Single Higgs Precision at Muon Colliders

2203.09425, 2308.02633 with Patrick Meade

Matthew Forslund

YITP, Stony Brook University
Brookhaven National Lab

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The P5 report

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

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So what's the big deal with muon colliders?

Muon colliders: the physics case

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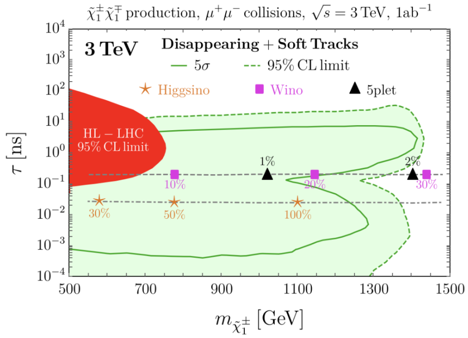
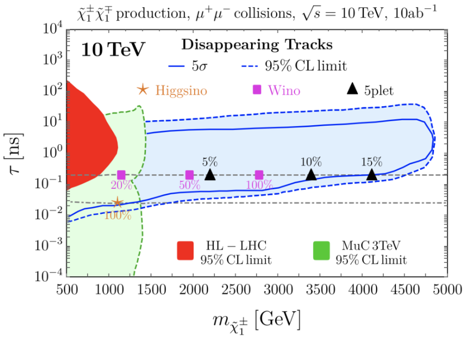
- 5σ discovery for Higgsino (3 TeV) / Wino (10 TeV) thermal targets

(Capdevilla, Meloni, Zurita 2405.08858; Capdevilla, Meloni, Simoniello, Zurita 2102.11292; Han, Liu, Wang, Wang 2203.07351; . . .)





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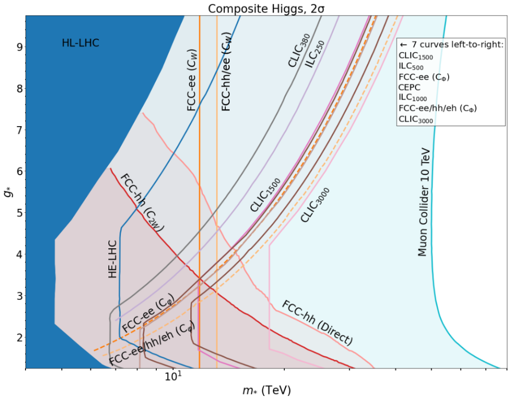
- Unparalleled tests of Higgs compositeness

Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509
EF report 2211.11084
Accettura et al. 2303.08533
Liu, Wang, Xie 2312.09117
. . .



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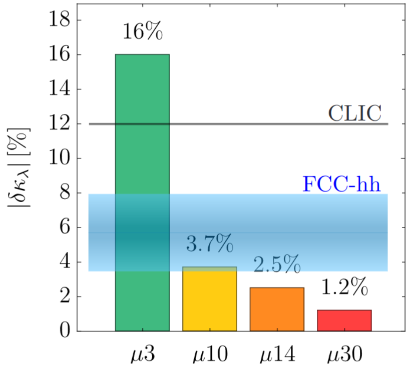
- $\sim 4\%$ level Higgs trilinear measurement
- $\mathcal{O}(1)$ measurement of Higgs quartic

Accettura et al. 2303.08533
Han, Liu, Low, Wang 2008.12204
Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao 2003.13628
...



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- Heavy EW BSM resonances up to $\sim E_{CM}/2$
- Lepton flavour universality
- Scalar singlets
- Dark sectors
- **Single Higgs precision** $\leftarrow$ (This talk)

and many more!

Muon smasher's guide 2103.14043
Muon collider forum report 2209.01318
Towards a muon collider 2303.08533
IMCC report 2407.12450
...

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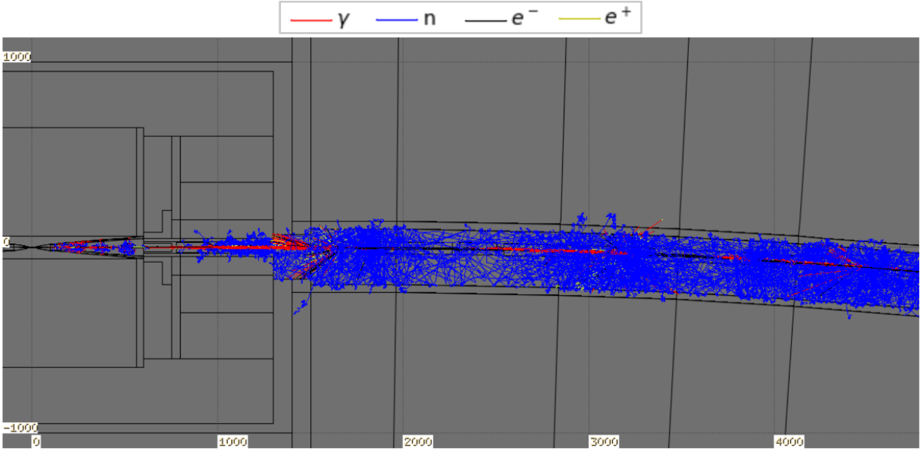
However, (3) affects physics performance in the detector!

Beam induced backgrounds (2203.07964)

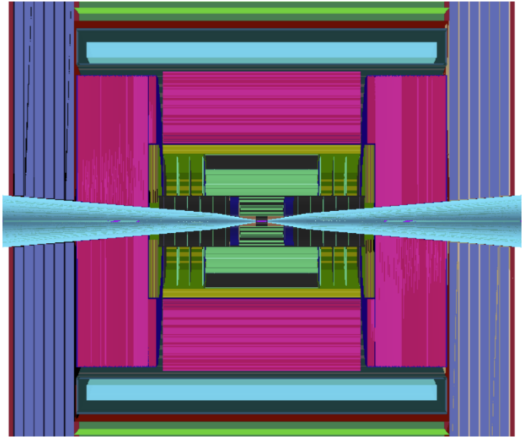


BIB mitigation (IMCC 2407.12450)

Simulations at 1.5 TeV: tungsten nozzles with $\theta = 10^\circ$ reduces BIB to tolerable level

Limiting factor in i.e. jet energy resolution

BIB more forward at higher energies



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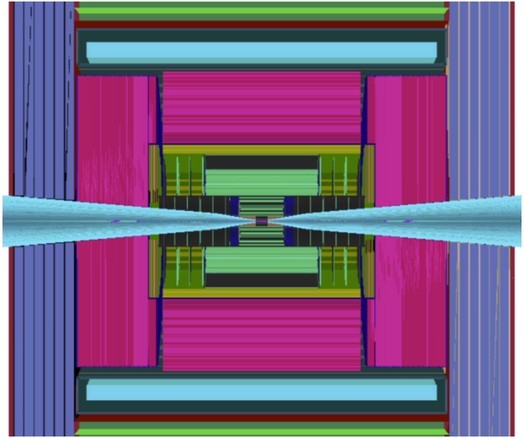

The effects of BIB on precision studies must be included eventually, still under development

Our input to the physics case:

(single) Higgs precision at muon colliders

The Higgs Precision Landscape (de Blas et al, 1905.03764)

κ-0:
$BR_{BSM} = 0$

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

$\delta\kappa_V \sim 0.1\%$

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

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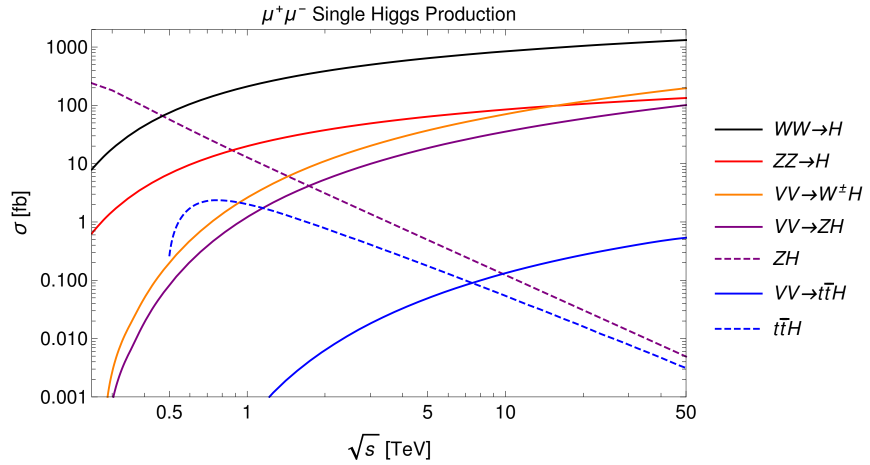

High energies dominated by $WW \to H$ and $ZZ \to H$.

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.

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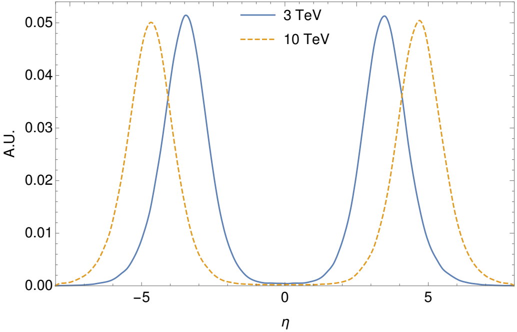

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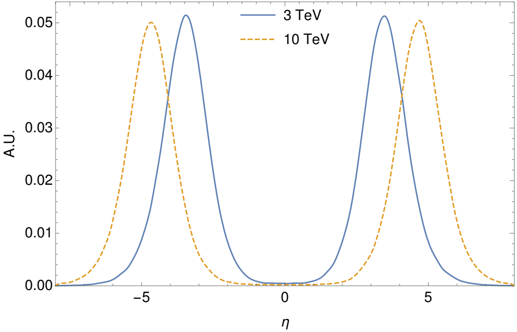

For ZZ-fusion, we include results considering (optimistic) tagging up to $|\eta| \leq 6$.

Event Generation and Detector Assumptions

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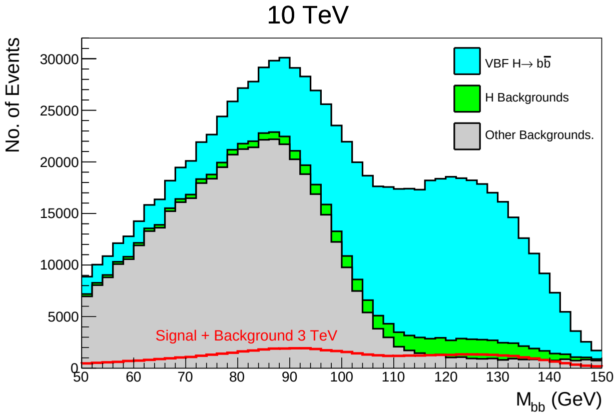
Estimate precision as $\frac{\delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$ (stat only!)

Hadronic Processes: $b\bar{b}$



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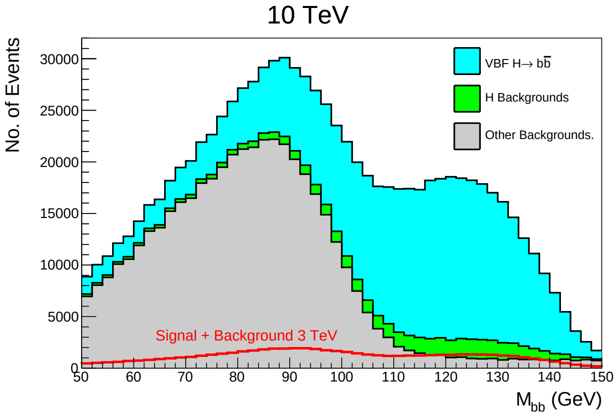

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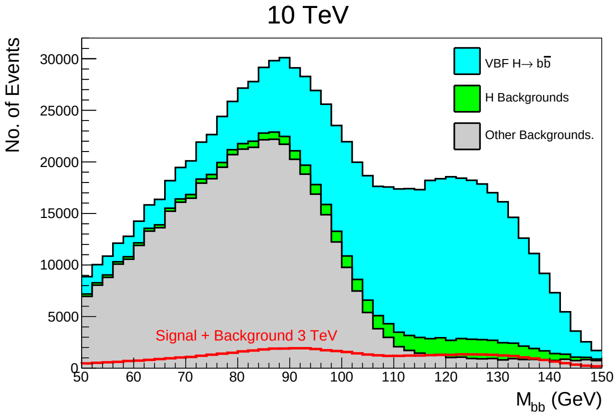

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$\rightarrow$ precision limited by JER?

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

Estimating the Effects of the BIB

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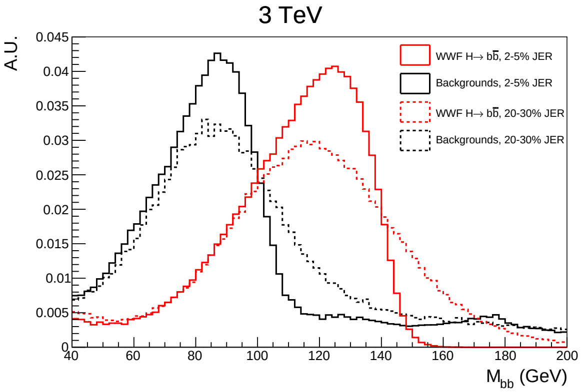

Worse JER based on fullsim – additional spreading roughly doubles the background contribution from the Z peak: 0.76% $\rightarrow$ 0.86% precision.

WW^*,ZZ^*

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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

The top Yukawa

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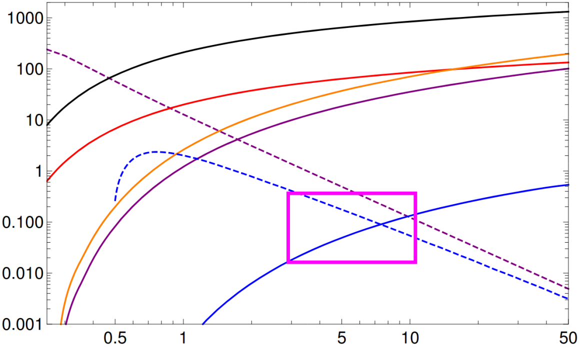

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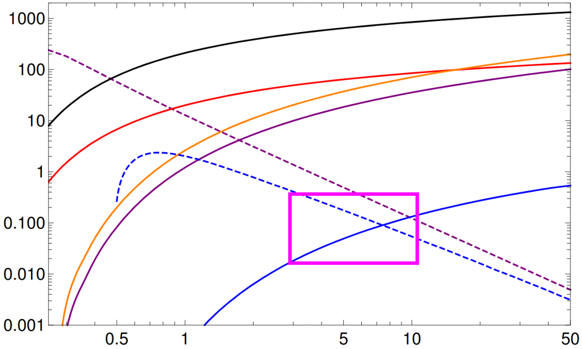
Find $\delta\sigma = 53\%$ at 10 TeV ($\delta y_t \sim 11\%$)



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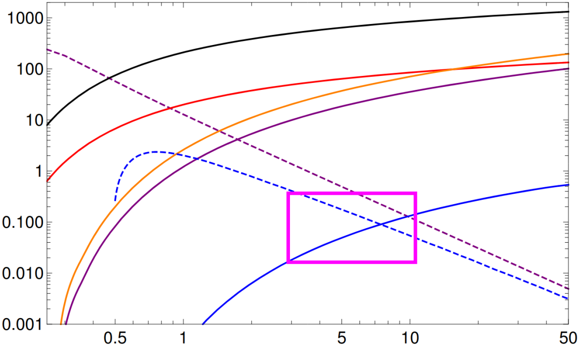
Off-shell y_t measurement from VBF tt could give $\delta y_t \sim 1.5\%$ at 10 TeV

Liu, Lyu, Mahbub, Wang 2308.06323; Chen, Liu 2212.11067

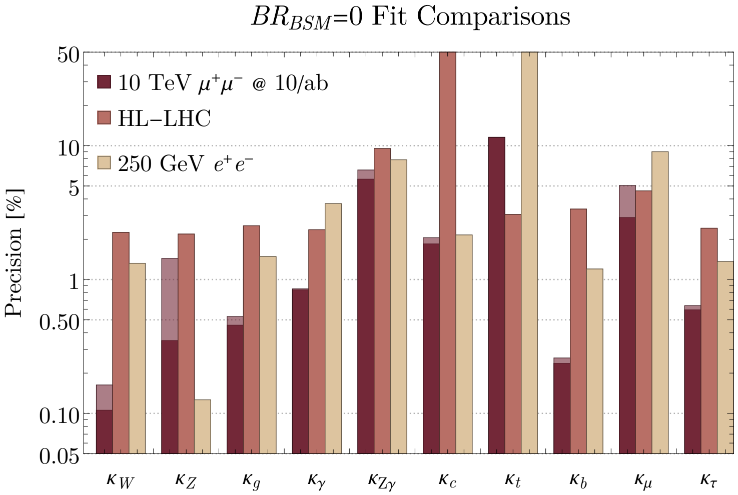


Repeat for all other channels...

Where do we stand?

Shaded:
forward tagging

$|\kappa_V| < 1$ fit
very similar



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.

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To remove this degeneracy, must either make assumptions or measure the width.

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

Using other colliders to fix $\delta\Gamma_H$

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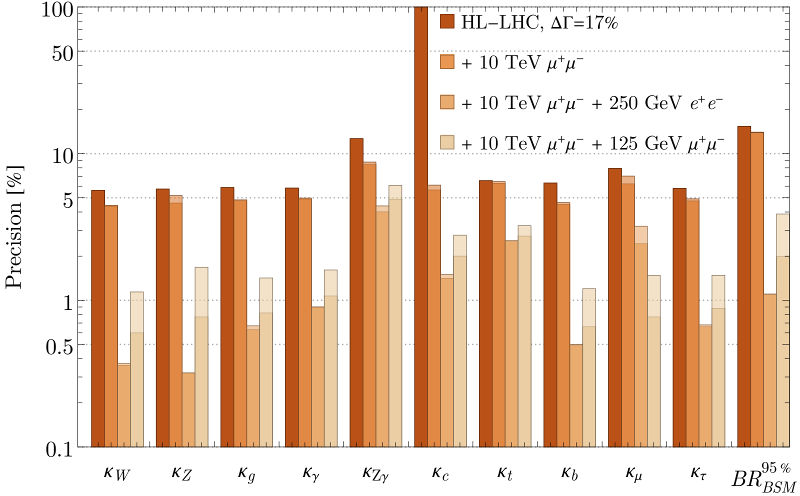

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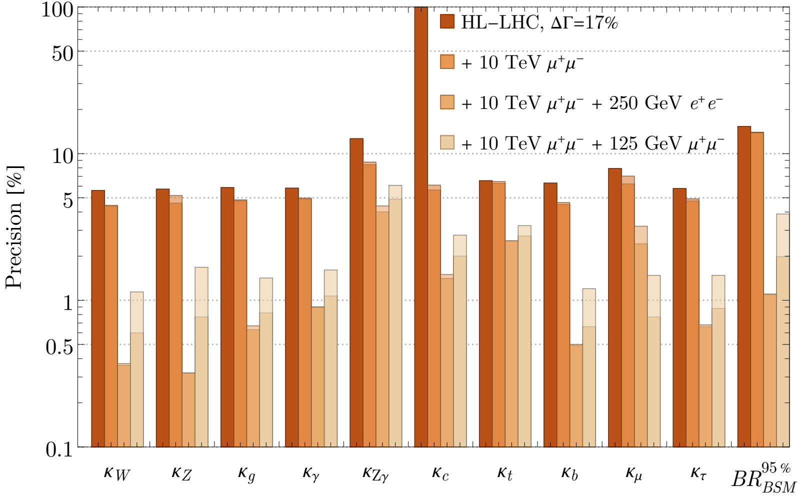

Would like to constrain the width at the MC itself!

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1. Perform a lineshape scan at 125 GeV $\mu^+\mu^-$ (de Blas, Gu, Liu 2203.04324)

   Only possible at $s = m_H^2$

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

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

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Let's look in more detail

Measuring σ_{Incl}

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

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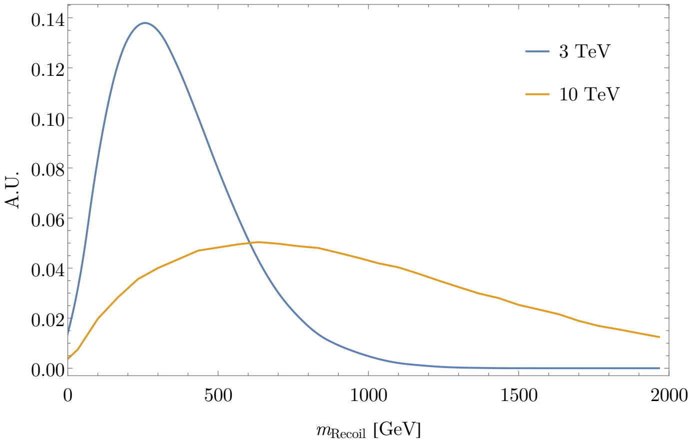
Nevertheless, could this be done at a muon collider via the forward muons in ZZF?

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



Maybe (Li, Liu, Lyu 2401.08756), but highly sensitive to forward detector properties

LHC techniques

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(Same method as the off-shell y_t measurement)

Off-shell $VV \to VV$ scattering

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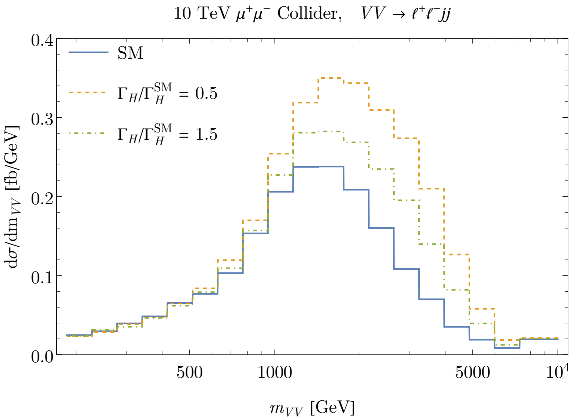
Fit each bin to a function $a + b\kappa_i\kappa_j + c\kappa_i^2\kappa_j^2$ by varying κ_V.



Off-shell $VV \to VV$ scattering

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

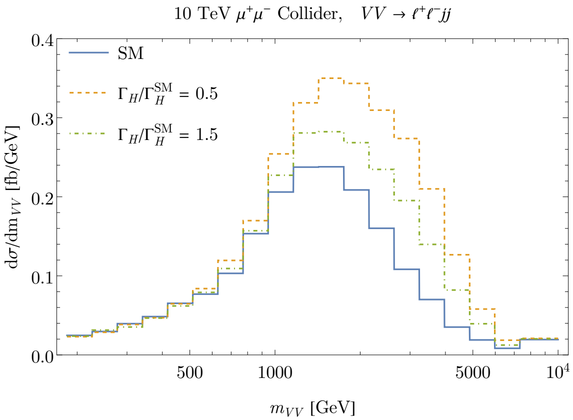
Stricter cuts than on-shell, BIB shouldn't matter much

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 $\delta\Gamma$ yields:

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

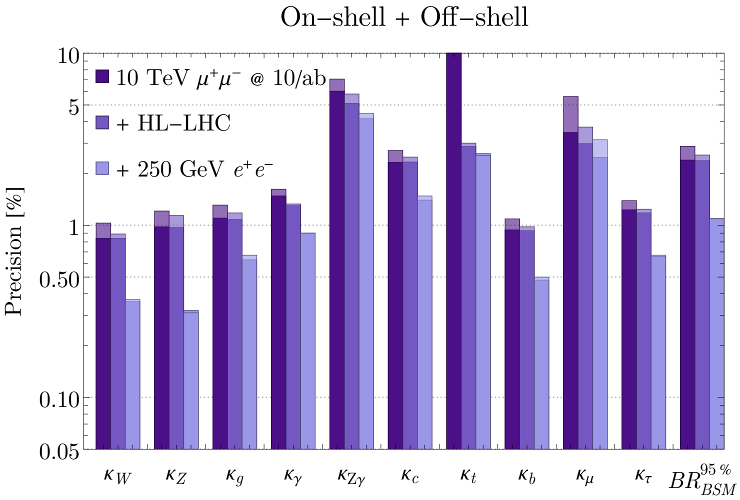
$\delta\Gamma = 58\%$ at 3 TeV
(not competitive with LHC)



Off-shell fit

Shaded:
forward tagging

Find
$\delta\kappa_V \approx \delta\Gamma/4$



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Are there concrete examples of models that can do this?

Higher multiplet scalars

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These models all have singly and doubly charged scalars. How do direct searches enter the story?

The minimal example: 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 $\langle \chi^0 \rangle = \langle \xi^0 \rangle$.

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Most general scalar potential with the added field content (Φ is SM Higgs doublet):

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

Georgi-Machacek model

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

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

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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.

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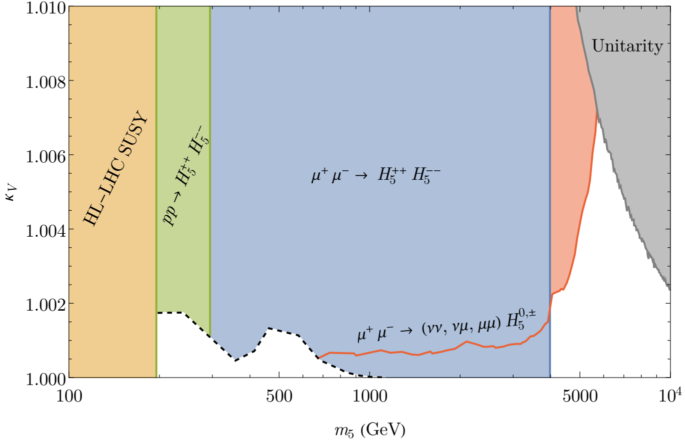
In the decoupling limit $\mu_3 \gg \mu_2$, can match onto the SMEFT and find:

$$\kappa_f^{dec} \approx 1 - \frac{1}{8}\frac{M_1^2 v^2}{\mu_3^4}, \qquad \kappa_V^{dec} \approx 1 + \frac{3}{8}\frac{M_1^2 v^2}{\mu_3^4}$$

Enter direct searches



With exception of rare (easily excludable) points: direct searches push to decoupling limit

Breaking the degeneracy: $\kappa_f < 1$

In decoupling limit, $|\kappa_f| < 1$: impose as assumption!

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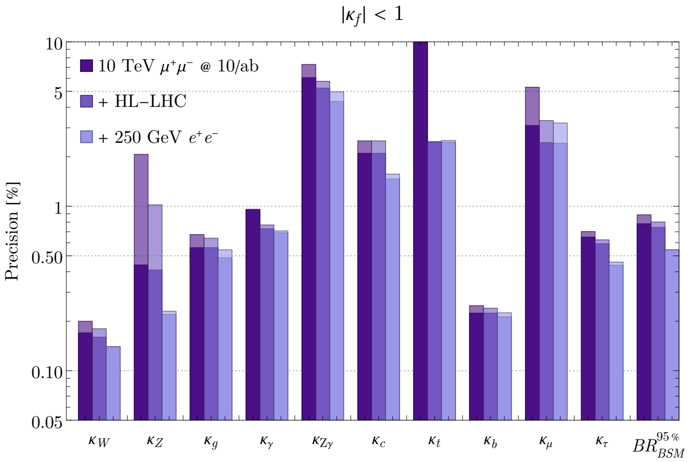
Precision restored to $\sim 0.1\%$ level



Breaking the degeneracy: $\kappa_f < 1$

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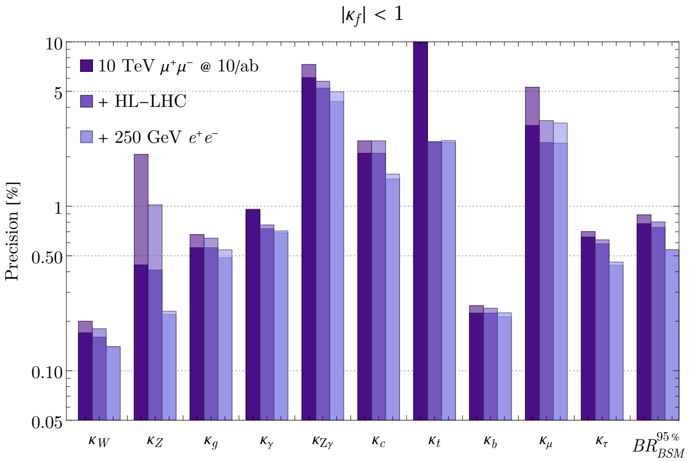
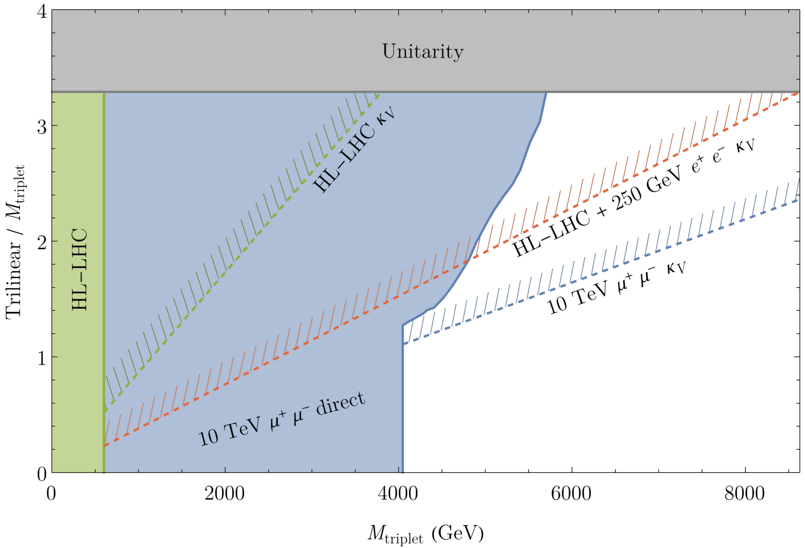
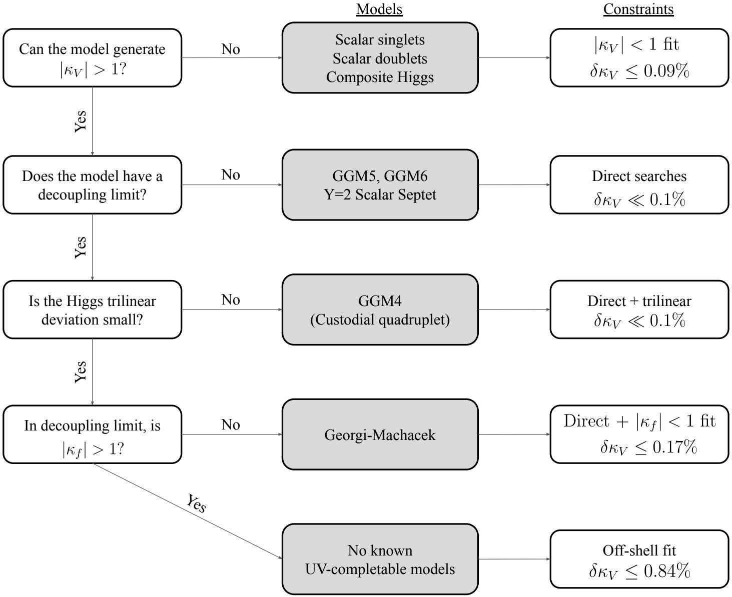
All other GM models (and 7-plet) would exclusively be *more* constrained

(Of these, only custodial quartet has a decoupling limit)



Putting the pieces together




Models
Constraints
Can the model generate $|\kappa_V| > 1$?
No
Scalar singlets
Scalar doublets
Composite Higgs
$|\kappa_V| < 1$ fit
$\delta\kappa_V \leq 0.09\%$
Yes
Does the model have a decoupling limit?
No
GGM5, GGM6
Y=2 Scalar Septet
Direct searches
$\delta\kappa_V \ll 0.1\%$
Yes
Is the Higgs trilinear deviation small?
No
GGM4
(Custodial quadruplet)
Direct + trilinear
$\delta\kappa_V \ll 0.1\%$
Yes
In decoupling limit, is $|\kappa_f| > 1$?
No
Georgi-Machacek
Direct + $|\kappa_f| < 1$ fit
$\delta\kappa_V \leq 0.17\%$
Yes
No known
UV-completable models
Off-shell fit
$\delta\kappa_V \leq 0.84\%$

What about probing BR_{BSM}?

Can constrain BR_{BSM} directly as well: suppose that $BR_{BSM} = BR_{inv}$

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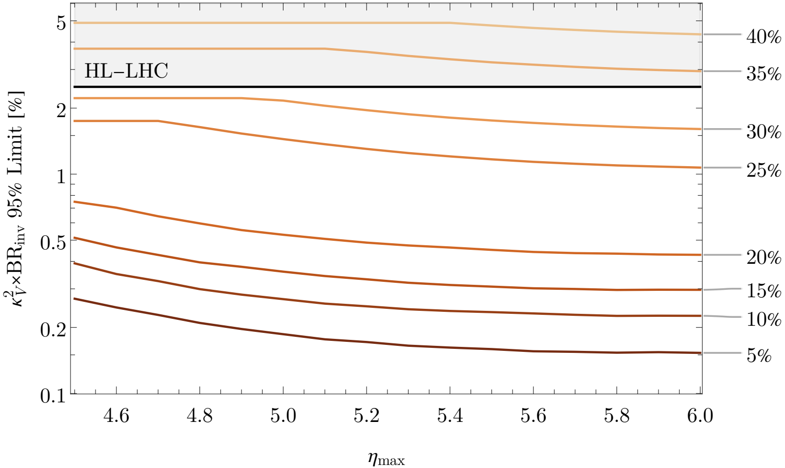
Measure forward μ's in $\mu^+\mu^- \to \mu^+\mu^- H, H \to inv$

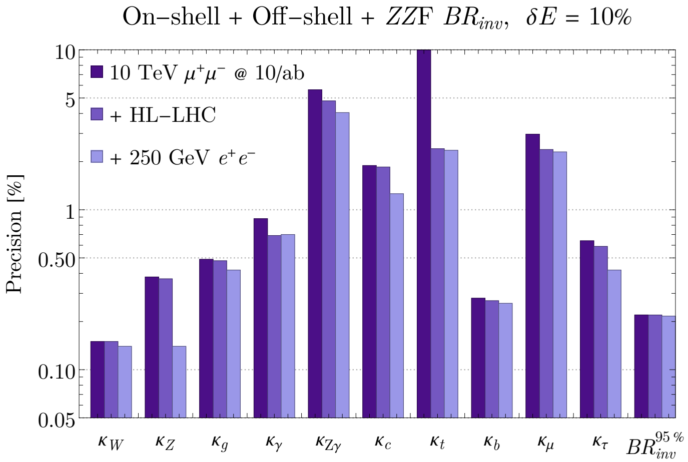
Highly sensitive to forward detector energy resolution



(see also M. Ruhdorfer, E. Salvioni, A. Wulzer 2303.14202)

What about probing BR_{BSM}?

Once again, restored to $\sim 0.1\%$ level, if δE is good enough



Without forward muons?

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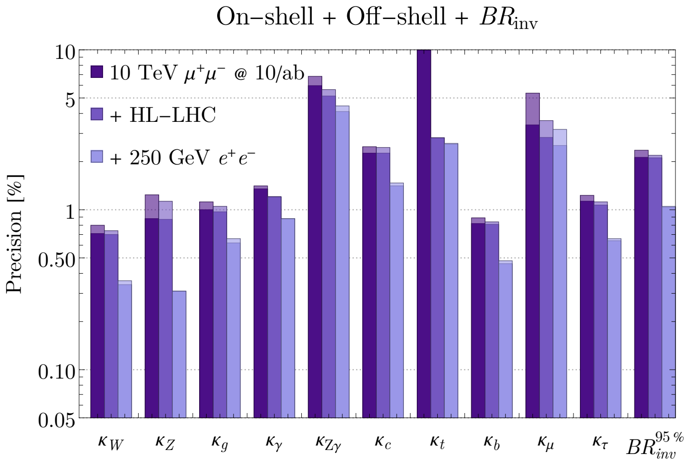
Results from VBF $HZ, HW^{\pm}, H\gamma$ without ZZF forward tags not nearly as good



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Great complementary between $\mu^+\mu^-$ collider and Higgs factories

Thank you!

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, take 20% as our working point inspired by ILC studies (1506.08371).

- 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 ∼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 $gg(+s\bar{s})$

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

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 $gg(+s\bar{s})$:

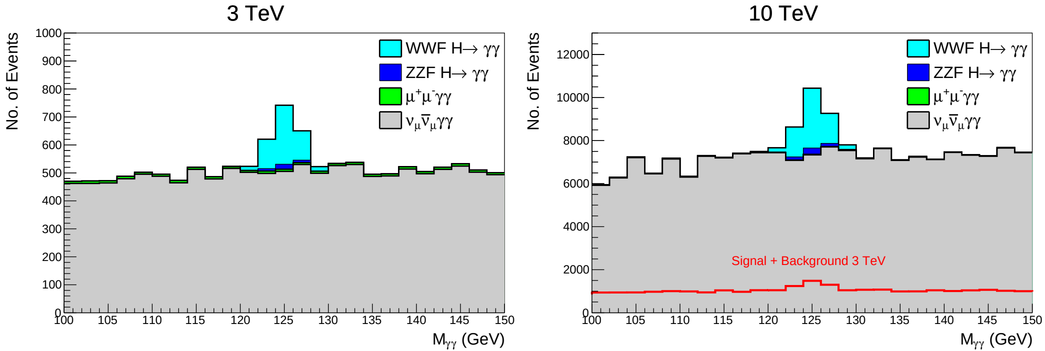
Precision (%)

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.

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

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

$$(\kappa^h_W)^2 + (\kappa^H_W)^2 + (\kappa^{H^0_5}_W)^2 - (\kappa^{H^{++}_5}_W)^2 = 1$$

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

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 – direct searches probe them

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