Single Higgs Precision at a Muon Collider

Matthew Forslund

with Patrick Meade

C. N. Yang Institute for Theoretical Physics

December 15, 2022

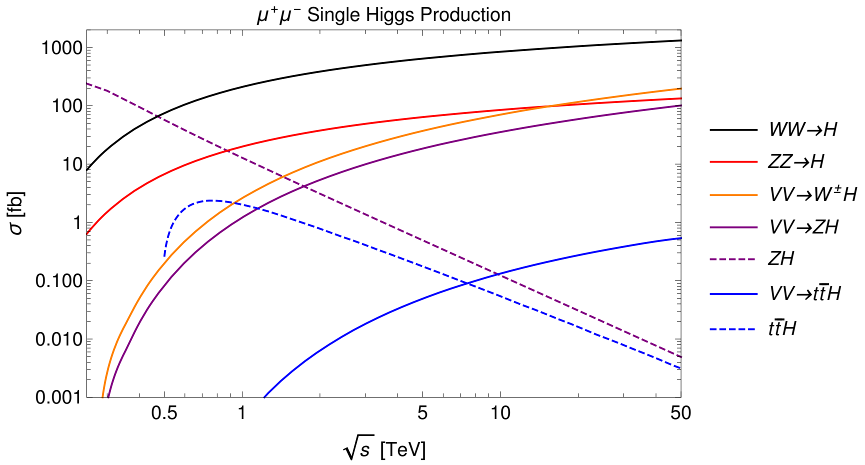
The current status (J. de Blas et al. 1905.03764)

κ-0: $BR_{BSM} = 0$

$\kappa_i \equiv g_i / g_i^{SM}$

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

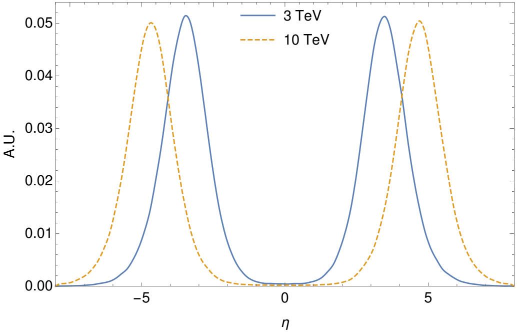
Single Higgs Production at Muon Colliders (2203.09425)



High energies dominated by $WW \to H$ and $ZZ \to H$.

Forward Muons

To distinguish between WW-fusion and ZZ-fusion, must be able to tag the forward muons beyond the $|\eta| \approx 2.5$ nozzles



For ZZ-fusion, we include results considering tagging up to $|\eta| \leq 6$.

Event Generation and Detector Assumptions

Event generation is done using MadGraph5 and showering with Pythia8

Use Delphes fast sim with the muon collider card for detector

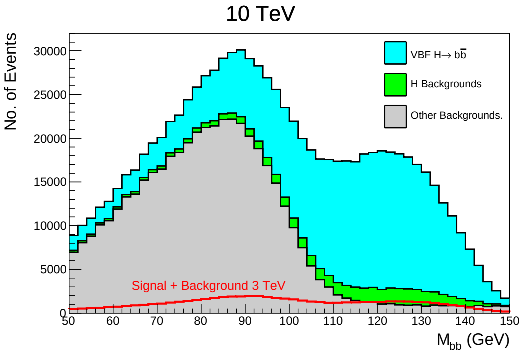
2-body final states required to have both particles satisfying $|\eta| < 2.5$ and $p_T > 40$ GeV

- Loosen to $p_T > 20$ GeV for non-hadronic 4-body final states.

Apply flavour tagging, additional process dependent cuts, estimate precision using $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$

Without forward tagging, combine WWF and ZZF- otherwise, consider separately

Hadronic Processes: $b\bar{b}$



Precision (%)

Energy	Combination	WWF	ZZF
3 TeV	0.76	0.80	2.6
10 TeV	0.21	0.22	0.77

Dominant background from Z-peak: distinguishing the two is crucial

3 TeV has also been done with fullsim: quite similar results (2209.01318)

The $c\bar{c}$ and gg channels are very similar, with mistagged $H \to b\bar{b}$ contributing a large background as well

WW^*, ZZ^*

For WW^* and ZZ^*, we generate the full $2 \to 6$ backgrounds such as $\mu\mu \to \nu\nu\ell\ell jj$ using MadGraph.

Consider $WW^* \to (\ell\nu jj, 4j)$, $ZZ^* \to (4\ell, 2\ell 2j, 4j)$

The $4j$ final states have a large background from $H \to b\bar{b}, gg$ from exclusive clustering, completely overwhelming all other backgrounds.

Number of Events

Process	3 TeV			10 TeV		
	$4j$	$2j2\ell$	4ℓ	$4j$	$2j2\ell$	4ℓ
$\mu^+\mu^- \to \nu_\mu\bar{\nu}_\mu H;\ H \to ZZ^* \to X$	124	103	5	2910	1590	66
$\mu^+\mu^- \to \mu^+\mu^- H;\ H \to ZZ^* \to X$	3	9	0	315	151	8
Others	6700	50	0	208000	1370	2

κ-0 Fit Result (**With Fwd Tagging**) [%]

	3 TeV @ 1 ab^{-1}	10 TeV @ 10 ab^{-1}
κ_W	0.37	0.10
κ_Z	1.2	0.34
κ_g	1.6	0.45
κ_γ	3.2	0.84
$\kappa_{Z\gamma}$	21	5.5
κ_c	5.8	1.8
κ_t	34	53
κ_b	0.84	0.23
κ_μ	14	2.9
κ_τ	2.1	0.59

Assume no BSM branching ratios

$\kappa_i = g_i/g_i^{SM}$

Removing forward tagging mainly affects κ_Z:

- 1.2% $\rightarrow$ 5.1%
- 0.34% $\rightarrow$ 1.4%

Where do we stand? (with forward tags)

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **3000**	$\mu^+\mu^-$ **10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.37	0.10
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	1.2	0.34
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	1.6	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98$\star$	5.0	2.2	3.7	4.7	3.9	0.29	3.2	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99$\star$	86$\star$	85$\star$	120$\star$	15	6.9	8.2	81$\star$	75$\star$	0.69	21	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	5.8	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	34	53
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.84	0.23
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320$\star$	13	5.8	8.9	10	8.9	0.41	14	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	2.1	0.59

Caveat: the Higgs width

The κ-precisions presented before rely on $BR_{inv} = BR_{exo} = 0$: Relaxing this assumption leads to a flat direction in the fit.

Consider a universal modifier κ and allow $BR_{BSM} > 0$:

$$\Gamma_H/\Gamma_H^{SM} = \kappa^2/(1 - BR_{BSM}) \rightarrow \mu_{i\rightarrow f}^{on-shell} \equiv \sigma_{i\rightarrow f}/\sigma_{i\rightarrow f}^{SM} = \kappa^2(1 - BR_{BSM})$$

So long as $\kappa > 1$, there is always a possible BR_{BSM} to make all $\mu_i^{on-shell} = 1$.

Constraining the Higgs width is necessary to remove this degeneracy.

For a width precision of $\Delta\Gamma$, can't obtain a coupling precision better than $\Delta\kappa \sim (1/4)\Delta\Gamma$.

Constraining Γ_H

There are three ways to constrain the width

1. Perform a lineshape scan (125 GeV $\mu^+\mu^-$: 2203.04324 (J. de Blas et al.))

   Only possible at $s = m_H^2$

2. Measure the inclusive production cross section to directly constrain a κ_i (e^+e^-)

   $$\mu_{Incl} \equiv \sigma_{Incl}/\sigma_{Incl}^{SM} = \kappa^2 \rightarrow \mu_i^{on-shell}/\mu_{Incl} = (1 - BR_{BSM})$$

3. Indirectly constrain (LHC)

Let's look in more detail

Measuring σ_{Incl}

At e^+e^- colliders, one measures the inclusive $e^+e^- \to ZH$ cross section via the recoil mass method:

Assuming one knows E_{CM}, then by kinematics

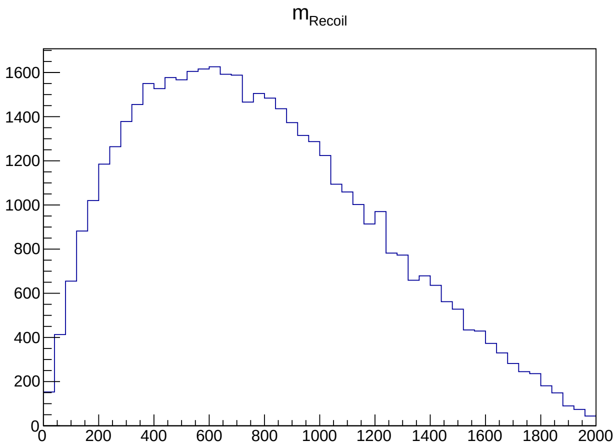
$$m_H^2 = s + m_Z^2 - 2E_Z\sqrt{s}$$

$\to$ Can measure σ_{Incl}^{ZH} by *only* measuring the Z decay products!

However, this technique relies on a precision measurement of E_Z...

Nevertheless, could this be done at a muon collider via the forward muons in $\mu^+\mu^-H$?

Can we do this for $\mu^+\mu^- \to \mu^+\mu^- H$?



Not really... would need unrealistically good energy resolution in forward detectors

LHC techniques

We are left with one option: indirectly constrain as at the LHC.

Off-shell, the width doesn't contribute to the Higgs diagrams, so one can constrain it:

$$\sigma^{off-shell}_{i\to H^*\to f} = \kappa^4 \sigma^{off-shell}_{SM} \to \mu^{off-shell}_{i\to H^*\to f} = \kappa^4, \qquad \frac{\mu^{off-shell}_{i\to H^*\to f}}{\mu^{on-shell}_{i\to H\to f}} = \frac{\Gamma_H}{\Gamma_H^{SM}} \equiv \xi = \frac{\kappa^2}{1 - BR_{BSM}}$$

so that $\mu^{off-shell} = 1$ and $\mu^{on-shell} = 1$ cannot simultaneously be satisfied if $BR_{BSM} > 0$.
(This would be an off-shell coupling measurement, not a width measurement).

However, the rate is much less off-shell... Exploit perturbative unitarity!

If $\kappa_V \neq 1$, then $W_L W_L \to W_L W_L$ scattering grows with energy, $\sigma \propto s^2$

High energy $VV \to VV$ scattering is highly sensitive to κ_V!

Off-shell $VV \to VV$ scattering

Consider $4j$, $\ell^\pm \nu_\ell jj$, and $\ell^+\ell^- jj$

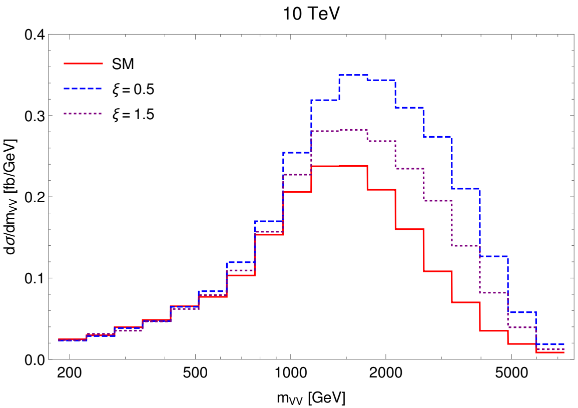
Stricter cuts than on-shell, BIB shouldn't matter much

Fit each bin to a function $a + b\kappa_i\kappa_j + c\kappa_i^2\kappa_j^2$ by varying κ_V.

Fitting κ_W, κ_Z, and ξ yields:

$\Delta\Gamma = 4.0\%$ at 10 TeV

$\Delta\Gamma = 58\%$ at 3 TeV
(not competitive with LHC)

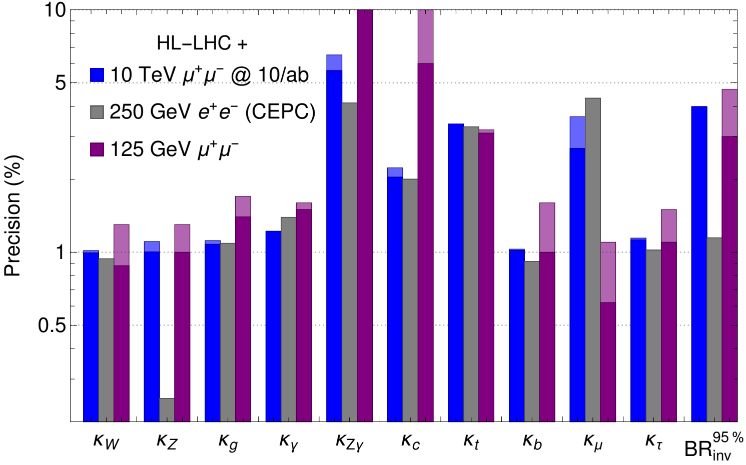


(Here $\xi \equiv \mu^{off-shell}/\mu^{on-shell}$)

Comparisons (combined with HL-LHC)

Blue shaded:
forward tagging

Purple shaded:
5 vs 20/ab



A loophole in the off-shell measurement

Even if both the on-shell and off-shell regions appear SM-like, there is still a loophole.

We assumed the off-shell region scaled like the SM, but this is not true if additional scalars contribute to electroweak symmetry breaking.

When these additional scalars contribute to $VV \to VV$, combination with SM will restore perturbative unitarity of off-shell region, making it appear to be SM, even if $\kappa_V \neq 1$.

This restoration only occurs above resonance: must be lighter than our off-shell analysis window!

Model requirements

Strict requirements for a model to invalidate the off-shell measurement and have a flat direction

1. The model must generate $\kappa_V > 1$ and have a BR_{BSM} (flat on-shell)
2. There must be a regime where $\kappa_V \approx \kappa_f \approx \kappa_\gamma > 1$ (flat on-shell)
3. There must be new electroweak charged scalars lighter than a few TeV that contribute to EWSB (off-shell loophole)
4. The new physics must be custodially symmetric at tree-level (off-shell loophole)
5. Direct search constraints must be satisfied (both)

Higher multiplet scalars

One of the only ways to generate a $\kappa_V > 1$ is by adding scalar multiplets larger than doublets that contribute to EWSB.

(2HDMs can have $\kappa_f > 1$, but not κ_V)

To satisfy electroweak precision ($\rho = 1$), can only be a septet with $Y = 2$ or a Georgi-Machacek model

In either case, there would be many new electroweak charged scalar states lighter than a few TeV to search for directly, which muon colliders are great at!

Searching for light states from $\mu^+\mu^- H$

Since a flat direction requires a BR_{BSM}, can constrain it directly as well. For example, suppose that $BR_{BSM} = BR_{inv}$ (all invisible decays).

Try to search for events in $\mu^+\mu^- H$ with no observed particles other than the forward $\mu^+\mu^-$

For the default p_T resolution of 10%, can obtain a 2σ constraint of 0.34%-2.2% on $\kappa_Z^2 BR_{inv}$ depending on the maximum η reach $(6 - 4.5)$

For worse p_T resolutions, $\mu^+\mu^- \to \mu^+\mu^-$ begins to leak in at a high rate... highly dependent on the forward detector properties

Further study necessary to see if this is feasible or not

Searching for light states

Since $\mu^+\mu^- H$ is dependent on forward tagging capabilities, what can we do without it?

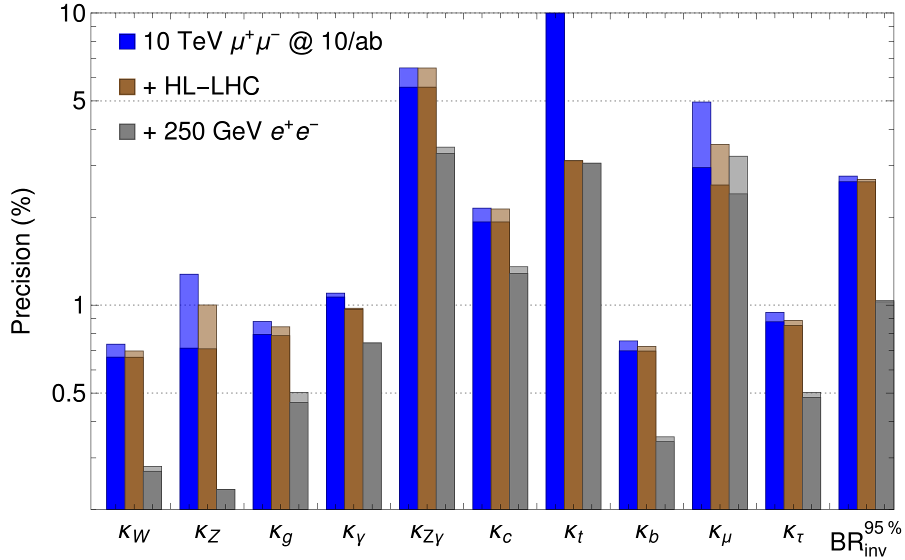
Can search for excesses in associated production modes:

γH, $W^\pm H \to \ell^\pm \nu_\ell H$, $ZH \to \ell^+\ell^- H$, and combined $(W^\pm, Z)H \to jjH$

Perform cuts similar to on-shell, fit each process to κ_W, κ_Z to include interference, similar to the off-shell analysis

All depend on κ_W, κ_Z, and BR_{inv}: must do the full fit to see impact

Including this in the fit



Conclusion

In the κ-0 framework, 10 TeV $\mu^+\mu^-$ collider is highly competitive with other future colliders.

Beyond κ-0, a 10 TeV $\mu^+\mu^-$ collider is still comparable to a 250 GeV e^+e^- or 125 GeV $\mu^+\mu^-$ collider only using off-shell coupling constraints, with more model dependence.

Invalidating the off-shell measurement requires electroweak charged scalars and a BR_{BSM}, which can both be searched for

A 3 TeV $\mu^+\mu^-$ collider **cannot** effectively constrain the width, even indirectly, beyond what the LHC can do.

Great complementary between a 10 TeV $\mu^+\mu^-$ collider and e^+e^- or 125 GeV $\mu^+\mu^-$ colliders, since they have different dominant production modes.

BACKUPS

Flavour Tagging

b-tagging is done using the tight working point (50%) inspired by CLIC (1812.07337)

- *c*-quark mistagging rate $\leq 3\%$
- light quark mistagging rate $\leq 0.5\%$

For *c*-tagging, we use the tagging rates of ILC reported in (1506.08371). We take 20% as our working point to match the Smasher's Guide.

- *b*-quark mistagging rate of flat 1.3%
- light quark mistagging rate of flat 0.66%

For $H \to \tau\tau$, we take a τ-tagging efficiency of 80% with a jet mistag rate of 2%.

Event Selection ($b\bar{b}, c\bar{c}, gg(+s\bar{s})$)

Apply an additional correction to b-jet p_T to account for energy losses during reconstruction (1811.02572)

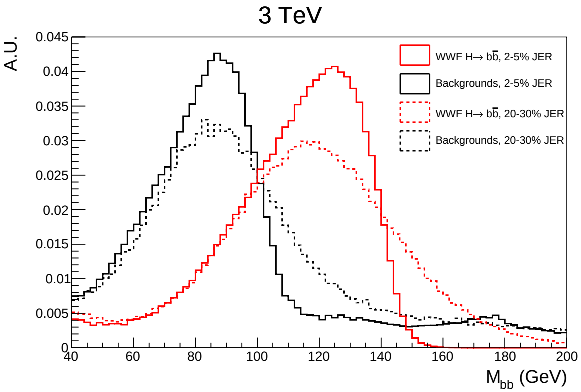
- Smoothly scales 4-momentum by up to $\sim$1.16 at low p_T
- Rough approximation to ATLAS *ptcorr* correction (1708.03299)
- Reproduces a Higgs peak centered near 125 GeV

Apply a similar correction to c-jets

Events that pass the P_T and η cuts are then selected based on an invariant mass cut:

- $100 < M_{b\bar{b}} < 150$ for $b\bar{b}$
- $105 < M_{c\bar{c}} < 145$ for $c\bar{c}$
- $95 < M_{jj} < 135$ for $gg(+s\bar{s})$

Estimating the Effects of the BIB



Worse JER based on current fullsim- additional spreading roughly doubles the background contribution from the Z peak: 0.76% $\rightarrow$ 0.86% precision, quite comparable to fullsim result (2209.01318).

$c\bar{c}, gg(+s\bar{s}), \tau^+\tau^-$

The dominant backgrounds for $c\bar{c}$ and $gg(+s\bar{s})$ are mostly the same as for $b\bar{b}$ and primarily removed via an M_{jj} cut

$H \to b\bar{b}$ becomes a large irreducible background

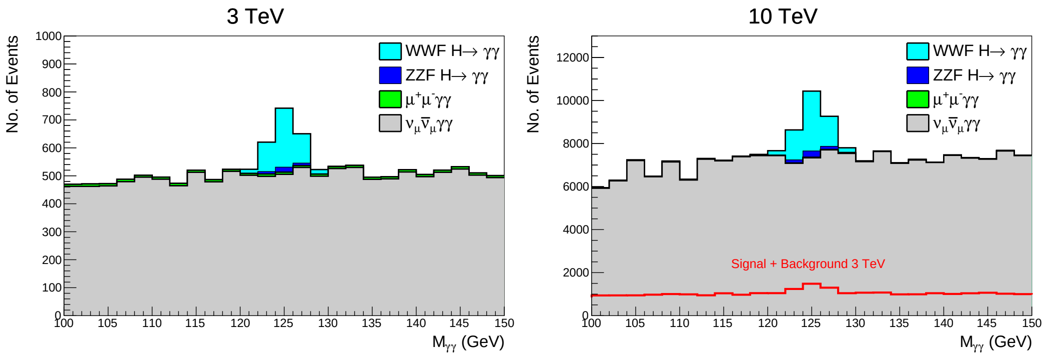
Following the same procedure as in $b\bar{b}$, we obtain results for $c\bar{c}$ and $gg(+s\bar{s})$:

	Precision (%)	
Energy	$c\bar{c}$	$gg(+s\bar{s})$
3 TeV	13	3.3
10 TeV	4.0	0.89

$\tau^+\tau^-$ follows a similar strategy with similar backgrounds, adding $\theta_{\tau\tau} > 15(20)$ cuts, to get 4.0(1.1)% precision.

$\gamma\gamma$ and $Z\gamma$

For $\gamma\gamma$, require no isolated leptons and a cut of $122 < M_{\gamma\gamma} < 128$.



The $Z(jj)\gamma$ process has similar backgrounds as the hadronic modes, but with more complicated cuts.

$t\bar{t}H$

This process requires special care: VBF at 10 TeV vs s-chan at 3, the cross section is small, and the $t\bar{t}$ background is large.

Select events with four b-tagged $p_T > 20$ jets and ≤ 1 leptons, apply various cuts on $E_{W,t,H}$, $m_{W,t,H}$

Obtain a precision of 61% at 3 TeV and 53% at 10 TeV

(Different y_t dependence at 3 and 10 TeV)

Number of Events

Process	3 TeV		10 TeV	
	SL	Had	SL	Had
$t\bar{t}H;\ H \to b\bar{b}$	34	63	49	59
$t\bar{t}H;\ H \not\to b\bar{b}$	9	21	6	11
$t\bar{t}$	609	2070	502	1440
$t\bar{t}Z$	207	362	530	663
$t\bar{t}b\bar{b}$	9	21	15	18

κ-0 Fit Result [%]

	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + 250 GeV e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.55	0.16	0.39	0.14	0.33	0.11
κ_Z	5.1	1.4	1.3	0.94	0.12	0.11
κ_g	2.0	0.52	1.4	0.50	0.75	0.43
κ_γ	3.2	0.84	1.3	0.71	1.2	0.69
$\kappa_{Z\gamma}$	24	6.5	24	6.5	4.1	3.5
κ_c	6.8	2.0	6.7	2.0	1.8	1.3
κ_t	35	55	3.2	3.2	3.2	3.2
κ_b	0.97	0.26	0.82	0.25	0.45	0.22
κ_μ	20	4.9	4.6	3.4	4.1	3.2
κ_τ	2.3	0.63	1.2	0.57	0.62	0.41

κ-0 Fit Result [%] with Forward Muon Tagging

	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + 250 GeV e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.37	0.10	0.35	0.10	0.31	0.10
κ_Z	1.2	0.34	0.89	0.33	0.12	0.11
κ_g	1.6	0.45	1.3	0.44	0.72	0.39
κ_γ	3.2	0.84	1.3	0.71	1.2	0.69
$\kappa_{Z\gamma}$	21	5.5	22	5.5	4.0	3.3
κ_c	5.8	1.8	5.8	1.8	1.7	1.3
κ_t	34	53	3.2	3.2	3.2	3.2
κ_b	0.84	0.23	0.80	0.23	0.44	0.21
κ_μ	14	2.9	4.7	2.5	4.0	2.4
κ_τ	2.1	0.59	1.2	0.55	0.61	0.40

10 TeV @ 10 ab^{-1}: κ-0 Fit Result [%] Without Fwd Tags

	Signal Only (2103.14043)	With Backgrounds (2203.09425)
κ_W	0.06	0.16
κ_Z	0.23	1.4
κ_g	0.15	0.52
κ_γ	0.64	0.84
$\kappa_{Z\gamma}$	1.0	6.5
κ_c	0.89	2.0
κ_t	6.0	55
κ_b	0.16	0.26
κ_μ	2.0	4.9
κ_τ	0.31	0.63

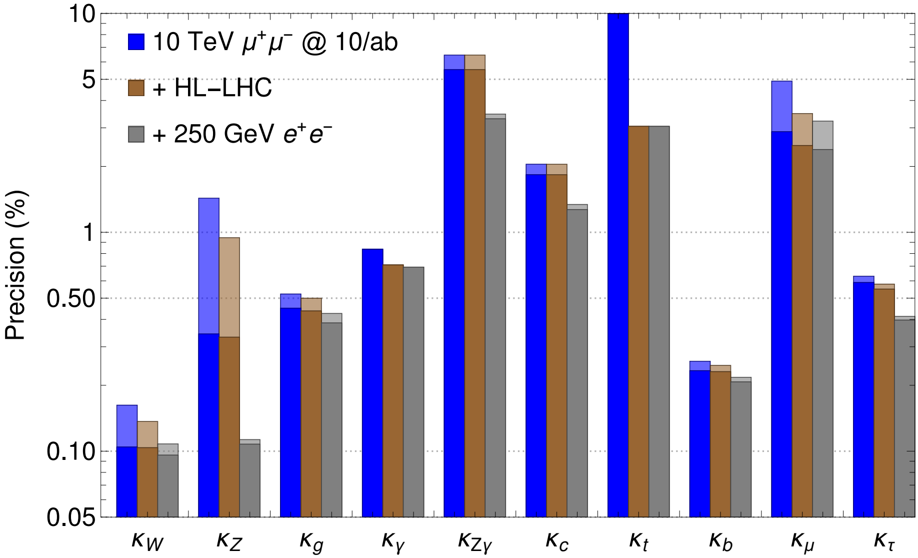
10 TeV @ 10 ab^{-1}: κ-0 Fit Result [%] With Fwd Tags

	Signal Only (2103.14043)	With Backgrounds (2203.09425)
κ_W	0.06	0.10
κ_Z	0.23	0.34
κ_g	0.15	0.45
κ_γ	0.64	0.84
$\kappa_{Z\gamma}$	1.0	5.5
κ_c	0.89	1.8
κ_t	6.0	53
κ_b	0.16	0.23
κ_μ	2.0	2.9
κ_τ	0.31	0.59

Where do we stand? (without forward tags)

κ-0 fit	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **3000**	$\mu^+\mu^-$ **10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.55	0.16
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	5.1	1.4
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	2.0	0.52
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	3.2	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	24	6.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	6.8	2.0
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	35	55
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.97	0.26
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	20	4.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	2.3	0.63

κ-0 Fit


10 TeV μ⁺μ⁻ @ 10/ab
+ HL–LHC
+ 250 GeV e⁺e⁻
Precision (%)
10
5
1
0.50
0.10
0.05
κW
κZ
κg
κγ
κZγ
κc
κt
κb
κμ
κτ

Full list of cuts: off-shell analysis

For $4j$, same cuts at 3 and 10 TeV:

- $p_{T_j} > 60$ GeV, $|\eta_j| < 2.5$, $30 < m_V^{min} < 100$ GeV, $40 < m_V^{max} < 115$ GeV

For $\ell^+\ell^- jj$:

- $p_{T_{\ell,j}} > 20$ GeV, $|\eta_{j,\ell}| < 2.5$, $70 < m_{\ell\ell} < 115$ GeV, $40 < m_{jj} < 115$ GeV
- $\theta_{\ell\ell}, \theta_{jj} < 25^\circ$ (10 TeV)

For $\ell^\pm \nu_\ell jj$:

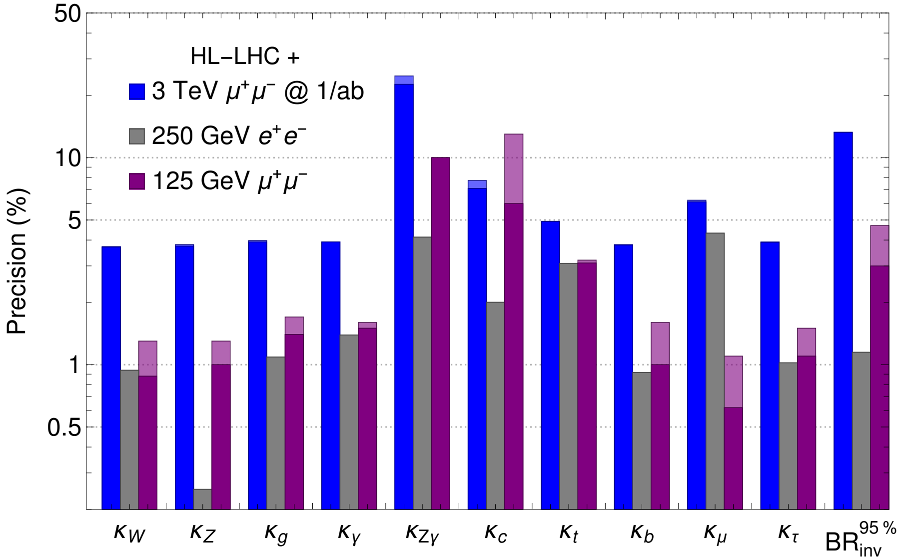
3 TeV:

- $p_{T_{\ell,j}} > 20$ GeV, $|\eta_{j,\ell}| < 2.5$, $p_{T_\ell} < 200$ GeV, $p_{T_{jj}} < 500$ GeV, $40 < m_{jj} < 115$ GeV

10 TeV:

- $p_{T_{\ell,j}} > 20$ GeV, $|\eta_{j,\ell}| < 2.5$, $p_{T_\ell} < 750$ GeV, $p_{T_{jj}} < 1200$ GeV, $40 < m_{jj} < 115$ GeV

Comparisons combined with HL-LHC



Perturbative unitarity

There is a delicate cancellation between the Higgs diagrams and the W/Z continuum diagrams that prevents the longitudinal pieces from growing like $\mathcal{M} \sim E^2$

In extended scalar sectors, this requirement becomes a sum rule for each process

$$(\kappa^h_{VV})^2 + \sum_i \alpha_i (\kappa^i_{VV})^2 = 1$$

For example, for the Georgi-Machacek model, $W_L^+ W_L^- \to W_L^+ W_L^-$ yields

$$(\kappa^h_W)^2 + (\kappa^H_W)^2 + (\kappa^{H_5^0}_W)^2 - (\kappa^{H_5^{++}}_W)^2 = 1$$

Therefore if m_H and m_5 are below our off-shell analysis window, everything appears the same as in the SM, even if $\kappa_V \neq 1$.

Georgi-Machacek Model

Add to the SM two scalar triplets in a custodial bi-triplet

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+} \\ \chi^{++*} & -\xi^{+*} & \chi^{0} \end{pmatrix}$$

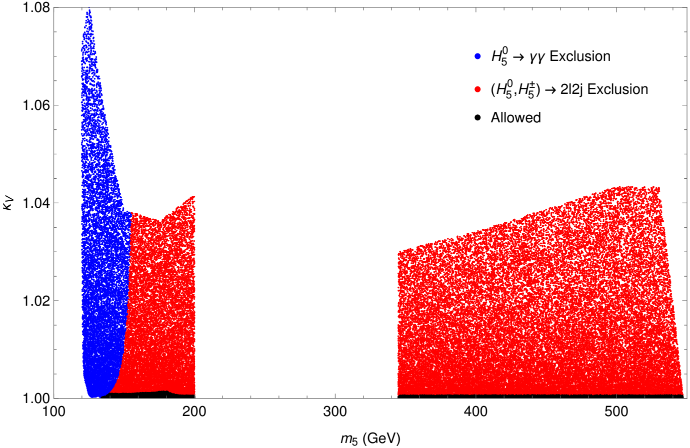
This is custodially symmetric if $\langle\chi^0\rangle = \langle\xi^0\rangle$.

After SSB, obtain a custodial fiveplet, a triplet, and two singlets

$$(H_5^0,\ H_5^{\pm},\ H_5^{\pm\pm}),\ (H_3^0,\ H_3^{\pm}),\ h,\ H$$

where the fiveplet does not couple to fermions. For simplicity, we will consider the "low-m_5" benchmark, in which all $\kappa_V > 1$ and $m_5 \lesssim 550$ GeV

Constraining the GM model (using GMCalc)



Expected constraint of $\kappa_V \lesssim 1.002$ from direct searches in low-m_5 benchmark

Georgi-Machacek model

Most general scalar potential with the added field content:

$$
\begin{aligned}
V(\Phi, X) =& \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1 \mathrm{Tr}[(\Phi^\dagger\Phi)]^2 + \lambda_2 \mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\
&+ \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4 \mathrm{Tr}[(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger \tau_a \Phi \tau_b)\mathrm{Tr}(X^\dagger t_a X t_b) \\
&- M_1 \mathrm{Tr}(\Phi^\dagger \tau_a \Phi \tau_b)(U X U^\dagger)_{ab} - M_2 \mathrm{Tr}(X^\dagger t_a X t_b)(U X U^\dagger)_{ab}
\end{aligned}
$$

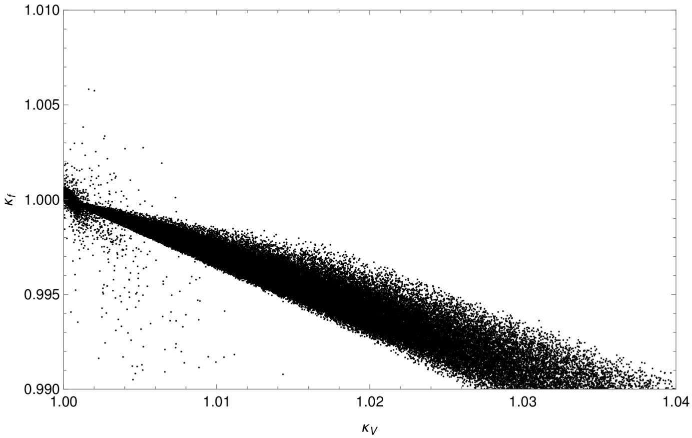
Model with a Z_2 symmetry would be ruled out by HL-LHC (de Lima, Logan, 2209.08393)

Higgs couplings straightforwardly given by

$$
\kappa_f = \frac{\cos\alpha}{\cos\theta}, \qquad \kappa_V = \cos\alpha\cos\theta - \sqrt{\frac{8}{3}}\sin\alpha\sin\theta
$$

with α the $h - H$ mixing angle, and $\cos\theta = \frac{v_\phi}{v}$ the SM Higgs doublet contribution to EWSB.

Constraining the GM model: general scan



Essentially no allowed points with $\kappa_V = \kappa_f > 1$ after expected direct search constraints

Full list of cuts: BR_{inv}

For γH, and $W^\pm H \to \ell^\pm \nu_\ell H$, only one observed particle, so only one set of cuts:

- $p_{T_{\gamma,\ell}} > 40$ GeV, $|\eta_{\gamma,\ell}| < 2.5$

For $ZH \to \ell^+ \ell^- H$:

- $p_{T_\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $80 < m_{\ell\ell} < 100$ GeV, $R_{\ell\ell} > 0.2$

For $VH \to jjH$:

- $p_{T_j} > 40$ GeV, $|\eta_j| < 2.5$, $60 < m_{jj} < 100$ GeV

For $\mu^+\mu^- H$ (forward tagging, only 10 TeV):

- $p_{T_\mu} > 20$ GeV, $p_{T_{\mu\mu}} > 100$ GeV, $R_{\mu\mu} > 9$, $m_{\mu\mu} > 8000$ GeV