Inclusive Higgs Rate, Higgs Width and Couplings with Forward Muon Detector

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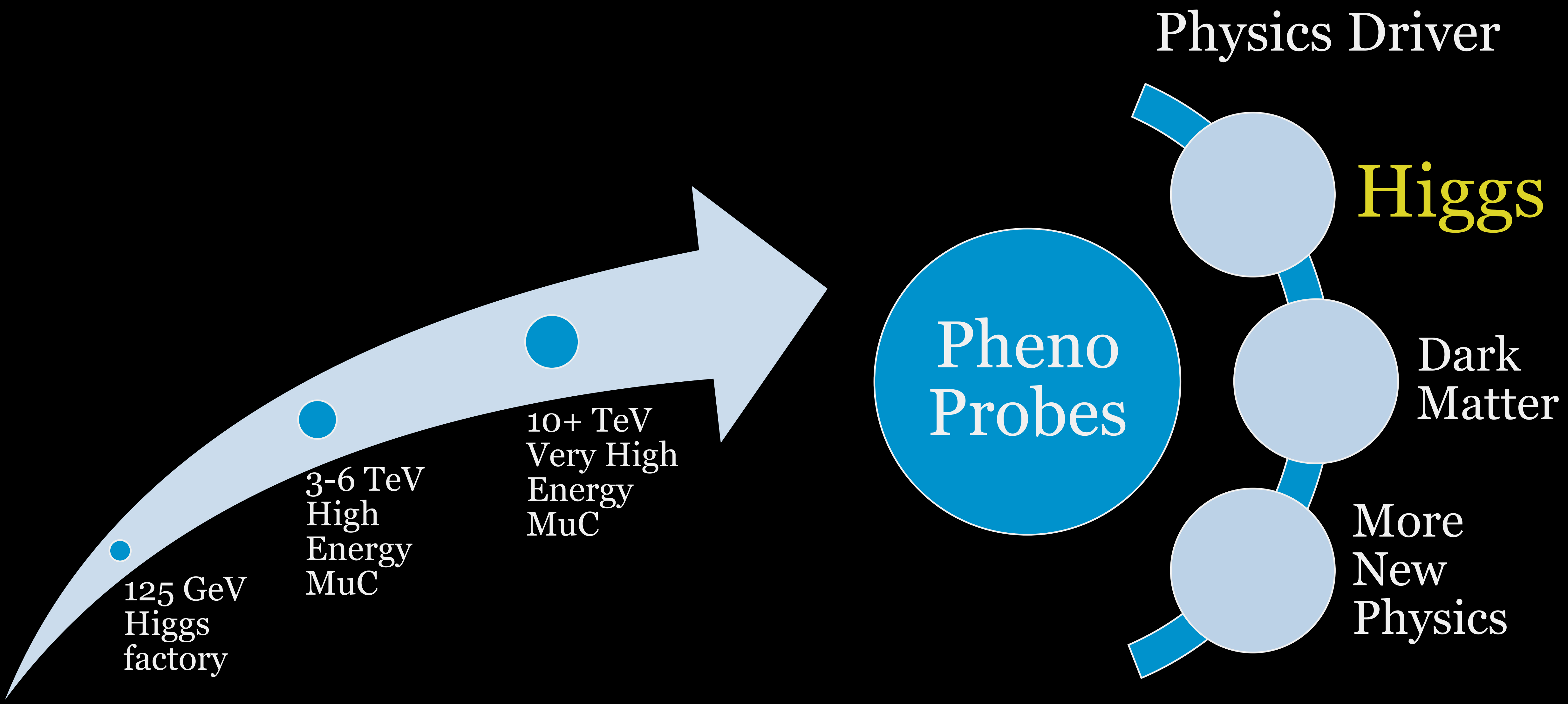
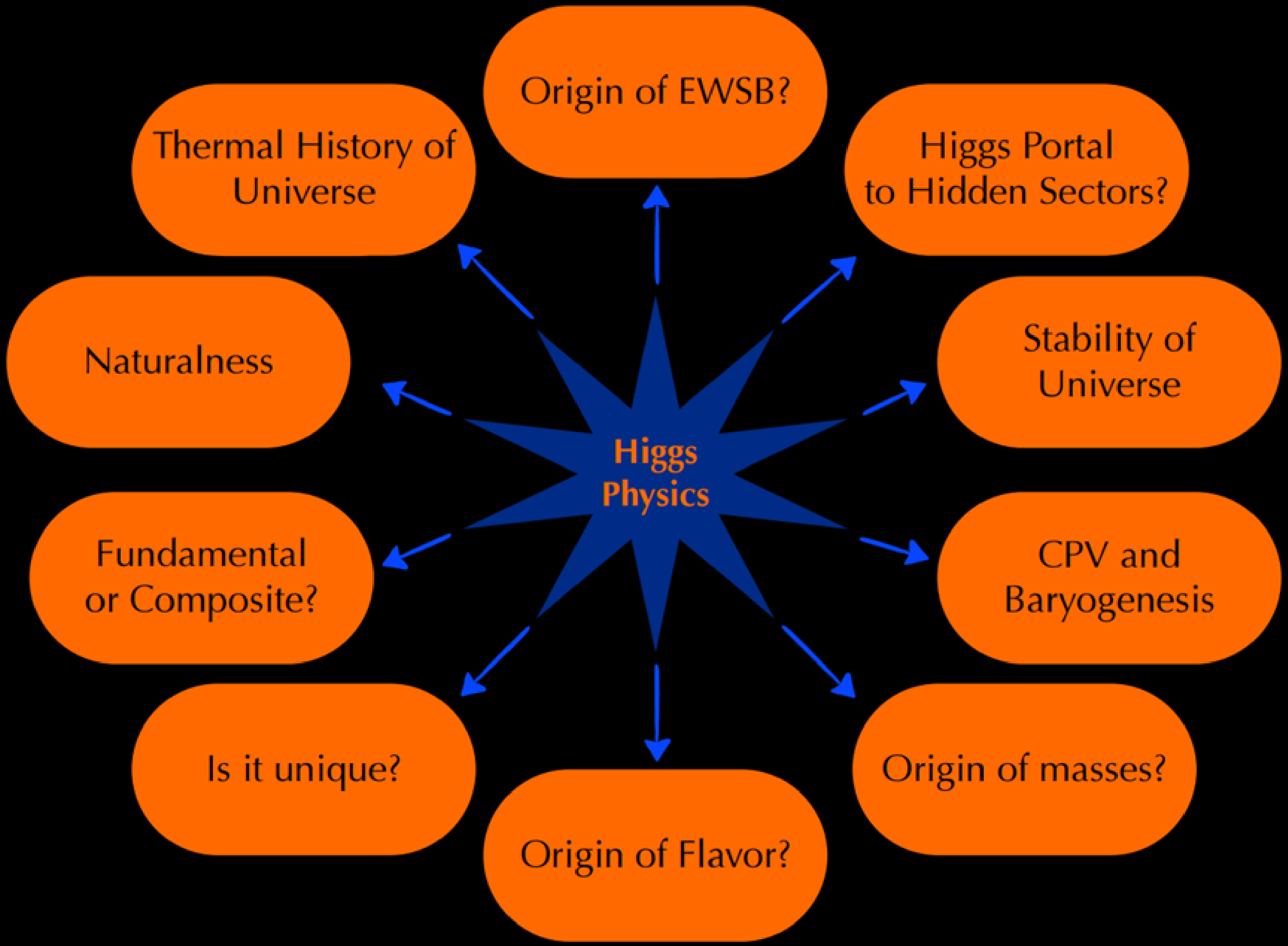
Work to appear this week, with Peiran Li, Kun-Feng Lyu, arXiv: 2401.xxxxx

Muon Collider is a Dream Machine



10 years after discovery, do we know the Higgs?

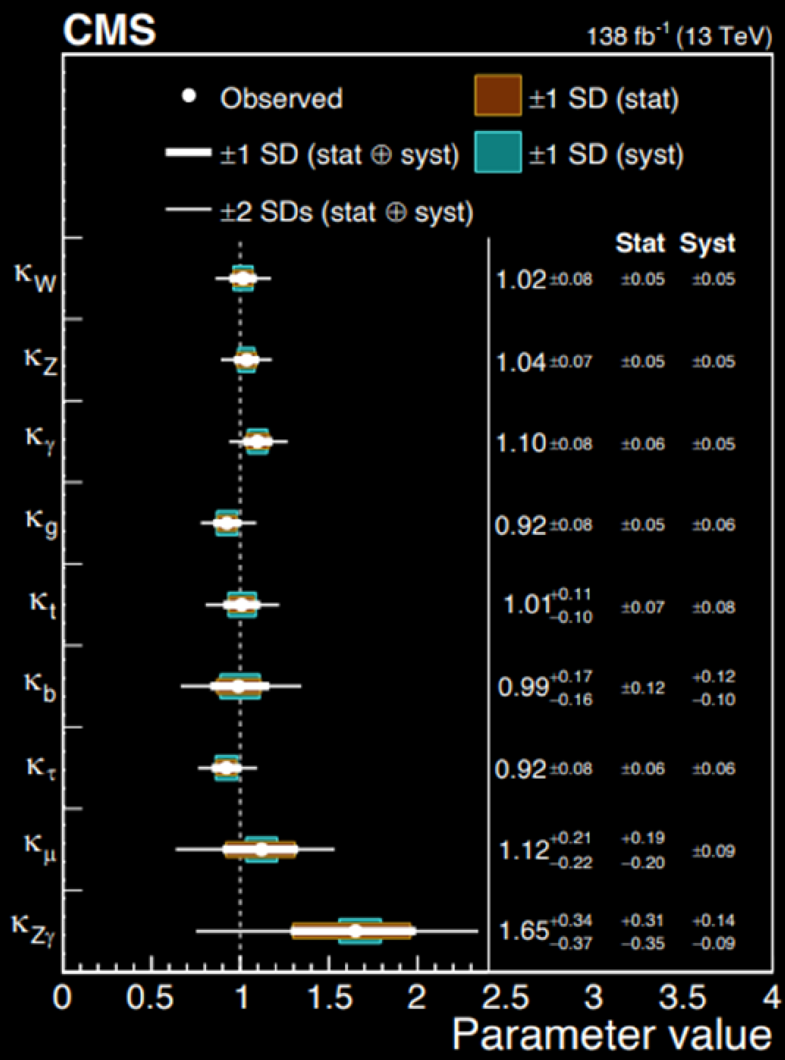


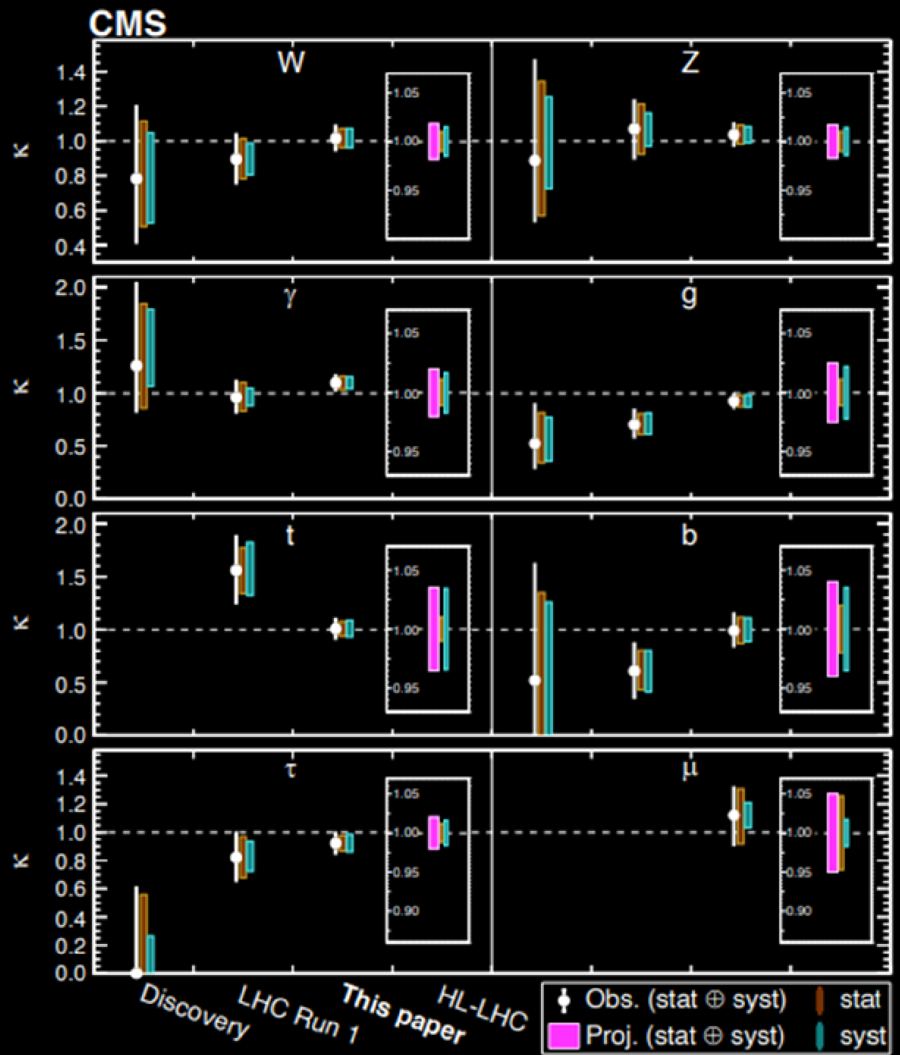
Higgs is still the central player of many puzzles in nature.

We realize that we need deeper and more precise understanding of Higgs.

Any future collider needs to have is Higgs potential understood.

10 years after Higgs discovery





Higgs looks like the Higgs boson at 10% level now.

We are to measure it to 5% level.

Measurements to be interpreted

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

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

For the hard scattering*:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

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

*zero-width approximation, Higgs width 10^{-5} of its mass, in general valid. Violations (% level correction) see Campbell, Carena, Harnik, ZL, PRL 18'

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For the hard scattering:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

If $\kappa_\Gamma = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

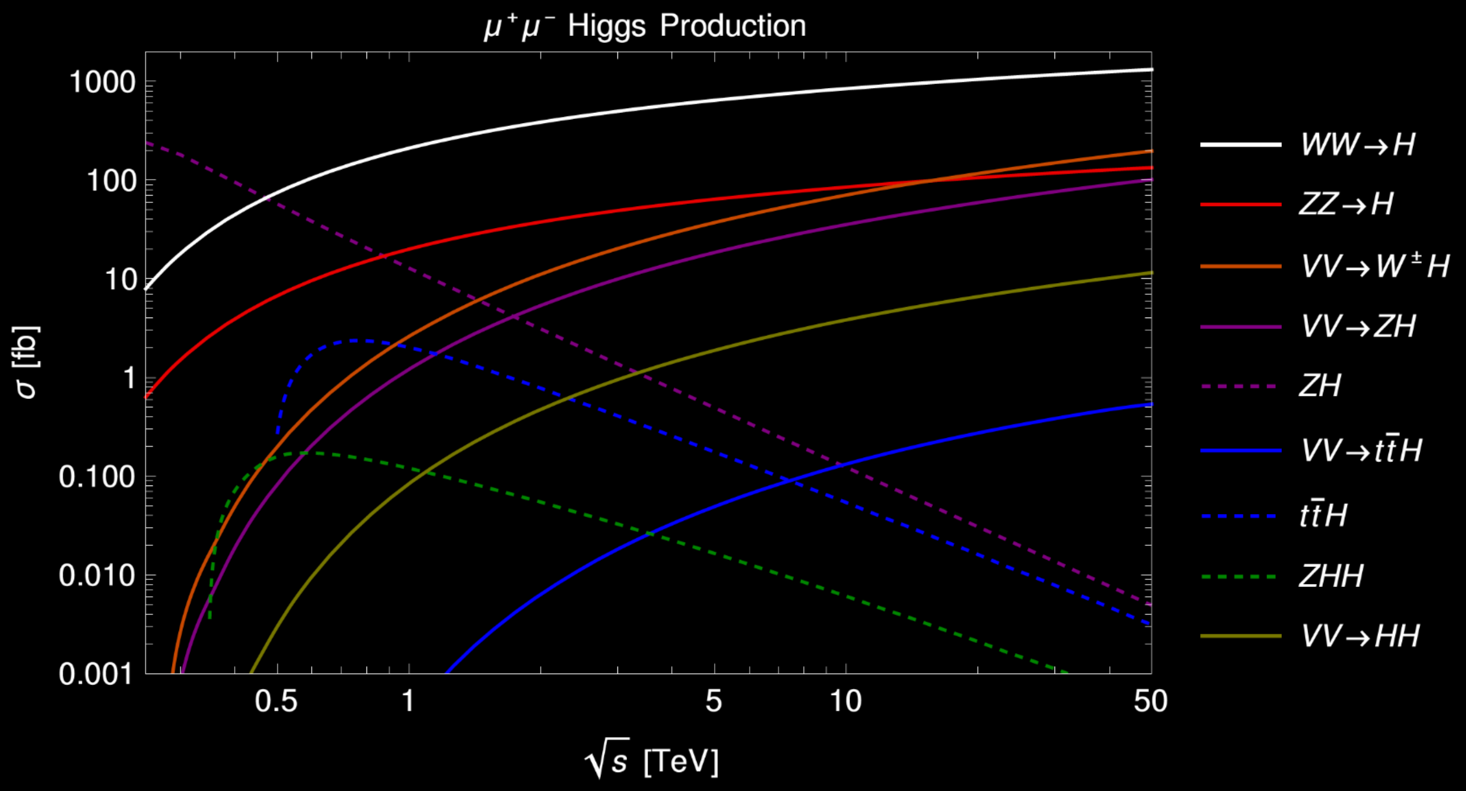
We **cannot** measure Higgs couplings strength, without some inputs to break this flat direction!

- All Kappas are positively correlated with the total width (from the point of cross sections);
- The naïve scaling of $\kappa_{tot} \propto \kappa_{i,f}^2$, does not reflect this flat direction, one needs additional particle width to enter;
- In principle, a given specific BSM model might have more constraints to all stronger constraints, but generally, this direction is unconstrained that leads to a bad projection of sensitivity (without the correlation matrix).

Is the Higgs fundamental?

Baseline Higgs Measurements

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



M. Forslund, P. Meade, 2203.09425

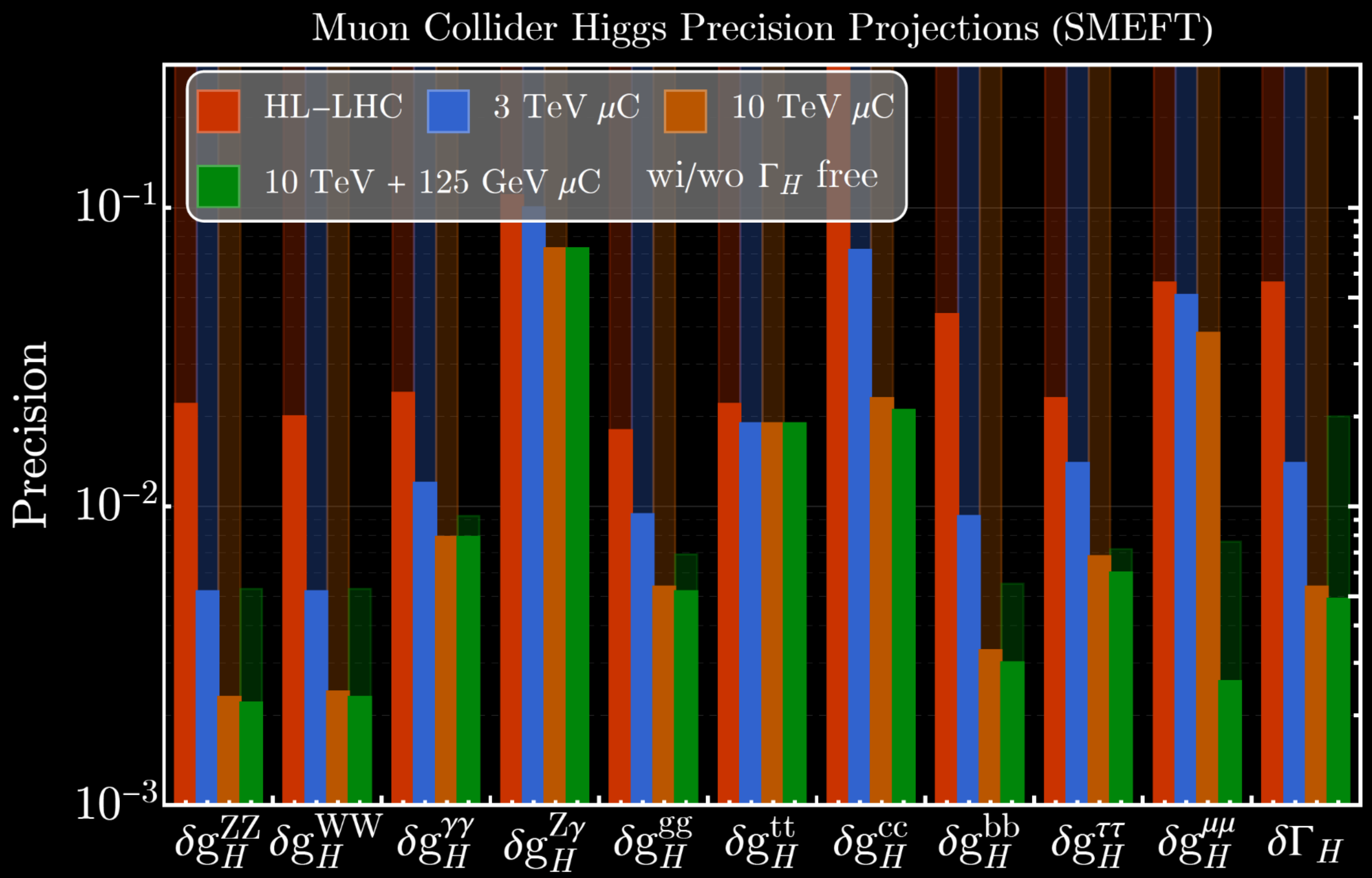
See also discussion in
Muon Smasher's Guide, 2103.14043
T. Han, Y. Ma, K.-P. Xie, 2007.14300;
Costanini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.10289

How well in Higgs precision?

- Without absolute coupling measurement (equivalently, a width determination), we cannot pin down the overall size of the Higgs coupling.
  - Look at the light shaded results with width being a free parameter

- High Energy Muon Collider seems to be handicapped in Higgs measurements (similar to hadron colliders).

- We propose a new search using forward muons.



**Note, this is a global SMEFT fit ; for those who claim SMEFT is a better basis than kappa, no such "problem exists"; that's wrong. Happy to discuss more.*
The conclusion in this paper holds in any basis with width as an effective free parameter.

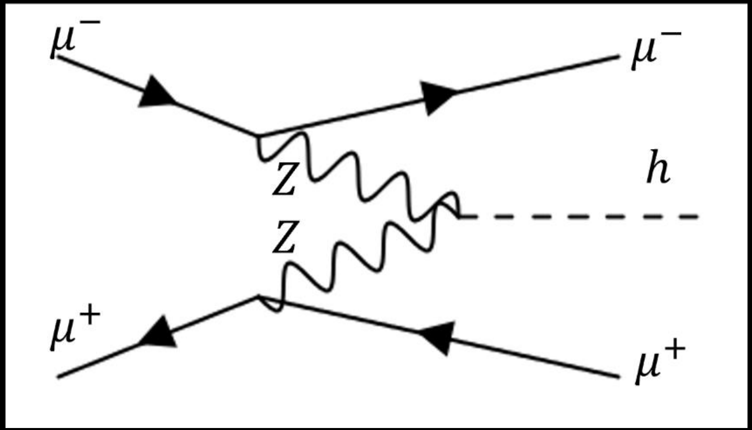
[2209.01318] Muon Collider Forum Report

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

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

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

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

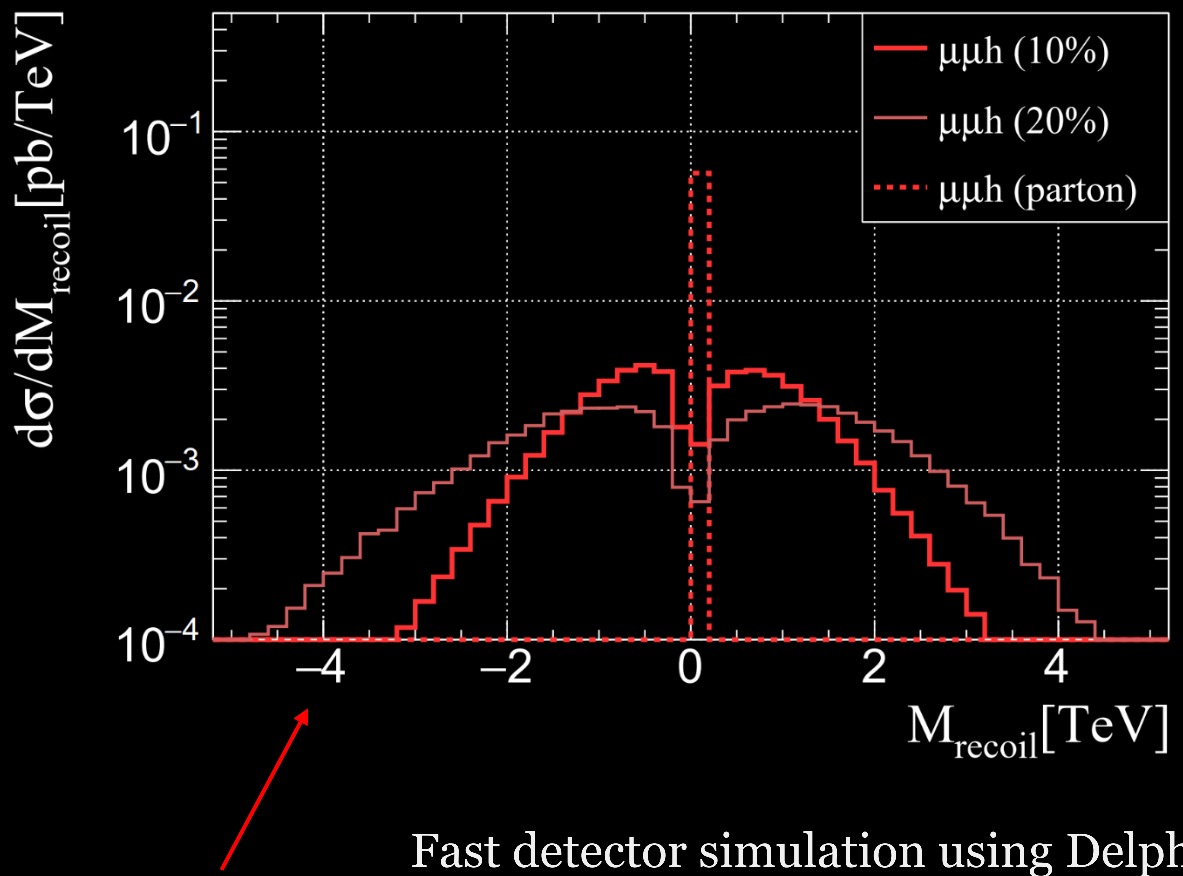


Recoil mass of dimuon

This subleading Higgs production channel, once tagged, does not rely on the detection of Higgs decay channel.

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

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

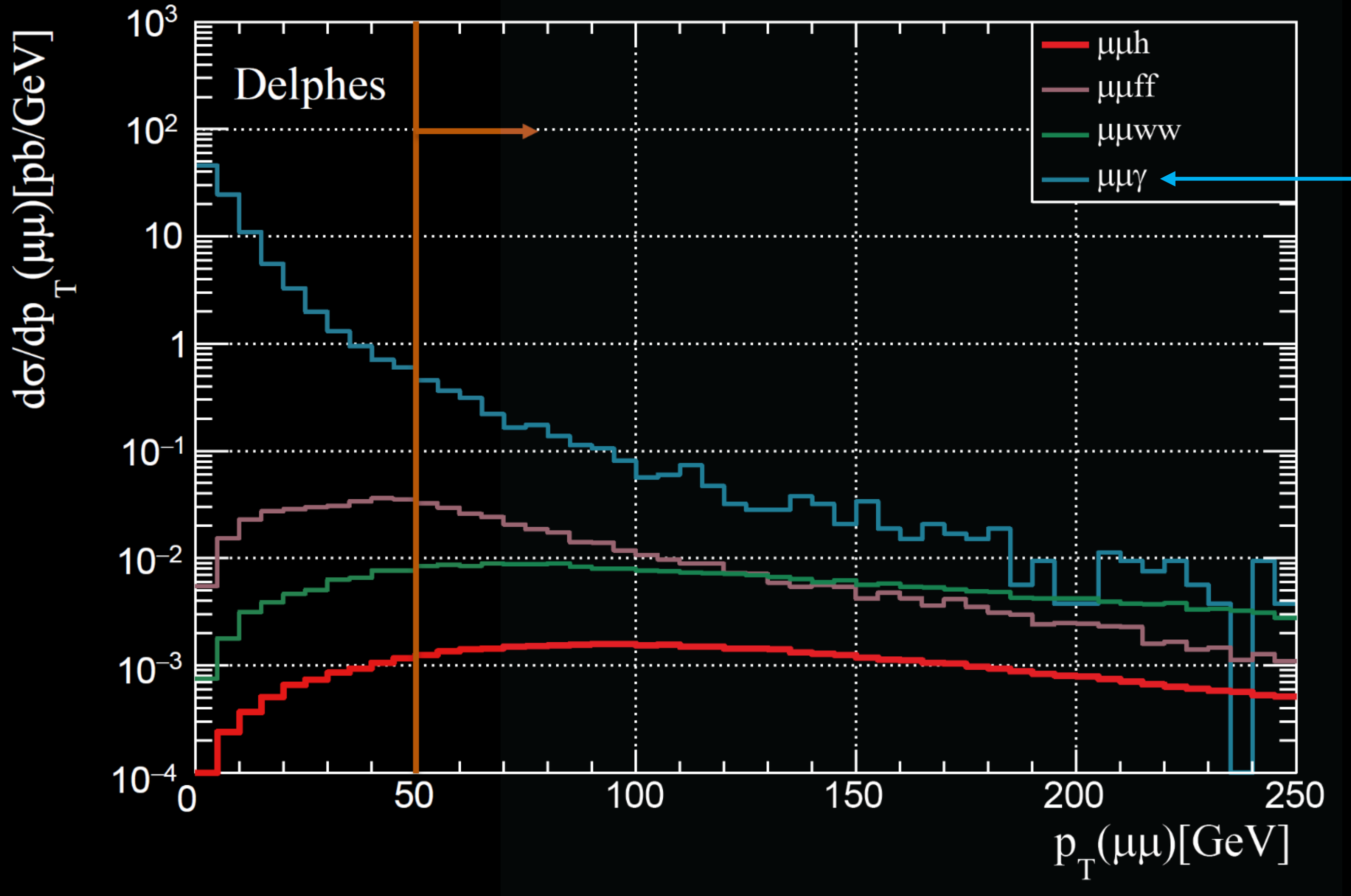


$[(\sqrt{s},0,0,0) - p_{\mu^+} - p_{\mu^-}]^2 < 0$

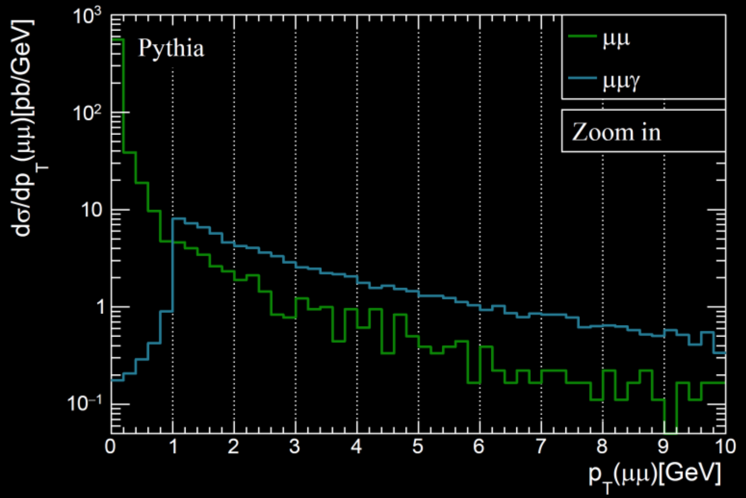
Fast detector simulation using Delphes.

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

Require $p_T(\mu\mu) > 50$ GeV

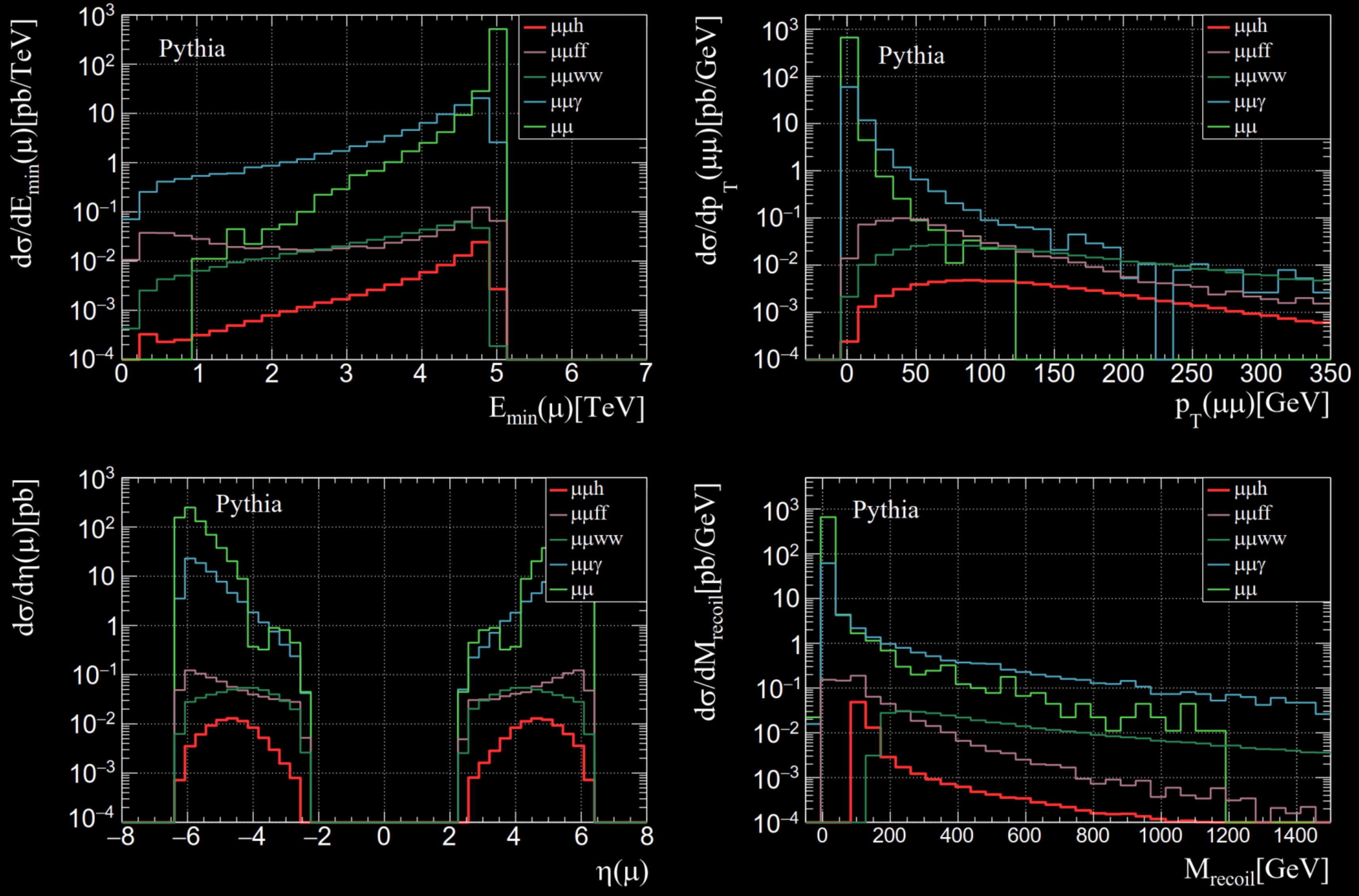


Merging $\mu\mu \to \mu\mu$ and $\mu\mu \to \mu\mu\gamma$



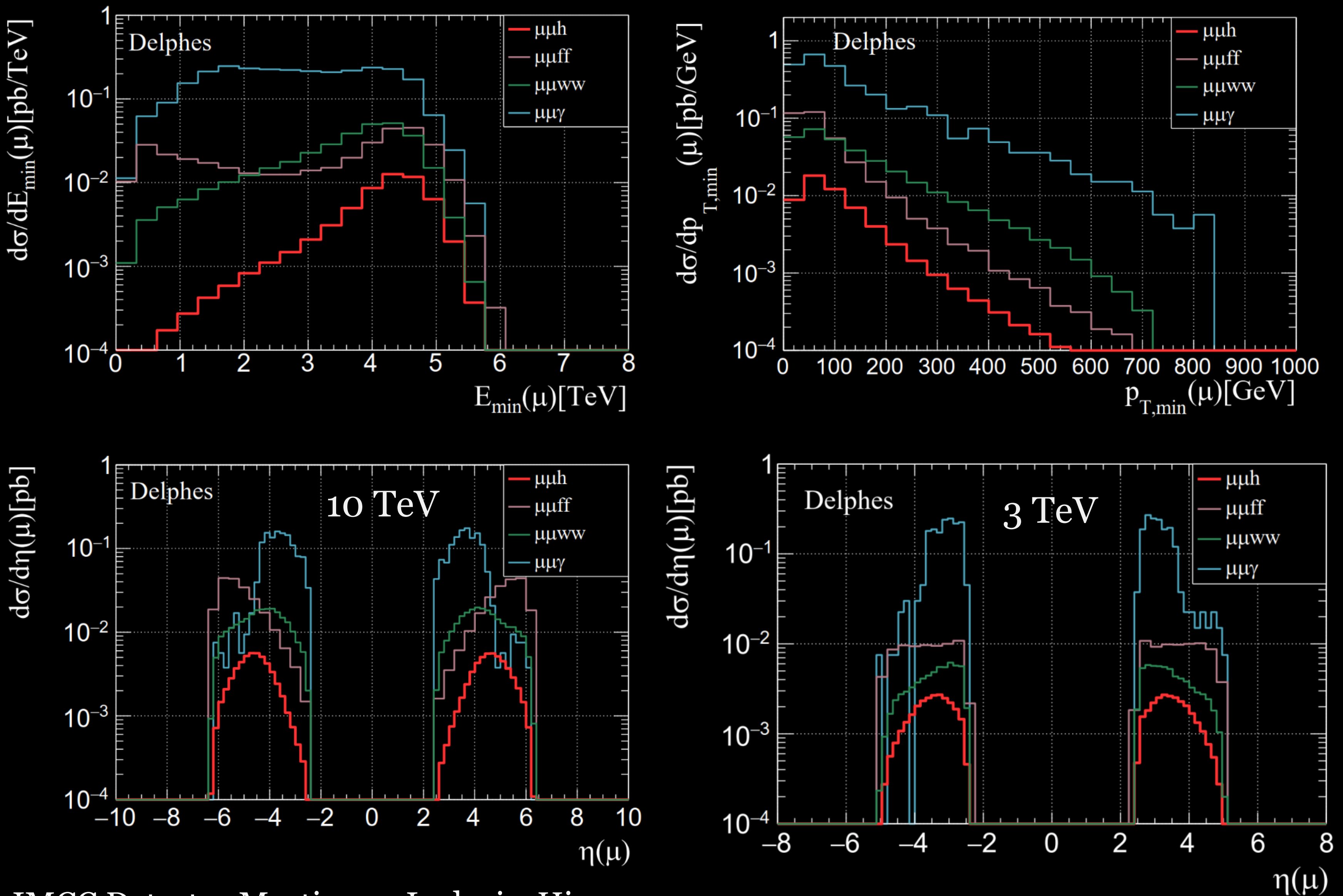
Also see a similar treatment in Higgs invisible study, Ruhdorfer, Salvioni, Wulzer, 2303.14202

Other relevant distributions



For the signal muons, the typical eta is around 5. Dominant background is more forward.

Other relevant distributions (reconstruction)



For the signal muons, the typical eta is around 5. Dominant background is more forward.

Sensitivity

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)

10 TeV

Benchmark	$\|\eta(\mu)\| < 4$	$\|\eta(\mu)\| < 6$	$\|\eta(\mu)\| < 8$
$\Delta\sigma/\sigma$	15%	0.75%	0.74%

Now High Energy Muon Collider is a full-fledged Higgs factory

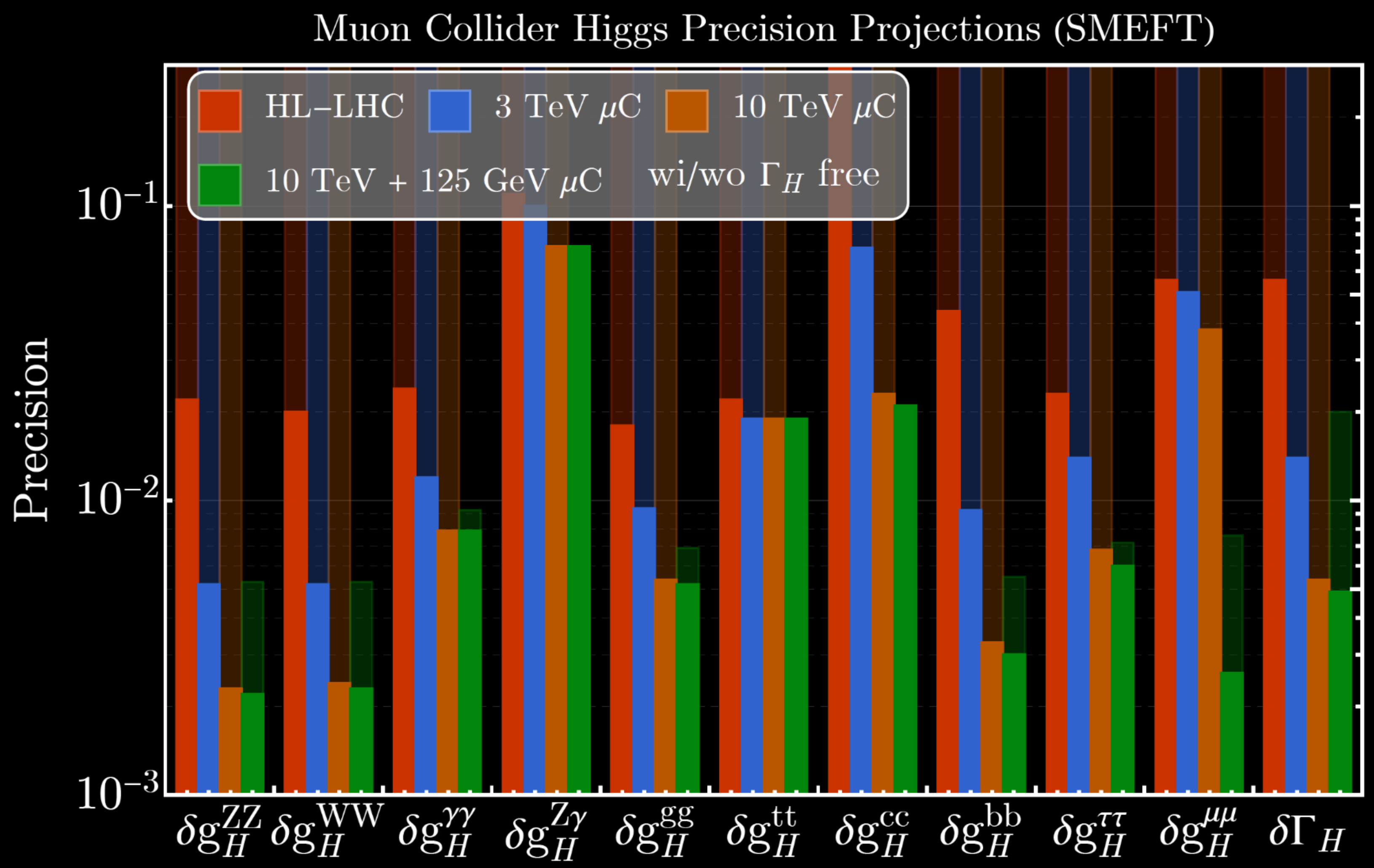
$\eta(\mu) < 6$

$\mu_{\text{production}}^{\text{decay}}$	μ_{VV}^{tt}	μ_{WW}^{bb}	μ_{WW}^{cc}	μ_{WW}^{gg}	$\mu_{WW}^{\tau\tau}$	μ_{WW}^{WW}	μ_{WW}^{ZZ}	$\mu_{WW}^{\gamma\gamma}$	$\mu_{WW}^{\mu\mu}$
$\Delta\sigma/\sigma(\%)$	2.8	0.22	3.6	0.79	1.1	0.40	3.2	1.7	5.7
$\mu_{\text{production}}^{\text{decay}}$	μ_{ZZ}^{bb}	μ_{ZZ}^{cc}	μ_{ZZ}^{gg}	$\mu_{ZZ}^{\tau\tau}$	μ_{ZZ}^{WW}	μ_{ZZ}^{ZZ}	$\mu_{ZZ}^{\gamma\gamma}$	μ_{ZZ}^{inv}	μ_{ZZ}^{H}
$\Delta\sigma/\sigma(\%)$	0.77	17	3.3	4.8	1.8	11	4.8	0.05	0.75

Requires forward muon

Other inputs used in this study.
- (Exclusive Higgs) M. Forslund and P. Meade. [2203.09425]
- (Invisible Higgs) M. Ruhdorfer, E. Salvioni, A. Wulzer. [2303.14202]
- (Top Yukawa) Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
- (off-shell Higgs; not used but relevant) M. Forslund and P. Meade [2308.02633]

Now High Energy Muon Collider is a full-fledged Higgs factory



New inclusive Higgs rate result (finalizing stage, P.R. Li, ZL, K.F. Lyu) enables a full-fledges Higgs precision.

- 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.

Other inputs used in this study.

- (Exclusive Higgs) M. Forslund and P. Meade. [2203.09425]
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- (Top Yukawa) Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
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Forward Muon Detector Required!

- Is it feasible?
- We only require to tag Energetic Muons.
- Muons pass through the nozzle regions
- Energy resolution is not important
- This is a very strong case for a forward muon detector
- Happy to discuss more and collaborate

Summary and Outlook

- Higgs Inclusive measurement is unique
  - Breaks scaling degeneracy with width
  - Improve the global fit results in Higgs precision in a significant way
  - Couplings to 0.5% level and width to 2% level.
  - Particularly important whenever one wants to show results about coupling precision (kappa or EFT) with width free.
- Forward muon detector can enable it
  - Up to η of 6 is important (especially for 10 TeV case)
  - Energy loss and resolution has room (no high precision needed)
  - Tagging forward, high energy muon is critical.

Results and approximate analytics

$$\kappa_\Gamma = \frac{(\mu^H_{ZZ})^2}{\mu^{WW}_{WW}} \left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2$$

$$\Delta\kappa_\Gamma = \left[4\left(\Delta\mu^H_{ZZ}\right)^2 + \left(\Delta\mu^{WW}_{WW}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + 4(\Delta\mu^{bb}_{ZZ})\right]^{1/2} = 2.2\%$$

$$\kappa^4_W = (\mu^{WW}_{WW})\kappa_\Gamma = (\mu^H_{ZZ})^2 \left(\frac{\mu^{bb}_{WW}}{\mu^{bb}_{ZZ}}\right)^2,$$

$$\Delta\kappa_W = \frac{1}{4}\left[4\left(\Delta\mu^H_{ZZ}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + 4(\Delta\mu^{bb}_{ZZ})^2\right]^{1/2} = 0.55\%.$$

$$\kappa^2_b = \frac{\mu^{bb}_{WW}\kappa^2_W}{\mu^{WW}_{WW}} = \frac{\mu^H_{ZZ}(\mu^{bb}_{WW})^2}{\mu^{bb}_{ZZ}\mu^{WW}_{WW}},$$

$$\Delta\kappa_b = \frac{1}{2}\left[\left(\Delta\mu^H_{ZZ}\right)^2 + 4(\Delta\mu^{bb}_{WW})^2 + (\Delta\mu^{bb}_{ZZ})^2 + \left(\Delta\mu^{WW}_{WW}\right)\right]^{1/2} = 0.61\%$$

	$\lvert\eta(\mu)\rvert < 4$			$\lvert\eta(\mu)\rvert < 6$		
	MuC@10TeV	+HL-LHC	$+e^+e^-$	MuC@10TeV	+HL-LHC	$+e^+e^-$
$\kappa_b(\%)$	+7.5	+1.7	+0.25	+0.56	+0.53	+0.24
	−0.25	−0.24	−0.18	−0.23	−0.23	−0.17
$\kappa_t(\%)$	+1.4	+1.3	+1.3	+1.4	+1.3	+1.3
	−7.1	−1.6	−1.2	−1.4	−1.2	−1.2
$\kappa_c(\%)$	+7.8	+2.6	+0.91	+1.8	+1.8	+0.89
	−2.1	−2.1	−0.91	−1.8	−1.8	−0.89
$\kappa_g(\%)$	+7.5	+1.7	+0.38	+0.67	+0.63	+0.35
	−0.52	−0.50	−0.35	−0.45	−0.44	−0.32
$\kappa_W(\%)$	+7.5	+1.7	+0.17	+0.51	+0.48	+0.16
	−0.15	−0.13	−0.099	−0.10	−0.10	−0.090
$\kappa_\tau(\%)$	+7.5	+1.8	+0.33	+0.76	+0.71	+0.32
	−0.62	−0.57	−0.27	−0.56	−0.55	−0.27
$\kappa_Z(\%)$	+7.3	+1.9	+0.13	+0.37	+0.37	+0.12
	−1.4	−0.93	−0.058	−0.25	−0.25	−0.056
$\kappa_\gamma(\%)$	+7.6	+1.8	+0.66	+0.97	+0.86	+0.65
	−0.83	−0.71	−0.64	−0.82	−0.71	−0.64
$\kappa_\mu(\%)$	+9.1	+3.8	+2.3	+2.9	+2.5	+1.9
	−5.0	−3.6	−2.4	−2.9	−2.5	−2.0
$\mathrm{Br}^{95\%}_{\mathrm{inv}}(\%)$	+0.64	+0.63	+0.13	+0.10	+0.10	+0.080
	0	0	0	0	0	0
$\mathrm{Br}^{95\%}_{\mathrm{unt}}(\%)$	+27	+6.6	+0.57	+2.0	+1.9	+0.54
	0	0	0	0	0	0
$\kappa_\Gamma(\%)$	+34	+6.9	+0.69	+2.1	+1.9	+0.65
	−0.45	−0.43	−0.31	−0.41	−0.40	−0.29

Top Yukawa (in an interesting way)

- At Large Energies, for $(\pm, \mp)$ the contribution from the γ, Z and t-channel contribution grows as $\mathcal{O}(E^2/m_W^2)$, which cancels off due to gauge invariance

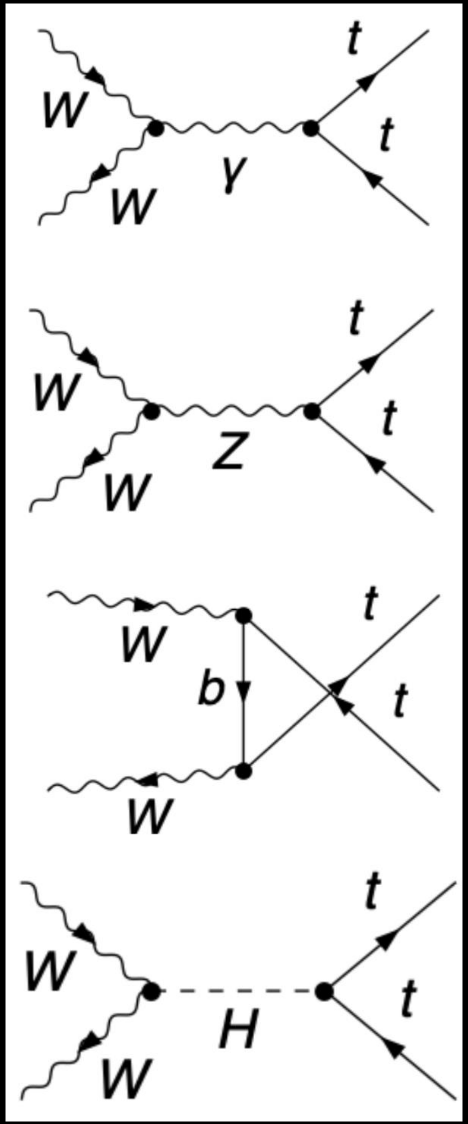
- Contribution from $(\pm, \pm)$ grows as $\mathcal{O}(E/m_W)$

$$\mathcal{M}^{\gamma+Z+b}(W_L^+ W_L^- \to t\bar{t}) \; = \; \frac{m_t}{v^2}\sqrt{s} \qquad ; \sqrt{s} >> m_t$$

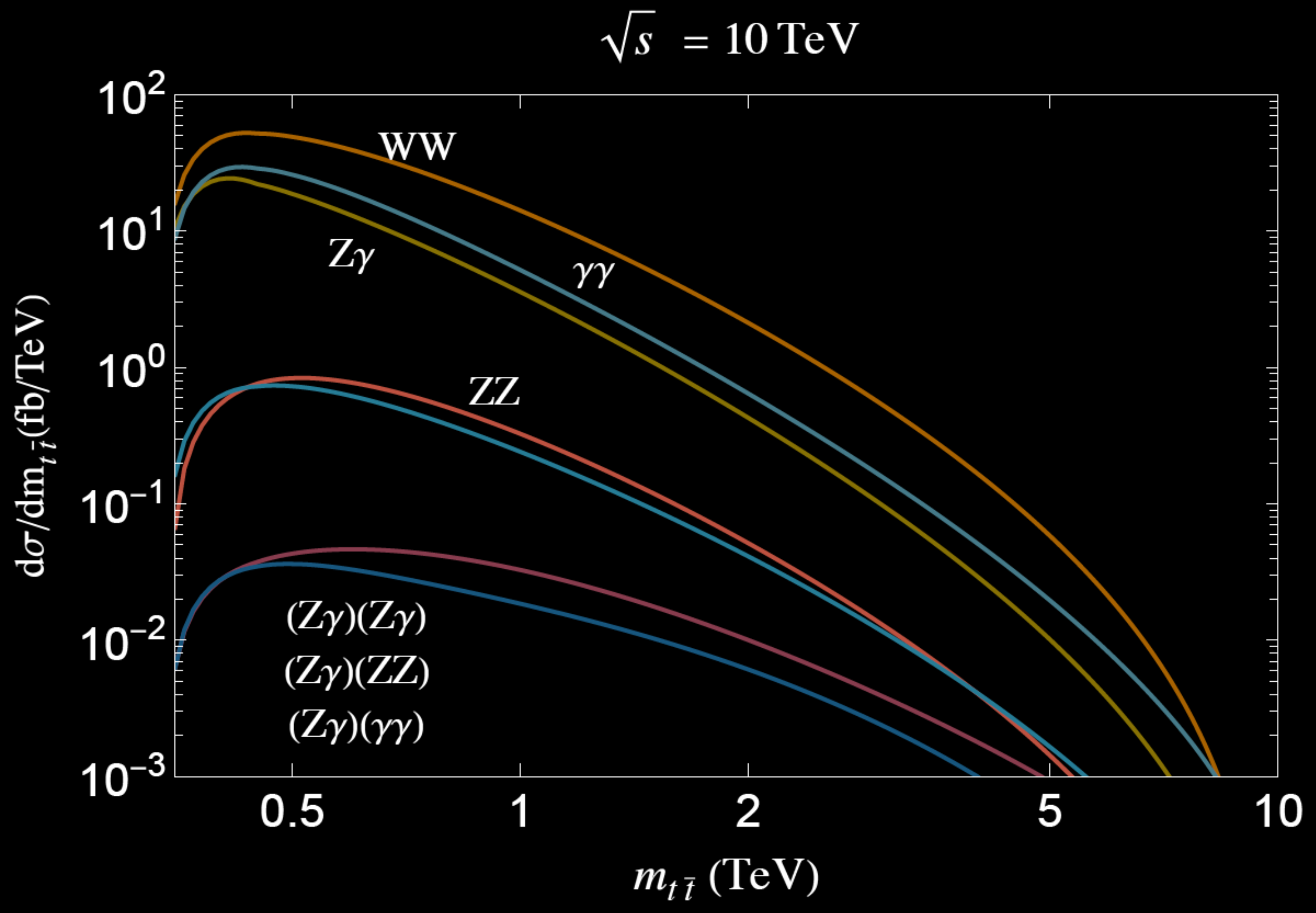
- Higgs channel precisely cancels this growing energy behavior

- Can be understood from Goldstone boson equivalence theorem

$$\mathcal{M}_{W_L^+ W_L^- \to t\bar{t}} = \mathcal{M}_{\phi^+\phi^- \to t\bar{t}} \left[1 + O\left(\frac{m_W^2}{E^2}\right)\right]$$



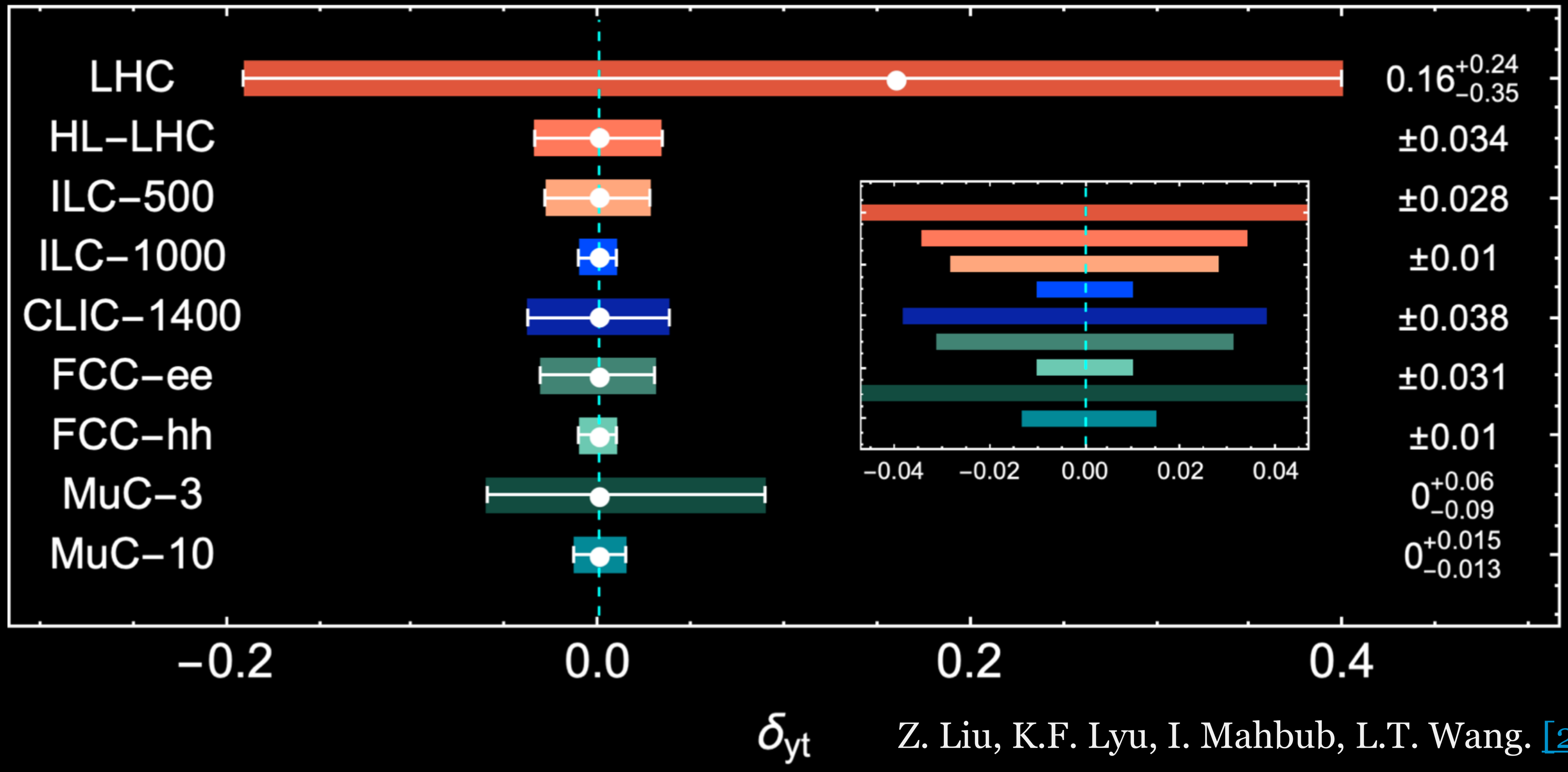
Anatomy of the amplitude and interference



W^+	W^-	$(t, \bar{t})$			
		$(+,+)$	$(-,+)$	$(+,-)$	$(-,-)$
0	0	$\hat{s}^{-1}$	$\hat{s}^{0}$	$\hat{s}^{0}$	$\hat{s}^{-1}$
+	0	$\hat{s}^{-2}$	$\hat{s}^{-1}$	$\hat{s}^{-1}$	$\hat{s}^{-2}$
−	0	$\hat{s}^{-2}$	$\hat{s}^{-1}$	$\hat{s}^{-1}$	$\hat{s}^{0}$
0	+	$\hat{s}^{0}$	$\hat{s}^{-1}$	$\hat{s}^{-1}$	$\hat{s}^{-2}$
+	+	$\hat{s}^{-1}$	$\hat{s}^{-2}$	$\hat{s}^{-2}$	$\hat{s}^{-3}$
−	+	$\hat{s}^{-1}$	$\hat{s}^{0}$	$\hat{s}^{-2}$	$\hat{s}^{-1}$
0	−	$\hat{s}^{-2}$	$\hat{s}^{-1}$	$\hat{s}^{-1}$	$\hat{s}^{-2}$
+	−	$\hat{s}^{-1}$	$\hat{s}^{0}$	$\hat{s}^{-2}$	$\hat{s}^{-1}$
−	−	$\hat{s}^{-3}$	$\hat{s}^{-2}$	$\hat{s}^{-2}$	$\hat{s}^{-1}$

Z. Liu, K.F. Lyu, I. Mahbub, L.T. Wang. [2308.06323]
also see discussions in M. Chen, D. Liu, 2212.11067

Projected Top Yukawa precision



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