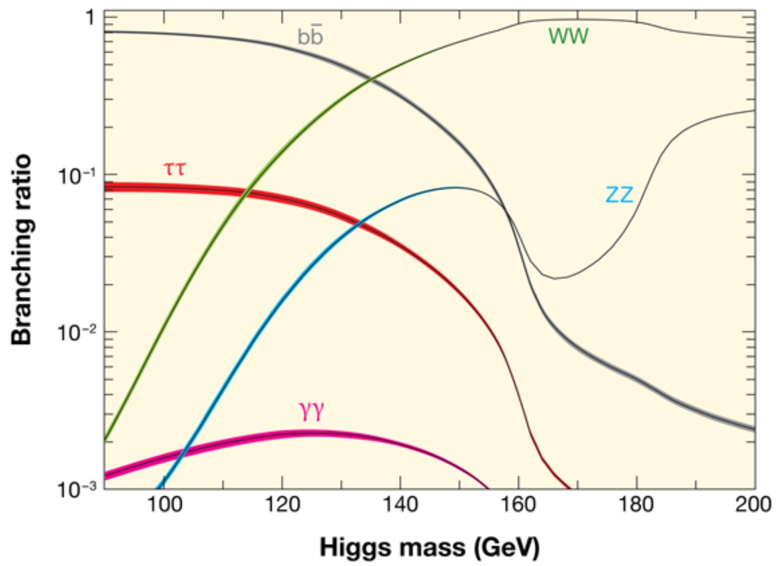
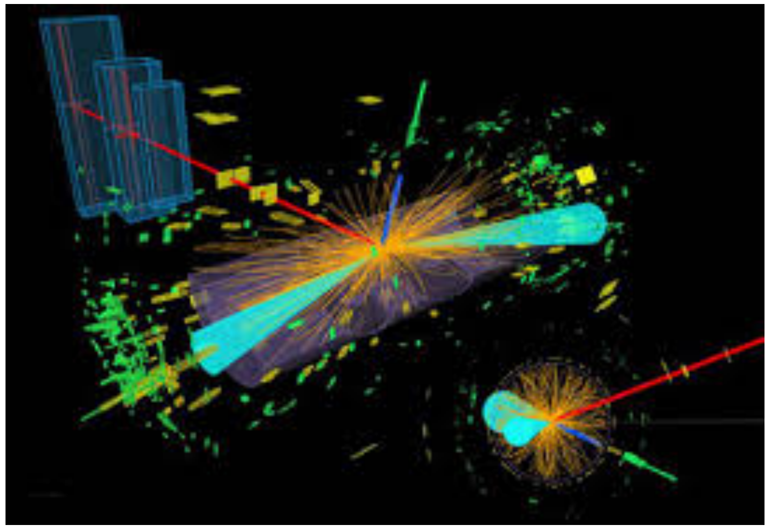


Power meets Precision to explore the Symmetric Higgs Portal

Michael Spannowsky

IPPP, Durham University

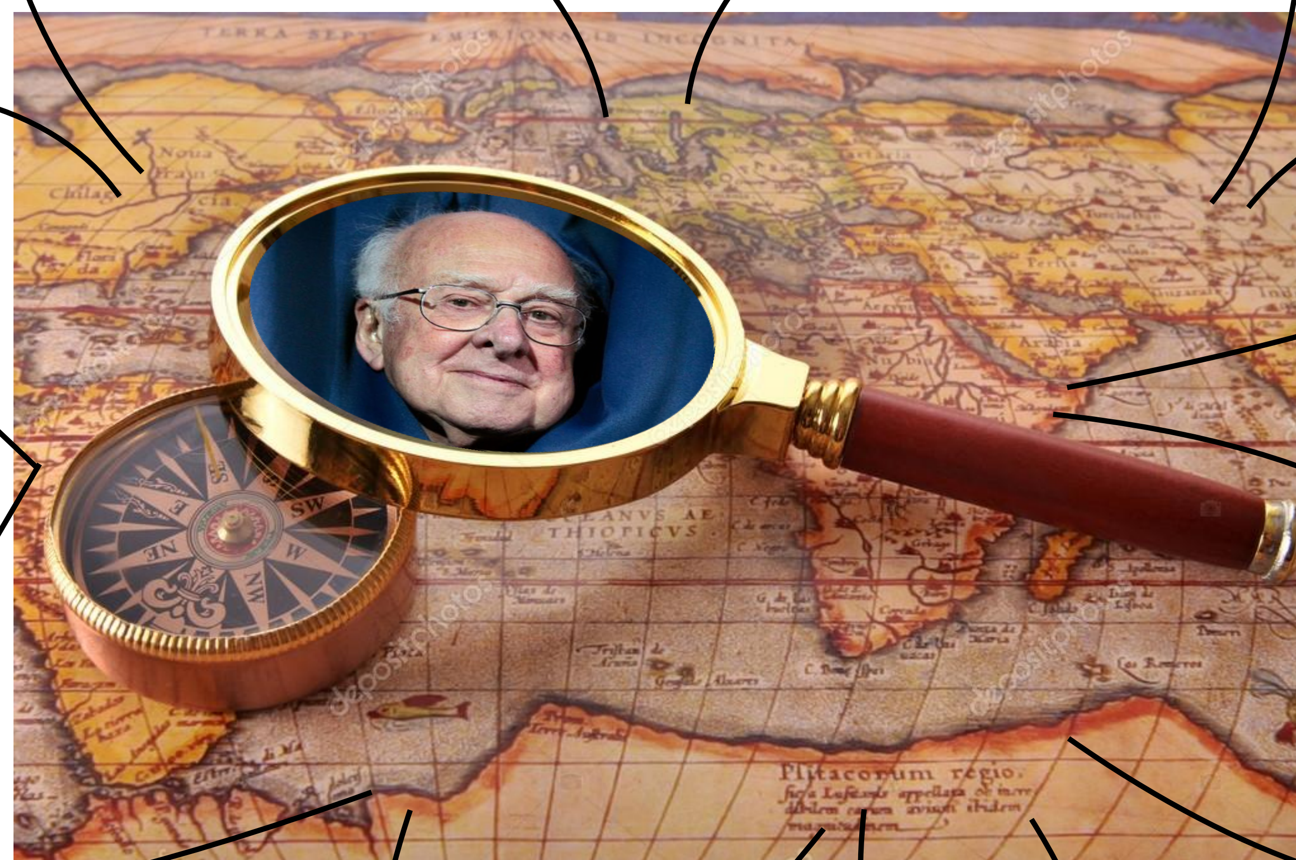
In collaboration with
C. Englert, J. Jaeckel and P. Stylianou

hierarchy problem

non-pert. topological defects

elementary or composite

Matter/Antimatter asymmetry



Inflation and Reheating

Global structure of SSB potential

CP violation

Existence of light dof

$\mathbb{Z}_2$-symmetric Higgs portal

- Close to most-minimal extension of SM: 1 scalar singlet and a discrete symmetry

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

above mh/2 or below

well-behaved theory

with Z2 or without

- Kinematically generic situation: Higgs portal without new Higgs decay
- S can serve as potential dark matter candidate
- S can only be pair produced and might be heavy
- Seemingly simple but phenomenologically highly challenging scenario
- Far less sensitivity than for other portals, eg. kinetic mixing or neutrino portal

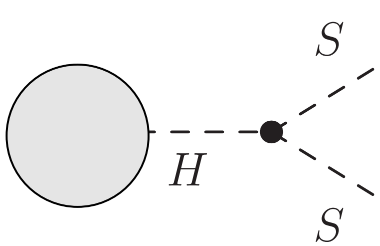
$\mathbb{Z}_2$-symmetric Higgs portal

- Close to most-minimal extension of SM: 1 scalar singlet and a discrete symmetry

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

[Englert, Jaeckel, MS, Stylianou `20]

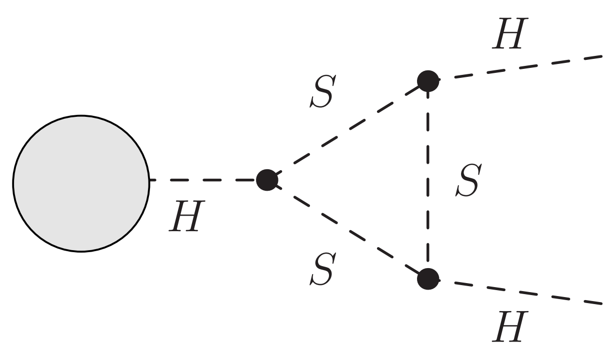
direct search



off-shell production

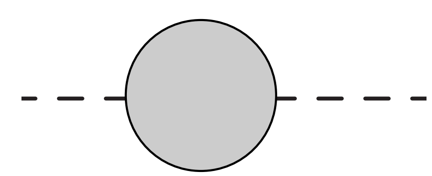
[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]

indirect probes



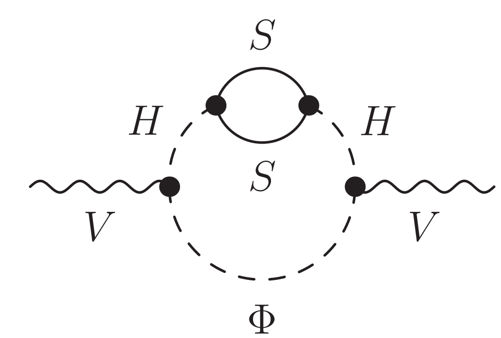
di-Higgs pheno

[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]



single Higgs couplings

[Englert, McCullough ` 13]
[Craig, Englert, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]



oblique corrections

[Englert, Jaeckel, MS, Stylianou ` 20]

Direct searches at a hadron colliders

Associate production

- Insensitive due to small cs

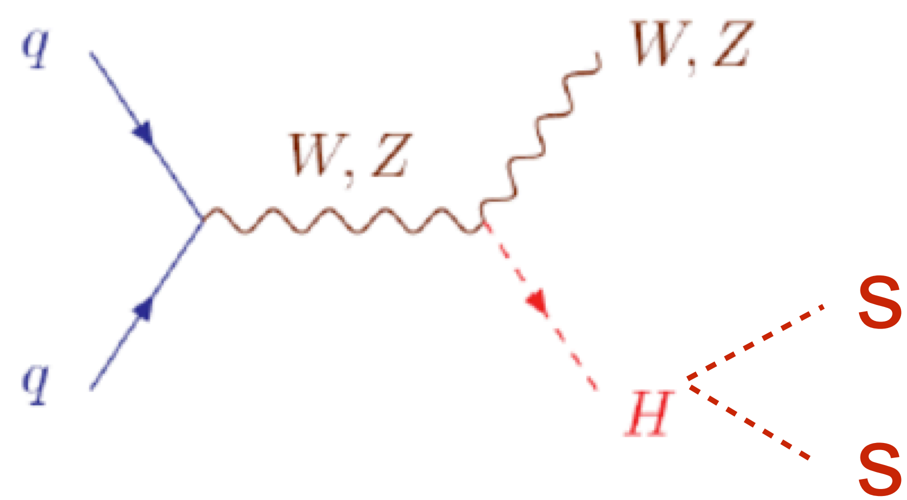
$\lambda = 1$

$m_S \simeq 100$ GeV

@ 100 TeV

$\mathcal{O}(10^{-2})$ fb

before any cuts



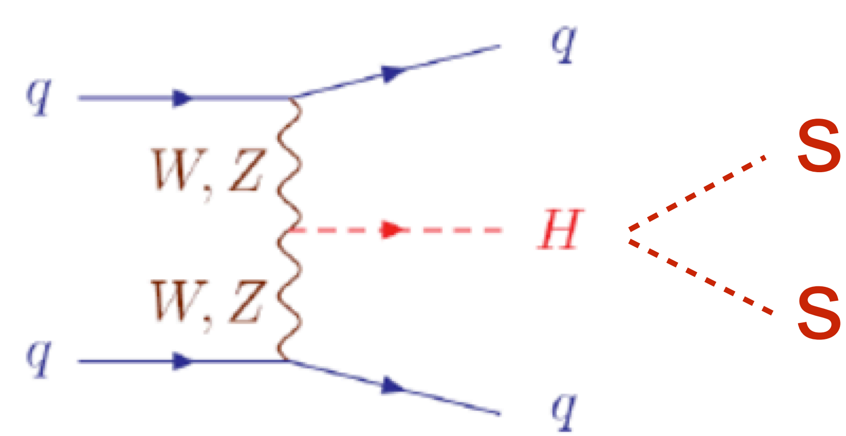
Weak boson fusion

- Search in MET + 2 jets

- Usual WBF cuts

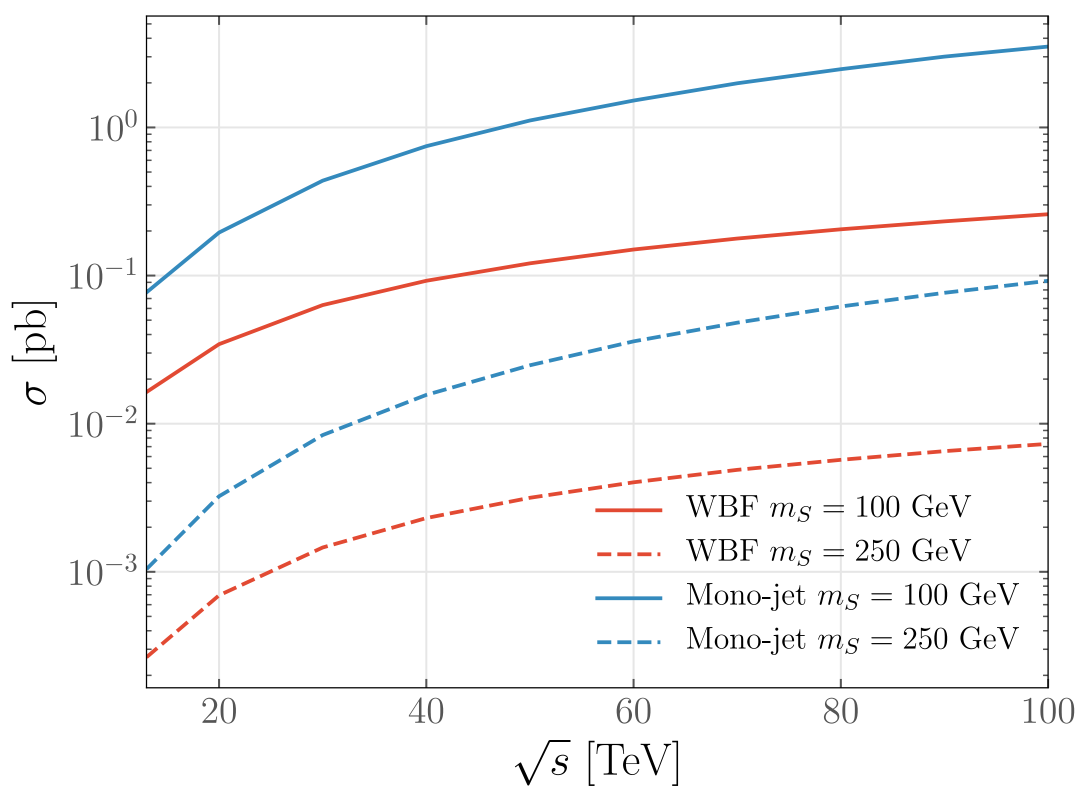
$|\Delta\eta(jj)| > 4.0 \qquad |\eta(j)| < 4.7$

$p_T(j) \geq 50$ GeV $\qquad \eta(j_1)\eta(j_2) < 0 \qquad |\Delta\phi_{jj}| < 1.5$

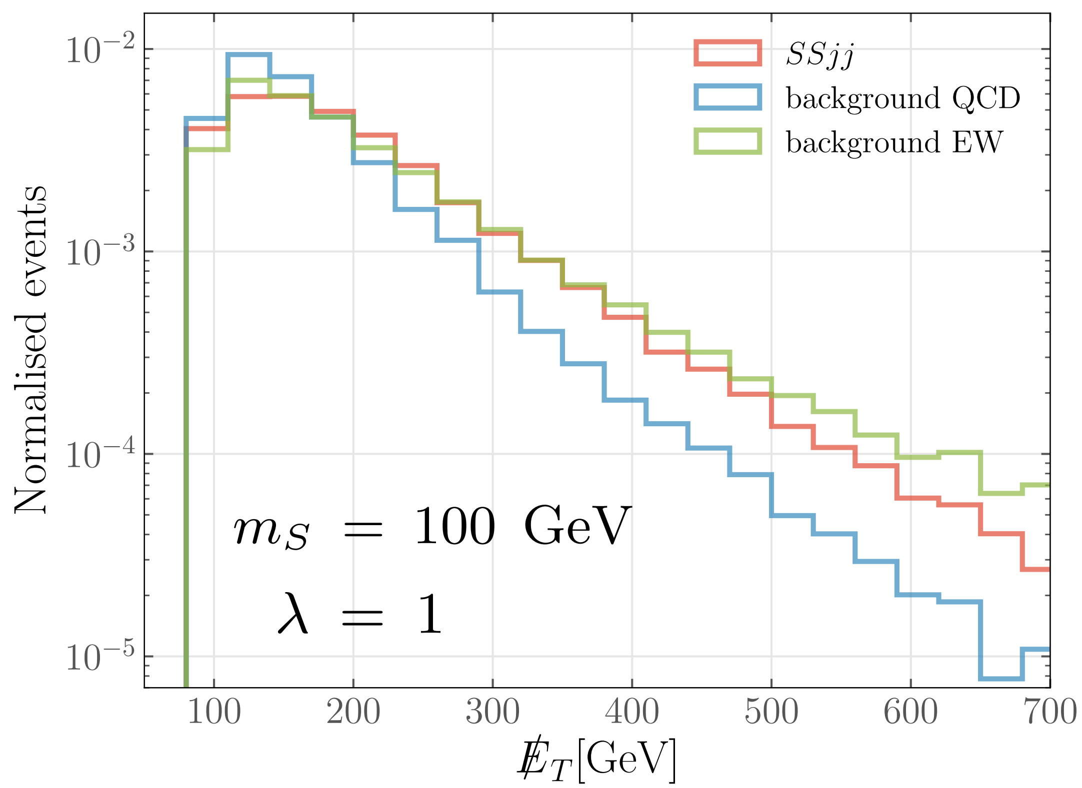


[Ruhdorfer, Salvioni, Weiler `19]

Cross sections for different sqrtS



Etmiss distribution at 100 TeV



event rates after reconstruction $m_S = 100$ GeV 100 TeV

Cuts	$SSjj$ [pb]	Zjj [pb]	W^+jj [pb]	W^-jj [pb]	Zjj EW [pb]	W^+jj EW [pb]	W^-jj EW [pb]
Baseline	0.0238	10.103	6.6287	3.0501	0.9386	0.5897	0.3833
$\Delta\eta > 4.2$	0.0217	6.6052	4.4727	1.9775	0.8325	0.5232	0.3384
$\not{E}_T > 200$ GeV	0.0080	1.5842	0.7633	0.2666	0.3952	0.1668	0.0940
$m_{jj} > 2300$ GeV	0.0041	0.3637	0.2409	0.0637	0.2256	0.1071	0.0594

S/B small significantly systematically limited...

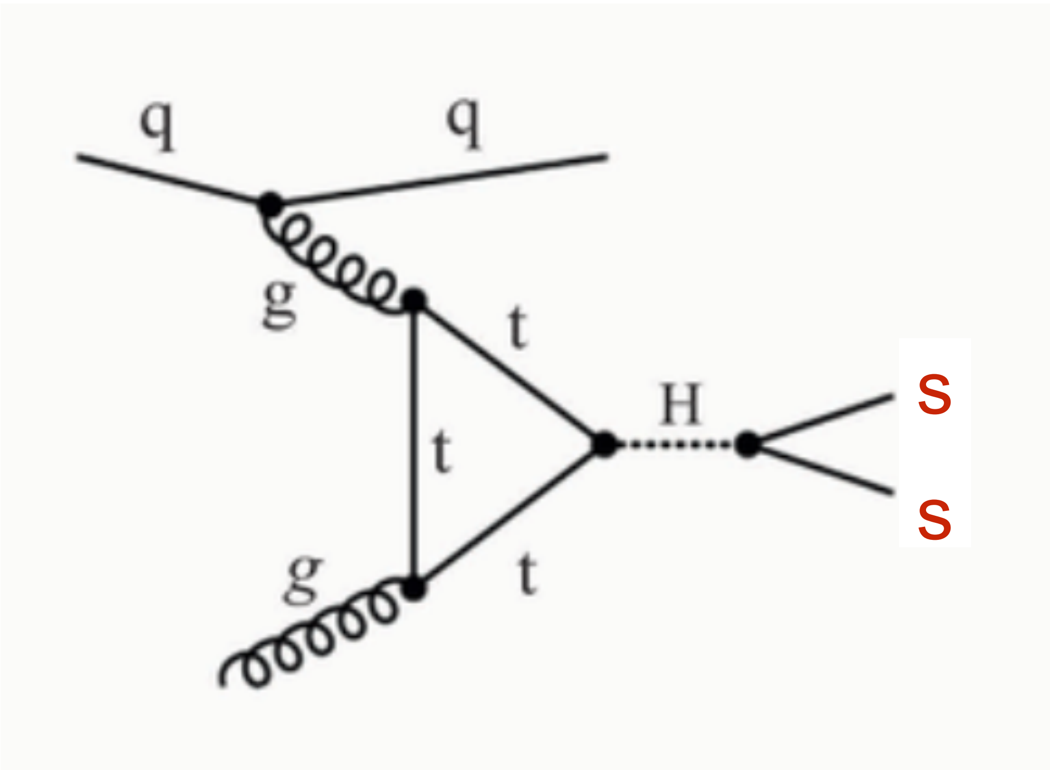
Monojet searches

Event selection:

MET $\not{E}_T > 150$ GeV

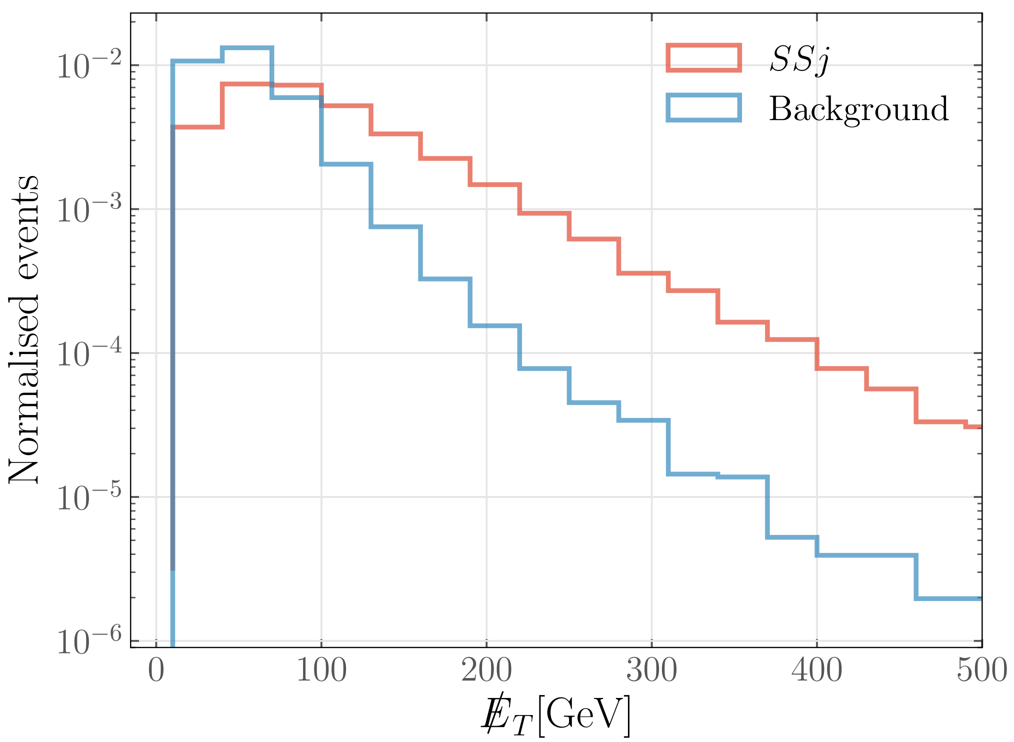
leading jet $p_T > 100$ GeV

subleading jet allowed if $|\Delta\phi(j_1, j_2)| < 2.5$



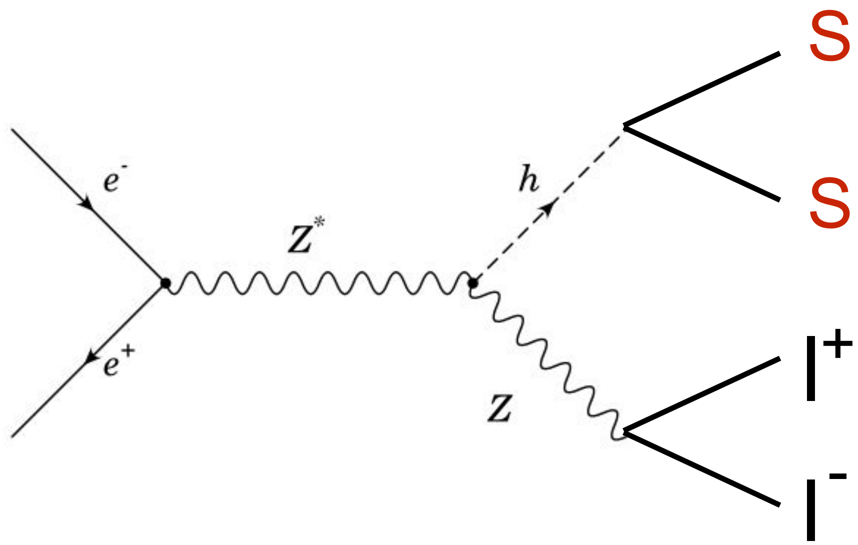
$m_S = 100$ $\lambda = 1$ 100 TeV

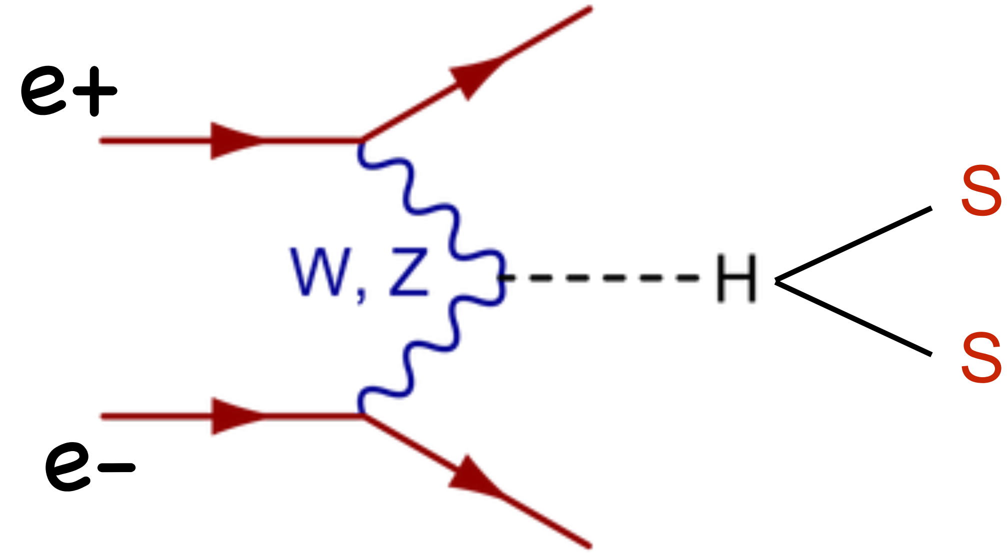
Cuts	SSj [pb]	Zj [pb]	W^-j [pb]	W^+j [pb]
Baseline	0.9322	15283	17495	19799
$p_T(j_1) > 100$ GeV	0.2858	820.54	553.20	670.02
$\not{E}_T > 150$ GeV	0.1810	298.28	87.381	138.12



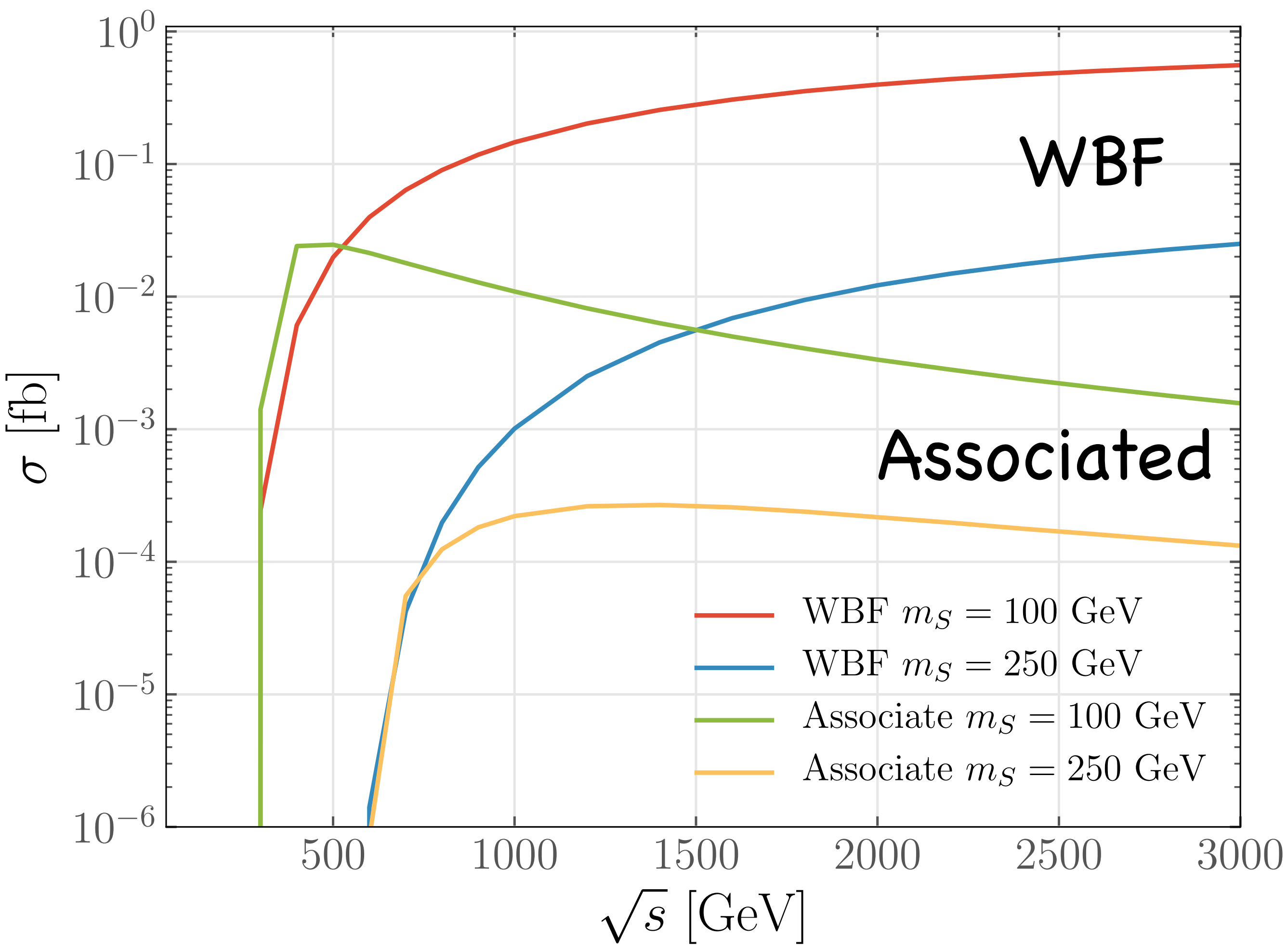
Very small S/B

Direct searches at an e+e- collider





production cross sections of SSLL final states for various ee-collider energies



Associate production

- At e+e- collider relevant

process $e^- e^+ \to Z(H \to SS)$

reconstruction

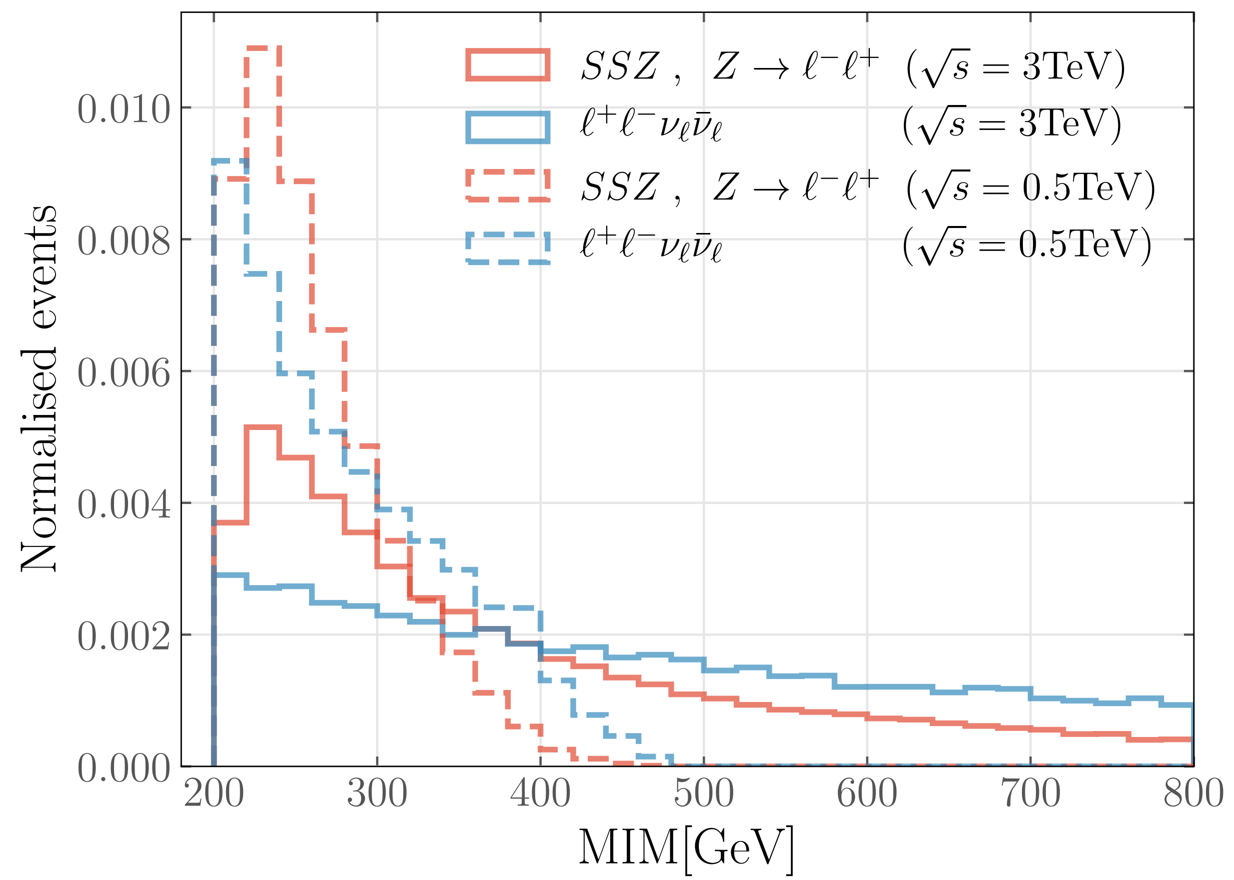
$\Delta\eta_{\ell\ell} < 1.3$ signal more central than bkg

$\not{E}_T > 150$ GeV ETmiss tails

$\not{p} = (\sqrt{s}, \mathbf{0}) - p_{\ell^-} - p_{\ell^+}$

$\text{MIM} = \sqrt{\not{p}_\mu \not{p}^\mu} \geq 200$ GeV

missing invariant mass



$m_S = 100$ GeV $\sqrt{s} = 500$ GeV

Cuts	$SSZ, Z \to \ell^+\ell^-$ [fb]	$\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ [fb]
Generation	0.0236	669.68
$\Delta\eta_{\ell\ell} < 1.3$	0.0194	139.64
$\not{E}_T > 150$ GeV	0.0113	13.786
MIM > 200 GeV	0.0113	2.8209
$M_{\ell\ell} < 120$ GeV	0.0113	2.3947

Weak boson fusion

ILC: $M_{ee} > 120$ GeV

$\Delta\eta_{ee} > 2.0$

CLIC: $M_{ee} > 2200$ GeV

$\Delta\eta_{ee} > 6$

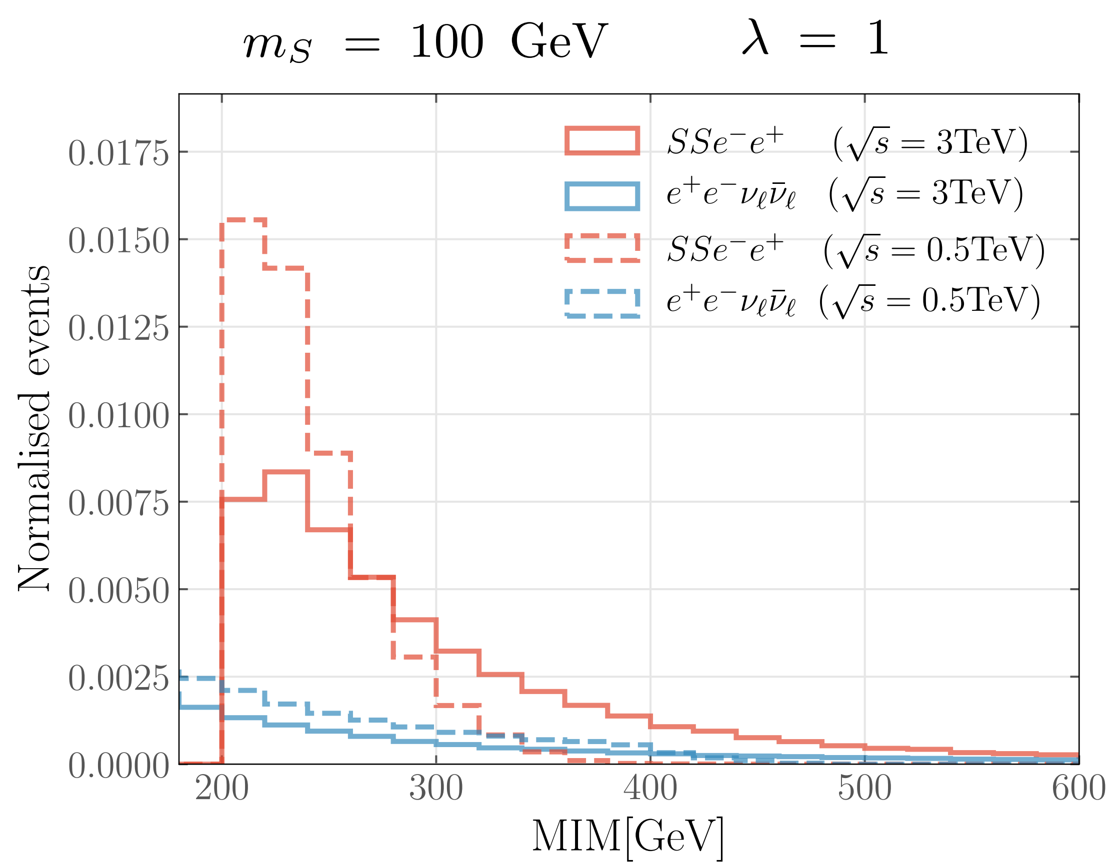
in both cases event reconstruction

$\not{E}_T > 80$ GeV

MIM > 200 GeV

WBF most sensitive channel

and very good S/B

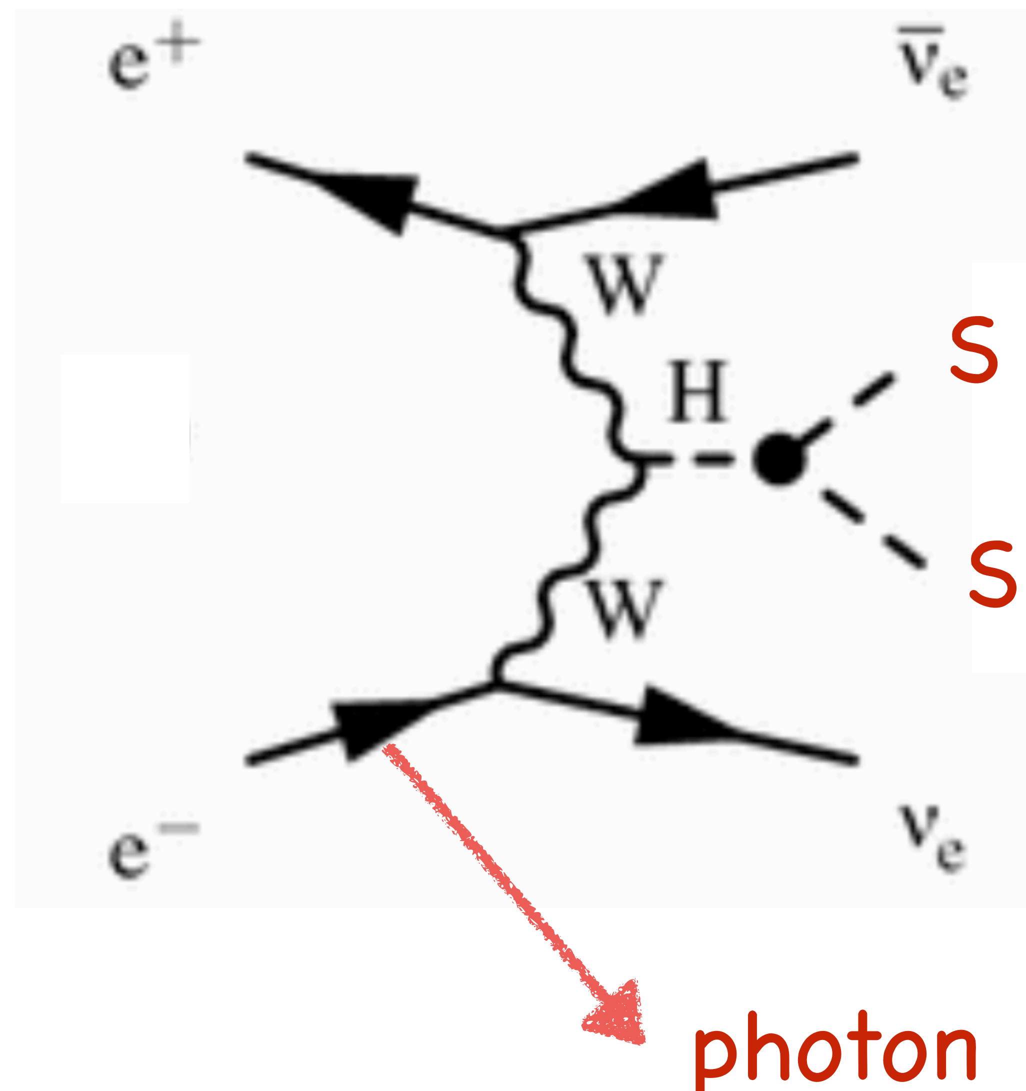


3 TeV CLIC

Cuts	SSe^-e^+ [fb]	$e^+e^-\nu_\ell\bar{\nu}_\ell$ [fb]
Generation	0.5364	43.86
MIM > 200 GeV	0.5364	9.257
$\Delta\eta_{ee} > 6$	0.4144	1.687
$\not{E}_T > 80$ GeV	0.2811	1.446
$M_{ee} > 2200$ GeV	0.2346	0.468

WBF bonus channel

- photon-ISR from incoming leptons
- Single-photon trigger
- Small cross section



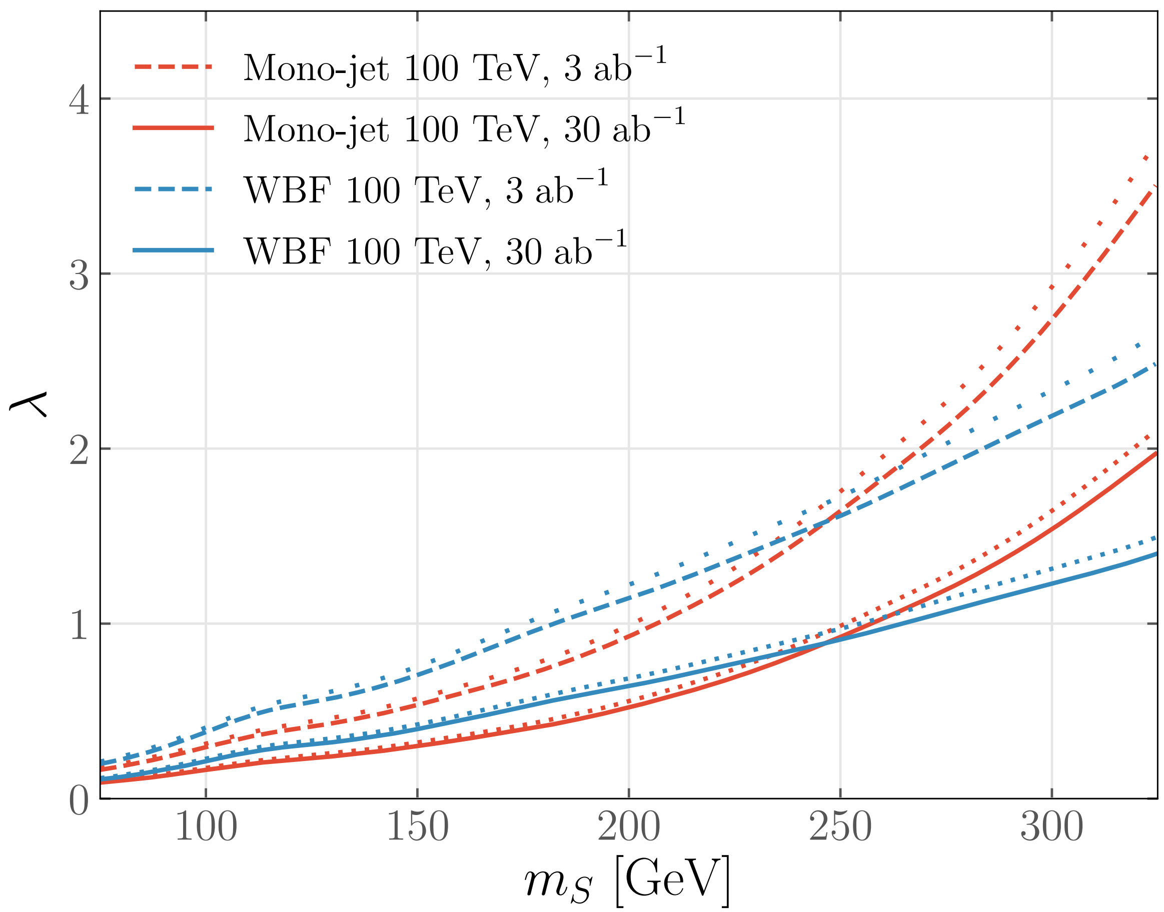
background

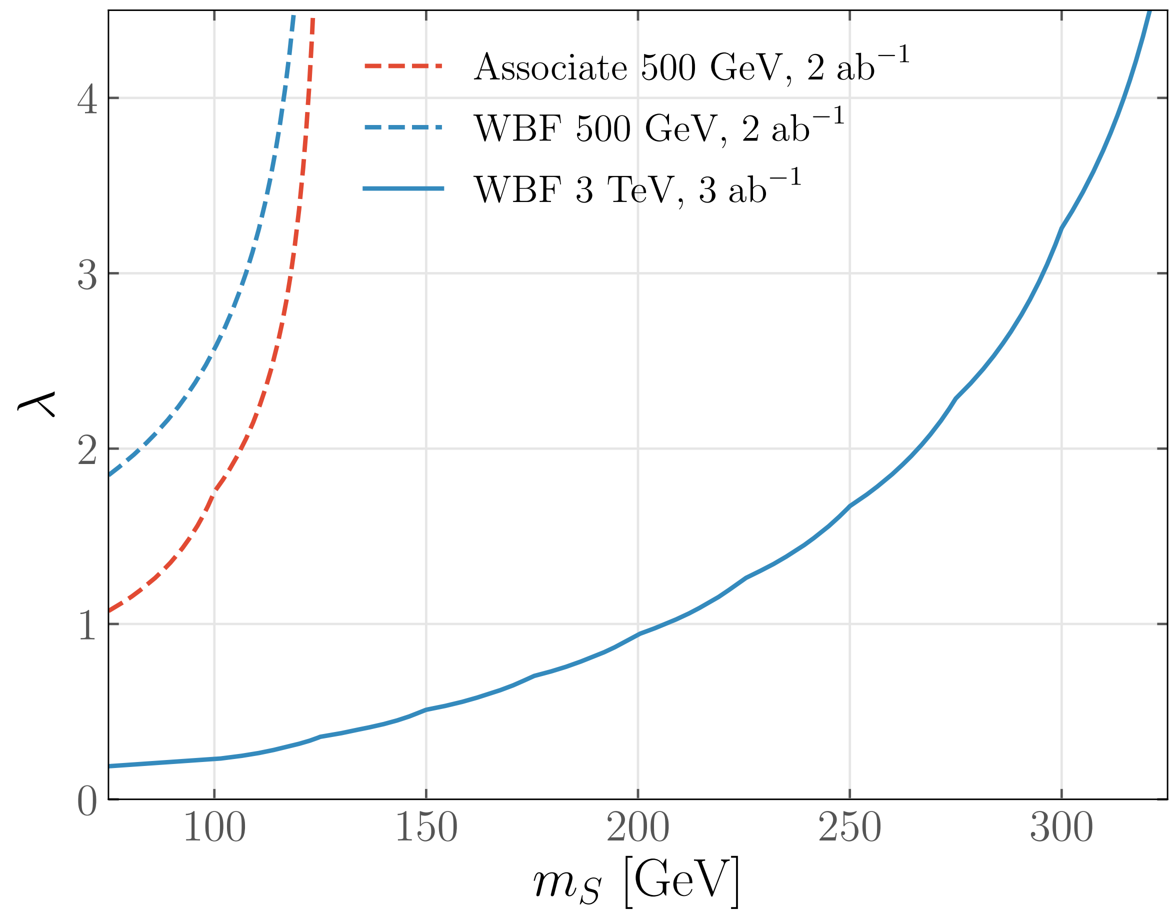
$$e^+e^- \to \gamma\nu_e\bar{\nu}_e$$

no sensitivity at 3 TeV

$$N_S/\sqrt{N_B} = 0.0082$$

Sensitivity from direct searches





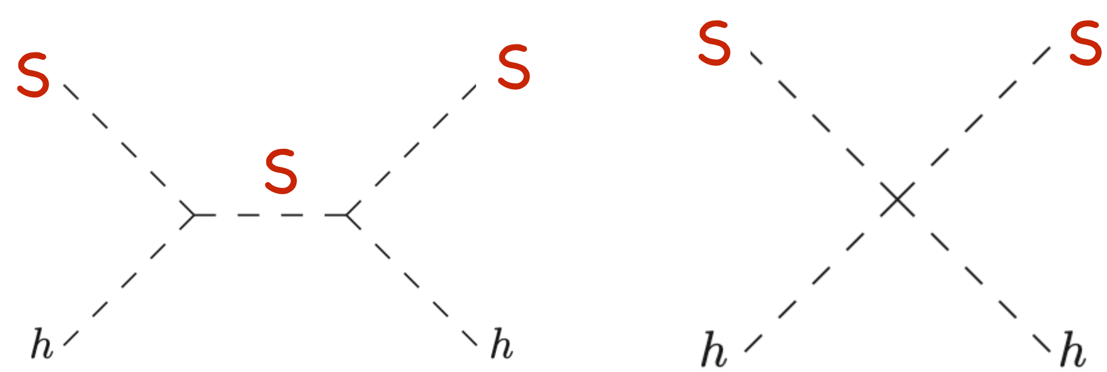
- dotted lines correspond to bkg k-factor of 1.3
- WBF channel takes over for larger mS

- very strong dependence on mS
- need high energies, else rate limited WBF only channel

Indirect searches at a hadron/lepton colliders

S probed indirectly through loops

- Unitarity constraints



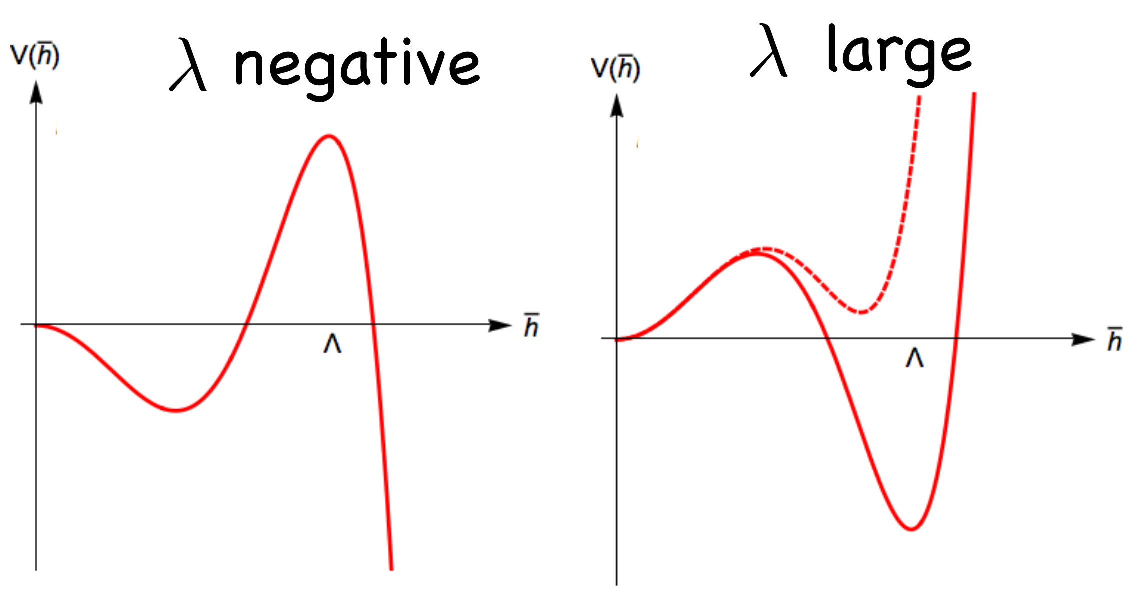
constraint on zero partial wave:

$$\mathrm{Re}\, a_0(SH \to SH) \leq \frac{1}{2}$$

$\lambda \lesssim 4\pi$ for $\sqrt{s} \simeq 3.5$ TeV

and $m_Z < m_S \lesssim 300$ GeV

- Vacuum stability constraints (T=0)



[Curtin, Meade, Yu '14]

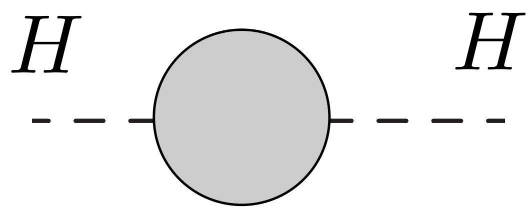
small field value instability

$$\lambda \lesssim \mathcal{O}(1)$$

large field value instability

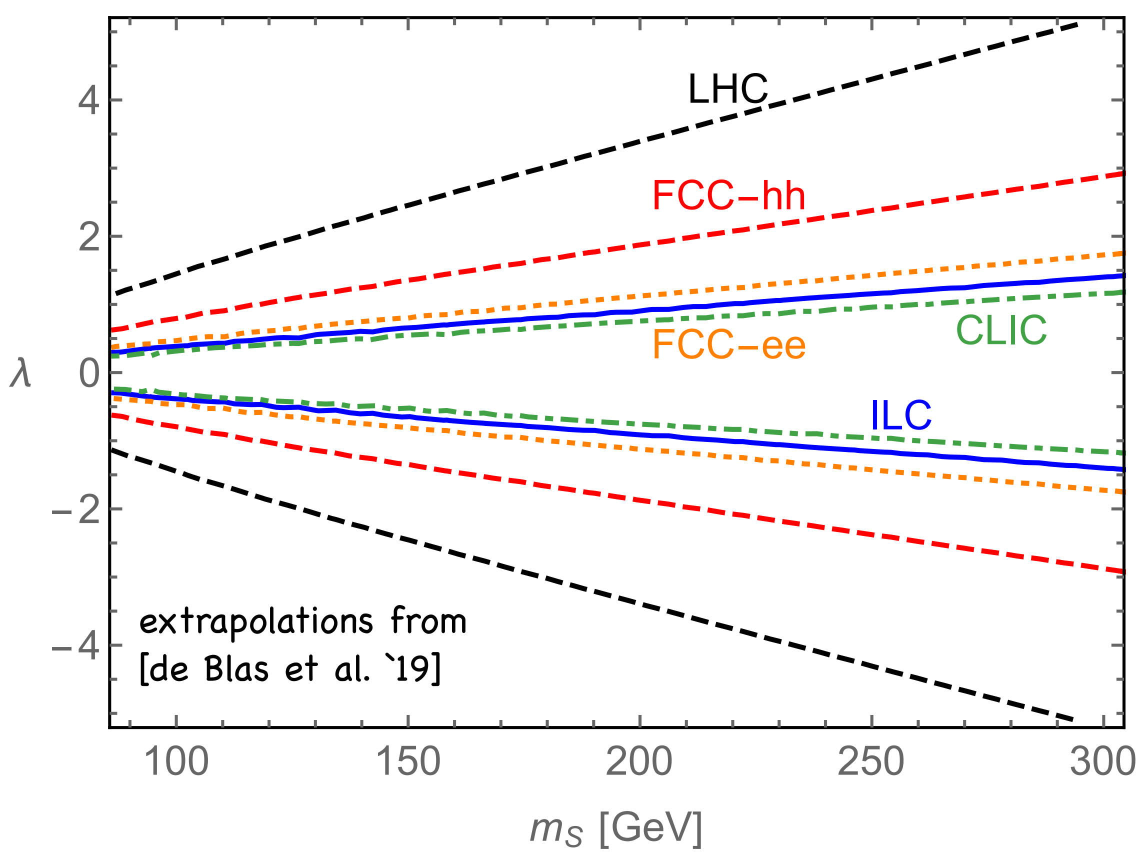
$$\lambda \gtrsim -1$$

- **Higgs couplings**



Higgs couplings receive uniform radiative corrections (no momentum-dependence), accessible through signal strength measurements

$$\frac{\sigma(H)}{[\sigma(H)]_{\rm SM}} = \frac{\Gamma_i}{[\Gamma_i]_{\rm SM}} = 1 + \delta Z_H \quad \Rightarrow \quad \mu = \frac{\sigma(H)\times {\rm BR}}{[\sigma(H)\times {\rm BR}]_{\rm SM}} = 1 + \delta Z_H \,.$$



Expected sensitivities:

$$\text{LHC}: \quad \mu = [0.96, 1.03]$$

$$\text{CLIC-380}: \quad \frac{\delta\mu}{\mu} = 0.44\%$$

$$\text{ILC-250}: \quad \frac{\delta\mu}{\mu} = 0.29\%$$

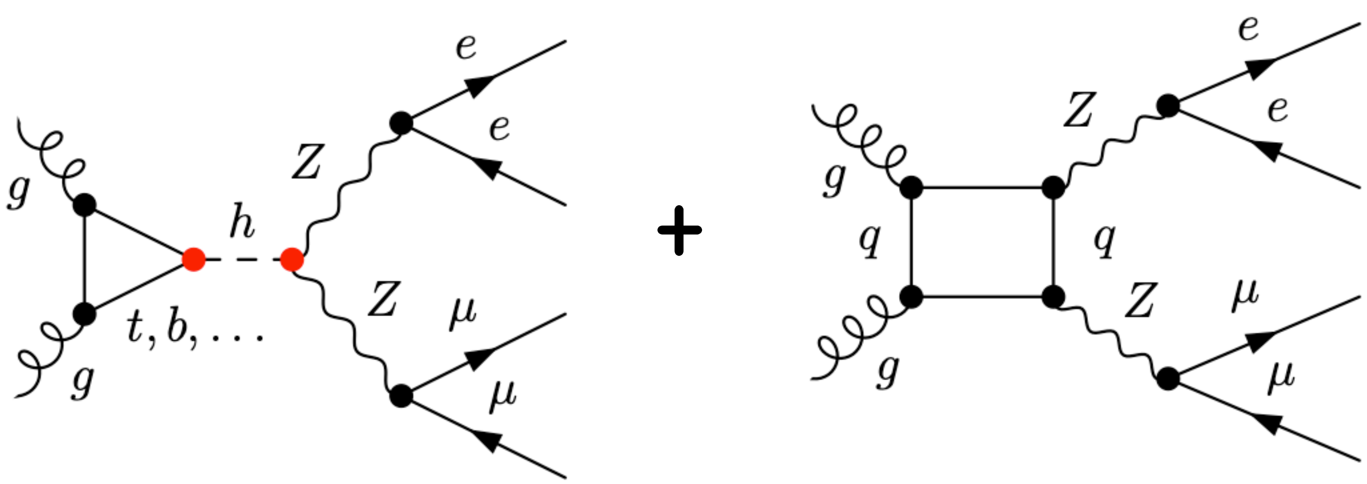
$$\text{FCC-ee(240)}: \quad \frac{\delta\mu}{\mu} = 0.2\%$$

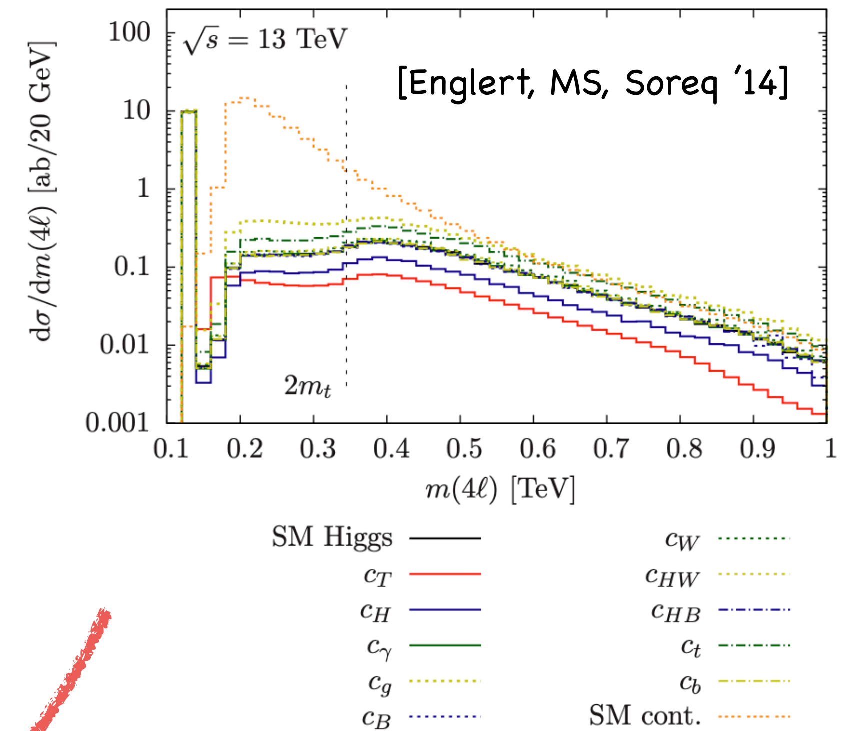
$$\text{FCC-hh}: \quad \frac{\delta\mu}{\mu} = 1.22 - 1.88\%$$

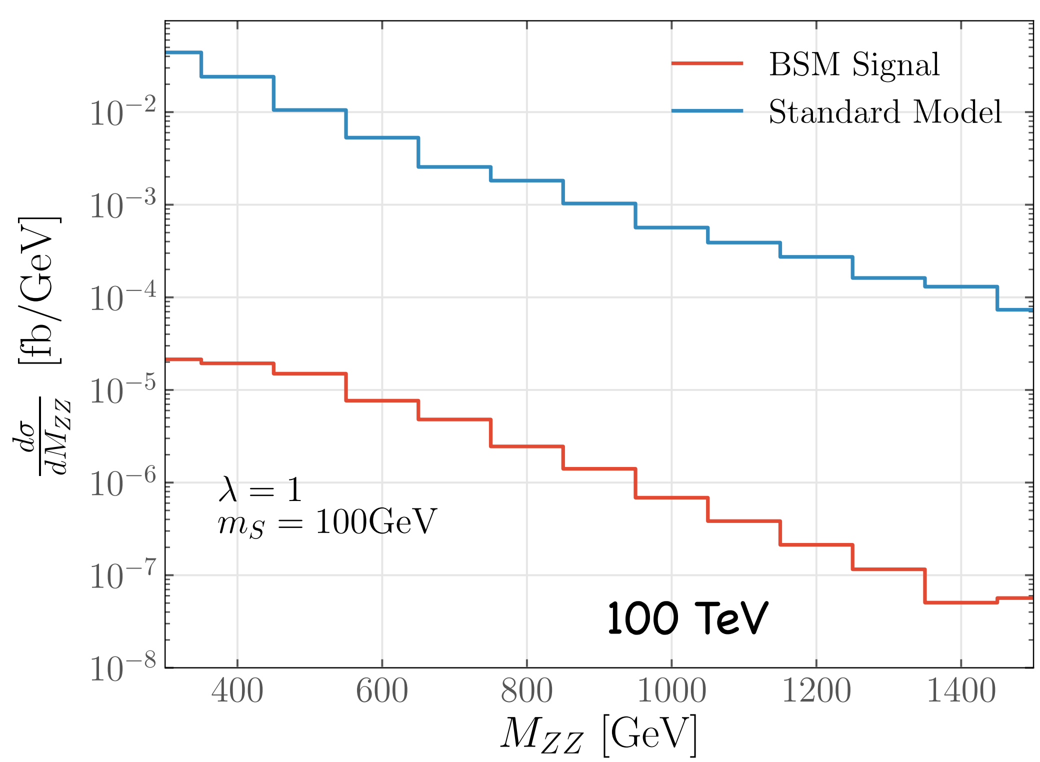
- Coupling limit through off-shell Higgs interference

correlating on-shell and off-shell Higgs in 4l final state provides sensitivity to Higgs couplings

[Kauer, Passarino '12]



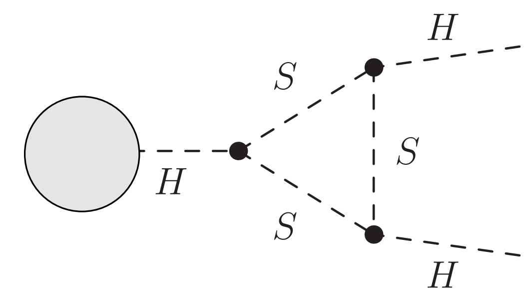




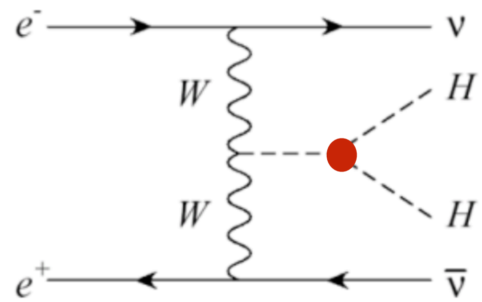
However here, sensitivity to coupling modifications not large enough

Even for 30 iab and 100 TeV no sensitivity

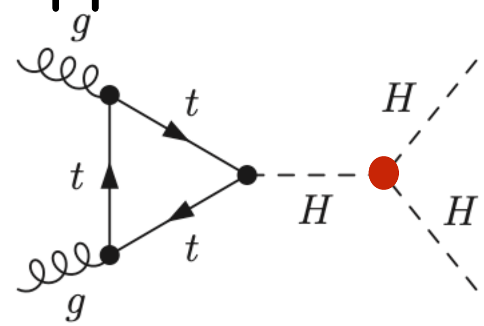
- Higgs pair phenomenology



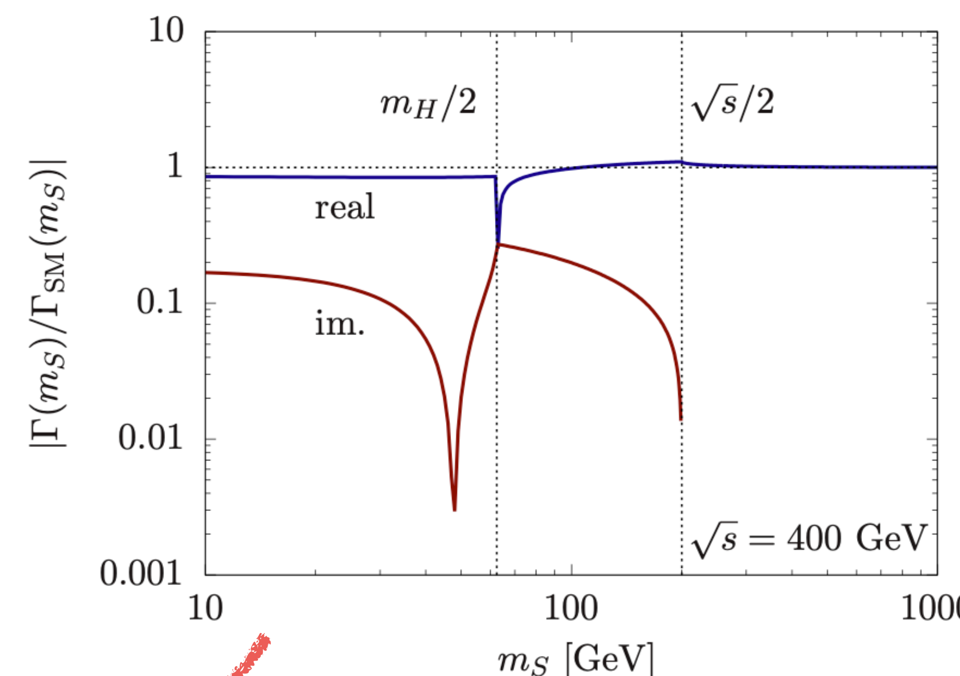
ILC/CLIC

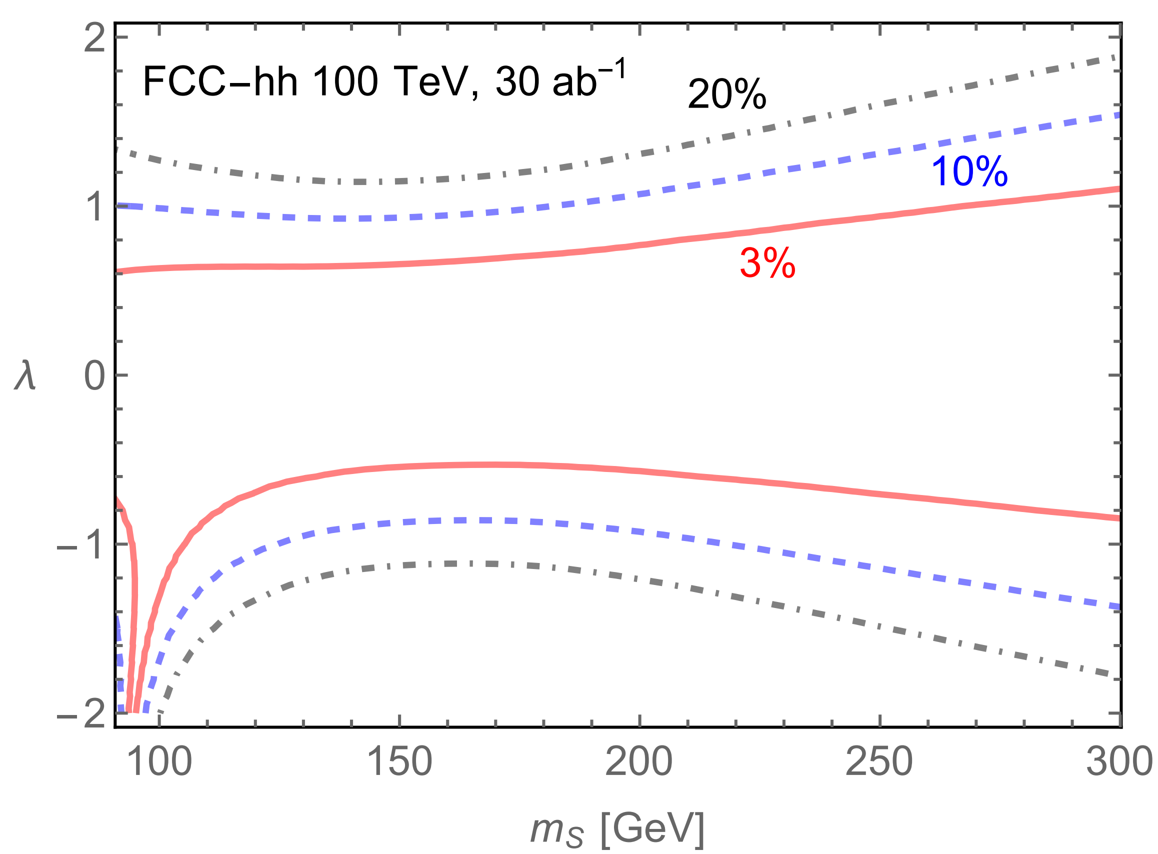


pp colliders



[Englert, Jaeckel '19]

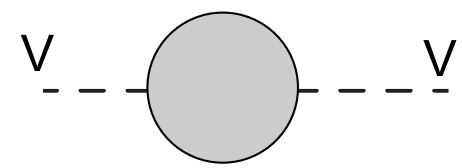




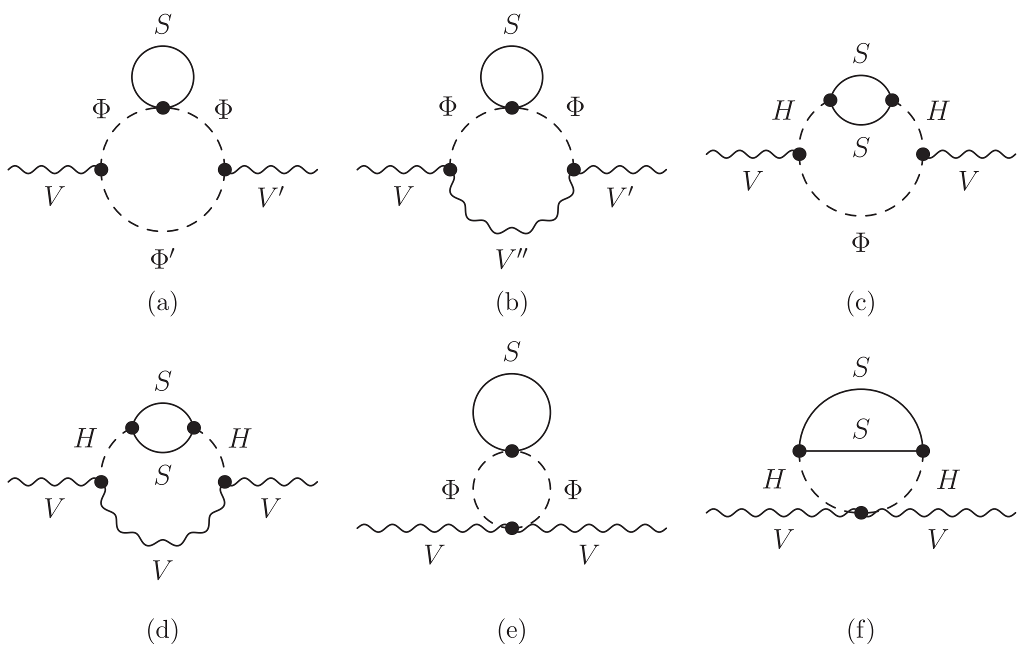
Absorptive parts in loops lead to modification of HHH coupling

differential measurement over mHH can retain sensitivity over large mS region

- Oblique corrections

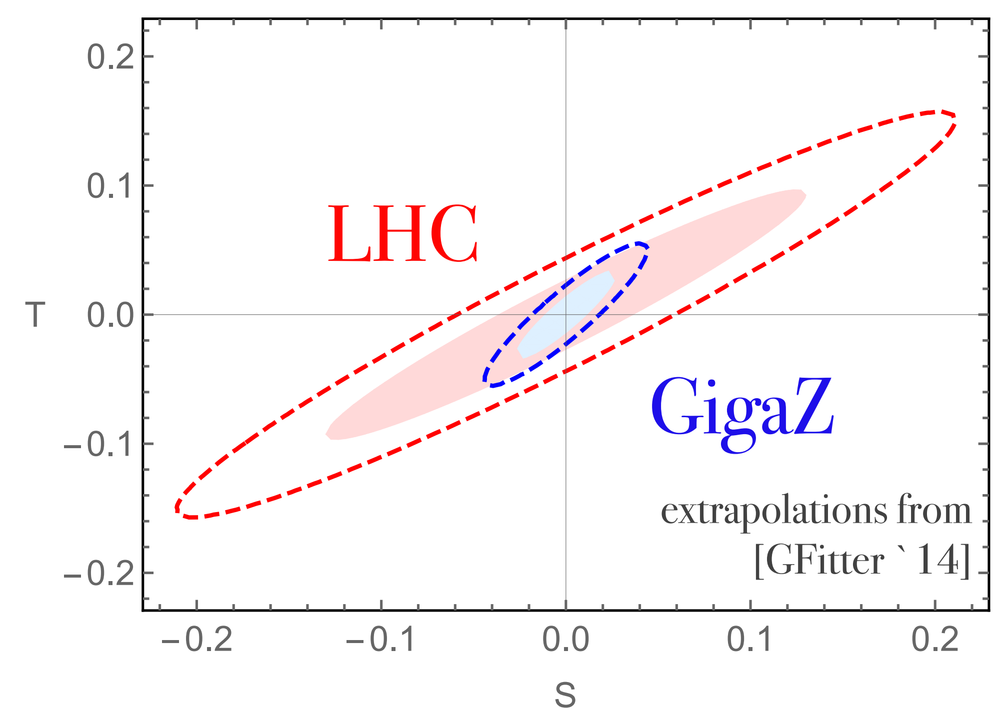


Precision analysis of Z-pole measurements ($e^+e^- \to ff'$) [Peskin, Takeuchi `90]

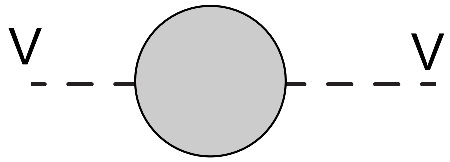


Oblique corrections are two-loop suppressed, but large statistics and particularly clean measurement at Higgs factories

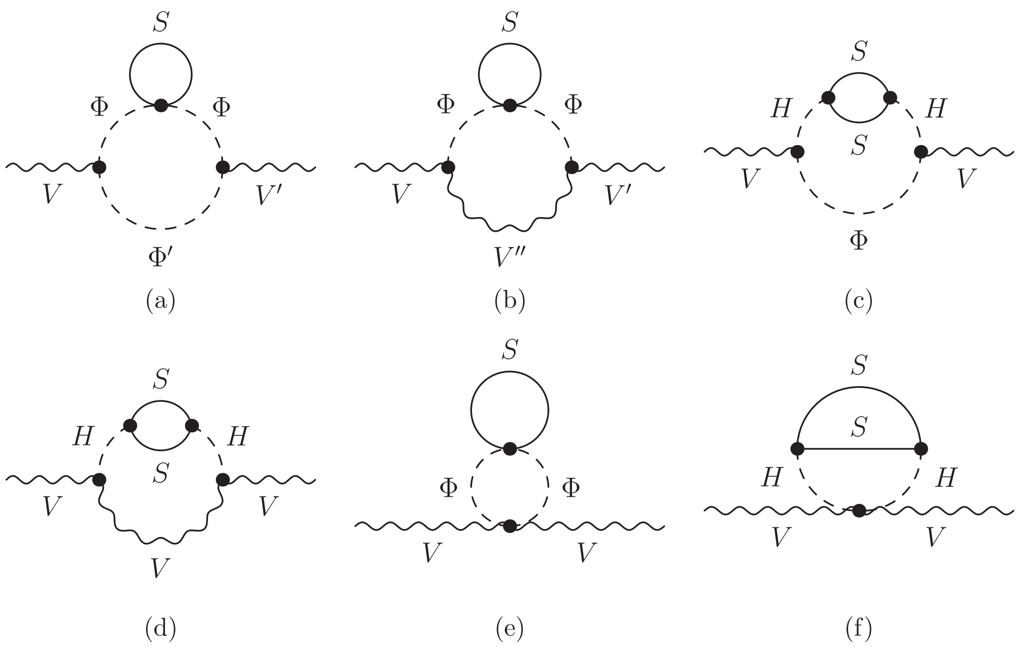
GigaZ gives non-trivial constraint



- Oblique corrections



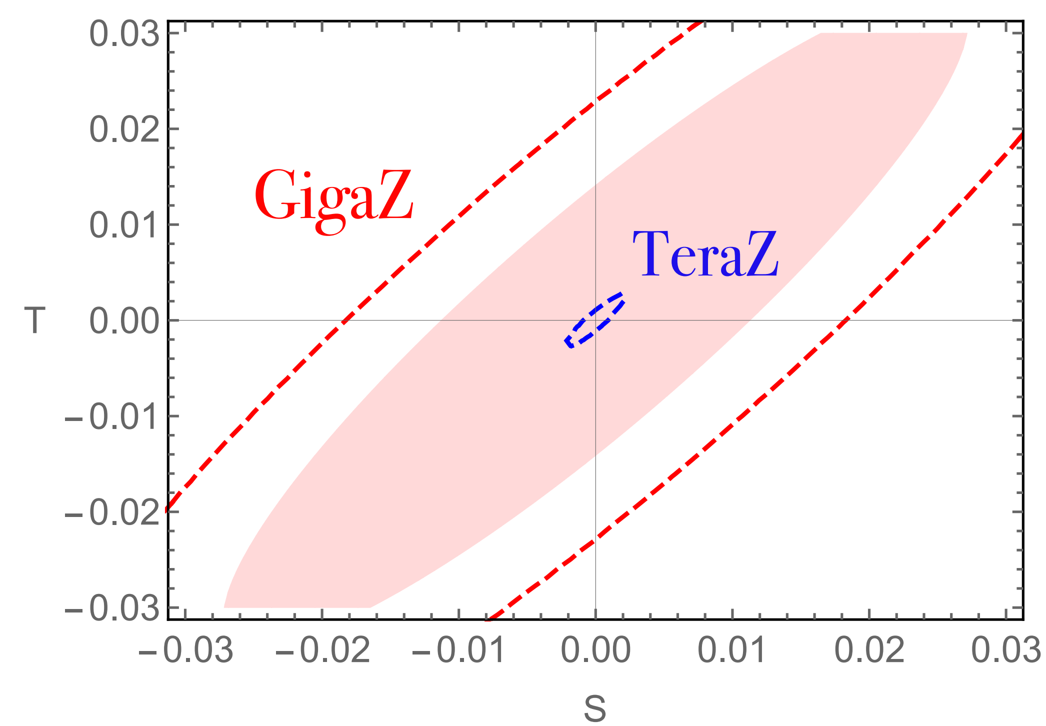
Precision analysis of Z-pole measurements ($e^+e^- \to ff'$) [Peskin, Takeuchi `90]



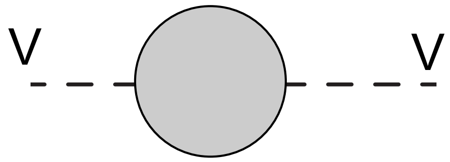
Oblique corrections are two-loop suppressed, but large statistics and particularly clean measurement at Higgs factories

GigaZ gives non-trivial constraint

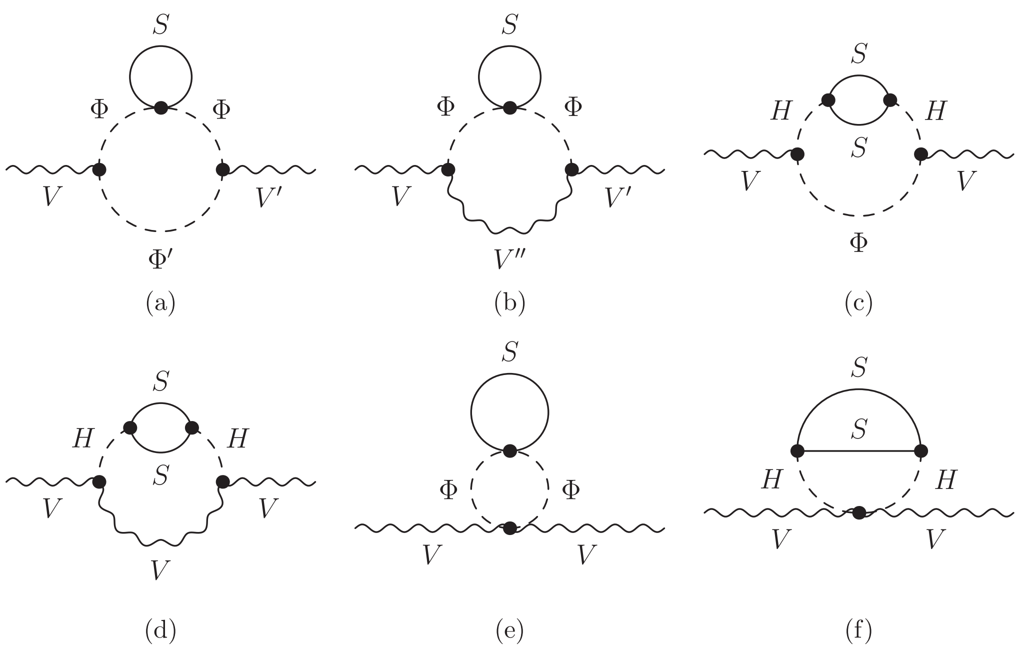
massive improvement for TeraZ (if attainable)



- Oblique corrections



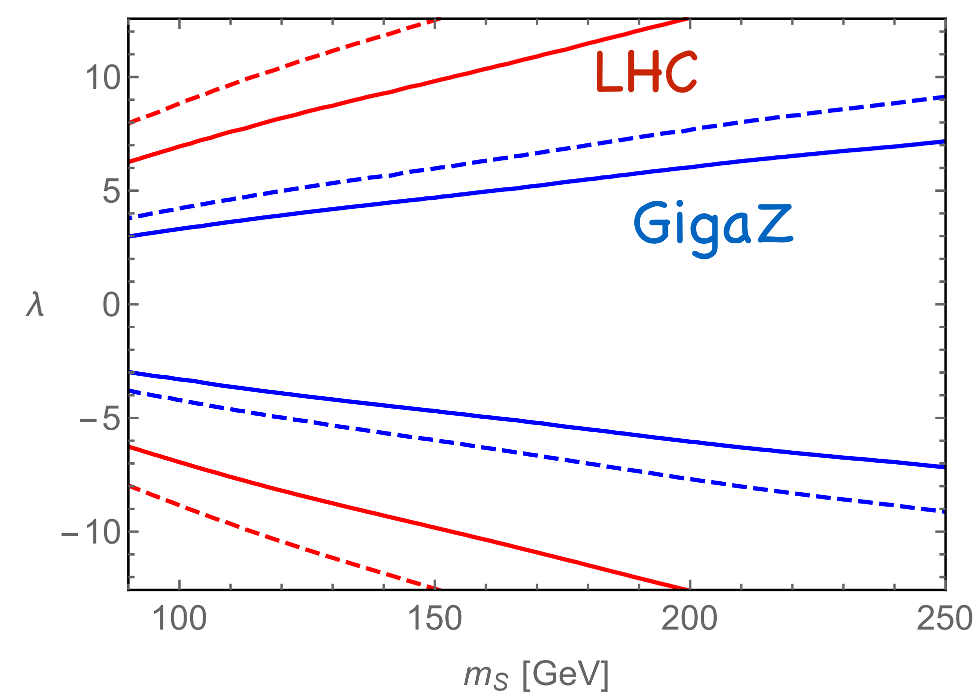
Precision analysis of Z-pole measurements ($e^+e^- \to ff'$) [Peskin, Takeuchi `90]



Oblique corrections are two-loop suppressed, but large statistics and particularly clean measurement at Higgs factories

LHC: $(\Delta S, \Delta T) = (0.086, 0.064)$

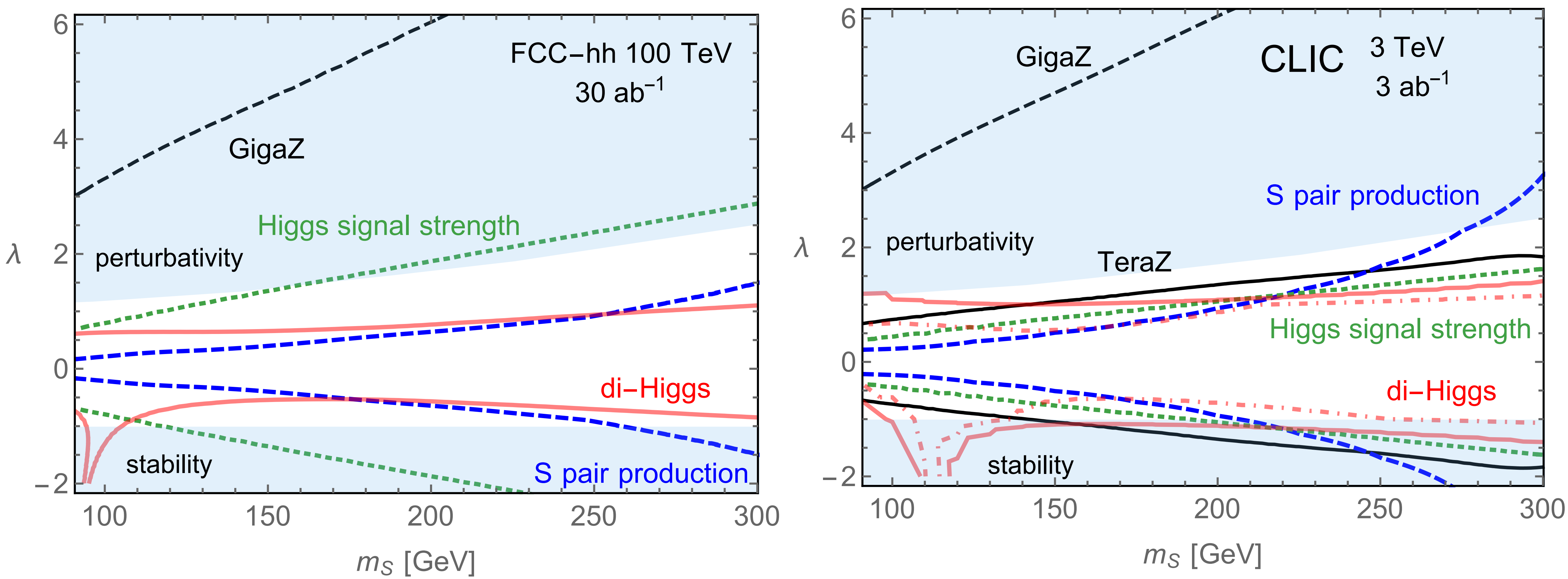
GigaZ: $(\Delta S, \Delta T) = (0.018, 0.023)$



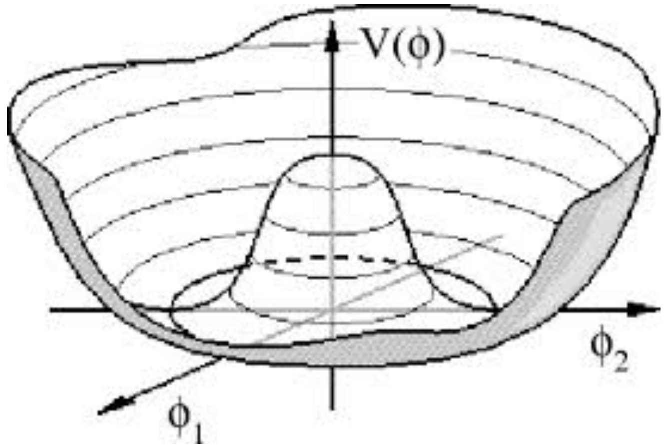
Limits on parameter space rather weak though.

Only TeraZ would become almost competitive with Higgs coup. measurements

Combination of probes for different colliders



- Di-Higgs production provides best sensitivity for this scenario, in particular at pp 100 TeV (best overall bound for larger mS)
- Direct searches are for low masses of relevance - more realistic for CLIC
- Higgs coupling measurements only for ee colliders competitive



Summary

- Rich tool box to test scalar extensions of the SM

- However, Higgs portal with heavy stable scalars notoriously difficult to test

- Multi-Higgs phenomenology at high-energy collider best option (i.e. pp 100 TeV and CLIC) **(power)**
  But Higgs coupling measurements not far behind (i.e. FCC-ee and CLIC) **(precision)**