Future collider constraints on top-quark operators

Results from arXiv:2503.11518

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Introduction & LHC data

SM Effective Field Theory

$$\mathscr{L}_{\mathrm{SMEFT}} = \boxed{\mathscr{L}_{\mathrm{SM}}} + \sum_{\forall i, \mathscr{D} \geq 5} \frac{\boxed{C_i}\,\boxed{O_i^{(\mathscr{D})}}}{\boxed{\Lambda^{\mathscr{D}-4}}}$$

Standard Model:

- Dimension 4 terms
- Interactions between all SM fields

Coupling strength constant:

- Can be constrained in global fits

Higher-dimension operators:

- Effective interactions with SM fields

New physics scale:

- Power series expansion of $\mathscr{L}$
- Keeps correct dimensionality
- Set to Λ = 1 TeV

SM Effective Field Theory

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{\forall i, \mathscr{D} \geq 5} \frac{C_i O_i^{(\mathscr{D})}}{\Lambda^{\mathscr{D}-4}}$$

- **New physics** effects can be encapsulated in higher order ($\mathscr{D} = 6$) operators O_i in a power series of the new physics scale Λ.
- High precision data can be used to **constrain** the coupling strengths coefficients C_i in a global fit
- For a given observable X:

$$X = X_{\text{SM}} + \boxed{\frac{1}{\Lambda^2} \sum_i C_i X_i^{(1)}} + \boxed{\frac{1}{\Lambda^4} \sum_{ij} C_i C_j X_{ij}^{(2)}} + \mathcal{O}(\Lambda^{-4})$$

Linear Terms **Quadratic Terms**

Λ^{-4} terms are less dominant in multiTeV lepton colliders

Analysis Tools

- Many of the EFT calculations were performed at **NLO** using the MadGraph5_aMC@NLO generator
  - Using the SMEFT@NLO (NLO) and SMEFTsim (LO) models
  - Expanding not he results from JHEP 02 (2022) 032
- Fits have been obtained using HEPfit code
  - Employs MCMC algorithm, based on a Bayesian Analysis of data

Global fit to the LHC (+ others)

- **Many** observables, **many** coefficients

$t\bar{t}H$

$C_{t\varphi}$

F_L, F_R

C_{tW}

$t\bar{t}, A_C^{t\bar{t}}$

C_{qqQQ}, C_{tG}

$t\bar{t}Z, t\bar{t}\gamma$

$C_{tW}, C_{\varphi Q}, C_{llQQ}$

R_b, A_{FBLR}^{bb}

$C_{\varphi Q}, C_{bW}$

D, D_n

C_{qqQQ}

Global fit to the LHC (+ others)

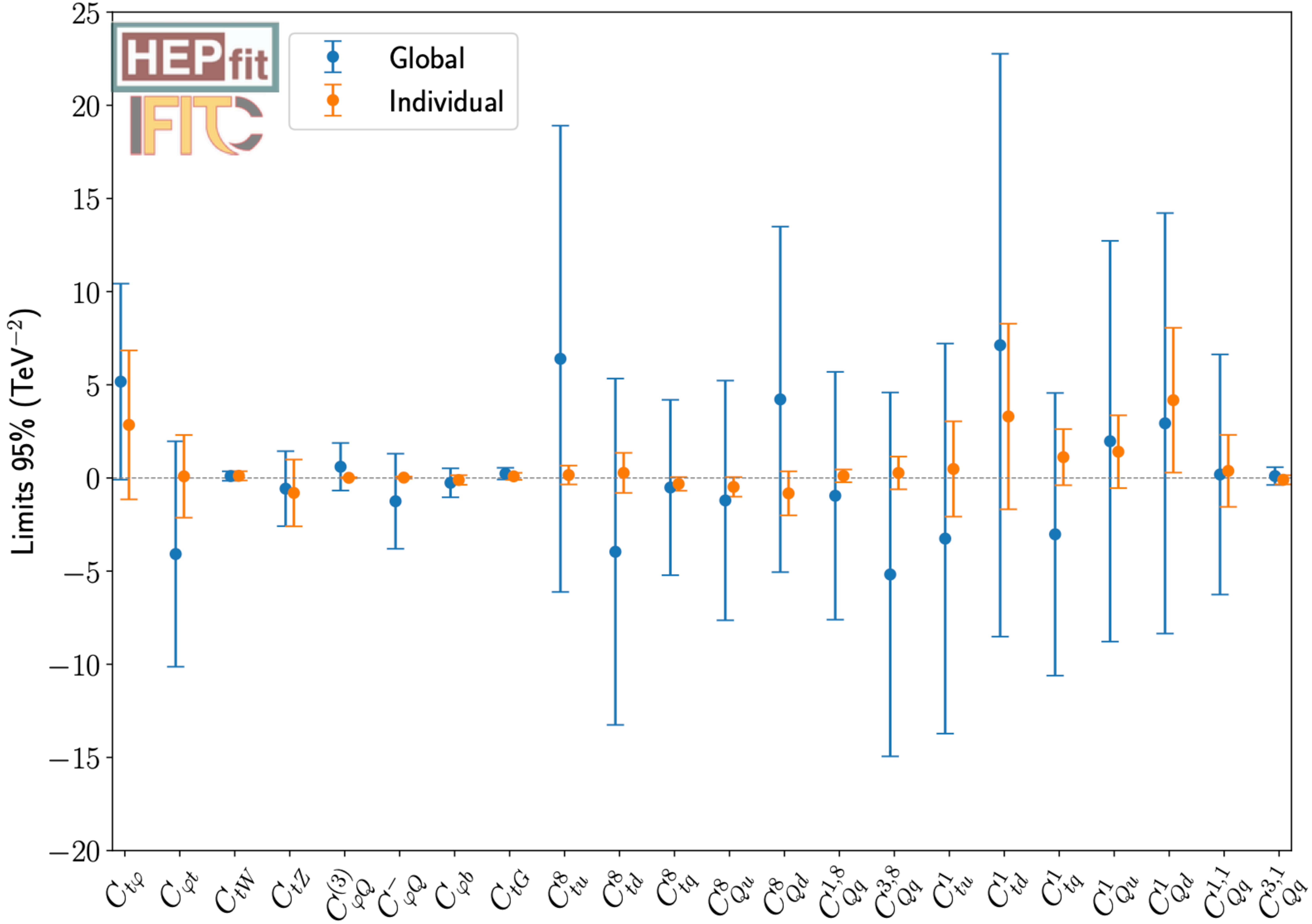
Coefficients

2-quark	C_{tG}	$C^3_{\varphi Q}$	$C^-_{\varphi Q} = C^1_{\varphi Q} - C^3_{\varphi Q}$
	$C_{\varphi t}$	$C_{\varphi b}$	$C_{tZ} = c_W C_{tW} - s_W C_{tB}$
	–	$C_{t\varphi}$	C_{tW}
4-quark	$C^8_{tu} = \sum_{i=1,2} 2C^{(i33i)}_{uu}$	$C^8_{td} = \sum_{i=1,2} C^{8(33ii)}_{ud}$	$C^{1,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	$C^8_{Qu} = \sum_{i=1,2} C^{8(33ii)}_{qu}$	$C^8_{Qd} = \sum_{i=1,2} C^{8(33ii)}_{qd}$	$C^{3,8}_{Qq} = \sum_{i=1,2} C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	$C^8_{tq} = \sum_{i=1,2} C^{8(ii33)}_{uq}$	$C^1_{td} = \sum_{i=1,2} C^{1(33ii)}_{ud}$	$C^1_{tu} = \sum_{i=1,2} C^{(ii33)}_{uu} + \frac{1}{3} C^{(i33i)}_{uu}$
	$C^1_{Qu} = \sum_{i=1,2} C^{1(33ii)}_{qu}$	$C^1_{Qd} = \sum_{i=1,2} C^{1(33ii)}_{qd}$	$C^{1,1}_{Qq} = \sum_{i=1,2} C^{1(ii33)}_{qq} + \frac{1}{6} C^{1(i33i)}_{qq} + \frac{1}{2} C^{3(i33i)}_{qq}$
	–	$C^1_{tq} = \sum_{i=1,2} C^{1(ii33)}_{uq}$	$C^{3,1}_{Qq} = \sum_{i=1,2} C^{3(ii33)}_{qq} + \frac{1}{6}\left(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}\right)$
2-quark 2-lepton	C_{eb}	C_{et}	$C^+_{lQ} = C^1_{lQ} + C^3_{lQ}$
	C_{lb}	C_{lt}	$C^-_{lQ} = C^1_{lQ} - C^3_{lQ}$
	–	–	C_{eQ}

Observables

Process	Observable	$\sqrt{s}$	$L_{\rm int}$	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15 bins)	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (5 bins)	13 TeV	139 fb^{-1}	ATLAS
$pp \to t\bar{t}$	$D(m_{t\bar{t}} \sim 2m_t)$	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}$	$D_n(m_{t\bar{t}} > 0.8$ TeV$)$	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}H$	$d\sigma/dp_T^H$ (6 bins)	13 TeV	139 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (8 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (10 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}W$	σ	13 TeV	138 fb^{-1}	CMS
$pp \to tZq$	σ	13 TeV	138 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8/13 TeV	20/140 fb^{-1}	LHC/ATLAS
$t \to Wb$	F_0, F_L	8/13 TeV	20/139 fb^{-1}	LHC/ATLAS
$p\bar{p} \to t\bar{t}$	$dA_{FB}/dm_{t\bar{t}}$ (4 bins)	1.96 TeV	9.7 fb^{-1}	Tevatron
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b, A^{bb}_{FBLR}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

Global fit to the LHC (+ others)

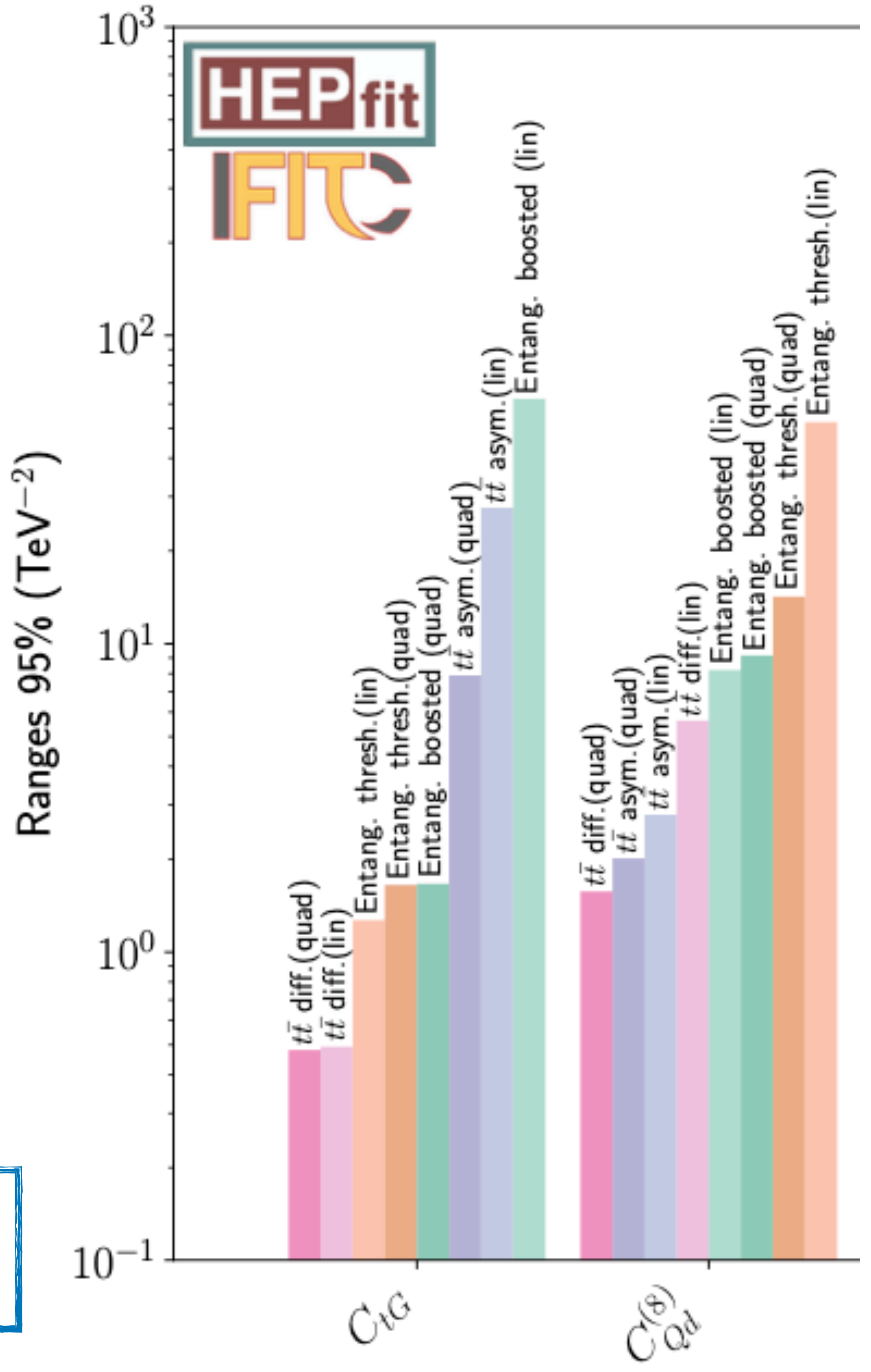


- Global **EFT Linear Fit** to LHCRun2 + LEP/SLD + Tevatron data
- Fit is consistent with other similar studies [JHEP 09 (2024) 091]
- Fit includes theoretical and experimental uncertainties (+ correlations)

Entanglement Measurements

- Top-quark pairs produced at high-energy colliders form a two-qubit system
- They are sensitive to C_{tG} and $q\bar{q}t\bar{t}$ operators
- CMS provides unfolded results at threshold (D) and in the boosted regime $m_{t\bar{t}} > 0.8$ TeV (D_n)
- Similar bounds on C_{tG} for D vs. $t\bar{t}$ diff.
- For other operators they are **not as competitive** as $t\bar{t}$ diff. cross-section and asymmetry

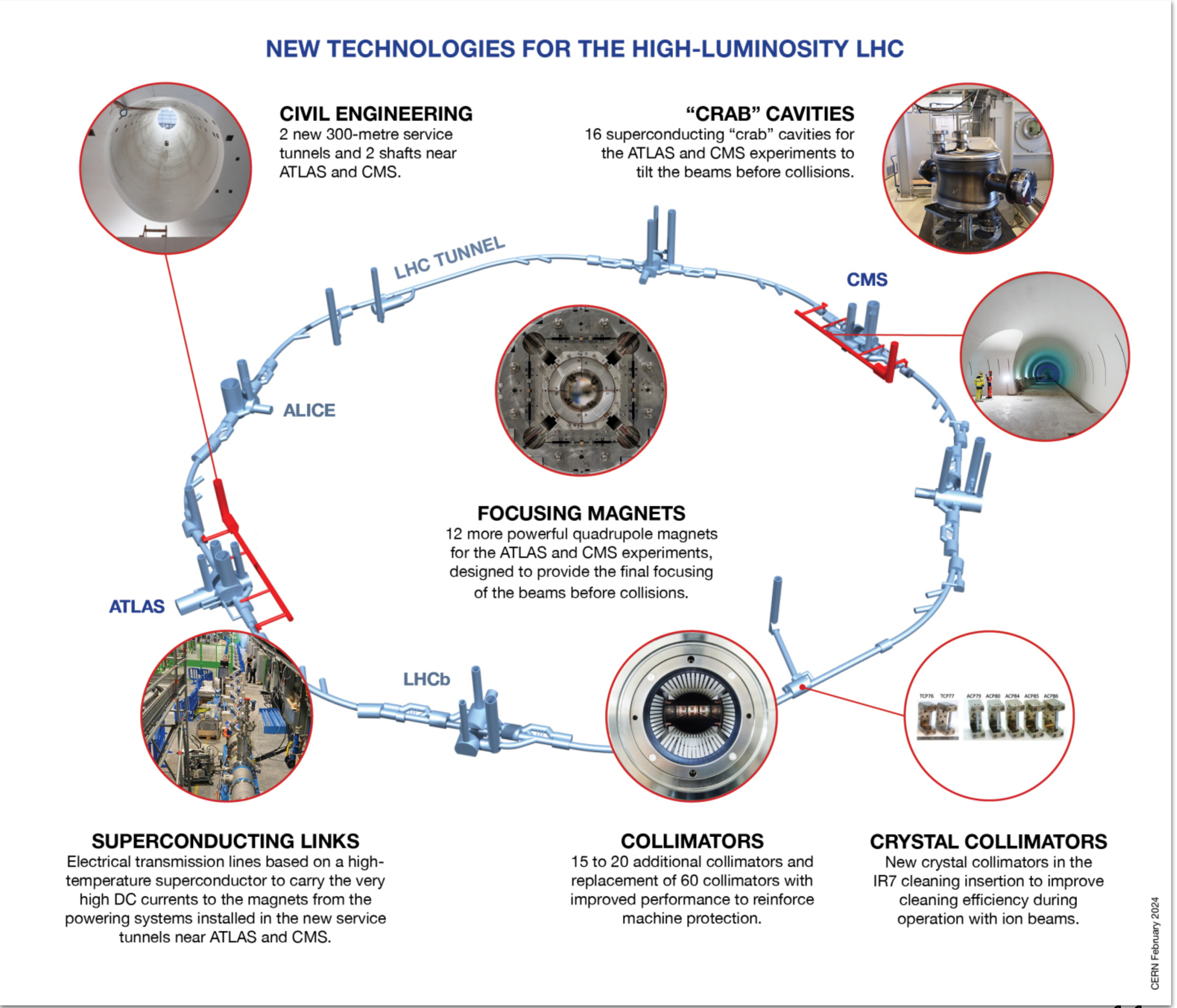
Although not explicitly shown, other spin matrix observables showed a similar sensitivity to the operators



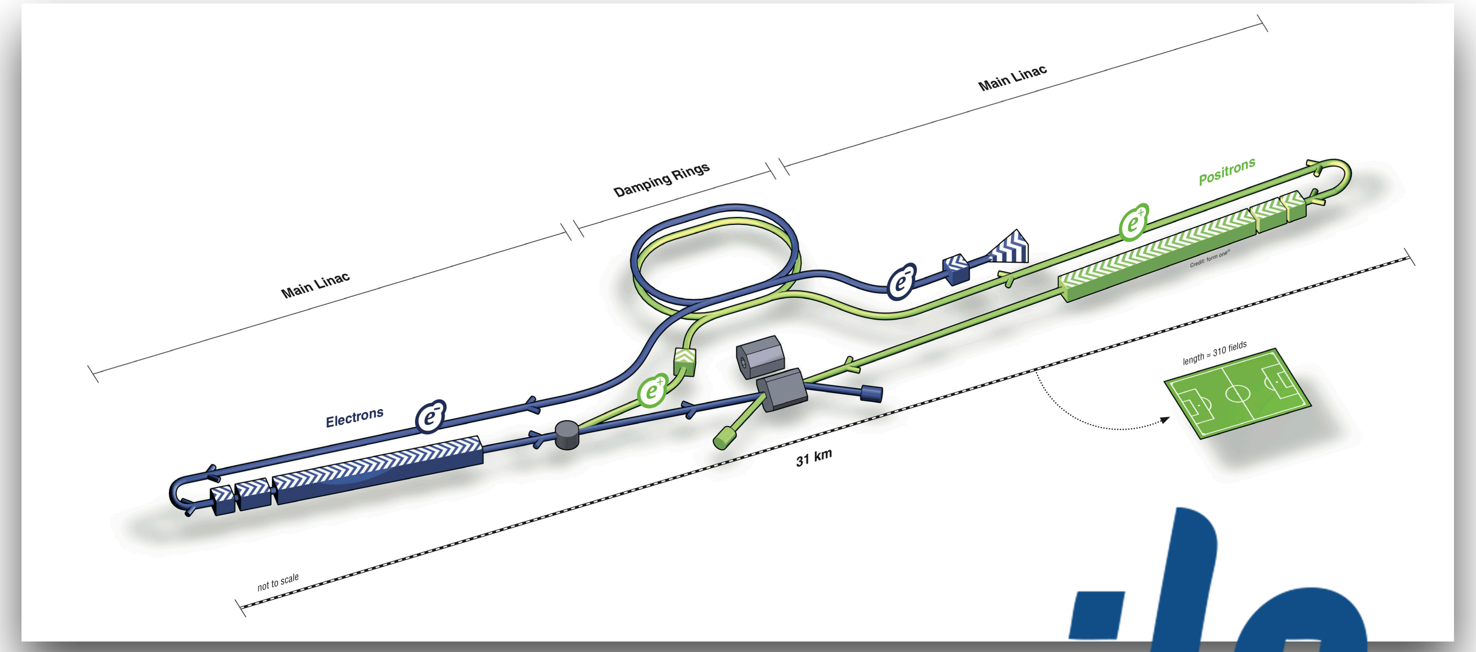
Future Colliders

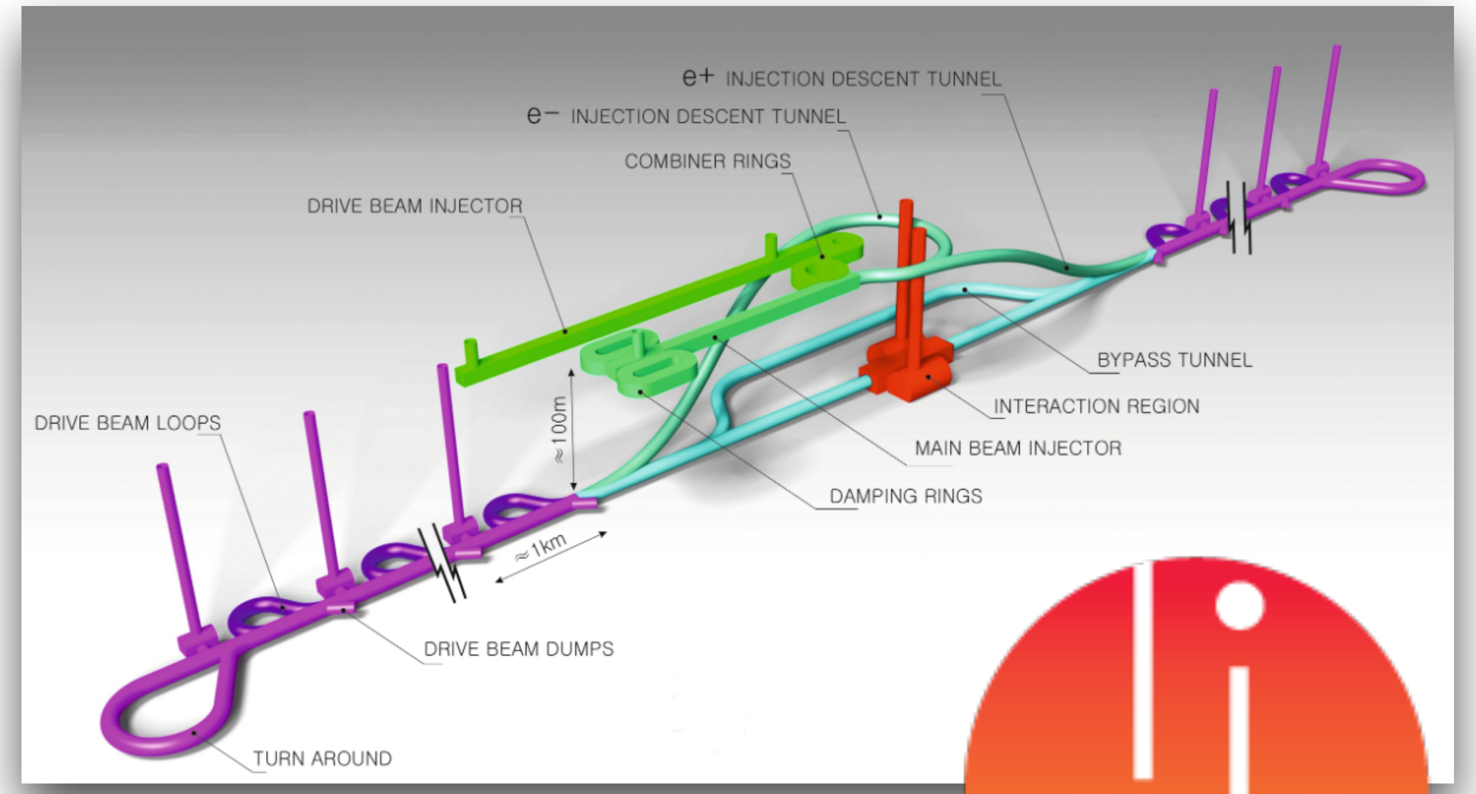
HL-LHC

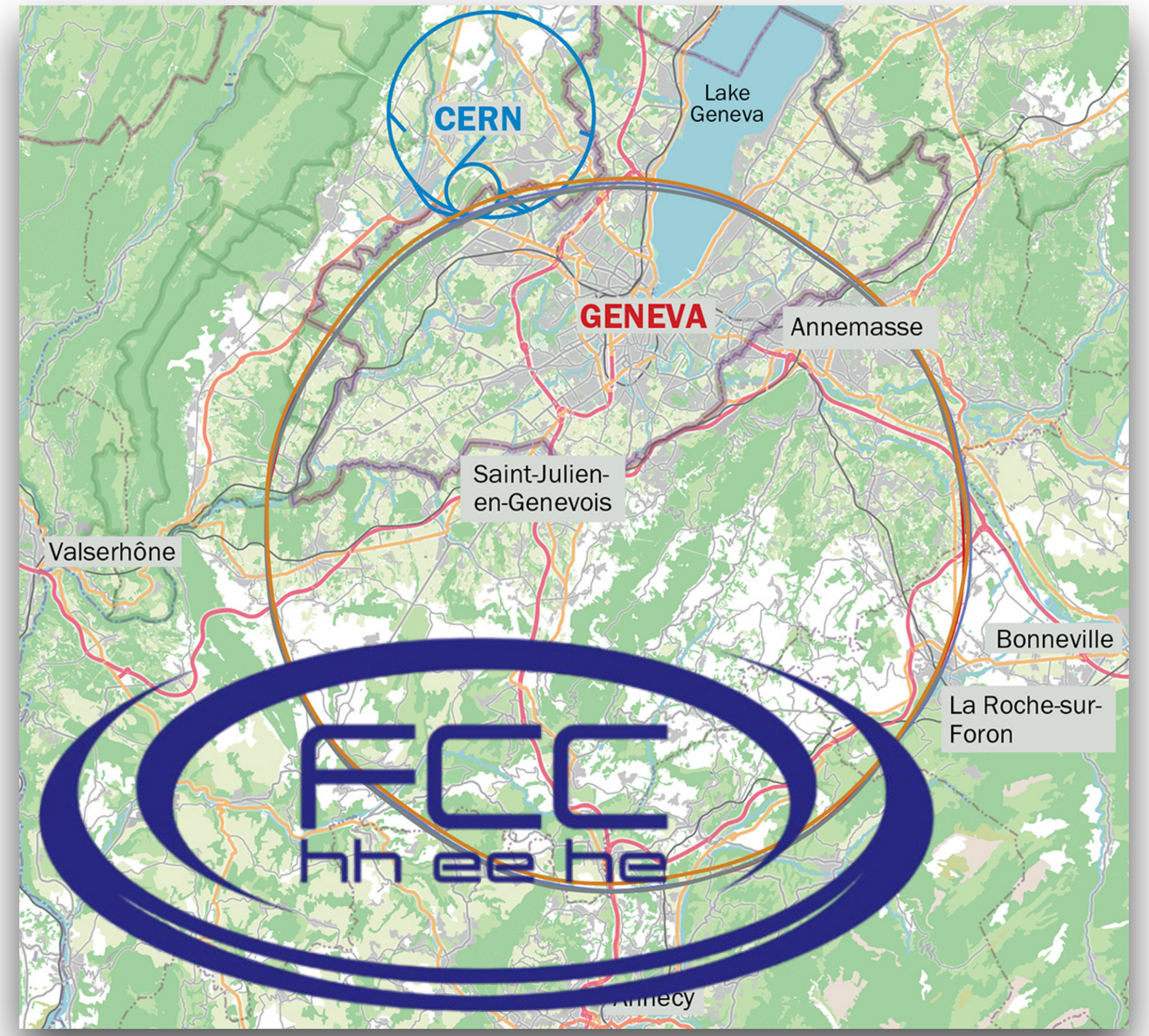
- Next upgrade for the LHC with an increase in luminosity
  - Expected ~3000 fb^{-1}
- "S2" scenario (ref)
  - Theoretical unc. reduced by $1/2$
    - Requires many N^{n+1}LO simulations
  - Statistical and experimental by $1/\sqrt{L}$
    - Is a bit *aggressive* in some cases

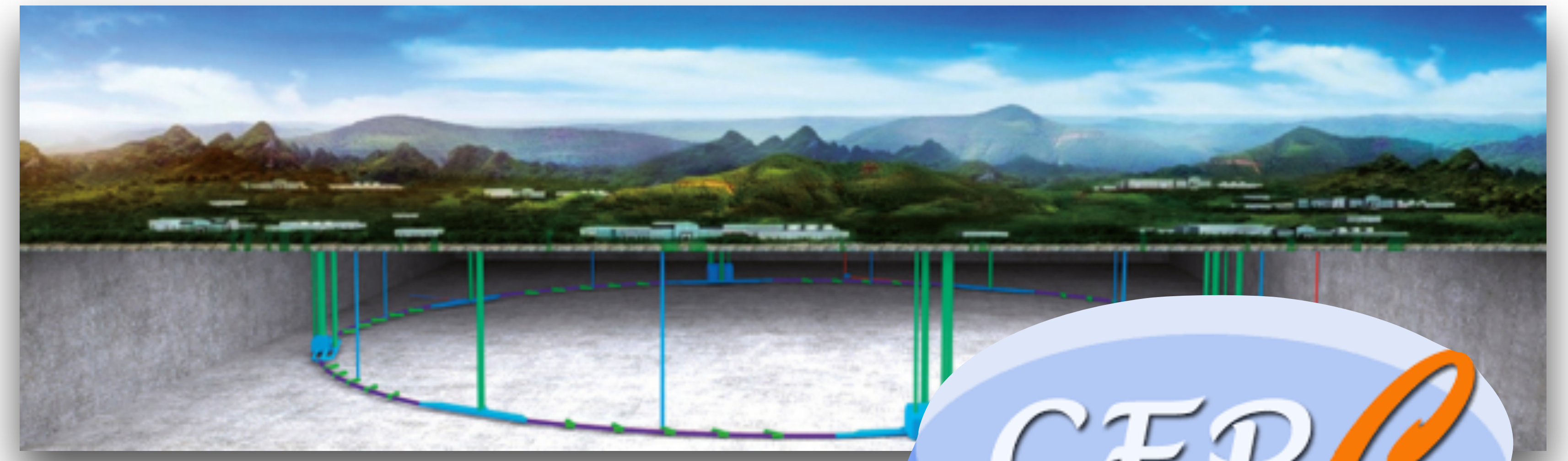


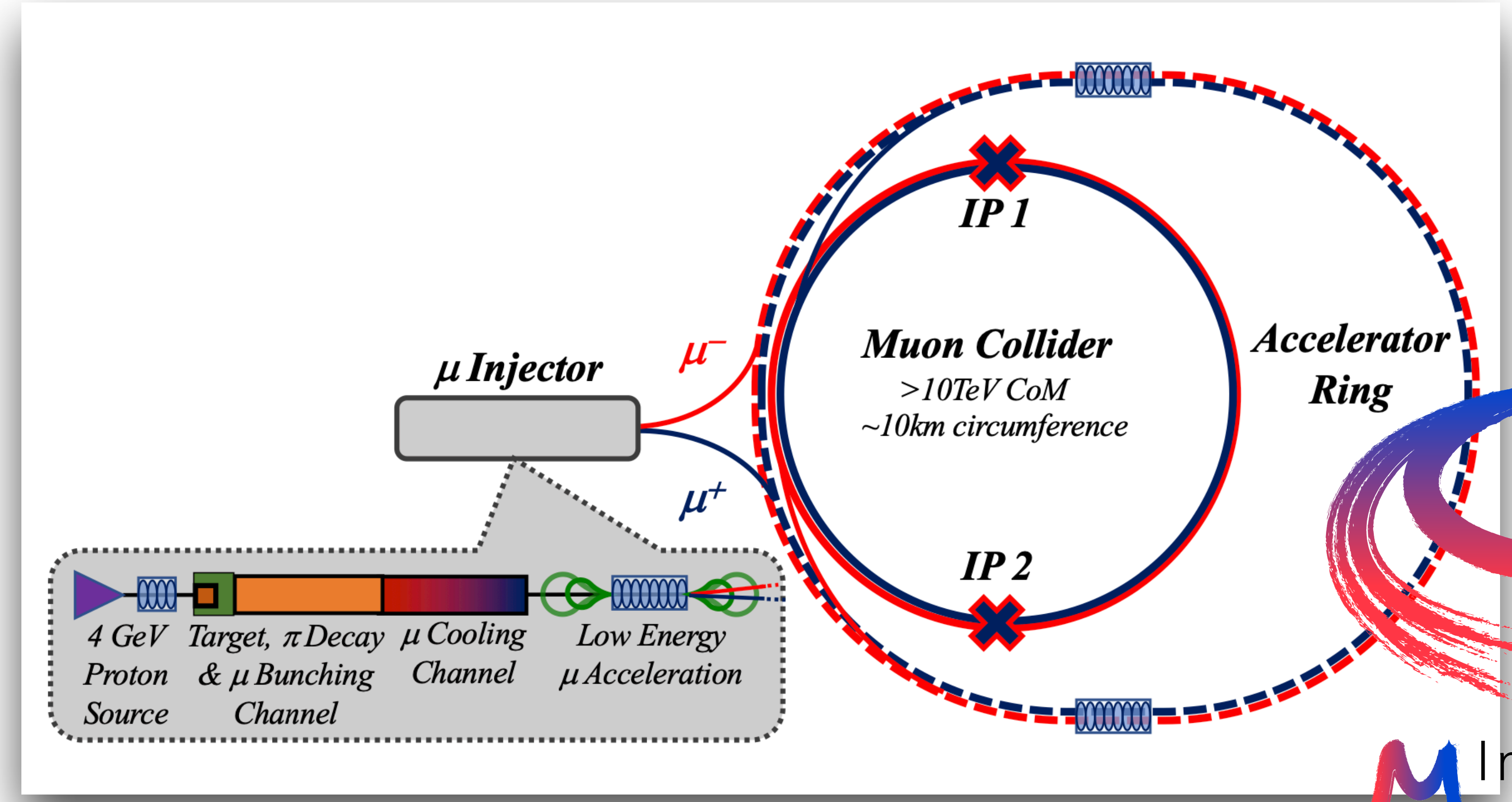
Lepton colliders











International MUON Collider Collaboration

Electron colliders

Machine	$P(e^+, e^-)$	Energy	Luminosity
ILC	$(\pm 30\%, \mp 80\%)$ $(\pm 20\%, \mp 80\%)$	250 GeV 500 GeV 1 TeV	2 ab^{-1} 4 ab^{-1} 8 ab^{-1}
CLIC	$(0\%, \pm 80\%)$	380 GeV 1.5 TeV 3 TeV	1 ab^{-1} 2.5 ab^{-1} 5 ab^{-1}
FCC-ee	Unpolarised	Z-pole 240 GeV 350 GeV 365 GeV	150 ab^{-1} 5 ab^{-1} 0.41 ab^{-1} 2.65 ab^{-1}
CEPC	Unpolarised	Z-pole 240 GeV 350 GeV 360 GeV	57.5 ab^{-1} 20 ab^{-1} 0.2 ab^{-1} 1 ab^{-1}

Future colliders are planned to run at different energies

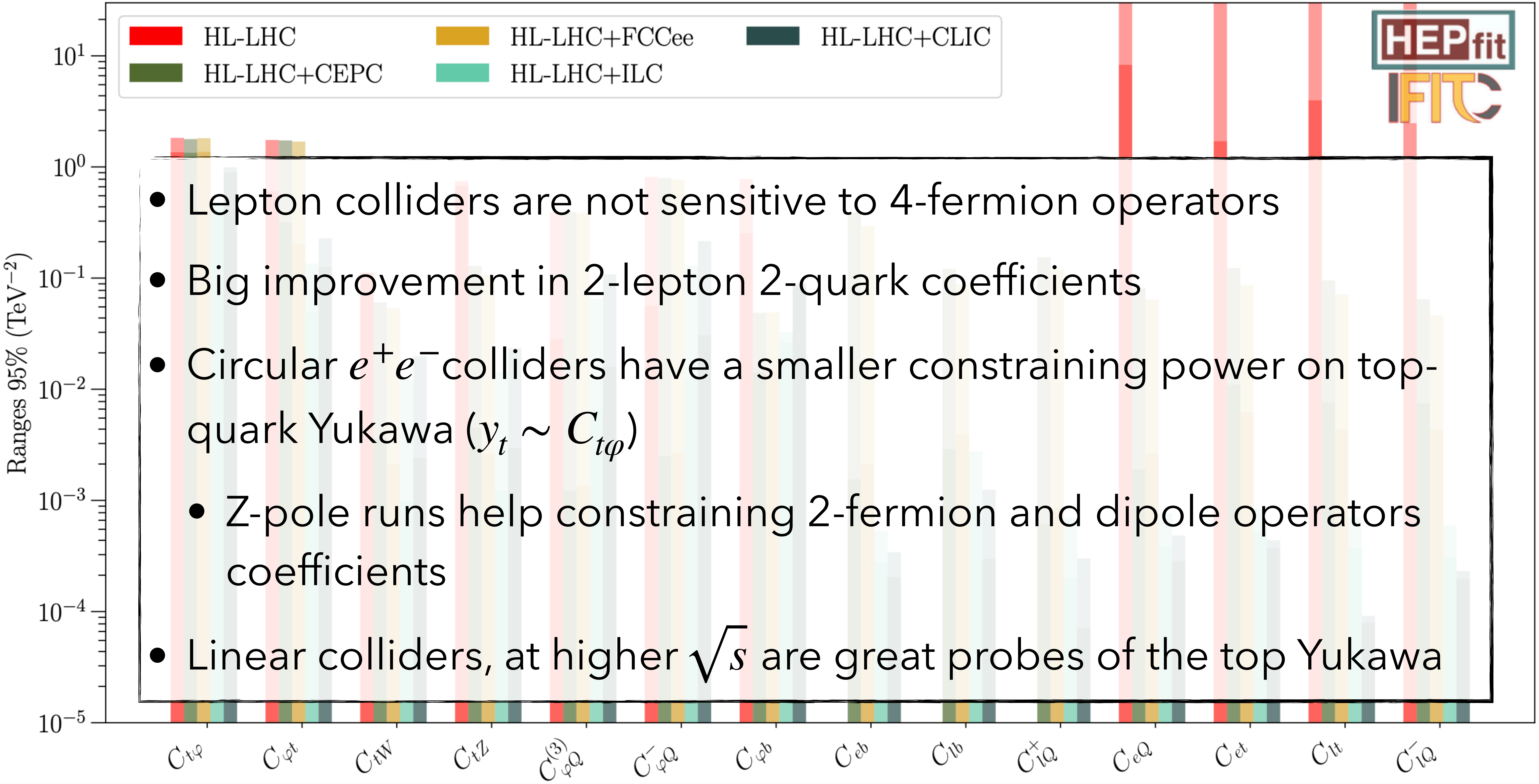
- $e^+e^- \to t\bar{t}$
  - Opens at $\sqrt{s} \gtrsim 350$ GeV
  - Statistically optimal observables are defined that exploit the $WbWb$ final state (ref)
- $e^+e^- \to t\bar{t}H$
  - Excellent channel for top Yukawa studies
  - Available at $\sqrt{s} = 500 - 550$ GeV

Future prospects

Future prospects

Individual

Marginalised

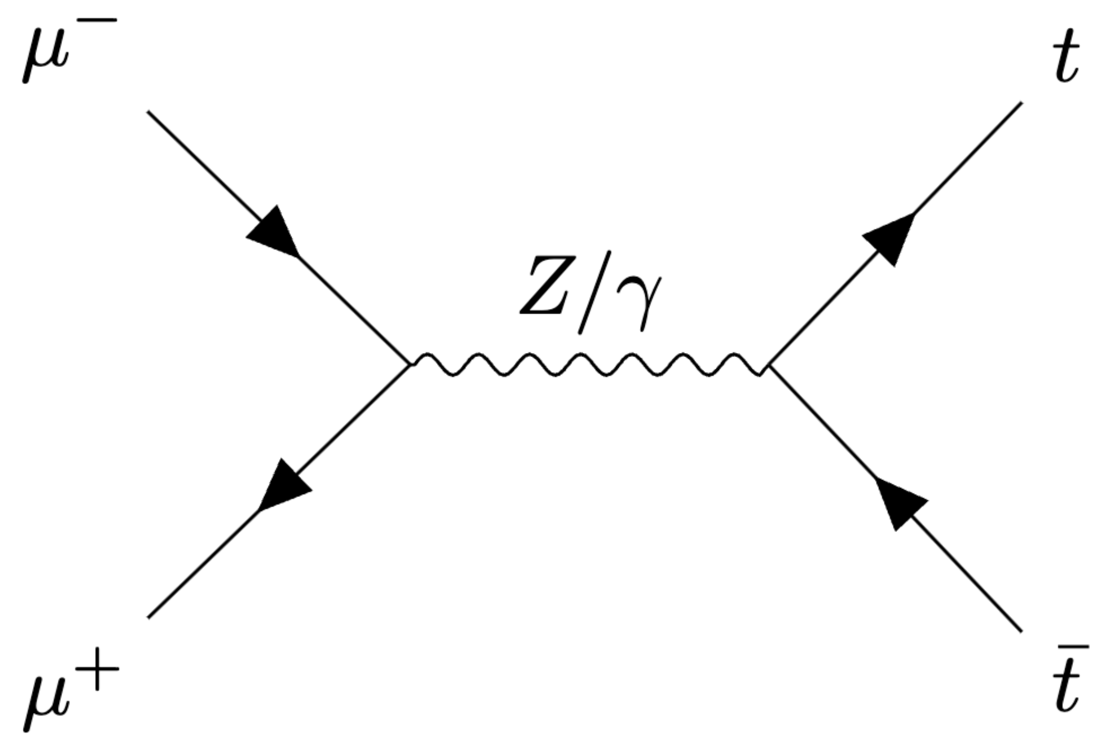


- Lepton colliders are not sensitive to 4-fermion operators
- Big improvement in 2-lepton 2-quark coefficients
- Circular e^+e^-colliders have a smaller constraining power on top-quark Yukawa ($y_t \sim C_{t\varphi}$)
  - Z-pole runs help constraining 2-fermion and dipole operators coefficients
- Linear colliders, at higher $\sqrt{s}$ are great probes of the top Yukawa

Muon collider

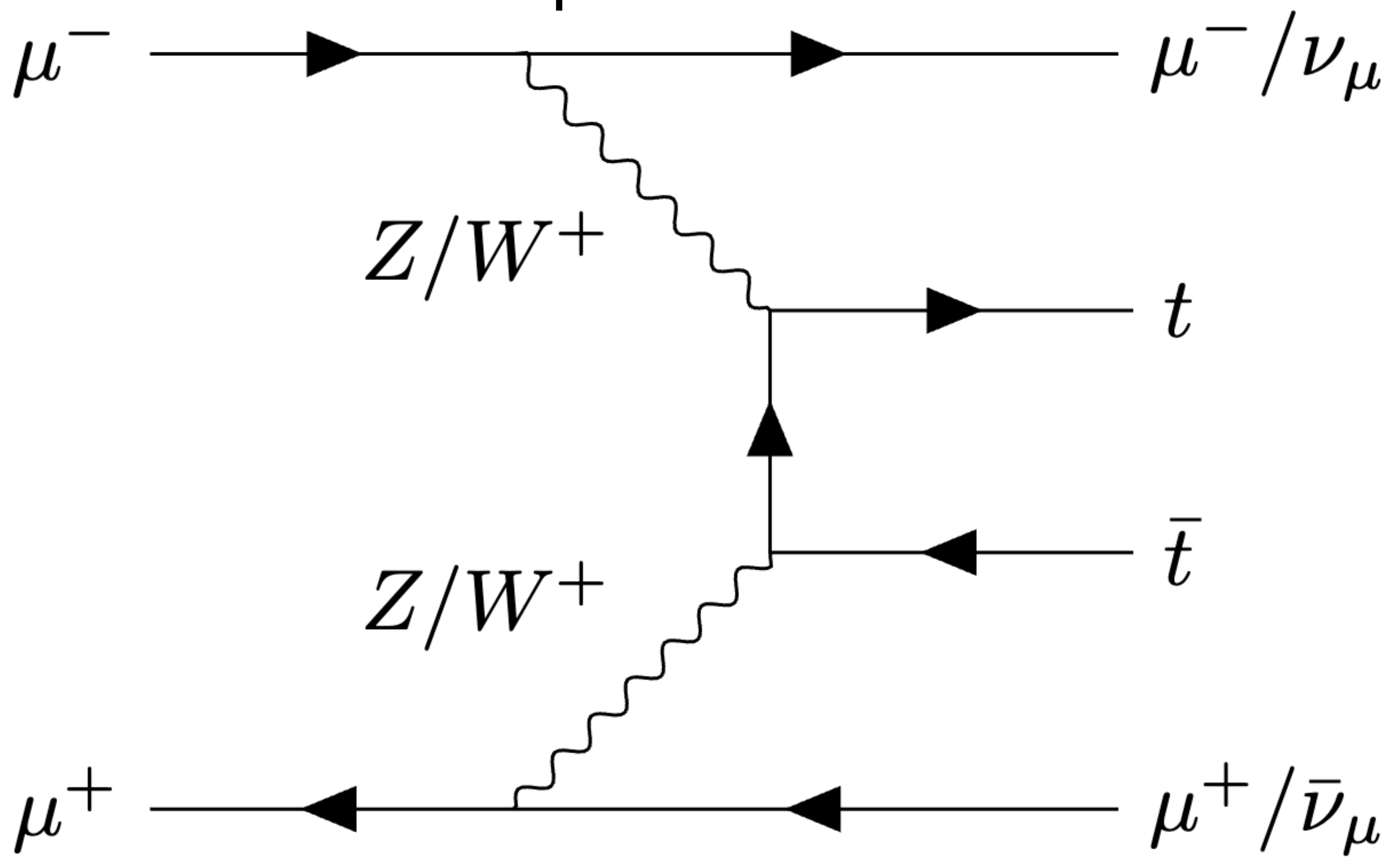
- Muon colliders have many technological challenges ahead
- They can access higher energies than electron colliders ~3-30 TeV (reduced synchrotron radiation energy loss)

s-channel production



$\sqrt{s}$ **energy**

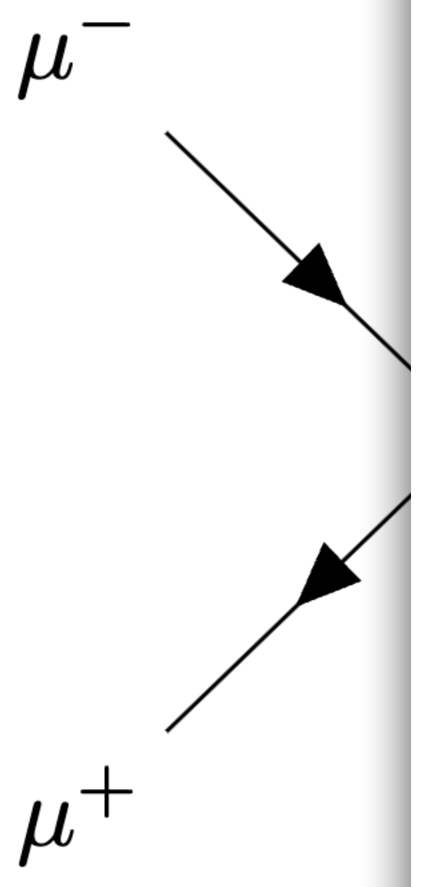
VBF production

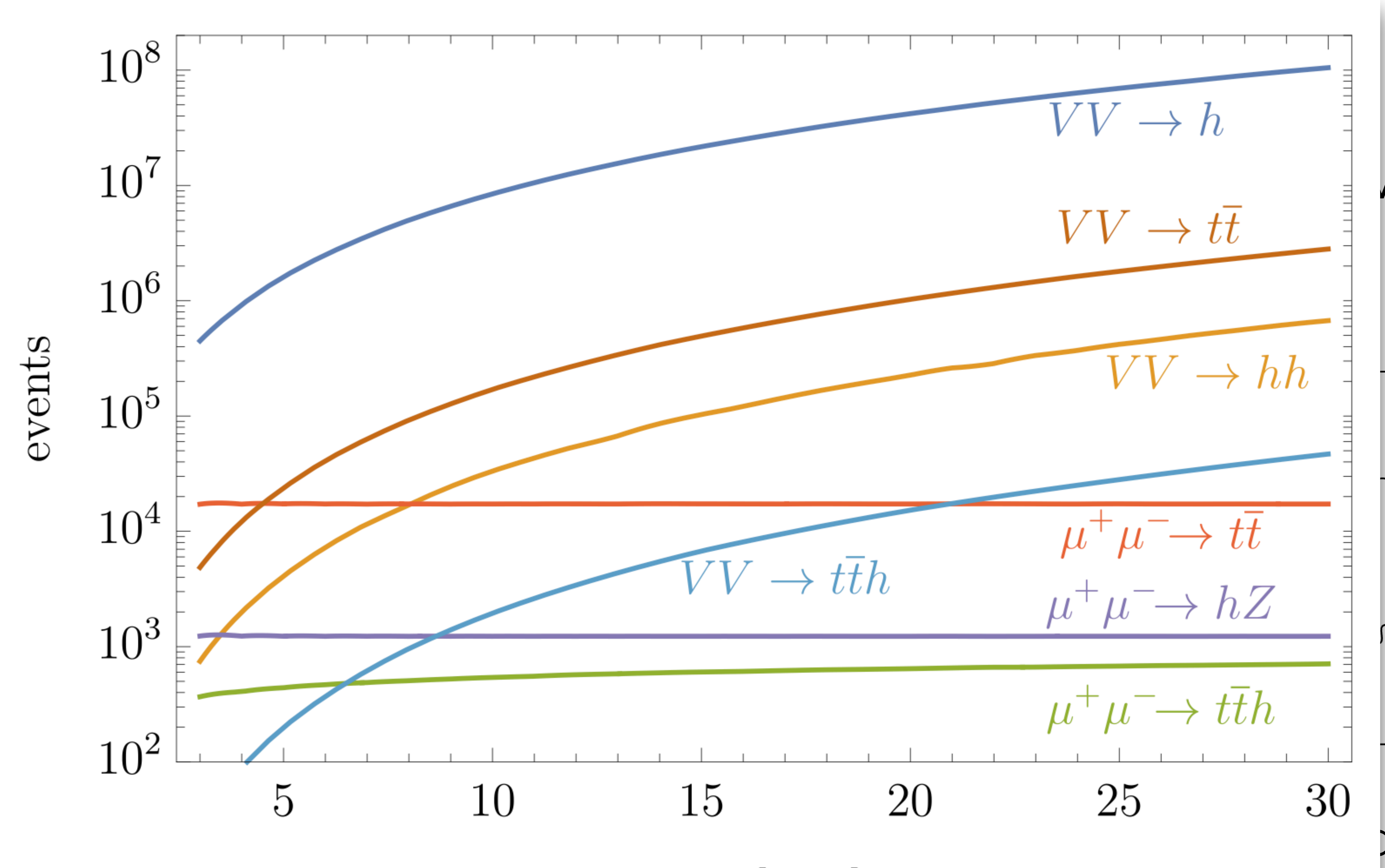


μ-coll	Unpolarised	3 TeV 10 TeV 30 TeV	1 ab^{-1} 10 ab^{-1} 90 ab^{-1}

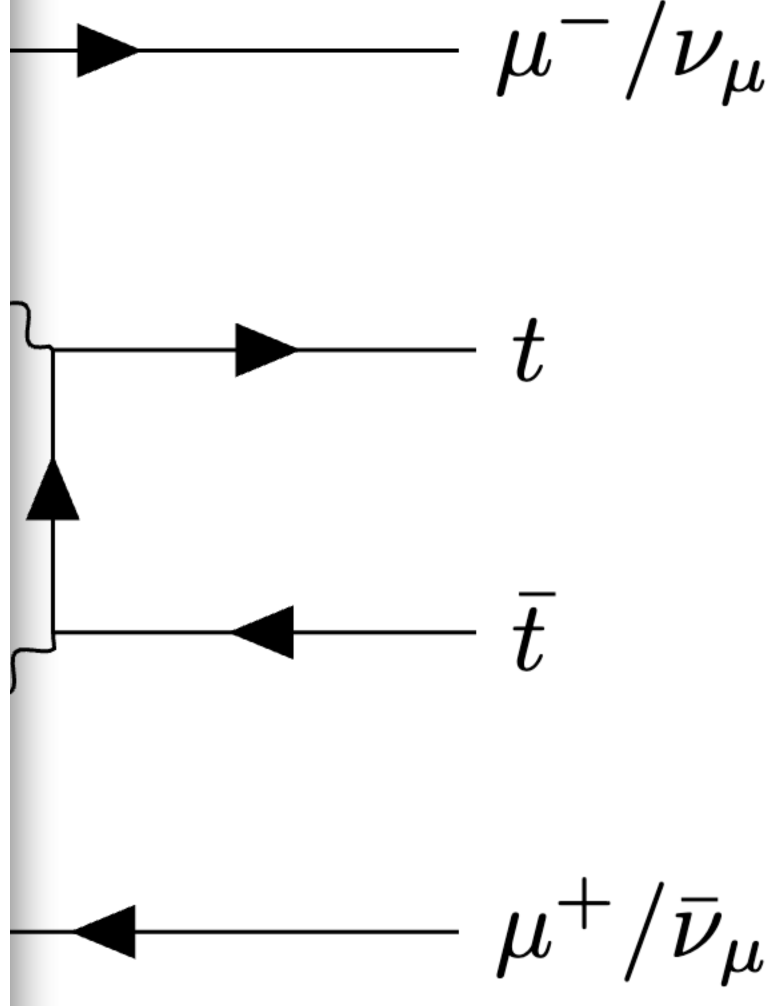
Muon collider

- Muon col
- They can ... / (no synchrotr





arXiv:2303.08533



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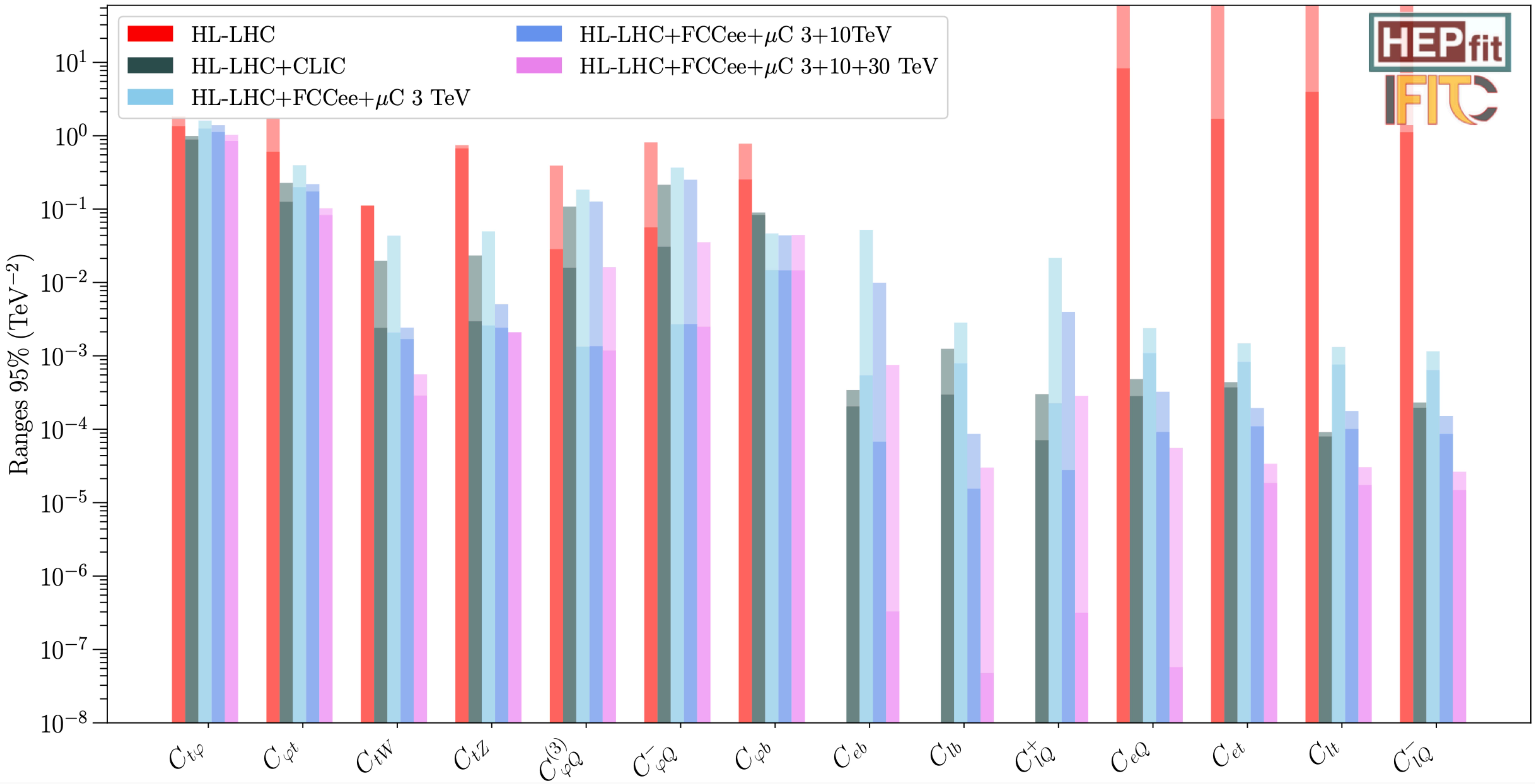
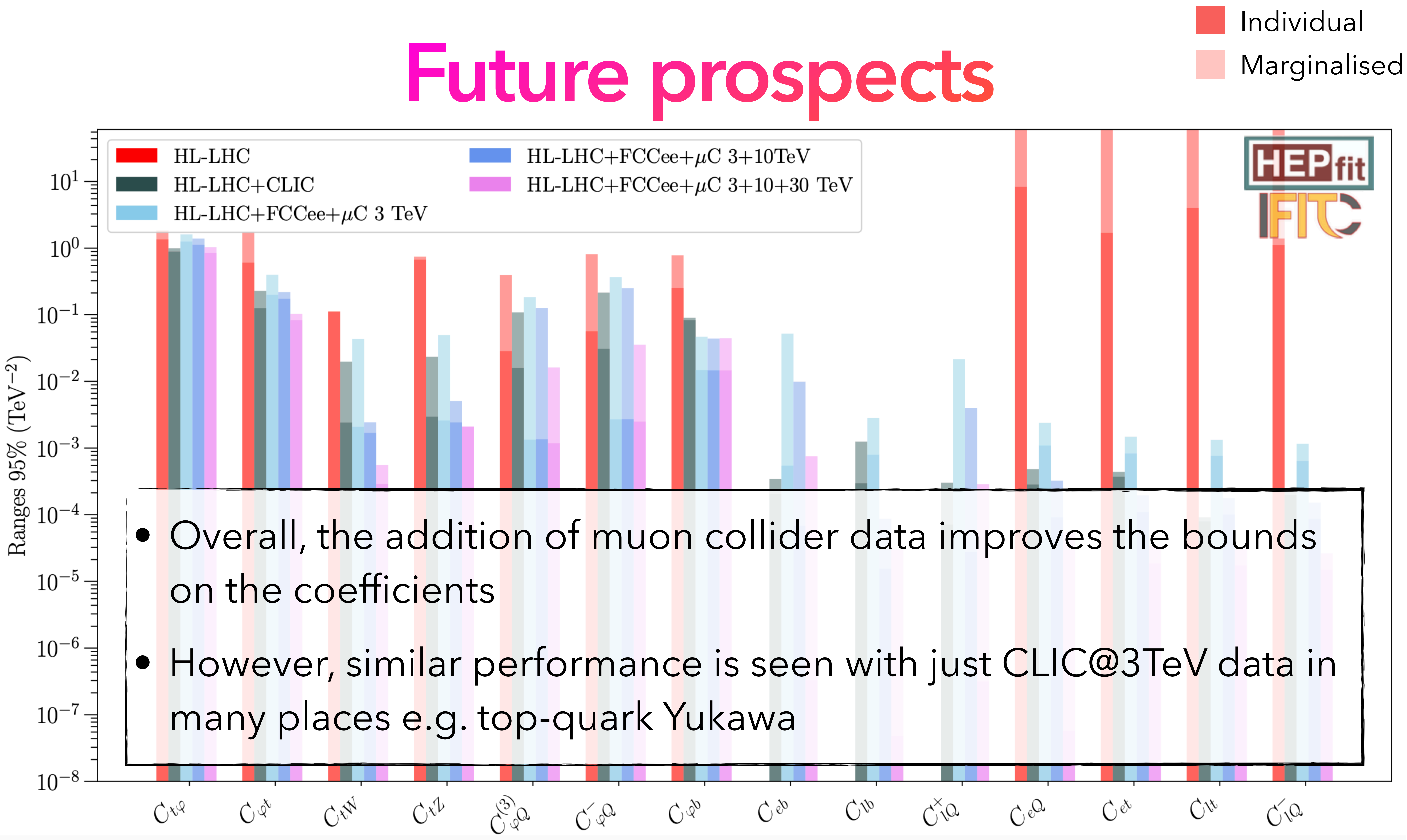
Individual
Marginalised



Future prospects



- Overall, the addition of muon collider data improves the bounds on the coefficients
- However, similar performance is seen with just CLIC@3TeV data in many places e.g. top-quark Yukawa

Summary

- We provide a global EFT analysis in the top-quark (and bottom-quark) sector
- We provide a **EFT Linear global fits** including updated and inclusion of new observables.
    - Run2 data dominates results but some legacy measurements remain important
- We include projections to HL-LHC and to **future lepton colliders**
    - Competitive individual constraints on some coefficients are set (such as $C_{t\varphi}$, $C_{\varphi t}$ and other 2-fermion operators)
    - Good performance is seen with HL-LHC + CLIC@3TeV: *beam polarisation* is a great asset.
    - Higher $\sqrt{s}$ runs (above specific production thresholds) can be the key for precision
    - **Z pole** runs at circular colliders like **CEPC** will bring improvements in 2-fermion sector

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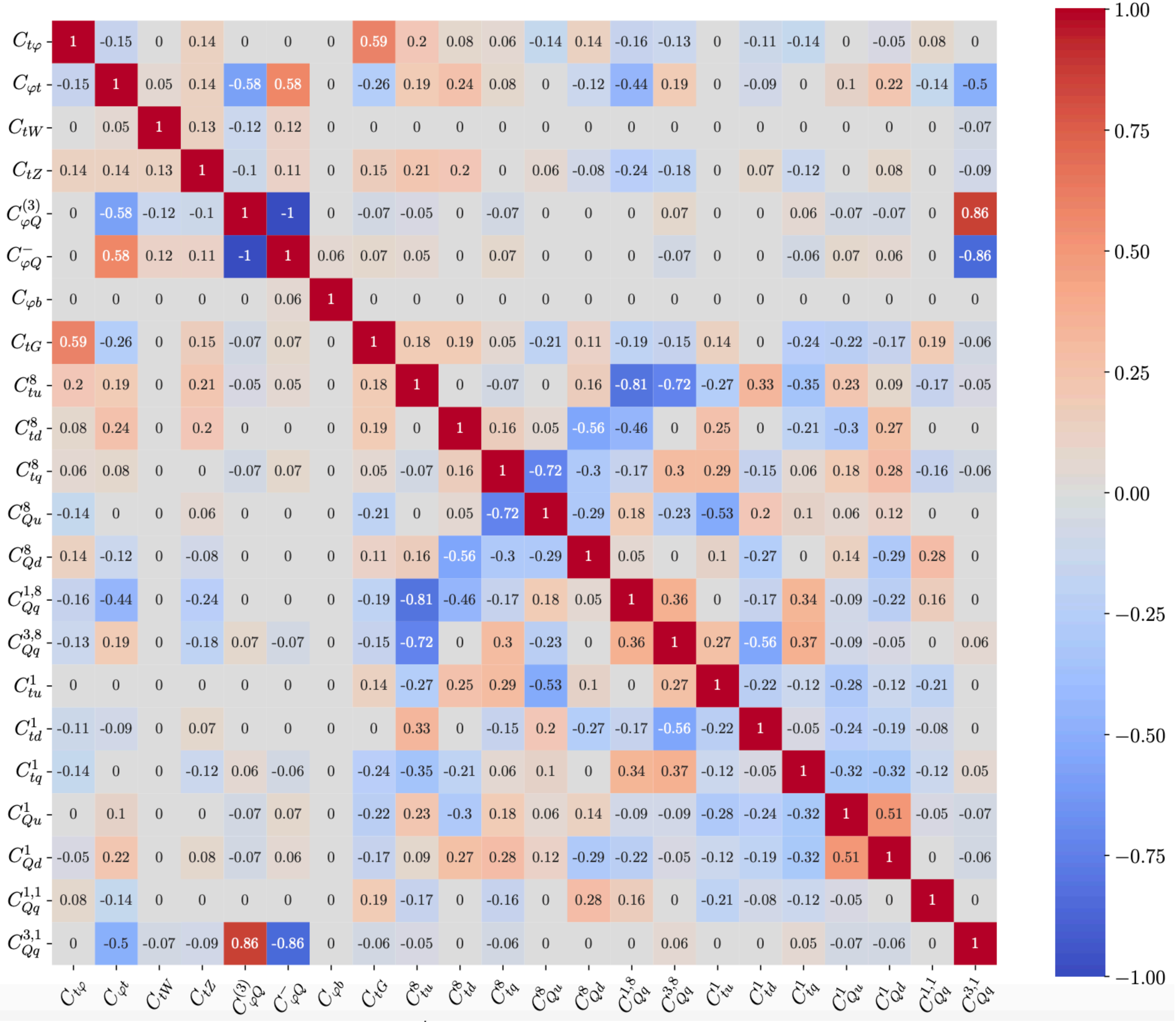
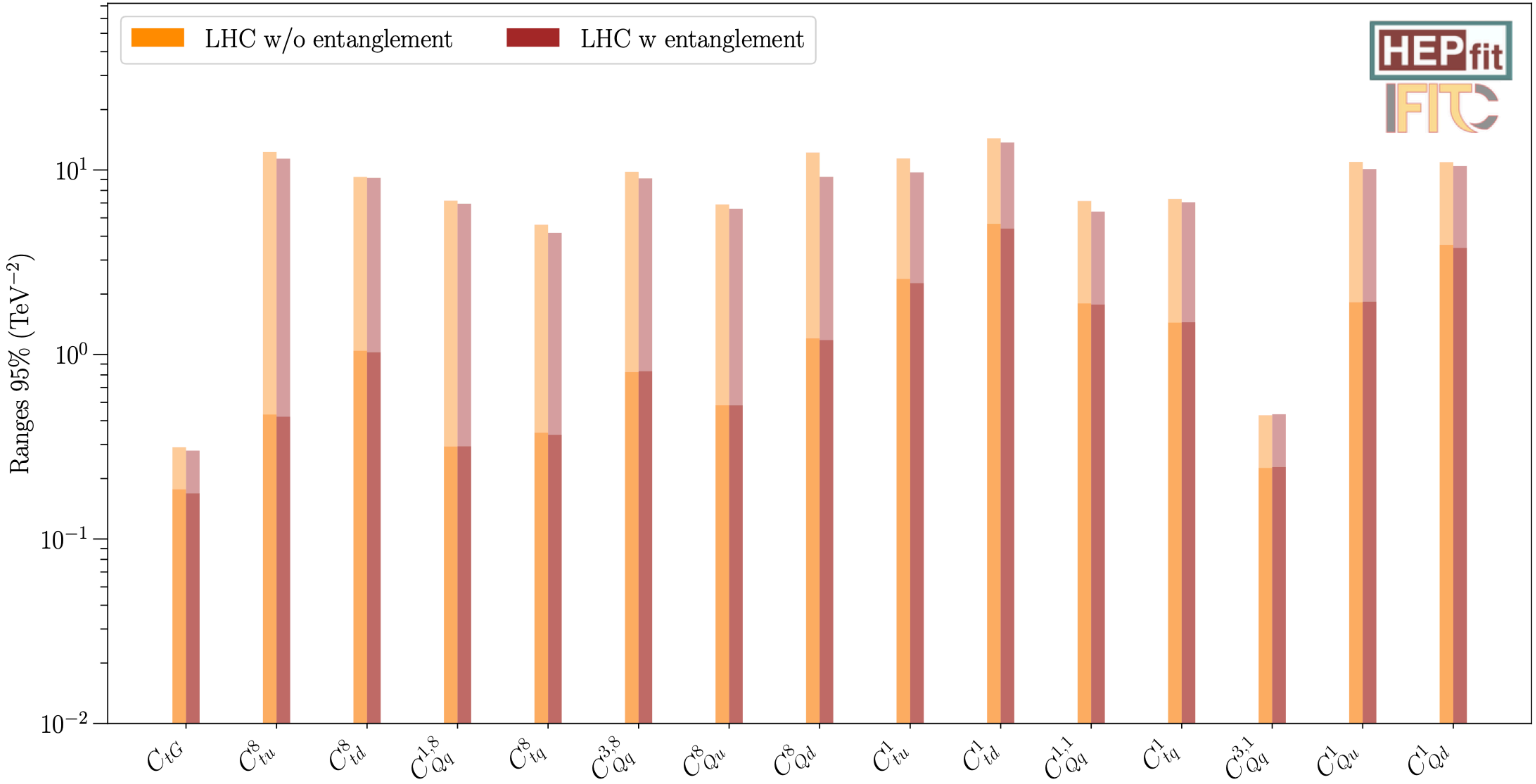
Thanks for your attention!

Backup

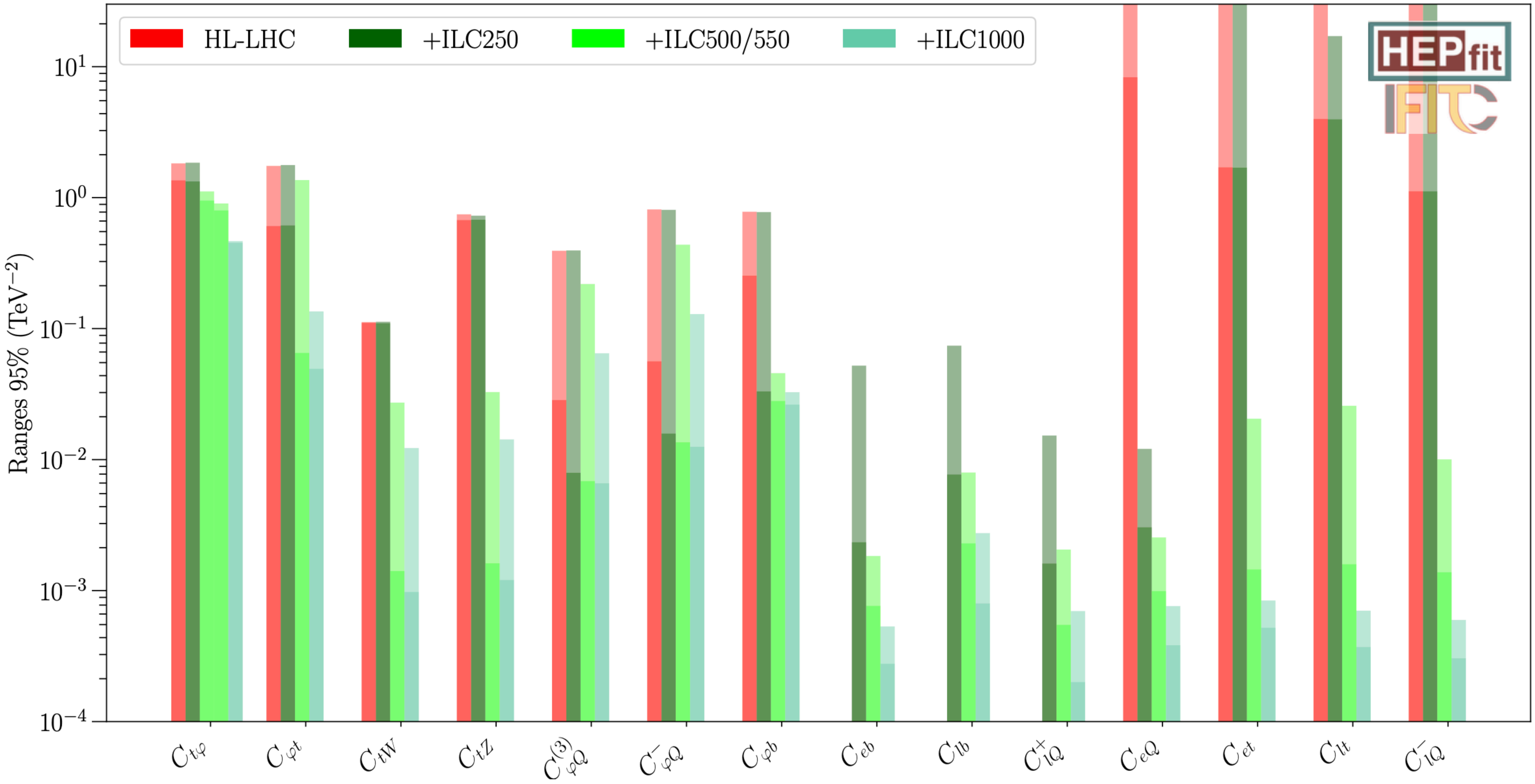
Correlations



Entanglement effect



ILC prospects



Top Yukawa

Uncertainty		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global	16%	5.6%	3.4%	2.8%	1.4%	3.0%
	Indiv.	13%	4.1%	2.9%	2.4%	1.4%	2.7%

Table 6. Uncertainties for the top-quark Yukawa coupling at 68% probability for different scenarios, in percent. The ILC500, ILC550 and CLIC scenarios also include the HL-LHC. The ILC1000 scenario includes also ILC500 and HL-LHC. Numbers for lepton colliders are based on an extrapolation in Ref. [27] of detailed studies in Refs. [125, 128].

The inclusion of high-energy *muon collider* data improves the precision of the top-quark Yukawa coupling to 2.5%.

Muon Collider