Experimental Physics Division (EPD) Seminar
Institute of High Energy Physics

A SELECTED REVIEW ON HIGGS COUPLINGS

Zhen Liu （刘真）

PITTsburgh Particle physics, Astrophysics and Cosmology Center (PITT-PACC), University of Pittsburgh

Fermi National Accelerator Laboratory

Higgs Discovery implies:

New Force(s)! Exciting!

New opportunities.

First time, a (maybe fundamental) scalar!

COUPLINGS

- Gauge coupling
- Yukawa coupling—new forces
- Self coupling—new force

Derived couplings

$$H\gamma\gamma, Hgg, HZ\gamma, \ldots$$

Measurements must be interpreted.

Observables at the LHC is the cross section, a convolution of PDF, hard scattering, parton shower, detector response …

(Similar for many observables at the CEPC)

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

For the hard scattering:

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

QUICK LOOK AT FITTING
--WITH PLAIN LANGUAGE

- A measurement itself provide a distribution function of the "true" underlying value of such measurement, e.g., for statistical dominated processes, it's a Poisson distribution → Gaussian distribution (with large numbers).
- Such a distribution can be interpreted as a (maybe convoluted) function of parameters, including theory input parameters, instrumental parameters, etc.

- For a set of measurements, define a likelihood function; provide the test input parameters, evaluate the set of parameters that maximizes the likelihood function.
- Then evaluate individual parameters error band by
- A) profiling other parameters by choosing their values freely such that for a given target parameter's value, the likelihood function is optimized;
- B) marginalizing other parameters by simply "integrating" them out.

κ-SCHEME

All SM Higgs couplings can be modified by factor κ(s).

e.g., SM Higgs mixes with a Singlet S

$$H \quad = \cos\theta \; h + sin\theta \; S$$

Basically all SM couplings reduced by a factor

$$\kappa = cos\theta$$

Theoretical motivation:

Hidden Valley, Higgs portal, singlet-assisted EWBG

κ-SCHEME

All SM Higgs couplings can be modified by factor κ(s).

e.g., 2HDM with Z_2

$$H \quad = \cos\alpha \; h_1 + sin\alpha \; h_2$$

Basically all SM couplings reduced by several factors (Type-II)

$$\kappa_{z,w}, \kappa_u, \kappa_d, \kappa_l$$

Determined by model parameters

$$tan\beta, \alpha, (\lambda s)$$

For MSSM, radiative corrections modifies the Yukawas differently, inducing more κs.

Measurements must be interpreted.

Observables at the LHC is the cross section, a convolution of PDF, hard scattering, parton shower, detector response …

(Similar for many observables at the CEPC)

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

For the hard scattering:

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

- If $\kappa_{tot} = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

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

So, I can "freely" scale all the couplings probed (indirectly) by experiment by a factor of f, as long as I scale the total width of the Higgs by a factor of f^4, the observed Higgs rates do not change.

How can we learn more about Higgs couplings?

Can we really scale the Higgs couplings "freely"?

- Couplings scaled by f, corresponding partial width as a result is scaled by f^2. To make the observed cross sections not change, the total width need to be scaled by f^4

- But total width is the sum of all partial widths, this implies
- For $f > 1$,

The total width need to contain some partial width that is not probed by experiments, so as to increase the total width faster than probed partial widths.

e.g., increased production rate, decreased BR, leads to same rate.

- For $f < 1$,

The total width need to decease more than partial widths; but it at least contains all the partial widths probed. So there exists a "model-

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

So, I can "freely" scale all the couplings probed (indirectly) by experiment by a factor of f, as long as I scale the total width of the Higgs by a factor of f^4, the observed Higgs rates do not change.

How can we learn more about Higgs couplings?

Can we really scale the Higgs couplings "freely"?

No.

- Changing the Higgs couplings arbitrarily could induce problems, non-pertubativity, unitarity violation, violates precision measurements.

Yes.

- It's like the other side of a coin, some effects above just implies BSM physics nearby. If the deviations are small, it could consistently point us to a feasible NP scale.
- Many theories does modify all the couplings, e.g. SUSY, composite Higgs, etc.

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

So, I can "freely" scale all the couplings probed (indirectly) by experiment by a factor of f, as long as I scale the total width of the Higgs by a factor of f^4, the observed Higgs rates do not change.

How can we learn more about Higgs couplings?

Can we really scale the Higgs couplings "freely"?

Assuming yes (conventionally people call this "model-independent")

Pros:
"minimum bias", "little caveats", interpretation almost independent of BSM physics scenarios.

Cons:
Difficult and large uncertainty since scale factor f could be arbitrary. Need to think hard to pin it down.

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

So, I can "freely" scale all the couplings probed (indirectly) by experiment by a factor of f, as long as I scale the total width of the Higgs by a factor of f^4, the observed Higgs rates do not change.

Before moving on to scenarios at different colliders,

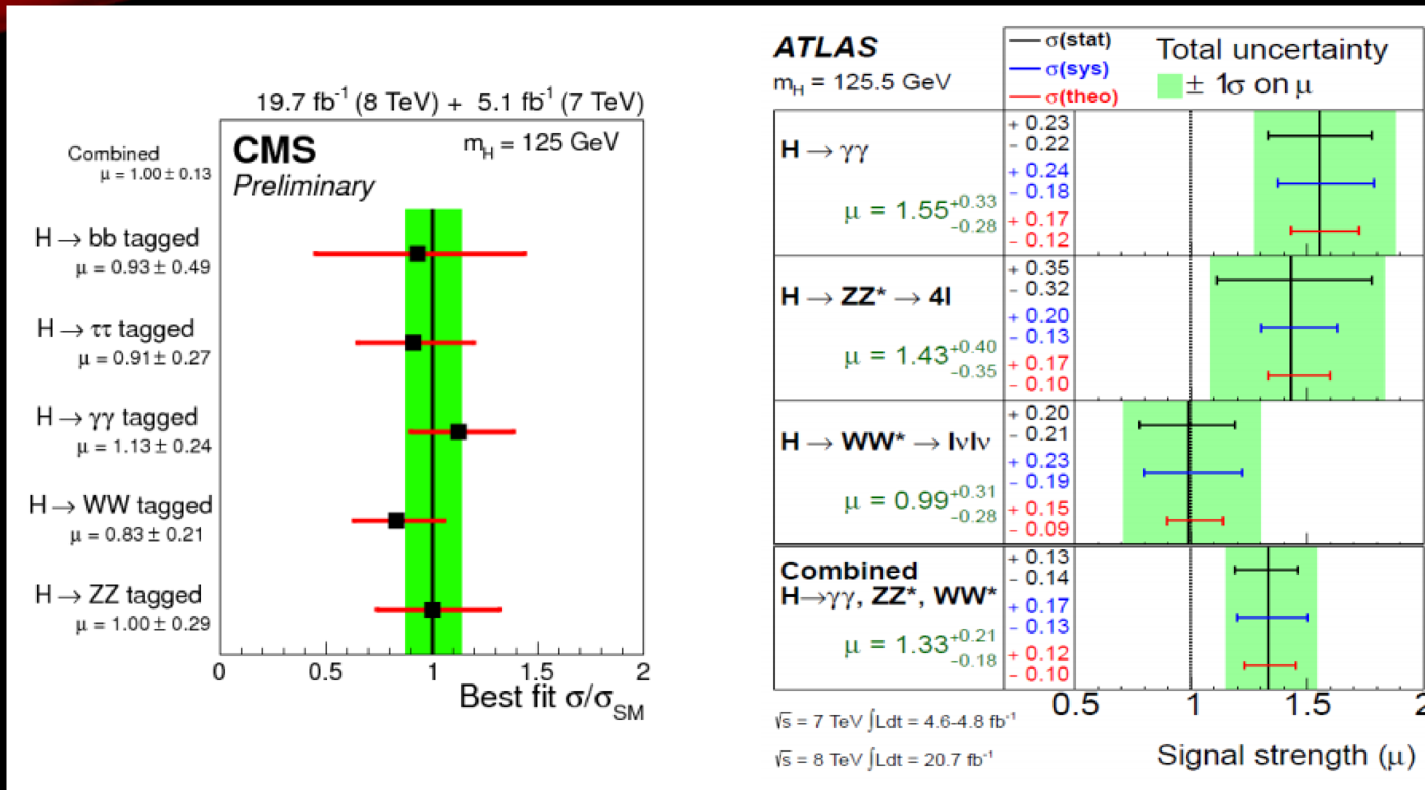
The real difficulty of this f-scaling "invariance" is that we cannot pin down the absolute values of any of the couplings, or the width.

Once we find a way to determine any of above κs, others absolute values can be determined subsequently.

For instance, if one can measure κ_Z, and $\sigma(Z \to H \to Z)$, $\kappa_{tot} \propto \frac{\kappa_Z^4}{\sigma(Z \to H \to Z)}$, and vice versa.

The width is often the quantity we are trying to pin down, because 1) this physical quantity has kinematical meaning; 2) a convenient quantity to derive others... (will explain later). We thus choose the total width as the symbolic quantity to determine. Following discussions of different colliders won't change much if we choose other κ.

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



Given this scaling-fact, really hard to extract the absolute values of the couplings (and width).

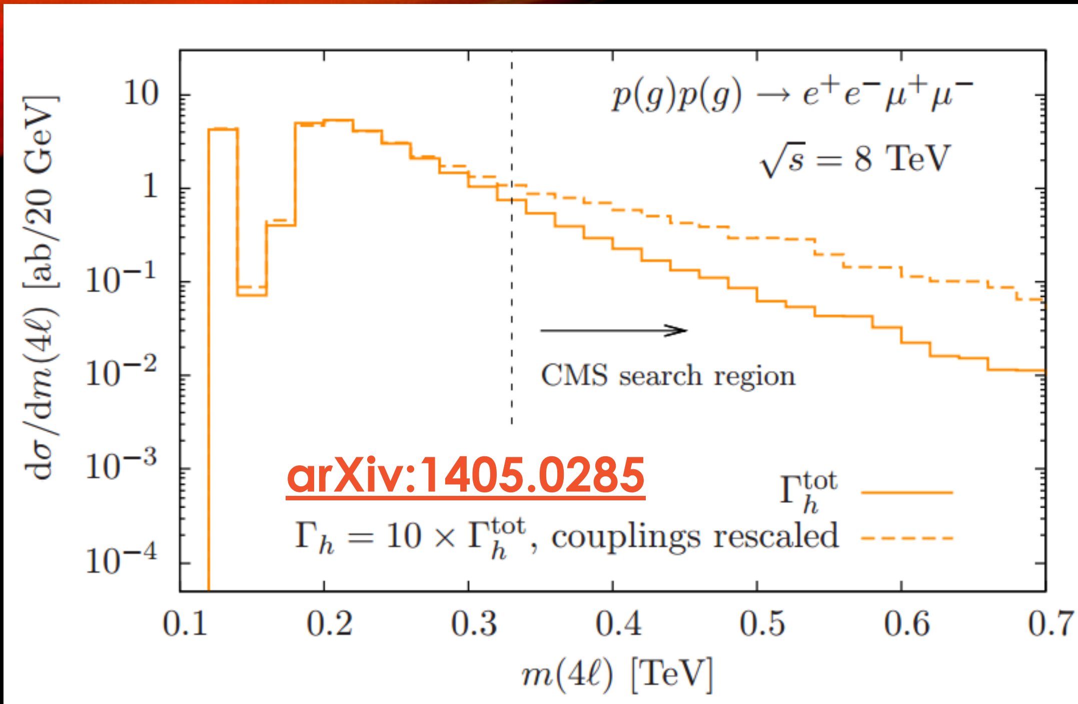
If we can measure one of the κ(s), all others will be simultaneously determined.

Higgs Width ~4.2 MeV

Extremely narrow to determine from the line-shape of the final states at colliders.

Before heading to the CEPC, we should try to see what we can learn from the LHC.

Total Width at the LHC (go off-shell!)

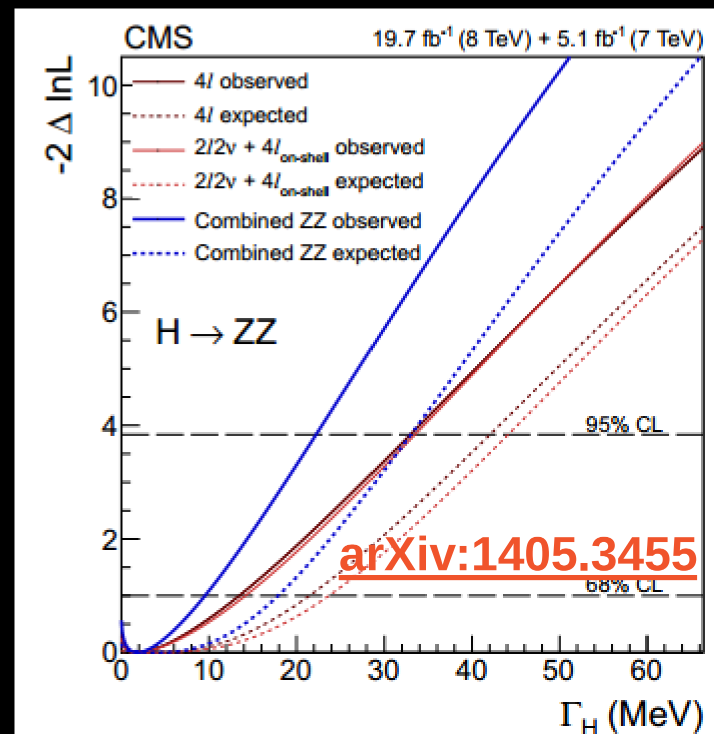


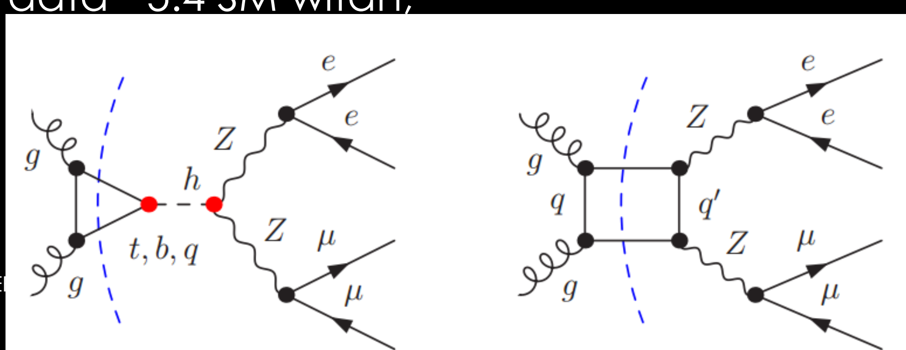
The cross sections:

On-shell: $\frac{g_{ggh}^2\, g_{hZZ}^2}{\Gamma_h}$

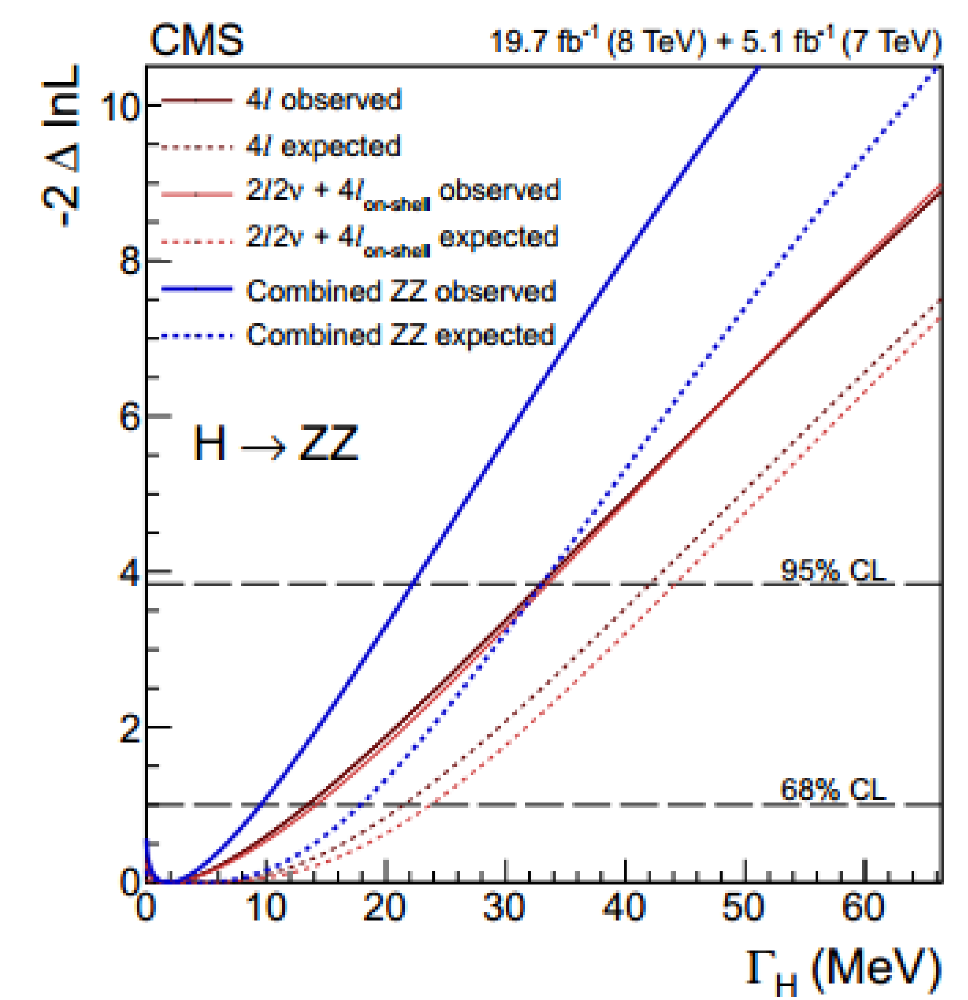
Off-shell: $g_{ggh}^2\, g_{hZZ}^2$

F. Caola and K. Melnikov **arXiv:1307.4935** And N. Kauer and G.Passarino **arXiv:1206.4803** estimated an "eventually" reach of ~10 SM width; CMS with current data ~5.4 SM witdh;





Total Width at the LHC



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Great measurement, but:

1) On-shell rate uncertainty
2) Loop-running⇔interplay of (at least) undetermined Top Yukawa
3) Many possible NP input at higher inv. masses.
4) Higher order corrections.

See discussions in e.g., arXiv:1405.0285, arXiv:1410.5440, arXiv:1412.7577, arXiv:1502.04678 , …

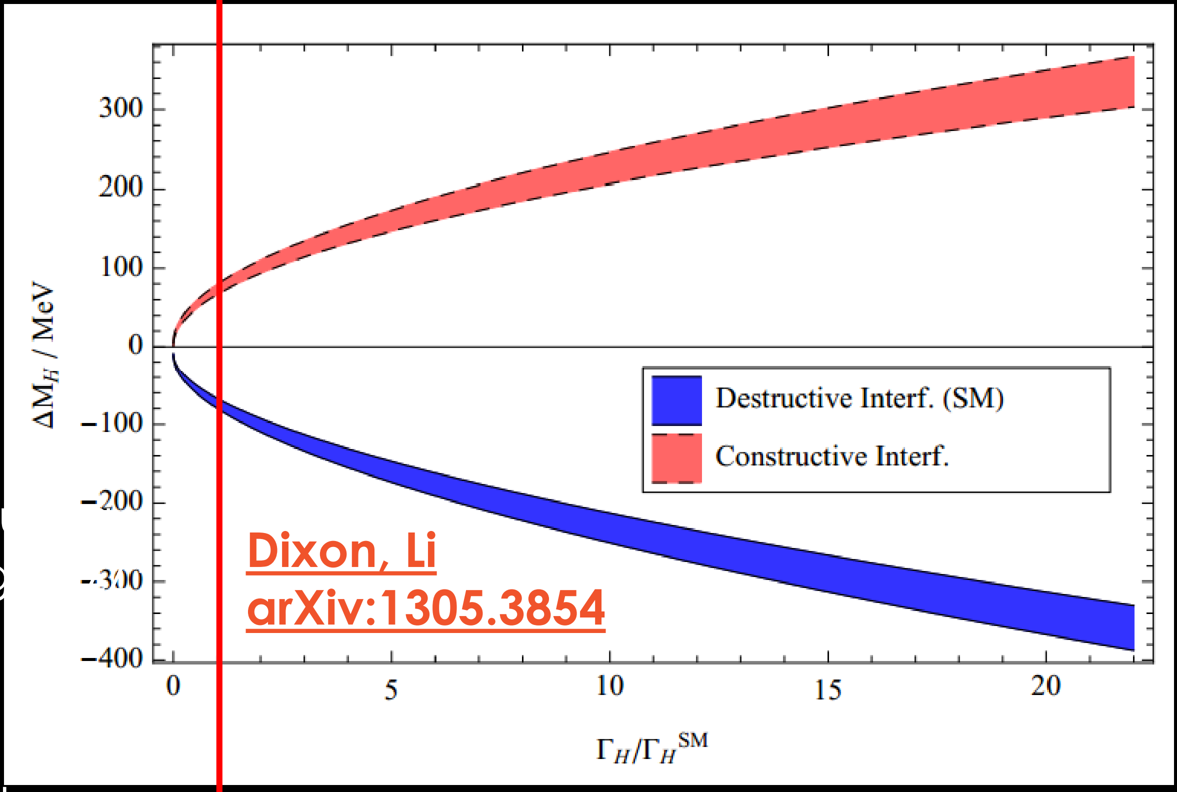
Higher order corrections at Hadron colliders is going limit the precision of this measurement at O(1) level.

OTHER POSSIBILITIES

- gg->H->ZZ
- gg->H->WW
- VBF->H->ZZ

etc.

Why not diphoton?



Large background.
So a different technic of meas[...] the mass peak shift comparing[...] channel is proposed.

Interference with the irreducib[...] background shifts the invariant mass peak.

LHC WIDTH SUMMARY

- Total width can be determined by making off-shell Higgs measurements
- With careful treatment, and assuming no new physics contribute to off-shell process other than modifying the Higgs directly, a few times the SM width precision can be achieved
- Future HL-LHC measurements will improve but is estimated at O(1) precision level from difficulties in higher order corrections.

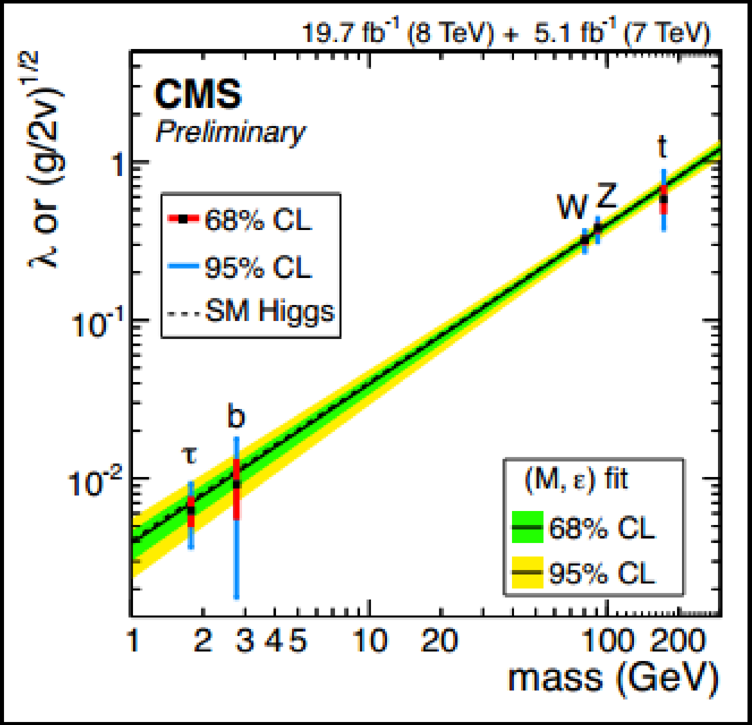
CONSTRAINED κ-SCHEME

Add some assumptions

- Choice 1: Assuming no Br_{exo}, so Γ_{tot} has to scale as f but not f^2 since $\Gamma_{tot} = \Sigma\Gamma_{observable}$

  Total width is no longer a free parameter, but rather a derived quantity from all observable partial widths.

  Most of the LHC result seen are under this assumption.



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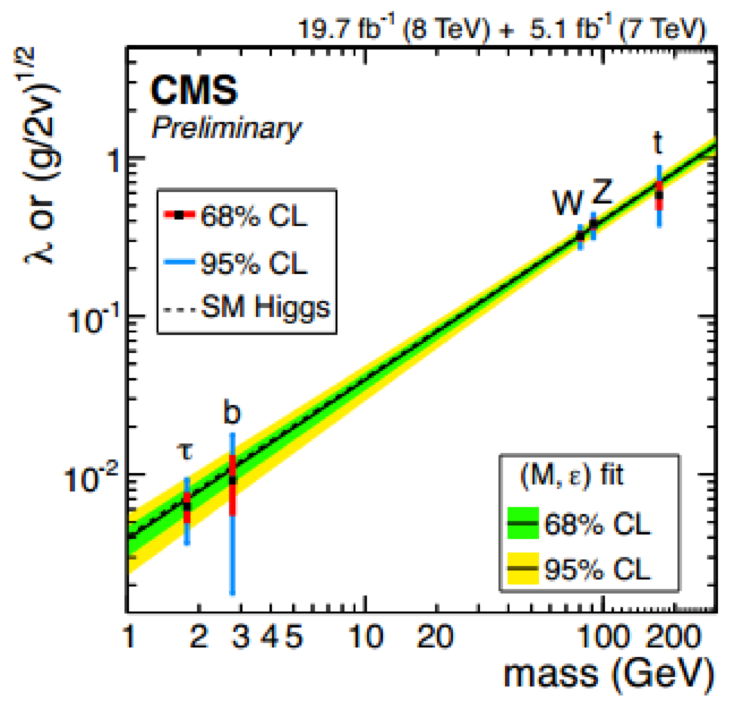


This assumption is justified that it's applicable to BSM models with no additional states lighter than the Higgs mass, provided that Higgs decays to light quarks not modified too much.

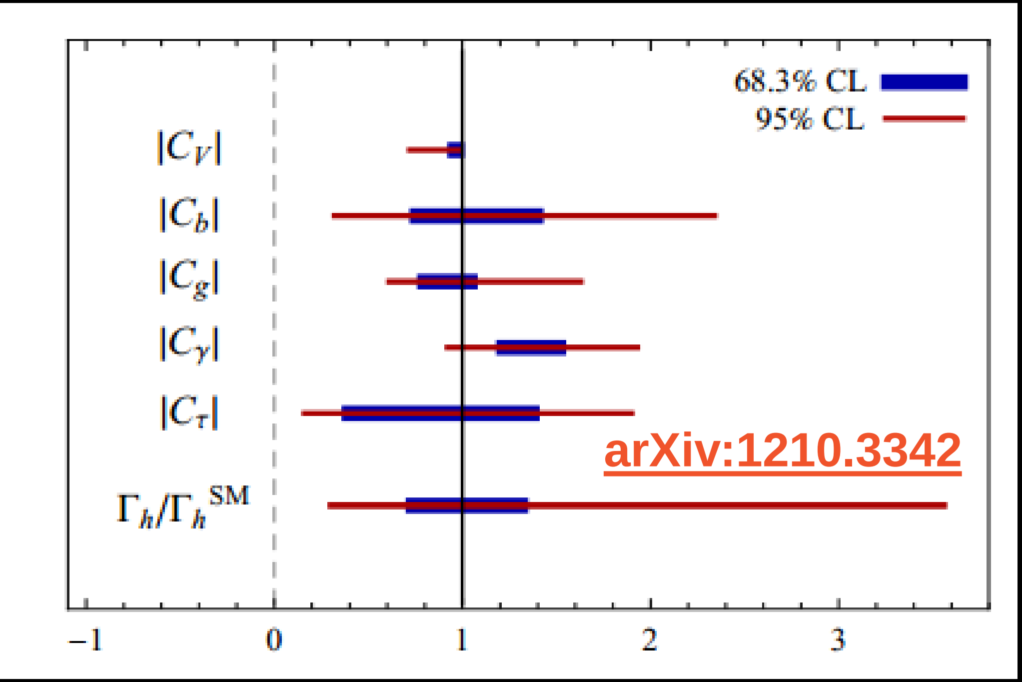
CONSTRAINED κ-SCHEME

Add some assumptions

- Choice 2: Assuming upper bound on certain couplings from theoretical requirement.

e.g. $\kappa_W, \kappa_Z \leq 1$, which is true for most models without Higgs triplet or higher reps.

e.g.,

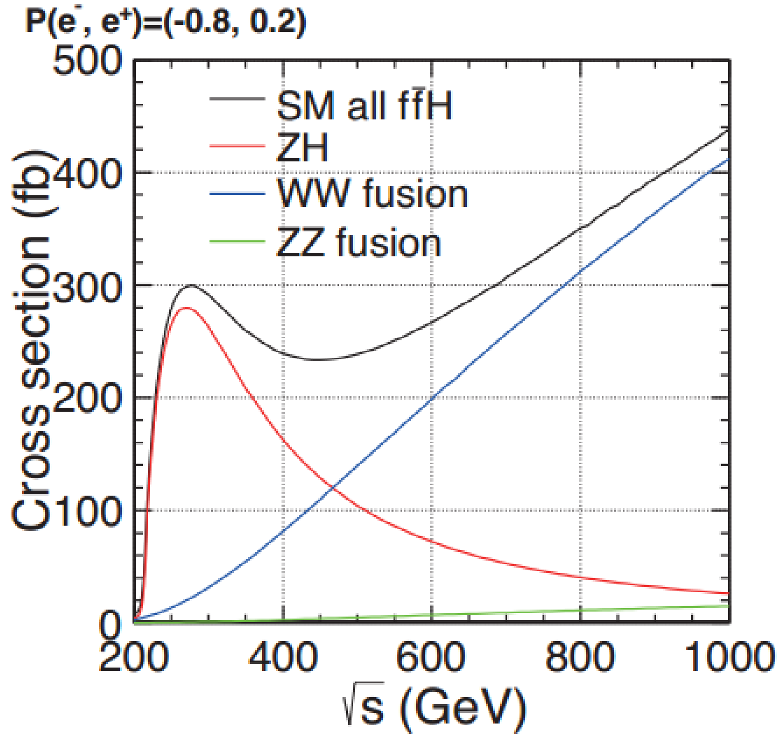


An obvious asymmetric error band on κ_W, κ_Z.

This results assumes $\kappa_W = \kappa_Z = \kappa_V$ as a result of constrains from ρ with some exceptions.

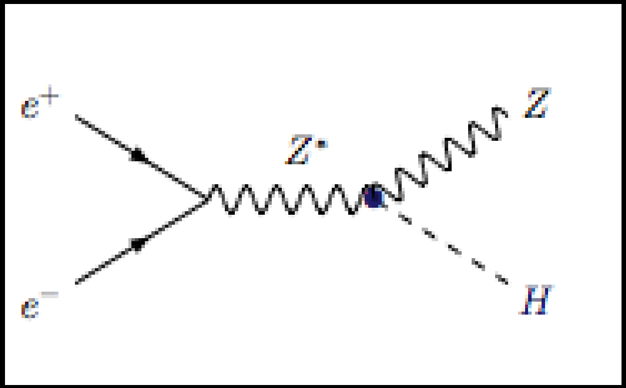
HIGGS PHYSICS AT CEPC HIGGS FACTORY

Higgs Production



Millions of Higgs at the CEPC clean environment
Especially these with the nice recoil Z-boson reconstructed

Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6



Knowing the Initial State Four momenta.

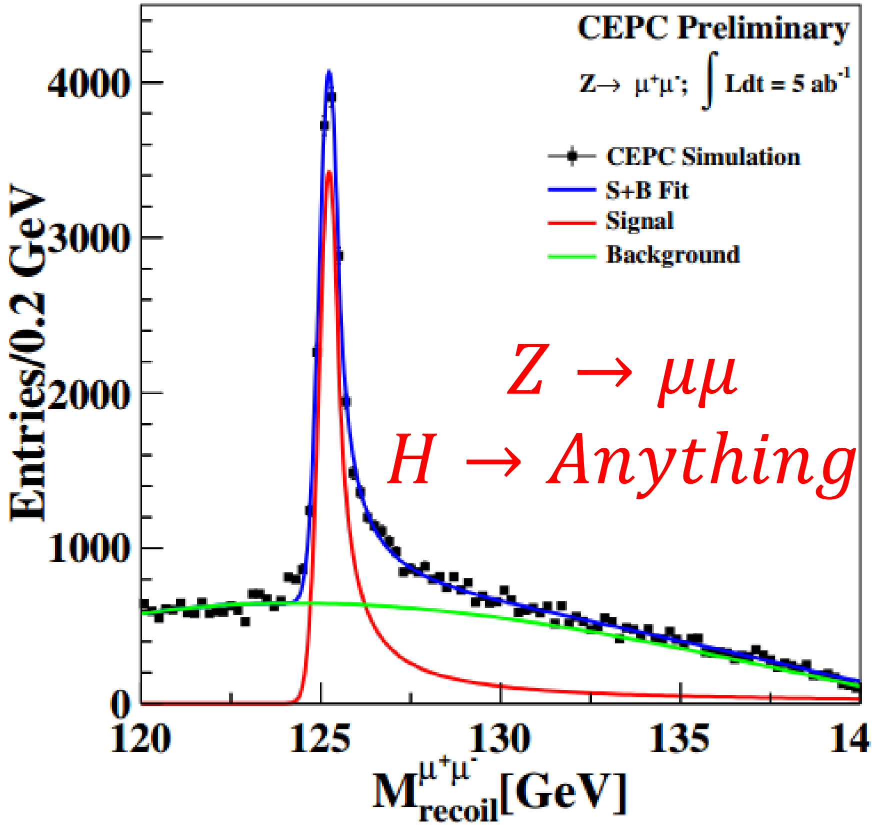
"recoil mass technique":

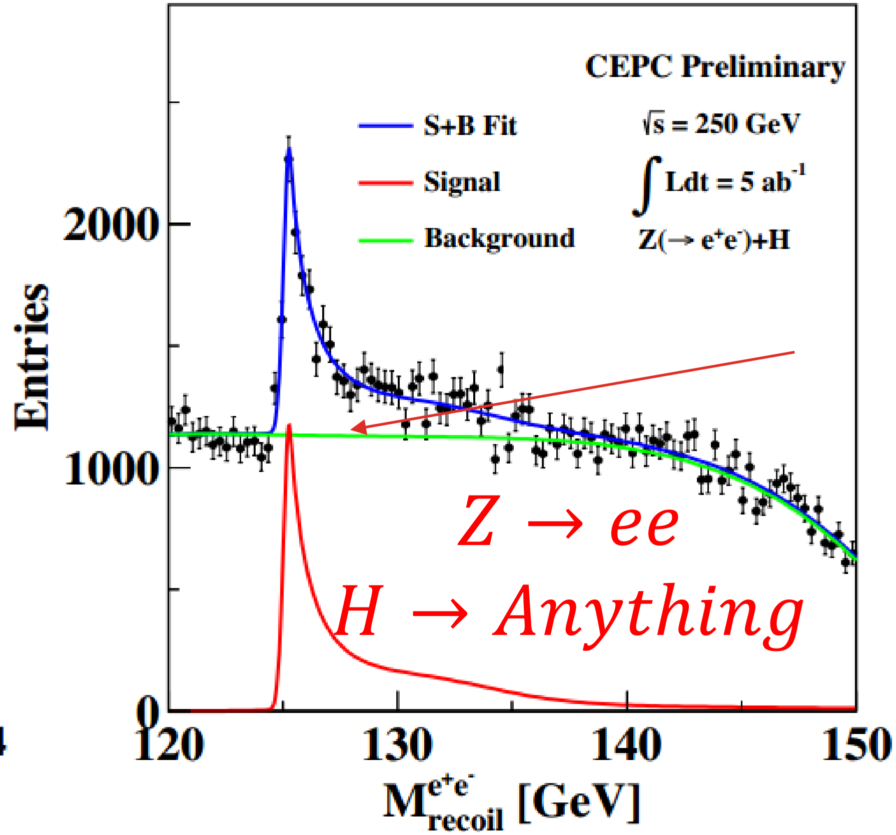
No additional assumption

Inclusive Higgs measurement

$\Rightarrow$Coupling square measurement (HZZ)

$\Rightarrow$ freeze scaling factor f

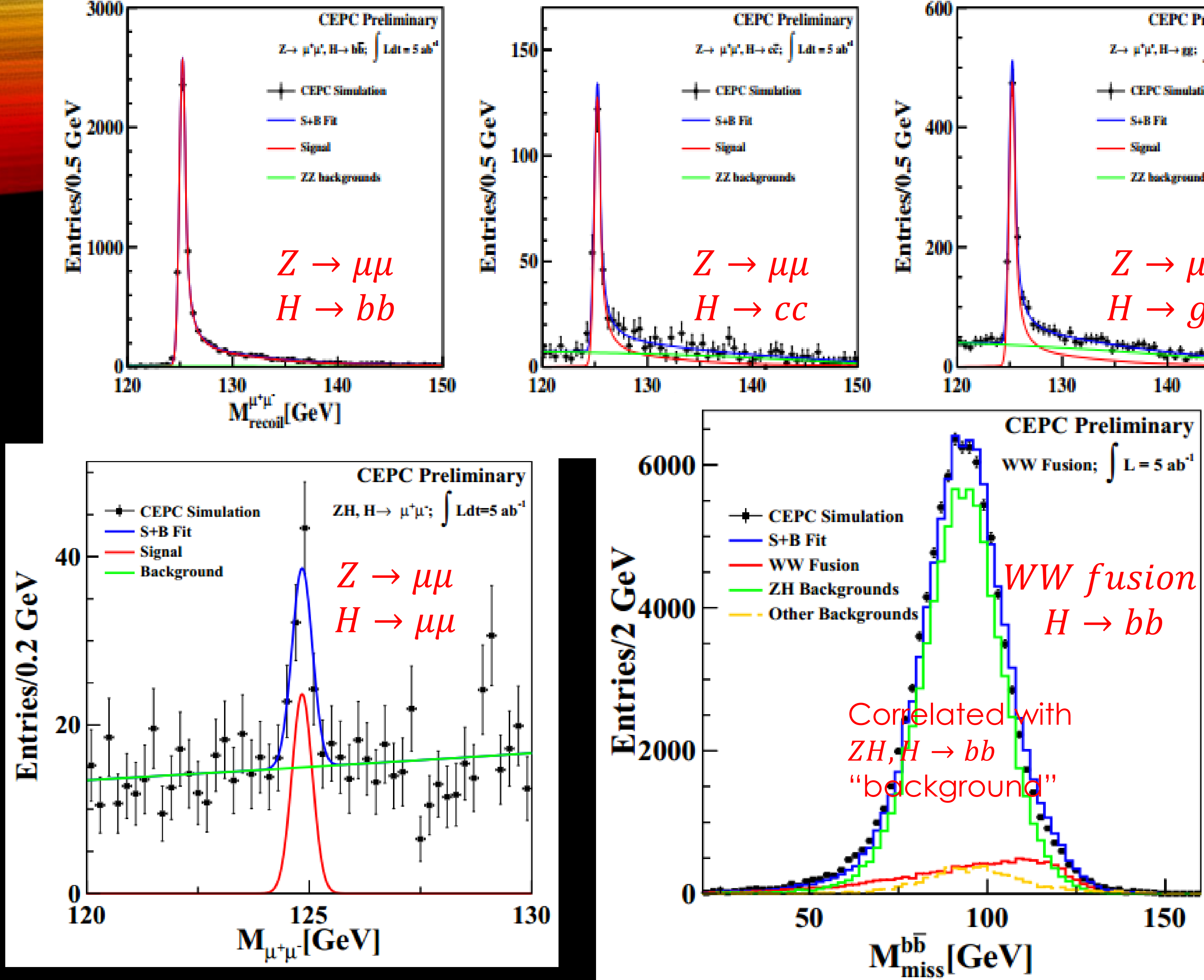


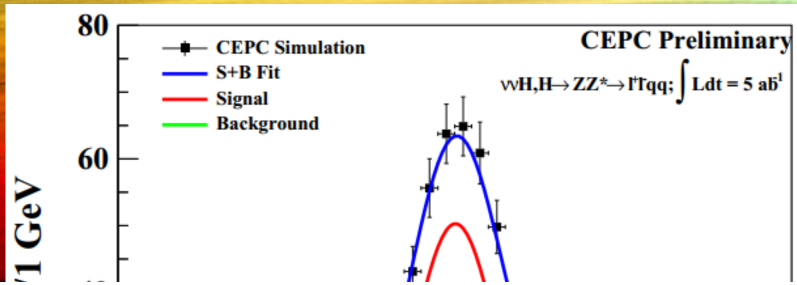


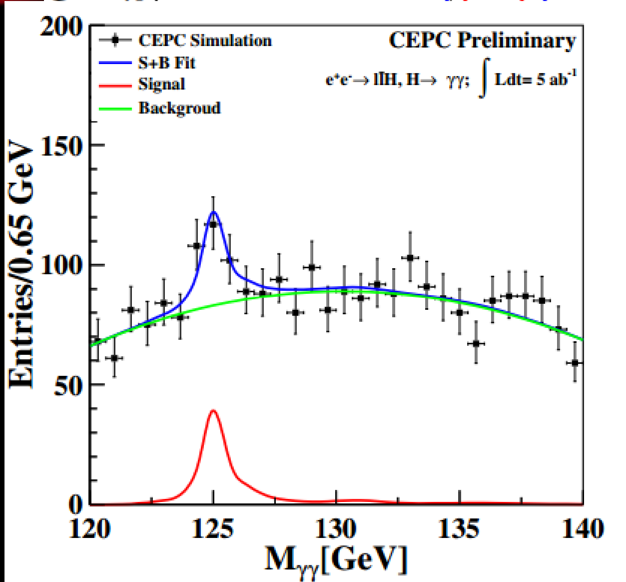
Nice recoil mass peak at 240~250 GeV, where ZH associated production rate is optimized. **The Key-measurement at the CEPC.**

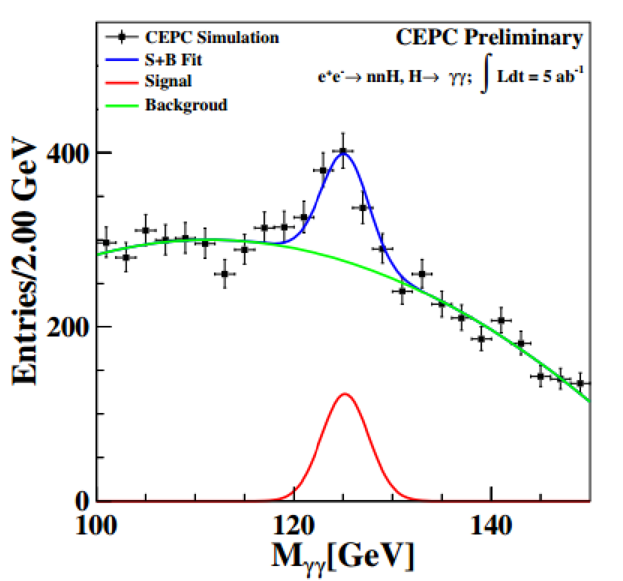
Using dilepton (also dijet) invariant mass to tag Z-boson, and then find the recoil mass peak.

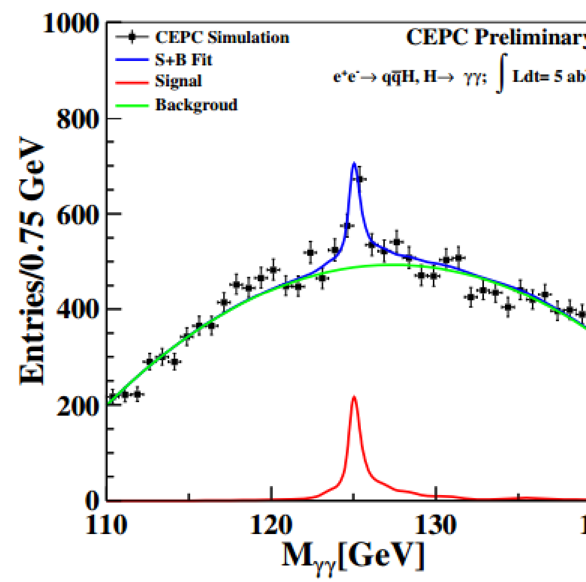
Z decay mode	ΔM_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$	$\Delta g(HZZ)/g(HZZ)$
ee	13	2.1%	
$\mu\mu$	6.6	0.9%	
$ee+\mu\mu$	5.9	0.8%	0.4%
qq		0.65%	0.32%
$ee+\mu\mu+qq$		0.5%	0.25%

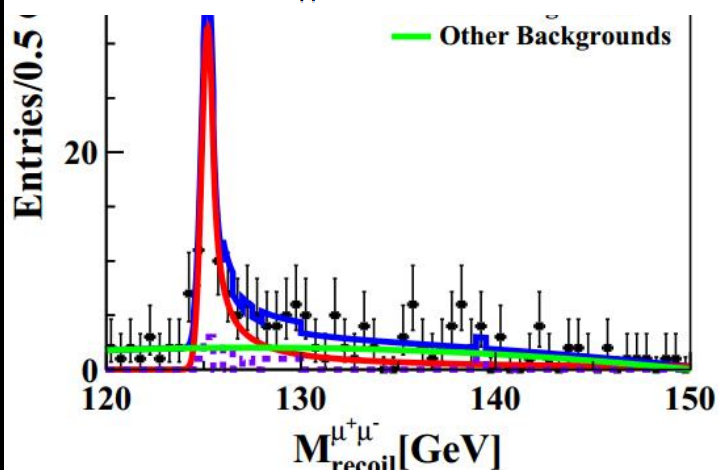

CEPC Preliminary
Z→ μ⁺μ⁻, H→ bb̄; ∫ Ldt = 5 ab⁻¹
CEPC Simulation
S+B Fit
Signal
ZZ backgrounds
Entries/0.5 GeV
M recoil μ⁺μ⁻ [GeV]
Z → μμ
H → bb
CEPC Preliminary
Z→ μ⁺μ⁻, H→ cc̄; ∫ Ldt = 5 ab⁻¹
CEPC Simulation
S+B Fit
Signal
ZZ backgrounds
Entries/0.5 GeV
Z → μμ
H → cc
CEPC Preliminary
Z→ μ⁺μ⁻, H→ gg; ∫ Ldt = 5 ab⁻¹
CEPC Simulation
S+B Fit
Signal
ZZ backgrounds
Entries/0.5 GeV
Z → μμ
H → gg
CEPC Preliminary
ZH, H→ μ⁺μ⁻; ∫ Ldt=5 ab⁻¹
CEPC Simulation
S+B Fit
Signal
Background
Entries/0.2 GeV
M μ⁺μ⁻ [GeV]
Z → μμ
H → μμ
CEPC Preliminary
WW Fusion; ∫ L = 5 ab⁻¹
CEPC Simulation
S+B Fit
WW Fusion
ZH Backgrounds
Other Backgrounds
Entries/2 GeV
M miss bb̄ [GeV]
WW fusion
H → bb
Correlated with
ZH, H → bb
"background"

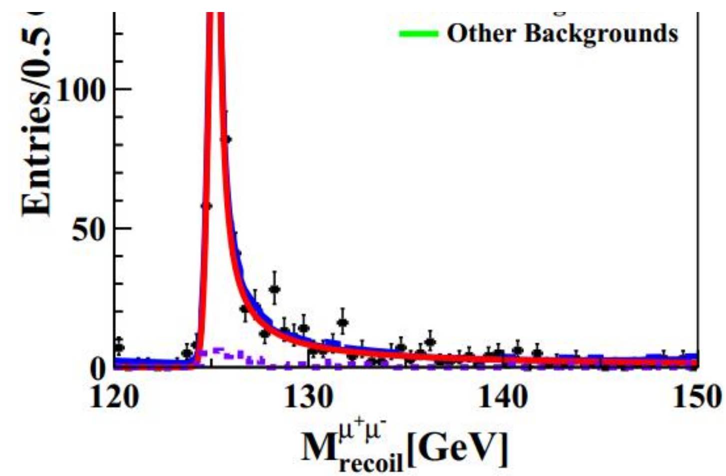

80
60
1 GeV
CEPC Simulation
S+B Fit
Signal
Background
CEPC Preliminary
νvH,H→ ZZ*→ l⁺l⁻qq; ∫ Ldt = 5 ab⁻¹


CEPC Simulation
S+B Fit
Signal
Backgroud
CEPC Preliminary
e⁺e⁻→ llH, H→ γγ; ∫ Ldt= 5 ab⁻¹
Entries/0.65 GeV
200
150
100
50
0
120
125
130
135
140
Mγγ[GeV]


CEPC Simulation
S+B Fit
Signal
Backgroud
CEPC Preliminary
e⁺e⁻→ nnH, H→ γγ; ∫ Ldt = 5 ab⁻¹
Entries/2.00 GeV
400
200
0
100
120
140
Mγγ[GeV]


CEPC Simulation
S+B Fit
Signal
Backgroud
CEPC Preliminary
e⁺e⁻→ qq̄H, H→ γγ; ∫ Ldt= 5 ab⁻¹
Entries/0.75 GeV
1000
800
600
400
200
0
110
120
130
Mγγ[GeV]


Other Backgrounds
Entries/0.5
20
0
120
130
140
150
M recoil μ⁺μ⁻ [GeV]


Other Backgrounds
Entries/0.5
100
50
0
120
130
140
150
M recoil μ⁺μ⁻ [GeV]

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
5.5 MeV	2.8%	0.51%	2.8%

Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to bb$	0.28%	0.58%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	0.28%	0.28%

A result of many efforts from different groups in universities and research institutes in China.
Some channels are full-detector simulation, some are fast simulation; some are with Z decaying to μ or e only, some are also with hadronic Z decays.

$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
2.8%

ΔM_H	Γ_H	$\sigma(ZH)$
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$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to \mathrm{inv}$	0.28%

That ILC 250 GeV as one example,

$$\Delta\sigma_{ZH}^{inclusive} = 0.5\% \Rightarrow \Delta\kappa_Z = 0.25\%$$

But

$$\Delta\sigma(ZH, H \to ZZ^*) = 4.3\%$$

All other couplings, e.g.

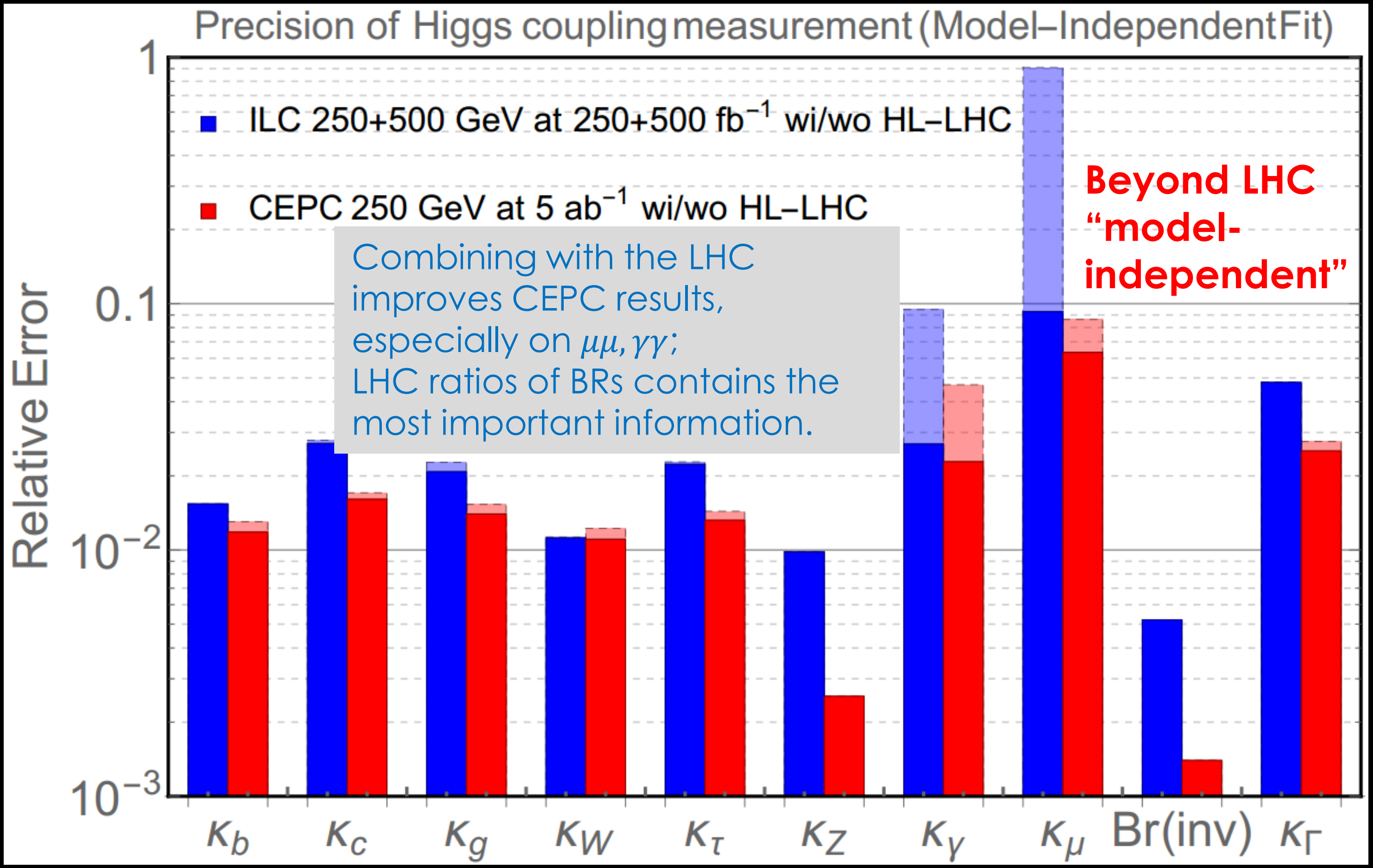
$$\Delta\kappa_\tau^2 = \Delta\left(\frac{\sigma(ZH, H \to \tau\tau)}{\sigma(ZH, H \to ZZ^*)} * \kappa_Z^2\right) > 4.3\%$$

Leading contribution at 250 GeV is,

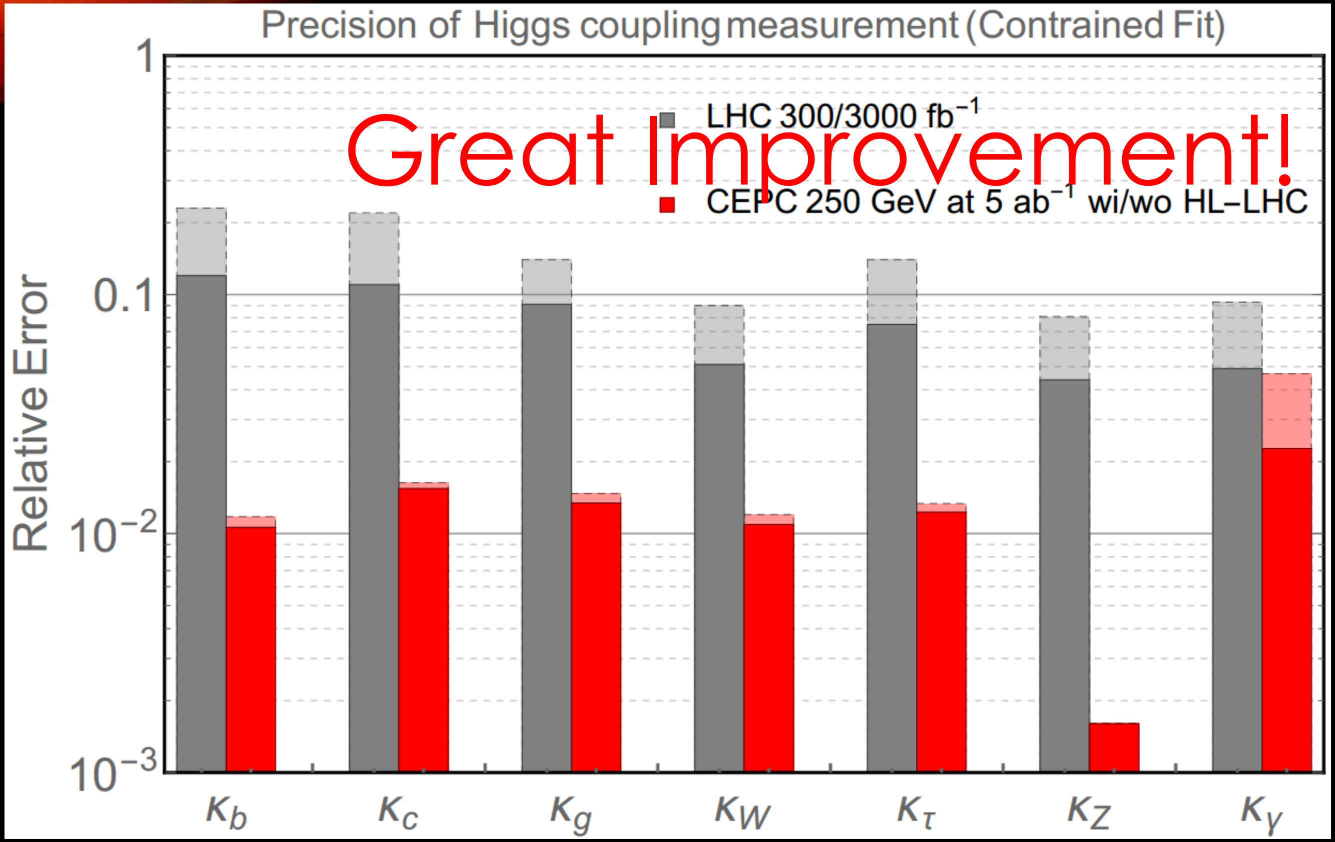
$$\Gamma_h \propto g_Z^2 \frac{\sigma_Z^{inc}\ \sigma_{Wb}}{\sigma_{ZW}\ \sigma_{Zb}}$$

see CEPC pre-CDR, CEPC Higgs Whitepaper.

A GLANCE AT THE GLOBAL FIT RESULT



CEPC fit result comparing with the LHC



The (HL-)LHC fit results are within the constrained fit scheme.

Since one of the biggest uncertainty of f-scaling is broken, the fitting result will be greatly improved comparing to the "model-independent" fit result from the CEPC.

Be careful when comparing results with/without/with-different assumptions/schemes.

FEW WORDS ON EFT SCHEME

One can write down all the allowed dim-6 operators that affects Higgs physics.

E.g. from RPP,

Operators involving bosons only

$$\mathcal{O}_H = 1/(2v^2)\left(\partial^\mu\left(\Phi^\dagger\Phi\right)\right)^2$$
$$\mathcal{O}_T = 1/(2v^2)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)^2$$
$$\mathcal{O}_6 = -\lambda/(v^2)\left(\Phi^\dagger\Phi\right)^3$$
$$\mathcal{O}_B = (ig')/(2m_W^2)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\partial^\nu B_{\mu\nu})$$
$$\mathcal{O}_W = (ig)/(2m_W^2)(\Phi^\dagger\sigma^i \overleftrightarrow{D}^\mu\Phi)(D^\nu W_{\mu\nu})^i$$
$$\mathcal{O}_{HB} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$$
$$\mathcal{O}_{HW} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)W^i_{\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{H\tilde{B}} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)\tilde{B}_{\mu\nu}$$
$$\mathcal{O}_{H\tilde{W}} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)\tilde{W}^i_{\mu\nu}$$
$$\mathcal{O}_{B\tilde{B}} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}\tilde{B}^{\mu\nu}$$
$$\mathcal{O}_{G\tilde{G}} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$

Ops. involving bosons and fermions

$$\mathcal{O}_t = y_t/v^2\,(\Phi^\dagger\Phi)\,(\bar{q}_L\Phi^c t_R)$$
$$\mathcal{O}_b = y_b/v^2\,(\Phi^\dagger\Phi)\,(\bar{q}_L\Phi b_R)$$
$$\mathcal{O}_\tau = y_\tau/v^2\,(\Phi^\dagger\Phi)\,(\bar{L}_L\Phi\tau_R)$$
$$\mathcal{O}_{Hq} = i/v^2\,(\bar{q}_L\gamma^\mu q_L)\,(\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)$$
$\mathcal{O}^{(3)}_{Hq}$

$\mathcal{O}_{Hu}$

$\mathcal{O}_{Hd}$

$\mathcal{O}_{Hud}$

$\mathcal{O}_{Hl}$

Ops. involving bosons and fermions

$$\mathcal{O}_{uB} = (g'\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}u_R)\,B_{\mu\nu}$$
$$\mathcal{O}_{uW} = (g\,y_u)/m_W^2\,(\bar{q}_L\sigma^i\Phi^c\sigma^{\mu\nu}u_R)\,W^i_{\mu\nu}$$
$$\mathcal{O}_{uG} = (g_S\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}t^A u_R)\,G^A_{\mu\nu}R$$
$$\mathcal{O}_{dB} = (g'\,y_d)/m_W^2\,(\bar{q}_L\Phi\sigma^{\mu\nu}d_R)\,B_{\mu\nu}$$
$$\mathcal{O}_{dW} = (g\,y_d)/m_W^2\,(\bar{q}_L\sigma^i\Phi\sigma^{\mu\nu}d_R)\,W^i_{\mu\nu}$$
$$\mathcal{O}_{dG} = (g_S\,y_d)/m_W^2\,(\bar{q}_L\Phi\sigma^{\mu\nu}t^A d_R)\,G^A_{\mu\nu}$$
$$\mathcal{O}_{lB} = (g'\,y_l)/m_W^2\,(\bar{L}_L\Phi\sigma^{\mu\nu}l_R)\,B_{\mu\nu}$$
$$\mathcal{O}_{lW} = (g\,y_l)/m_W^2\,(\bar{L}_L\sigma^i\Phi\sigma^{\mu\nu}l_R)\,W^i_{\mu\nu}$$

Only 8 **primary** Higgs operators (CP-conserving)

[Pomarol, Riva 2013; Elias-Miro et al. 2013; Gupta, Pomarol, Riva 2014]

g_s	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	➢ $gg \to h$
g'	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	➢ $h \to \gamma\gamma$
g	$\lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	
m_W	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$	➢ $h \to VV^*$
m_f	$\lvert H\rvert^2 \overline{f}_L H f_R + \text{h.c.}$	➢ $h \to bb, \tau\tau$ and $gg \to tth$
m_H	$\lvert H\rvert^6$	

Already probed at the LHC

g_s	$\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	➢ $gg \to h$	
g'	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	➢ $h \to \gamma\gamma$	
g	$\lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$	➢ $h \to Z\gamma$	Now only upper bound wait for next LHC run
m_W	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$	➢ $h \to VV^*$	
m_f	$\lvert H\rvert^2 \overline{f}_L H f_R + \text{h.c.}$	➢ $h \to bb, \tau\tau$ and $gg \to tth$	
m_H	$\lvert H\rvert^6$	➢ affects h^3	Probed in $gg \to hh$ very late LHC

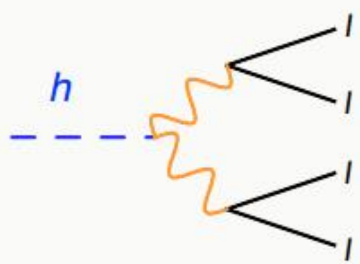
FEW WORDS ON EFT SCHEME

One can write down all the allowed dim-6 operators that affects Higgs physics.

- Use E.o.M to write down a unique set of operators
- A single operator could be constrained by EWPO, e.g. STU, Z-pole, TGC, Dipole
- There exists a set of operators only affecting Higgs physics→ justifying the κ-scheme.
- **Possible co-existence of dim-6 operators that modify e.g. HZZ coupling, with different Lorentz structures.**

Lessons from LHC8 recasts

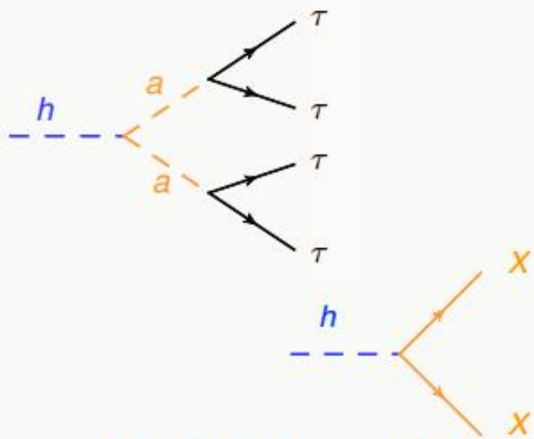
- Prospects depend in detail on the particles in the final state, and range from spectacular to very hard



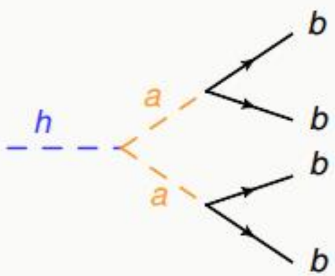
Easy: multiple resonant light leptons

$\mathrm{Br} \lesssim 4 \times 10^{-4}$

Moderate: multiple electroweak objects, poor mass resolution



$\mathrm{Br} \lesssim 0.1 - 0.6$



Hard: all-hadronic

$\mathrm{Br} \lesssim 0.9$

[Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, JS, Strassler, Surujon, Tweedie, Zhong]

FEW WORDS ON THEORETICAL UNCERTAINTIES

Table 1-2. *Parametric uncertainties used by the Higgs Cross Section Working group to determine Higgs branching ratio and width uncertainties [15, 17].*

Parameter	Central Value	Uncertainty
$\alpha_s(M_Z)$	0.119	± 0.002 (90% CL)
m_c	1.42 GeV	± 0.03 GeV
m_b	4.49 GeV	± 0.06 GeV
m_t	172.5 GeV	± 2.5 GeV

Tables from Snowmass Higgs report.

Table 1-3. *Theory uncertainties on $M_H = 126$ GeV Higgs partial widths [17].*

Decay	QCD Uncertainty	Electroweak Uncertainty	Total
$H \to b\bar{b}, c\bar{c}$	$\sim 0.1\%$	$\sim 1-2\%$	$\sim 2\%$
$H \to \tau^+\tau^-, \mu^+\mu^-$	–	$\sim 1-2\%$	$\sim 2\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW^*/ZZ^* \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$

	$\delta m_b(10)$	$\delta \alpha_s(m_Z)$	$\delta m_c(3)$	δ_b	δ_c	δ_g
current errors [10]	0.70	0.63	0.61	0.77	0.89	0.78
+ PT	0.69	0.40	0.34	0.74	0.57	0.49
+ LS	0.30	0.53	0.53	0.38	0.74	0.65
+ LS^2	0.14	0.35	0.53	0.20	0.65	0.43
+ PT + LS	0.28	0.17	0.21	0.30	0.27	0.21
+ PT + LS^2	0.12	0.14	0.20	0.13	0.24	0.17
+ PT + LS^2 + ST	0.09	0.08	0.20	0.10	0.22	0.09
ILC goal				0.30	0.70	0.60

Table 1: Projected fractional errors, in percent, for the $\overline{\text{MS}}$ QCD coupling and heavy quark masses under different scenarios for improved analyses. The improvements considered are: PT - addition of 4^{th} order QCD perturbation theory, LS, LS^2 - reduction of the lattice spacing to 0.03 fm and to 0.023 fm; ST - increasing the statistics of the simulation by a factor of 100. The last three columns convert the errors in input parameters into errors on Higgs couplings, taking account of correlations. The bottom line gives the target values of these errors suggested by the projections for the ILC measurement accuracies.

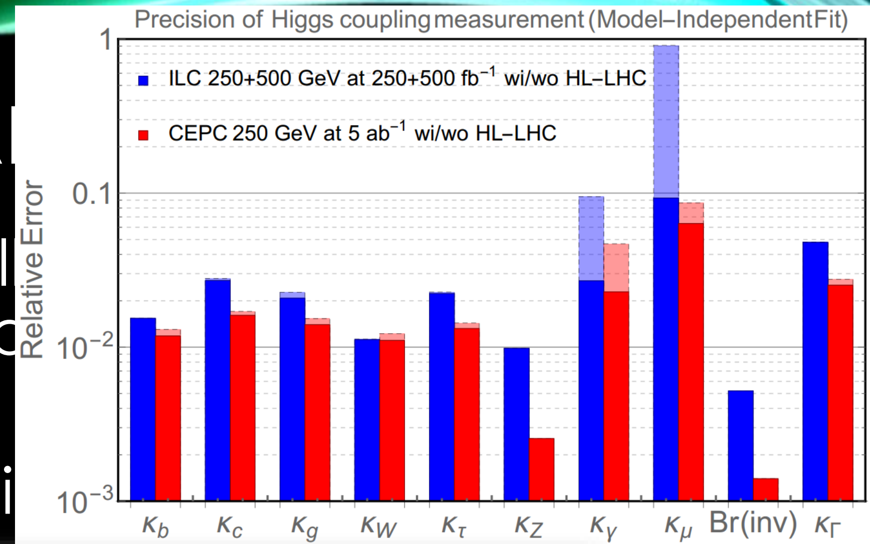
Lepage, Mackenzie, Peskin, arXiv:1404.0319

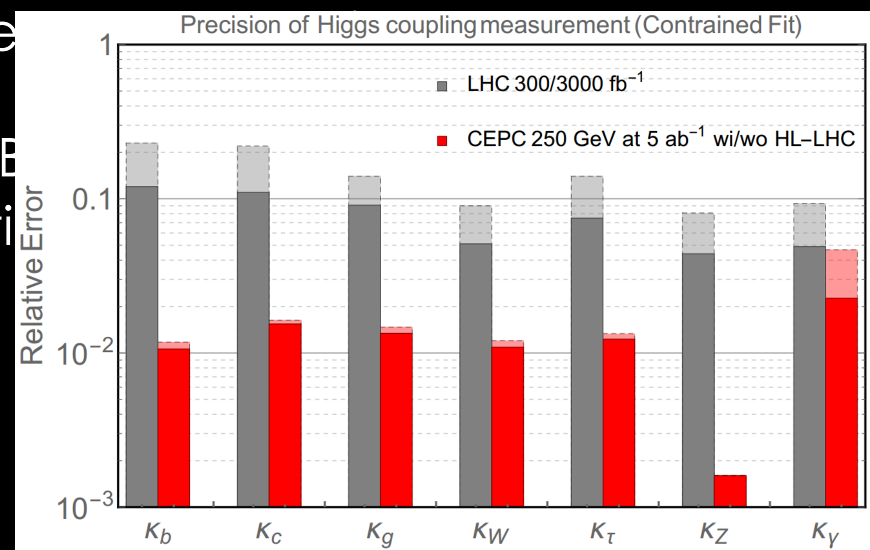
SUMMA

- Higgs physics is rich and chal
new lamppost for our explora
physics.
- Many efforts from different di
promising to provide valuable information through
Higgs prec
- A lot to ex
  - more sub ZH
processes
  - detector design and study on je
identification
  - key background reduction like E
  - reducing theoretical uncertainti
  - Study for rare decays, CP, etc.

Looking forward to the great physics at CEPC and SPPC
We all need to contribute!

Thank you!





OUTLOOK

- Jet-clustering/identification at the CEPC, where the picture could be completely different from hadron colliders, and their applications to BSM physics in addition to serving as QCD tests;
- Tau-lepton tag and its polarization at CEPC, and its application to asymmetries at both Z-pole and ZH;
- The CEPC sensitivities to some "not so rare" Higgs exotic decays, especially for these with trigger problems at the LHC (as CEPC triggering efficiency can be considered as 100% for any exotics);
- The CEPC sensitivity to Higgs "CP violation" as it probably is going to pin down the CP phase;
- A longer term plan for fully correlated analysis of Higgs precisions (systematic, interference in signal processes) should be in place.

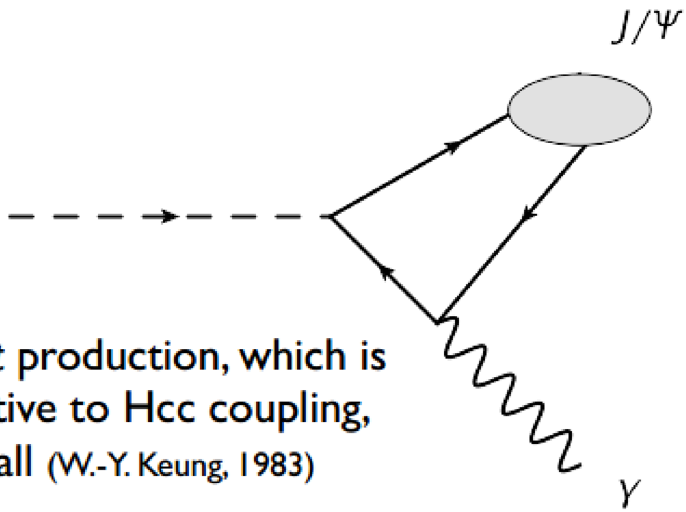
BACKUP

THINGS I WANT TO SHOW AT LEAST ONE SLIDE

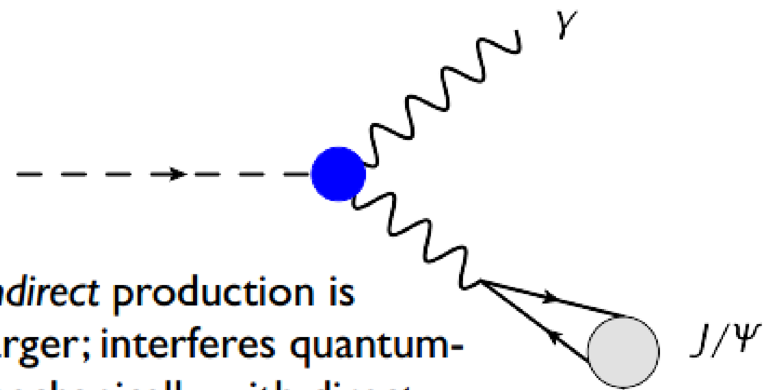
- κ-scheme
- EFT-scheme
- Exotic rare decays
- Flavor rare decays
- To mention: indirect, Higgs production from other decays, triple-Higgs couplings, CP, tth, etc.

Quarkonium interferometry

- Access this coupling using H→J/Ψ+γ! Bodwin, FP, Stoynev, Velasco 1306.5770



Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)



Indirect production is larger; interferes quantum-mechanically with direct production

- Larger indirect mechanism drags up the direct one; provides sensitivity to the Hcc coupling
- Theoretically very clean; few-percent uncertainties: Bodwin, Chung, Ee, Lee, FP 1407.6695
- Interference gives unique information on the phase of the Hcc coupling

Theory prediction for J/ψ

- Partial width for general Hcc coupling:

$g_{Hcc}=\kappa_c\,(g_{Hcc})_{SM}$

$$\Gamma(H \to J/\psi + \gamma) = \left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \mathrm{GeV}$$

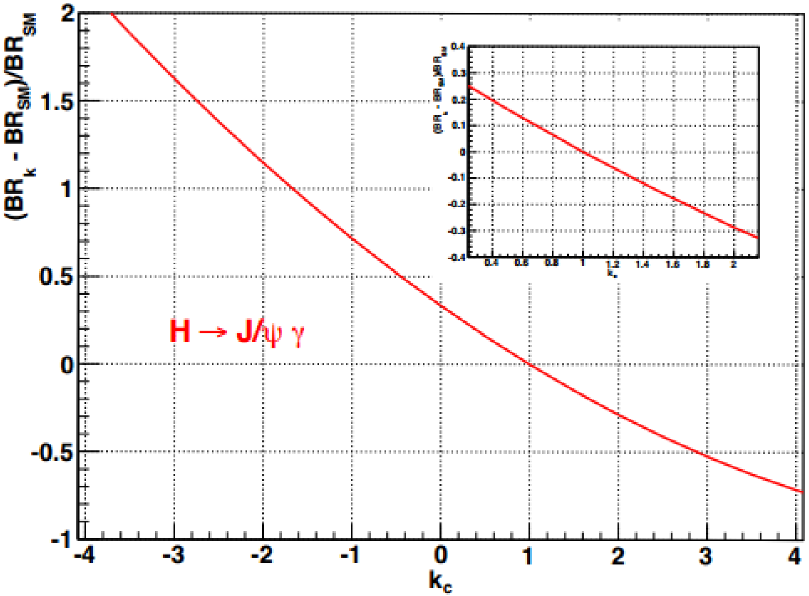
Dominant uncertainty on indirect amplitude: leptonic width of J/ψ

Dominant uncertainty on direct amplitude: uncalculated v^4 corrections in NRQCD

- Branching ratio in the SM:

$$\mathcal{B}_{\rm SM}(H \to J/\psi + \gamma) = 2.79^{+0.16}_{-0.15} \times 10^{-6}$$

This is a 3 ab^{-1} measurement! Only possible with a high luminosity LHC; O(100) $l^+l^-\gamma$ events in the SM after acceptance×efficiency



OUT OF THE BOX: DIRECT SEARCHES

Table 1-6. *Projected future uncertainties in α_s, m_c, and m_b, compared with current uncertainties estimated from various sources. Details of the lattice 2018 projections are given in the Snowmass QCD Working Group report [18].*

	Higgs X-section Working Group [15]	PDG [19]	non-lattice	Lattice (2013)	Lattice (2018)
$\Delta\alpha_s$	0.002	0.0007	0.0012 [19]	0.0006 [20]	0.0004
Δm_c (GeV)	0.03	0.025	0.013 [21]	0.006 [20]	0.004
Δm_b (GeV)	0.06	0.03	0.016 [21]	0.023 [20]	0.011

Z-factor definitely will improve the case further!

The factors F_i can be written

$$F_i = S_i G_i \quad \text{where } S_i = (\frac{\sigma_{ZH}}{g_Z^2}),\ (\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}),\ \text{or } (\frac{\sigma_{t\bar{t}H}}{g_t^2}),\ \text{and } G_i = (\frac{\Gamma_i}{g_i^2}). \tag{6.1}$$

These are theoretical calculations with parametric and theoretical uncertainties. Because the relevant quantities are ratios of cross sections and partial widths to couplings squared, the total theory errors for S_i, and particularly G_i, should be less than the total theory errors for the corresponding cross sections and partial widths. We believe that a total theory error of 0.5% or less can be achieved for the F_i parameters at the time of ILC running. We quote coupling results assuming total theory errors of $\Delta F_i/F_i = 0.1\%$ and $\Delta F_i/F_i = 0.5\%$.

The fitted couplings and width are obtained by minimizing the chi-square function χ^2 defined by

$$\chi^2 = \sum_{i=1}^{34} (\frac{Y_i - Y_i'}{\Delta Y_i})^2, \tag{6.2}$$

where ΔY_i is the square root of the sum in quadrature of the error on the measurement Y_i and the total theory error for Y_i'. The results for theory errors of $\Delta F_i/F_i = 0.1\%$ and $\Delta F_i/F_i = 0.5\%$ are summarized in Table 6.1 and Table 6.2, respectively.

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
$\Gamma_T(h)$	12 %	5.0 %	4.6 %	2.5 %

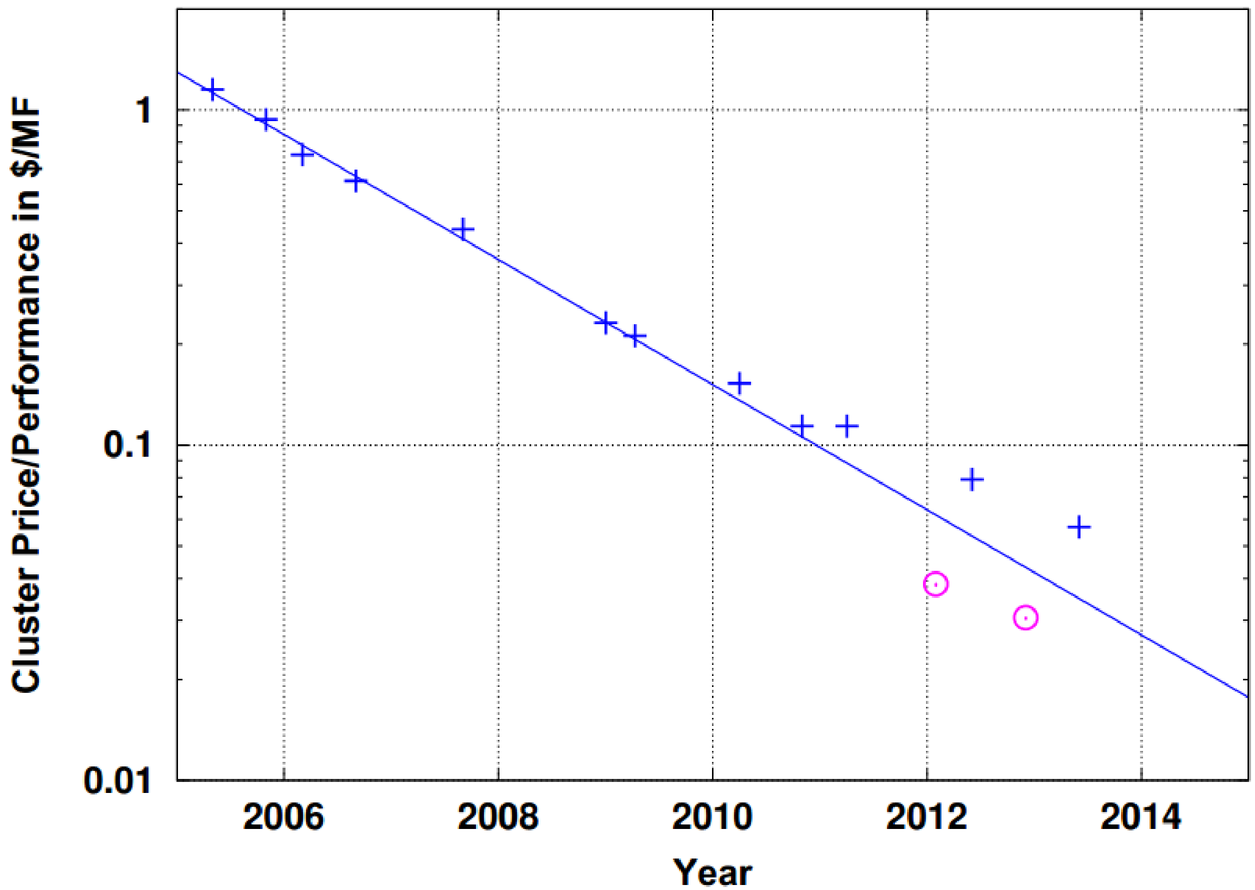


Figure 1: Measured cost per megaflop of lattice QCD computing on the USQCD cluster facilities at Fermilab and Jefferson Lab, plotted versus year. The exponentially improving price/performance of conventional cluster hardware (blue crosses) that was observed through 2011 has fallen off somewhat in the last few years. This has been mitigated by the introduction, where possible, of GPU-accelerated clusters (magenta circles) for lattice calculations.

Table 1-5. *Uncertainties on M_H = 126 GeV Standard Model widths arising from the parametric uncertainties on α_s, m_b, and m_c and from theory uncertainties [16]. For the total uncertainty, parametric uncertainties are added in quadrature and the result is added linearly to the theory uncertainty.*

Channel	$\Delta\alpha_s$	Δm_b	Δm_c	Theory Uncertainty	Total Uncertainty
$H \to \gamma\gamma$	0%	0%	0%	±1%	±1%
$H \to b\bar{b}$	∓2.3%	$^{+3.3\%}_{-3.2\%}$	0%	±2%	±6%
$H \to c\bar{c}$	$^{-7.1\%}_{+7.0\%}$	∓0.1%	$^{+6.2\%}_{-6.1\%}$	±2%	±11%
$H \to gg$	$^{+4.2\%}_{-4.1\%}$	∓0.1%	0%	±3%	±7%
$H \to \tau^+\tau^-$	0%	0%	0%	±2%	±2%
$H \to WW^*$	0%	0%	0%	±0.5%	±0.5%
$H \to ZZ^*$	0%	0%	0%	±0.5%	±0.5%

Table from Higgs Snowmass Report