PITT-PACC Workshop: Muon Collider Physics

Physics at Higgs factories

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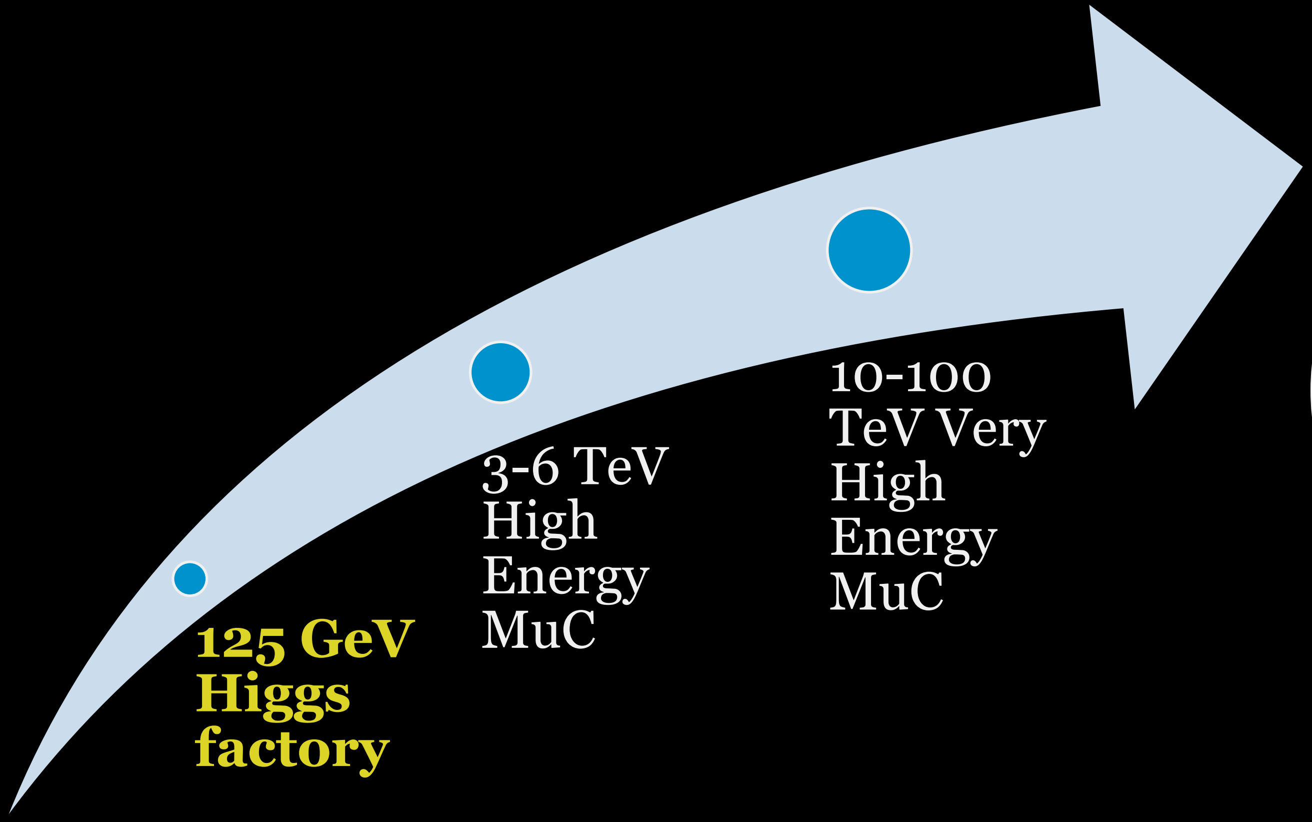
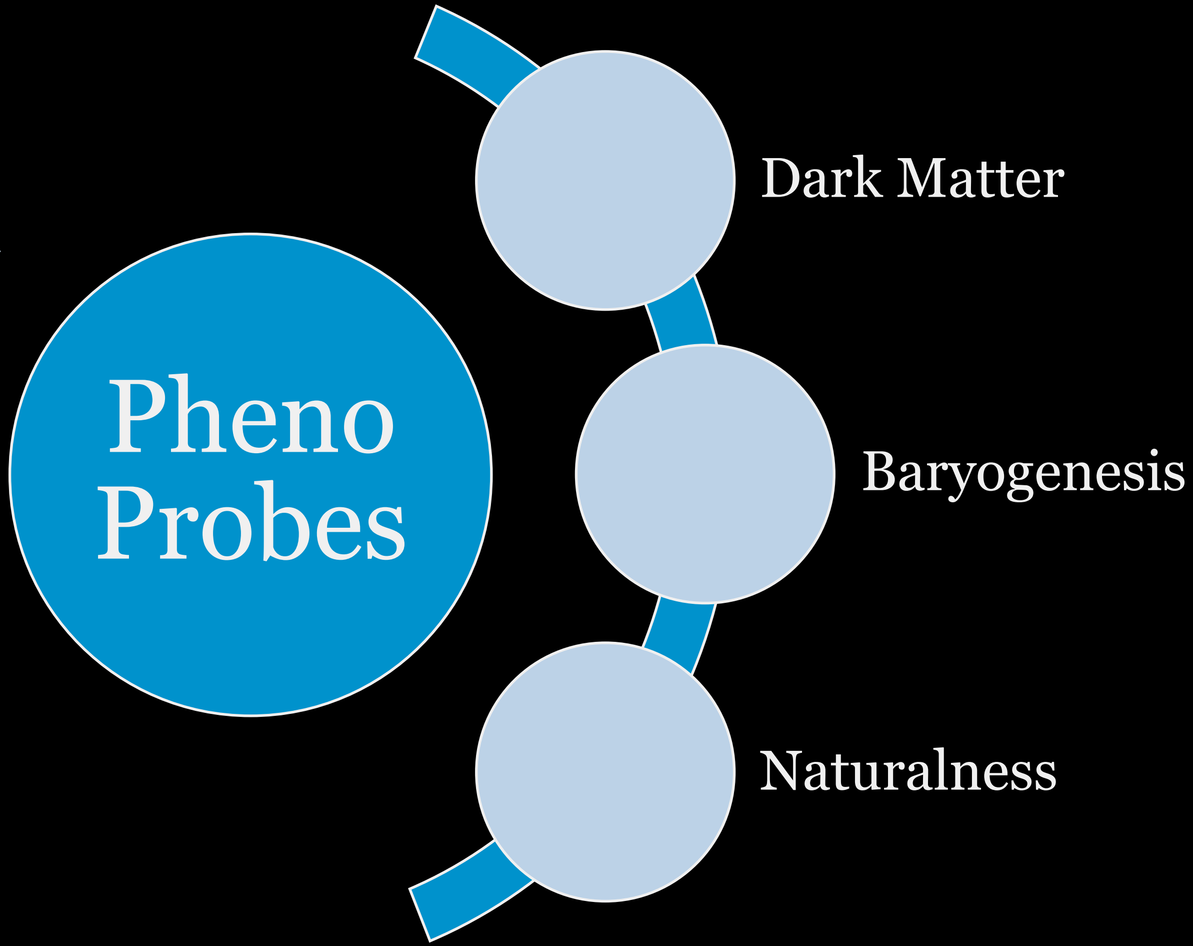
12/01/2020

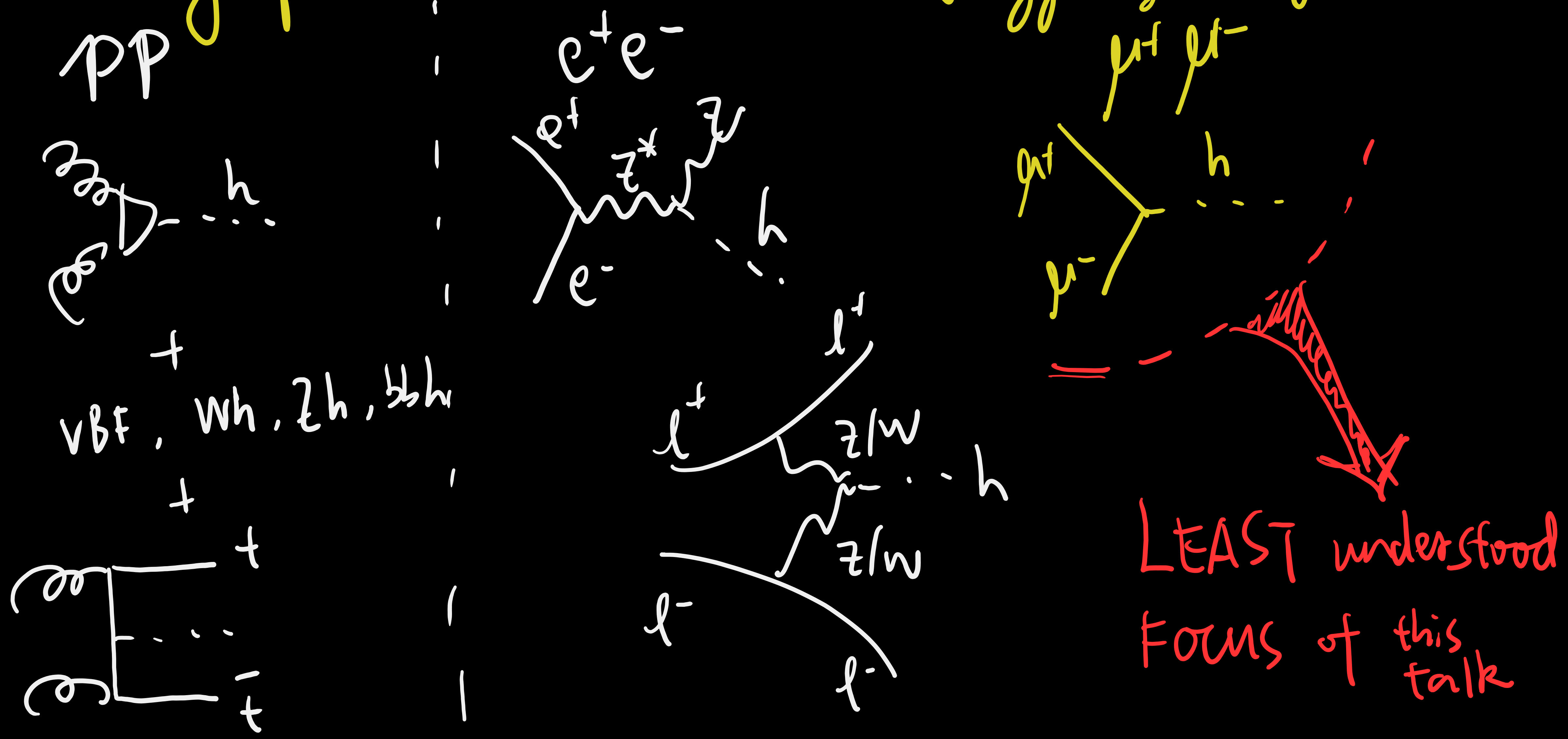
Exciting Muon Collider Program ahead



Physics Driver



Every future collider is a Higgs Factory!

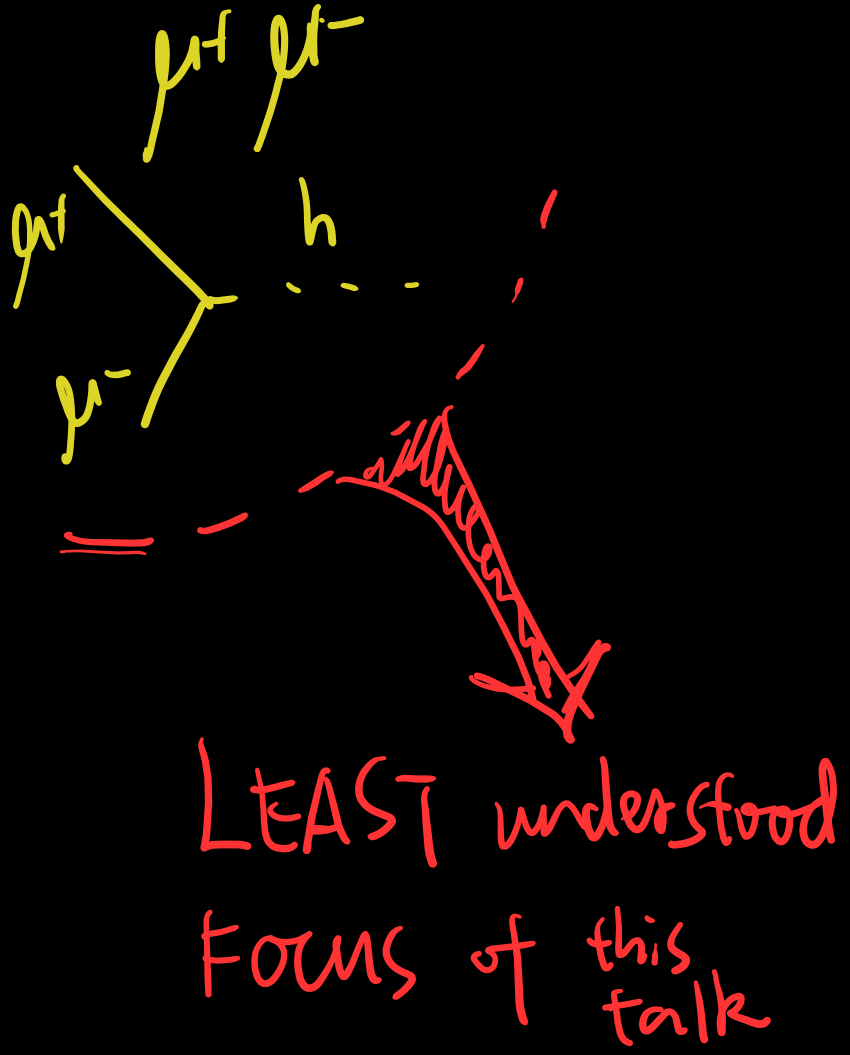


Outline

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

Mark Palmer's talk (as well as talks by Diktys Stratakis, Daniel Schulte, Nadia Pastrone) nicely addressed the technological status of a 125 GeV Higgs factory.

Here I focus on the unique physics capabilities.



Basics: clean lepton collider envirorment matters!

pp

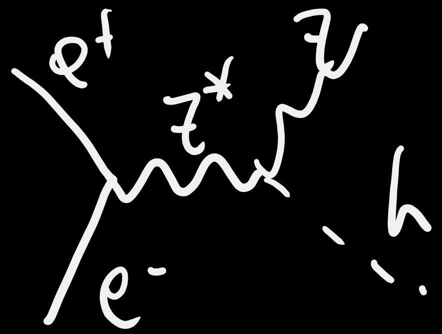
LHC 14 TeV

50 pb

3 ab^{-1}

0.15 billion Higgs

e^+e^-



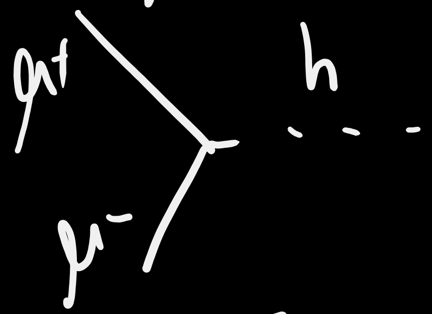
e^+e^- 240~250 GeV

200 fb

5 ab^{-1}

1 million Higgs

$\mu^+\mu^-$



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

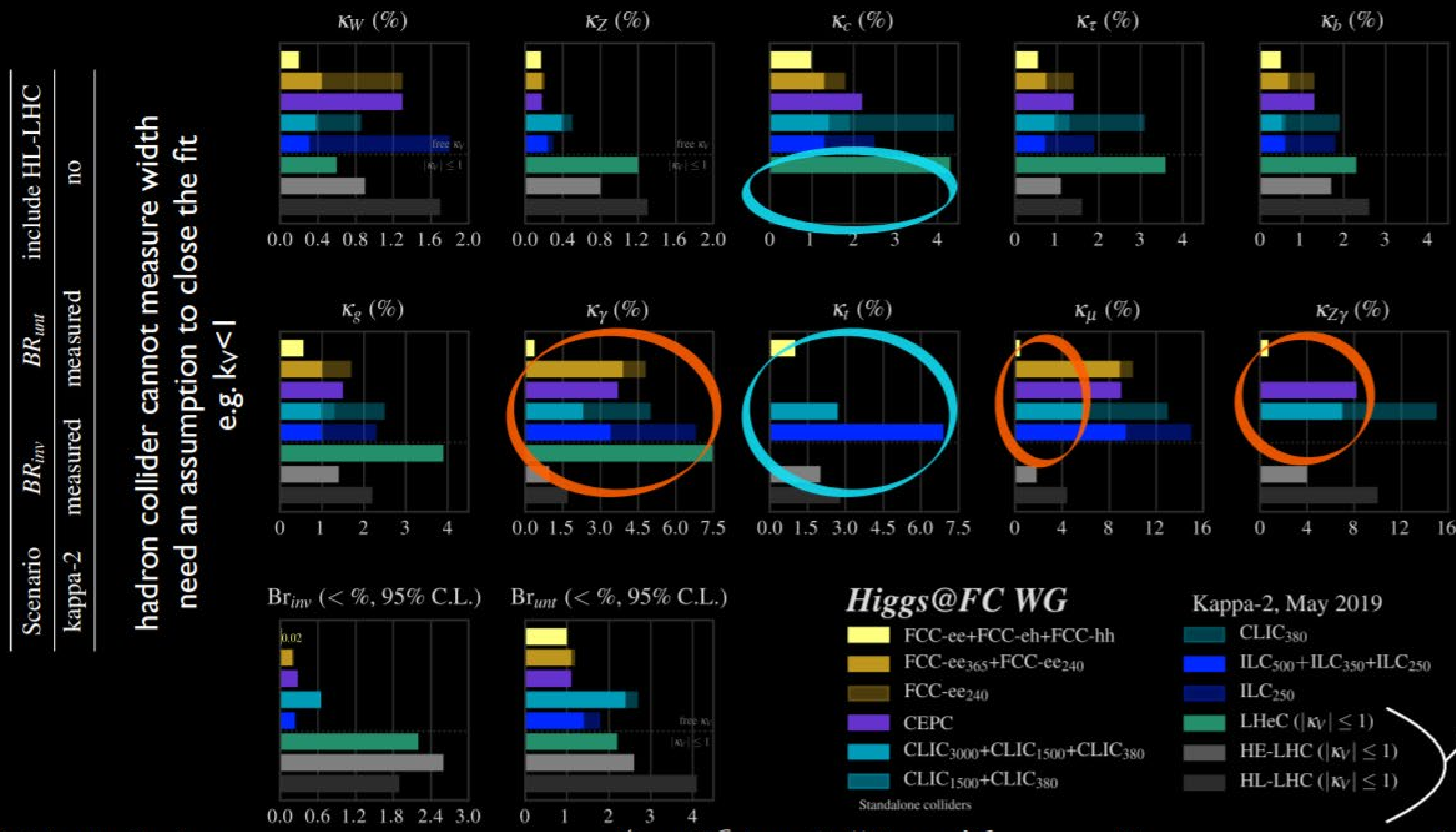
20 pb

1 fb^{-1}

20 thousand Higgs

Higgs Coupling Fit (Future Collider Standalone)

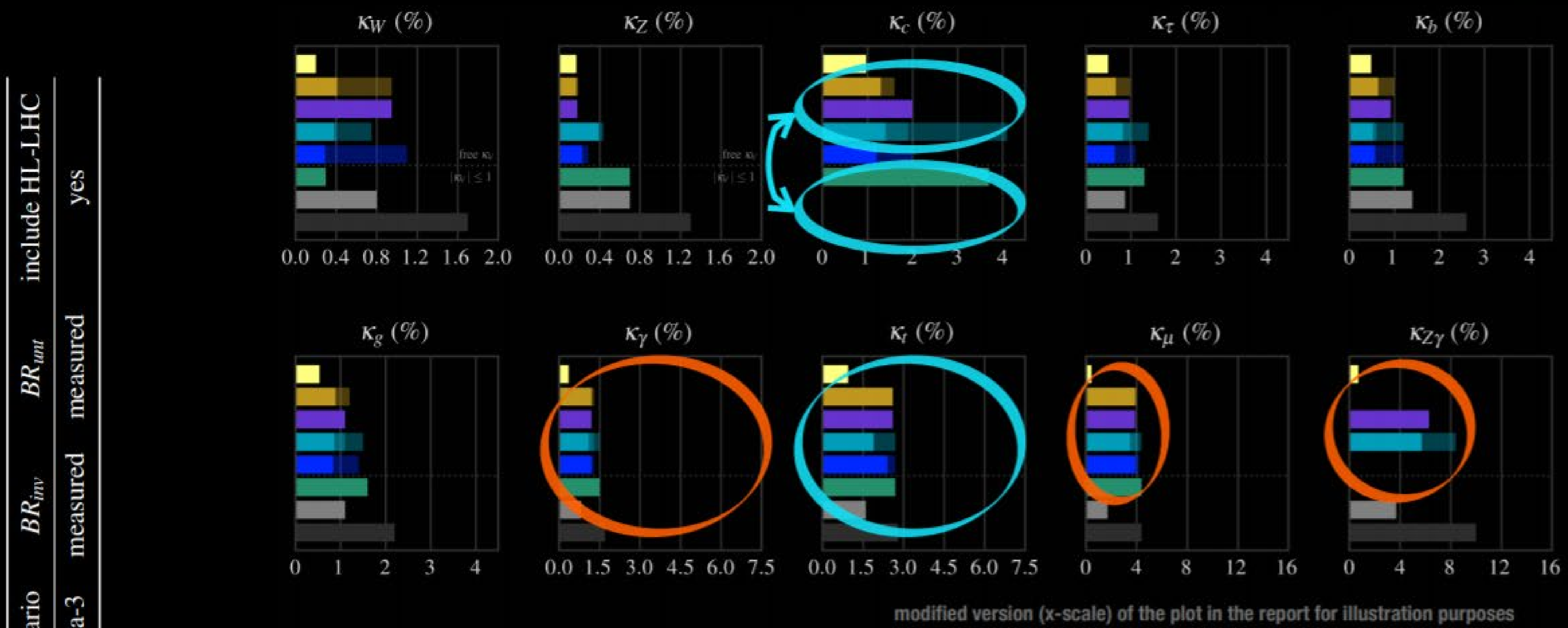
ECFA Higgs study group '19

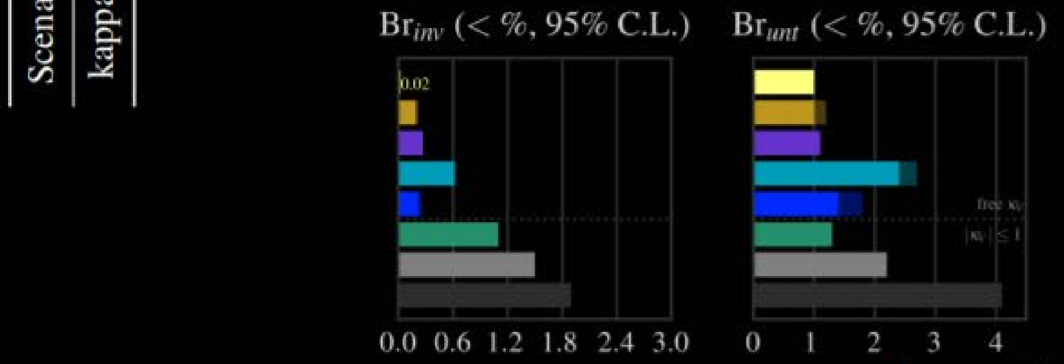


assumption needed for the fit to close at hadron machines

Higgs Coupling Fit (HL-LHC+Future Collider)

ECFA Higgs study group '19



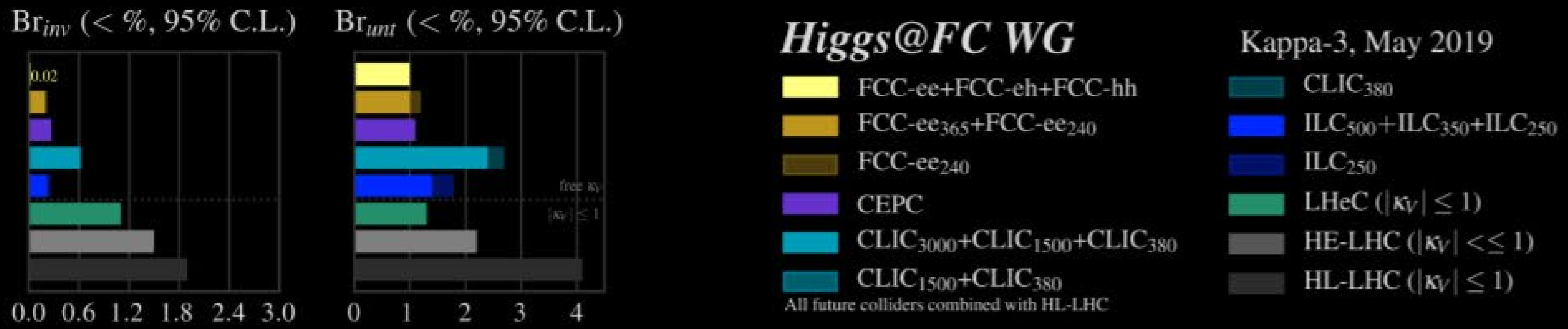


Higgs@FC WG Kappa-3, May 2019

Important **synergy** HL-LHC — low energy lepton colliders

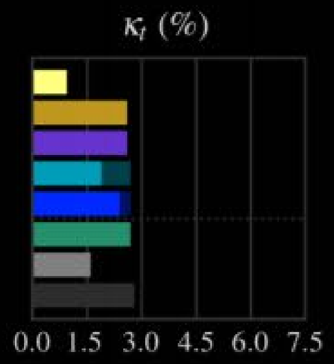
1. Top/Charm Yukawa
2. Statistically limited channels: γγ, mumu, Zγ

Synergy ee-hh

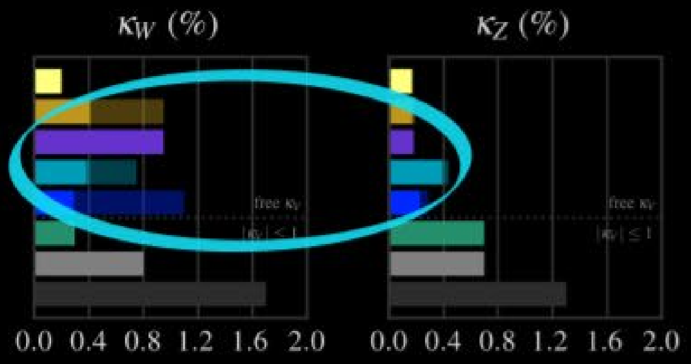


FCC-hh without ee could still bound BR_{inv}

but it could say nothing about BR_{unt}



FCC-hh is determining top Yukawa through ratio tth/ttZ
So the extraction of top Yukawa heavily relies on the knowledge of ttZ from FCC-ee

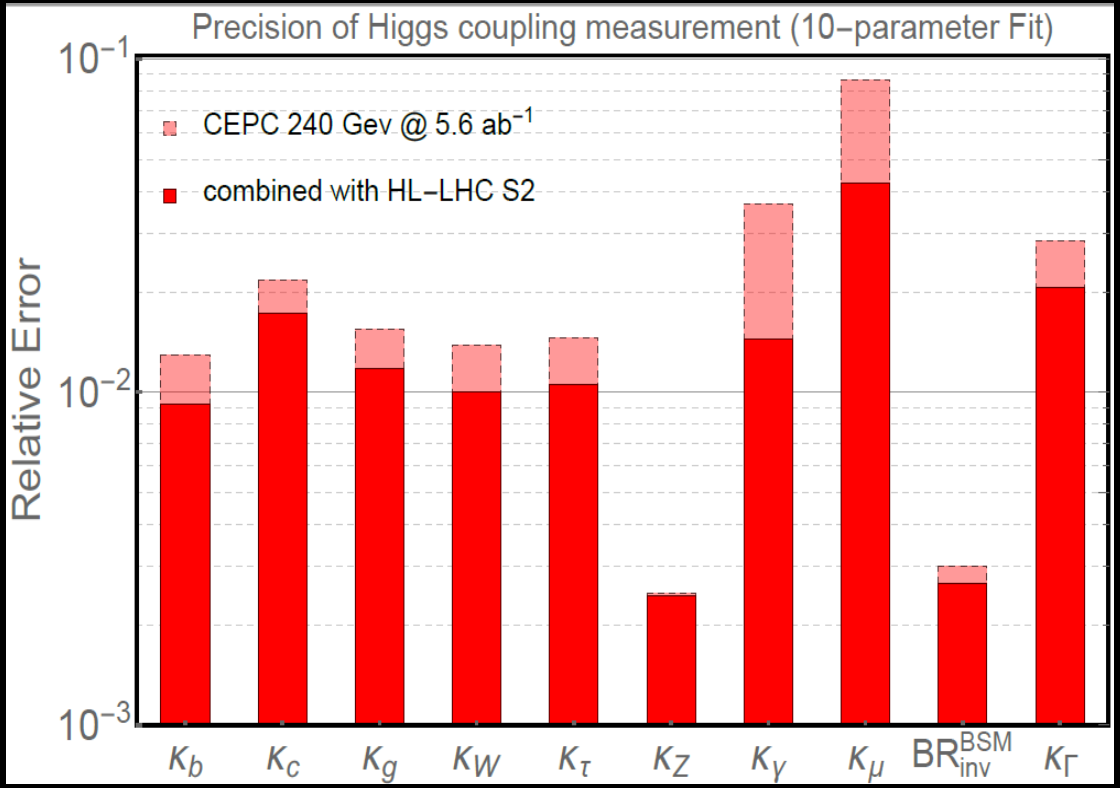


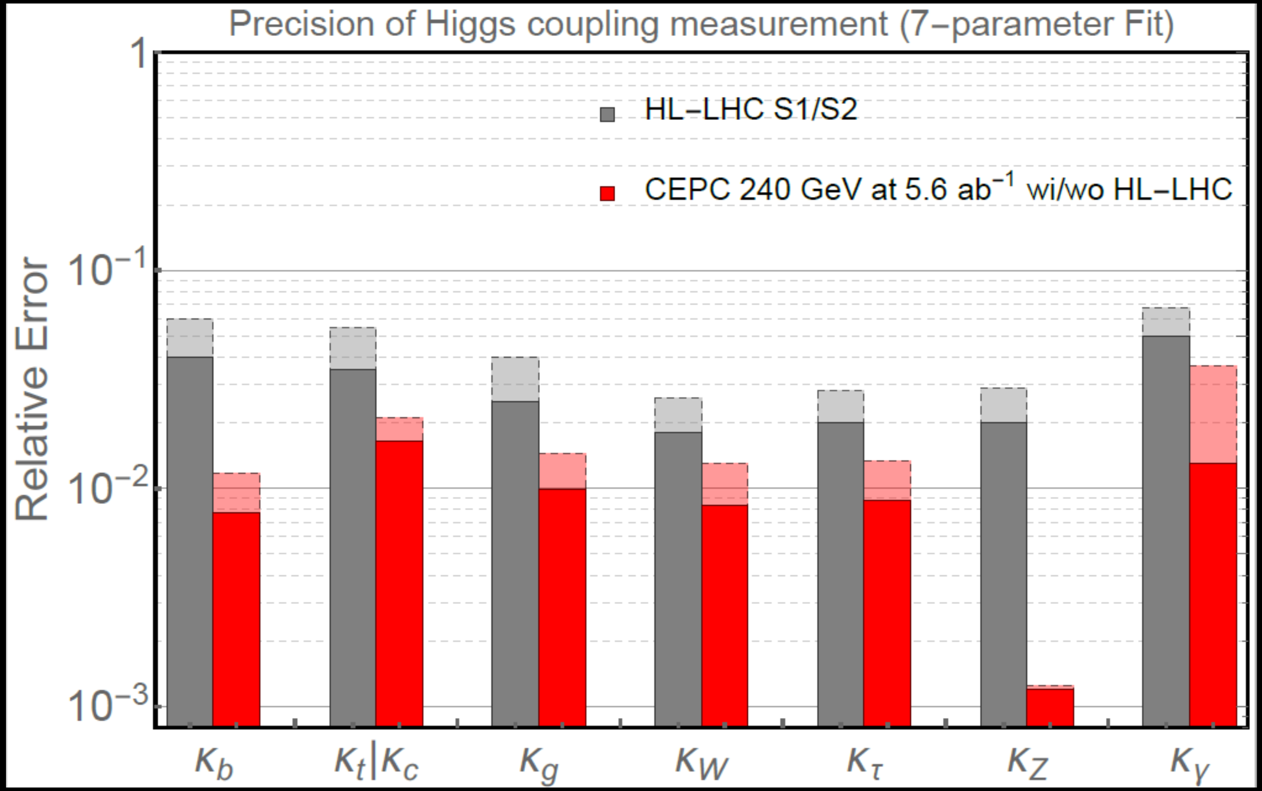
k_W improves significantly with energy increase

But it also benefits a lot from a synergy with EW measurements.
This cannot be captured by the kappa's and requires a full EFT analysis

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

Switch to 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)*

*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)

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.

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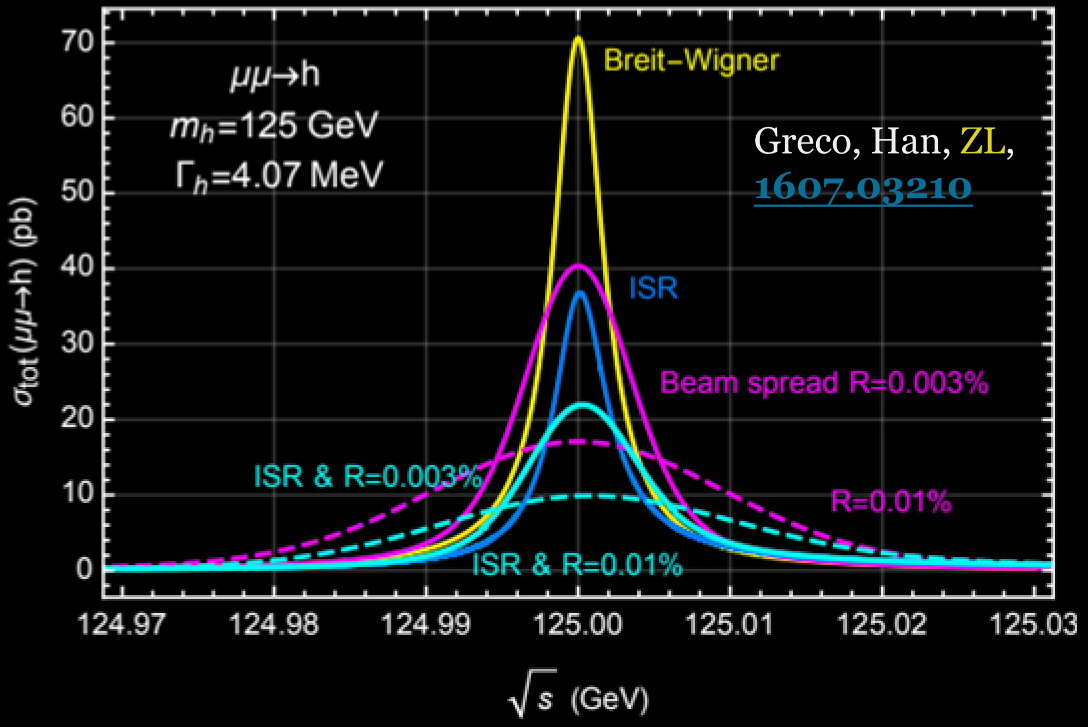

Greco, Han, ZL, 1607.03210

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF (including CEPC, treating the beam energy spread), 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*:

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

(Almost) all 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 et al, 1704.08259

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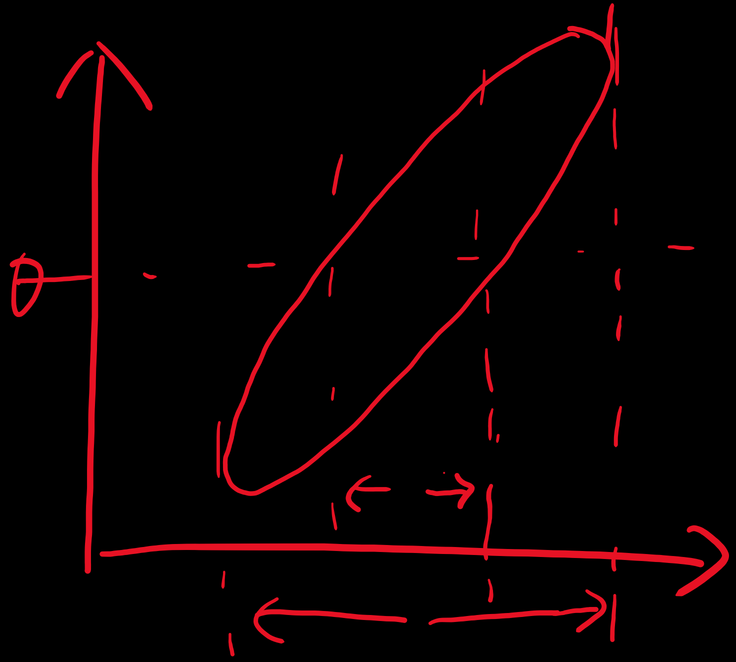
For the hard scattering:

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

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

- All κs 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.
- This highlights the importance and complementarity of the exotic decay program.



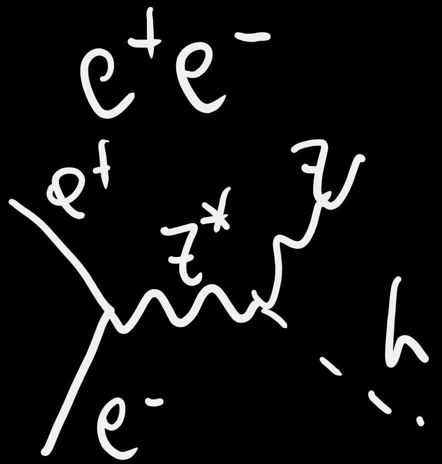
***Flat direction is not disastrous, just give some seemingly worse results when projected to useful basis.

Resolving flat direction: e+e-'s option

For the hard scattering:

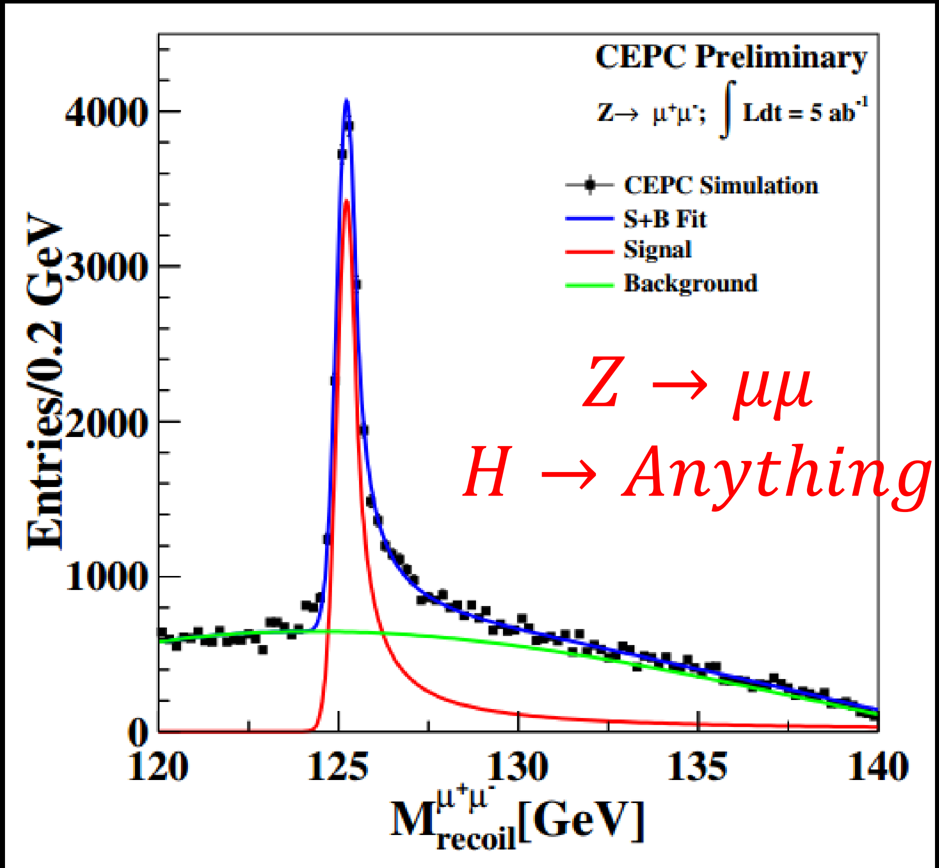
$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

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



This leads to a large flat direction of the Higgs coupling extraction, the future lepton colliders such as ILC/FCC-ee/CEPC can handle this by the unique inclusive cross section measurement

$$\sigma(ee \to ZH, H \to anything) \propto \kappa_Z^2$$



Unique physics for 250~400 GeV lepton collider, direct determination of the HZZ coupling. At higher energies, one might rely on ZZ-fusion for such a inclusive measurement (Han, ZL, Qian, Sayre, 1504.01399).

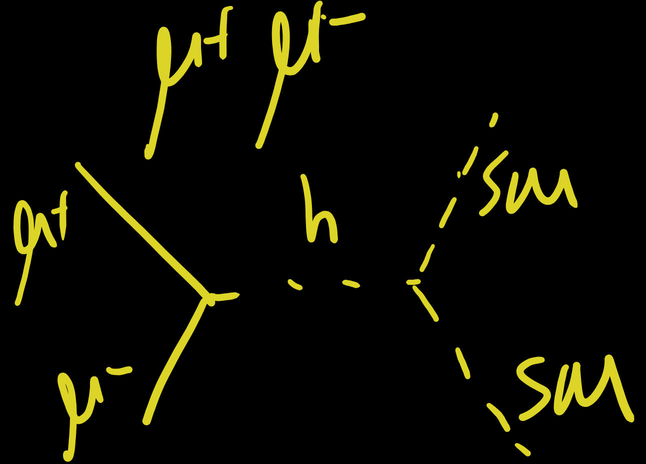
PP collider closes the fit by assuming zero $\Gamma_{undetected}$ or $|\kappa_V| < 1$

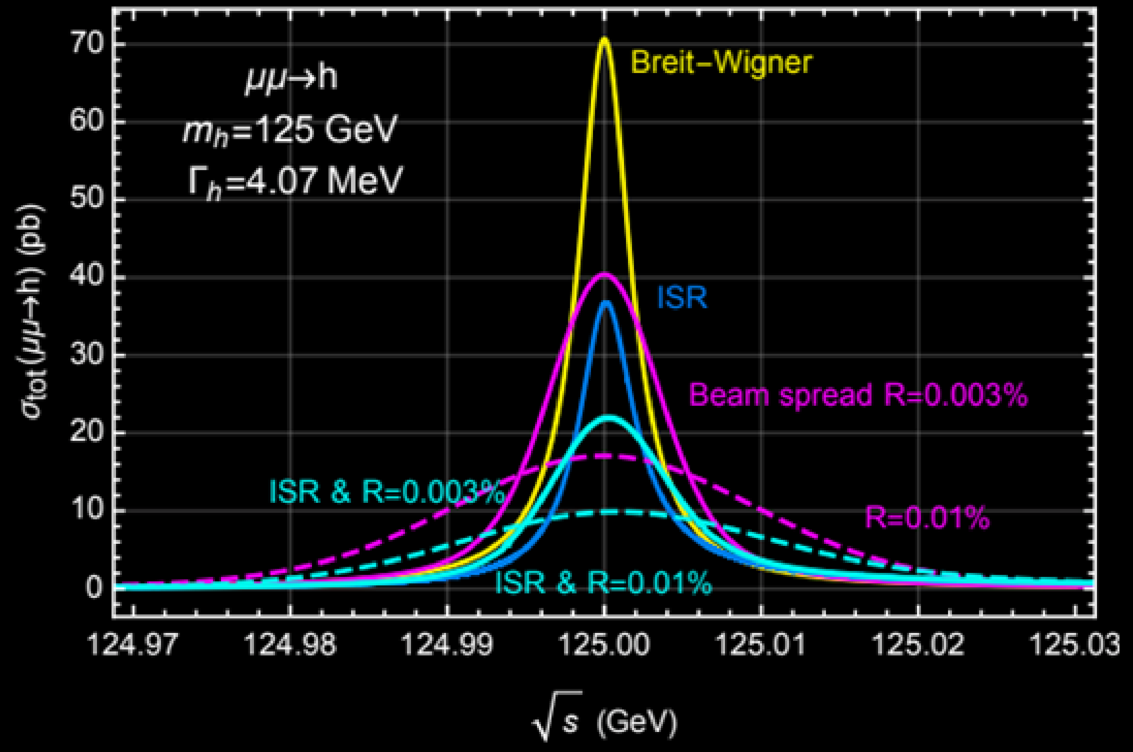
Hitting the resonance & scan

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

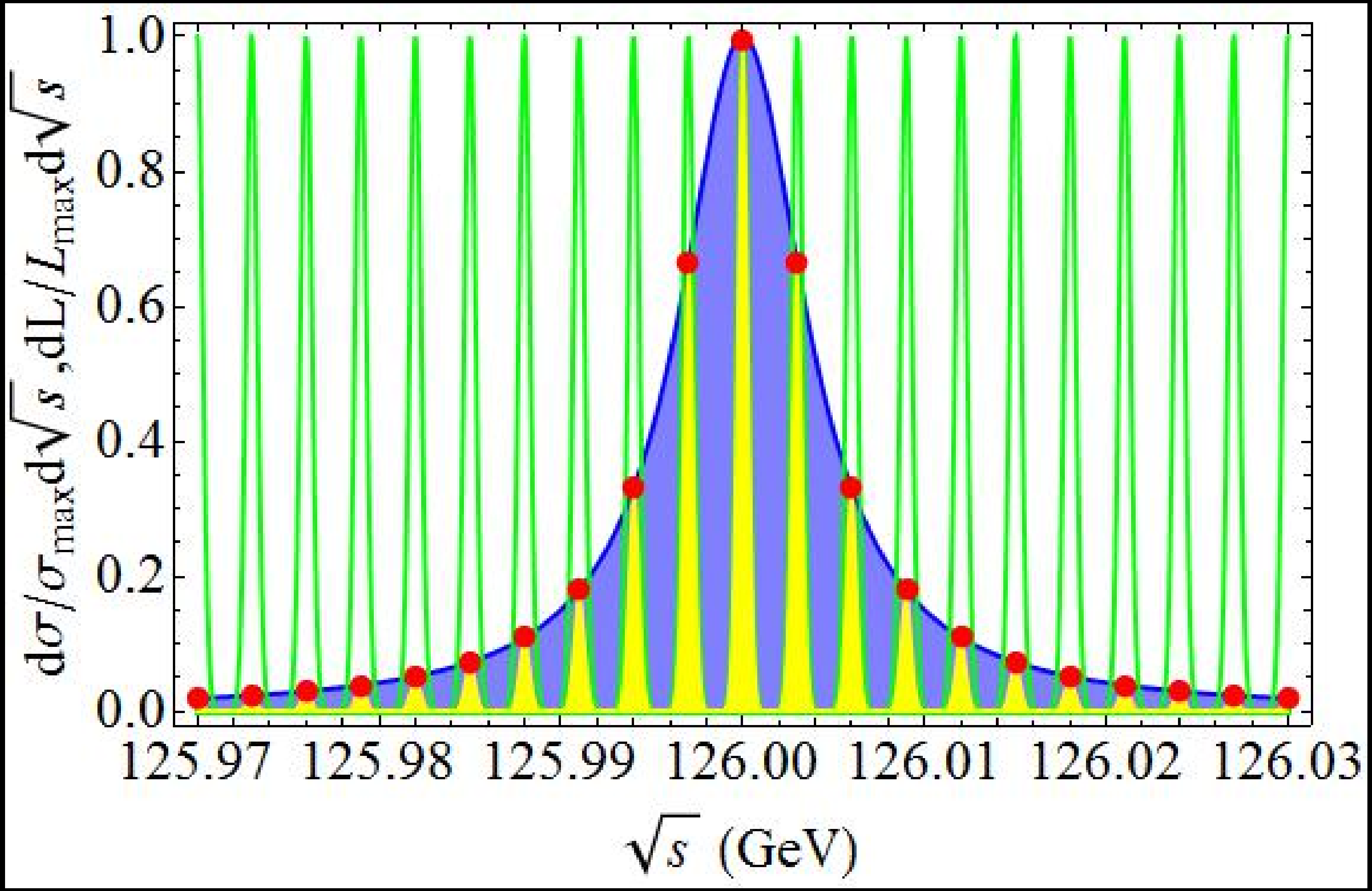
$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$





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

Extreme (good) Case:



Energy Spread much narrower than the physical width:

Δ = 0.3 MeV

Γ_h = 4.2 MeV

Breit-Wigner

Gaussian Profile (beam)

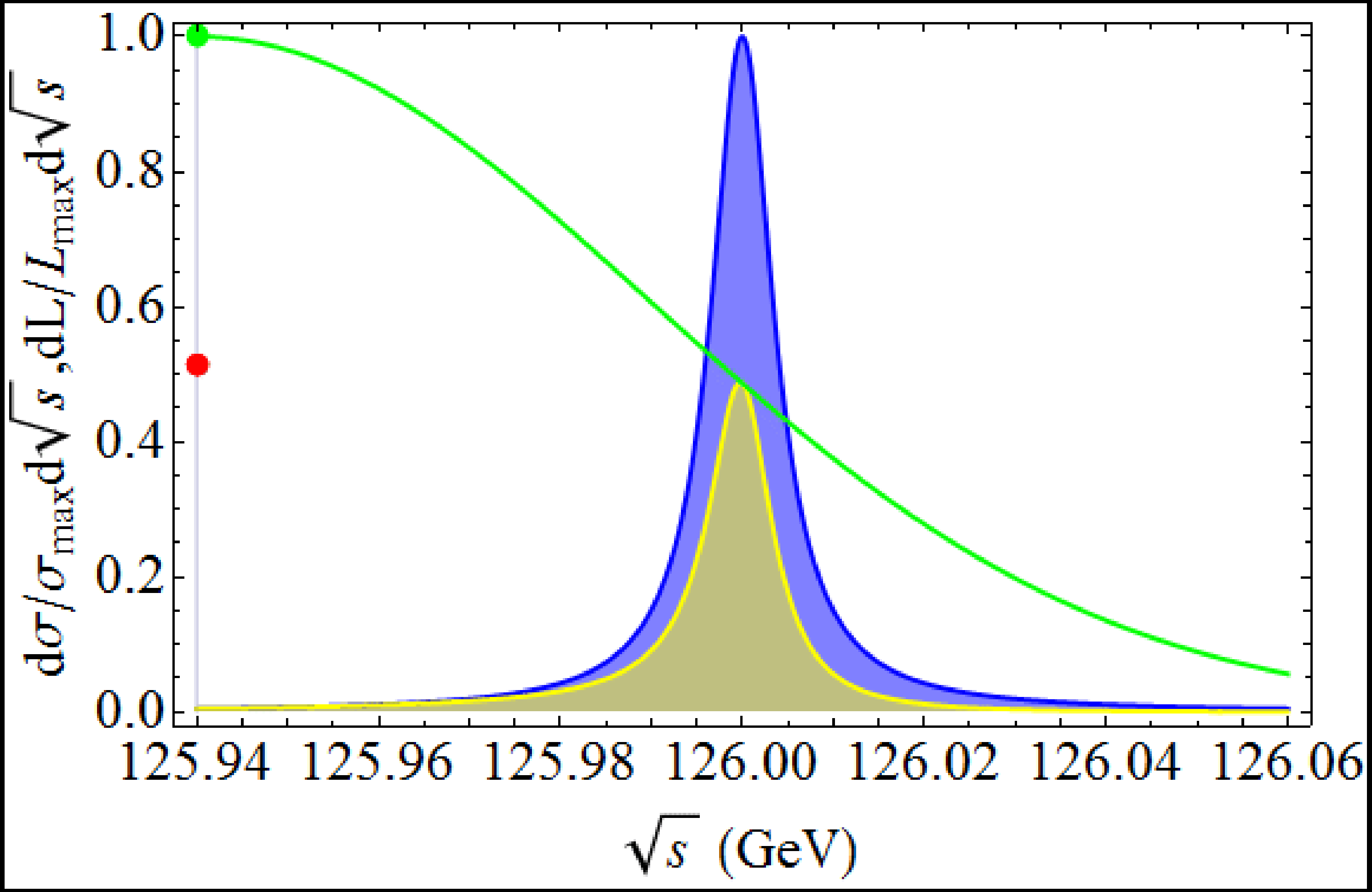
Overlap (observable rate)

Effective cross section (observable scan)

Recall: Z scan @LEP

Γ = 2.5 GeV

Extreme (bad) Case:



Energy Spread much broader than the physical width:

Δ = 50 MeV

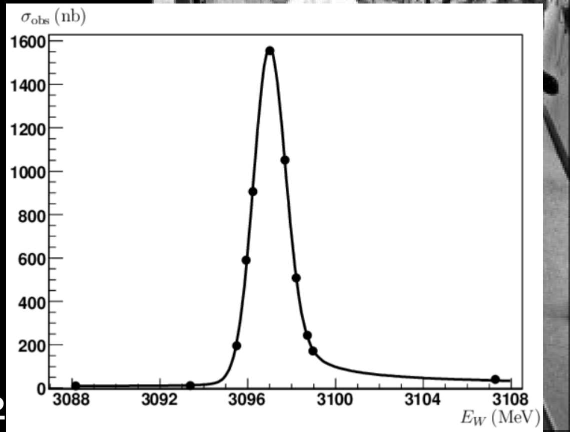
Γ_h = 4.2 MeV

Breit-Wigner

Gaussian Profile (beam)

Overlap (observable rate)

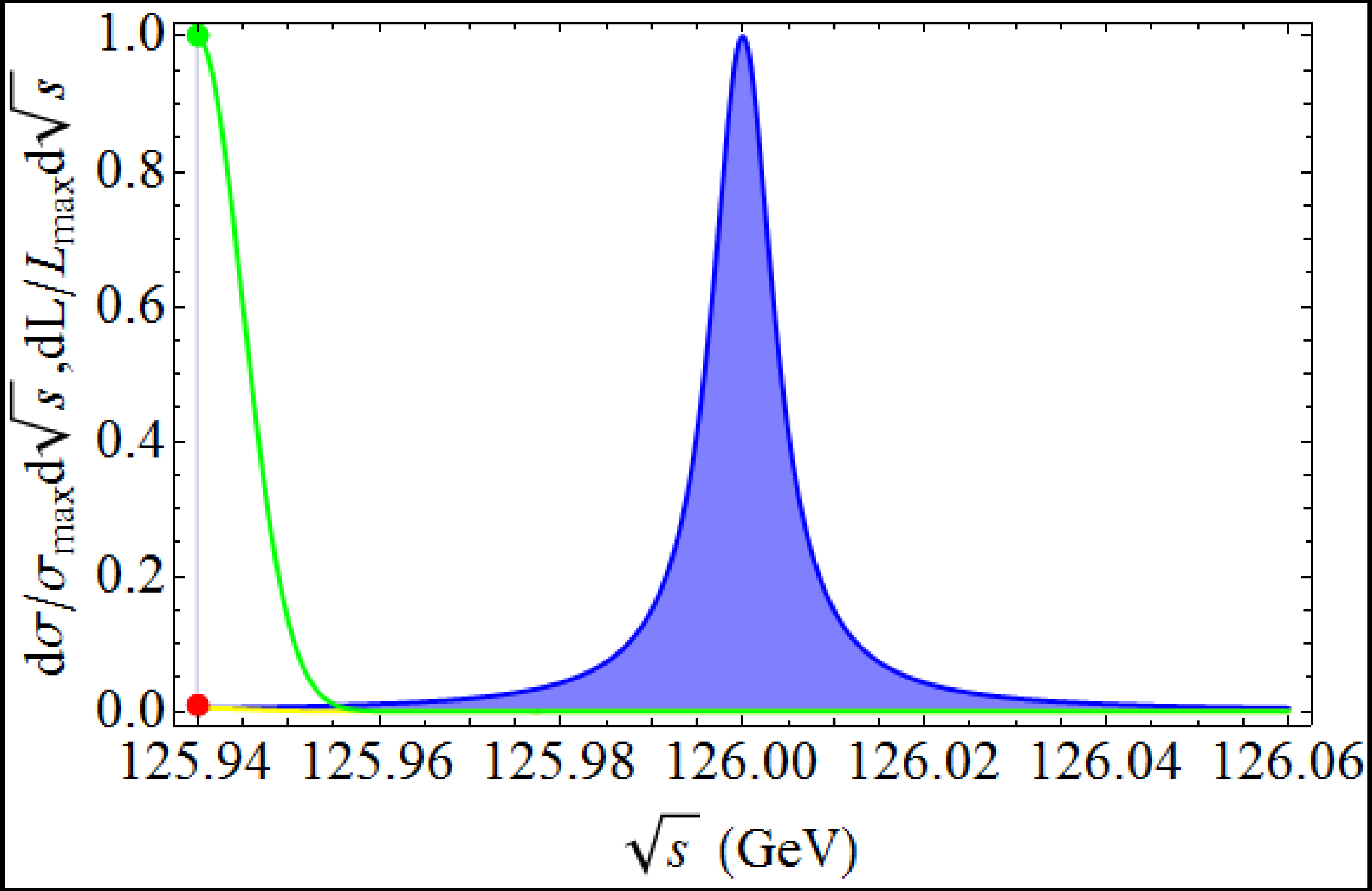
Effective cross section (observable scan)



Recall: J/ψ scan Γ ≈ 93 keV

Close to reality:

Han, ZL, 1210.7803;



Energy Spread comparable to the physical width:

Δ = 5 MeV

(R=0.003%)

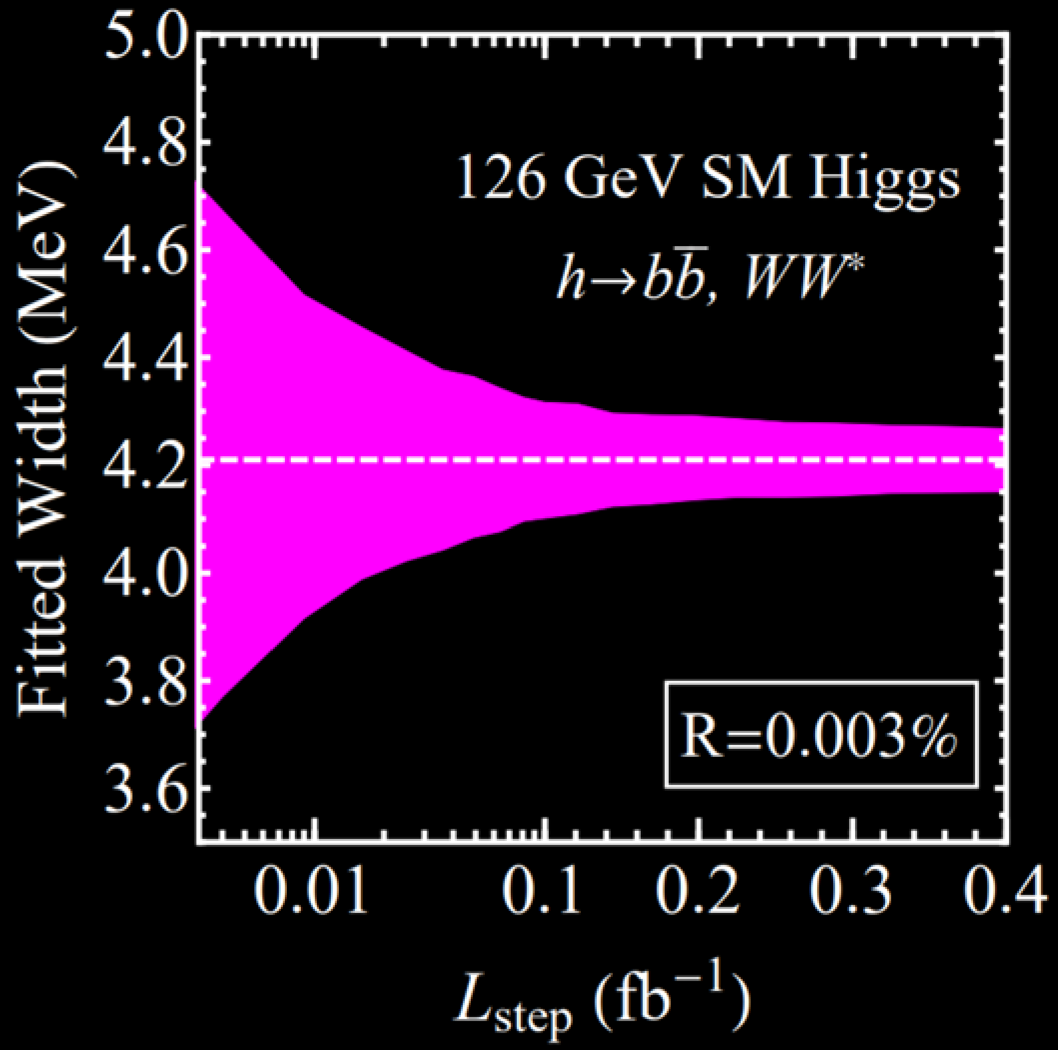
Γ_h = 4.2 MeV

Breit-Wigner
Gaussian Profile (beam)
Overlap (observable rate)
Effective cross section (observable scan)

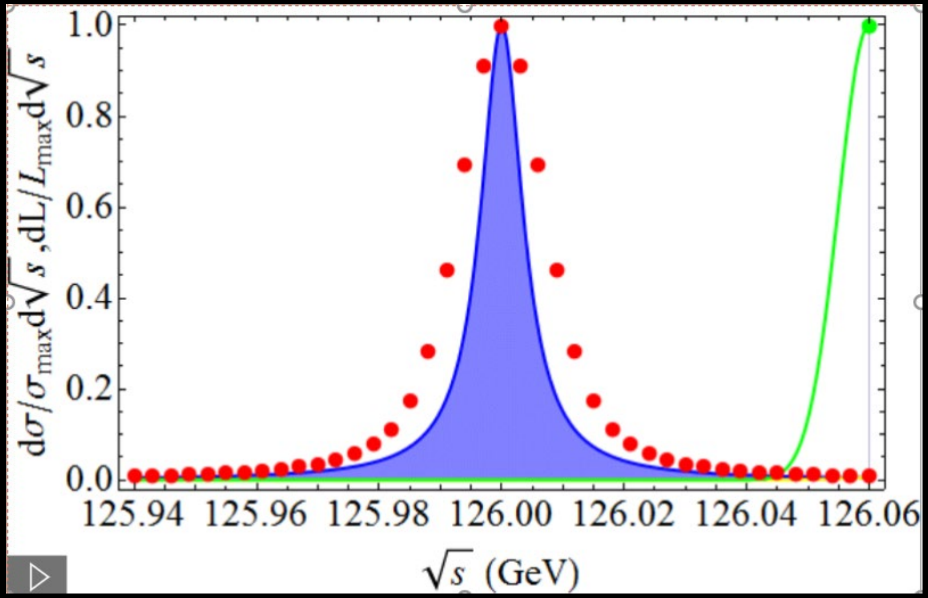
An optimal fitting would reveal Γ_h

Han, ZL, 1210.7803; also see Conway, Wenzel 1304.5270
With ISR effects: Greco, Han, ZL, 1607.03210

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



Outline

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- Higgs Width
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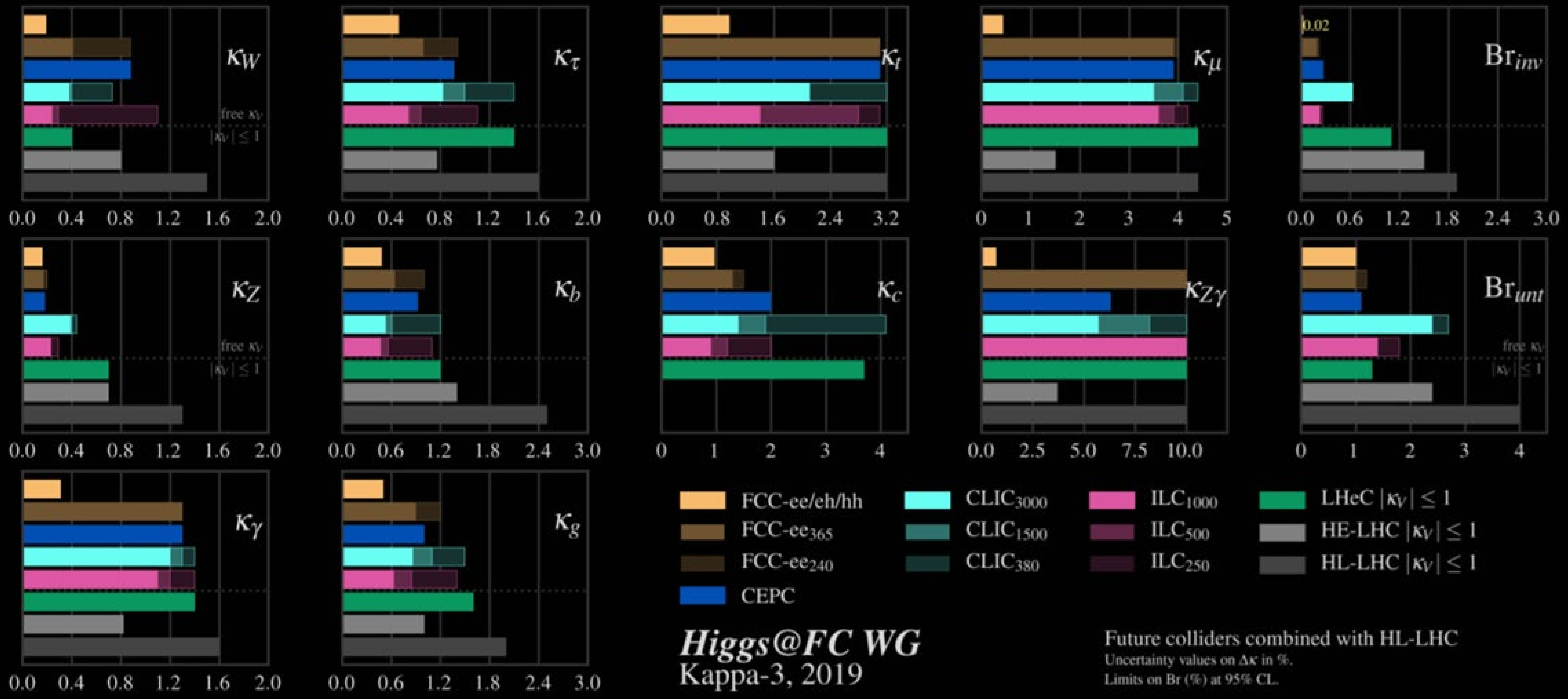
Where would MuC Higgs factory stand?



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

50 pb
3 ab^{-1}
0.15 billion Higgs

200 fb
5 ab^{-1}
1 million Higgs

20 pb
1 fb^{-1}
20 thousand Higgs

HOPE LESS ?

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	$\sigma(ZH) \times \mathrm{BR}$
$H \to bb$	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%
$H \to \mathrm{inv}$	0.28%

Signature numbers

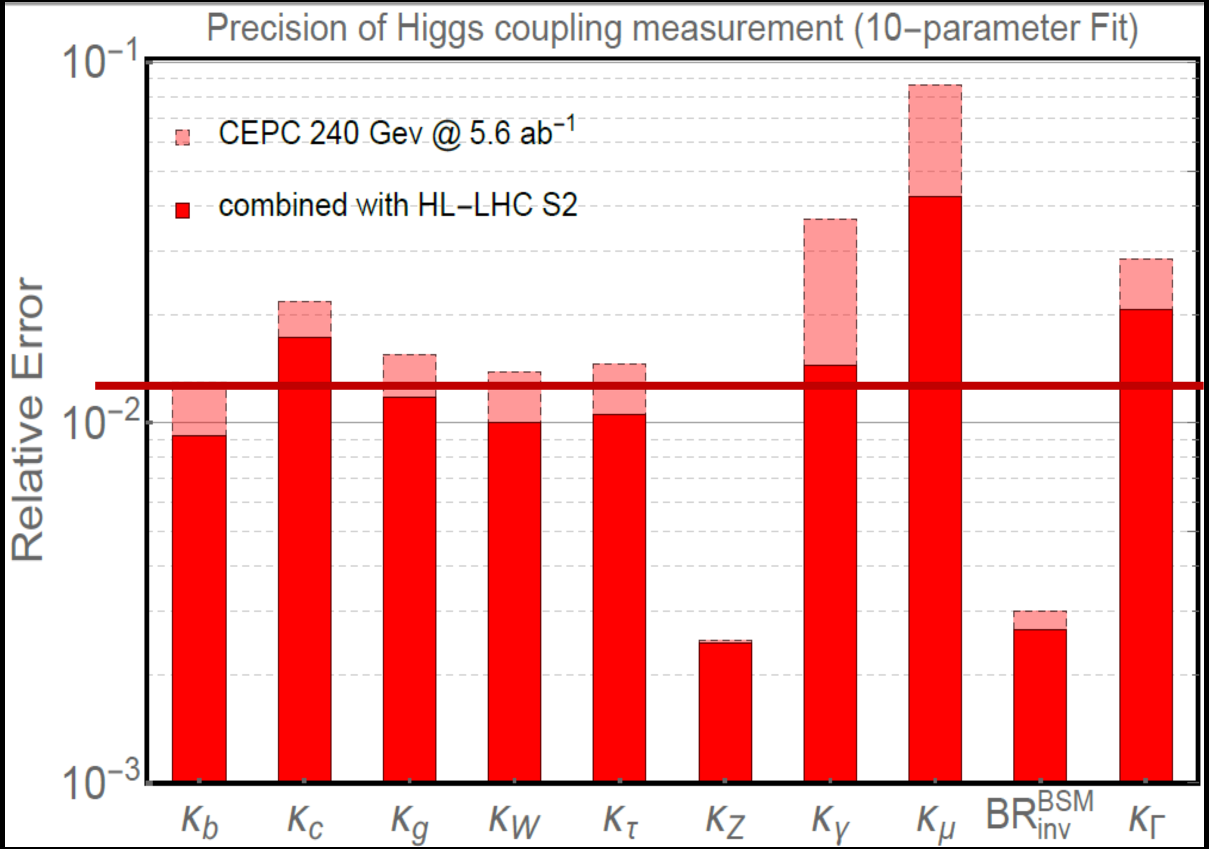
- κ_Γ 2.8%
- κ_Z 0.25%
- κ_b 1.3%
- κ_τ 1.5%

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

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

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

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



Constrained κ fit

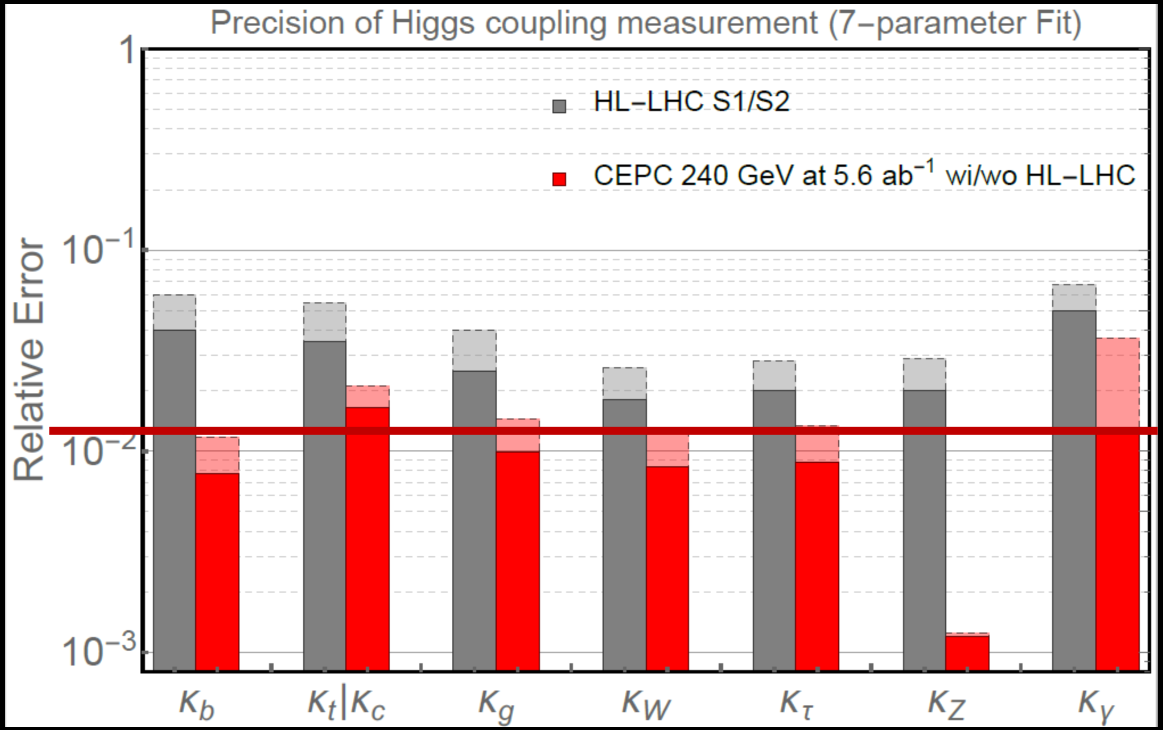
(No BR(undetectable)—Width not free)

New Insight: The total width (still!) sets a floor for the individual coupling extraction.

- Can be compared with the HL-LHC
- Large improvement (~one order of magnitude)
- Result improved from additional constraints
- Signature numbers
    - κ_Γ 2.8%→(2.4%)*
    - κ_Z 0.25%→0.13%
    - κ_b 1.3%→1.2%

*not a free parameter; but useful intermediate quantity

*Significant "improvement" for the κ_Z from the additional constraints (fit assumption are critical in comparing results, always be careful)



Now the Model-Independent MuC Width matters!

Let's check precision with 1/50 statistics (with different bkg)

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

CEPC per channel precision

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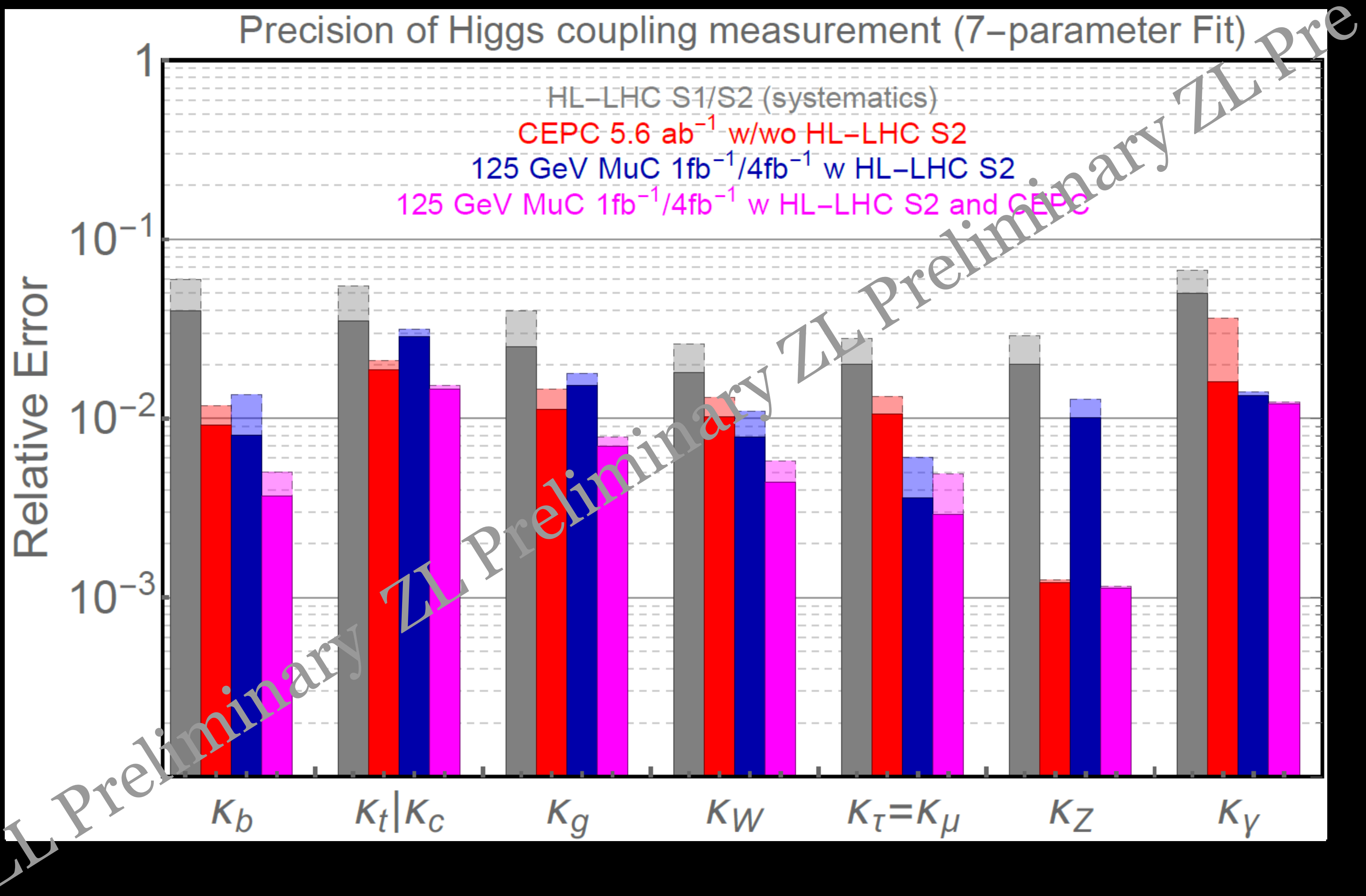
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to \mathrm{inv}$	0.28%

	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%

Good results with 1/50 (1/12) Higgs statistics!

- 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)



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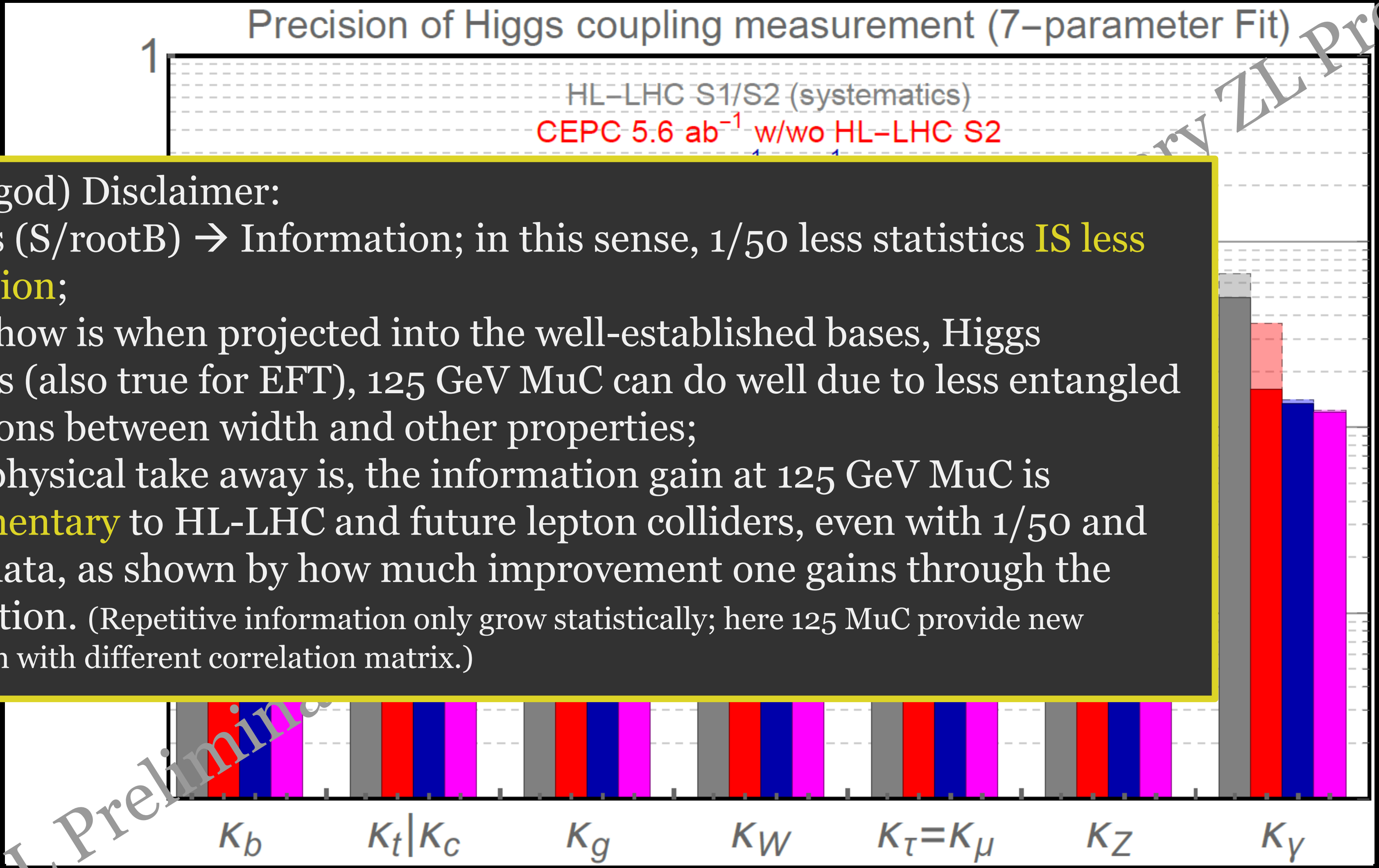

(Honest to god) Disclaimer:

- Statistics (S/rootB) → Information; in this sense, 1/50 less statistics IS less information;
- What I show is when projected into the well-established bases, Higgs couplings (also true for EFT), 125 GeV MuC can do well due to less entangled correlations between width and other properties;
- A more physical take away is, the information gain at 125 GeV MuC is complementary to HL-LHC and future lepton colliders, even with 1/50 and 1/7500 data, as shown by how much improvement one gains through the combination. (Repetitive information only grow statistically; here 125 MuC provide new information with different correlation matrix.)

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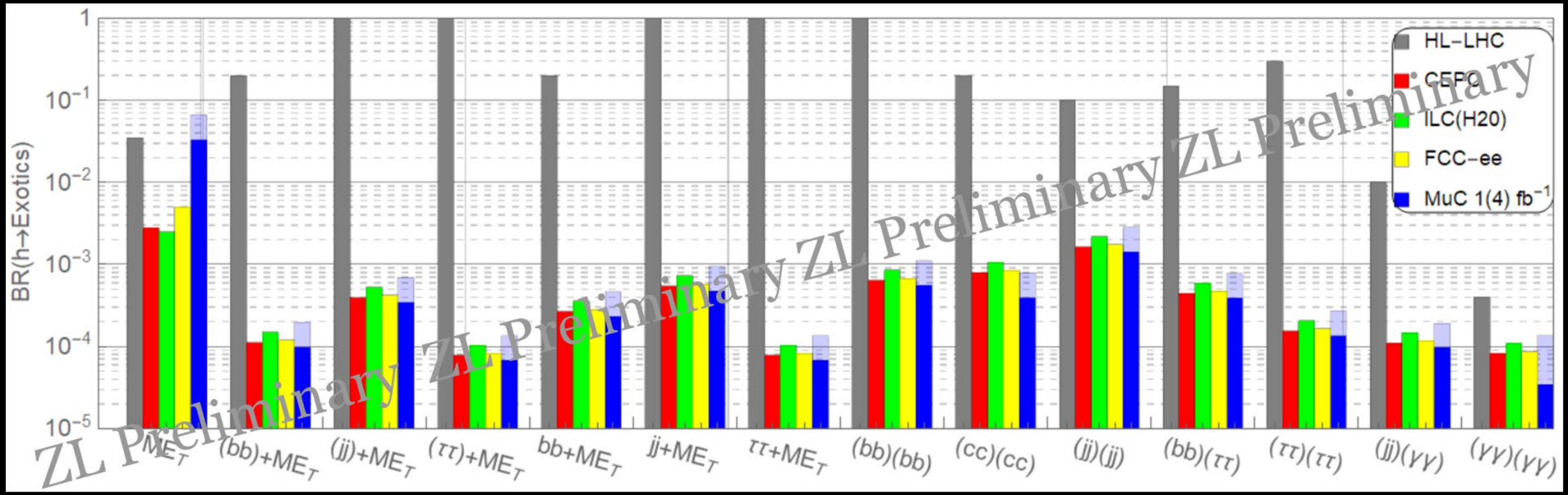
- Higgs Exotic Decays



Why Exotic Decays?

- While most current searches focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.

(checking all the possibility; theoretical interests.)

((H^+H) lowest mass dimensional spinless gauge singlet structure, easily a portal to BSM)

- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

(complementarity)

From Raman Sundrum's talk this morning.

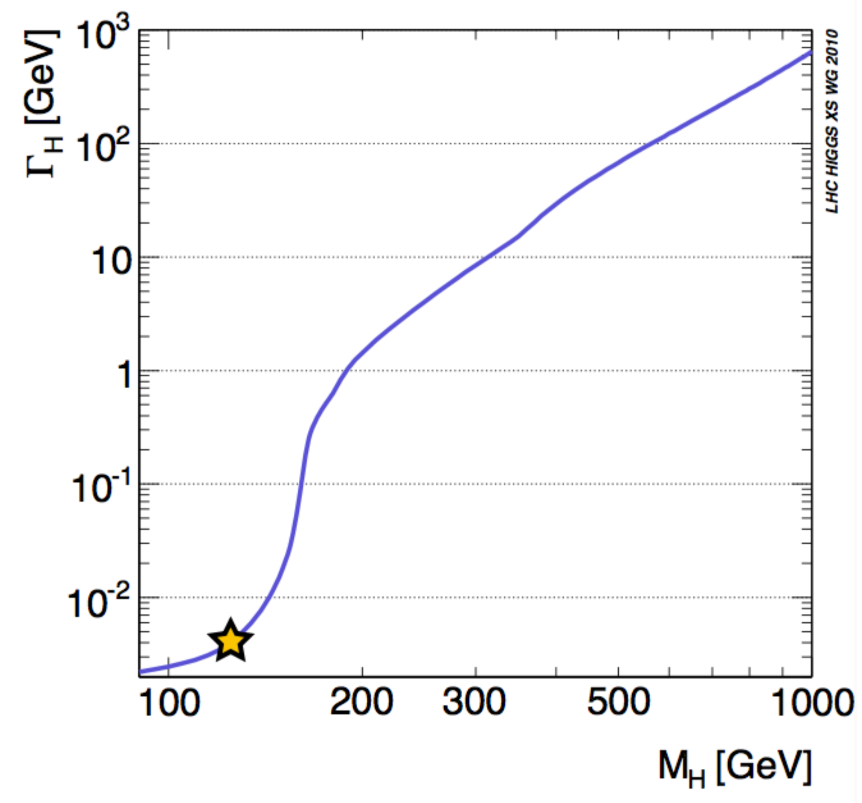
Why Exotic Decays? (continued)

- Higgs has tiny width ~4 MeV

$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.

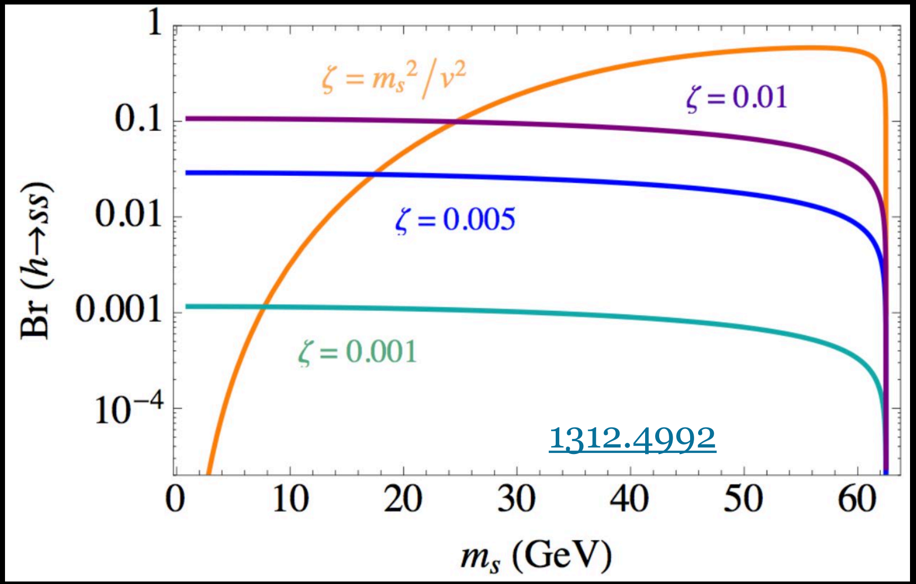
Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$



- small couplings to BSM could have sizable branching, e.g.,

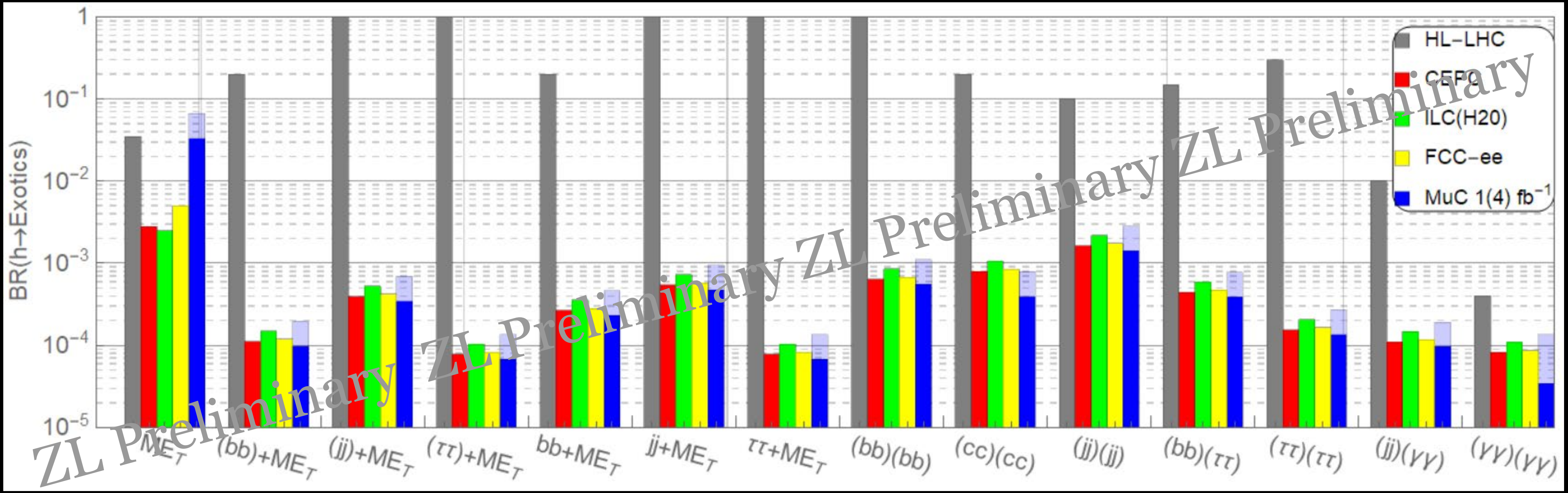
$$L = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs sectors) can give BR(h➞ss)~O(10%) for ζ *as small as* 0.01 !



Exotic Decay Overall Picture

Our study on CEPC/ILC/FCC-ee only used Z(->ll)H, there is 10x statistics yet 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 pre-preliminary results compiled by ZL.

Summary

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- Higgs Couplings
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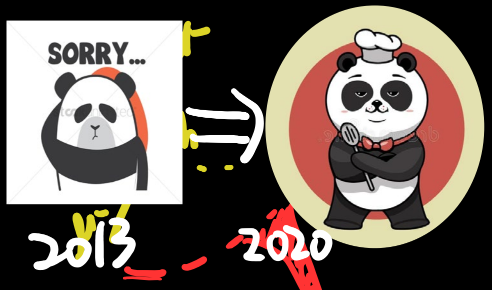
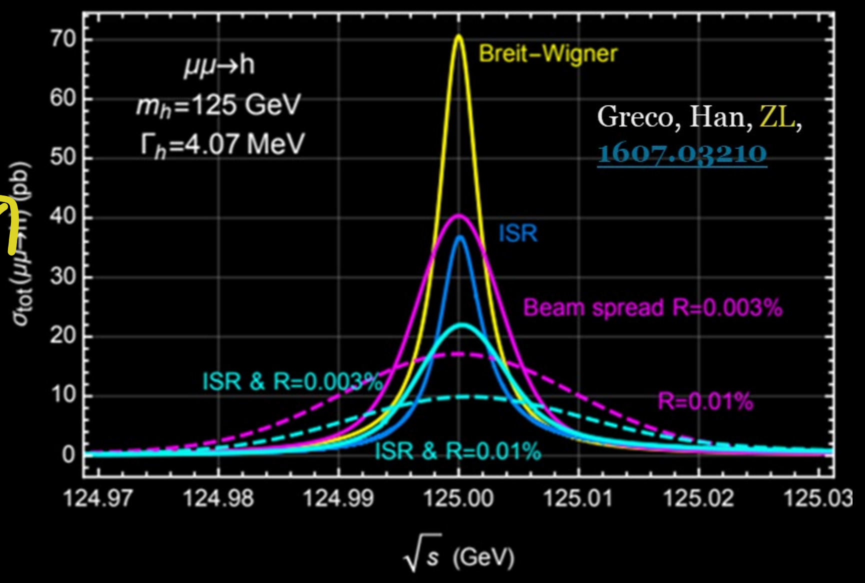
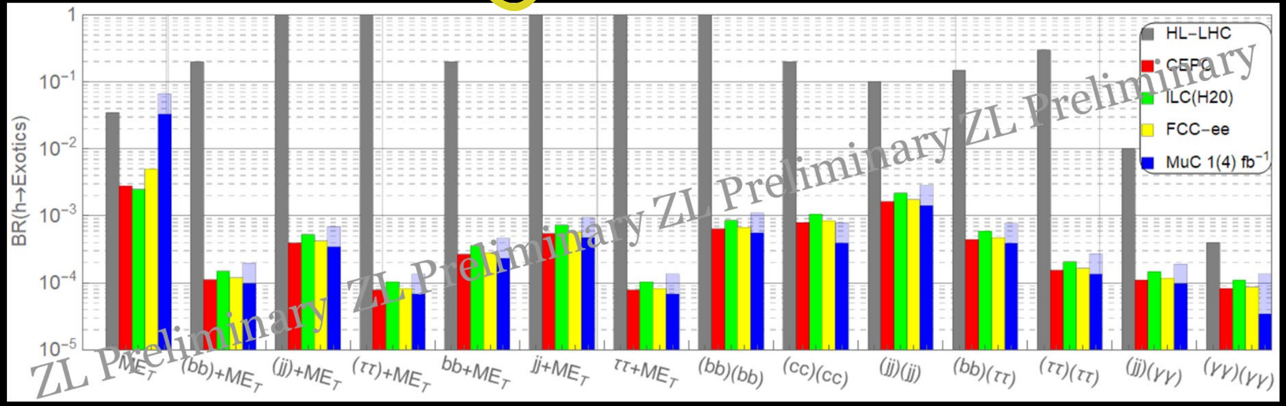


LEAST understood
Focus of this talk

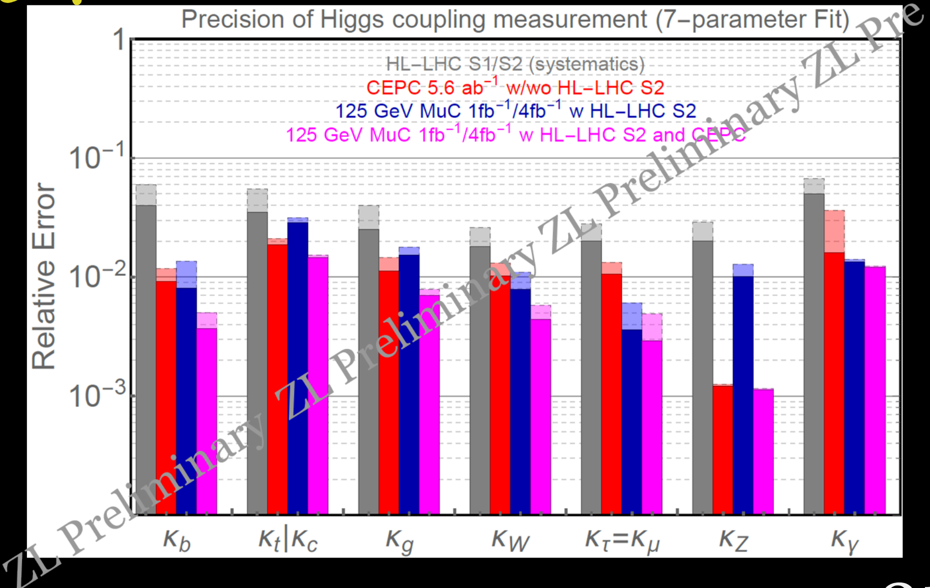
State-of-art



A First Estimation!

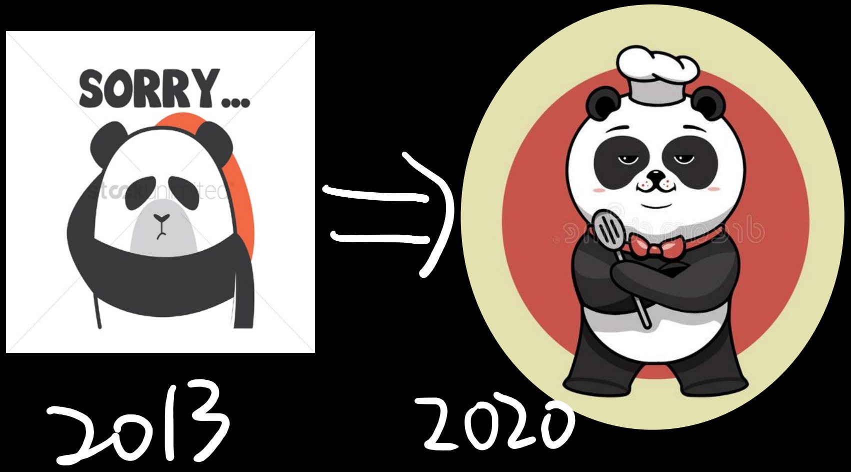


A FIRST Estimation



Summary: Outlook

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



Many more to do:

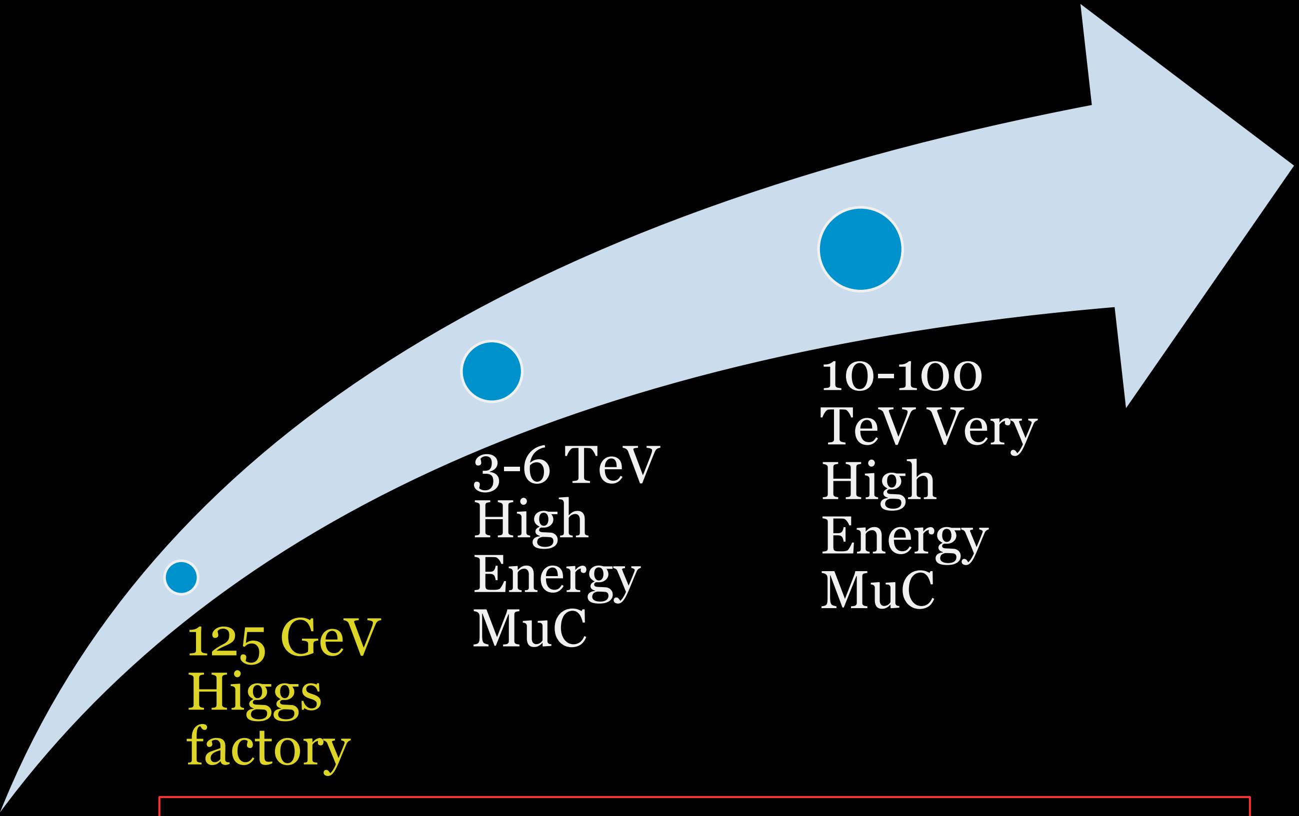
A Comprehensive Physics Case for 125 GeV MuC Higgs Factory is "structured"

(Do we need it?)

Some core tasks:

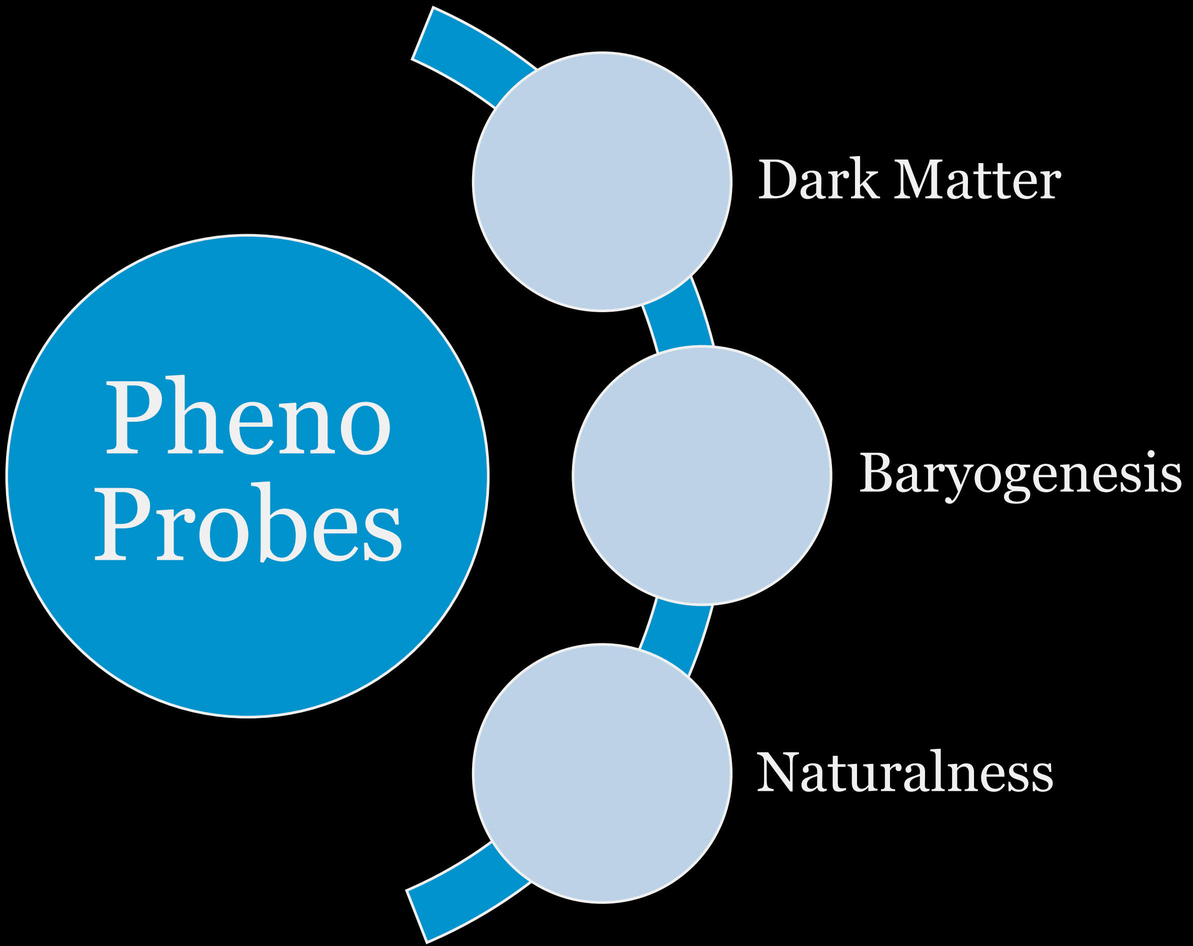
- (Semi-)optimal scanning strategy development (width v.s. BES, step size, and step luminosity);
- Fast detector simulation for major Higgs channels for Higgs precision;
- Fast simulation for exotic decays;

The Dream Machine



This new set of analysis shows its unique physics cases with 10^2 less Higgs bosons. A physics-wise motivated step towards high energy MuC.

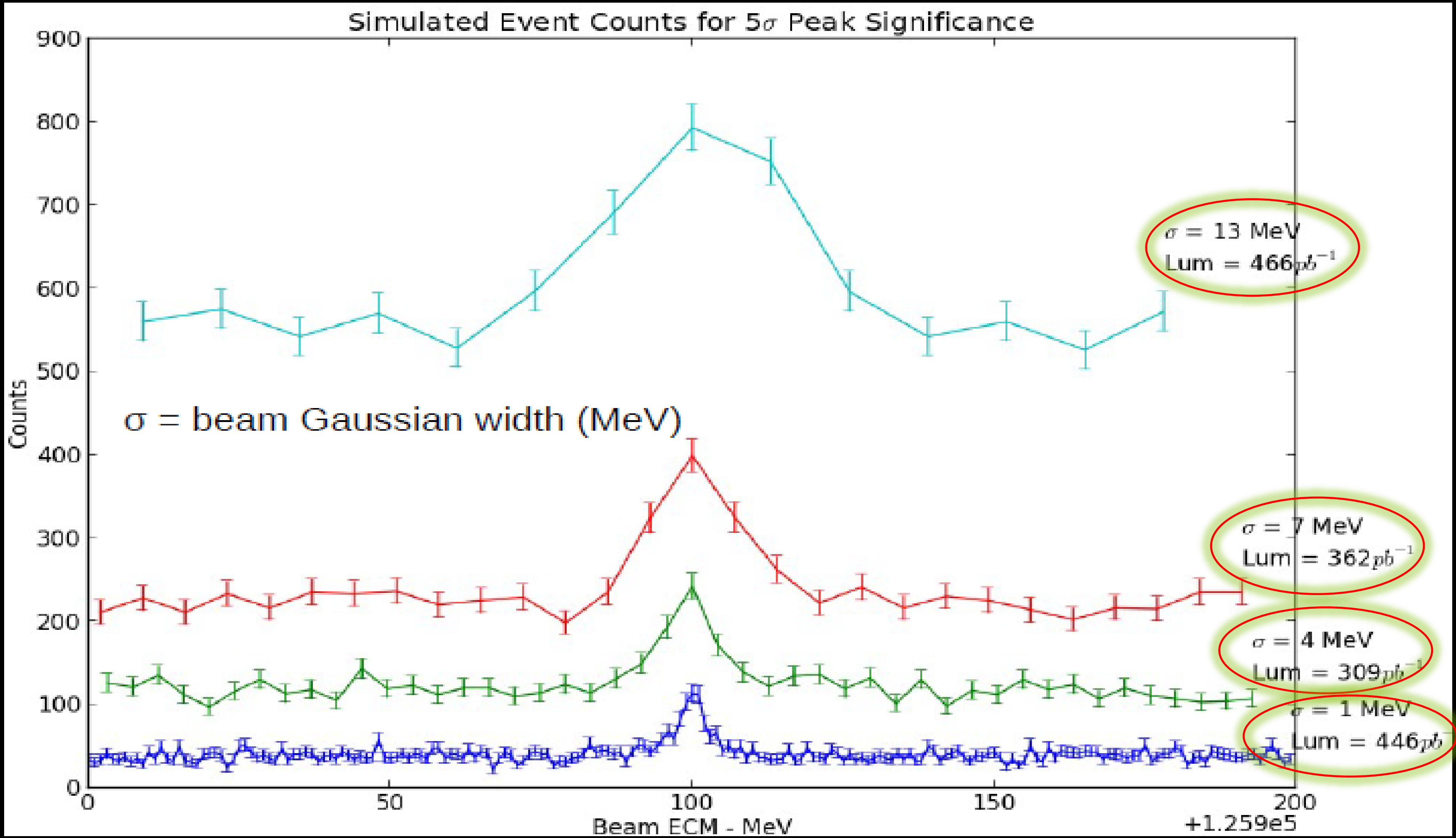
Physics Driver



Thank you!

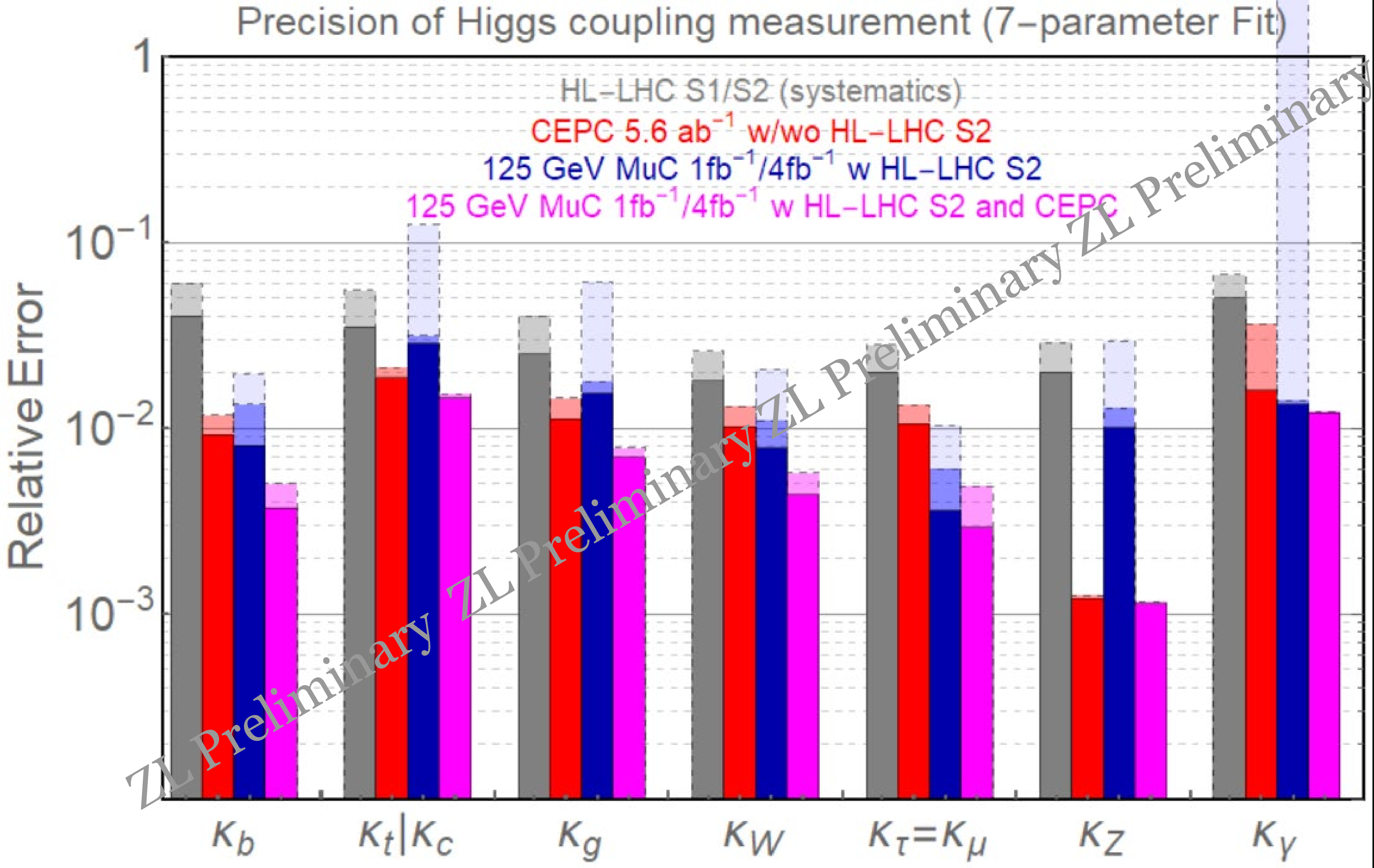
Backup

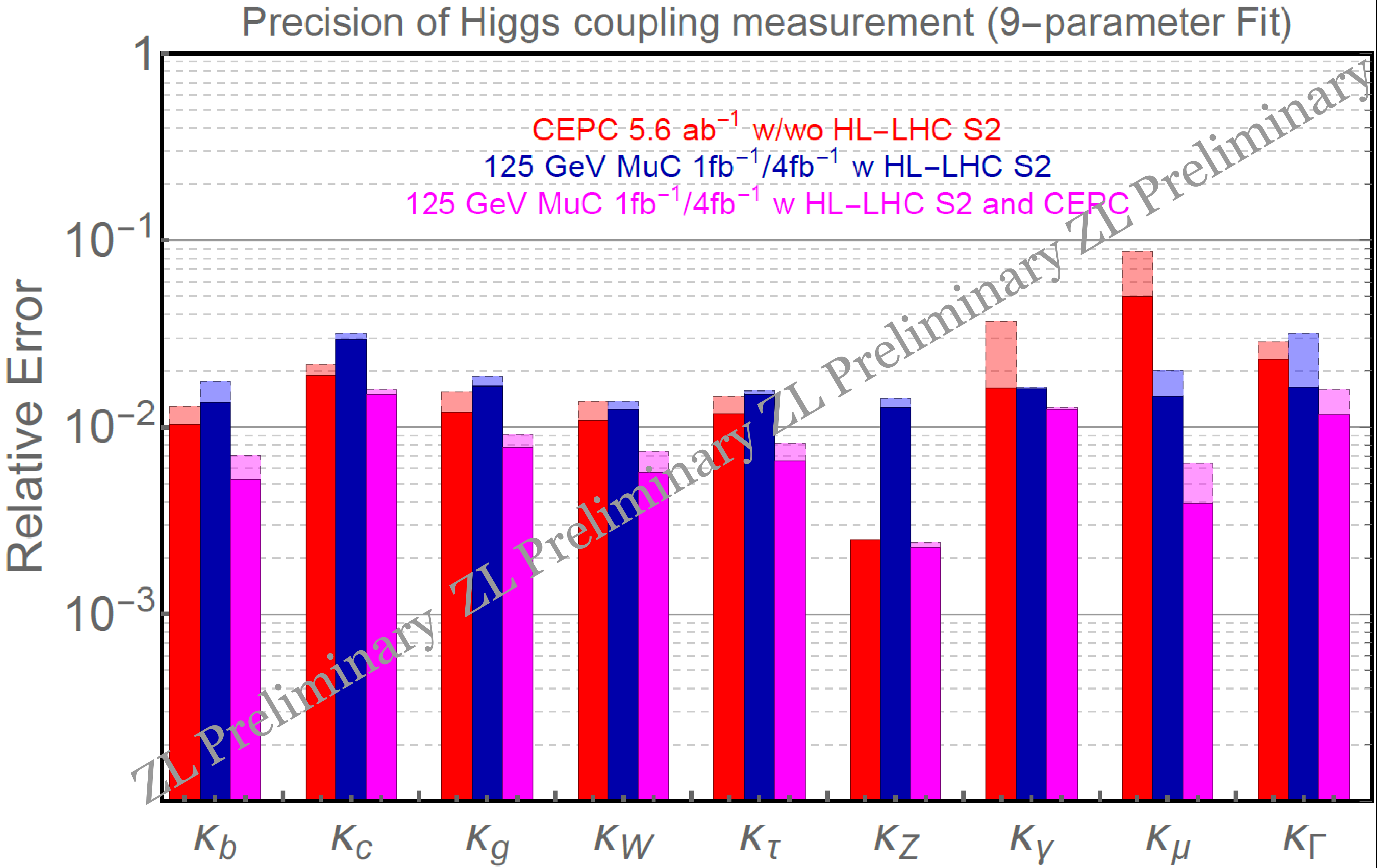
Pinning down the mass of the Higgs



arxiv:1304.5270

	Br	Rate (pb)	Used Sig Rate	Bkg Rate	Composed Bkg Rate	Precision
Inclusive	100%	22				---
bbar	57.80%	12.72	10.30	18.71	21.24	1.72%
tautau	6.37%	1.40	0.59	9.50	10.45	17.75%
mumu	0.02%	0.00	0.00	9.50	9.50	2005.62%
ss	0.04%	0.01	0.01	18.71	56.13	2447.71%
cc	2.68%	0.59	0.59	19.66	21.53	25.23%
gg	8.56%	1.88	1.88	0.00	56.13	12.79%
$\gamma\gamma$	0.23%	0.05	0.05	35.78	35.78	374.09%
WW*	21.60%	4.75	3.85	0.05	0.05	1.62%
ZZ*	2.67%	0.59	0.54	0.05	0.05	4.49%
invisible	0.01%	0.00				---


Precision of Higgs coupling measurement (7-parameter Fit)
HL-LHC S1/S2 (systematics)
CEPC 5.6 ab^{-1} w/wo HL-LHC S2
125 GeV MuC 1fb^{-1}/4fb^{-1} w HL-LHC S2
125 GeV MuC 1fb^{-1}/4fb^{-1} w HL-LHC S2 and CEPC
Relative Error
1
10^{-1}
10^{-2}
10^{-3}
κ_b
$\kappa_t|\kappa_c$
κ_g
κ_W
$\kappa_\tau=\kappa_\mu$
κ_Z
κ_γ
ZL Preliminary ZL Preliminary ZL Preliminary ZL Preliminary ZL Preliminary



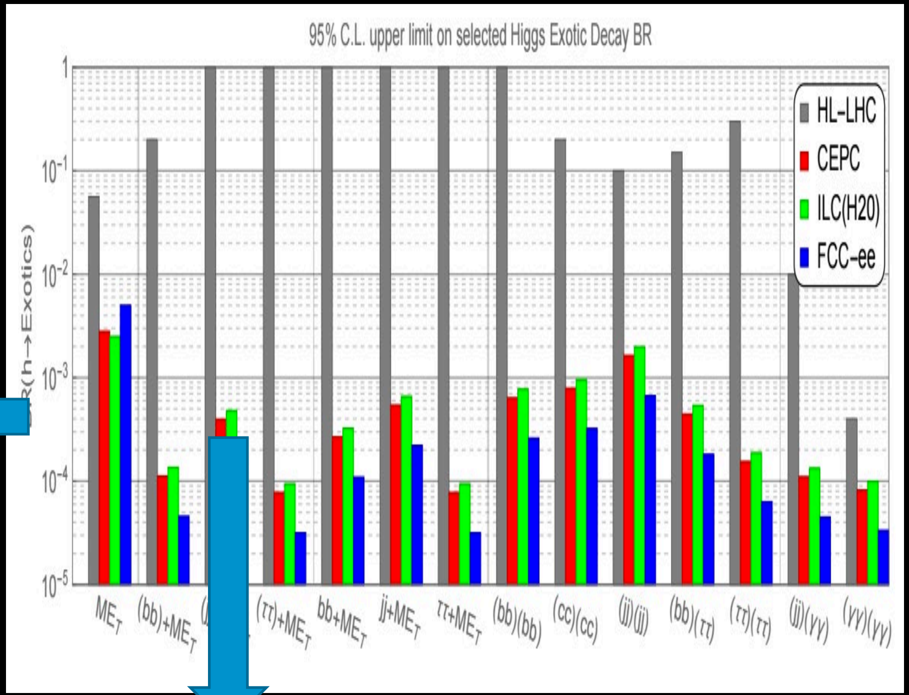
Precision of Higgs coupling measurement (9−parameter Fit)
CEPC 5.6 ab^{-1} w/wo HL−LHC S2
125 GeV MuC 1fb^{-1}/4fb^{-1} w HL−LHC S2
125 GeV MuC 1fb^{-1}/4fb^{-1} w HL−LHC S2 and CEPC
Relative Error
1
10^{-1}
10^{-2}
10^{-3}
κ_b
κ_c
κ_g
κ_W
κ_τ
κ_Z
κ_γ
κ_μ
κ_Γ
ZL Preliminary ZL Preliminary ZL Preliminary ZL Preliminary

κ_γ	1.00	0.66	0.57	0.29	0.18	0.65	0.66	0.27
κ_W	0.66	1.00	0.58	0.39	0.25	0.74	0.59	0.27
κ_Z	0.57	0.58	1.00	0.24	0.24	0.56	0.50	0.23
κ_g	0.29	0.39	0.24	1.00	0.34	0.67	0.43	0.09
κ_t	0.18	0.25	0.24	0.34	1.00	0.38	0.26	0.09
κ_b	0.65	0.74	0.56	0.67	0.38	1.00	0.70	0.26
κ_τ	0.66	0.59	0.50	0.43	0.26	0.70	1.00	0.25
κ_μ	0.27	0.27	0.23	0.09	0.09	0.26	0.25	1.00
	κ_γ	κ_W	κ_Z	κ_g	κ_t	κ_b	κ_τ	κ_μ

L = 3000 fb-1		Expected uncertainty [%]				
POI	Scenario	Total	Stat	SigTh	BkgTh	Expt
κ_γ	S1	2.9	1.1	1.8	1.0	1.7
	S2	2.0	1.1	0.9	0.8	1.2
κ_W	S1	2.6	1.0	1.7	1.1	1.1
	S2	1.8	1.0	0.9	0.8	0.8
κ_Z	S1	2.4	1.0	1.7	0.9	0.9
	S2	1.7	1.0	0.9	0.7	0.7
κ_g	S1	4.0	1.1	3.4	1.3	1.2
	S2	2.5	1.1	1.7	1.1	1.0
κ_t	S1	5.5	1.0	4.4	2.7	1.6
	S2	3.5	1.0	2.2	2.1	1.2
κ_b	S1	6.0	2.0	4.3	2.9	2.3
	S2	4.0	2.0	2.0	2.2	1.8
κ_τ	S1	2.8	1.2	1.8	1.1	1.4
	S2	2.0	1.2	1.0	0.9	1.0
κ_μ	S1	6.7	4.7	2.5	1.0	3.9
	S2	5.0	4.7	1.3	0.8	1.1

Exotic Decay Outlook

- Higgs Exotic decays is a very important component of Higgs program at future colliders
- Lepton colliders show great advantage for decays that are very challenging at the LHC, such as Higgs decays into jets and Higgs decays with missing energy
- Hadron colliders and lepton colliders are complementary* in probing Higgs exotic decays and could together provide a much more coherent picture for discovery
- Many more interesting work for Higgs exotic decays at both the LHC and future colliders are needed**:
    - More channels (potential statistical improvement)
    - Light masses
    - Semi-visible
    - Higgs into dark showers
    - Weird signatures (LLPs, Quirks, etc.)



Statistical limit

* LC usually have 1 Million clean Higgs boson produced, HL-LHC has 0.2 Billion.
Also complementary to the Z-pole runs of Lepton colliders. For instance, heavy neutral leptons (HNLs) are better probed at Tera-Z factories. Flavor non-Universal theories induced Higgs exotic decays, e.g., Chiu, ZL, Wang, 1909.04549
**See many of the Snowmass Energy Frontier LOIs