Inclusive Higgs Rate with Forward Detection at High Energy Muon Collider

Kun-Feng Lyu

University of Minnesota

In collaboration with Peiran Li and Zhen Liu

DPF - PHENO 2024 May 16, 2024

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  - Motivation
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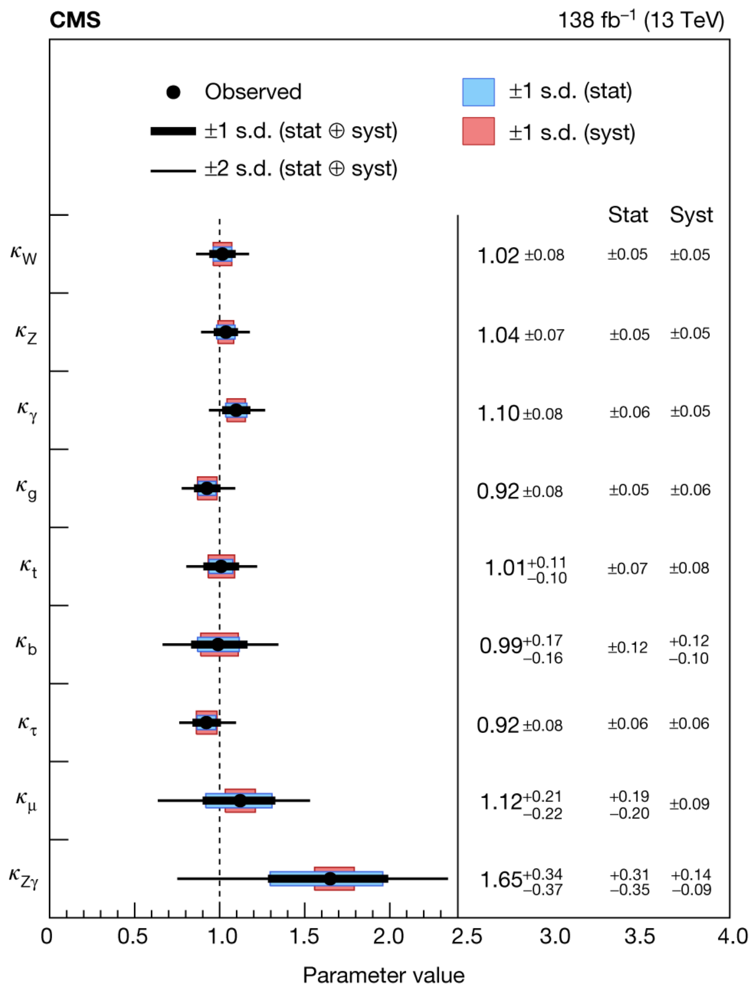
Motivation

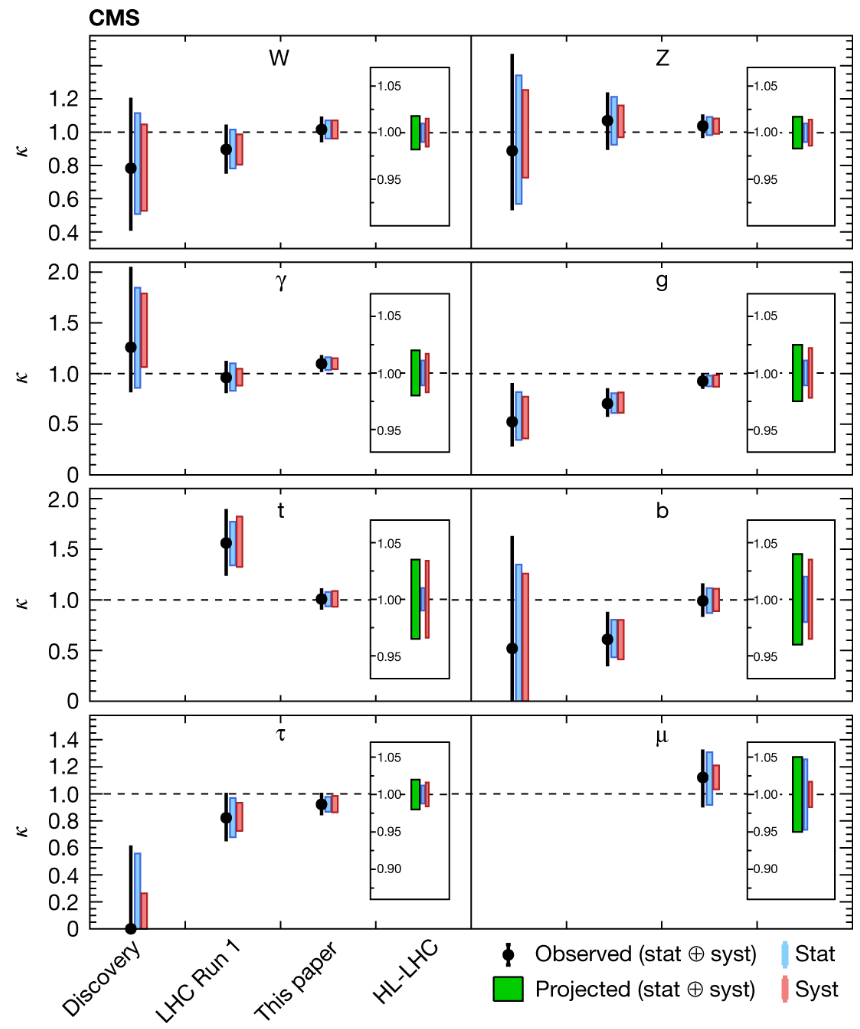
Nature volume 607, 60–68 (2022)

Higgs boson has been discovered over ten years ago.

Higgs is still the central player of many mysteries and puzzles.

We need to have deeper understanding of the Higgs properties.





Currently we can measure the higgs coupling to above 5%

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF, hard scattering, parton shower, detector response $\cdots$

$$\kappa_i = \frac{g_i}{g_i^{\text{SM}}}, \kappa_\Gamma = \frac{\Gamma_{\text{tot}}}{\Gamma_{\text{tot}}^{\text{SM}}}$$

For the hard scattering under the narrow width approximation:

$$\sigma(a \to H \to b) \propto \frac{\Gamma_a \Gamma_b}{\Gamma_{\text{tot}}} \propto \frac{\kappa_a^2 \kappa_b^2}{\kappa_\Gamma} = \mu_a^b$$

$$\kappa_\Gamma = \frac{\sum_i \kappa_i^2 \text{Br}_{i,\text{SM}}}{1 - \text{Br}_{\text{exo}}}$$

All onshell channels can be parametrized this way, simple extension possible for more channels/observables.

Higgs Fit Degeneracy

Under the rescaling $\kappa_{a/b} \to t\,\kappa_{a/b}$,
μ_a^b would be invariant if $\kappa_\Gamma \to t^4\,\kappa_\Gamma$

- For $t < 1$

$$t^4 \quad \kappa_\Gamma = \frac{\sum_i \kappa_i^2 \mathrm{Br}_{i,\mathrm{SM}}}{1 - \mathrm{Br}_{\mathrm{exo}}} \quad \begin{matrix} t^2 \\ t^{-2} \end{matrix}$$

No exotic branching ratio can satisfy, so degeneracy is broken

- For $t > 1$

$$t^4 \quad \kappa_\Gamma = \frac{\sum_i \kappa_i^2 \mathrm{Br}_{i,\mathrm{SM}}}{1 - \mathrm{Br}_{\mathrm{exo}}} \quad \begin{matrix} t^2 \\ t^{-2} \end{matrix}$$

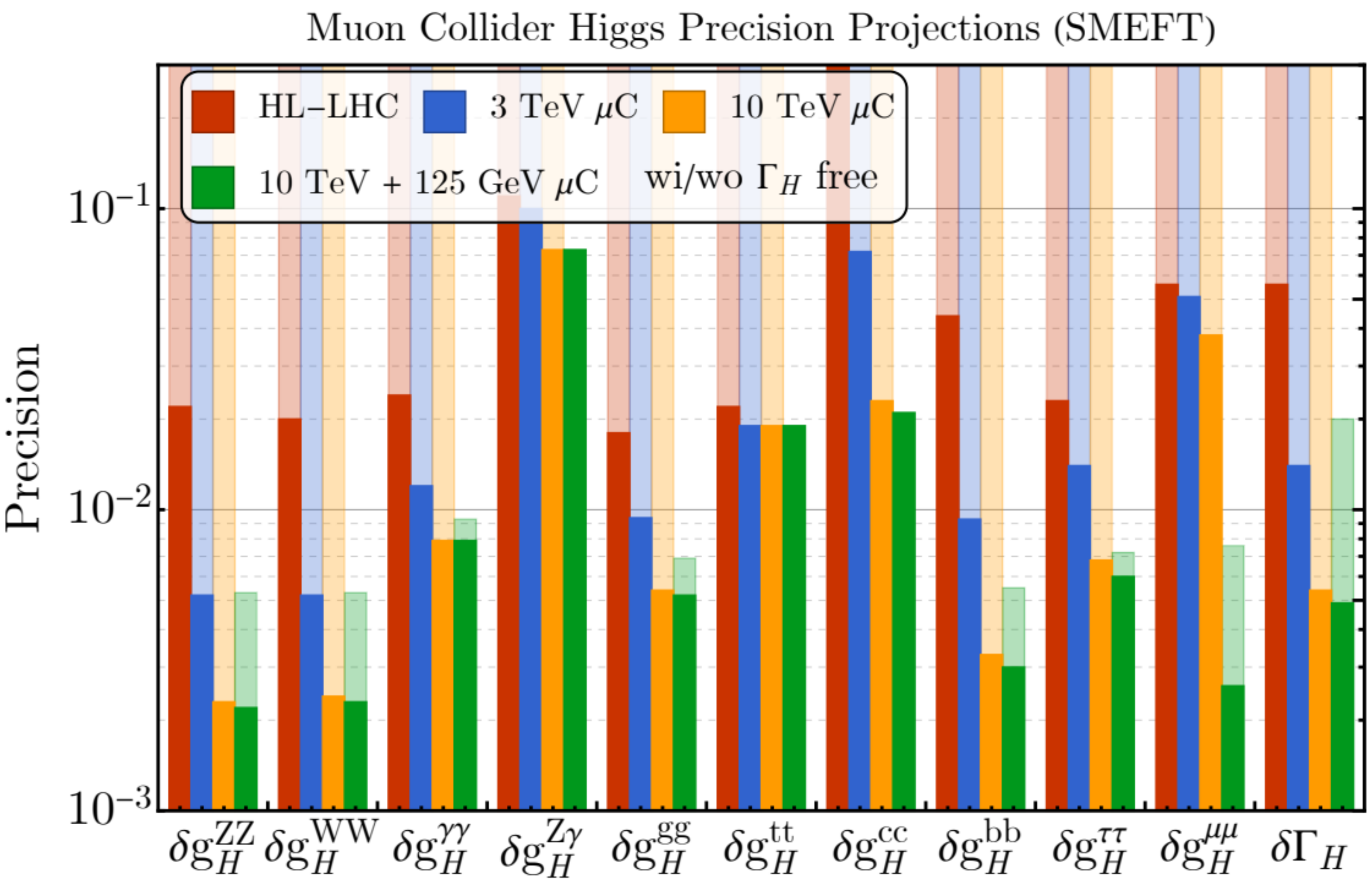
Certain exotic branching ratio can always satisfy, we cannot break the degeneracy.

People typically assume $|\kappa_V| < 1$ or $\mathrm{Br}_{\mathrm{exo}} = 0$ which means κ_Γ is not a free parameter

We need to introduce new types of observables. One possibility is just κ_V^2 from the inclusive measurement.

- Previous Higgs studies, at 3/10 TeV MuC alone do not have constraint on Higgs total width.

- Our study will be directly sensitive to g_H^{ZZ}. Combining with other channels will be able to constraint Γ_H



[2209.01318] Muon Collider Forum Report

Inclusive Higgs rate from ZZ fusion ($\sqrt{s} = 10$ TeV)

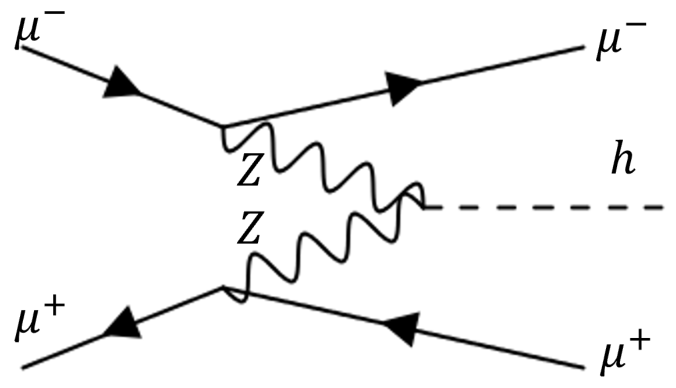
Forward muon detector: $2.5 < \eta(\mu) < 4, 6, 8$

Ultra-energetic muons would penetrate the shielding nozzles

$$p_h = (\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}$$

$$m_h^2 = \left[(\sqrt{s}, 0,0,0) - p_{\mu^+} - p_{\mu^-}\right]^2$$

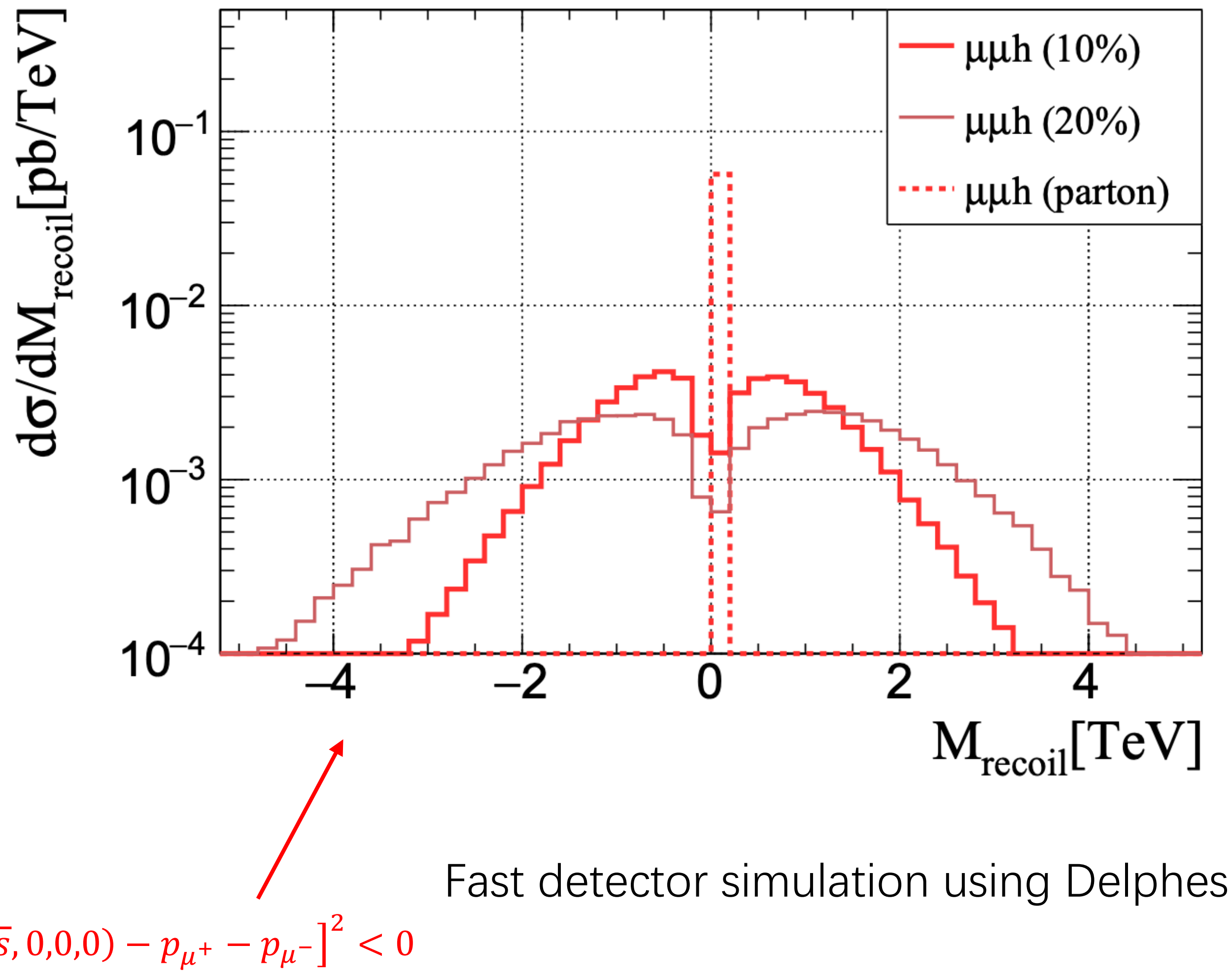
Recoil mass of dimuon



Does not rely on the detection of Higgs decay product.

Inclusive Higgs rate from ZZ fusion ($\sqrt{s} = 10$ TeV)

Due to the uncertainty of high energy measurement, the smearing effect will distort the recoil mass distribution.



Fast detector simulation using Delphes.

Signal vs. Background ($\sqrt{s} = 10$ TeV)

Only tag 2 forward muons

Do not have any requirements on other detection.

Type	Scattering process	cross section σ (pb)
VBF	$\mu^+\mu^- \to \mu^+\mu^- h$	0.0867
t-channel	$\mu^+\mu^- \to \mu^+\mu^-$	1.12×10^4
t-channel	$\mu^+\mu^- \to \mu^+\mu^-\gamma$	754.8
VBS	$\mu^+\mu^- \to \mu^+\mu^-\ell^+\ell^-$	3.96
VBS	$\mu^+\mu^- \to \mu^+\mu^- jj$	2.06
VBS	$\mu^+\mu^- \to \mu^+\mu^-\nu_\ell\bar{\nu}_\ell$	1.68
VBS	$\mu^+\mu^- \to \mu^+\mu^- W^+W^-$	0.939

Cross section for both signal and background after parton-level pre-selection.

Pre-selection at parton-level:

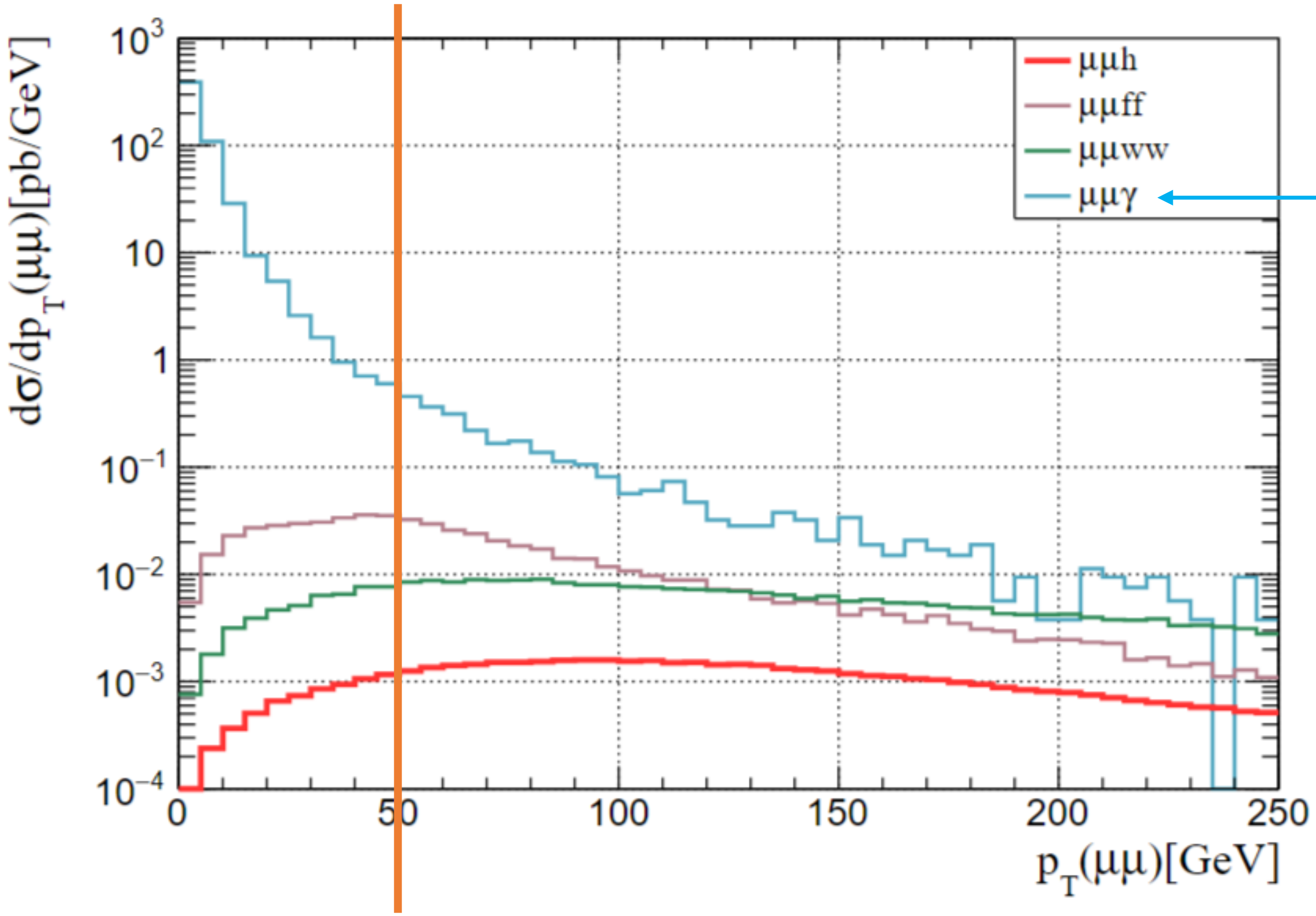
$p_T(l,j) > 5$ GeV,
$p_T(\gamma) > 1$ GeV,
$|\eta(l)| < 10$,
$\Delta R(ll, lj, jj) > 0.2$

3 types of background

- $\mu\mu \to \mu\mu(\gamma)$
- $\mu\mu \to \mu\mu + ff$
- $\mu\mu \to \mu\mu + WW$

Signal vs. Background $(\sqrt{s} = 10\ \mathrm{TeV})$

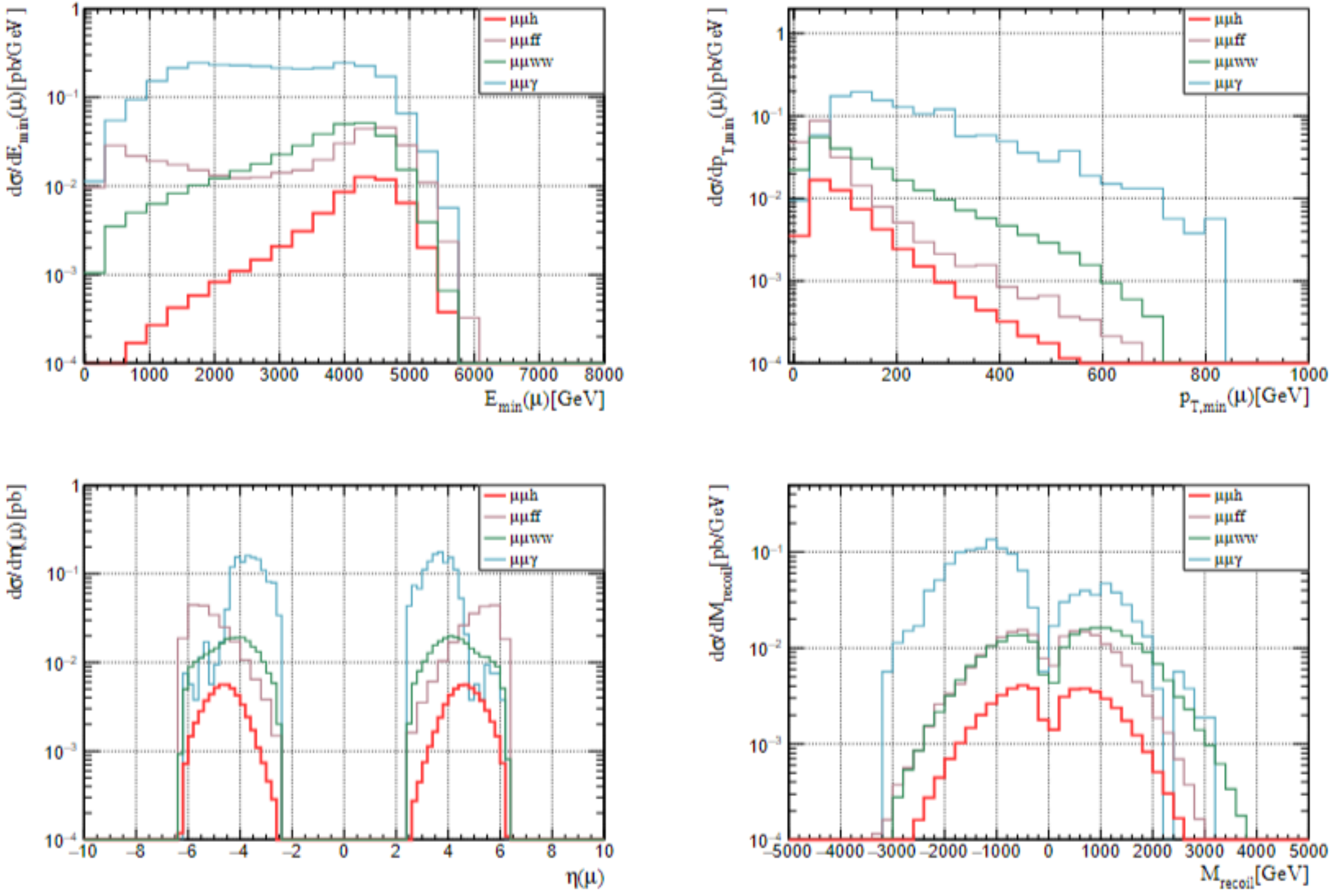
Require $p_T(\mu\mu) > 50\ \mathrm{GeV}$



Merging $\mu\mu \to \mu\mu$ and $\mu\mu \to \mu\mu\gamma$

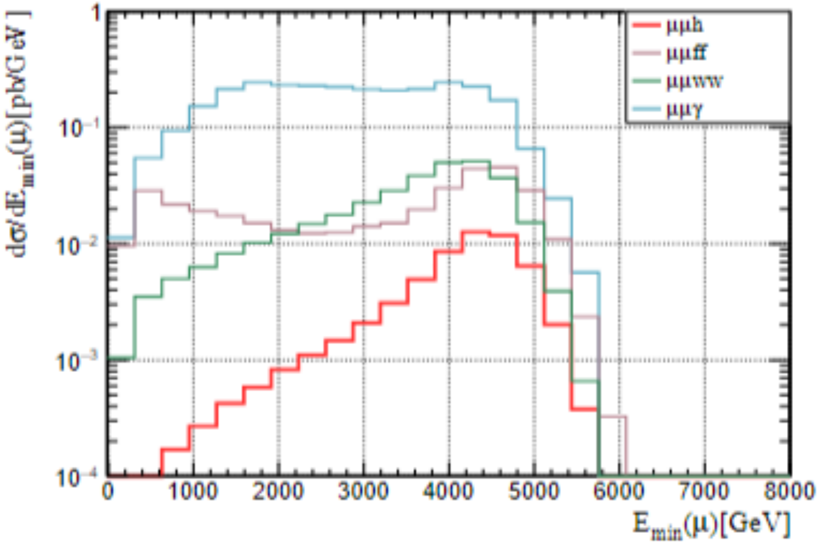
Cutflow analysis

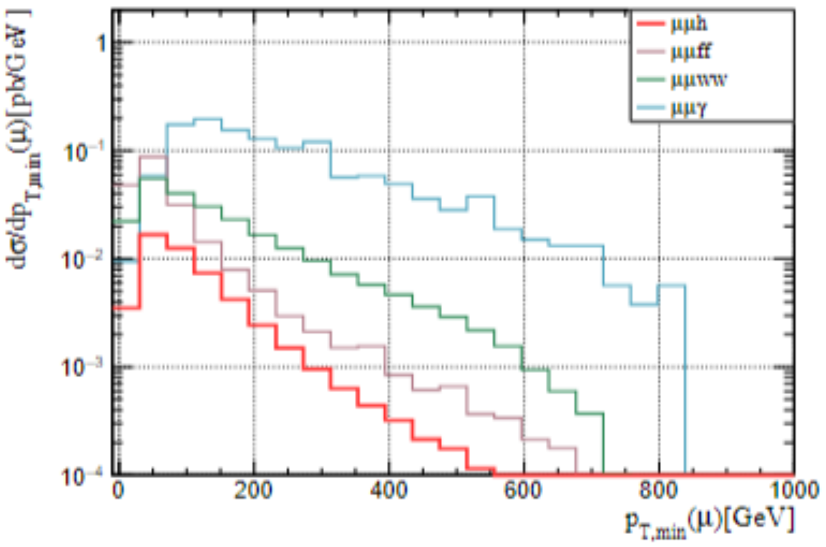
Checking other kinematics and applying a few cuts.



Cutflow analysis

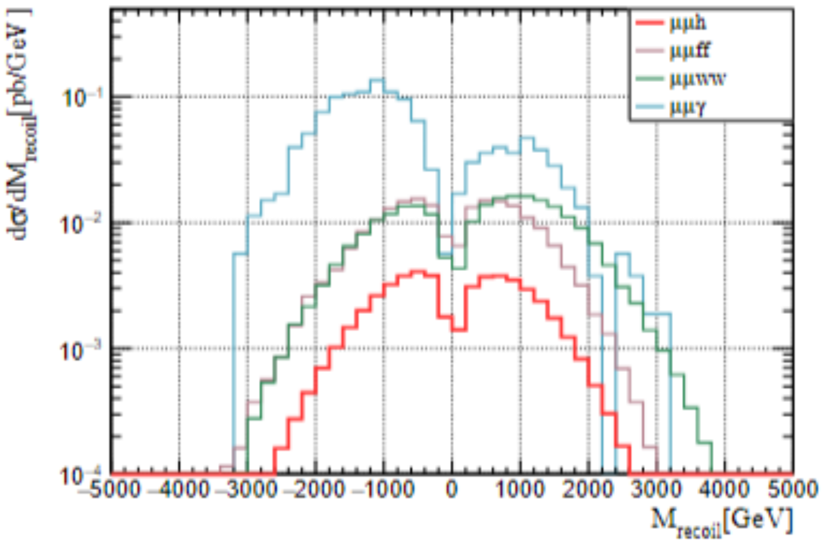
Checking other kinematics and applying a few cuts.





Process	Pre-selection	$p_T(\mu\mu) > 50$ GeV	$E(\mu) > 3000$ GeV & $p_{T,min}(\mu) < 300$ GeV
$\mu^+\mu^- \to \mu^+\mu^- h$	73.3%	65.7%	56.4% (0.0489 pb)
$\mu^+\mu^- \to \mu^+\mu^- \gamma$	13.1%	0.38%	0.12% (0.906 pb)
$\mu^+\mu^- \to \mu^+\mu^- f\bar{f}$	8.13%	4.69%	2.58% (0.199 pb)
$\mu^+\mu^- \to \mu^+\mu^- W^+W^-$	40.0%	34.9%	22.0% (0.207 pb)

TABLE II. Cutflow table for both signal and background events. All processes before the pre-selection cuts are set to 100%.



Detector level pre-selection:

- Only two visible muons in forward region ($2.5 < \eta(\mu) < 8.0$).
- Back-to-back muons: $\eta(\mu^-) \cdot \eta(\mu^+) < 0$.
- Sufficient transverse momentum: $p_T(\mu) > 20$ GeV.

Sensitivity

3 TeV

Benchmark	$\eta(\mu) < 4$	$\eta(\mu) < 6$	$\eta(\mu) < 8$
$\Delta\sigma/\sigma$	6.2%	3.94%	3.94%

TABLE V. The 68% projected sensitivity on the Higgs inclusive rate from ZZ fusion at 3 TeV muon collider.

10 TeV

Benchmark	$\eta(\mu) < 4$	$\eta(\mu) < 6$	$\eta(\mu) < 8$
$\Delta\sigma/\sigma$	15.2%	0.75%	0.74%

TABLE III. The 68% projected sensitivity on the Higgs inclusive rate from ZZ fusion at 10 TeV muon collider.

Higgs coupling global fit

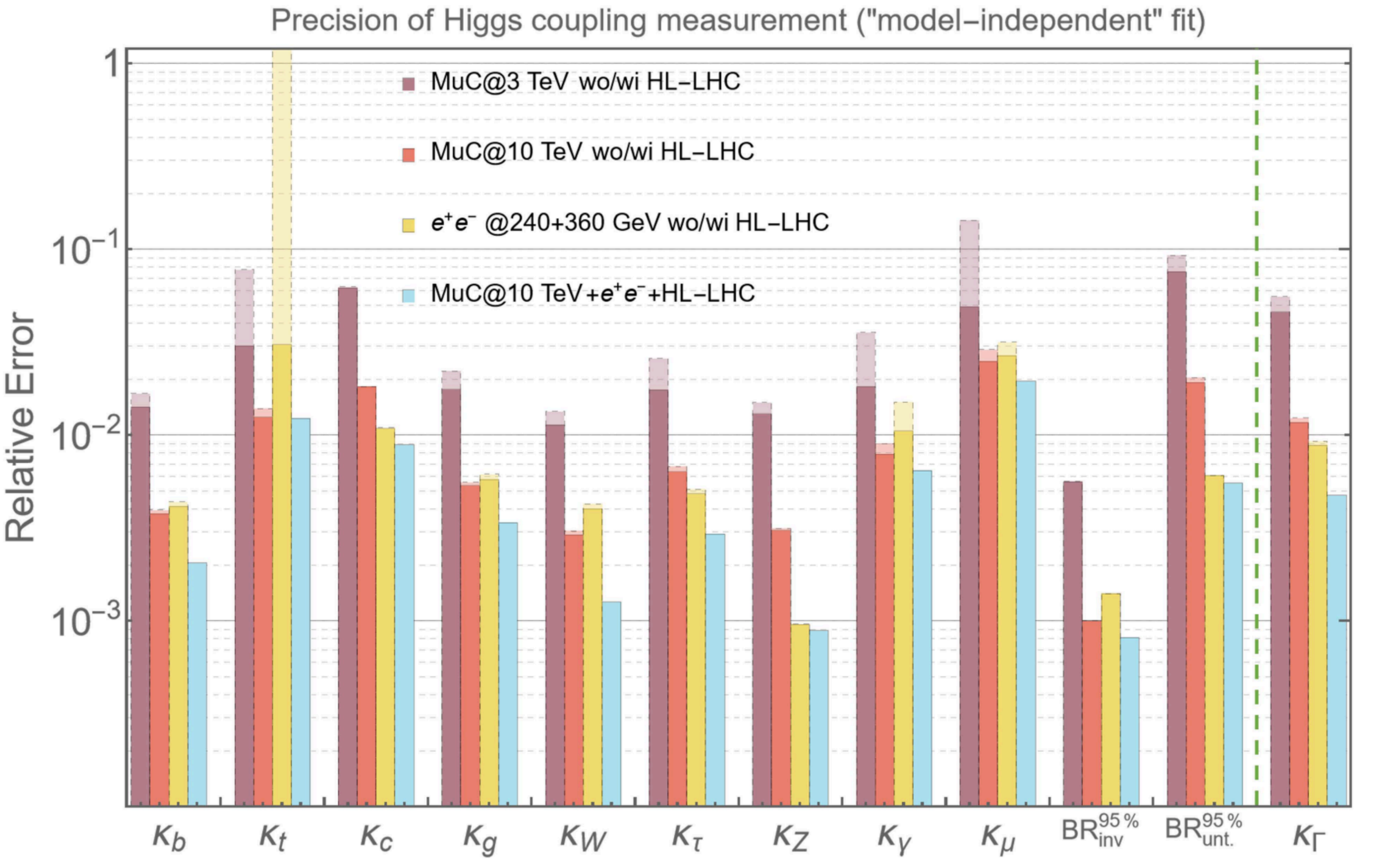
We preform the chi square analysis via combining
(1) All kinds of on-shell channels,
(2) Indirect search for top yukawa,
(3) Invisible decay branching ratio using forward muon
(4) Our inclusive ZZ fusion measurement at 3/10 TeV Muon Collider

We further combine with HL-LHC and CEPC.

Production	Decay	$\Delta\sigma/\sigma$ (%) 3 TeV	10 TeV
WW-fusion	bb	0.84	0.24
	cc	14	4.4
	gg	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.50
	$WW^*(4j)$	5.7	1.4
	$ZZ^*(4\ell)$	48	13
	$ZZ^*(jj\ell\ell)$	12	3.5
	$ZZ^*(4j)$	67	16
	$\gamma\gamma$	7.7	2.1
	$Z(jj)\gamma$	73	20
	$\mu^+\mu^-$	43	11
ZZ-fusion	bb	7.9	2.2
	bb, $(N_\mu \geq 2)$	2.6	0.77
	$WW^*(4j)$	49	12
	$WW^*(4j)$, $(N_\mu \geq 2)$	17	4.3
tth	bb	61	53

1. Matthew Forslund and Patrick Meade. [2203.09425] High Precision Higgs from High Energy Muon Colliders
2. Zhen Liu, Kun-Feng Lyu, Ishmam Mahbub, Lian-Tao Wang. [2308.06323] Top Yukawa Coupling Determination at High Energy Muon Collider
3. M. Ruhdorfer, E. Salvioni, A. Wulzer. [2303.14202] Invisible Higgs from forward muons at a muon collider
4. Our inclusive Higgs rate result.

Higgs coupling global fit



- With forwarded detection $2.5<\eta(\mu)<6$, the cross-section precision is ~0.75%
- Combining with other studies, we can constraint on Γ_H~2% and Higgs couplings in 0.5% level.

Conclusion

- We study the $ZZ \to h$ inclusive rate channel only using forward muon detection.
- Only sensitive to κ_Z
- With forwarded detection $2.5 < \eta(\mu) < 6$, the cross-section precision is ~0.75%.
- This measurement can break the degeneracy relation and constrain the Higgs total decay width.

Backup

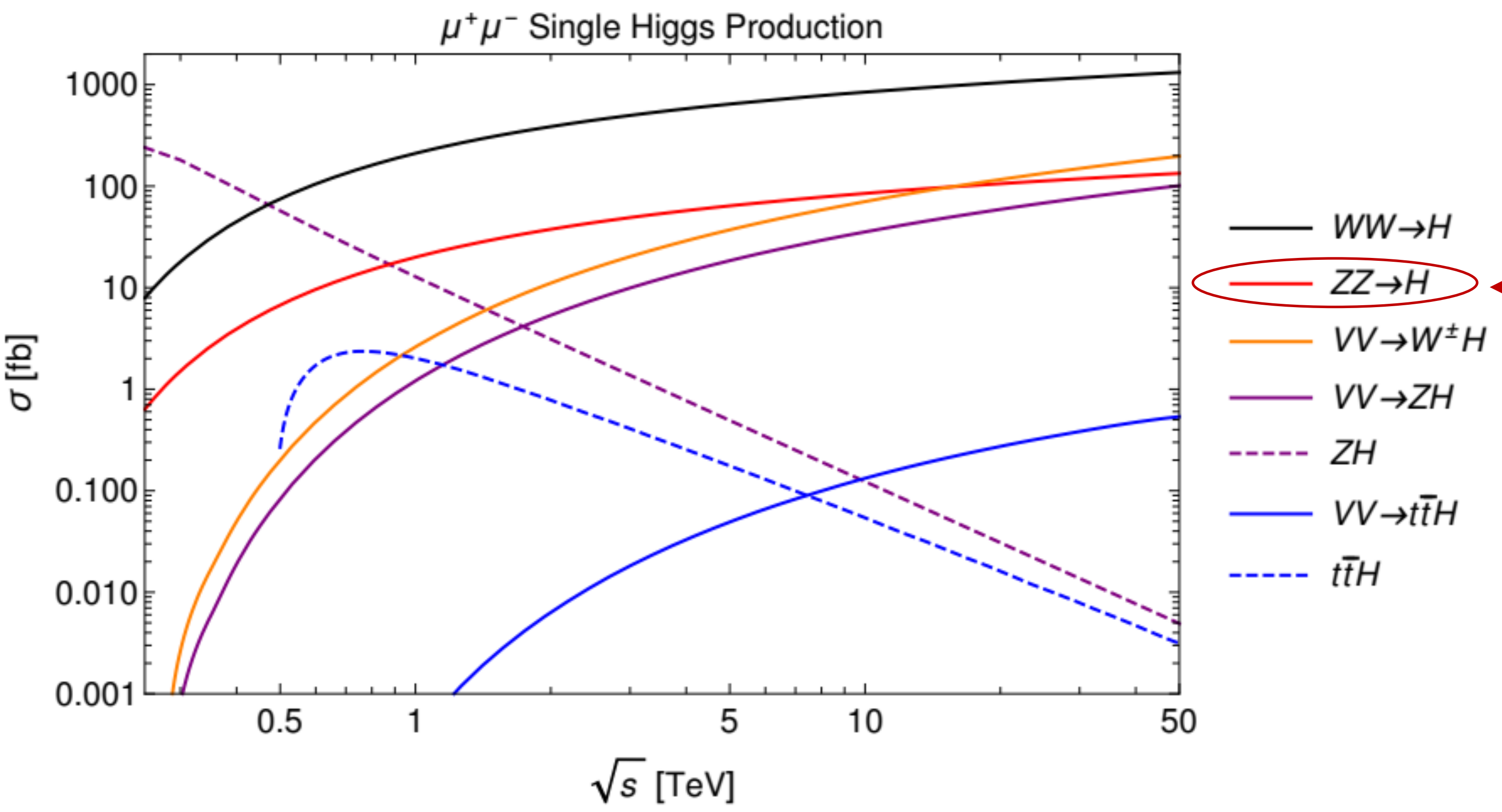
Kappa Basis Choice

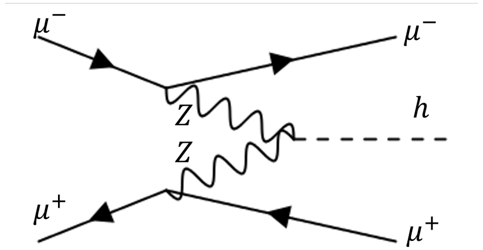
$\mathrm{Br}_{\mathrm{exo}} = \mathrm{Br}_{\mathrm{inv}}^{\mathrm{BSM}} + \mathrm{Br}_{\mathrm{unt}}^{\mathrm{BSM}}$

$(\mathrm{Br}_{\mathrm{inv}}^{\mathrm{BSM}}, \mathrm{Br}_{\mathrm{unt}}^{\mathrm{BSM}})$

(%)	Postive	Negative
κ_b	$+0.557$	-0.232
κ_t	$+1.42$	-1.36
κ_c	$+1.83$	-1.82
κ_g	$+0.665$	-0.450
κ_W	$+0.509$	-0.102
κ_τ	$+0.762$	-0.595
κ_Z	$+0.374$	-0.254
κ_γ	$+0.974$	-0.824
κ_μ	$+2.86$	-2.90
$\mathrm{Br}_{\mathrm{inv}}^{95\%}$	$+1.0$	0
$\mathrm{Br}_{\mathrm{unt}}^{95\%}$	$+2.02$	0

Higgs productions at Muon Collider





Matthew Forslund, Patrick Meade, [2203.09425]