Precision Higgs Physics at Current and Future Colliders

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Physics Potential of Future Colliders
TRIUMF
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Time flies ….

>10 Years into Higgs Discovery !

Time for Precision Higgs Era !

Where Are We Now?

- Our wish list has not change much from 10 years ago.
- Discovery of Higgs and measurements of its property
  - ➡ Exclude certain models (technicolor,…)
  - ➡ Narrow down parameter space
- Non-discovery of anything else
  - ➡ New physics gets heavier
  - ➡ A bit uncomfortable, big picture unchanged

Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

- Direct search for new particles

  Need colliders with larger energies (pp or e+e- with large E_{cm})

- Indirect search for imprints on W, Z, top and Higgs

  Need colliders/measurements with unprecedented accuracy

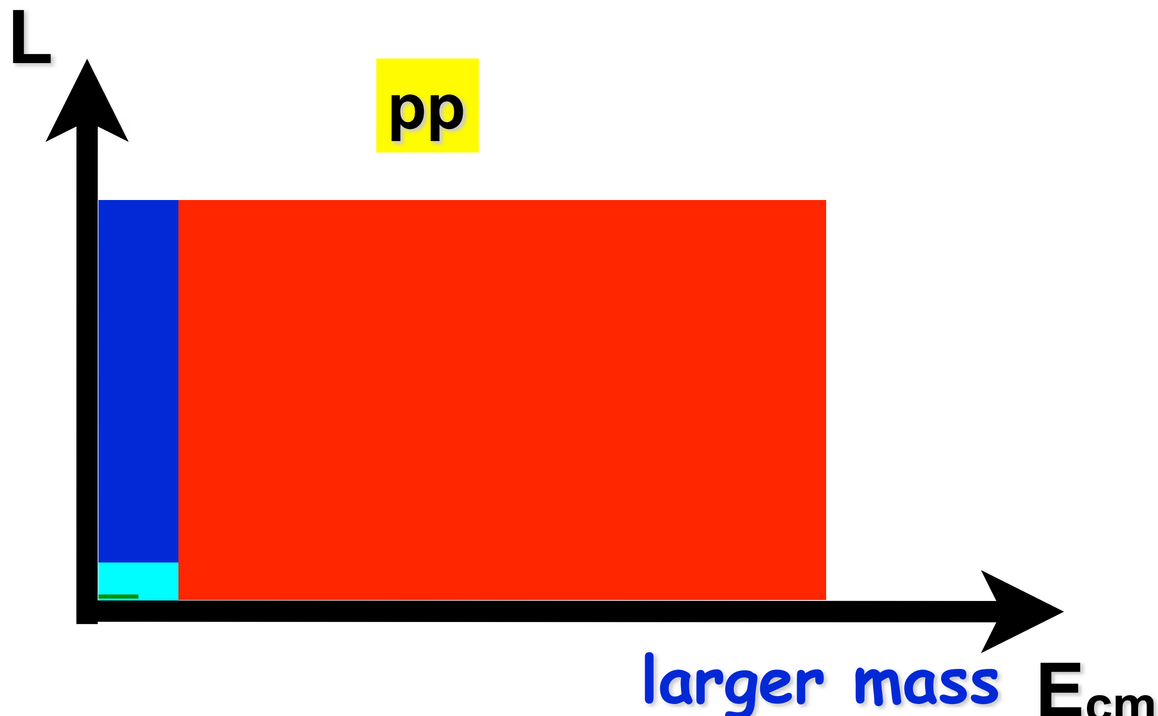
  (e+e- or pp with high luminosity)

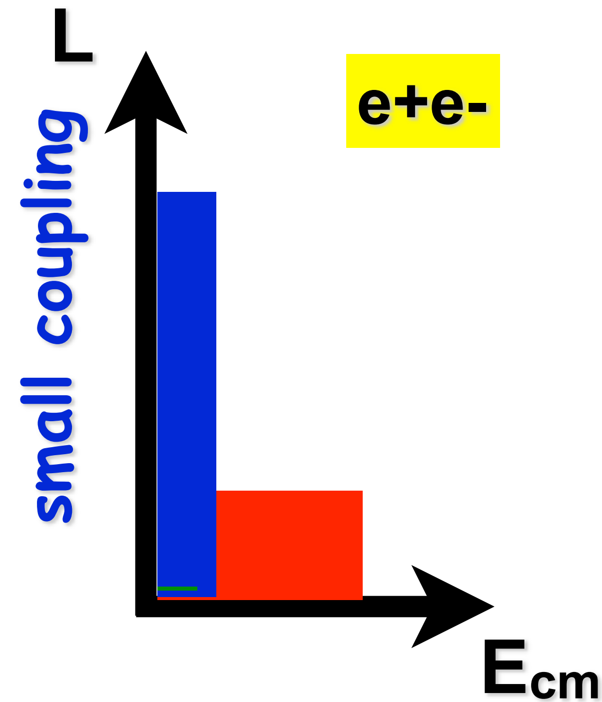
LHC / HL-LHC Plan

LHC is a Higgs factory: 15 M Higgs

HL-LHC: 170 M Higgs, 120 K HH pair

Current and Future Colliders





LHC
HL-LHC
SPPC
FCC-hh
...

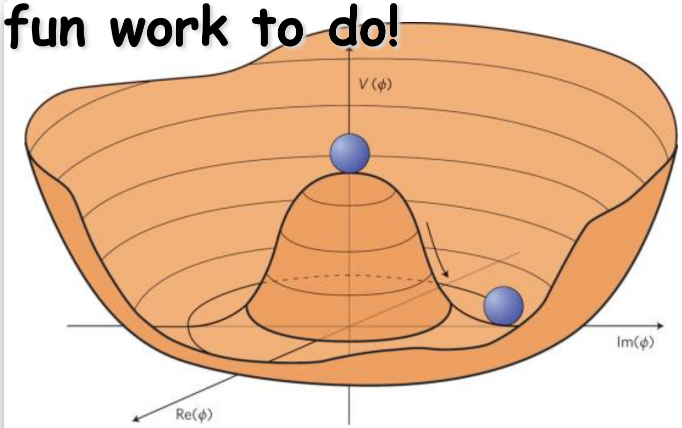
CEPC
FCC-ee
ILC
...

A Light Higgs is Puzzling...

- Light, weakly coupled boson: m_h = 125-126 GeV, $\Gamma << 1$ GeV
  - ➡ spin 0, a new kind of fundamental particle, no charge, no structure
  - ➡ Nothing protects its mass ⇒ New physics beyond the SM

Then What? Theoretically hard, but fun work to do!

- $\lambda \sim 1/8$, origin of λ ?
- extended Higgs sector?
- stabilization of EW scale?
- ...



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W\frac{v}{2}$$

$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

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Then What?

light, weakly coupled boson: m_h = 125-126 GeV, Γ << 1 GeV

Then What? experimentally...

- Is it a SM Higgs? Mass, width, spin, coupling, CP,...
- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Can we use H to look for new physics?
- Where is new physics? Top partners? Dark matter?
- ...

This talk focuses on the Higgs precision measurements.

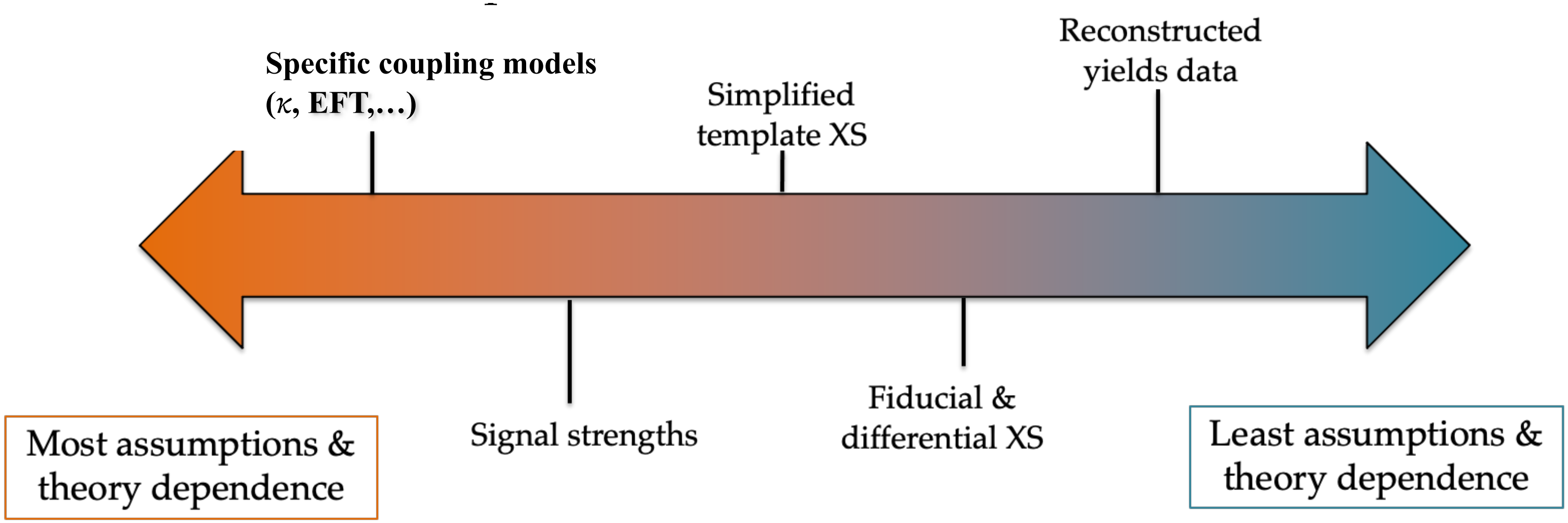
Outline

- Introduction
- Precision Higgs measurements: current/future
- Implication of Higgs precision measurements

Precision Higgs Measurements

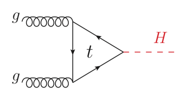
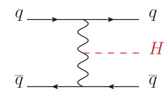
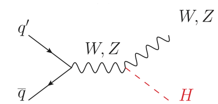
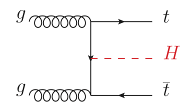
Precision Higgs Measurements

- Mass, width, spin, CP
- Higgs couplings
- differential distributions, STXS, Global fits



from Ed Scott

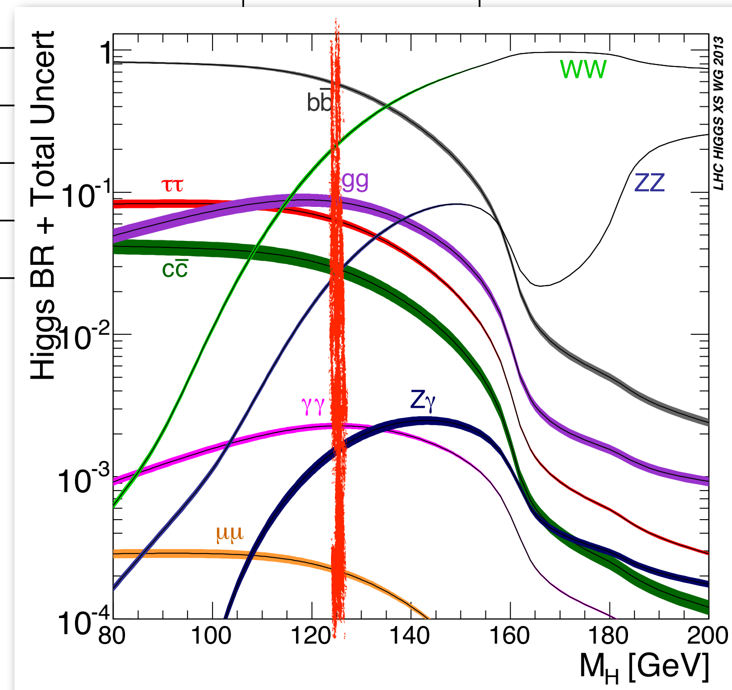
LHC Higgs Observation

Channel categories	Br	ggF  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~40 k evts produced
Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
γγ	0.2 %	✓	✓	✓	✓
ZZ	3%	✓	✓	✓	✓
WW	22%	✓	✓	✓	✓
ττ	6.3 %	✓	✓		
bb	55%	✓	✓		
Zγ and γγ*	0.2 %	✓	✓		
μμ	0.02 %	✓	✓		
Invisible	0.1 %	✓ (monojet)	✓		

Observed modes: γγ, ZZ, WW, ττ, bb

Remaining to be observed: Zγ and γγ*, μμ

Limits: Invisible



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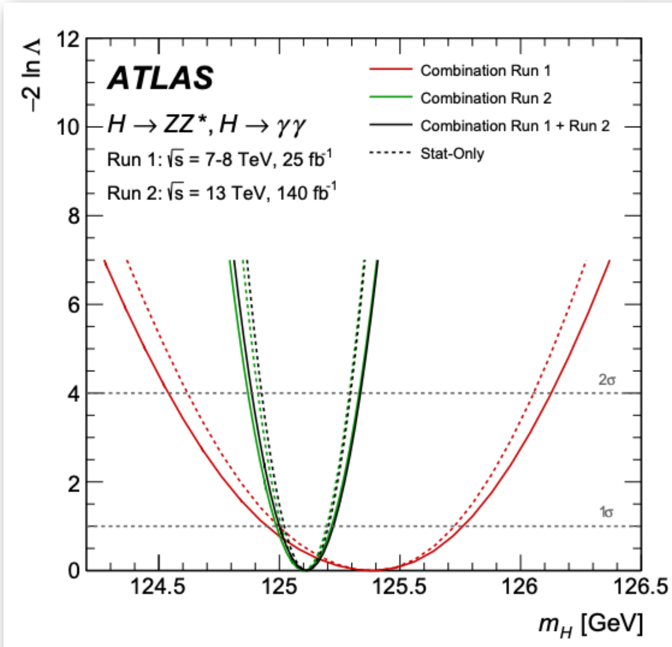
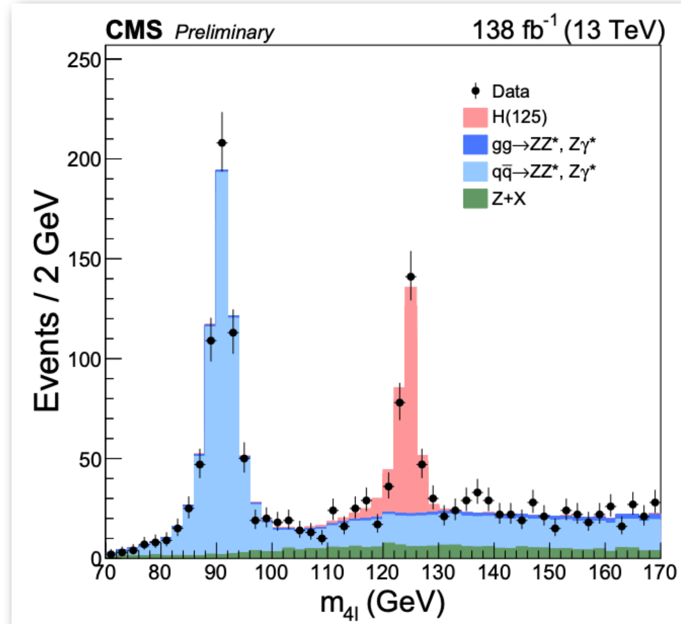
LHC Precision Higgs Measurements

Mass





LHC

ATLAS $m_H = 125.11 \pm 0.09\,(\text{stat.}) \pm 0.06\,(\text{syst.}) = 125.11 \pm 0.11\,\text{GeV}.$ PRL 131 (2023) 251802 CERN-EP-2023-156

CMS $m_\mathrm{H} = 125.08 \pm 0.12\,\text{GeV} = 125.08 \pm 0.10(\text{stat.}) \pm 0.05(syst.)\,\text{GeV}$ CMS-PAS-HIG-21-019

HL-LHC: 10-20 MeV

e+e- Higgs factory: < 6 MeV

LHC Precision Higgs Measurements

Width

LHC

- **On-shell (CMS 4l)** $\Gamma_{\mathrm{H}} < 60$ MeV at 68% confidence level

CMS-PAS-HIG-21-019

- **Off-shell**

$$\frac{\sigma^{\text{off-shell}}_{vv\to H\to 4\ell}}{\sigma^{\text{on-shell}}_{vv\to H\to 4\ell}} \propto \Gamma_H$$

ATLAS $\Gamma_{\mathrm{H}} = 4.3^{+3.3}_{-2.5}$ MeV PLB 846 (2023) 138223

CMS $\Gamma_{\mathrm{H}} = 2.9^{+2.3}_{-1.7}$ MeV CMS-PAS-HIG-21-019

HL-LHC $\Gamma_H = 4.1^{+1.0}_{-1.1}$

e+e- Higgs factory: 0.1 MeV

LHC Precision Higgs Measurements

Couplings

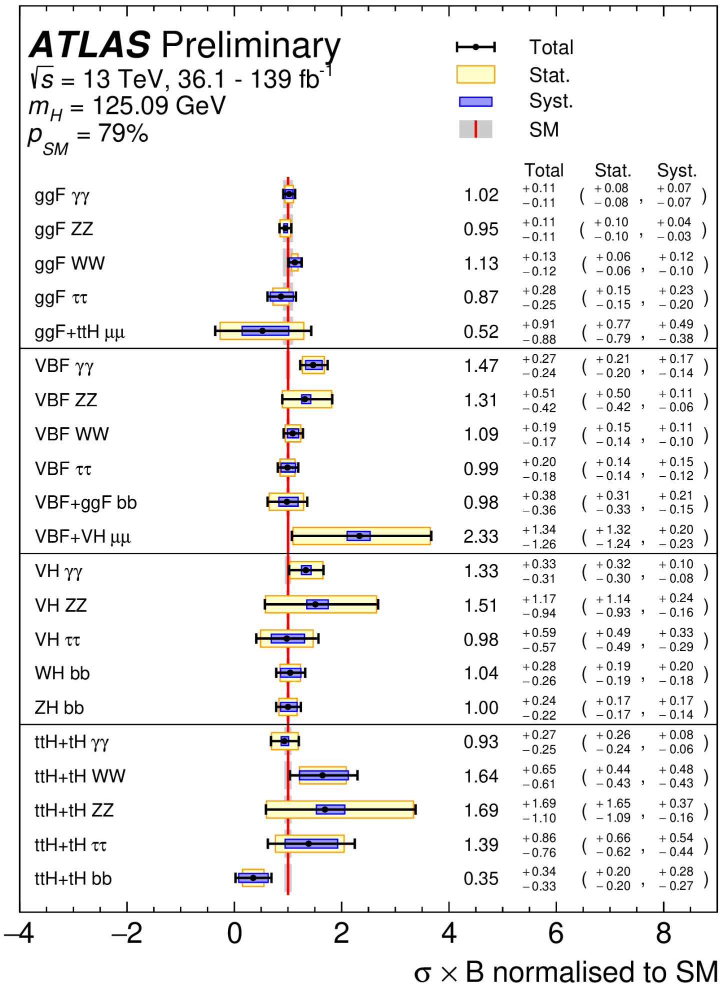
$$\mathcal{L}_{\rm SM} = \cdots + |D_\mu \phi|^2 + \psi_i y_{ij} \psi_j \phi - V(\phi)$$

Gauge interactions studied for many decades now with a scalar

Higgs self-interactions currently under study

Yukawa interactions new study started in 2018

LHC Precision Higgs Measurements



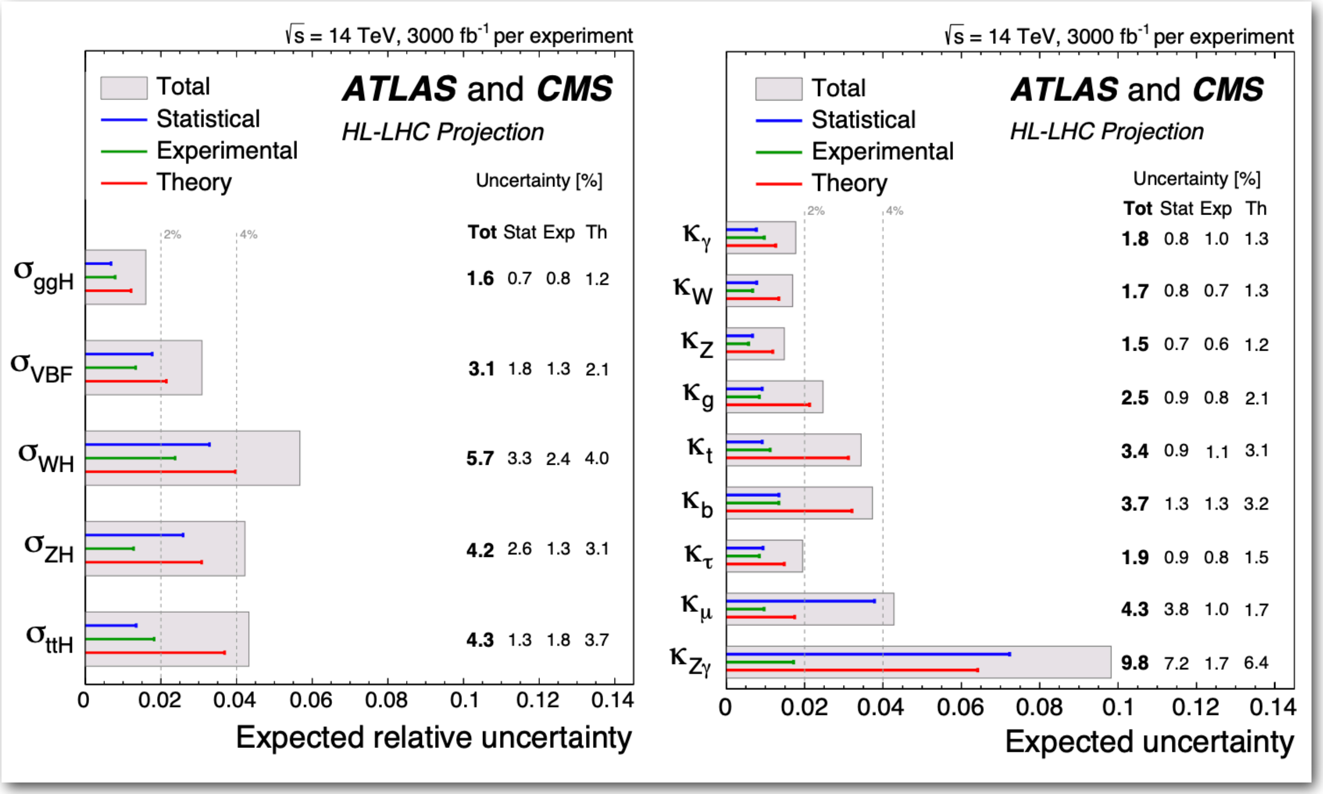
ATLAS-CONF-2021-053

$$\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})},\ \kappa_V = \frac{g(hVV)}{g(hff;\mathrm{SM})}$$

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	$1.01^{+0.09}_{-0.14}$	6%
κ_W	11%	1.06 ± 0.06	$-1.11^{+0.14}_{-0.09}$	6%
κ_Z	11%	0.99 ± 0.06	0.96 ± 0.07	6%
κ_g	14%	$0.92^{+0.07}_{-0.06}$	$1.16^{+0.12}_{-0.11}$	7%
κ_t	30%	0.92 ± 0.10	1.01 ± 0.11	11%
κ_b	26%	0.87 ± 0.11	$1.18^{+0.19}_{-0.27}$	11%
κ_τ	15%	0.92 ± 0.07	0.94 ± 0.12	8%

JHEP 08 (2016) 045　　ATLAS-CONF-2021-053　　CMS-PAS-HIG-19-005

HL-LHC



- 2-4% for most couplings, $Z\gamma$ 10%
- $\mu\mu$, $Z\gamma$ statistical limited
- Others dominated by theoretical uncertainties

Theoretical Uncertainties

from Gavin Salam

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, f_{i/p}(x_1) f_{j/p}(x_2)\, \hat{\sigma}(x_1 x_2 s) \times \left[1 + \mathcal{O}(\Lambda/M)^p\right]$$

Parton distribution functions (PDFs)
(non-perturbative, universal)

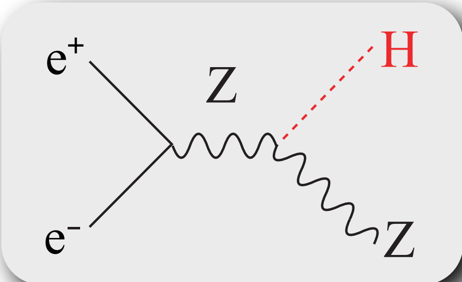
non-perturbative effects
(power suppressed)

hard scattering
(perturbative)

$$\sigma_{ggF} = 48.68 \pm 3.9\ (\text{scales}) \ \pm 1.9\ (\text{PDF}) \ \pm 2.6\ (\alpha_S) \ \ \text{Pb}$$

Lots of hard work to be done to reduce the theoretical uncertainty.

Precision Measurements @ Higgs Factory

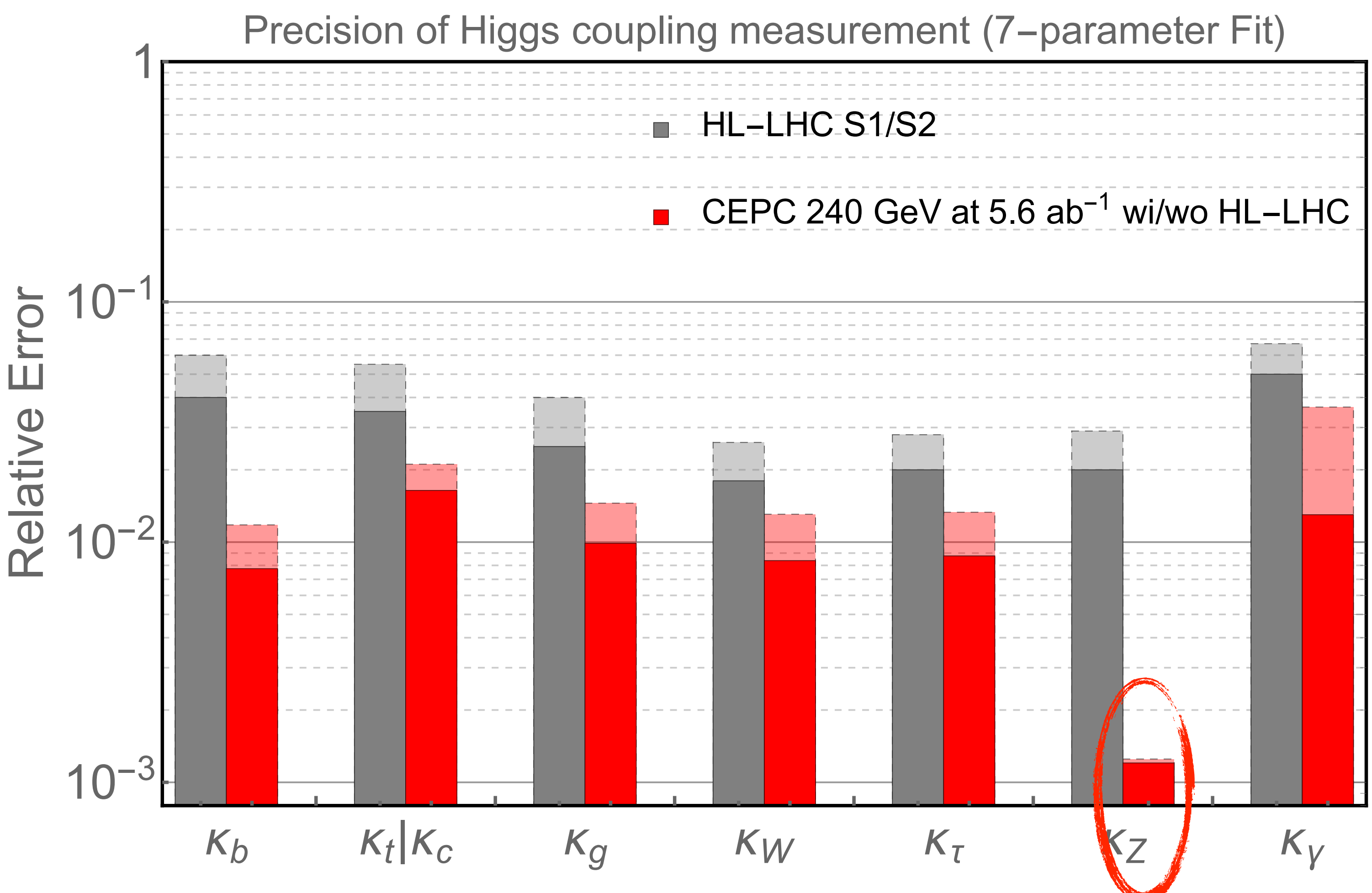


- Determine all Higgs couplings (model-independent)
- Infer Higgs total decay width
- probe invisible/exotic Higgs decay

collider	CEPC	FCC-ee			ILC				
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5.6 ab^{-1}	240 GeV 5 ab^{-1}	365 GeV 1.5 ab^{-1}		250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}	
production	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.71%	2.0%	–	1.05	–
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.23%
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%	2.9%	12.3%	21.2%	4.5%	2.2%
$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
$h \to WW^*$	1.0%	1.2%	2.6%	3.0%	1.6%	6.3%	6.4%	1.9%	0.85%
$h \to \tau^+\tau^-$	0.8%	0.9%	1.8%	8.0%	1.1%	4.5%	17.9%	1.5%	2.5%
$h \to ZZ^*$	5.1%	4.4%	12%	10%	6.4%	28.0%	22.4%	8.8%	3.0%
$h \to \gamma\gamma$	6.8%	9.0%	18%	22%	12.0%	43.6%	50.3%	12.0%	6.8%
$h \to \mu^+\mu^-$	17%	19%	40%	–	25.5%	97.3%	178.9%	30.0%	25.0%
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

Precision Measurements @ Higgs Factory

CEPC, 1810.09037

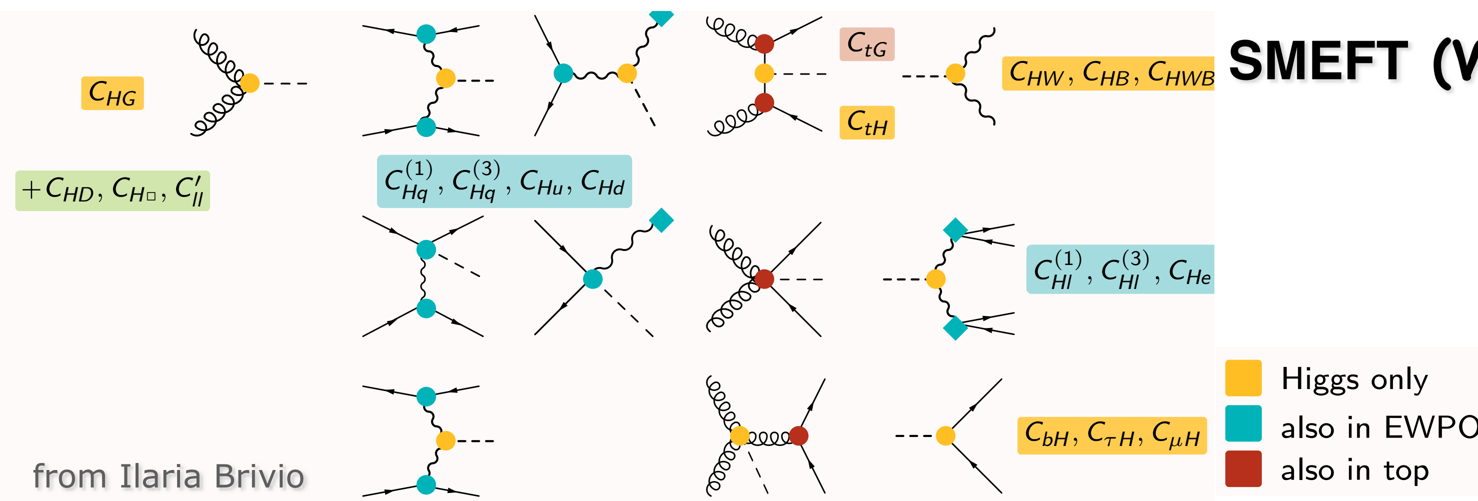


EFT Description

$$\mathcal{L}_{\mathrm{Eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

- EFT: Operators with coefficient suppressed by NP scale Λ
- standard tool to study large exp data set
- correlate Higgs, top, EW sector
- model independent
- caveat…

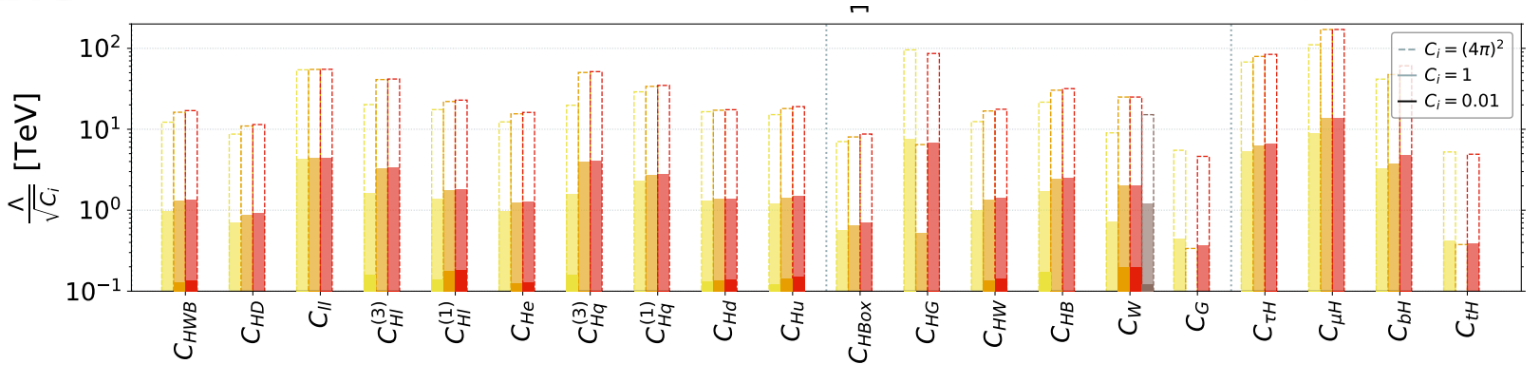
SMEFT (Warsaw basis)



EFT

LHC

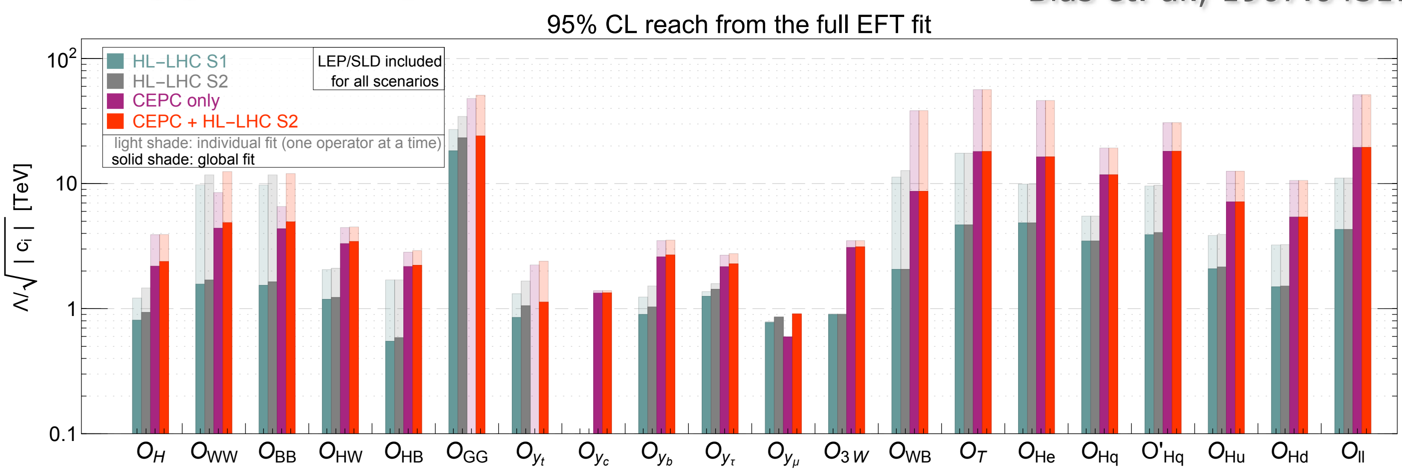
Ellis et. al., 2012.02779



tree-level: $\sim$ 17 operators

HL-LHC/Higgs factory

Blas et. al., 1907.04311



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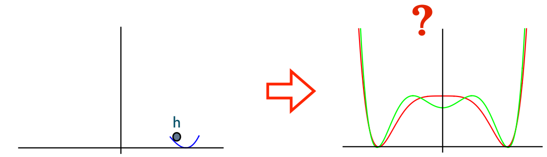
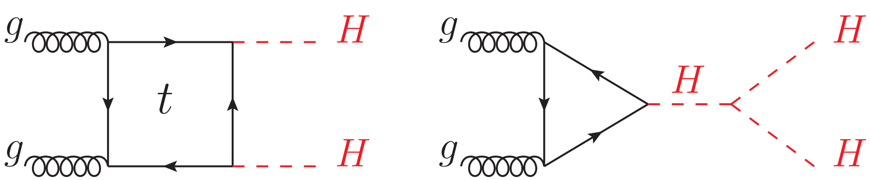
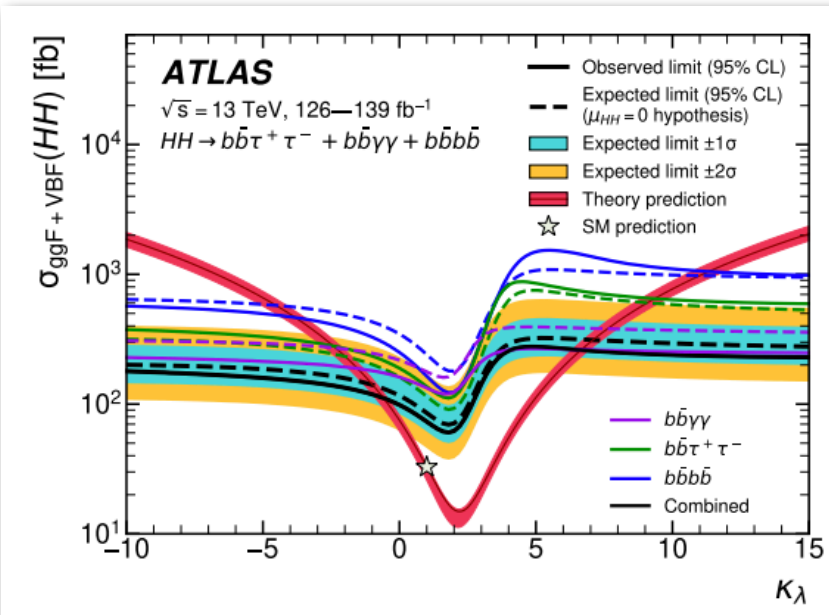
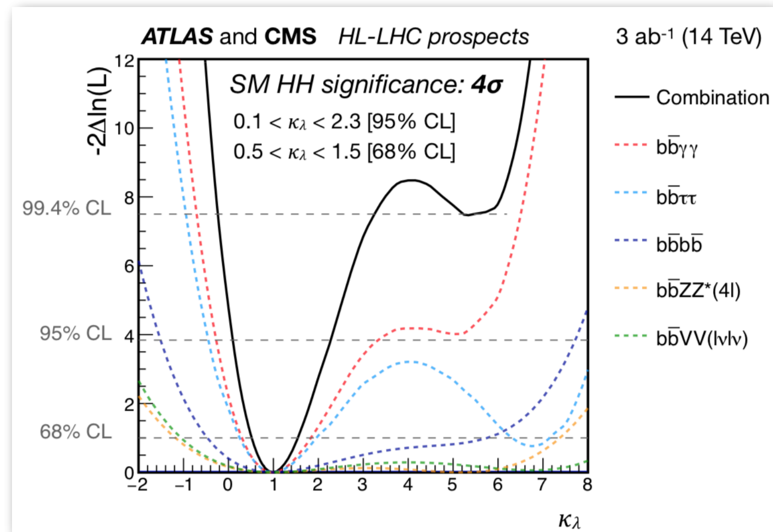
Higgs self-coupling





- small CS: 1000 times smaller than Higgs
- 120 K HH events at HL-LHC



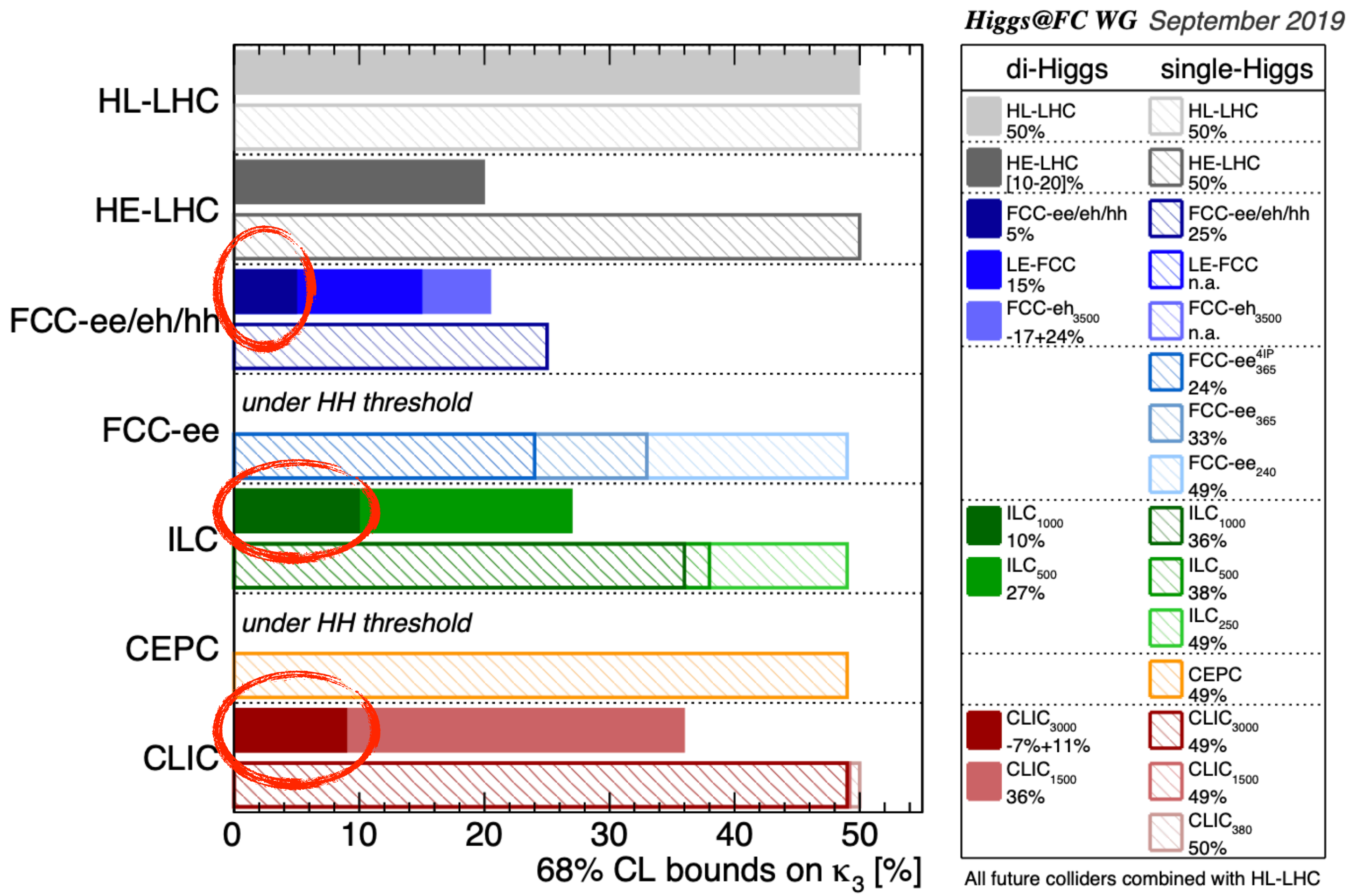


LHC $-0.4 < \kappa_\lambda < 6.3$

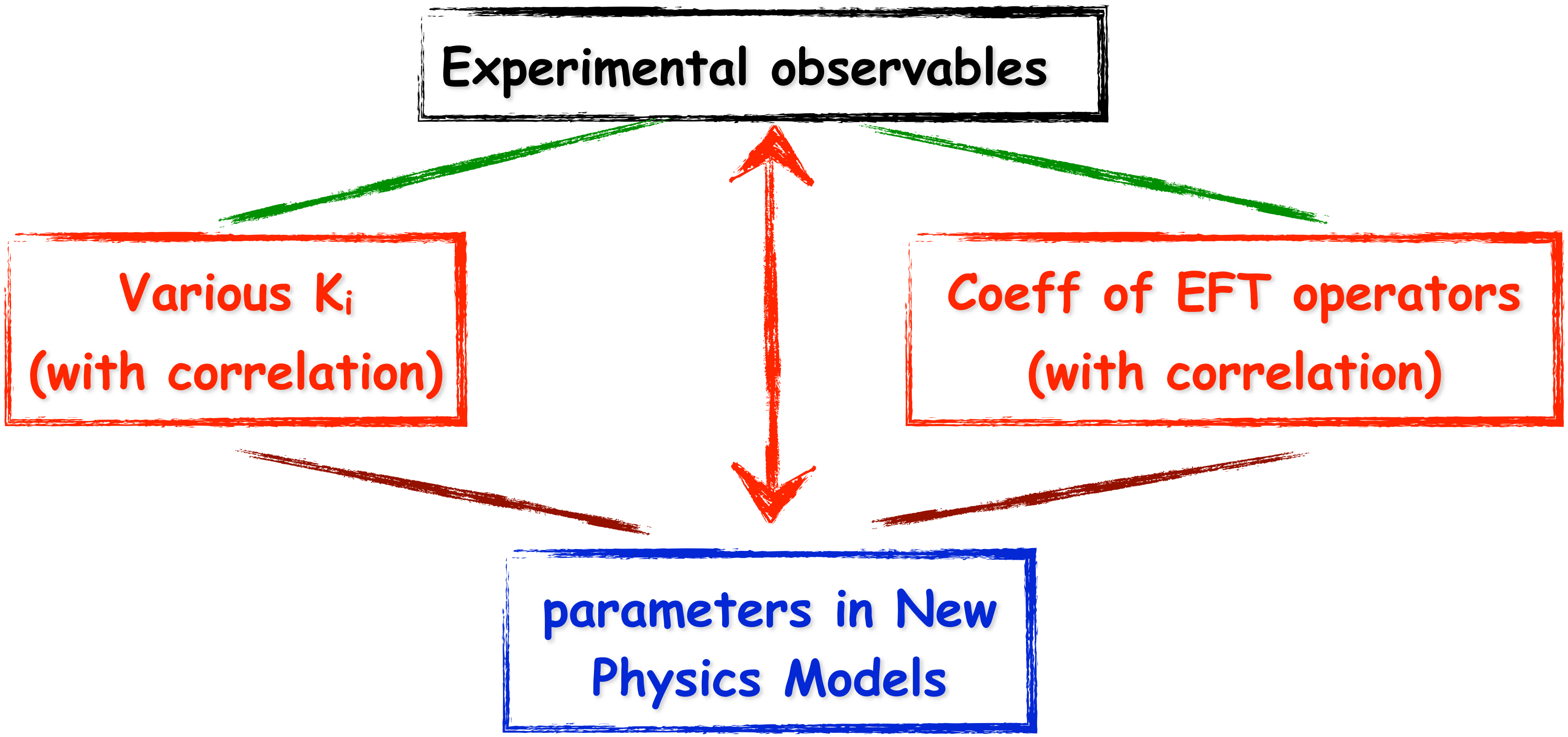
HL-LHC $0.5 < \kappa_\lambda < 1.5$

CERN-EP-2022-149

Higgs self-coupling

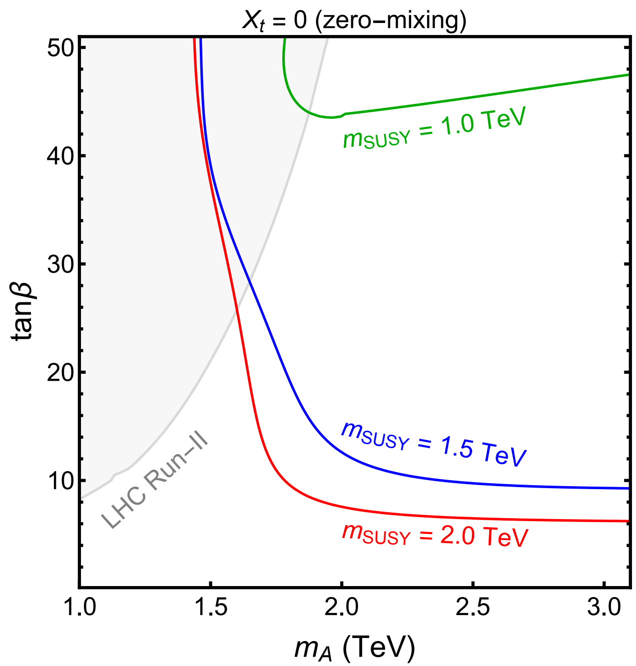


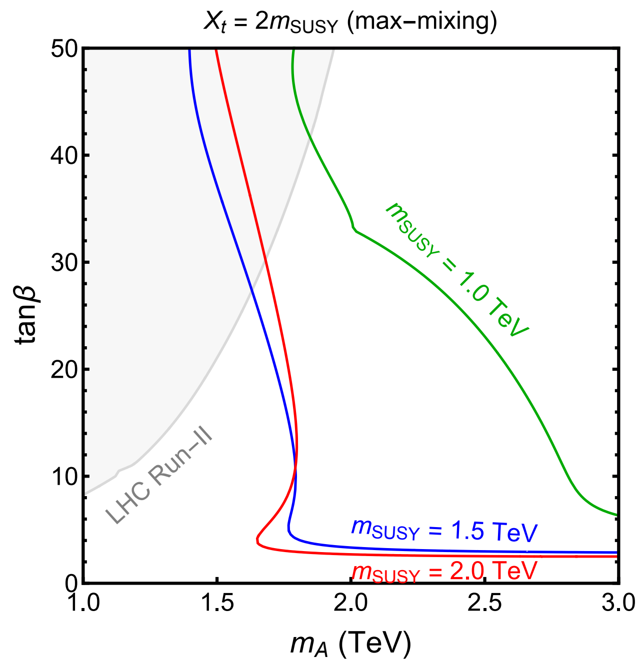
New Physics Implication

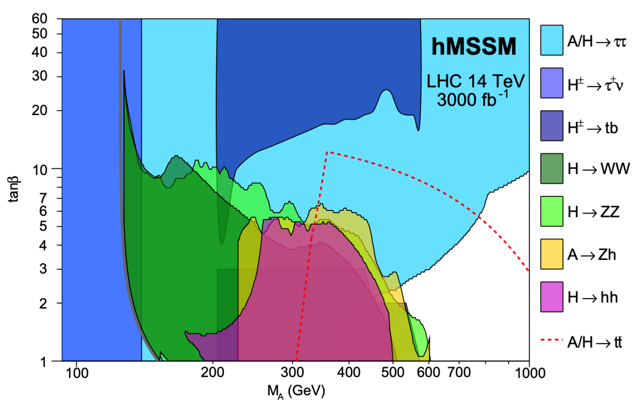


MSSM: m_A vs. $\tan\beta$

H. Li, SS, W. Su, J. Yang, 2010.09782



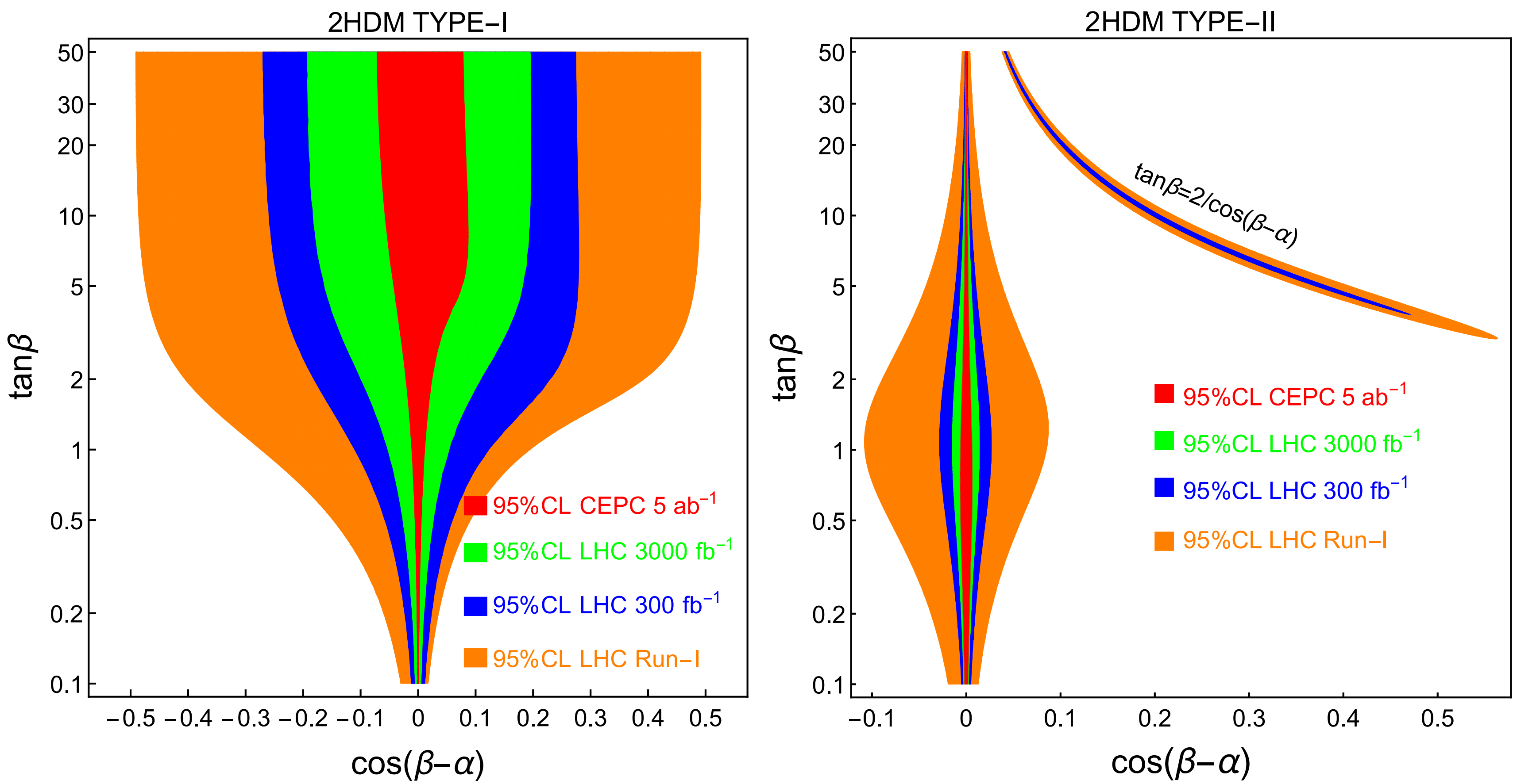




complementary to LHC direct search

Tree-level 2HDM fit

2HDM, LHC/CEPC fit



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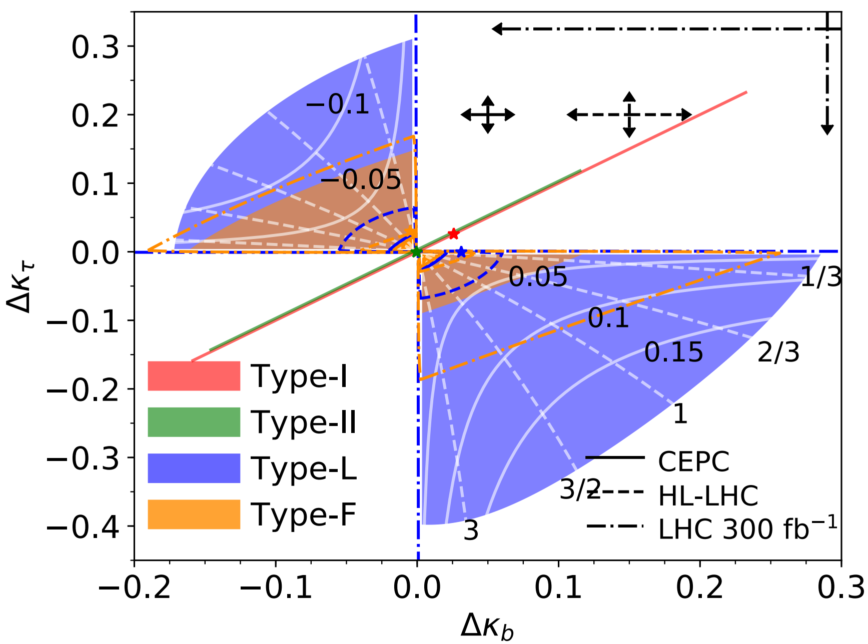
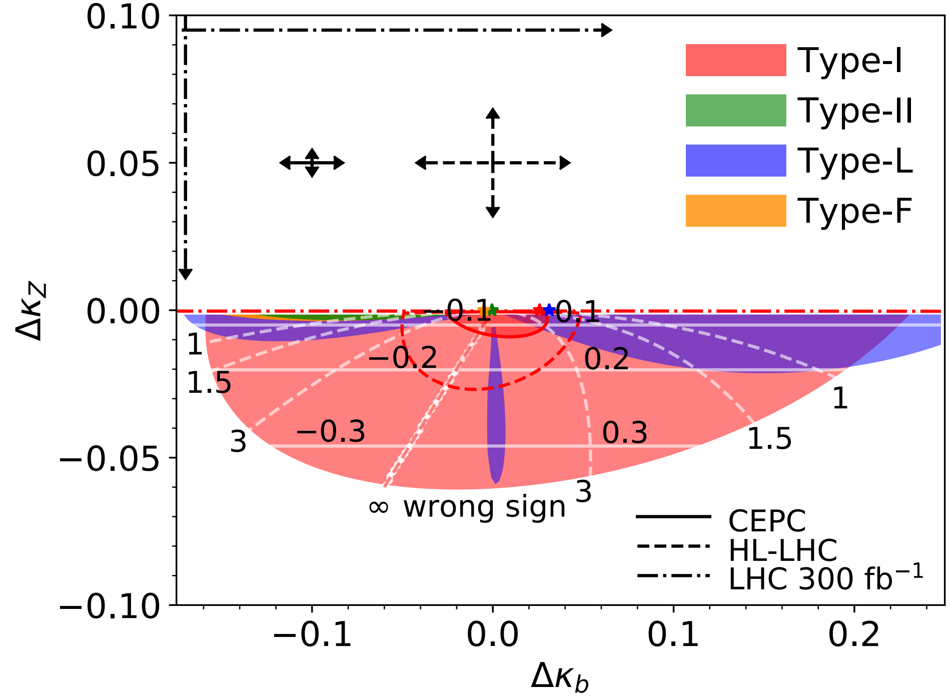
J. Gu, H. Li, Z. Liu, SS, W. Su, 1709.06103

Distinguish different types of 2HDMs

T. Han, S. Li, SS, W. Su, Y. Wu, 2008.05492





Conclusion

- The discovery of Higgs is a remarkable triumph in particle physics
- A light weakly coupled Higgs argues for new physics beyond SM
- Search for new physics calls for both high precision machine and high energy machine
- LHC Run II and beyond
  - Higgs precision measurements: mass, width, couplings, CP,…
- Future Higgs factories: FCC-ee, CEPC, ILC/CLIC…
  - Higgs coupling to sub-percent level
  - Higgs self-coupling 10% @ ILC, CLIC
- Implication: model independent (kappa, EFT), model dependent
- Higgs precision measurements complementary to direct search/Z pole precision