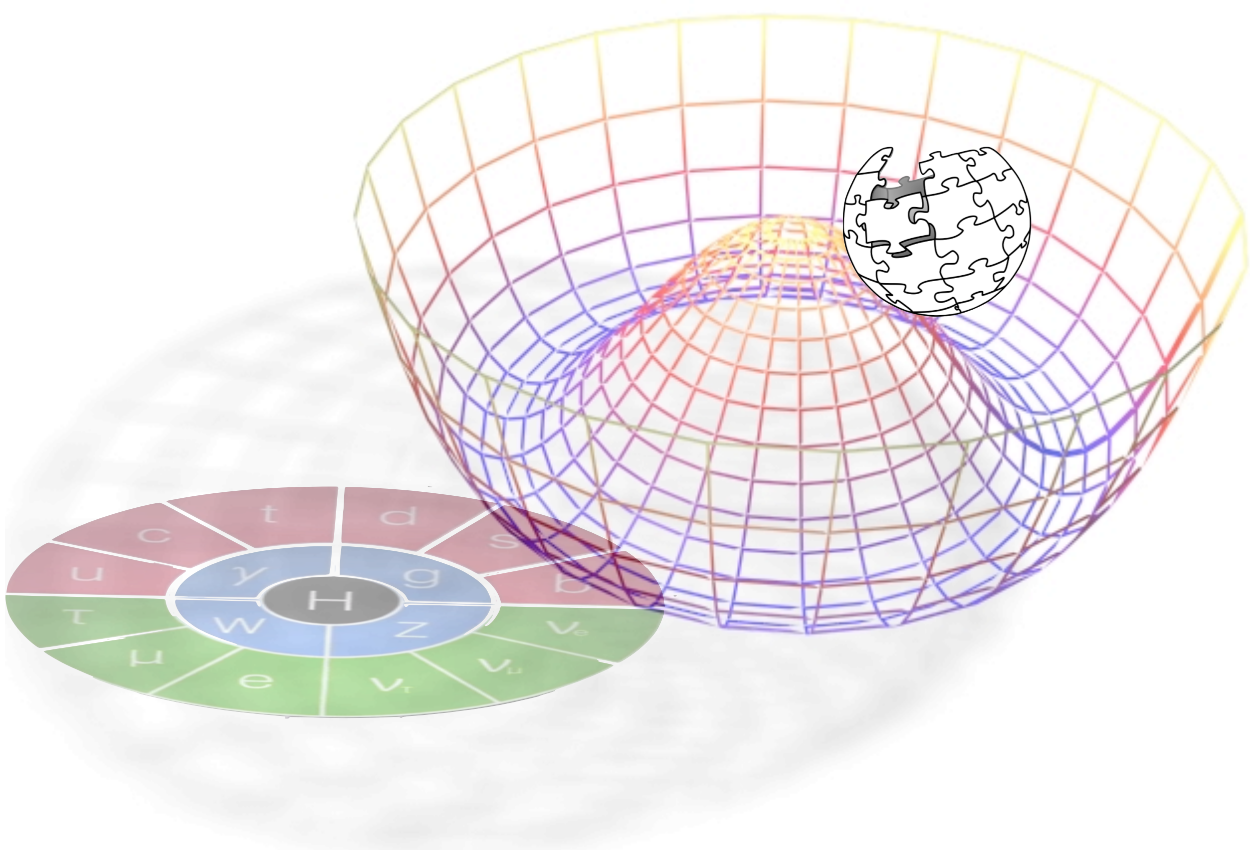
Higgs Synergies/ Complementarities

Berlin, May 30, 2017
" FCC week"



Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)
(christophe.grojean@desy.de)

The Higgs in the (B)SM landscape

The fundamental principles governing the structure of **Higgs sector** are yet unknown
(many arbitrary parameters taking seemingly un-natural values)
The Higgs plays a vital role in our life
(masses, stability of vacuum, DM?, inflation?)
It has an intimate link with the high energy completion of the SM

The Higgs in the (B)SM landscape

The fundamental principles governing the structure of **Higgs sector** are yet unknown
(many arbitrary parameters taking seemingly un-natural values)
The Higgs plays a vital role in our life
(masses, stability of vacuum, DM?, inflation?)
It has an intimate link with the high energy completion of the SM

The Higgs discovery has been an important milestone
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{g^2\, v^2}{\Lambda^2_{\rm BSM}}$

current (and future) LHC sensitivity O(10-20)% ⇔ $\Lambda_{\rm BSM}$ > 500-700 GeV

not doing better than direct searches
(except maybe for flavor violating processes, e.g. h→$\mu\tau$)

The Higgs in the (B)SM landscape

The fundamental principles governing the structure of **Higgs sector** are yet unknown
(many arbitrary parameters taking seemingly un-natural values)
The Higgs plays a vital role in our life
(masses, stability of vacuum, DM?, inflation?)
It has an intimate link with the high energy completion of the SM

The Higgs discovery has been an important milestone
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $\frac{\delta g_h}{g_h} \sim \frac{g^2 \, v^2}{\Lambda^2_{\rm BSM}}$

current (and future) LHC sensitivity O(10-20)% ⇔ $\Lambda_{\rm BSM}$ > 500-700 GeV

not doing better than direct searches
(except maybe for flavor violating processes, e.g. h→$\mu\tau$)

Higgs precision programme is very much wanted
complementary and synergetic measurements are essential to achieve this goal

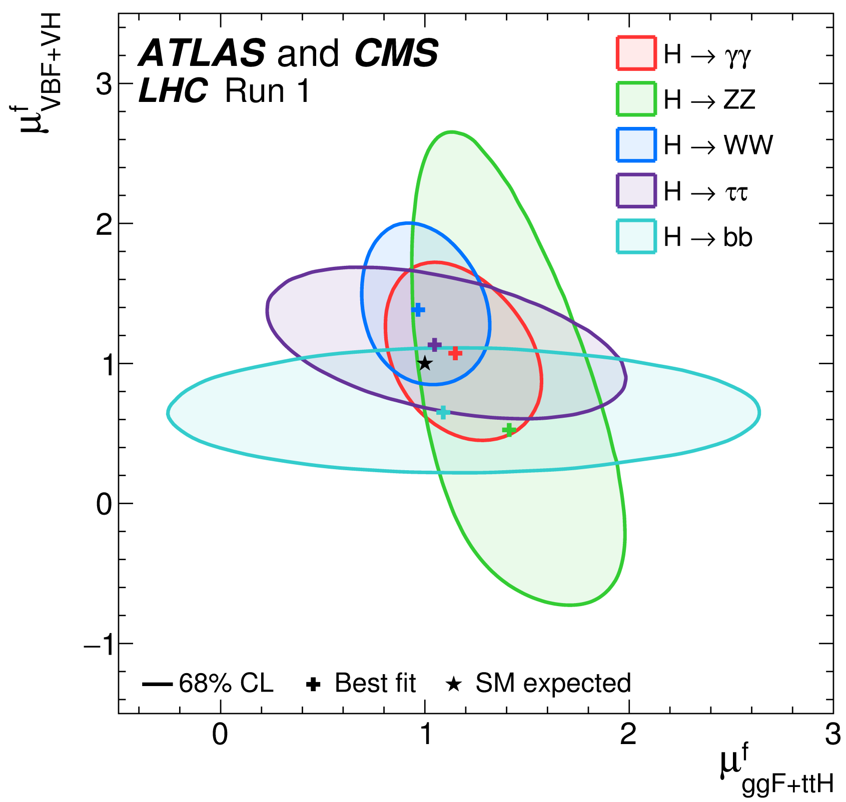
Higgs precision: from κ to EFT

LHCHXSWG '12

Higgs precision: from κ to EFT

LHCHXSWG '12

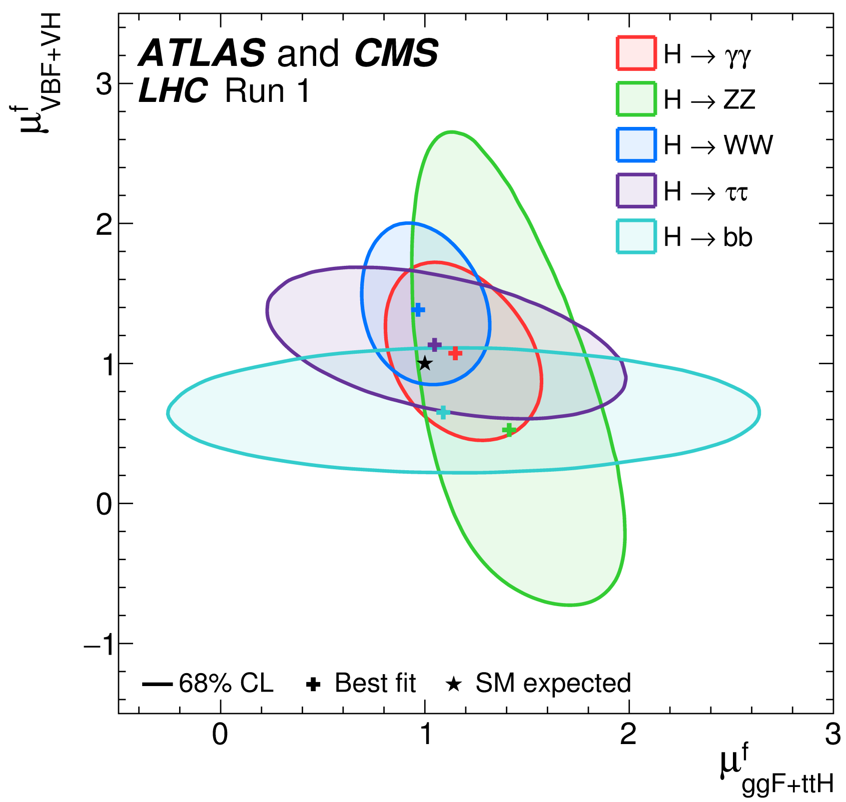
$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$

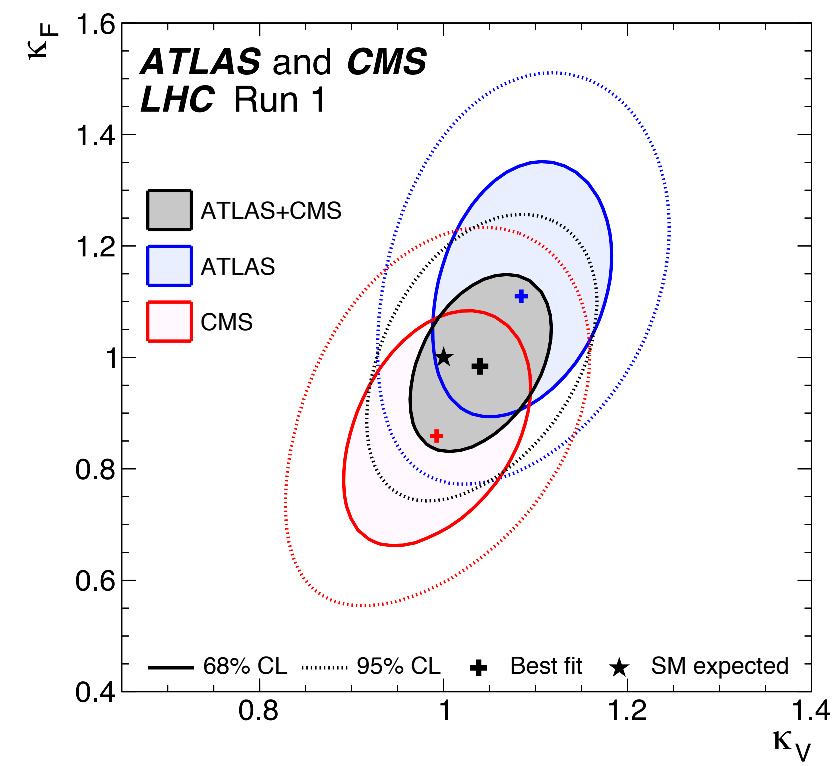


Higgs precision: from κ to EFT

LHCHXSWG '12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$





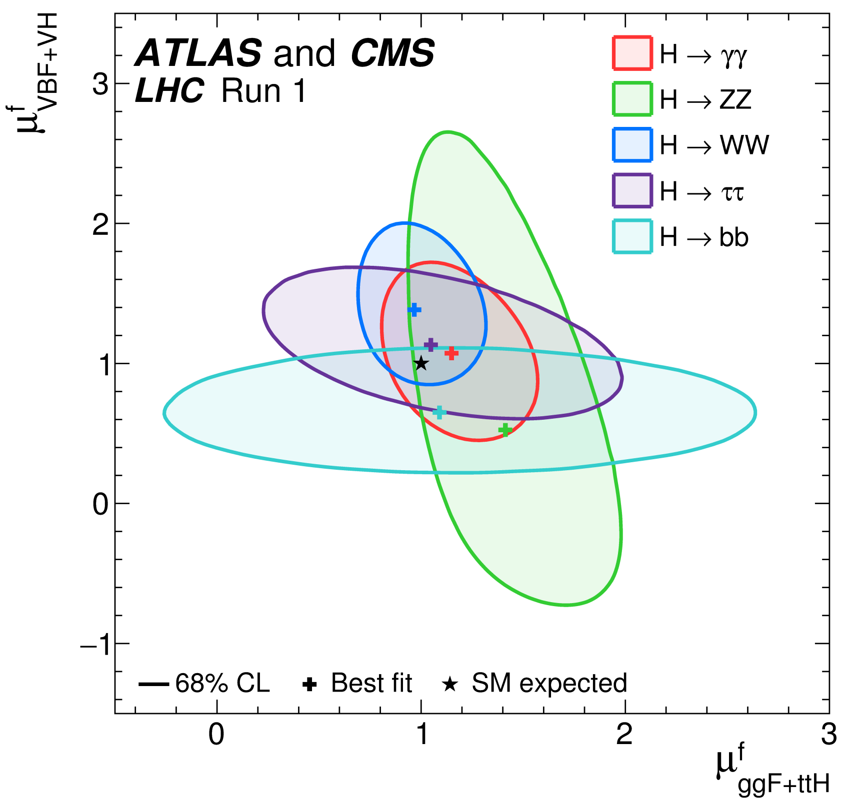
$$(\sigma \cdot {\rm BR})\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{\rm SM}(gg \to H) \cdot {\rm BR}_{\rm SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

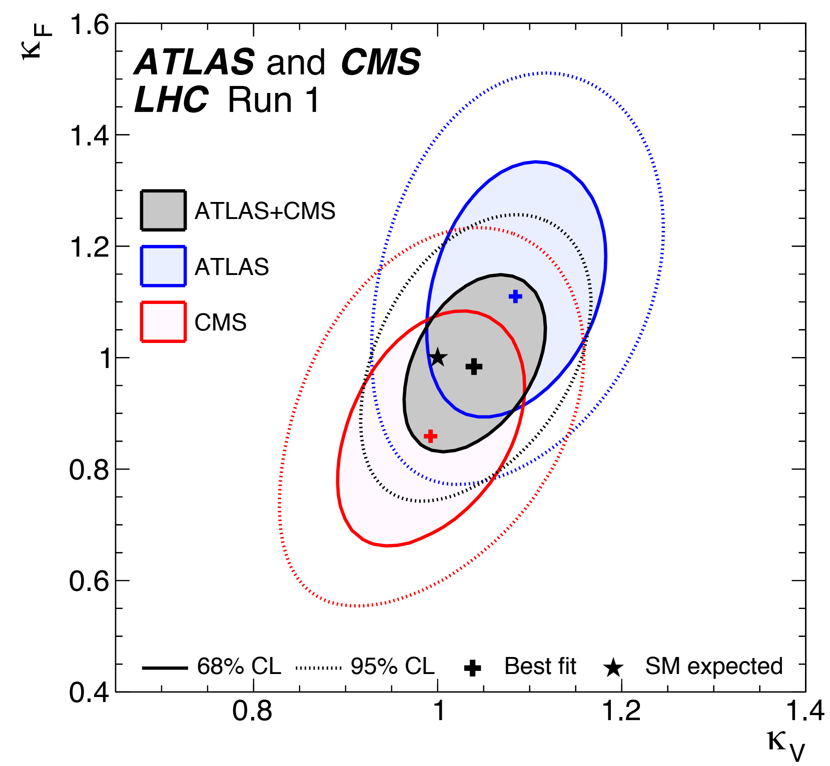
individual coupling rescaling factors

Higgs precision: from κ to EFT

LHCHXSWG '12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$





$$(\sigma \cdot {\rm BR})\,(gg \to H \to \gamma\gamma) = \sigma_{\rm SM}(gg \to H) \cdot {\rm BR}_{\rm SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

individual coupling rescaling factors

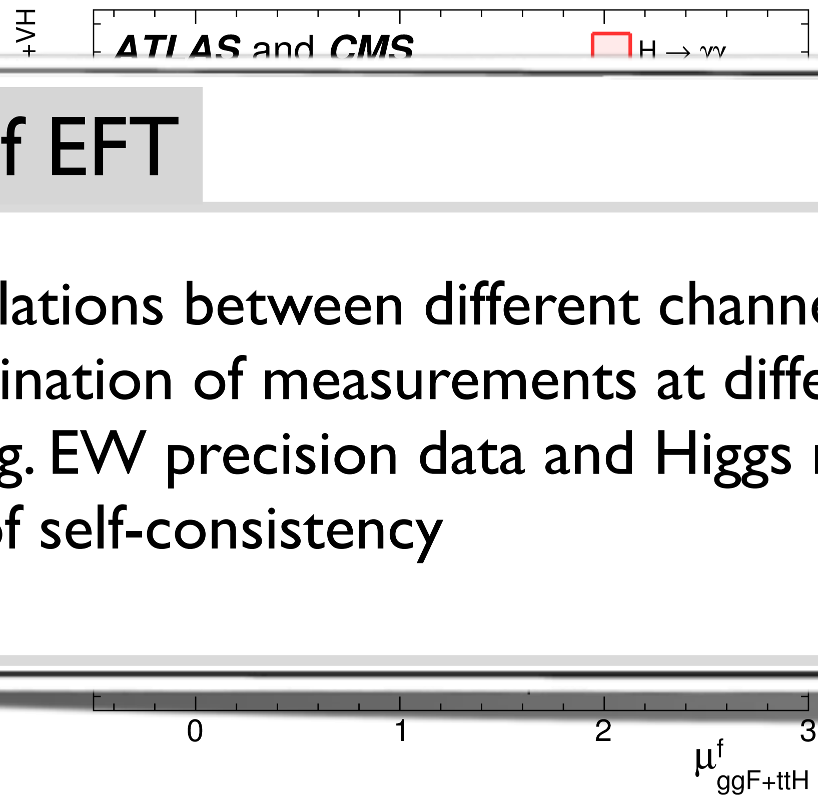
Well suited parametrization for inclusive measurements

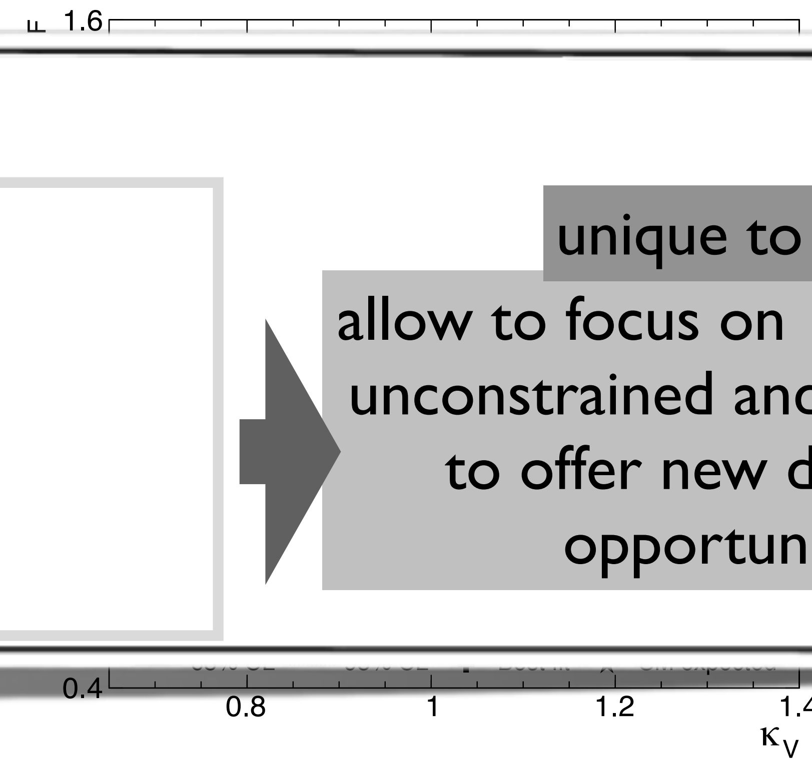
But doesn't do justice to wealth of information available (in particular at e^+e^- colliders)

Higgs precision: from κ to EFT

LHCHXSWG '12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$





Pros of EFT

- correlations between different channels/observables
- combination of measurements at different energies
  e.g. EW precision data and Higgs measurements
- test of self-consistency

unique to EFT

allow to focus on channels yet unconstrained and more likely to offer new discovery opportunities

$$(\sigma \cdot {\rm BR})\,({\rm gg} \to {\rm H} \to \gamma\gamma) \;=\; \sigma_{\rm SM}({\rm gg} \to {\rm H}) \cdot {\rm BR}_{\rm SM}({\rm H} \to \gamma\gamma) \cdot \frac{\kappa_{\rm g}^2 \cdot \kappa_\gamma^2}{\kappa_{\rm H}^2}$$

individual coupling rescaling factors

Well suited parametrization for inclusive measurements

But doesn't do justice to wealth of information available (in particular at e^+e^- colliders)

Higgs synergy/complementarity

"$(A \cup B) > A+B$"

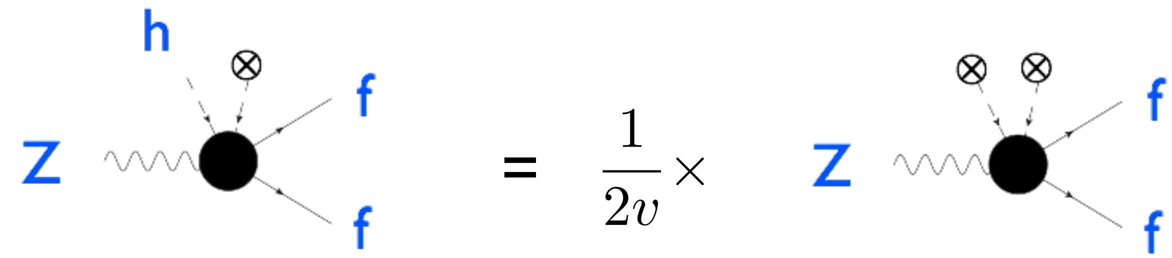
Higgs synergy/complementarity

"($A \cup B$) > A+B"

1. (SM input parameter determination to control parametric uncertainties)
2. EW precision to achieve precision in Higgs measurements
3. Diboson data and Higgs data
4. LHC and FCC-ee for top Yukawa measurement
5. Distributions complementing rate measurements
6. 240 + 350 runs
7. ee/ep/pp (...PDF measurements to control PDF uncertainties in Higgs data)

EW + Higgs

I Reducing numbers of parameters



$H^\dagger D_\mu H \bar{f}\gamma^\mu f$

Modifications in h→Zff related to Z→ff

EW + Higgs

1 **Reducing numbers of parameters**

2 **Exploring different regions of parameter space** (in specific models)

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}_{\mathrm{BSM}}^{d=6} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

EW + Higgs

1. **Reducing numbers of parameters**

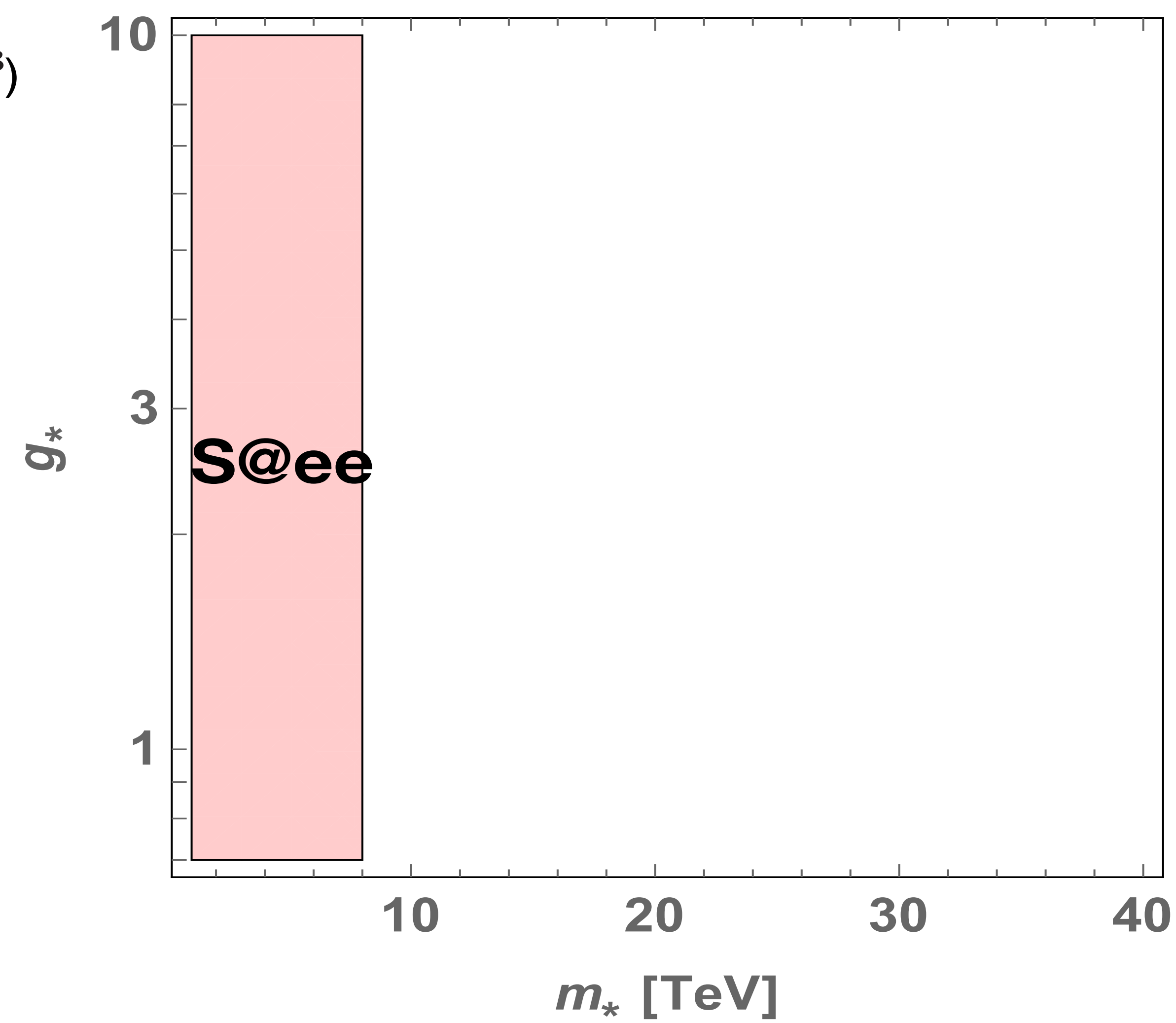
2. **Exploring different regions of parameter space** (in specific models)

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$



Grojean-Wulzer @ FCC physics week '17

EW + Higgs

1. **Reducing numbers of parameters**
2. **Exploring different regions of parameter space** (in specific models)

Assuming **composite** Higgs, **elementary** gauge bos.:

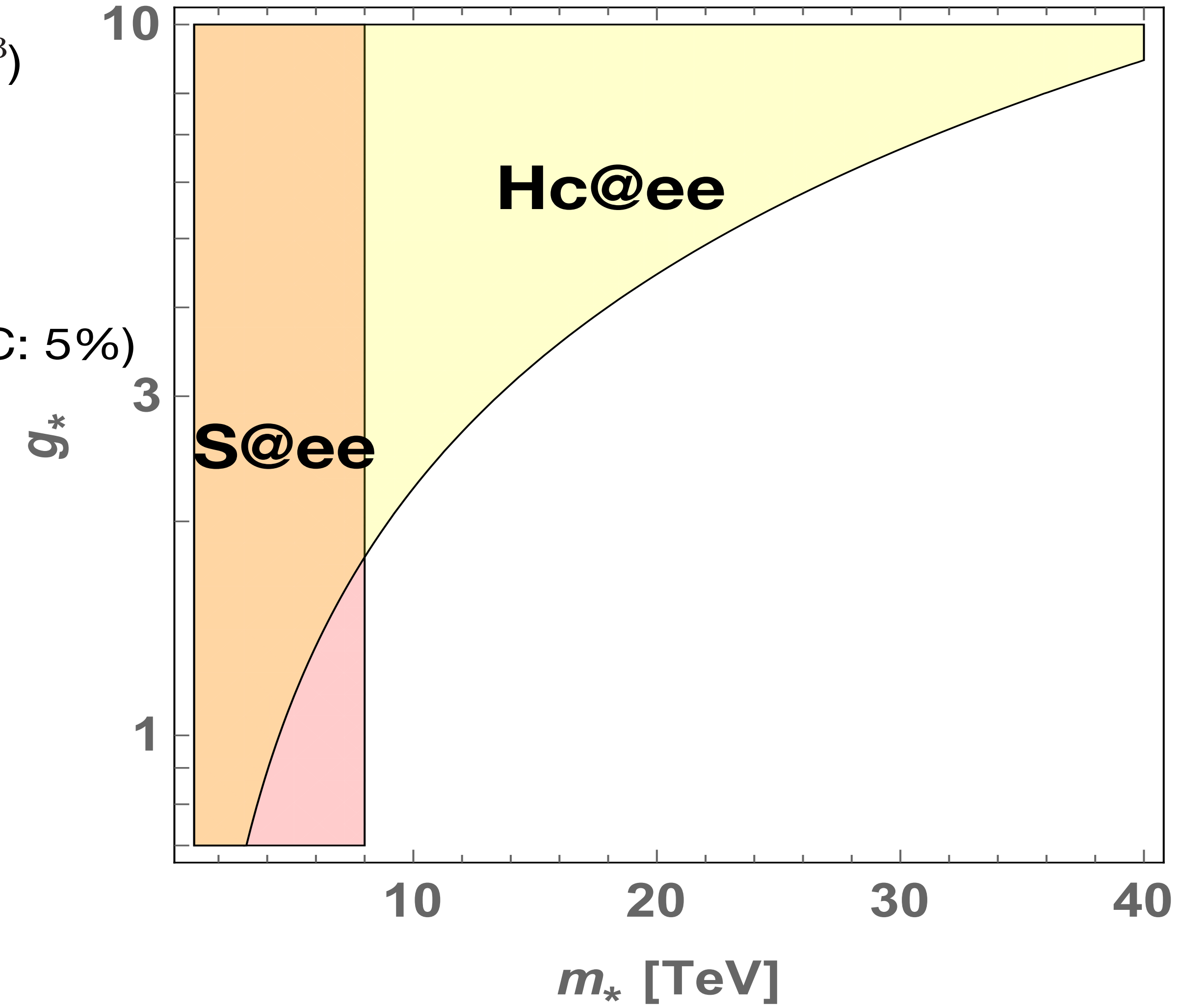
$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \;\Rightarrow\; \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \;\Rightarrow\; \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$



Grojean-Wulzer @ FCC physics week '17

EW + Higgs

1. **Reducing numbers of parameters**
2. **Exploring different regions of parameter space** (in specific models)

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

S-parameter @ee: [De Blas et. al.] (LEP: 10^{-3})

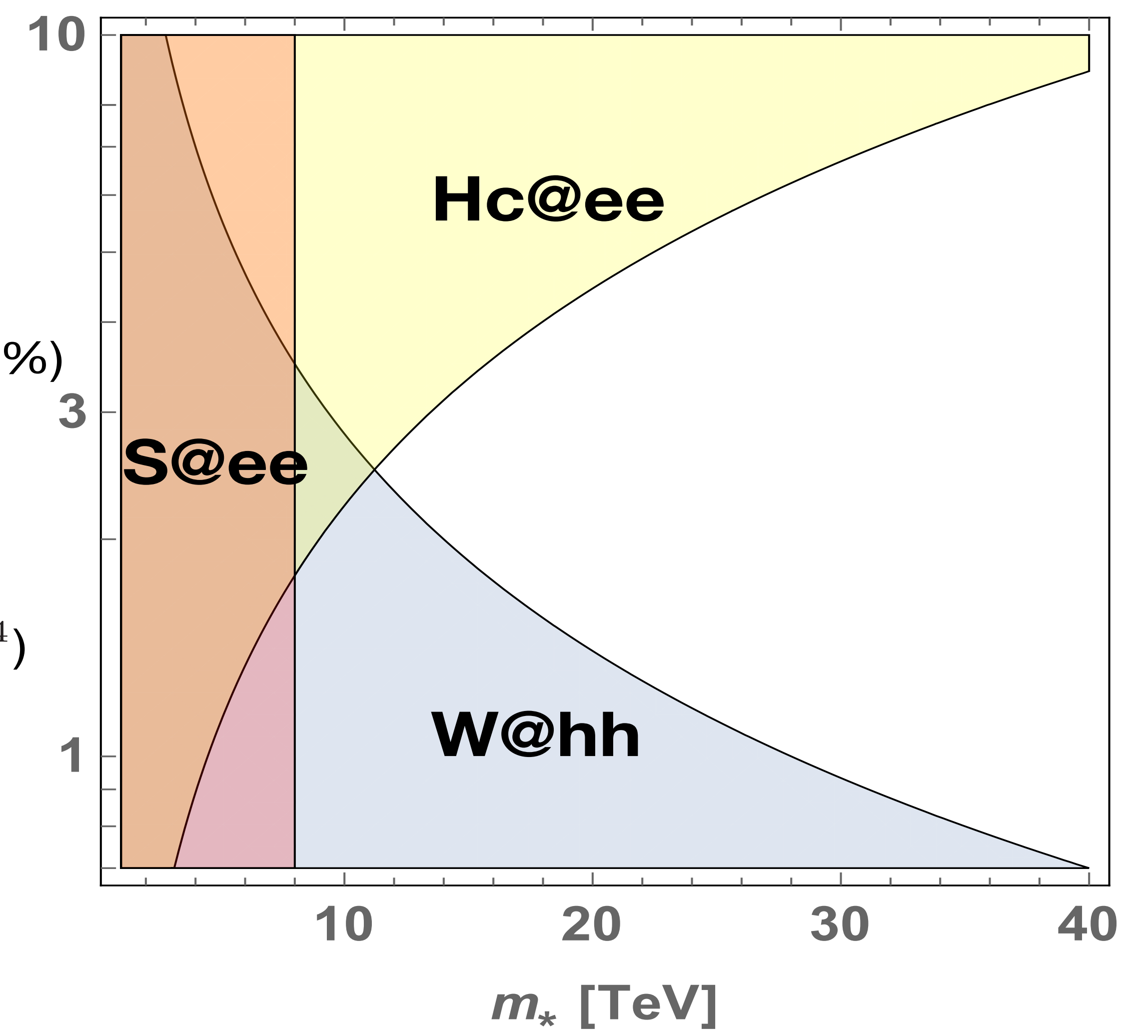
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \quad \Rightarrow \quad \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \quad \Rightarrow \quad \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$

W @hh: (energy + accuracy) (HL-LHC$<10^{-4}$)

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \quad \Rightarrow \quad W = \frac{g_w^2 m_w^2}{g_*^2 m_*^2} < 4\,10^{-6}$$



Grojean-Wulzer @ FCC physics week '17

Gauge bosons + Higgs

In $\mathrm{EFT}_{(\text{dim-6})}$

8 deformations affecting Higgs physics alone

2 deformations affecting Higgs and diboson data

TGC (1%) are a priori more

constraining than Higgs (10%)

Is there any value in doing a global fit?

Gauge bosons + Higgs

In EFT$_{(dim-6)}$

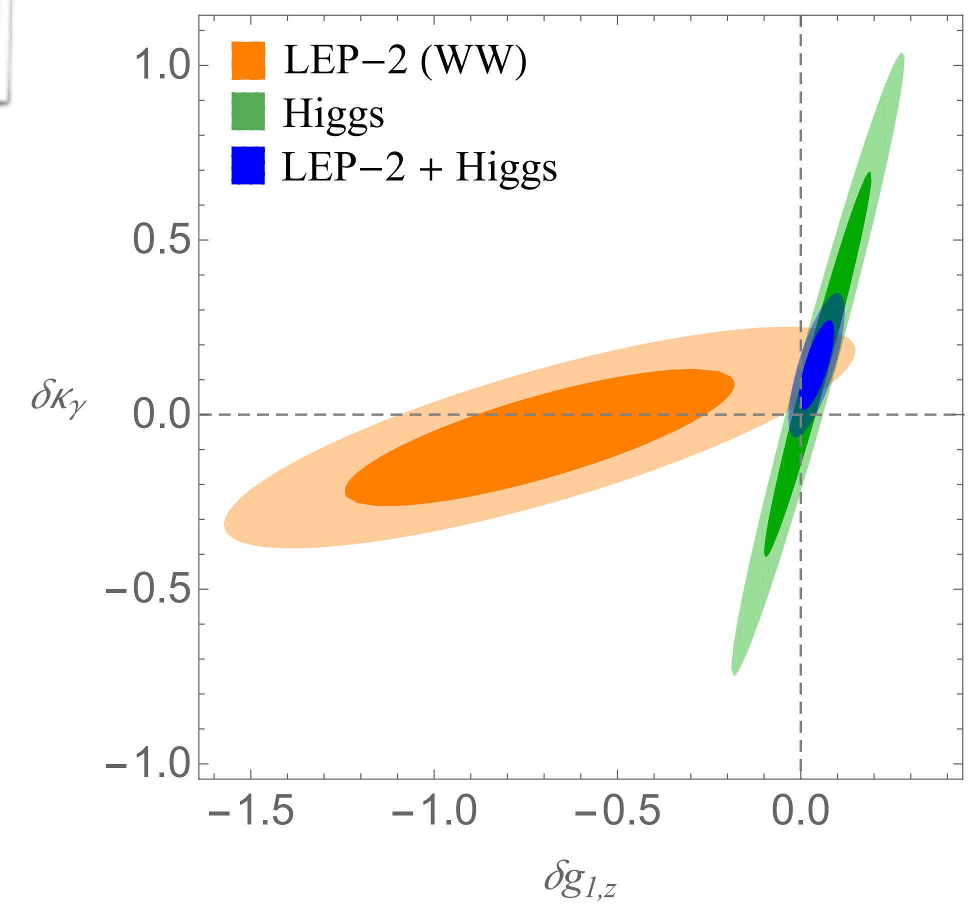
8 deformations affecting Higgs physics alone

2 deformations affecting Higgs and diboson data

TGC (1%) are a priori more constraining than Higgs (10%)

Is there any value in doing a global fit?

Falkowski et al '15



(TGC ∪ Higgs) > (TGC) + (Higgs)

Strong correlations between 2 data sets

Gauge bosons + Higgs

In EFT$_{\text{(dim-6)}}$

8 deformations affecting Higgs physics alone

2 deformations affecting Higgs and diboson data

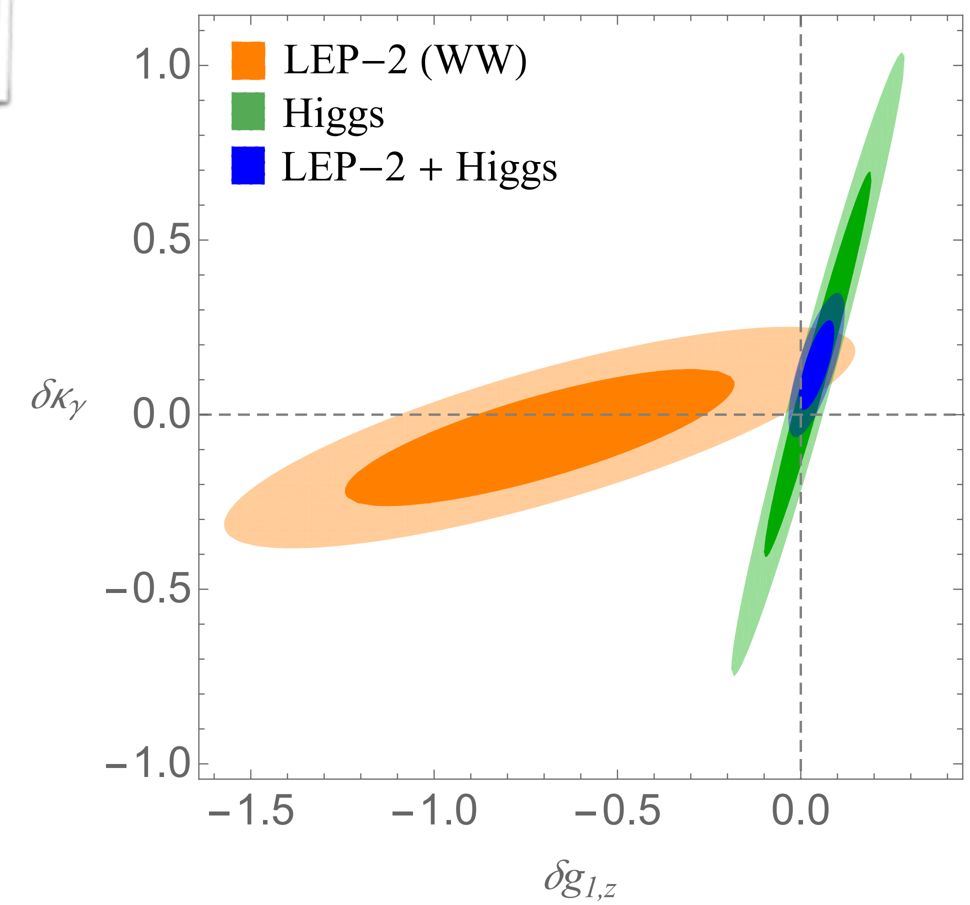
TGC (1%) are a priori more constraining than Higgs (10%)

Is there any value in doing a global fit?

Impact of LHC WW data?

Impact of FCC-ee$_{350\text{GeV}}$ WW data?

Falkowski et al '15

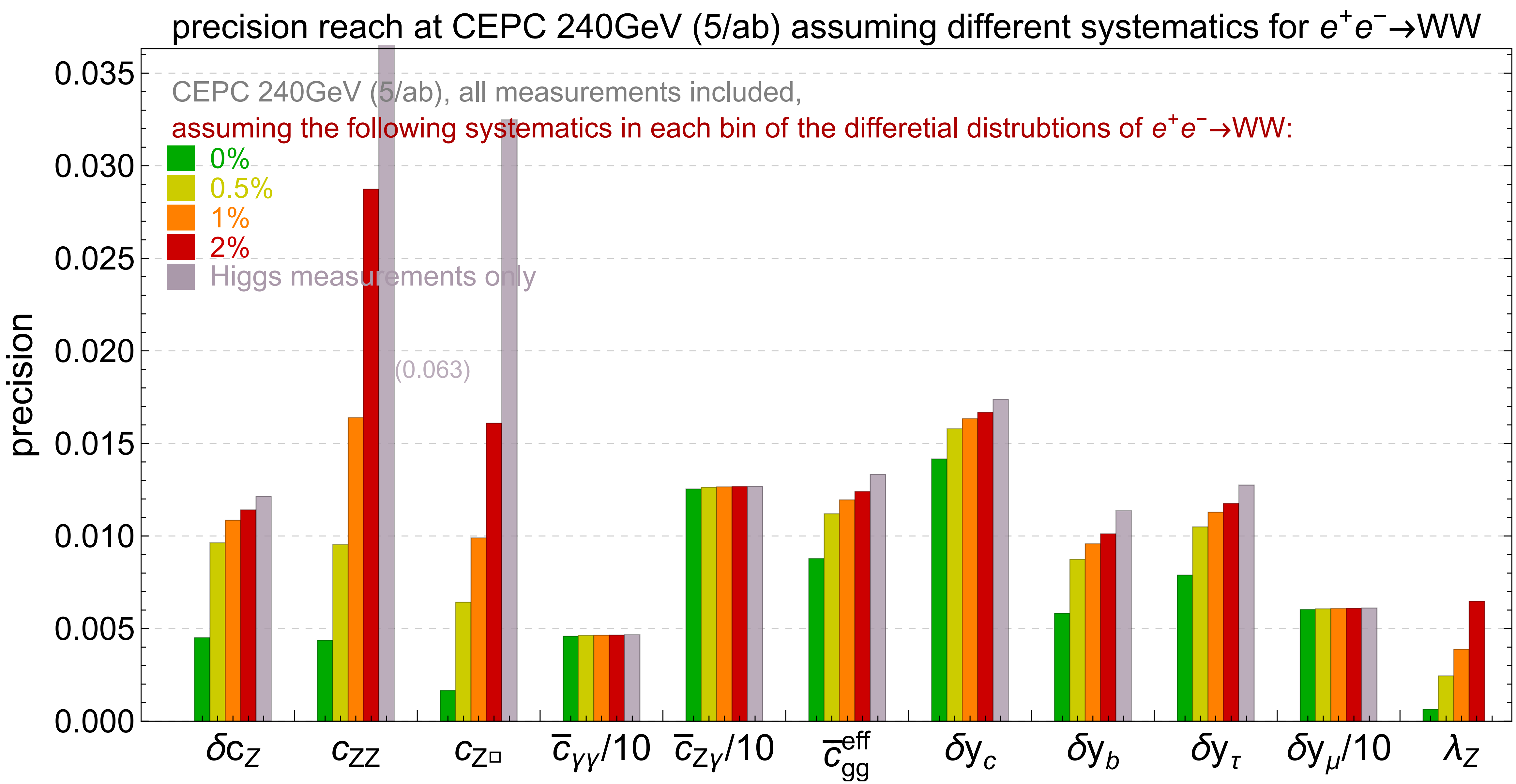


(TGC ∪ Higgs) > (TGC) + (Higgs)

Strong correlations between 2 data sets

Gauge bosons + Higgs

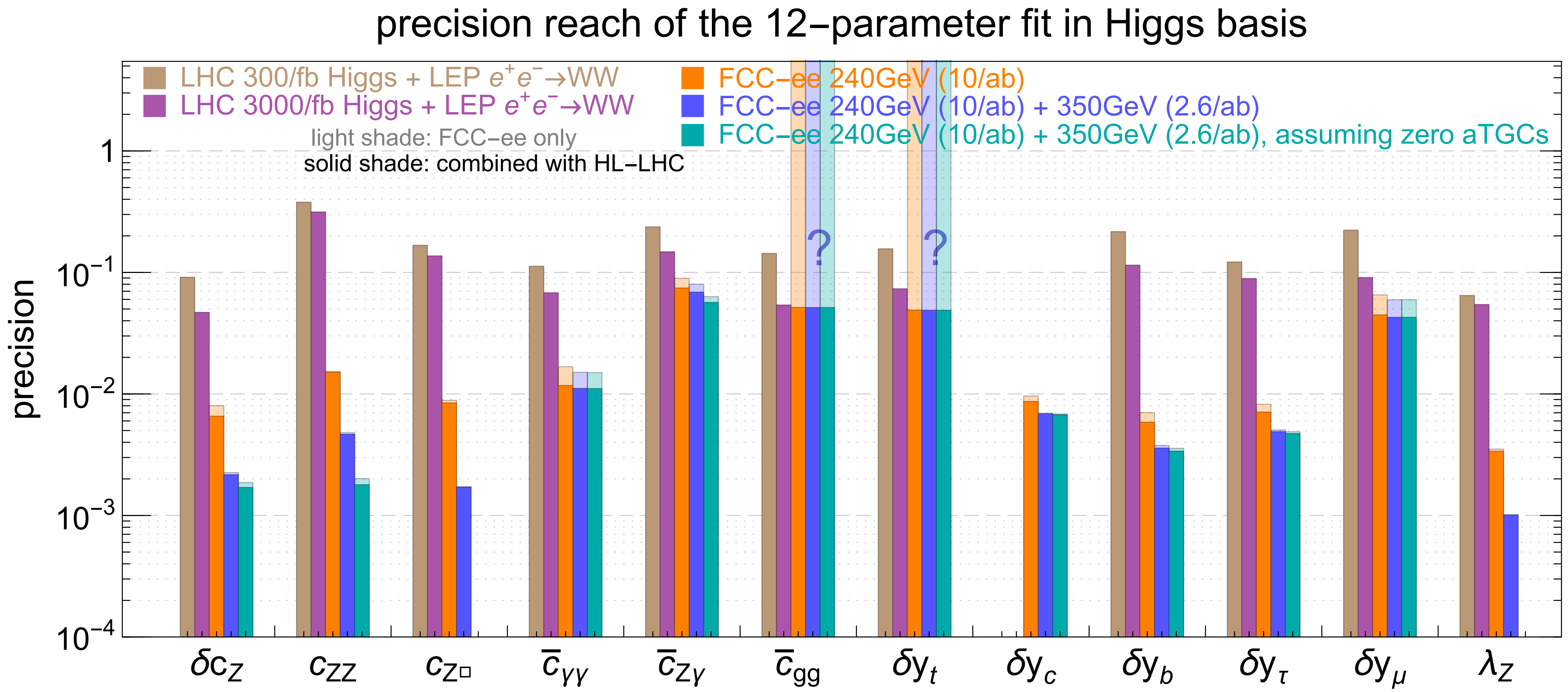
In EFT$_{(\text{dim-6})}$



Durieux, Grojean, Gu, Wang '17

Top + Higgs

I low energy ee collider doesn't have access to top Yukawa



Durieux, Grojean, Gu, Wang '17

Top + Higgs

1. **low energy ee collider doesn't have access to top Yukawa**

2. **Exploring different regions of parameter space** (in specific models)

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

Top + Higgs

1. **low energy ee collider doesn't have access to top Yukawa**

2. **Exploring different regions of parameter space** (in specific models)

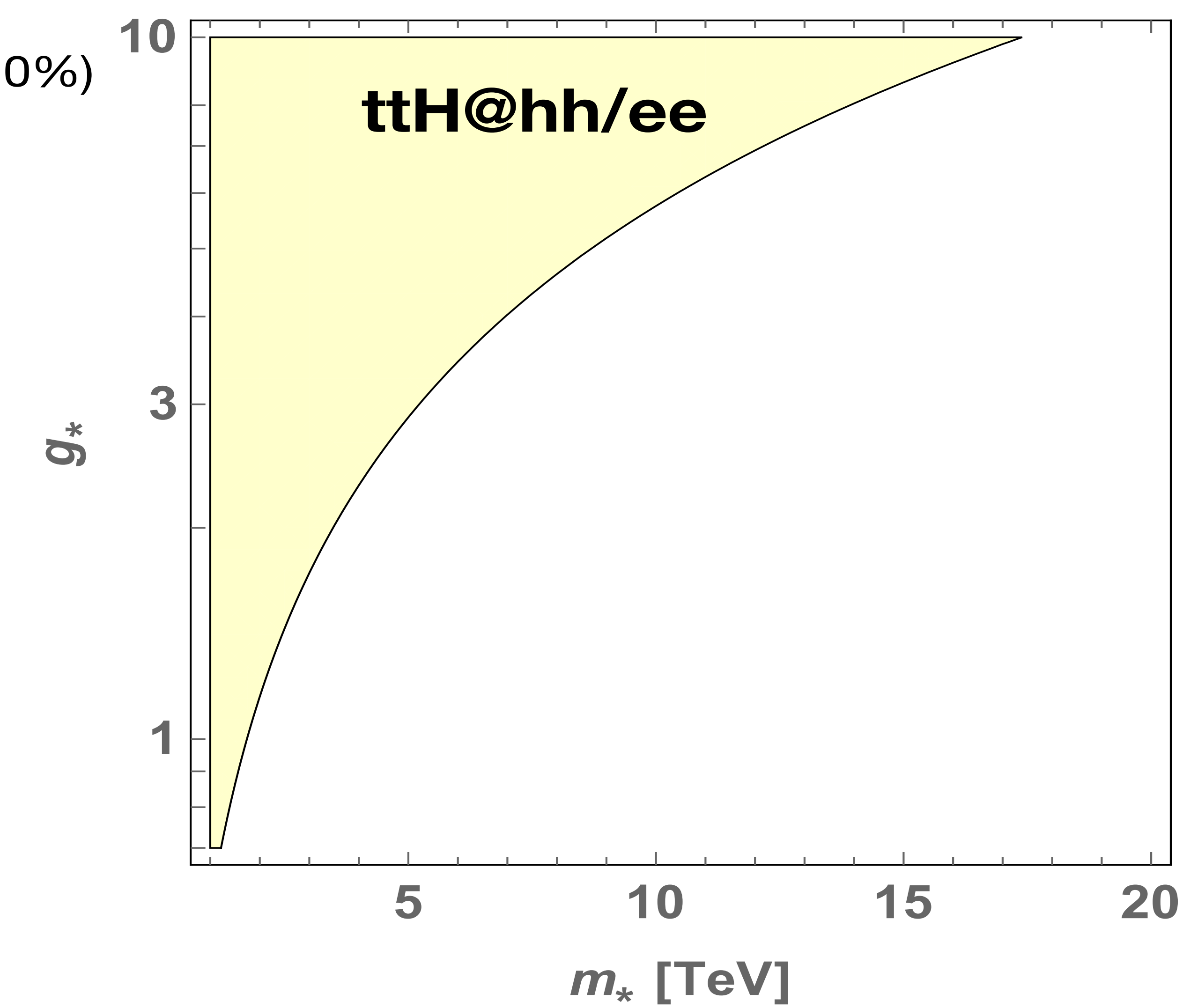
Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \overline{q}_L H t_R \quad \Rightarrow \quad \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!



Grojean-Wulzer @ FCC physics week '17

Top + Higgs

1. **low energy ee collider doesn't have access to top Yukawa**

2. **Exploring different regions of parameter space** (in specific models)

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

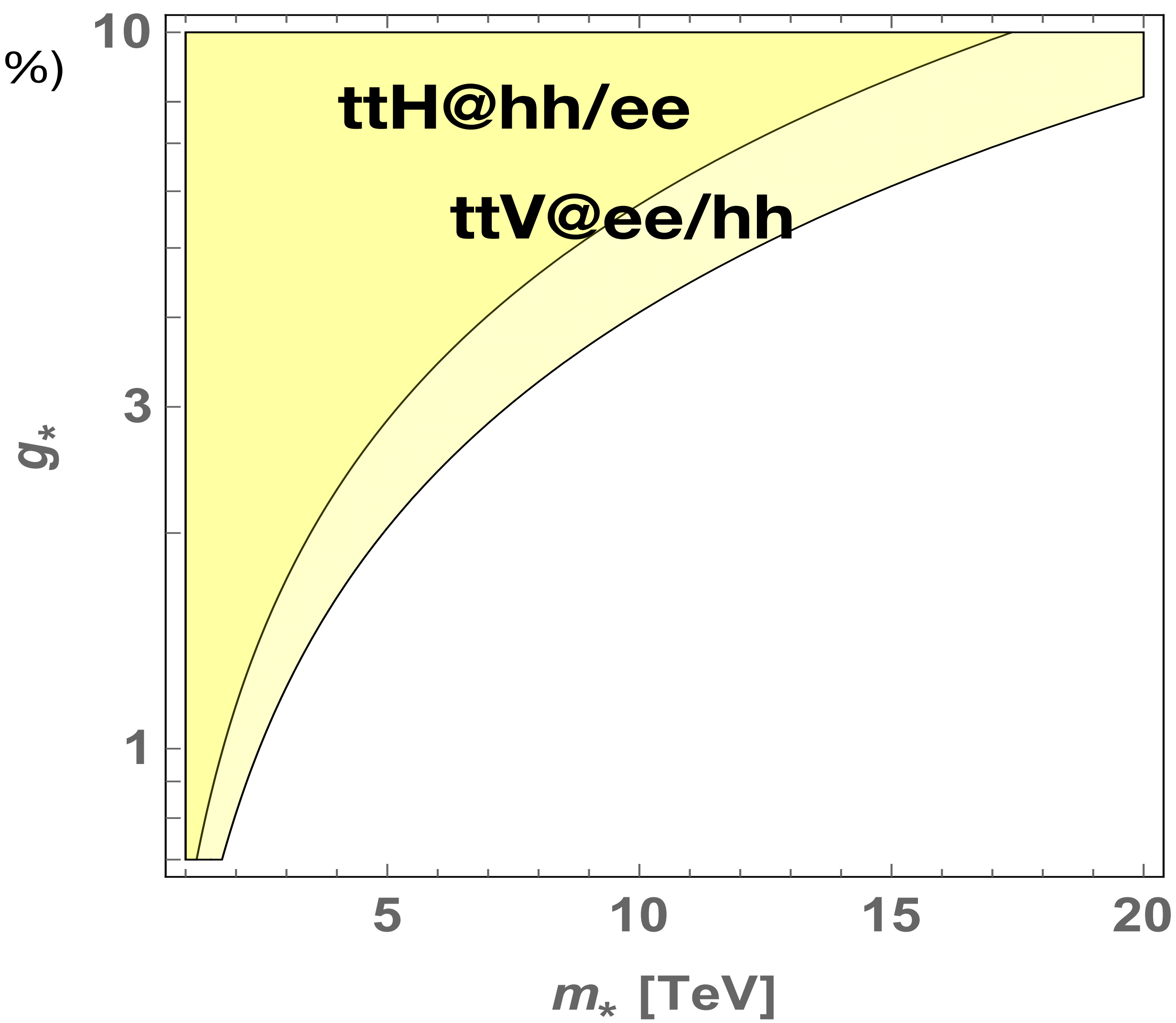
$$\frac{y_t g_*^2}{m_*^2}|H|^2\bar{q}_L H t_R \;\Rightarrow\; \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{t}_R \gamma^\mu t_R \;\Rightarrow\; \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?



Grojean-Wulzer @ FCC physics week '17

Top + Higgs

1. **low energy ee collider doesn't have access to top Yukawa**

2. **Exploring different regions of parameter space** (in specific models)

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \overline{q}_L H t_R \Rightarrow \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

ttV coupling @ee/hh: [Janot / Farina et.al.]

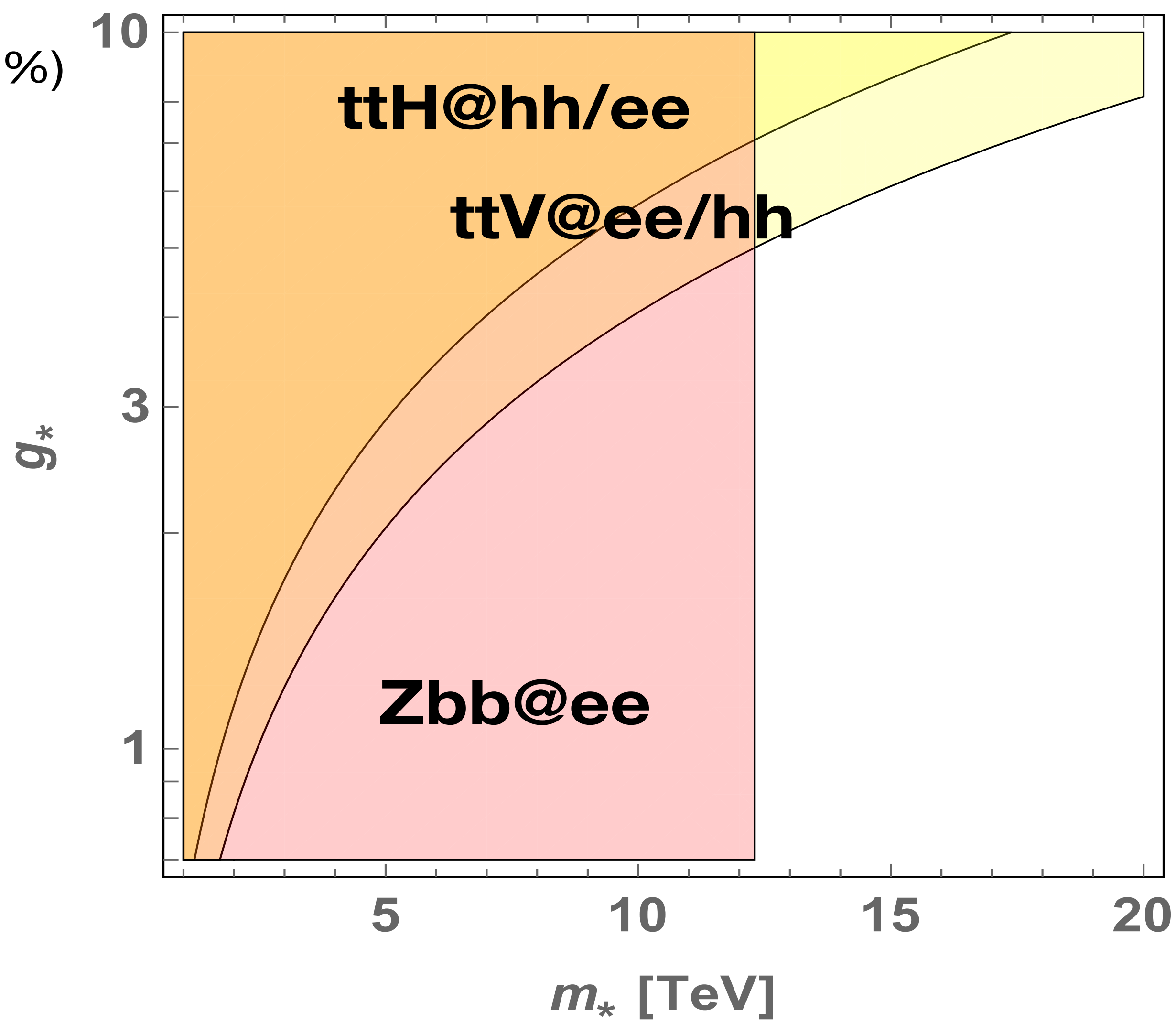
$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{t}_R \gamma^\mu t_R \Rightarrow \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?

Zbb coupling @ee: [ee Report] (LEP: 10^{-3})

$$\frac{y_t^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \overline{q}_L \gamma^\mu q_L + .. \Rightarrow \frac{\delta g_b}{g_b} = \frac{m_t^2}{m_*^2} < 2\,10^{-4}$$

Grojean-Wulzer @ FCC physics week '17



Top + Higgs

1. **low energy ee collider doesn't have access to top Yukawa**

2. **Exploring different regions of parameter space** (in specific models)

Composite tR, comp. Higgs, **elementary tL** and gauge

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

ttH coupling @hh/ee: [Reports] (HL-LHC:10%)

$$\frac{y_t g_*^2}{m_*^2}|H|^2 \bar{q}_L H t_R \;\Rightarrow\; \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

Diff. oper.s comb. in ee and hh!!

4-top contact interactions @hh:

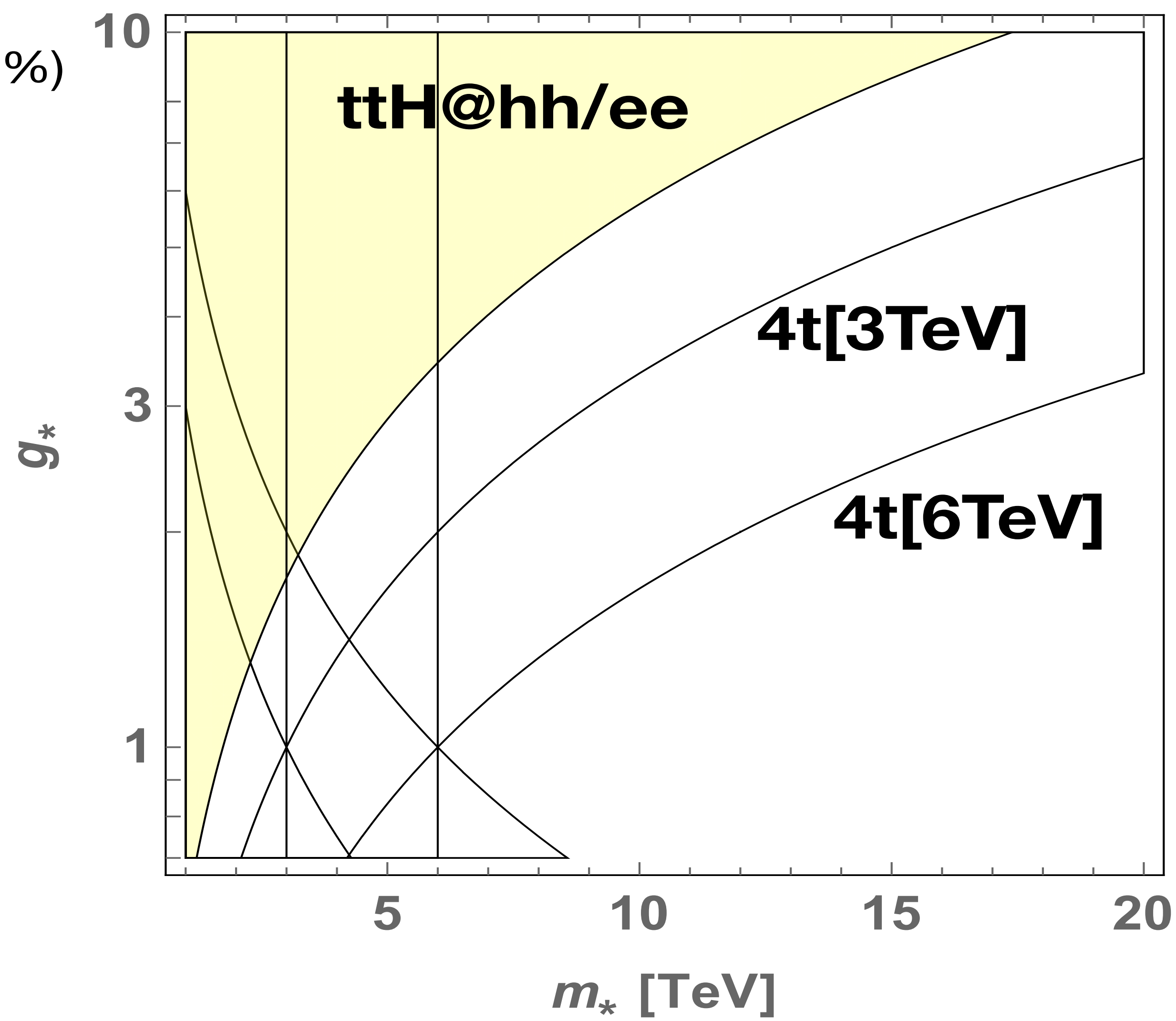
$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \;\Rightarrow\; \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \;\Rightarrow\; \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^4}{g_*^2 m_*^2}(\bar{q}_L\gamma_\mu q_L)^2 \;\Rightarrow\; \frac{y_t^4}{g_*^2 m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

No study available (?)

Grojean-Wulzer @ FCC physics week '17



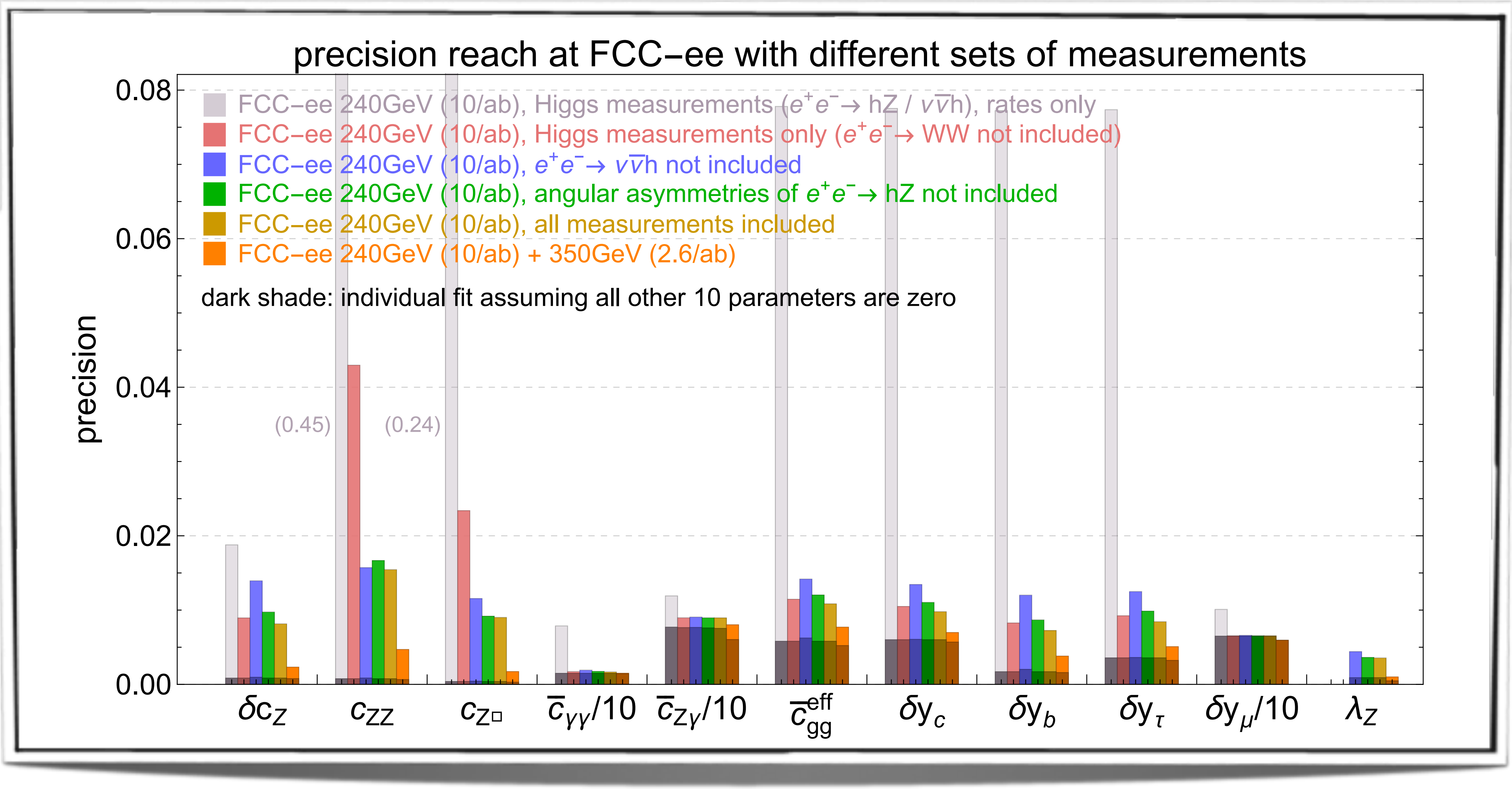
Distributions + rates

☾

in progress

240 + 350

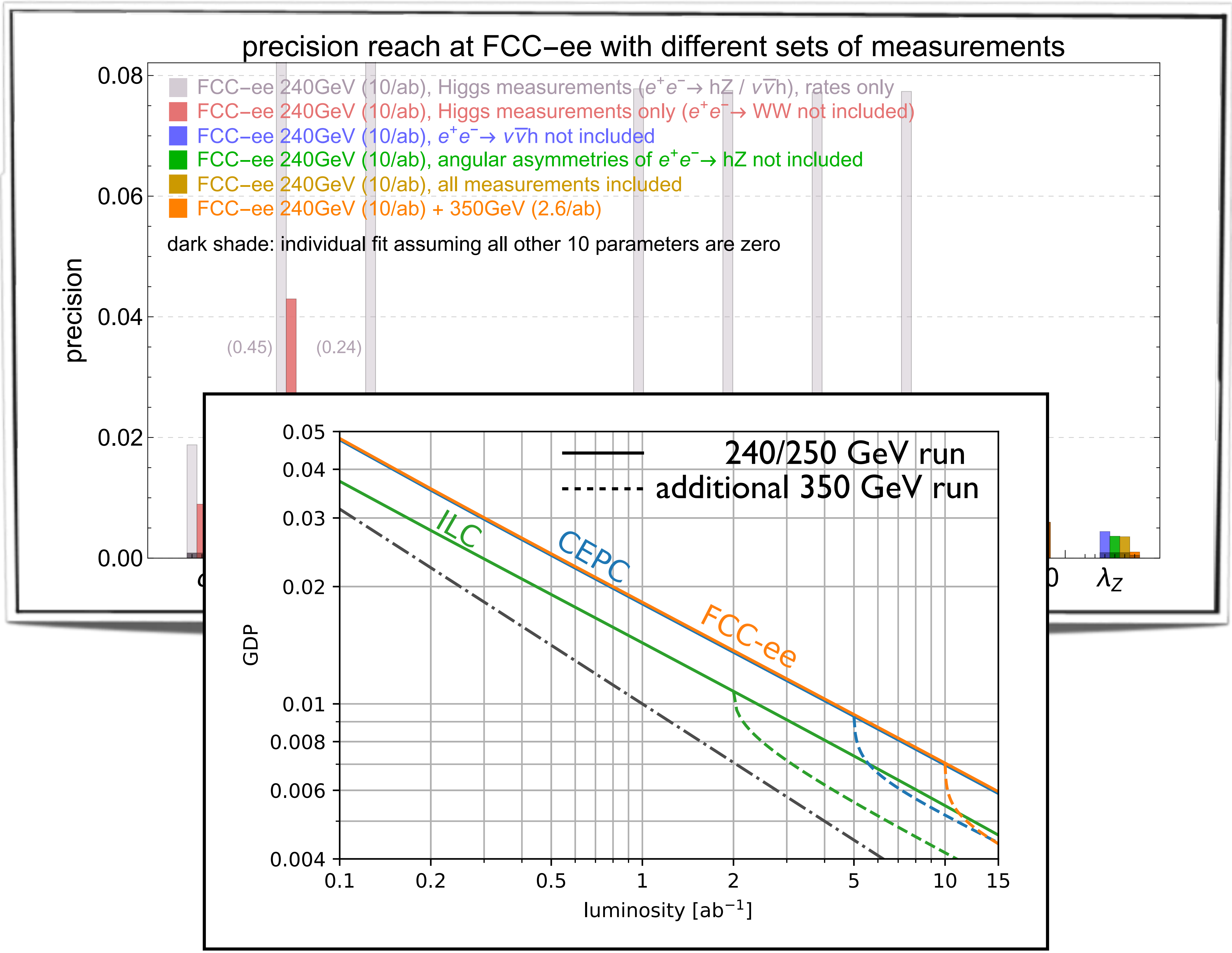
Runs at different energies break degeneracies plaguing coupling fits at 240GeV alone



Durieux, Grojean, Gu, Wang '17

240 + 350

Runs at different energies break degeneracies plaguing coupling fits at 240GeV alone



Higgs self-coupling(s)

in progress

Backup

e^+e^- Colliders

CepC

5/ab @ 240GeV
(200/fb @ 350GeV)

FCC-ee

10/ab @ 240GeV
(2.6/ab @ 350GeV)

ILC

2/ab @ 250GeV
$P(e^-,e^+)=(\pm 80\%,\pm 30\%)$
(200/fb @ 350GeV)
(4/ab @ 500GeV)

CLIC

0.5/ab @ 350GeV
(1.5/ab @ 1.4TeV)
(3/ab @ 3TeV)

	CEPC				FCC-ee			
	[240 GeV, 5 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[240 GeV, 10 ab^{-1}]		[350 GeV, 2.6 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	0.50%	-	2.4%	-	0.40%	-	0.67%	-
	$\sigma\times$ BR				$\sigma\times$ BR			
$h\to b\bar{b}$	0.21%*	0.39%$^\diamond$	2.0%	2.6%	0.20%	0.28%$^\diamond$	0.54%	0.71%
$h\to c\bar{c}$	2.5%	-	15%	26%	1.2%	-	4.1%	7.1%
$h\to gg$	1.2%	-	11%	17%	1.4%	-	3.1%	4.7%
$h\to\tau\tau$	1.0%	-	5.3%	37%	0.7%	-	1.5%	10%
$h\to WW^*$	1.0%	-	10%	9.8%	0.9%	-	2.8%	2.7%
$h\to ZZ^*$	4.3%	-	33%	33%	3.1%	-	9.2%	9.3%
$h\to\gamma\gamma$	9.0%	-	51%	77%	3.0%	-	14%	21%
$h\to\mu\mu$	12%	-	115%	275%	13%	-	32%	76%
$h\to Z\gamma$	25%	-	144%	-	18%	-	40%	-

ILC

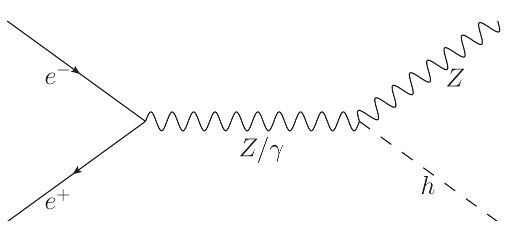
	[250 GeV, 2 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[500 GeV, 4 ab^{-1}]			[1 TeV, 1 ab^{-1}]		[1 TeV, 2.5 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$
σ	0.71%	-	2.1%	-	1.1%	-	-	-	-	-	-
	$\sigma\times$ BR										
$h\to b\bar{b}$	0.42%	3.7%	1.7%	1.7%	0.64%	0.25%	9.9%	0.5%	6.0%	0.3%	3.8%
$h\to c\bar{c}$	2.9%	-	13%	17%	4.6%	2.2%	-	3.1%	-	2.0%	-
$h\to gg$	2.5%	-	9.4%	11%	3.9%	1.4%	-	2.3%	-	1.4%	-
$h\to\tau\tau$	1.1%	-	4.5%	24%	1.9%	3.2%	-	1.6%	-	1.0%	-
$h\to WW^*$	2.3%	-	8.7%	6.4%	3.3%	0.85%	-	3.1%	-	2.0%	-
$h\to ZZ^*$	6.7%	-	28%	22%	8.8%	2.9%	-	4.1%	-	2.6%	-
$h\to\gamma\gamma$	12%	-	44%	50%	12%	6.7%	-	8.5%	-	5.4%	-
$h\to\mu\mu$	25%	-	98%	180%	31%	25%	-	31%	-	20%	-
$h\to Z\gamma$	34%	-	145%	-	49%	-	-	-	-	-	-

CLIC

	[350 GeV, 500 fb^{-1}]		[1.4 TeV, 1.5 ab^{-1}]		[3 TeV, 2 ab^{-1}]
production	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$
σ	1.6%	-	-	-	-
	$\sigma\times$ BR				
$h\to b\bar{b}$	0.84%	1.9%	0.4%	8.4%	0.3%
$h\to c\bar{c}$	10.3%	14.3%	6.1%	-	6.9%
$h\to gg$	4.5%	5.7%	5.0%	-	4.3%
$h\to\tau\tau$	6.2%	-	4.2%	-	4.4%
$h\to WW^*$	5.1%	-	1.0%	-	0.7%
$h\to ZZ^*$	-	-	5.6%	-	3.9%
$h\to\gamma\gamma$	-	-	15%	-	10%
$h\to\mu\mu$	-	-	38%	-	25%
$h\to Z\gamma$	-	-	42%	-	30%

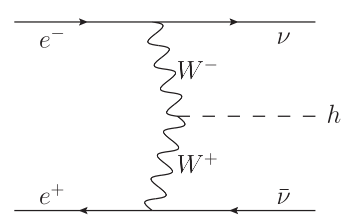
Future measurements used in the fit

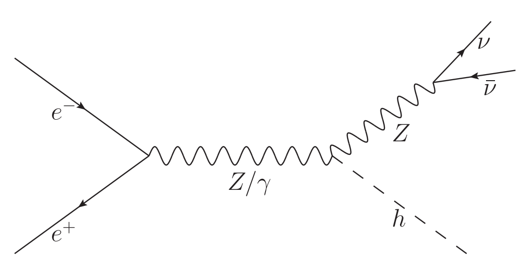
- Higgsstrahlung production: $e^+e^- \to hZ$ (rates and distributions), followed by Higgs decays in various channels,
- Higgs production through weak-boson-fusion: $e^+e^- \to \nu\bar{\nu}h$,
- Higgs production in association with top quarks: $e^+e^- \to t\bar{t}h$,
- weak boson pair production: $e^+e^- \to WW$ (rate and distributions).

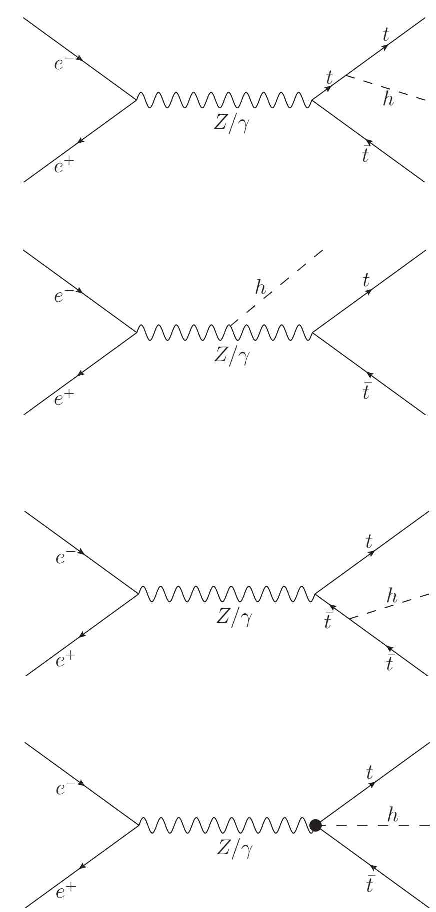


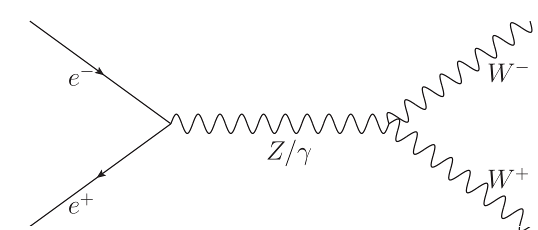
5/ab @ 240GeV
1.06×10^6 Higgses

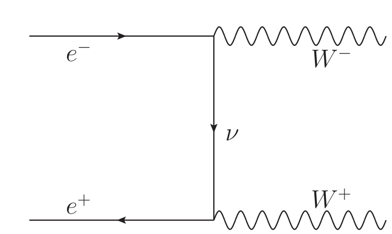
2/ab @ 250GeV
$P(e^-,e^+)=(-80\%,+30\%)$
6.4×10^5 Higgses











Higgs Basis

A. Falkowski '15

LHCHXSWG YR4 '16

$$\mathcal{L} \supset \frac{h}{v}\Big[\delta c_w \frac{g^2v^2}{2} W^+_\mu W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu$$

$$+ c_{ww}\frac{g^2}{2} W^+_{\mu\nu}W^{-\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu}$$

$$+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Big]$$

$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right]$$

$$- (\kappa_\lambda - 1)\lambda_3^{SM} v h^3 ,$$

with

$$\delta c_w = \delta c_z ,$$

$$c_{ww} = c_{zz} + 2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma} + \frac{g'^4}{\pi^2(g^2+g'^2)^2}\hat{c}_{\gamma\gamma} ,$$

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

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

$$\hat{c}^{(2)}_{gg} = \hat{c}_{gg} ,$$

$$\delta y_f^{(2)} = 3\delta y_f - \delta c_z .$$

10 parameters

6 deformations of Higgs couplings to gauge bosons

$$\delta c_z\,,\ c_{zz}\,,\ c_{z\Box}\,,\ \hat{c}_{z\gamma}\,,\ \hat{c}_{\gamma\gamma}\,,\ \hat{c}_{gg}$$

3 deformations of Higgs couplings to fermions

$$\delta y_t\,,\ \delta y_b\,,\ \delta y_\tau\,,$$

1 deformations of Higgs self-couplings

$$\kappa_\lambda$$

Higgs Basis

A. Falkowski '15

LHCHXSWG YR4 '16

$$\mathcal{L} \supset \frac{h}{v}\Big[\delta c_w \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu$$
$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W^{-\mu\nu} + c_{w\Box} g^2 \left(W_\mu^- \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu}$$
$$+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Big]$$
$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}_{gg}^{(2)}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right]$$
$$- (\kappa_\lambda - 1)\lambda_3^{SM} v h^3\,,$$

with

$$\delta c_w = \delta c_z\,,$$
$$c_{ww} = c_{zz} + 2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma} + \frac{g'^4}{\pi^2(g^2+g'^2)^2}\hat{c}_{\gamma\gamma}\,,$$
$$c_{w\Box} = \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{\gamma\gamma} - (g^2-g'^2)\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma}\right],$$
$$c_{\gamma\Box} = \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)\, c_{zz} - \frac{e^2}{\pi^2}\hat{c}_{\gamma\gamma} - \frac{g^2-g'^2}{\pi^2}\hat{c}_{z\gamma}\right],$$
$$\hat{c}_{gg}^{(2)} = \hat{c}_{gg}\,,$$
$$\delta y_f^{(2)} = 3\delta y_f - \delta c_z\,.$$

12 parameters

6 deformations of Higgs couplings to gauge bosons

$\delta c_z\,,\ c_{zz}\,,\ c_{z\Box}\,,\ \hat{c}_{z\gamma}\,,\ \hat{c}_{\gamma\gamma}\,,\ \hat{c}_{gg}$

5 deformations of Higgs couplings to fermions

$\delta y_t\,,\ \delta y_c\,,\ \delta y_b\,,\ \delta y_\tau\,,\ \delta y_\mu$

1 deformations of gauge boson self-couplings

λ_Z

Introducing the Global Determinant Parameter

Durieux, Grojean, Gu, Wang '17

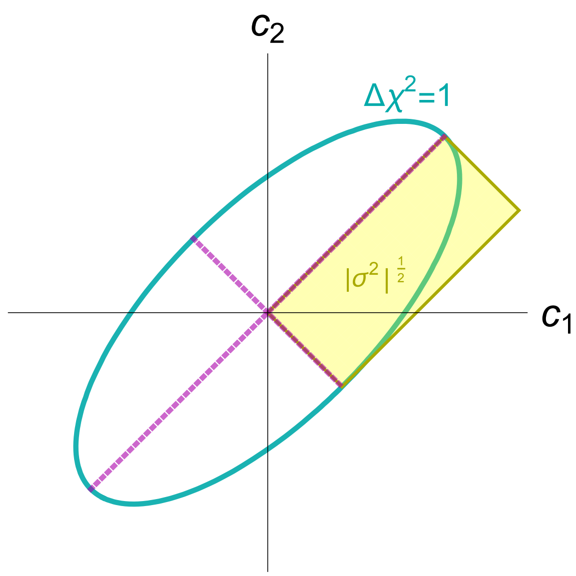


Figure 6: In a two-dimensional parameter space, the area of the Gaussian one-sigma ellipse is proportional to the square root of the determinant of the covariance matrix, $\sqrt{\det \sigma^2}$. In n dimensions, the nth root of this quantity or *global determinant parameter* (GDP) provides an average of constraints strengths. GDP $\equiv \sqrt[2n]{\det \sigma^2}$ ratios measure improvement in global constraint strengths independently of effective-field-theory operator basis.

ratios of GDP are independent of parameters normalization
ratios of GDP are independent of EFT operator basis

smaller GDP = better precision