Higgs, Top & their interplay@FCC

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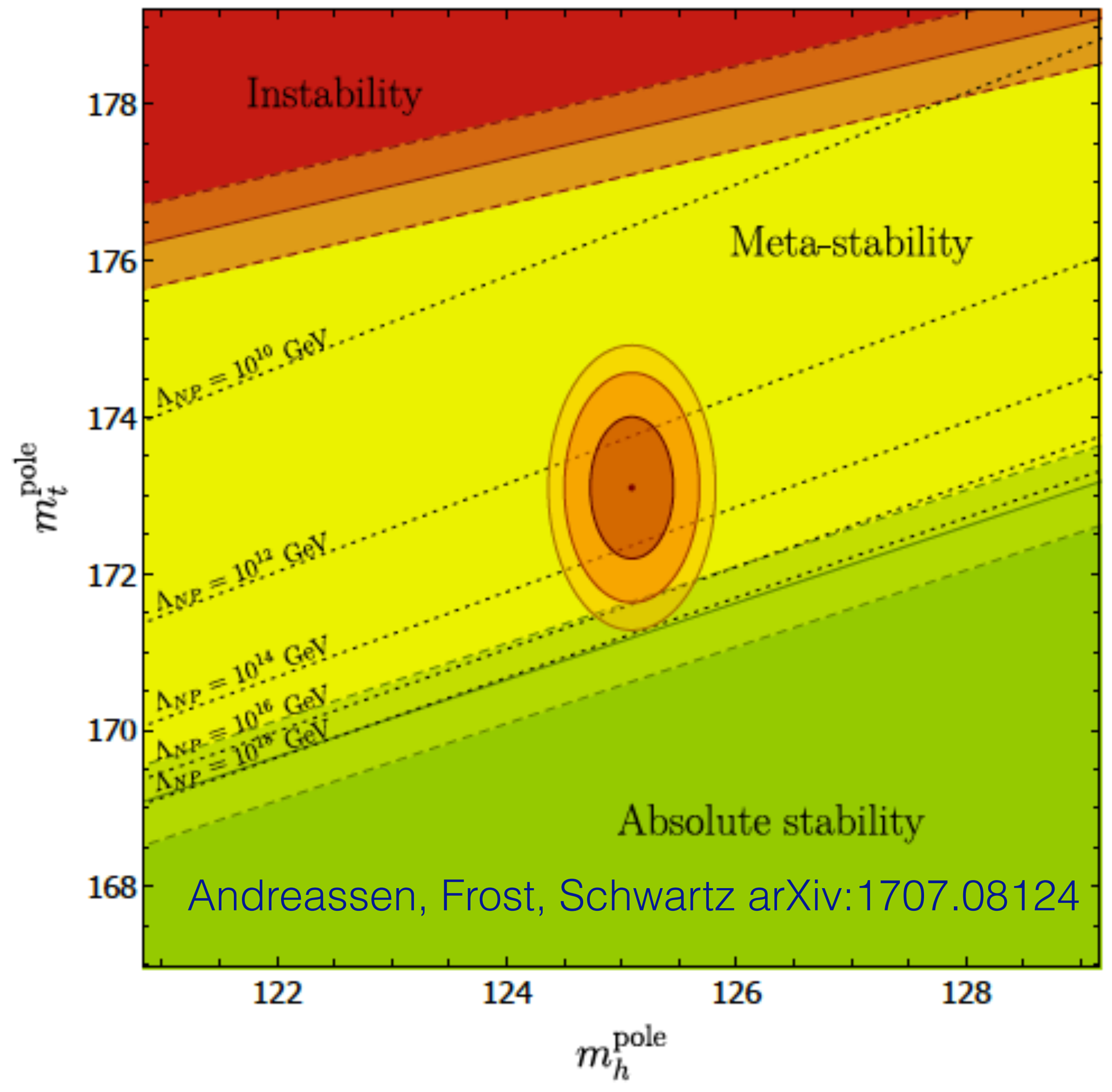
Why are top and Higgs friends?

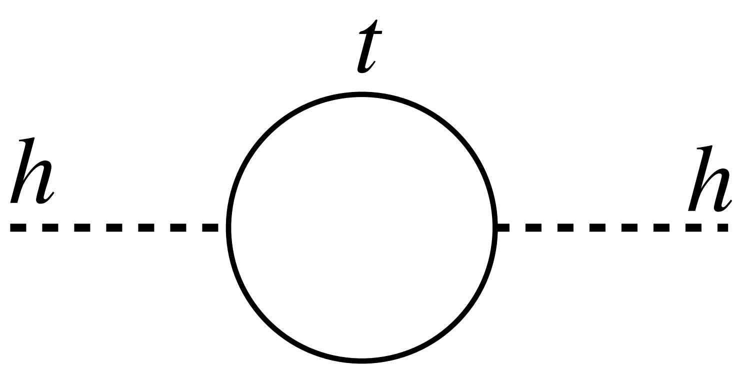
The top has the largest Yukawa coupling: $m_t = \frac{y_t}{\sqrt{2}} = 173\text{GeV} \longrightarrow y_t = 0.99$

The top quark is the only "natural" quark



Andreassen, Frost, Schwartz arXiv:1707.08124

Large corrections for the Higgs mass



$M_H^2 \propto y_t^2 \Lambda^2$

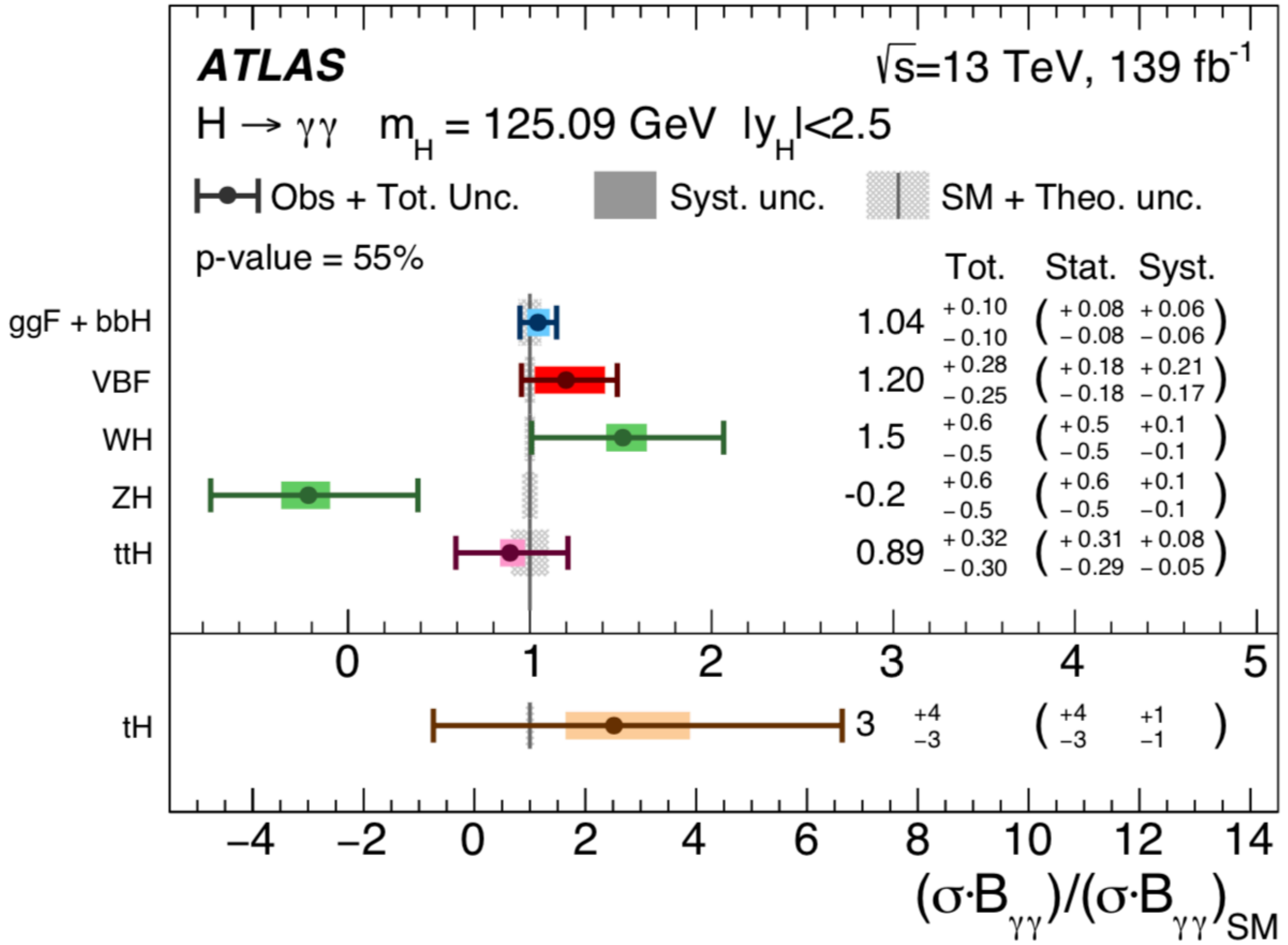
The (little) hierarchy problem

Top and Higgs play a
special role in the stability of the Universe

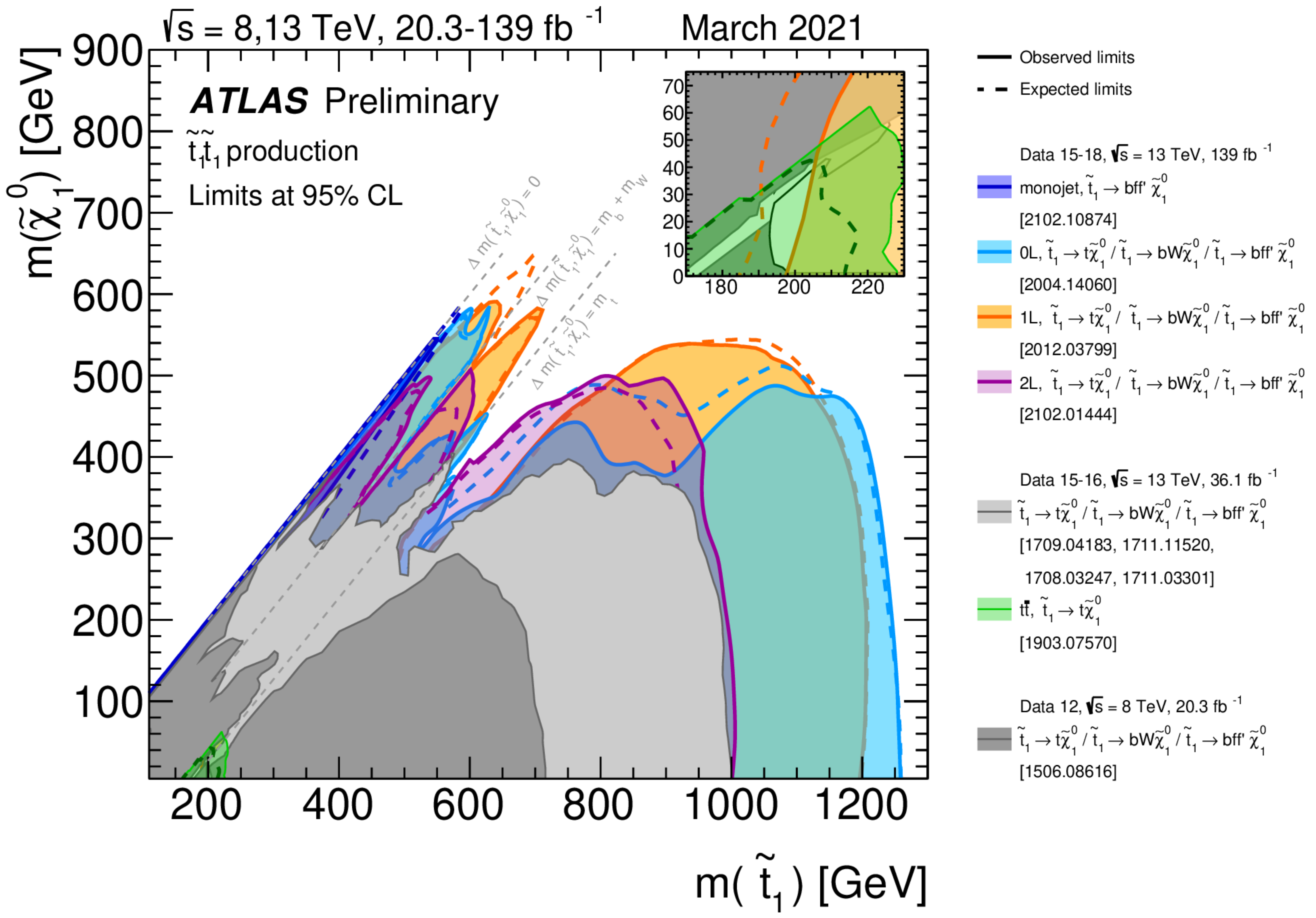
Motivation for BSM with special connection to top:
top partners, modified Yukawas etc

Looking for the (un)known

"SM" Higgs measurements



Exotic searches for top partners

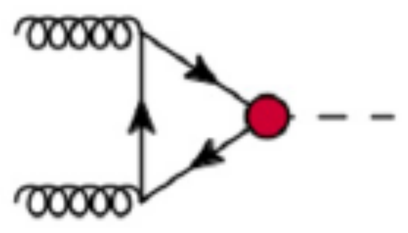


The LHC offers a unique testing ground for New Physics

Expect the FCC to push this frontier even further

Top lessons from Higgs measurements

H



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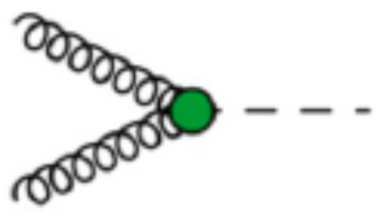
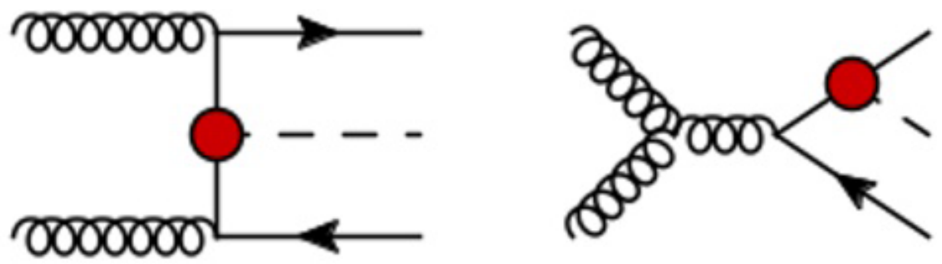
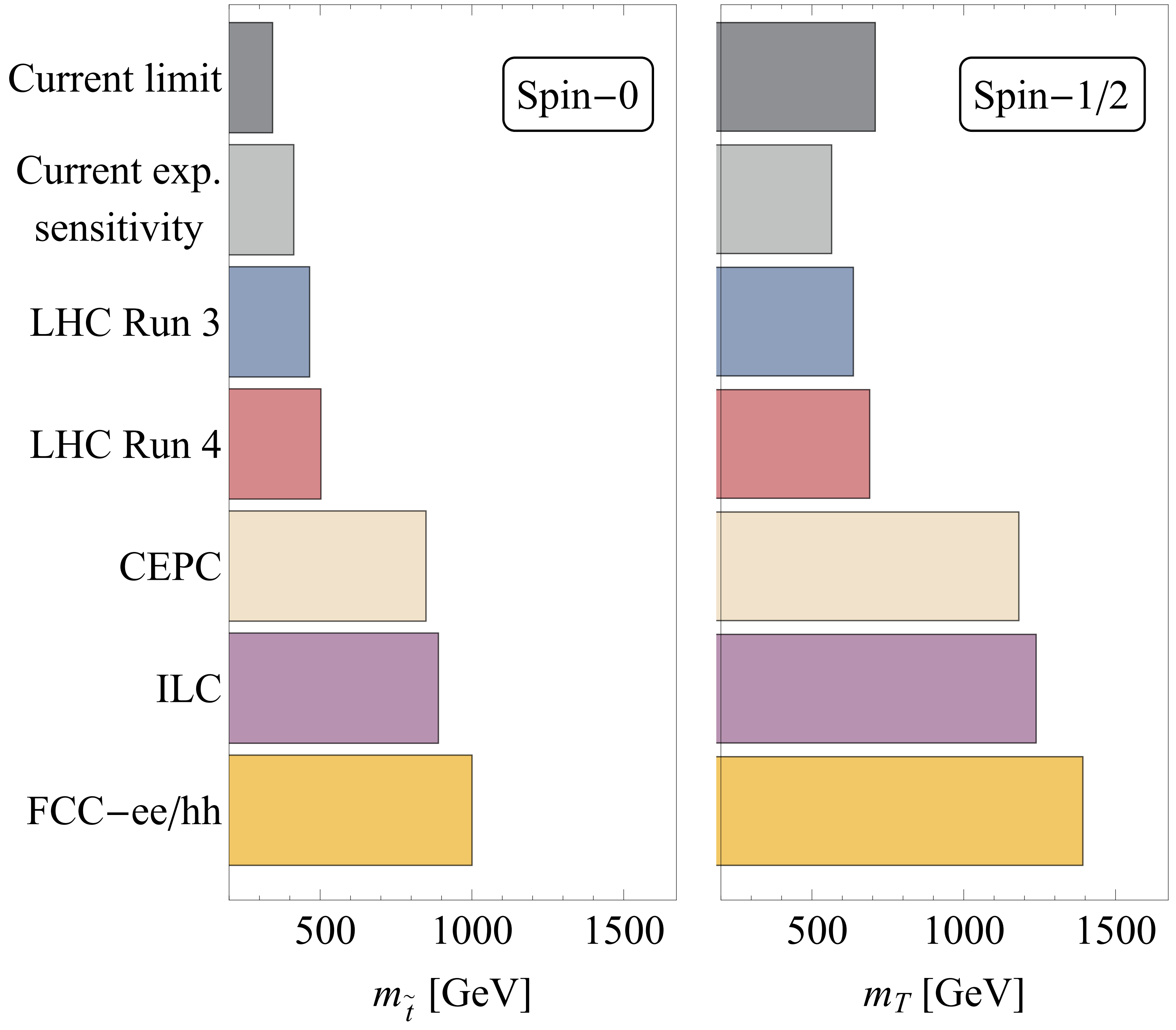
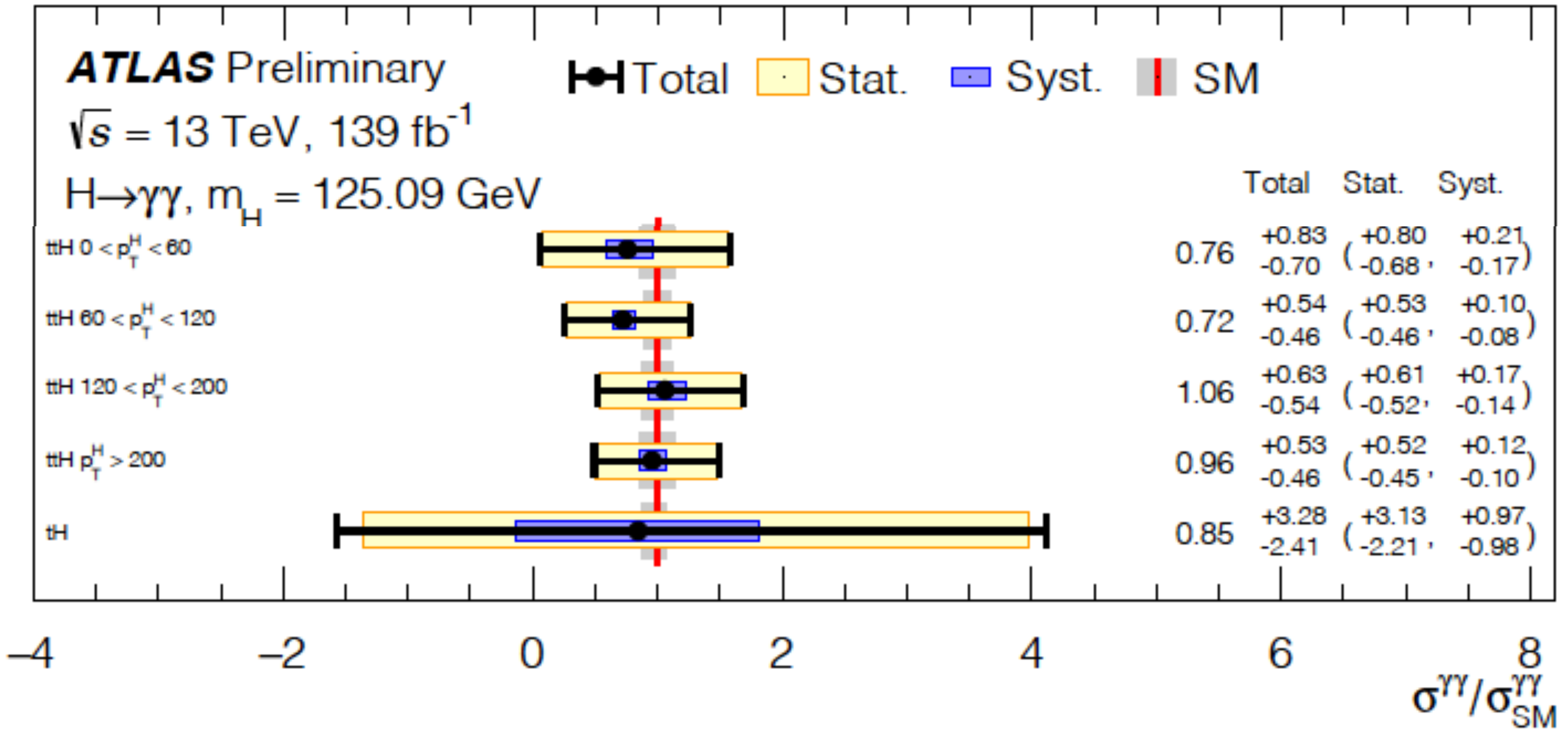


ttH





Essig, Meade, Ramani, Zhong arXiv:1707.03399

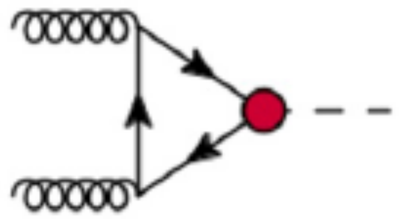


Direct evidence of the top Yukawa coupling

SMEFT interpretations

Top lessons from Higgs measurements

H



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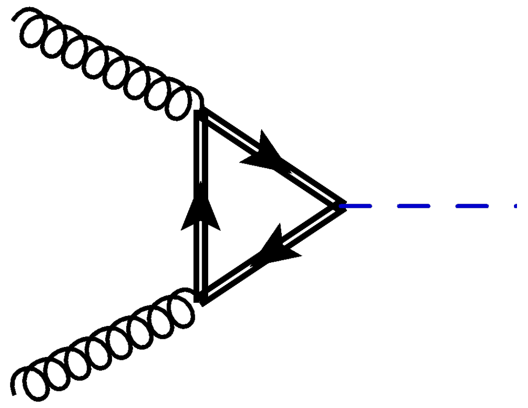
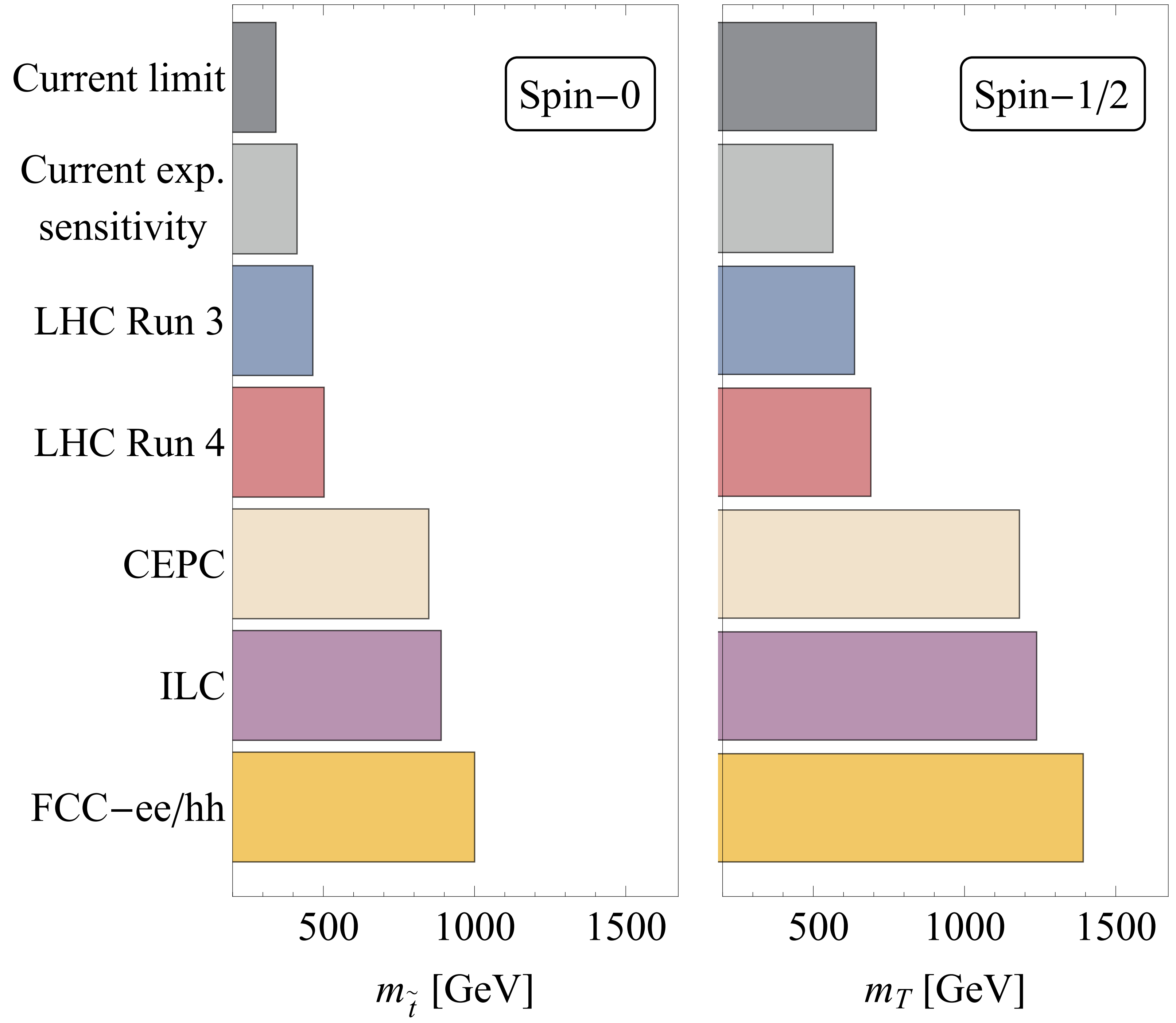


Top partners



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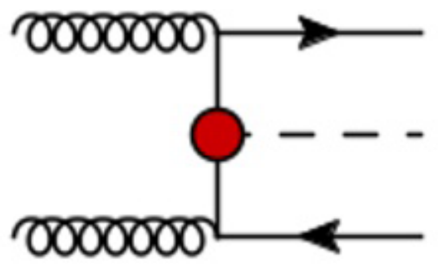

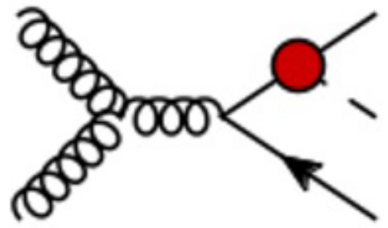

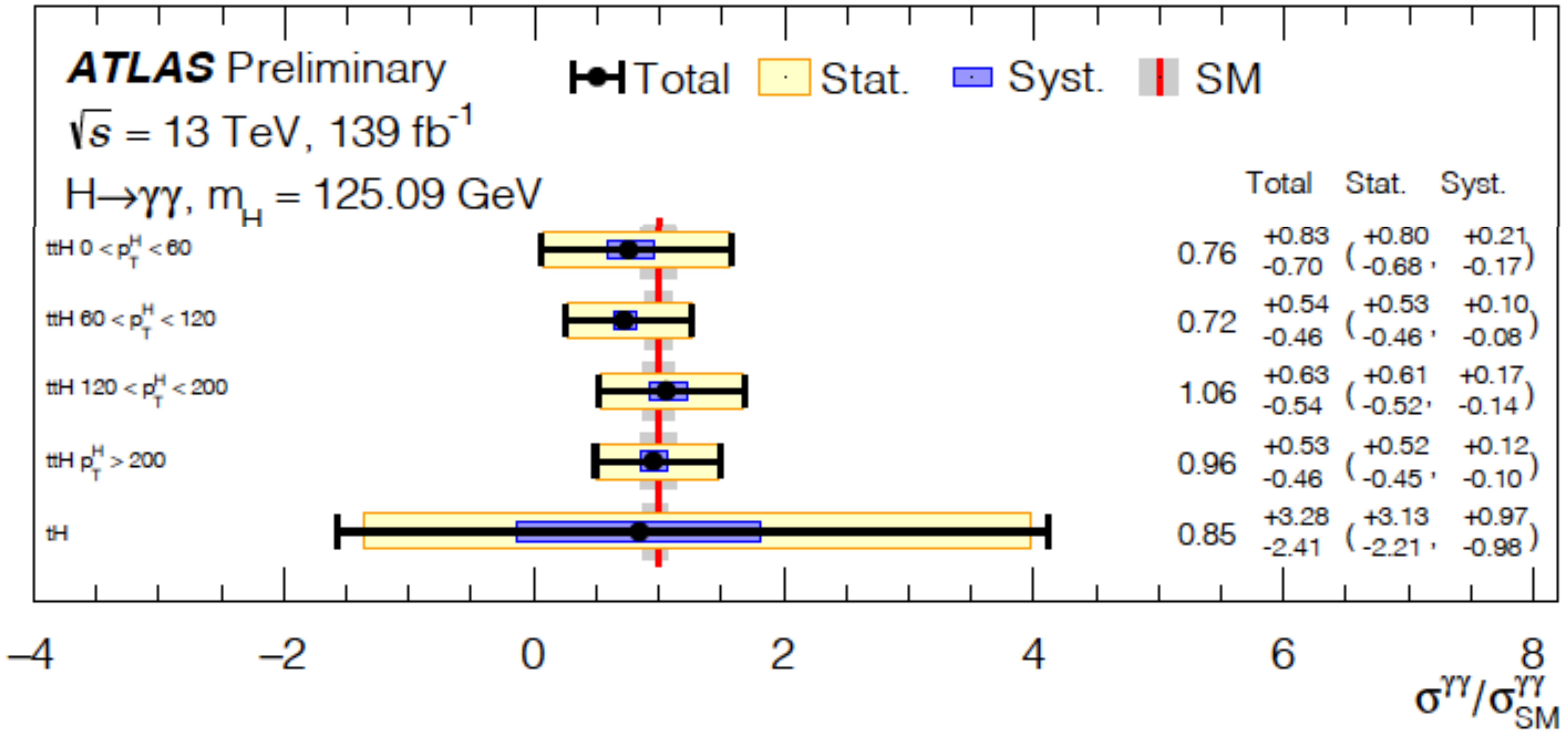

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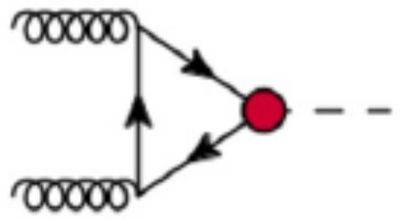

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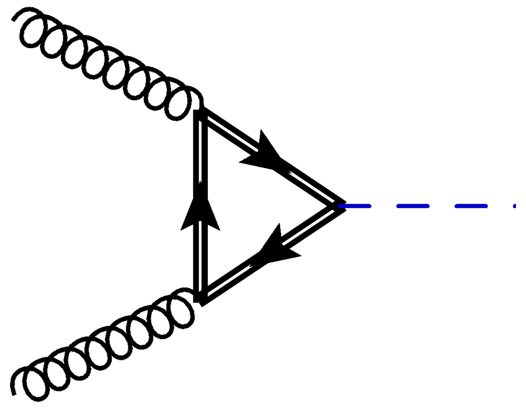
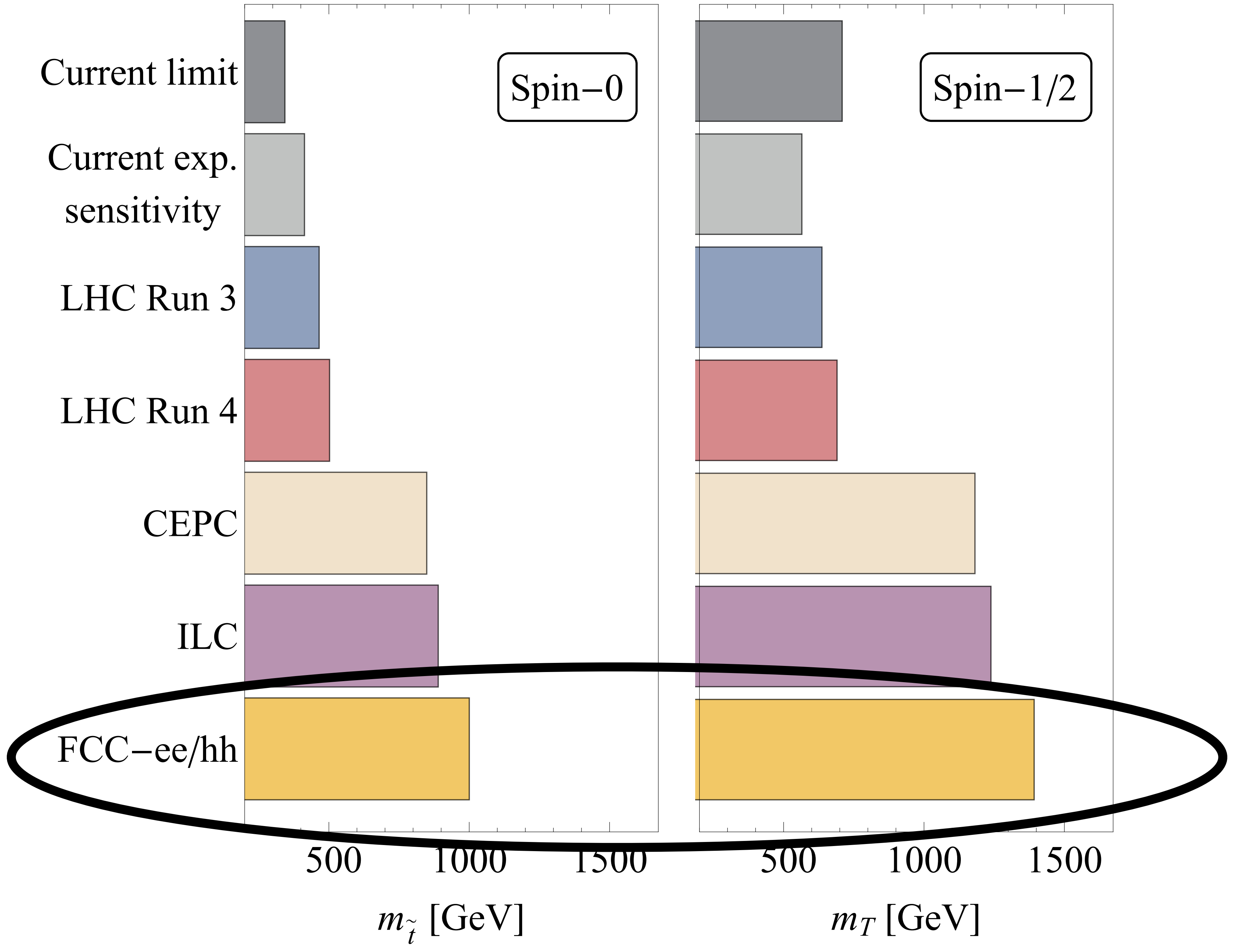


Top partners



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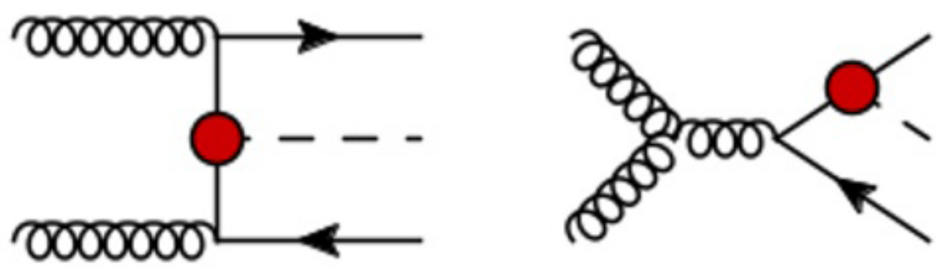
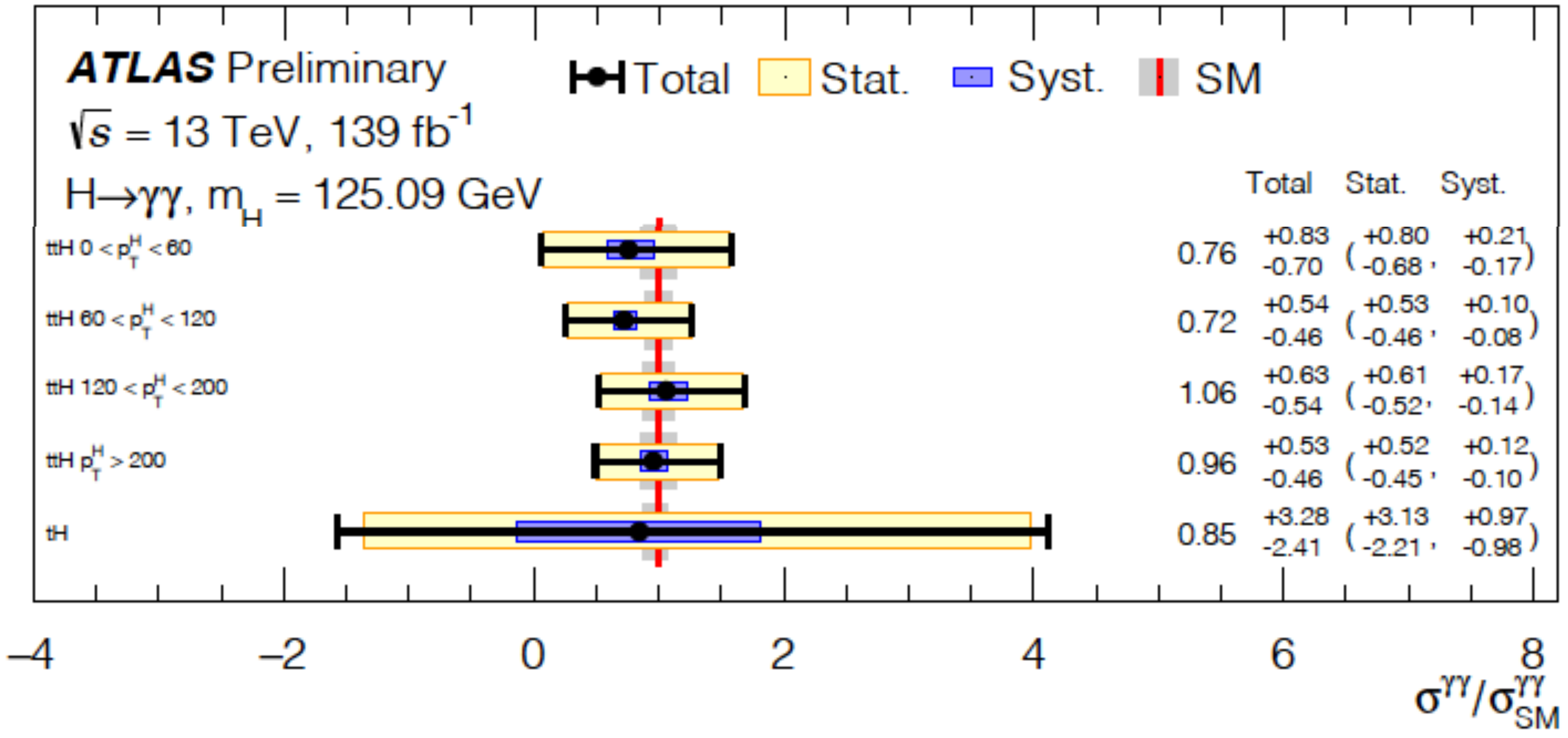
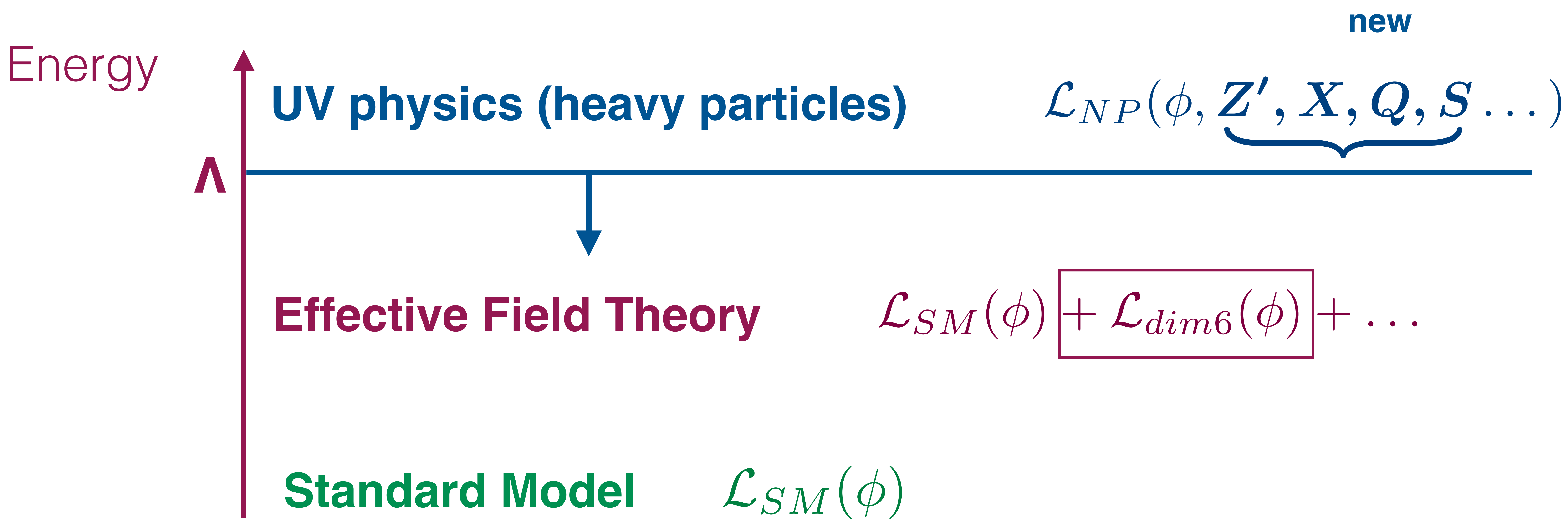




Direct evidence of the top Yukawa coupling

SMEFT interpretations

SMEFT: What is it all about?



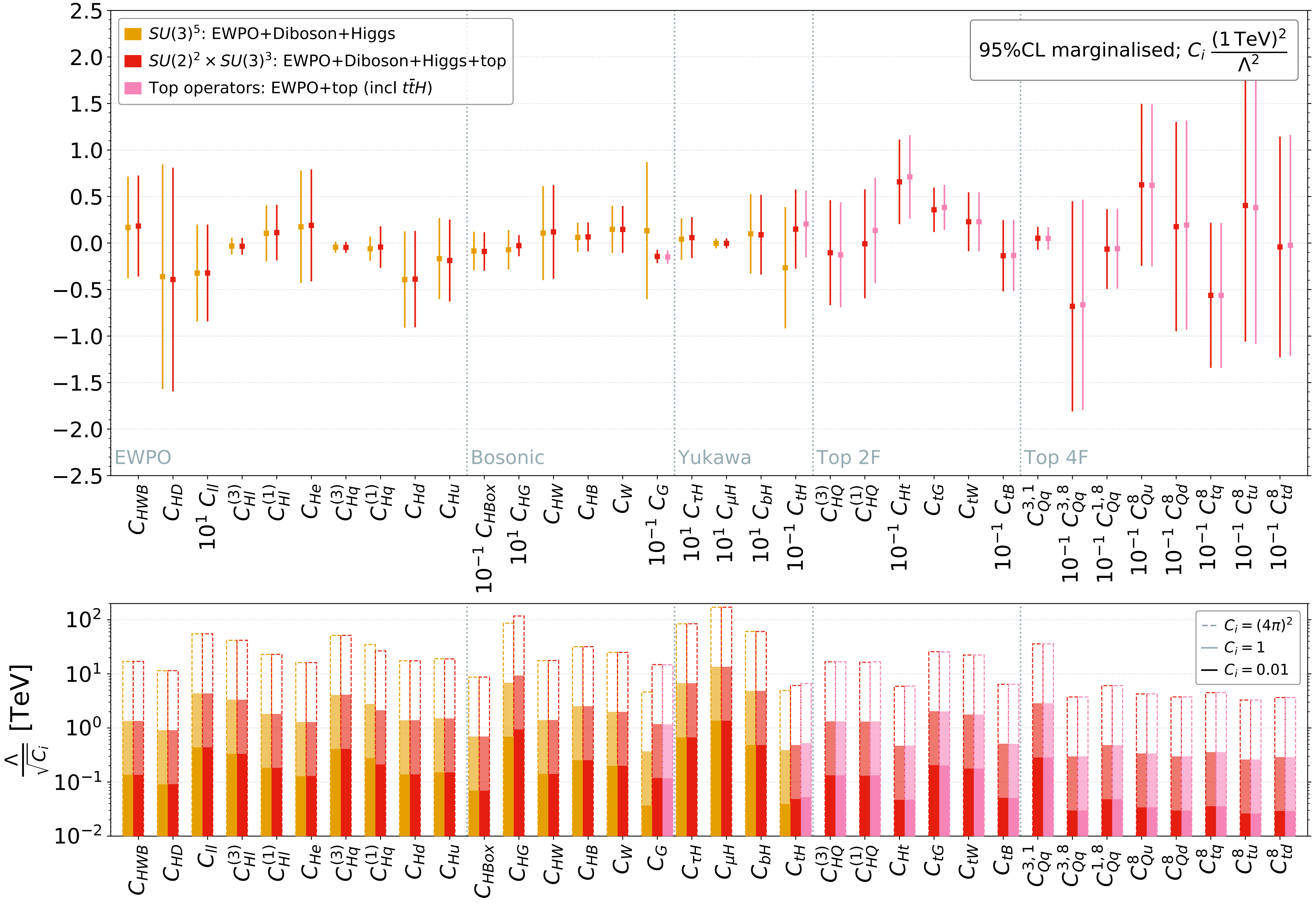
UV physics (heavy particles) $\mathcal{L}_{NP}(\phi, \underbrace{\boldsymbol{Z', X, Q, S}} \ldots)$

Effective Field Theory $\mathcal{L}_{SM}(\phi) \boxed{+ \mathcal{L}_{dim6}(\phi)} + \ldots$

Standard Model $\mathcal{L}_{SM}(\phi)$

Effective Field Theory reveals high energy physics through precise measurements at low energy.

LHC global EFT fit: marginalised (1)



Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

All coefficients allowed to be non-zero

For weakly coupled theories Λ bound below the TeV scale: **EFT Validity???**

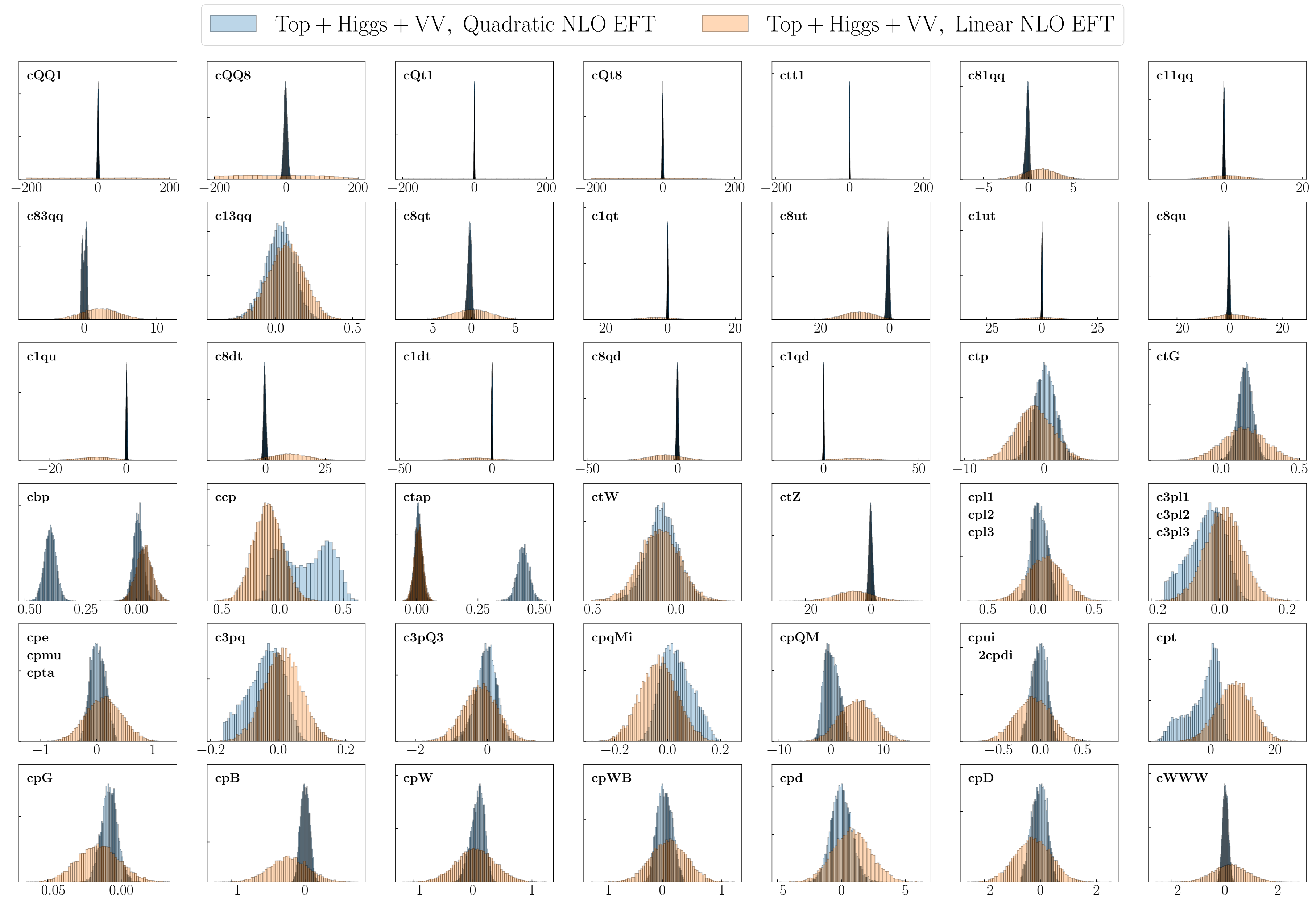
↓ Strongly coupled

Weakly coupled

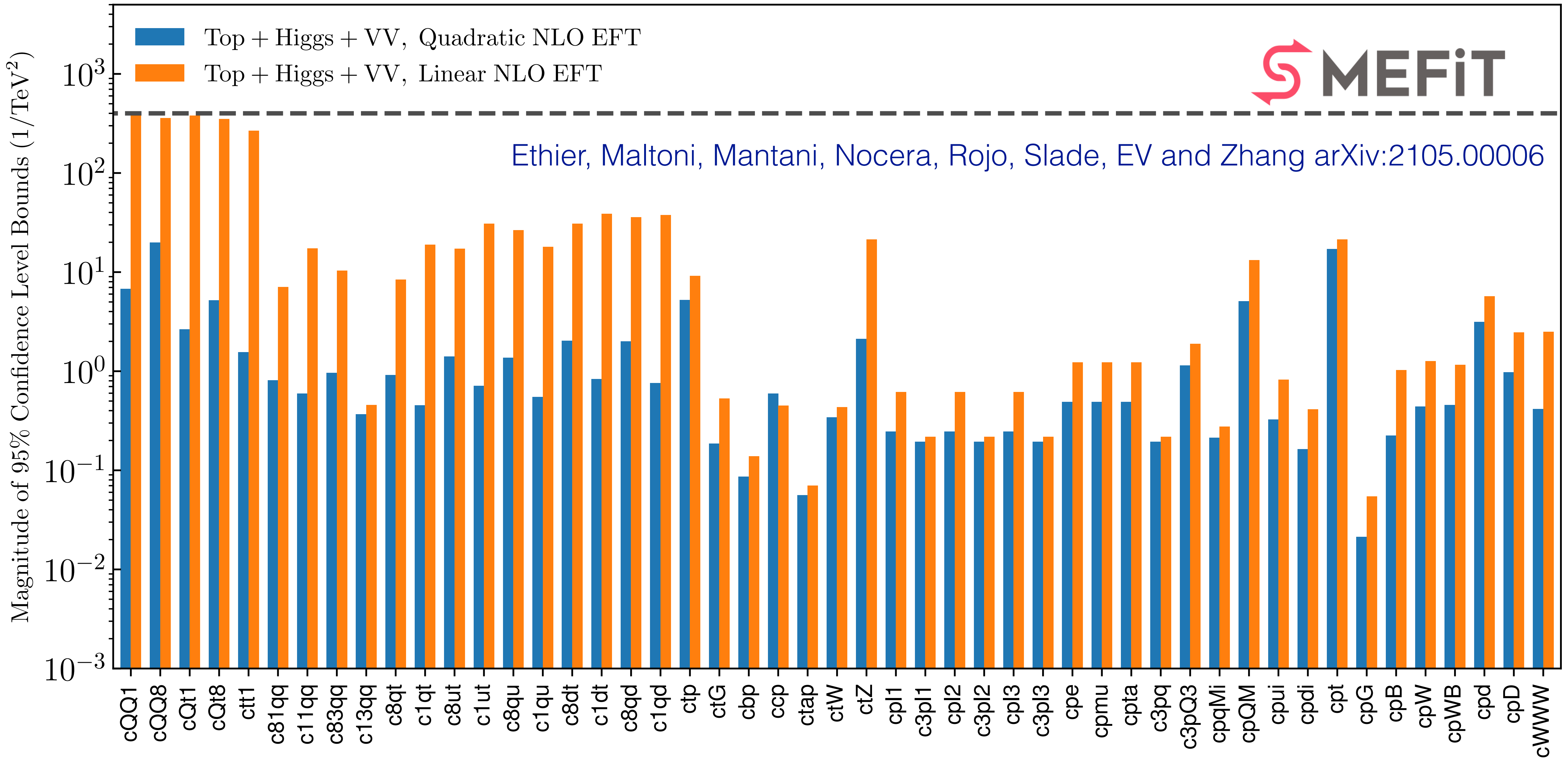
$$\frac{c_i^6(\mu)}{\Lambda^2}$$

LHC global EFT fit: marginalised (2)

- Higher Orders in $1/\Lambda^4$
  - squared dim-6 contributions



Posterior distributions

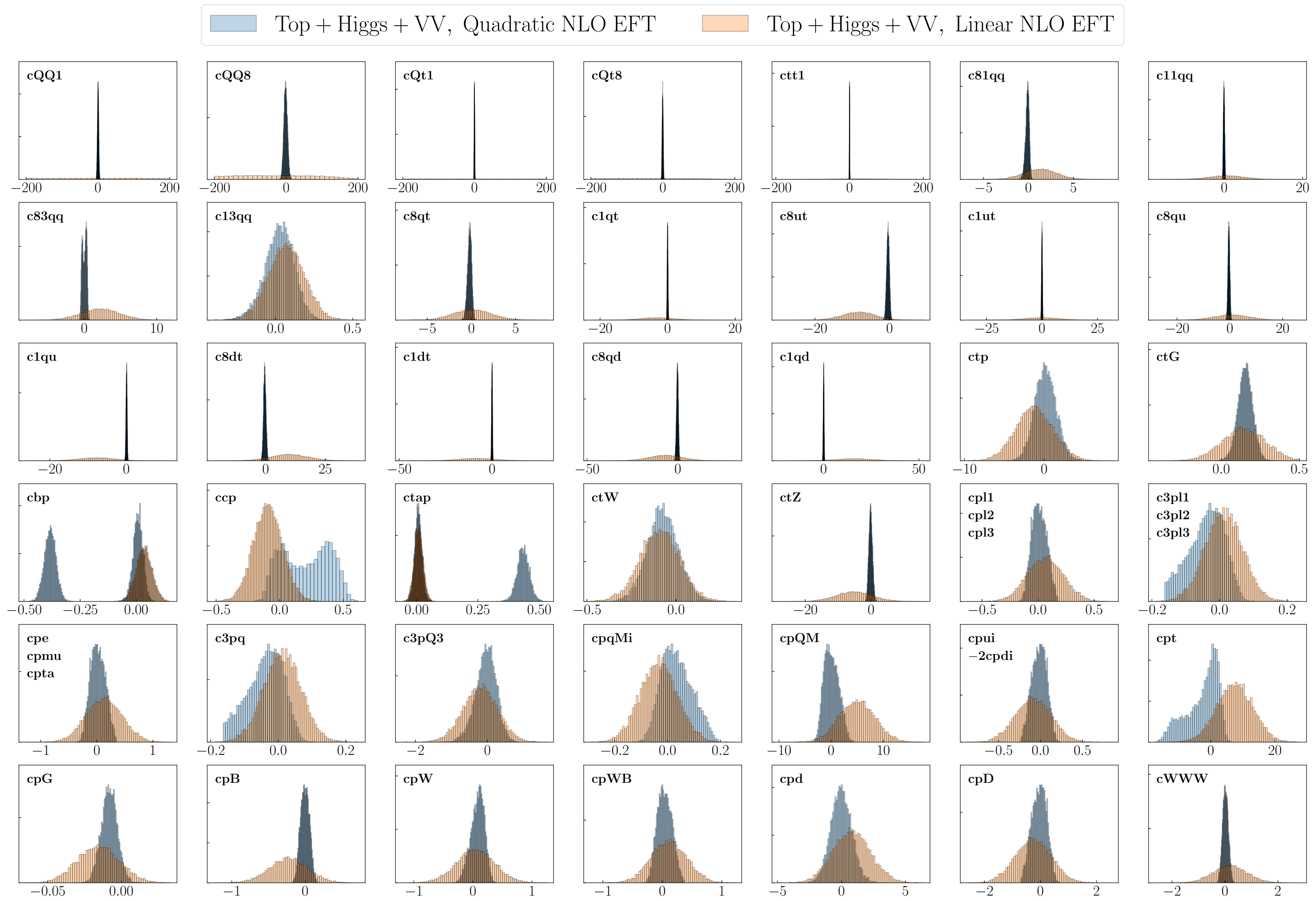


Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

Significant impact for most operators
in particular 4-fermion operators

LHC global EFT fit: marginalised (2)

- Higher Orders in 1/Λ^4
  - squared dim-6 contributions



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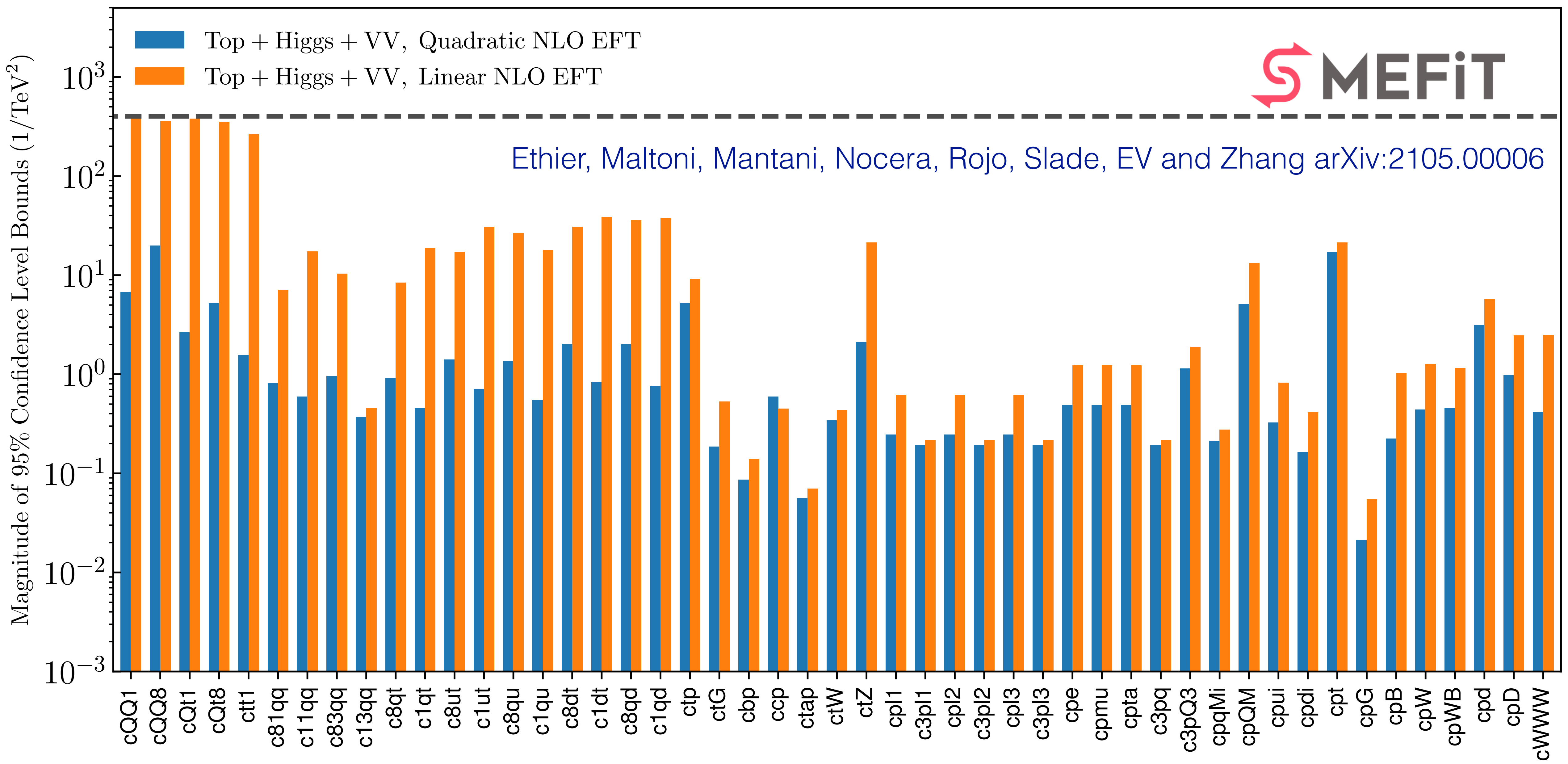

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Significant impact for most operators
in particular 4-fermion operators

Some operators remain unconstrained: Need more data/better probes/new colliders!

What can we hope for the FCC?

Which operators:

FCC-ee

Cleaner environment

Precision frontier

- can make very precise measurements

4-lepton, 2-fermion, pure gauge, Higgs-gauge, top operators at 365 GeV

FCC-hh

Messier environment

Energy frontier:

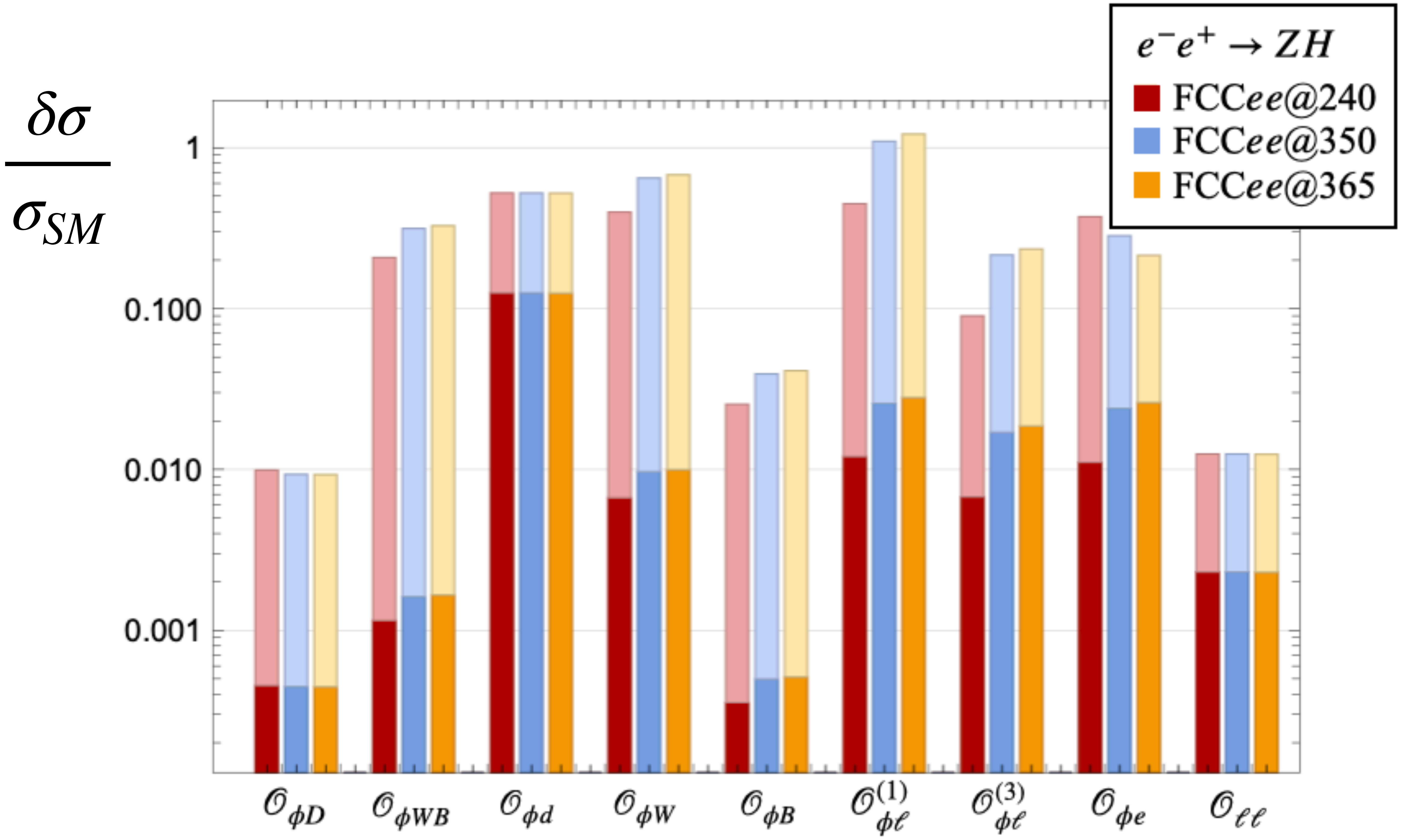
- can push energy probed to 10s of TeV

4-quark, 2-fermion, pure gauge, Higgs-gauge, top operators, 4-heavy operators

What can we hope for?

Example: ZH production

Expected total cross-section uncertainty at FCC-ee: ~0.5%



Using current LHC bounds from fitmaker: arXiv:2012.02779

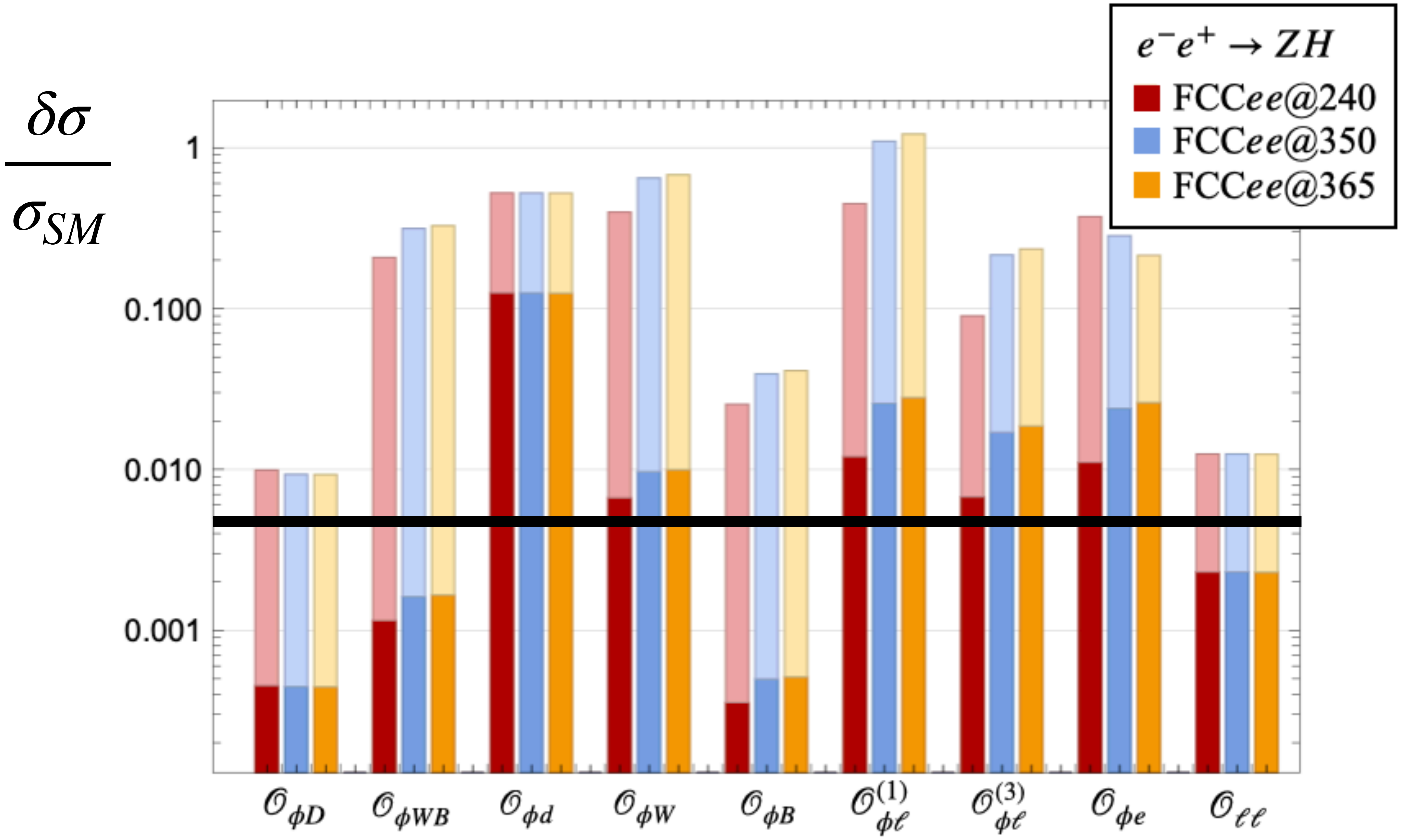
Celada, EV et al in preparation

Bounds will be significantly better at the FCC-ee!

What can we hope for?

Example: ZH production

Expected total cross-section uncertainty at FCC-ee: ~0.5%



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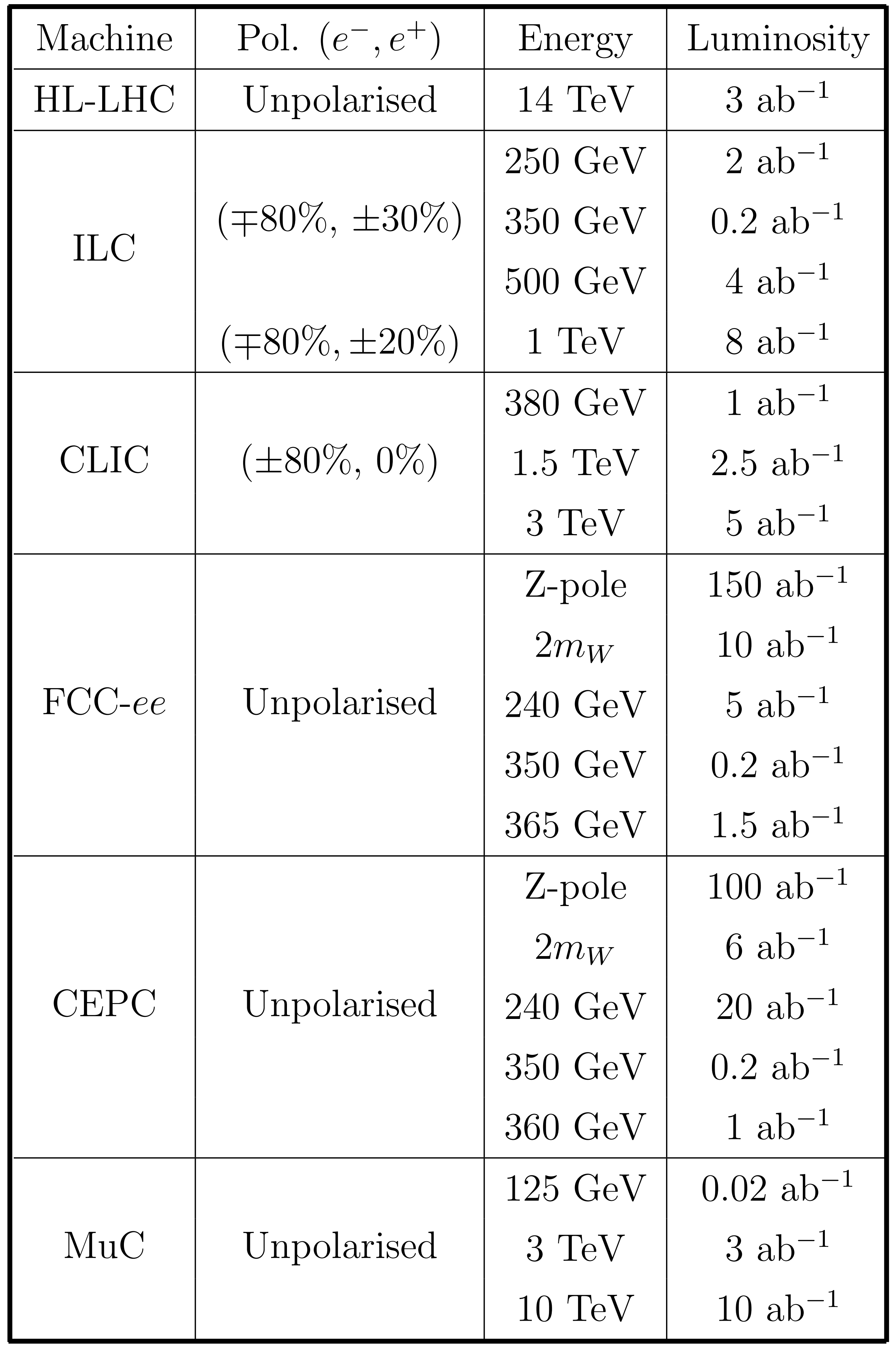
Bounds will be significantly better at the FCC-ee!

SMEFT prospects for FCC(-ee)

Snowmass study: arXiv: 2206.08326

	Higgs	diBoson (WW,WZ)	EWPO (Z pole, m_W, …)	Top
HL-LHC	Yes (μ)	**HL-LHC** **Full EFT param.**	LEP/SLD	**Yes**
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	**Full EFT param.**	**Updated** Yes	Yes (365 GeV, Ztt)

Update European Strategy study of de Blas et al., arXiv:1905.03764



Machine	Pol. (e^-, e^+)	Energy	Luminosity
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	$(\mp 80\%, \pm 30\%)$	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
	$(\mp 80\%, \pm 20\%)$	1 TeV	8 ab^{-1}
CLIC	$(\pm 80\%, 0\%)$	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

Setup:

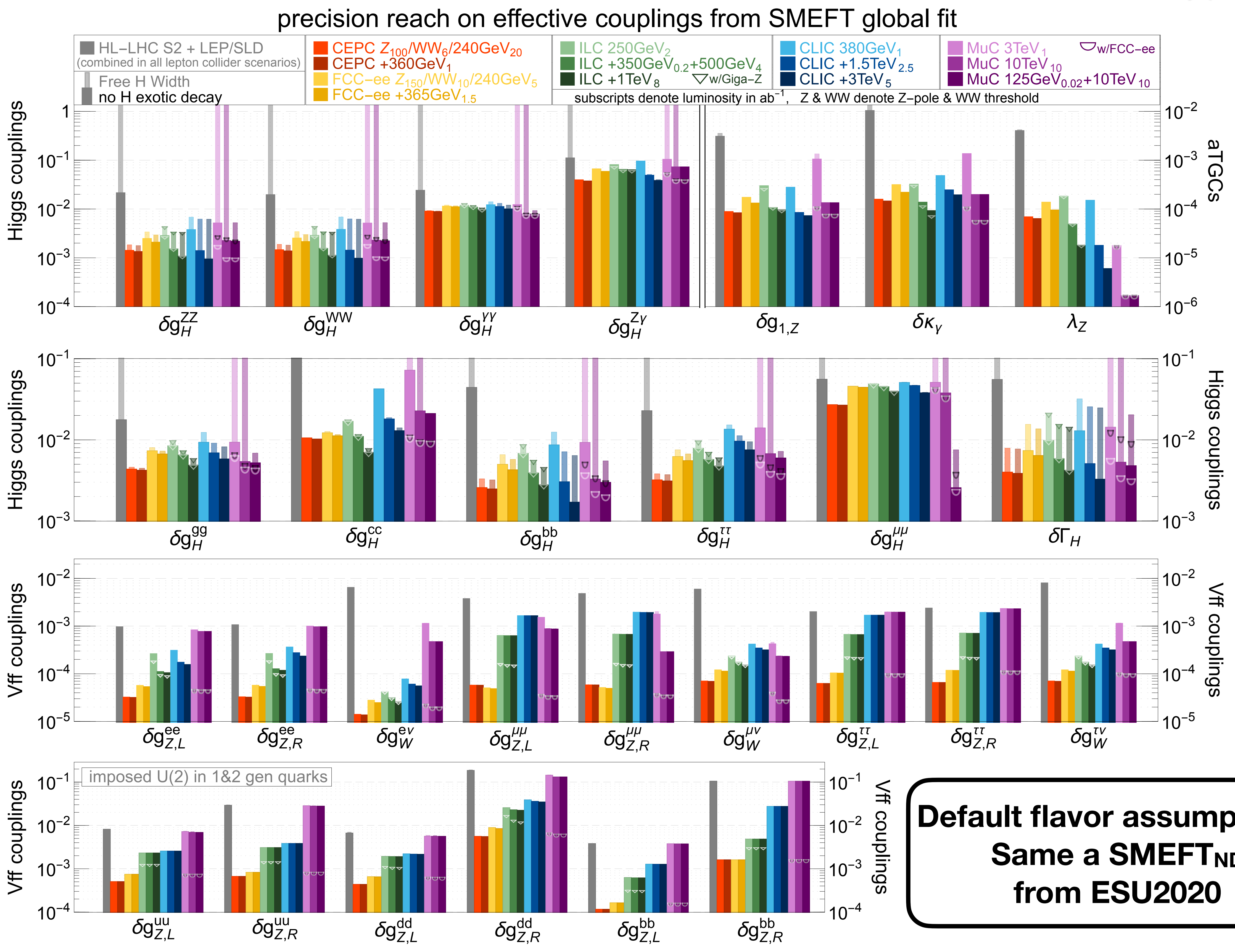
SMEFT truncated at linear level

CP-conserving

No 4-fermion operators (apart from Gf ones), no dipoles

Flavour universal (18 parameters) and flavour diagonal (30)

What we can learn: Higgs+EW



Default flavor assumptions:
Same a SMEFT_{ND}
from ESU2020

Snowmass study:
de Blas, Du, Grojean, Gu, Miralles, Peskin, Tian, Vos, EV arXiv: 2206.08326

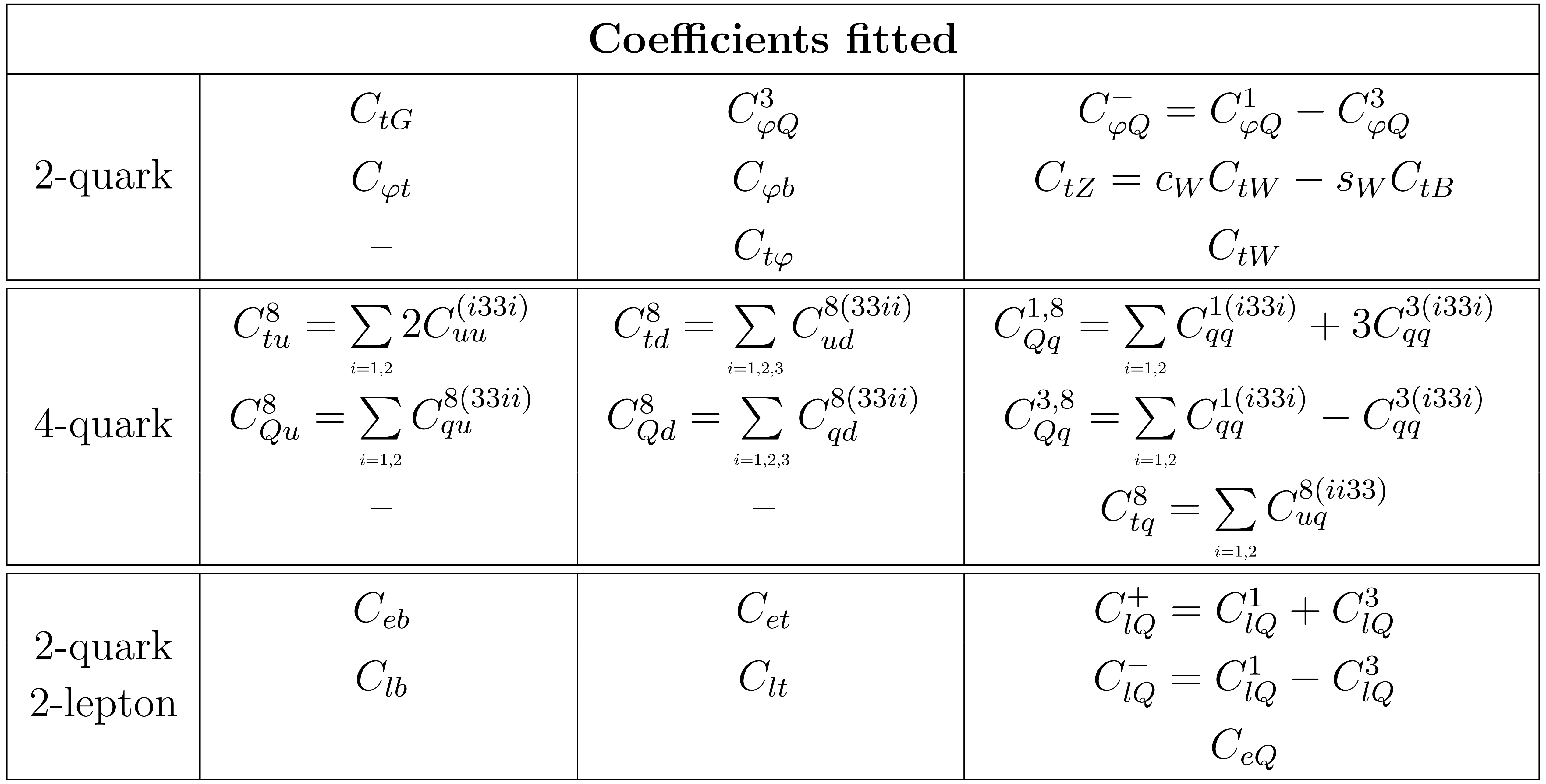
Busy plot: compare grey (HL-LHC) with yellow (FCC-ee) and dark yellow (FCC-ee+365)

- Typically FCC-ee improves bounds by more than an order of magnitude compared to HL
- This is true for both Higgs couplings and Vff couplings
- Improvement is not significant for Zγ, γγ, μμ (dominated by HL-LHC)

What we can learn: Top sector

Goals of the Snowmass study:

- Explore HL-LHC prospects
- Explore future collider prospects
- Do this in some some unified fit setup, with reasonable uncertainty assumptions

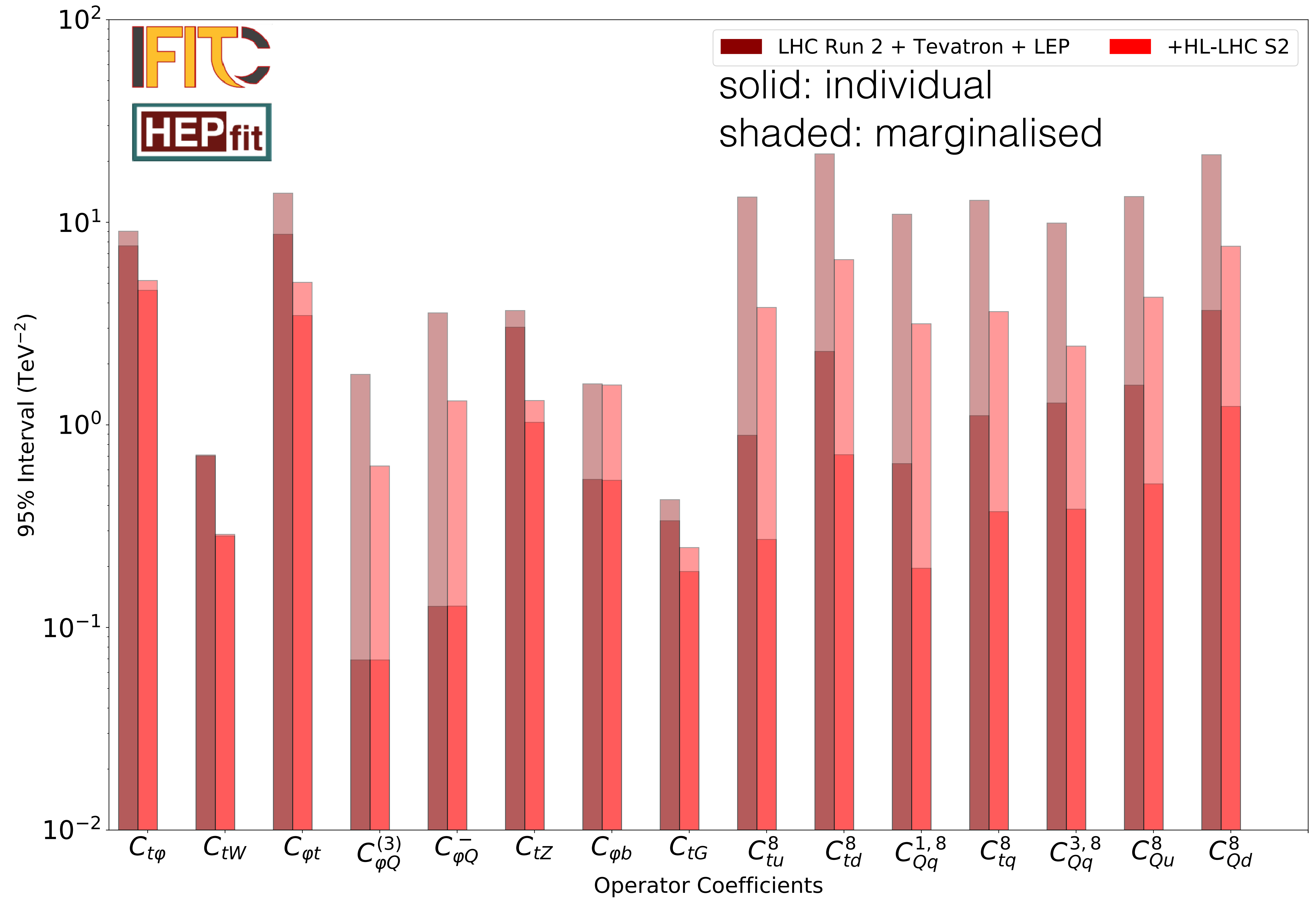


	Coefficients fitted		
2-quark	C_{tG} $C_{\varphi t}$ –	$C^{3}_{\varphi Q}$ $C_{\varphi b}$ $C_{t\varphi}$	$C^{-}_{\varphi Q} = C^{1}_{\varphi Q} - C^{3}_{\varphi Q}$ $C_{tZ} = c_W C_{tW} - s_W C_{tB}$ C_{tW}
4-quark	$C^{8}_{tu} = \sum_{i=1,2} 2C^{(i33i)}_{uu}$ $C^{8}_{Qu} = \sum_{i=1,2} C^{8(33ii)}_{qu}$ –	$C^{8}_{td} = \sum_{i=1,2,3} C^{8(33ii)}_{ud}$ $C^{8}_{Qd} = \sum_{i=1,2,3} C^{8(33ii)}_{qd}$ –	$C^{1,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$ $C^{3,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$ $C^{8}_{tq} = \sum_{i=1,2} C^{8(ii33)}_{uq}$
2-quark 2-lepton	C_{eb} C_{lb} –	C_{et} C_{lt} –	$C^{+}_{lQ} = C^{1}_{lQ} + C^{3}_{lQ}$ $C^{-}_{lQ} = C^{1}_{lQ} - C^{3}_{lQ}$ C_{eQ}

- Following Top WG note
- Only colour octet 2-light-2-heavy operators
- No 4-heavy operators (see later)
- Only linear $\mathcal{O}(1/\Lambda^2)$contributions

Durieux, Gutierez, Mantani, Miralles, Mirrales, Moreno, Poncelet, EV, Vos arXiv:2205.02140

LHC vs HL-LHC



solid: individual

shaded: marginalised

arXiv:2205.02140

Best improvement: 4-fermion operators driven by differential measurements extending to higher energies

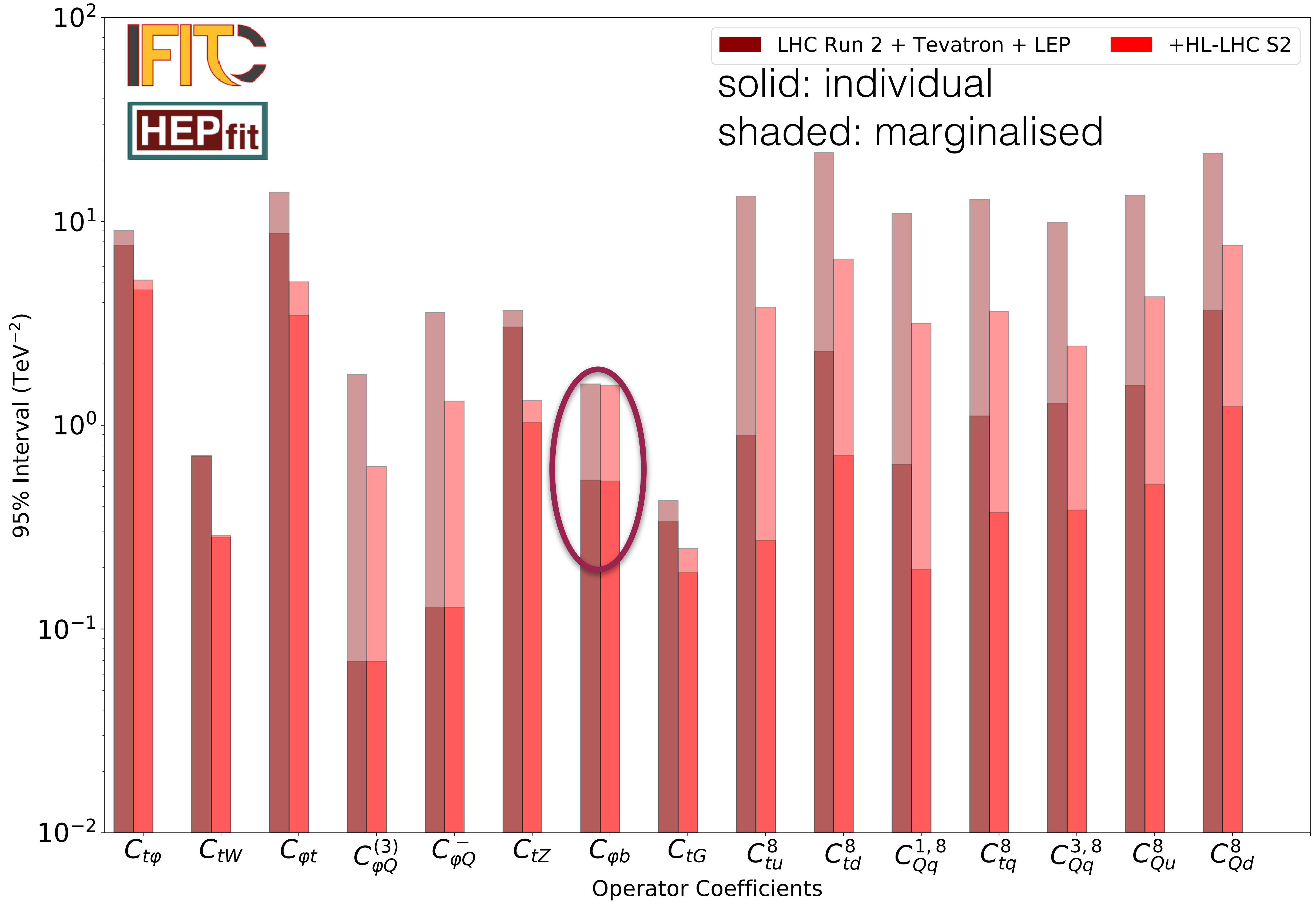
Not much improvement $C_{\phi Q}^{-}$ and $C_{\phi Q}^{3}$ (dominated by b at LEP but better at FCC)

Limited by theory and modelling uncertainties

2-quark-2-lepton not fitted (need $t\bar{t}\ell\bar{\ell}$)

Difference in individual and marginalised limits persists at HL for 4-fermion operators

LHC vs HL-LHC



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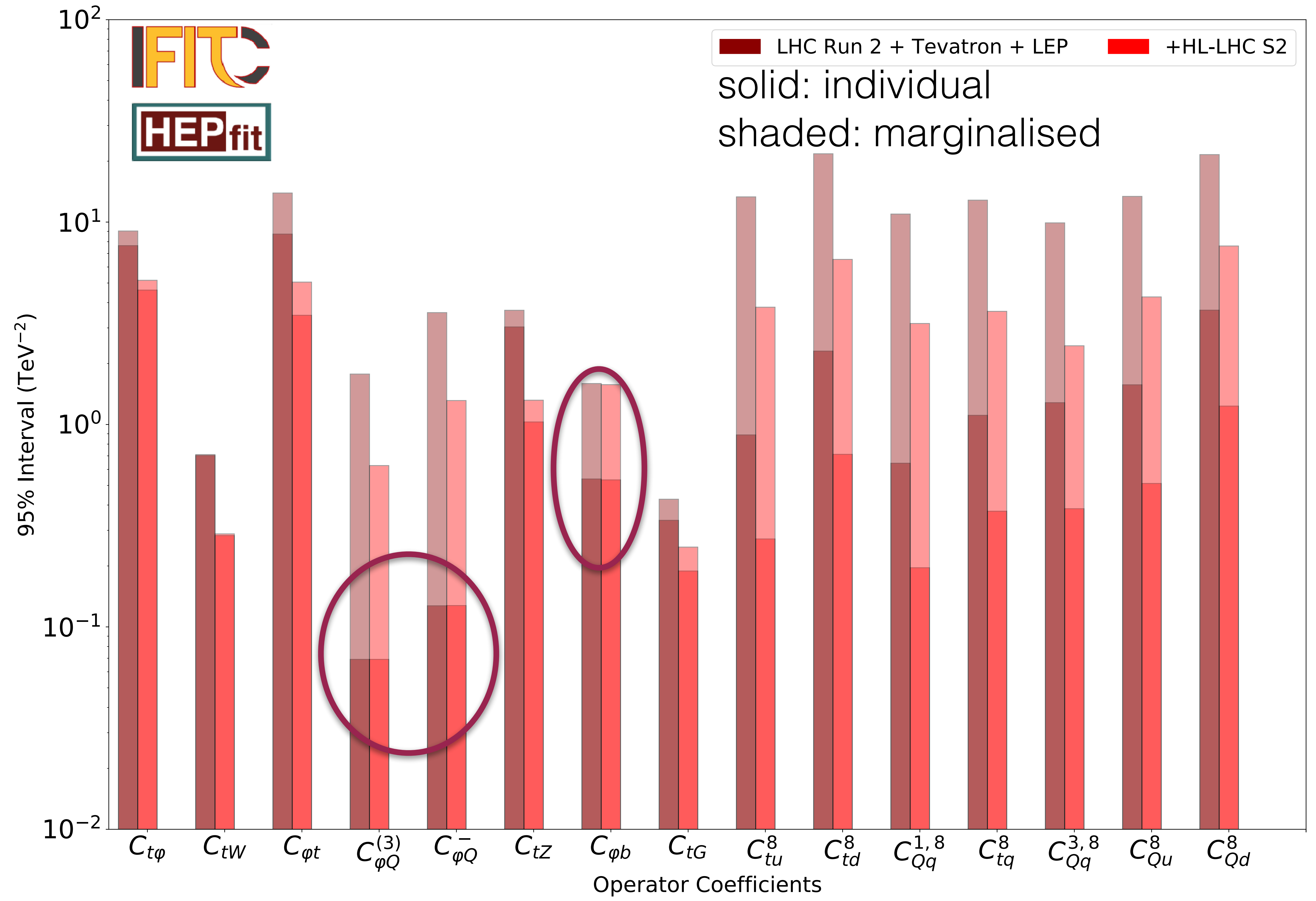

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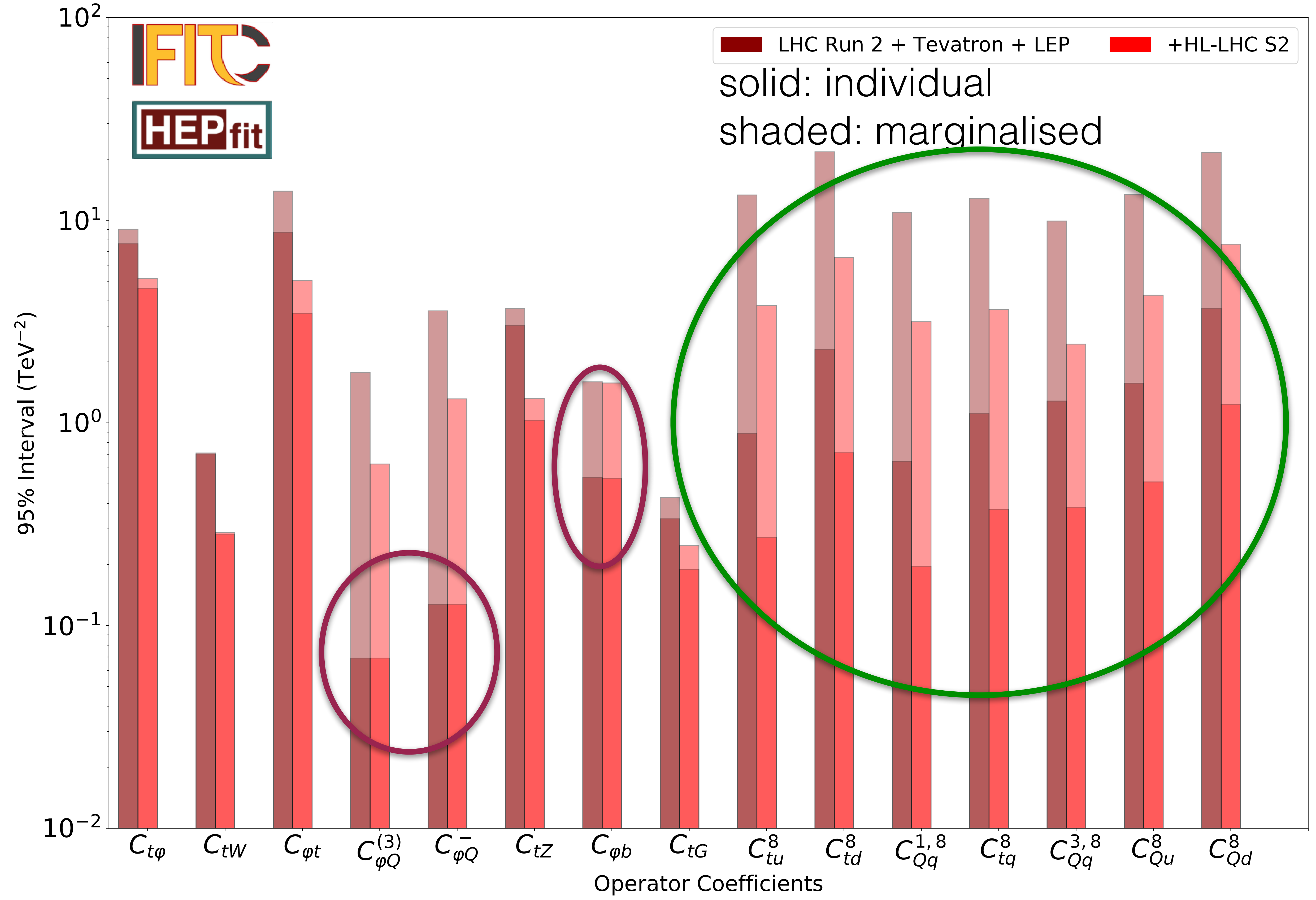

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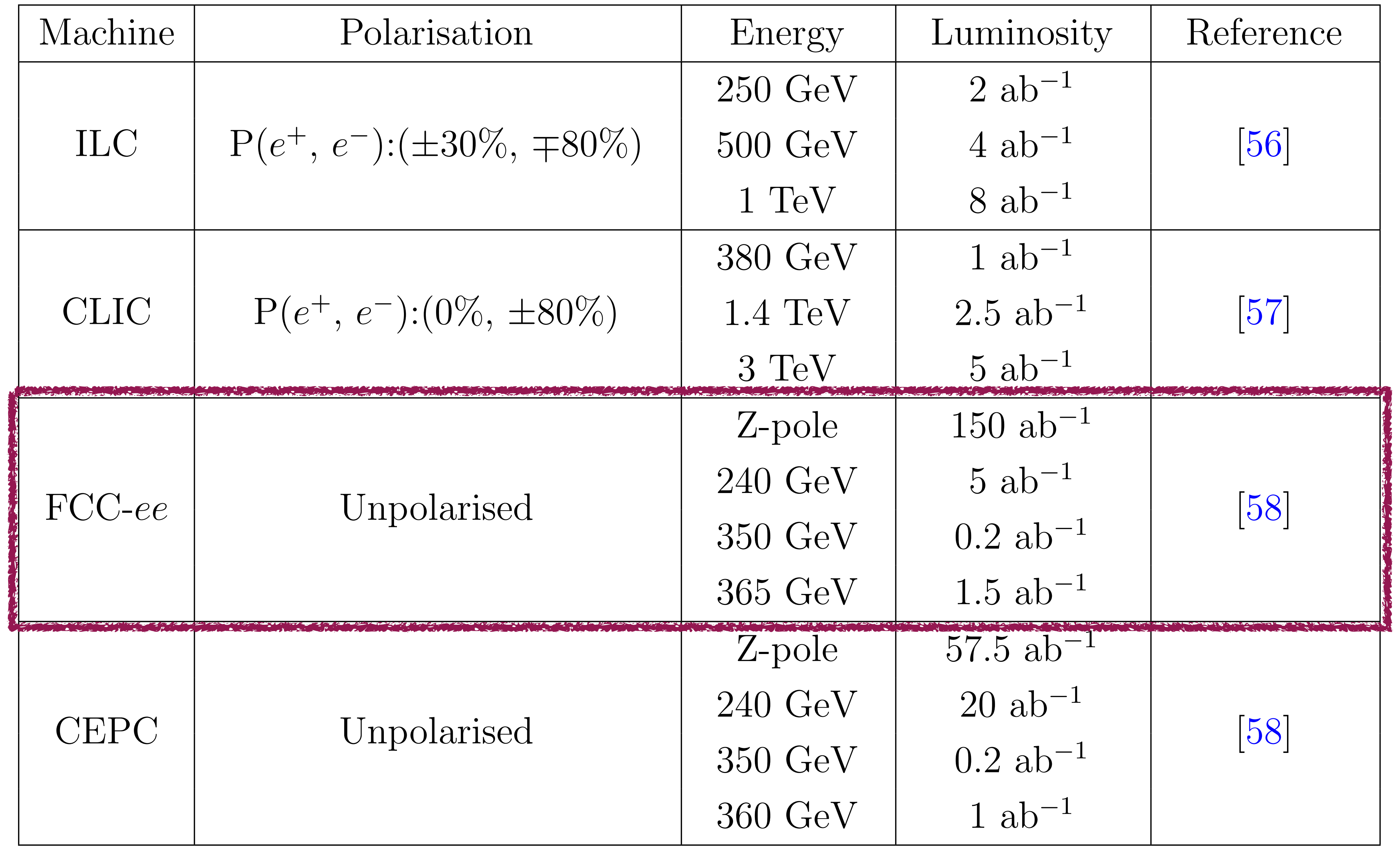
Top quarks at future lepton colliders

Scenarios considered:



Machine	Polarisation	Energy	Luminosity	Reference
ILC	P(e^+, e^-):(±30%, ∓80%)	250 GeV 500 GeV 1 TeV	2 ab^{-1} 4 ab^{-1} 8 ab^{-1}	[56]
CLIC	P(e^+, e^-):(0%, ±80%)	380 GeV 1.4 TeV 3 TeV	1 ab^{-1} 2.5 ab^{-1} 5 ab^{-1}	[57]
FCC-*ee*	Unpolarised	Z-pole 240 GeV 350 GeV 365 GeV	150 ab^{-1} 5 ab^{-1} 0.2 ab^{-1} 1.5 ab^{-1}	[58]
CEPC	Unpolarised	Z-pole 240 GeV 350 GeV 360 GeV	57.5 ab^{-1} 20 ab^{-1} 0.2 ab^{-1} 1 ab^{-1}	[58]

Observables:

$e^+e^- \to b\bar{b}$: σ_b, A^b_{FB}

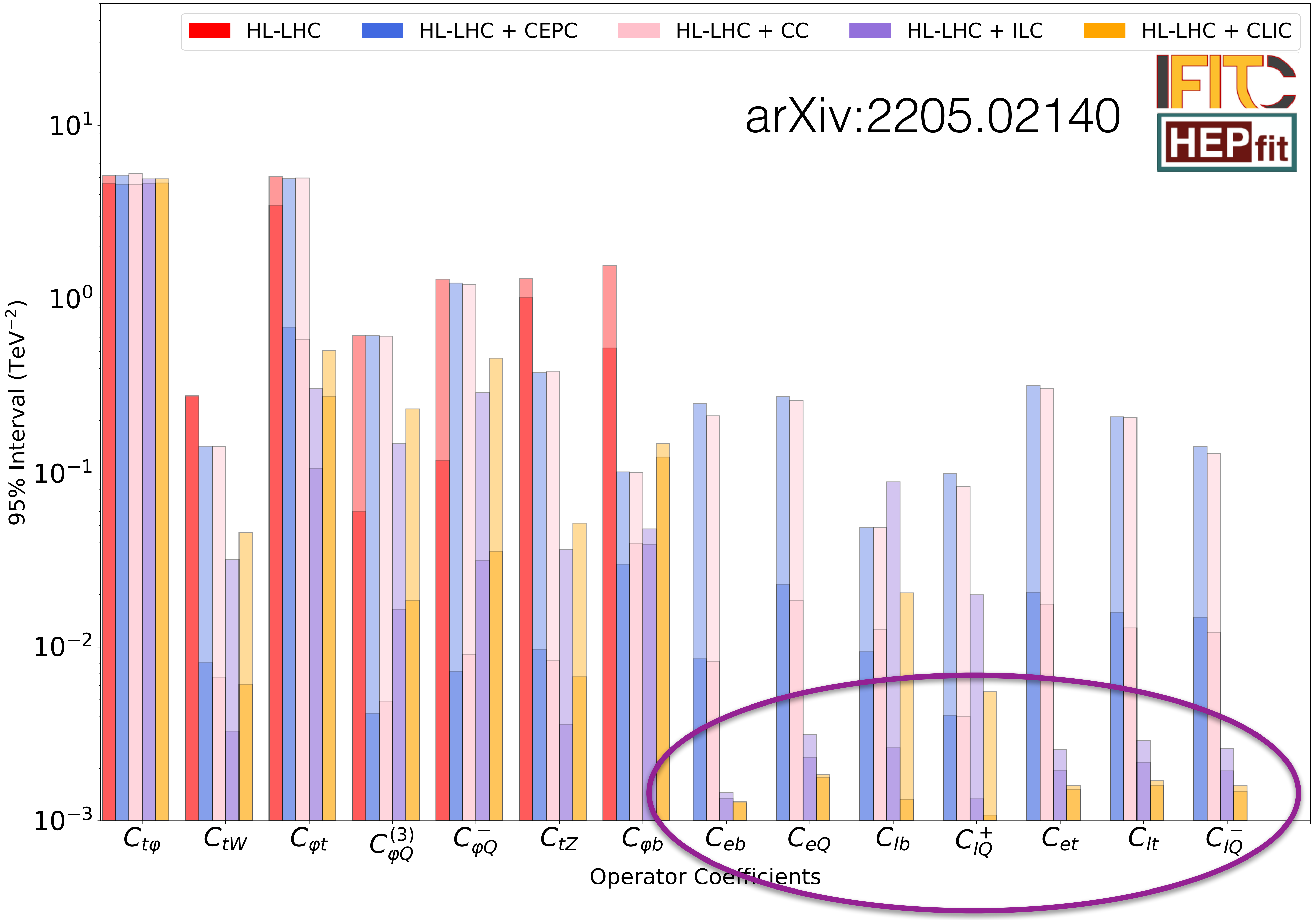
$e^+e^- \to t\bar{t}$: optimal observable constraints from arXiv:1807.02121 for ILC, CLIC, FCC-ee, CEPC

Optimal observables based on $WbWb$

Input from arXiv:1807.02121 bounds for ttZ and top-lepton 4F operators

ttH is not included here for ILC and CLIC

Putting everything together



FCC-ee improves: ttZ, bbZ, tbW

First access to ttll interactions with runs above the threshold

No bounds for 2Q2l operators at the (HL)LHC, no 4Q bounds for lepton colliders
Runs above ttbar threshold needed for constraining 2Q2l well
Extremely well bounded at higher energy lepton colliders

Pushing the energy frontier

How about top quarks at the FCC-hh?

No full study but expect much better sensitivity:

LHC14

$$\sigma(m_{t\bar{t}} > 1.4\ \mathrm{TeV}) = 1.8\ \mathrm{pb} \times [1 + 0.3 \cdot C_{tG} + 0.1 \cdot C_{tG}^2 + 0.1 \cdot C_{tu}^8 + 0.3 \cdot (C_{tu}^8)^2 + \ldots]$$

FCC-hh

$$\sigma(m_{t\bar{t}} > 10\ \mathrm{TeV}) = 0.1\ \mathrm{pb} \times [1 + 0.3 \cdot C_{tG} + 1.8 \cdot C_{tG}^2 + 3 \cdot C_{tu}^8 + 256 \cdot (C_{tu}^8)^2 + \ldots]$$

Expect bounds to improve from $\mathcal{O}(1\mathrm{TeV}^{-2})$ down to $\mathcal{O}(0.1\mathrm{TeV}^{-2})$

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FCC-hh

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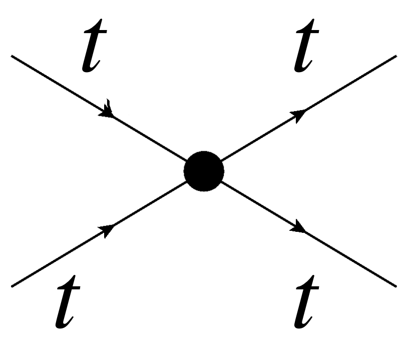
Where can the FCC-hh help?

4-heavy operators



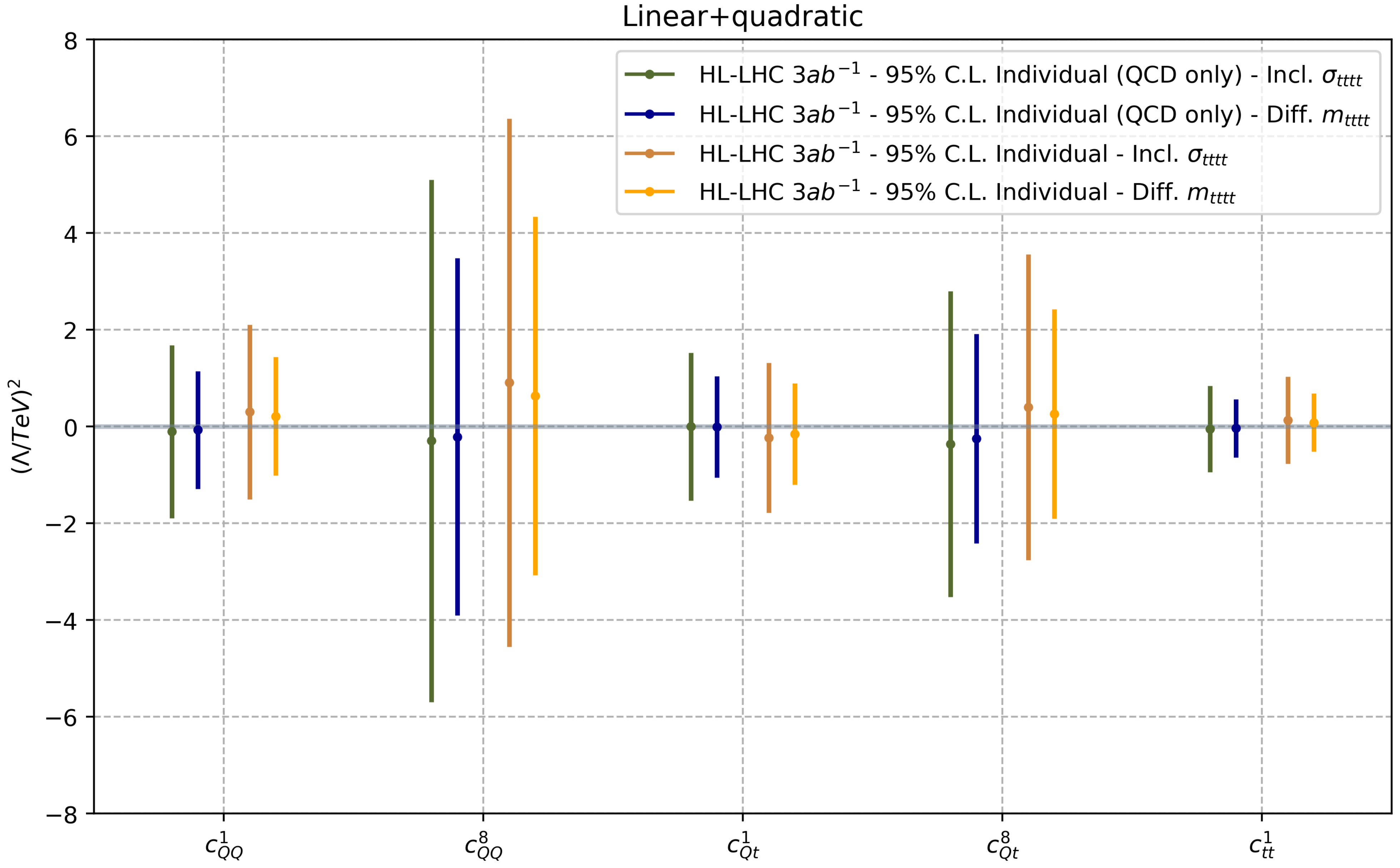
$$\mathcal{O}^8_{QQ} = (\bar{Q}\gamma^\mu T^A Q)(\bar{Q}\gamma_\mu T^A Q)$$

$$\mathcal{O}^1_{QQ} = (\bar{Q}\gamma^\mu Q)(\bar{Q}\gamma_\mu Q)$$

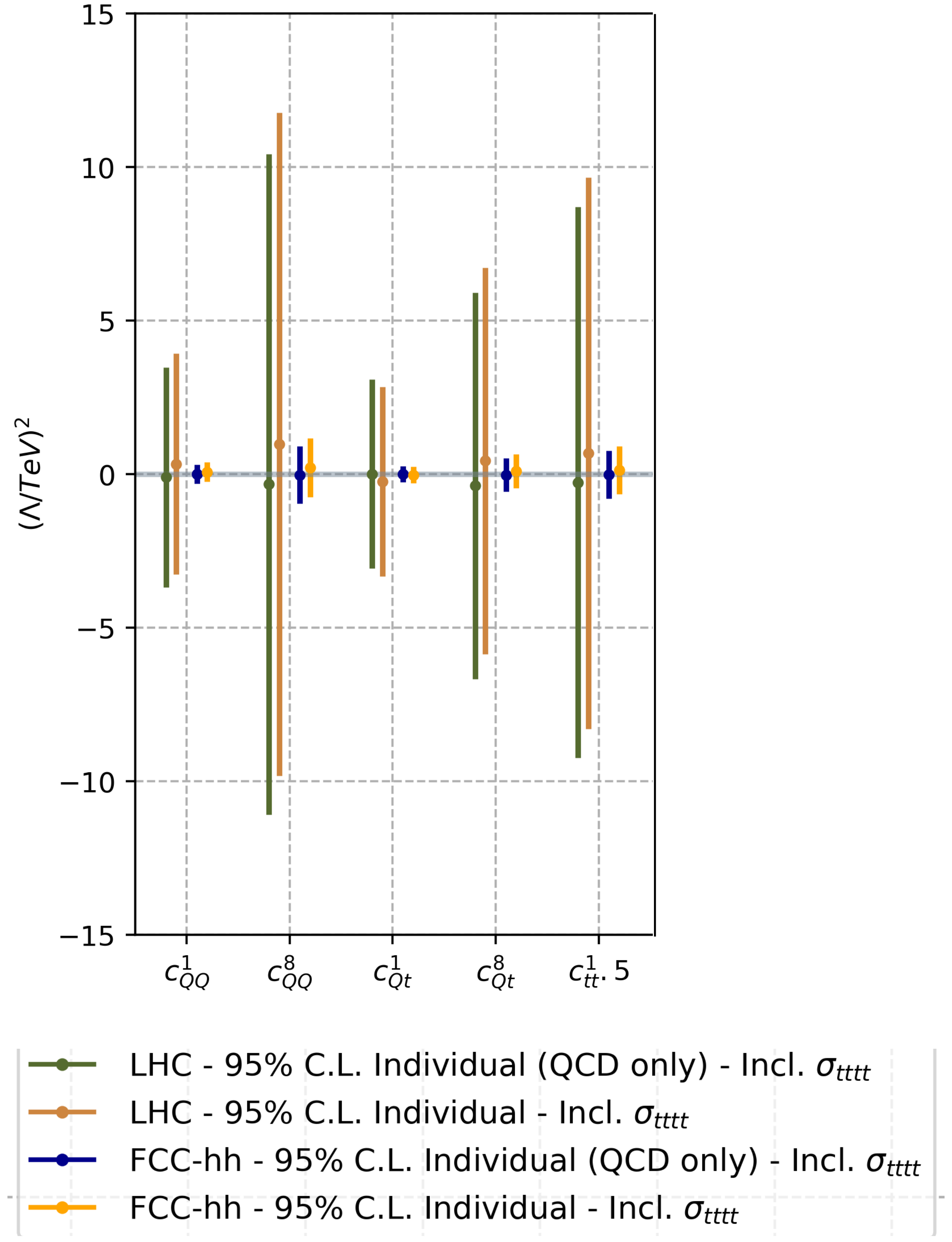
$$\mathcal{O}^8_{Qt} = (\bar{Q}\gamma^\mu T^A Q)(\bar{t}\gamma_\mu T^A t)$$

$$\mathcal{O}^1_{Qt} = (\bar{Q}\gamma^\mu Q)(\bar{t}\gamma_\mu t)$$

$$\mathcal{O}^1_{tt} = (\bar{t}\gamma^\mu t)(\bar{t}\gamma_\mu t)$$



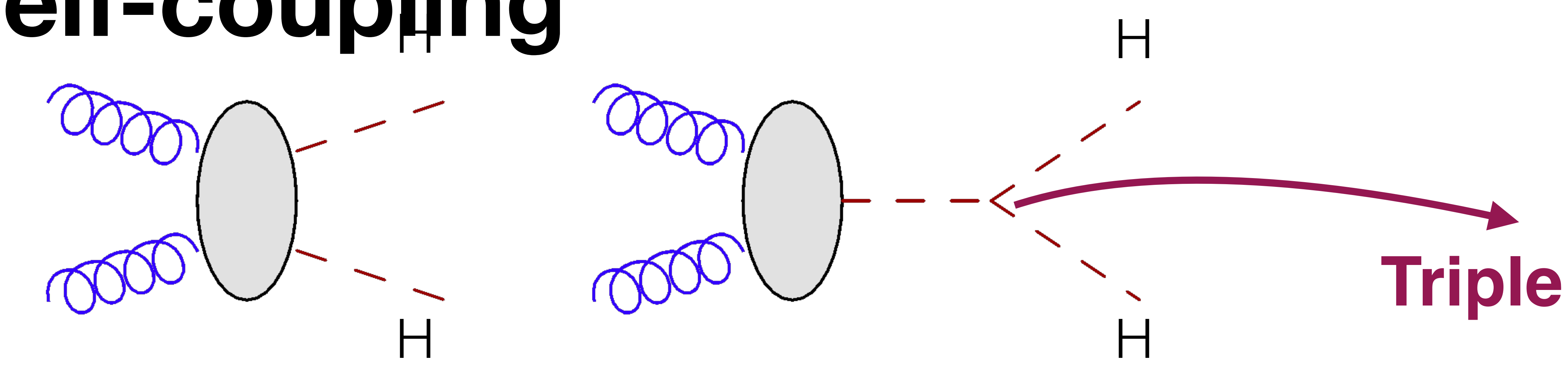
Aoude, El Faham, Maltoni, EV arXiv:2208.04962



HL-LHC differential information helps
FCC needed to really pin down these coefficients

Knowing the top helps us know the Higgs

Example: Higgs self-coupling



Triple Higgs coupling

Constraints

$O_{t\phi} = \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}\,,$ → Inclusive H, Higgs plus jets, ttH

$O_{\phi G} = \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$ → Inclusive H, Higgs plus jets, ttH

$O_{tG} = (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$ → tt, ttH, ttV….

$O_H = (\partial_\mu (\phi^\dagger \phi))^2$ → All Higgs couplings

$O_6 = (\phi^\dagger \phi)^3$ → HH (single Higgs@NLO)

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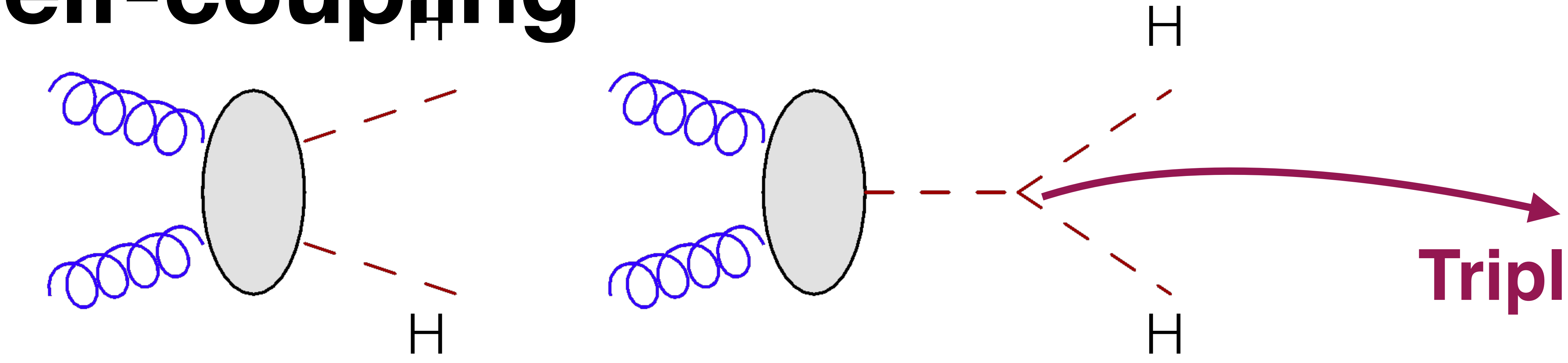

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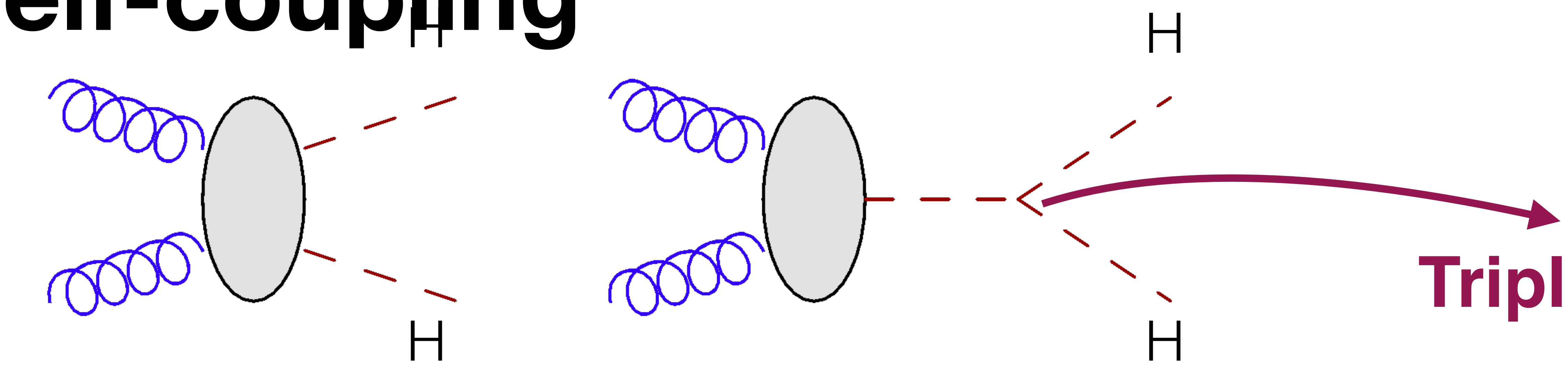

Triple Higgs coupling

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$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$	tt, ttH, ttV….
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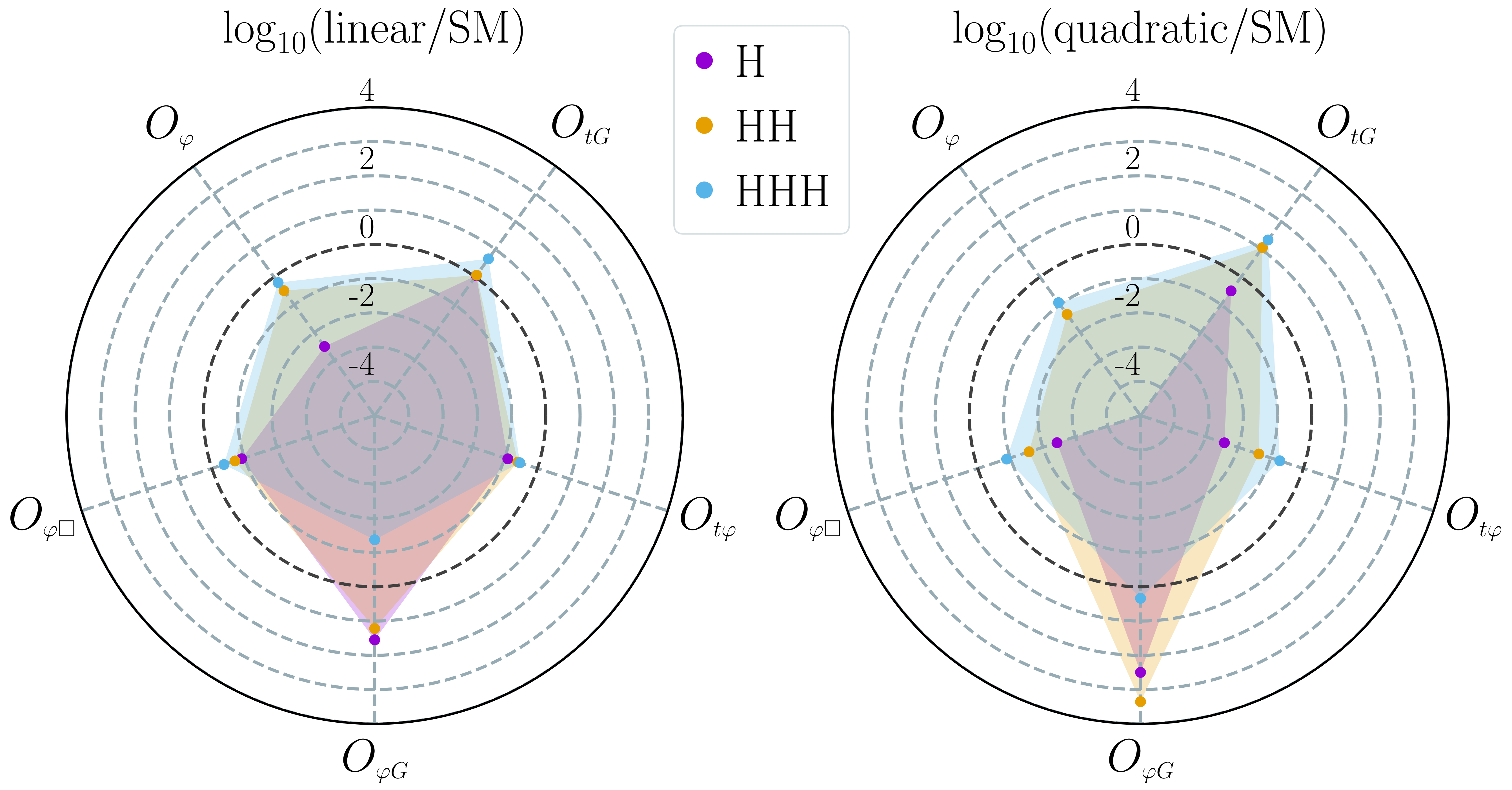
HH(H) at FCC-hh

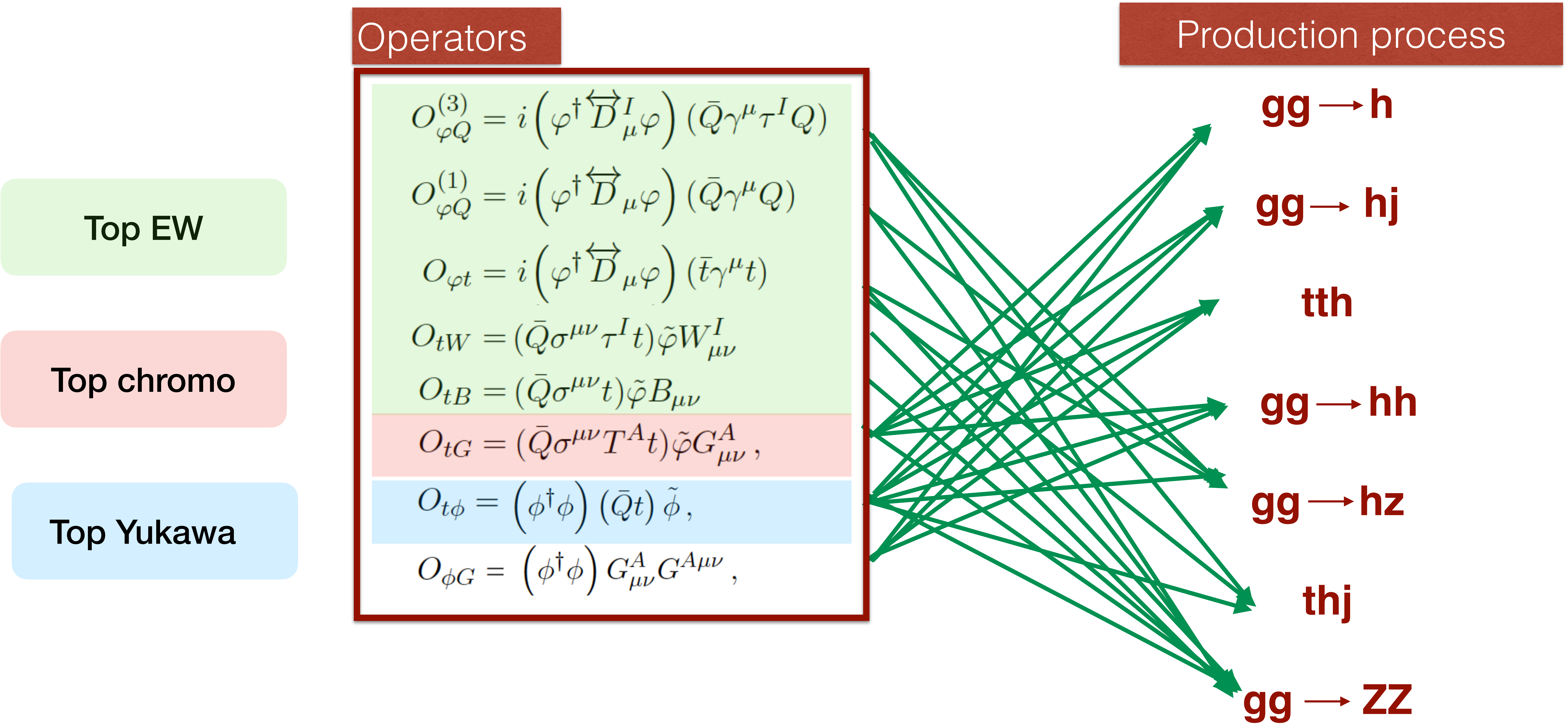


Different sensitivity patterns for H, HH and HHH in SMEFT

Differential distributions in HH and HHH cross-section can help

FCC-hh reach: 1%, 5% and 50% on H, HH and HHH cross-sections

Broader Higgs-top interplay



Top EW

Top chromo

Top Yukawa

Operators

$$O^{(3)}_{\varphi Q} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$

$$O^{(1)}_{\varphi Q} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

$$O_{\varphi t} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{t\phi} = \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}\,,$$

$$O_{\phi G} = \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}\,,$$

Production process

gg → h

gg → hj

tth

gg → hh

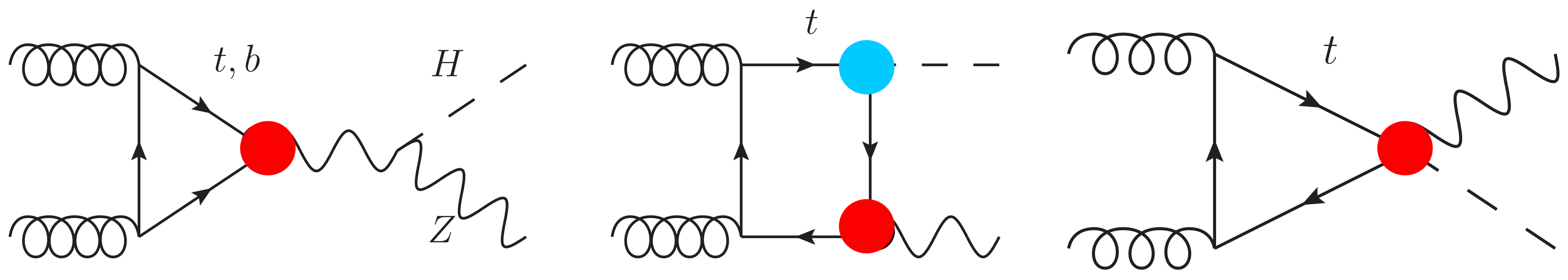
gg → hz

thj

gg → ZZ

Top-Higgs are deeply connected

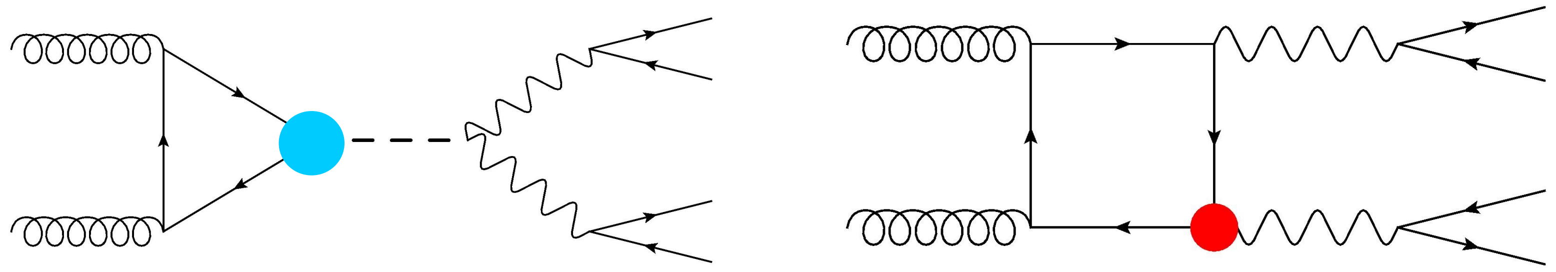
Why are loop processes so important?



ZH production

$\mathscr{M}_{++00} \sim$

$\mathcal{O}_{\varphi t}$ 🔴	$\mathcal{O}_{\varphi Q}^{(-)}$ 🔴	$\mathcal{O}_{t\varphi}$ 🔵
$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v\, e\, g_s^2}{32\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t\, v^2\, e\, g_s^2}{32\sqrt{2}\pi^2\, m_Z\, c_W\, s_W}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$



ZZ production

$\mathscr{M}_{++00} \sim$

$\mathcal{O}_{t\varphi}$ 🔵	$\mathcal{O}_{\varphi t}$ 🔴	$\mathcal{O}_{\varphi Q}^{(-)}$ 🔴
$\frac{m_t\, v^3\, e^2\, g_s^2}{128\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$	$\frac{m_t^2\, v^2\, e^2\, g_s^2}{32\sqrt{2}\,\pi^2\, m_Z^2\, c_W^2\, s_W^2}\left[\log\left(\frac{s}{m_t^2}\right) - i\pi\right]^2$

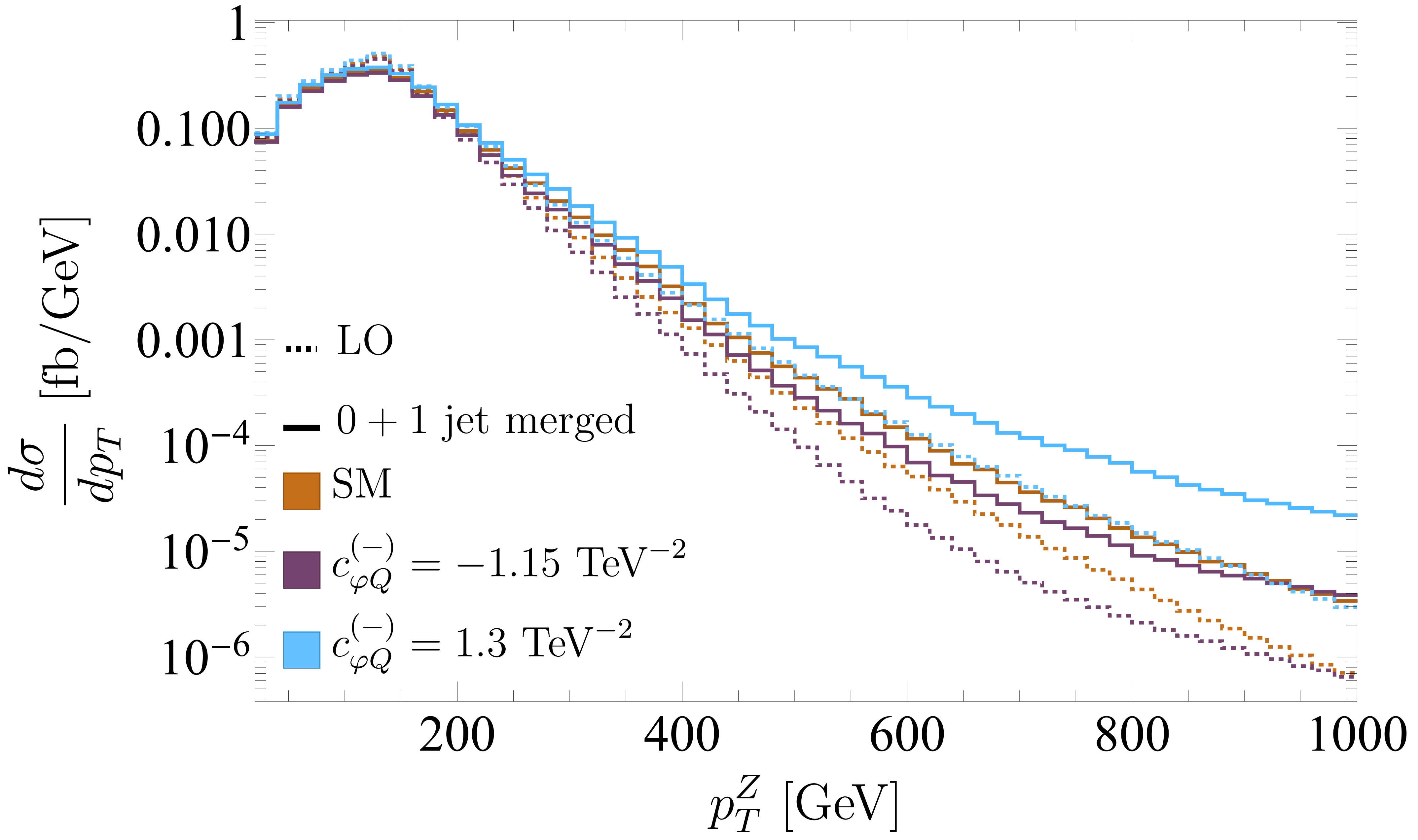
Logarithmic energy growth in one-loop helicity amplitudes

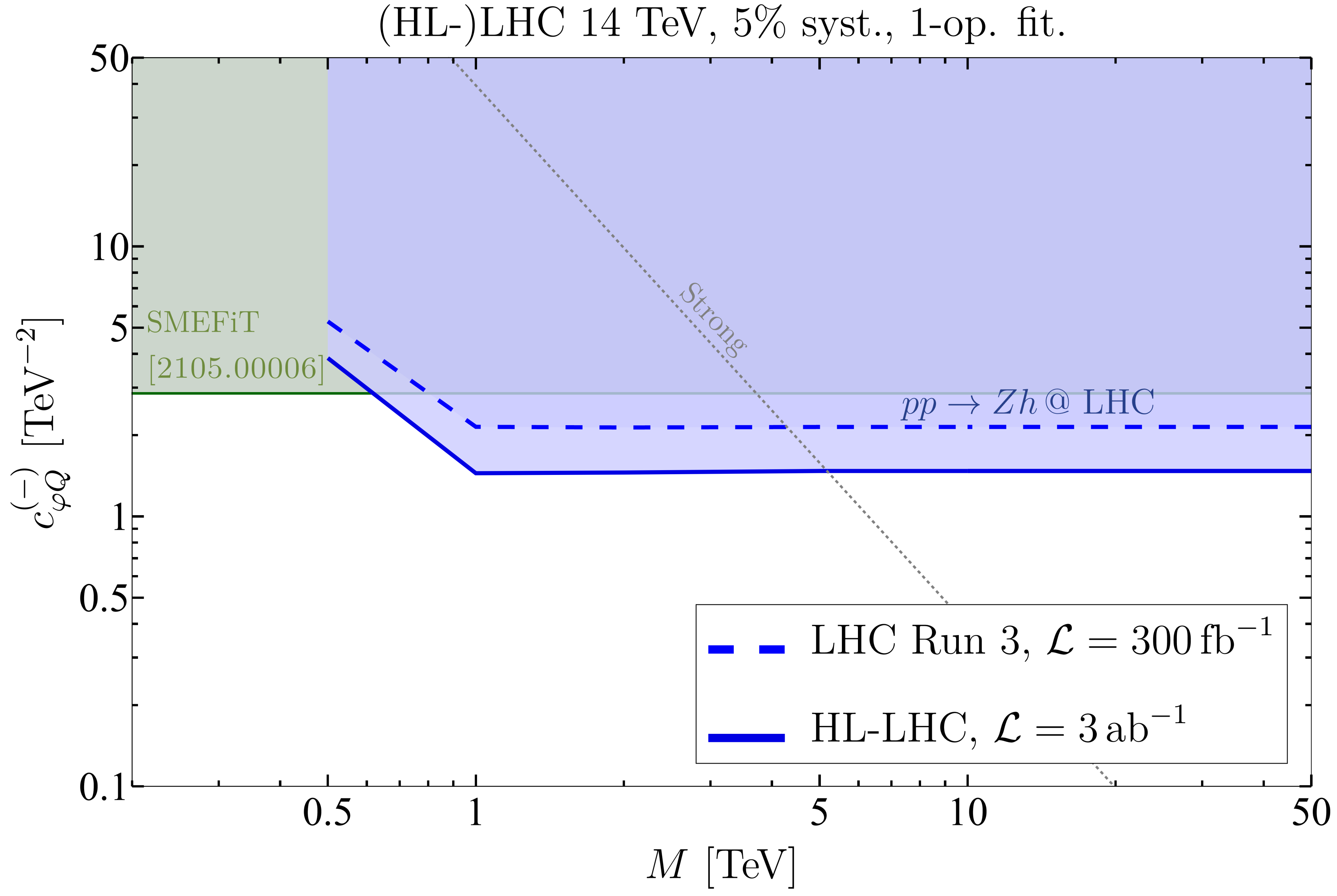
Rossia, Thomas, EV arXiv:2306.09963

Impact of loops on precision

Can we use these growing amplitudes to probe unconstrained couplings?

Test Case: analysis of ZH production@LHC





Rossia, Thomas, EV arXiv:2306.09963

IMPROVEMENT OF CONSTRAINTS ON TOP-Z COUPLINGS

FCC-hh perfect place to explore high-energy region

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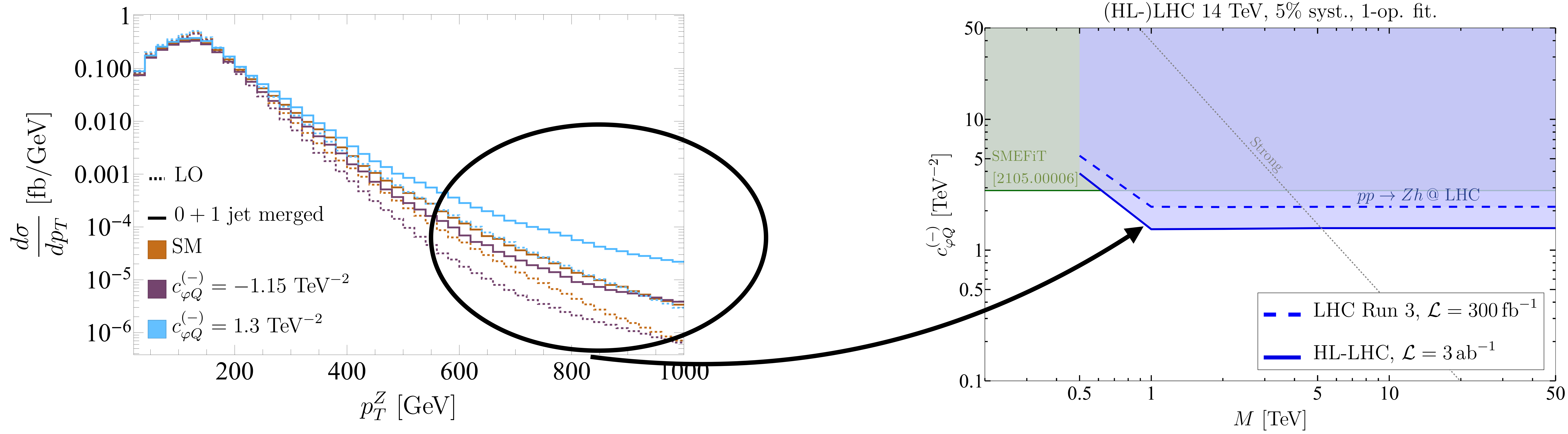

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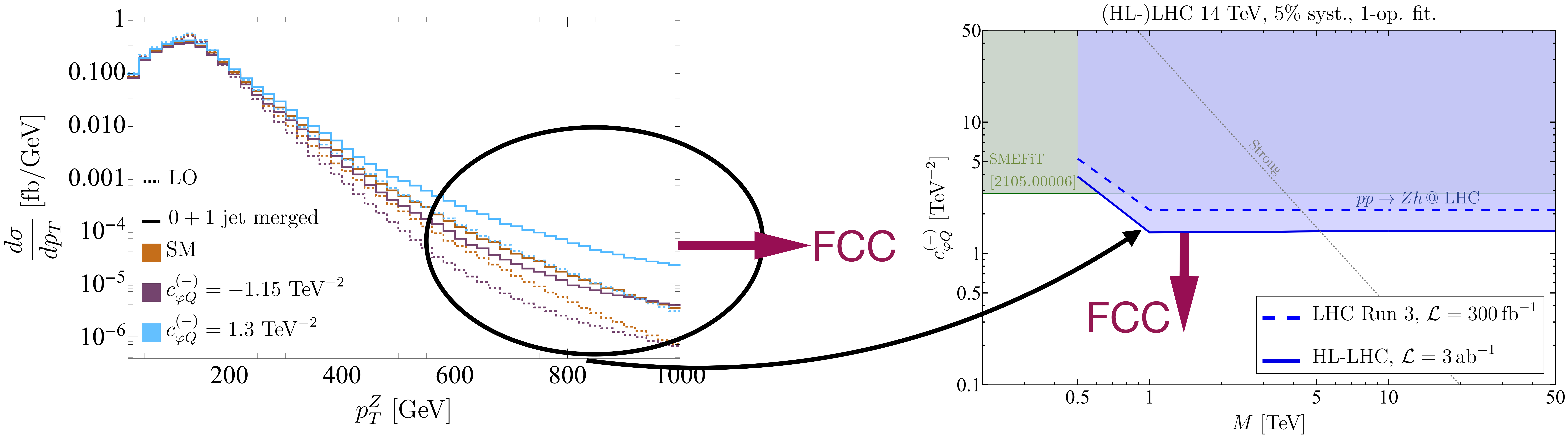


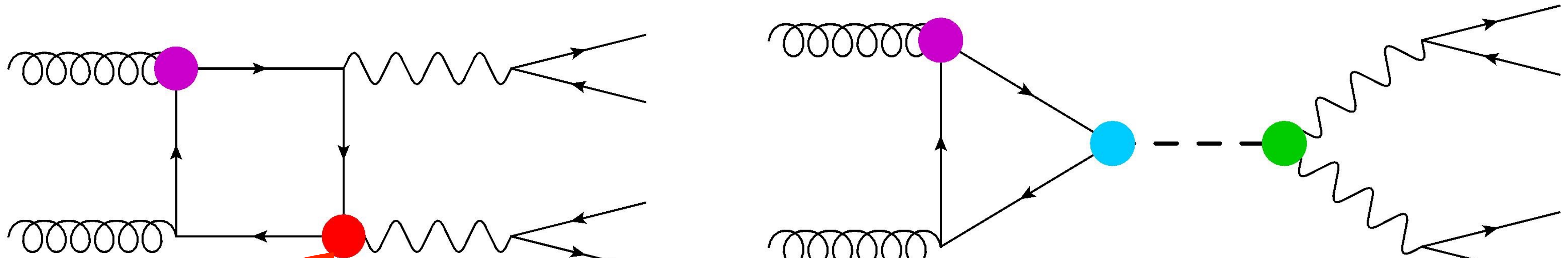
Rossia, Thomas, EV arXiv:2306.09963

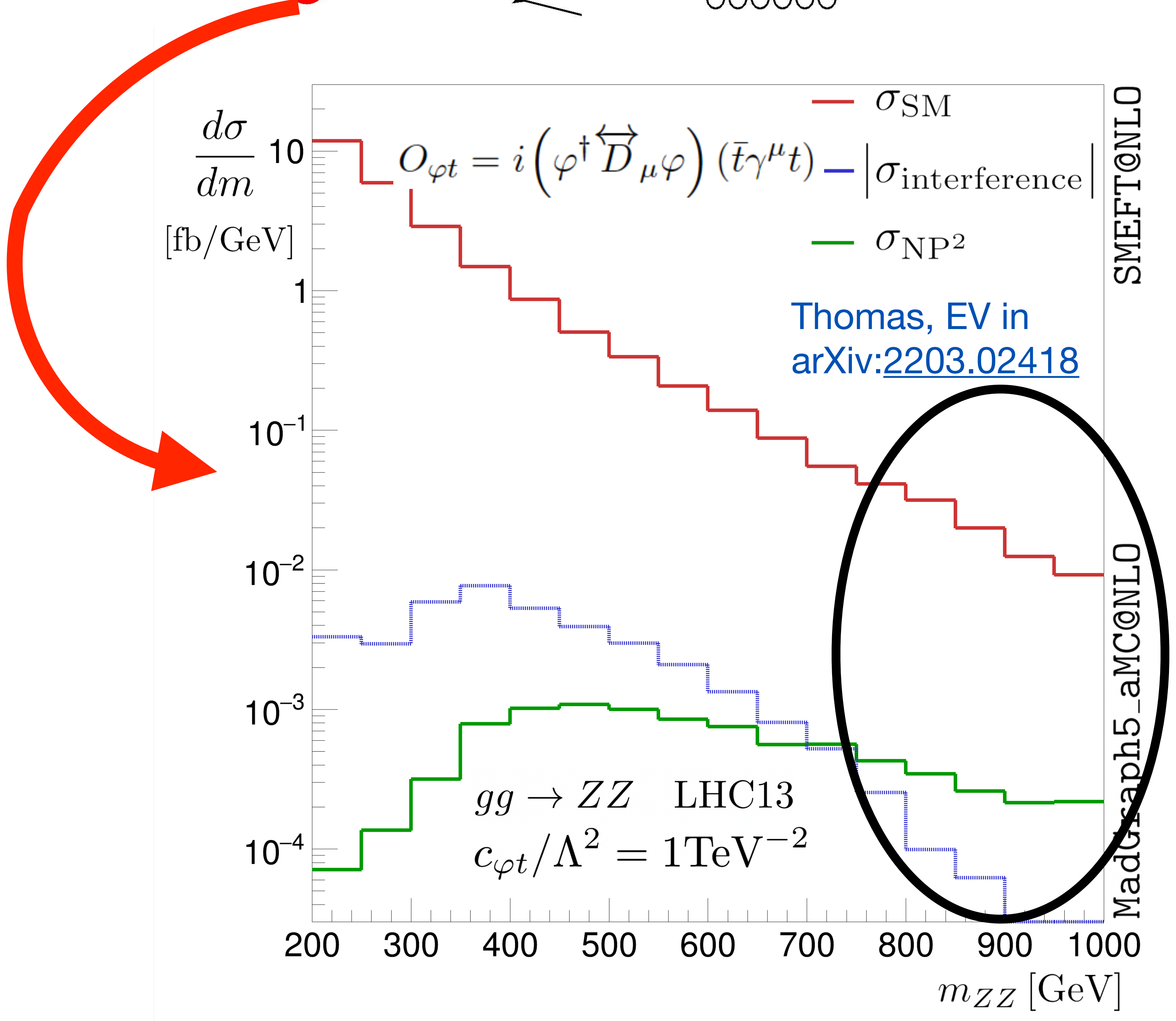
IMPROVEMENT OF CONSTRAINTS ON TOP-Z COUPLINGS

FCC-hh perfect place to explore high-energy region

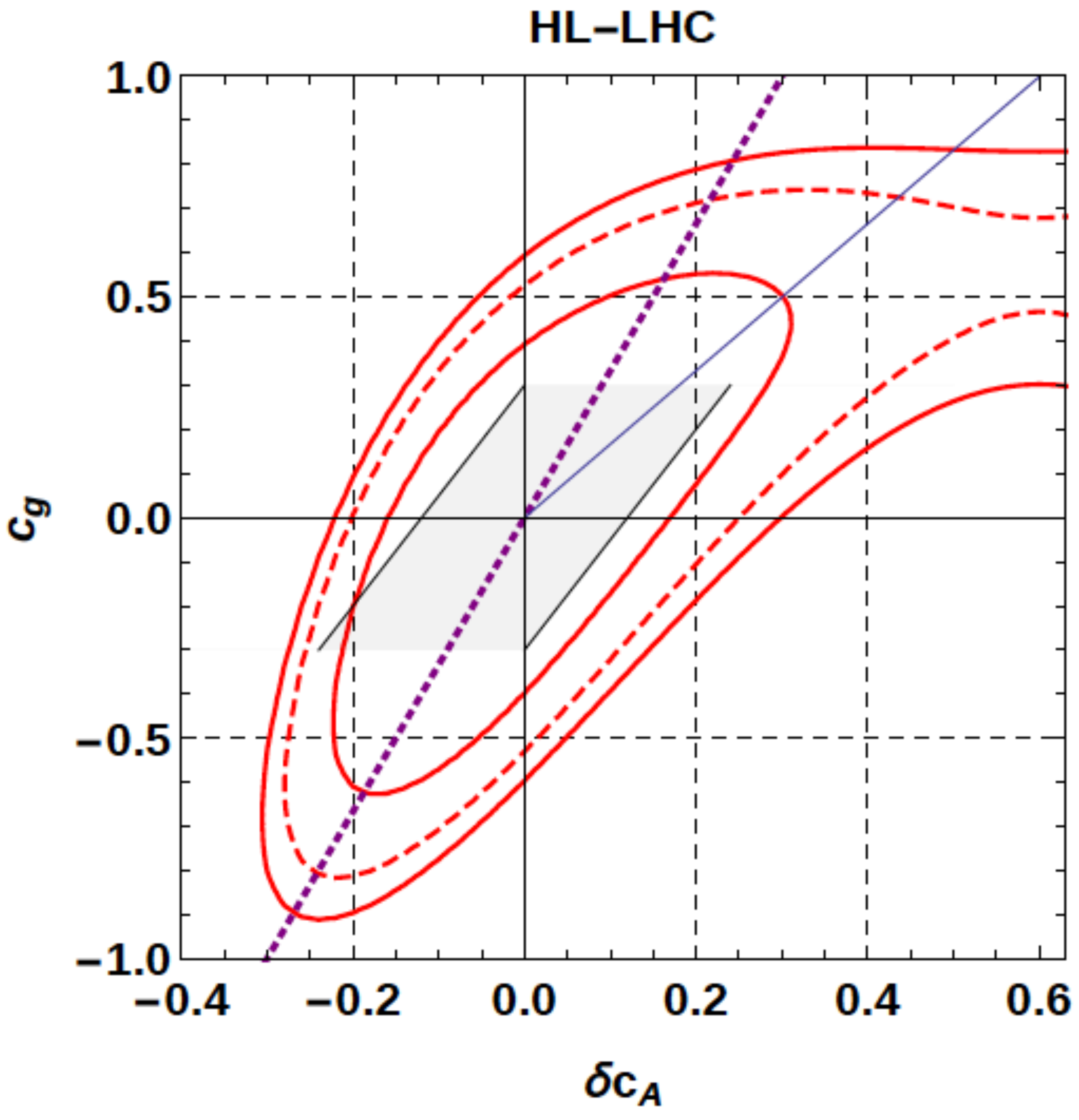
What can the Higgs tell us about the top?

Diboson (off-shell Higgs) sensitivity to top couplings





Thomas, EV in arXiv:2203.02418



Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

See also: Englert, Soreq, Spannowsky arXiv:1410.5440
Cao et al 2004.02031

Expect much better sensitivity@FCC

Dedicated studies for FCC welcome!

Conclusions

- FCC can provide a great testing ground for SMEFT, pushing in either the precision or energy reach
- Global SMEFT fits at FCC-ee show that one can improve over HL-LHC bounds by an order of magnitude in higgs and gauge-fermion couplings
- To access top couplings we need runs above the top threshold
- FCC-hh can significantly improve bounds on Vff and hVV couplings, as well as unconstrained 4-quark operators
- FCC-hh can probe energy growing amplitudes, improving sensitivity to poorly constrained interactions

Thanks for your attention