EW + Higgs (+ top) Physics at the FCC

Christophe Grojean, **Andrea Wulzer**

Introduction

Particle Physics before LHC

Particle Physics before FCC

Introduction

Particle Physics before LHC

Particle Physics before FCC

Introduction

Particle Physics before LHC

Particle Physics before FCC

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories ***

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

Indirect Exploration

Measuring and comparing with SM predictions is a **systematic, BSM-independent exploration strategy**

Indirect Exploration

Measuring and comparing with SM predictions is a **systematic, BSM-independent exploration strategy**

Drawing implications from measurements however **requires BSM**, both if agree or disagree

Indirect Exploration

Measuring and comparing with SM predictions is a **systematic, BSM-independent exploration strategy**

Drawing implications from measurements however **requires BSM**, both if agree or disagree

BSM guidance essential to **assess complementary:**
BSM “maps” to guide ourselves in the FCC ocean

Indirect Exploration

Measuring and comparing with SM predictions is a **systematic, BSM-independent exploration strategy**

Drawing implications from measurements however **requires BSM**, both if agree or disagree

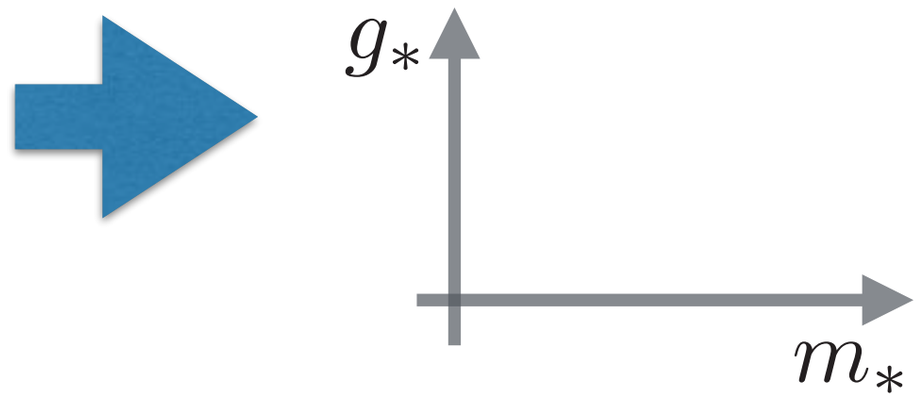
BSM guidance essential to **assess complementary: BSM "maps"** to guide ourselves in the FCC ocean

If N.P. is heavy, **EFT map:**

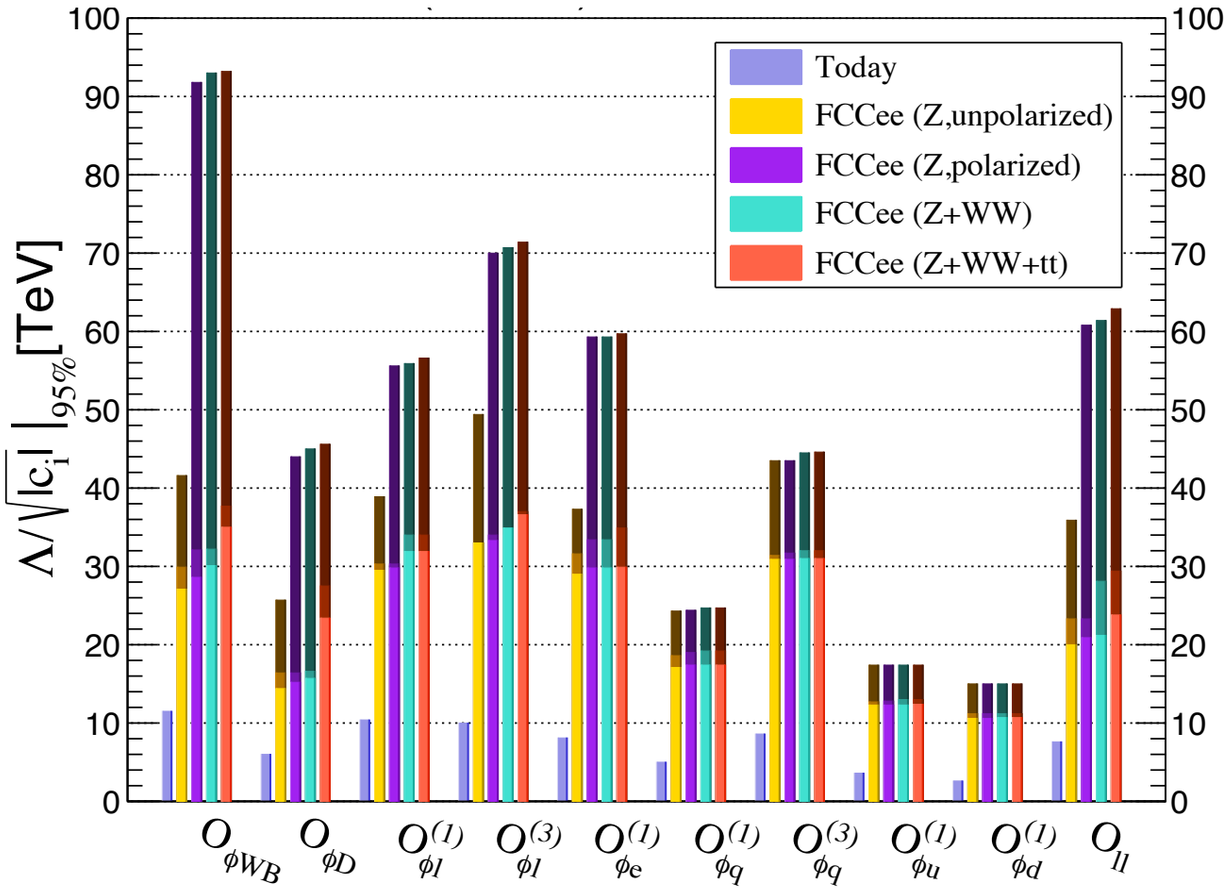
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}^{d=6}$$

operator estimate from structural BSM assumptions. **Different assumptions produce different maps**

N.P **mass:** m_*
N.P **coupling:** g_*



“Λ” ≠ new physics scale ! ; Λ = interaction scale !

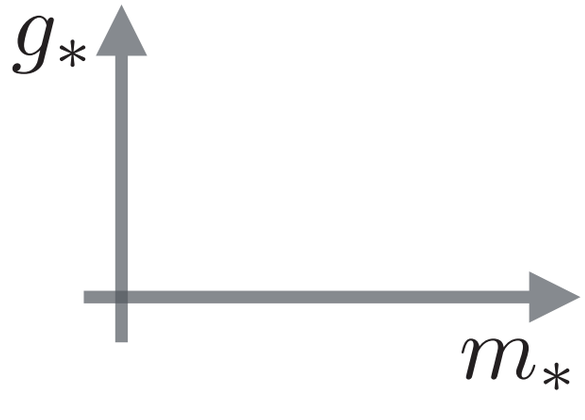


Bound on interaction scale is just the first step.

Coupling is also essential to assess EFT validity

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{d=6}_{\rm BSM}$$

operator estimate from structural BSM assumptions. **Different assumptions produce different maps**



ctions is a
tion strategy

ts however

lementary:
CC ocean

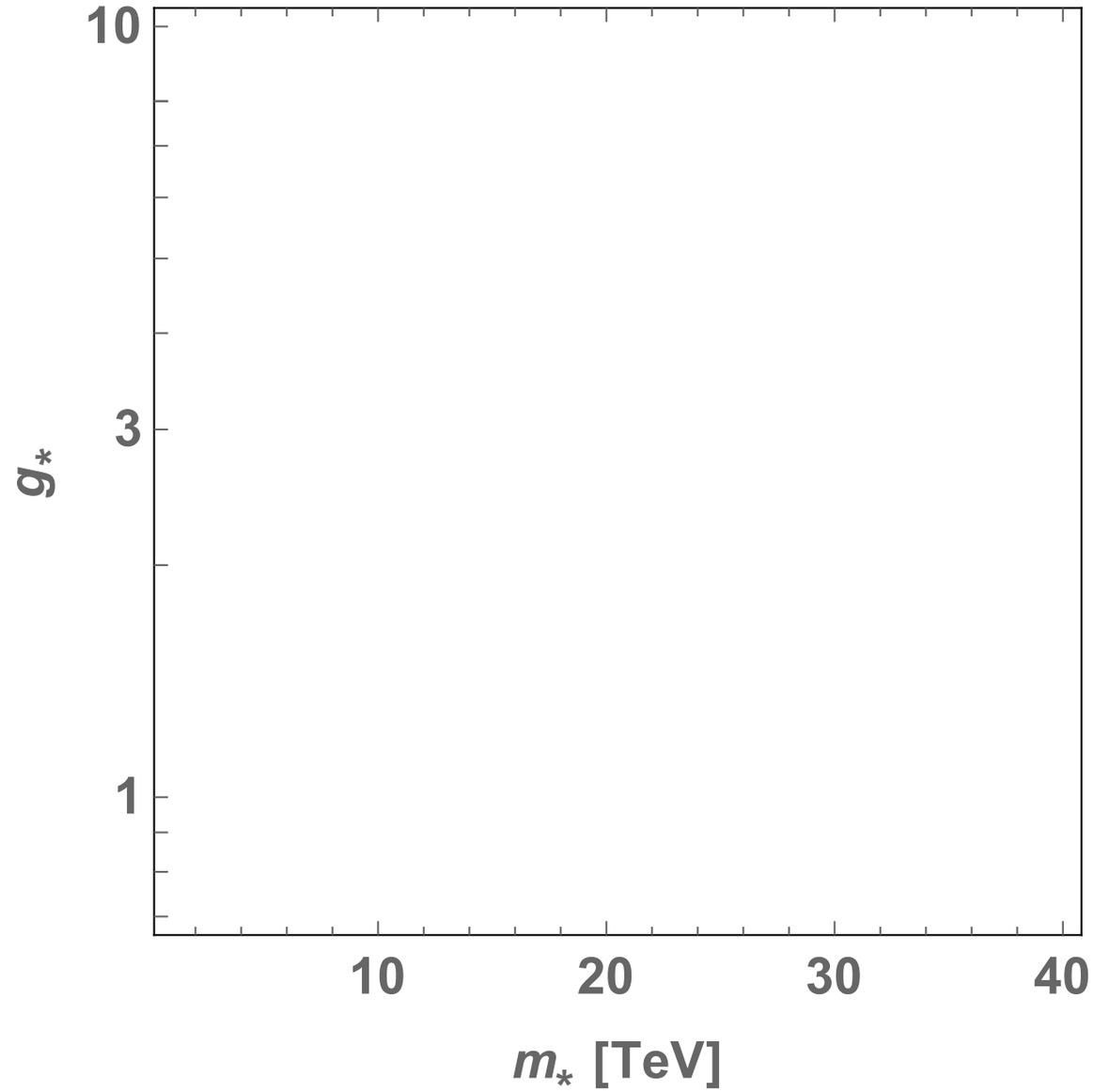
N.P **mass:** m_*

N.P **coupling:** g_*

EW+Higgs Measurements

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

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



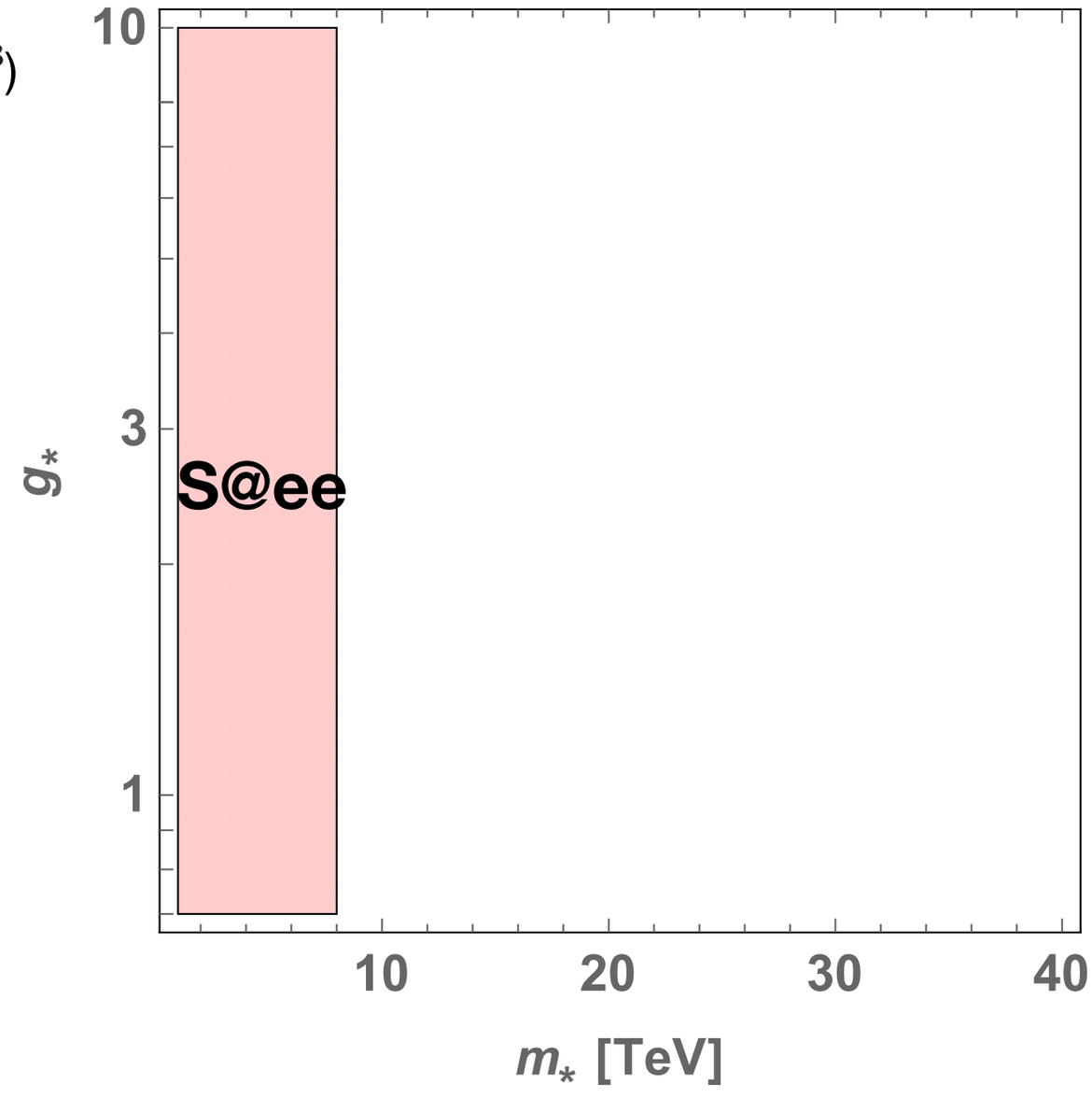
EW+Higgs Measurements

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

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

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

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



EW+Higgs Measurements

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

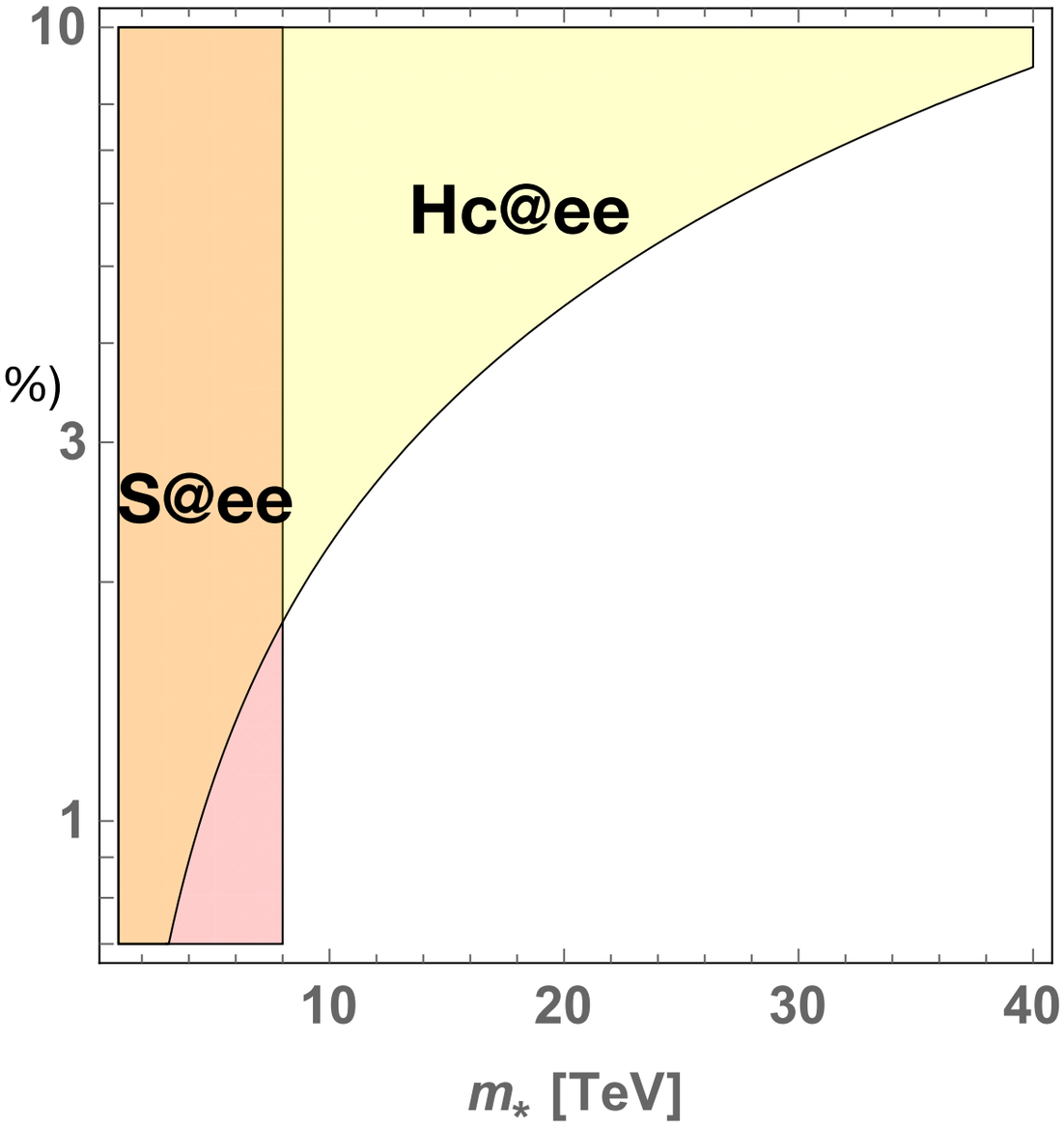
$$\mathcal{L}_{\rm BSM}^{d=6} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

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%)

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



EW+Higgs Measurements

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

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

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

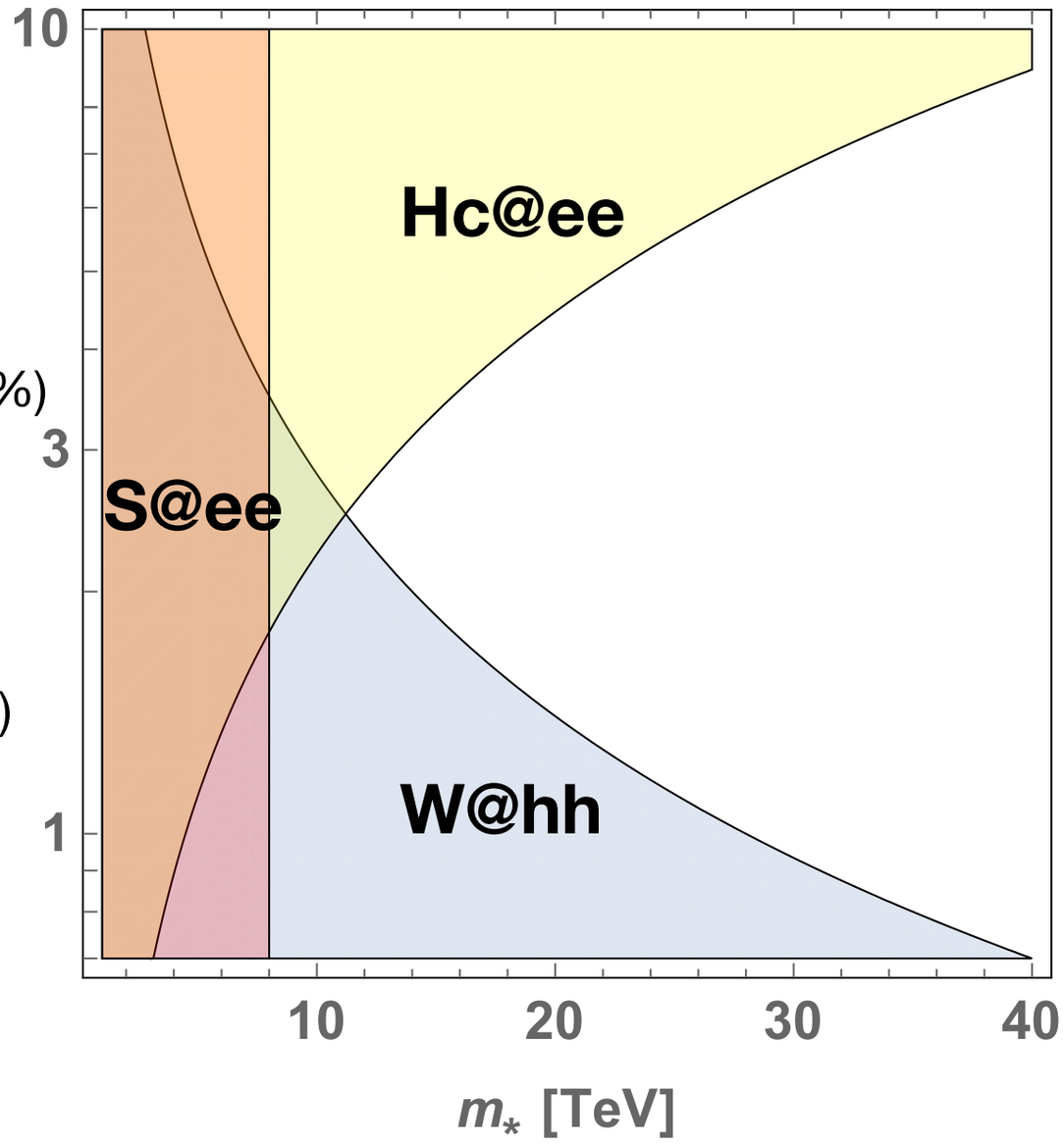
$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \Rightarrow \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

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

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

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

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



EW+Higgs Measurements

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

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

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

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

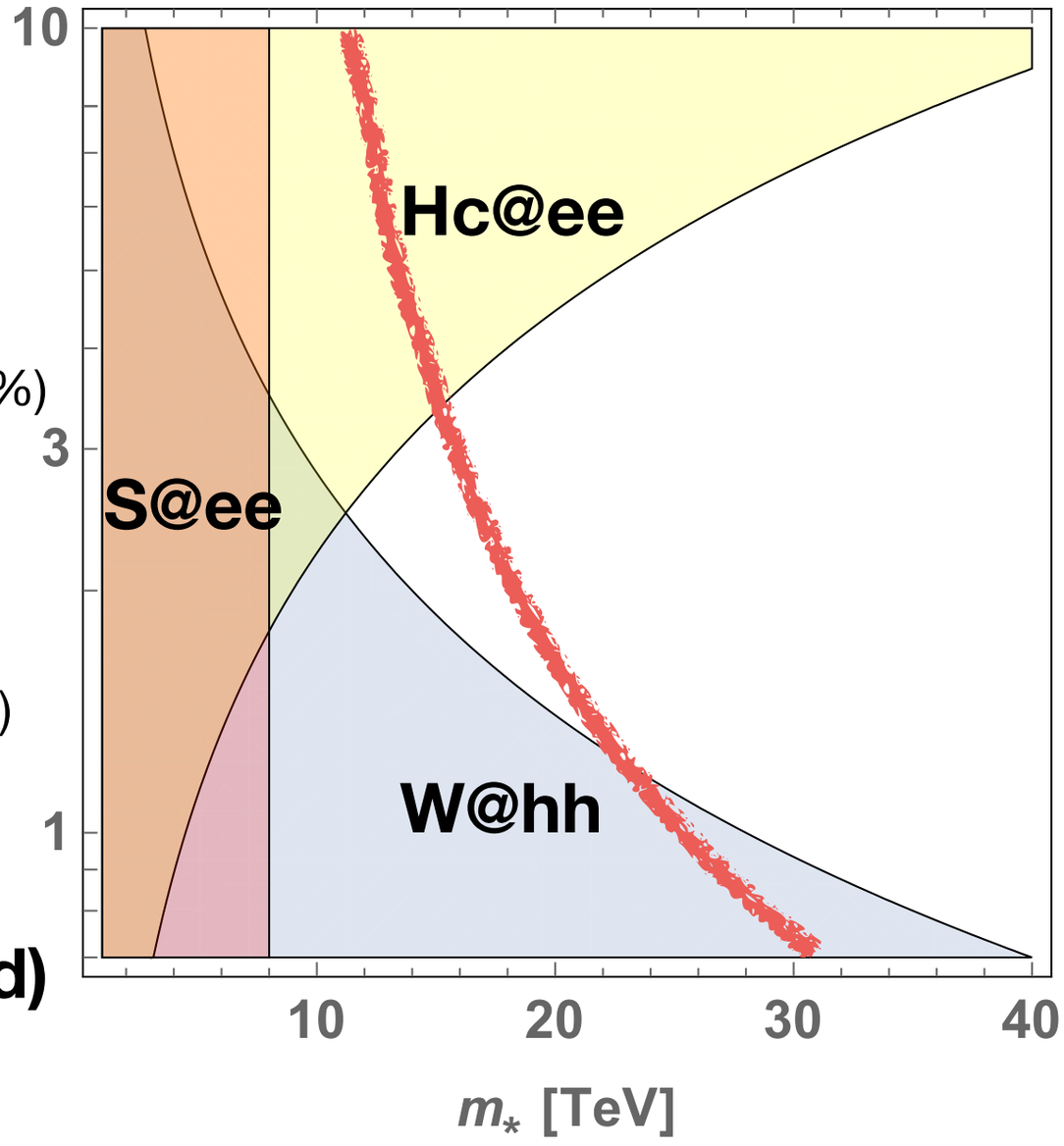
Higgs Couplings @ee: [ee Report] (HL-LHC: 5%)

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

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

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

Direct searches: (once model specified)



EW+Higgs+Top Measurements

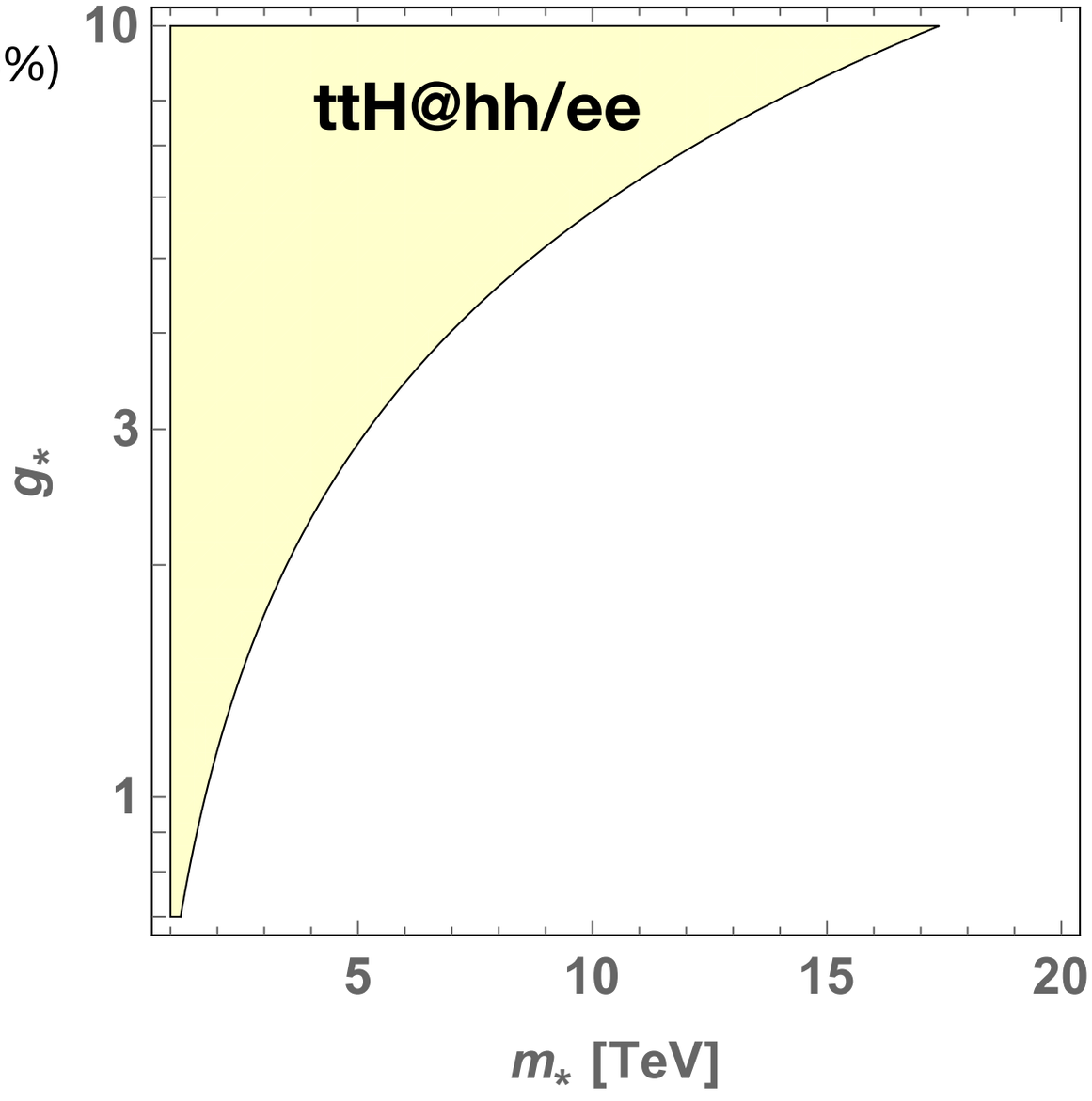
Composite tR, comp. Higgs, **elementary tL** and gauge

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

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!!



EW+Higgs+Top Measurements

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

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

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

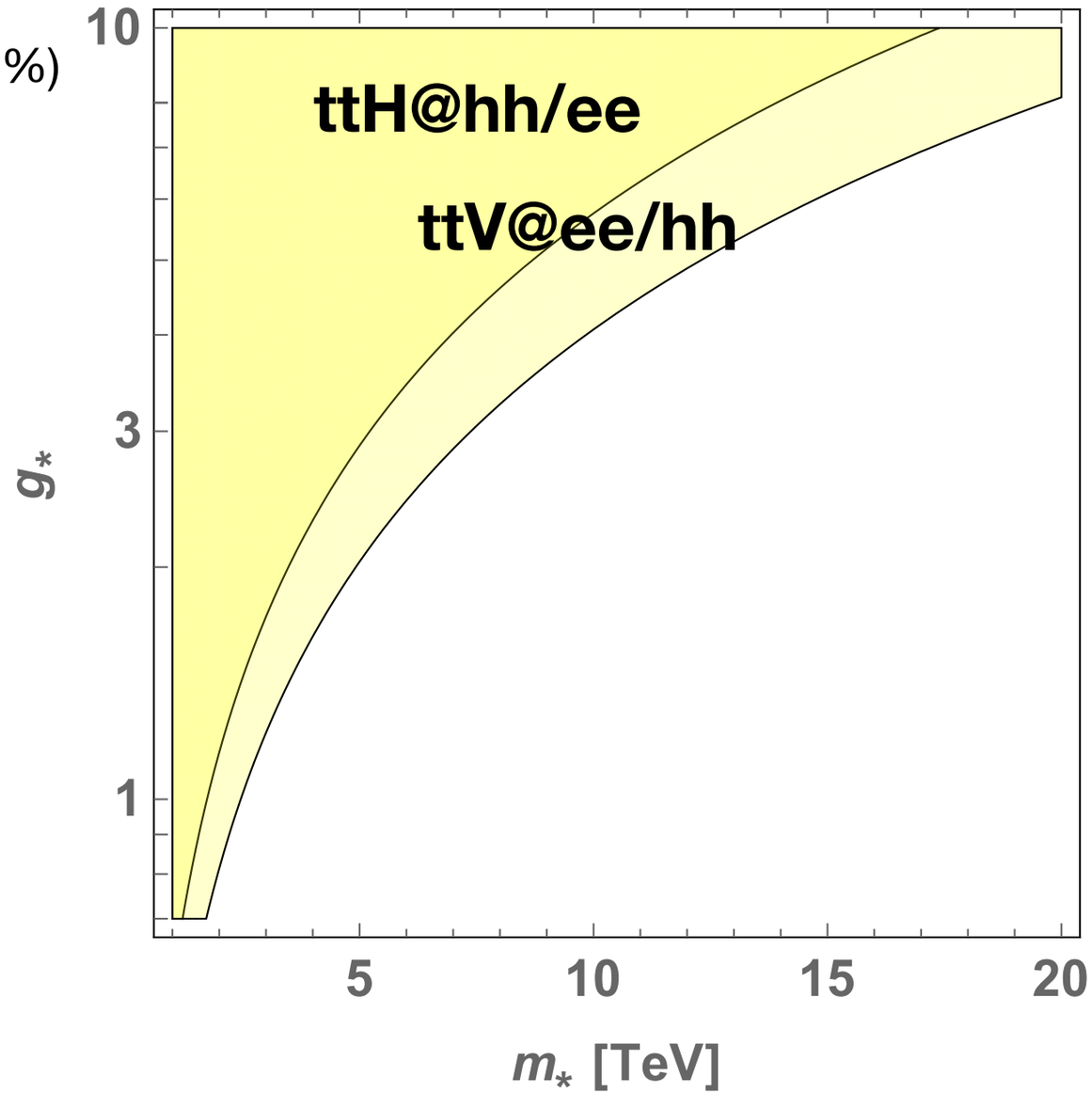
$$\frac{y_t g_*^2}{m_*^2}|H|^2 \overline{q}_L H t_R \quad\Rightarrow\quad \frac{\delta y_t}{y_t} = \frac{g_*^2 v^2}{m_*^2} < 2\,10^{-2}$$

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

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

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

Same hh reach from en. + acc.?



EW+Higgs+Top Measurements

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!!

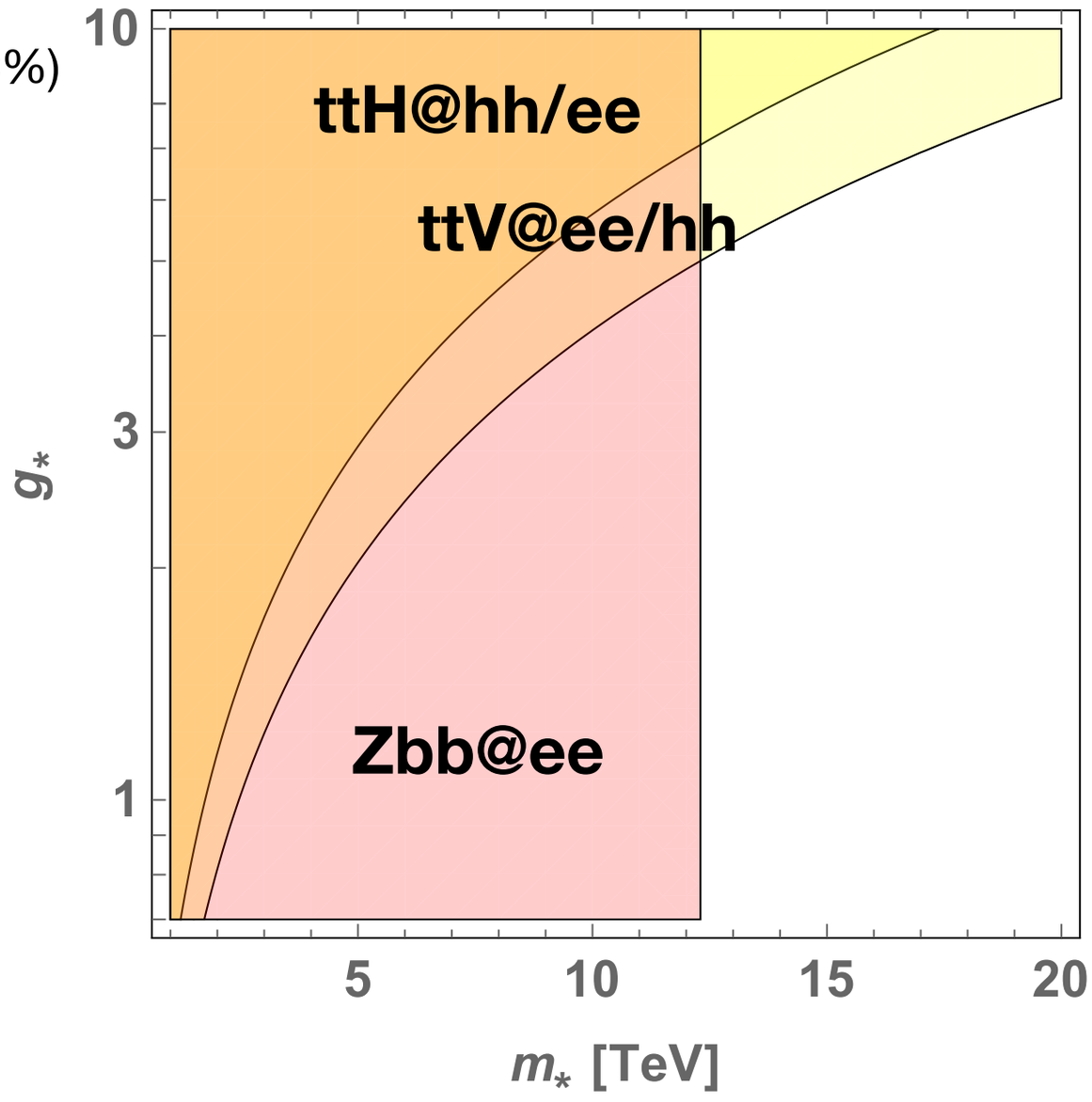
ttV coupling @ee/hh: [Janot / Farina et.al.]

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

Same hh reach from en. + acc.?

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

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



EW+Higgs+Top Measurements

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!!

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

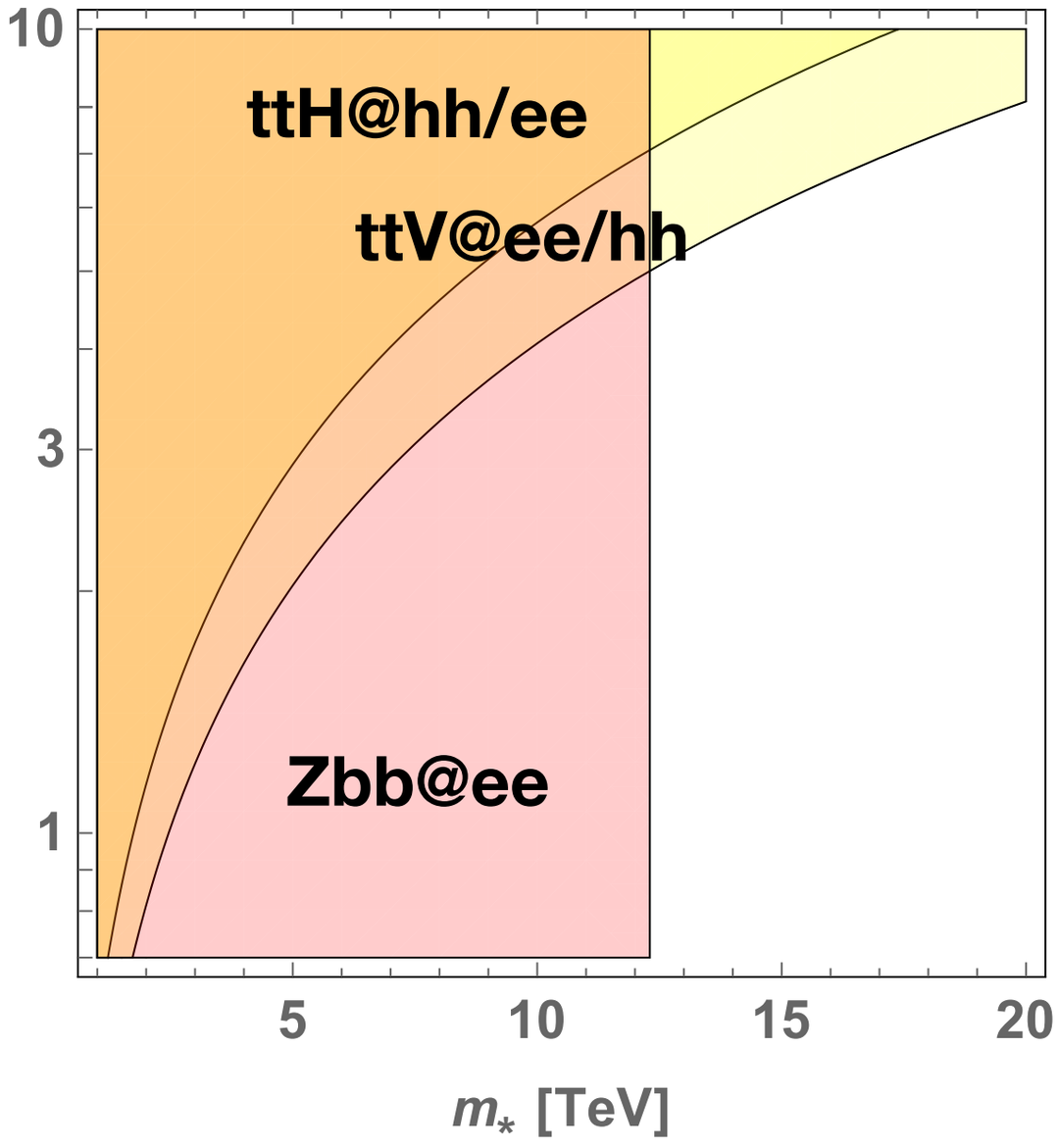
$$\frac{g_*^2}{m_*^2} H^\dagger D_\mu H\, \overline{t}_R \gamma^\mu t_R \quad\Rightarrow\quad \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reconstruction en. + acc.?

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

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

PLR Custodial eliminates these effects !



EW+Higgs+Top Measurements

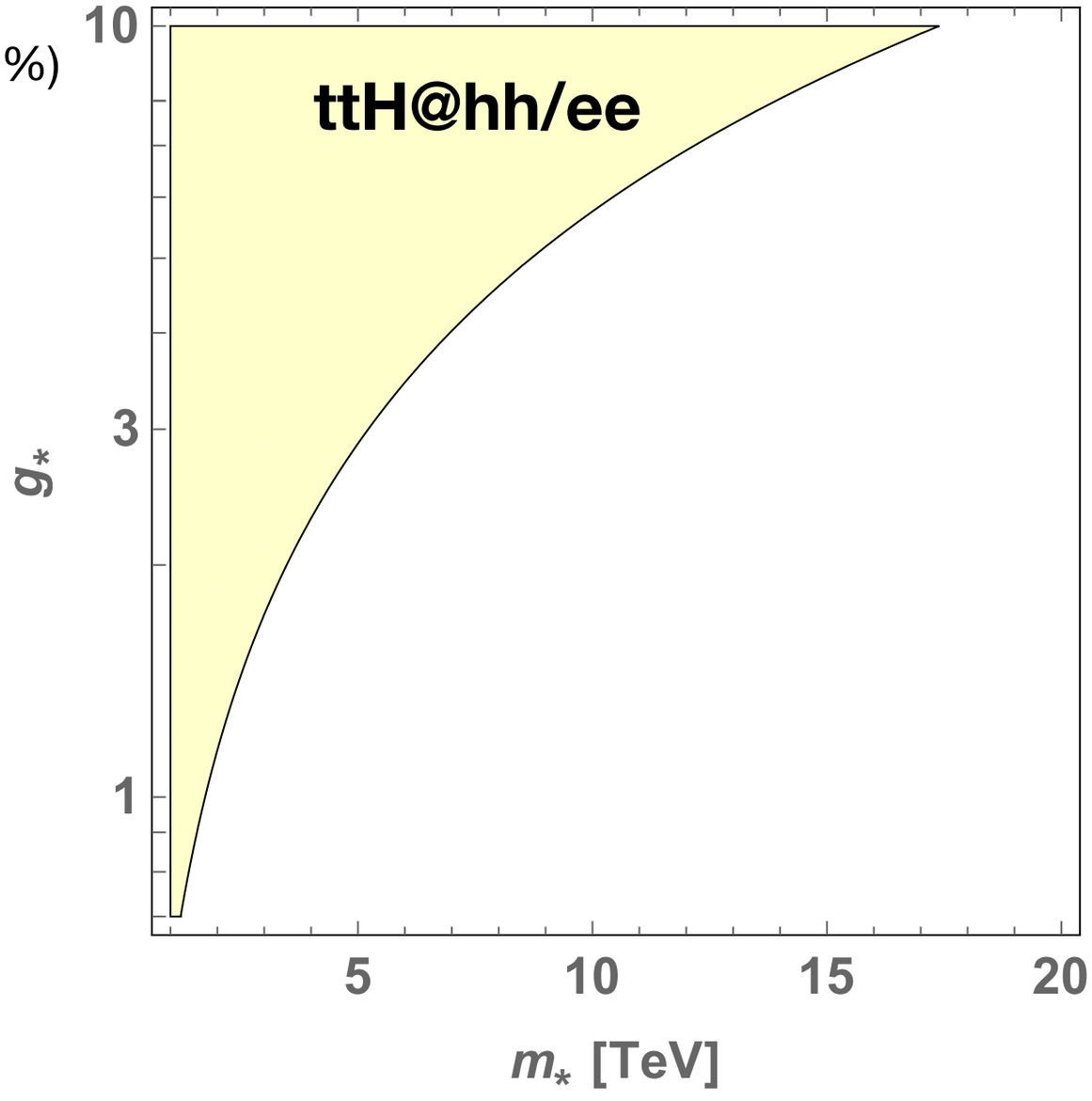
Composite tR, comp. Higgs, **elementary tL** and gauge

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

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!!



EW+Higgs+Top Measurements

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

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

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

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

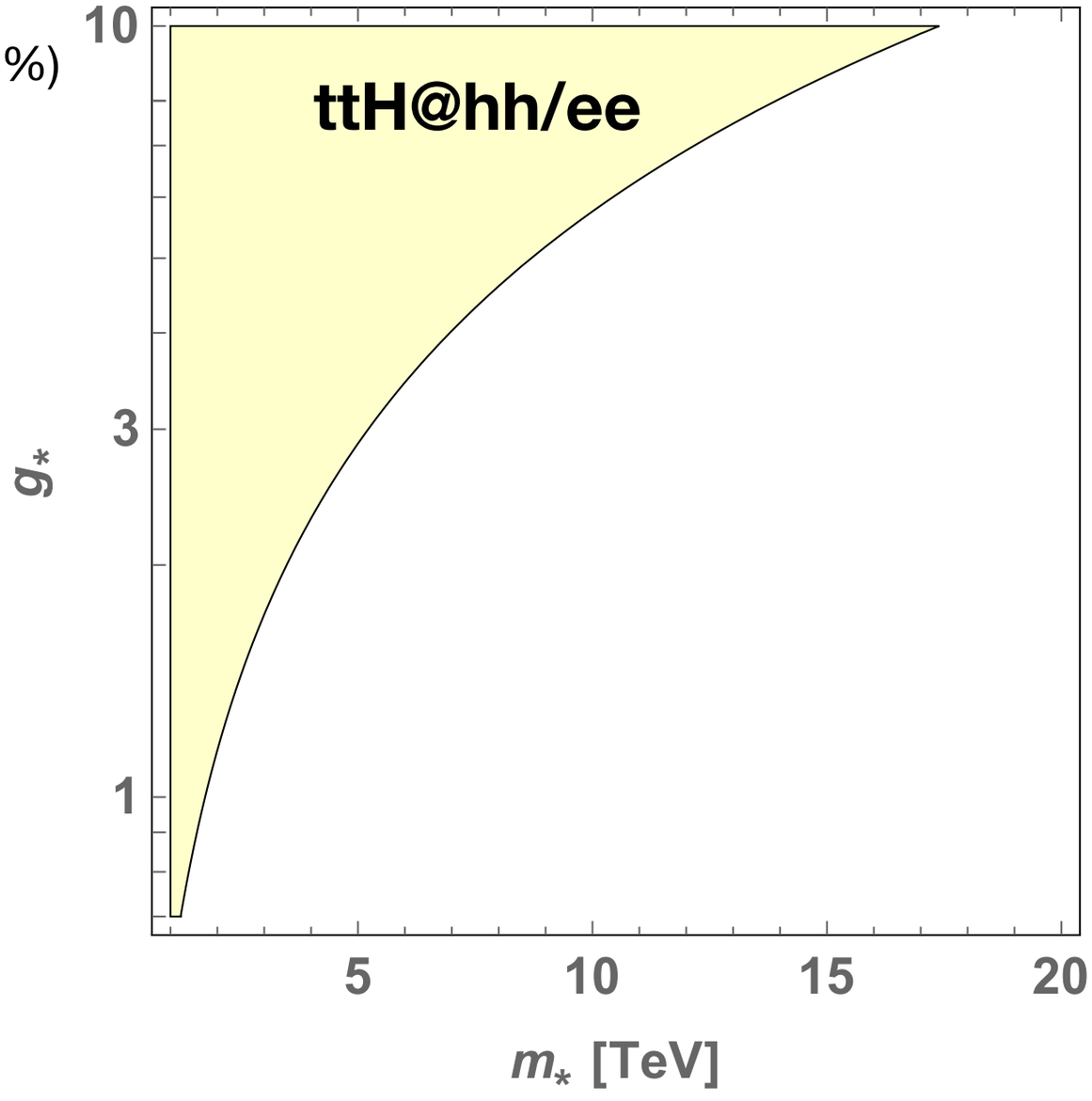
Diff. oper.s comb. in ee and hh!!

4-top contact interactions @hh:

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

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

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



EW+Higgs+Top Measurements

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

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

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!!

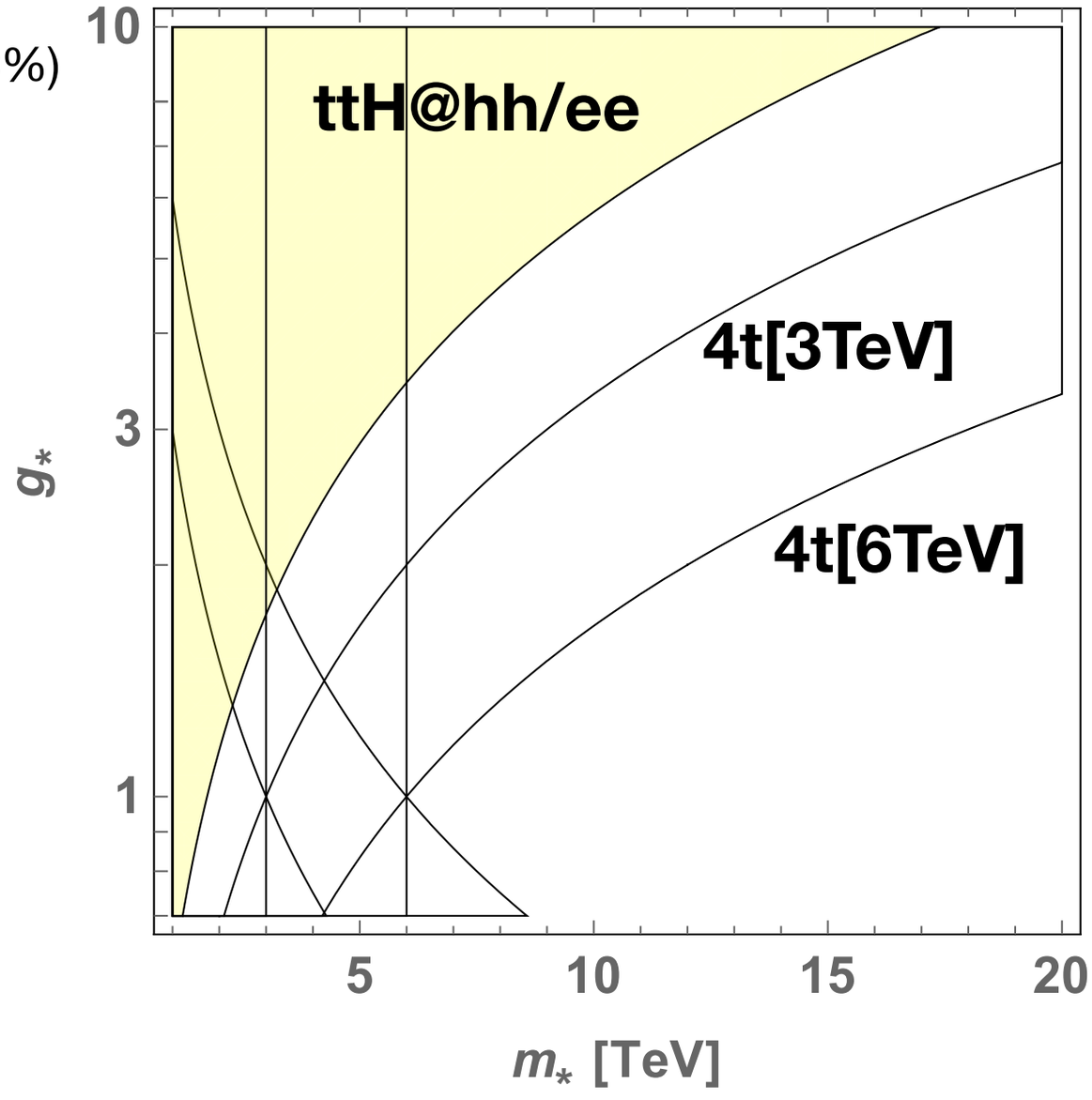
4-top contact interactions @hh:

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

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

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

No study available (?)



Food for thoughts

- Complementarity breaks degeneracy in EFT space (e.g., ttH vs ggH vs ttZ)
- How to fit rare Higgs channels on a map? Light weakly-coupled new physics?
- PDF measurements @ ep useful to control PDF uncertainty for Higgs precision program and new physics tests?
- Independent alpha_S(Mz) measurement @ ep improves EW precision tests @ ee?
- LHC/ILC Higgs complementarity [Peskin 1312.4974] : BR(γγ)/BR(ZZ) @LHC plus Kv @ILC => Kγ. Something similar @FCC?

Food for thoughts

g_{HXY}	FCC-ee	FCC-hh	FCC-ep?
ZZ	0.16%		
WW	0.85%		
γ γ	1.7%	<1% ?	
Zγ	?	1% ?	
tt		1% ?	
bb	0.42%		
τ τ	0.94%		
cc	1.0%		
ss	H→Vγ, in progr.		
μμ	6.4%	2% ?	
uu,dd	H→Vγ, in progr.		
ee	e^+e^-→H, in progr.		
HH		5% ?	
BR_{exo}	0.48%	< 10^{-6} ?	