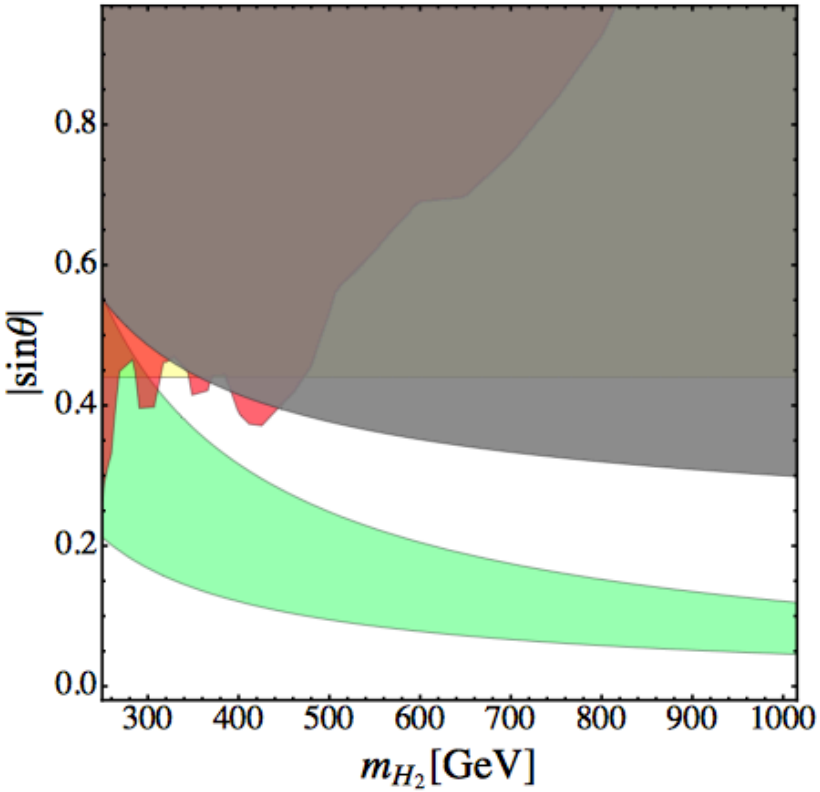
Where we expect 300 fb^{-1} LHC limits to be from Higgs coupling constraints.

Why would any sane person write a paper about Higgs exclusions on July 17th 2012???

Higgs Portal so far at 8 TeV

Stronger constraints may come from searching for the scalar directly (Bertolini, MM) and recently Falskowski, Gross, Lebedev (also Robens, Stefaniak):





Higgs Portal at 100 TeV

Additional ~~complication~~ opportunity:

$$\Gamma_\phi = \sin^2(\theta)\Gamma_{h,m_\phi} + \Gamma_{\phi\to hh}$$

Depends on scalar potential

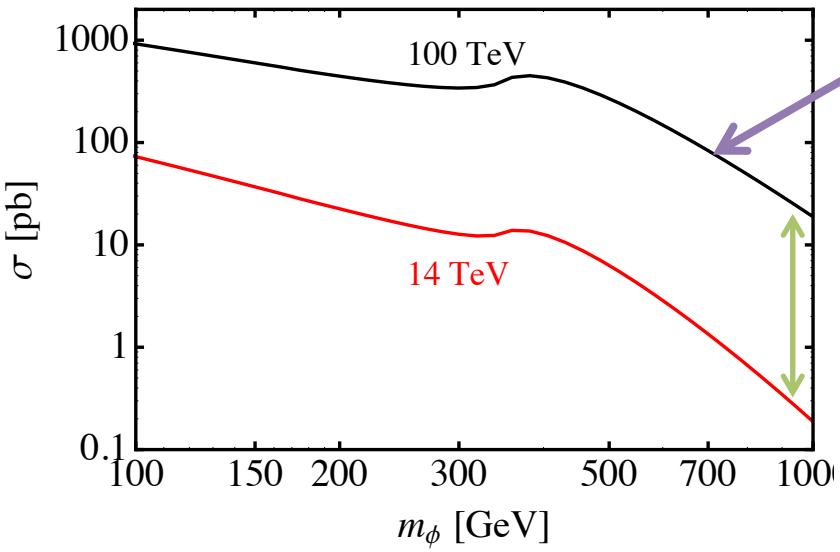
What you lose in Higgs-like signal, you will get back in resonant di-Higgs production!

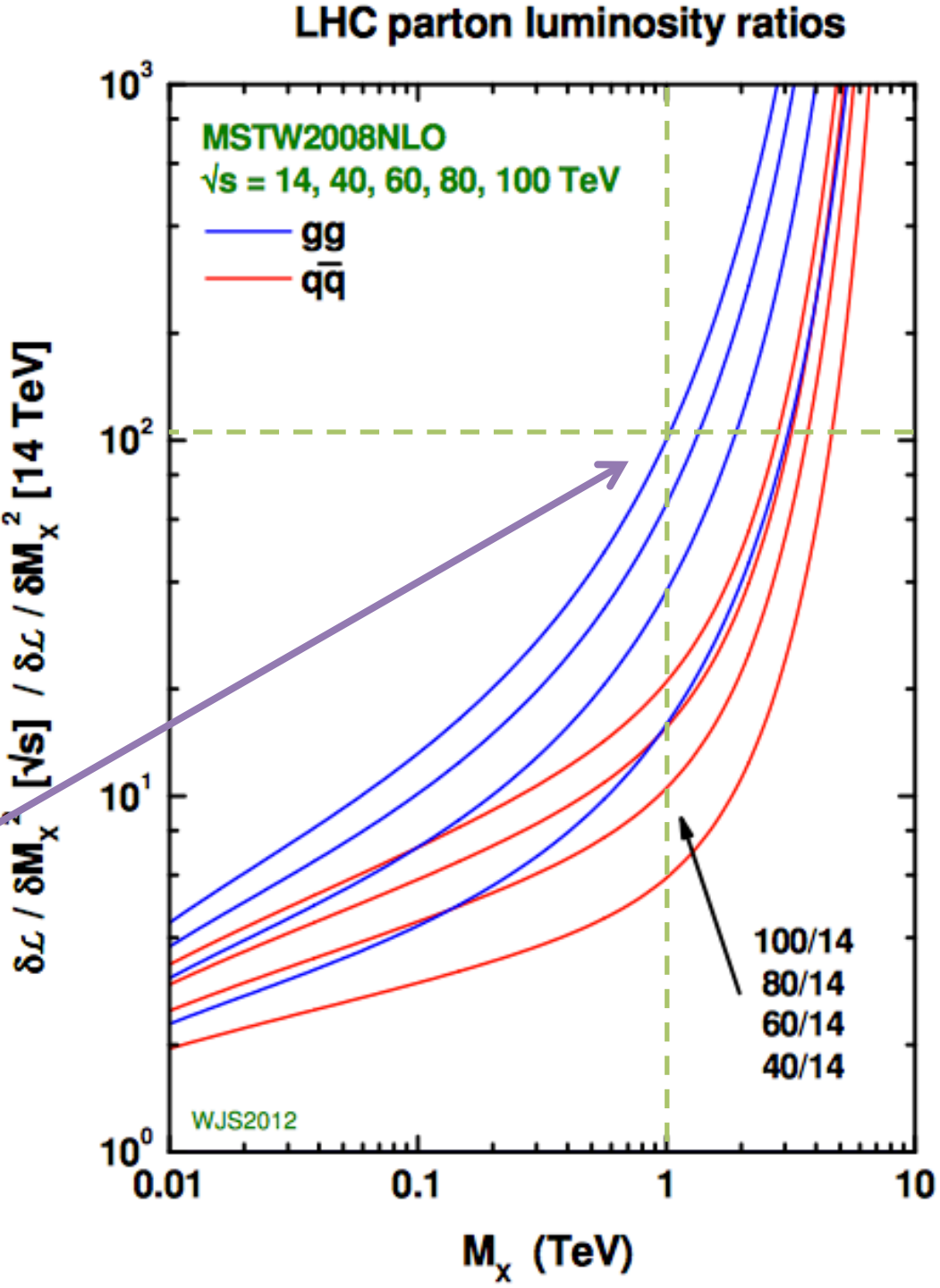
A sort of Higgs Portal no-lose theorem...

Caveat: Any additional decay channels, such as to DM, will violate this,

SM Higgs Production from 14 to 100 TeV.

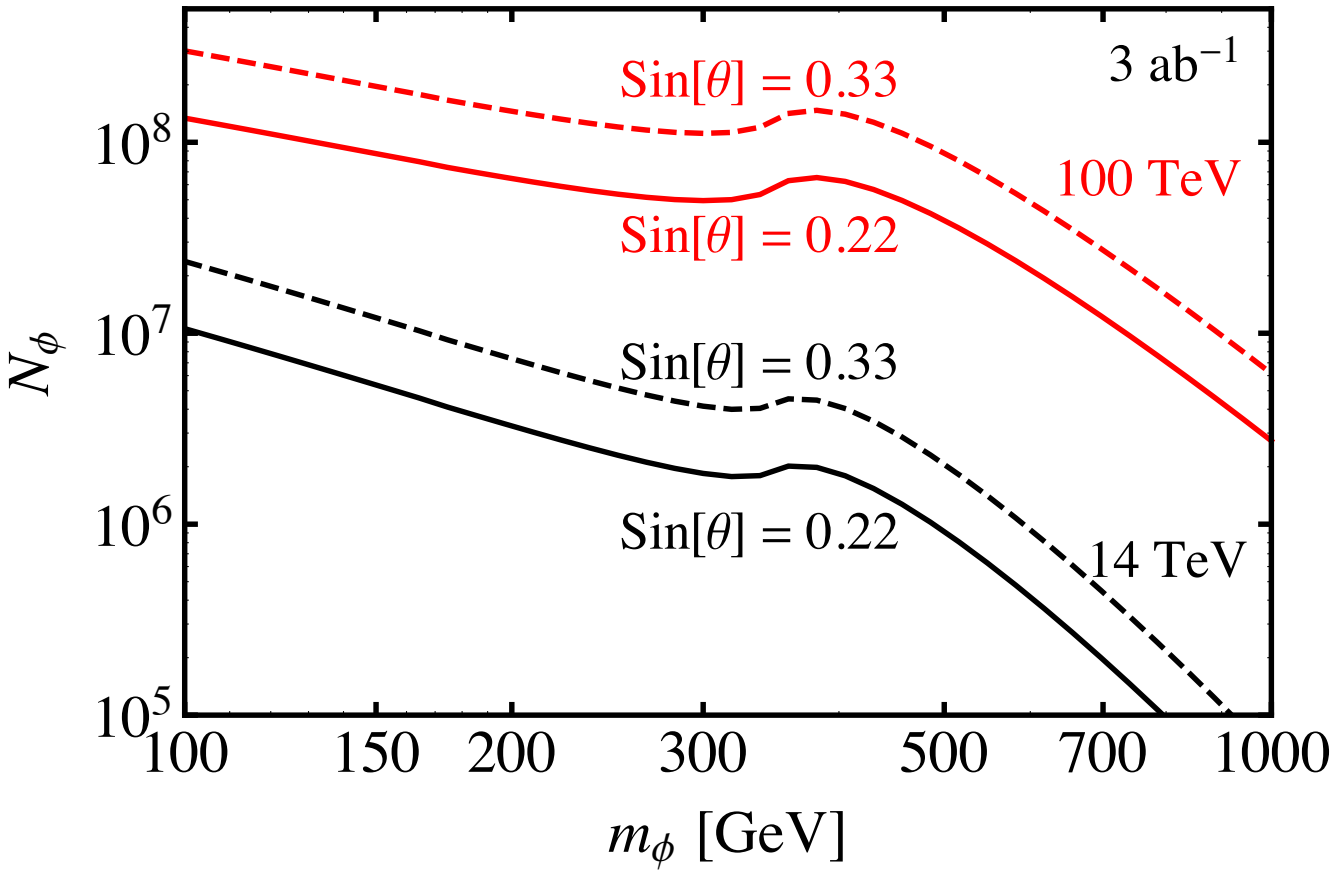
Two orders of magnitude at 1TeV?





Higgs Portal at 100 TeV

How many events do we expect?



All events end up Higgs-like, or di-Higgs.

Summary

- Higgs portal: simple possibility for making a connection with the dark sector.

- Signatures potentially rich:
  - MET
  - Modified Higgs couplings
  - Di-Higgs + MET
  - Di-Displaced + MET

- At 100 TeV could probe Higgs portal even further, especially for rare/exotic signatures.