The Higgs Portal at Lepton Colliders

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Introduction

The existence of a hidden sector that does not transform under the SM gauge groups is one of the most intriguing possibilities for physics beyond the SM.

Since the Higgs bilinear $H^\dagger H$ is the lowest dimension operator gauge invariant operator in the SM, the simplest possibility is that it is through this `Higgs Portal' that the hidden sector communicates with the SM. (Patt & Wilczek)

A hidden sector which communicates with the SM through the Higgs portal can explain many of the puzzles of the SM.

- **hidden sector states could be the dark matter (Silveira & Zee)**
- **hidden mirror SM can stabilize weak scale (ZC, Goh & Harnik)**
- **can help with electroweak baryogenesis (Pietroni)**

The hidden sector states can be accessed through the Higgs portal at colliders. There are two classes of theories.

- The SM Higgs mixes with hidden sector states

- No mixing between SM Higgs and hidden sector states

In scenario where the Higgs mixes with hidden sector states, the mass eigenstates are linear combinations of the Higgs with electroweak singlets.

$$H^\dagger H\,\phi^2 \Rightarrow H^\dagger \langle H\rangle\,\phi\langle\phi\rangle$$

In this scenario, couplings of the 125 GeV resonance to other SM particles are proportional to, but less than, those of SM Higgs.

Furthermore, we expect to find new state(s) with couplings also proportional to those of SM Higgs, but somewhat suppressed.

In scenarios where there is no mixing, the hidden sector states must be pair produced through their couplings to the Higgs.

$$H^{\dagger}H\,\phi^{2} \Rightarrow H^{\dagger}\langle H\rangle\,\phi^{2}$$

If some of the hidden sector states are lighter than half the Higgs mass, the Higgs can simply decay into them.

If, however, all the hidden sector states are heavier than half the Higgs mass, this is no longer possible. Hidden sector states can still be accessed, but through an off-shell Higgs.

Once produced, the hidden sector states may remain invisible at colliders, giving rise to missing energy signals.

Alternatively, the hidden sector states may decay back into SM states, as in `Hidden Valley' models. These scenarios are often associated with exotic signals, such as displaced vertices.

For the rest of this talk, will focus on the scenario where there is no mixing between the Higgs and the hidden sector states.

$$H^\dagger H\,\phi^2 \Rightarrow H^\dagger \langle H\rangle\,\phi^2$$

Will further assume that the hidden sector states remain invisible, and do not decay back to the SM.

This includes the important class of theories where the particle ϕ is stable and constitutes some or all of the observed dark matter.

Specifically, we consider the simplest Higgs portal model, where the hidden sector consists of a single real scalar ϕ. Focus on the scenario where ϕ is stable as a consequence of a Z_2 symmetry, and could constitute dark matter.

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}M_S^2\phi^2 - \frac{c_S}{2}|H|^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

After the Higgs acquires a VEV, v = 246 GeV, the physical mass of the scalar ϕ is given by

$$m_\phi^2 = M_S^2 + \frac{c_S v^2}{2}.$$

We use the physical mass m_ϕ and the coupling c_s to parametrize the model.

There are limits from the LHC on the invisible branching faction of the Higgs, which translate into bounds on this theory when m_ϕ is lighter than half the Higgs mass.

The direct bound stands at about 70%. It arises from searches for *Z* + Higgs, with the Higgs decaying invisibly.

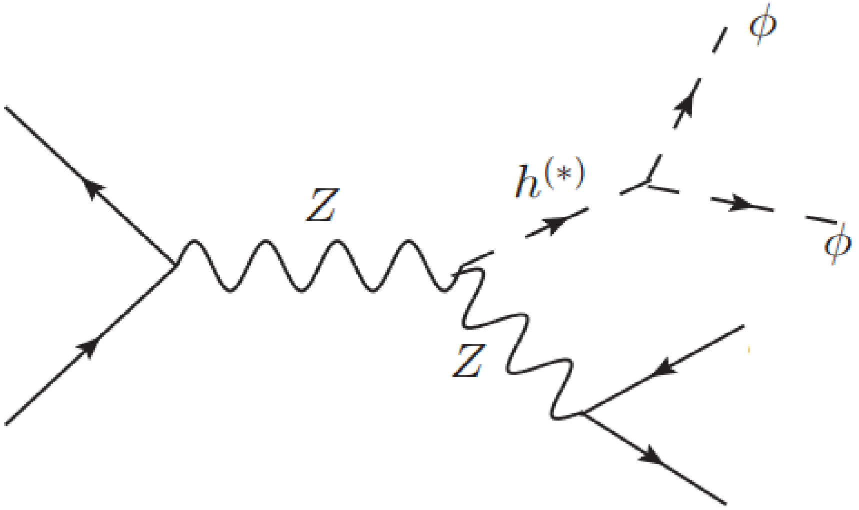
Assuming the production cross section for the Higgs is unchanged, the presence of invisible decays implies a uniform reduction in the rate to all SM final states. This leads to an indirect bound that currently stands at about 20%.

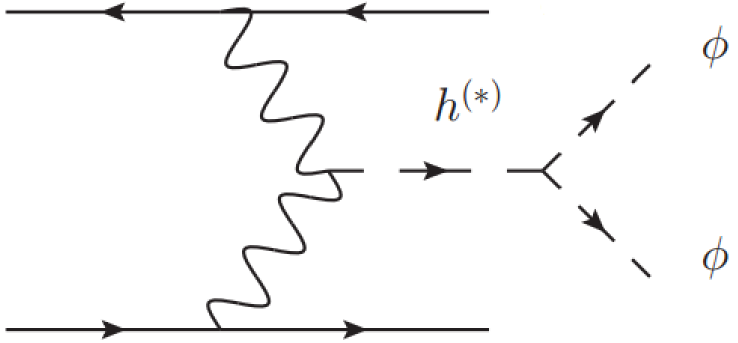
In the future these limits are expected to improve significantly. The direct bound will eventually improve to about 10%, from the VBF channel.

If, however, the hidden sector states are heavy, the Higgs cannot decay into them. Then, to leading order, the Higgs production cross section and decay width are unaffected.

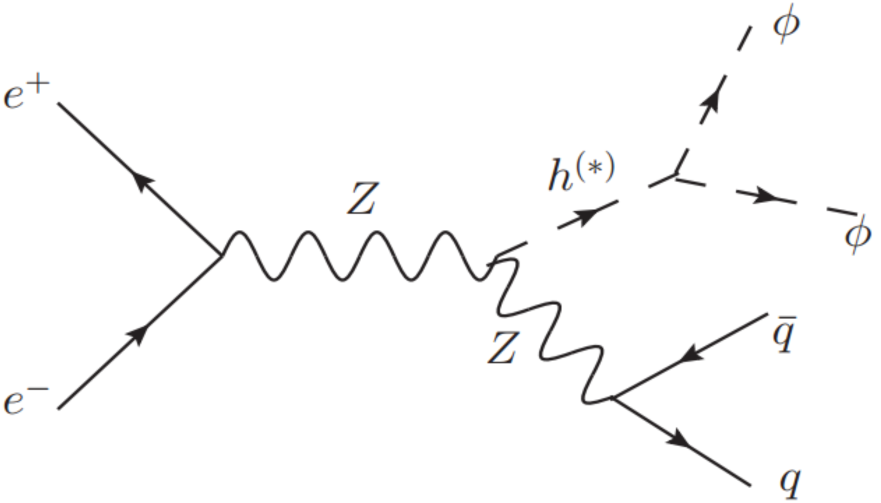
In this scenario, the LHC limits are very weak and are expected to remain so. (Kanemura, Matsumoto, Nabeshima, Okada)

The problem is that the hidden sector states must now be pair produced through an off-shell Higgs. The production cross section therefore receives additional phase space suppression, but without any corresponding reduction in the backgrounds.

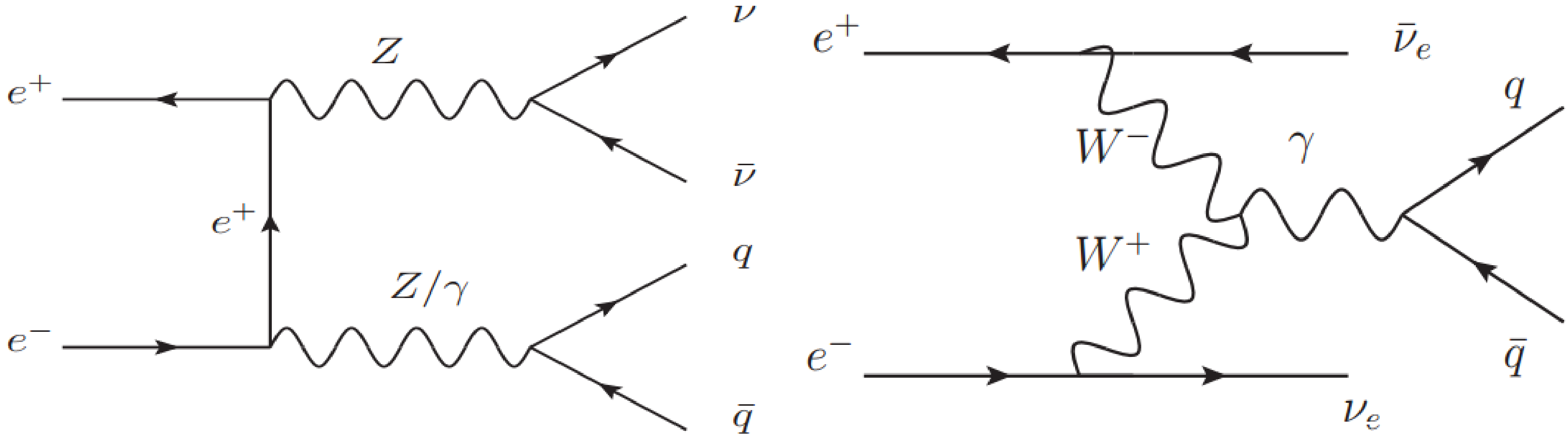




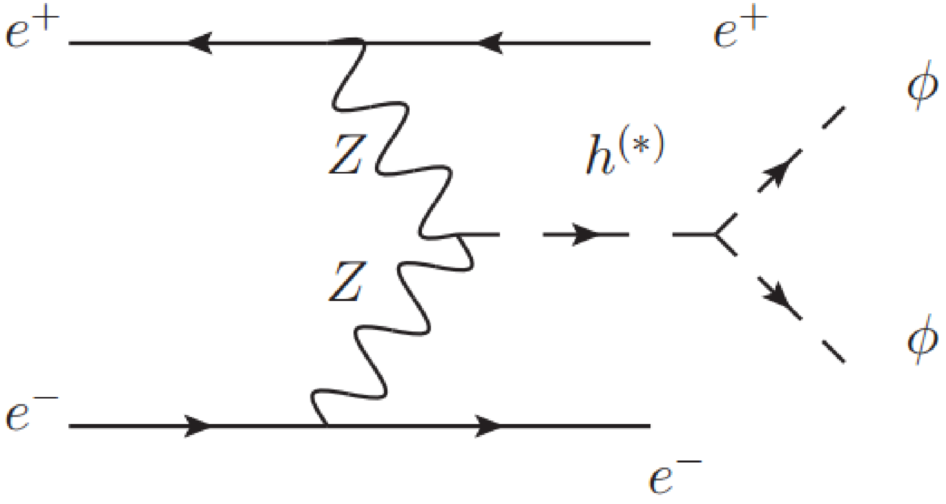
At a lepton collider there are 2 signal channels. The first involves associated production (AP) with a Z, $e^+e^- \to Z\,h^{(*)} \to Z\,\phi\,\phi$.



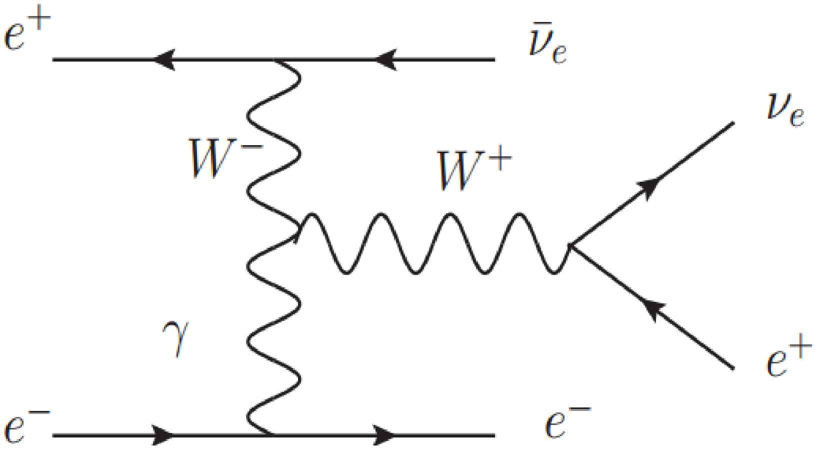
There are significant backgrounds from $e^+e^- \to Z\,Z^{(*)}$ and also processes involving vector boson fusion (VBF).

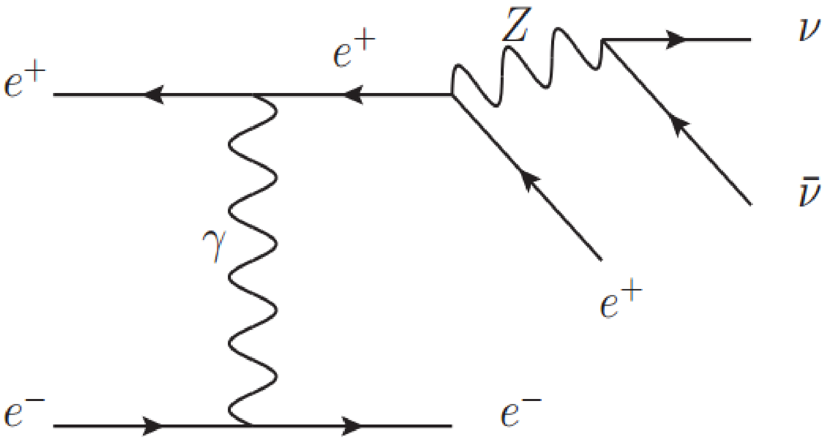


The second involves Z-fusion (ZF), $e^+e^- \rightarrow e^+e^-h^{(*)} \rightarrow e^+e^-\phi\,\phi$.

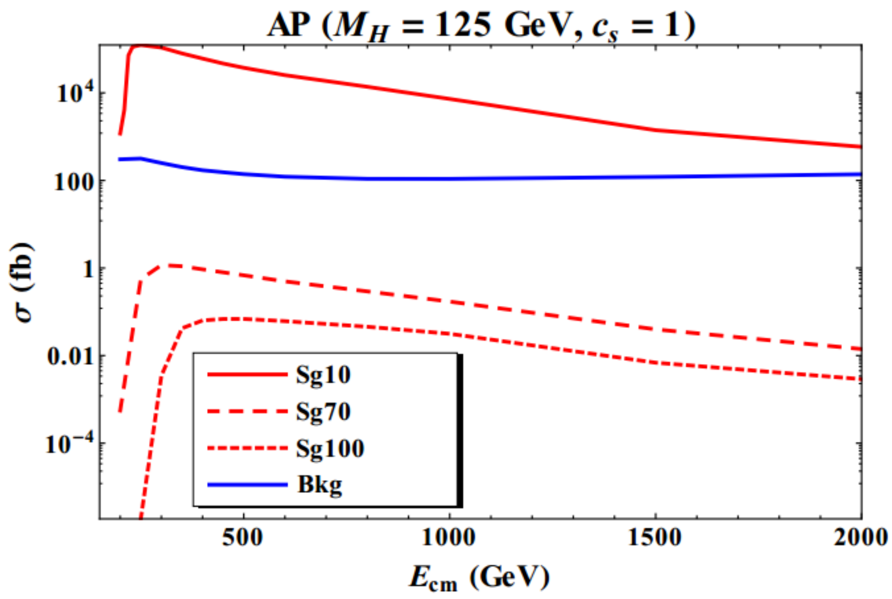


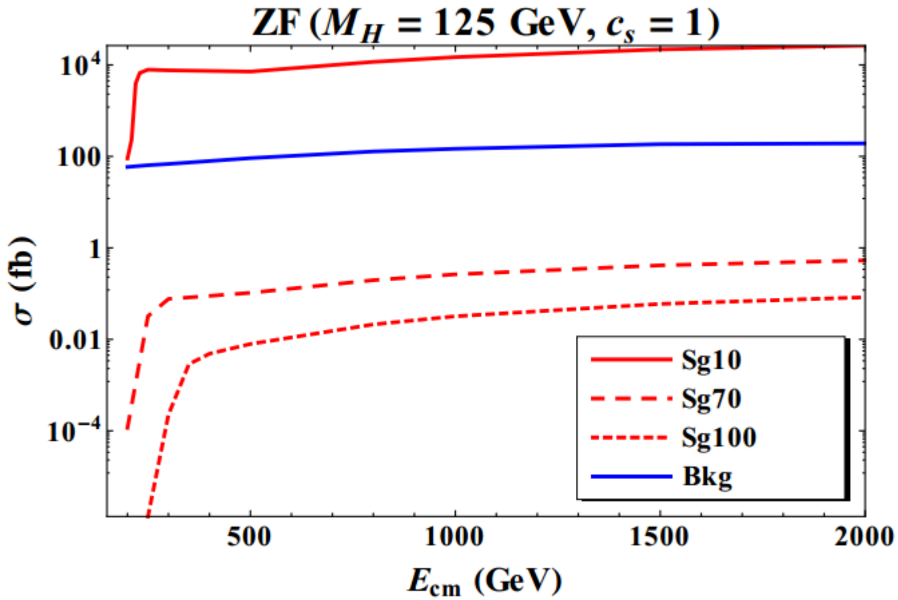
There are sizable backgrounds from $e^+e^- \rightarrow e^+e^-\,Z^{(*)}$ and processes involving VBF.





Compare signals and backgrounds for the AP and ZF channels.



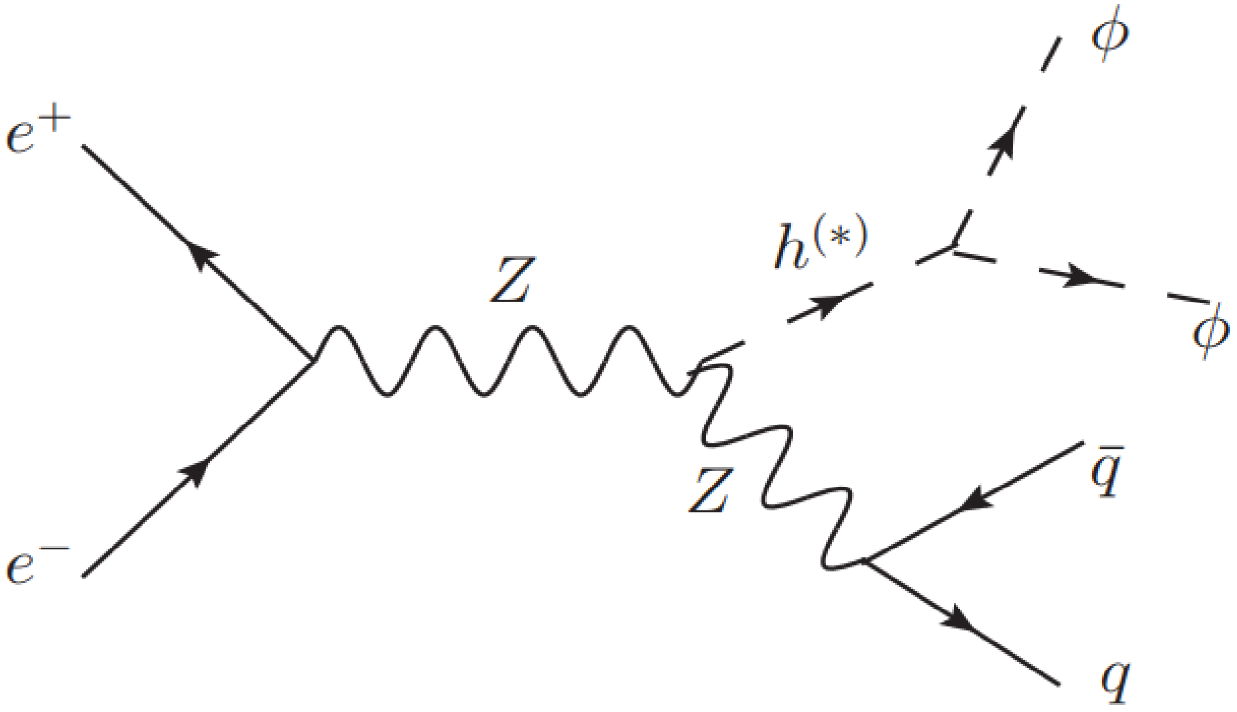


As expected, the signal cross sections plummet once the ϕ mass exceeds half the Higgs mass.

The AP channel seems more promising for smaller center of mass energies, with ZF taking over once E_{CM} is of order a TeV.

The AP Channel

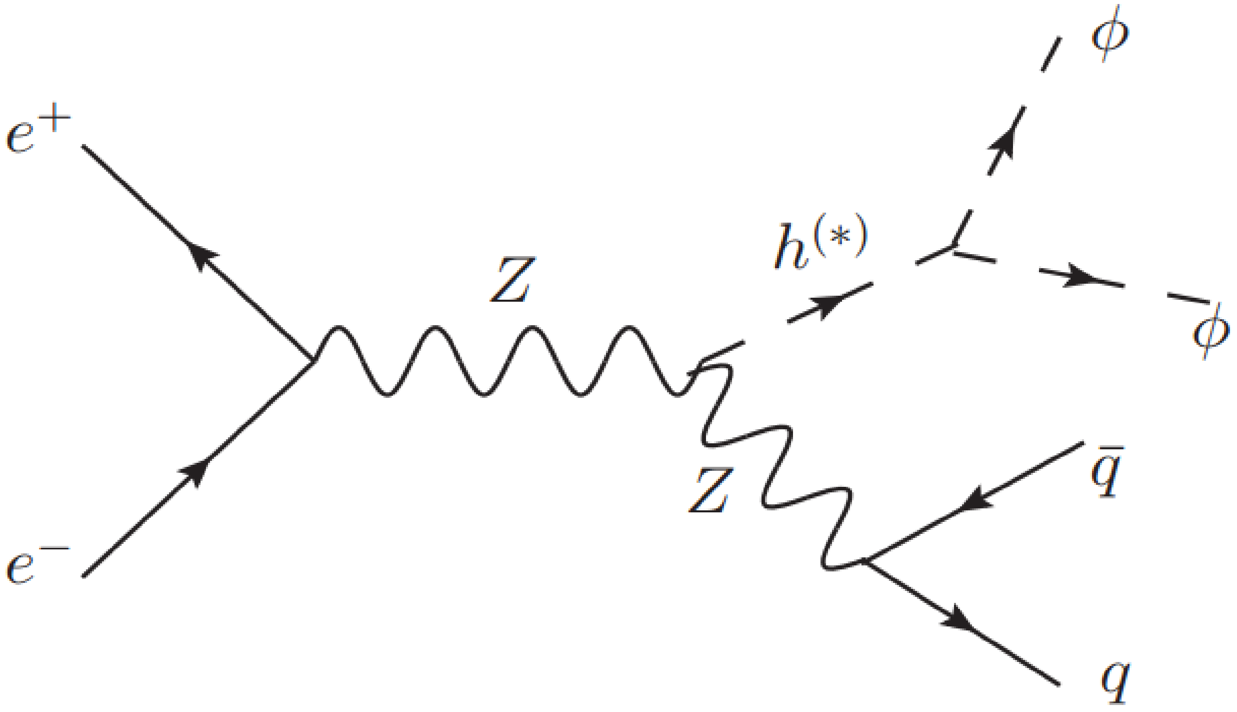
In the AP channel we look for 2 fermions that reconstruct to a *Z*, plus missing energy, $e^+e^- \to Z\,h^{(*)} \to \bar{q}q\ \phi\,\phi$.



We perform a parton level analysis using MadGraph/MadEvent.

We consider ILC center of mass energies of 250, 350 and 500 GeV.

In the AP channel, a very useful cut is on the total Missing Invariant Mass (MIM) in the event.



$$\text{MIM} = \sqrt{E_h^2 - p_h^2} \geq 2m_\phi$$

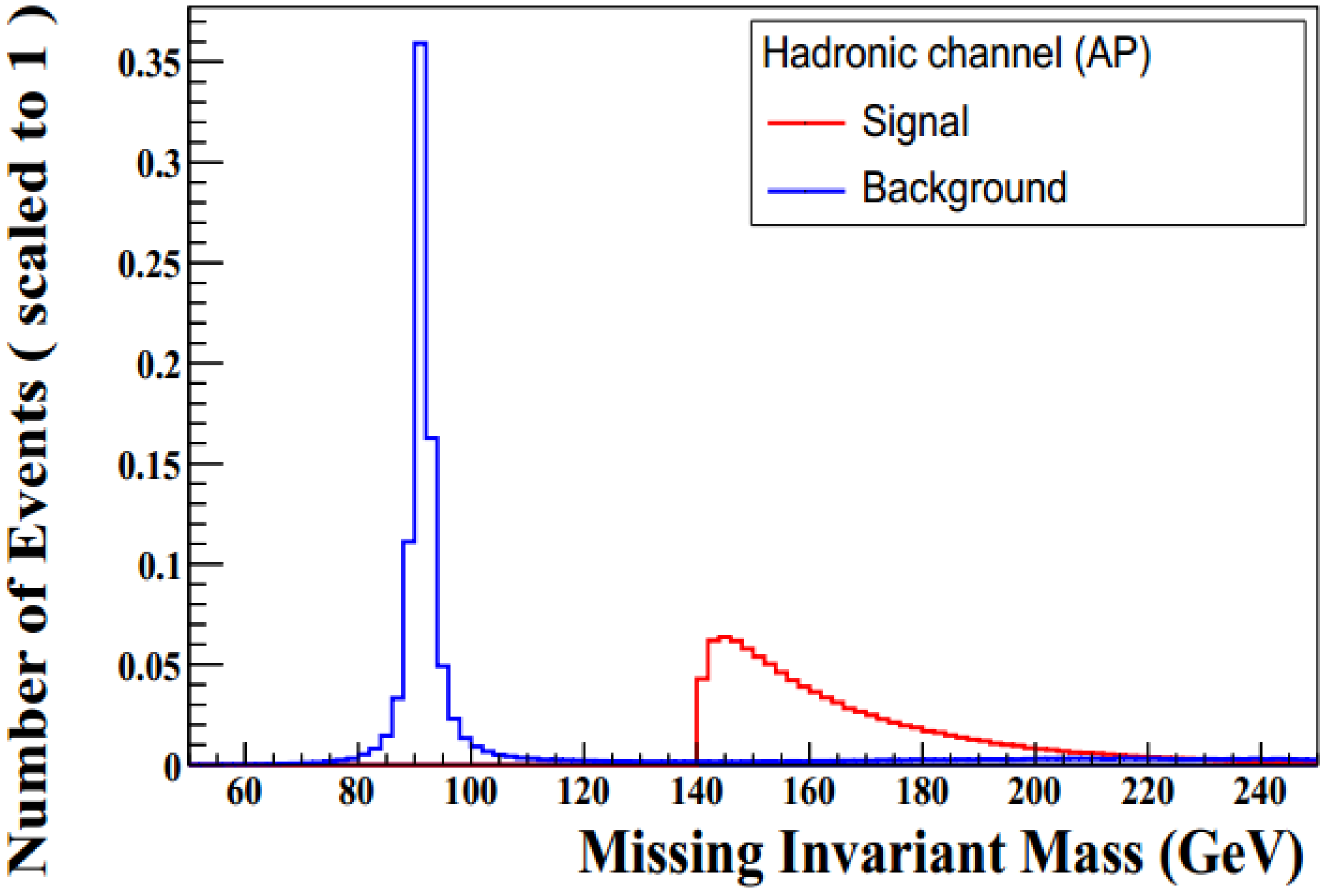
In the case when ϕ is lighter than half the Higgs mass, the MIM in signal events is a narrow peak centered at the Higgs mass.

The background, which largely arises from the decays of on-shell *Z* bosons to neutrinos, has MIM peaked at the *Z* mass.

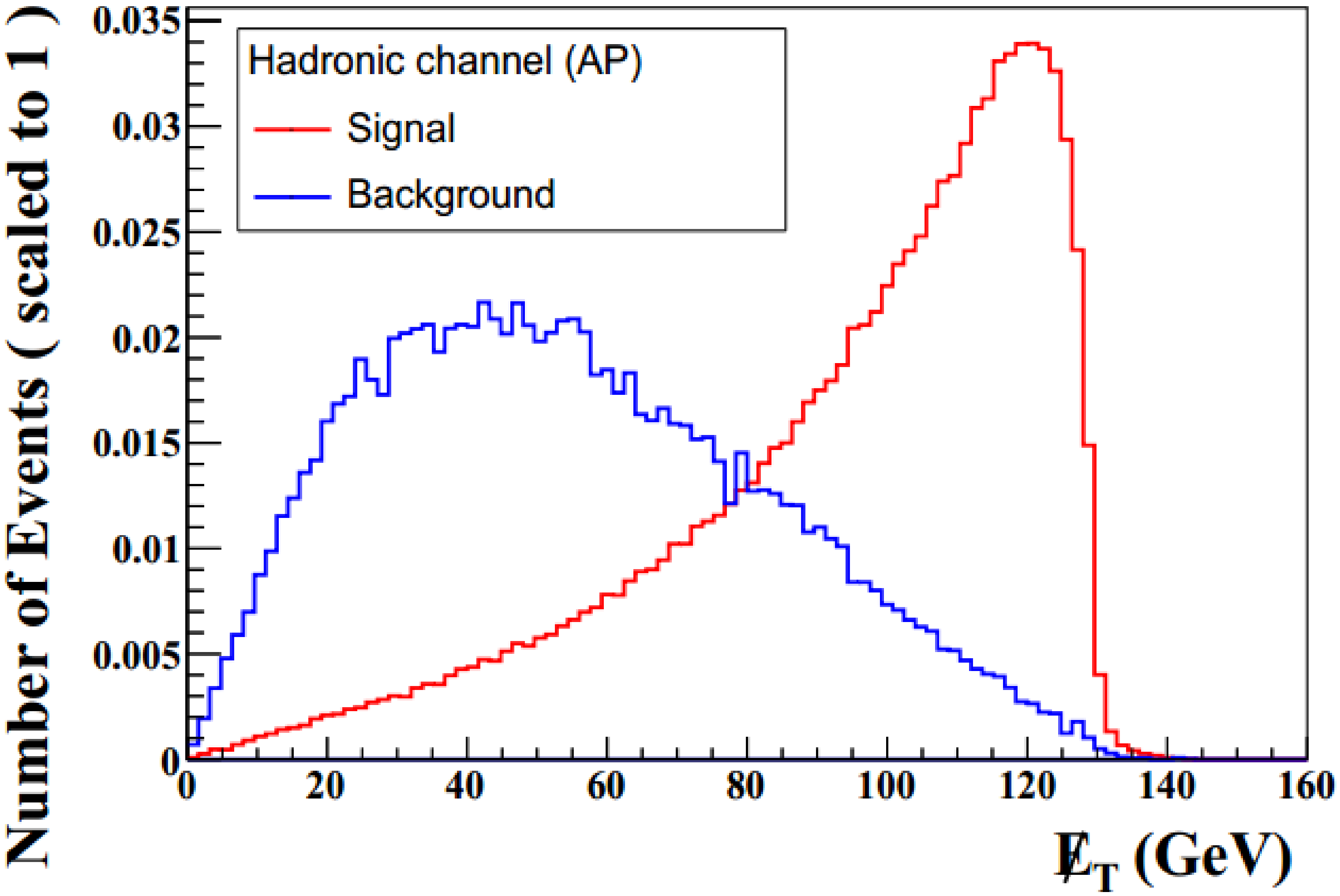
The signal and background are well separated. We assume 3% jet energy resolution, which allows them to be easily distinguished for center of mass energies of order 250 GeV.

There is no analogue of the MIM observable at a hadron collider.

If ϕ is heavier than half the Higgs mass, the signal arises from events involving decays of an off-shell Higgs. In this scenario, the MIM is no longer sharply peaked, but has a distribution that satisfies the condition MIM > $2m_\phi$. As a consequence, signal and background are still well separated for sufficiently low E_{CM}.



In the AP channel, the signal events are typically more central than the background events, so that missing E_T and H_T are also useful variables to cut on.



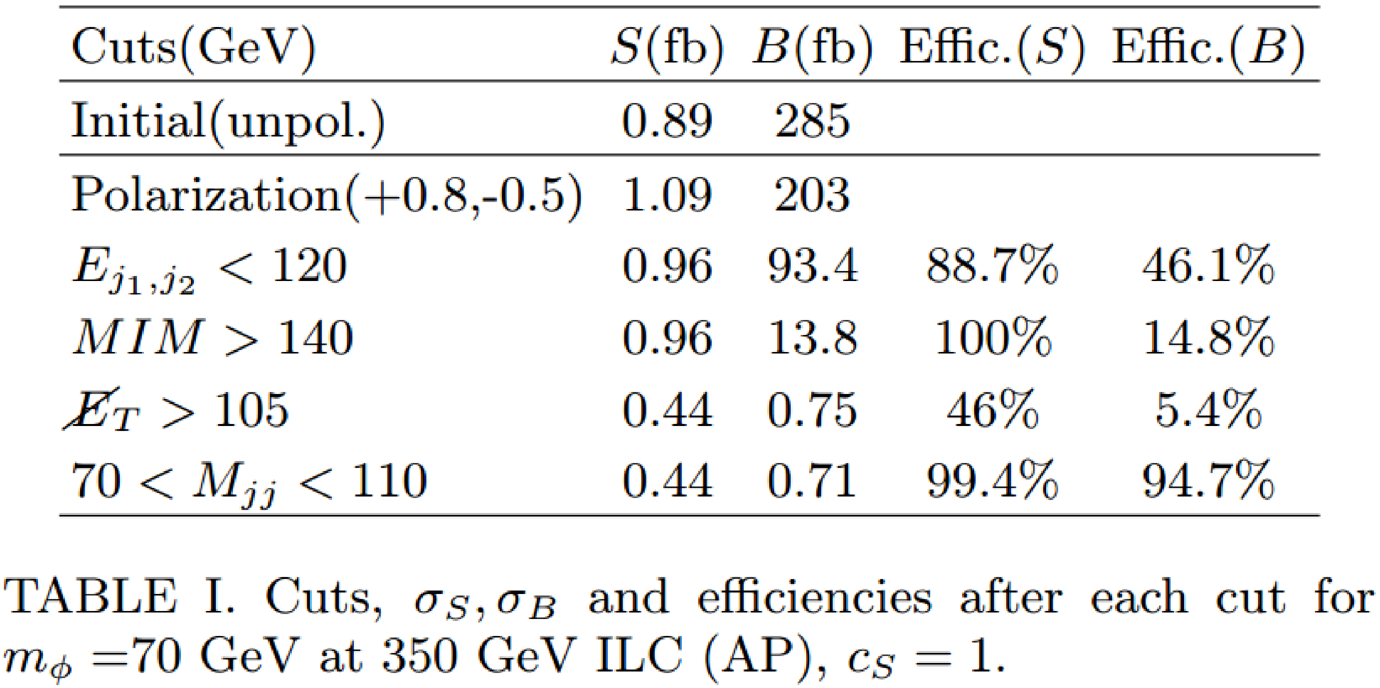
To set limits on invisible Higgs decays from AP, the optimium center of mass energy is of order 250 GeV.

With the help of these cuts, and assuming a favorable beam polarization P$(e^+, e^-) = (+0.8, -0.5)$, the fraction of invisible Higgs decays can be bounded to about 0.15% with 1000 fb^{-1}.

Since this is a parton level analysis, this is probably a best case scenario.

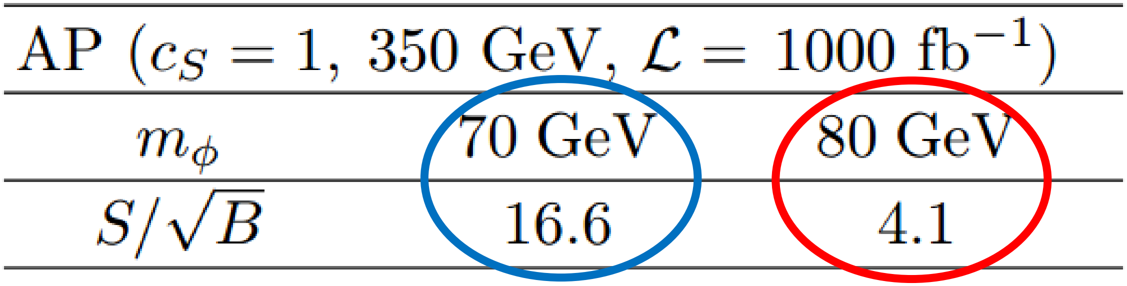
To access heavier hidden sectors, we must operate at higher center of mass energies.

For a ϕ mass of about 70 GeV, the optimum center of mass energy in the AP channel is about 350 GeV.



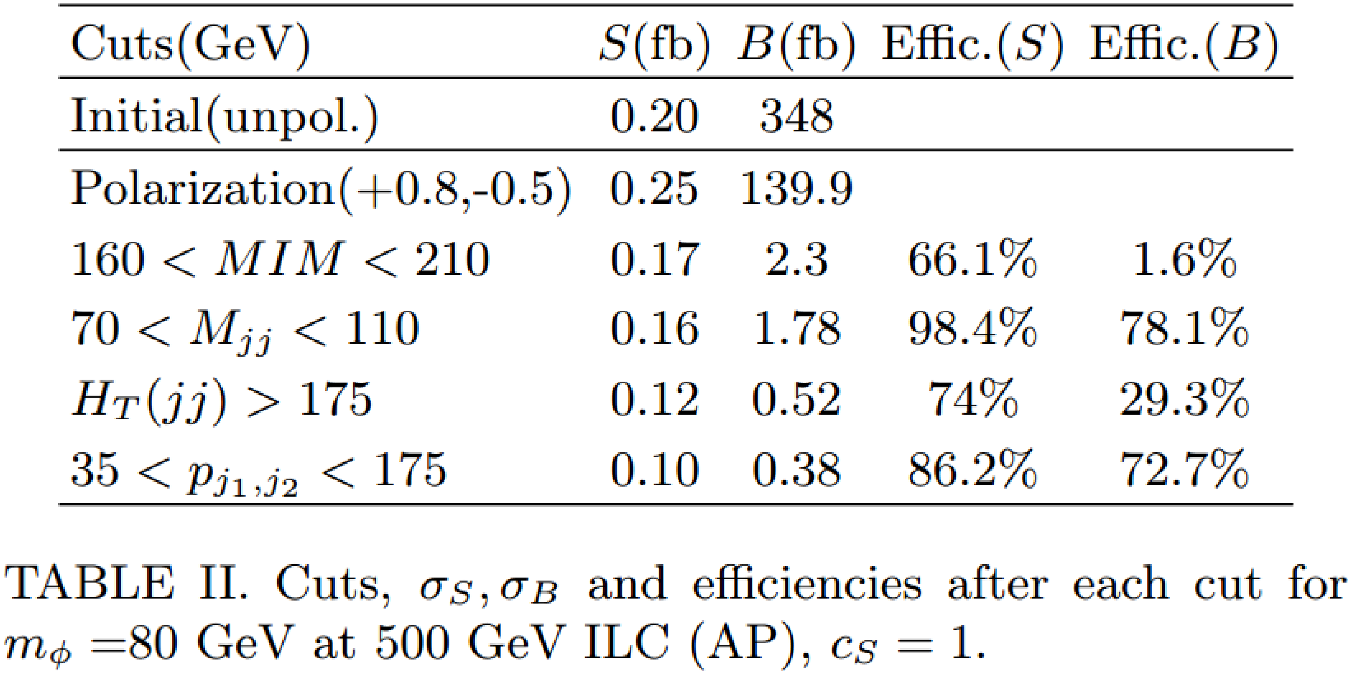
Cuts(GeV)	S(fb)	B(fb)	Effic.(S)	Effic.(B)
Initial(unpol.)	0.89	285		
Polarization(+0.8,-0.5)	1.09	203		
$E_{j_1,j_2} < 120$	0.96	93.4	88.7%	46.1%
$MIM > 140$	0.96	13.8	100%	14.8%
$\not{E}_T > 105$	0.44	0.75	46%	5.4%
$70 < M_{jj} < 110$	0.44	0.71	99.4%	94.7%

TABLE I. Cuts, σ_S, σ_B and efficiencies after each cut for m_ϕ =70 GeV at 350 GeV ILC (AP), $c_S = 1$.



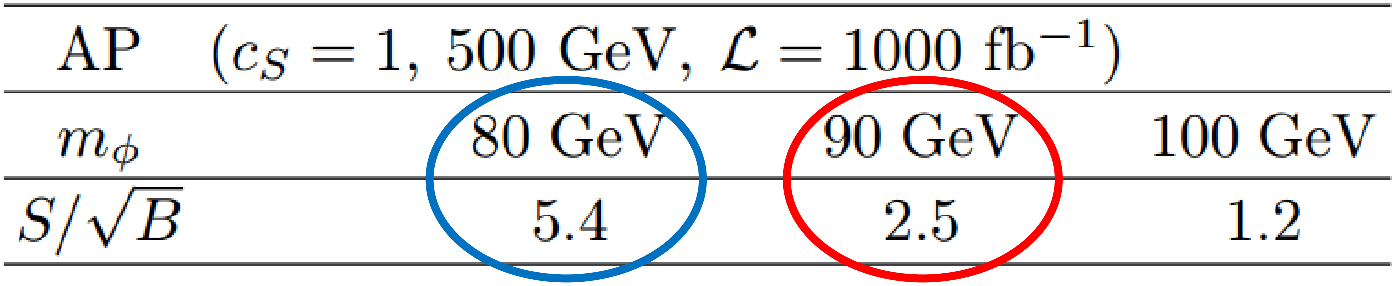
AP ($c_S = 1$, 350 GeV, $\mathcal{L} = 1000\ \text{fb}^{-1}$)		
m_ϕ	70 GeV	80 GeV
$S/\sqrt{B}$	16.6	4.1

For a ϕ mass of 80 GeV, we obtain greater sensitivity with a center of mass energy of 500 GeV.



Cuts(GeV)	S(fb)	B(fb)	Effic.(S)	Effic.(B)
Initial(unpol.)	0.20	348		
Polarization(+0.8,-0.5)	0.25	139.9		
$160 < MIM < 210$	0.17	2.3	66.1%	1.6%
$70 < M_{jj} < 110$	0.16	1.78	98.4%	78.1%
$H_T(jj) > 175$	0.12	0.52	74%	29.3%
$35 < p_{j_1,j_2} < 175$	0.10	0.38	86.2%	72.7%

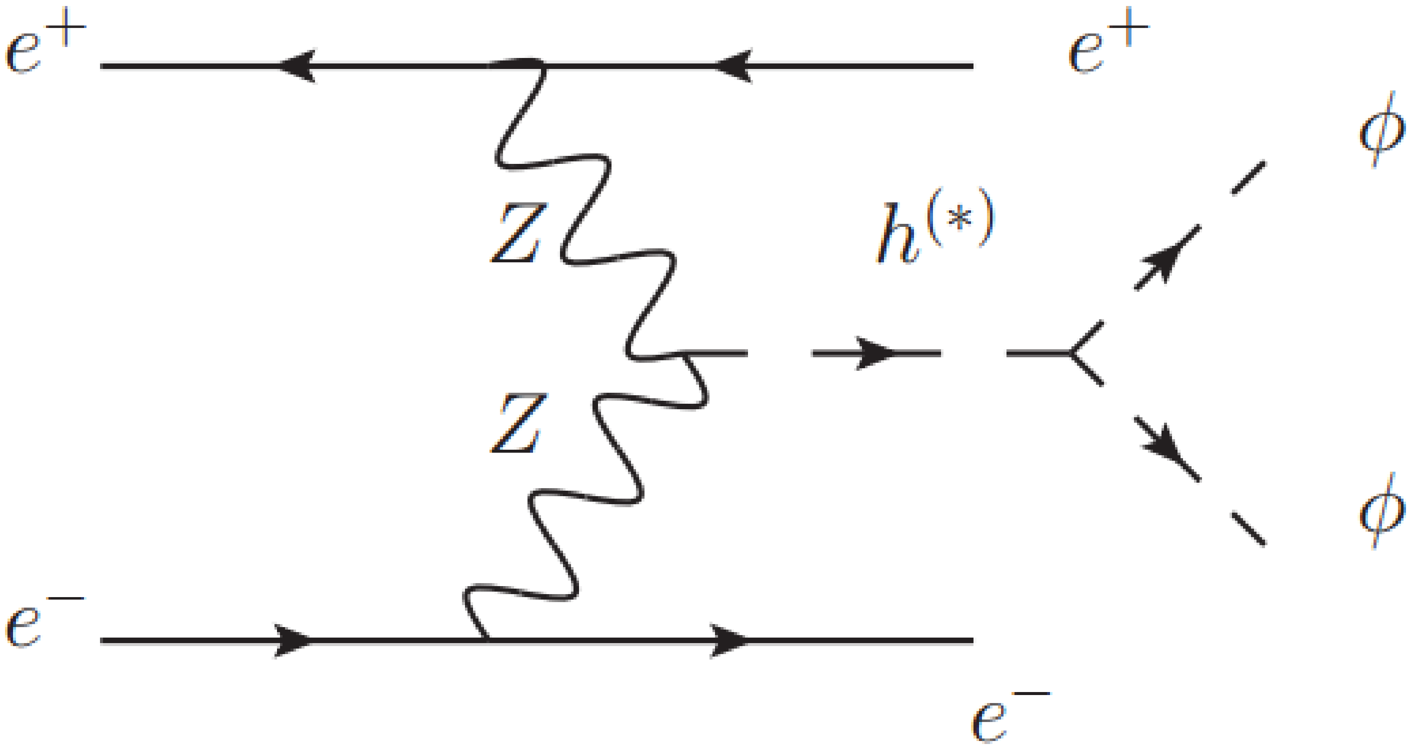
TABLE II. Cuts, σ_S, σ_B and efficiencies after each cut for m_ϕ =80 GeV at 500 GeV ILC (AP), $c_S = 1$.



AP $(c_S = 1,\ 500\ \text{GeV},\ \mathcal{L} = 1000\ \text{fb}^{-1})$			
m_ϕ	80 GeV	90 GeV	100 GeV
$S/\sqrt{B}$	5.4	2.5	1.2

The ZF Channel

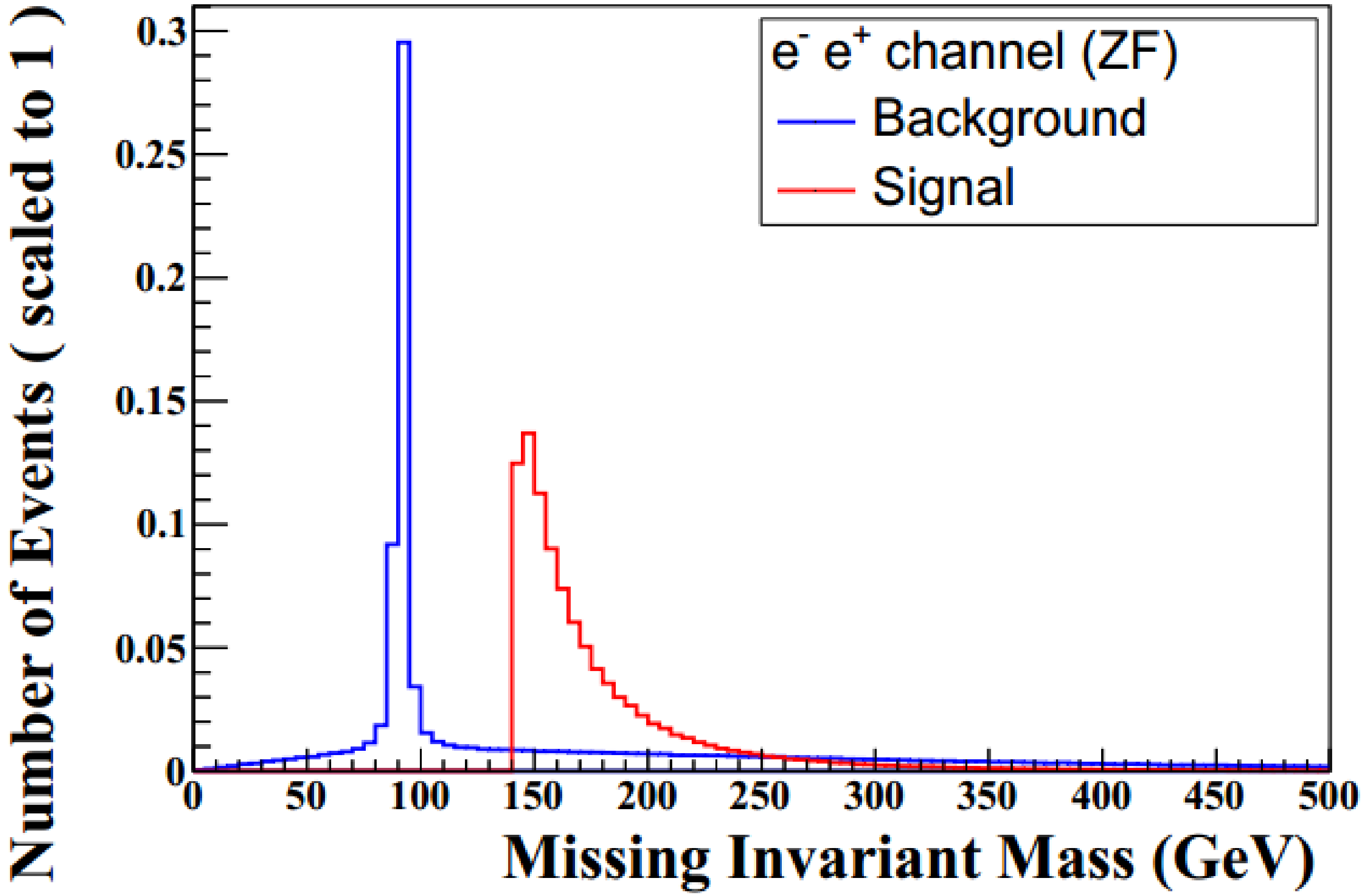
In the ZF channel we look for an e^+e^- pair plus missing energy,
$e^+e^- \to e^+e^-h^{(*)} \to e^+e^-\phi\,\phi$.



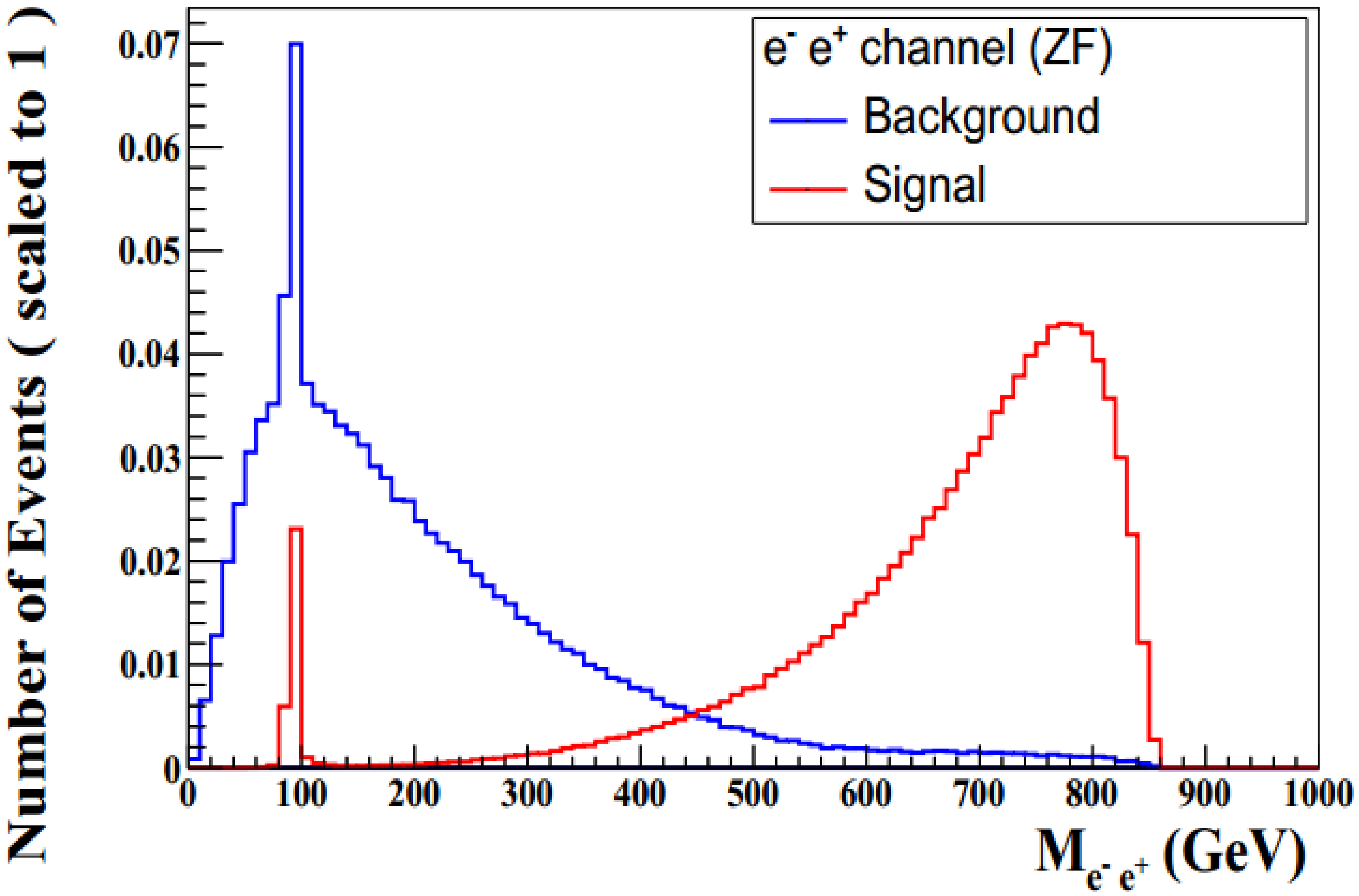
We perform a parton level analysis using MadGraph/MadEvent.

We consider ILC center of mass energy of 1 TeV.

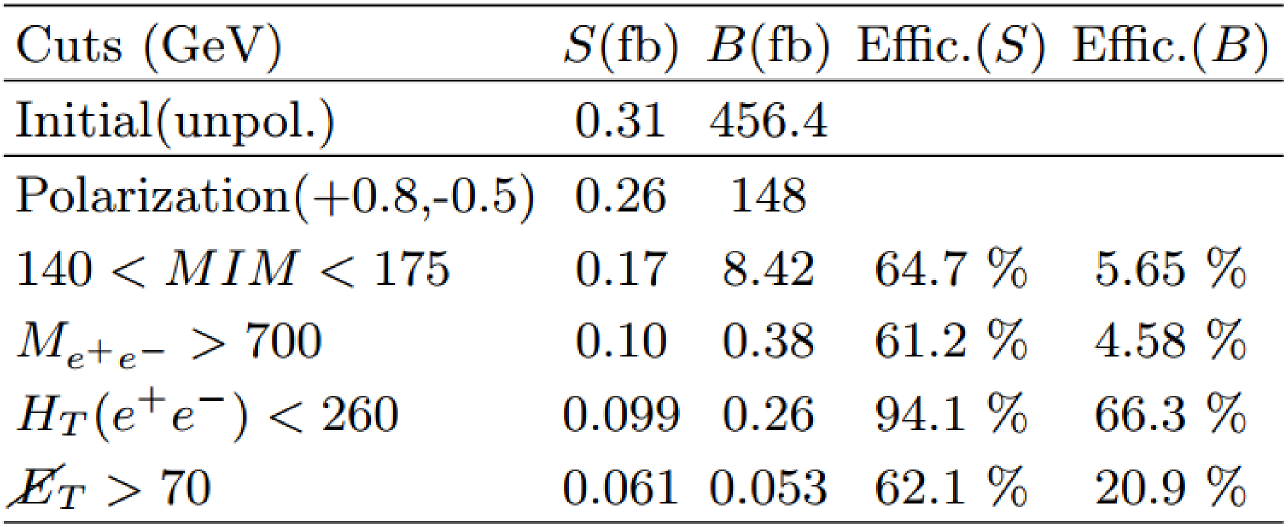
Once again MIM is a useful variable to cut on.



The invariant mass of the e^+e^- pair is also a useful variable to cut on. In the signal events, the e^+ and e^- tend to lie along the forward and backward directions, and have large invariant mass.

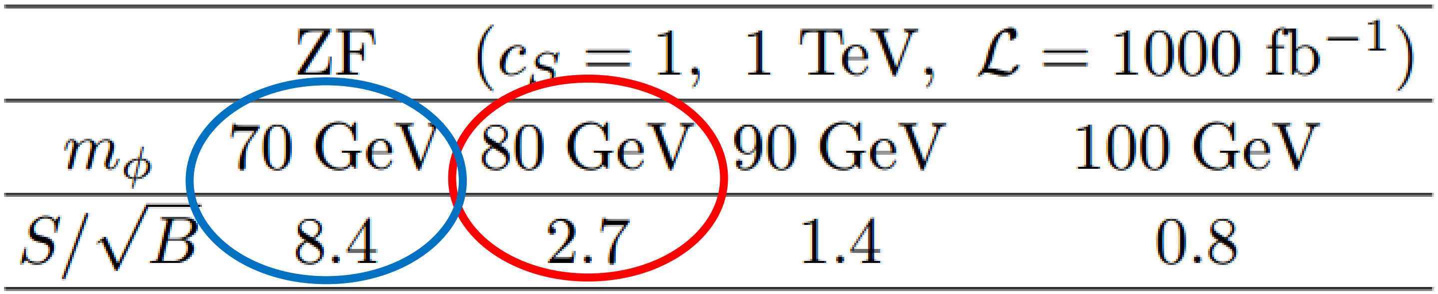


With 1000 fb^{-1} of data at center of mass energy 1 TeV, we are sensitive to ϕ masses up to about 80 GeV.



Cuts (GeV)	S(fb)	B(fb)	Effic.(S)	Effic.(B)
Initial(unpol.)	0.31	456.4		
Polarization(+0.8,-0.5)	0.26	148		
$140 < MIM < 175$	0.17	8.42	64.7 %	5.65 %
$M_{e^+e^-} > 700$	0.10	0.38	61.2 %	4.58 %
$H_T(e^+e^-) < 260$	0.099	0.26	94.1 %	66.3 %
$\not{E}_T > 70$	0.061	0.053	62.1 %	20.9 %

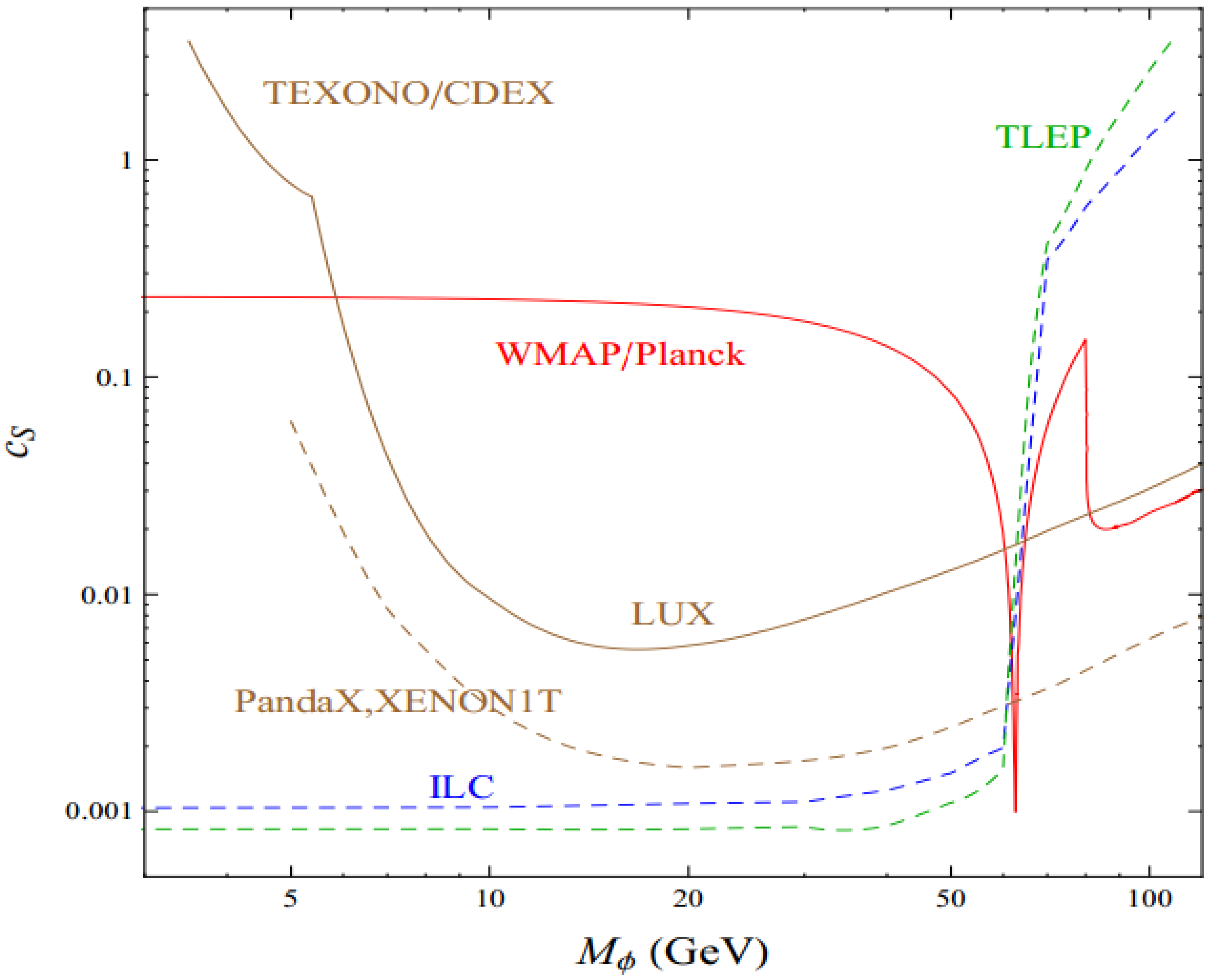
TABLE III. Cuts, σ_S, σ_B and efficiencies after each cut for m_ϕ =70 GeV at 1 TeV ILC (ZF), $c_S = 1$.



	ZF	$(c_S = 1,\ 1\ \text{TeV},\ \mathcal{L} = 1000\ \text{fb}^{-1})$		
m_ϕ	70 GeV	80 GeV	90 GeV	100 GeV
$S/\sqrt{B}$	8.4	2.7	1.4	0.8

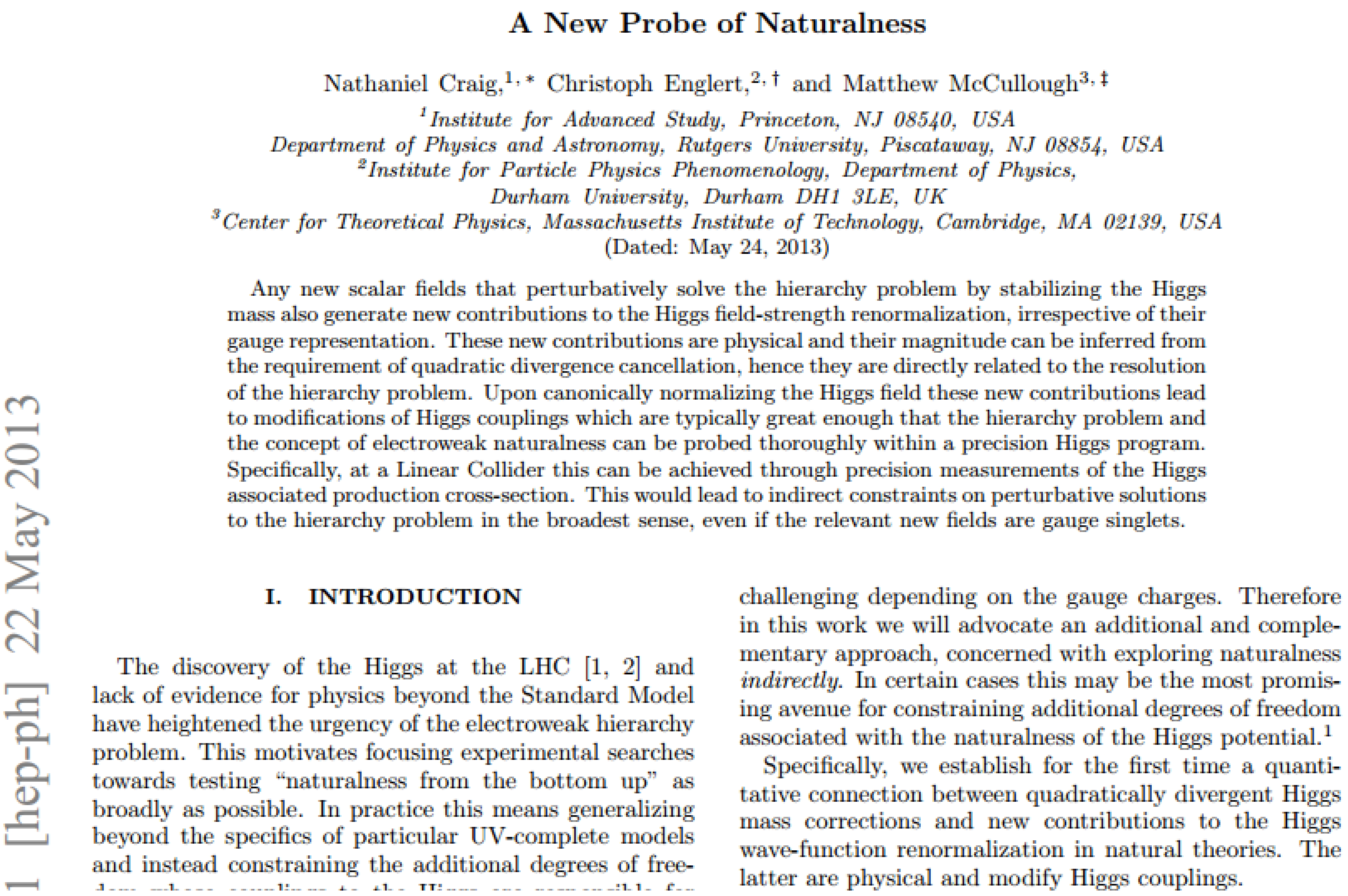
Results

We show the expected 2σ limits on this scenario as a function of the parameters m_ϕ and c_s. The preferred range for thermal relic dark matter and the limits from direct detection are also shown.



Indirect Signals

Craig, Englert & McCullough



A New Probe of Naturalness

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Any new scalar fields that perturbatively solve the hierarchy problem by stabilizing the Higgs mass also generate new contributions to the Higgs field-strength renormalization, irrespective of their gauge representation. These new contributions are physical and their magnitude can be inferred from the requirement of quadratic divergence cancellation, hence they are directly related to the resolution of the hierarchy problem. Upon canonically normalizing the Higgs field these new contributions lead to modifications of Higgs couplings which are typically great enough that the hierarchy problem and the concept of electroweak naturalness can be probed thoroughly within a precision Higgs program. Specifically, at a Linear Collider this can be achieved through precision measurements of the Higgs associated production cross-section. This would lead to indirect constraints on perturbative solutions to the hierarchy problem in the broadest sense, even if the relevant new fields are gauge singlets.

I. INTRODUCTION

The discovery of the Higgs at the LHC [1, 2] and lack of evidence for physics beyond the Standard Model have heightened the urgency of the electroweak hierarchy problem. This motivates focusing experimental searches towards testing "naturalness from the bottom up" as broadly as possible. In practice this means generalizing beyond the specifics of particular UV-complete models and instead constraining the additional degrees of free-

challenging depending on the gauge charges. Therefore in this work we will advocate an additional and complementary approach, concerned with exploring naturalness *indirectly*. In certain cases this may be the most promising avenue for constraining additional degrees of freedom associated with the naturalness of the Higgs potential.[1]

Specifically, we establish for the first time a quantitative connection between quadratically divergent Higgs mass corrections and new contributions to the Higgs wave-function renormalization in natural theories. The latter are physical and modify Higgs couplings.

The limits on the off-shell Higgs portal are rather weak. Even with 1000 fb^{-1} of data, the reach is limited to ϕ masses less than, or of order, 200 GeV.

Is it possible to do better by making precision measurements of the Higgs couplings?

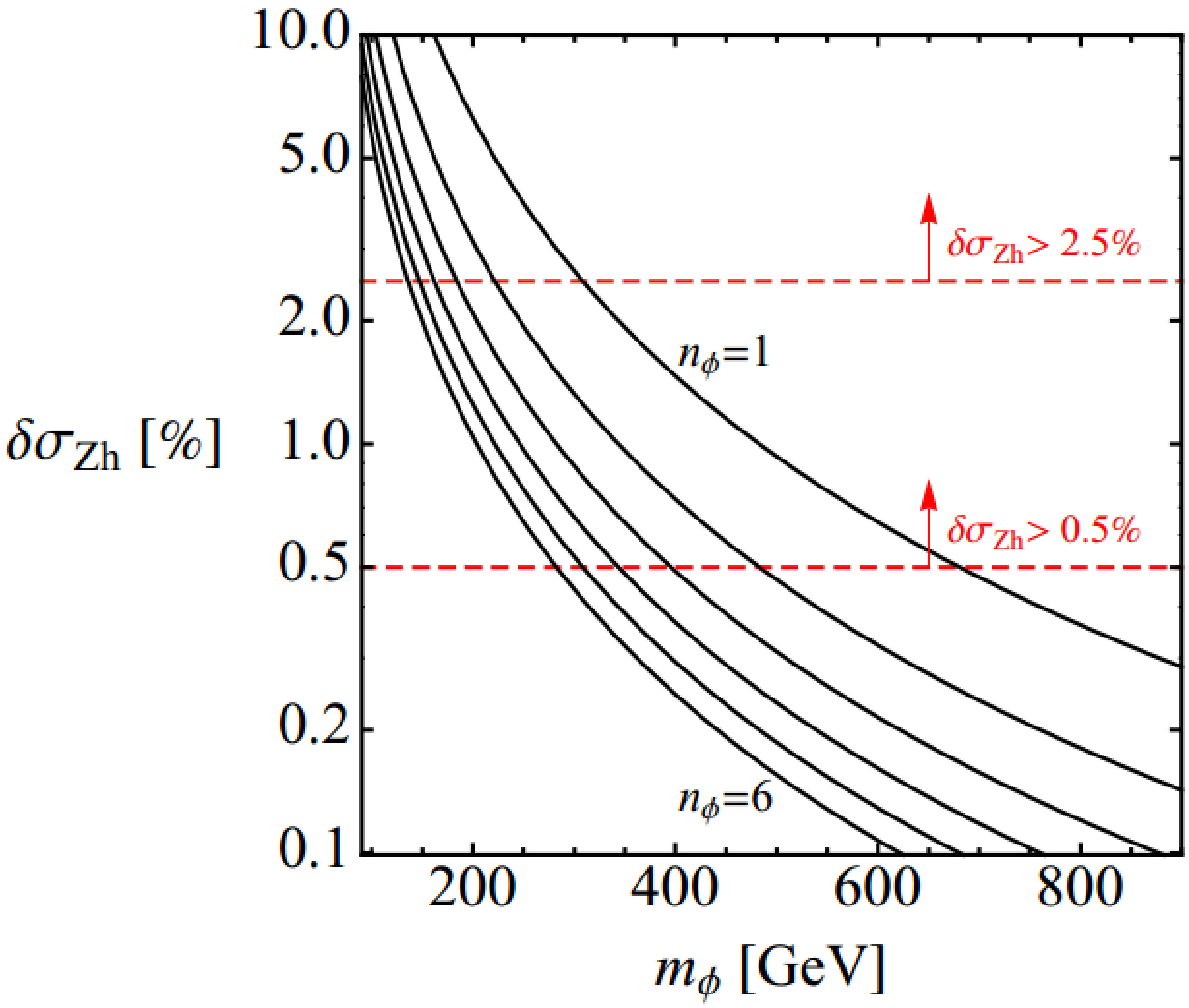
Craig, Englert and McCullough showed that when the scalar is heavy and can be integrated out, there is a correction to the *ZZH* vertex.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \ldots$$

This in turn leads to a correction to the AP cross section.

$$\delta\sigma_{Zh} = -2c_H \frac{v^2}{m_\phi^2} = -\frac{n_\phi |\lambda_\phi|^2}{48\pi^2}\frac{v^2}{m_\phi^2}$$

For heavier ϕ masses, these indirect constraints lead to stronger limits than can be obtained from direct ϕ production.



Conclusions

Lepton colliders can be used to probe Higgs portal scenarios to much greater sensitivity than the LHC.

Light hidden sectors can be probed through invisible decays of the Higgs. Bounds on invisible decays at a lepton collider are expected to be up to 2 orders of magnitude better than at LHC.

Heavier hidden sectors can be probed up to ϕ masses of order 100 GeV. The LHC has only minimal sensitivity to this scenario.

For dark matter masses lighter than half the Higgs mass, lepton colliders are expected to be more sensitive than the next generation direct detection experiments.

However, for heavier dark matter masses, current direct detection experiments are more sensitive.

Precision measurements of AP can probe ϕ masses even heavier than 100 GeV, provided the couplings are large enough.