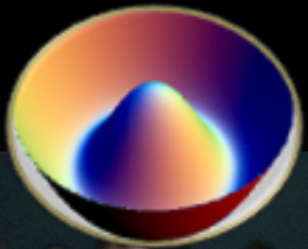
Les expériences du futur : potentiel de physique

Physique du Higgs



Road Map of Higgs Physics

Run-I

✓ Discovery of the Higgs boson at 125 GeV
✓ overall consistency with SM prediction

Run-2

Higgs boson as test of SM

✓ observe VBF and VH productions
✓ observe ττ and bb decay modes
✓ observe $t\bar{t}H$ production

Run-3

✓ measure Higgs couplings at <10%
◉ observe super-rare decays μμ and Zγ
◉ measure Higgs couplings at <5%

HL-LHC

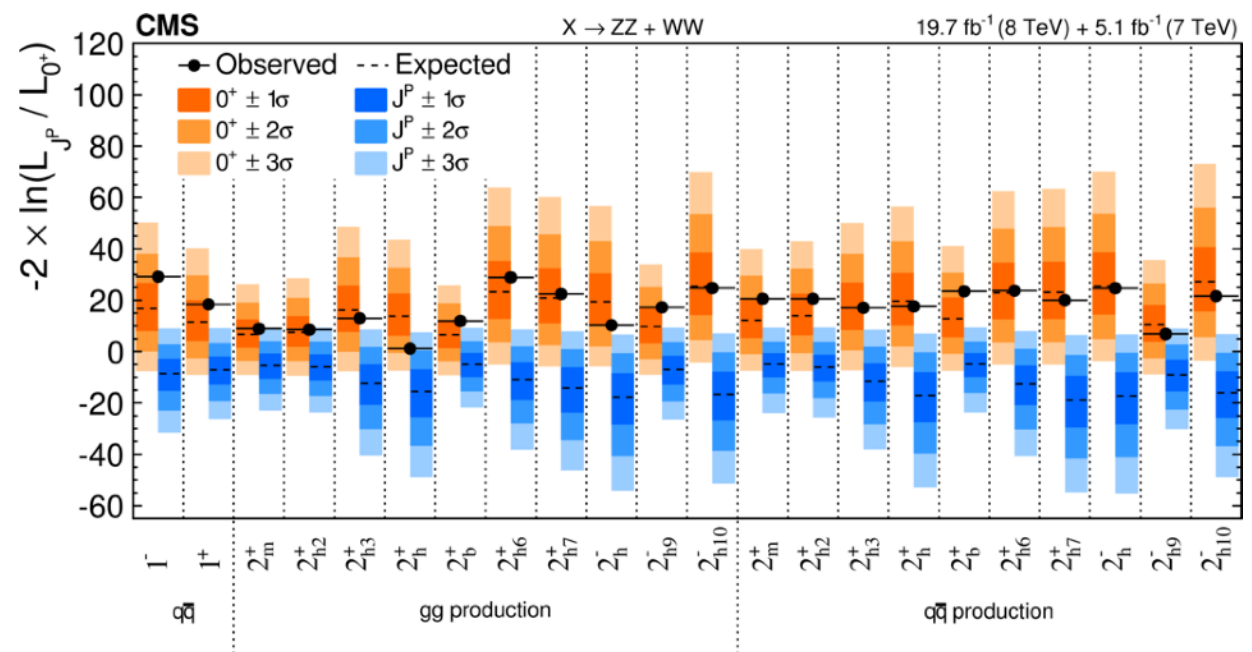
◉ observe di-Higgs production

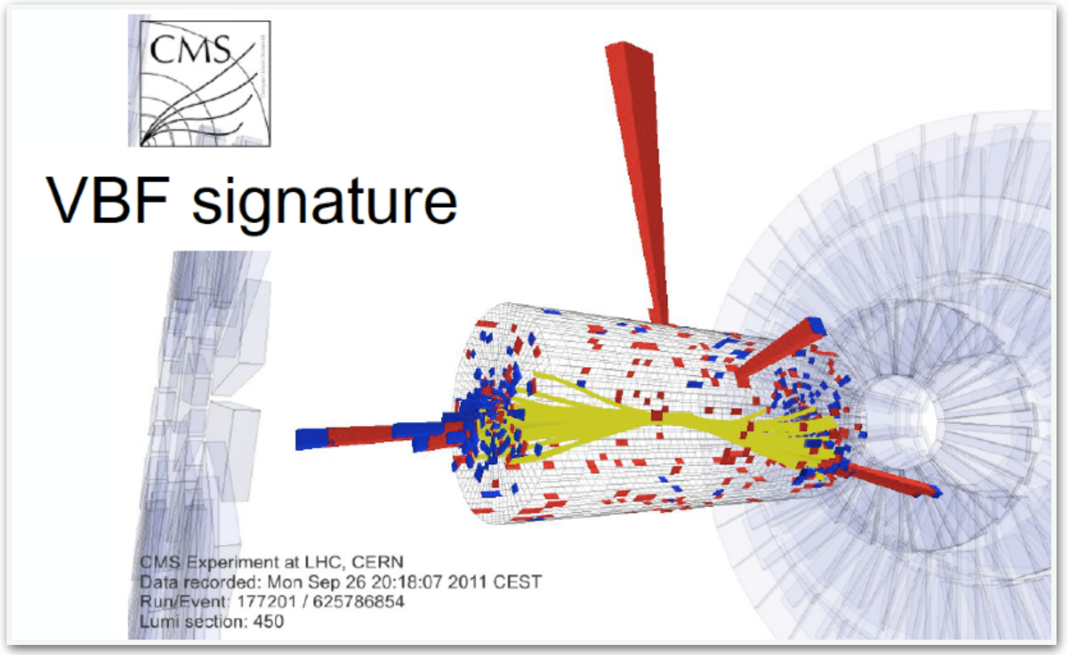
Higgs boson as a probe for New Physics

✓ constrain total width (via off-shell)
✓ constrain invisible width (via VBF)

and also

✓ investigate Higgs boson as DM portal
✓ constrain self-coupling
✓ investigate CP mixing in the Higgs sector
✓ investigate flavour-violating decays
✓ search for other partners in the scalar sector



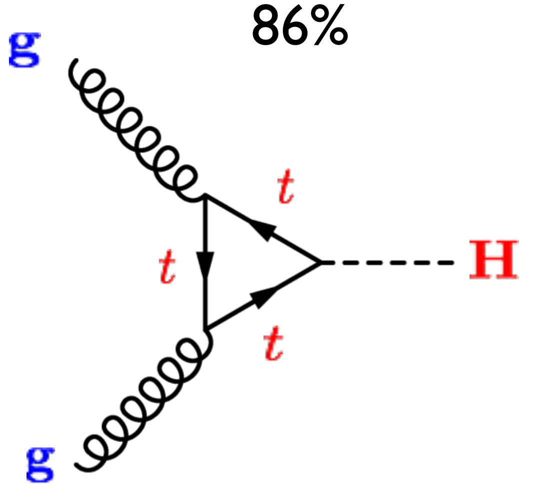


Higgs Boson Production and Decay

Main production modes

ggH

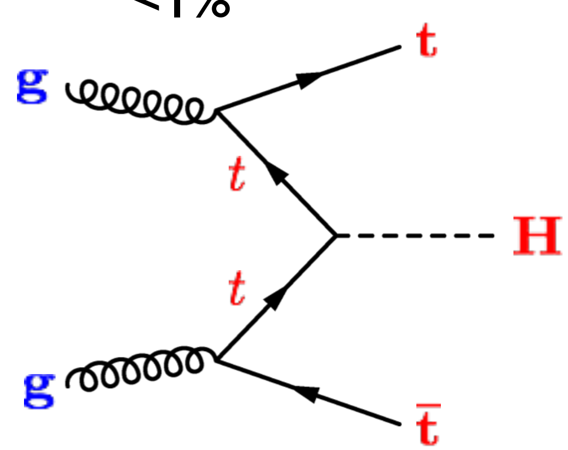
86%



« gluon fusion »

ttH

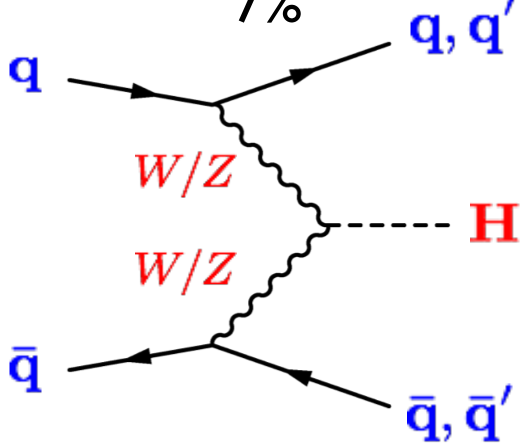
<1%



« in association with a top quark pair »

VBF

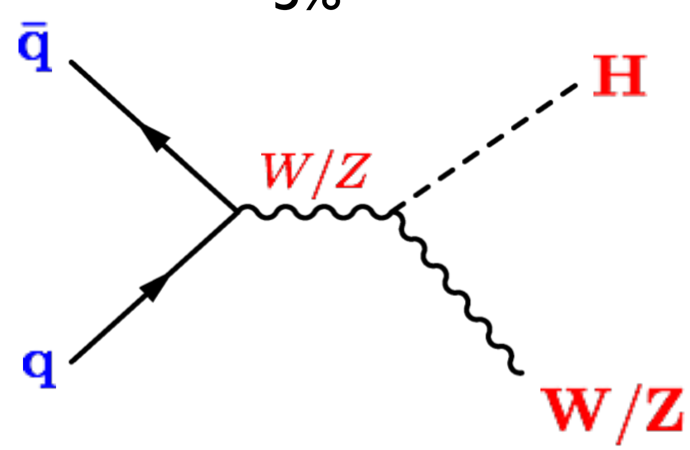
7%



« vector boson fusion »

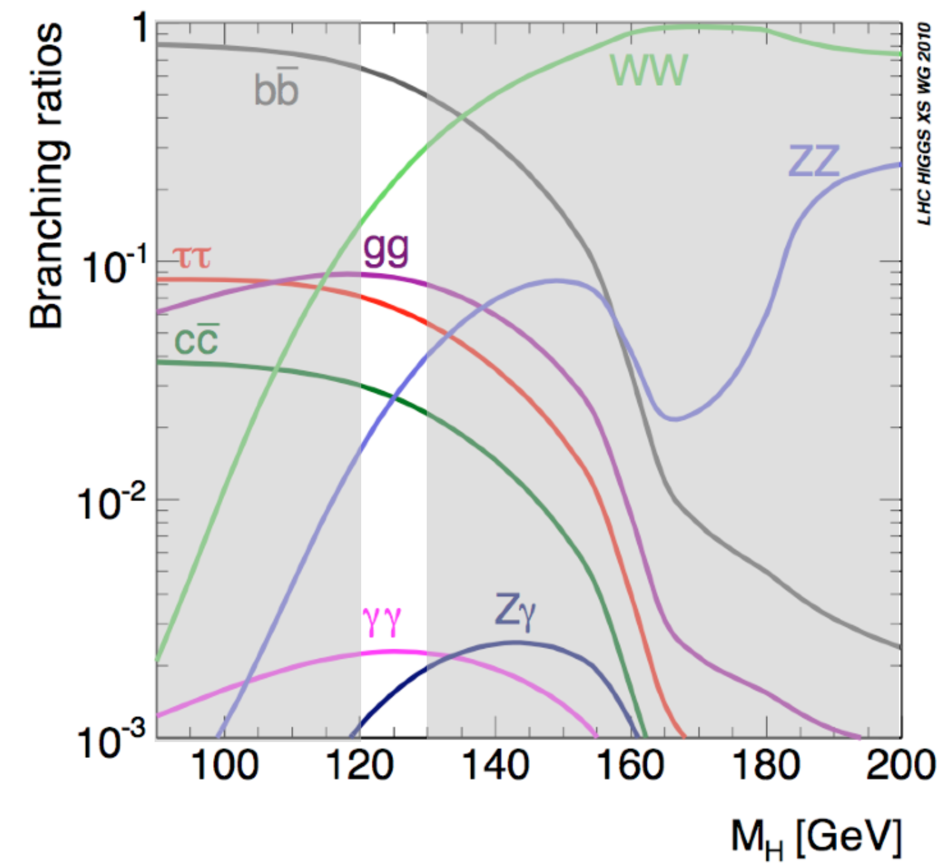
WH, ZH

5%



« in association with a W or Z boson »

Main decay channels



BF (m_H = 125 GeV)

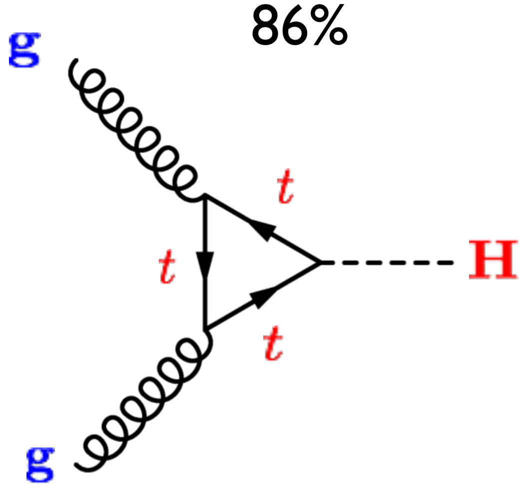
$H \to b\bar{b}$	58%
$H \to WW^*$	21%
$H \to \tau\tau$	6.4%
$H \to c\bar{c}$	2.9%
$H \to ZZ^*$	2.7%
$H \to \gamma\gamma$	0.25%
$H \to Z\gamma$	0.15%
$H \to \mu\mu$	0.022%

Higgs Boson Production and Decay

Main production modes

ggH

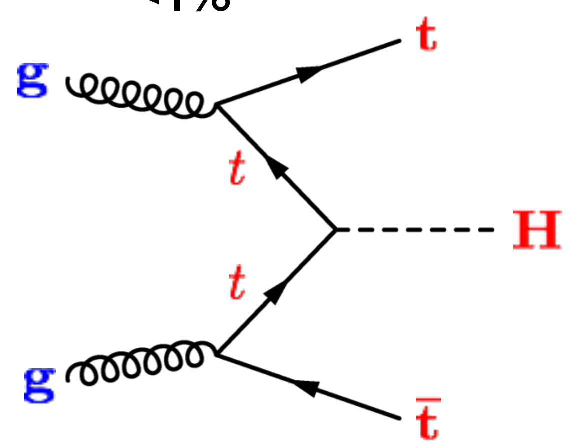
86%



« gluon fusion »

ttH

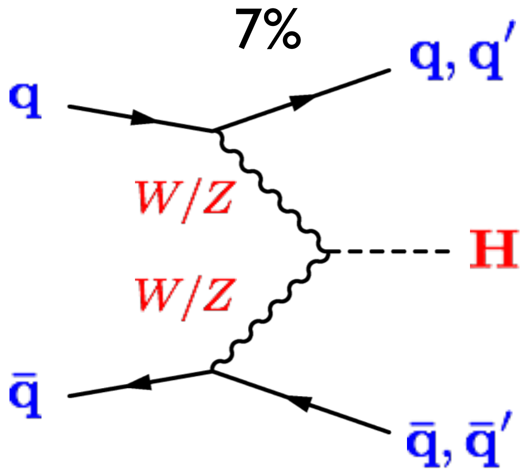
<1%



« in association with a top quark pair »

VBF

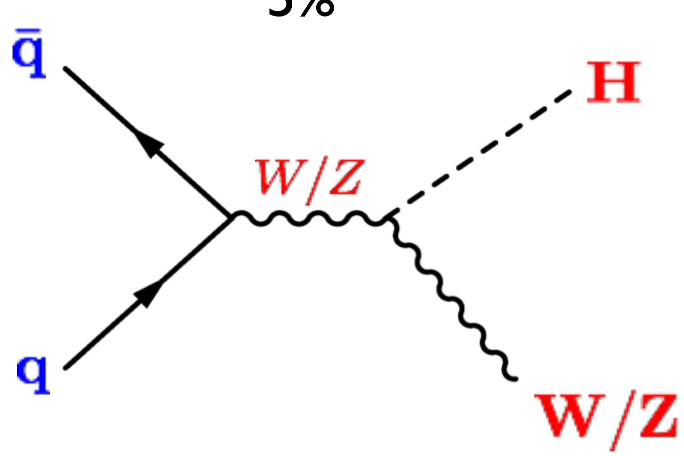
7%



« vector boson fusion »

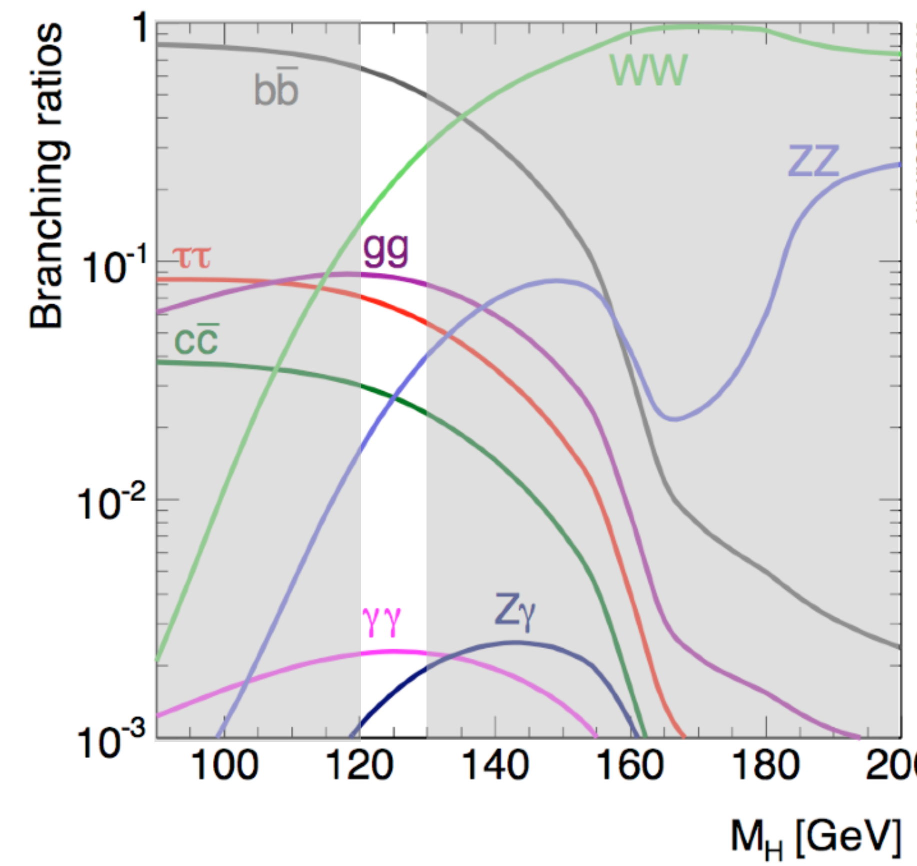
WH, ZH

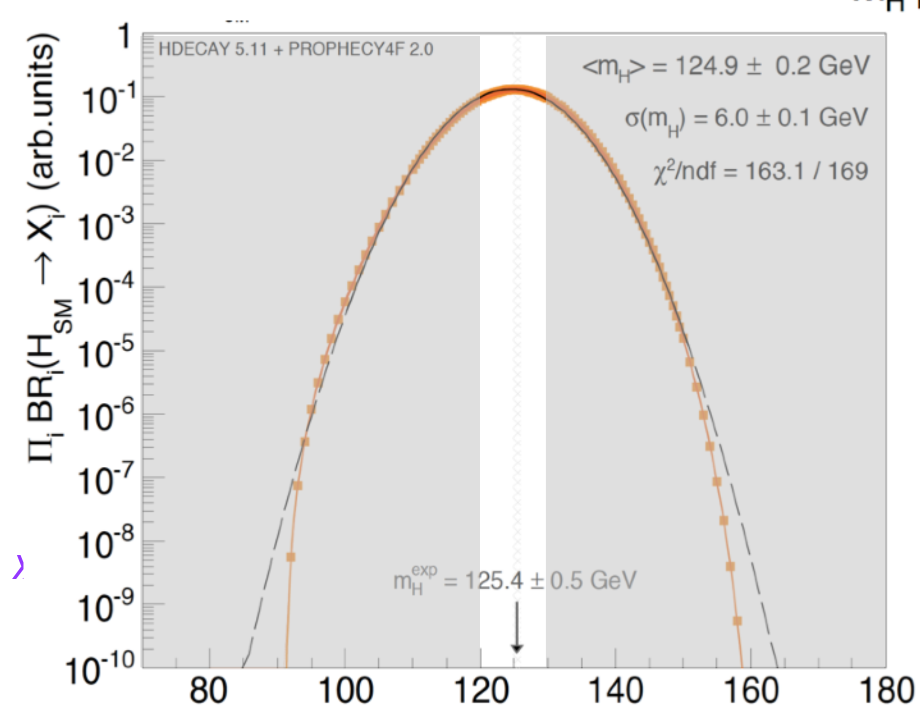
5%



« in association with a W or Z boson »

Main decay channels





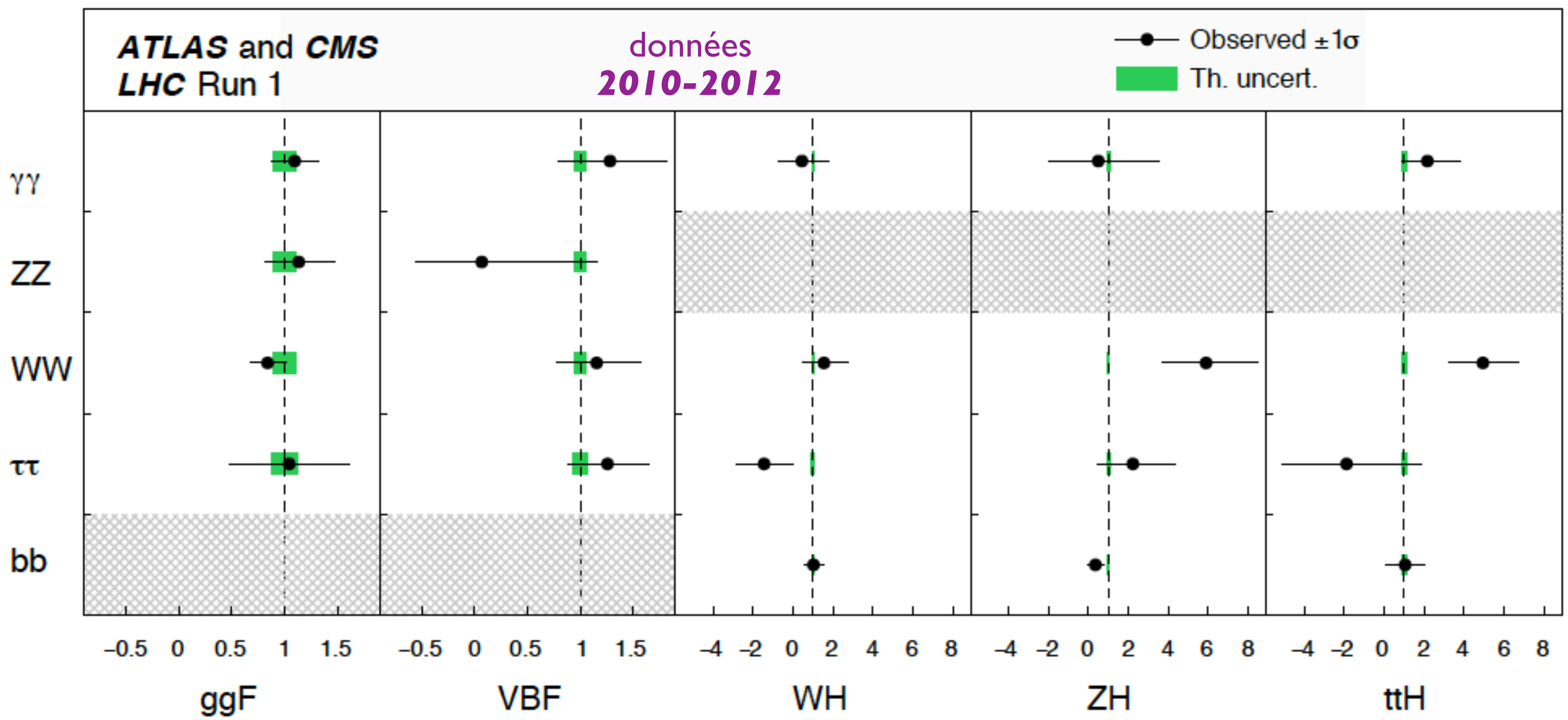
product of decay fractions

Production and Decay: Run-1

Combination of ATLAS and CMS Run 1 Results

production modes

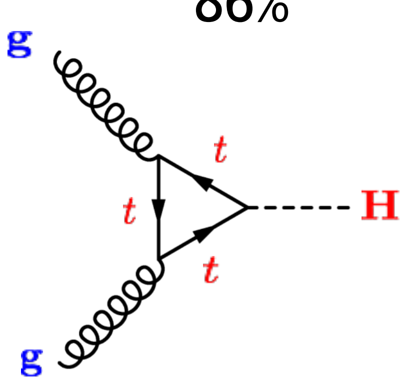
decay channels

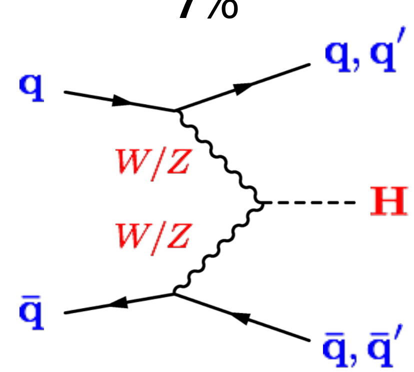


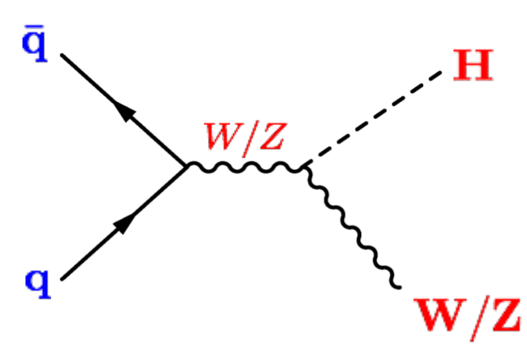
0.2%
2.7%
21%
6.4%
58%

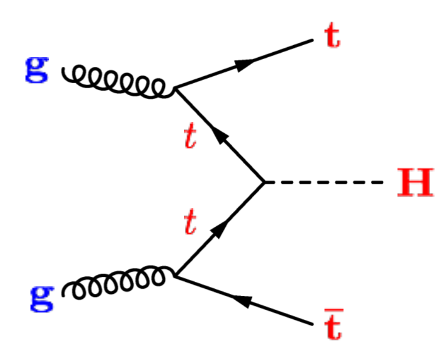
mesures rapportées aux prédictions théoriques (MS = 1)

ggF	VBF	WH / ZH	ttH
86%	7%	5%	<1%









theoretical uncertainties

ggH	15 %
VBF	5 %
VH	5 %
ttH	15 %

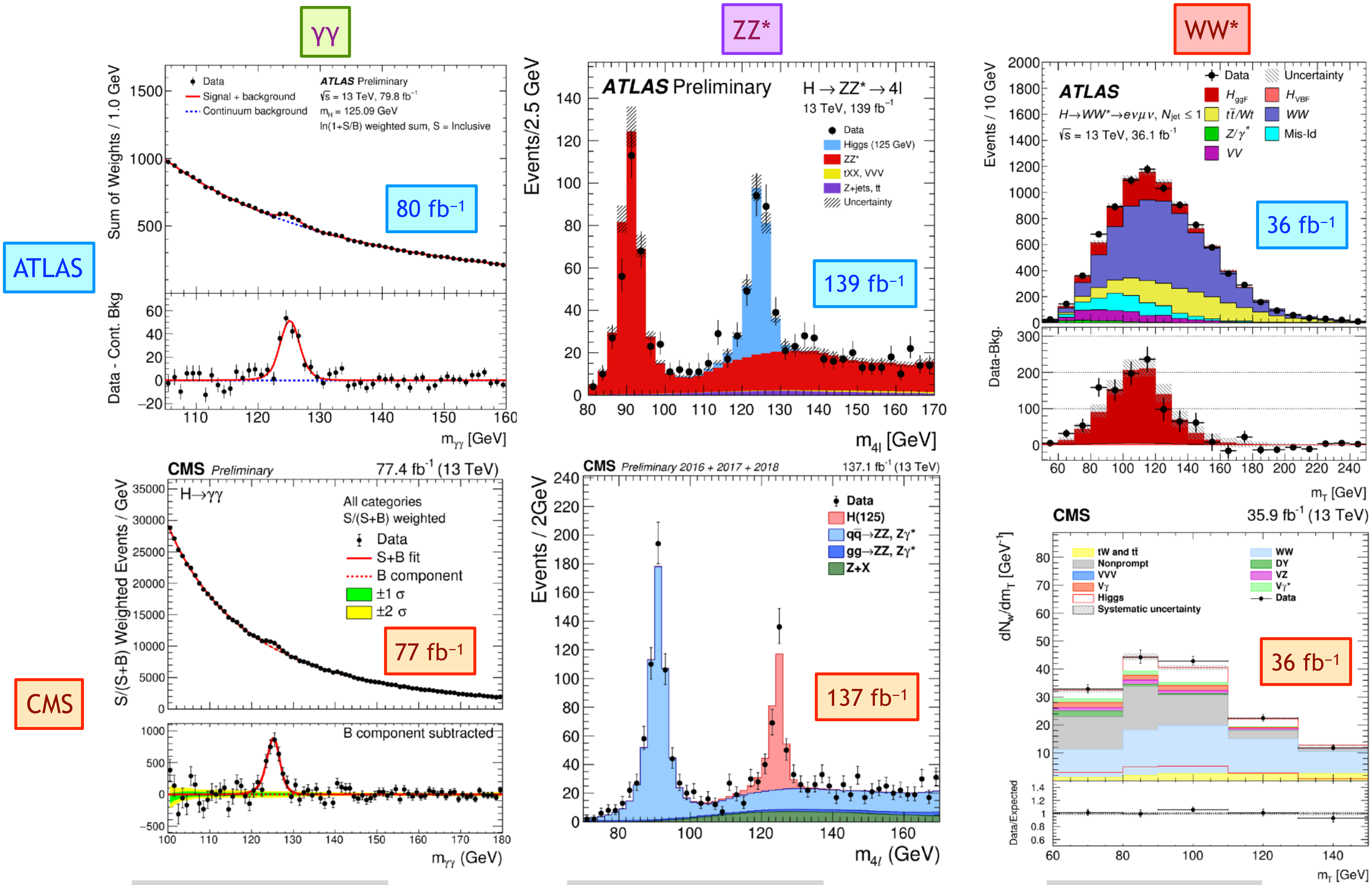
ggH : observation (>5σ) in γγ, ZZ and WW

VBF : strong indication (>3σ) in γγ, WW and ττ

VH : first indication (3σ) in bb

ttH : first hints

Higgs Decays to Bosons, Run-2



ATLAS-CONF-2018-028

CMS-PAS-HIG-18-029

ATLAS-CONF-2019-025

CMS-PAS-HIG-19-001

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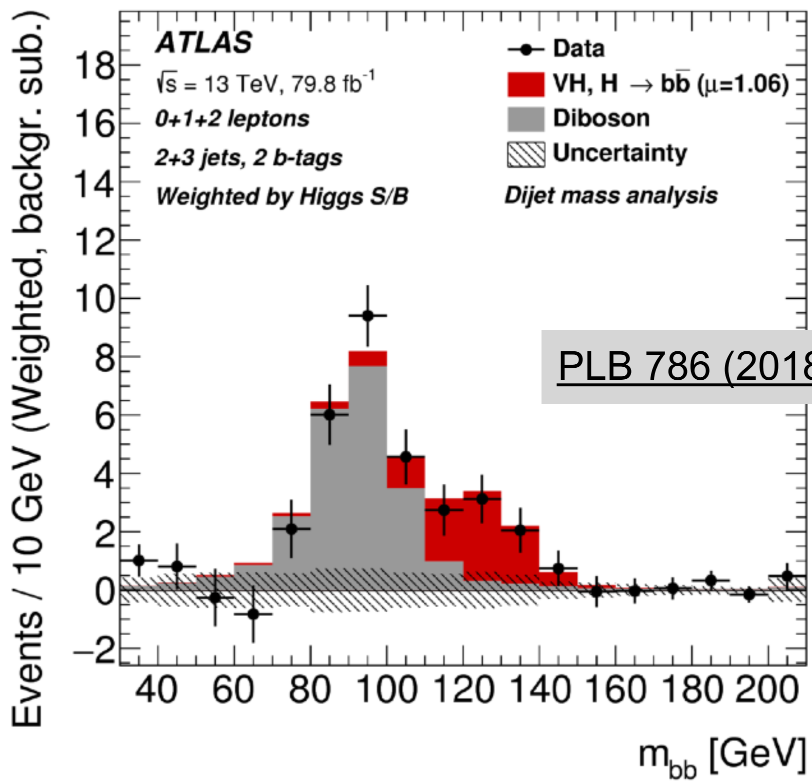
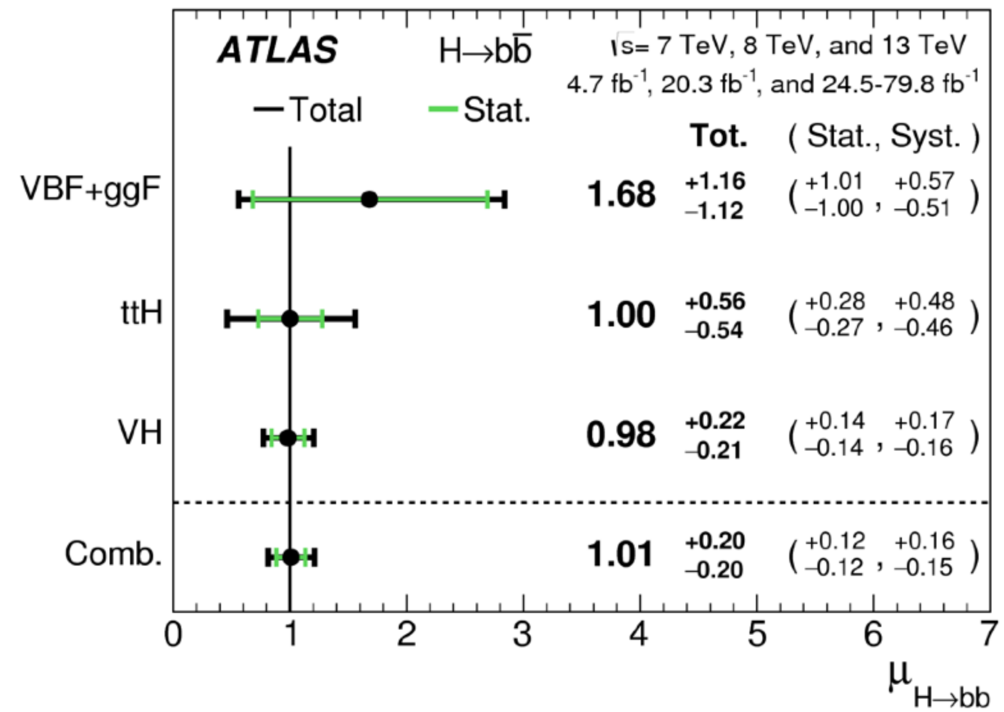
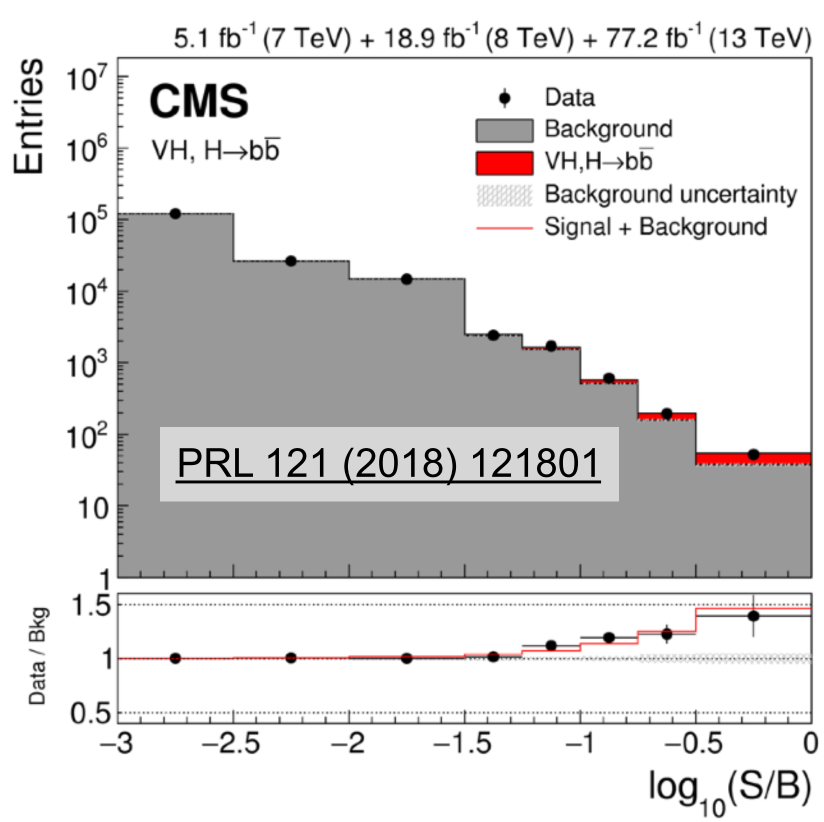
Observation of VH ($H \to b\bar{b}$)

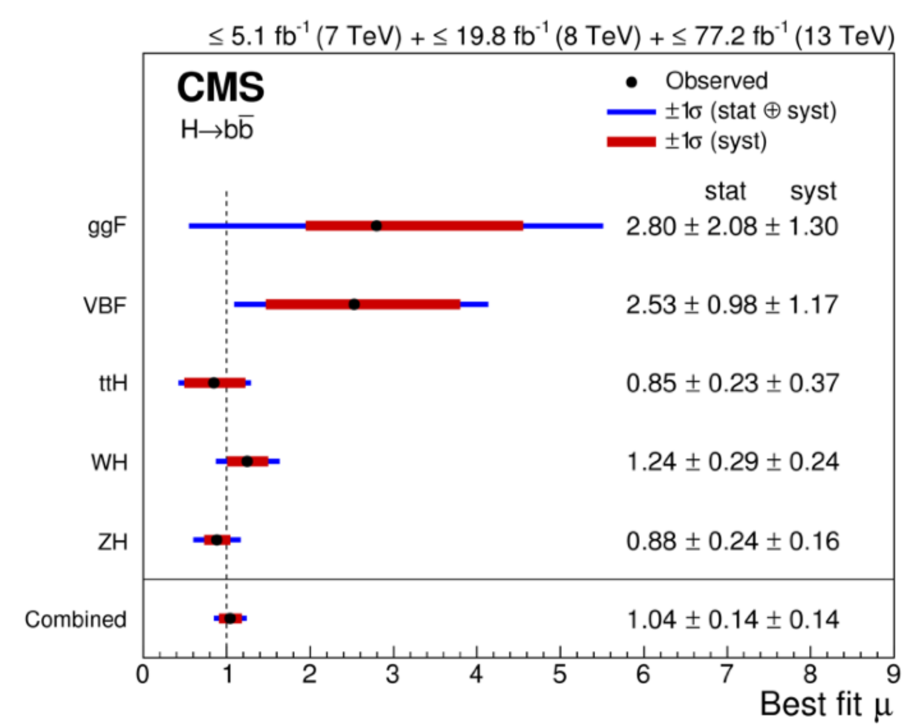




ATLAS 13 TeV
2016-2017
L = 36-80 fb⁻¹

CMS 7-8-13 TeV
2010-2017
5+19+77 fb⁻¹





ttH Production, Run-2

☛ Essential to constrain directly the top Yukawa coupling

CMS
2016-2017
36+42 fb⁻¹

Four main channels

Systematics-limited

H → $b\bar{b}$

- high yield
- theory limited $t\bar{t}$+HF bkg

In between

multi-leptons

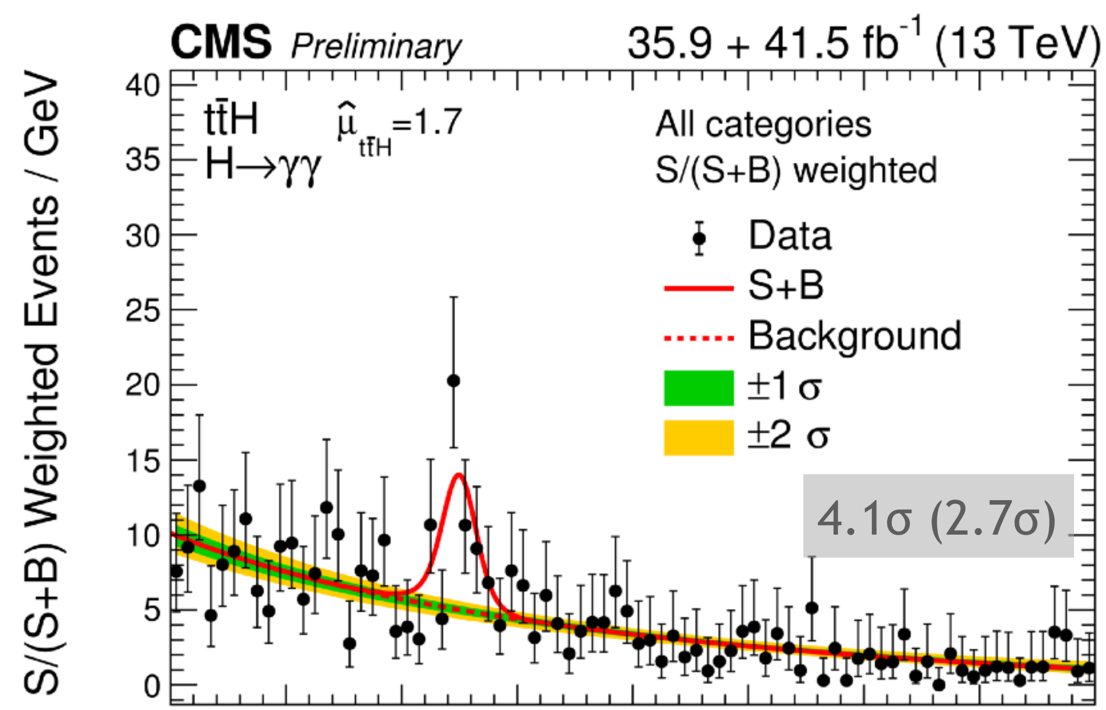
- moderate yield
- reducible background

Statistics-limited

H → 4ℓ

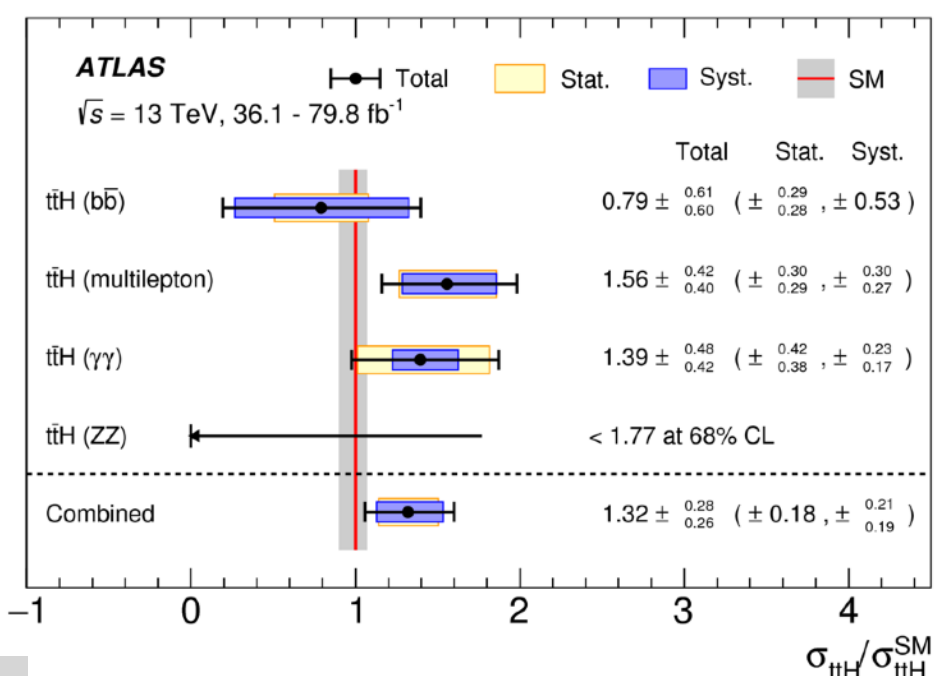
H → γγ

CMS-PAS-HIG-18-018



4.1σ (2.7σ)

ATLAS
2016-2017
36-80 fb⁻¹



with Run-1
6.3σ (5.1σ)

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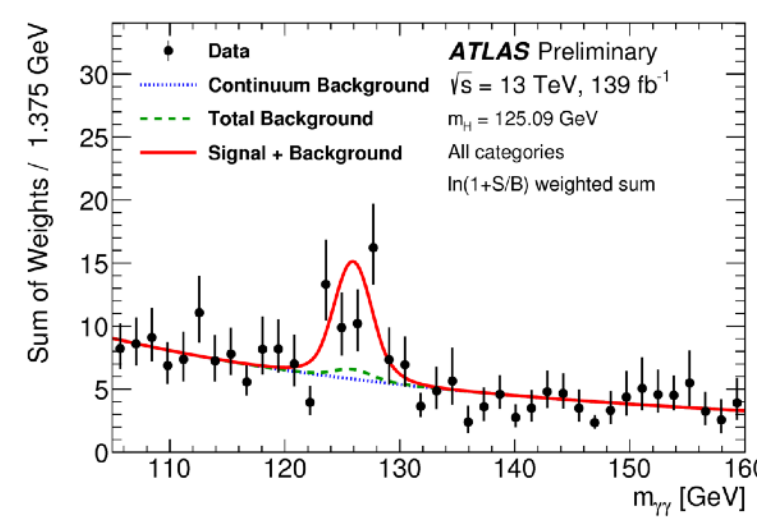


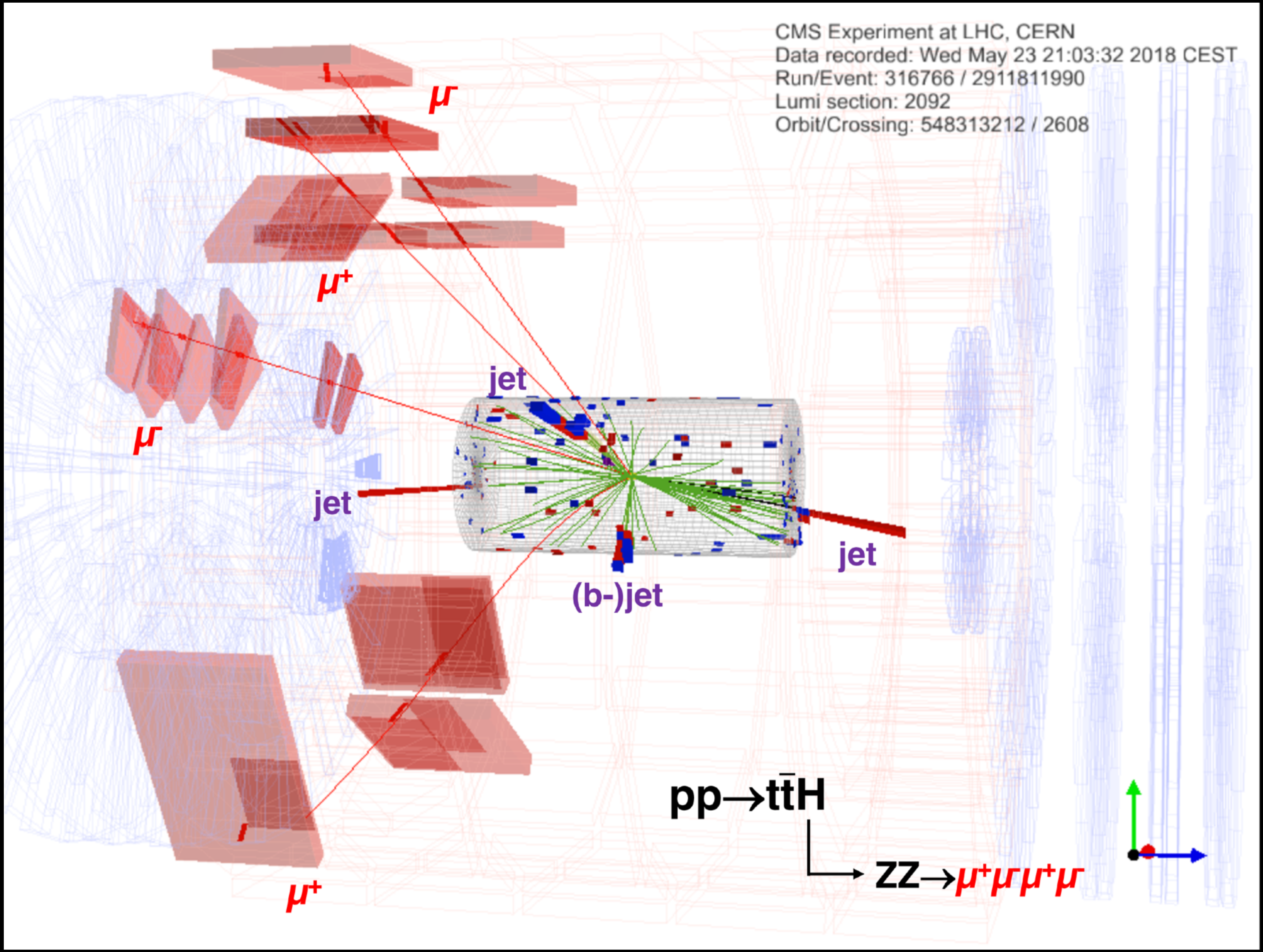
ATLAS Run-2
139 fb⁻¹

4.9σ (4.2σ)

ATLAS-CONF-2019-004

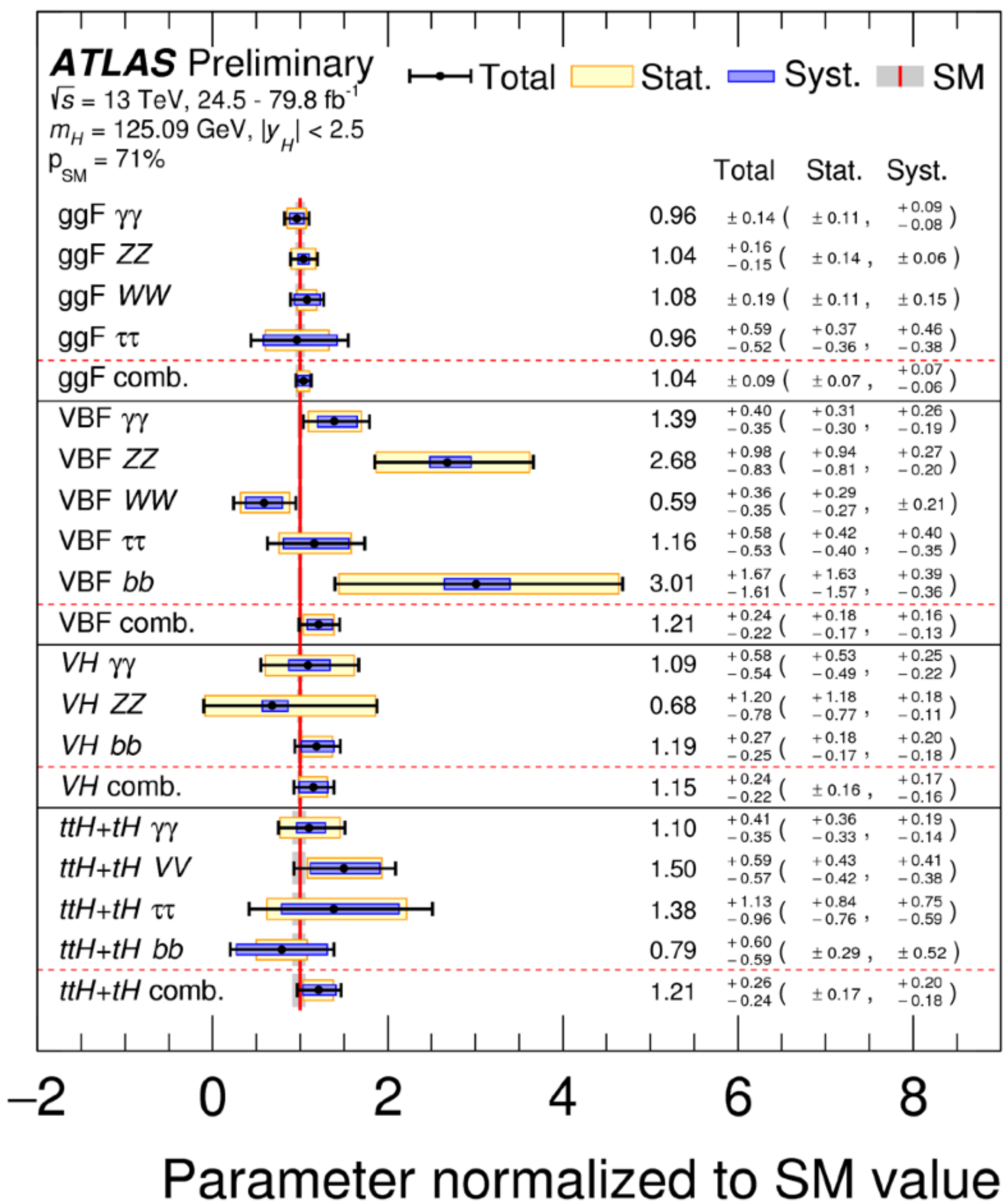
Combined observations by both experiments

ttH (H → 4ℓ) Candidate in CMS



Production and Decays: Partial Run-2

ATLAS 2016-2017
L = 24-80 fb^{-1}



9%

6.5σ (5.3σ)

5.3σ (4.7σ)

5.8σ (5.4σ)

$$\mu = 1.11^{+0.09}_{-0.08}$$

(stat ≈ syst ≈ theory)

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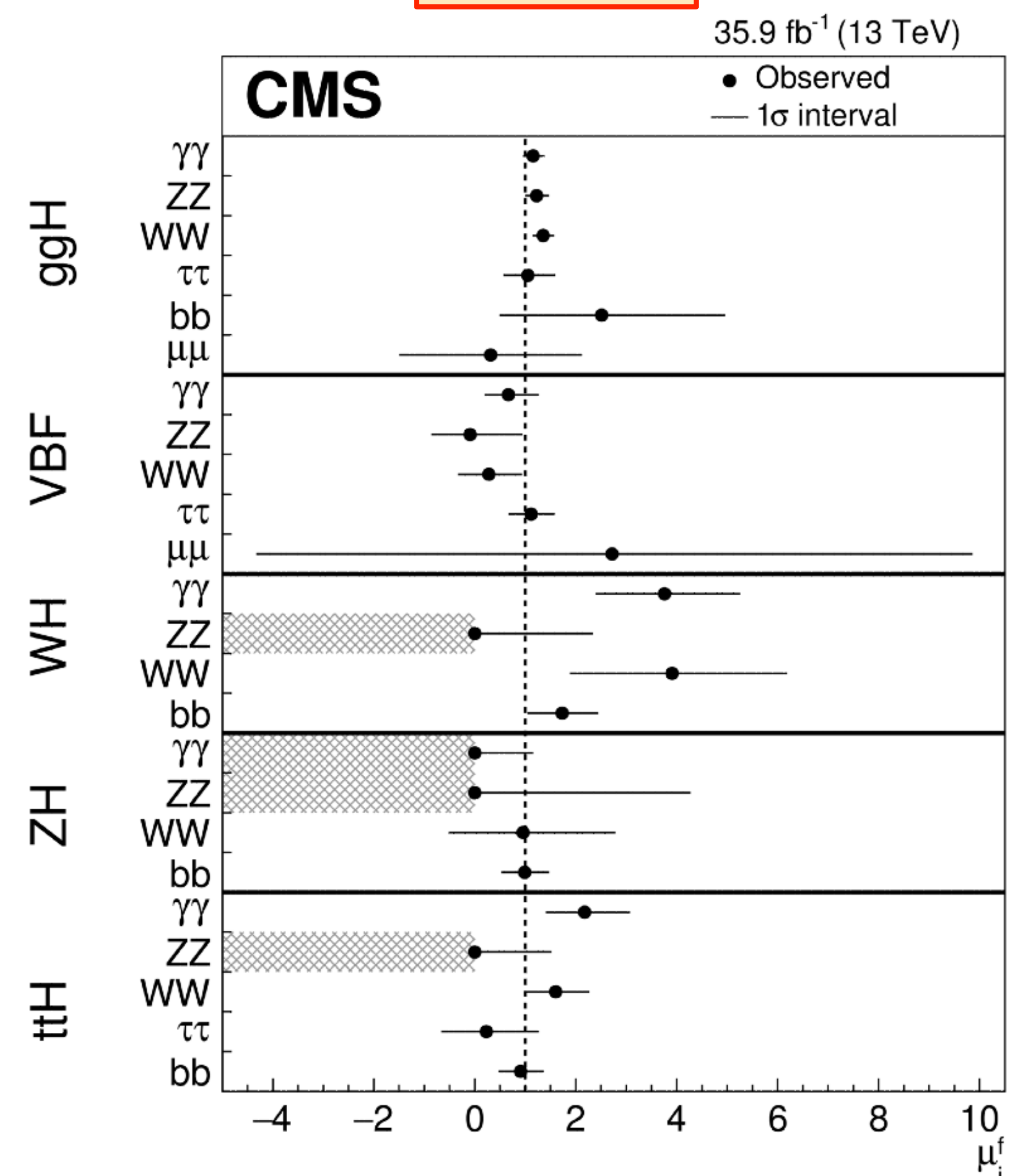
CMS 2016
L = 36 fb^{-1}



$$\mu = 1.17 \pm 0.10$$

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Patterns of Deviation

Different new physics (NP) models lead to different **patterns of deviations**

The size of deviations depends on the NP scale

MSSM and 2-Higgs doublets models (2HD)

- one light CP-even state (h) with SM couplings
- deviations induced through mixing with extra Higgs states
- types I, II, X and Y: discrete symmetries to protect FCNC

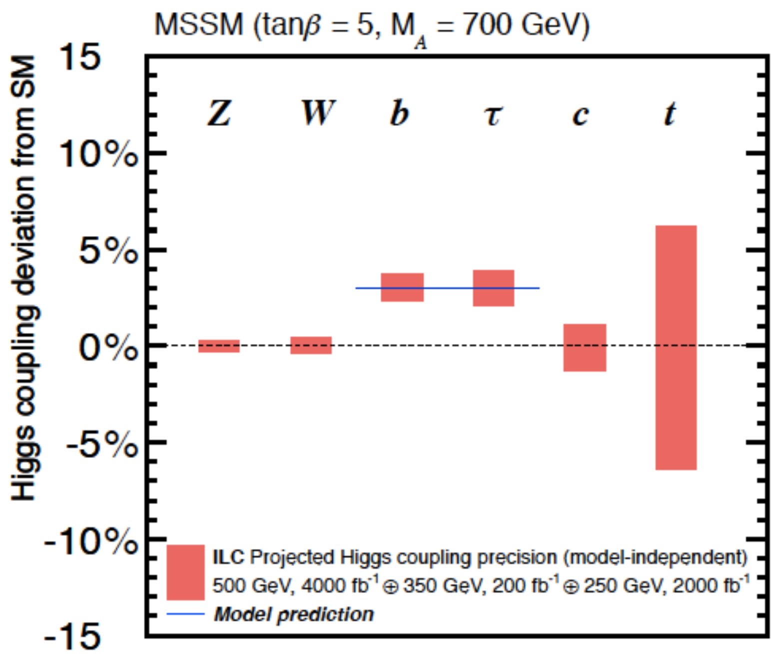
$$\frac{g_{\rm hbb}}{g^{\rm SM}_{\rm hbb}} = \frac{g_{{\rm h}\tau\tau}}{g^{\rm SM}_{{\rm h}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\,{\rm TeV}}{m_{\rm A}}\right)^2$$

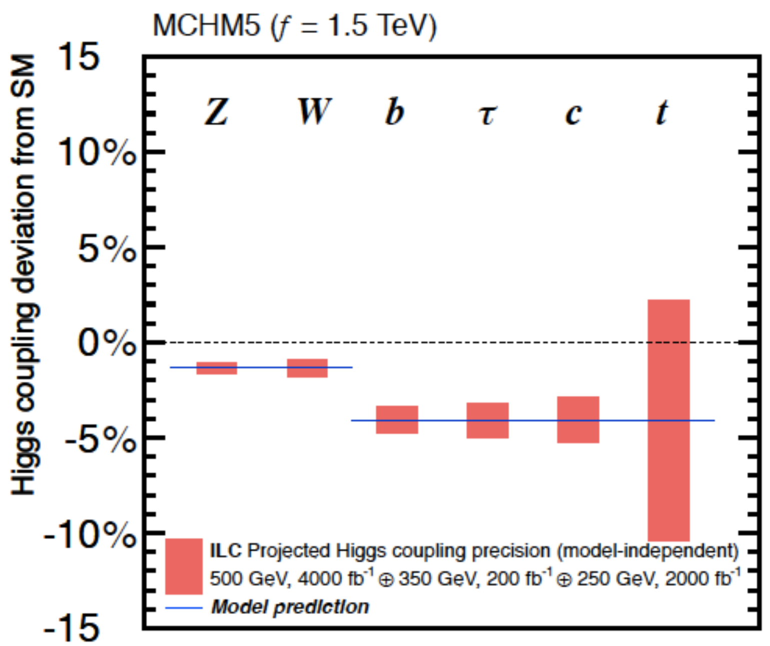
Composite Higgs

- solves hierarchy problem
- all coupling reduced according to composite scale f

$$\frac{g_{\rm hff}}{g^{\rm SM}_{\rm hff}} = \frac{g_{\rm hVV}}{g^{\rm SM}_{\rm hVV}} \simeq 1 - 3\% \left(\frac{1\,{\rm TeV}}{\rm f}\right)^2$$

Percent level precision is required !

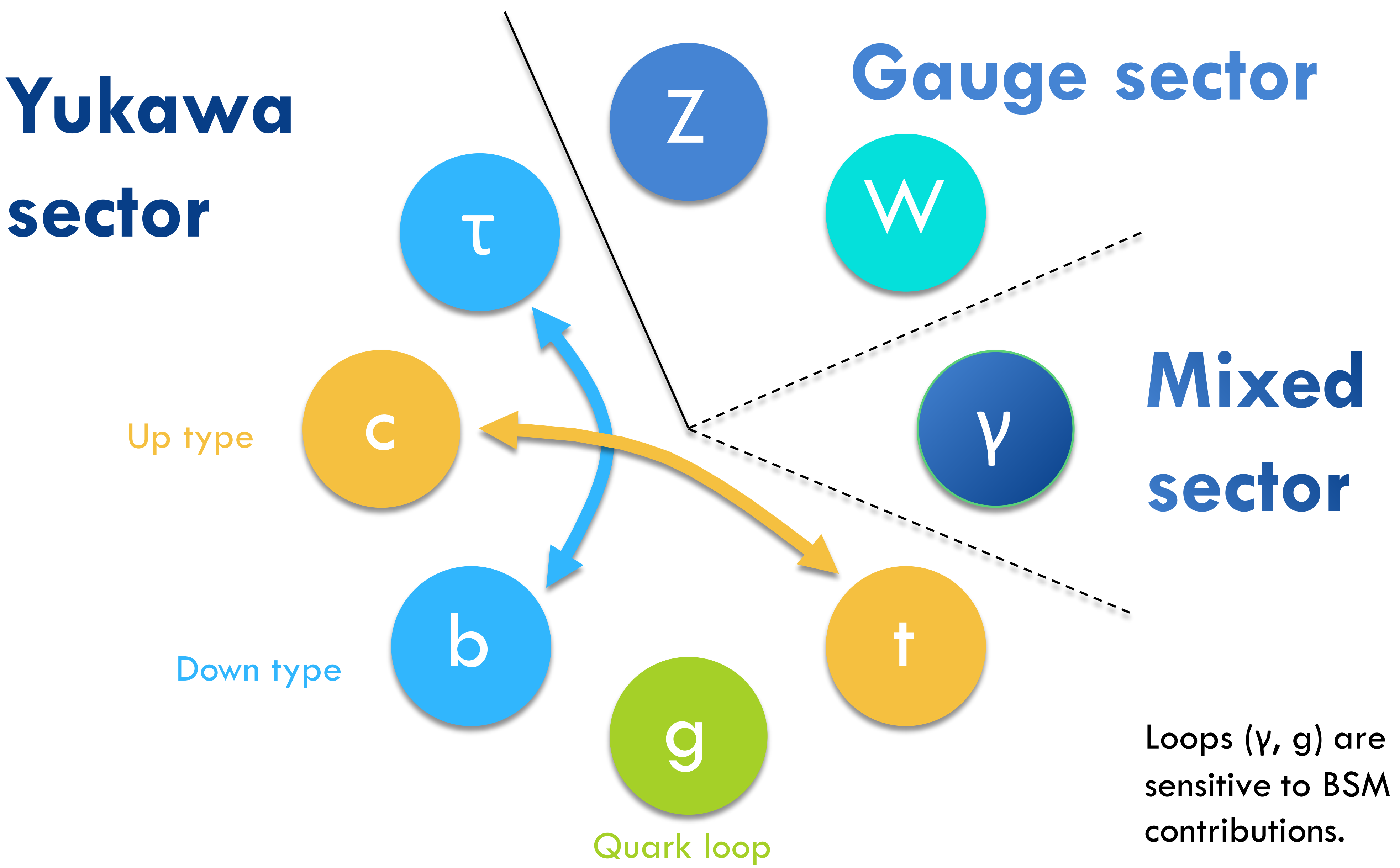




Coupling precision
after full ILC running

credit: M.L. Mangano

Higgs Coupling Sectors



Next: from signal strength measurements to constraints on Higgs couplings

The Kappa Framework

Parameterisation based on **multiplicative coupling modifiers**, used to characterise Higgs boson couplings

- *tree-level* couplings to particles: κ_W, κ_Z, κ_t, κ_b, κ_c, κ_τ, κ_μ
- additional *effective* couplings: κ_g, κ_γ, $\kappa_{Z\gamma}$

Way to identify potential deviations in HIggs couplings to bosons and fermions

Link to signal strength measurements:

$$\mu_{if} \equiv \frac{\sigma_i \times B_f}{(\sigma_i \times B_f)^{\rm SM}} = \frac{\kappa_i^2 \times \kappa_f^2}{\kappa_{\rm H}^2}, \text{ where } \begin{cases} \kappa_i^2 = \sigma_i/\sigma_i^{\rm SM} \\ \kappa_f^2 = \Gamma_f/\Gamma_f^{\rm SM} \end{cases}, \text{ and } \kappa_{\rm H}^2 = \Gamma_{\rm H}/\Gamma_{\rm H}^{\rm SM}$$

assumes narrow width approximation

Generalisation to incorporate a BSM (invisible) width and untagged decays:

$$\Gamma_{\rm H} = \frac{\kappa_{\rm H}^2 \times \Gamma_{\rm H}^{\rm SM}}{1 - (B^{\rm inv} + B^{\rm unt})}, \text{ where } \kappa_{\rm H}^2 = \sum_f B_f^{\rm SM} \kappa_f^2$$

Untagged decays: rare SM (or BSM) decays that are not directly probed by searches

Ratio of coupling modifiers, immune from dependance in Γ_H

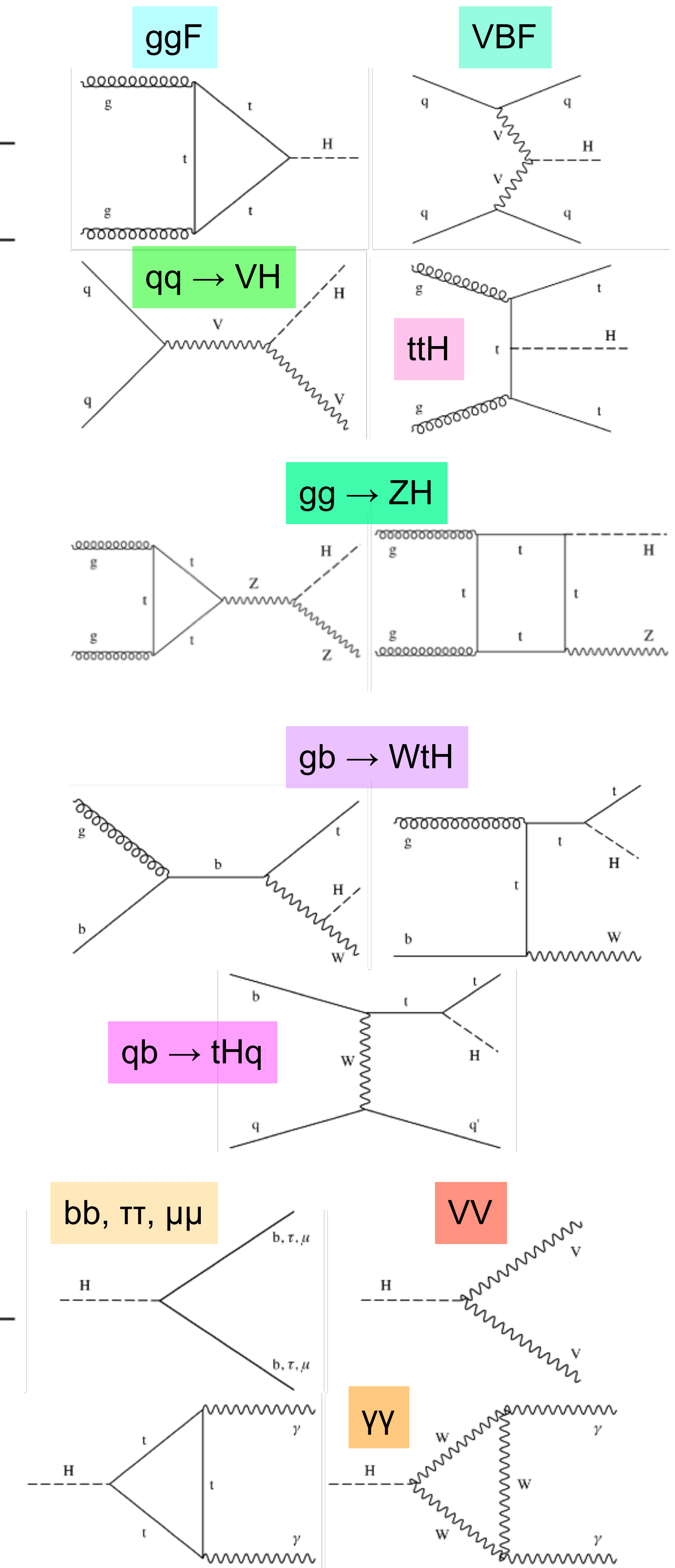
$$\lambda_{ij} = \kappa_i/\kappa_j \text{ , compared to } \kappa_{\rm gZ} = \kappa_{\rm g}\kappa_{\rm Z}/\kappa_{\rm H}$$

Resolved and Effective Kappas

production modes

decay channels

	Loops	Interference	Effective scaling factor	Resolved scaling factor
Production				
$\sigma(\mathrm{ggH})$	✓	g-t	κ_g^2	$1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.038\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	—	—		$0.73\kappa_W^2 + 0.27\kappa_Z^2$
$\sigma(\mathrm{WH})$	—	—		κ_W^2
$\sigma(qq/qg \to \mathrm{ZH})$	—	—		κ_Z^2
$\sigma(gg \to \mathrm{ZH})$	✓	Z-t		$2.46\kappa_Z^2 + 0.47\kappa_t^2 - 1.94\kappa_Z\kappa_t$
$\sigma(\mathrm{ttH})$	—	—		κ_t^2
$\sigma(gb \to \mathrm{WtH})$	—	W-t		$2.91\kappa_t^2 + 2.31\kappa_W^2 - 4.22\kappa_t\kappa_W$
$\sigma(qb \to \mathrm{tHq})$	—	W-t		$2.63\kappa_t^2 + 3.58\kappa_W^2 - 5.21\kappa_t\kappa_W$
$\sigma(\mathrm{bbH})$	—	—		κ_b^2
Partial decay width				
Γ^{ZZ}	—	—		κ_Z^2
Γ^{WW}	—	—		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	W-t	κ_γ^2	$1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	—	—		κ_τ^2
Γ^{bb}	—	—		κ_b^2
$\Gamma^{\mu\mu}$	—	—		κ_μ^2
Total width for $\mathcal{B}_{\mathrm{BSM}} = 0$				
Γ_H	✓	—	κ_H^2	$0.58\kappa_b^2 + 0.22\kappa_W^2 + 0.08\kappa_g^2 + 0.06\kappa_\tau^2 + 0.026\kappa_Z^2 + 0.029\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0015\kappa_{Z\gamma}^2 + 0.00025\kappa_s^2 + 0.00022\kappa_\mu^2$



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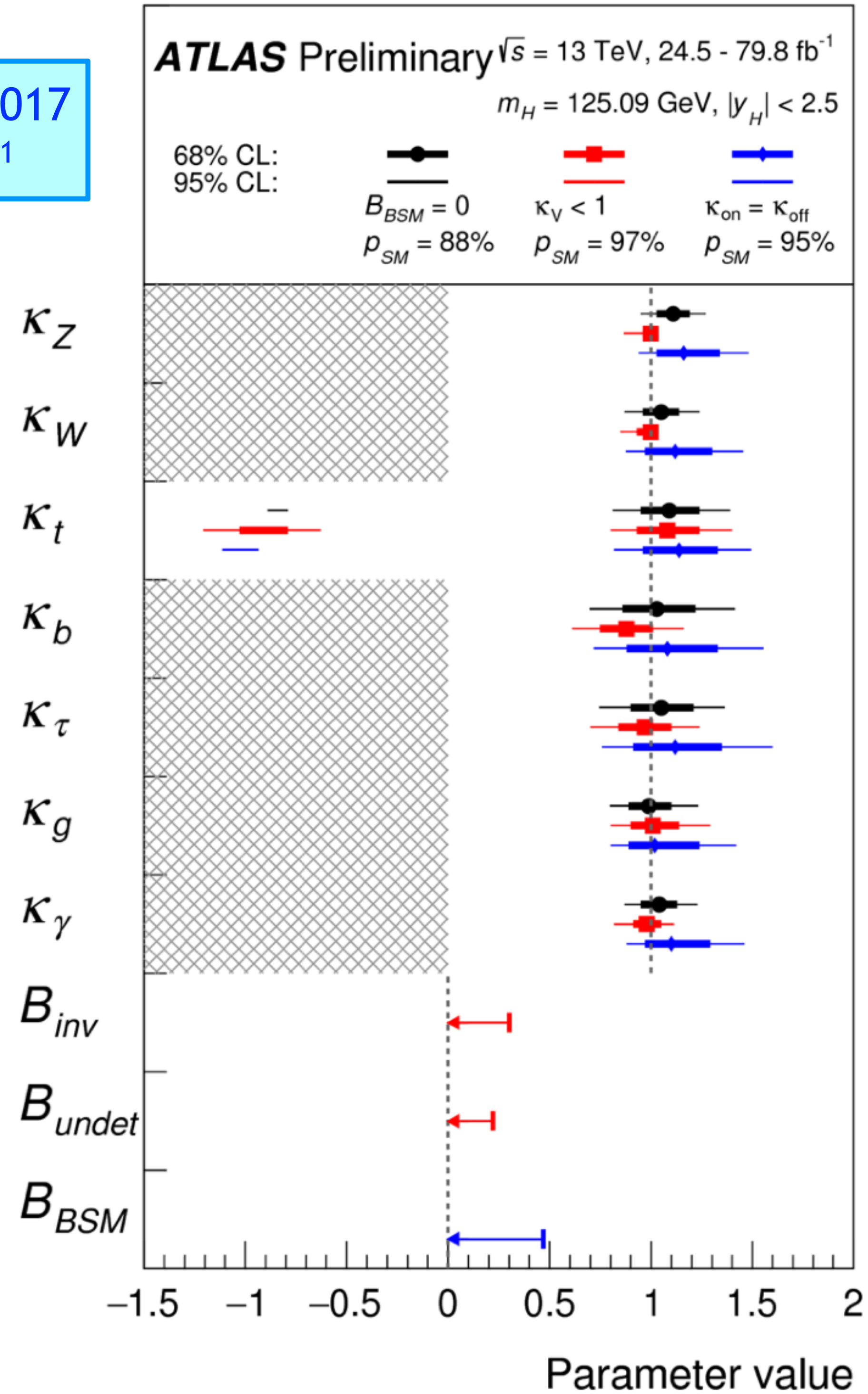
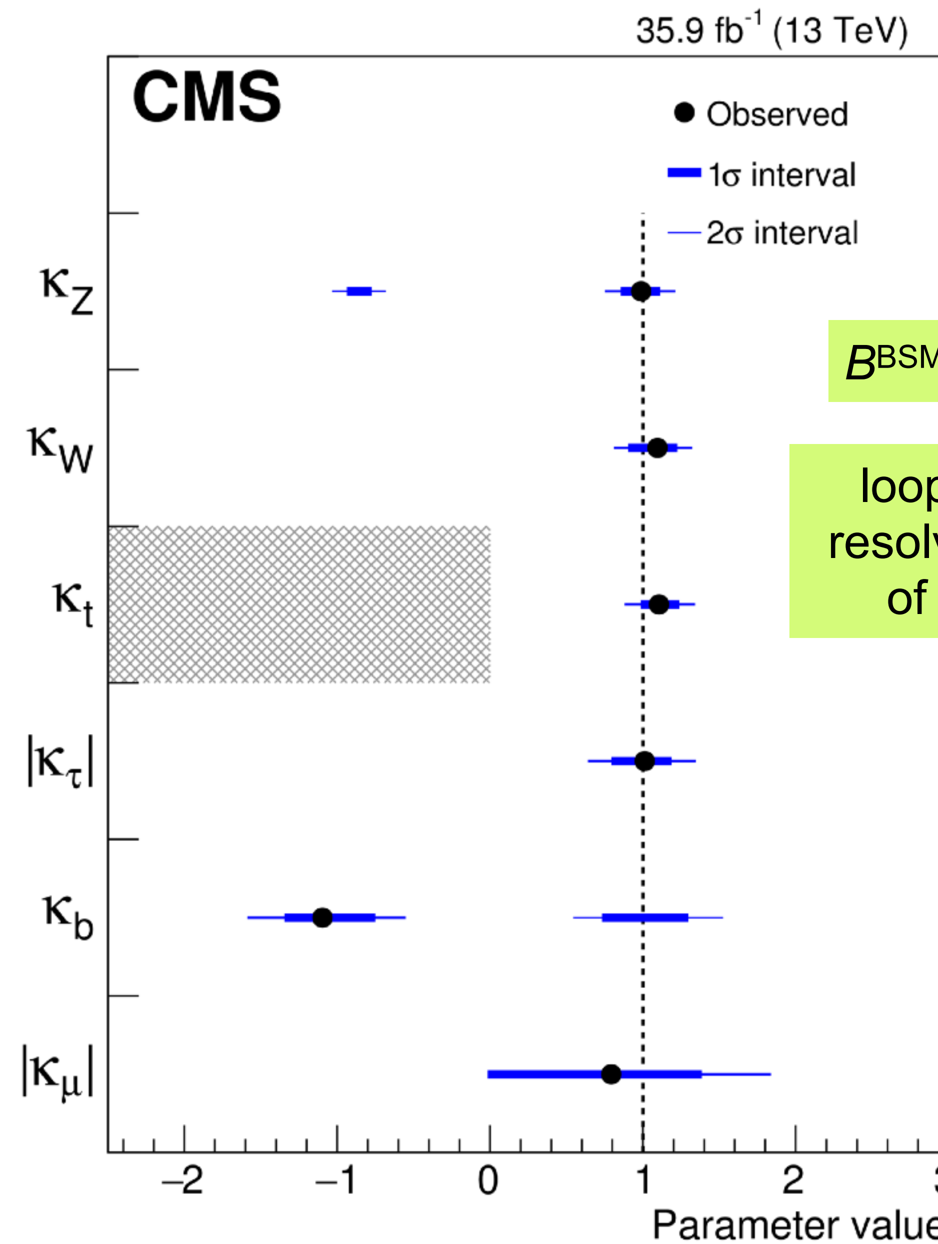
K Coupling Modifiers, LHC Physics (2017) CERN YR4

Kappa Coupling Modifiers

ATLAS 2016-2017
L = 24-80 fb^{-1}



CMS 2016
L = 36 fb^{-1}



$B^{BSM} = 0$

loop diagrams resolved in terms of W, Z, t, b

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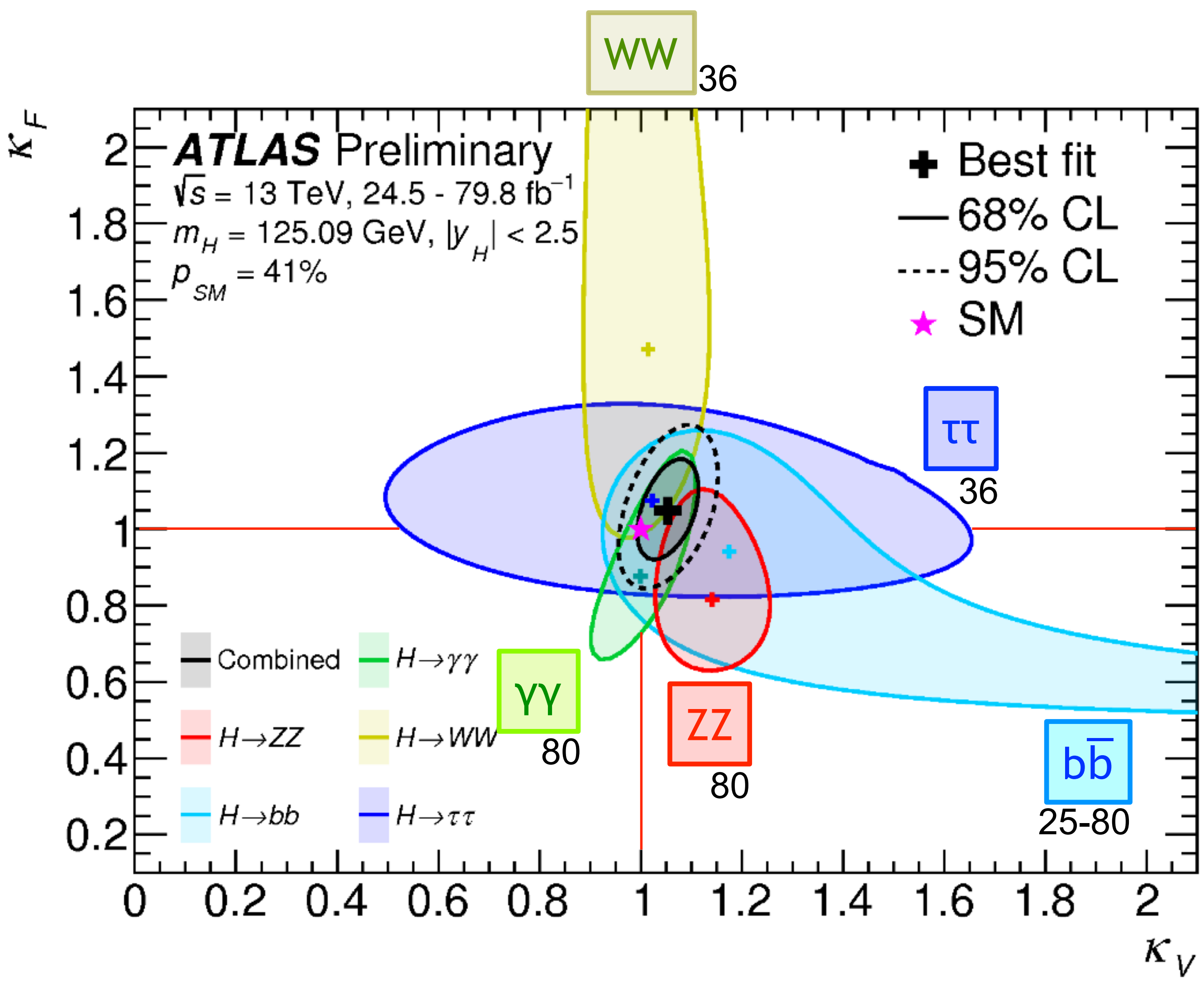
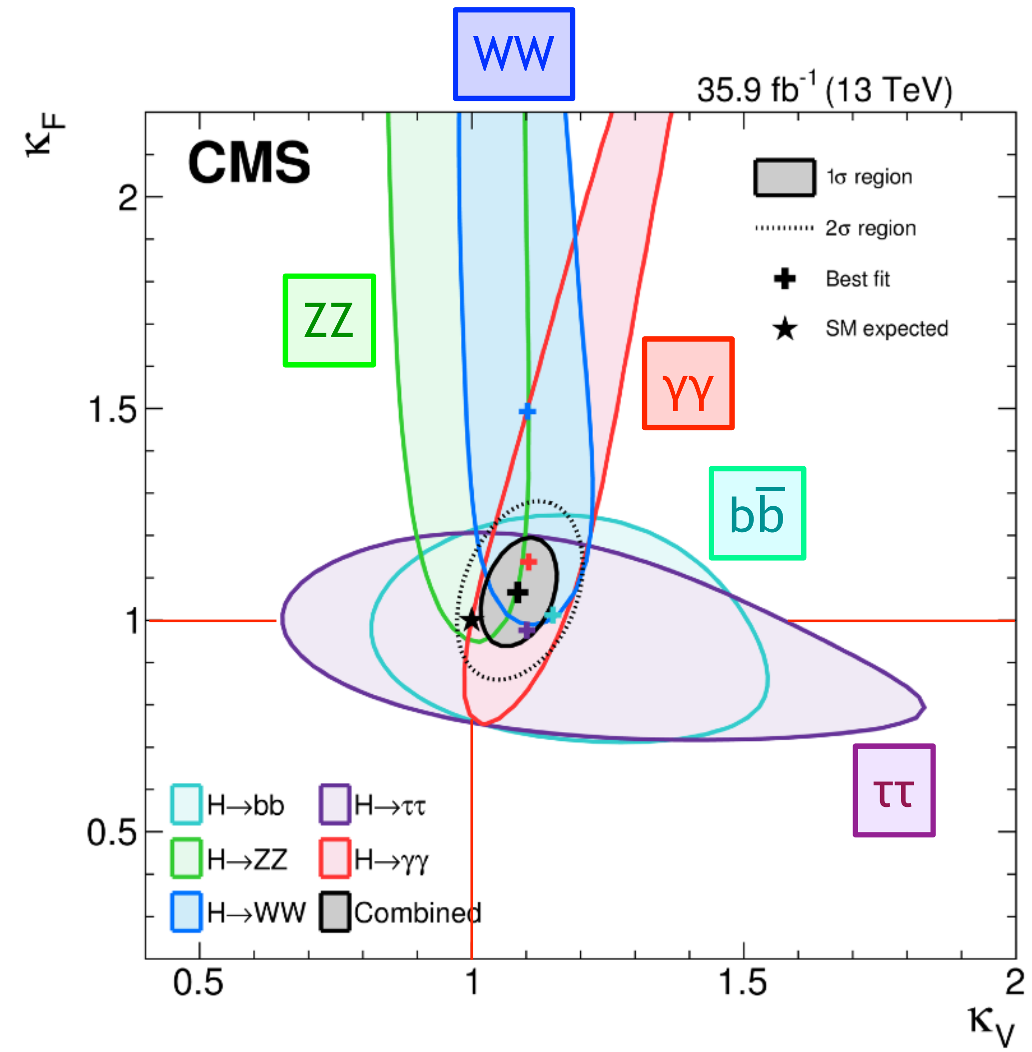
Fermions versus Bosons

ATLAS 2016-1017
25-80 fb⁻¹



CMS 2016
36 fb⁻¹



☛ with ×2 lumi, γγ and 4ℓ close κ_F (mostly ggF and ttH constraints)

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assuming same scaling for
vector bosons and fermions

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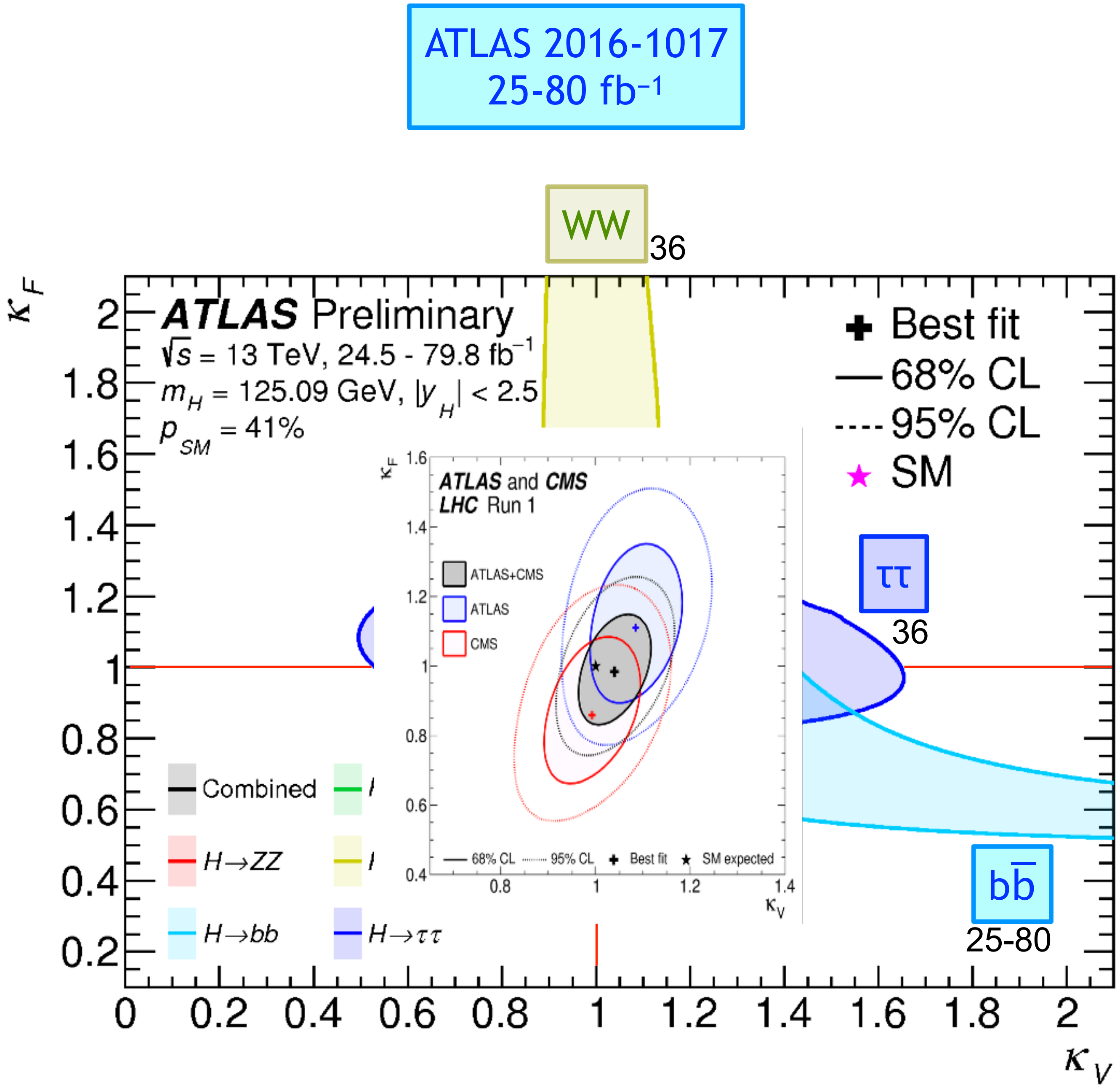
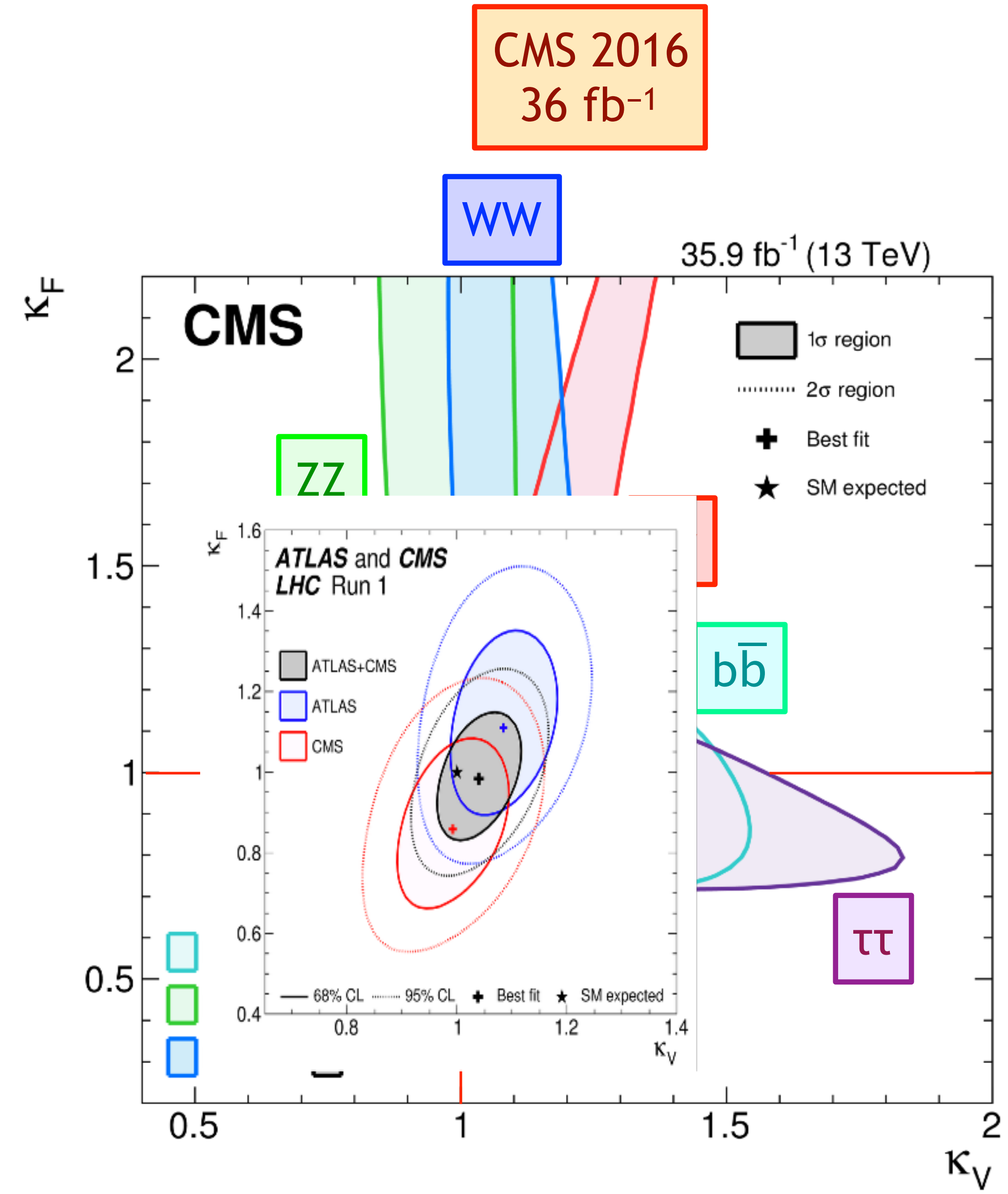
Fermions versus Bosons





☛ partial Run-2 per experiment already betted than Run-1 combination

ATLAS-CONF-2019-005

JHEP 08 (2016) 045

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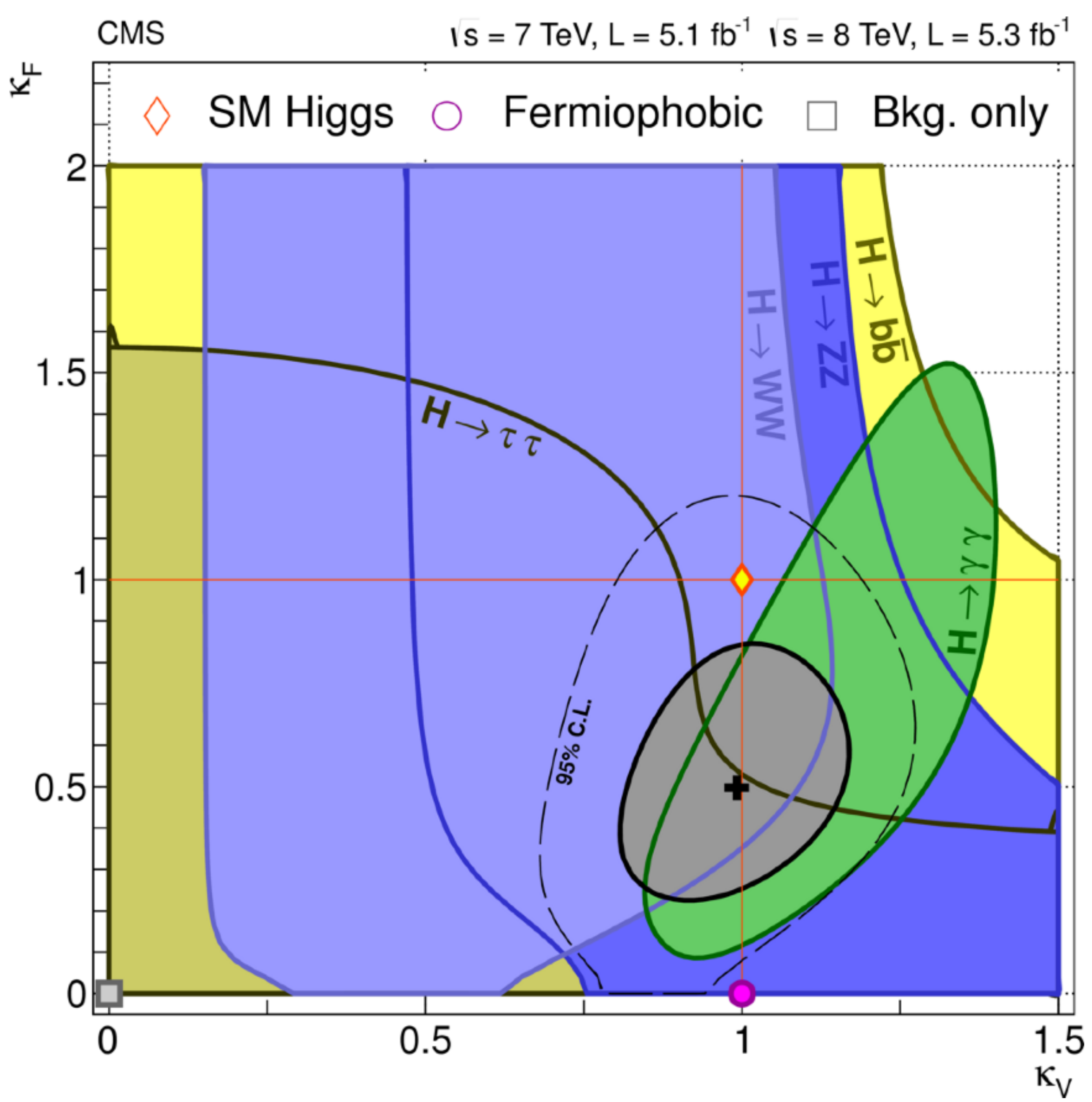
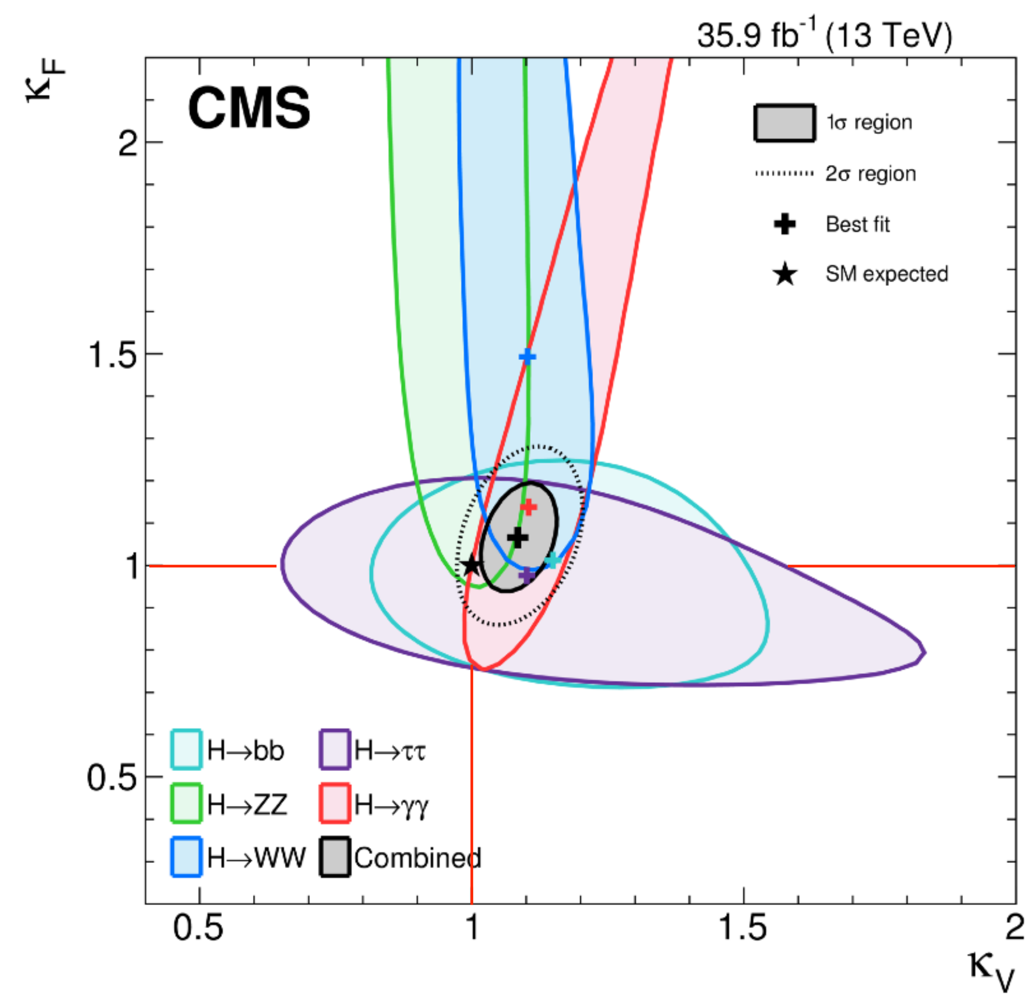
Fermions versus Bosons

CMS 2012
7-8 TeV
10 fb^{-1}

CMS 2016
13 TeV
36 fb^{-1}





remember, at the time of the discovery…

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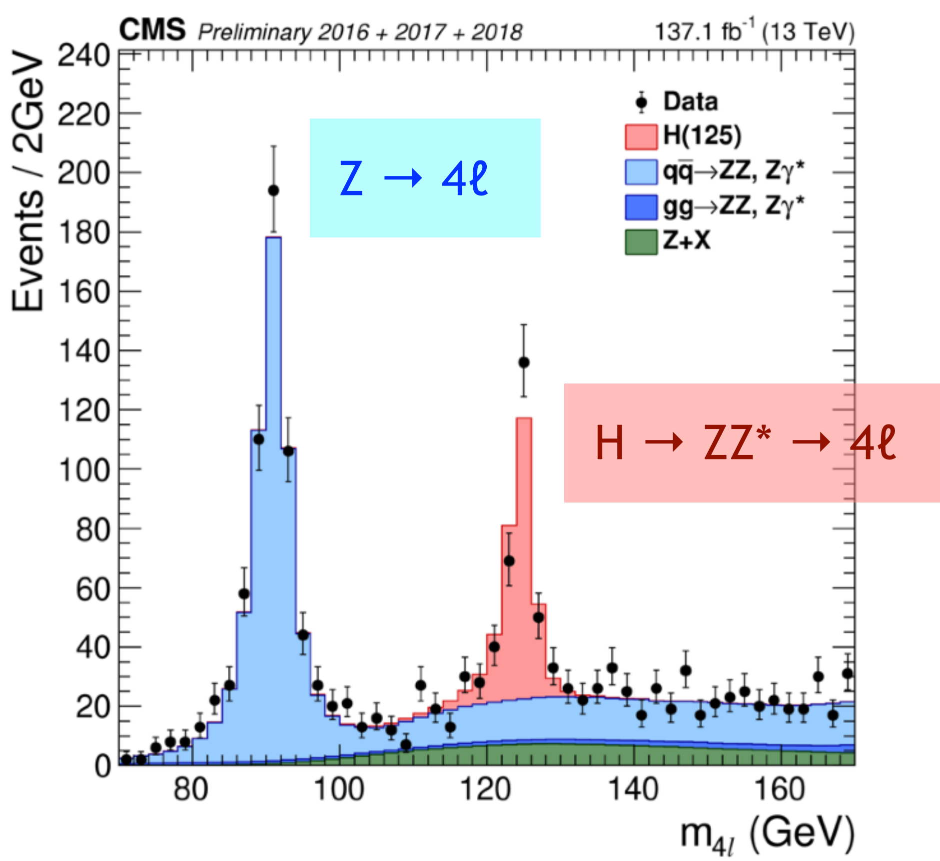
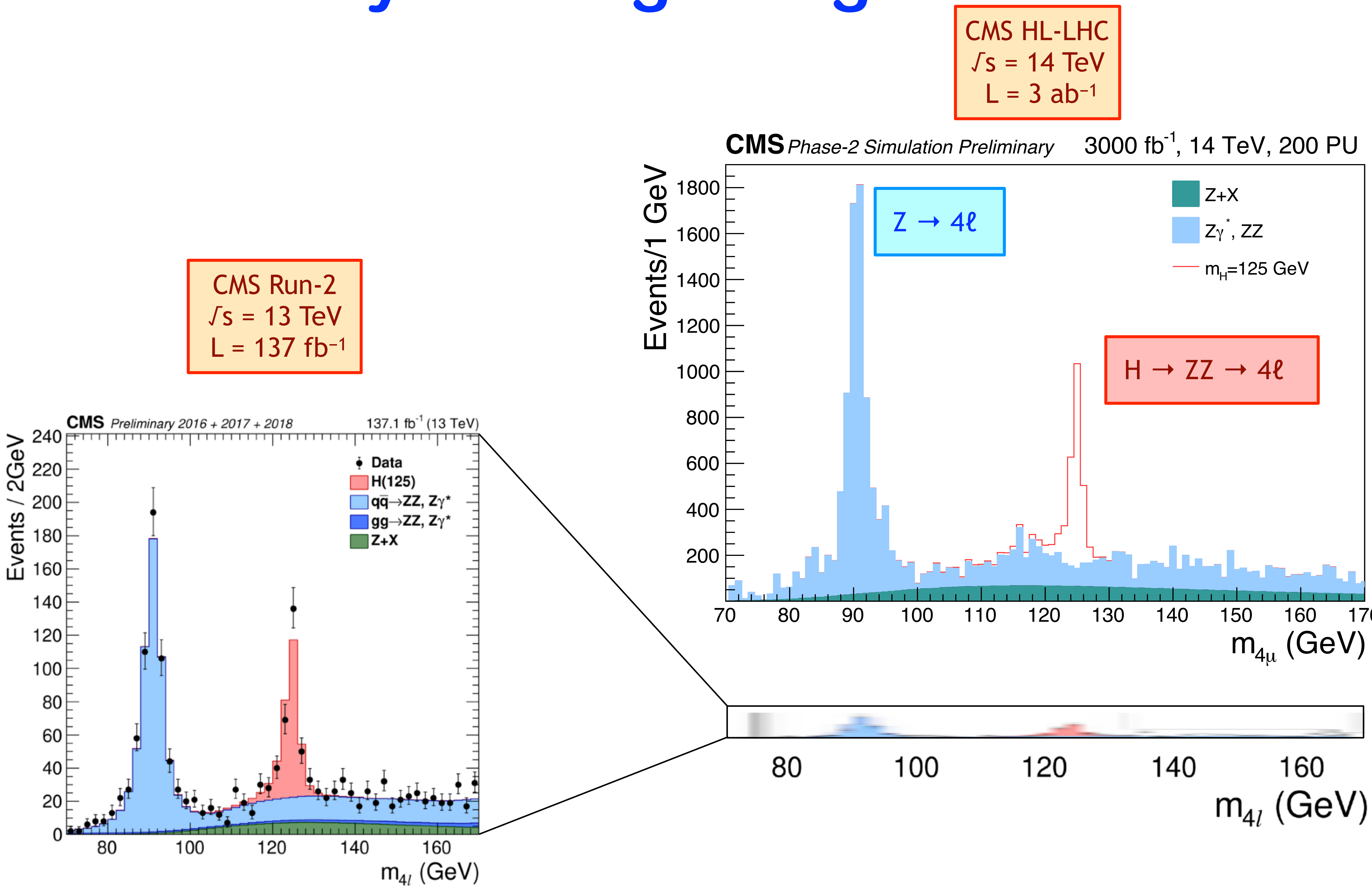
LHC: It's Only the Beginning

CMS Run-2
$\sqrt{s}$ = 13 TeV
L = 137 fb^{-1}



LHC: It's Only the Beginning



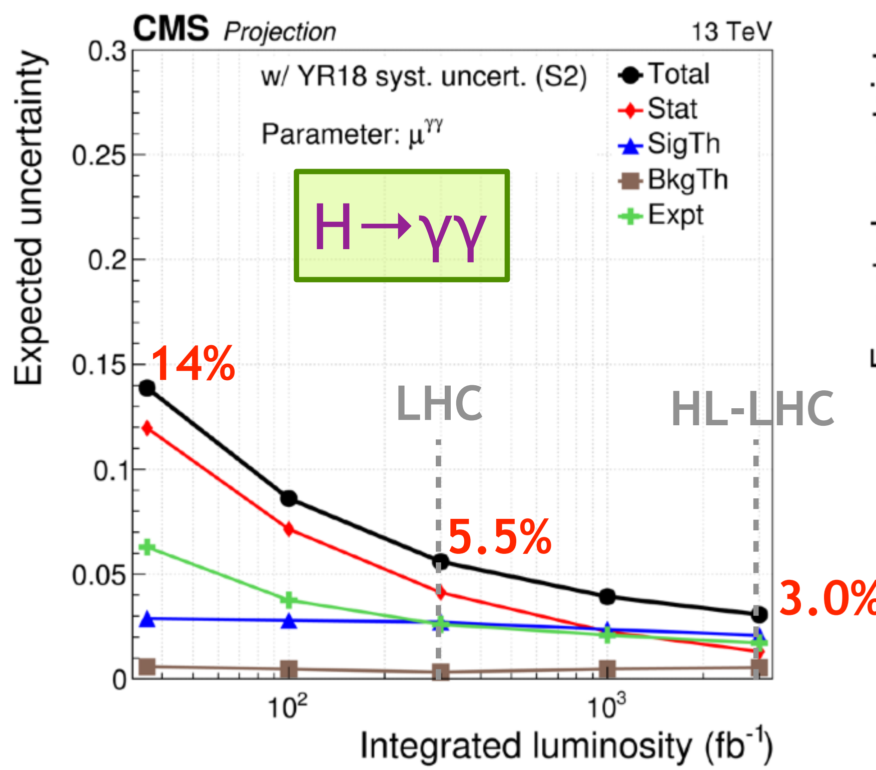
CMS-TDR-17-002

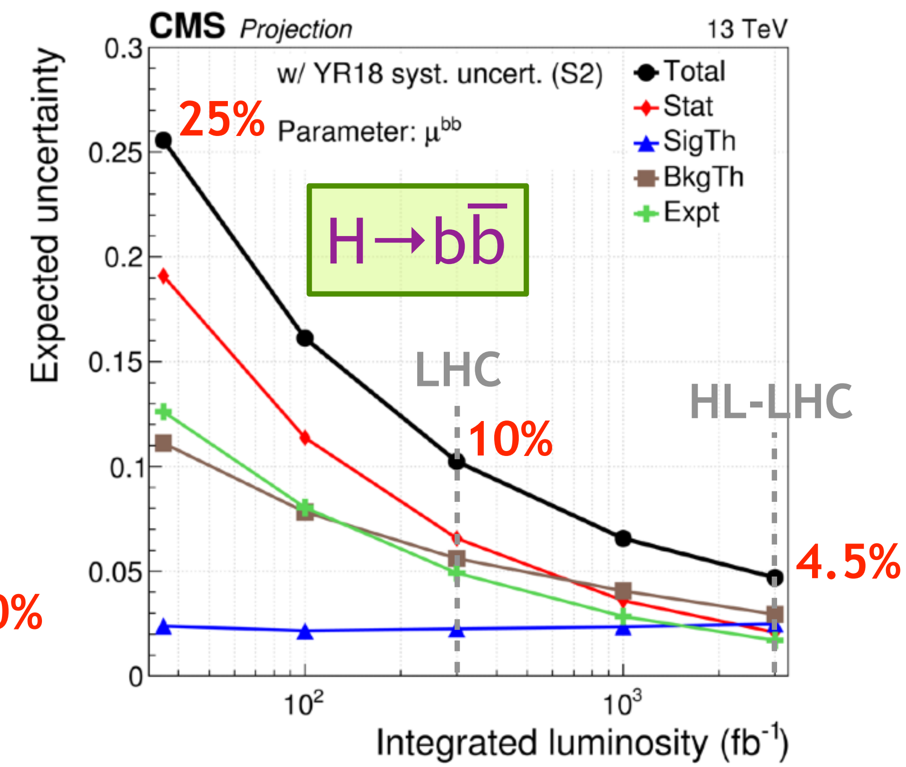
➠ HL-LHC ATLAS/CMS: expect 20-30 MeV resolution on Higgs boson mass

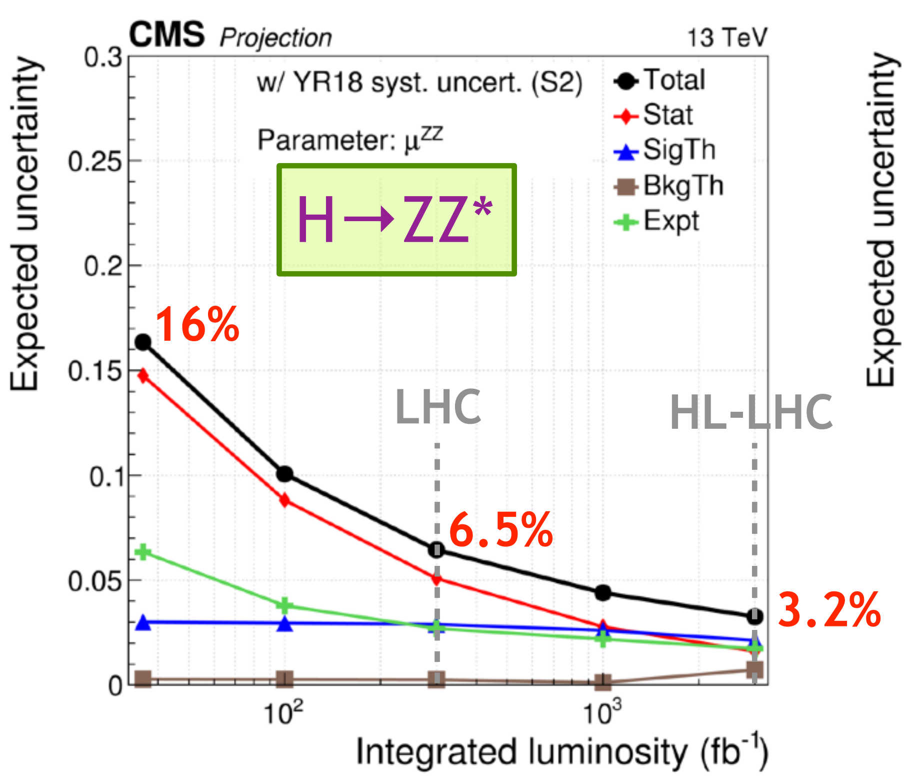
From LHC to HL-LHC

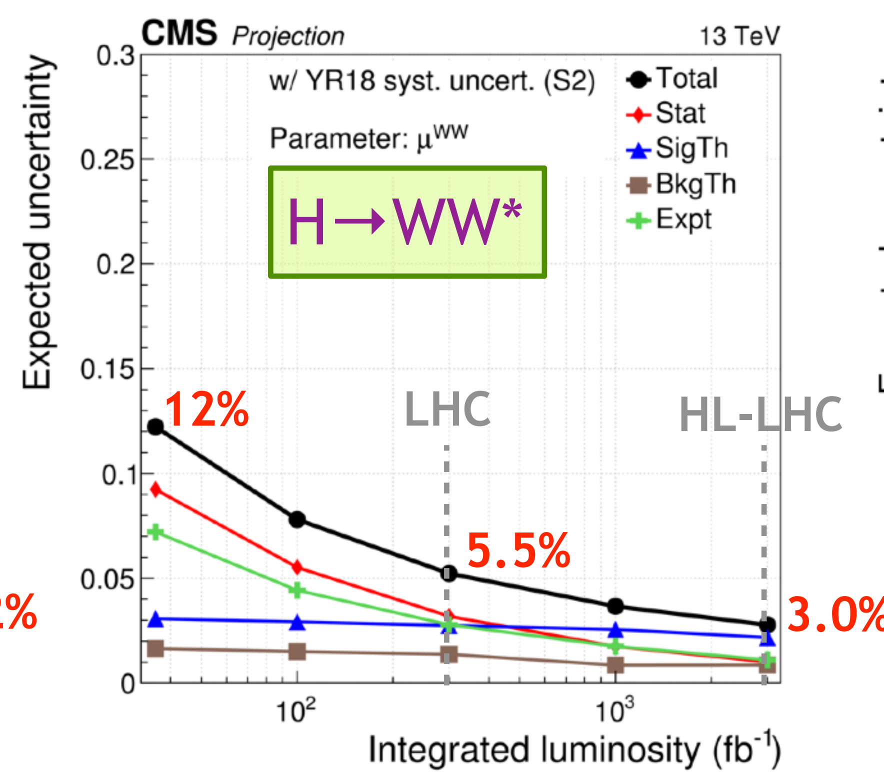
CMS expected uncertainties:

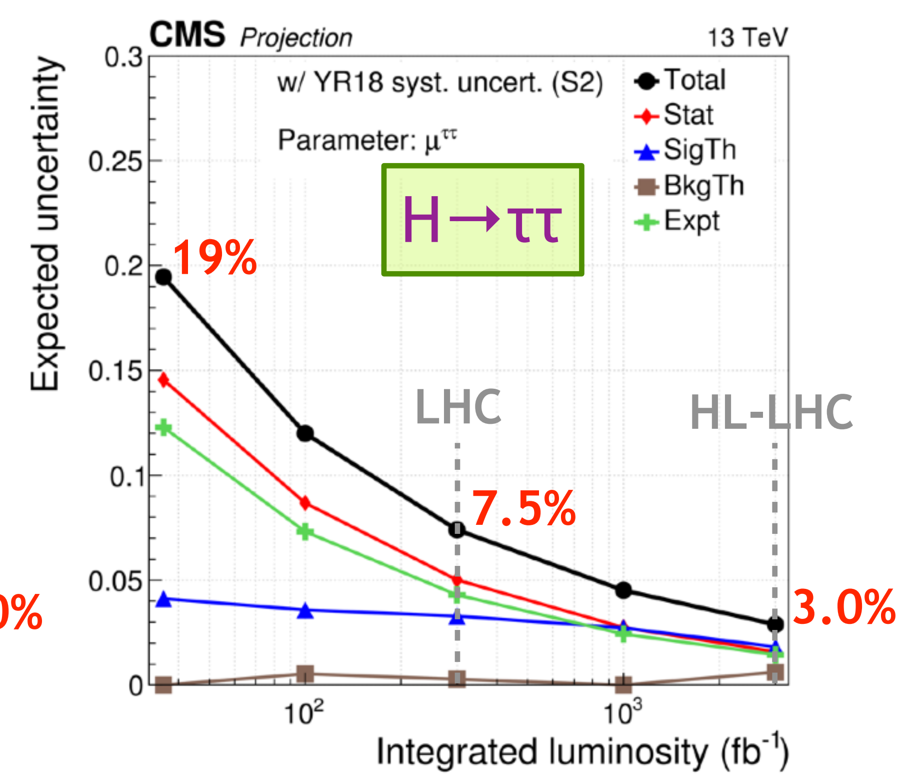
- per-decay signal strength parameters μ^f
- with YR18 systematic uncertainties (S2)
- as a function of integrated luminosity









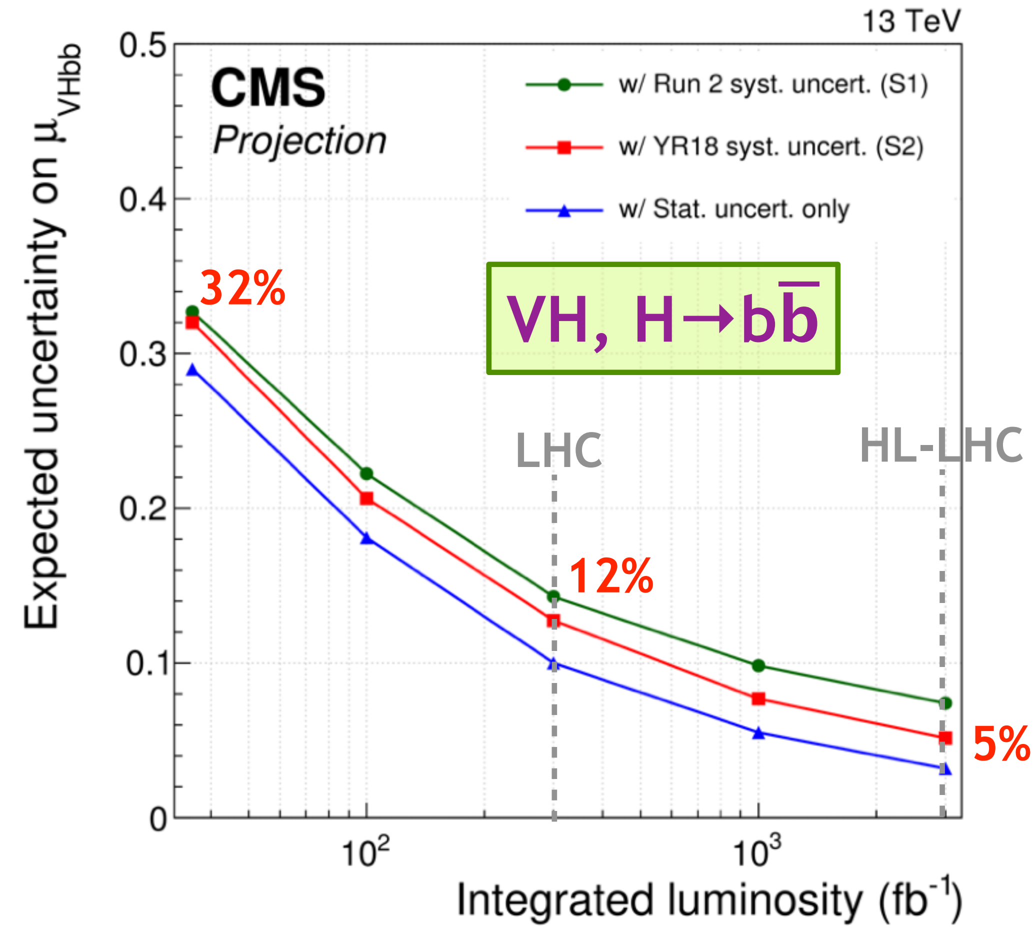


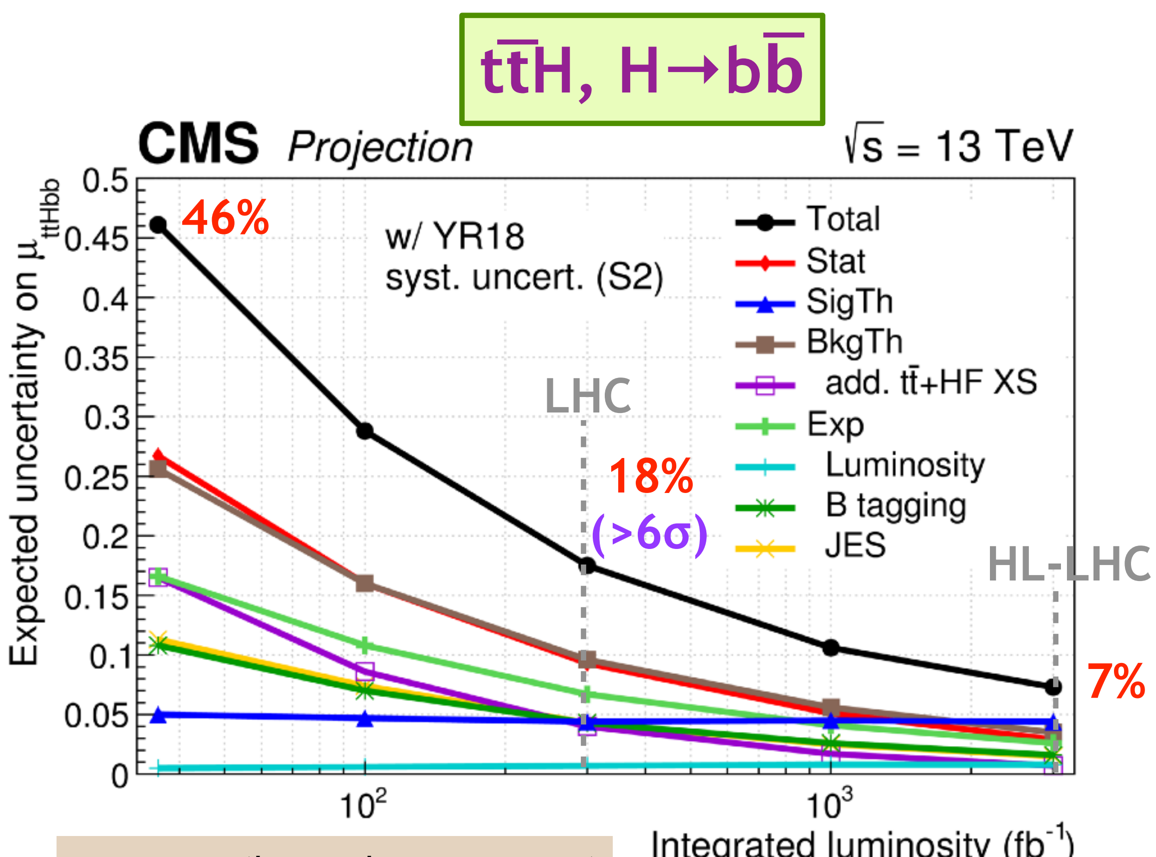
CMS-PAS-FTR-18-011

from LHC to HL-LHC

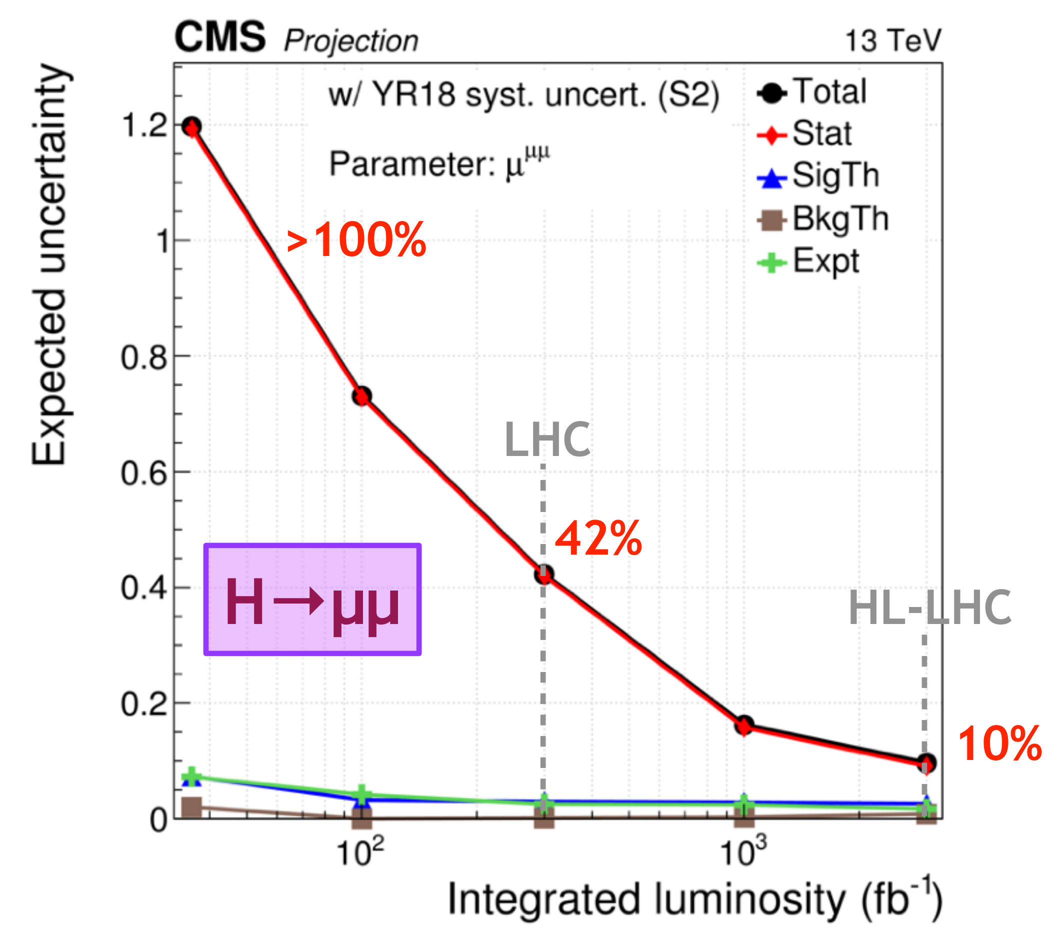
Significant improvement for those rare processes that are statistics-dominated

For many of this processes, large improvement of theory uncertainties for signal and background is mandatory



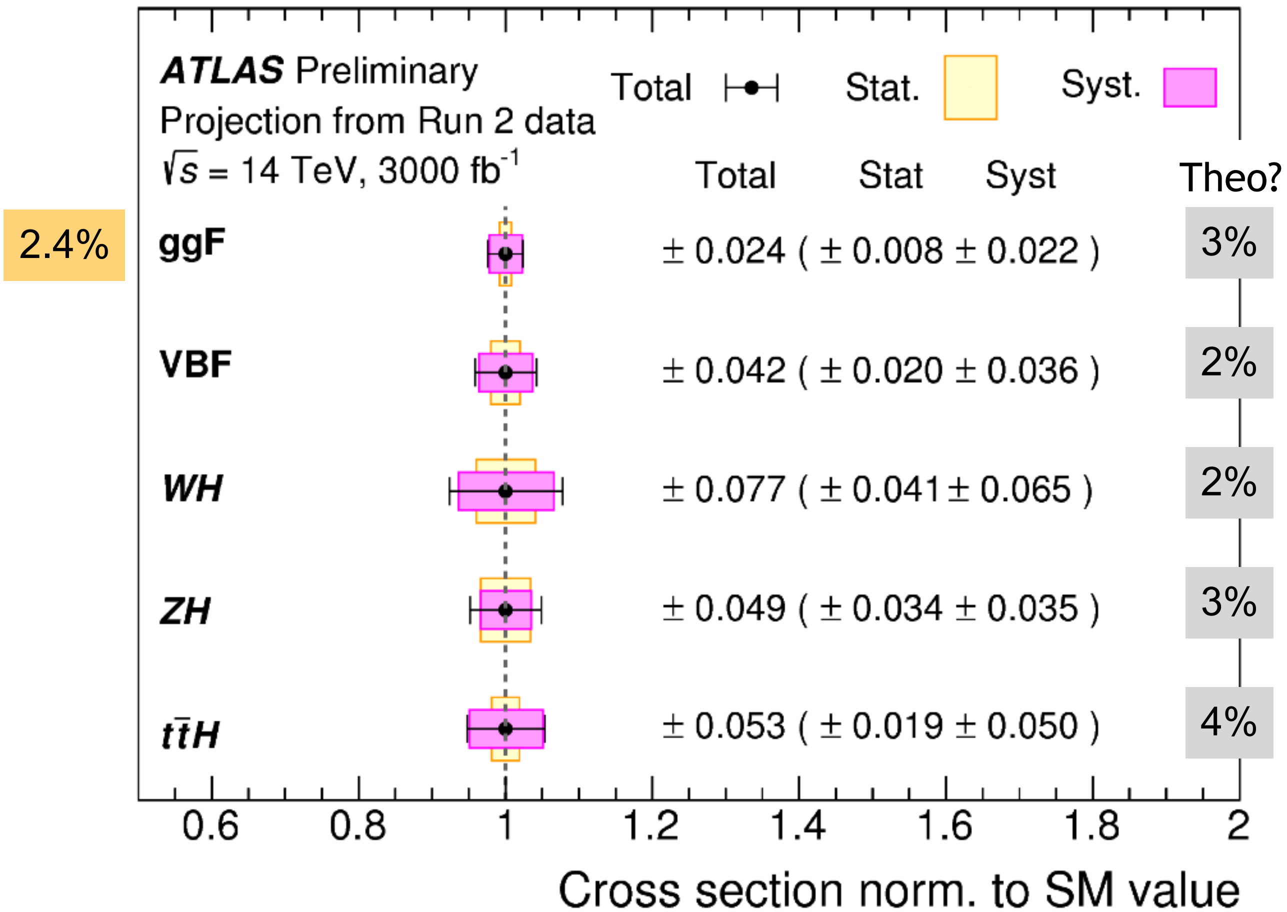


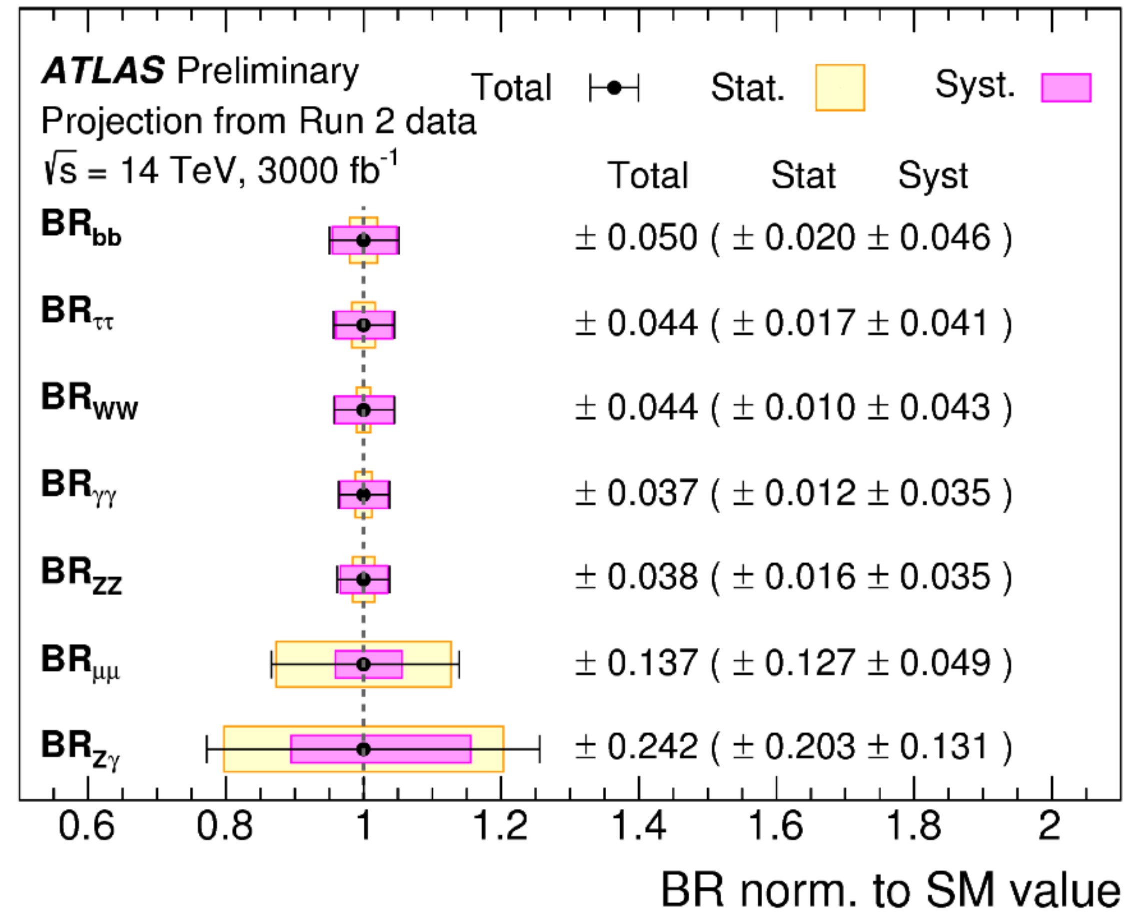
assumes theory improvement on tt̄+HF processes



HL-LHC: Higgs Production and Decays

ATLAS HL-LHC, S2 scenario, L = 3 ab⁻¹, √s = 14 TeV



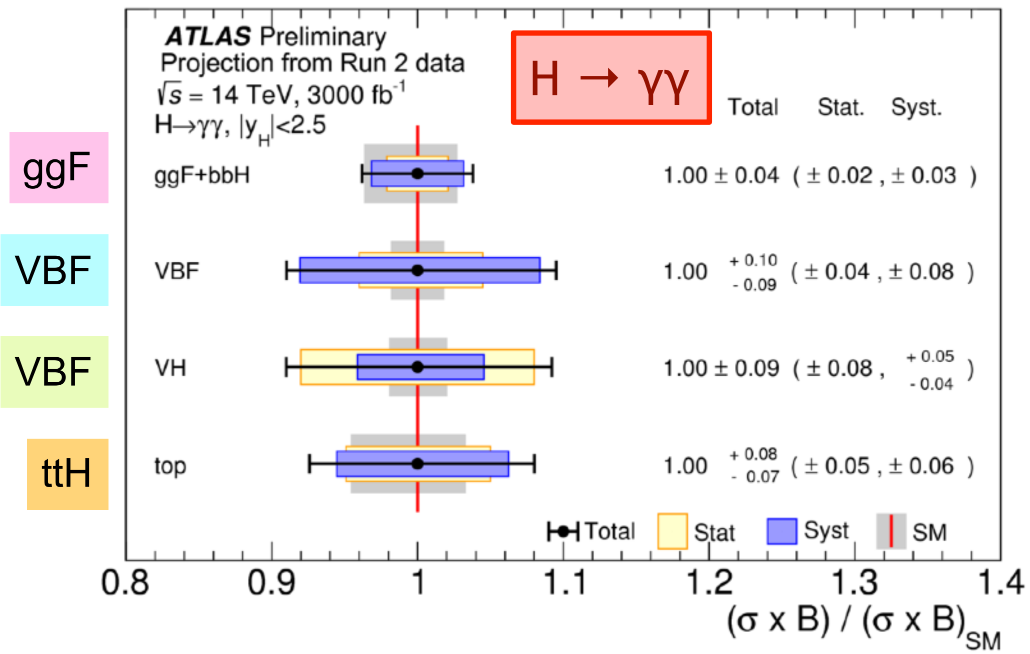


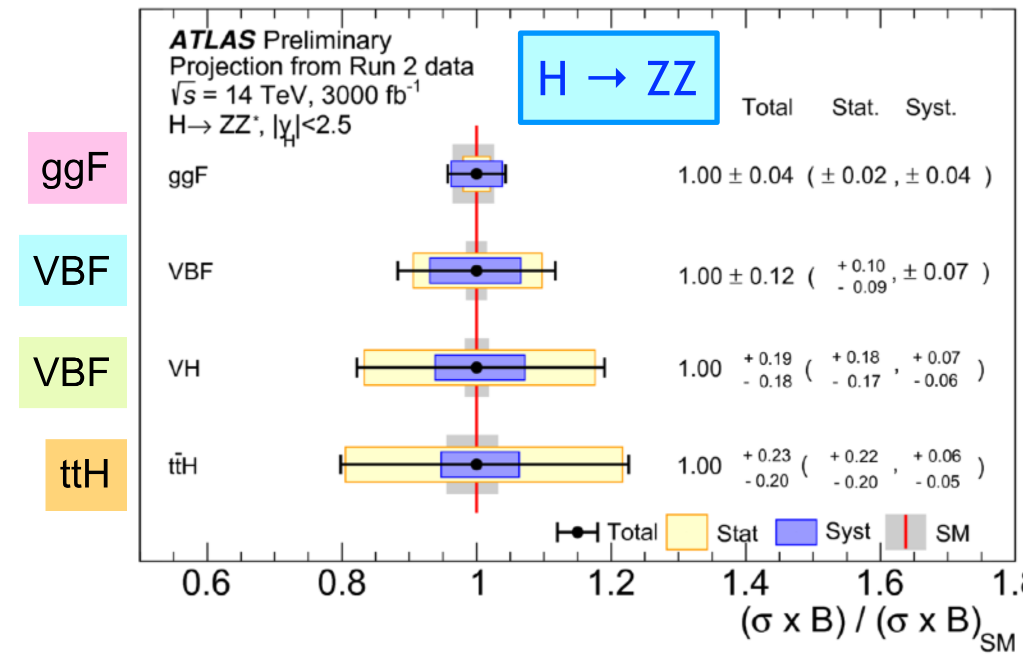
- assume production and measure decay, and vice-versa
- all measurements are systematics dominated,
  except for μμ (clearly seen) and Zγ (≲5σ)

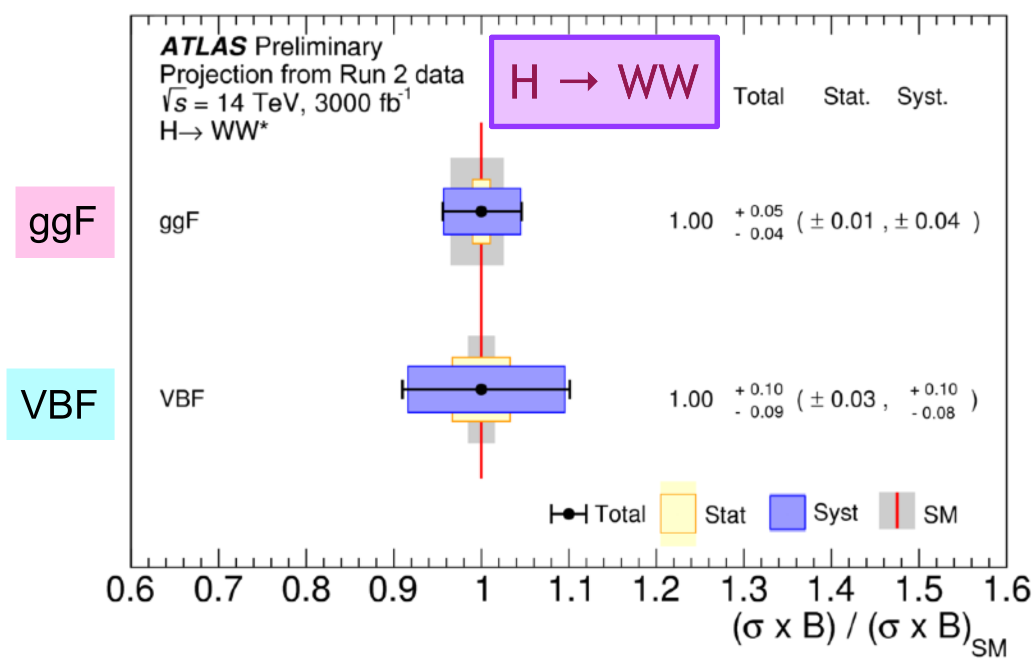
ATL-PHYS-PUB-2018-054

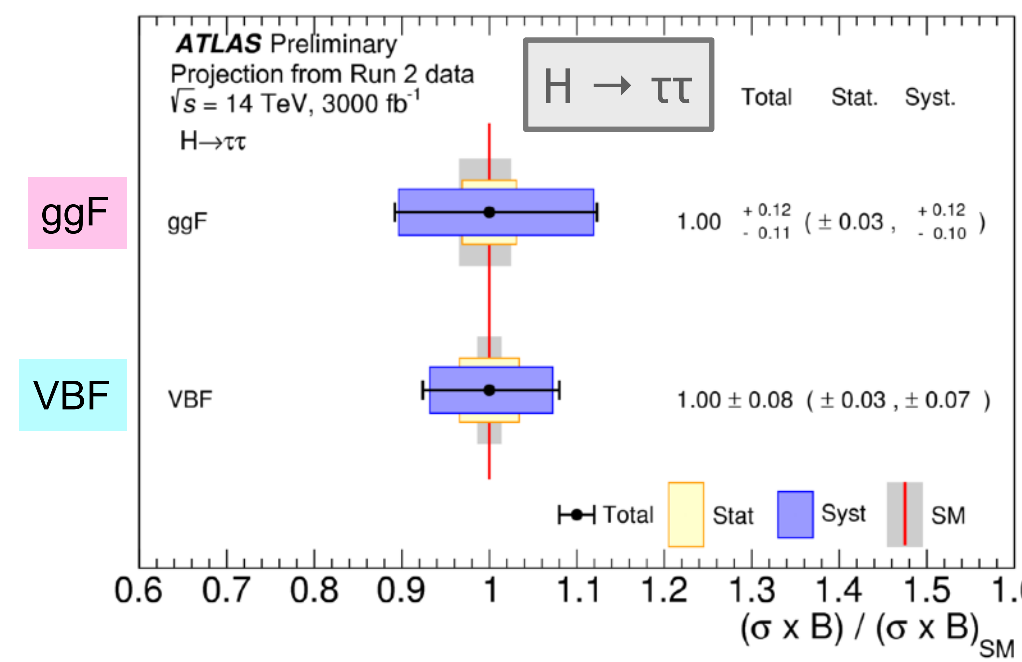
HL-LHC: Higgs Production, per Decay

ATLAS HL-LHC, S2 scenario, L = 3 ab⁻¹, √s = 14 TeV









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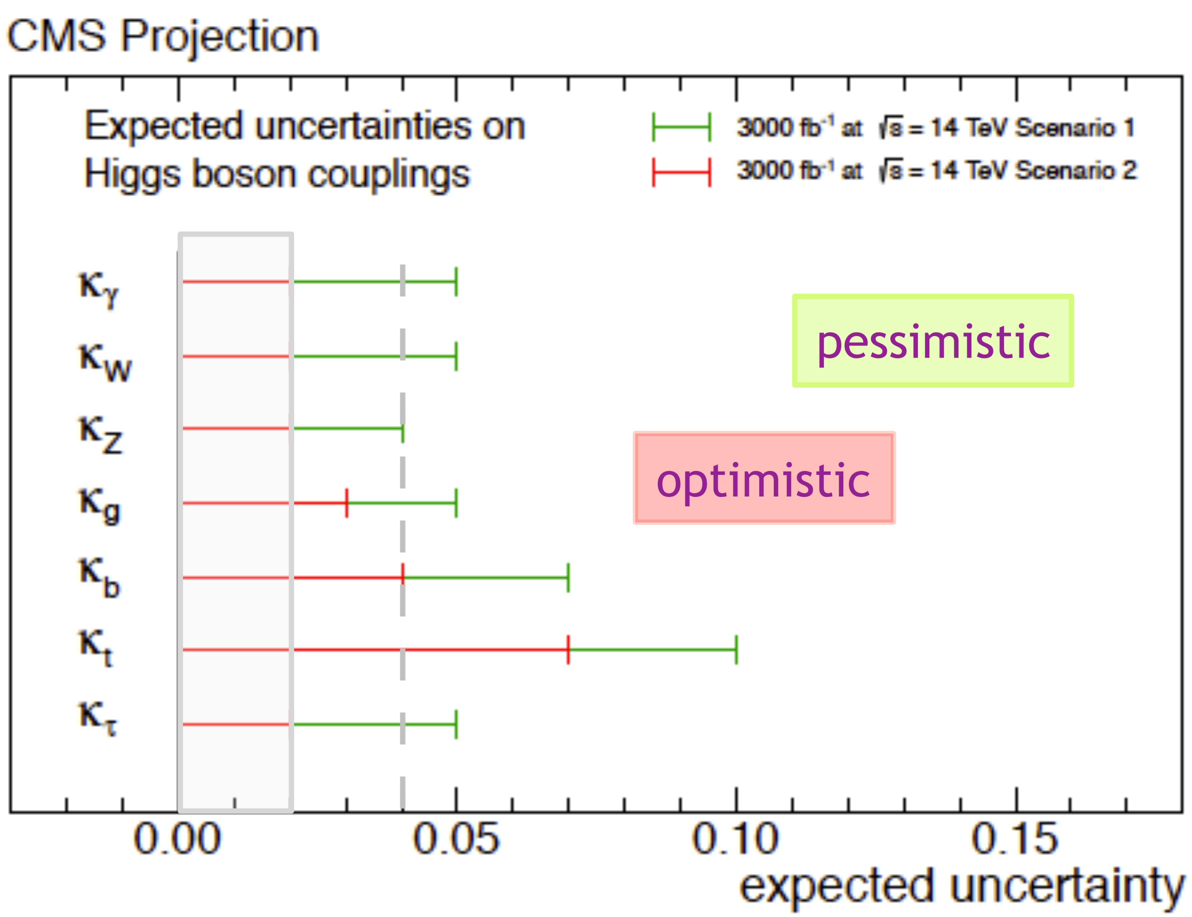
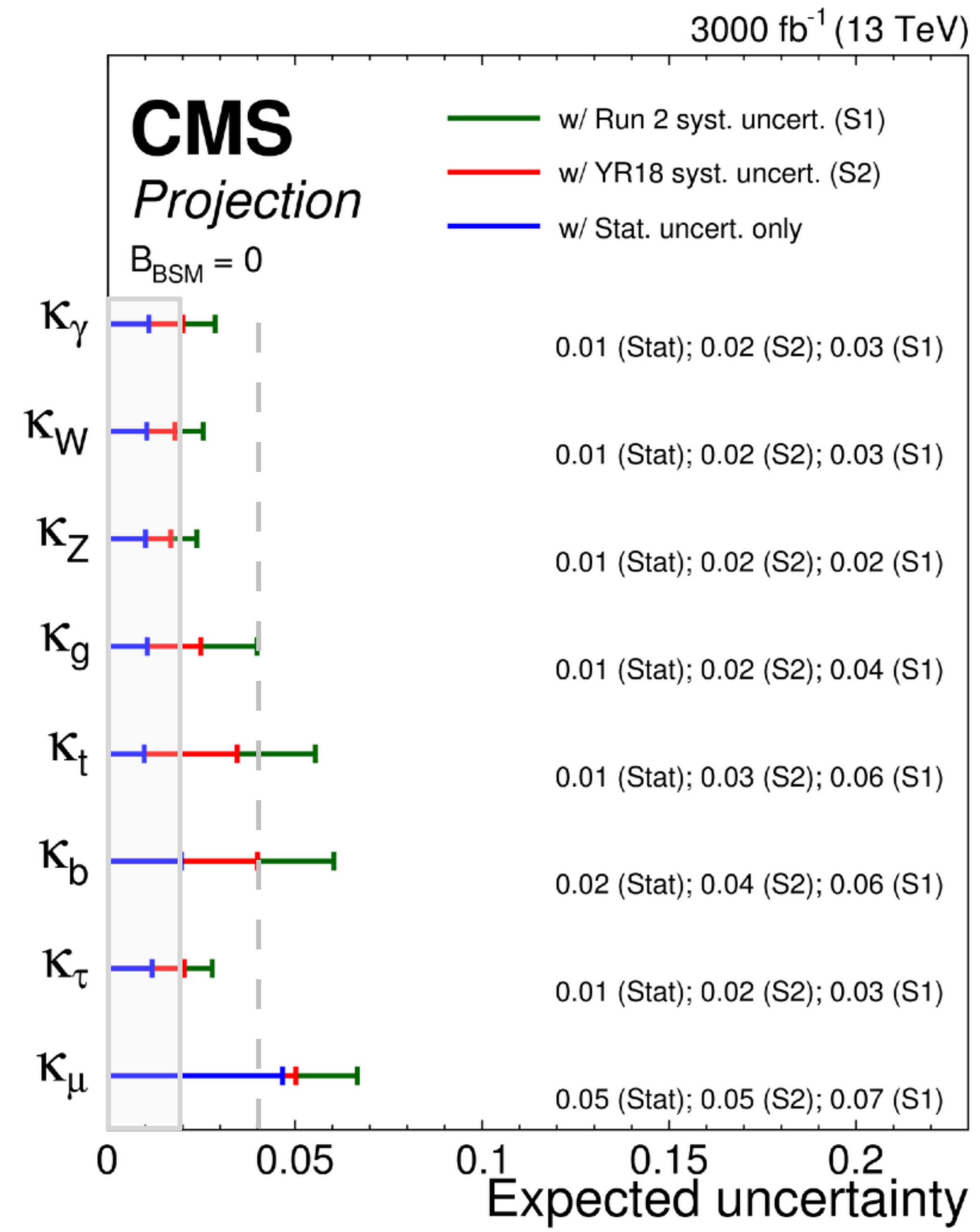
Evolution of Projections

CMS Projections 2013



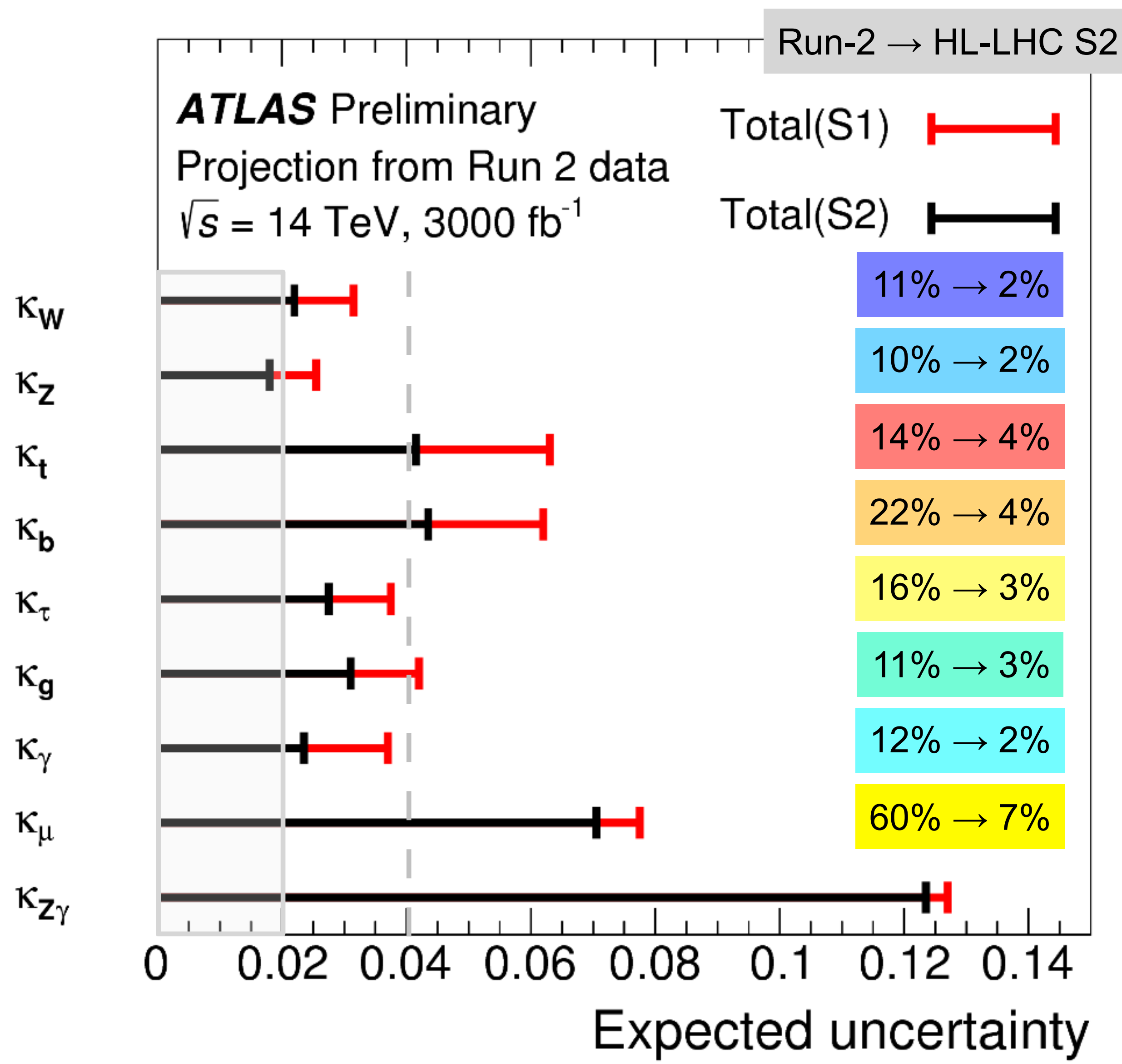
CMS Projections 2018



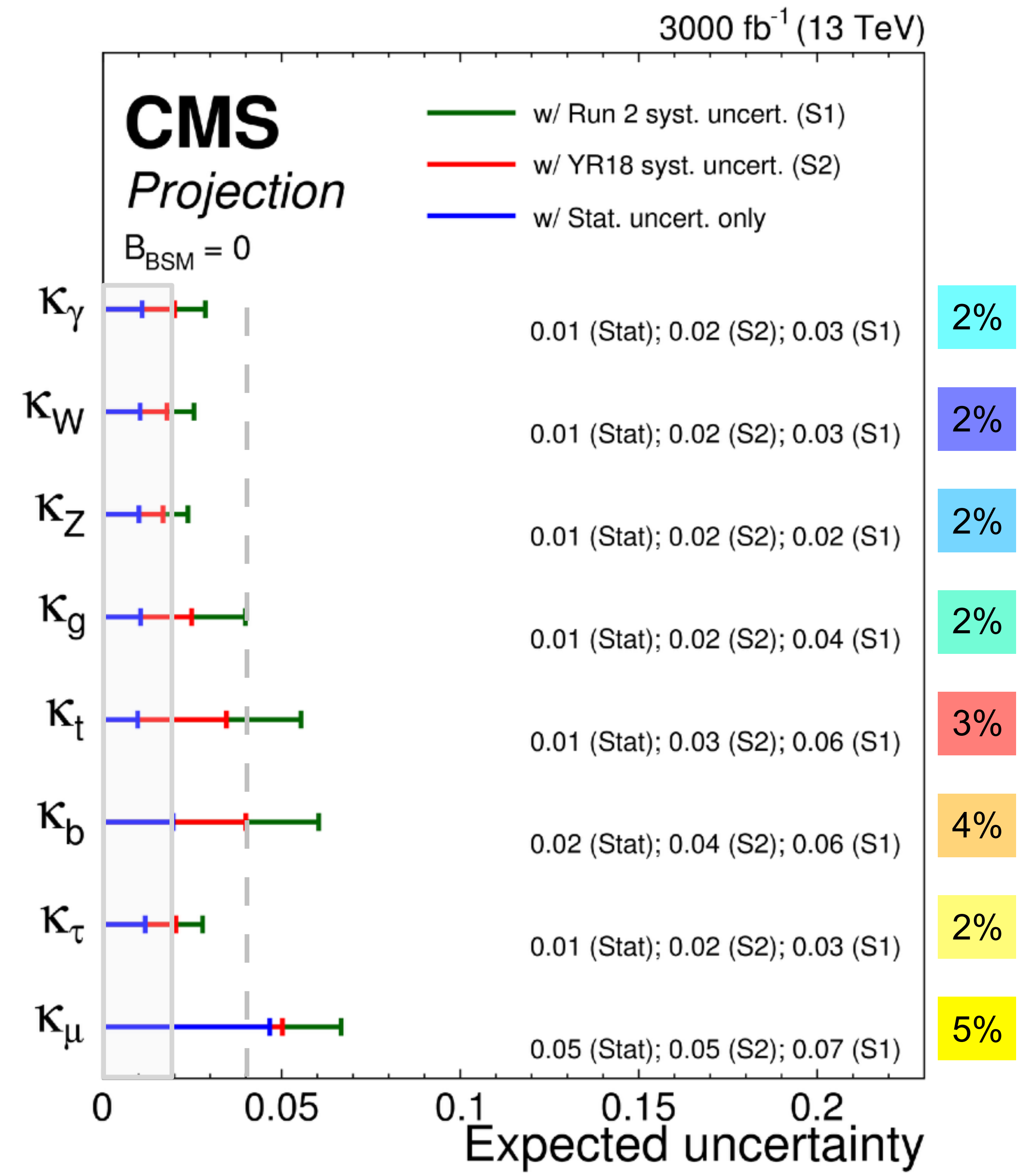
➠ taking into account experience gained and innovative techniques, what was optimistic in 2013 seems realistic in 2019

Coupling Modifiers

ATLAS HL-LHC
14 TeV
3 ab⁻¹



CMS HL-LHC
13 TeV
3 ab⁻¹



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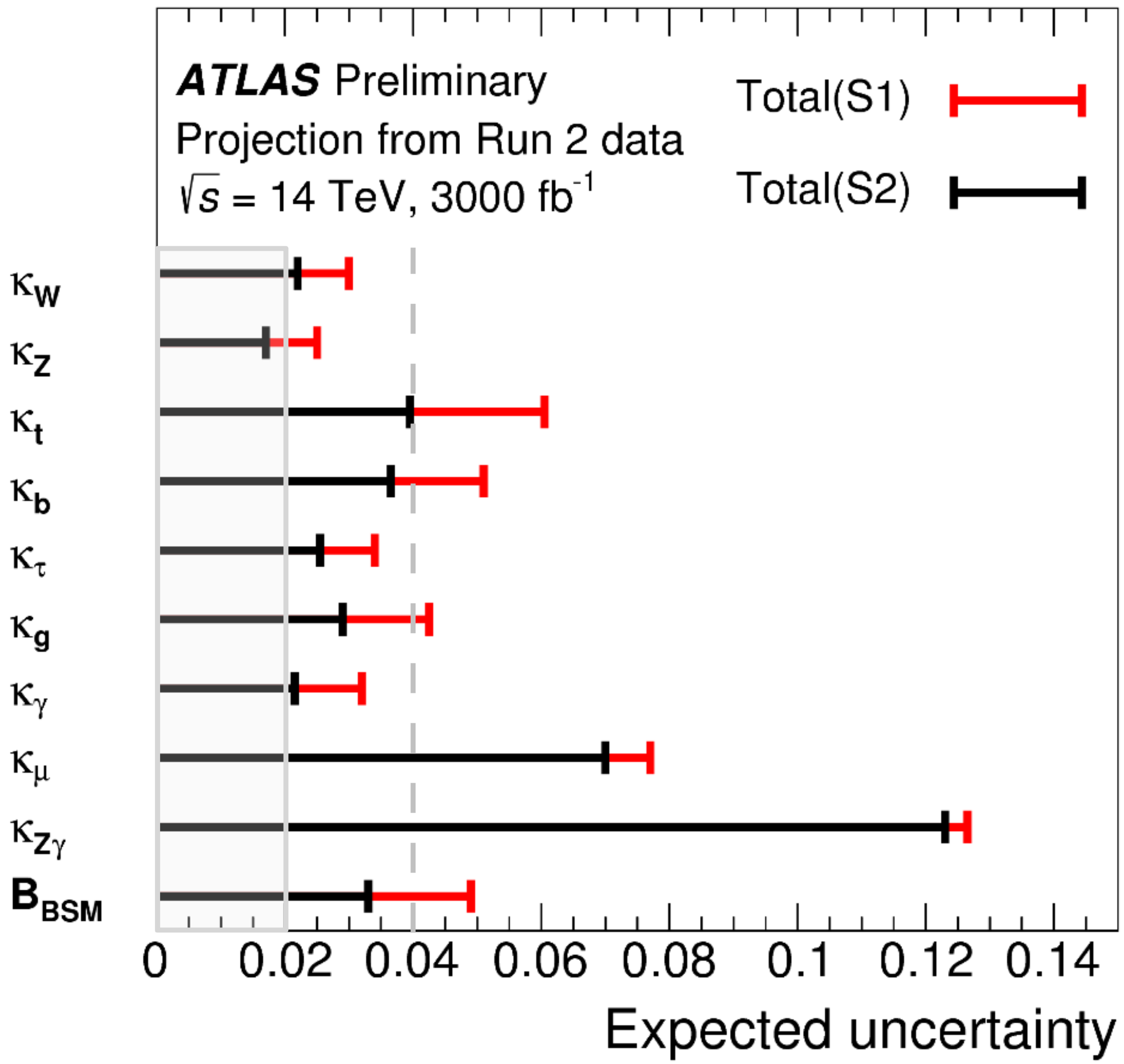
small differences are not significant

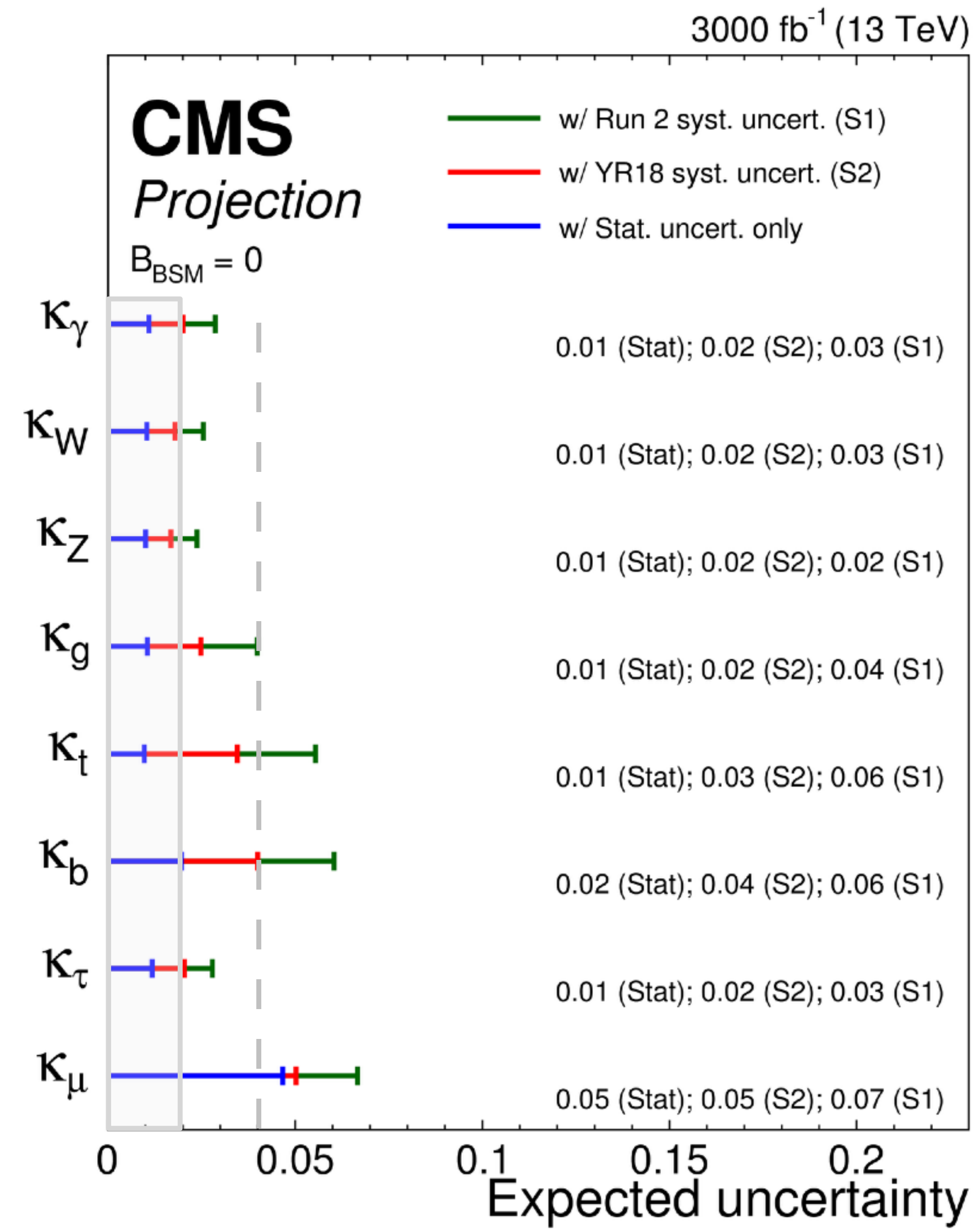
CMS-PAS-FTR-18-011

HL-LHC: Coupling Modifiers

CMS HL-LHC
13 TeV
3 ab⁻¹

ATLAS HL-LHC
14 TeV
3 ab⁻¹



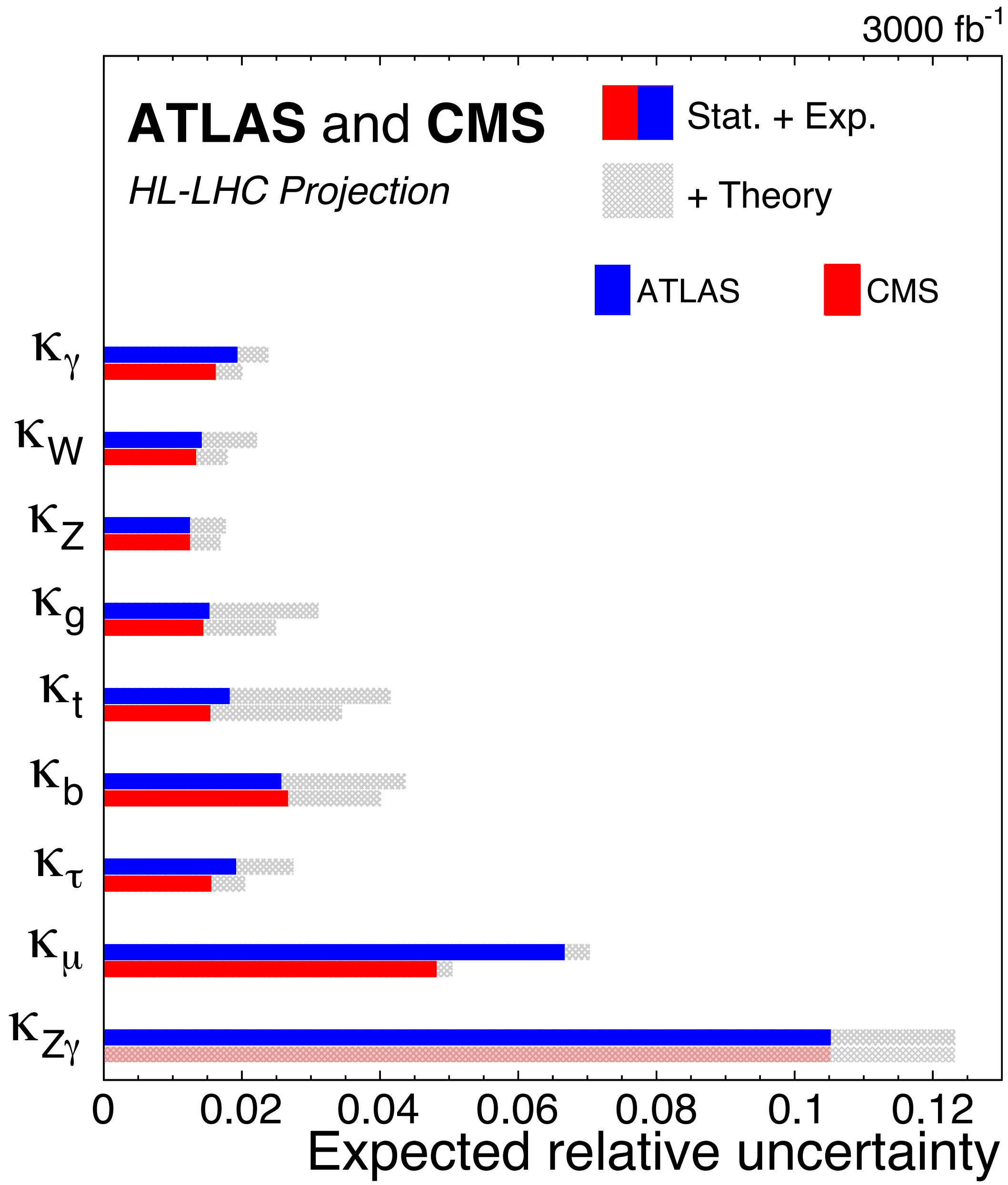


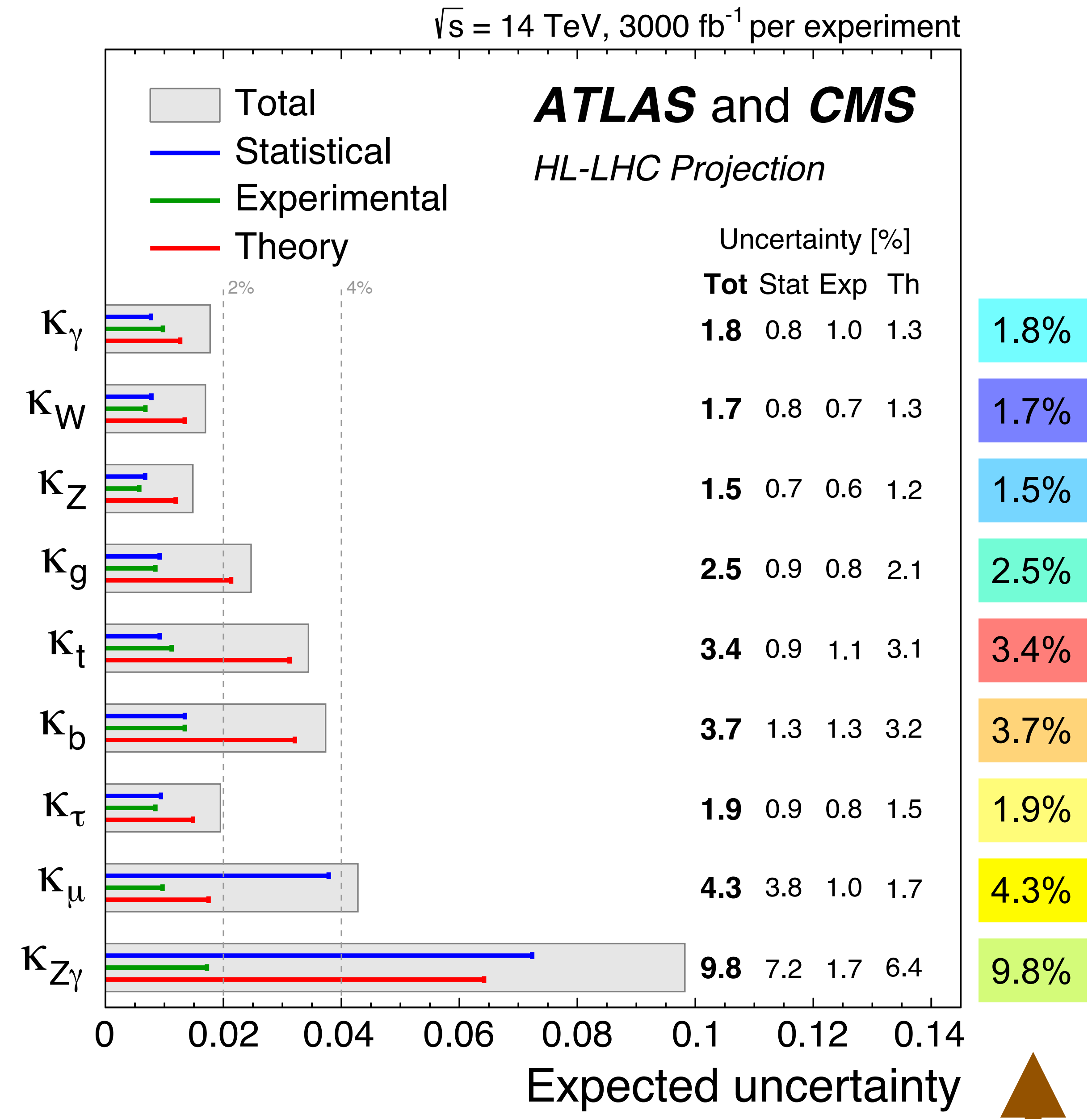
ATL-PHYS-PUB-2018-054

floating B^{BSM} does not affect the general picture

CMS-PAS-FTR-18-011

Combination of Projections

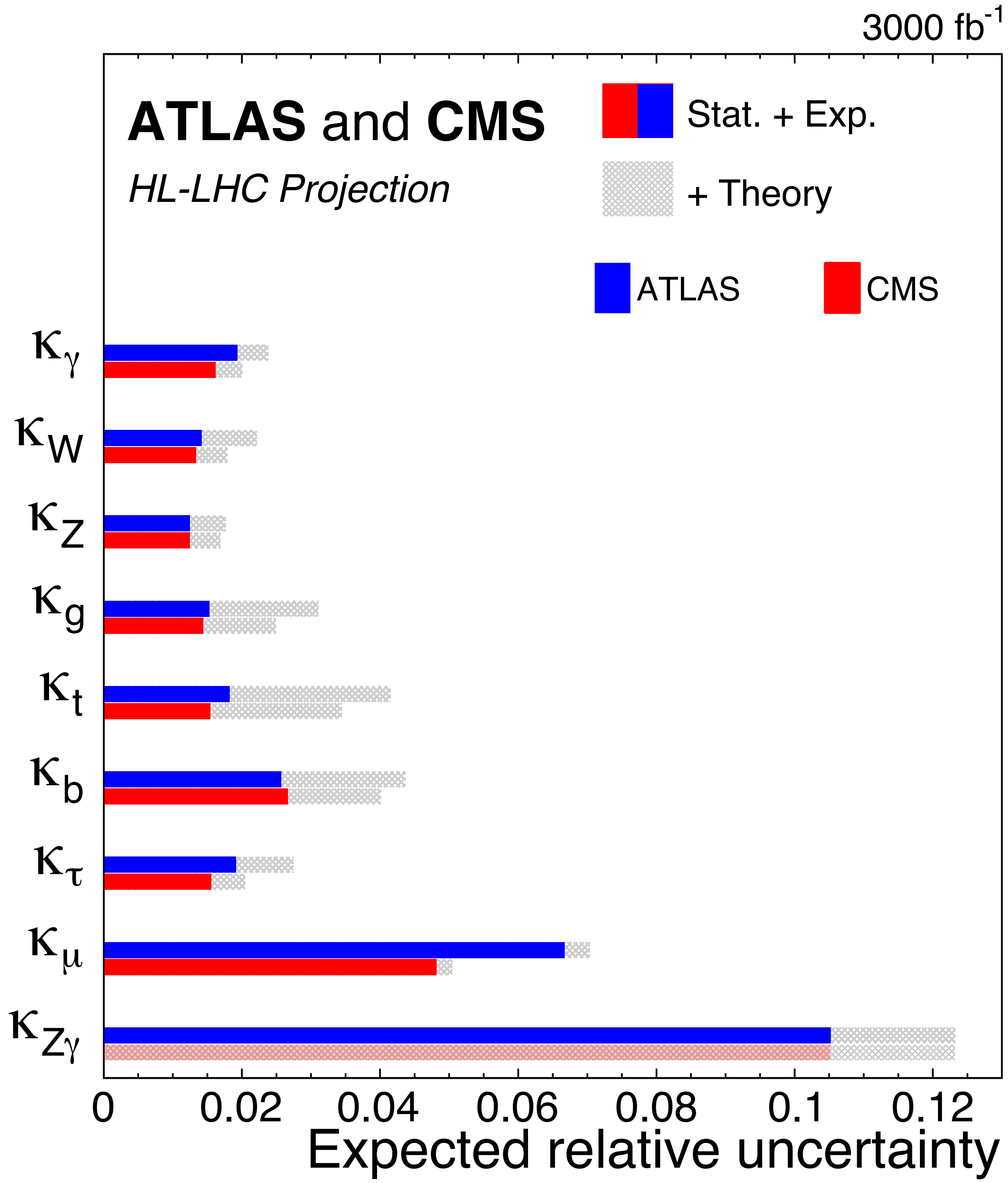


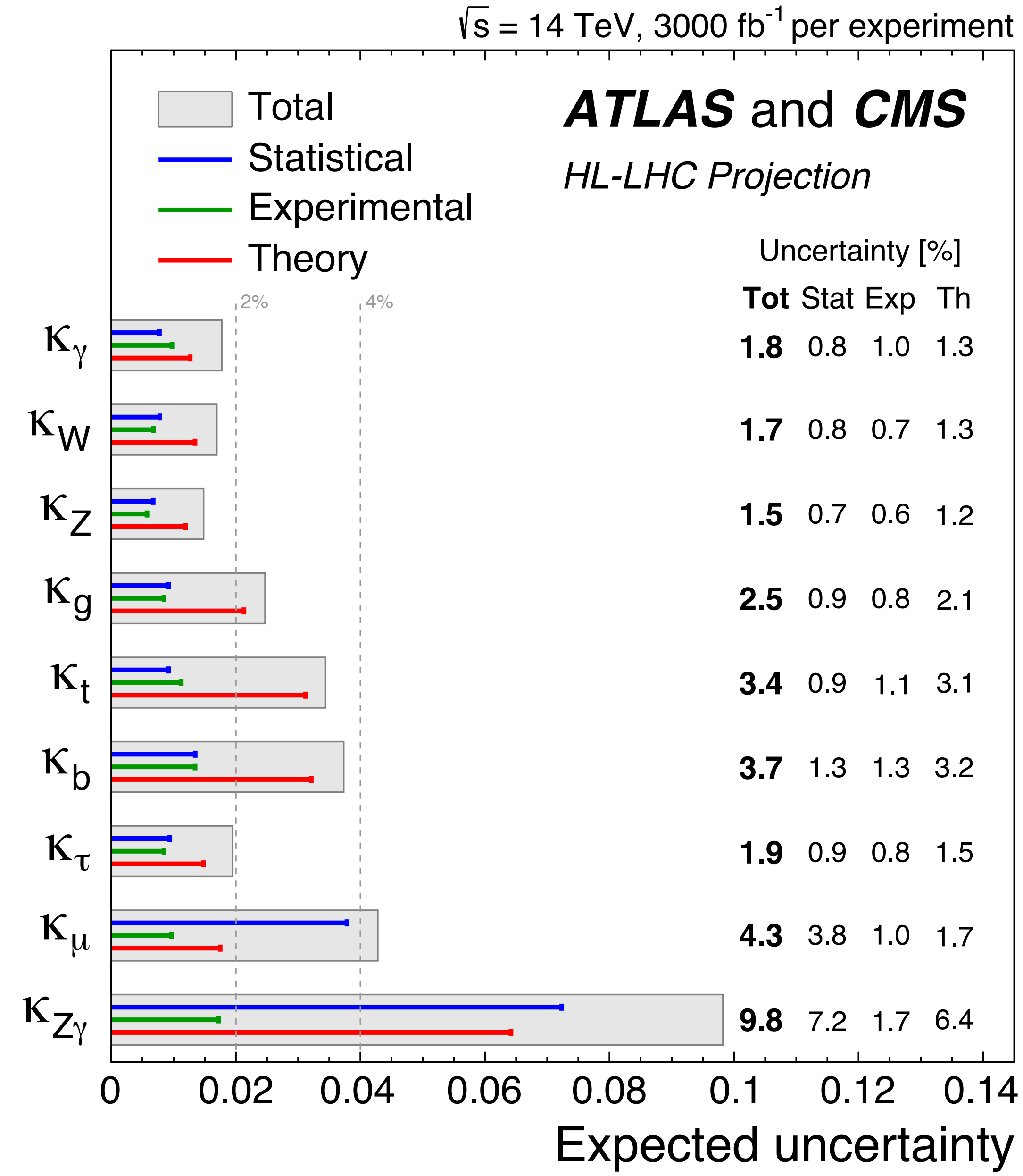


consistency of CMS and ATLAS projections

Ultimate HL-LHC projections

Combination of Projections





1.8%	1.2%
1.7%	1.0%
1.5%	0.8%
2.5%	1.3%
3.4%	1.9%
3.7%	2.1%
1.9%	1.1%
4.3%	**1.7%**
9.8%	**4.1%**

consistency of CMS and ATLAS projections

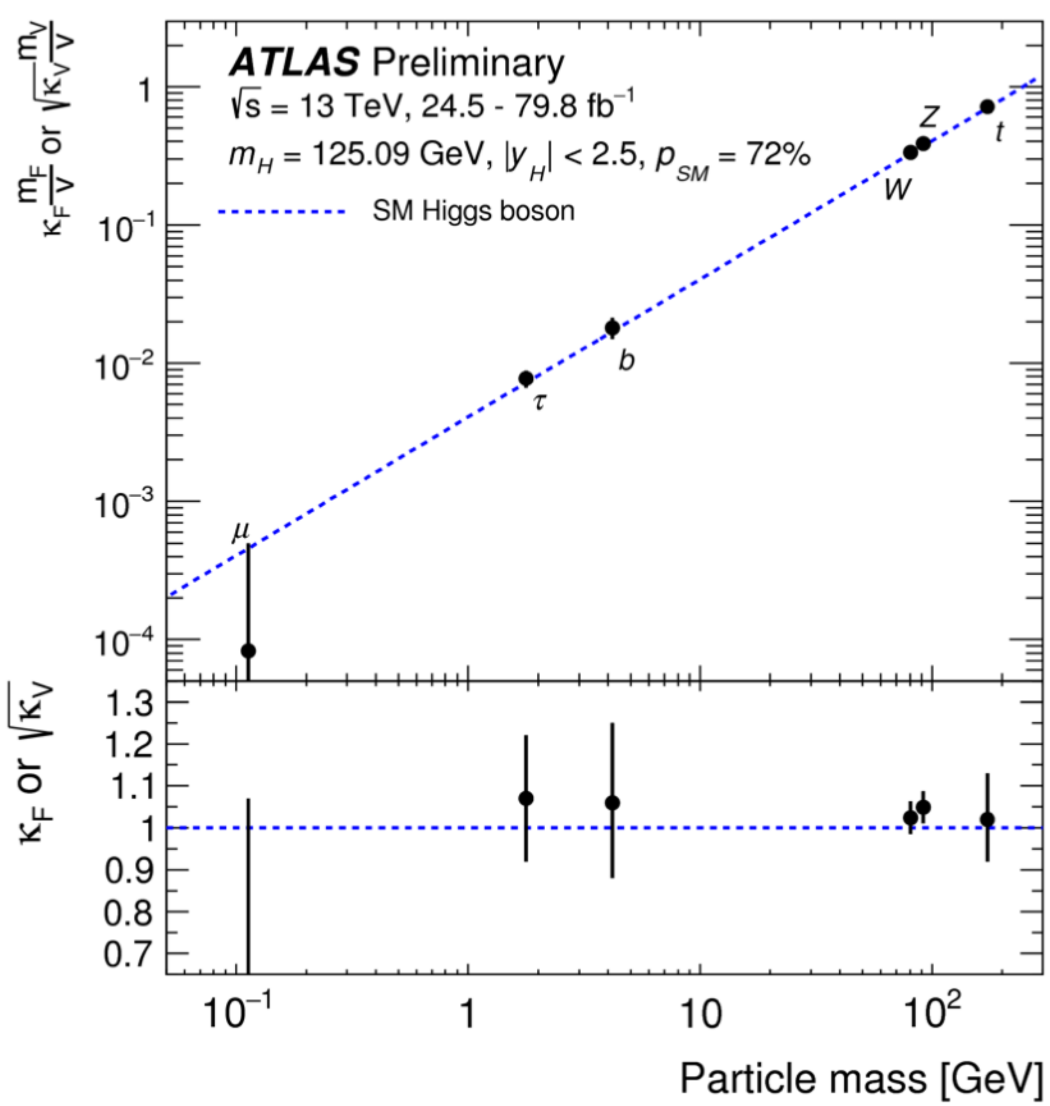
Ultimate HL-LHC projections

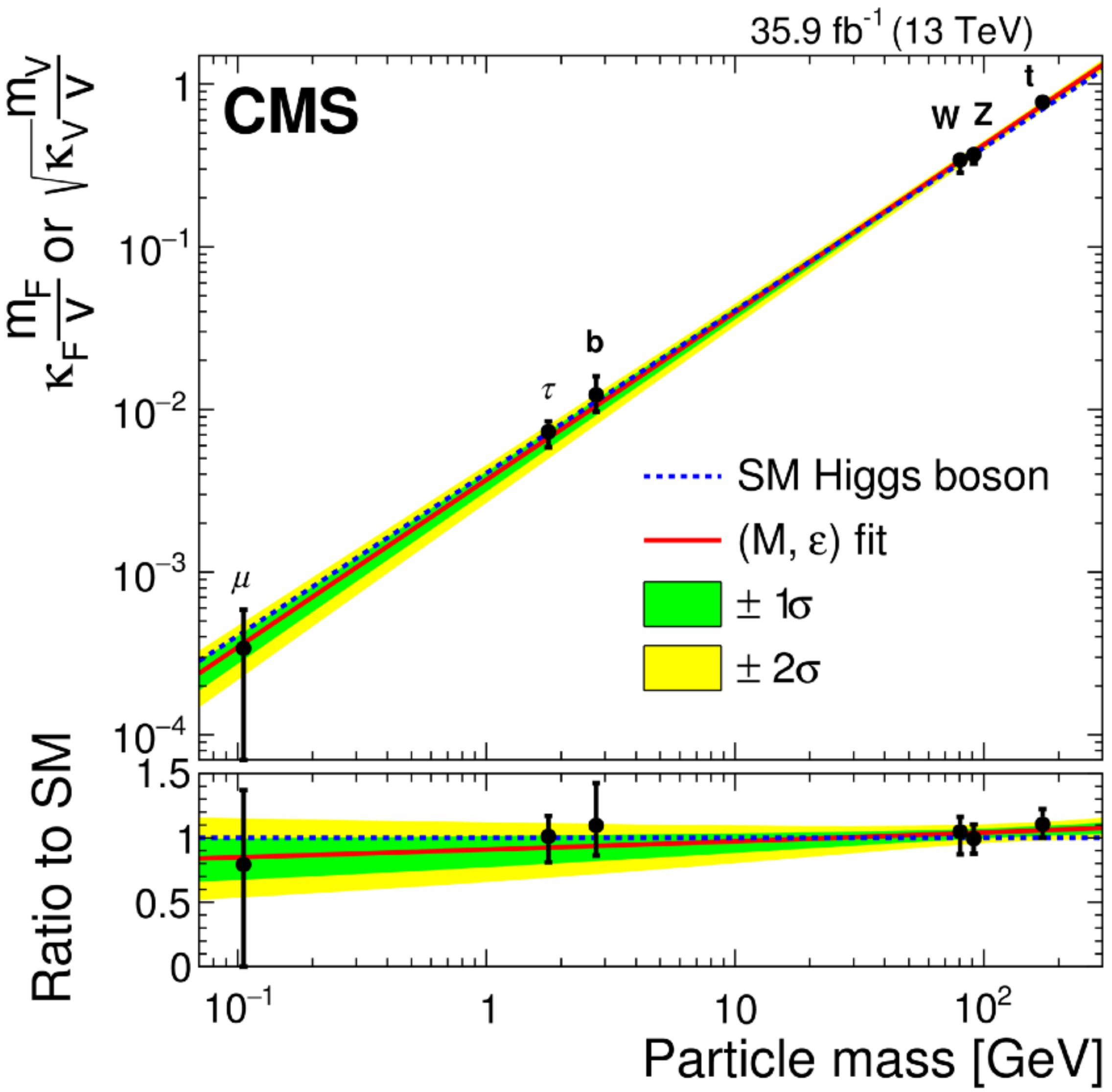
HE-LHC projections
15 ab^{-1} @ $\sqrt{s}$ = 27 TeV
(assuming theory unc. ½)

Coupling vs Mass

ATLAS 2016-1017
25-80 fb⁻¹

CMS 2016
36 fb⁻¹



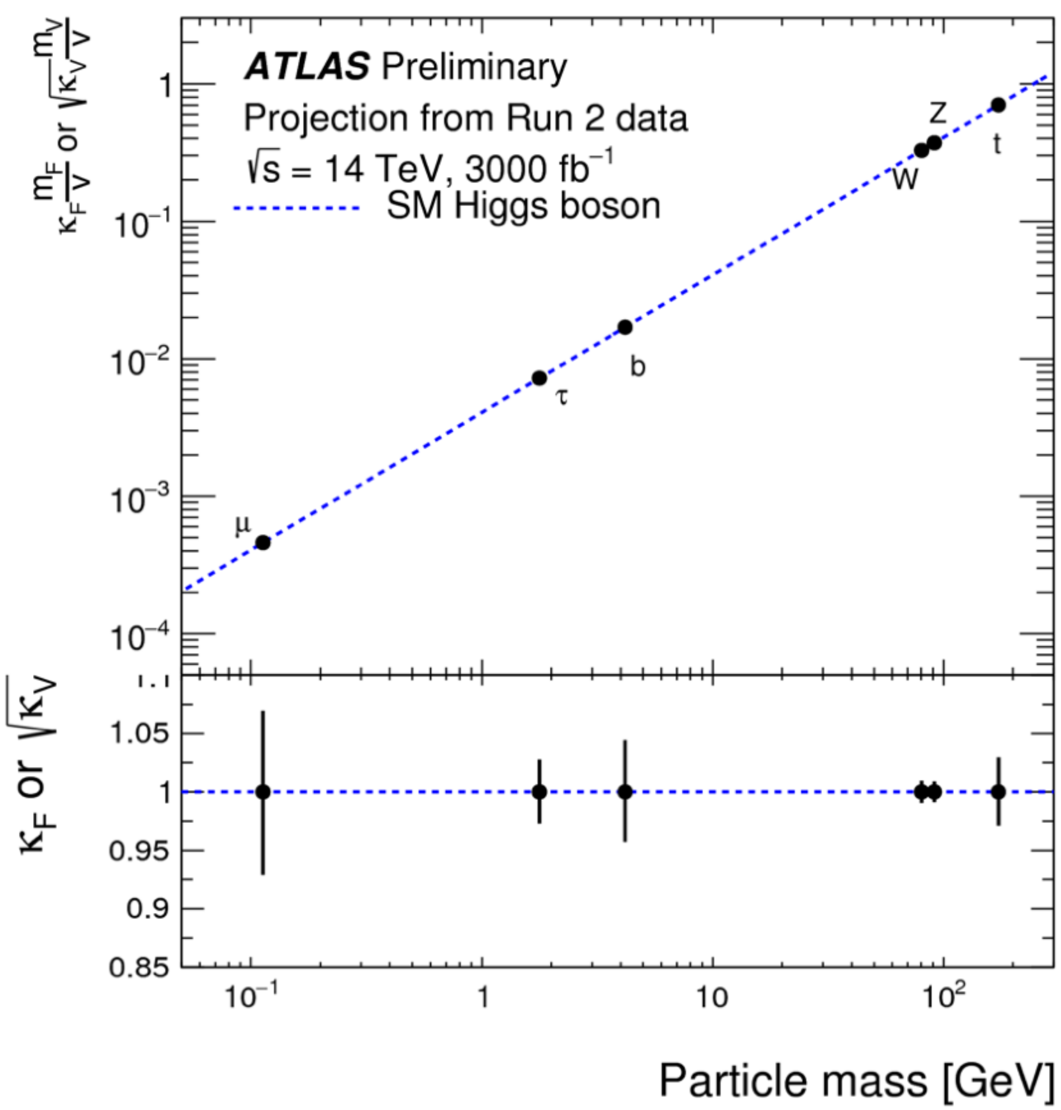


ATLAS-CONF-2019-005

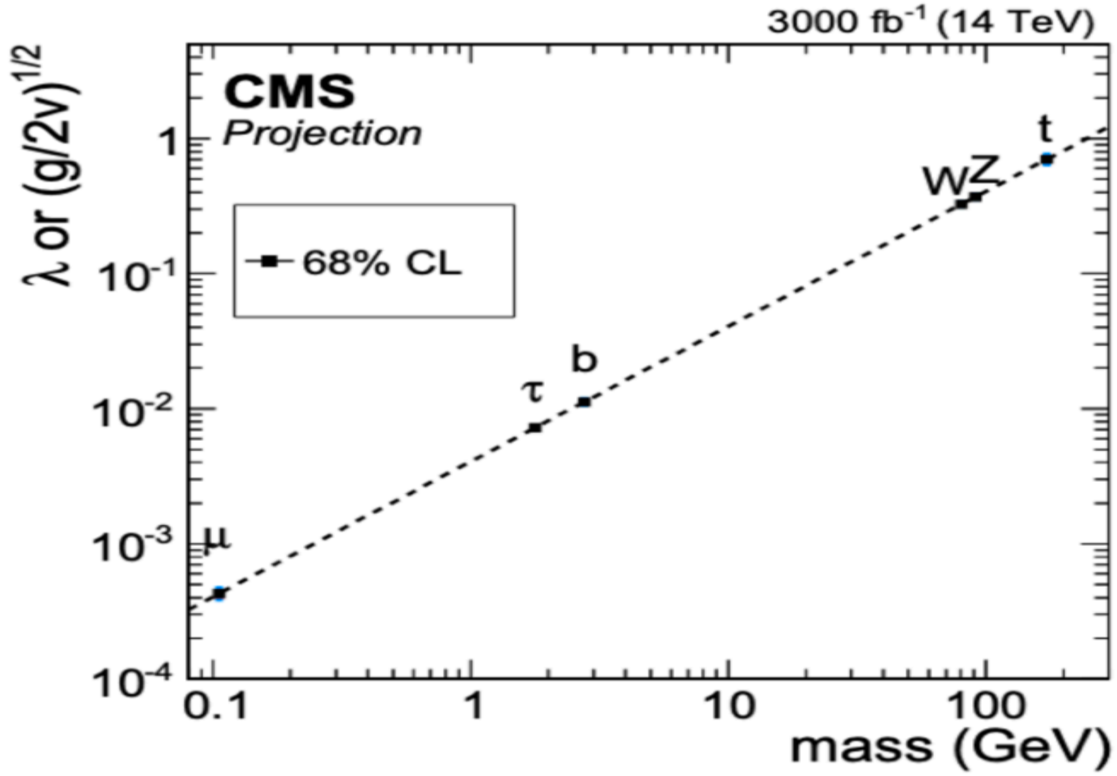
EPJC 79 (2019) 421

Coupling vs Mass

ATLAS HL-LHC
14 TeV
3 ab⁻¹



CMS HL-LHC
14 TeV
3 ab⁻¹



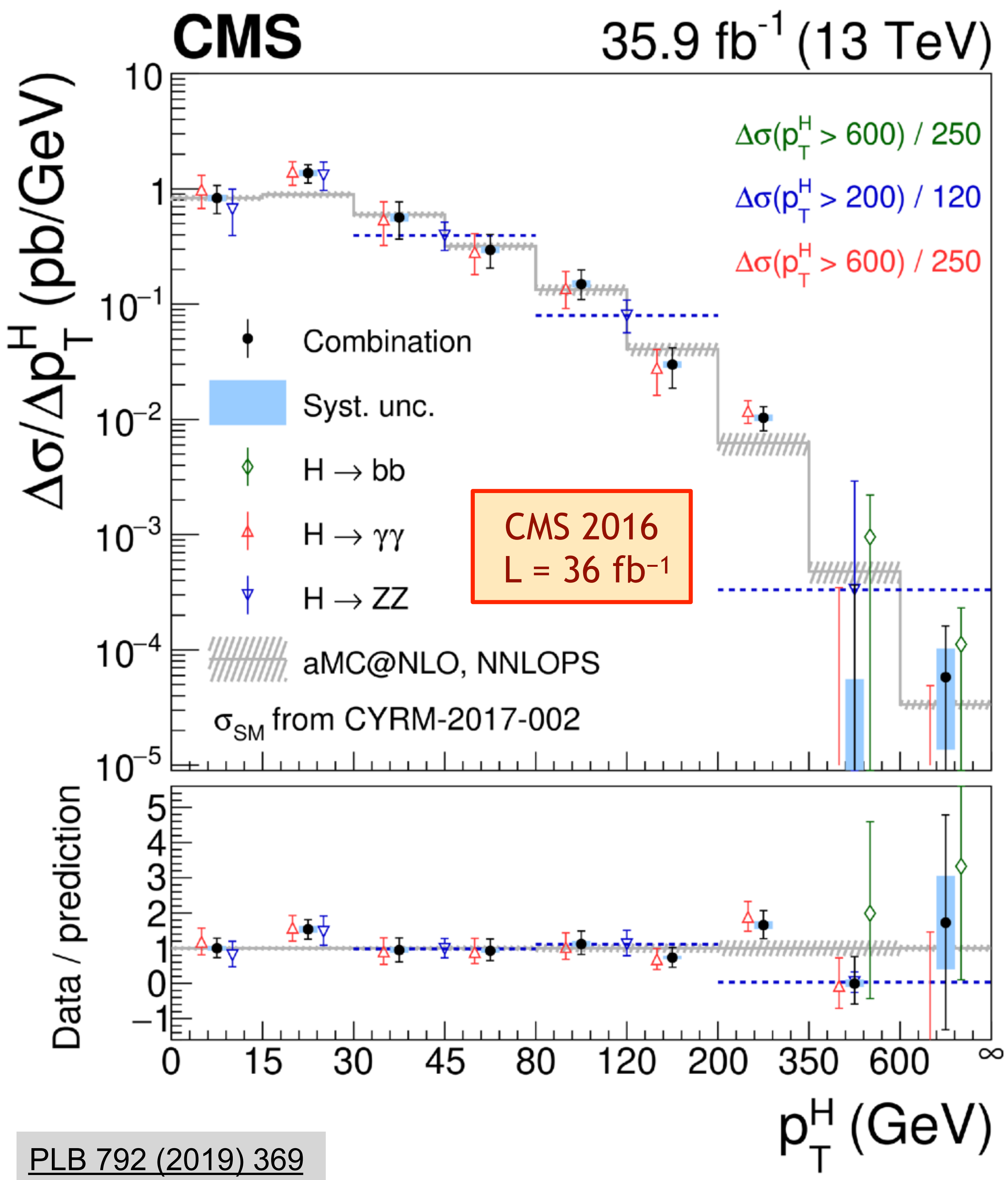
Yet missing:

- charm?
- self?
- invisible?

ATL-PHYS-PUB-2018-054

CMS-TDR-15-002

Higgs Differential Cross Sections



PLB 792 (2019) 369

- ☛ p_T^H distribution
- potential NP in high-p_T^H tails
- measured in γγ and 4ℓ
- high-p_T^H improved by *boosted* H → $b\bar{b}$

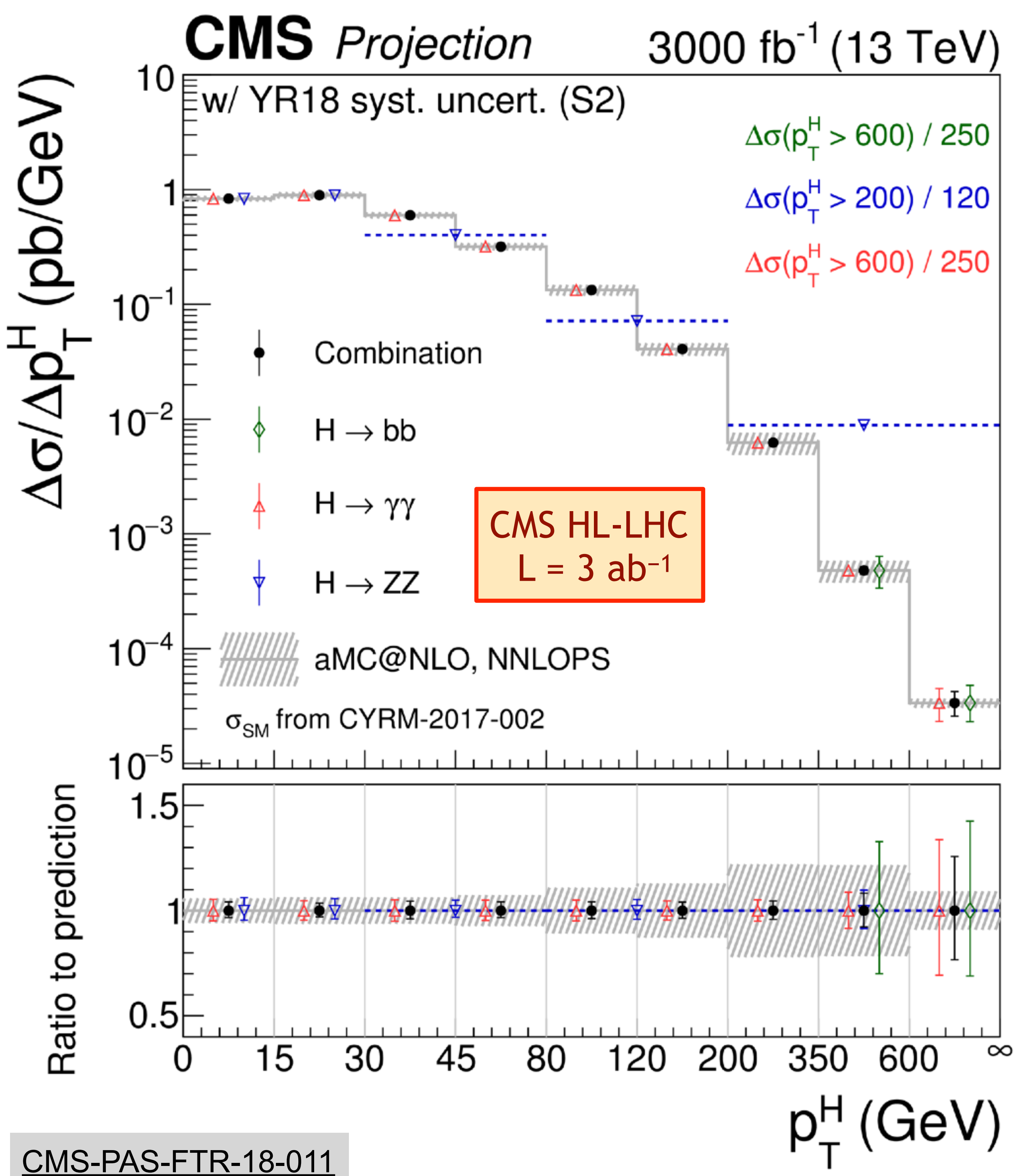
H → ZZ

H → γγ

H → $b\bar{b}$

H → $b\bar{b}$, γγ, ZZ

Higgs Differential Cross Sections



CMS-PAS-FTR-18-011

- ☛ p_T^H distribution
- potential NP in high-p_T^H tails
- *precisely* measured in γγ and 4ℓ
- high-p_T^H improved by *boosted* H → $b\bar{b}$

H → ZZ

H → γγ

H → $b\bar{b}$

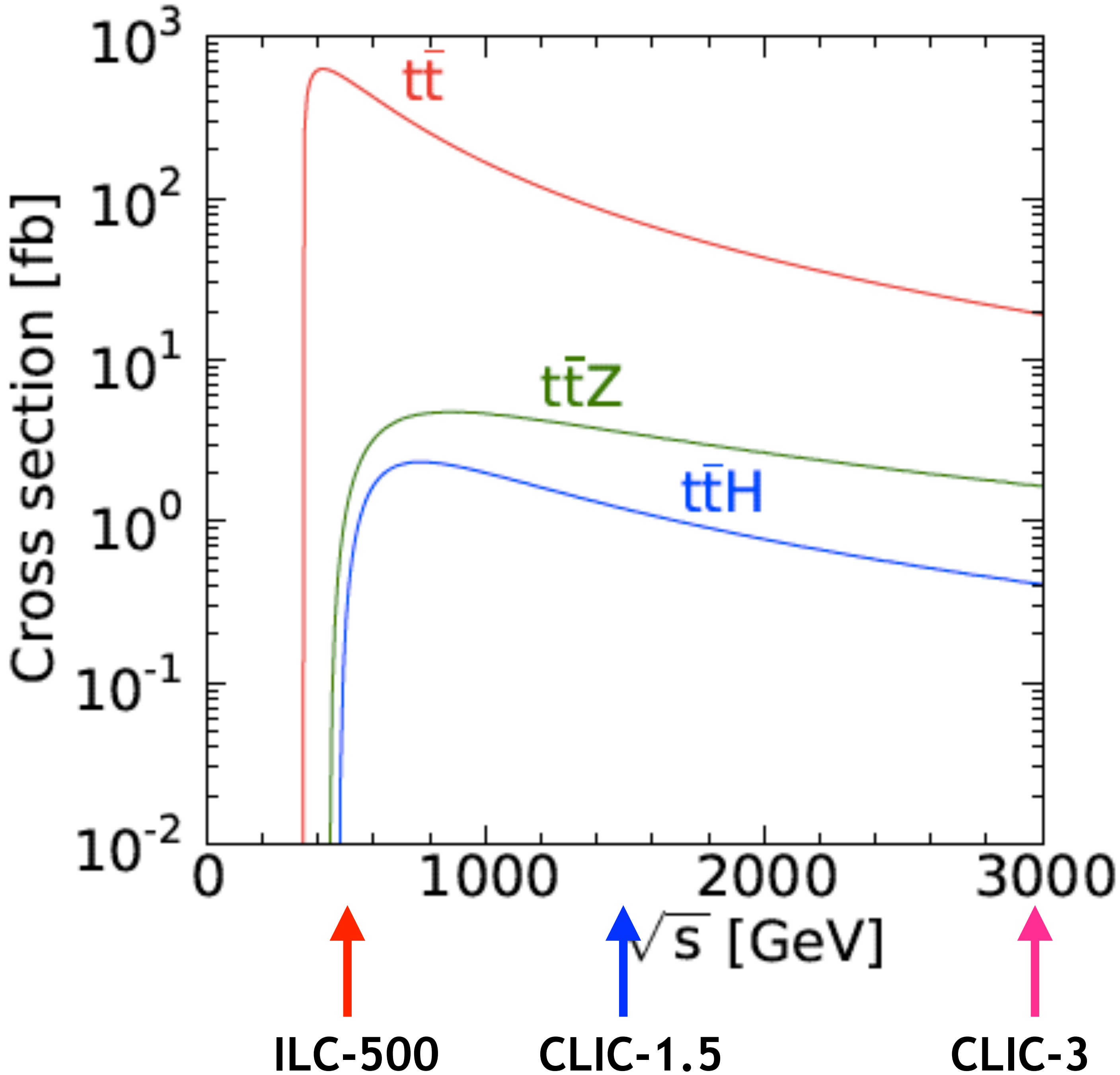
H → $b\bar{b}$, γγ, ZZ

probe modelling of ggH up to about p_T^H = 1TeV, with 8% precision for $p_T^H \in$ [350, 600] GeV

uncertainties in the high-p_T^H region reduced by a factor of 10

S2 *vs* S1: ~25% reduction in systematics

Top Yukawa at High Energy e^+e^- Colliders



cross sections in the fb range!

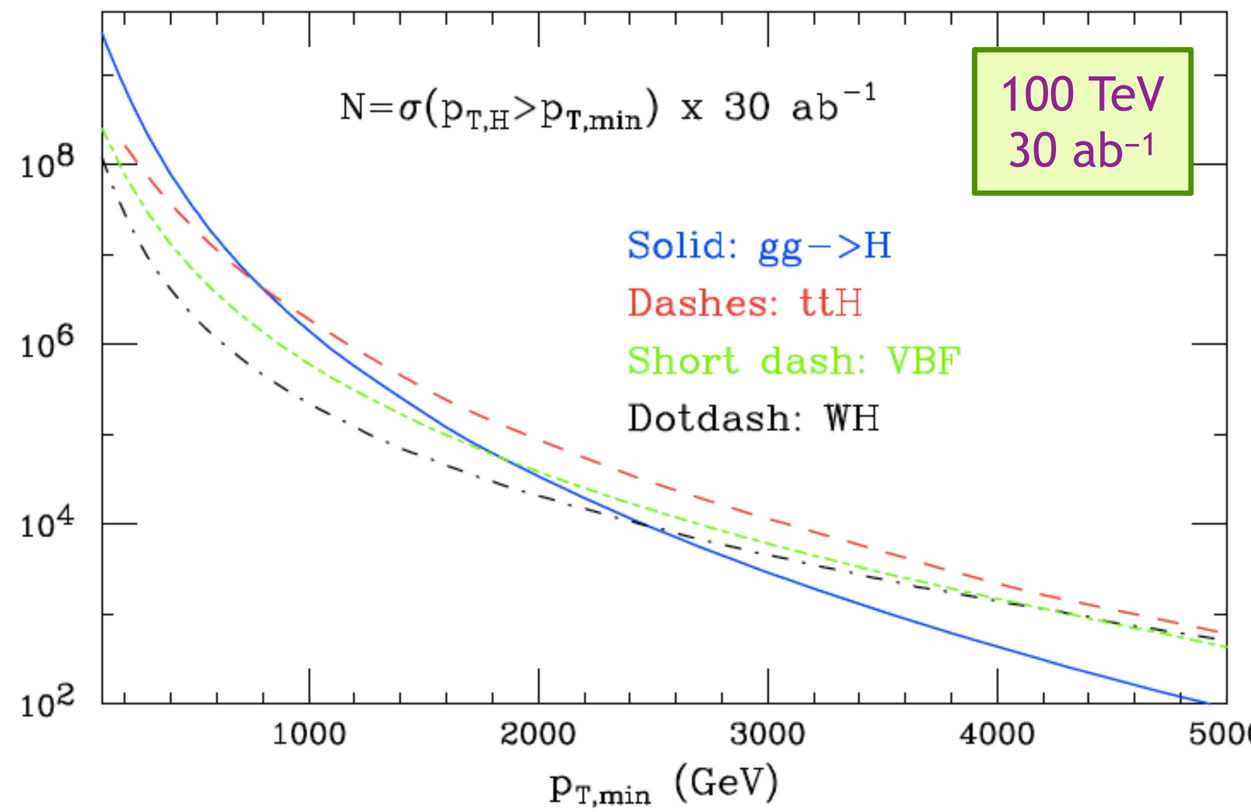
Higgs Studies at 100 TeV

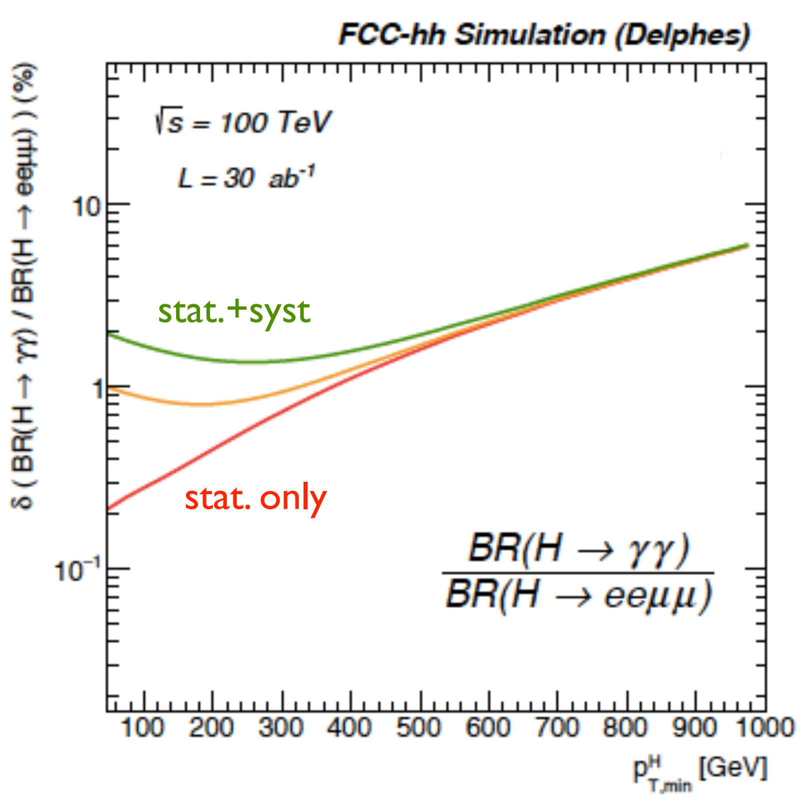
Large kinematic range for Higgs production

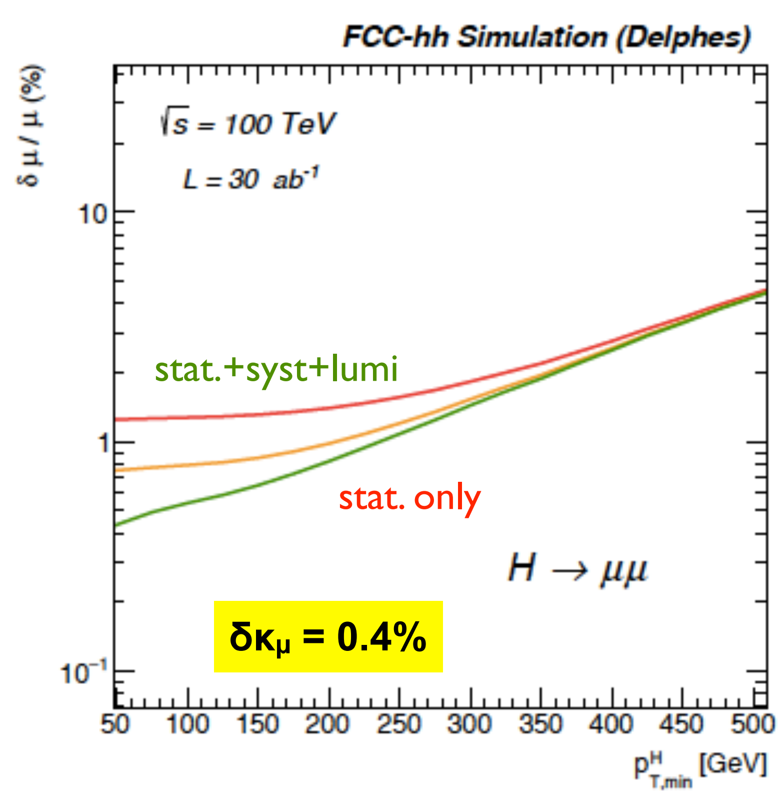
- different hierarchy of production processes
- sensitivity to effects at large Q^2

At p_T > 800 GeV

- millions of events
- ttH production becomes dominant







Rare decays

- absolute measurements
- ratio to known decay in fiducial region
- reduced systematic uncertainties at high p_T

☛ sub percent-level coupling measurements

needs to normalise to precision (%-level) measurement of *BR(4ℓ)* from e^+e^-

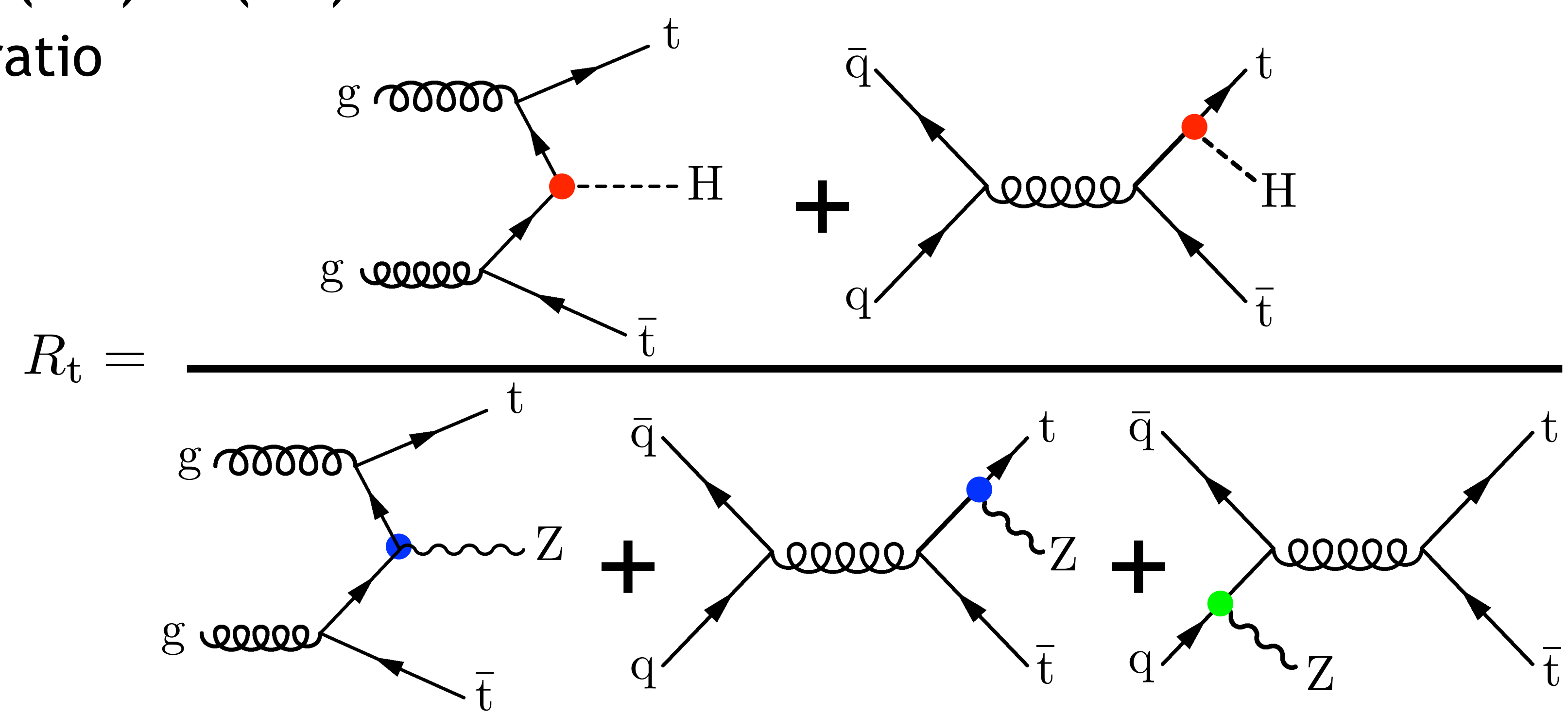
complementarity FCC-ee/hh

Next: Higgs measurements at e^+e^- colliders…

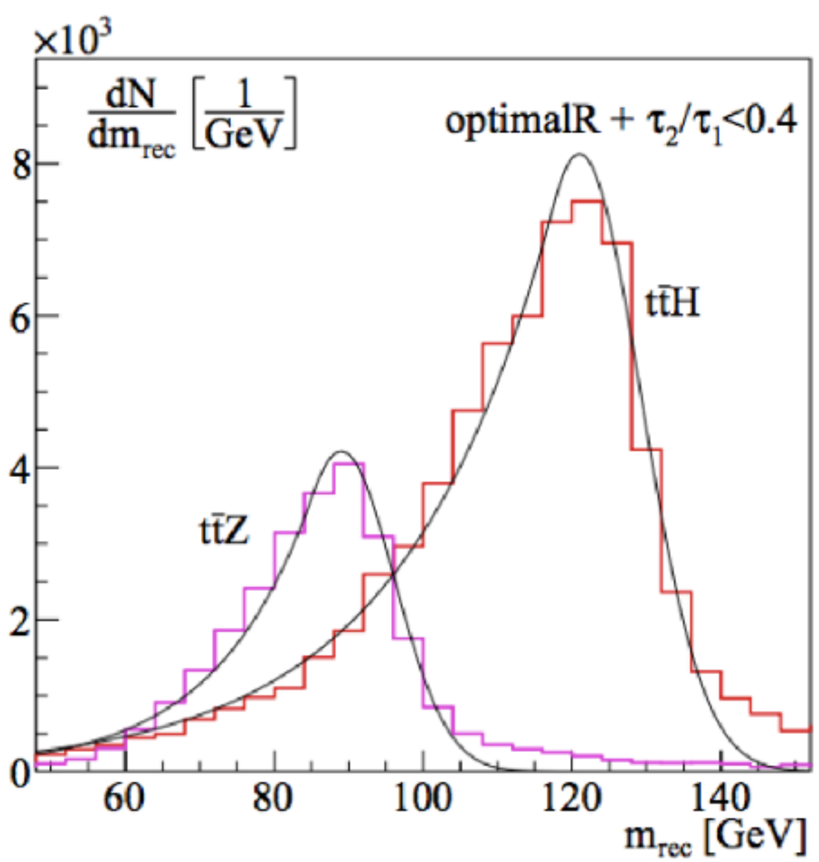
Top Yukawa Coupling at FCC-hh

FCC-hh: extraction y_t from $R_t = \sigma(ttH) / \sigma(ttZ)$

- most systematics cancel in the ratio
- measure of R_t with $\Delta R_t / R_t \approx 2\%$



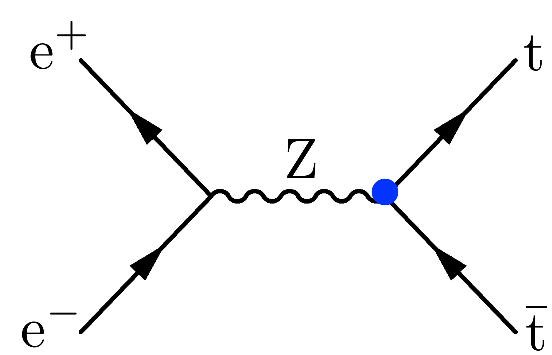
Use all combinations of final states
- exclusive and boosted Higgs and Z decays
- semileptonic and boosted hadronic top



➠ $\delta y_{top}/y_{top} \sim 1\%$ (stat+syst$_{TH}$)

FCC-ee @ 365 GeV:

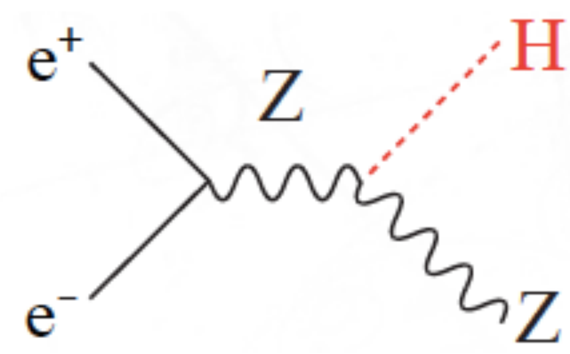
- measure of g_{Ztt} with $\Delta g_{Ztt}/g_{Ztt} \approx 1\%$



complementarity FCC-hh/ee

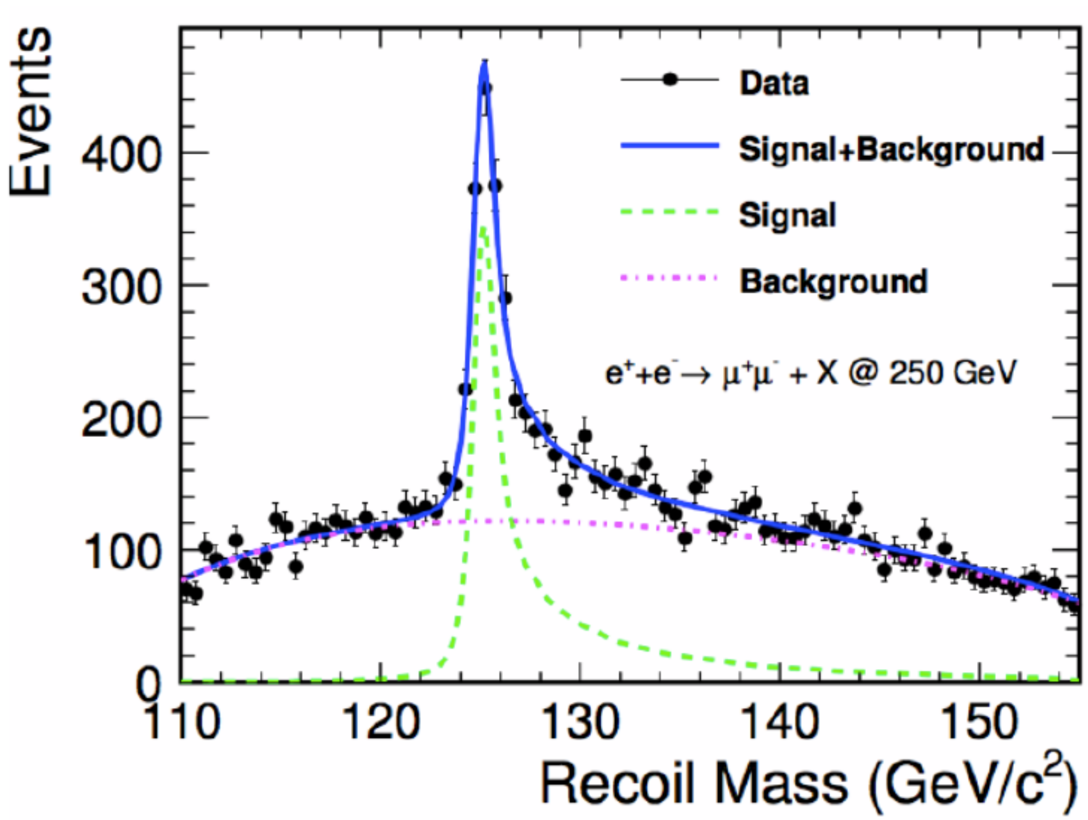
Recoil-Mass Analysis at e^+e^- Colliders

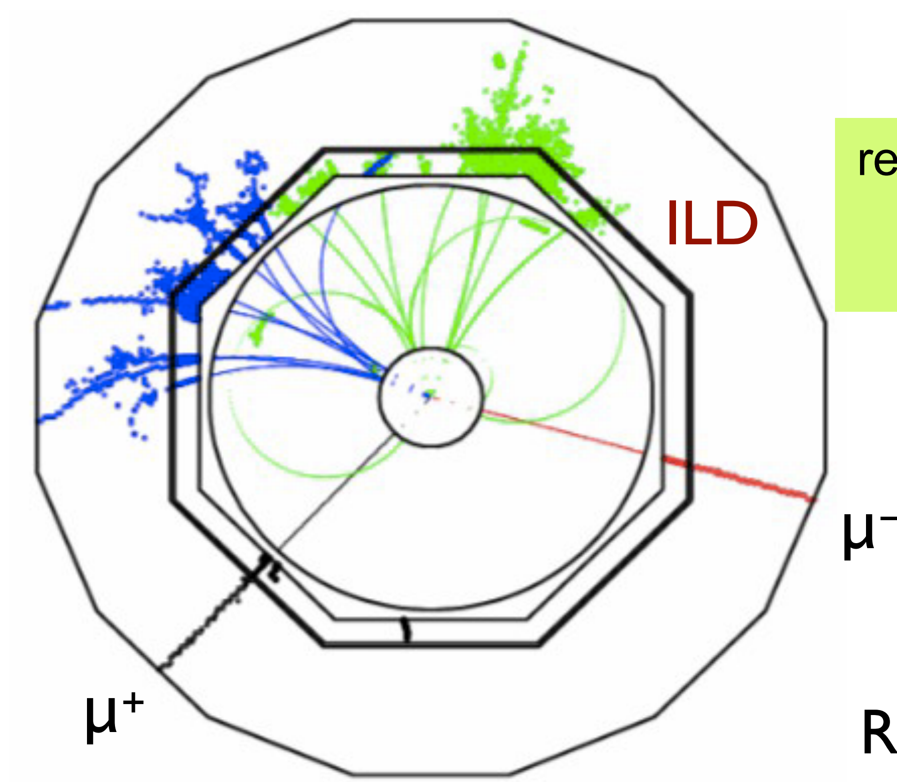
- Higgsstrahlung in leptonic mode
  $e^+e^- \to ZH \to \ell^+\ell^- H$
- selection and acceptance independent of Higgs decay channel
- high signal purity
- major backgrounds: Zγ, **ZZ**, and WW



$\sqrt{s}$ = 250 GeV
σ ≈ 200 fb

less than 3 orders of magnitude below $e^+e^- \to qq$





reconstruct Higgs events independently of the decay channel

Recoil mass:

$$M_X^2 = s + M_Z^2 - 2\sqrt{s}(p_{\mu^+} + p_{\mu^-})$$

$Z \to qq$ (60% vs 3.5% for $Z \to \mu\mu$) can also exploited at the price of a small dependence on the Higgs decay

- ILC at $\sqrt{s}$ = 250 GeV (LR+LR)
  - 500 fb^{-1} (6y)
    ✓ δM_H = 28 MeV
  - 2 ab^{-1} (15y)
    ✓ δM_H = 14 MeV

J. Yan et al, PRD 94 (2016) 113002

Higgs Decay Branching Ratios

Typical precision on σ × BR meas.
ILC at 250 fb^{-1} at $\sqrt{s}$ = 250 GeV
(~75 000 ZH events with LR pol.)

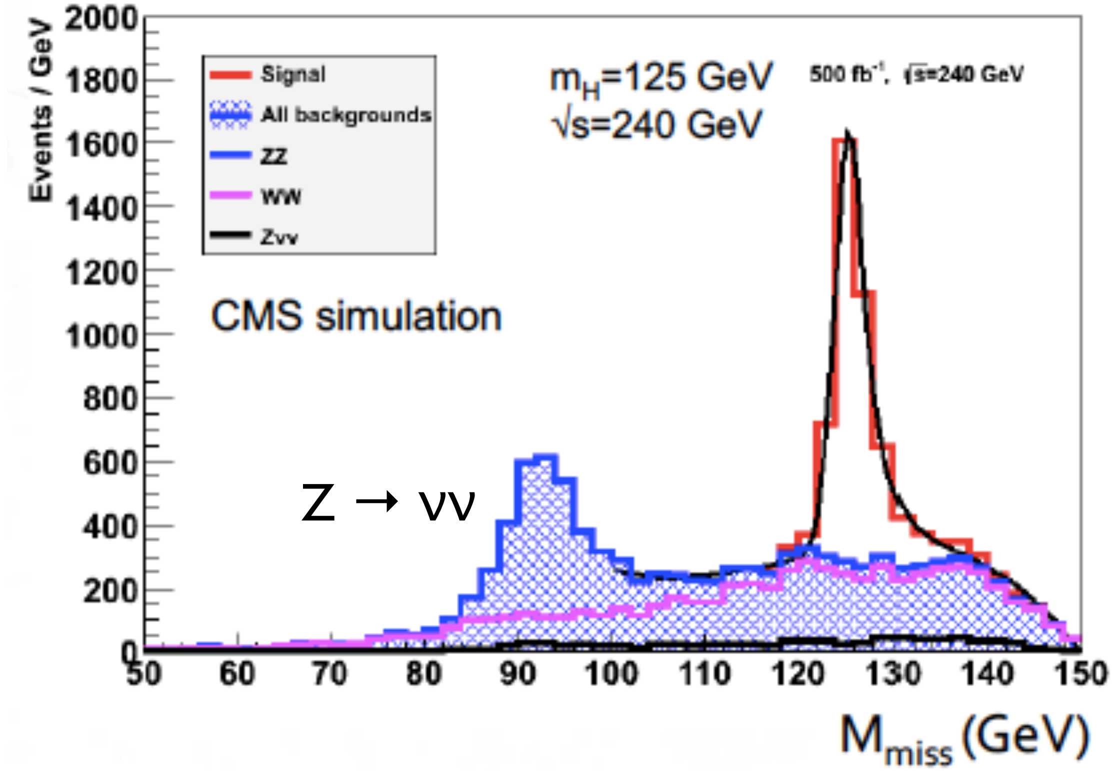
ILC TDR Vol. 2 - Physics (2013)

$\delta\sigma_{ZH}/\sigma_{ZH}$
2.6%

	BR (125 GeV)	$\delta(\sigma\times BR)/(\sigma\times BR)$
$H \to bb$	58.4%	**1.1%**
$H \to cc$	2.9%	7.4%
$H \to gg$	8.2%	9.1%
$H \to WW^*$	21.4%	6.4%
$H \to \tau^+\tau^-$	6.3%	4.2%
$H \to ZZ^*$	2.6%	19%
$H \to \gamma\gamma$	0.23%	34%
$H \to \mu^+\mu^-$	0.02%	--
$H \to inv$	0%	<0.9%

Neat, but still, statistics is an issue

$ZH \to \ell^+\ell^-$ + nothing
assuming BF(H → invisible) = 100%



$\sigma(ZH)\times BF(H\to ZZ^*)$ is proportional to g_{HZZ}^4/Γ_H
➠ measurement of Γ_H

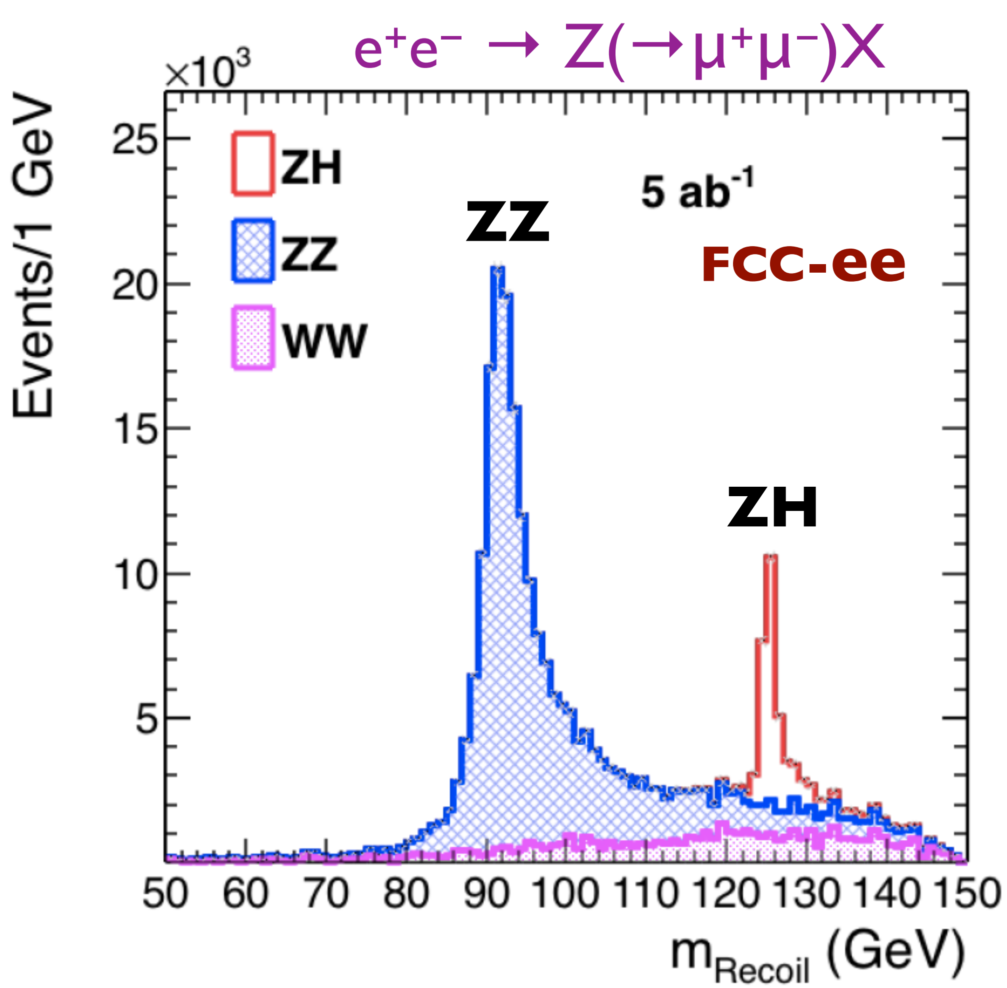
Also:
Higgs spin determination from rise of HZ cross section near threshold (measurements at $\sqrt{s}$ = 215 and 225 GeV)

Predicted Statistics of Higgs Events

now aiming at *much* higher statistics

	integrated $\mathscr{L}$ in ab^{-1} (√s in GeV)	# of years	# of H events	
ILC-250	2 (250)	13	0.5M	
ILC	2 (250) + 0.2 (350) + 4 (500)	25	1.6M	linear
CLIC	1 (380) + 3 (1500) + 5 (3000)	25	1.5M	
FCC-ee	5 (240) + 0.2 (350) + 1.5 (365)	8	1.2M	circular
CEPC	5 (240)	10	1.0M	

one "year" data-taking time between 0.5 and $1.6{\times}10^7$ s



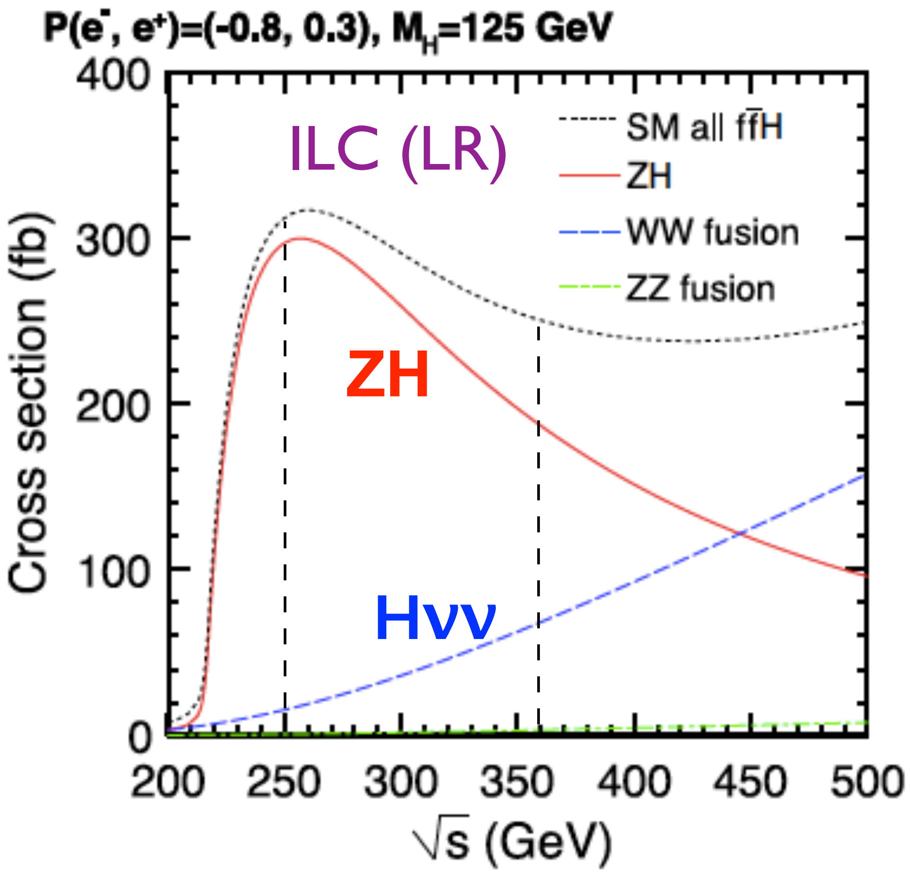
From the recoil analysis (√s = 250 GeV) with of the order of 1M events, σ_{ZH} can be determined at the 0.5% level

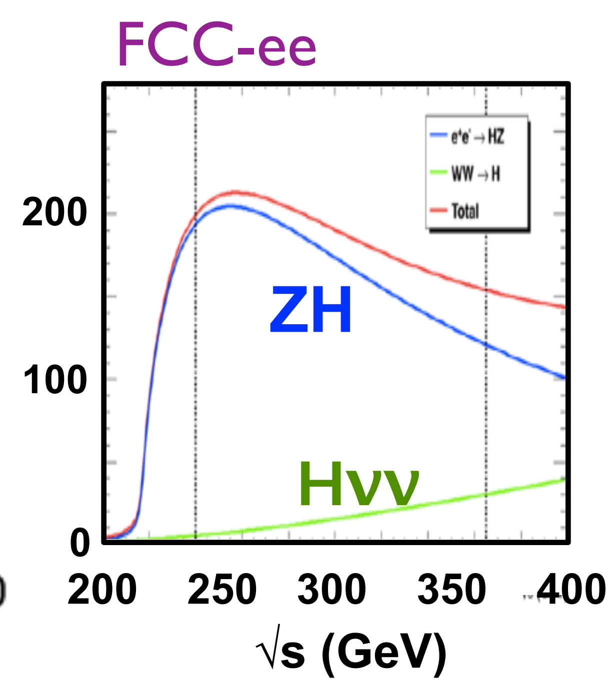
$$\sigma(e^+e^- \to ZH) = \sigma_{ZH} \propto g^2_{HZZ}$$

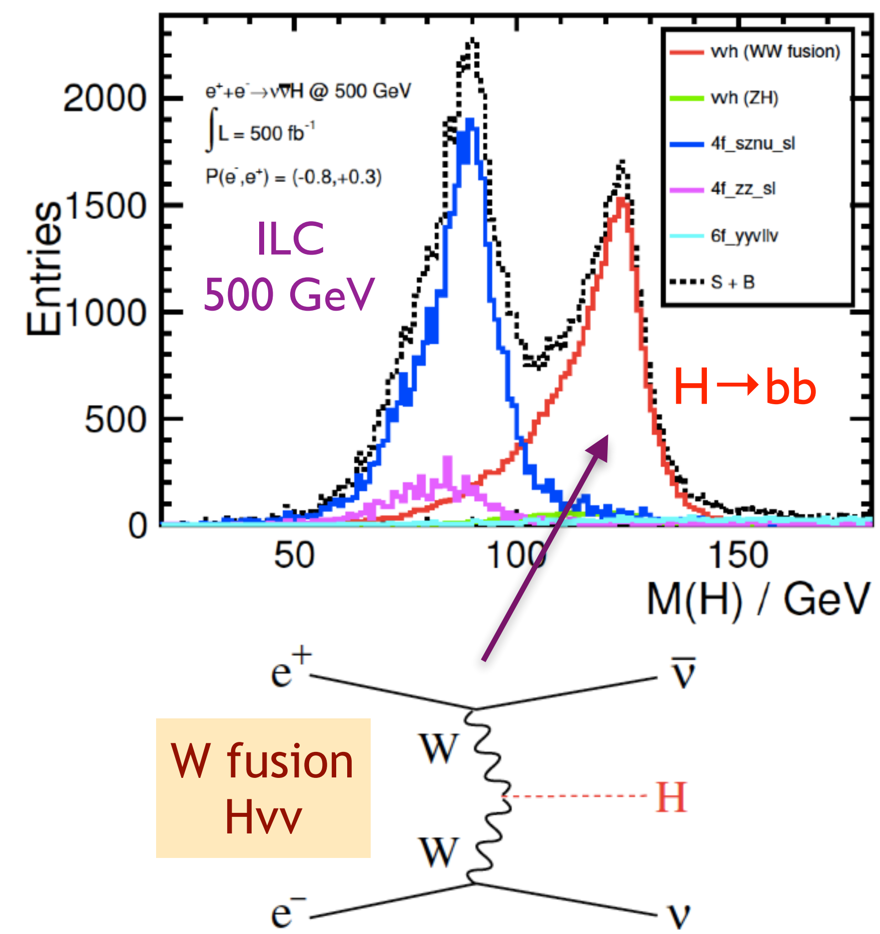
Note:
30 ab^{-1} at FCC-hh 100 TeV (25 y)
➔ 40 billion Higgs boson produced!
(a small fraction usable due to backgrounds)

Higgs Couplings

- ☛ to extract couplings from BR, one needs a measurement of the total width Γ_H
- ☛ to measure the total width, one needs at least one partial width and BR







At given energy (>250 GeV)

$$\frac{\sigma(\mathrm{WW}\to\mathrm{H})\times\mathcal{B}(\mathrm{H}\to\mathrm{XX})}{\sigma(\mathrm{ZH})\quad\times\mathcal{B}(\mathrm{H}\to\mathrm{XX})}=\frac{(g^2_{\mathrm{HWW}}\times g^2_{\mathrm{HXX}})/\Gamma_{\mathrm{H}}}{(\;g^2_{\mathrm{HZZ}}\;\times g^2_{\mathrm{HXX}})/\Gamma_{\mathrm{H}}}=\frac{g^2_{\mathrm{HWW}}}{g^2_{\mathrm{HZZ}}}$$

$$\mathrm{XX}=\mathrm{b\bar{b}},\ \mathrm{W^+W^-}$$

☛ Measurements of g_{HWW} and Γ_H

Higgs Couplings

inspired from

FCC-ee TDR (2018)

	HL-LHC	ILC		CLIC	FCC-ee		CEPC
√s (GeV)	14000	250	+500	380	90-240	+365	90-250
L (ab^{-1})	3	2	+4	0.5	5	+1.5	5
Years	13	15	+10	7	3	+6	7
ZZ (%)	3.5	0.38	0.30	0.80	0.25	0.22	0.25
WW (%)	3.5	1.8	0.4	1.3	1.3	0.46	1.2
ττ (%)	6.5	1.9	0.8	4.2	1.4	0.8	1.4
tt (%)	4.2	–	–	–	–	3.3(*)	–
bb (%)	8.2	1.8	0.6	1.3	1.4	0.7	1.3
cc (%)	–	2.4	1.2	1.8	1.8	1.2	1.8
gg (%)	–	2.2	1.0	1.4	1.7	0.9	1.4
γγ (%)	3.6	1.1(*)	1.0(*)	4.7	4.7	1.3(*)	4.7
Γ_H (%)	50	3.9	1.7	6.3	2.8	1.5	2.6
exo (%)	–	<1.6	<1.3	<1.2	<1.2	<1.0	<1.2

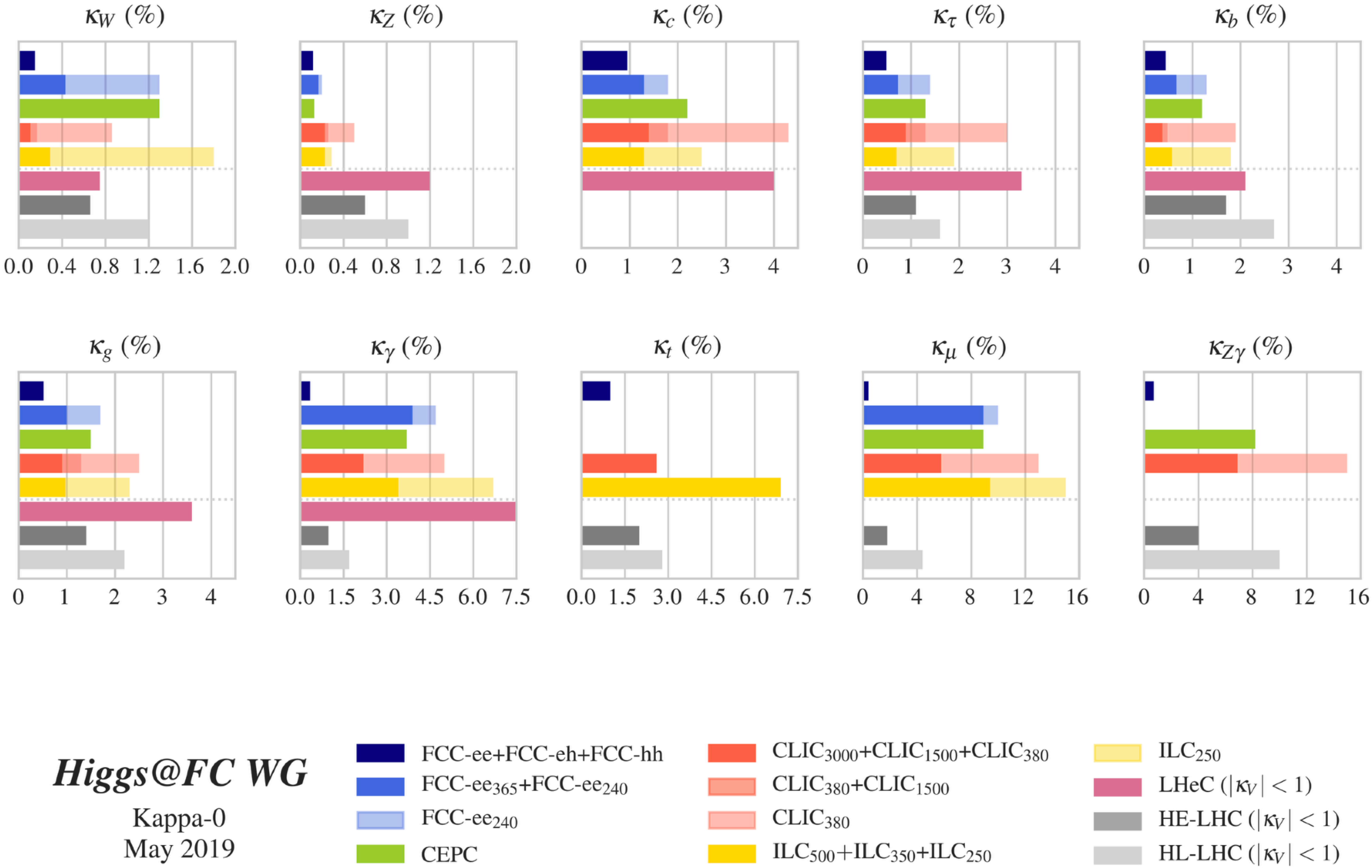
(*) incorporating HL-LHC results

ILC: using κ-framework
- simple scaling of the couplings
- no operator formalism
- no assumption on total width

HL-LHC measures σ_{ttH} but the extraction of g_{ttH} is model-dependent (through σ_{prod} and Γ_H)
- benefits from Γ_H at e^+e^- machines

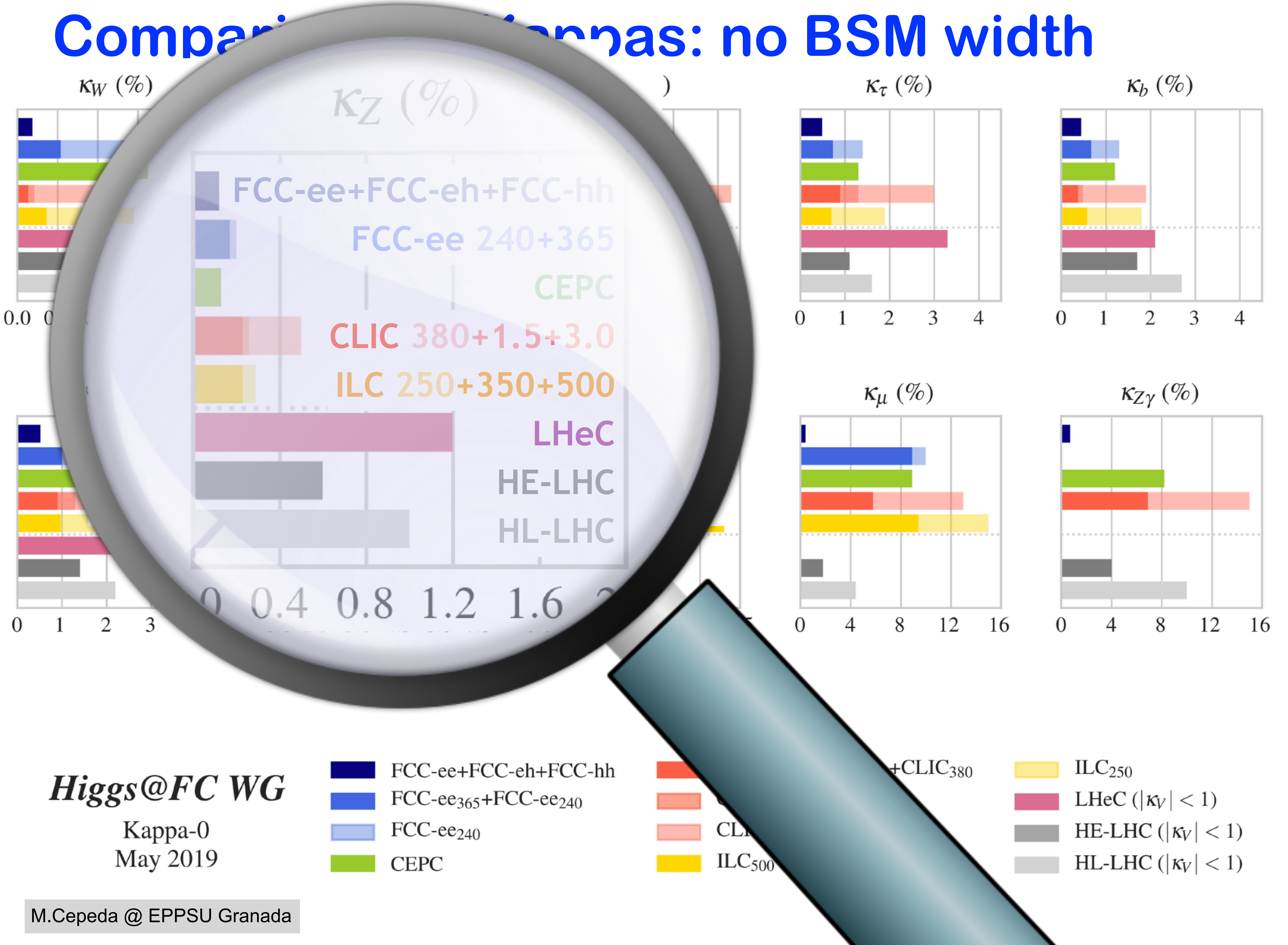
ILC Physics TDR

Comparison of Kappas: no BSM width



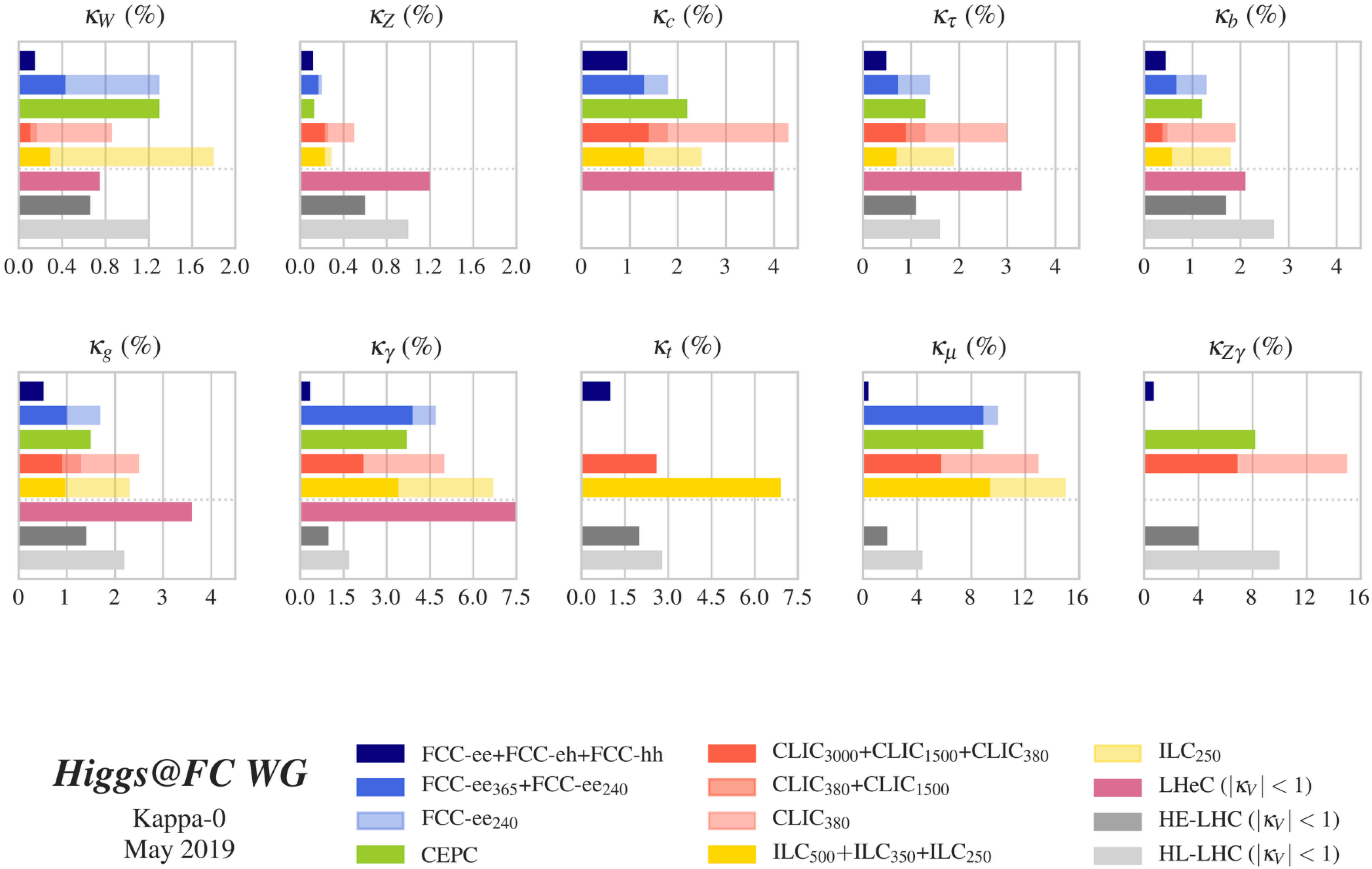
M.Cepeda @ EPPSU Granada

Compari... Kappas: no BSM width



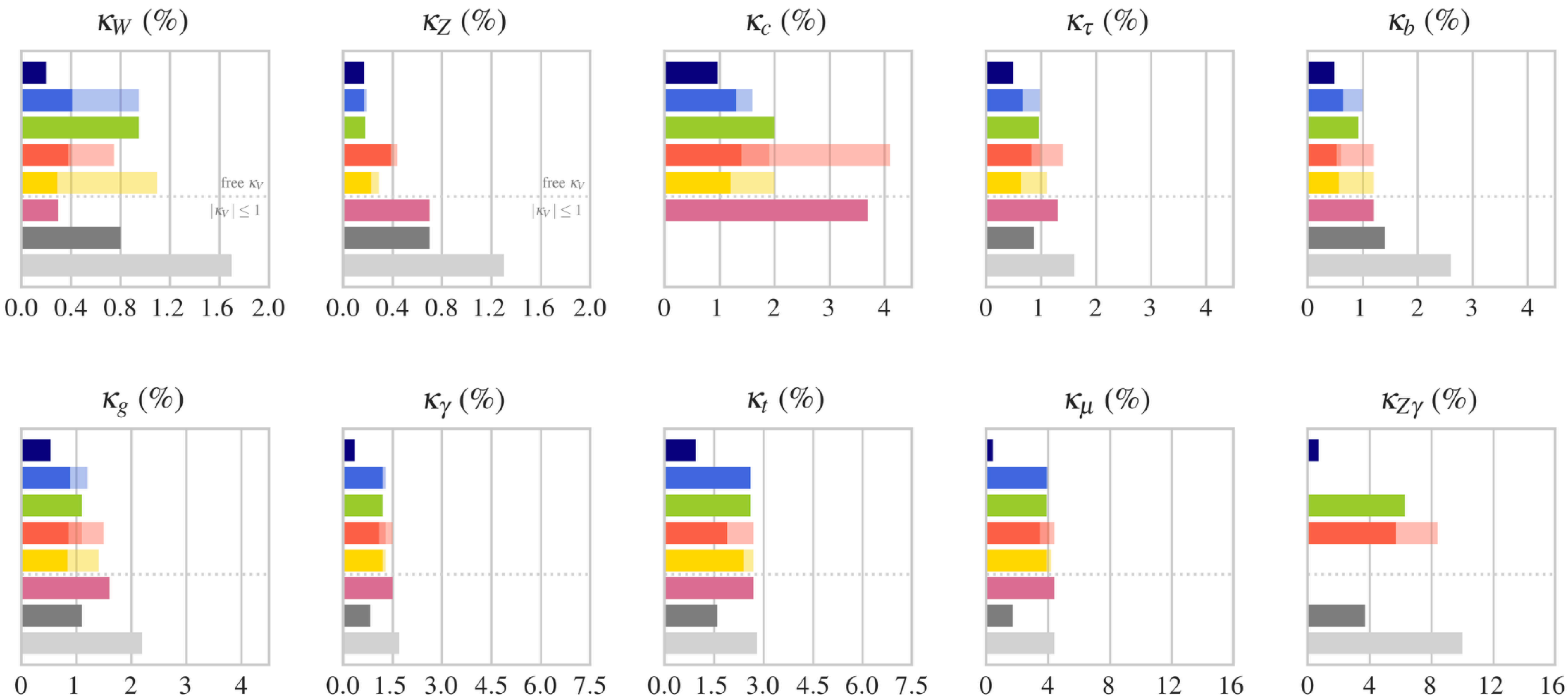
M.Cepeda @ EPPSU Granada

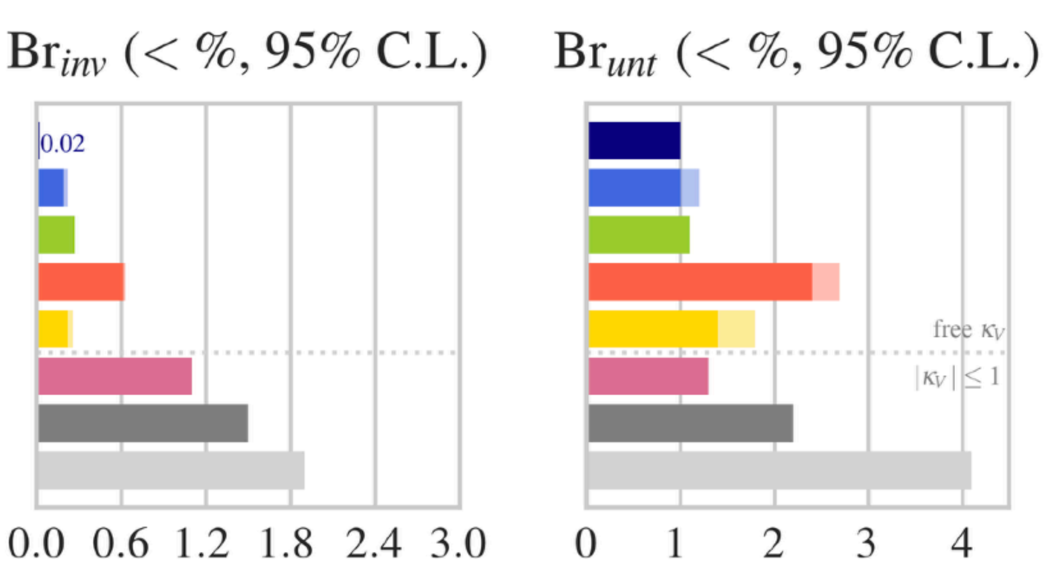
Comparison of Kappas: no BSM width



M.Cepeda @ EPPSU Granada

Comparison of Kappas: with BSM width





Fit including HL-LHC constraints to demonstrate the complementarity with lepton colliders:

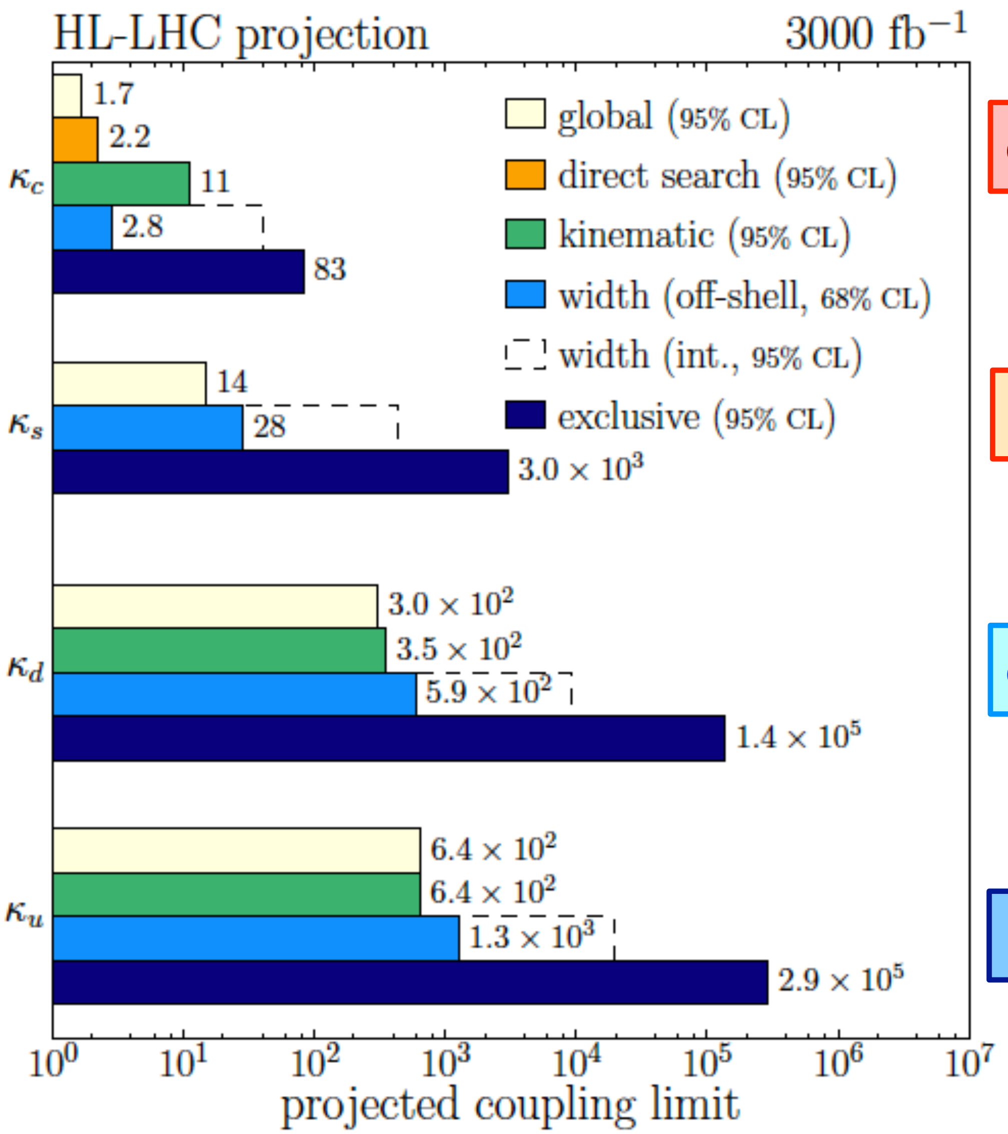
- rare decays: γγ, γZ, μμ
- top
- charm

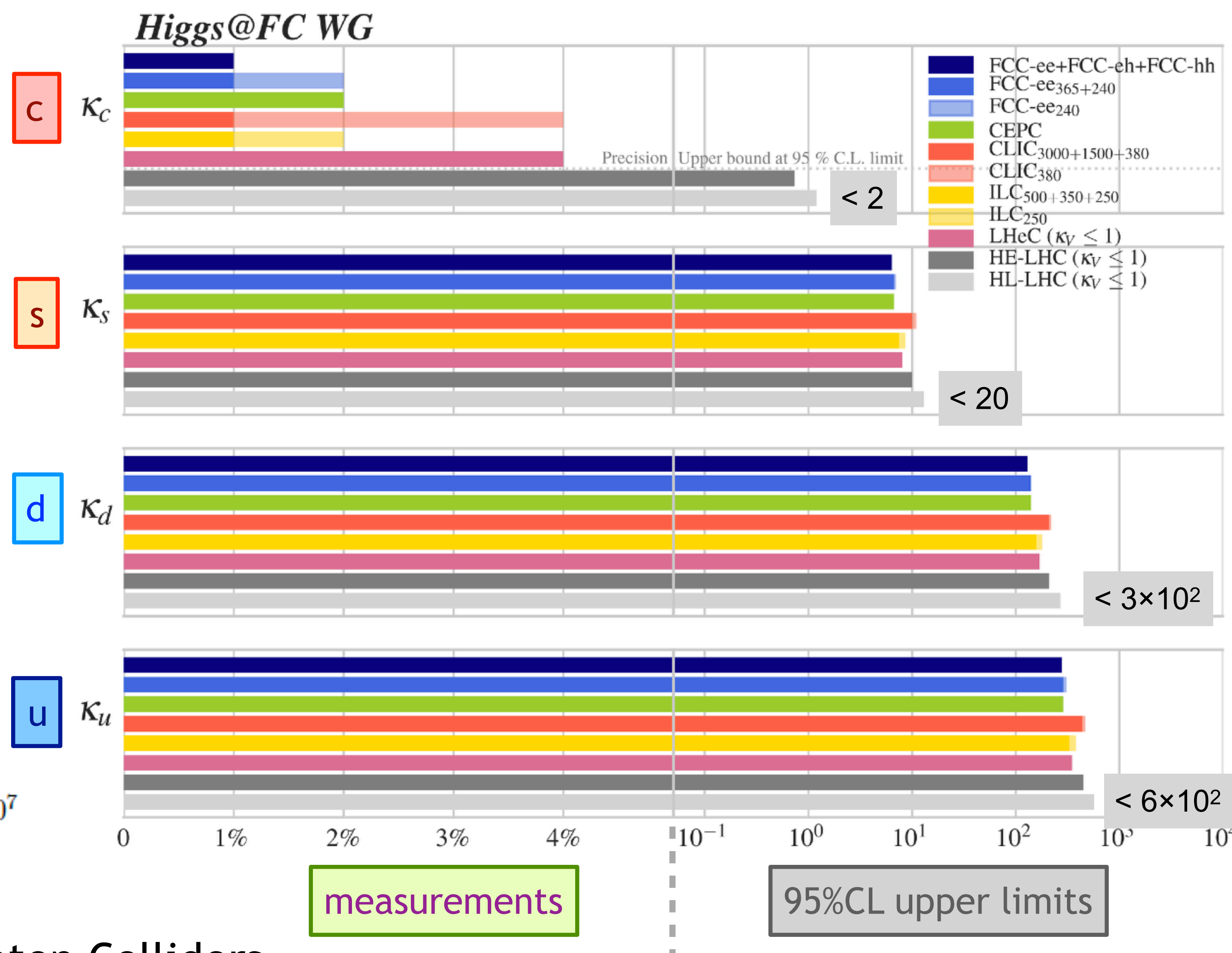
NB: hadron collider cannot measure width
need an assumption to close the fit
e.g. $|\kappa_V| < 1$

Yukawa Couplings of Light Quarks

HL-LHC on charm Yukawa coupling

- LHCb might play a role here (direct and exclusive searches)
- constrains include differential distributions, off- and on-shell couplings, and limits on B^{unt}





HE-LHC improves limits on charm coupling by factor 2

Lepton Colliders

- percent level measurements of the charm Yukawa coupling
- couplings of light quarks s, d, u are out of reach

Global SMEFT Fit

Effective Field Theories (EFT) are tools to probe indirectly New Physics (NP)

SMEFT :
bottom-up approach

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \underbrace{\frac{c^{(5)}}{\Lambda} O^{(5)}} + \sum_i \underbrace{\frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}} + \ldots$$

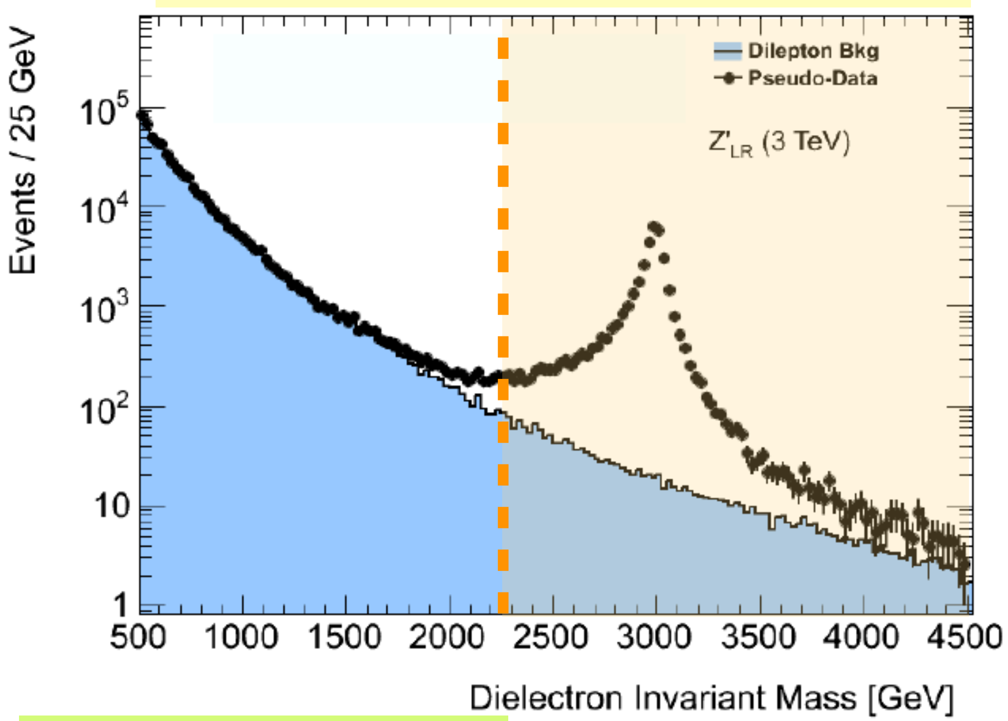
1 operator
ΔL = 2

2499 operators
(59 B-, L-, F-Conserving)

Beyond the κ-framework
global fit include also the di-boson and
EWK precision observables

Λ = cut-off of the EFT

effect of a Z' in the dilepton spectrum



no resonance seen
but *deviations* wrt SM

☛ Non-renormalisable terms imply violation of unitarity at high energies

$$\sigma \propto \left(c_i^{(6)}/\Lambda^2\right)^2 s$$

☛ NP must manifest itself before unitarity is violated

$$E_i^{\rm max} \lesssim \Lambda/\sqrt{c_i^{(6)}}$$

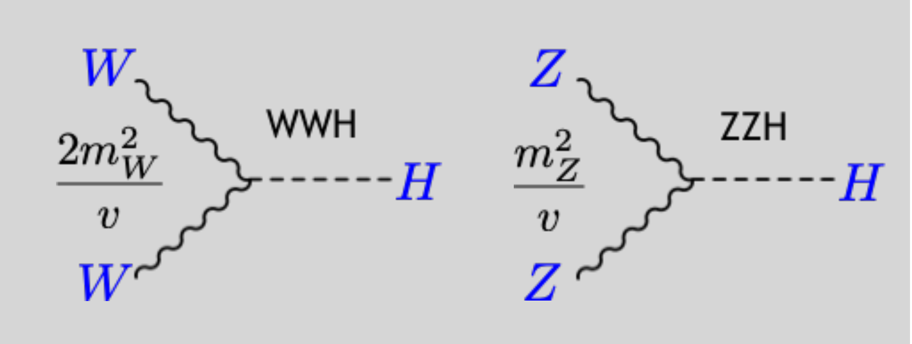
$c_i^{(6)}$ can modify gauge, Higgs, and top couplings

see P. Hernándes & J. deBlas @ EPPSU Granada

Anomalous hVV Couplings

- SM hVV Lagrangian:

$$\mathcal{L}_{\rm SM}^{hVV} = \frac{h}{v}\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$



- dim-6 SMEFT hVV Lagrangian:

$$\Delta\mathcal{L}_6^{hVV} = \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu + c_{ww}\frac{g^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + c_{w\Box} g^2\left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) + c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu}\Big]$$

➠ 7 independent parameters

- Parameters are related by gauge invariance:

$$\delta c_w = \delta c_z + 4\delta m$$

NP contributions to m_W: only source of custodial symmetry breaking

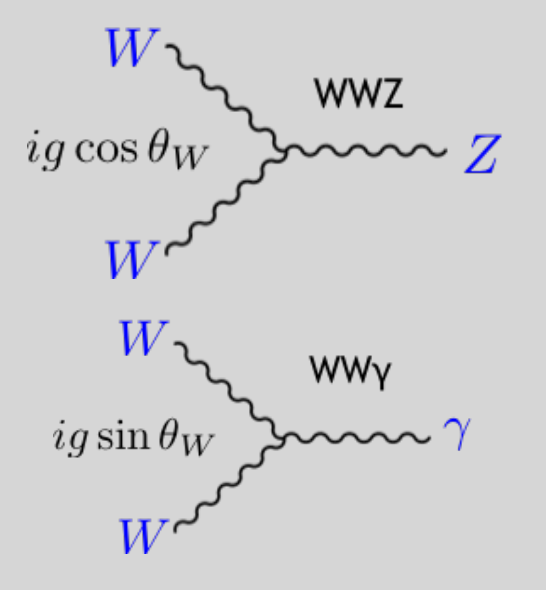
$$c_{ww} = c_{zz} + 2\sin^2\theta_w c_{z\gamma} + \sin^4\theta_w c_{\gamma\gamma}$$

$$c_{w\Box} = \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\sin^2\theta_w c_{\gamma\gamma} - (g^2-g'^2)\sin^2\theta_w c_{z\gamma}\right]$$

$$c_{\gamma\Box} = \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)c_{zz} - e^2 c_{\gamma\gamma} - (g^2-g'^2)c_{z\gamma}\right]$$

A. Falkowski arxiv:1505.00046 de Blas et al, arxiv:1907.04311

Anomalous TGC



- SM TGC Lagrangian:

$$\mathcal{L}^{\rm TGC}_{\rm SM} = ig\cos\theta_w\left[(W^-_{\mu\nu}W^{+\mu} - W^+_{\mu\nu}W^{-\mu})Z^\nu + Z_{\mu\nu}W^{+\mu}W^{-\nu}\right] + ig\sin\theta_w\left[(W^-_{\mu\nu}W^{+\mu} - W^+_{\mu\nu}W^{-\mu})A^\nu + F_{\mu\nu}W^{+\mu}W^{-\nu}\right]$$

- dim-6 SMEFT TGC Lagrangian:

$$\Delta\mathcal{L}^{\rm aTGC} = ie\delta\kappa_\gamma A^{\mu\nu}W^+_\mu W^-_\nu + ig\cos\theta_w\left[\delta g_{1Z}(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})Z^\nu + \left(\delta g_{1Z} - \frac{g'^2}{g^2}\delta\kappa_\gamma\right)Z^{\mu\nu}W^+_\mu W^-_\nu\right] + \frac{ig\lambda_z}{m_W^2}\left(\sin\theta_w W^{+\nu}_\mu W^{-\rho}_\nu A^\mu_\rho + \cos\theta_w W^{+\nu}_\mu W^{-\rho}_\nu Z^\mu_\rho\right)$$

- 2 aTGC parameters can be expressed in terms of anomalous hVV parameters:

$$\delta g_{1,z} = \frac{1}{2(g^2 - g'^2)}\left[c_{\gamma\gamma}e^2 g'^2 + c_{z\gamma}(g^2 - g'^2)g'^2 - c_{zz}(g^2 + g'^2)g'^2 - c_{z\Box}(g^2 + g'^2)g^2\right]$$

$$\delta\kappa_\gamma = -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2 + g'^2} + c_{z\gamma}\frac{g^2 - g'^2}{g^2 + g'^2} - c_{zz}\right)$$

➠ 1 independent parameter

A. Falkowski arxiv:1505.00046

de Blas et al, arxiv:1907.04311

Anomalous hff and (h)Vff Couplings

☛ dim-6 SMEFT hff Lagrangian:

$$\Delta\mathcal{L}_6^{hff} = -\frac{h}{v}\sum_{f\in u,d,e}(\delta y_f)_{ij}\,(m_f)_{jj}\bar{f}_i f_j + \text{h.c.}$$

- CP-violating phases are set to zero and off-diagonal terms are not considered
  ➠ keep 5 independent hff parameters
  δy_t $(=(dy_u)_{33})$, δy_c $(=(dy_u)_{22})$, δy_b $(=(dy_d)_{33})$, δy_τ $(=(dy_e)_{33})$, δy_μ $(=(dy_e)_{22})$

☛ dim-6 SMEFT (h)Vff Lagrangian:

$$\Delta\mathcal{L}_6^{(h)Vff} = \frac{g}{\sqrt{2}}\left(1+2\frac{h}{v}\right)W_\mu^+\left((\delta g_W^\ell)_{ij}\,\bar{\nu}_L^i\gamma^\mu\ell_L^j + (\delta g_{W,L}^q)_{ij}\,\bar{u}_L^i\gamma^\mu d_L^j + (\delta g_{W,R}^q)_{ij}\,\bar{u}_R^i\gamma^\mu d_R^j + \text{h.c.}\right)$$
$$+\sqrt{g^2+g'^{\,2}}\left(1+2\frac{h}{v}\right)Z_\mu\left[\sum_{f=u,d,e,\nu}(\delta g_{Z,L}^f)_{ij}\,\bar{f}_L^i\gamma^\mu f_L^j + \sum_{f=u,d,e}(\delta g_{Z,R}^f)_{ij}\,\bar{f}_R^i\gamma^\mu f_R^j\right]$$

with

$$\delta g_W^\ell = \delta g_{Z,L}^\nu - \delta g_{Z,L}^\ell$$
$$\delta g_{W,L}^q = \delta g_{Z,L}^u V_{CKM} - V_{CKM}\,\delta g_{Z,L}^d$$

- assume flavour-diagonal couplings
- impose U(2) for the first 2 families

➠ keep 15 independent parameters: 6 (Zℓℓ) + 3 (Wℓv) + 2 (Zu$\bar{u}$) + 4 (Zd$\bar{d}$)

Equivalence Theorem: Vff ↔ hVff

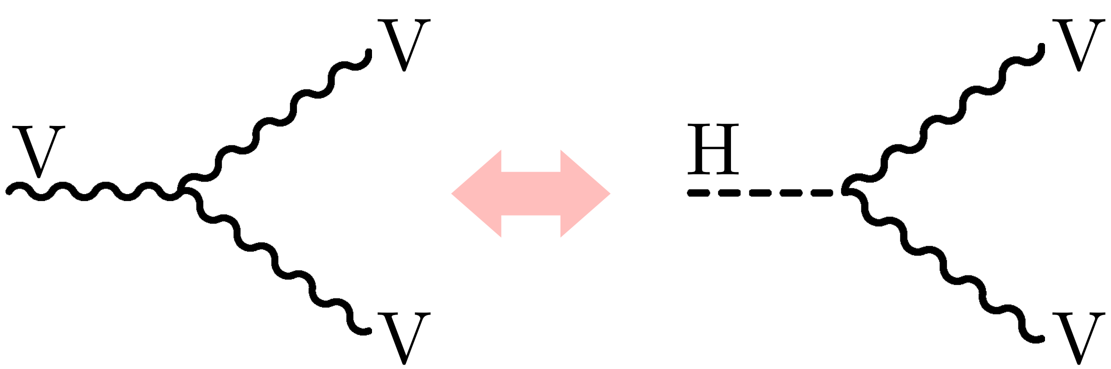
In the SM, the Higgs boson field h is one of 4 ddl as part of an $SU(2)_L$ doublet

F. Riva, HL/HE-LHC symposium, 2019
Ch. Grojean, ECFA/EPS, 2019

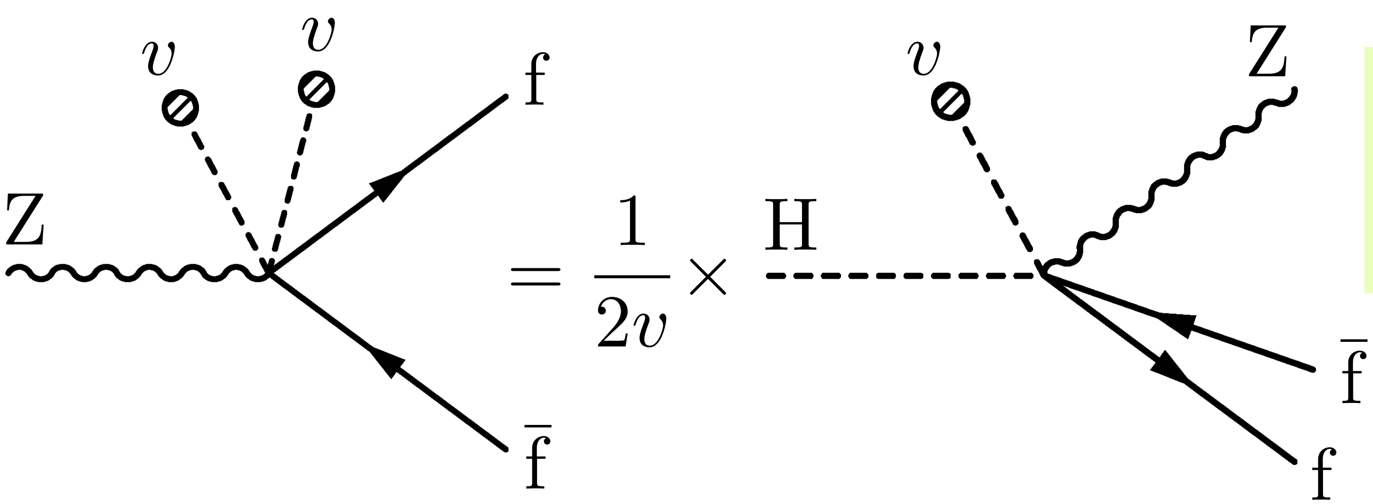
$$\phi = \begin{pmatrix} h^{\pm} \\ (v+h) + ih^0 \end{pmatrix}$$

$W_L^{\pm}$ ($h^{\pm}$), H (h), Z_L (h^0)

At some level of precision (not yet reached at the LHC) electroweak and diboson processes will interfere with Higgs measurements



connection between vector boson scattering and Higgs couplings to bosons



connection between Z decays to fermions and Higgs decay to Zff̄

contact interaction term (grows with energy)

one of the purposes of SMEFT is to exploit fully the connections between the electroweak and Higgs sectors

SMEFT Fit Parameters for Higgs Studies

Neutral Diagonal (ND) scenario

- a sufficient set of SMEFT parameters to describe Z-pole EWPO, diboson and single Higgs processes at colliders
- assumes flavour-diagonal neutral couplings
- assumes flavour universality for the first two families

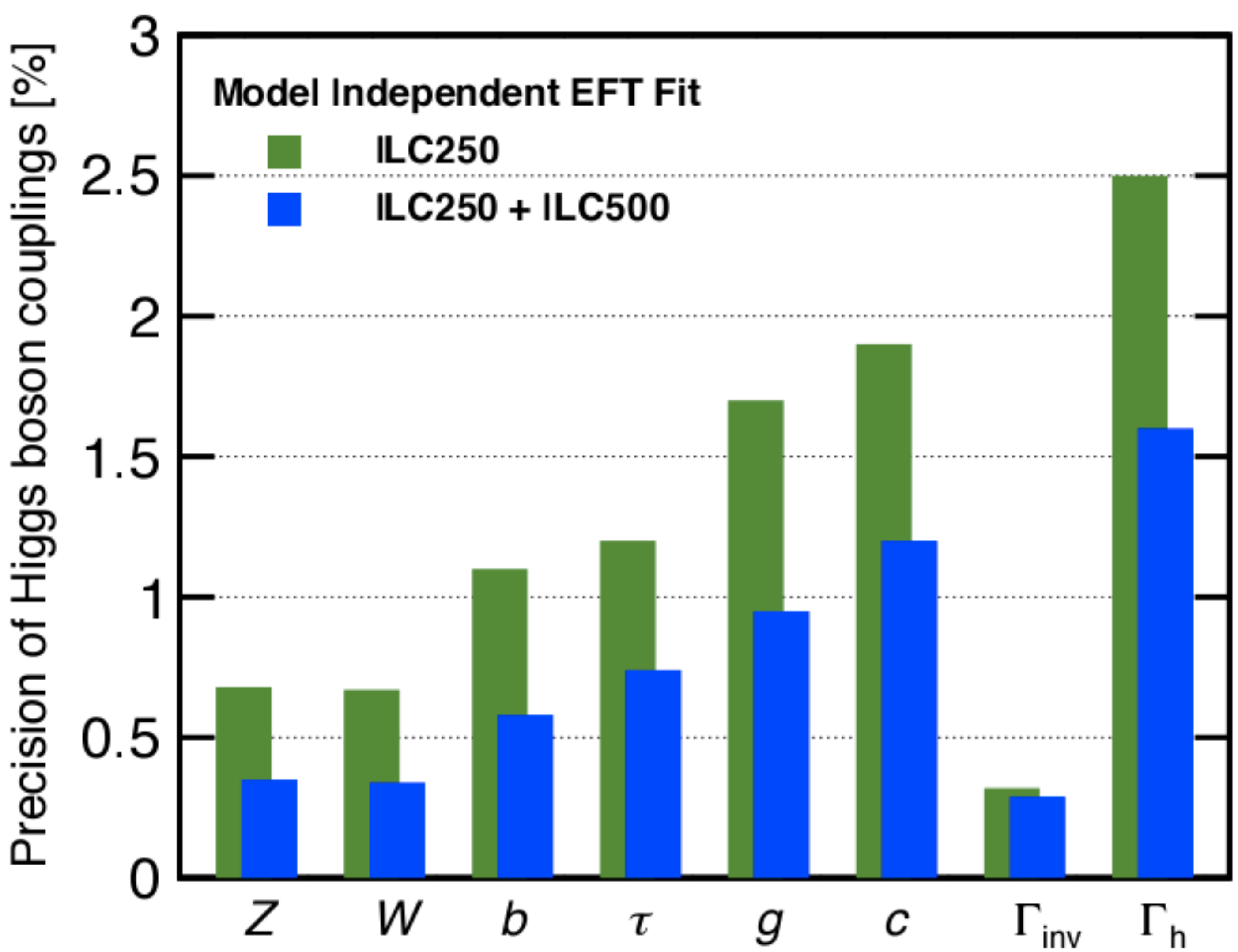
- 1 (δm) + 6 (hVV/aTGC) + 1 (aTGC)
- 5 (hff)
- 6 ($Z\ell\ell$) + 3 ($W\ell\nu$) + 2 ($Zu\bar{u}$) + 4 ($Zd\bar{d}$)

➠ 28 new physics parameters

To compare with results from the kappa-framework studies

- project the ND SMEFT fit results onto observables similar to Higgs coupling modifiers and Zff effective couplings
- complete with TGC modifiers to get the correct number of independent parameters

ILC: Higgs Couplings with SMEFT



Z	W	b	τ	g	c	Γ_{inv}	Γ_h
0.68	0.67	1.1	1.2	1.7	1.9	0.32	2.5
0.35	0.34	0.6	0.8	1.0	1.2	0.29	1.6

	HL-LHC (ATLAS) **3 ab^{-1}**
Green	+ ILC-250 **2 ab^{-1}**
Blue	+ ILC-500 **4 ab^{-1}** + ILC-360 **200 fb^{-1}**

SMEFT-based ILC framework

- invisible decay of H boson as new degree of freedom

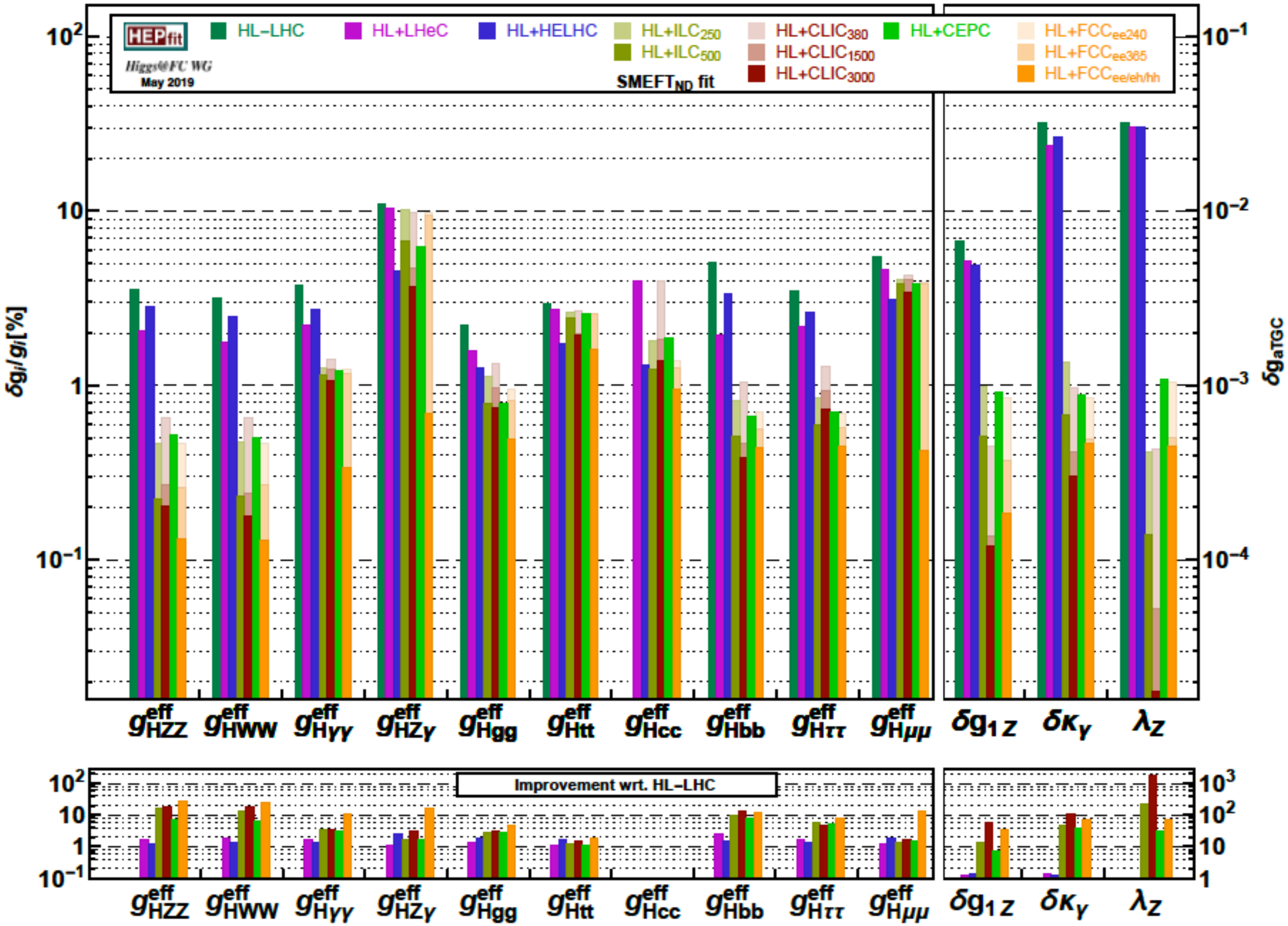
through EWPO and other constraints the *custodial* symmetry prevails!

Results obtained with the SMEFT with 2 ab^{-1} at 250 GeV already in the 1% range for the main couplings, *including HWW*

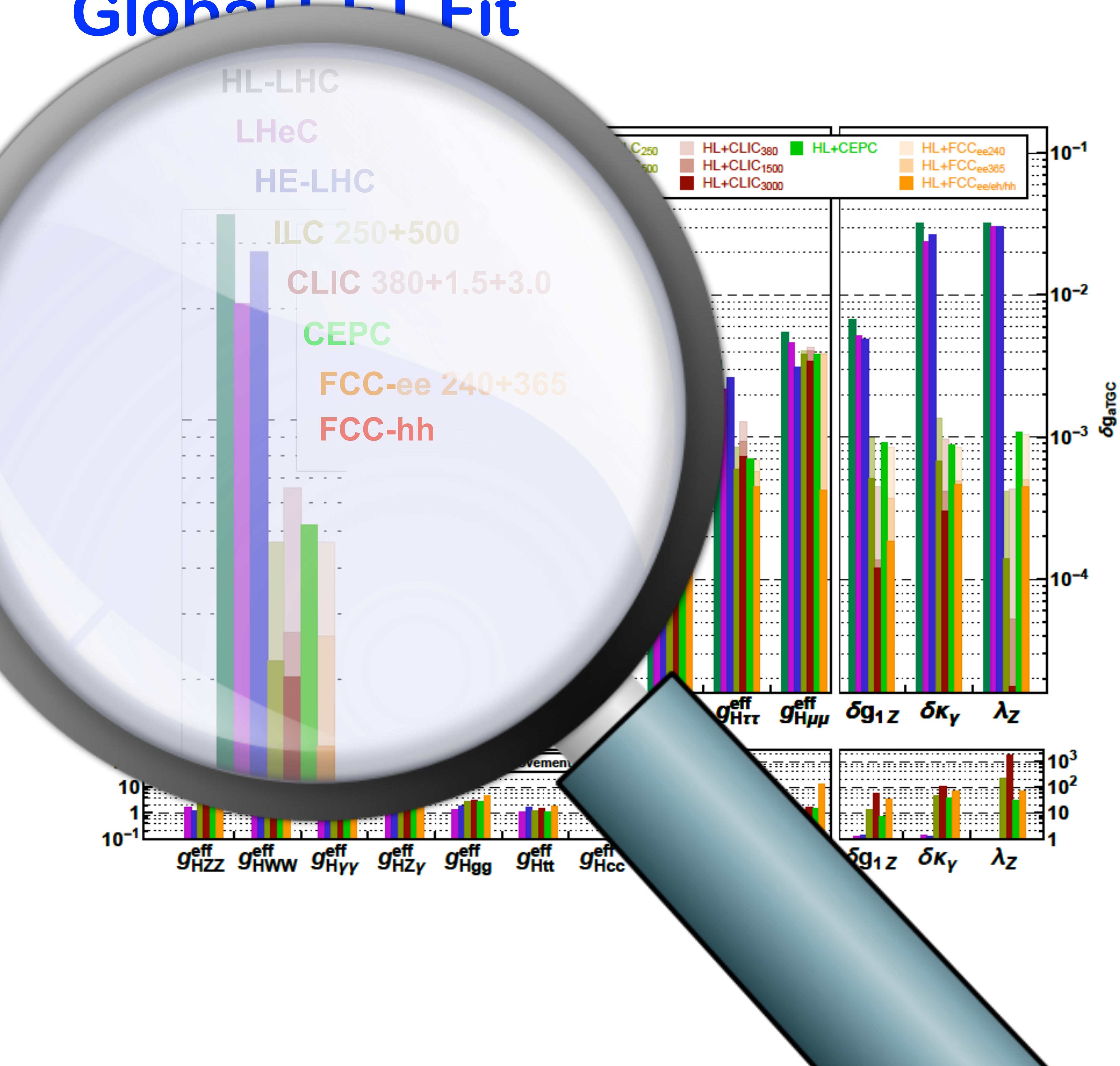
So, are there still a compelling reasons to run ILC at $\sqrt{s}$ = 500 GeV?

- access to W fusion production for independent *HWW* coupling meas.
- top physics with polarisation
- mild constraints on λ
- better BSM reach

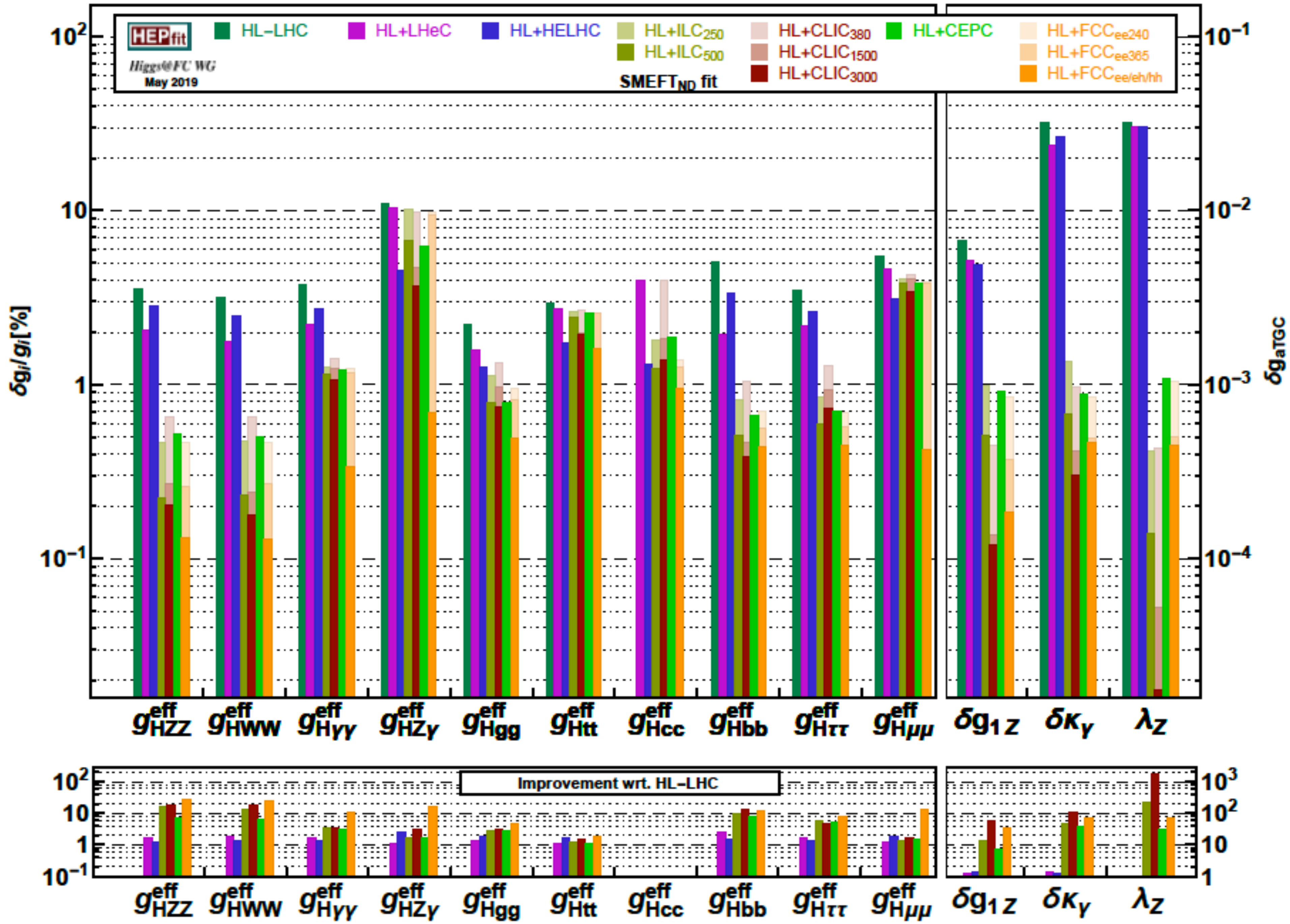
Global EFT Fit



Global EFT Fit



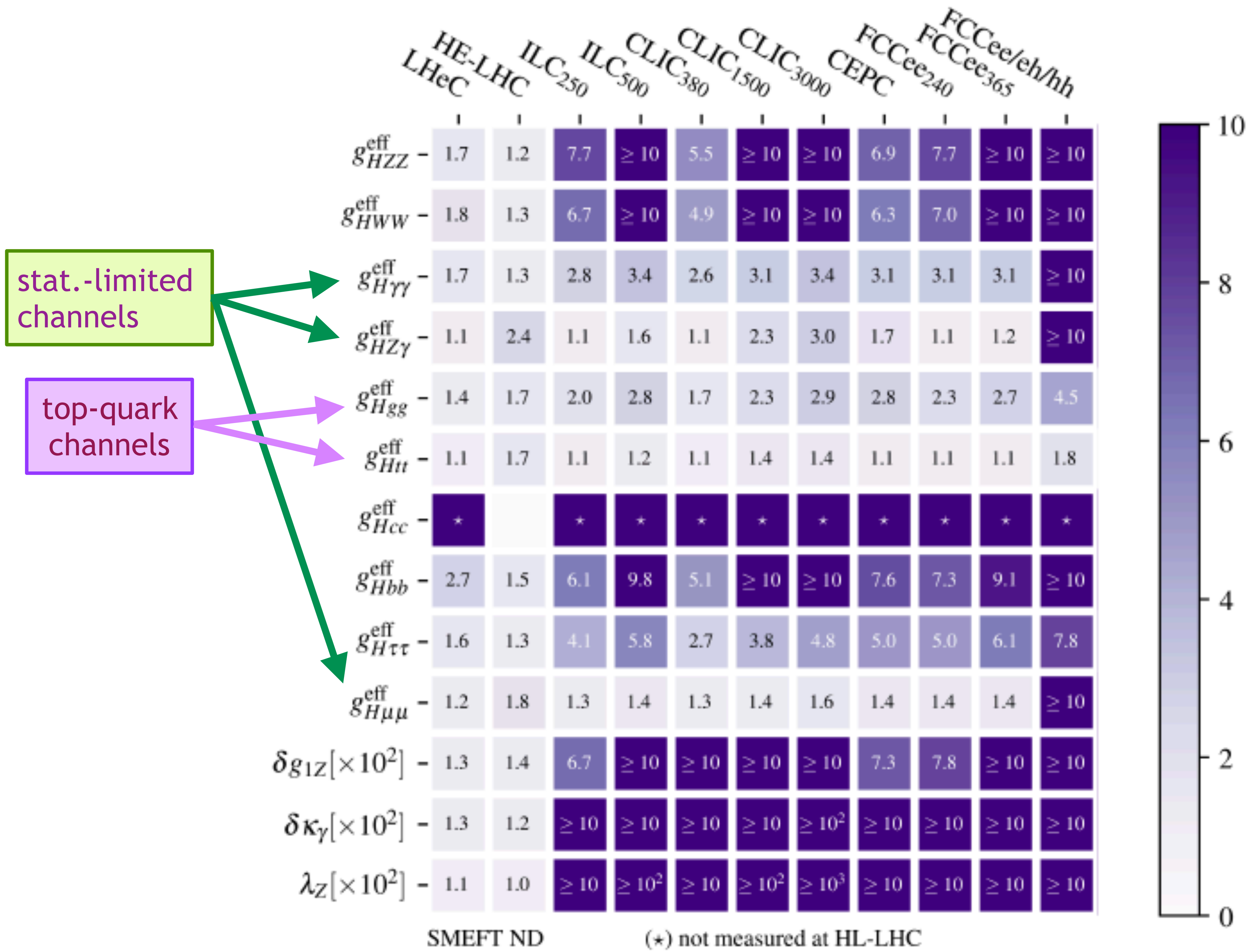
Global EFT Fit



includes Higgs but also di-boson and electroweak precision observables

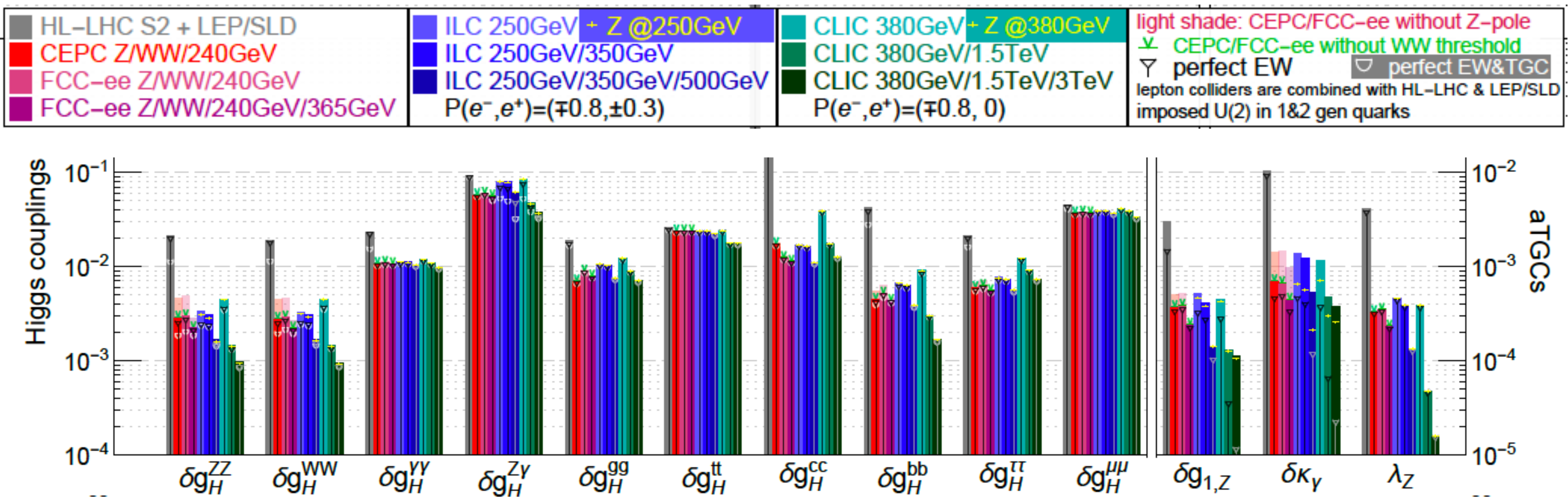
improvement beyond HL-LHC

Improvement beyond HL-LHC

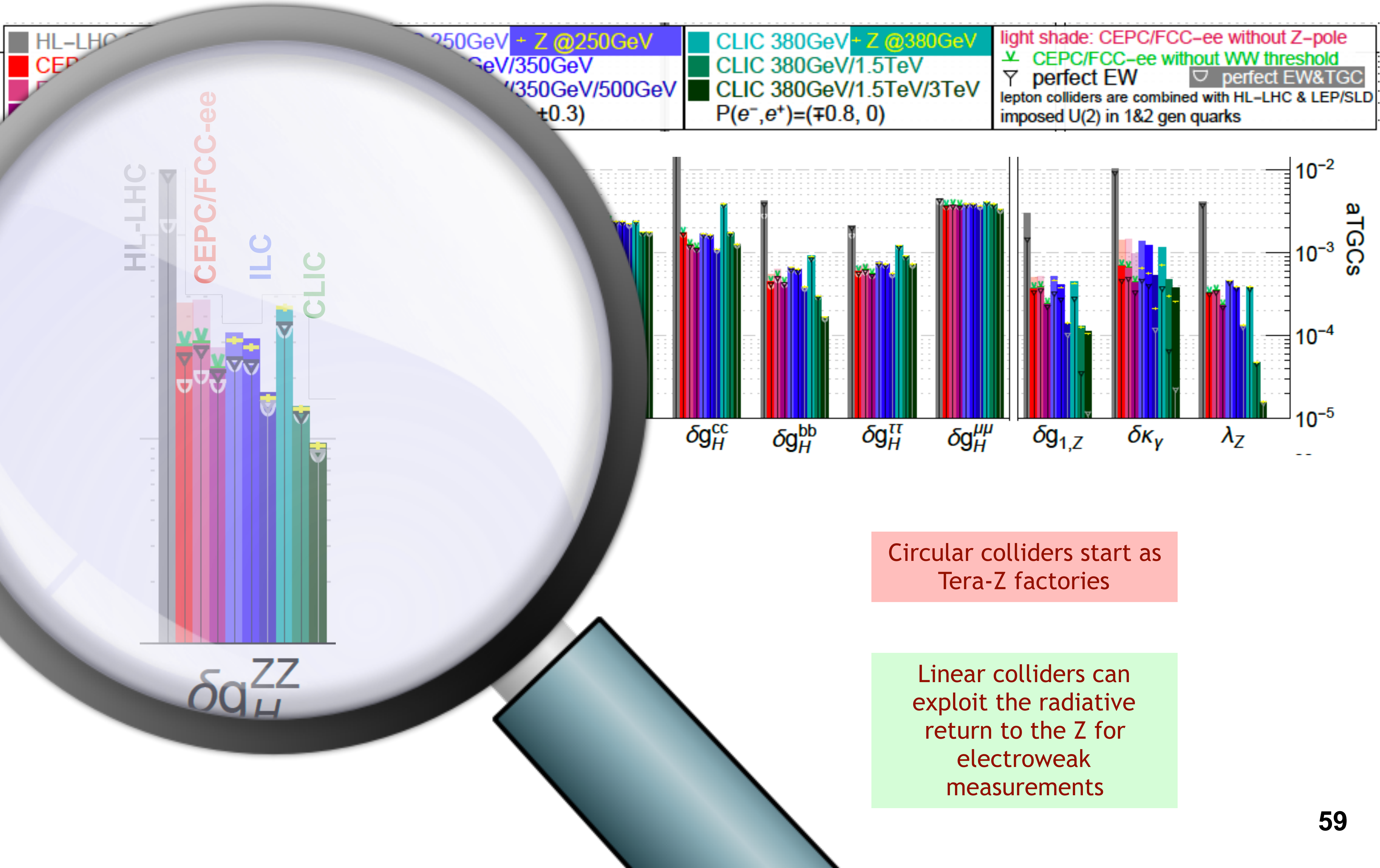


if no deviations seen at HL-LHC, discoveries are still possible at future colliders

Focus on Lepton Colliders



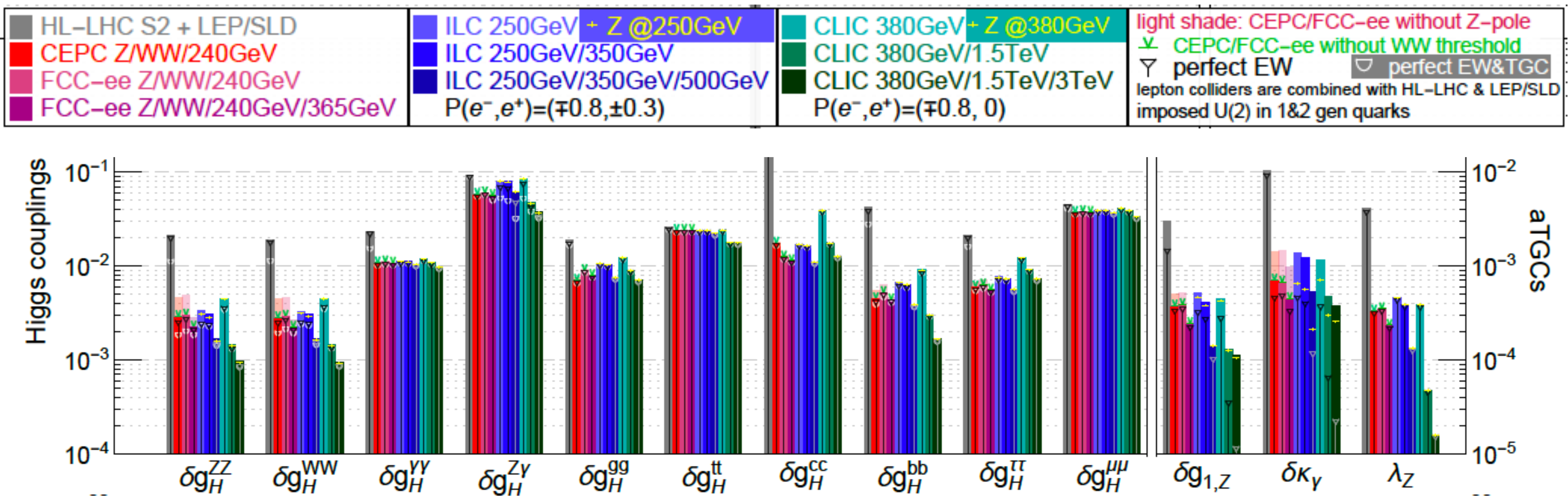
Focus on Lepton Colliders



Circular colliders start as Tera-Z factories

Linear colliders can exploit the radiative return to the Z for electroweak measurements

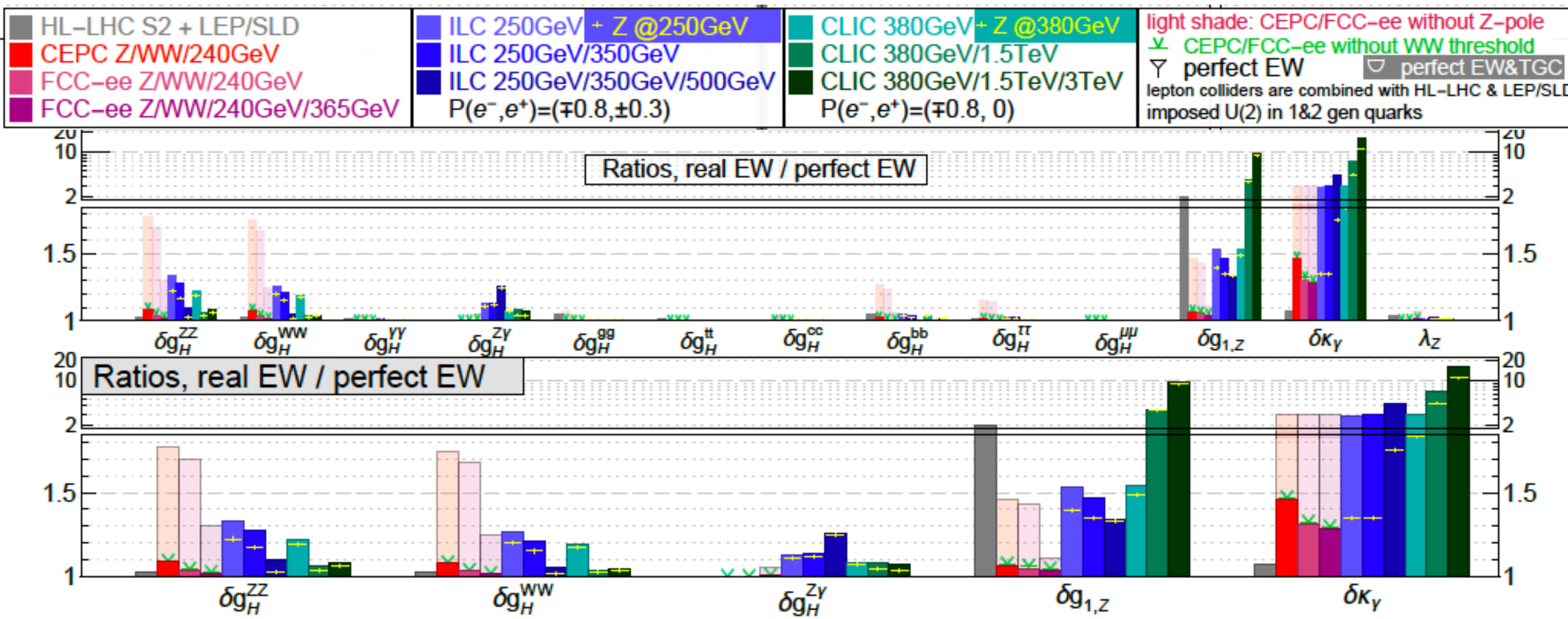
Focus on Lepton Colliders



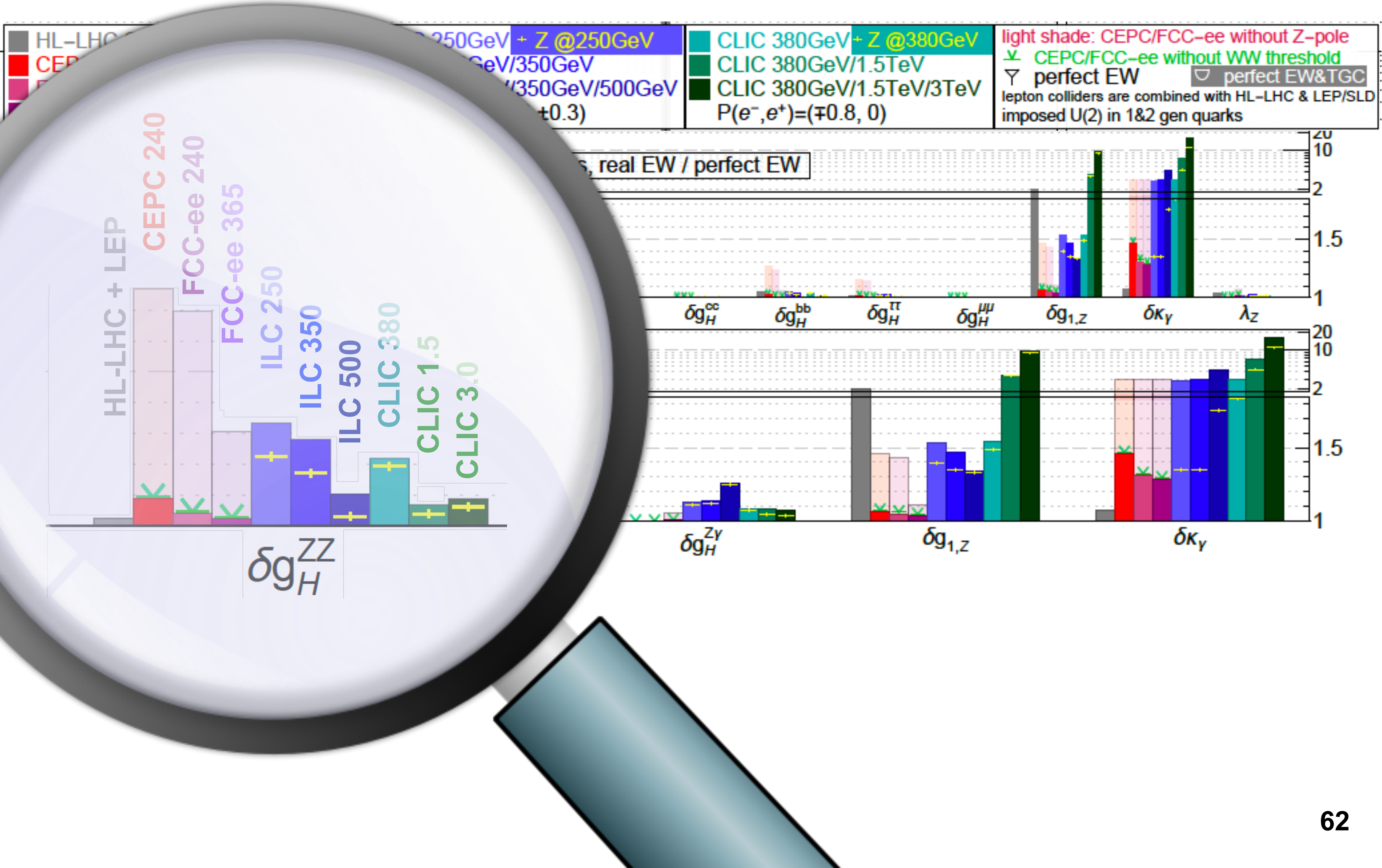
Comparing 3 scenarios:

- only LEP/SLD electroweak measurements
- actual electroweak measurements
- perfect electroweak measurements

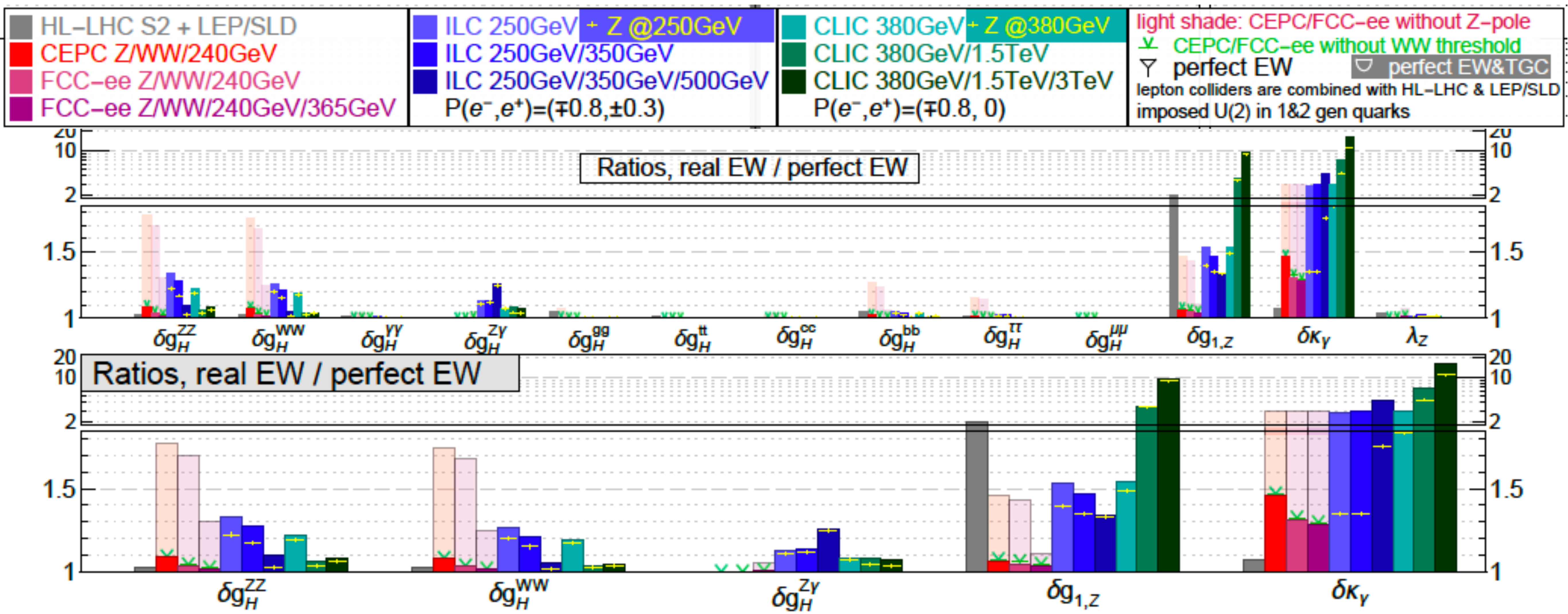
Z Pole Running?



Impact of Z Pole Running



Z Pole Running?



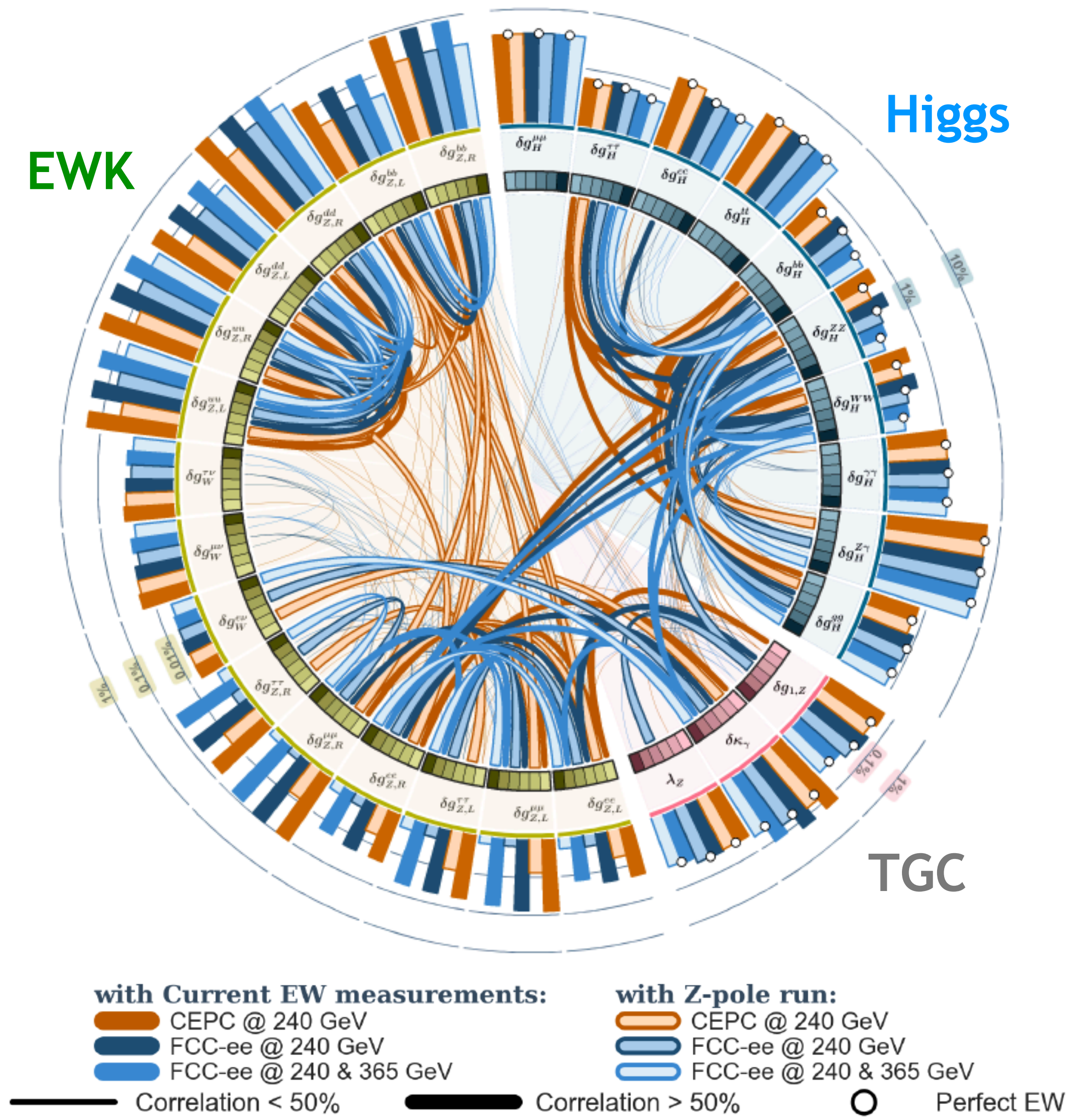
- FCC-ee and CEPC benefit a lot from Z pole running
- measurements are quasi-perfect as far as Higgs couplings are concerned

- at ILC and CLIC, the absence of Z-pole running is a limiting factor for Higgs precision (~30%)
- measurements via radiative return to the Z help mitigate the issue, especially at high energy

- at ILC, the 500 GeV run is important to reduce the impact of electroweak measurements on Higgs precision

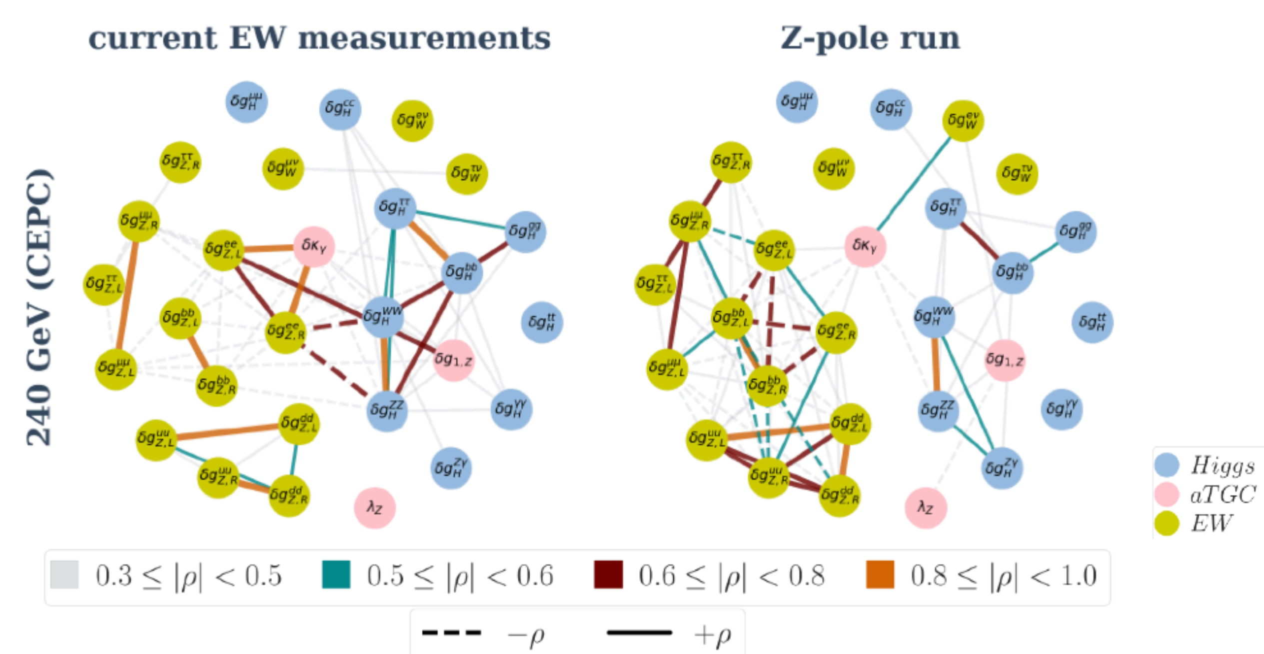
Z-Pole Running Fit Correlations

CEPC/FCC-ee with or without Z-pole running

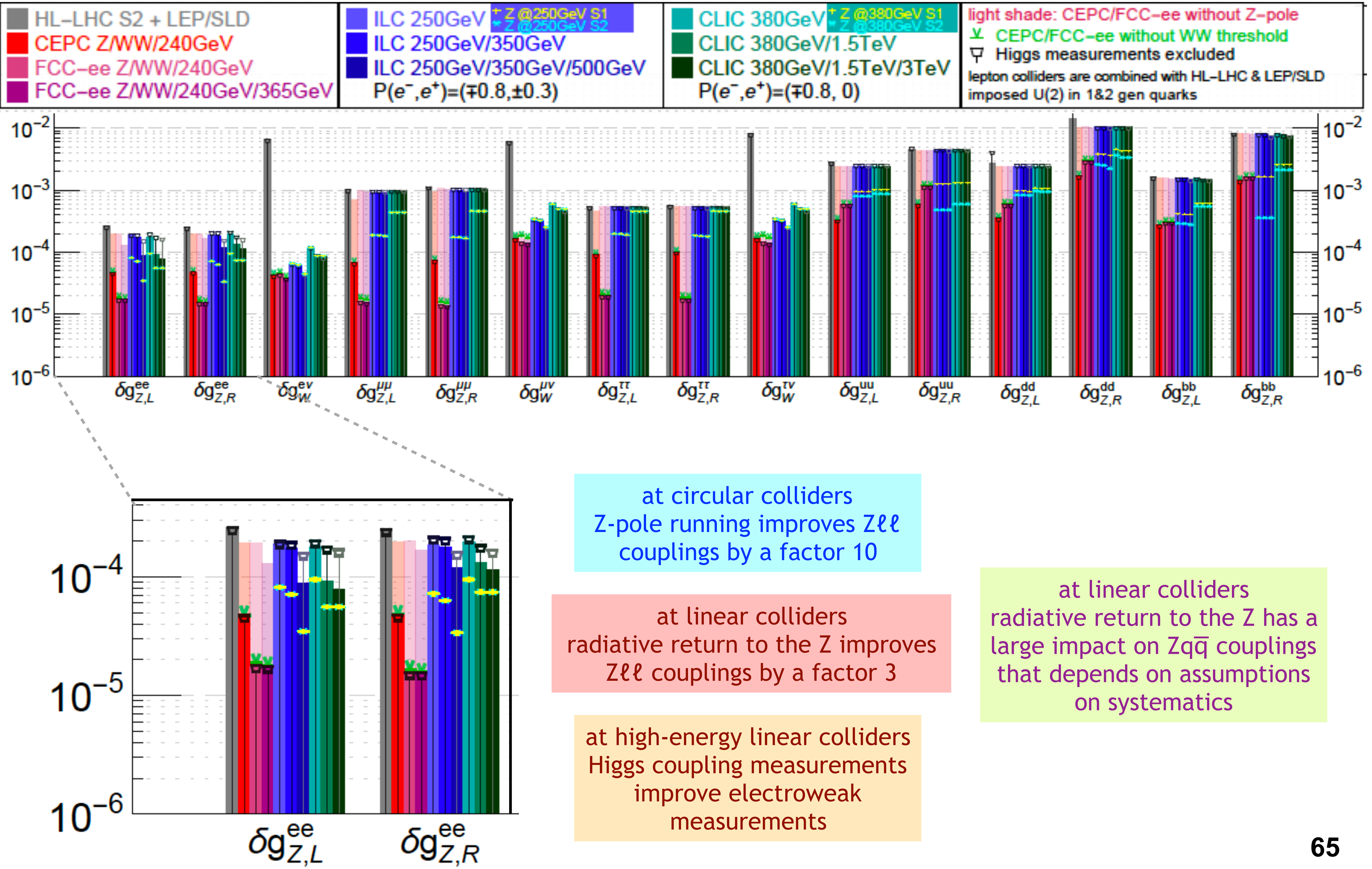


- without Z-pole running, large correlations between Higgs and EWK/TGC observables
- with Z-pole running, only correlations between EWK and TGC observables remain

Z-pole running at circular colliders isolate Higgs and electroweak measurements



Sensitivity on Electroweak Couplings



at circular colliders
Z-pole running improves Zℓℓ couplings by a factor 10

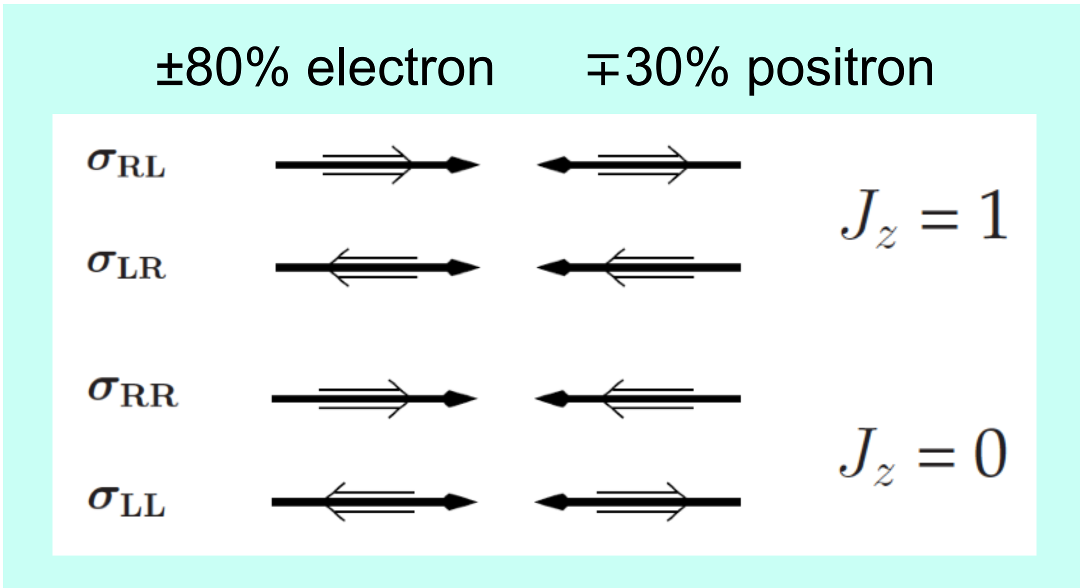
at linear colliders
radiative return to the Z improves Zℓℓ couplings by a factor 3

at high-energy linear colliders
Higgs coupling measurements improve electroweak measurements

at linear colliders
radiative return to the Z has a large impact on $Zq\bar{q}$ couplings that depends on assumptions on systematics

Beam Polarisation at the ILC

nominal ILC@250 GeV



unpolarised x-section $\sigma_0 = \frac{1}{4}\{\sigma_{RL} + \sigma_{LR} + \sigma_{RR} + \sigma_{LL}\}$

effective luminosity $\mathcal{L}_{eff}/\mathcal{L} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})$

effective polarisation $\mathcal{P}_{eff} = (\mathcal{P}_{e^-} - \mathcal{P}_{e^+})/(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})$

$e^+e^- \to HZ$

$$\sigma_{(-80\%,+30\%)} \approx 1.4\,\sigma_0$$
$$\sigma_{(+80\%,-30\%)} \approx 1.1\,\sigma_0$$

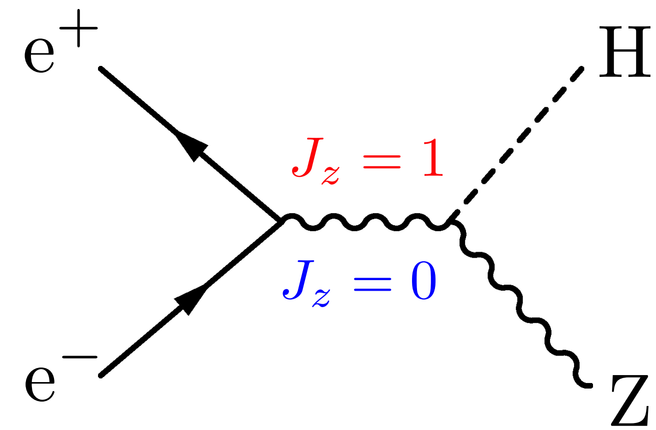
$e^+e^- \to H\nu\bar{\nu}$

$$\sigma_{(-80\%,+30\%)} \approx 2.3\,\sigma_0$$
$$\sigma_{(+80\%,-30\%)} \approx 0.14\,\sigma_0$$

typically: (RL,LR,RR,LL) = (45%,45%,5%,5%)

$$\sigma = 2\sigma_0(\mathcal{L}_{eff}/\mathcal{L})(1 - \mathcal{P}_{eff}A_{LR})$$

s-channel Z/γ exchange

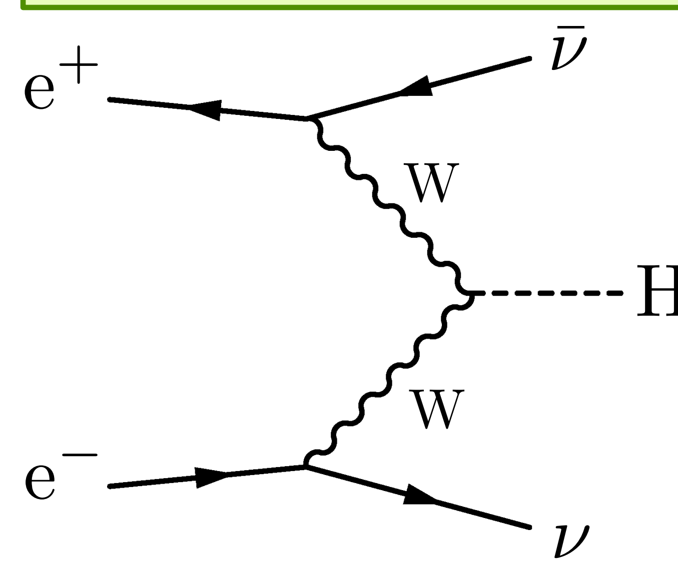


SM: RL, LR

NP: RR, LL

$$A_{LR} \simeq \frac{1 - 4\sin\theta_w{}^2}{1 - 4\sin\theta_w{}^2 + 8\sin\theta_w{}^4} \approx 0.15$$

t-channel W or ν exchange



SM: LR

$A_{LR} = 0$

Impact of Polarisation at the ILC

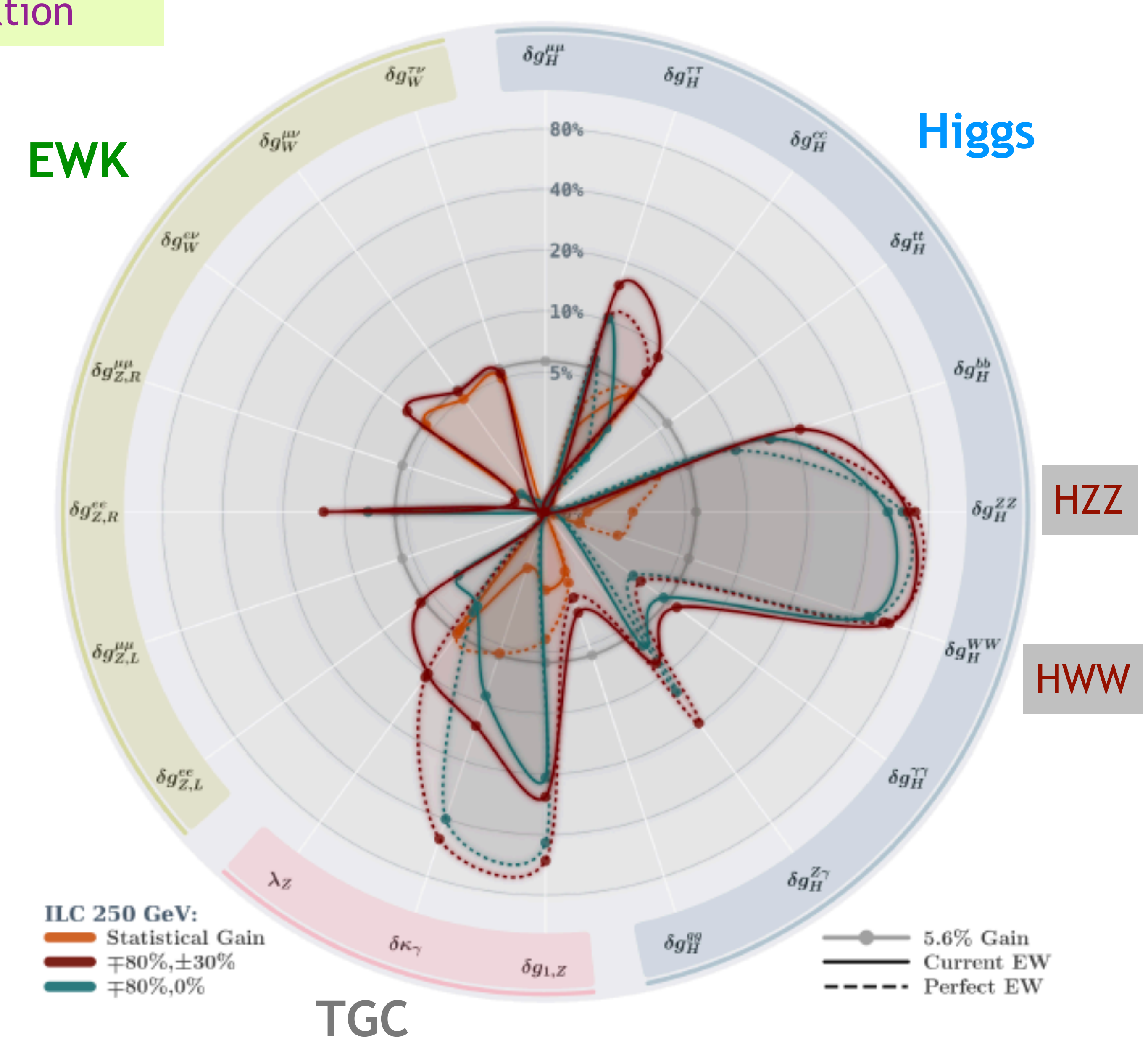
Electroweak interactions have $\mathcal{O}(1)$ parity-violation
signal and background x-section depend on polarisation

Positron polarisation has a marginal impact: it does not play a significant role for Higgs measurements (<10%)

Electron polarisation

- leads to a large improvement of hVV determination (>50%)
- benefits from polarisation less important at high-energy (<10%)

In the EFT, the gain from polarisation is higher than the mere increase in statistics because polarisation removes degeneracies among operators

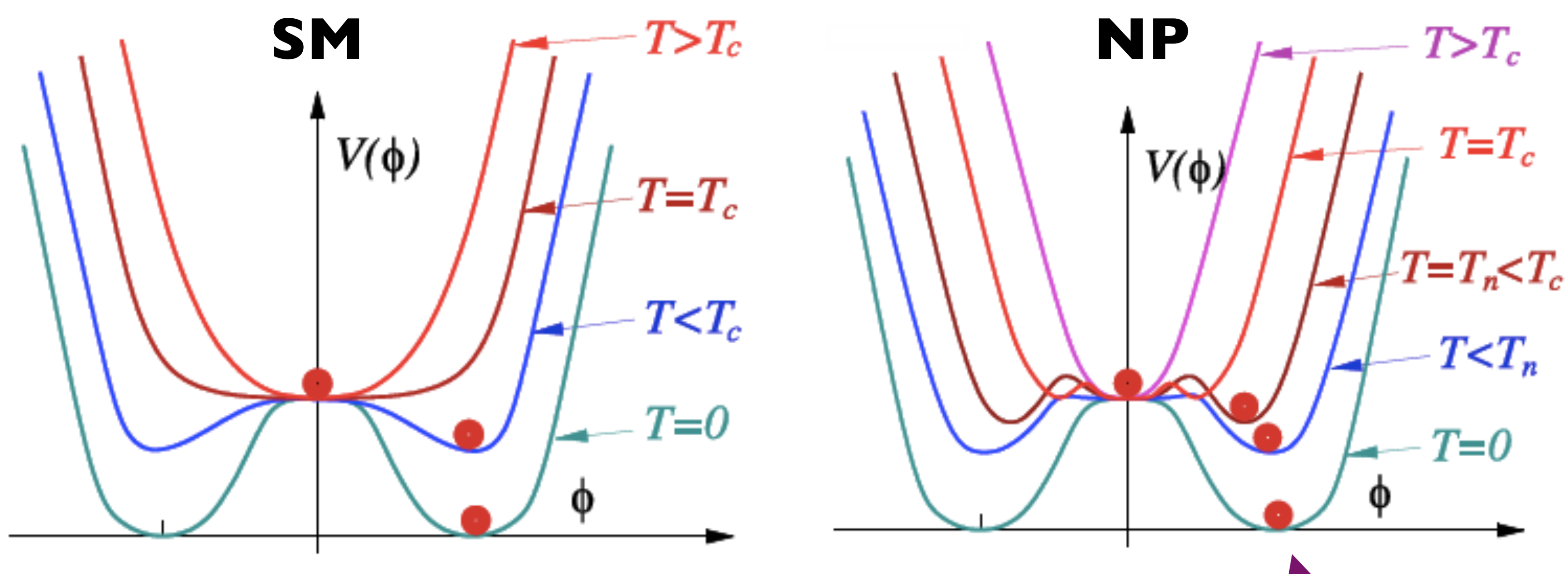


ILC@250 GeV
improvement in constraints with polarisation

(∓80%,±30%) (∓80%,0%)

BAU, Higgs Potential and Self-Coupling

Higgs potential: $V_{\mathrm{H}} = -\mu^2|\phi|^2 + \lambda|\phi|^4$



2[d] order

1[st] order

?

Baryon Asymmetry of the Universe (BAU)

- baryogenesis requires 1[st] order phase transition to sustain *out of equilibrium condition* during EWSB
- M_H > 80 GeV → 2[d] order
- EWK BAU *implies* a modification of the Higgs potential
- New Physics must modify the potential and the self-coupling

$$V(h) = \frac{1}{2}M_{\mathrm{H}}^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$$

tri-linear　quartic

in SM

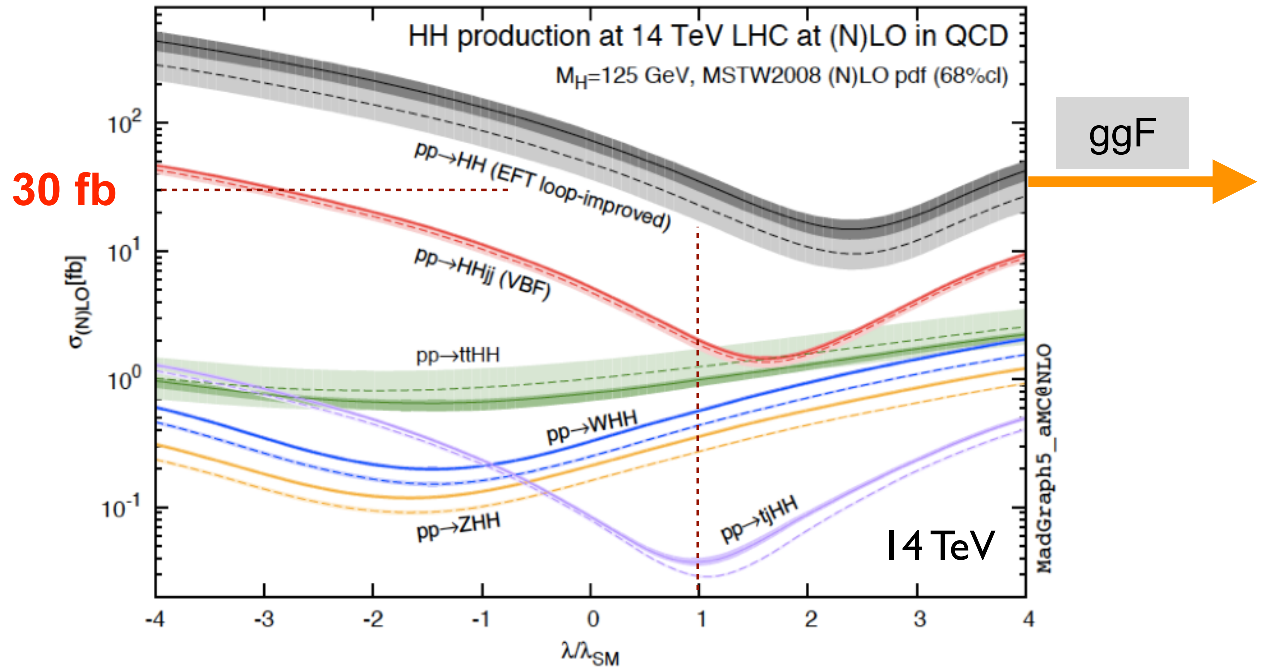
$$\lambda_{3,4} = \lambda = \frac{M_{\mathrm{H}}^2}{2v^2}$$

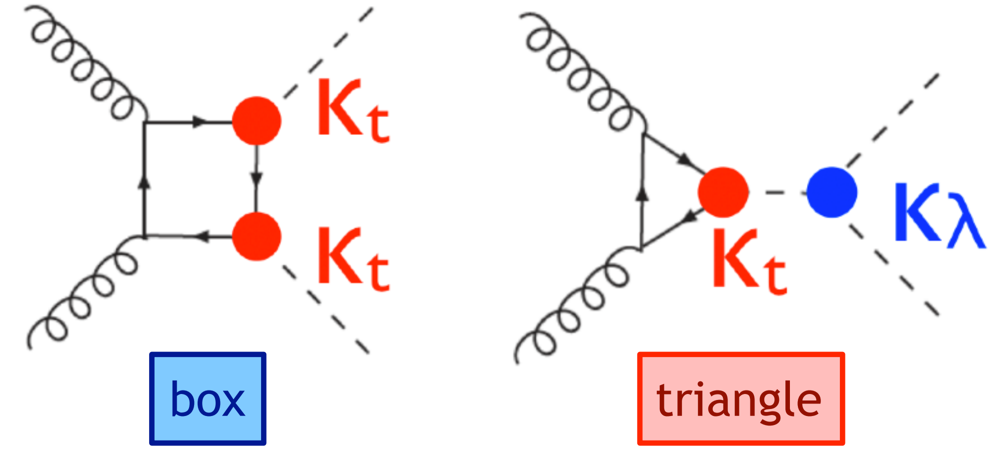
in the spirit of the κ-framework, define $\kappa_\lambda = \lambda/\lambda_{SM}$

The direct measurement of the tri-linear self-coupling λ is a key goal of future colliders
☛ first order EW transition implies large deviation from the SM prediction (κ_λ = 1)

HH Production & Self-Coupling at LHC

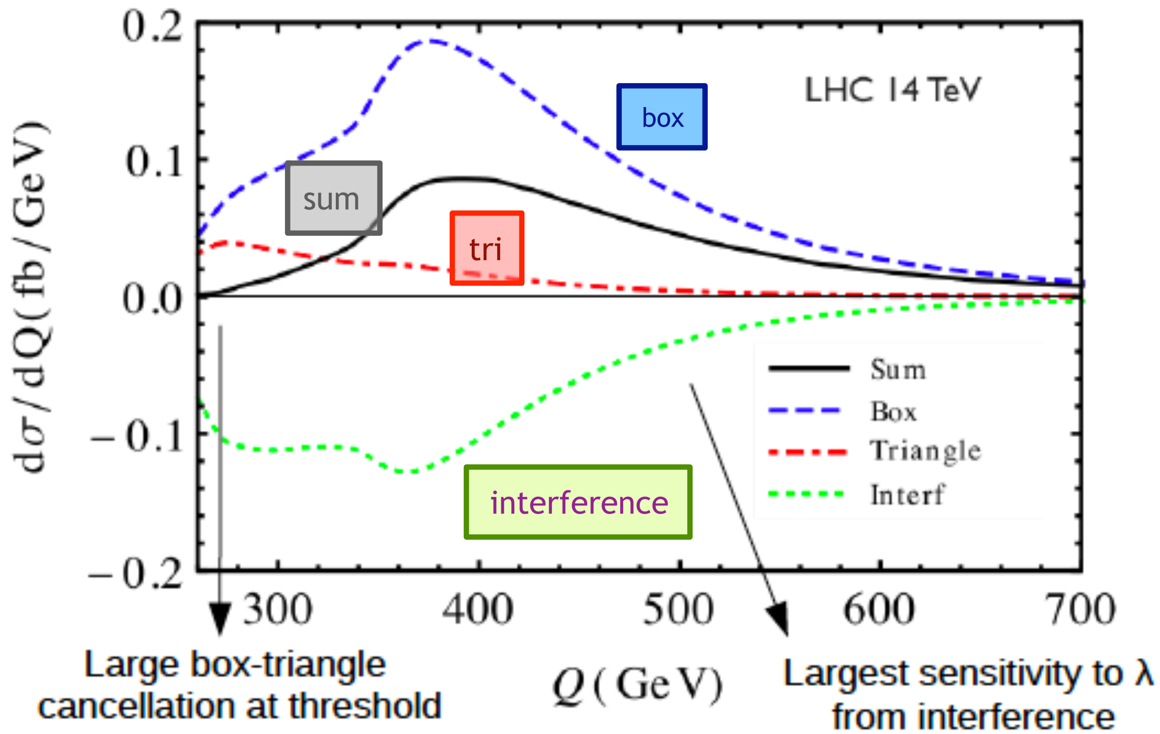
pp → HH



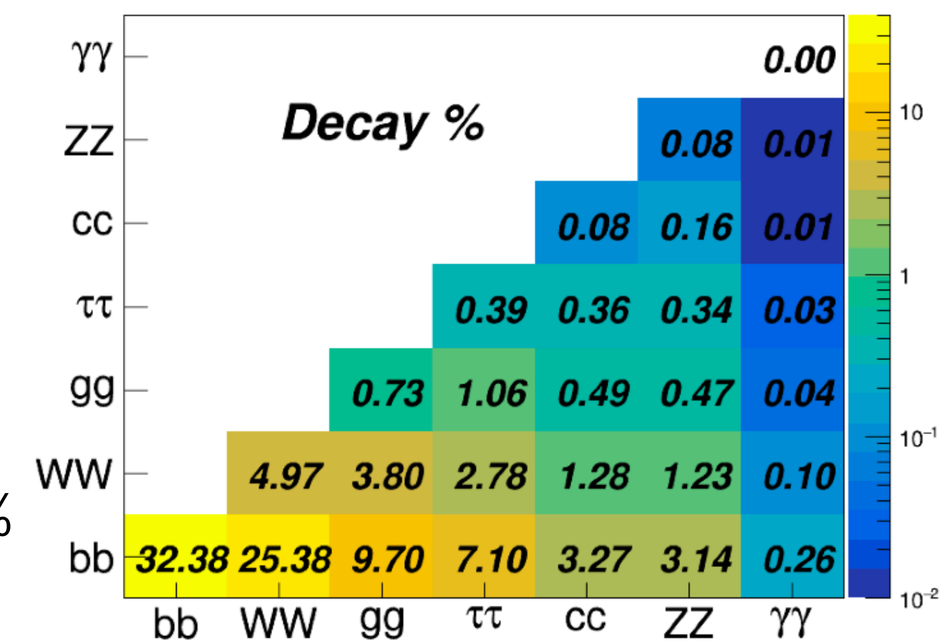


- $\sigma(pp \to HH)$ = 30 fb at $\sqrt{s}$ = 14 TeV
- $\sigma(pp \to HH)/\sigma(pp \to H)$ = 1‰

destructive interference between box and triangle



- $b\bar{b}b\bar{b}$: 32%
- $b\bar{b}WW$: 25%
- $b\bar{b}ZZ$: 3%
- $b\bar{b}\tau\tau$: 7%
- $b\bar{b}\gamma\gamma$: 0.3%

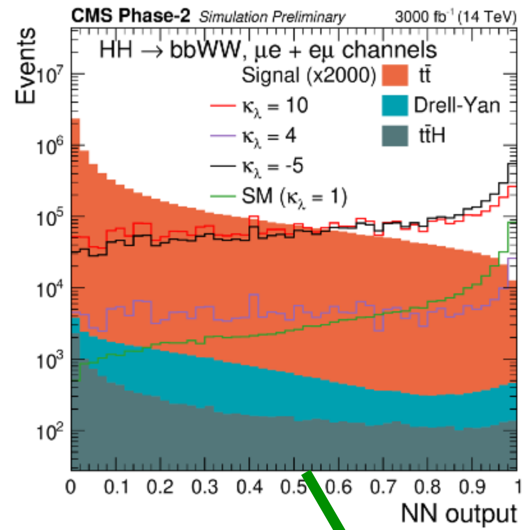


	bb	WW	gg	ττ	cc	ZZ	γγ
γγ							0.00
ZZ						0.08	0.01
cc					0.08	0.16	0.01
ττ				0.39	0.36	0.34	0.03
gg			0.73	1.06	0.49	0.47	0.04
WW		4.97	3.80	2.78	1.28	1.23	0.10
bb	32.38	25.38	9.70	7.10	3.27	3.14	0.26

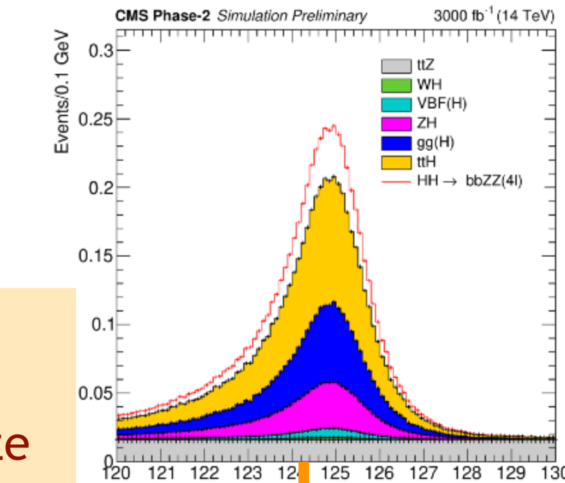
☛ lots of information from differential cross section in m_{HH}

HH at HL-LHC

☛ for most channels, $t\bar{t}H$ is the main background

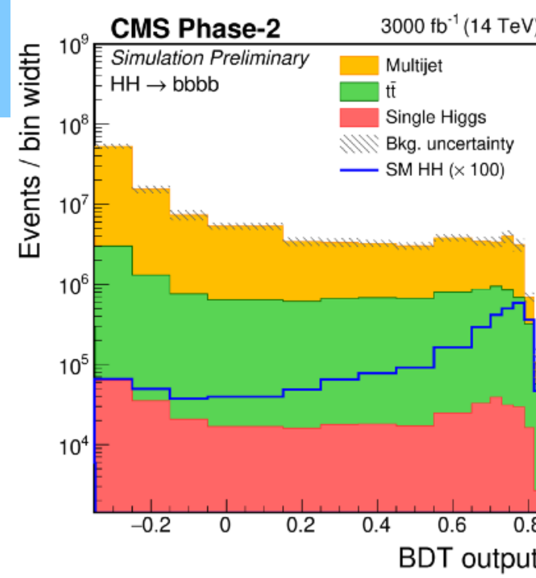


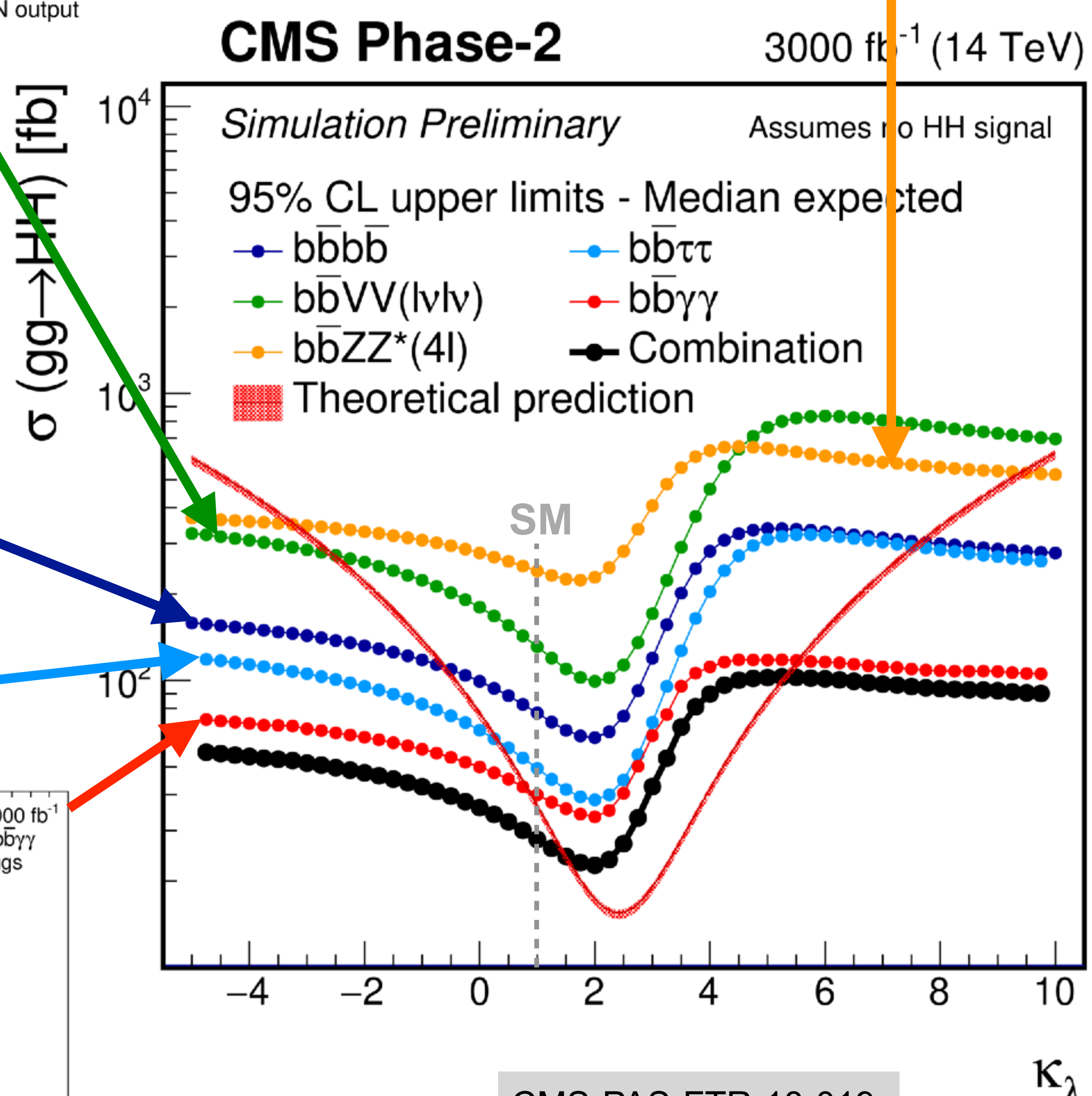
$b\bar{b}WW^*(\ell\nu\ell\nu)$
main bkg: $t\bar{t}$



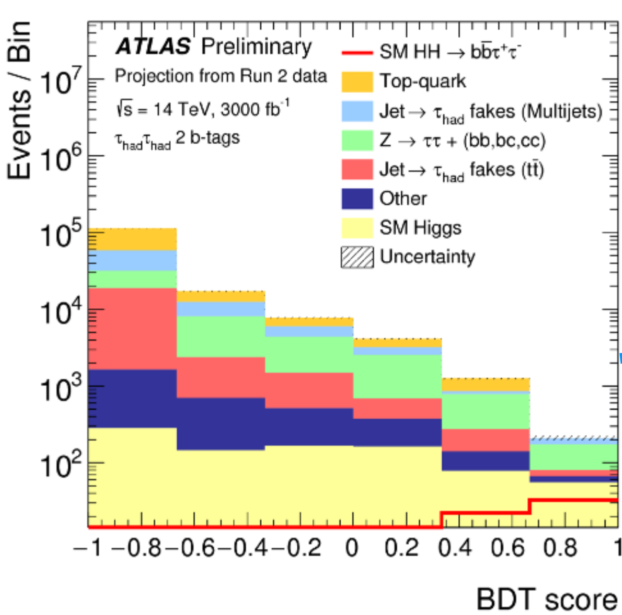
$b\bar{b}ZZ^*(4\ell)$
very rare but
clean final state

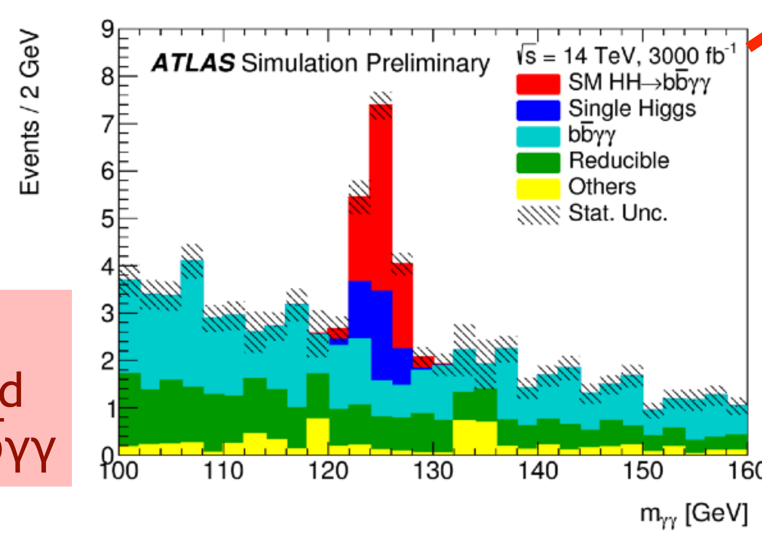
$b\bar{b}b\bar{b}$
exploit resolved and
boosted b-jets





$b\bar{b}\tau\tau$
irreducible bkg: $Z(\tau\tau)b\bar{b}$



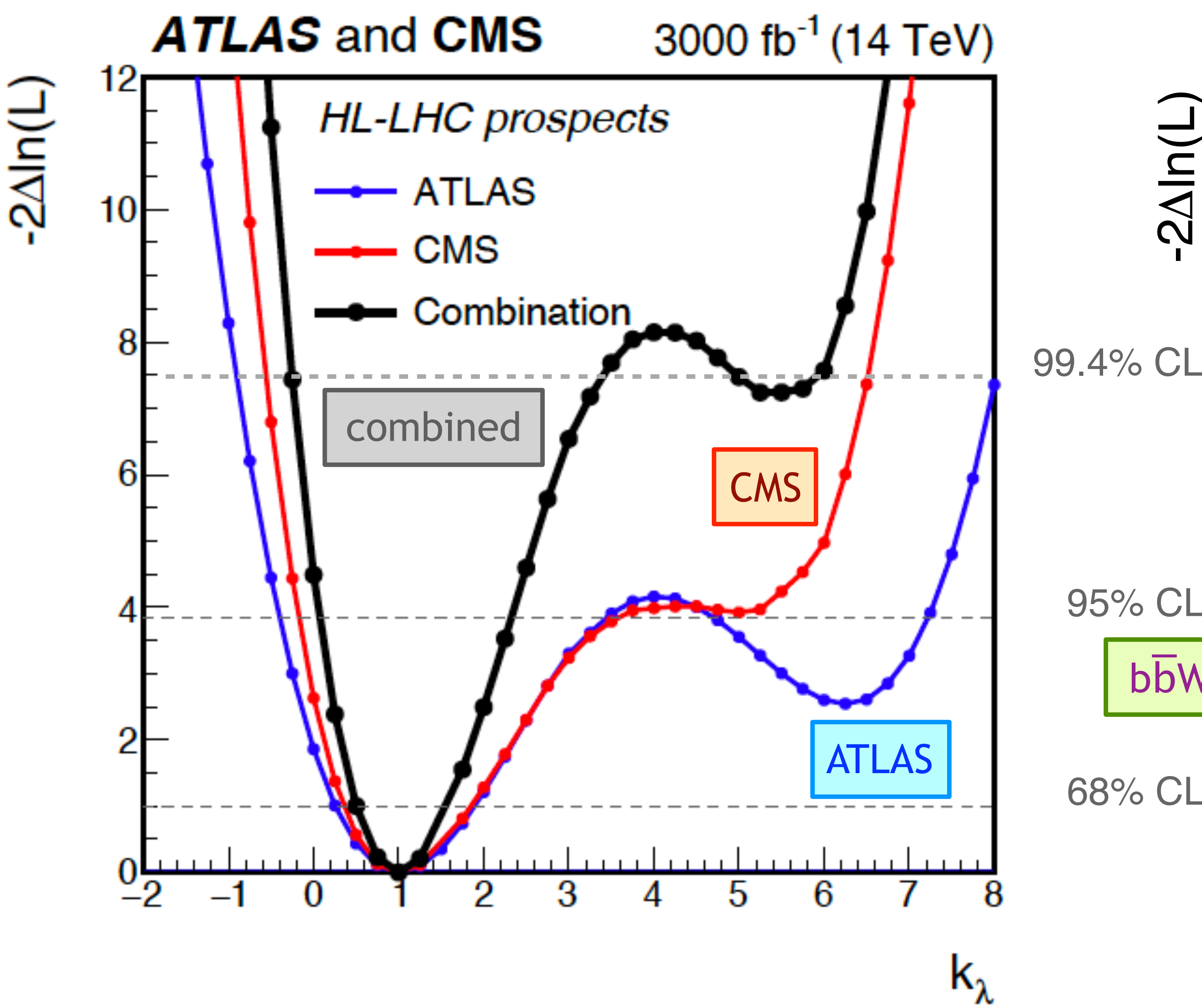


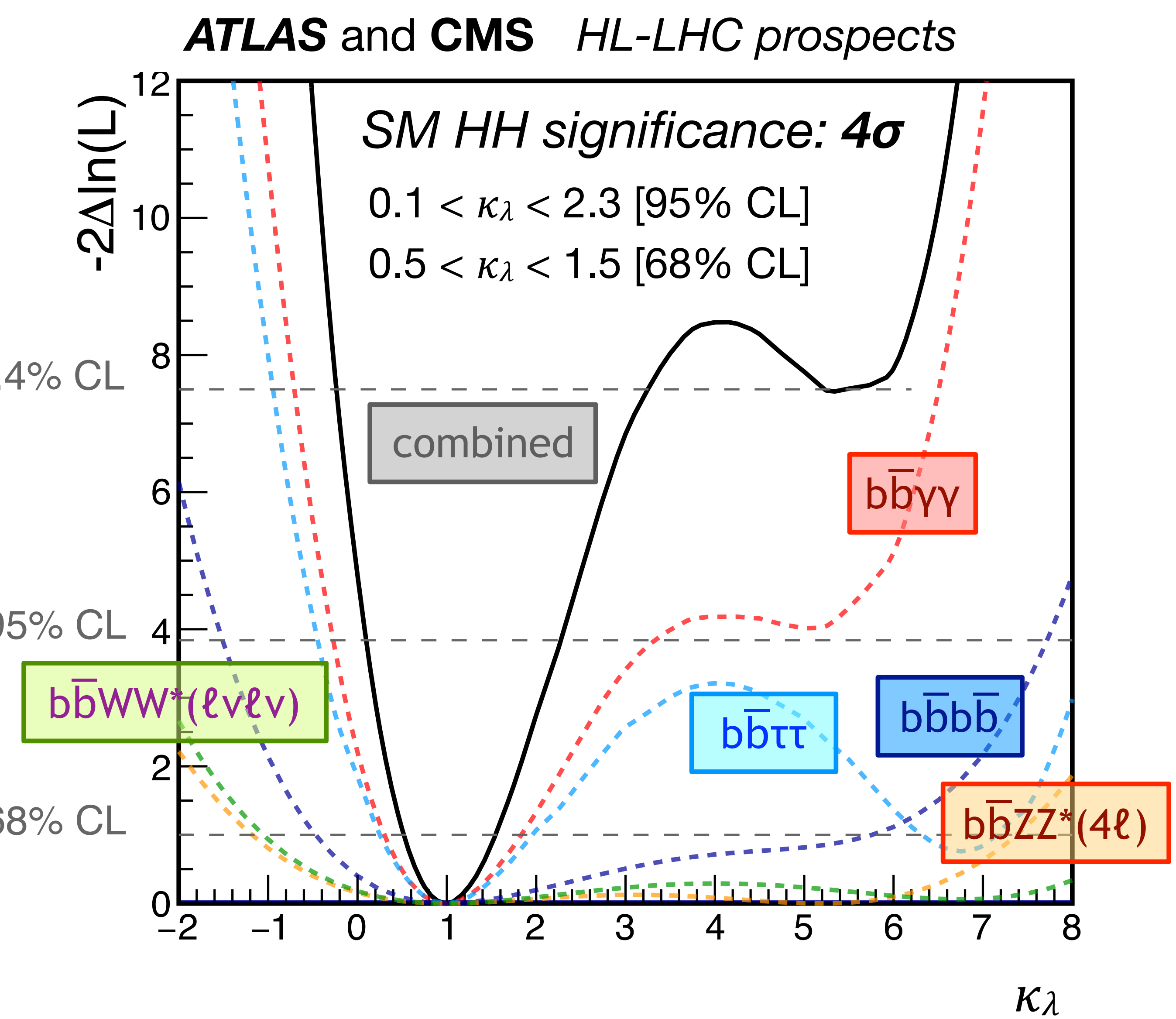
$b\bar{b}\gamma\gamma$
peaking $t\bar{t}H$ and
non-resonant $b\bar{b}\gamma\gamma$

CMS-PAS-FTR-18-019

ATL-PHYS-PUB-2018-053

Self-Coupling: ATLAS+CMS Combined





- approximate cross-section degeneracy between $\kappa_\lambda = 1$ and 4, with different kinematics
- this results in a second minimum in the likelihood ratio versus κ_λ around κ_λ = 5-6
- best sensitivity: $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ (then $b\bar{b}b\bar{b}$)

HL/HE-LHC WG2

Self-Coupling: ATLAS+CMS Combined

expected measured 68% CI, channel by channel

bb̅γγ

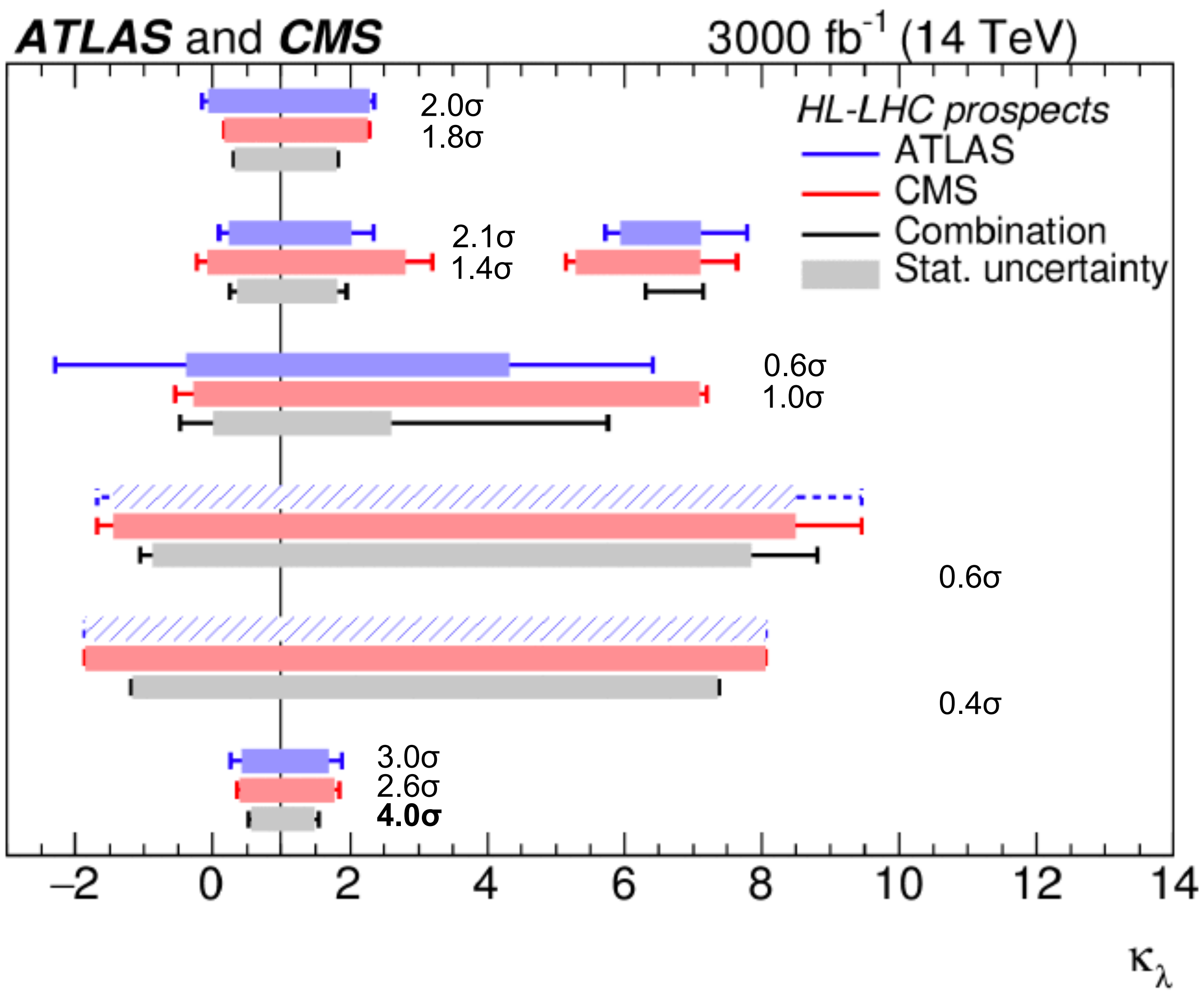
bb̅ττ

bb̅bb̅

bb̅WW*(ℓνℓν)

bb̅ZZ*(4ℓ)

combined



ATLAS HL-LHC
3 ab⁻¹

CMS HL-LHC
3 ab⁻¹

combined significance: 4σ

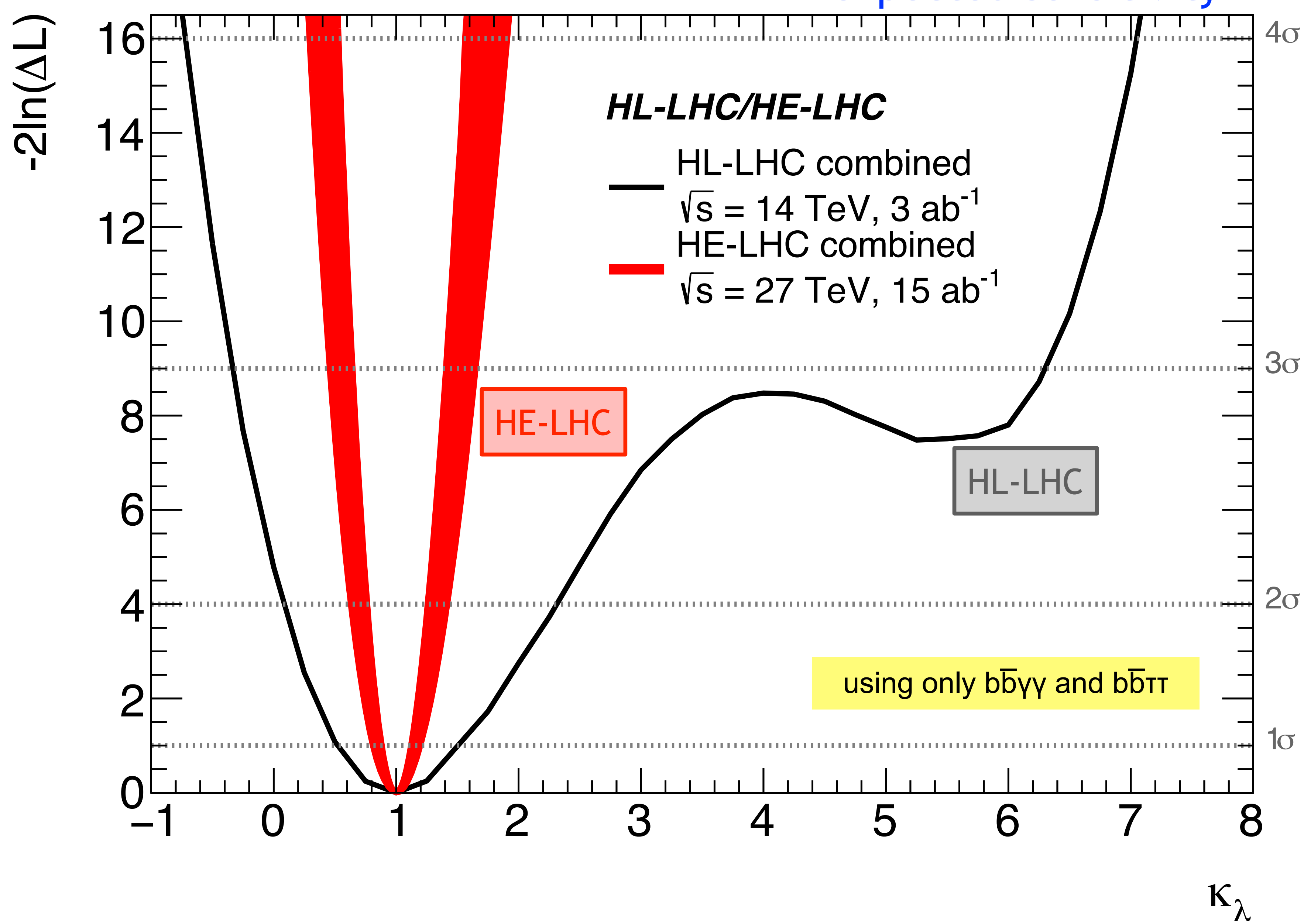
HL-LHC ($\sqrt{s}$ = 14 TeV, L = 3 ab^{-1})
κ_λ measured with a precision of ±40-50%

- only 90k HH pairs produced
- ultimate goal = observation of trilinear coupling: not impossible, but challenging

HL/HE-LHC WG2

HE-LHC: Self-Coupling

expected sensitivity



HL-LHC ($\sqrt{s}$ = 14 TeV, L = 3 ab^{-1})
κ_λ measured with a precision of ±40-50%

HE-LHC ($\sqrt{s}$ = 27 TeV, L = 15 ab^{-1})
κ_λ measured with a precision of ±15%

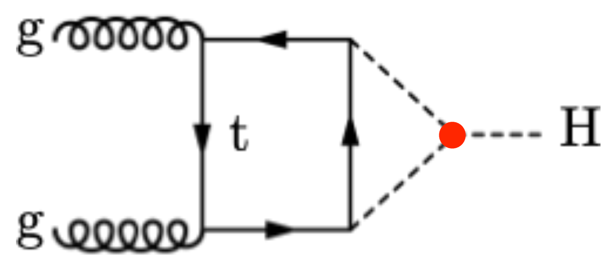
- more than 1M HH pairs produced
- clear observation of trilinear coupling

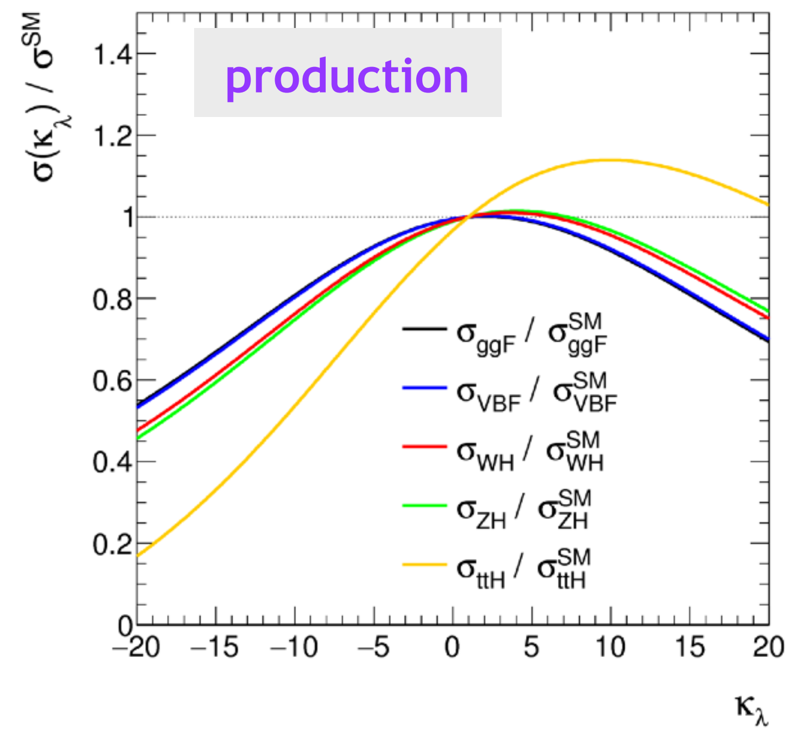
HL/HE-LHC WG2

Self-Coupling from Single Higgs at LHC

- ☛ constraints on the Higgs self-coupling via single Higgs measurements

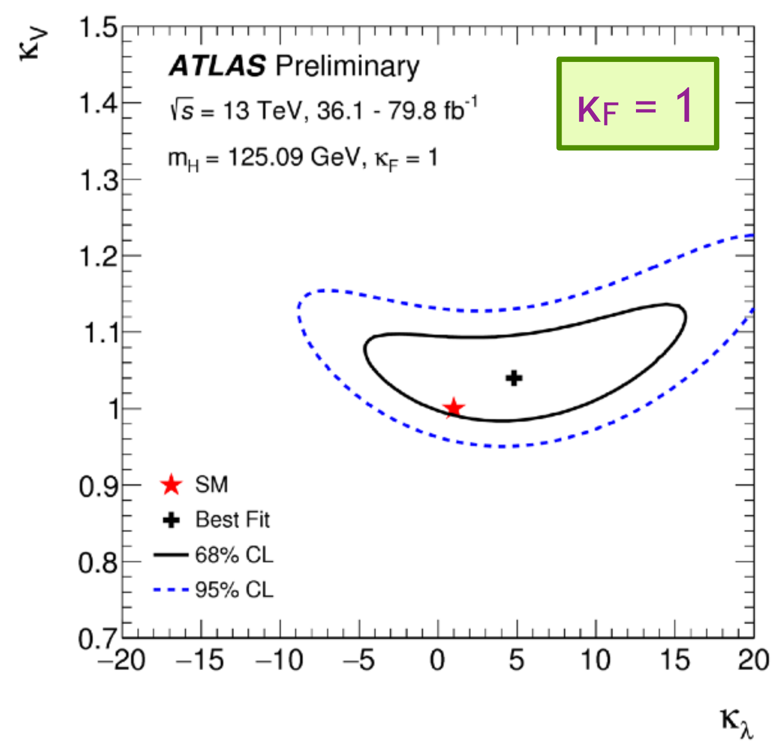
  - κ_λ-dependent NLO electroweak corrections modify Higgs boson production rates (also branching fractions)

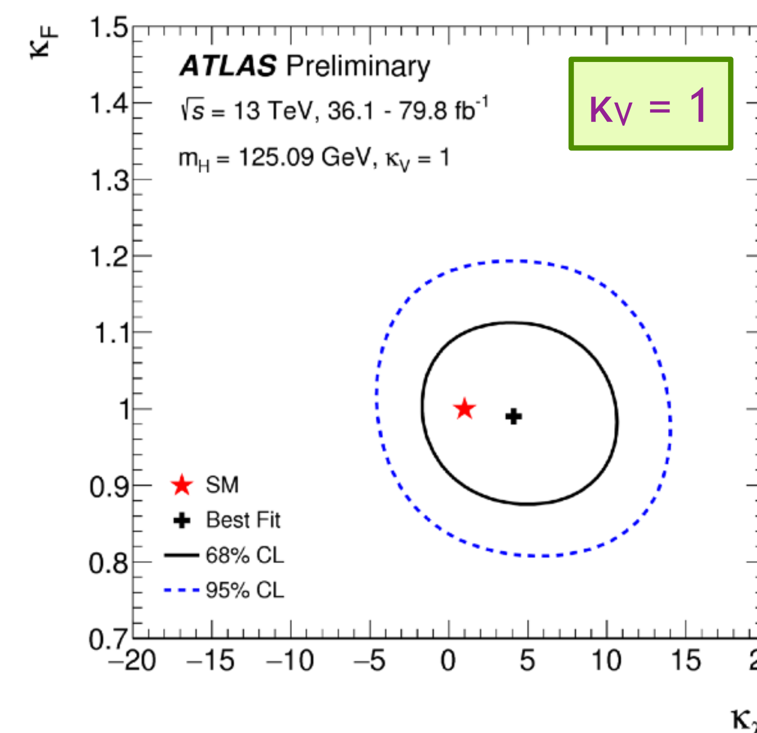




ATLAS 2016-1017
25-80 fb^{-1}

  - by reanalysing the rate measurements, obtain limits on κ_λ that are competitive with present direct HH analyses





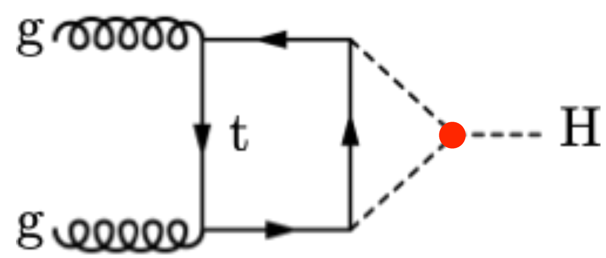
assuming that NP only affects κ_λ:
$-3.2 < \kappa_\lambda < 11.9$ @ 95%CL

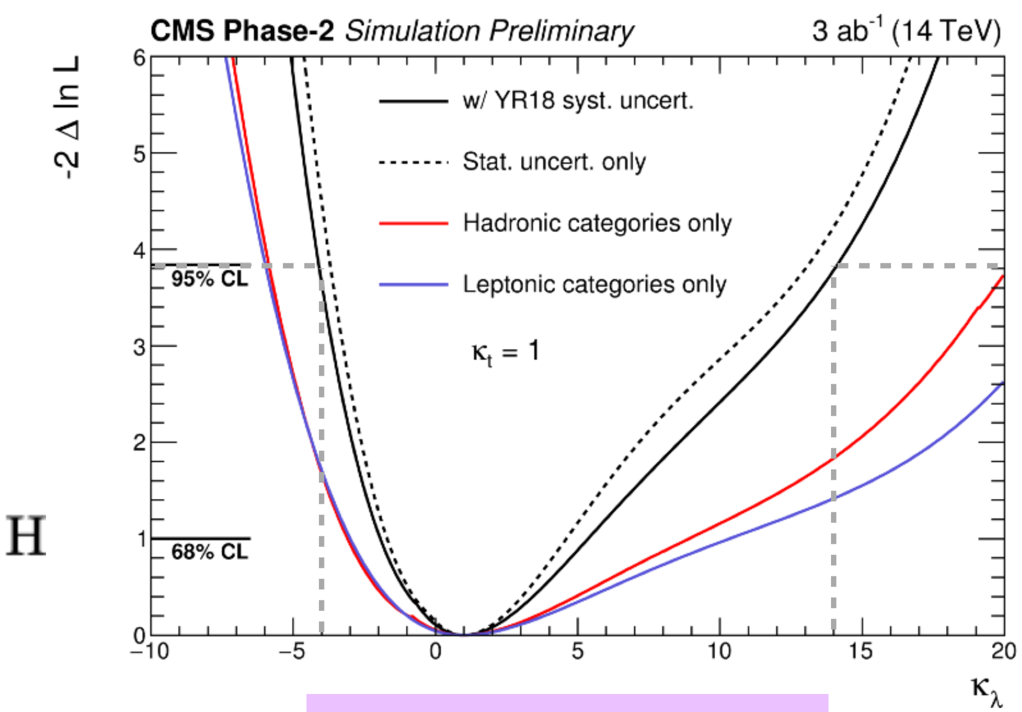
ATL-PHYS-PUB-2019-009

Self-Coupling from Single Higgs at HL-LHC

☛ constraints on the Higgs self-coupling via single Higgs measurements

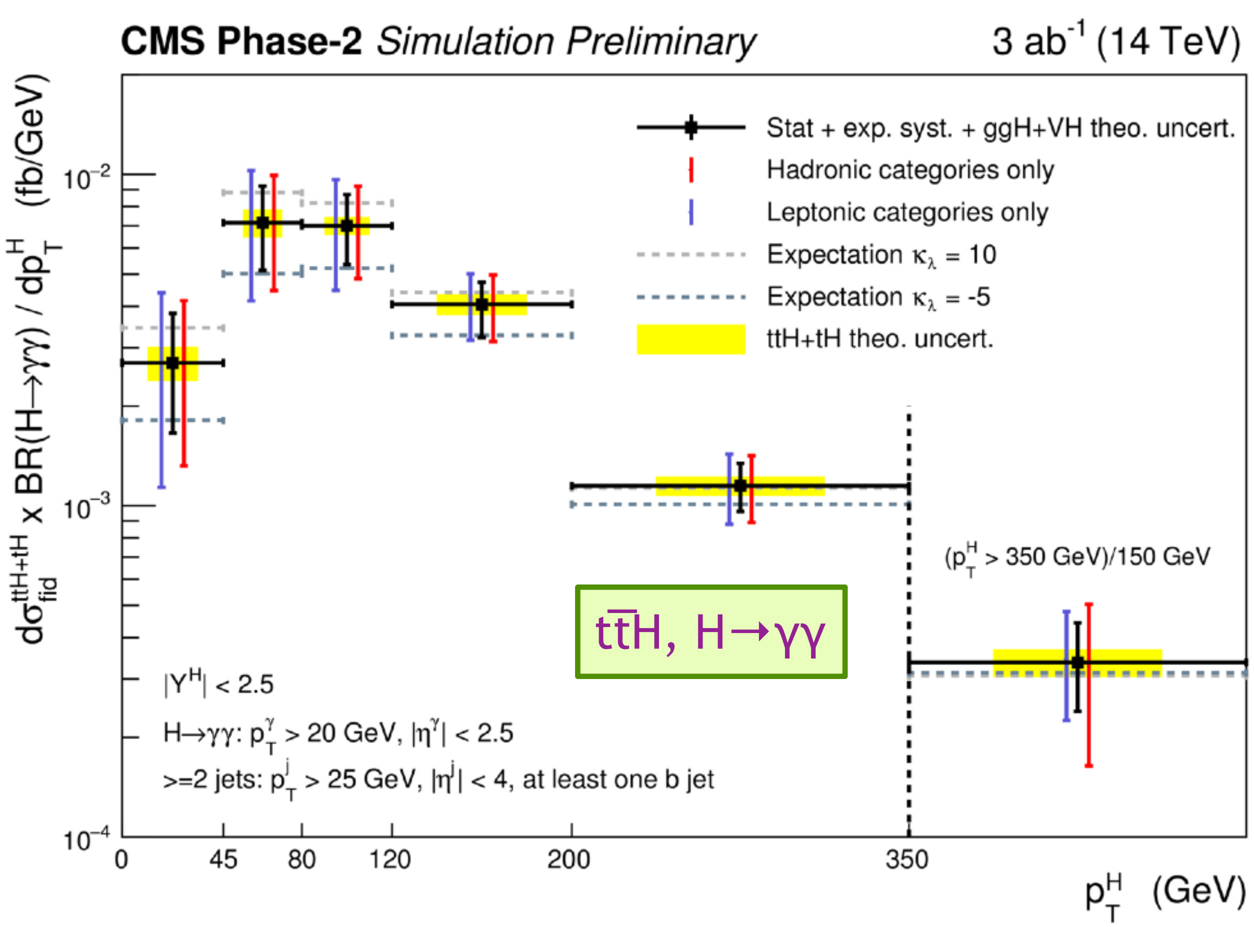
- NLO electroweak corrections also affect kinematics
- HL-LHC statistics needed



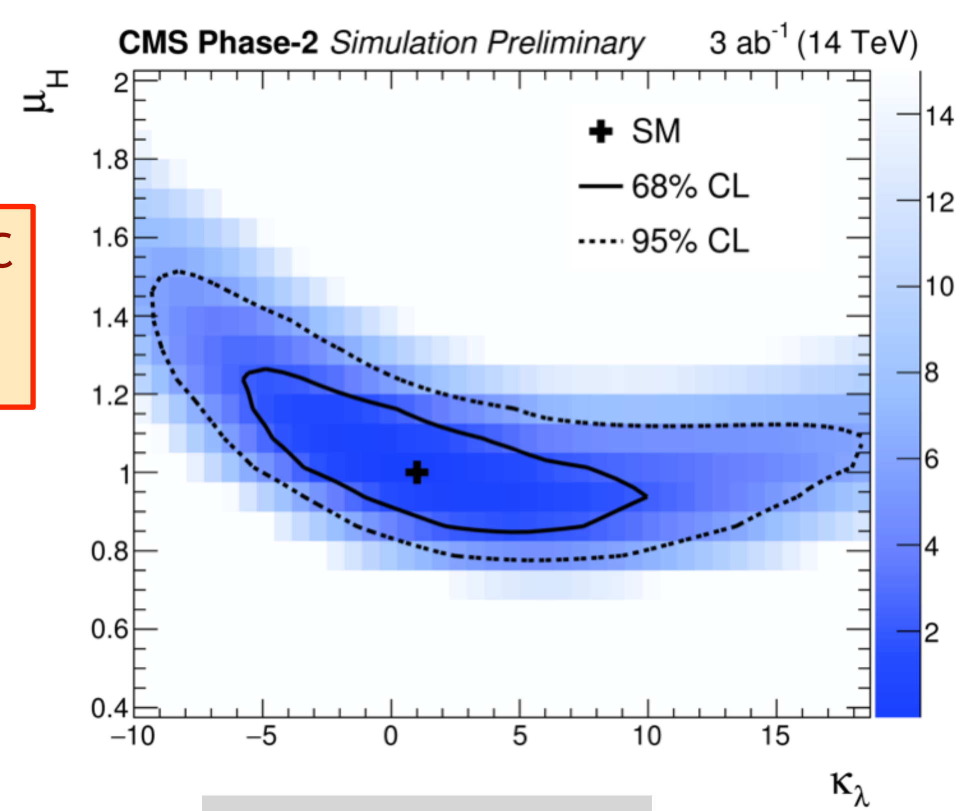


nice, but still not competitive with HH production

$-4 < \kappa_\lambda < 14$ @ 95%CL



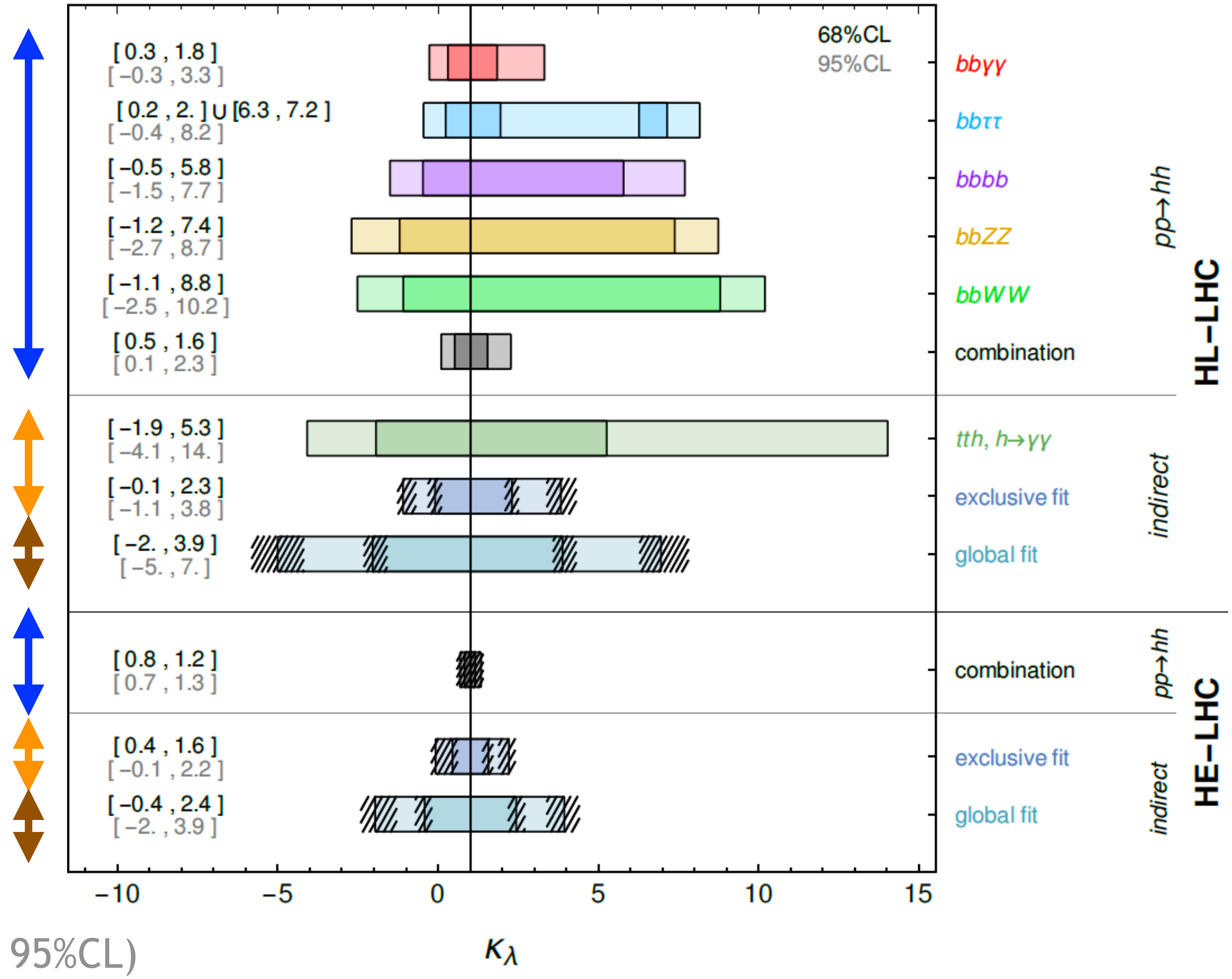
CMS HL-LHC
14 TeV
3 ab^{-1}



CMS-PAS-FTR-18-020

Summary of Self-Coupling at HL/HE-LHC

1. **di-H, excl.:**
   di-Higgs production
2. **di-H, glob.:**
   di-Higgs + global fit
3. **single-H, excl.:**
   single-Higgs production
4. **single-H, glob.:**
   single-Higgs + global fit



☛ HL-LHC

- 4σ evidence of HH prod.
- κ_λ: 50% @ 68%CL (>100% @ 95%CL)

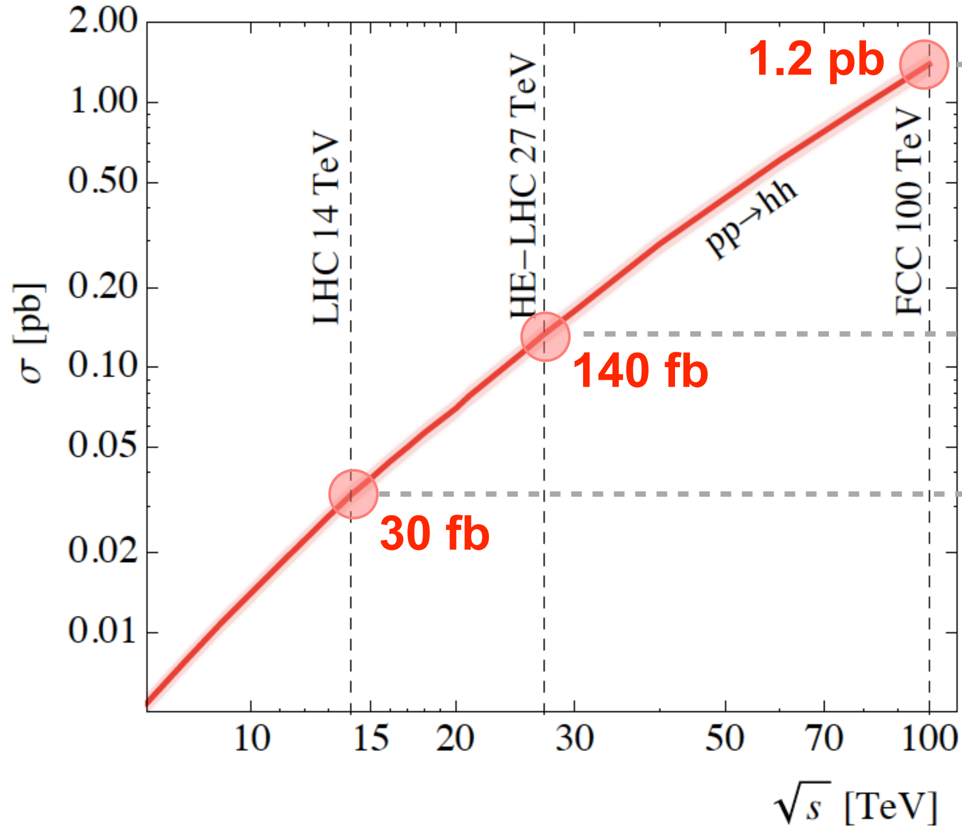
☛ HE-LHC

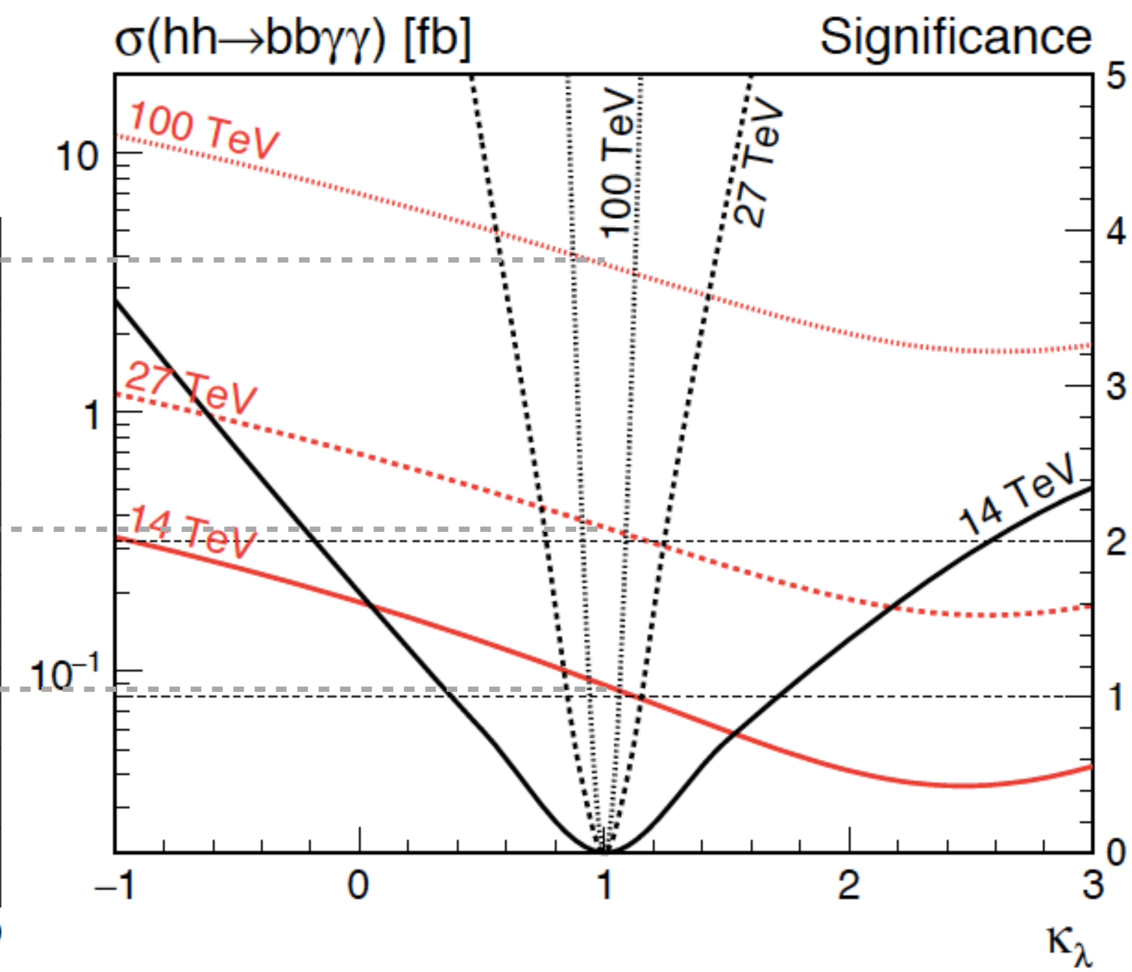
- observation of HH prod.
- κ_λ: 10-15% @ 68%CL / 95%CL

method 1 (di-H, excl.) is the most useful at hadron colliders

FCC-hh: Self Coupling at 100 TeV

Factor 40 in cross-section / HL-LHC

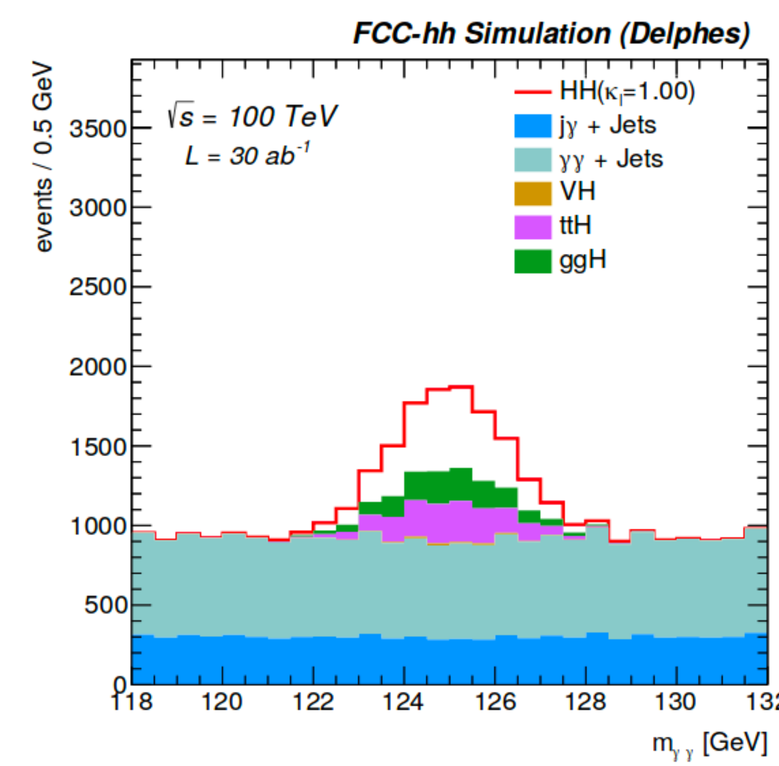




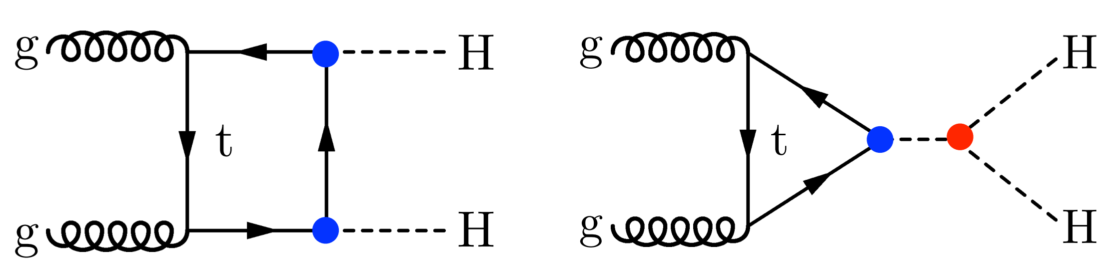
PRD 97, 113004 (2018)

☛ HH → bbγγ is the Golden channel the FCC-hh
- ttH is a resonant background

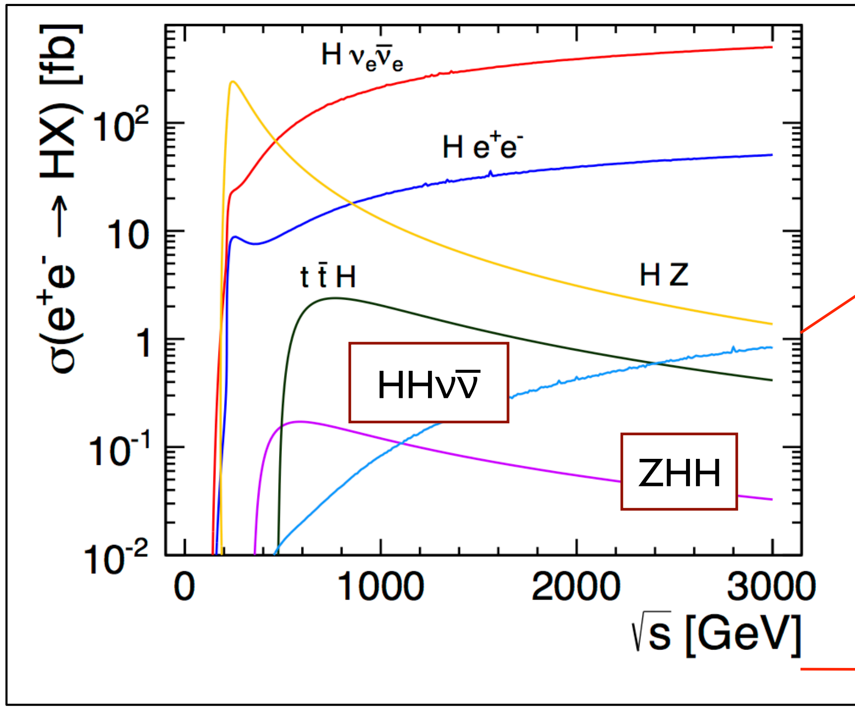
	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$	$b\bar{b}WW^*[\to 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

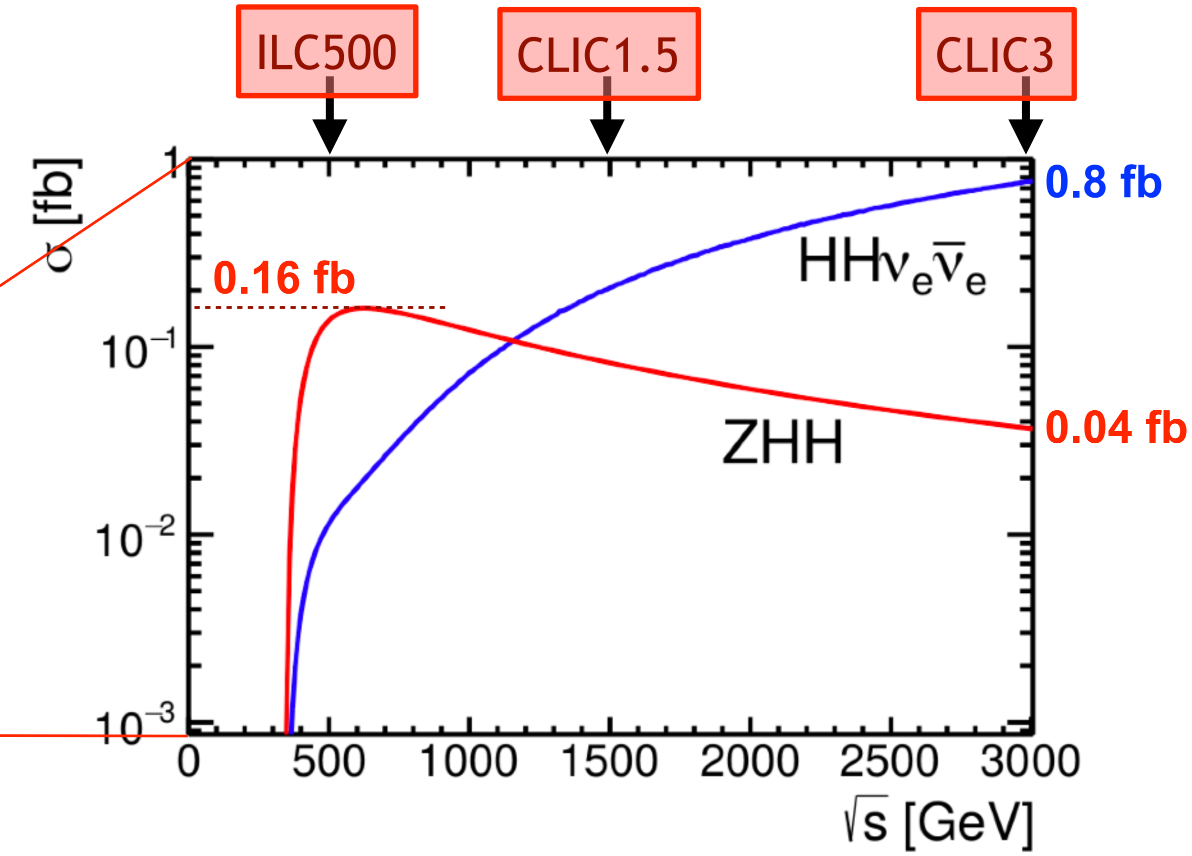


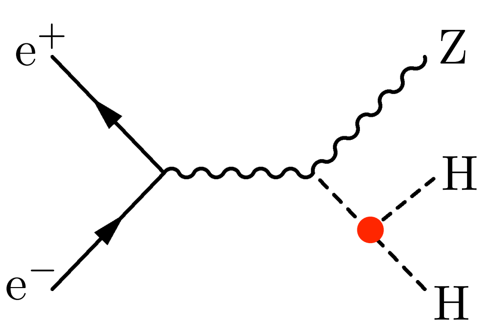
requires y_t at % level!

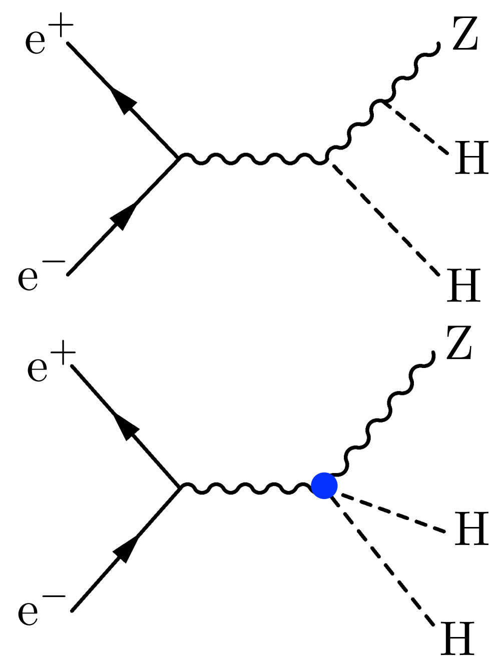


Di-Higgs Production at Lepton Colliders

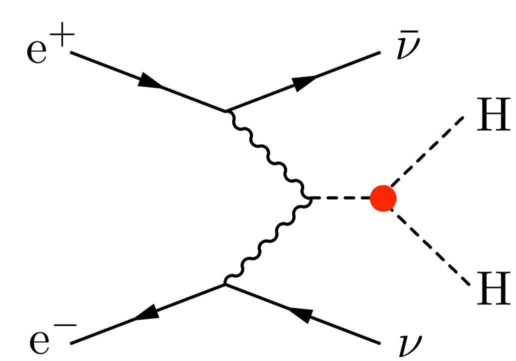


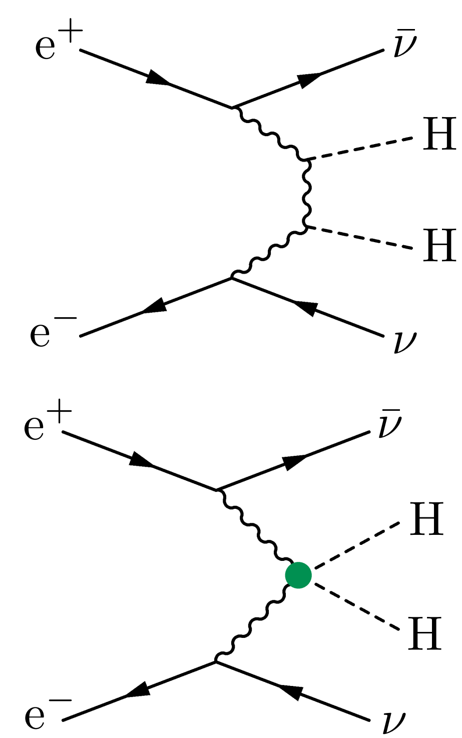




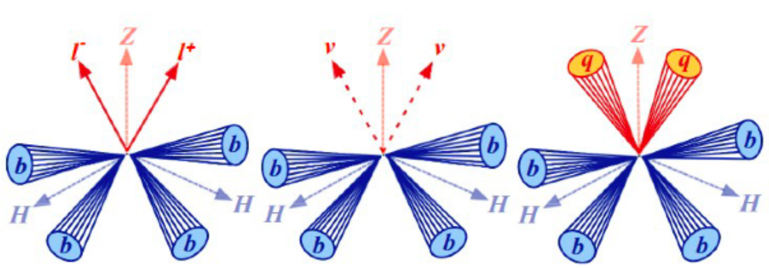


e+e− → ZHH



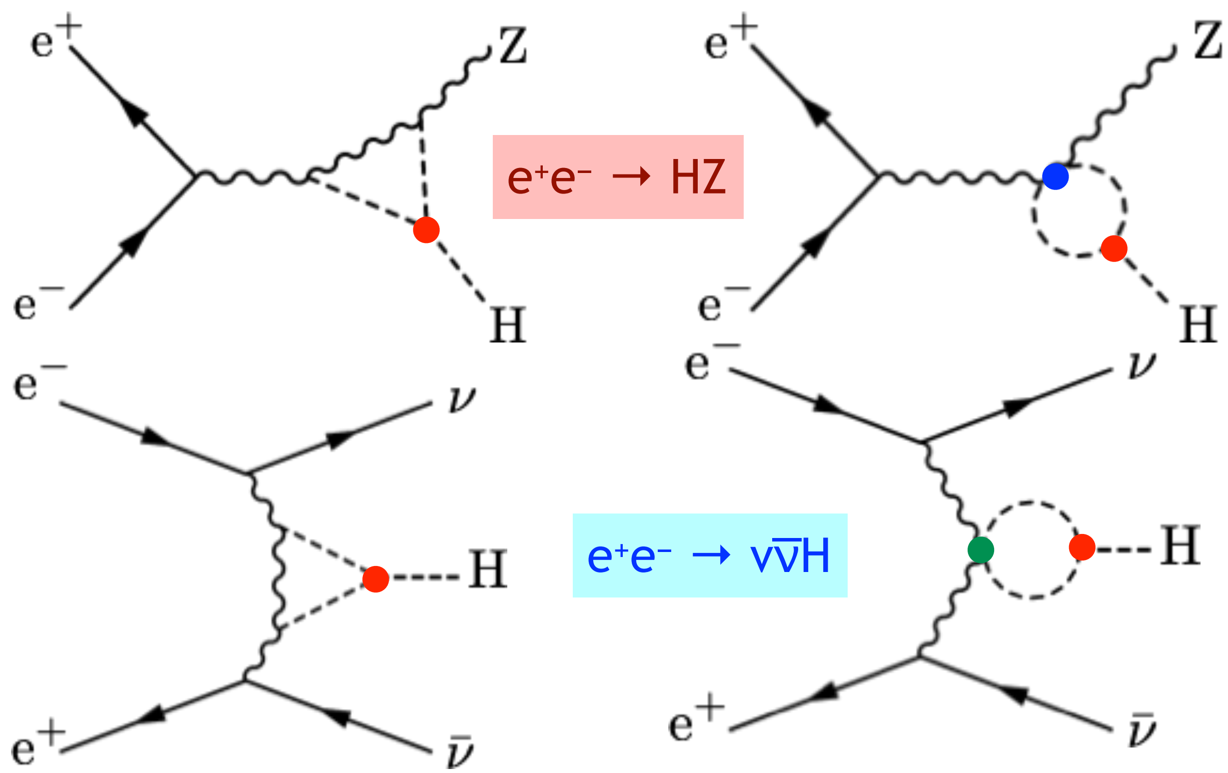


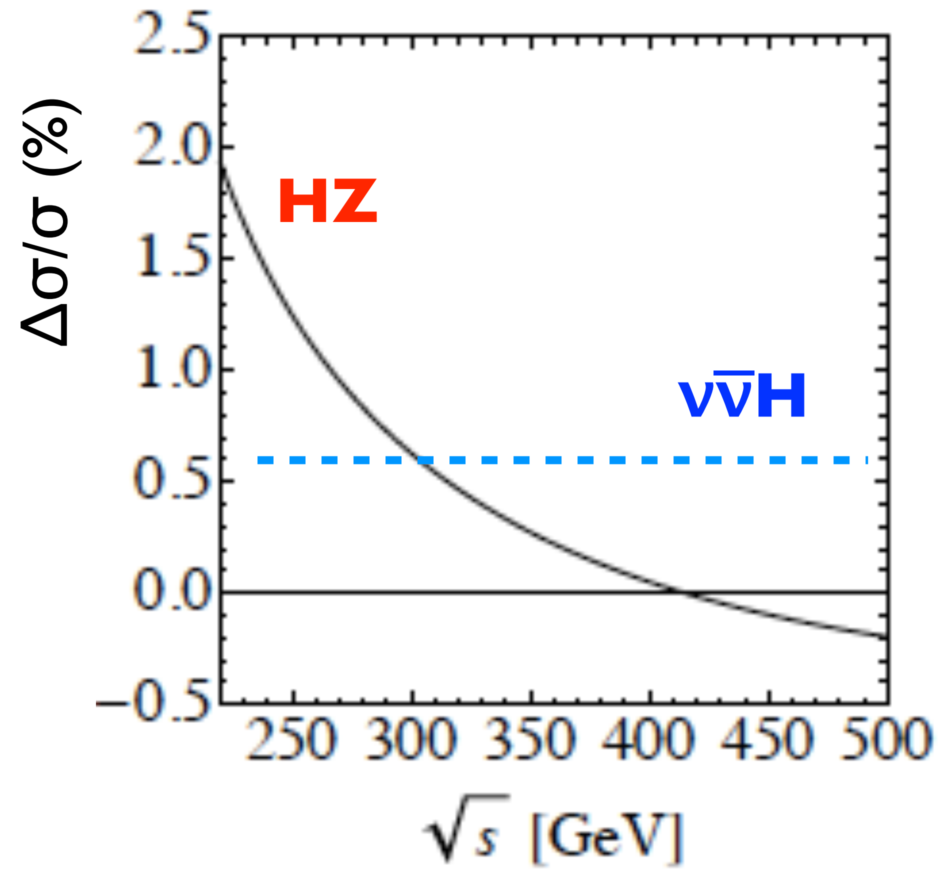
e+e− → HHνν̄



CLIC e+e− → νν̄HH
➠ 3.6σ at 1.4 TeV (2.5 ab⁻¹) and ≫5σ at 3 TeV (5 ab⁻¹)

Self Coupling from Single Higgs at e^+e^-



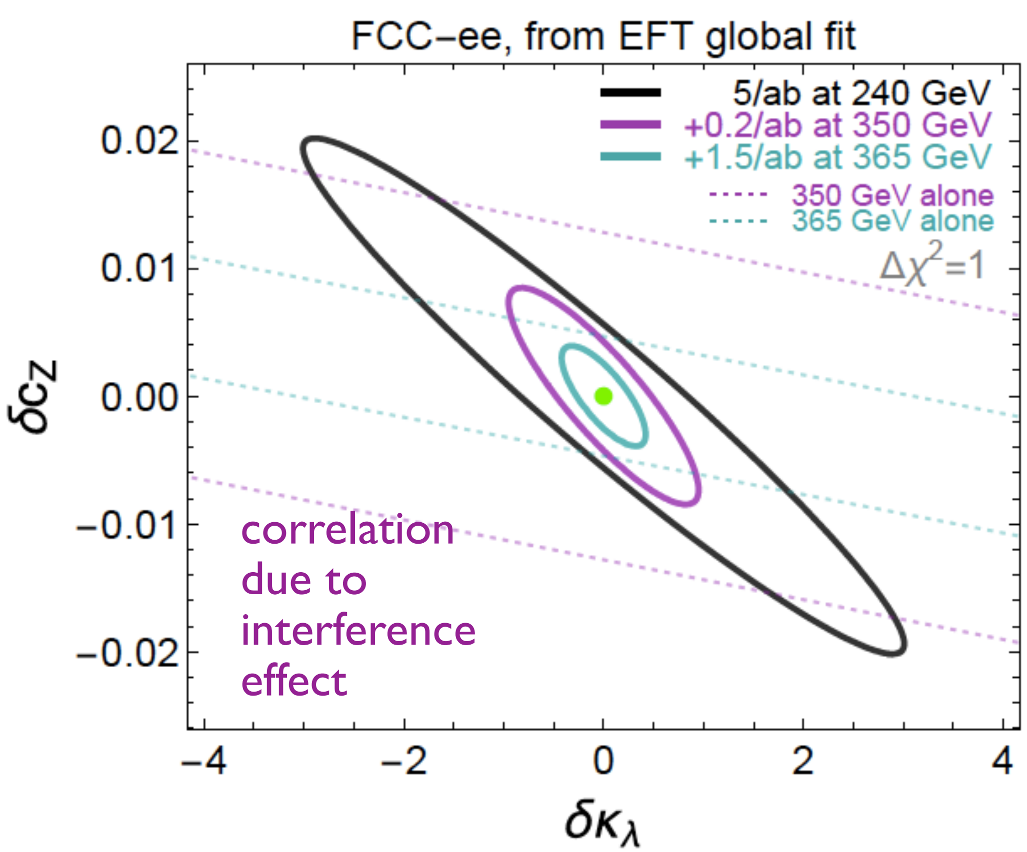


- Up to 1.5% effect on σ_{ZH} at $\sqrt{s}$ = 240 GeV
  - σ_{ZH} with 0.5% accuracy
  - degeneracy between $\delta\kappa_\lambda$ and $\delta\kappa_Z$

Two energy points are necessary to break the degeneracy

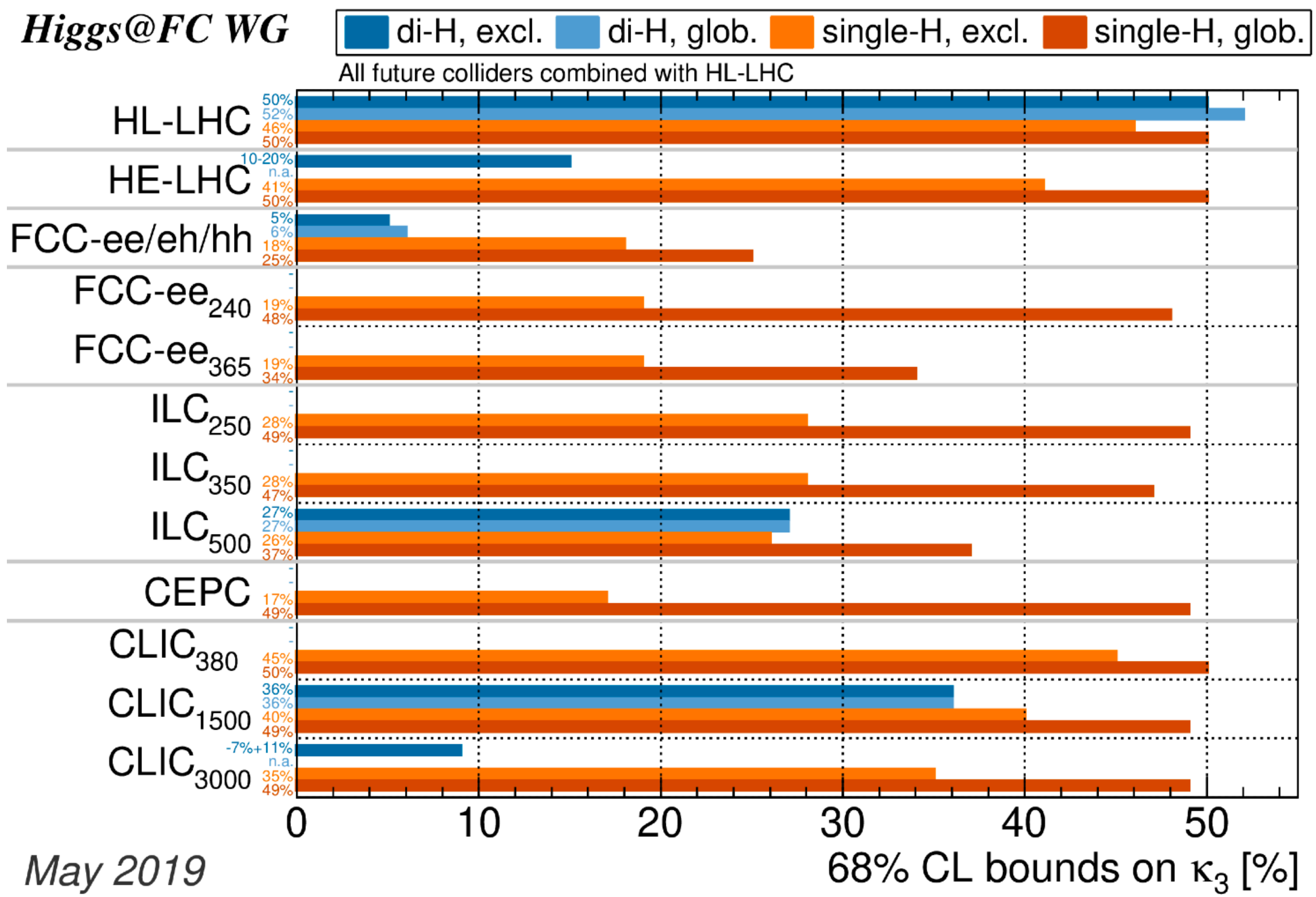
FCC-ee (2IPs) : modelindependent constraint on $\delta\kappa_\lambda$ at the ±35% level

see also arXiv:1711.03978



Self-Coupling, Summary

- **di-H, excl.**: di-Higgs production
- **di-H, glob.**: di-Higgs + single-Higgs couplings (global fit)
- **single-H, excl.**: single-Higgs production
- **single-H, glob.**: single-Higgs + single-Higgs couplings (global fit)



FCC — ee: ~20%, hh: ~5%

ILC — ~27%

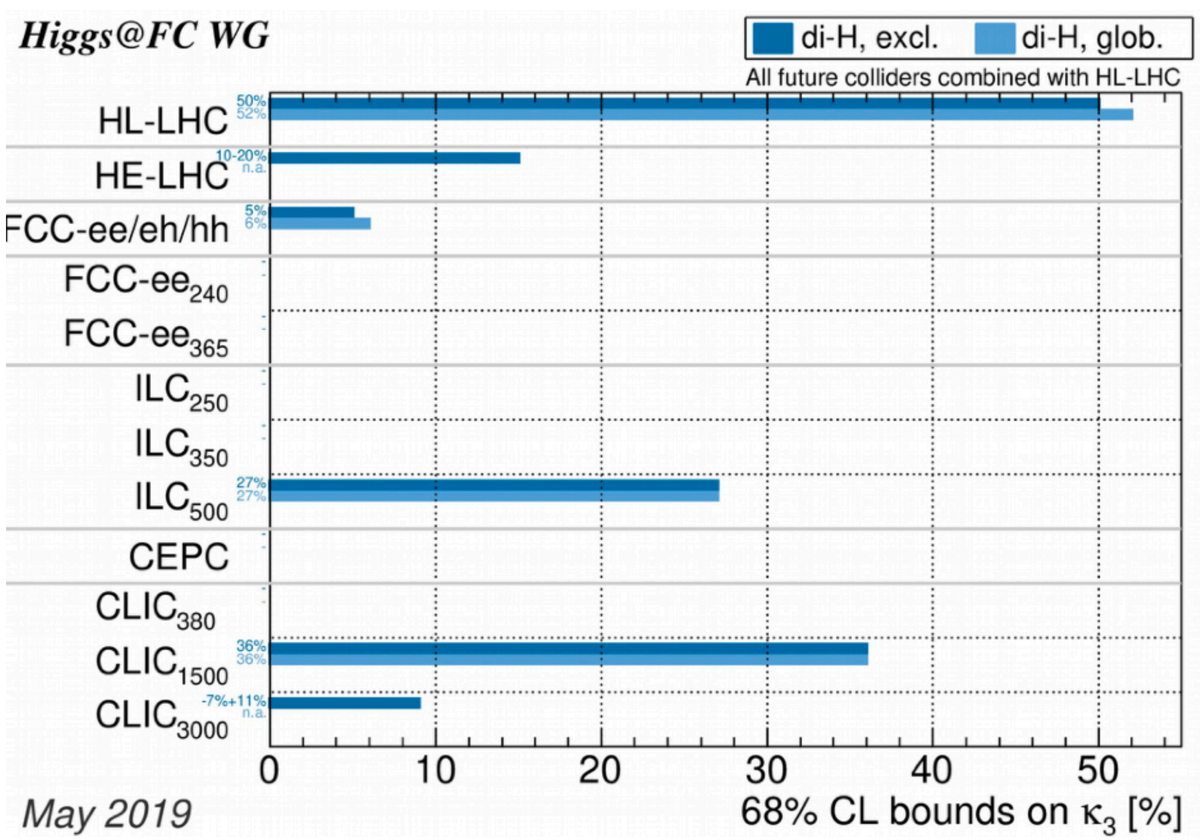
CEPC — ~20%

CLIC — ~10%

Self-Coupling, Summary

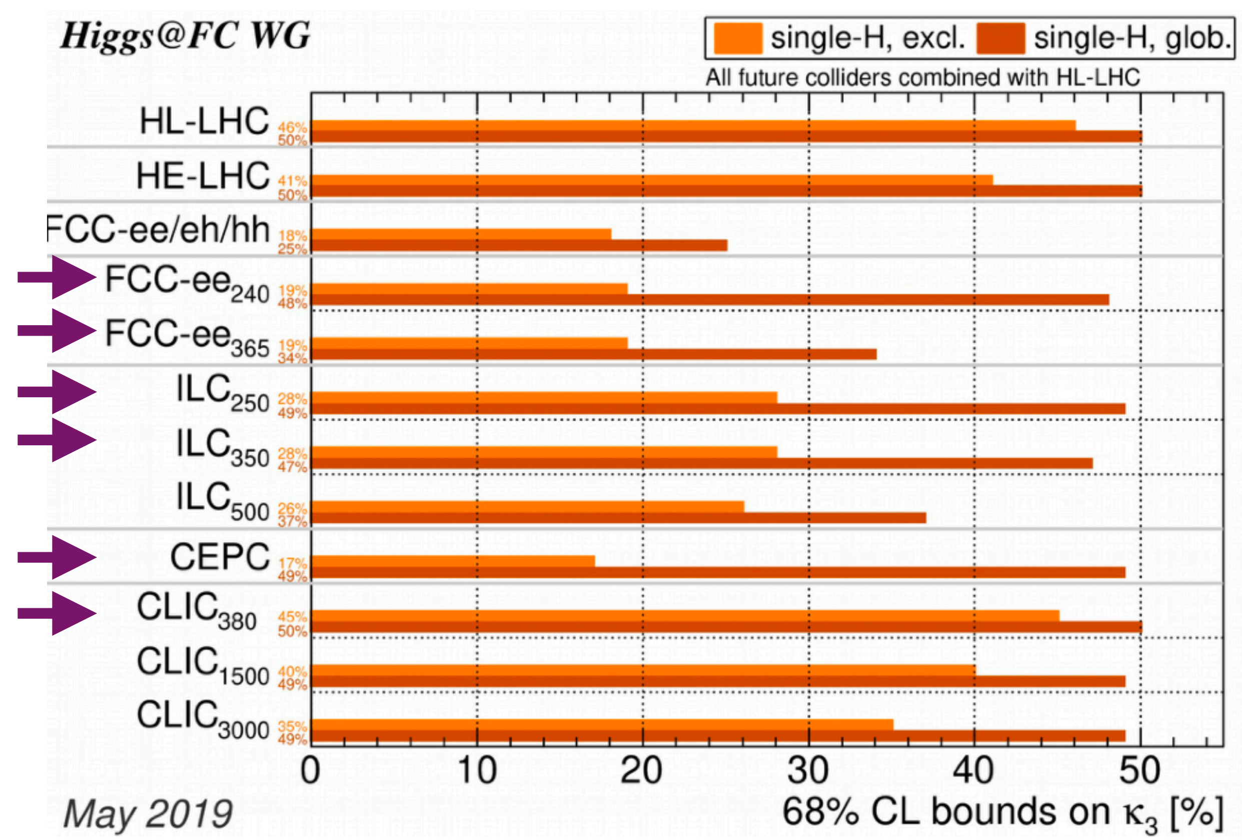
5% sensitivity needed to get sensitive to quantum corrections to the Higgs potential (Ch.Grojean)

from di-Higgs production



- small impact from global analysis
- at FCC-hh, a 1% uncertainty on the top Yukawa κ_t induces a deviation of the HH rate comparable to the uncertainty on κ_λ

indirect (single Higgs)



- single-Higgs analyses relevant for lepton colliders at $\sqrt{s}$ < 400 GeV below the ZHH production threshold
- global analyses to get more robust results

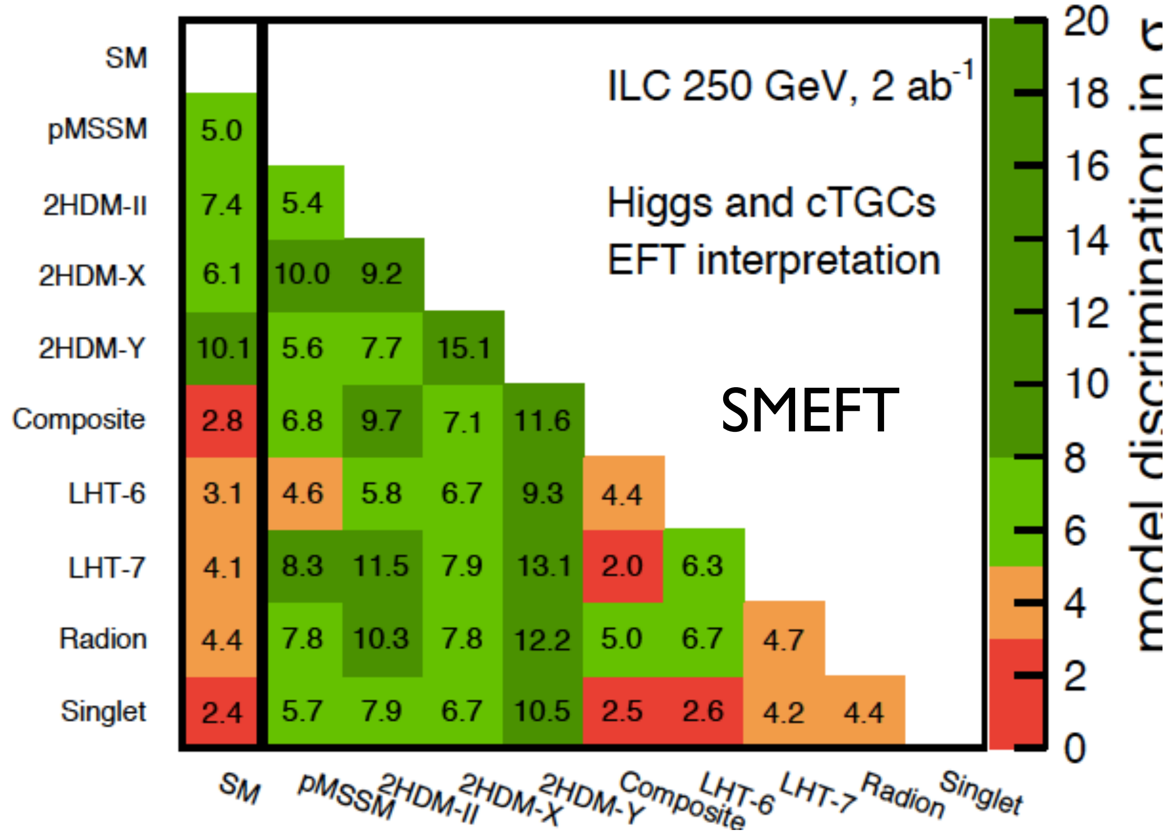
Higgs Couplings: Sensitivity to BSM Models

models consistent with no discovery at the HL-LHC (incl. Higgs partners)

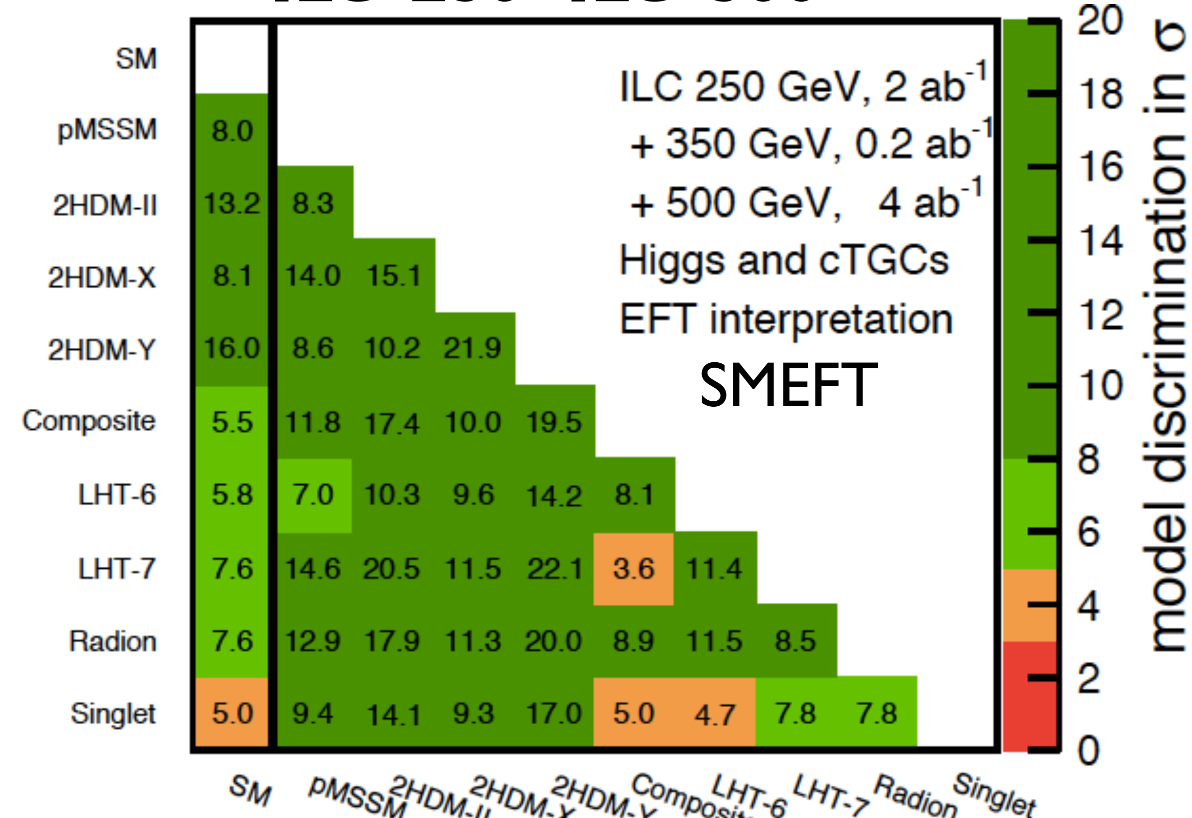
Deviations to SM Higgs boson couplings (in %)

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [38]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [39]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [39]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [39]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [40]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4

ILC-250



ILC-250+ILC-500



T. Barlow et al., arxiv:1708.08912

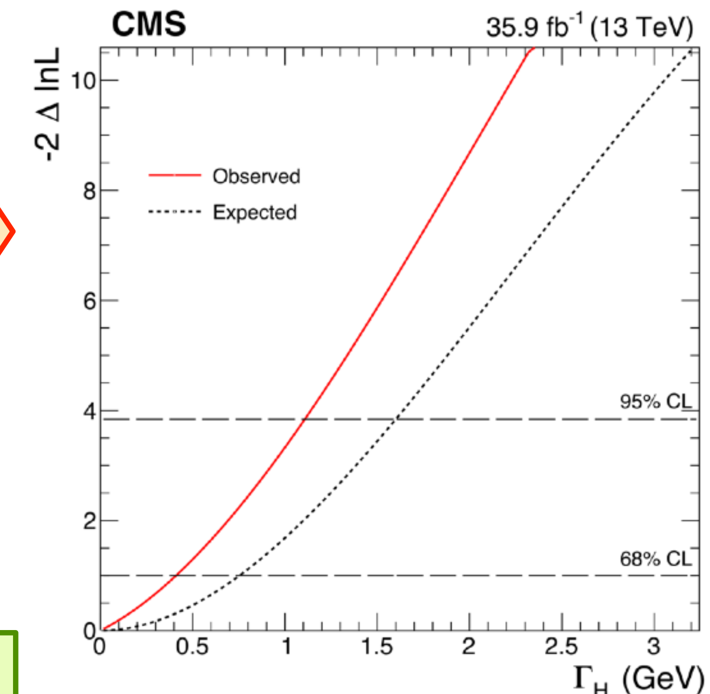
Higgs Boson Width as Probe of BSM

☛ The Higgs total decay width Γ_H contains information on the interaction with all particles, including possible BSM states

☛ Direct Γ_H measurements from line-shape limited by typical 1-GeV mass resolution

CMS 2016
L = 36 fb^{-1}

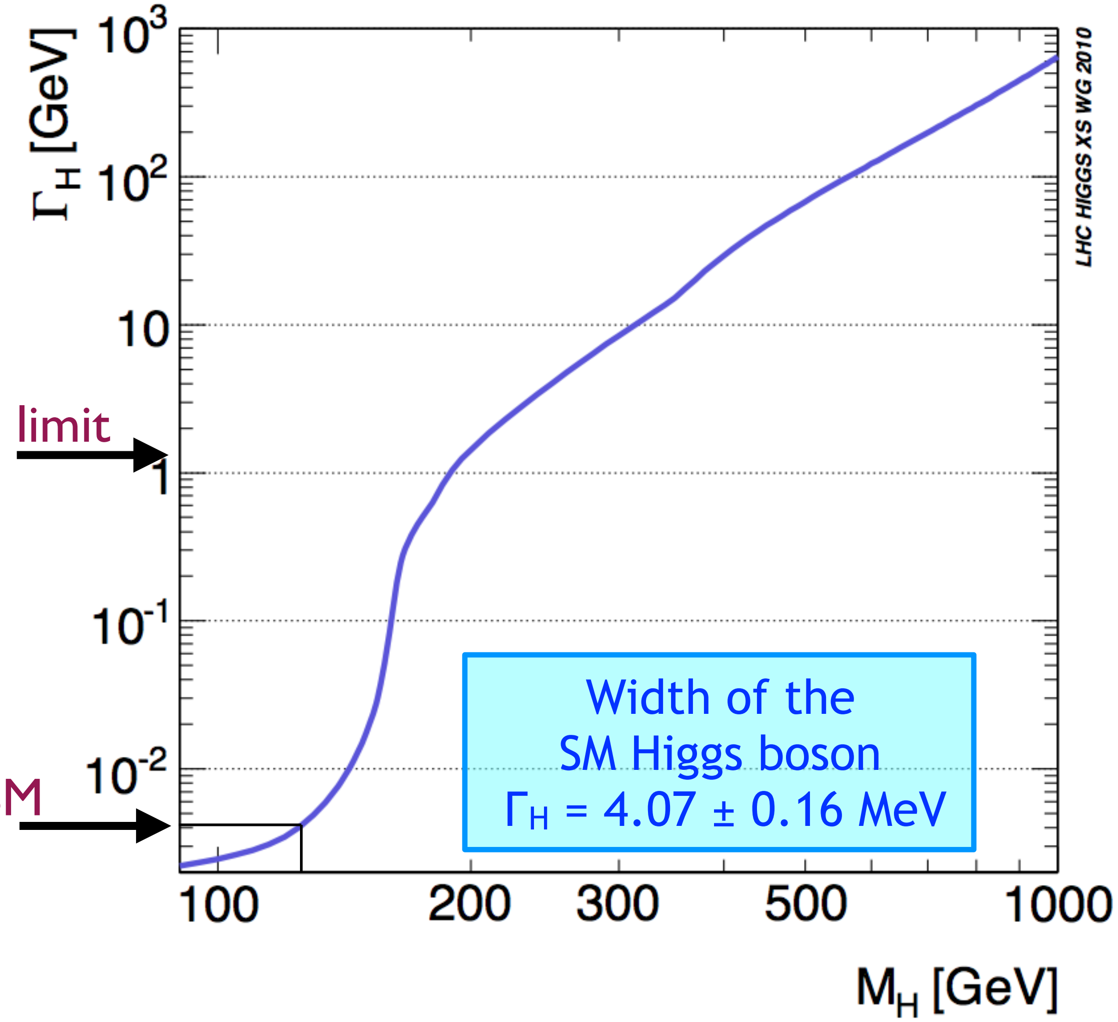
Γ_H < 1.1 GeV @ 95% CL



JHEP 11 (2017) 047

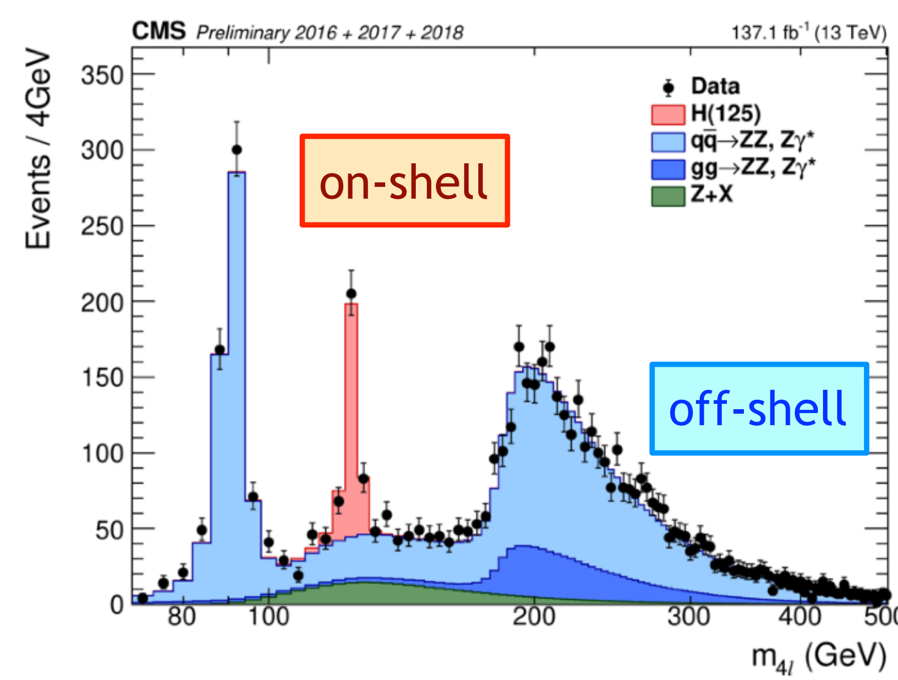
CMS limit

SM



Width of the SM Higgs boson
Γ_H = 4.07 ± 0.16 MeV

Solution:
compare H → ZZ off-shell and on-shell production

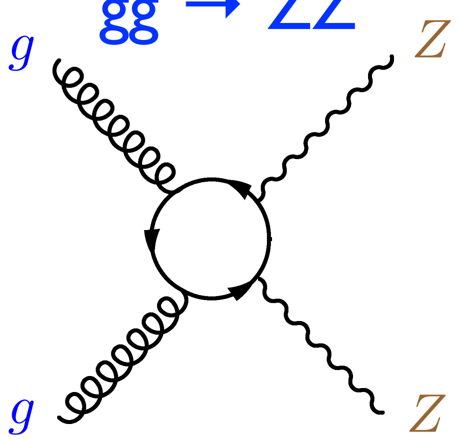


Indirect Higgs Boson Width

ZZ production = $q\bar{q} \to ZZ$

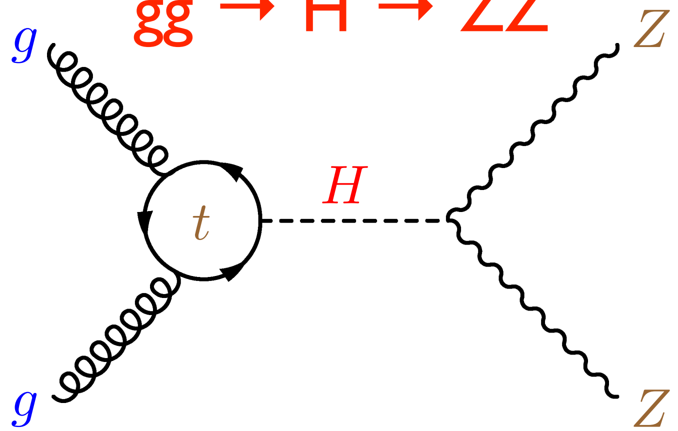
but also

$gg \to ZZ$

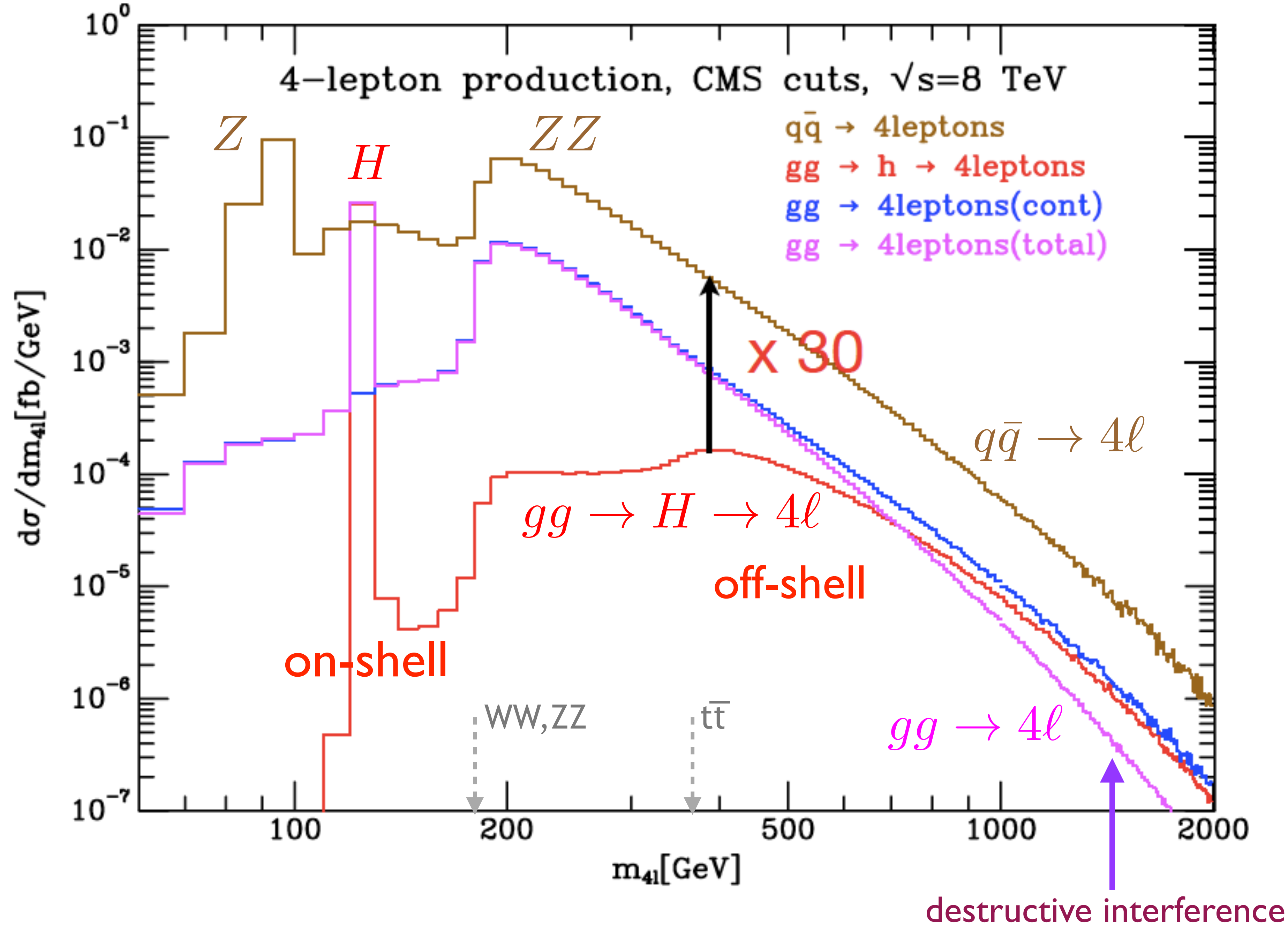


and

$gg \to H \to ZZ$



$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

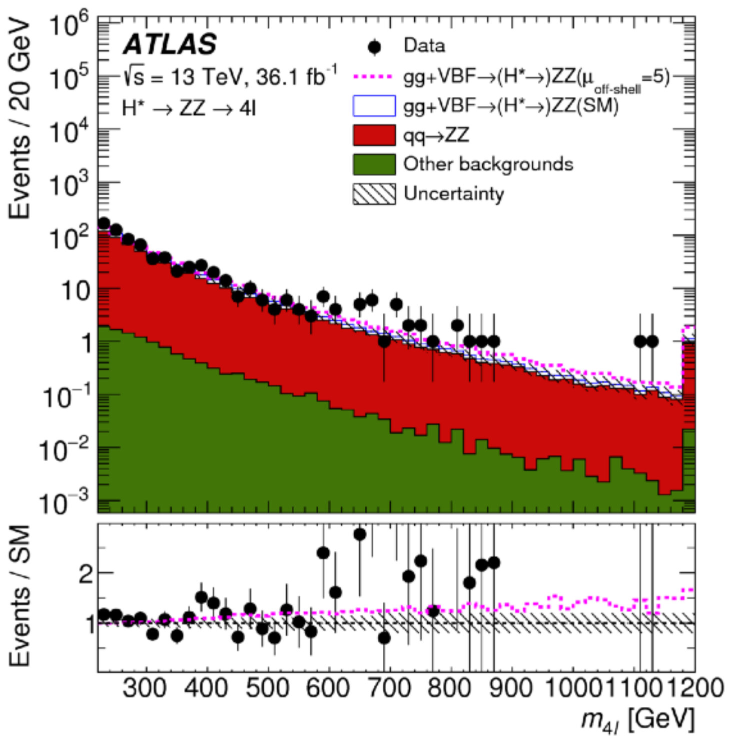


by studying the high mass ZZ region

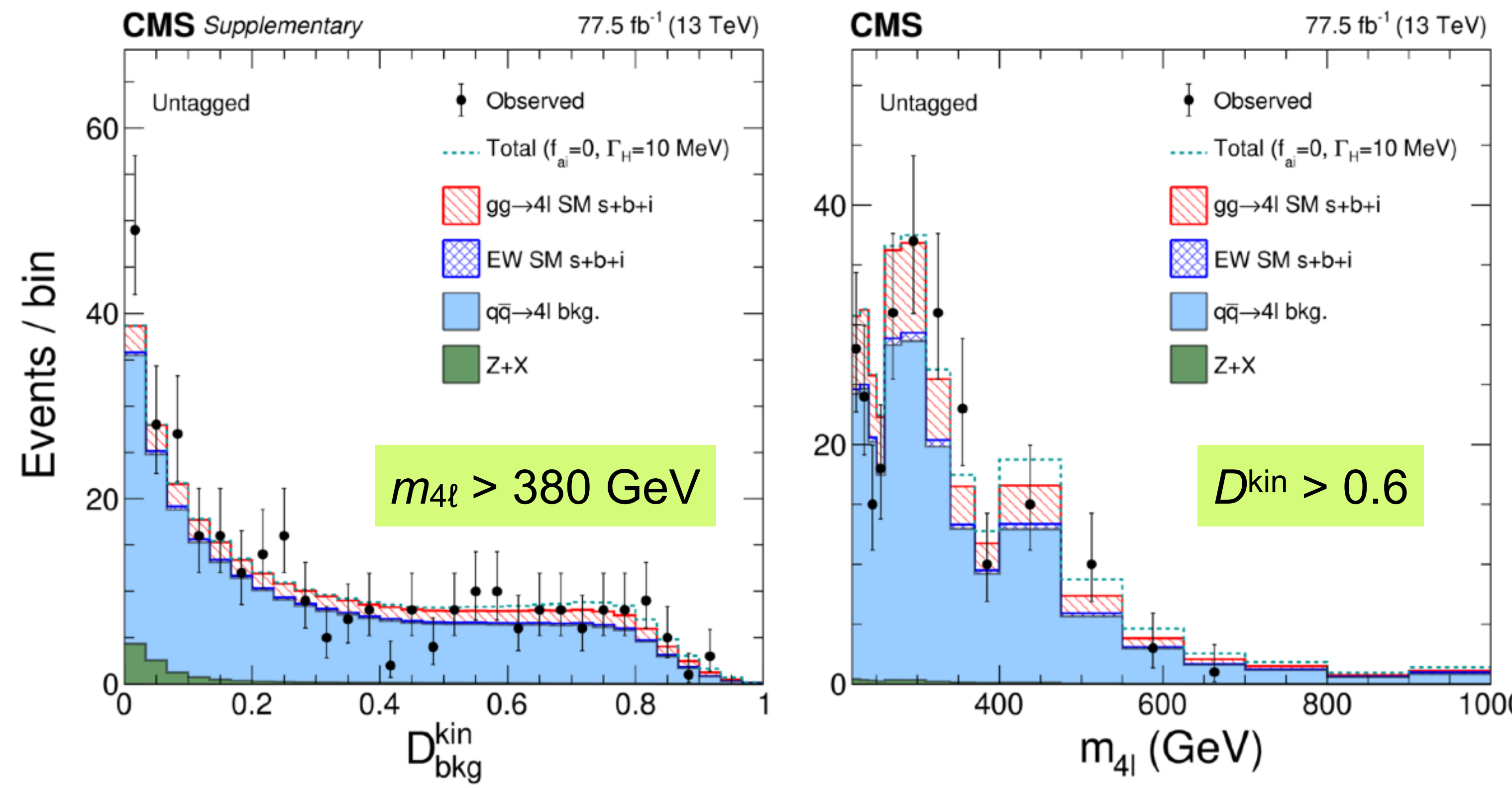
CMS and ATLAS are able to set indirect limits on Γ_H

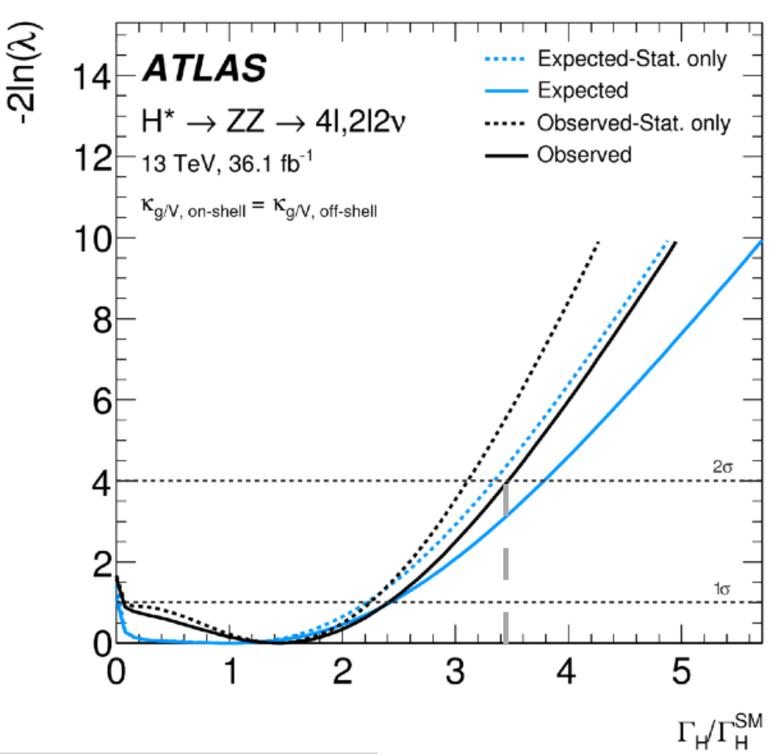
Higgs Boson Width from Off-Shell at LHC

$H \rightarrow ZZ^* \rightarrow 4\ell, 2\ell 2\nu$



$H \rightarrow ZZ^* \rightarrow 4\ell$



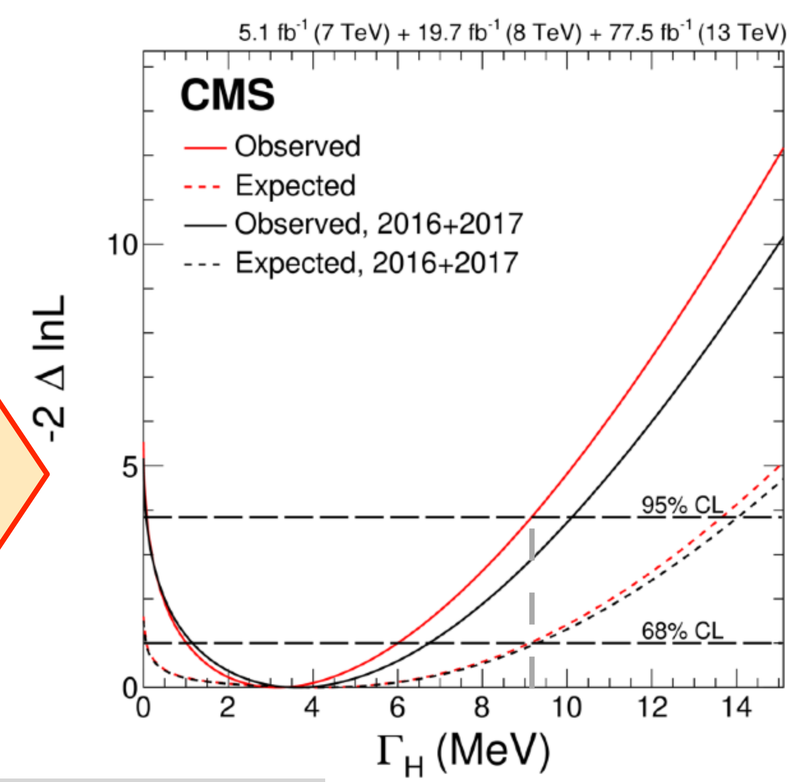


ATLAS 2016
$L = 36\ fb^{-1}$

$\Gamma_H < 14.4$ MeV @ 95% CL

CMS 2016-2017
$L = 78\ fb^{-1}$

$\Gamma_H < 9.2$ MeV @ 95% CL
$\Gamma_H \neq 0$ @ 2σ



PLB 786 (2018) 223

PRD 99 (2019) 112003

Higgs Boson Width at HL-LHC

Three approaches explored

☛ interference between Higgs γγ signal and QCD background

- weak contraint: 8-22 × SM

☛ fit in the κ-framework (with assumption)

- Γ_H 100% correlated with B^{unt} and: B^{unt} < 4.1% @ 95%CL

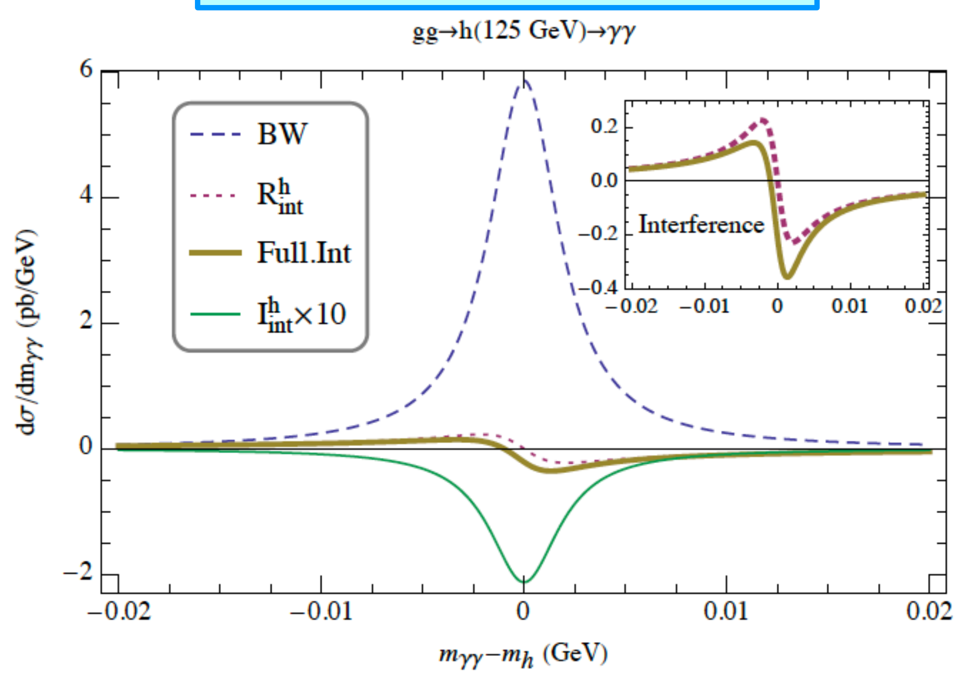
☛ H → ZZ off-shell vs on-shell

- 20% precision, but model dependent

Fundamental difference between hadron and lepton colliders:

- hadron collider not directly sensitive to the width Γ_H
- an additional assumption is needed (e.g. $|\kappa_V| \leq 1$) when untagged decays are allowed

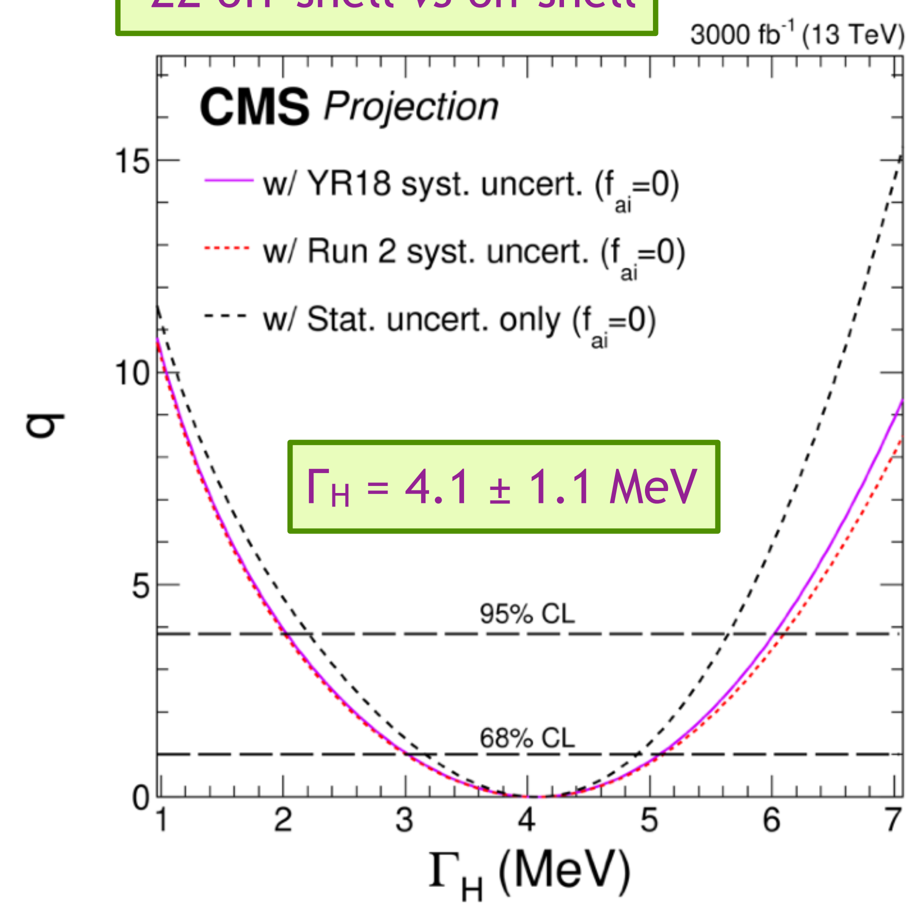
interference between gg → H → γγ and gg → γγ



R_{int} induces a mass shift of −35 ± 9 MeV for Γ_H = 4.1 MeV

ATL-PHYS-PUB-2016-009

ZZ off-shell *vs* on-shell



Γ_H = 4.1 ± 1.1 MeV

CMS HL-LHC
13 TeV
3 ab^{-1}

CMS-PAS-FTR-18-011 ATL-PHYS-PUB-2015-024

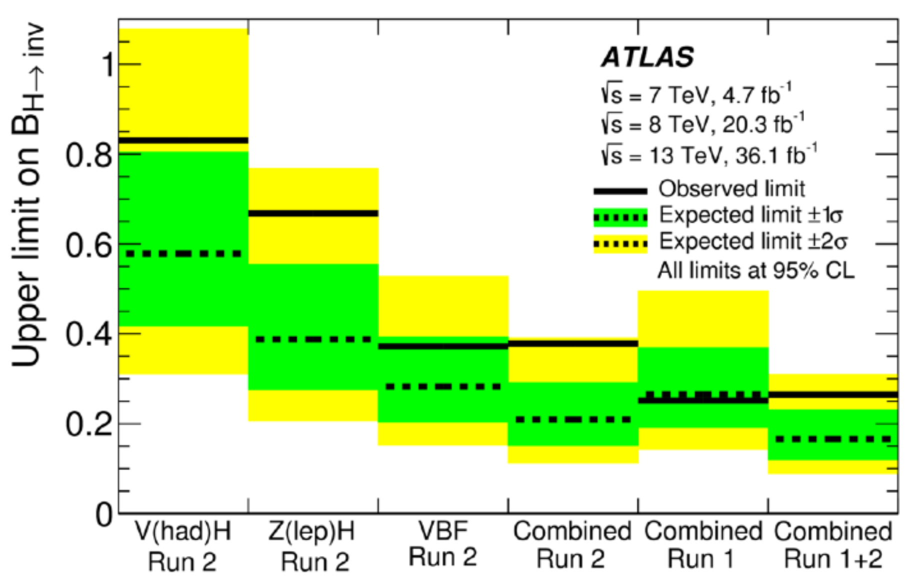
combination ATLAS/CMS ➠ 800 MeV

Higgs Invisible Decays at (HL-)LHC

Higgs portal:
window on the Dark sector?

Connection between Higgs and Dark Matter ($m_{DM} < m_H/2$)

- SM: $B^{inv} \approx 0.1\%$ from $H \to ZZ^* \to 4\nu$
- signature: large E_T^{miss}
- sensitivity dominated by VBF channel



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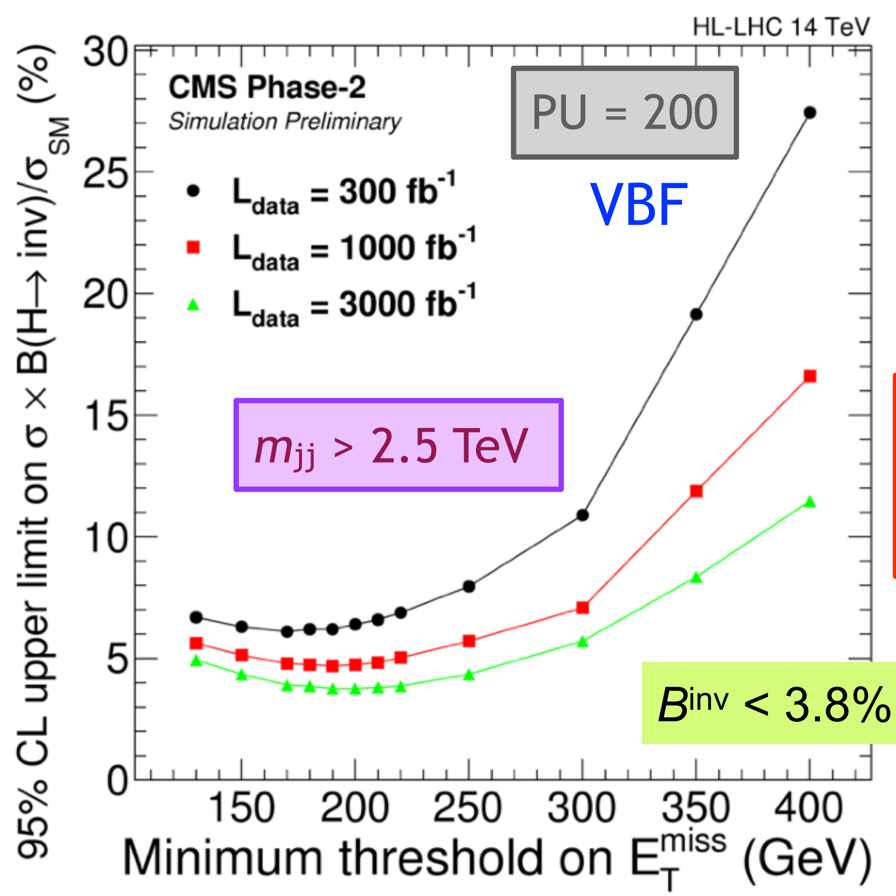
Run-1 + 2016 (36 fb^{-1})

- ATLAS: $B^{inv} < 26\%$ @ 95%CL (17%)
- CMS: $B^{inv} < 19\%$ @ 95%CL (15%)



CMS HL-LHC
14 TeV
3 ab^{-1}

$B^{inv} < 3.8\%$ @ 95%CL

CMS-PAS-FTR-18-016

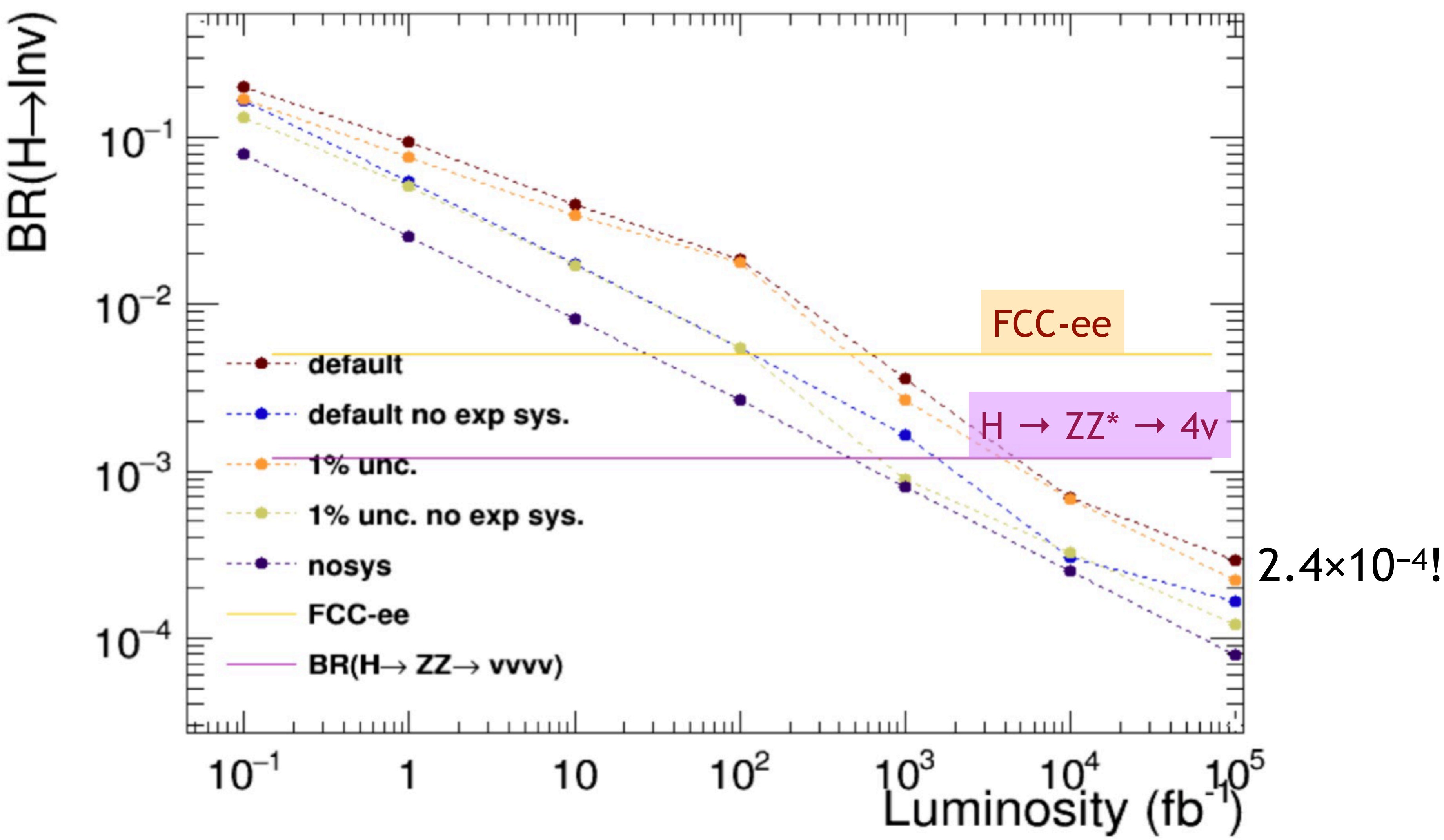
HL-LHC, using VBF and VH channels

- ATLAS+CMS: $B^{inv} < 2.5\%$ @ 95%CL

Higgs Invisible Decays at FCC-hh

☛ Exploit Higgs production at very large p_T

☛ Constrain the background HZ ($Z \to \nu\bar{\nu}$) at the 1% level using NLO QCD/EWK to relate to measured HZ ($Z \to \ell^+\ell^-$), HW and Hγ spectra



sensitivity to SM invisible width with few inverse attobarns

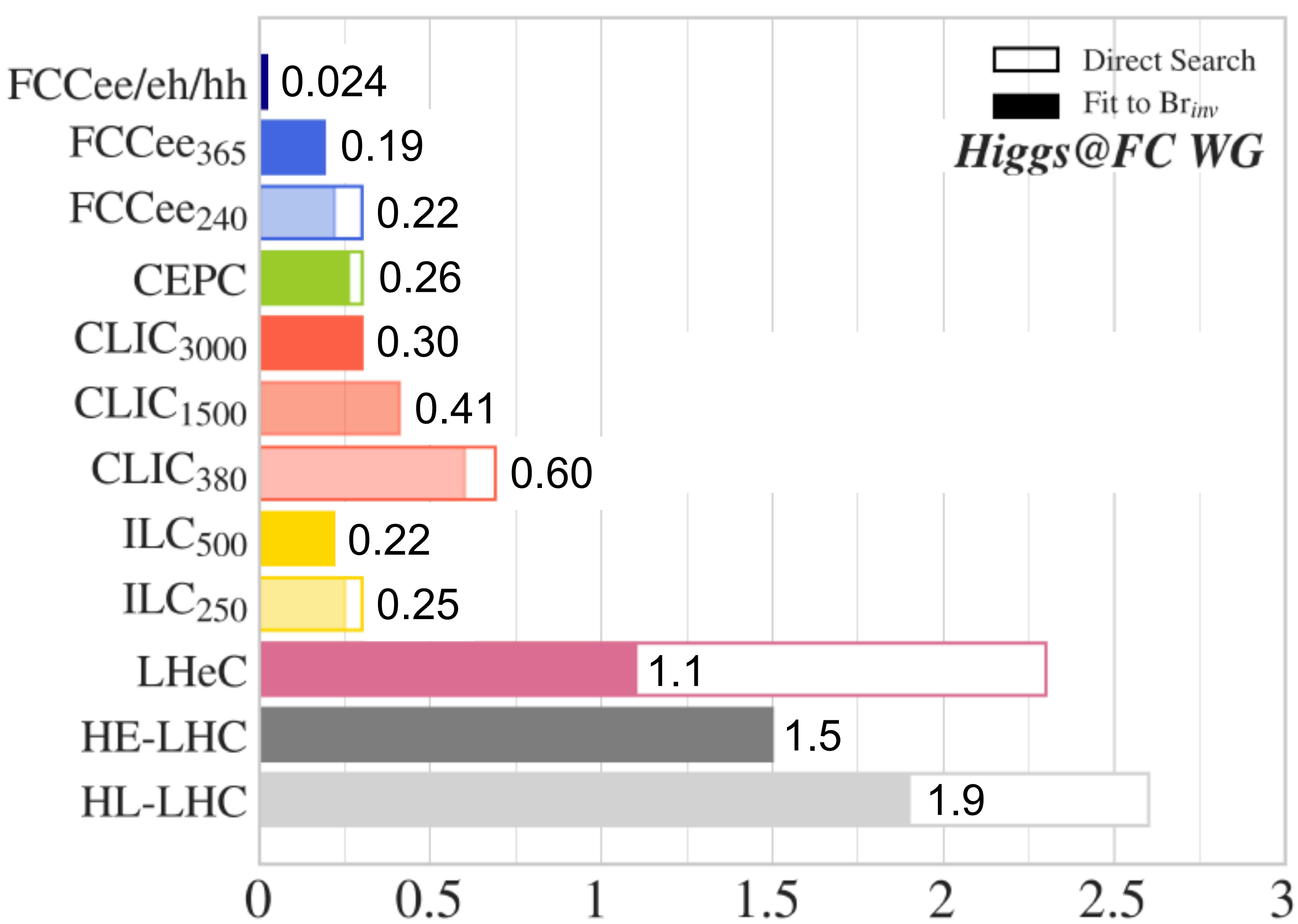
sensitive to possible Higgs decays to DM particles

Invisible Width

Typical current LHC limits: 20% at 95%CL

Hadron Colliders: limited by MET uncertainties
Lepton Colliders: from Z recoil in HZ events

Hadron Colliders cannot measure the total width. An assumption is needed to close the fit, e.g. $|\kappa_V|<1$



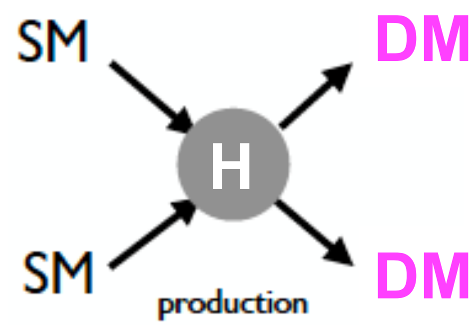
- Lepton Colliders would improve upon HL-LHC limits by one order of magnitude
- FCC-hh would gain another order of magnitude, reaching close to the SM sensitivity

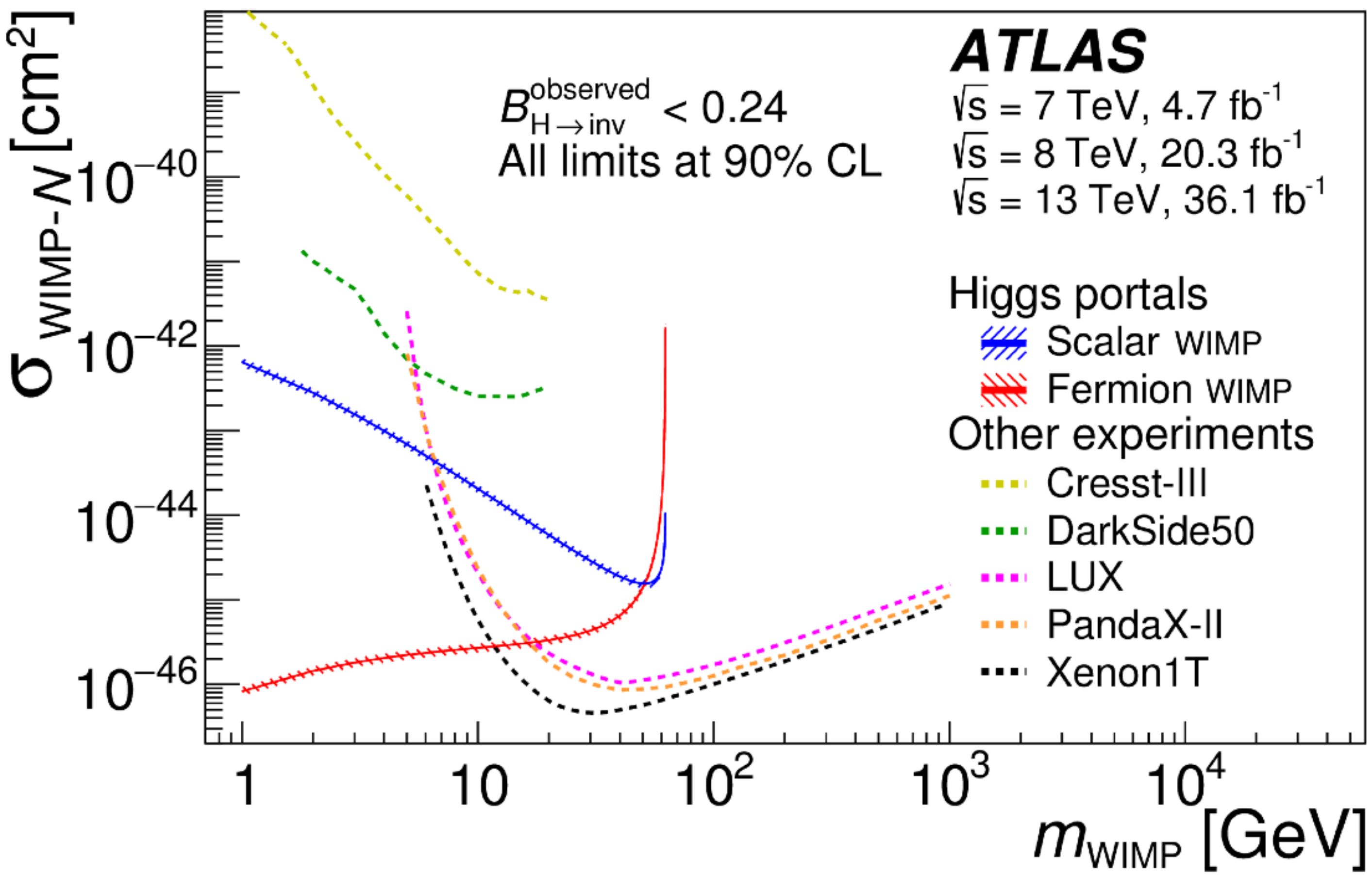
ECFA Higgs Study Group 2019

Constraints on Dark Matter

Note: not affected by neutrino floor for $m_{WIMP} < 10$ GeV (at 20 GeV, $\sigma_{\nu\text{-floor}} = 10^{-49}$ cm²)

Dark matter production through Higgs portal





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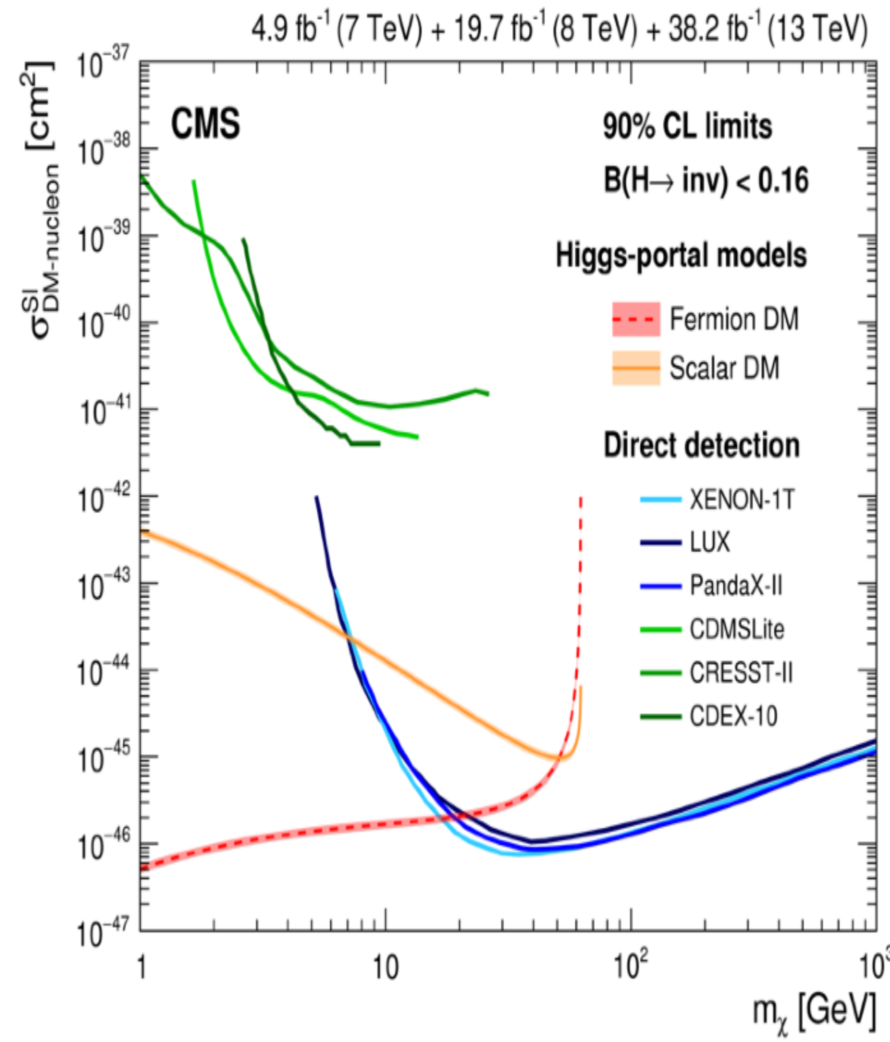

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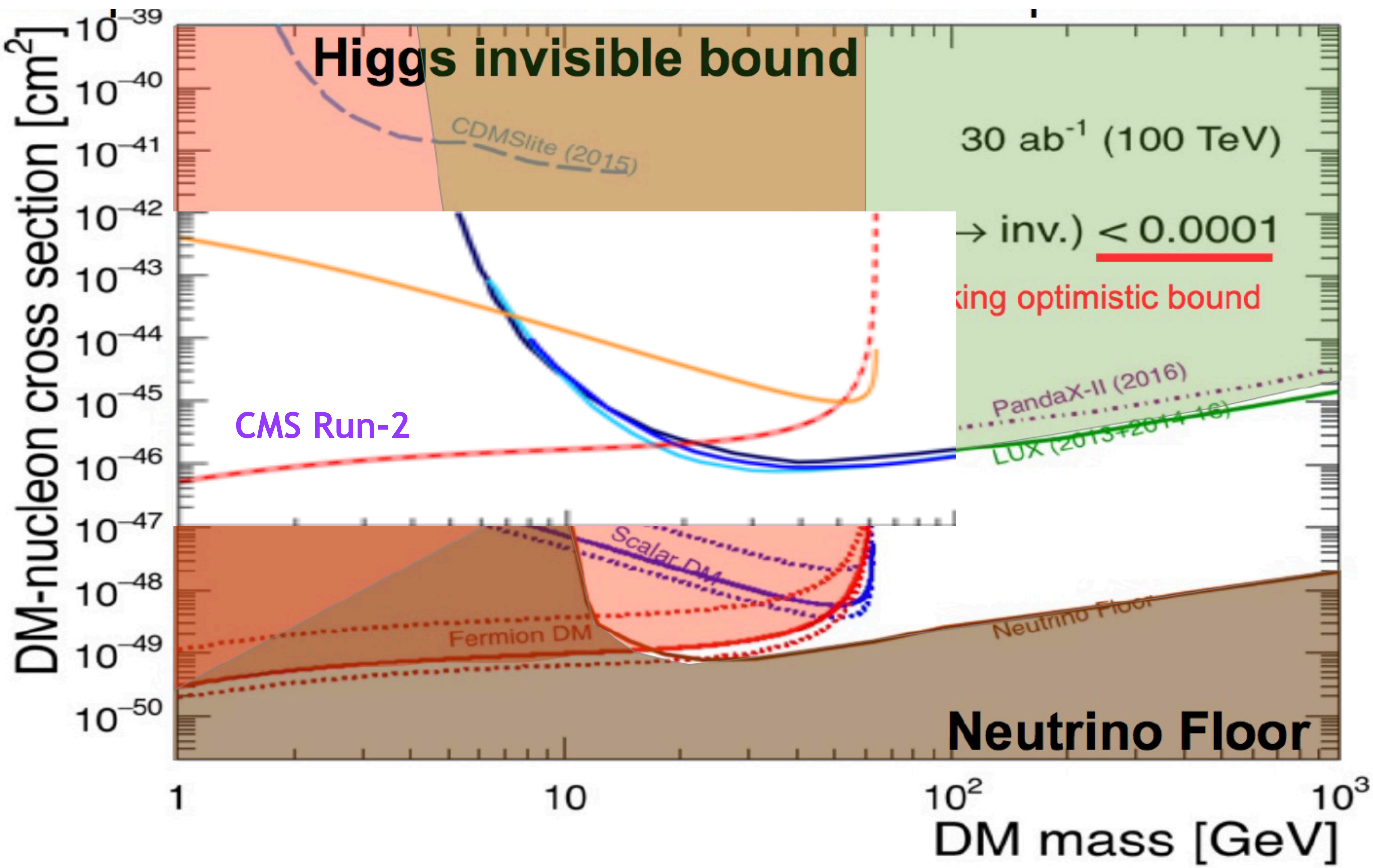
HL-LHC: improvement of these limits by one order of magnitude on $\sigma_{WIMP\text{-}n}$ ➠ 10^{-47} cm²

FCC-hh: Impact on DM Constraints



Complementary to direct detection experiment to reach the neutrino floor cea Irfu

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