Snowmass SMEFT global fit for top physics

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Based on
2206.08326, with Jorge de Blas, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou

Introduction

Big picture of the SMEFT global fit:

Fit 1 for Higgs + electroweak physics (**Jiayin Gu's talk on Monday**)

Fit 2 & 3 for four-fermion ($f \neq t$) and bosonic CP-violating operators (**My talk tomorrow**)

Fit 4 for top physics (**This talk**)

Introduction

Top, the heaviest particle in the SM, has very interesting physics

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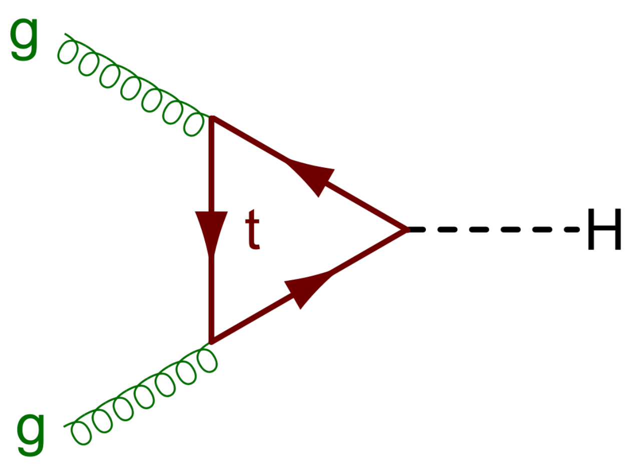

Higgs production

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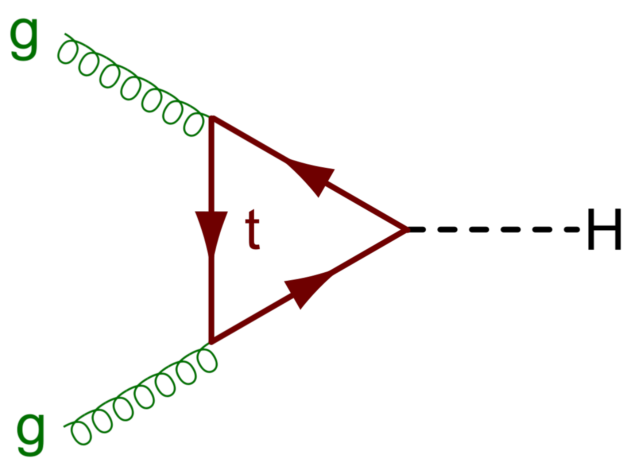

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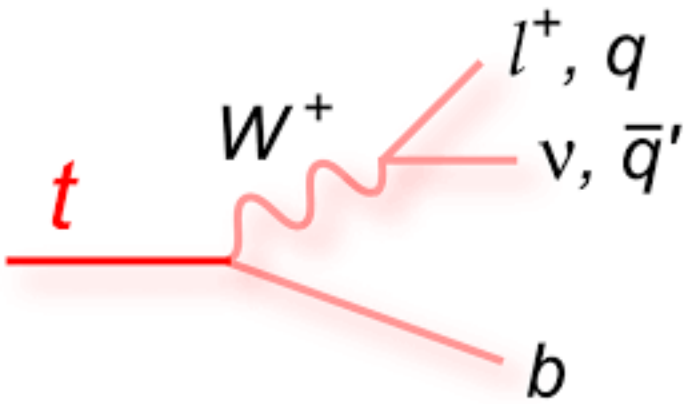

V_{tb} measurement

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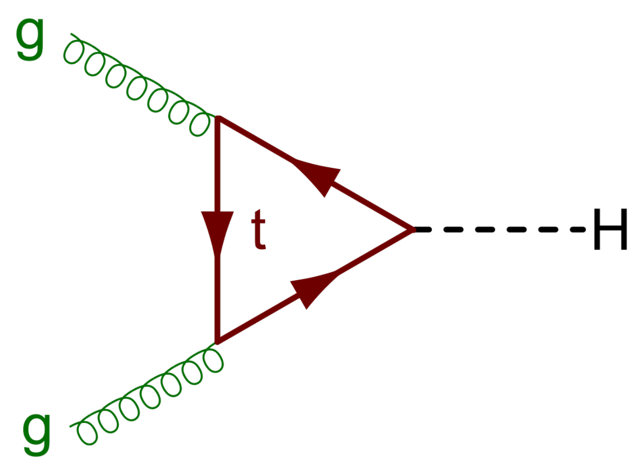

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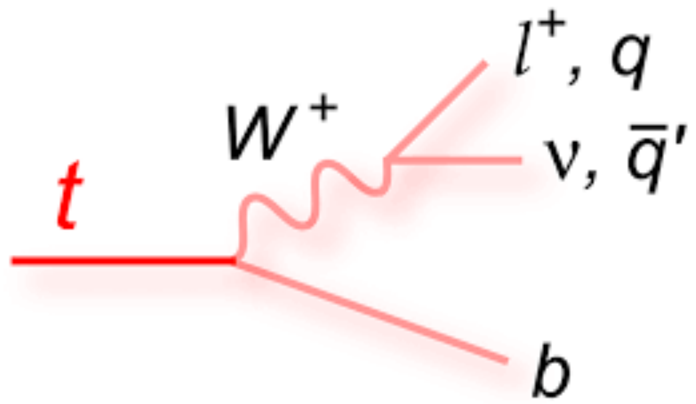

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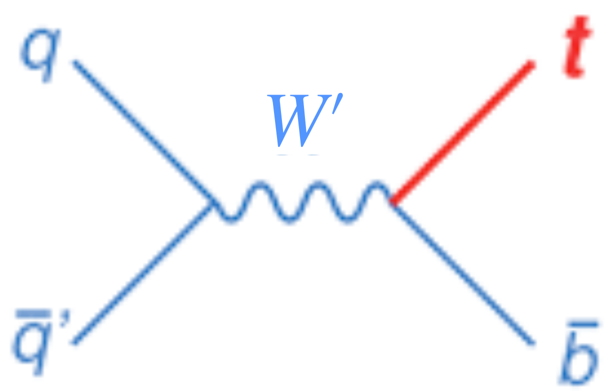

Connection to new physics

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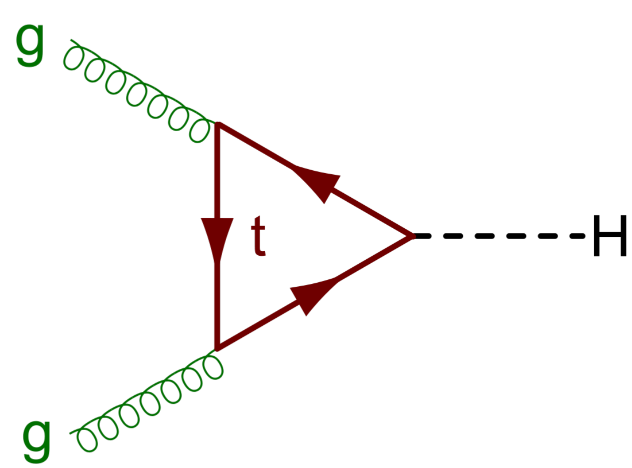
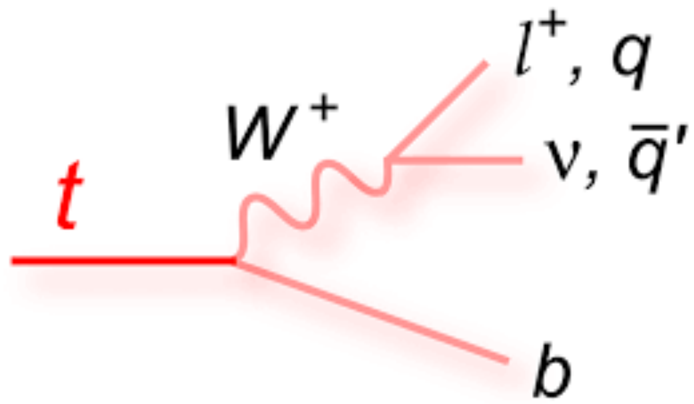


Higgs production



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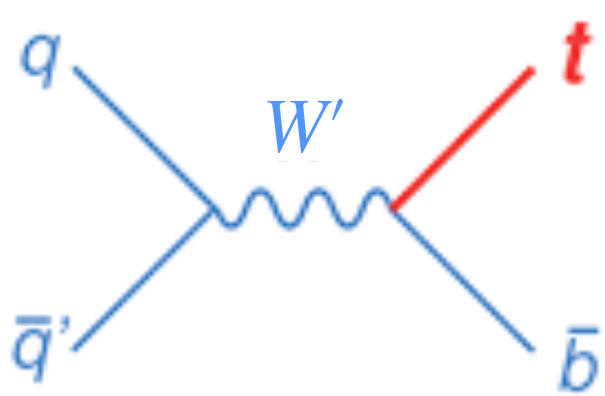

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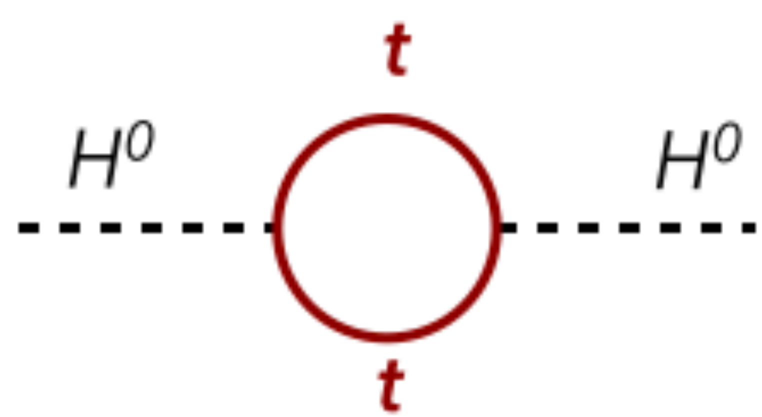
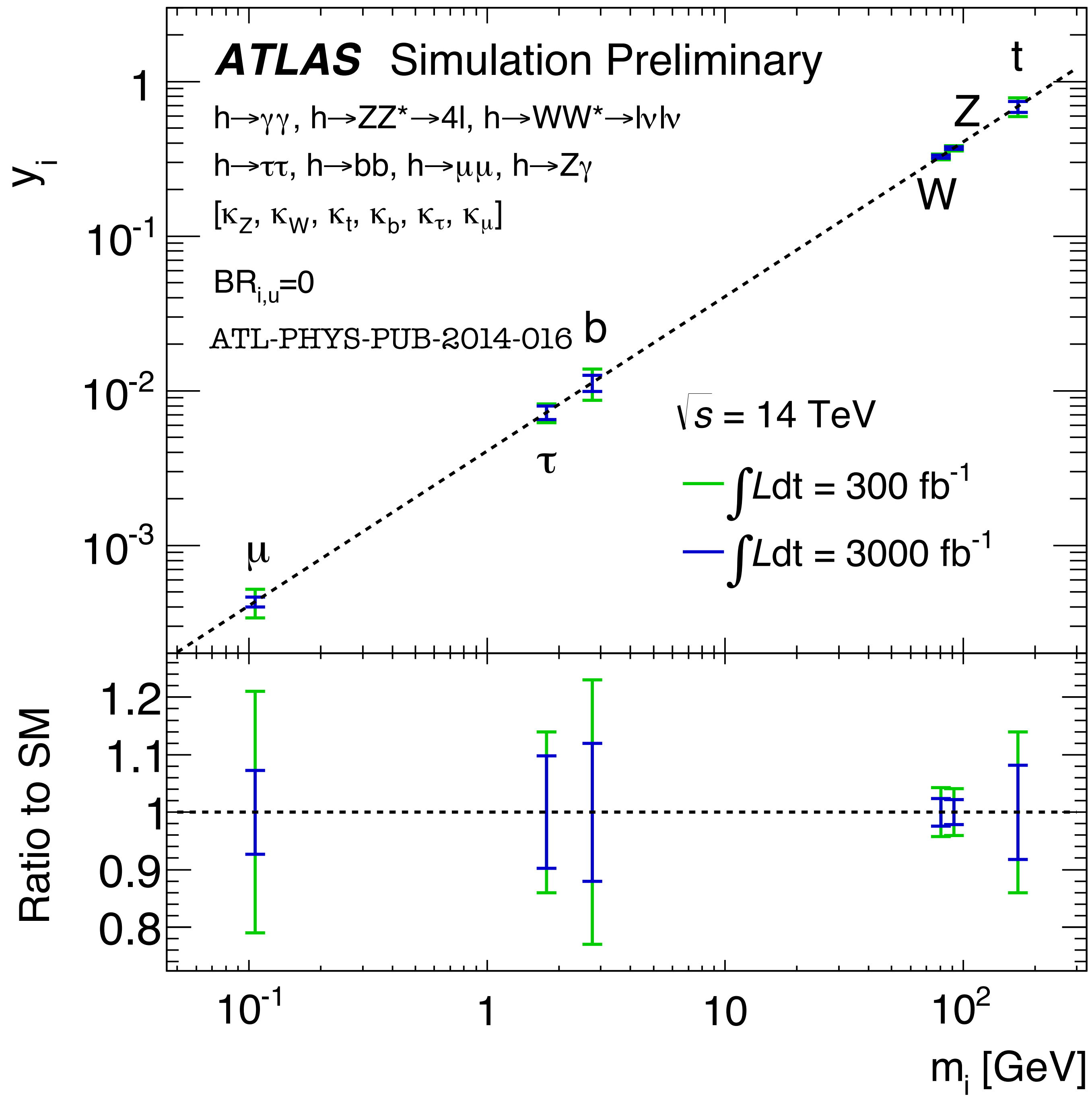


Hierarchy problem

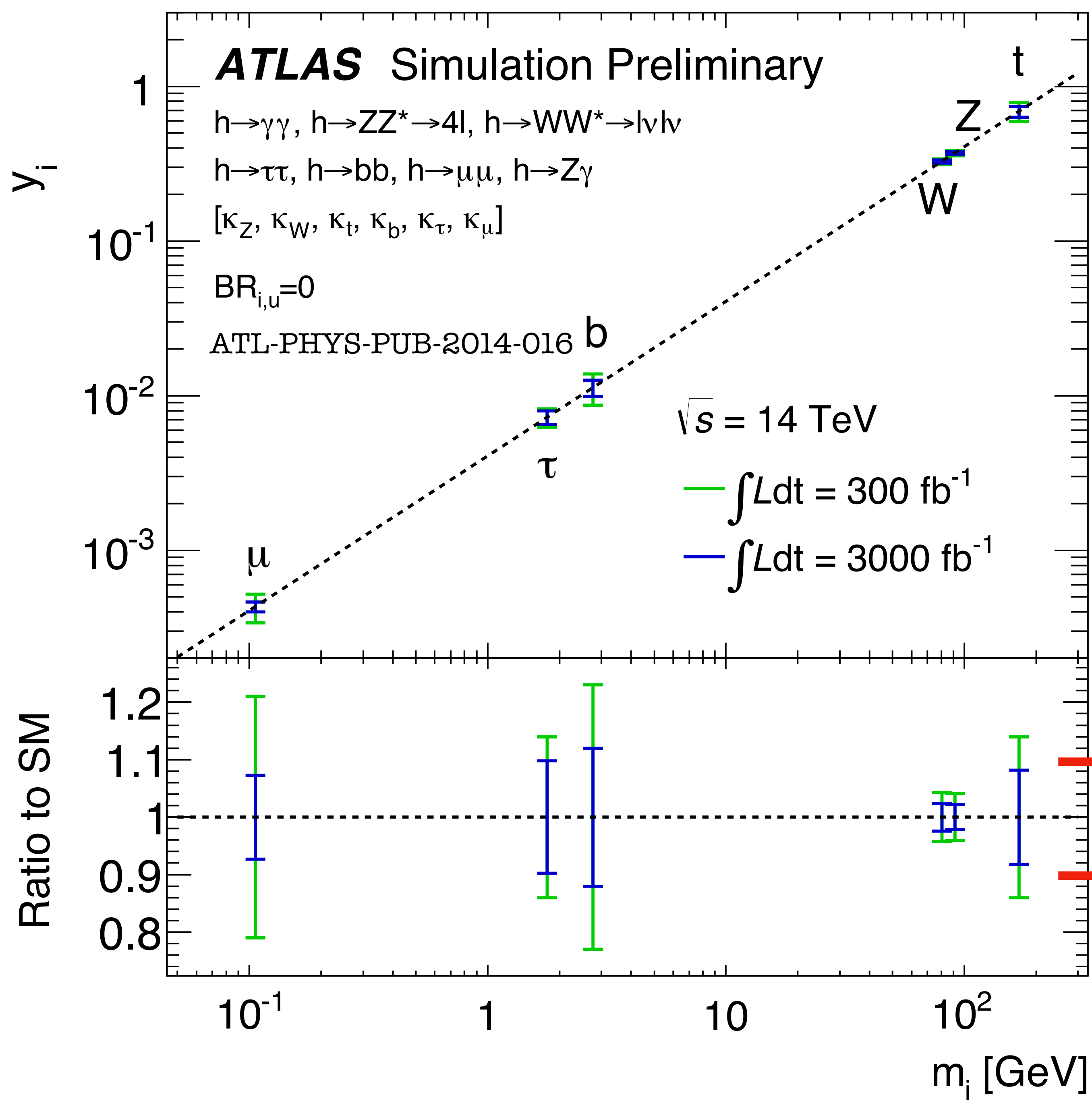
Introduction

Within the SM



Introduction

Within the SM

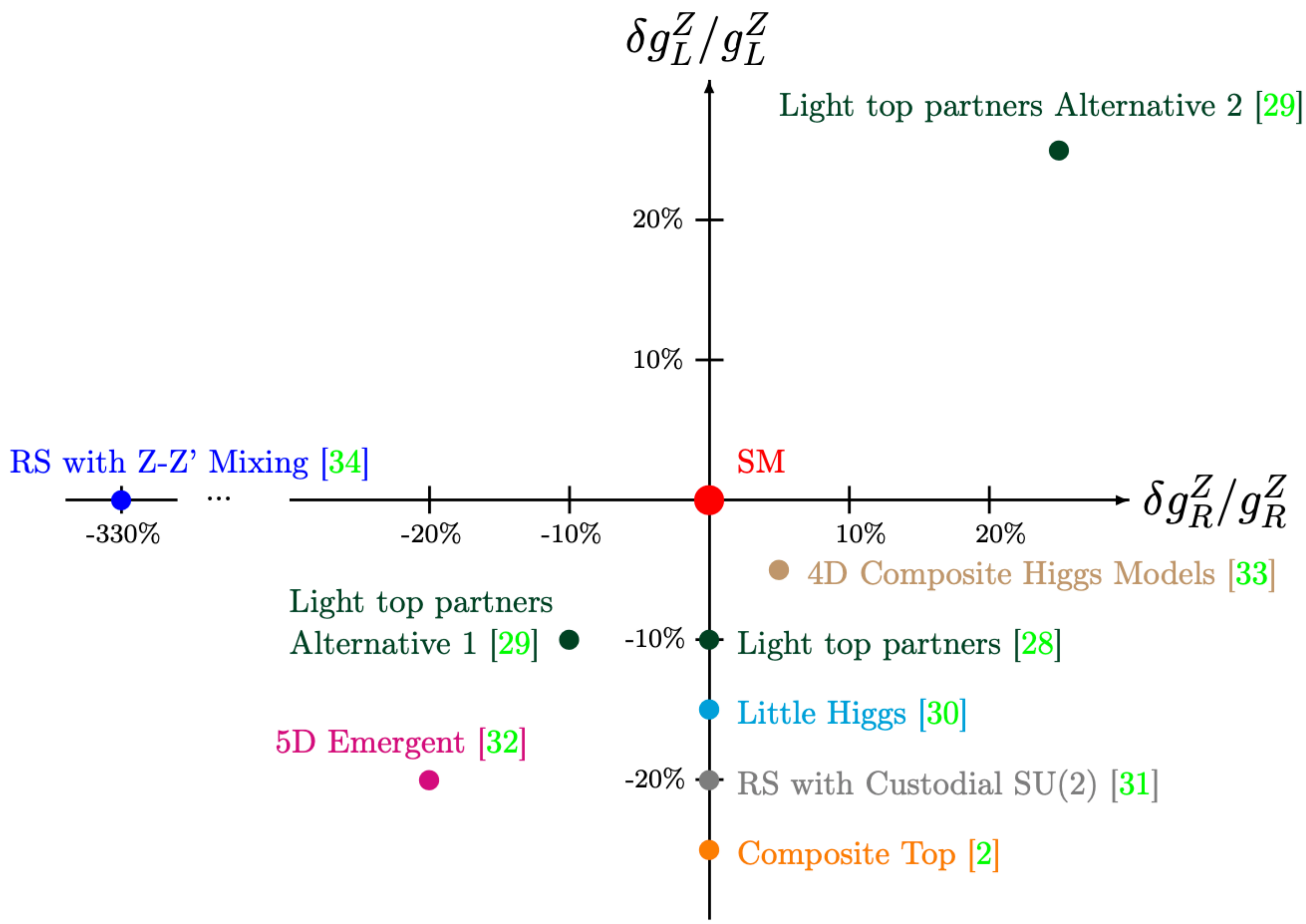


Within 10% at HL-LHC

Introduction

Amjad et al, 1505.06020

Beyond the SM



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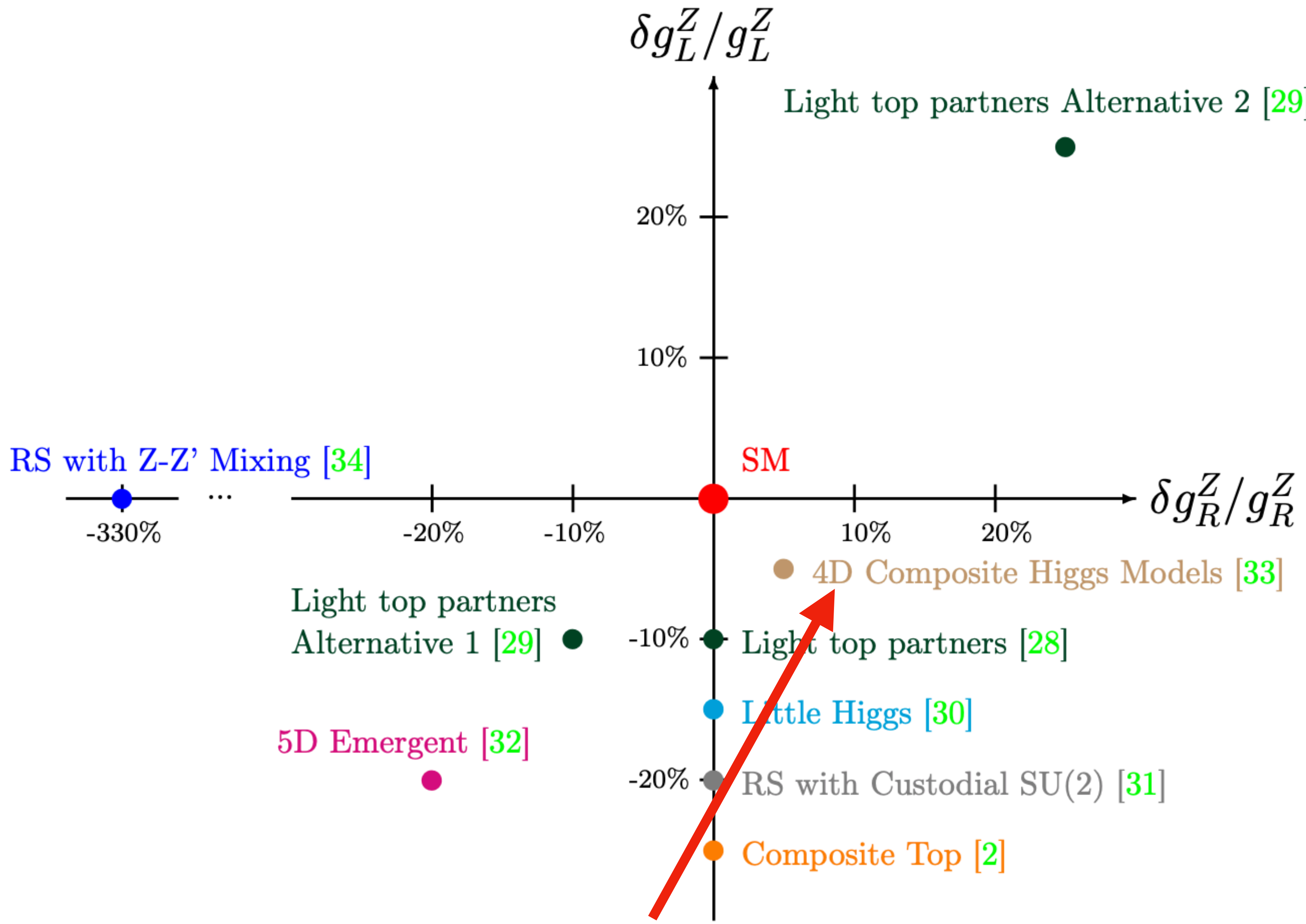
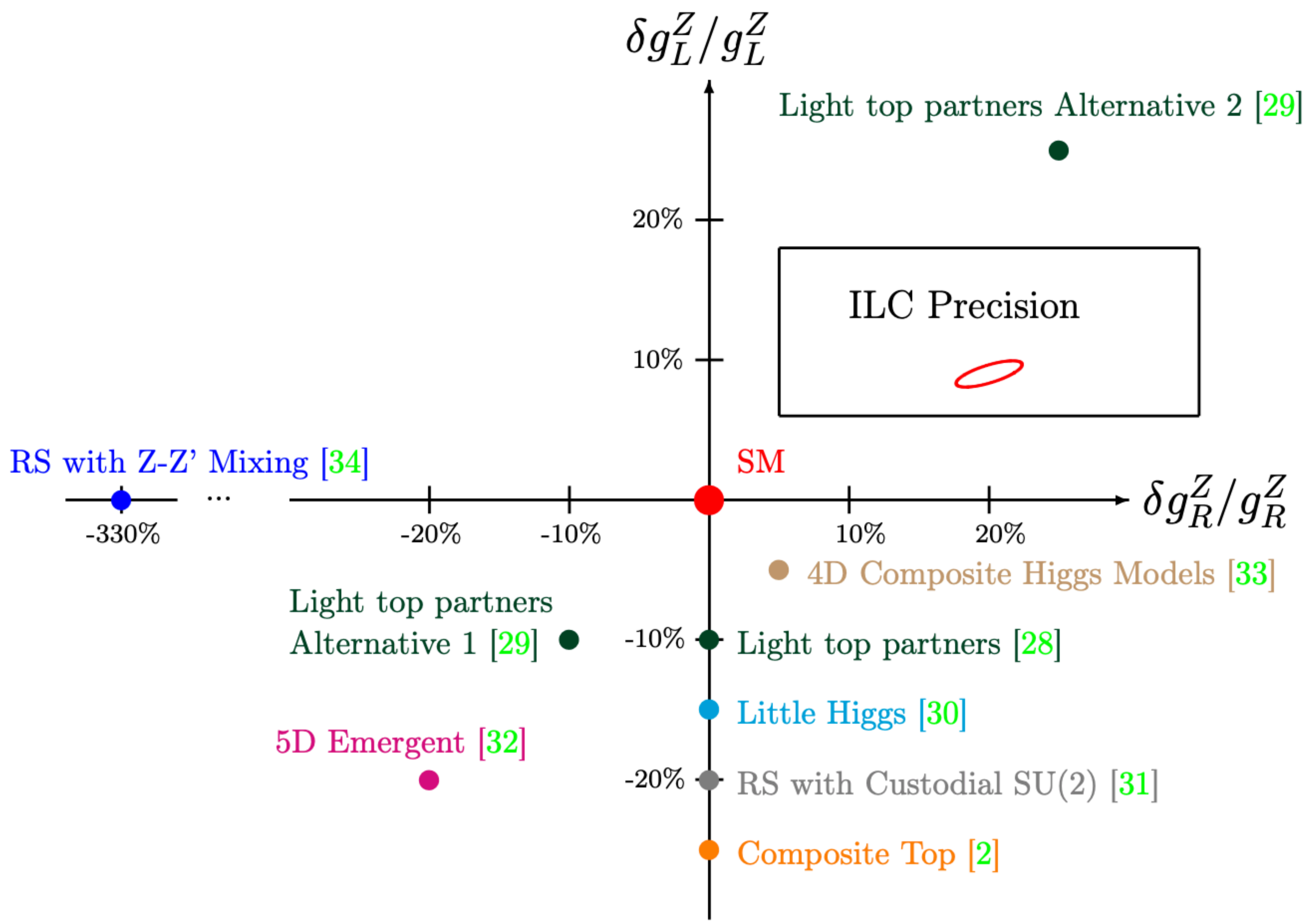


HL-LHC is very promising, except perhaps the 4D Composite Higgs models. This in turn motivates new colliders like CEPC, FCCee or linear ones like ILC and CLIC.

Introduction

Amjad et al, 1505.06020

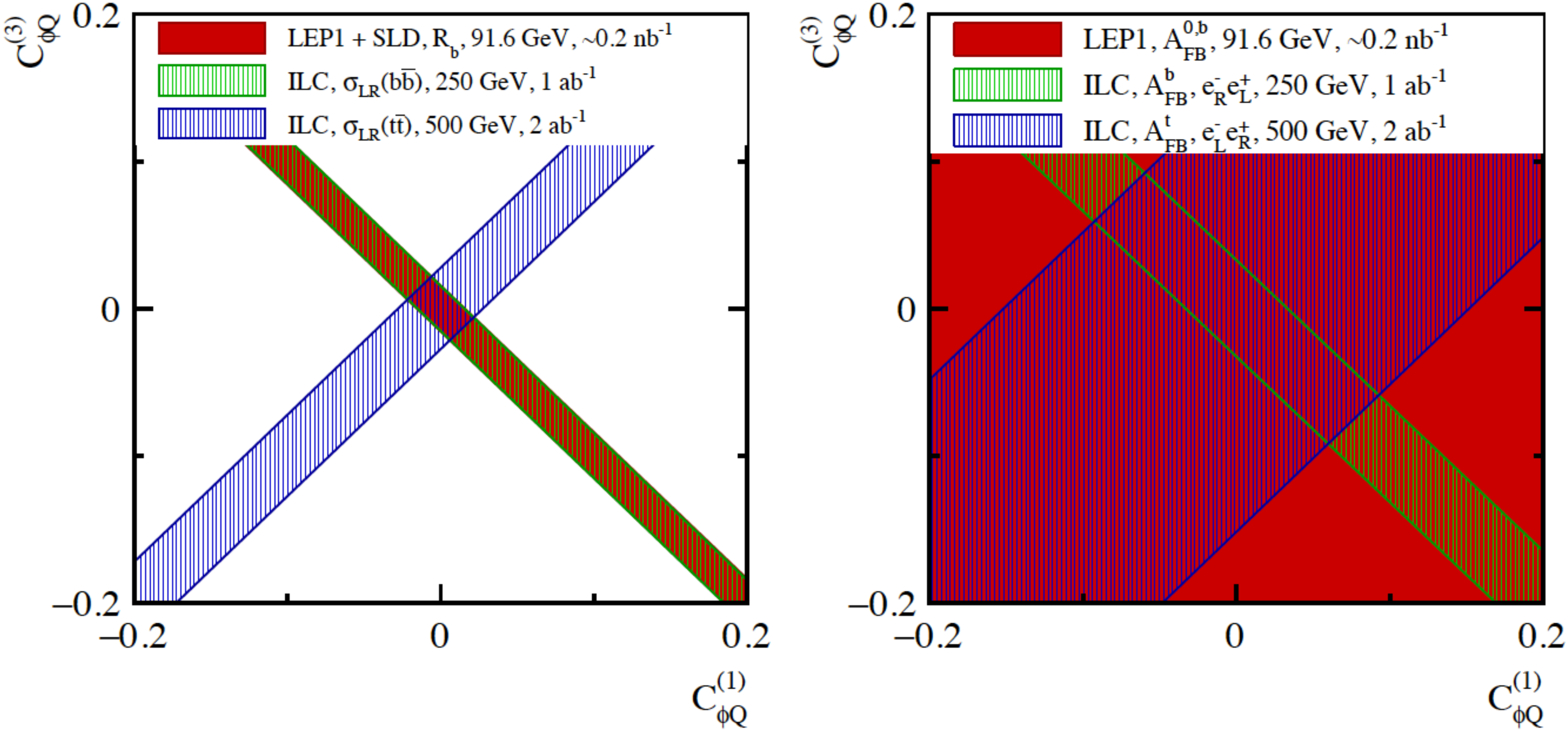
Beyond the SM



Introduction

Durieux et al, 1807.02121

Beyond the SM



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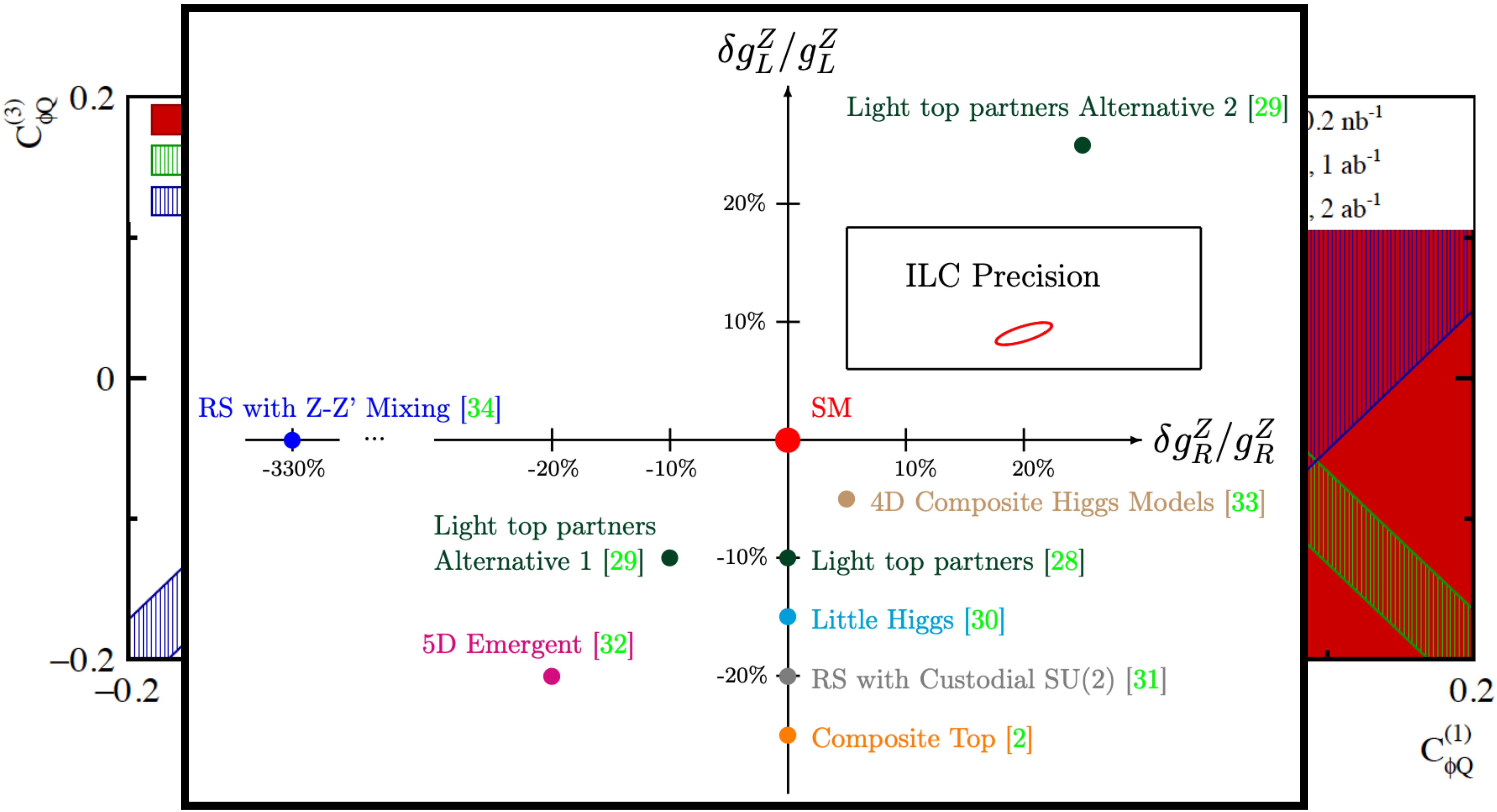

$C_{\phi Q}^{(1)}$ and $C_{\phi Q}^{(3)}$ are just $Zb\bar{b}$ and $Zt\bar{t}$ couplings.

SMEFT global fit: ***Setup***

SMEFT respects the local gauge symmetry of the SM. At dimension 6, there are 79 operators for 1 generation, 2499 for 3 generations:

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

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$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_i \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} \approx \mathscr{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

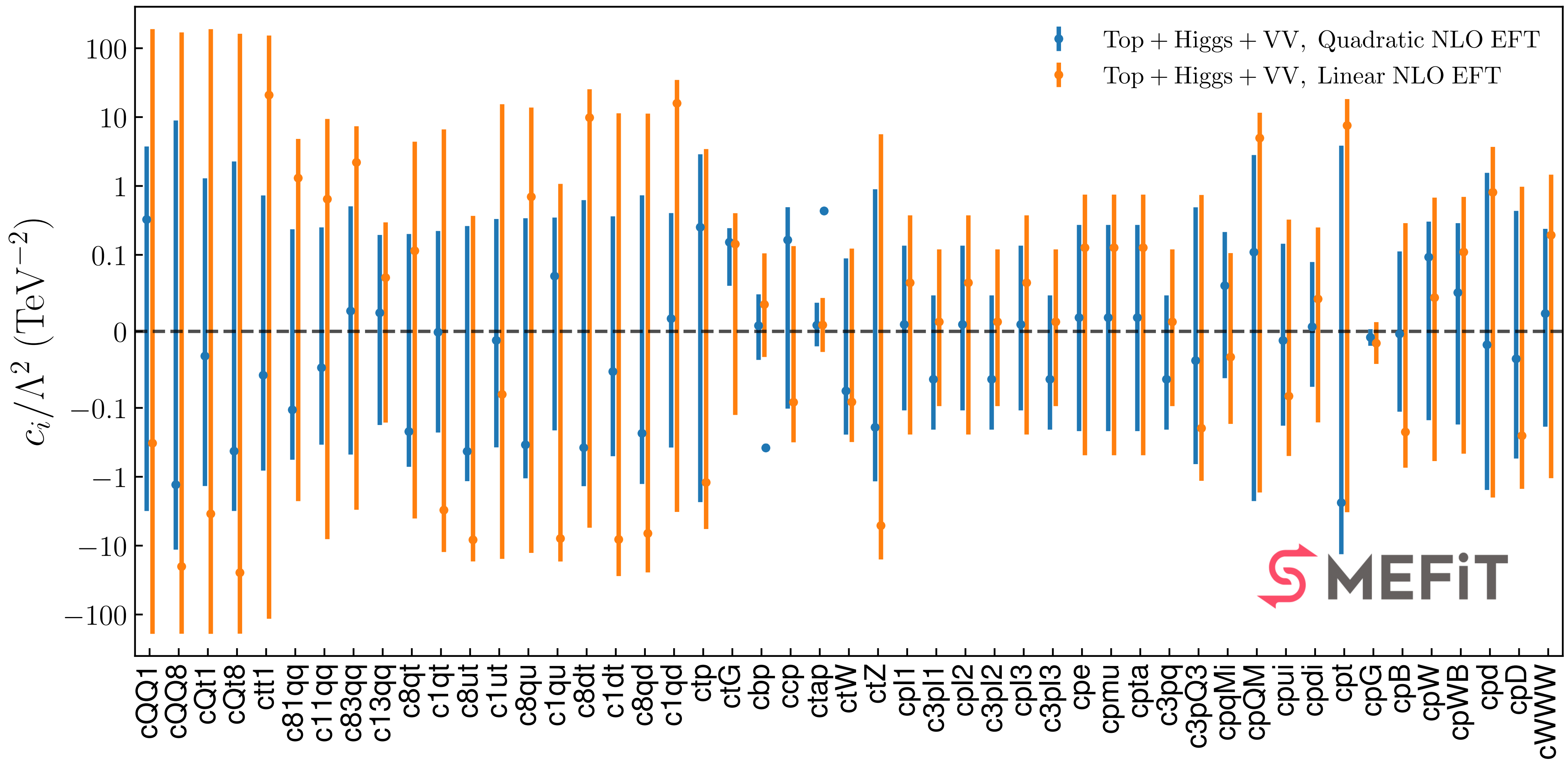
Buchmuller and Wyler, Nucl.Phys.B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 10 (2010) 085

We include all operators for the processes under consideration. We only keep operators at dimension 6.

SMEFT global fit: ***Setup***

Quadratic effects

SMEFiT collaboration, 2105.00006



We also ignore $(\text{dim-6})^2$ terms to be consistent, thus our results will be conservative.

SMEFT global fit: ***Setup***

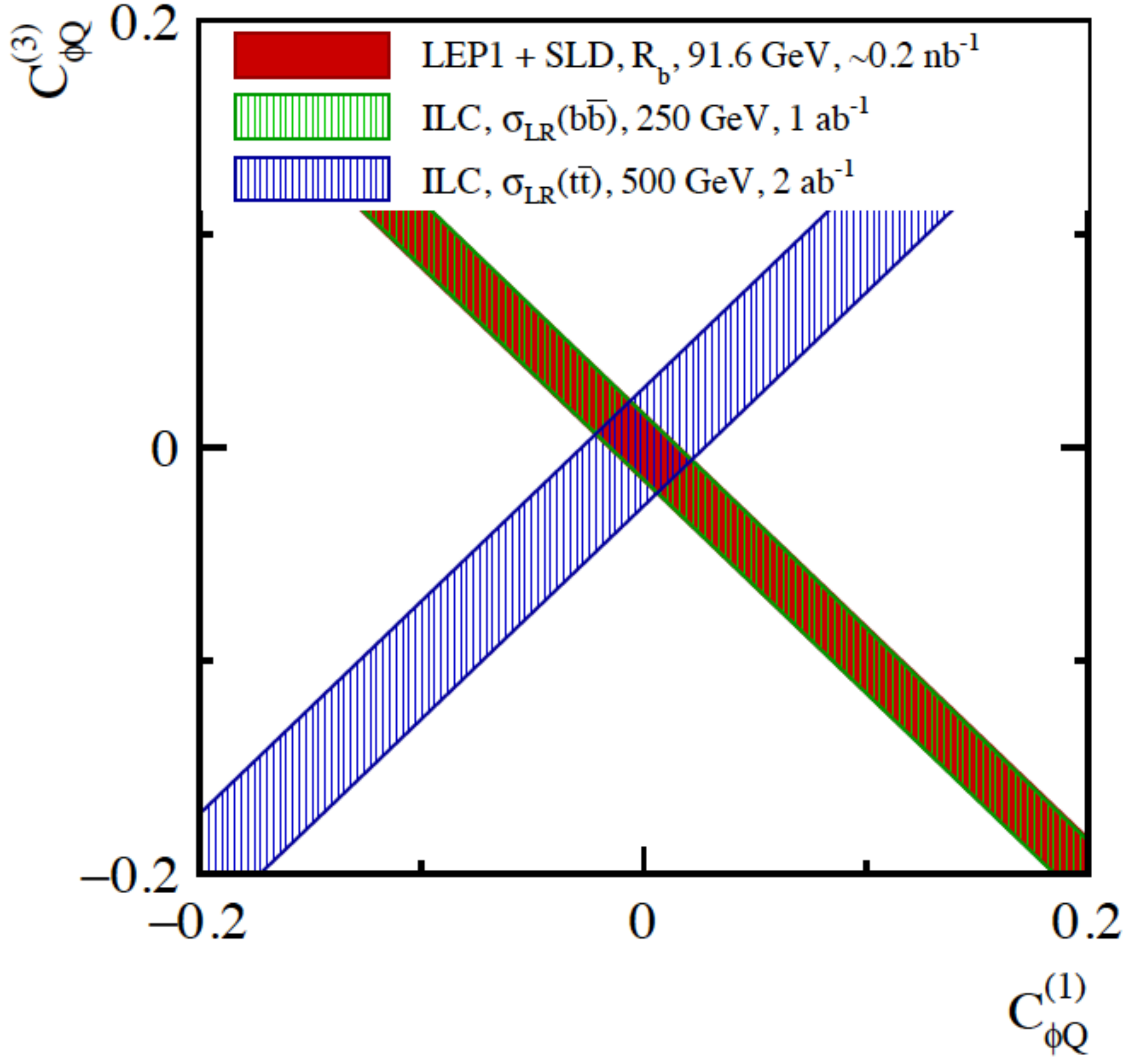
The operator set for top fit

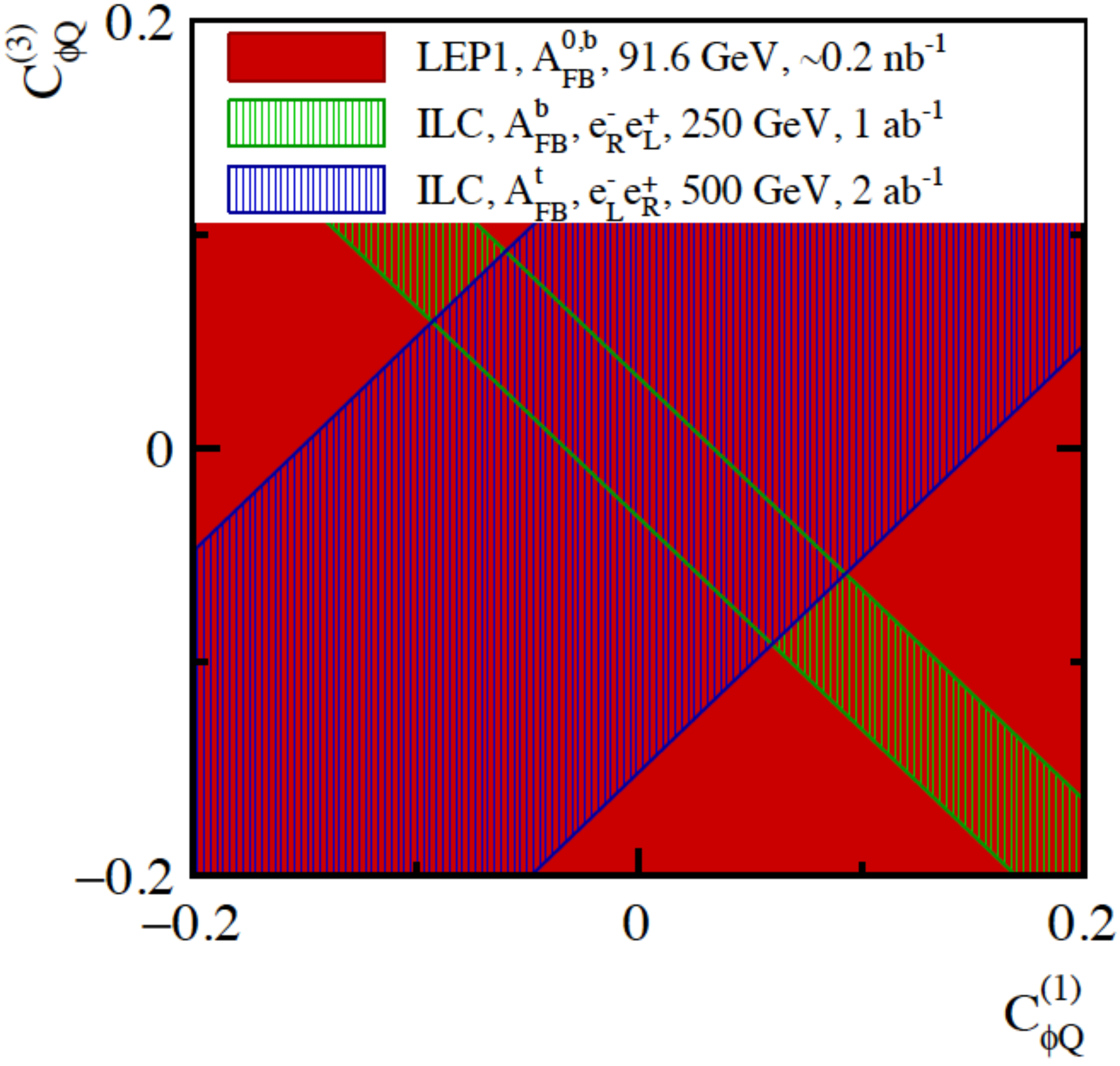
de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Relevant operators			
Coefficient	Operator	Coefficient	Operator
$C^1_{\varphi Q}$	$(\bar{Q}\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C^3_{\varphi Q}$	$(\bar{Q}\tau^I\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi\right)$
$C_{\varphi t}$	$(\bar{t}\gamma^\mu t)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$
$C_{t\varphi}$	$(\bar{Q}t)\left(\epsilon\varphi^*\,\varphi^\dagger\varphi\right)$	C_{tG}	$(\bar{t}\sigma^{\mu\nu}T^A t)\left(\epsilon\varphi^* G^A_{\mu\nu}\right)$
C_{tW}	$(\bar{Q}\tau^I\sigma^{\mu\nu}t)\left(\epsilon\varphi^* W^I_{\mu\nu}\right)$	C_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\left(\epsilon\varphi^* B_{\mu\nu}\right)$
$C^{1(ijkl)}_{qq}$	$(\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$	$C^{3(ijkl)}_{qq}$	$(\bar{q}_i\tau^I\gamma^\mu q_j)(\bar{q}_k\tau^I\gamma_\mu q_l)$
$C^{(ijkl)}_{uu}$	$(\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$	$C^{8(ijkl)}_{ud}$	$(\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$
$C^{8(ijkl)}_{qu}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$	$C^{8(ijkl)}_{qd}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$
C^1_{lQ}	$(\bar{Q}\gamma_\mu Q)\,(\bar{l}\gamma^\mu l)$	C^3_{lQ}	$(\bar{Q}\tau^I\gamma_\mu Q)\,(\bar{l}\tau^I\gamma^\mu l)$
C_{lt}	$(\bar{t}\gamma_\mu t)\,(\bar{l}\gamma^\mu l)$	C_{lb}	$(\bar{b}\gamma_\mu b)\,(\bar{l}\gamma^\mu l)$
C_{eQ}	$(\bar{Q}\gamma_\mu Q)\,(\bar{e}\gamma^\mu e)$	C_{et}	$(\bar{t}\gamma_\mu t)\,(\bar{e}\gamma^\mu e)$
C_{eb}	$(\bar{b}\gamma_\mu b)\,(\bar{e}\gamma^\mu e)$	–	–

SMEFT global fit: *Setup*

Wilson coefficients to fit, following LHC Top WG recommendation





Linear combinations to separate up and down?

SMEFT global fit: Setup

Aguilar-Saavedra et al, 1802.07237

Wilson coefficients to fit, following LHC Top WG recommendation

de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Coefficients fitted in the top-quark processes			
2-quark	$C_{tG}=(C_{uG})_{33}$ $C_{\phi t}=(C_{\phi u})_{33}$ –	$C^3_{\phi Q}=\left(C^{(3)}_{\phi q}\right)_{33}$ $C_{\phi b}=(C_{\phi d})_{33}$ $C_{t\phi}=(C_{u\phi})_{33}$	$C^-_{\phi Q}=\left(C^{(1)}_{\phi q}\right)_{33}-\left(C^{(3)}_{\phi q}\right)_{33}$ $C_{tZ}=\cos\theta_w(C_{uW})_{33}-\sin\theta_w(C_{uB})_{33}$ $C_{tW}=(C_{uW})_{33}$
4-quark	$C^8_{tu}=\sum_{i=1,2}2\,(C_{uu})_{i33i}$ $C^8_{Qu}=\sum_{i=1,2}\left(C^{(8)}_{qu}\right)_{33ii}$ –	$C^8_{td}=\sum_{i=1,2,3}\left(C^{(8)}_{ud}\right)_{33ii}$ $C^8_{Qd}=\sum_{i=1,2,3}\left(C^{(8)}_{qd}\right)_{33ii}$ –	$C^{1,8}_{Qq}=\sum_{i=1,2}\left(\left(C^{(1)}_{qq}\right)_{i33i}+3\left(C^{(3)}_{qq}\right)_{i33i}\right)$ $C^{3,8}_{Qq}=\sum_{i=1,2}\left(\left(C^{(1)}_{qq}\right)_{i33i}-\left(C^{(3)}_{qq}\right)_{i33i}\right)$ $C^8_{tq}=\sum_{i=1,2}\left(C^{(8)}_{qu}\right)_{ii33}$
2-quark 2-lepton	$C_{eb}=(C_{ed})_{1133}$ $C_{lb}=(C_{ld})_{1133}$ –	$C_{et}=(C_{eu})_{1133}$ $C_{lt}=(C_{lu})_{1133}$ –	$C^+_{lQ}=\left(C^{(1)}_{lq}\right)_{1133}+\left(C^{(3)}_{lq}\right)_{1133}$ $C^-_{lQ}=\left(C^{(1)}_{lq}\right)_{1133}-\left(C^{(3)}_{lq}\right)_{1133}$ $C_{eQ}=(C_{qe})_{3311}$

For example, C^+_{lQ} and C^-_{lQ} would stand for $eebb$ and $eett$ couplings, respectively.

SMEFT global fit: ***Setup***

Brivio et al, 1910.03606

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

[…]: NLO QCD interference

The number of operators also decreases. Shaded operator for example.

We go beyond to also investigate the $\mathcal{O}_{t\phi}$ operator that modifies the top Yukawa.

SMEFT global fit: *Collider options*

Future collider options included thus far

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Machine	Pol. (e^-, e^+)	Energy	Luminosity	Reference
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}	[17]
ILC	$(\mp 80\%, \pm 30\%)$	250 GeV	2 ab^{-1}	[18]
		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}	[19]
		1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}	[20]
		$2m_W$	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}	[21]
		$2m_W$	6 ab^{-1}	
		240 GeV	20 ab^{-1}	
		350 GeV	0.2 ab^{-1}	
		360 GeV	1 ab^{-1}	

Muon collider options not yet considered for top fit.

SMEFT global fit: *Input*

Input from current/past colliders

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

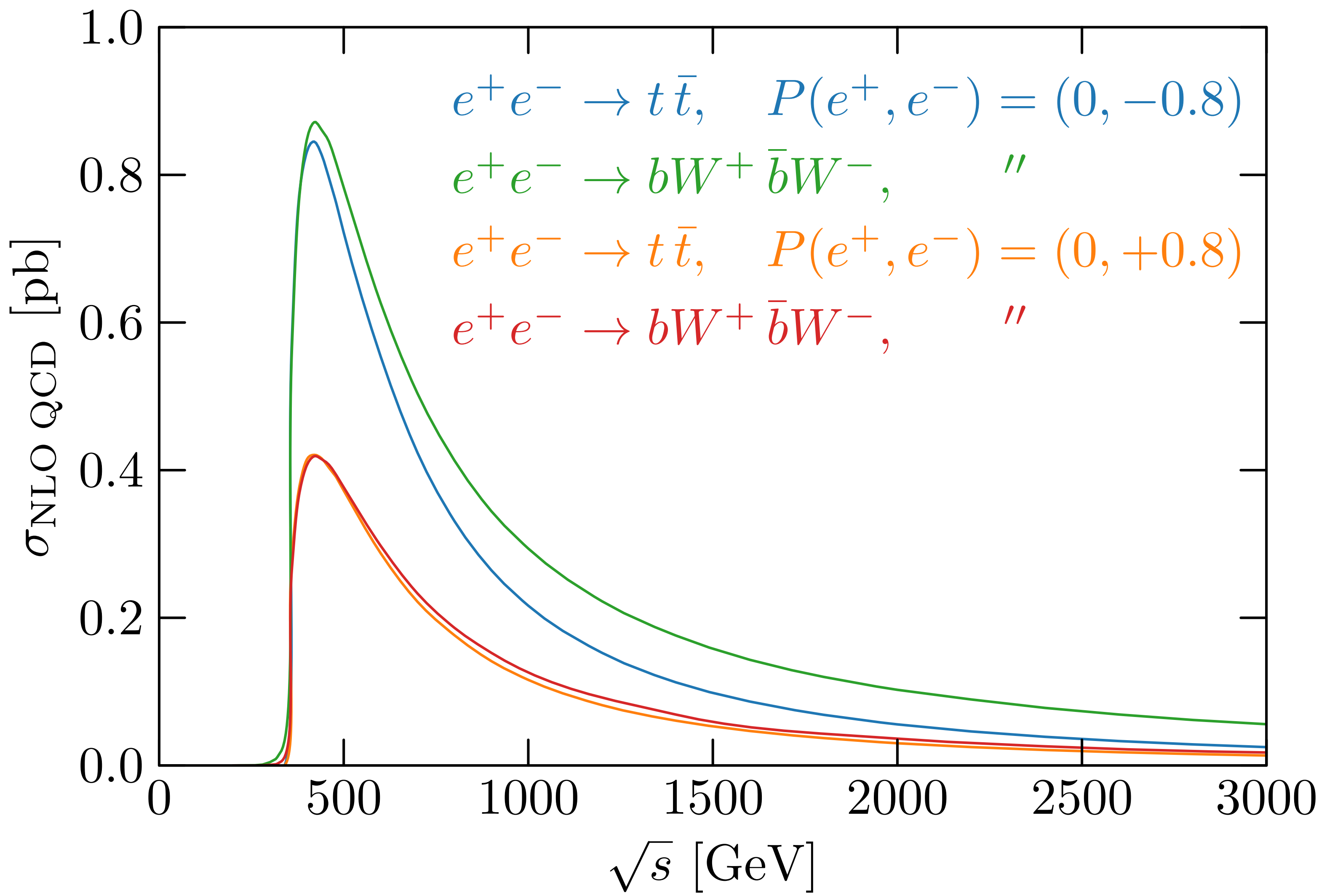
WC	Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment	SM	Ref.
$C_{tG}+4q$	$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS	[129]	[130]
$C_{tG}+4q$	$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS	[129]	[131]
$C_{t\phi,tW}$	$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS	[132]	[133]
$C_{tZ,tG,\phi t}$	$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS	[134]	[135]
$C_{tZ,tG,tW}$	$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS	[136, 137]	[138]
$C_{\phi Q}^-, C_{\phi Q}^{(3)}$	$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS	[139]	[140]
$C_{\phi Q}^-, C_{\phi Q}^{(3)}$	$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS	[141]	[141]
$C_{tG}+4q$	$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS	[132, 142]	[143]
C_{tW}	$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC	[144, 145]	[146]
$C_{tG,tW}$	$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC	[147]	[146]
C_{tW}	$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC	[144, 145]	[146]
C_{tW}	$t \to Wb$	$F_0,\ F_L$	8 TeV	20 fb^{-1}	LHC	[148]	[149]
C_{tW}	$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron	[150]	[151]
$C_{\phi b}, C_{\phi Q}^{-,(3)}, 2\ell 2q$	$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD	–	[49]

* examples for illustration

SMEFT global fit: *Optimal observables*

Durieux et al, 1807.02121

Input from future e^+e^- colliders: $A_{FB}^{bb,tt}$ and $\sigma_{bb,tt}$



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Durieux et al, 1807.02121

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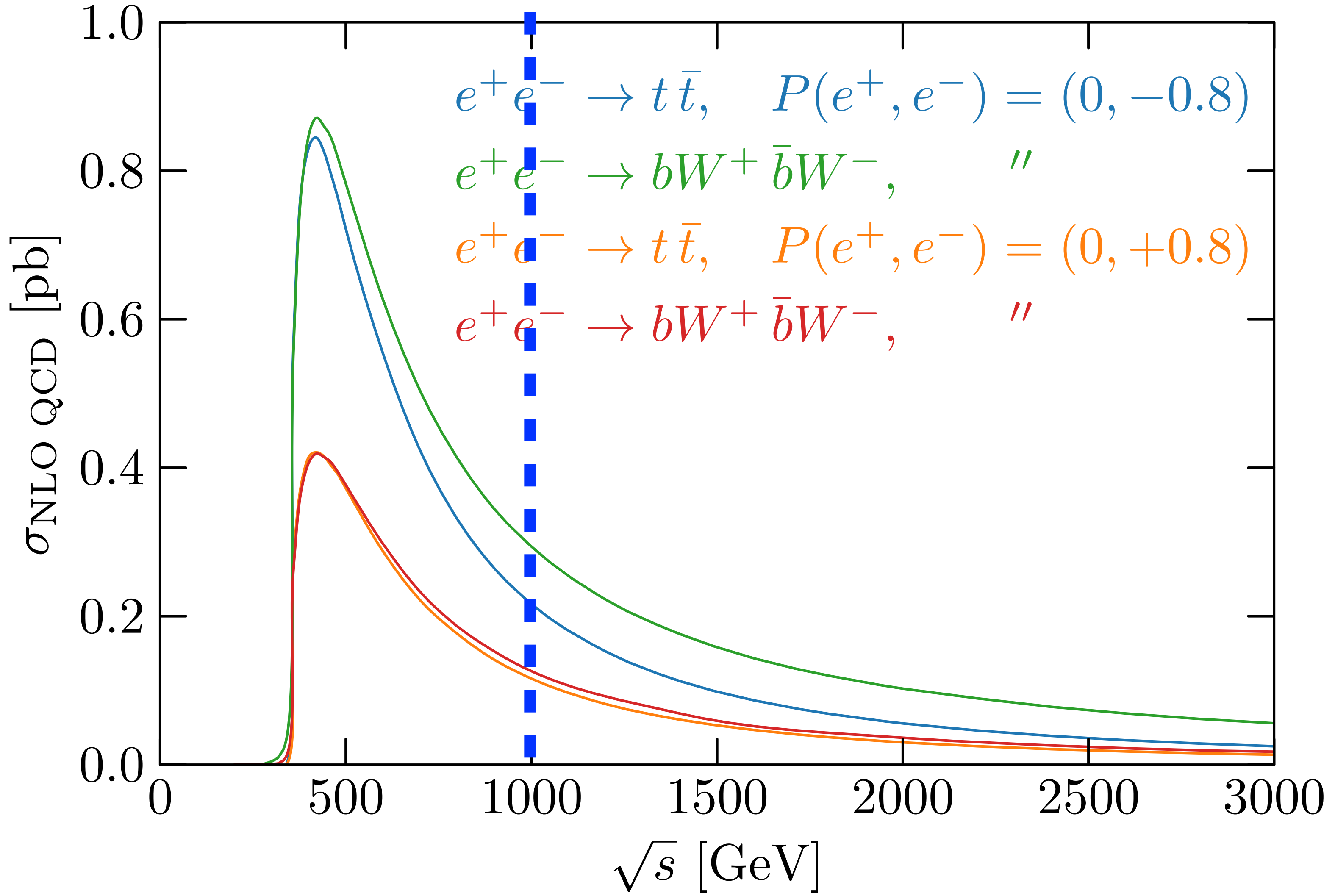

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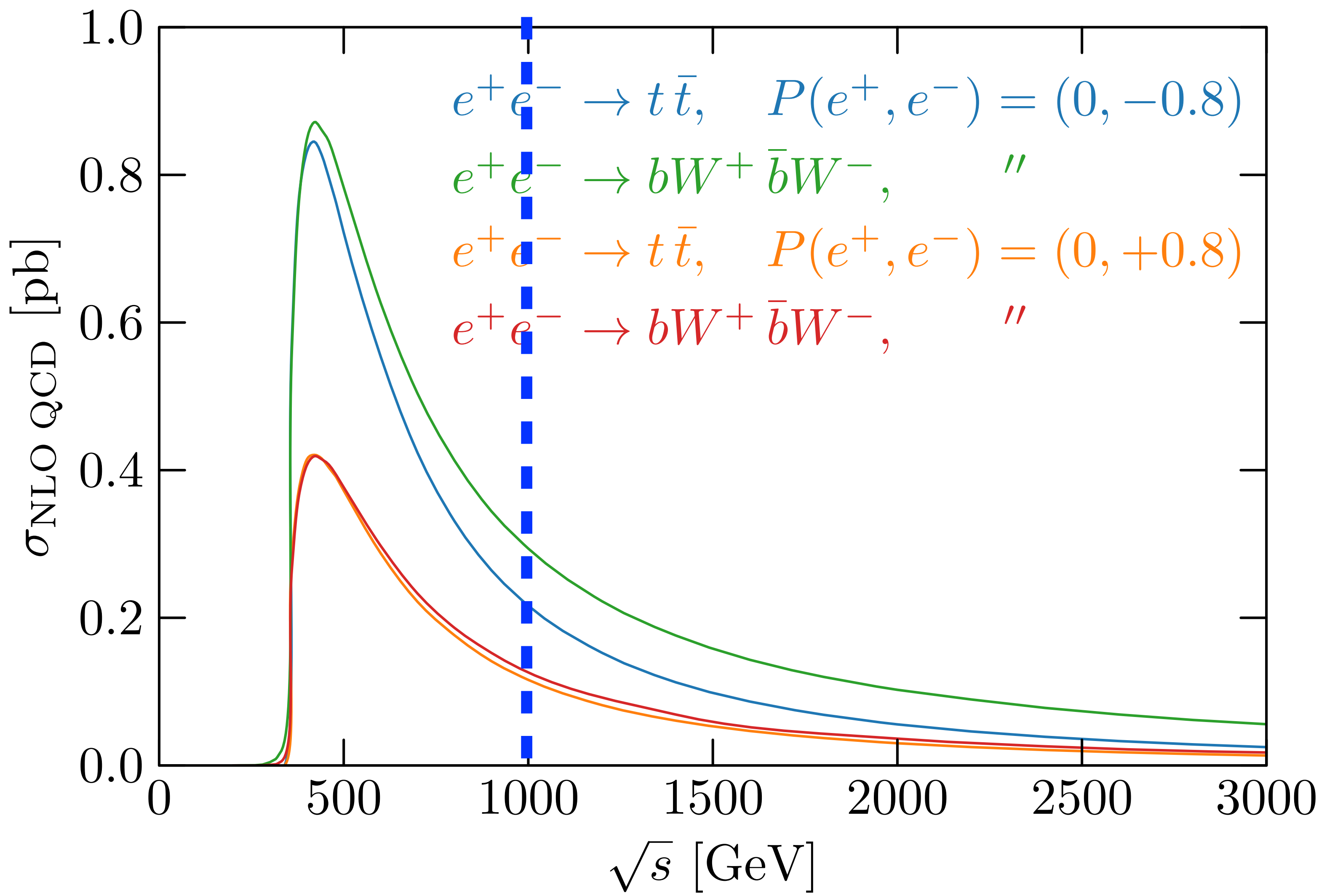

Optimal observable approach is adopted to maximize the constraints.

SMEFT global fit: *Optimal observables*

Durieux et al, 1807.02121

Optimal observable short review

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} = \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}\Phi} + \sum_i C_i \frac{\mathrm{d}\sigma_i}{\mathrm{d}\Phi} \quad \longrightarrow \quad O_i = N \frac{\mathrm{d}\sigma_i}{\mathrm{d}\Phi} / \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}\Phi}$$

SMEFT global fit: *Optimal observables*

Durieux et al, 1807.02121

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Optimal observables at colliders

$$\overline{O}_i = \epsilon \mathscr{L} \int \mathrm{d}\Phi \left(\frac{\mathrm{d}\sigma_i}{\mathrm{d}\Phi} / \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}\Phi} \right) \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi}$$

SMEFT global fit: *Optimal observables*

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$$\overline{O}_i = \epsilon \mathscr{L} \int d\Phi \left(\frac{d\sigma_i}{d\Phi} / \frac{d\sigma_{SM}}{d\Phi} \right) \frac{d\sigma}{d\Phi}$$

Parameter sensitivity

$$S_j^{O_i} \equiv \frac{1}{\bar{O}_i} \frac{\partial \bar{O}_i}{\partial C_j} \bigg|_{C_k=0,\forall k} = \frac{\int d\Phi \left(\frac{d\sigma_i}{d\Phi} \frac{d\sigma_j}{d\Phi} / \frac{d\sigma_{SM}}{d\Phi} \right)}{\int d\Phi \frac{d\sigma_i}{d\Phi}}$$

SMEFT global fit: *Optimal observables*

Durieux et al, 1807.02121

Optimal observable short review

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$$\bar{O}_i = \epsilon \mathscr{L} \int d\Phi \left(\frac{d\sigma_i}{d\Phi} / \frac{d\sigma_{SM}}{d\Phi} \right) \frac{d\sigma}{d\Phi}$$

Parameter sensitivity

$$S_j^{O_i} \equiv \frac{1}{\bar{O}_i} \frac{\partial \bar{O}_i}{\partial C_j} \bigg|_{C_k=0,\forall k} = \frac{\int d\Phi \left(\frac{d\sigma_i}{d\Phi} \frac{d\sigma_j}{d\Phi} / \frac{d\sigma_{SM}}{d\Phi} \right)}{\int d\Phi \frac{d\sigma_i}{d\Phi}}$$

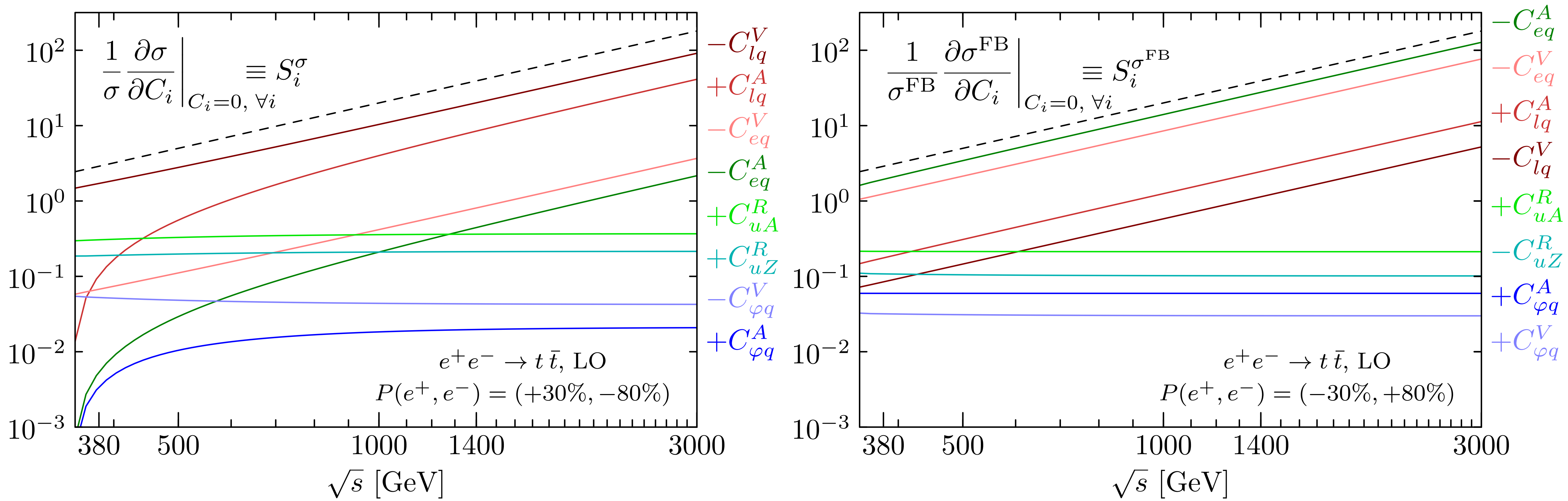
The inverse covariance matrix

$$V^{-1}\Big|_{ij} = \epsilon \mathscr{L} \int d\Phi \left(\frac{d\sigma_i}{d\Phi} \frac{d\sigma_j}{d\Phi} / \frac{d\sigma_{SM}}{d\Phi} \right)$$

SMEFT global fit: *Optimal observables*

Non-optimal analysis

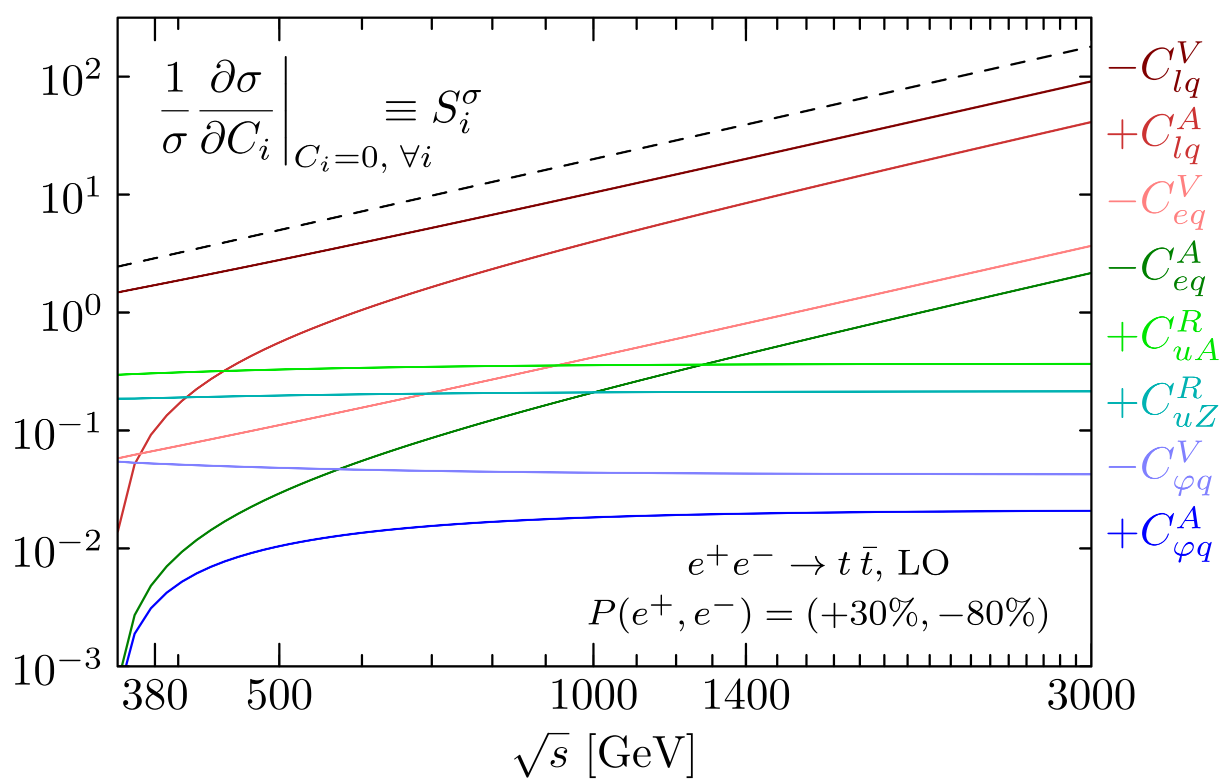
Durieux et al, 1807.02121

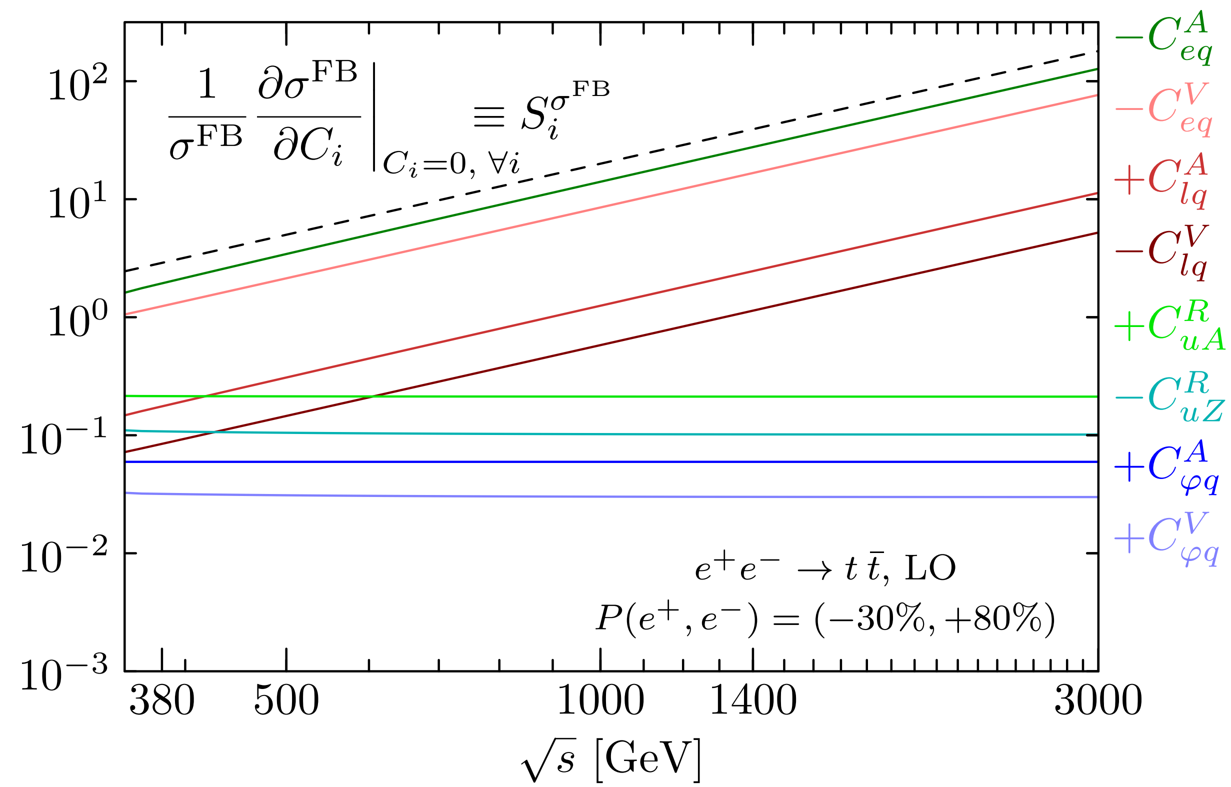


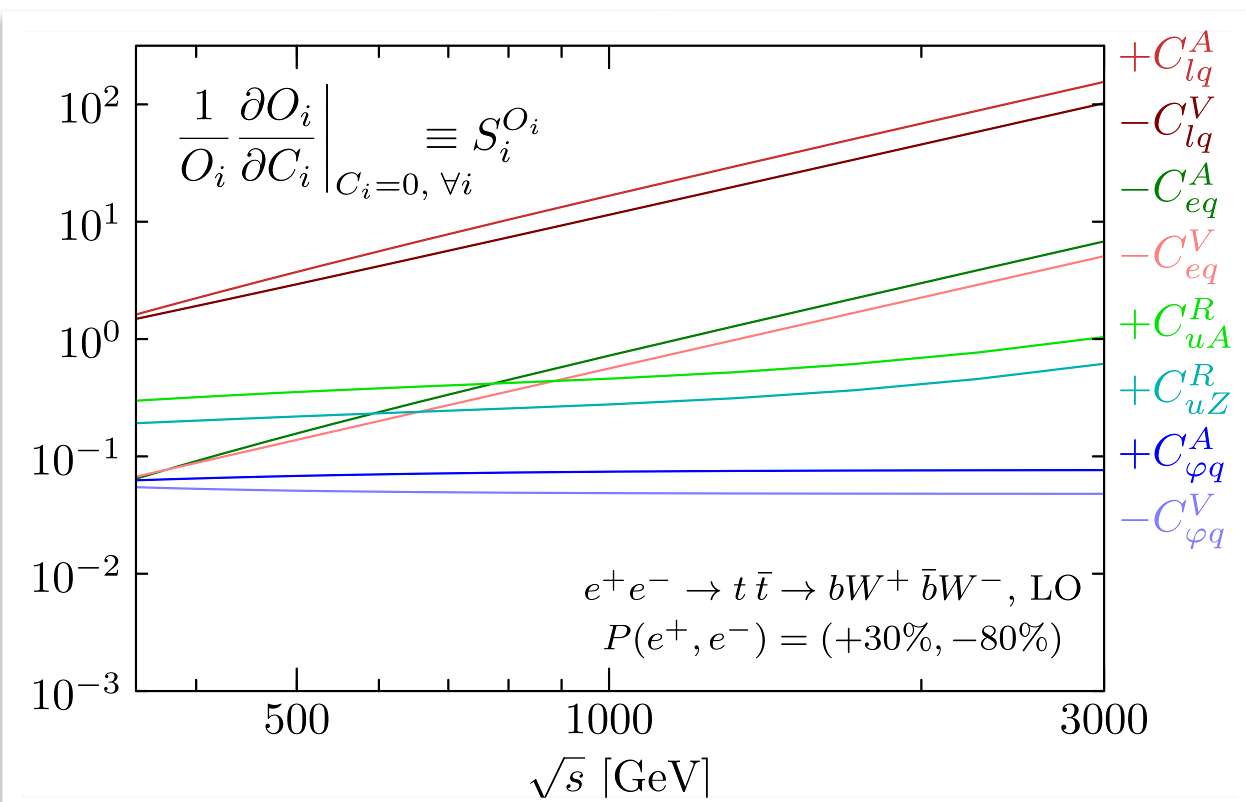
SMEFT global fit: *Optimal observables*

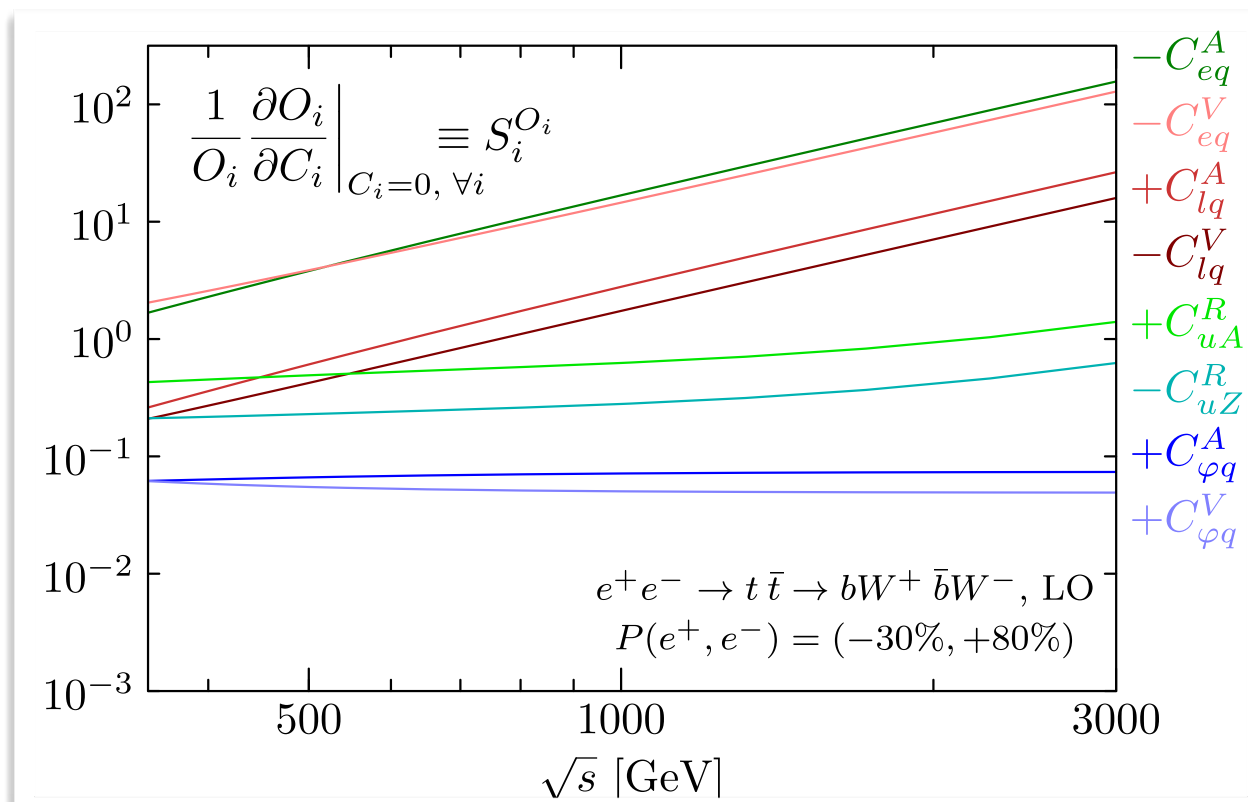
Non-optimal analysis *vs optimal observable analysis*

Durieux et al, 1807.02121





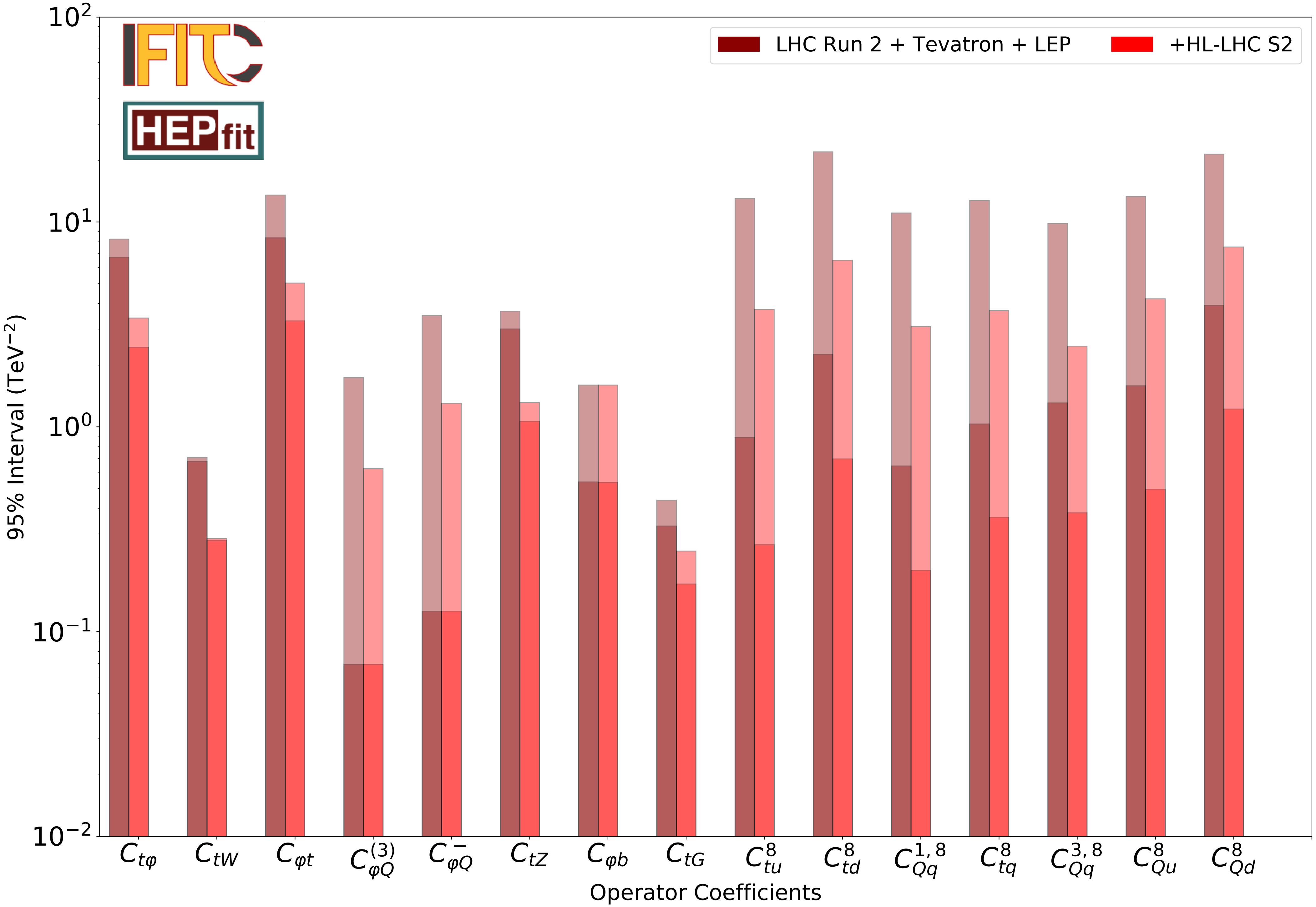




SMEFT global fit: ***Results***

Current fit vs the HL era of the LHC

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326



SMEFT global fit: ***Results***

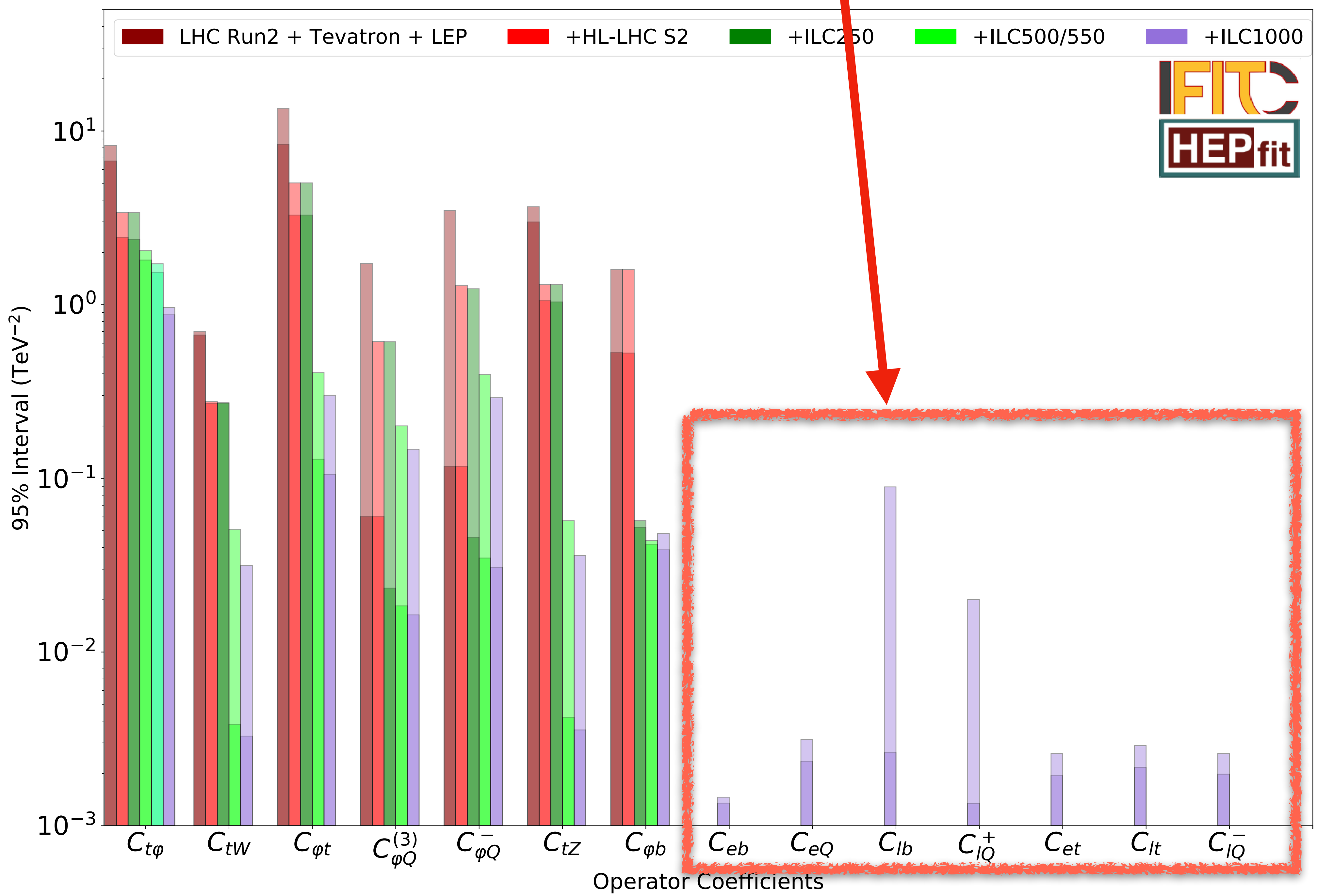
Hadron colliders vs ILC

SMEFT global fit: ***Results***

Hadron colliders vs ILC

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Colliders run at *two different energy scales* are essential to close the fit.

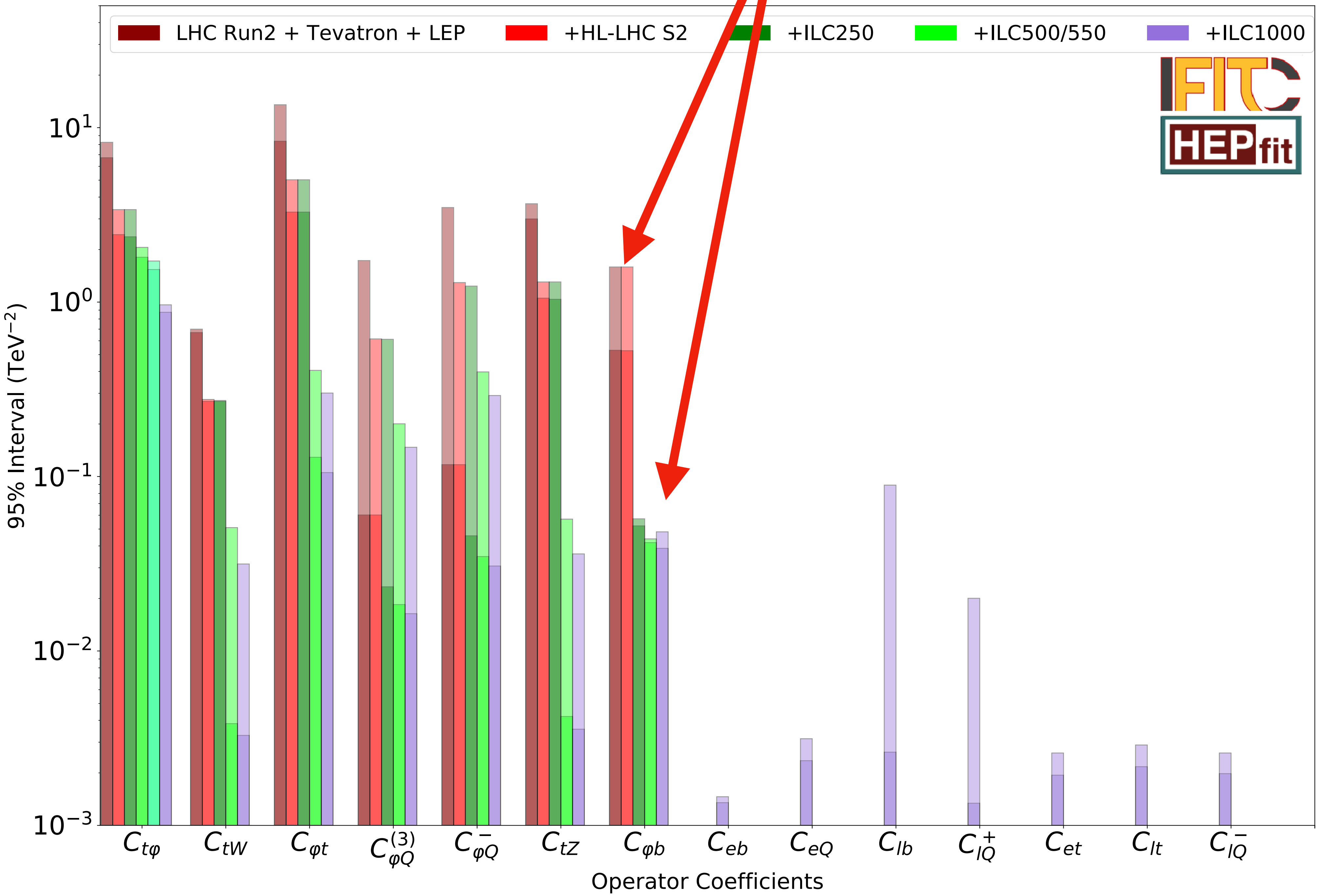


SMEFT global fit: ***Results***

Hadron colliders vs ILC

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Energy wins!

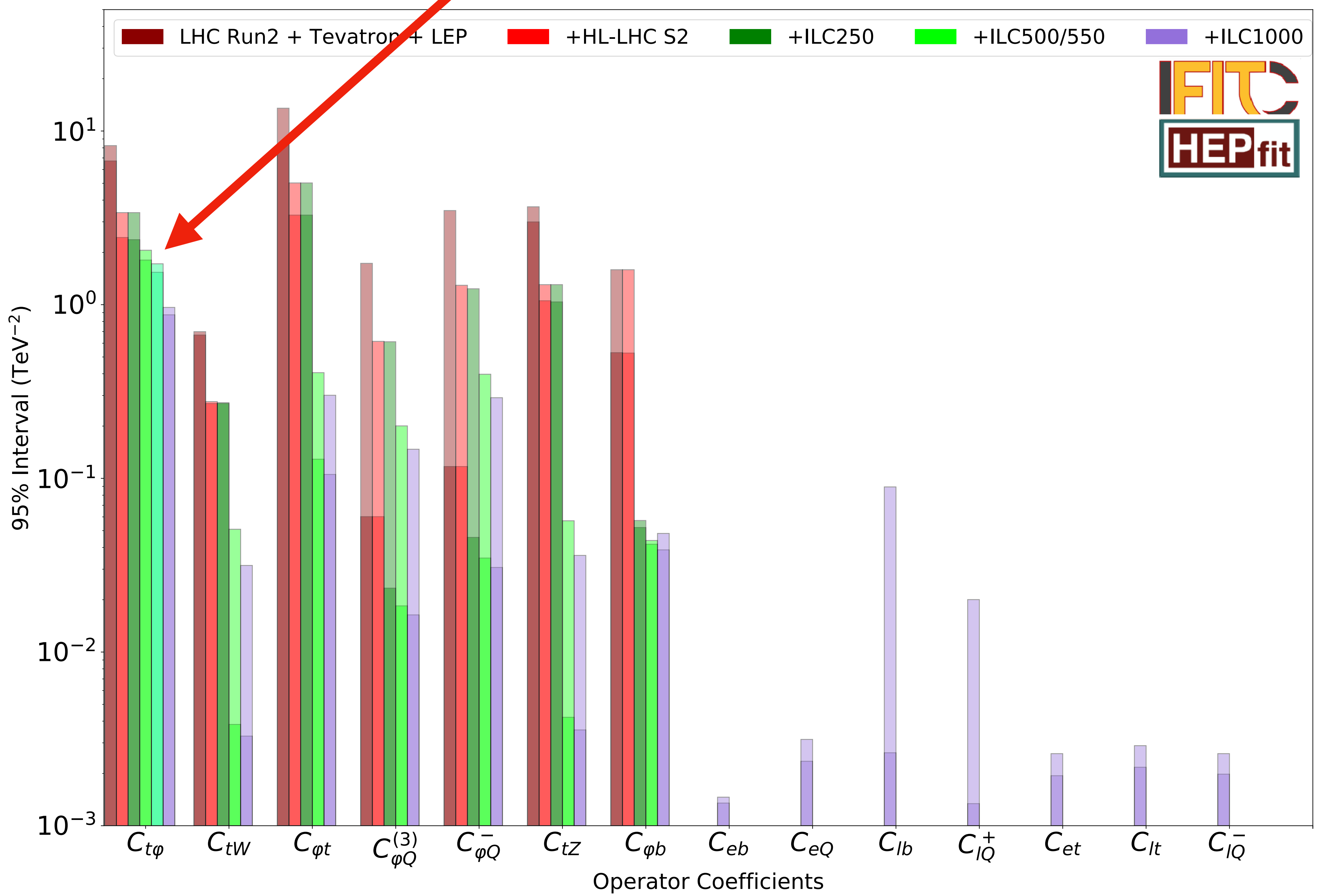


SMEFT global fit: *Results*

Hadron colliders vs ILC

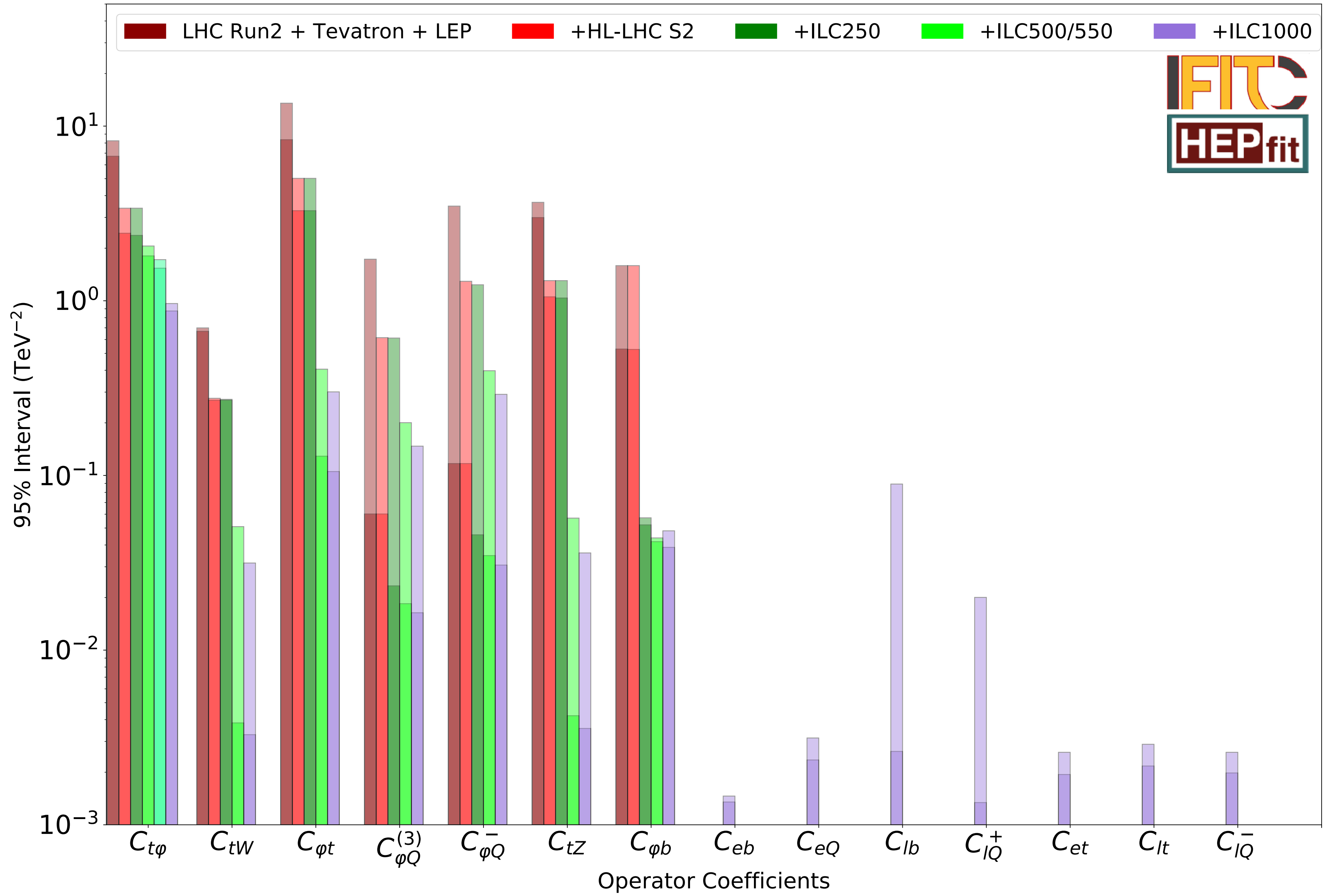
de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

$e^+e^- \to t\bar{t}h$ at 550GeV enhances the sensitivity top Yukawa.



SMEFT global fit: *Results*

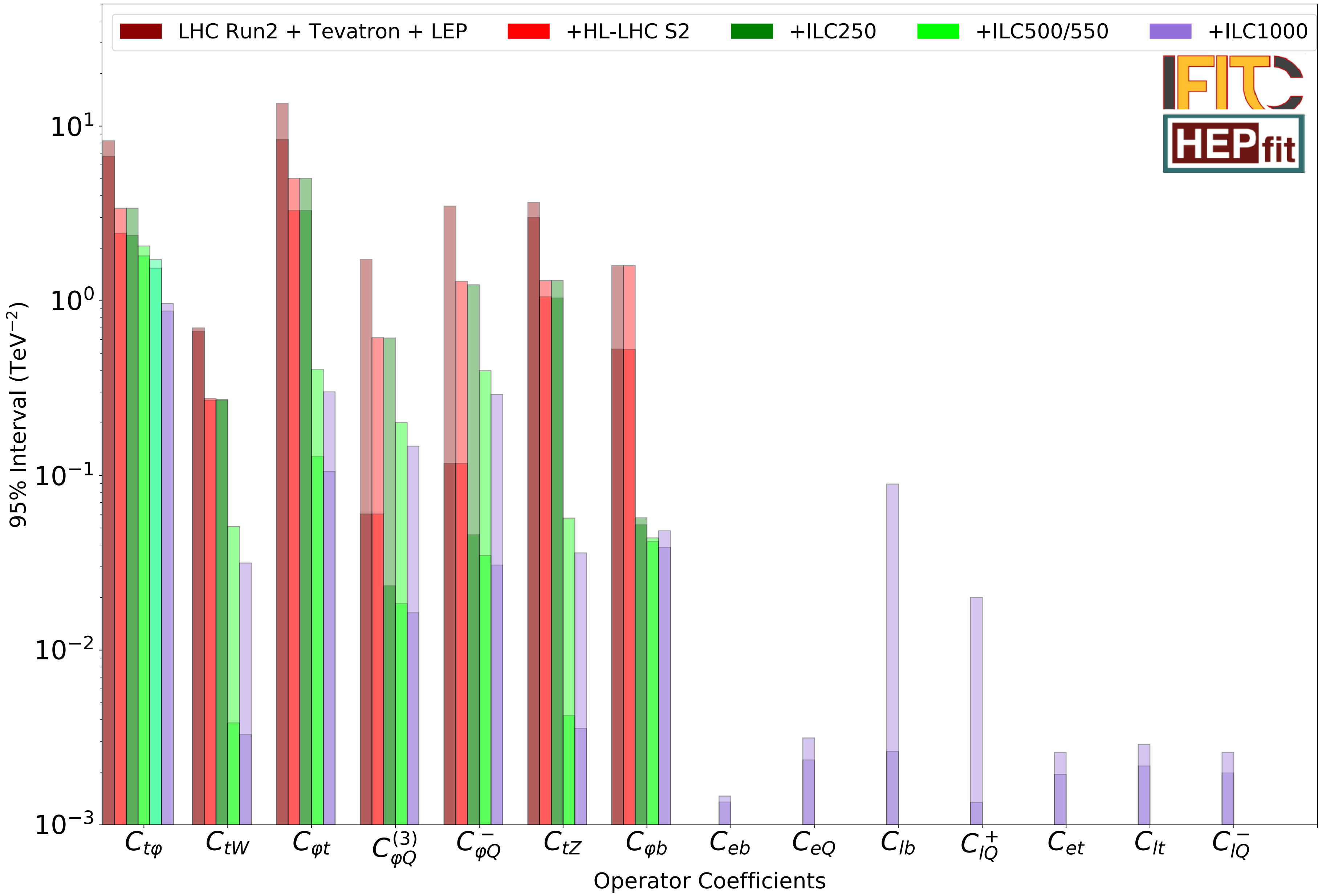
de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326



Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48
	Indiv. fit	10.2	3.70	2.82	2.34	1.41

SMEFT global fit: *Results*

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326



Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top selection & flavor-tagging efficiency drop.

SMEFT global fit: ***Results***

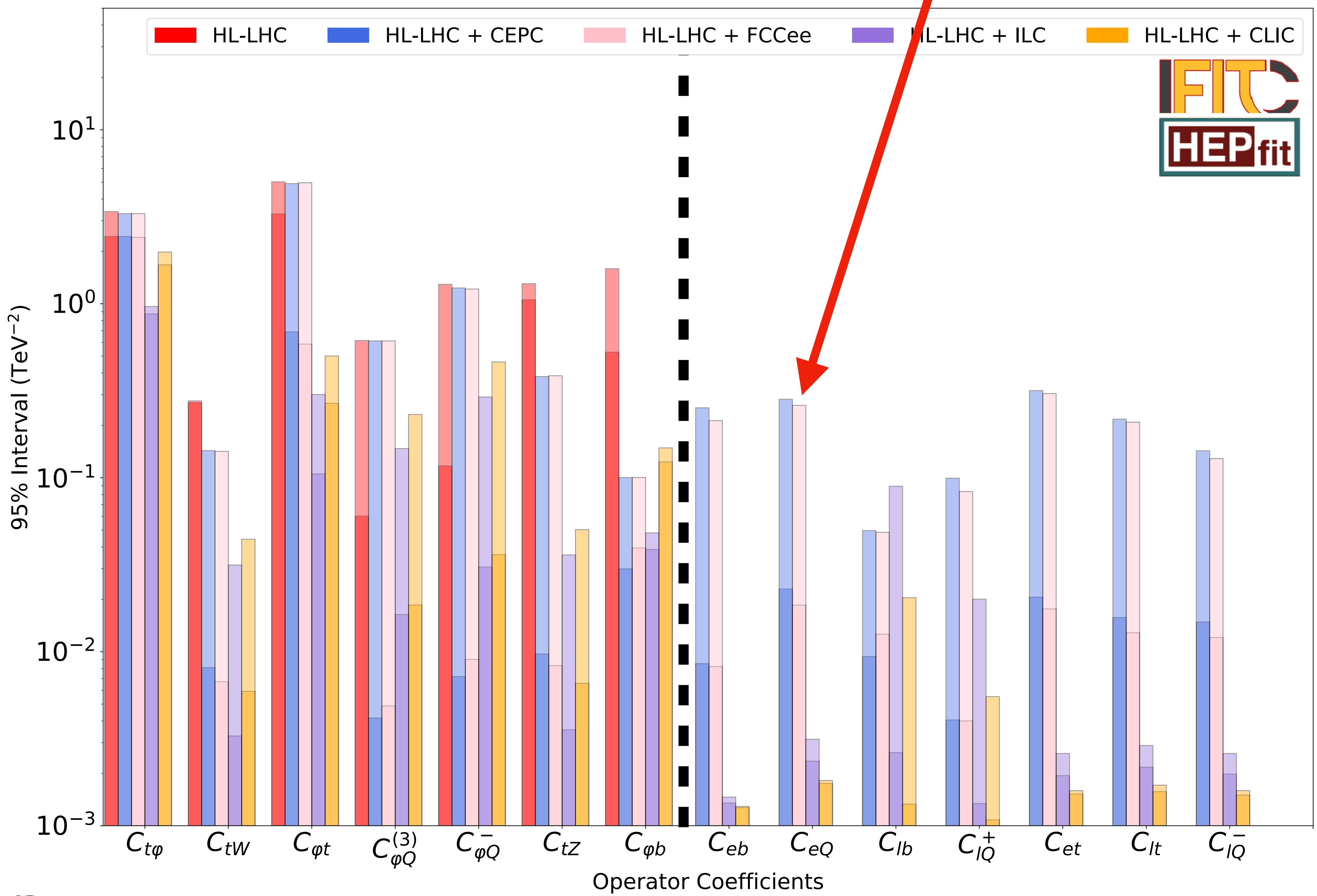
Comparison of different collider options

SMEFT global fit: *Results*

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Comparison of different collider options

Circular colliders limited by energy reach

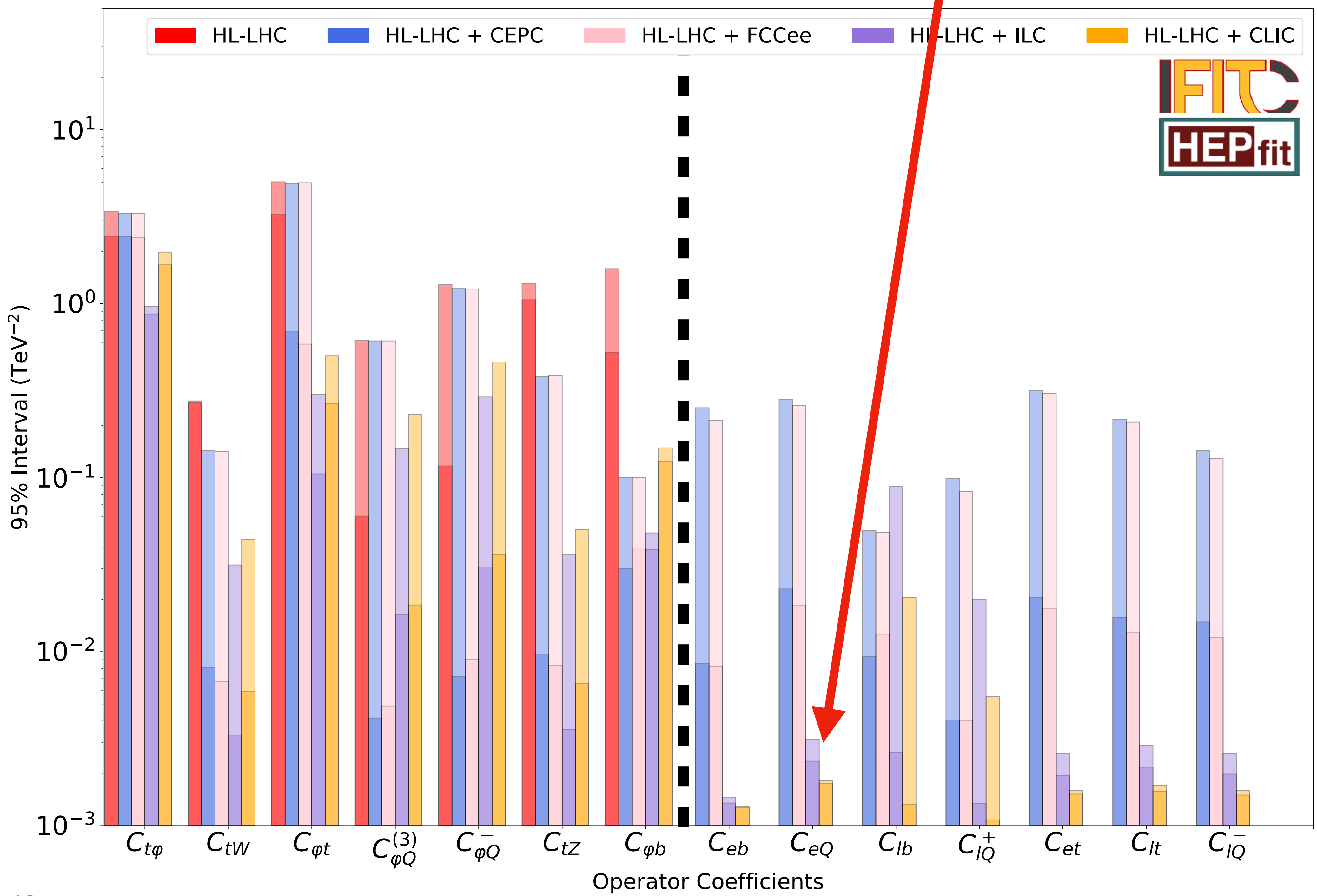


SMEFT global fit: ***Results***

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Comparison of different collider options

CoM energy (well-separated) is the key for linear colliders

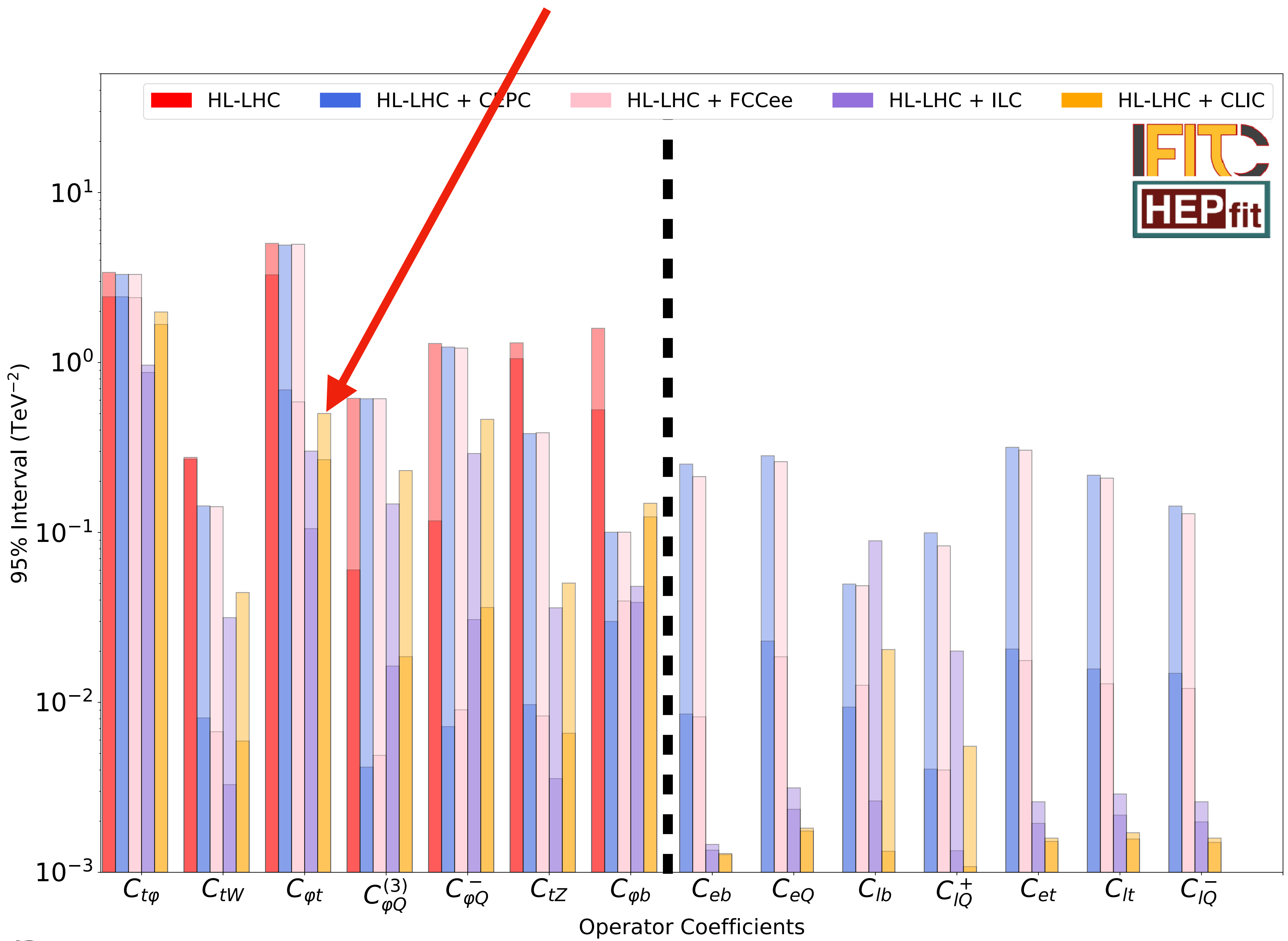


SMEFT global fit: ***Results***

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Comparison of different collider options

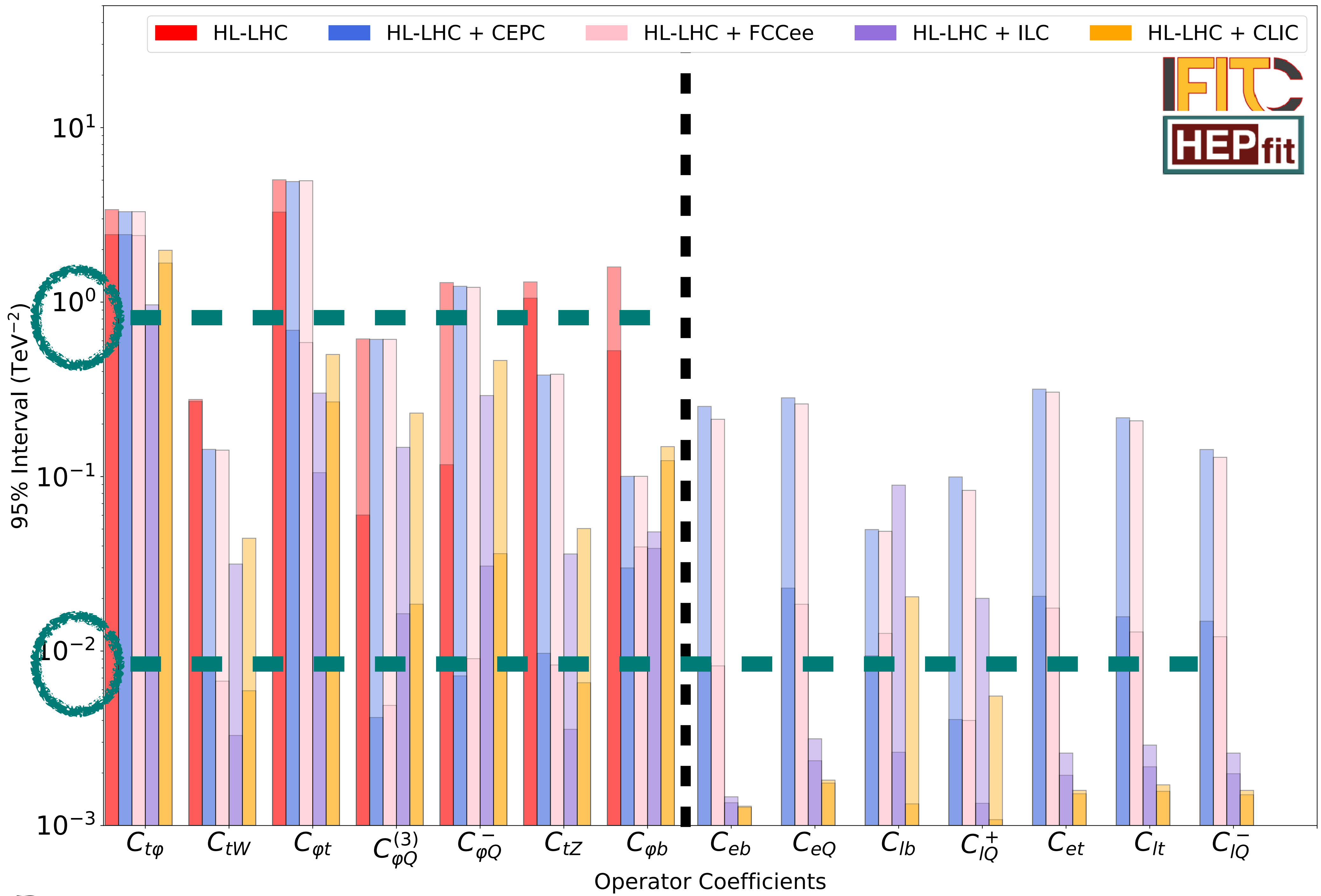
ILC vs CLIC: Top selection & flavor-tagging efficiency drop above 1TeV.



SMEFT global fit: *Results*

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Comparison of different collider options



Summary

- We perform a global fit of top operators in SMEFT by keeping only the linear terms and using data collected at LEP, Tevatron, LHC run 2 and projections at various future e^+e^- colliders:

  - We find the 2-fermion and the 4-quark operators can all be improved by a factor of a few at the HL-LHC thanks to the luminosity.
  - Future e^+e^- colliders operated above top pair threshold could extend the sensitivity to several semi-leptonic operators, and they are generically complementary probes of current colliders.
  - Circular colliders (CEPC, FCC-ee) largely improve the fit of 2f operators by a factor of a few, but their precision reach is limited by their operating energies.
  - 4-fermion operators would be better constrained at linear colliders (ILC, CLIC) due to energy reach of the latter.
  - Top Yukawa could be improved by one order of magnitude compared with current result, and would be determined at the 1% level.

Backup

Backup

Global Determinant Parameter (GDP $= \sqrt[2n]{\det V}$)