Snowmass Muon Collider Forum

Physics at 125 GeV Muon Collider

Zhen Liu
University of Minnesota
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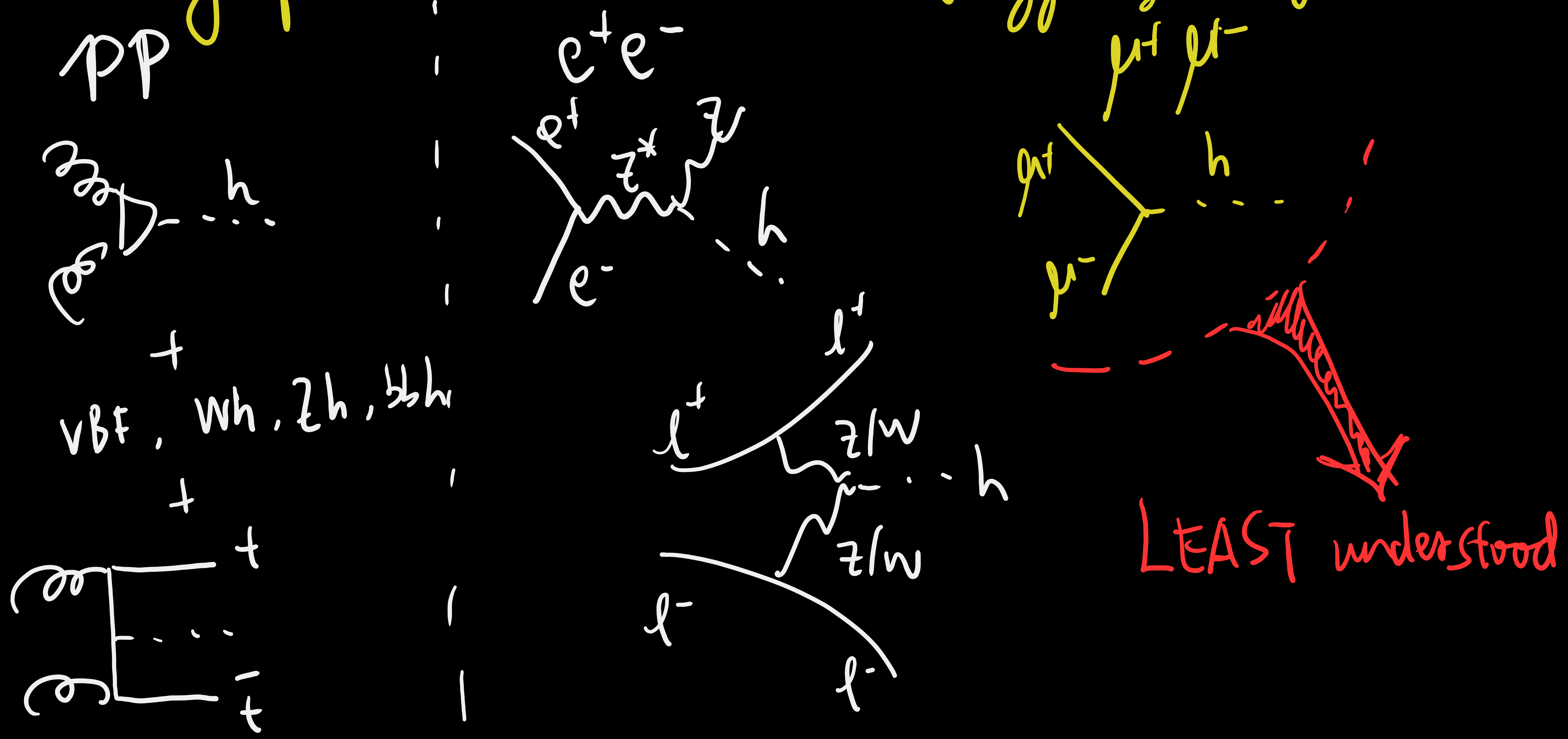
Every future collider is a Higgs factory!



Basics:

pp

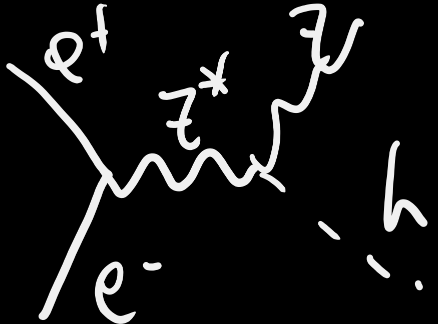
LHC 14 TeV

50 pb

3 ab^{-1}

0.15 billion Higgs

e^+e^-



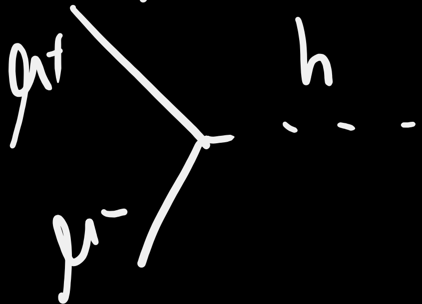
e^+e^- 240~250 GeV

200 fb

5 ab^{-1}

1 million Higgs

$\mu^+\mu^-$



$\mu^+\mu^-$ 125 GeV

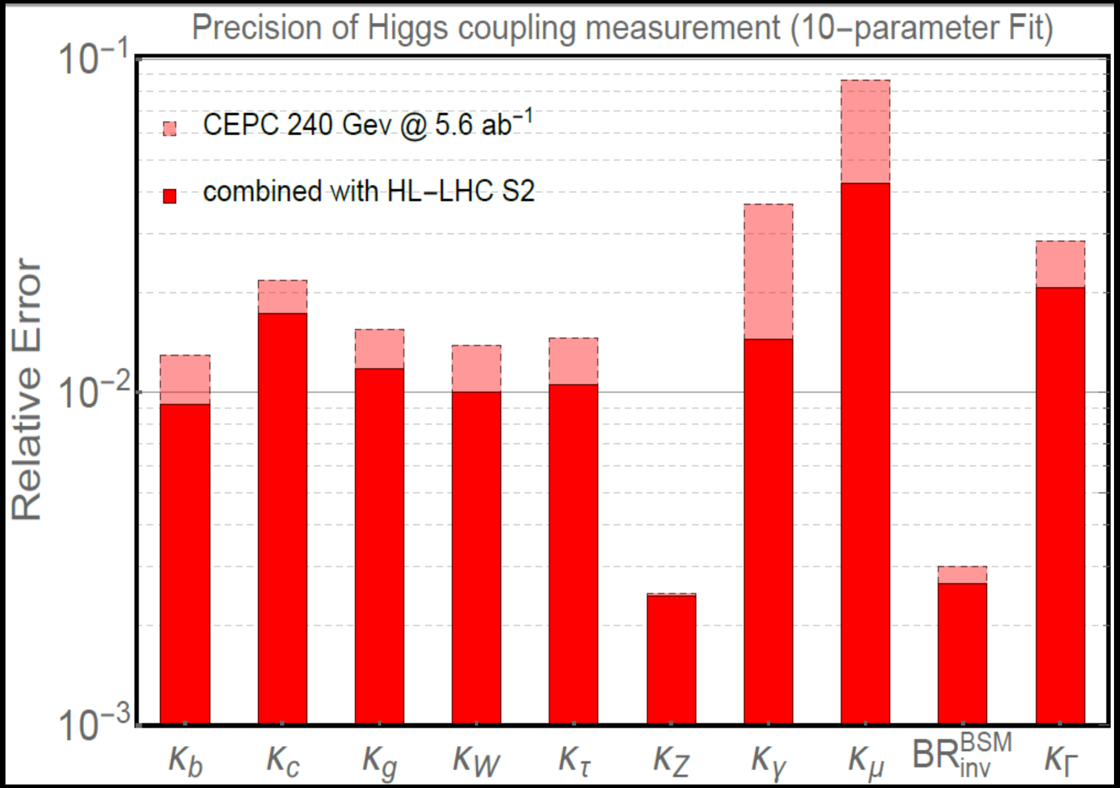
15 pb

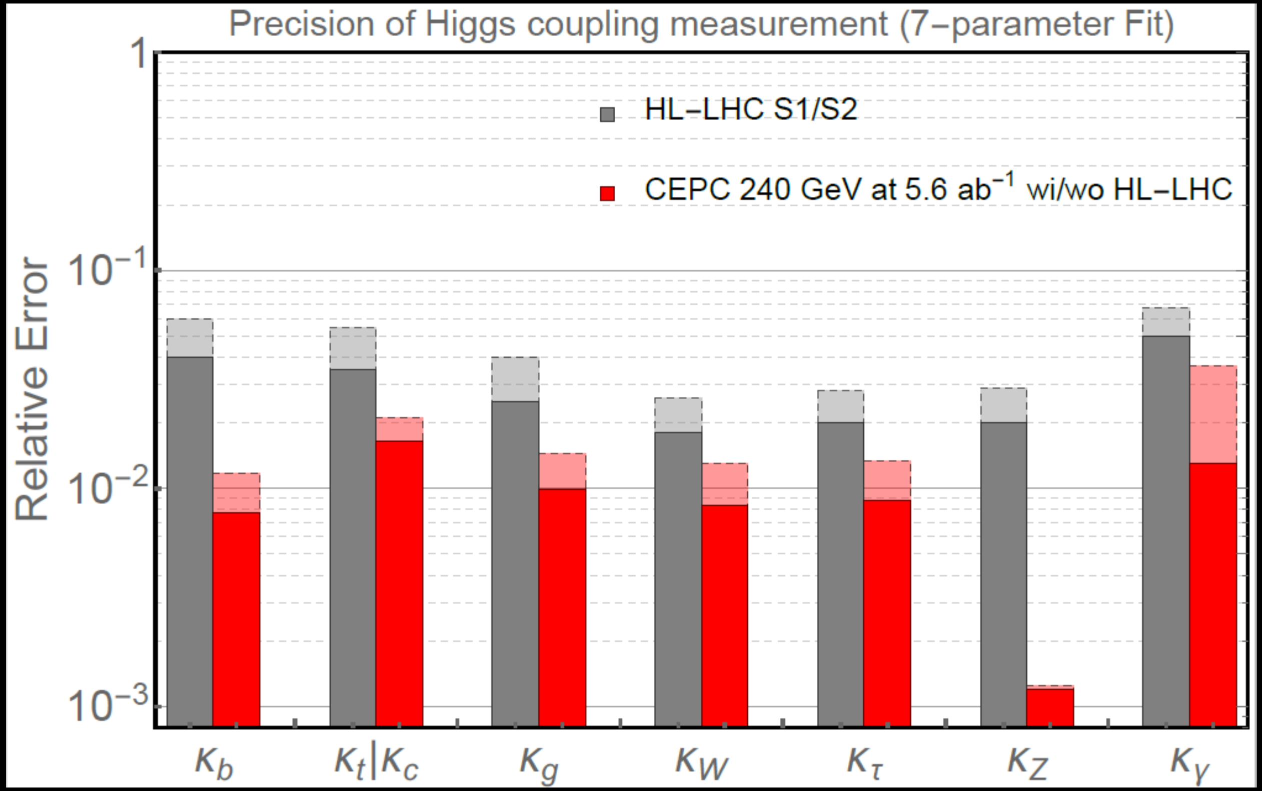
1 fb^{-1}

0.15 million Higgs

Official CEPC results, updated with HL-LHC projection for ESU

A representative view (CEPC/FCC-ee/ILC)





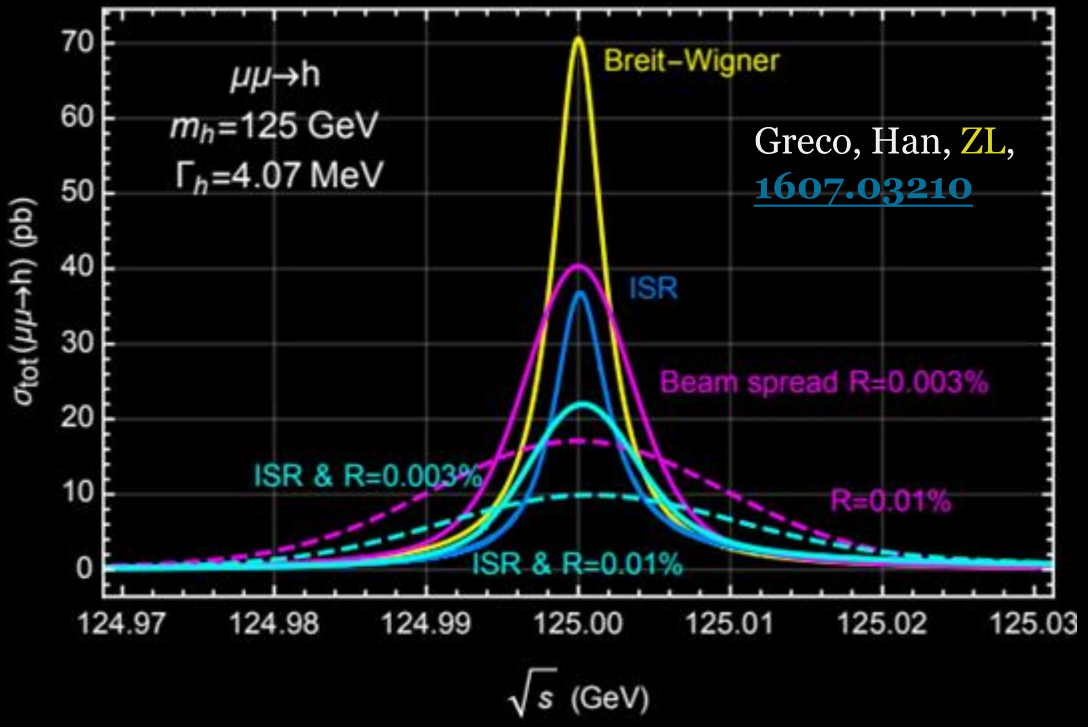
Without external constraints on the coupling strength (width), HL-LHC fit has huge flat direction (the fit does not close)*

Higgs factories improves in b, c, g, W, and especially Z coupling.
HL-LHC provide crucial inputs for muon Yukawa, Higgs to $\gamma\gamma$, etc.

*since LHC width measurement is poor, putting a universal floor of around 10%~20% for LHC measurements interpreted in this framework, assuming additional input from off-shell ZZ measurements to bound the Higgs total width)

Outline

- Overall picture
- Higgs Width
- Higgs Couplings
- Higgs Exotic Decays



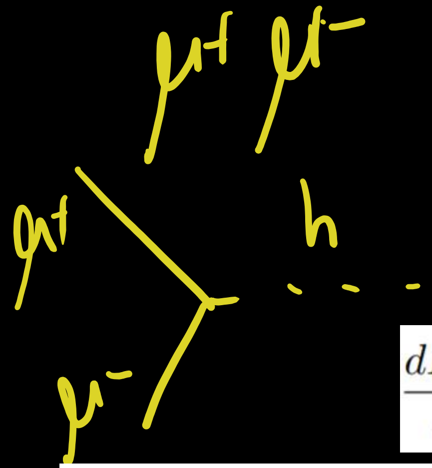
Greco, Han, ZL, 1607.03210

Hitting the resonance & scan

σ(BW)	ISR alone	R (%)	BES alone	BES+ISR
$\mu^+\mu^-$: **71 pb**	37	0.01	17	10
		0.003	41	22

Han, ZL, 1210.7803;
With ISR effects
Greco, Han, ZL,
1607.03210

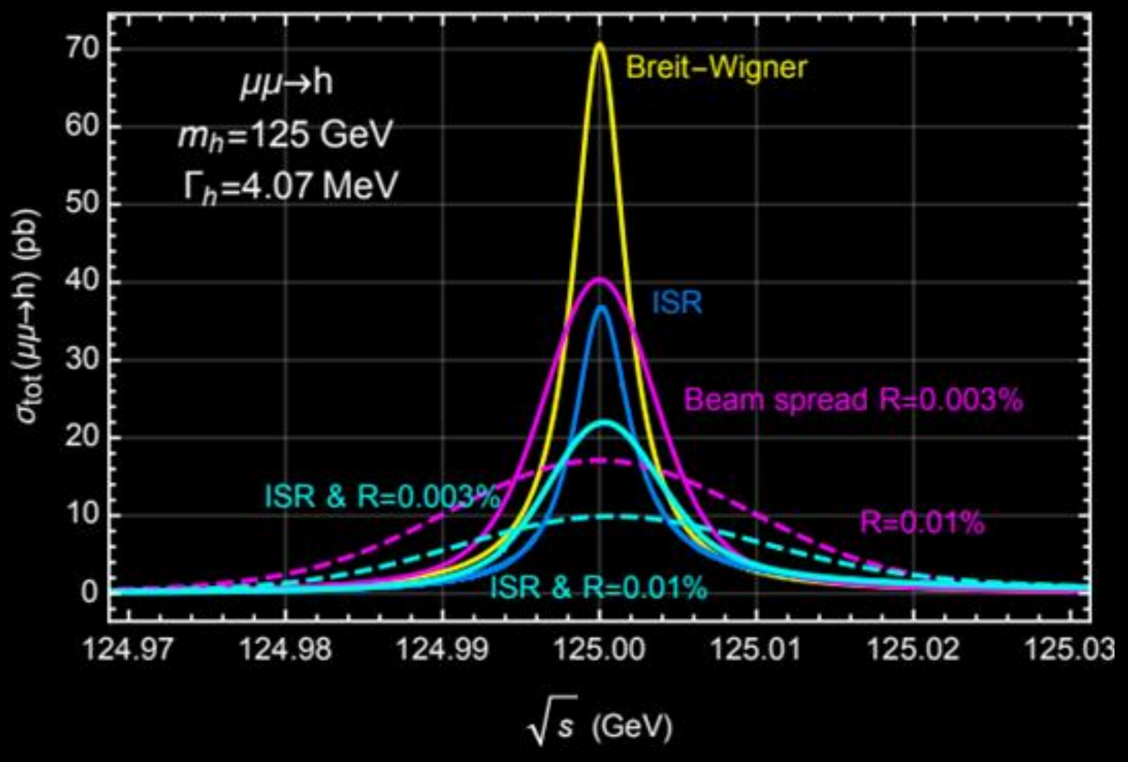
$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$



$$R = 0.01\%\ (\Delta = 8.9\,\mathrm{MeV}),$$
$$R = 0.003\%\ (\Delta = 2.7\,\mathrm{MeV})$$

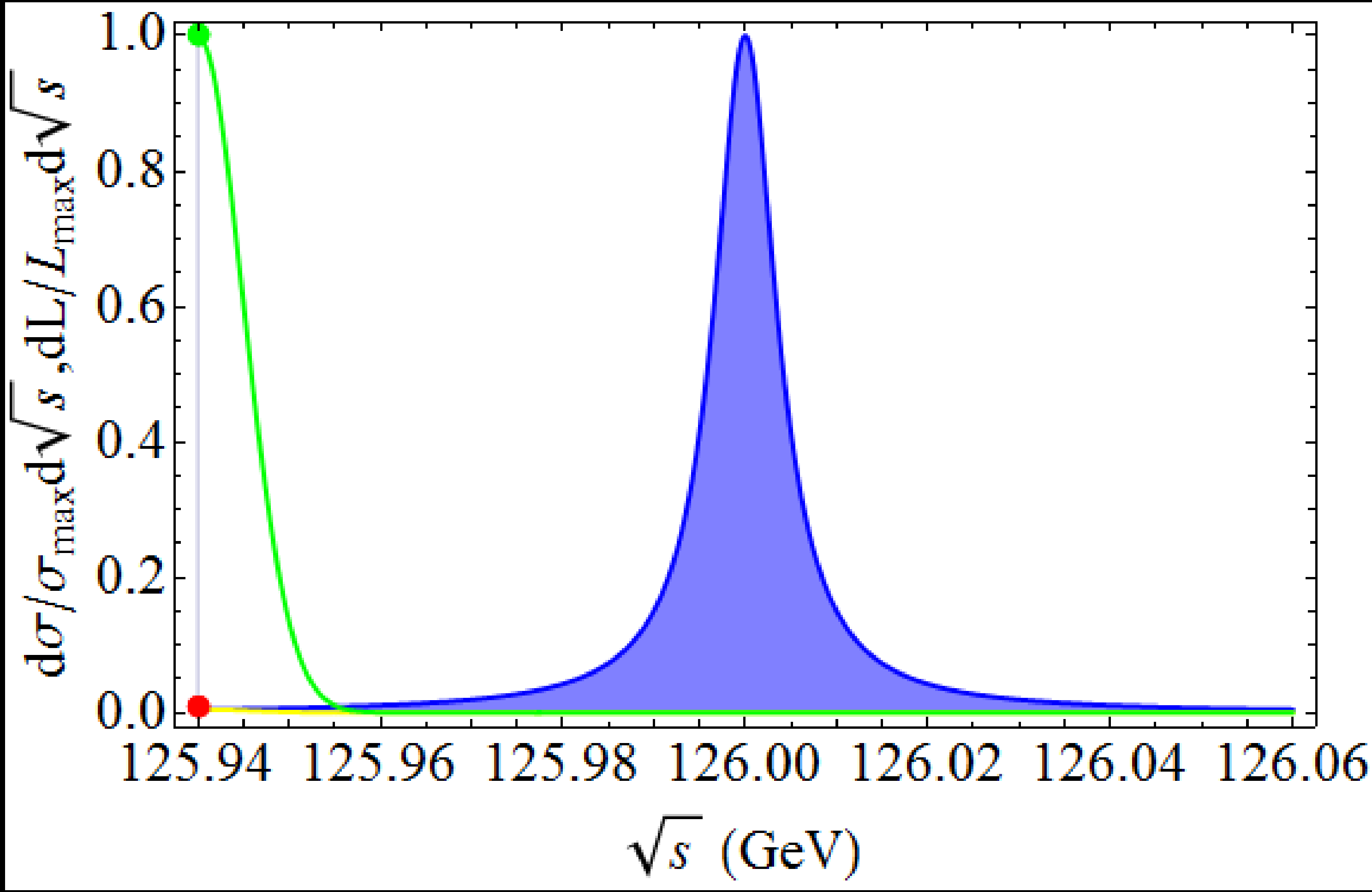
$$\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}} = \frac{1}{\sqrt{2\pi}\Delta}\exp\left[\frac{-(\sqrt{\hat{s}} - \sqrt{s})^2}{2\Delta^2}\right]$$

$$\sigma_{\mathrm{eff}}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\,\sigma(\ell^+\ell^- \to h \to X)(\hat{s})$$



Normal Case:

Han, ZL, 1210.7803;



Energy Spread comparable to the physical width:

Δ = 5 MeV

(R=0.003%)

Γ_h = 4.2 MeV

Breit-Wigner

Gaussian Profile (beam)

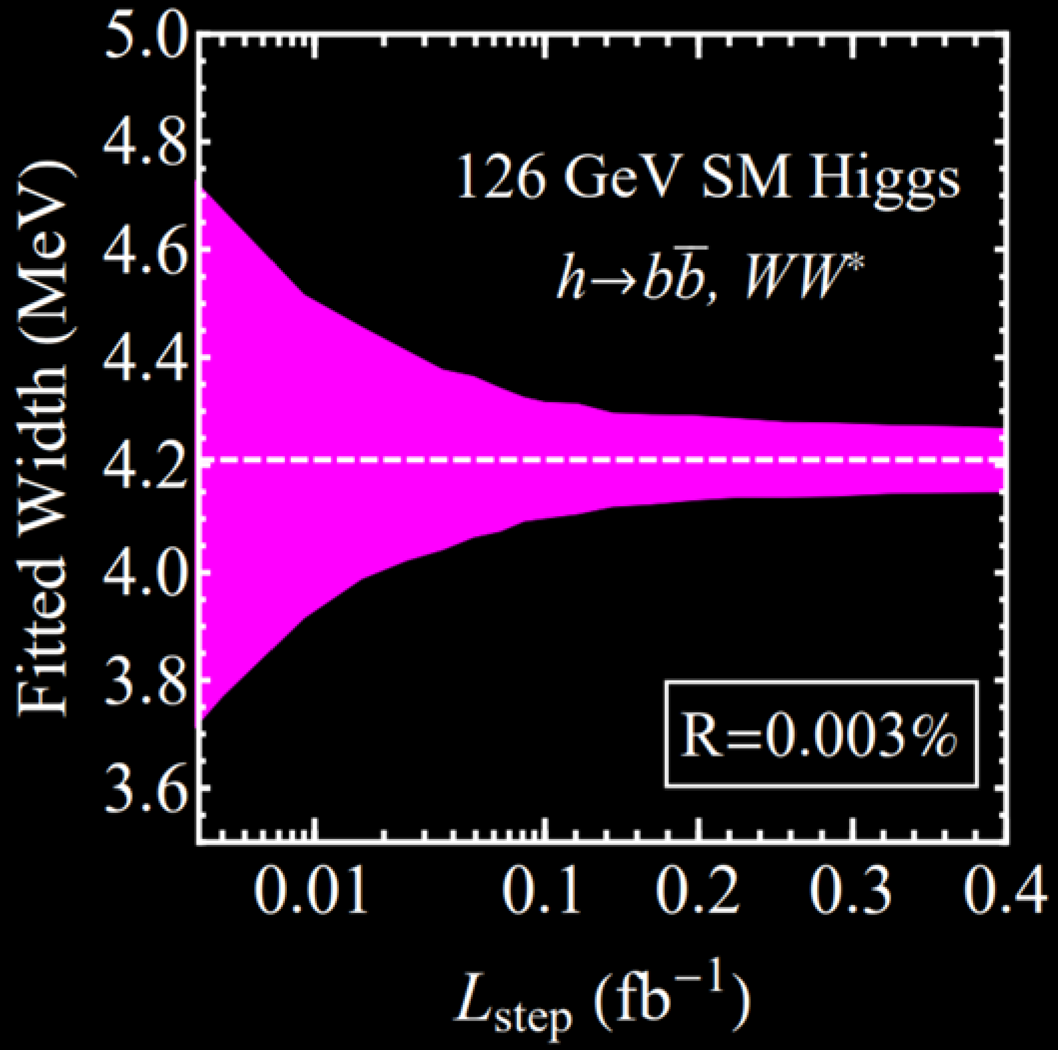
Overlap (observable rate)

Effective cross section (observable scan)

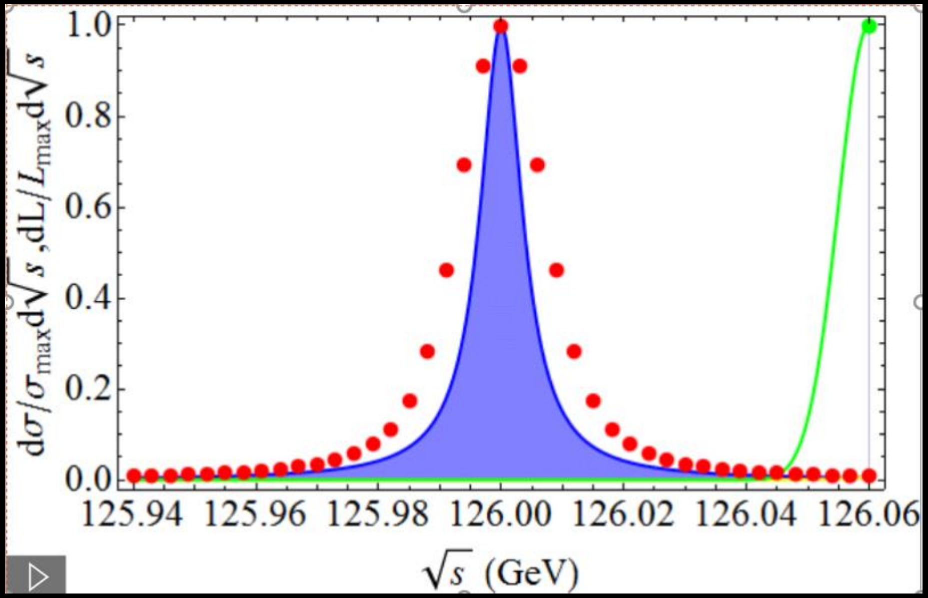
An optimal fitting would reveal Γ_h

Han, ZL, 1210.7803; also see Conway, Wenzel 1304.5270
With ISR effects: Greco, Han, ZL, 1607.03210
New results in preparation by JB-JG-ZL

Fitting the SM Higgs



$\Gamma_h = 4.07$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.05	0.79	3.0%	0.36
	0.2	0.39	1.1%	0.18
$R = 0.003\%$	0.05	0.30	2.5%	0.14
	0.2	0.14	0.8%	0.07



Lots of open questions

How would the width, mass, signal strength fit scale in various scenarios?

- Change of Luminosity (expecting some non-linearities from the beam energy spread);
- Lineshape scanning steps
- Lineshape scanning range
- Inclusion of more channels

The convolution of various effects are highly non-trivial. So new studies will help understand better:

- 125 MuC Higgs physics
- Robustness of the width fit
- Allowing future studies on systematics

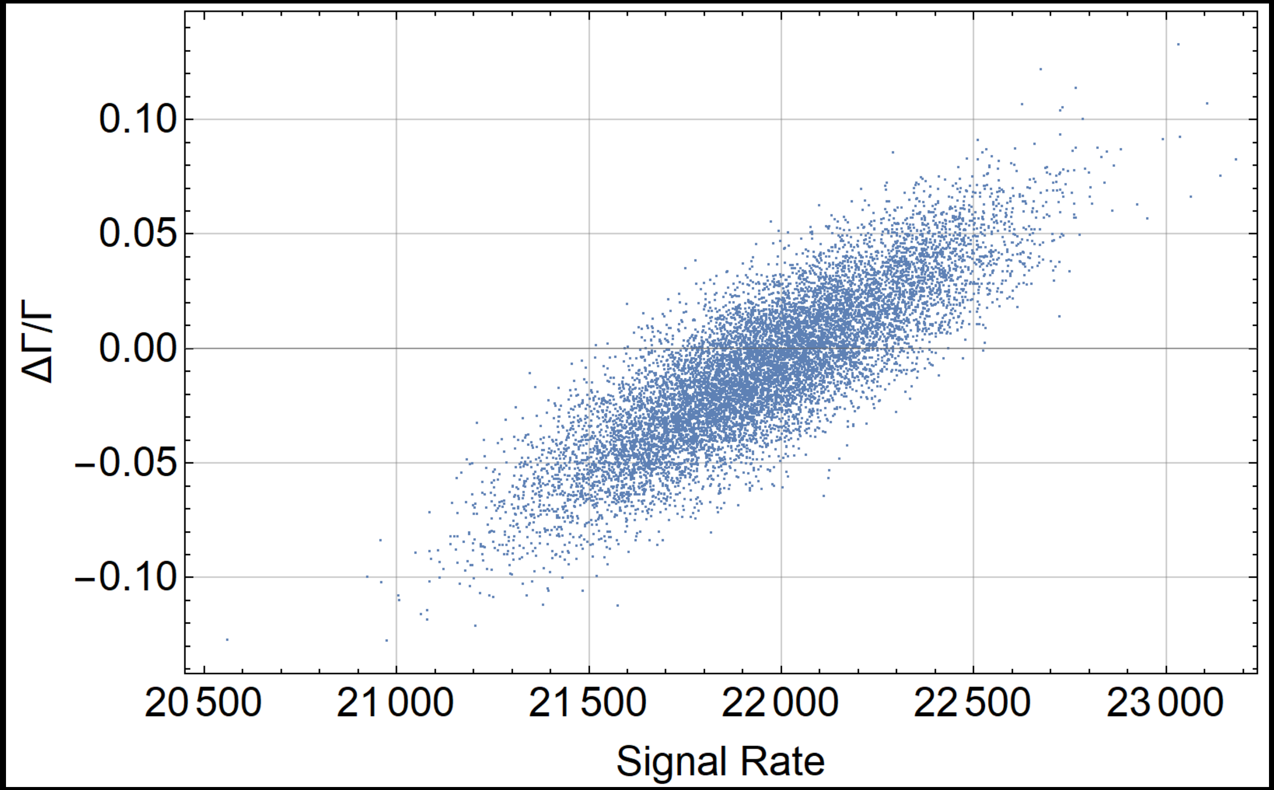
Beginning of 2021, formed a small team to address these:

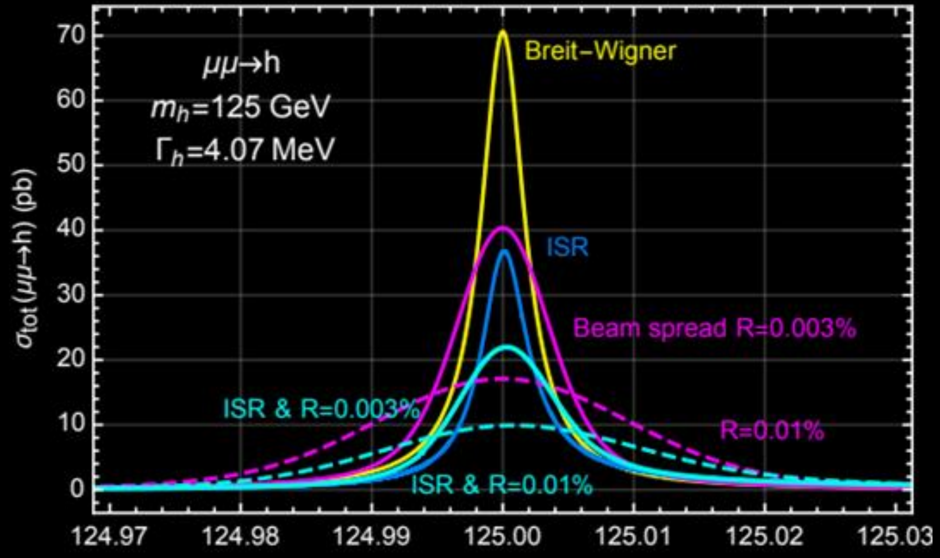
Jorge de Blas

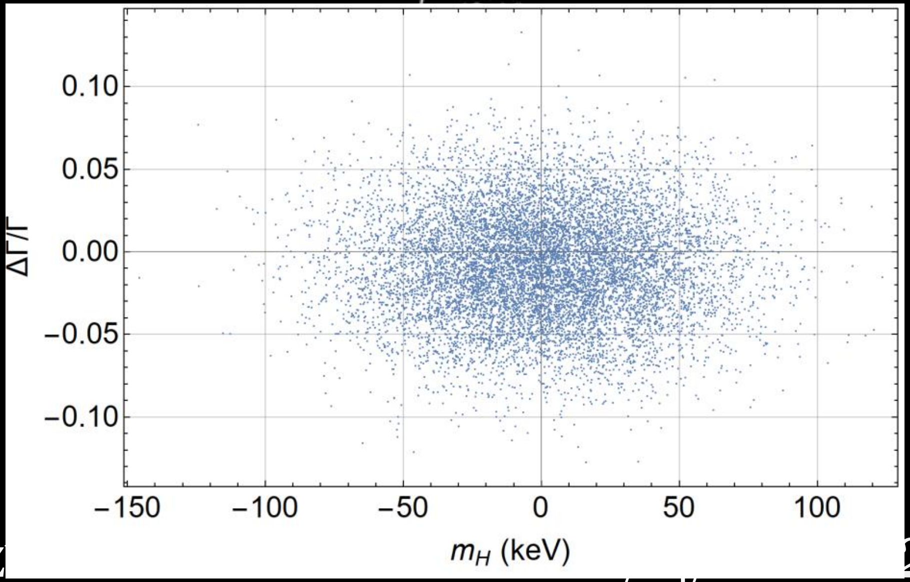
Jiayin Gu

Zhen Liu

New Developments (JB-JG-ZL, in progress)

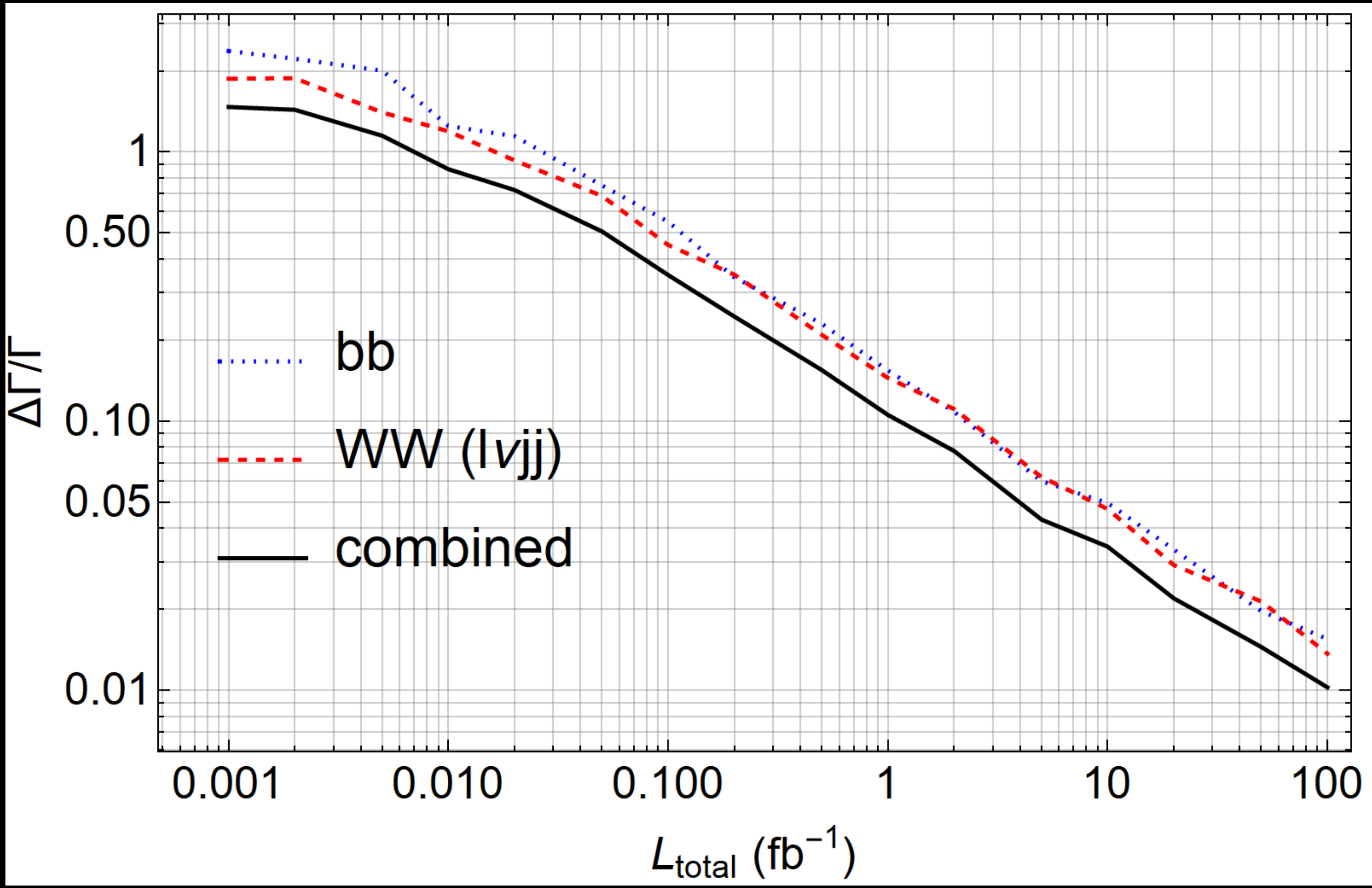


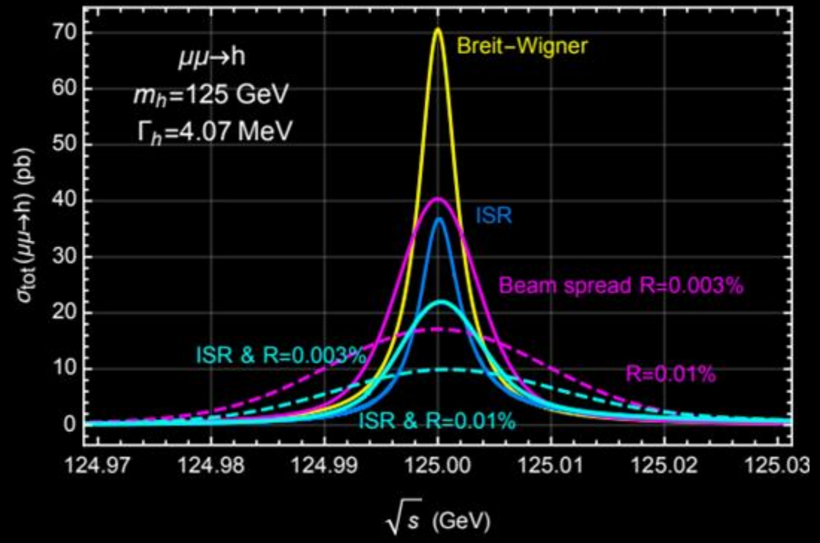




Larger width corresponds to larger coupling^2.
Note: this is a different power compared to the normal "flat direction", which is coupling^4.

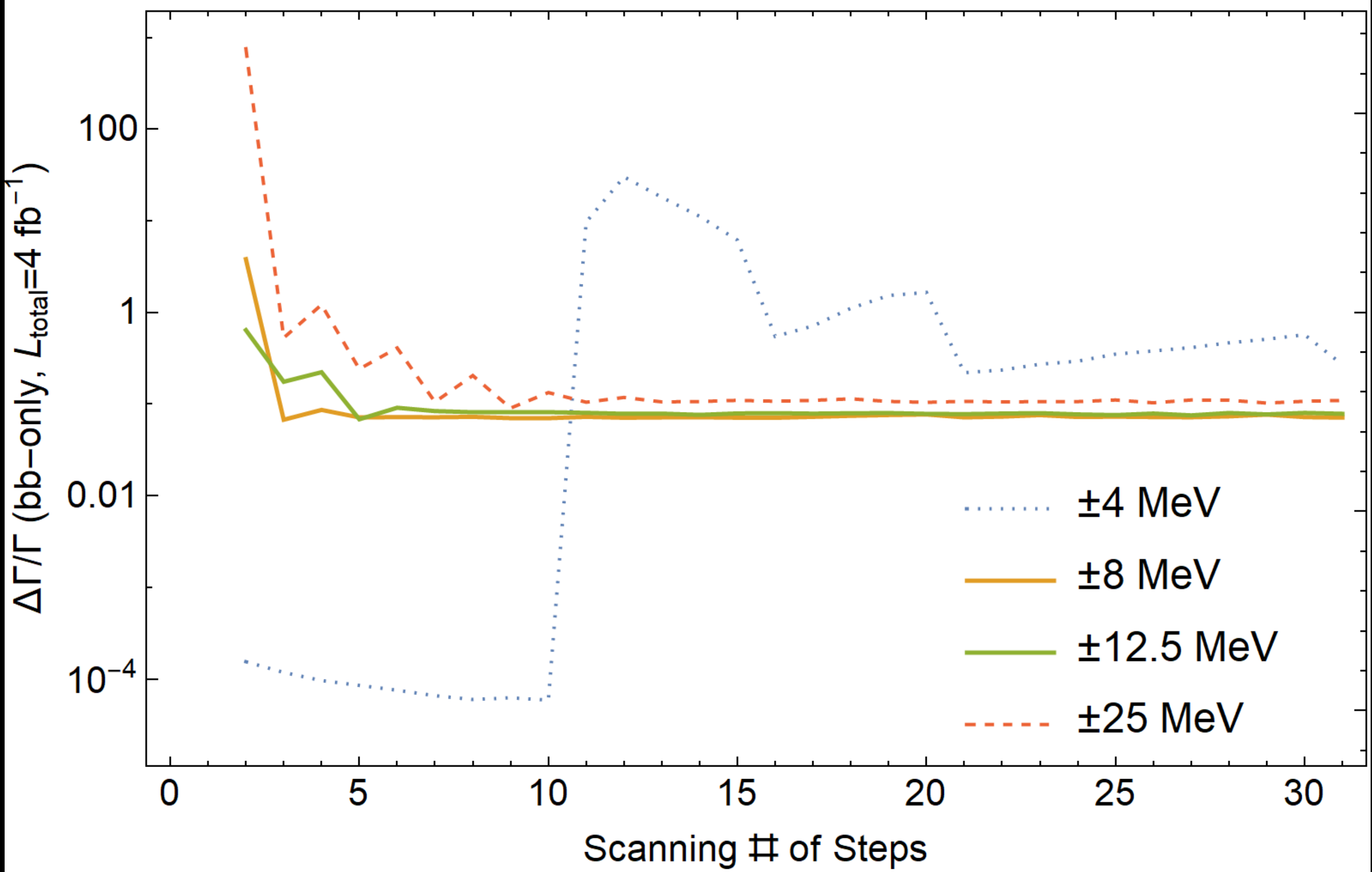
Luminosity Scaling (JB-JG-ZL, in progress)

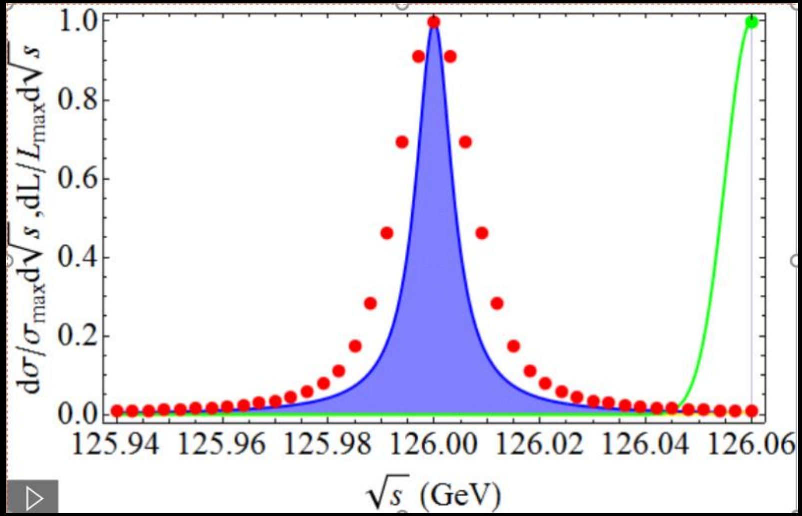




Using our new Monte Carlo fit, we show that:
Width precision basically scales as 1/Sqrt[L], so we can gain a lot with higher lumi.

Scanning Range & Steps (JB-JG-ZL, in progress)



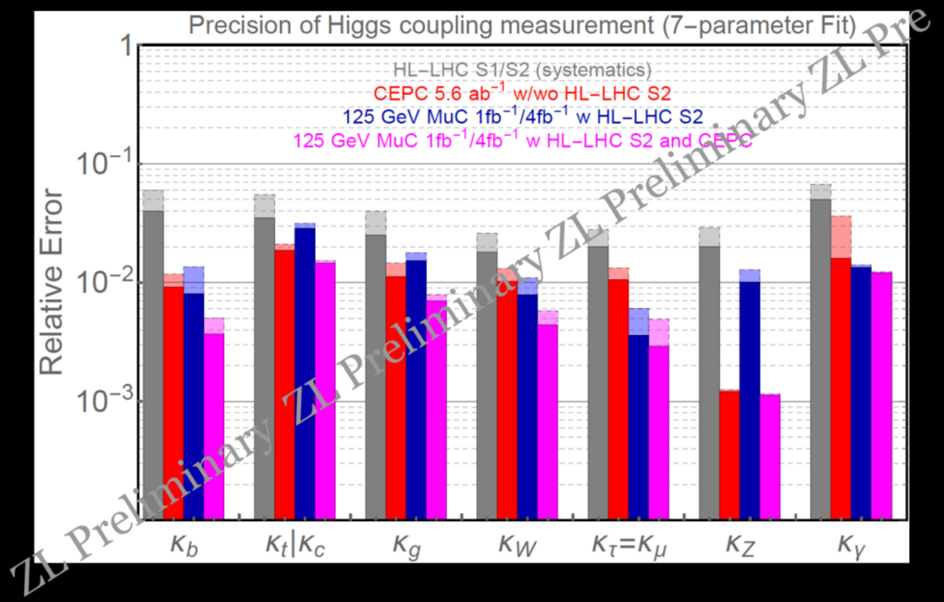


New insights:

- Optimal scanning range around +-10 MeV
- Need at least 6 points to stabilize, 10 points scan should be sufficient

Outline

- Overall picture
- Higgs Width
- Higgs Couplings
- Higgs Exotic Decays



Basics:

pp | e^+e^- | $\mu^+\mu^-$

Table 1-18. *Muon collider statistical precisions on Higgs production rates into various final states X from a 5-point energy scan centered at m_H with a combined yield of 39,000 Higgs bosons. The $\tau\tau$ uncertainty is an average of asymmetric uncertainties. The rates are proportional to* $\mathrm{BR}(H \to \mu\mu)\times\mathrm{BR}(H \to X) \propto \kappa_\mu^2\kappa_X^2/\Gamma_H^2$.

Snowmass Higgs Report 1310.8361

Final state	$b\bar{b}$	WW^*	$\tau\tau$	$c\bar{c}$	gg	$\gamma\gamma$	ZZ^*	$Z\gamma$	$\mu\mu$	Γ_H	m_H
$\sigma(\mu\mu \to H \to X)$	9%	5%	60%	–	–	–	–	–	–	4.3%	0.06 MeV

pp	e^+e^-	$\mu^+\mu^-$
50 pb	200 fb	15 pb
3 ab^{-1}	5 ab^{-1}	1 fb^{-1}
0.15 billion Higgs	1 million Higgs	0.15 million Higgs

New Insight: the total width sets a floor for the individual coupling extraction as:

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

$$\Delta\kappa_j = 1/2(\Delta\kappa_j^2)$$

$$= 1/2(\Delta\kappa_\Gamma \oplus \Delta\sigma(i \to H \to j) \oplus \Delta\kappa_i^2)$$

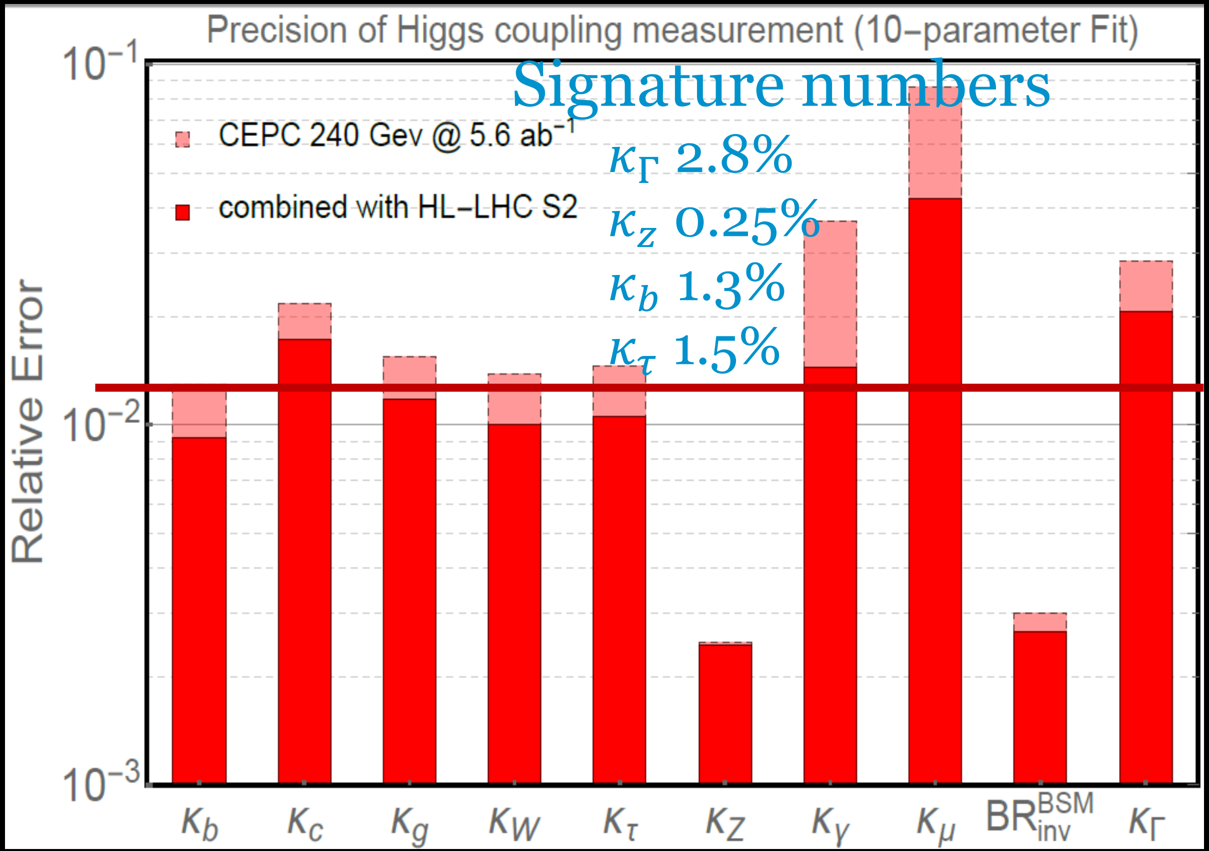
General κ fit

(so called "model independent fit")

ΔM_H	Γ_H	$\sigma(ZH)$
5.5 MeV	2.8%	0.51%

CEPC per channel precision

Decay mode	$\sigma(ZH) \times$ BR
$H \to bb$	0.28%
$H \to cc$	2.2%
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to$ inv	0.28%



Now the Model-Independent MuC Width matters!

Let's check precision with 1/5 on-shell statistics (with different bkg)

ΔM_H	Γ_H	$\sigma(ZH)$
5.5 MeV	2.8%	0.51%

e+e- collider per channel precision

Decay mode	$\sigma(ZH) \times \mathrm{BR}$
$H \to bb$	0.28%
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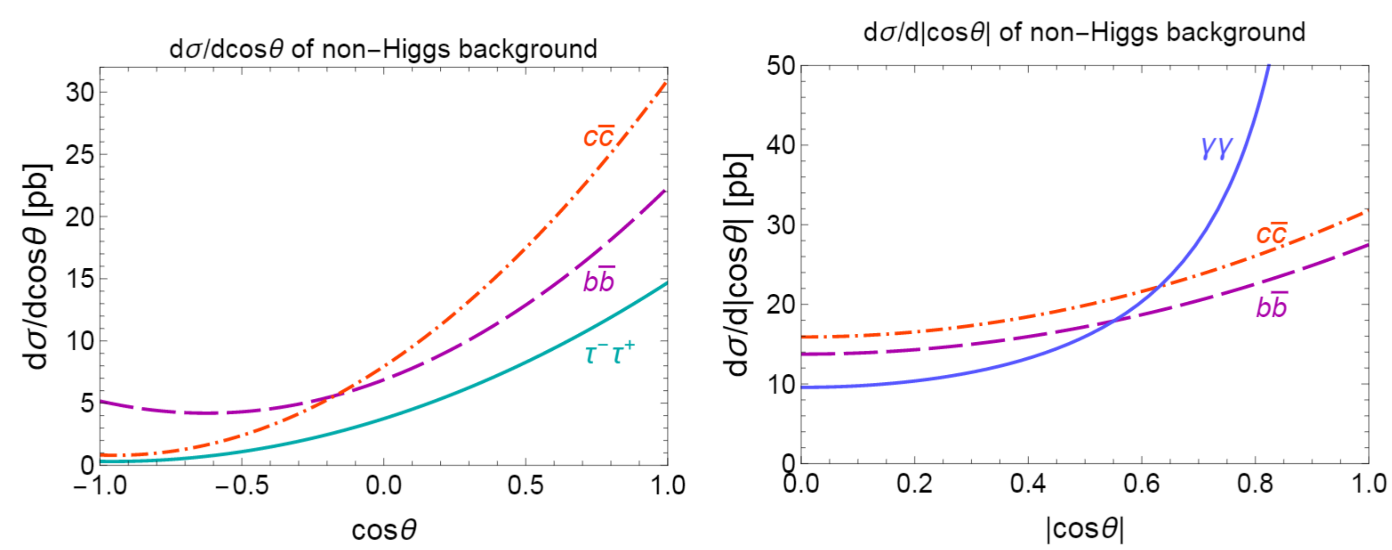
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to \mathrm{inv}$	0.28%

	Br	Rate (pb)	Precision
Inclusive	100%	22	---
bbar	57.80%	12.72	1.7%
tautau	6.37%	1.40	18%
mumu	0.02%	0.00	2005%
cc	2.68%	0.59	25%
gg	8.56%	1.88	13%
$\gamma\gamma$	0.23%	0.05	374%
WW*	21.60%	4.75	1.6%
ZZ*	2.67%	0.59	4.5%
invisible	0.01%	0.00	---
Γ_{total}	4.2 (MeV)		3.3%

New Developments (JB-JG-ZL, in progress)

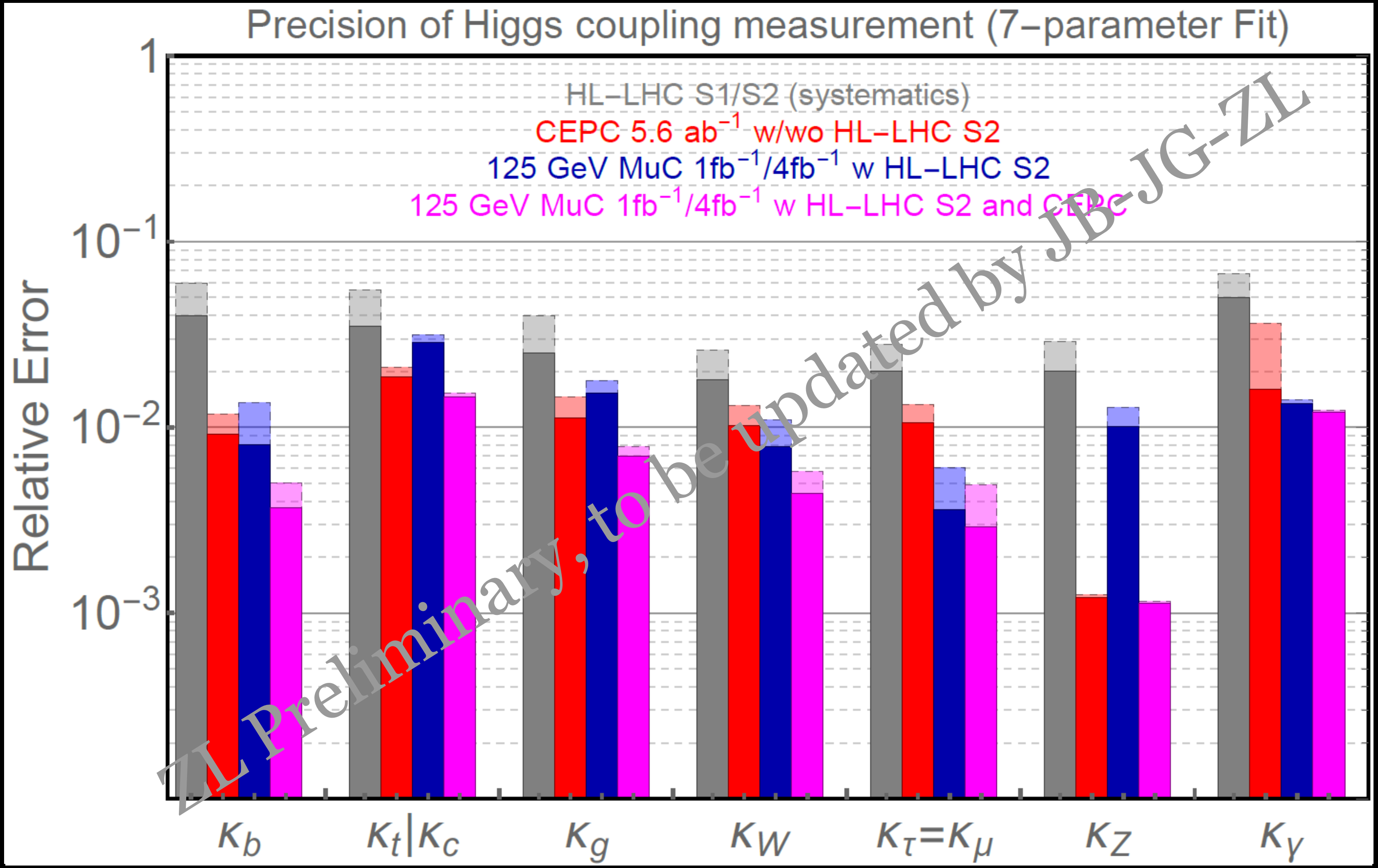


	actual		
	b	c	g
tagged as b	0.7	0.04	0.004
tagged as c	0.2	0.6	0.07
tagged as g	0.1 (0.01)	0.36 (0.05)	0.926 (0.99)

Channel $\mu^+\mu^- \to h \to X$	Rate [pb]	Signal Events	Background Events	Precision [%] JG	Precision [%] JB
$b\bar{b}$	13	22022	30609	0.8%(0.8%)	0.78
$c\bar{c}$	0.59	2361	29359	16% (18%)	17
gg	1.9	7042	209760	7.3% (6.2%)	7.6
$\tau^+\tau^-$	1.4			2.8%	5.6
$\mu^+\mu^-$					−−
$\gamma\gamma$	0.051			125%	195)
$e\nu\mu\nu$					6.8
$\ell\nu\tau\nu$ $(\ell = e, \mu)$					4.1
$\ell\nu jj$ $(\ell = e, \mu, \tau)$		5556	92		1.35

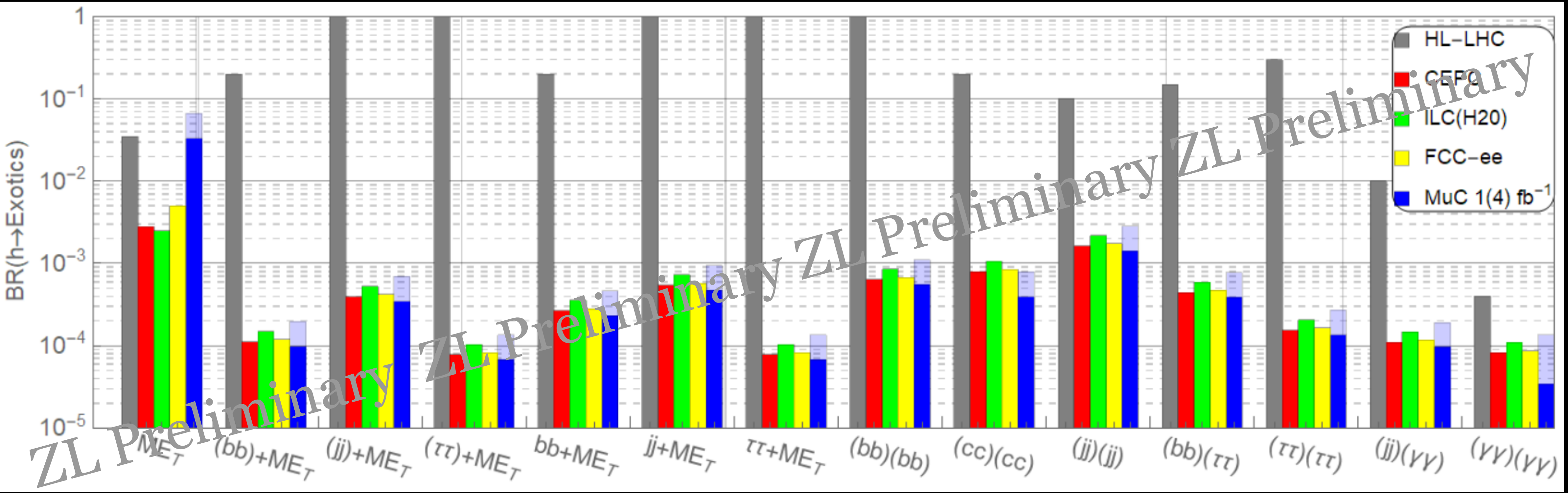
Now the Model-Independent MuC Width matters!

- This MuC Width is a pure measurement, uncorrelated with all the other parameters;
- When combined with the HL-LHC, comparable to other lepton collider Higgs factories (except for kZ)
- Sub-percent muon Yukawa
- Good lumi scaling with couplings
- Excellent improvement when combined with CEPC (kb, kg, kW, kmu)



Exotic Decay Overall Picture

Our study on CEPC/ILC/FCC-ee only used Z(->ll)H, there is 10x statistics to be used



125 GeV MuC: no tagging spectator Z issues and less combinatoric background.

with missing Energy (SUSY motivated, DM motivated channels)

3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

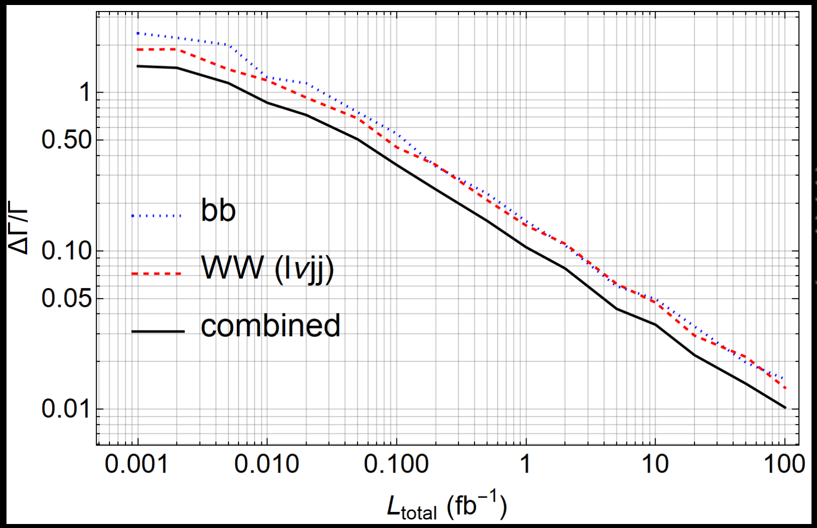
$h \to 4f$ generic Higgs sector extensions, also Higgs portals

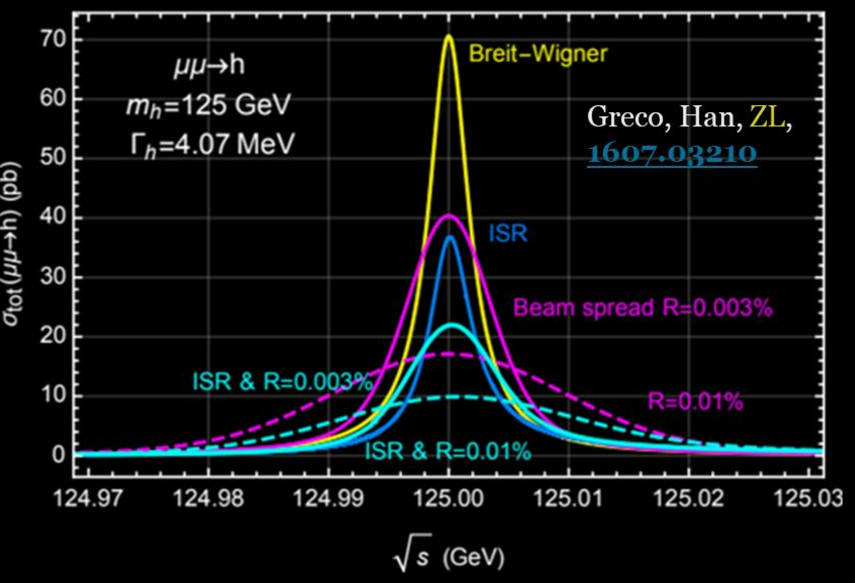
2-3 orders of magnitude improvement for the constraints on such exotic branching fractions

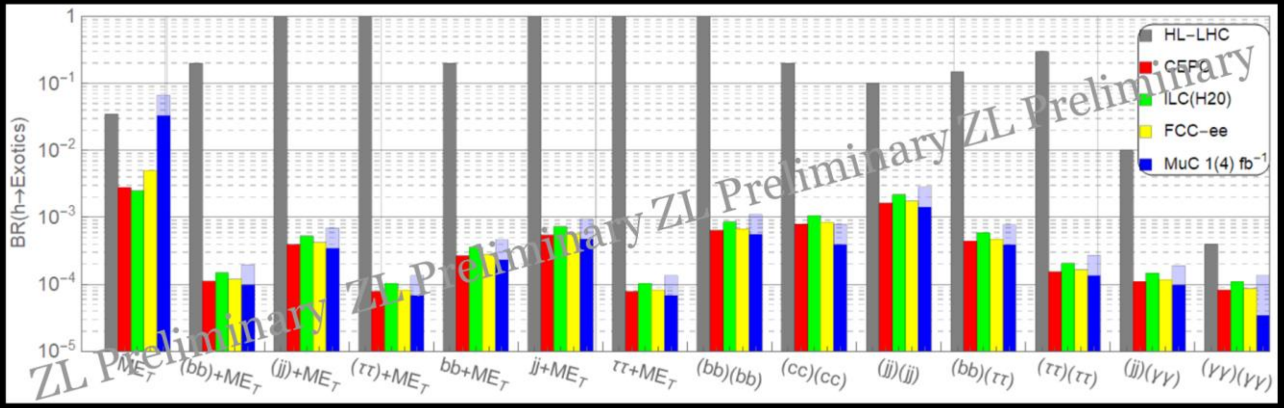
Original plot without MuC, ZL, Wang, Zhang, 1612.09284 , updated by ZL following future collider program updates; MuC very preliminary results compiled by ZL.

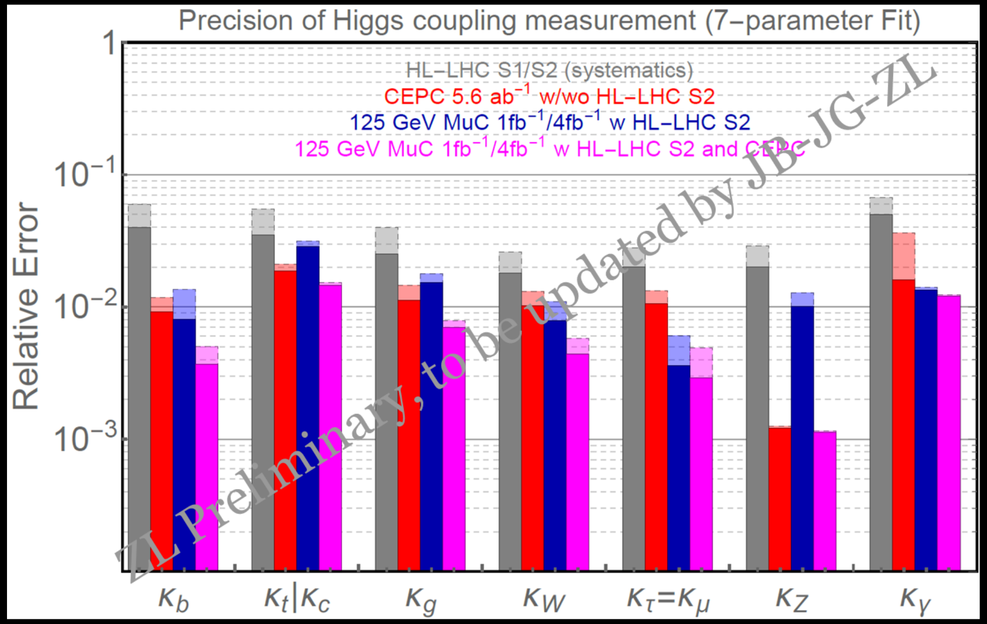
Summary

- Higgs Width
- Higgs Couplings
- Higgs Exotic Decays









Additionally…

- What should be the standard lumi assumption now?
- What should be the standard beam energy spread? And its uncertainty?
- EFT fit result to come, by JB-JG-ZL;
- Studying how results change by different beam energy spread;
- All the above assumes a precisely SM Higgs. What if muon Yukawa is anomalous to SM? Any experimental hints immediately boost the necessity of the precision measurement of muon Yukawa.