

Connecting scales in the SMEFT at the LHC and future colliders

DAMTP seminar Based on arXiv: 2502.20453, 2504.05974

In collaboration with Luca Mantani, Juan Rojo, Alejo Rossia, Eleni Vryonidou

> Jaco ter Hoeve 02/05/25



This talk

- A brief introduction to the SMEFT
- Renormalisation Group Evolution in global SMEFT fits
- The SMEFT at future colliders
- The Higgs self-coupling at FCC-ee
- Summary



How to look for New Physics

1. Directly: bump hunting



2. Indirectly: tiny deviations in tails





Rate

Accessible region

Adapted from E. Vryonidou

The SMEFT: the way to probe new physics beyond the direct collider energy reach

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Energy



Standard Model

Adapted from E. Vryonidou

Rate

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Standard Model

Adapted from E. Vryonidou

Rate

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Standard Model

Adapted from E. Vryonidou

Rate

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Standard Model

Adapted from E. Vryonidou

Rate

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Rate Known particle **Standard Model**

Adapted from E. Vryonidou

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The SMEFT philosophy

The SM



Goal: find the value of *c*, and precisely!

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EFT

c .

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New Physics





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The SMEFT philosophy

The SM



Goal: find the value of *c*, and precisely!

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New Physics



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SMEFT requirements

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{i}^{N_{d5}} \frac{c_i}{\Lambda} \mathscr{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d$$

- The SMEFT parameterises the **theory space around the SM**
- Defines a perfectly valid QFT that is **renormalisable** order by order in Λ
- Operators are constructed out of SM fields only
- Respects the SM symmetries
- Forms a **complete basis** at any given mass dimension ►





X^3		φ^6 and $\varphi^4 D^2$		
Q_G	$f^{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$	Q_{arphi}	$(arphi^\dagger arphi)^3$	Q_{earphi}
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	$Q_{arphi \Box}$	$(arphi^\dagger arphi) \Box (arphi^\dagger arphi)$	$Q_{u\varphi}$
Q_W	$\varepsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$	$Q_{arphi D}$	$\left(arphi^{\dagger} D^{\mu} arphi ight)^{\star} \left(arphi^{\dagger} D_{\mu} arphi ight)$	Q_{darphi}
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$			
	$X^2 \varphi^2$		$\psi^2 X \varphi$	
$Q_{arphi G}$	$\varphi^{\dagger}\varphiG^{A}_{\mu u}G^{A\mu u}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu u} e_r) \tau^I \varphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$
$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi \widetilde{G}^A_{\mu u} G^{A\mu u}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu u} e_r) \varphi B_{\mu u}$	$Q^{(3)}_{arphi l}$
$Q_{arphi W}$	$\varphi^{\dagger}\varphiW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu u} T^A u_r) \widetilde{\varphi} G^A_{\mu u}$	$Q_{arphi e}$
$Q_{arphi \widetilde{W}}$	$\varphi^{\dagger}\varphi\widetilde{W}^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu u} u_r) \tau^I \widetilde{\varphi} W^I_{\mu u}$	$Q^{(1)}_{arphi q}$
$Q_{arphi B}$	$arphi^\dagger arphi B_{\mu u} B^{\mu u}$	Q_{uB}	$(ar{q}_p \sigma^{\mu u} u_r) \widetilde{arphi} B_{\mu u}$	$Q^{(3)}_{arphi q}$
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu u} T^A d_r) \varphi G^A_{\mu u}$	$Q_{arphi u}$
$Q_{arphi WB}$	$arphi^\dagger au^I arphi W^I_{\mu u} B^{\mu u}$	Q_{dW}	$(ar{q}_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$
$Q_{arphi \widetilde{W}B}$	$arphi^\dagger au^I arphi \widetilde{W}^I_{\mu u} B^{\mu u}$	Q_{dB}	$(ar{q}_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{arphi u d}$

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Current operators



- Shift SM $f\bar{f}V$ couplings ►
- $f\bar{f}Vh$ contact interactions

Contact interactions grow with energy and thus provide a sensitive probe in the TeV region







X^3			$arphi^6$ and $arphi^4 D^2$	
Q_G	$\int f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	Q_{arphi}	$(arphi^\dagger arphi)^3$	Q_{earphi}
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	$Q_{arphi \Box}$	$(arphi^\dagger arphi) \Box (arphi^\dagger arphi)$	$Q_{u\varphi}$
Q_W	$\varepsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$	$Q_{arphi D}$	$\left(\varphi^{\dagger} D^{\mu} \varphi \right)^{\star} \left(\varphi^{\dagger} D_{\mu} \varphi \right)$	Q_{darphi}
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$			
	$X^2 \varphi^2$		$\psi^2 X \varphi$	
$Q_{arphi G}$	$\varphi^{\dagger}\varphiG^{A}_{\mu u}G^{A\mu u}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu u} e_r) \tau^I \varphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$
$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi \widetilde{G}^A_{\mu u} G^{A\mu u}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu u} e_r) \varphi B_{\mu u}$	$Q^{(3)}_{arphi l}$
$Q_{arphi W}$	$\varphi^{\dagger}\varphi W^{I}_{\mu u}W^{I\mu u}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu u} T^A u_r) \widetilde{\varphi} G^A_{\mu u}$	$Q_{arphi e}$
$Q_{arphi \widetilde{W}}$	$arphi^\dagger arphi \widetilde{W}^I_{\mu u} W^{I\mu u}$	Q_{uW}	$(ar{q}_p \sigma^{\mu u} u_r) au^I \widetilde{arphi} W^I_{\mu u}$	$Q^{(1)}_{arphi q}$
$Q_{arphi B}$	$arphi^\dagger arphi B_{\mu u} B^{\mu u}$	Q_{uB}	$(ar{q}_p \sigma^{\mu u} u_r) \widetilde{arphi} B_{\mu u}$	$Q^{(3)}_{arphi q}$
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(ar{q}_p \sigma^{\mu u} T^A d_r) arphi G^A_{\mu u}$	$Q_{arphi u}$
$Q_{arphi WB}$	$arphi^\dagger au^I arphi W^I_{\mu u} B^{\mu u}$	Q_{dW}	$(ar{q}_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$
$Q_{arphi \widetilde{W}B}$	$arphi^\dagger au^I arphi \widetilde{W}^I_{\mu u} B^{\mu u}$	Q_{dB}	$(ar{q}_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{arphi u d}$

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Contact interactions grow with energy and thus provide a sensitive probe in the TeV region

$$\begin{split} \psi^{2}\varphi^{3} \\ (\varphi^{\dagger}\varphi)(\bar{l}_{p}e_{r}\varphi) \\ (\varphi^{\dagger}\varphi)(\bar{q}_{p}u_{r}\widetilde{\varphi}) \\ (\varphi^{\dagger}\varphi)(\bar{q}_{p}d_{r}\varphi) \\ \psi^{2}\varphi^{2}D \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{l}_{p}\gamma^{\mu}l_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{l}_{p}\tau^{I}\gamma^{\mu}l_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{e}_{p}\gamma^{\mu}e_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{q}_{p}\gamma^{\mu}q_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{q}_{p}\tau^{I}\gamma^{\mu}q_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{q}_{p}\gamma^{\mu}u_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{u}_{p}\gamma^{\mu}u_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{d}_{p}\gamma^{\mu}d_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{d}_{p}\gamma^{\mu}d_{r}) \\ (\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{u}_{p}\gamma^{\mu}d_{r}) \end{split}$$







					-
X^3		φ^6 and $\varphi^4 D^2$			
Q_G	$\int f^{ABC} G^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	Q_{arphi}	$(arphi^\dagger arphi)^3$	Q_{earphi}	
$Q_{\widetilde{G}}$	$\int f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	$Q_{arphi \Box}$	$(arphi^\daggerarphi)\Box(arphi^\daggerarphi)$	Q_{uarphi}	
Q_W	$\varepsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$	$Q_{arphi D}$	$\left(arphi^{\dagger} D^{\mu} arphi ight)^{\star} \left(arphi^{\dagger} D_{\mu} arphi ight)$	Q_{darphi}	
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$				
	$X^2 \varphi^2$		$\psi^2 X \varphi$		
$Q_{arphi G}$	$\varphi^{\dagger}\varphiG^{A}_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu u} e_r) \tau^I \varphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$	ſ
$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi \widetilde{G}^A_{\mu u} G^{A\mu u}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu u} e_r) \varphi B_{\mu u}$	$Q^{(3)}_{arphi l}$	
$Q_{arphi W}$	$\varphi^{\dagger}\varphiW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu u} T^A u_r) \widetilde{\varphi} G^A_{\mu u}$	$Q_{arphi e}$	
$Q_{arphi \widetilde{W}}$	$\varphi^{\dagger}\varphi\widetilde{W}^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uW}	$(ar{q}_p \sigma^{\mu u} u_r) au^I \widetilde{arphi} W^I_{\mu u}$	$Q^{(1)}_{arphi q}$	
$Q_{arphi B}$	$arphi^\dagger arphi B_{\mu u} B^{\mu u}$	Q_{uB}	$(ar{q}_p \sigma^{\mu u} u_r) \widetilde{arphi} B_{\mu u}$	$Q^{(3)}_{arphi q}$	
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu u} T^A d_r) \varphi G^A_{\mu u}$	$Q_{arphi u}$	
$Q_{arphi WB}$	$arphi^\dagger au^I arphi W^I_{\mu u} B^{\mu u}$	Q_{dW}	$(ar{q}_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$	
$Q_{arphi \widetilde{W}B}$	$arphi^\dagger au^I arphi \widetilde{W}^I_{\mu u} B^{\mu u}$	Q_{dB}	$(ar{q}_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{arphi u d}$	

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		<u> </u>		
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$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_{\mu} G^{B\rho}_{\nu} G^{C\mu}_{\rho}$	$Q_{arphi\square}$	$(arphi^\dagger arphi) \Box (arphi^\dagger arphi)$	$Q_{u\varphi}$
Q_W	$\varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$Q_{arphi D}$	$\left(arphi^{\dagger} D^{\mu} arphi ight)^{\star} \left(arphi^{\dagger} D_{\mu} arphi ight)$	Q_{darphi}
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$			
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$Q_{arphi W}$	$\varphi^{\dagger}\varphiW^{I}_{\mu\nu}W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu u} T^A u_r) \widetilde{\varphi} G^A_{\mu u}$	$Q_{arphi e}$
$Q_{arphi \widetilde{W}}$	$\varphi^{\dagger} \varphi \widetilde{W}^{I}_{\mu u} W^{I\mu u}$	Q_{uW}	$(ar{q}_p \sigma^{\mu u} u_r) au^I \widetilde{arphi} W^I_{\mu u}$	$Q^{(1)}_{arphi q}$
$Q_{arphi B}$	$arphi^\dagger arphi B_{\mu u} B^{\mu u}$	Q_{uB}	$(ar{q}_p \sigma^{\mu u} u_r) \widetilde{arphi} B_{\mu u}$	$Q^{(3)}_{arphi q}$
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu u} T^A d_r) \varphi G^A_{\mu u}$	$Q_{arphi u}$
$Q_{arphi WB}$	$\varphi^\dagger \tau^I \varphi W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(ar{q}_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$
$Q_{arphi \widetilde{W}B}$	$arphi^\dagger au^I arphi \widetilde{W}^I_{\mu u} B^{\mu u}$	Q_{dB}	$(ar{q}_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{arphi u d}$



Bosonic operators



- H^6 modifies the Higgs self-coupling
- Enters at NLO EW in $e^+e^- \rightarrow ZH$

arXiv: 2406.03557





X ³		$arphi^6~~{ m an}$	nd $\varphi^4 D^2$			
Q_G		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		
$Q_{\widetilde{G}}$	Q_{ll}	$(ar{l}_p \gamma_\mu l_r) (ar{l}_s \gamma$	$^{\mu}l_{t})$	Q_{ee}	$(ar{e}_p \gamma_\mu e_r) (ar{e}_s \gamma^\mu)$	e_t)
Q_W	$Q_{qq}^{(1)}$	$(ar{q}_p \gamma_\mu q_r) (ar{q}_s \gamma_\mu q_r)$	$q^{\mu}q_t$)	Q_{uu}	$ig (ar{u}_p \gamma_\mu u_r) (ar{u}_s \gamma^\mu$	(u_t)
$Q_{\widetilde{W}}$	$Q_{qq}^{(3)}$	$\left(ar{q}_p \gamma_\mu au^I q_r) (ar{q}_s \gamma_\mu au^I q_r) (ar{q}_s \gamma_\mu a$	$\langle {}^{\mu} au^{I} q_{t} \rangle$	Q_{dd}	$(ar{d}_p\gamma_\mu d_r)(ar{d}_s\gamma^\mu$	d_t)
	$Q_{lq}^{(1)}$	$ig (ar{l}_p \gamma_\mu l_r) (ar{q}_s \gamma$	$^{\mu}q_{t})$	Q_{eu}	$(ar{e}_p \gamma_\mu e_r) (ar{u}_s \gamma^\mu)$	u_t)
	$Q_{lq}^{(3)}$	$\left(ar{l}_p \gamma_\mu au^I l_r) (ar{q}_s \gamma$	$^{\mu}\tau^{I}q_{t})$	Q_{ed}	$(ar{e}_p \gamma_\mu e_r) (ar{d}_s \gamma^\mu)$	d_t) $\ \cdot \ $
$Q_{arphi G}$				$Q_{ud}^{\left(1 ight) }$	$ig (ar{u}_p \gamma_\mu u_r) (ar{d}_s \gamma^\mu$	d_t)
$Q_{arphi \widetilde{G}}$				$Q_{ud}^{(8)}$	$\left \ (\bar{u}_p \gamma_\mu T^A u_r) (\bar{d}_s \gamma^\mu \right.$	$(T^A d_t) \parallel 0$
$Q_{\varphi W}$						
$Q_{arphi \widetilde{W}}$	$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$			-	B-violat	
$Q_{arphi B}$	Q_{ledq}	$(ar{l}_p^j e_r) (ar{d}_s q$	$\binom{j}{t}$	Q_{duq}	$\varepsilon^{lphaeta\gamma}arepsilon$	$f_{jk}\left[(d_p^lpha)^T ight]$
$Q_{\omega\widetilde{B}}$	$ig Q^{(1)}_{quqd}$	$(ar{q}_p^j u_r)arepsilon_{jk}(ar{q}_s^j$	$^k_s d_t)$	Q_{qqu}	$\varepsilon^{lphaeta\gamma}arepsilon_{j}$	$_{jk}\left[(q_p^{lpha j})^T ight.$
$Q_{\omega WB}$	$Q_{quqd}^{(8)}$	$\left(ar{q}_{p}^{j}T^{A}u_{r})arepsilon_{jk}(ar{q}_{s}^{j}) ight)$	$s^k_s T^A d_t$)	Q_{qqq}	$arepsilon^{lphaeta\gamma}arepsilon_{jn}arepsilon$	$\zeta_{km}\left[(q_p^{lpha j}) ight]$
$Q \simeq -$	$Q_{lequ}^{(1)}$	$\left (ar{l}_p^j e_r) arepsilon_{jk} (ar{q}_s^k$	(u_t)	Q_{duu}	$\varepsilon^{lphaeta}$	$^{\gamma}\left[(d_{p}^{lpha})^{T}C ight.$
$\nabla \varphi WB$	$Q_{lequ}^{(3)}$	$\left \ (\bar{l}_p^j \sigma_{\mu u} e_r) arepsilon_{jk} (\bar{q}_s^k) ight ^2$	$\sigma^{\mu u}u_t$			

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Four-fermion operators



- Contact interactions
- 2205 B/L preserving



SMEFT predictions

 $\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{i}^{N_{d5}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$

Linear EFT corrections: interference with SM

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Quadratic EFT corrections

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Building the likelihood

$$\chi^2 = \frac{1}{n_{\text{dat}}} \sum_{i,j=1}^{n_{\text{dat}}} \left(\sigma_{i,\text{SMEFT}}(c) - \sigma_{i,\text{exp}} \right) \left(\text{cov}^{-1} \right)_{ij} \left(\sigma_{j,\text{SMEFT}}(c) - \sigma_{j,\text{exp}} \right)$$

[ATL-PHYS-PUB-2023-039]



Status: October 2023



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$$\operatorname{cov}^{(\operatorname{tot})}_{ij} = \operatorname{cov}^{(\operatorname{th})}_{ij} + \operatorname{cov}^{(\exp)}_{ij}$$

Analytic if $\mathcal{O}(\Lambda^{-2})$, fast! Nested Sampling $\mathcal{O}(\Lambda^{-2})$ or $\mathcal{O}(\Lambda^{-4})$



 X_4 X_3 $X_2 X_1$

Feroz et al [1306.2144]



Why global SMEFT fits?

- ► observables) requires a global analysis
- degeneracies





[2012.02779] Fitmaker collaboration

[2105.00006] SMEFiT collaboration

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Cross-talk between Higgs, top, diboson and EWPO (and flavour and low energy

Challenge: a large number of operators, with many datasets needed to break

Anke Biekötter - HET seminar Brookhaven



Previously on global fits...

- SMEFIT: EW + Higgs + diboson + top + projections, NLO, quadratic [2105.00006, 2309.04523 , 2404.12809]
- •ATLAS: EW + Higgs, LO, quadratic [ATL-PHYS-PUB-2022-037]
- •simuNET: simultaneous EFT + PDF fit in EW + Higgs + diboson + top, NLO, linear [2402.03308]
- Fitmaker: EW + Higgs + top + diboson, linear [2012.02779, 2204.05260]
- **SFitter**: EW + Higgs, top, NLO, quadratic [1812.07587, 1910.03606]
- •HEPfit: EW, flavour, projections, LO, linear [1910.14012]
- •**TopFitter:** top, linear, LO [1901.03164]
- EFTfitter: top + DY + flavour, LO, quadratic, RG effects [1605.05585, 2304.12837]
- Mainz group: EW + Higgs + top + flavour + dijet + PV + lepton scattering, NLO, linear [2311.04963]
- Zurich group: EW + flavour + (DY, LEPII, Jet observables), individual, RG effects [2311.00020]

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simuNET: a simultaneous PDF + EFT fit

- Most EFT global fits assume a fixed PDF set. Ideally, a full treatment fits the EFT and PDF parameters simultaneously, as done by simuNET
- EFT parameters are stable, while the PDF fits undergo shifts at high invariant mass in e.g. the gluon-gluon luminosity



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Costantini, Hammou, Madigan, Mantani, Moore, Morales, Ubiali [2402.03308]









RGE in the SMEFT

Connecting scales

- from m_{Z} at LEP to $m_{t\bar{t}} \sim 3 \text{ TeV}$ in tails at LHC
- Wilson coefficients run with energy

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\rm op}} \gamma_{ij}^{(6)}(\bar{g}) c_j(\mu)$$

Jenkins, Manohar, Trott, Alonso arXiv:1308.2627, 1310.4838, 1312.2014

Operator mixing through the anomalous dimension

Experimental input to global fits spans a wide range of different energy scales,



- 90	
- 80	
- 70	
- 60	
- 50	nts
- 40	a poi
- 30	Data
- 20	# of
- 10	
- 5	
- 2	
- 1	
- 0	

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RGE in SMEFT phenomenology



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Higgs production

 $\begin{array}{l} \text{Sum} \\ \sigma(c_{Qu}^{(1)}) \\ \sigma(c_{Qu}^{(8)}) \end{array}$



Maltoni, Ventura, Vryonidou arXiv: 2406.06670



RGE in SMEFiT

• We include RG effects in the Matrix evolution approximation interfaced to Wilson

$$c_i(\mu) = \sum_{j=1}^{n_{\text{op}}} \Gamma_{ij}(\mu, \mu_0; \alpha_s, \alpha) c_j(\mu_0)$$

• Express theory predictions at a common scale μ_0

$$egin{aligned} T_{ ext{EFT}}(m{c}(\mu)/\Lambda^2) &= T_{ ext{SM}} + \sum_{i=1}^{n_{ ext{op}}} \kappa_i T_i \ &= T_{ ext{SM}} + \sum_{i,j=1}^{n_{ ext{op}}} \kappa_i T_i \ &= T_{ ext{SM}} + \sum_{j=1}^{n_{ ext{op}}} \kappa'_j rac{c_j}{T_i} \end{aligned}$$

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 $\mathcal{L}_{t\phi}$



[1804.05033] Aebischer, Kumar, Straub









RGE in SMEFiT

 We associate a fixed 	Process
characteristic scale choice μ	Higgs (ggF
to each bin	Higgs (VB
$ " \Box $	VH
Event by event running	$t\bar{t}H$
ot al in arXiv: 2212 05067	tH
	$t\overline{t}$
 We have studied the impact 	Single- t
of our scale choice by	$tar{t}\gamma$
varying $\mu \rightarrow \tilde{\mu} = \kappa \mu^{-1}$	$t\overline{t}t\overline{t}$
	HH

	Scale Choice μ	Process	Scale Choice μ
F)	$\sqrt{m_H^2+(p_T^H)^2}$	$\left t \overline{t} b \overline{b} ight $	$2m_t$
SF)	$\sqrt{m_H^2 + (p_T^H)^2}$	$t\bar{t}V$	$\sqrt{(2m_t + m_V)^2 + (p_T^V)^2}$
	$\sqrt{(m_V+m_H)^2+(p_T^V)^2}$	tV	$m_t + m_V$ or $\sqrt{(m_t + m_V)^2 + (p_T^t)^2}$
	$\sqrt{(2m_t + m_H)^2 + (p_T^H)^2}$	W-helicities	m_t
	$m_t + m_H$	WZ	m_T^{WZ} or $\sqrt{(m_Z+m_W)^2+(p_T^Z)^2}$
	m_{tt}	WW	$m_{e\mu}$
	m_t	V pole (incl. EWPOs)	m_V
	$2m_t$	Bhabha scattering	\sqrt{s}
	$4m_t$	$e^+e^- \to WW / t\bar{t} / f\bar{f}$	\sqrt{s}
	$2m_H$	$e^+e^- \rightarrow ZH$	\sqrt{s}



RG in restricted operator basis



Jaco ter Hoeve



Mantani, Rojo, Rossia, Vryonidou, JtH arXiv: 2502.20453

Example: 4 heavy operators flow into operators sensitive to the EWPOs at low energy

In general one may see two competing effects:

- Ill constrained operators may flow into a precisely determined observable
- More operators enter the same observable, making bounds weaker



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RG in the global fit







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Fisher information moves from $t\bar{t}V$ to LEP $t + t\bar{t}b\bar{b}$ Higgs LEP ttv t $t\bar{t}t\bar{t}$ tV15.6 83.8 0.6 $c_{arphi t}$ 0.0 0.0 0.0 0.0 0.0 00.0 0.0 0.0 w/RGE w/o RGE $\overline{}$ $c_{arphi t}$ -1 0 **S**MEFiT -5050 0



Global fits neglecting RGE effects can severely overestimate the bounds!











Global fits neglecting RGE effects can severely overestimate the bounds!













Global fits neglecting RGE effects can severely underestimate the bounds!



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SMEFT at future colliders

• •
The SMEFT at HL-LHC

arXiv: 2404.12809

- We project all RunII datasets from the SMEFiT 3.0 baseline: one for each process and final state see backup for details
- We see an improvement ranging from 20 to 70 % in the marginalised fit
- EW operators improve only in the marginalised fit



The SMEFT at FCC-ee

- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgstrahlung and VBF
- Gauge boson pair production
- Top-quark pair production
- Optimal Observables

Enorgy ((s)	$\mathcal{L}_{\mathrm{int}}$ (Ru	in time)
Energy (\sqrt{s})	FCC-ee	CEPC
91 GeV (Z-pole)	$300 \text{ ab}^{-1} (4 \text{ years})$	$100 \text{ ab}^{-1} (2 \text{ years})$
$161~{ m GeV}~(2m_W)$	$20 \text{ ab}^{-1} (2 \text{ years})$	$6 \text{ ab}^{-1} (1 \text{ year})$
$240~{ m GeV}$	$10 \text{ ab}^{-1} (3 \text{ years})$	20 ab^{-1} (10 years)
$350~{ m GeV}$	$0.4 \text{ ab}^{-1} (1 \text{ years})$	-
$365~{ m GeV}~(2m_t)$	$3 \text{ ab}^{-1} (4 \text{ years})$	1 ab^{-1} (5 years)

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}(\Lambda^{-2})$, Marginalised





UV complete models

The ultimate goal of the EFT program at the LHC is to bridge the gap to explicit UV models



Mantani, Rojo, Rossia, Vryonidou, **JtH** arXiv: 2502.20453

> Slide from A. Rossia at SMEFT-tools 2025





UV complete models

RGE effects matter, and so do theory uncertainties!



 $\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_{\mu}\phi|^2 - m_{\phi}^2 \phi^{\dagger}\phi - \left((y_{\phi}^e)_{ij}\phi^{\dagger}\bar{e}_R^i\ell_L^j + (y_{\phi}^d)_{ij}\phi^{\dagger}\bar{d}_R^i q_L^j\right)$ $+(y^{u}_{\phi})_{ij}\phi^{\dagger}i\sigma_{2}\bar{q}^{T,i}_{L}u^{j}_{R}+\lambda_{\phi}\phi^{\dagger}\varphi|\varphi|^{2}+\text{h.c.}
ight)-\text{scalar potential}$

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The Higgs self-coupling in the SMEFT



From Gavin Salam

Jaco ter Hoeve

The Higgs potential sheds light on ...

- the vacuum stability of our universe
- EW phase transition
- Matter anti-matter asymmetry



$$\delta\kappa_3 = -\frac{2v^4}{m_h^2}\frac{c_{\varphi}}{\Lambda^2} + \frac{3v^2}{\Lambda^2}\left(c_{\varphi\Box} - \frac{1}{4}c_{\varphi D}\right)$$











The Higgs self-coupling in the SMEFT



From Gavin Salam

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The Higgs potential sheds light on ...

- the vacuum stability of our universe
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$$\delta\kappa_3 = -\frac{2v^4}{m_h^2}\frac{c_{\varphi}}{\Lambda^2} + \frac{3v^2}{\Lambda^2}\left(c_{\varphi\Box} - \frac{1}{4}c_{\varphi D}\right)$$











The Higgs self-coupling in the SMEFT

- HL-LHC + FCC-ee can pin down the Higgs self coupling to 15%
- Individual and marginalised bounds on κ_3 no longer agree at FCC-ee
- Significantly improving on HL-LHC is not possible without the 365 GeV run



arXiv: 2406.03557





Summary and conclusion

- ► be included
- trilinear coupling to 15%
- The SMEFiT code is open source and can be installed from



The SMEFT provides a convenient tool to search for new physics in an agnostic way

The impact of RGE effects on the SMEFT parameter space is non trivial and should

Complementarity between the different FCC-ee runs is key to pin down the Higgs

<u>lhcfitnikhef.github.io/smefit_release</u>



Summary and conclusion

- ►
- ► be included
- trilinear coupling to 15%
- The SMEFiT code is open source and can be installed from ►

Contact: jaco.ter.hoeve@ed.ac.uk Thanks for your attention!

The SMEFT provides a convenient tool to search for new physics in an agnostic way

The impact of RGE effects on the SMEFT parameter space is non trivial and should

Complementarity between the different FCC-ee runs is key to pin down the Higgs

cfitnikhef.github.io/smefit_release



Backup

Future colliders

- pair production, each with an unprecedented luminosity!
- ► $2 \cdot 10^6$ top quark pairs within 16 years



At the FCC-ee, we will separately target Z-pole EWPOs, diboson, Higgs and top

Expected production: $6 \cdot 10^{12} Z$ bosons, $2.4 \cdot 10^8 W$ pairs, $2 \cdot 10^6 H$ bosons and



Dataset upgrade

Category	Processes		dat
		SMEFIT2.0	SMEFIT3.0
	$t\bar{t} + X$	94	115
	$t\bar{t}Z,t\bar{t}W$	14	21
	$t ar{t} \gamma$	-	2
Top quark production	single top (inclusive)	27	28
	tZ, tW	9	13
	$tar{t}tar{t}$, $tar{t}bar{b}$	6	12
	Total	150	189
	Run I signal strengths	22	22
Higgs production	Run II signal strengths	40	40
and decay	Run II, differential distributions & STXS	35	71
	Total	97	133
	LEP-2	40	40
Diboson production	LHC	30	41
	Total	70	81
Z-pole EWPOs	LEP-2	-	44
Baseline dataset	Total	317	449

We extended SMEFiT2.0 with recent Run II datasets from top, diboson and Higgs production



SMEFiT



dataset X.json

```
"best_sm": [3.0],
 "scales": [91.0],
 "theory_cov": [[1.0]],
  "LO": {"SM": 1.0, "Op1": -0.2, "Op1*Op1": 0.4},
  "NLO_QCD": {"SM": 1.5, "0p1": -0.3, "0p1*0p1": 0.6}
}
```

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Ihcfitnikhef.github.io/smefit_release

Data

447 measurements from Higgs, top, diboson and EWPO

Full experimental correlations







SMEFiT



dataset X.json

```
"best_sm": [3.0],
 "scales": [91.0],
 "theory_cov": [[1.0]],
  "LO": {"SM": 1.0, "Op1": -0.2, "Op1*Op1": 0.4},
  "NL0_QCD": {"SM": 1.5, "0p1": -0.3, "0p1*0p1": 0.6}
}
```

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Data

447 measurements from Higgs, top, diboson and EWPO

Full experimental correlations

SMEFit

X tosetch

dataset_name: ATLAS_ttW_13TeV_2016 doi: 10.1103/PhysRevD.99.072009 location: Figure 13 arxiv preprint arxiv: 1901.03584 hepdata: https://www.hepdata.net/record/ins1713423 units: fb description: inclusive ttW cross-section luminosity: 36.1 num_data: 1 num_sys: 1 data_central: 3.1 statistical_error: 0.1 systematics: - 0.2 sys_names: UNCORR sys_type: MULT





SMEFiT



dataset X.json

```
"best_sm": [3.0],
  "scales": [91.0],
  "theory_cov": [[1.0]],
  "LO": {"SM": 1.0, "Op1": -0.2, "Op1*Op1": 0.4},
  "NLO_QCD": {"SM": 1.5, "0p1": -0.3, "0p1*0p1": 0.6}
}
```

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Ihcfitnikhef.github.io/smefit_release

Data

447 measurements from Higgs, top, diboson and EWPO

Full experimental correlations

SMEFit

Projections

HL-LHC, FCCee, CEPC

+ Automatic projection module

Aatacot X

dataset_name: ATLAS_ttW_13TeV_2016 doi: 10.1103/PhysRevD.99.072009 location: Figure 13 arxiv preprint arxiv: 1901.03584 hepdata: https://www.hepdata.net/record/ins1713423 units: fb description: inclusive ttW cross-section luminosity: 36.1 num_data: 1 num_sys: 1 data_central: 3.1 statistical_error: 0.1 systematics: - 0.2 sys_names: UNCORR sys_type: MULT





Report module

Automatised fit reports that analyse the SMEFiT results







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Report module

Automatised fit reports that analyse the SMEFiT results





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Report module

Automatised fit reports that analyse the SMEFiT results





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Report module

Automatised fit reports that analyse the SMEFiT results















Result: FCC-ee energy breakdown

- The FCC-ee plans to operate sequentially, hence we need to study the impact at the various energies
- Largest impact for Z-pole at 91 GeV plus the Higgs factory run at 240 GeV
- We can try other combinations too in order to find the most optimal run order for the SMEFT

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}(\Lambda^{-2})$, Marginalised



-- HL - LHC + FCC - ee (91 + 240 GeV)



Fisher information study

 The sensitivity of the EFT parameters to the Run II, HL-LHC and FCC-ee datasets is quantified by the fisher information

$$I_{ij} = \sum_{m=1}^{n_{\text{dat}}} \frac{\sigma_{m,i}^{(\text{eft})} \sigma_{m,j}^{(\text{eft})}}{\delta_{\exp,m}^2}$$

- The highest sensitivity in the 2FB sector comes in via the FCC-ee
- The FCC-ee run at 161 GeV is the least sensitive for the SMEFT

	LEP	$tar{t}$ 8 TeV	$tar{t}$ 13 TeV	$tar{t}\gamma$	$t\bar{t}W$	$t\bar{t}Z$	$t \ 8 \ { m TeV}$	$t \; 13 \; { m TeV}$	tW	tZ	$t\bar{t}A_c$	W helicities	$t\bar{t}t\bar{t}+t\bar{t}b\bar{b}$	Higgs-run I	Higgs-run II	VV	$t\bar{t}$ 13 TeV HL-LH	$t\bar{t}W$ HL-LHC	$t\bar{t}Z$ HL-LHC	t 13 TeV HL-LHC	tW HL-LHC	tZ HL-LHC	$t\bar{t}$ A_c HL-LHC	W helicities HL-L	$t\bar{t}t\bar{t} + t\bar{t}b\bar{b}$ HL-LH	Higgs HL-LHC	VV HL-LHC	FCC-ee 91 GeV	FCC-ee 161 GeV	FCC-ee 240 GeV	FCC-ee 365 GeV
$\begin{bmatrix} 1\\ 0 \\ 0 \end{bmatrix}$									1		1		14.0							1		1		1	86.0						
8 00													15.1												84.9						
,1 (Ot													18.1												81.9						
$\frac{8}{Ot}$													14.1												85.9						
c_{tt}^1													14.0												86.0						
1,8 Oa		0.4	8.4	0.2	1.6	1.3					9.1		0.0	0.0	0.1		22.7	7.9	6.3				41.7		0.1	0.1					
1,1 Oa		0.3	10.4								11.6		0.0				31.2						46.4		0.2						
$\vec{3,8}$ Qq		0.3	2.2	0.3	1.9	1.0	1.2	0.3			13.6		0.0	0.0	0.1		4.3	9.2	4.6	1.3			59.6		0.1	0.0					
$\tilde{3,1}$ Qq		0.0	0.0				15.2	7.7		4.8	0.1		0.0		0.0		0.1			40.0		31.6	0.4		0.0	0.0					
c_{tq}^8		0.5	6.9	1.0	4.1	2.3					8.1		0.1	0.0	0.3		7.0	20.1	10.4				38.6		0.5	0.1					
c_{tq}^1		0.2	10.1								12.3		0.0				29.1						48.2		0.1						
$\frac{28}{tu}$		0.4	8.9	0.3		0.1					13.5		0.0	0.0	0.1		14.9		0.8				60.7		0.2	0.1					
tu		0.2	8.9								12.7		0.0				26.9						51.1		0.2						
$\frac{3}{2u}$		0.8	3.7	2.5		1.0					13.7		0.1	0.0	0.4		6.9		5.2				64.8		0.7	0.2					
$\begin{bmatrix} 1\\ Qu \end{bmatrix}$		0.3	11.0								12.4		0.0				27.7						48.5		0.1						
.8 7td		0.7	14.4	0.3		0.4					9.7		0.0	0.0	0.2		29.1		2.0				42.8		0.2	0.1					
$\frac{1}{td}$		0.5	13.8								9.6		0.0				38.8						37.1		0.2						
$^{8}_{Qd}$		1.5	8.7	0.2		2.4					9.4		0.1	0.0	0.5		21.2		12.1				42.9		0.8	0.2					
$\frac{1}{Qd}$		0.4	13.8								10.2		0.0				35.6						40.0		0.1						
$c\varphi$														0.0	0.0											0.1				78.8	21.1
$b\varphi$														0.0	0.1											0.3				70.5	29.1
$t\varphi$														0.5	3.9											16.9				53.6	25.1
$\tau \varphi$														0.0	0.1											0.0	_			78.7	21.2
dG		1.8	1.3	0.1	0.0	0.1			0.0		0.0	0.0	0.1	1.3	9.1		7.5	0.1	0.9		0.0		0.0	0.0	0.4	39.9				25.4	11.9
tW				0.0		0.0	0.0	0.0	0.0	0.0		1.9		2.3	12.5				0.0	0.1	0.0	0.0		4.1		41.8				26.1	10.9
tZ (3)				0.0		0.0				0.0				2.5	13.3				0.0			0.0				44.6	0.5			27.9	11.6
φq	3.2				0.0	0.0	0.0	0.0		0.0				0.0	0.1	0.0		0.0	0.0	0.0		0.0				1.8	0.5	84.8	3.4	3.5	2.7
Q =	1.8					0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0			0.0	0.0	0.0	0.0				0.0	0.0	98.1		14.5	0.0
pq'	1.5					0.0				0.0				0.0	0.0	0.0			0.0			0.0				0.0	0.0	90.7		14.5	1.5
\hat{Q} .	1.0					0.0				0.0				0.0	0.0	0.0			0.0			0.0				1.1	0.0	95.1		0.0	0.0
φu	4.5					0.0								0.0	0.1	0.0			0.0							0.2	0.0	95.2		0.0	0.0
φd	1.0					11.2				0.1				0.3	1.8	0.0			74.8			0.5				6.2	0.0	00.2		3.6	1.5
φt	1.6													0.0	0.0	0.0										0.0	0.0	42.5	0.0	28.7	27.2
μ_1	4.6													0.0	0.0	0.0										0.0	0.0	78.1		15.6	1.7
ρ_{12}	3.1													0.0	0.0	0.0										0.0	0.0	81.4		13.9	1.5
(3)	0.1			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0				0.0	0.0	3.1	4.2	79.6	12.9
$\begin{pmatrix} \rho l_1 \\ (3) \end{pmatrix}$	0.1			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0				0.0	0.0	1.1	5.1	82.5	11.2
$\begin{pmatrix} \rho l_2 \\ (3) \end{pmatrix}$	2.4													0.0	0.0	0.0										0.0	0.0	68.5	6.7	16.2	6.3
ρl ₃ - ωe	1.5													0.0	0.0	0.0										0.0	0.0	31.0	0.0	41.5	25.9
' - φμ	4.3													0.0	0.0	0.0										0.0	0.0	78.6		15.4	1.7
$\varphi_{\varphi\tau}$	3.5													0.0	0.0	0.0										0.0	0.0	81.7		13.3	1.5
c_{ll}	0.0			0.0	0.0	0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0				0.0	0.0	0.1	2.5	52.9	44.5
G														0.3	2.5											10.9				58.7	27.6
ρB														2.5	13.2											44.1				28.6	11.7
W														1.1	5.8											19.4				46.4	27.3
B	0.0			0.0		0.0				0.0				0.0	0.0	0.0			0.0			0.0				0.1	0.0	0.0	0.0	88.6	11.1
W	0.2									0.0						0.1						0.0					4.8		0.0	63.4	31.4
<i>₀</i> □ -														0.0	0.1											0.2				75.2	24.5
. n	0.1			0.0		0.0				0.0				0.0	0.0	0.0			0.0			0.0				0.0	0.0	0.1	0.0	88.8	11.0





Fisher information study

 The sensitivity of the EFT parameters to the Run II, HL-LHC and FCC-ee datasets is quantified by the **fisher** information

$$I_{ij} = \sum_{m=1}^{n_{\text{dat}}} \frac{\sigma_{m,i}^{(\text{eft})} \sigma_{m,j}^{(\text{eft})}}{\delta_{\exp,m}^2}$$

- The highest sensitivity in the 2FB sector comes in via the FCC-ee
- The FCC-ee run at 161 GeV is the least sensitive for the SMEFT

	LEP	$t\overline{t}$ 8 TeV	$ar{t}~13~{ m TeV}$	$t\bar{t}\gamma$	$\overline{t}W$	$\overline{t}Z$	8 TeV	$13 \mathrm{TeV}$	M	Z	$t \overline{t} A_c$	W helicities	$t\bar{t}t\bar{t}+t\bar{t}bar{b}$	Higgs-run I	Higgs-run II	$\Lambda\Lambda$	$i\bar{t}$ 13 TeV HL-LH($\overline{H}W$ HL-LHC	$i\bar{t}Z$ HL-LHC	13 TeV HL-LHC	W HL-LHC	Z HL-LHC	$i \overline{t} A_c$ HL-LHC	W helicities HL-L	$t\bar{t}t\bar{t} + t\bar{t}b\bar{b}$ HL-LH	Higgs HL-LHC	VV HL-LHC	FCC-ee 91 GeV	FCC-ee 161 GeV	FCC-ee 240 GeV	FCC-ee 365 GeV				
$c^1_{QQ}_{8}$												-	14.0											ŗ	86.0									100	
c_{QQ}° c_{Ot}^{1}													18.1												81.9										
c_{Qt}^8													14.1												85.9										
c_{tt}^{1}		0.4	8.4	0.2	1.6	1.3					9.1		14.0 0.0	0.0	0.1		22.7	7.9	6.3				41.7		86.0 0.1	0.1							-		
c_{Qq} $c_{Qq}^{1,1}$		0.3	10.4								11.6		0.0			(3						0 F			0.2										
c_{Qq}^{Qq}		0.3	2.2	0.3	1.9	1.0	1.2	0.3			13.6		0.0		C	φq	$\frac{1}{l}$	84.	8	3.4		3.5		2.7	D.	0.0									
$c_{Qq}^{3,1}$		0.0	0.0				15.2	7.7		4.8	0.1		0.0		C	(3))	98.	1			0.0		0.0	0.0	0.0									
c_{tq}^8		0.5	6.9 10.1	1.0	4.1	2.3					8.1		0.1		C	arphiG	? -								0.5	0.1							-	80	
c_{tq}^{8}		0.4	8.9	0.3		0.1					13.5		0.0		c_{c}	φq		82.	2			14.5	5	1.5	0.2	0.1									
c_{tu}^1		0.2	8.9								12.7		0.0		0	(-))]	80.	7			16.1		1.6	0.2										
c_{Qu}^8	_	0.8	3.7	2.5		1.0					13.7		0.1		C_{c}	φQ	? -								0.7	0.2									
c_{Qu}^1		0.3	11.0	0.3		0.4					9.7		0.0		0	$\dot{\varphi}$	ı	95.	1			0.0		0.0).1	0.1									
c_{td}°		0.5	13.8	0.0		0.4					9.6		0.0		(,	, 1	95.	2			0.0		0.0	0.2	0.1									
c_{Od}^8		1.5	8.7	0.2		2.4					9.4		0.1		C	$-\varphi c$									0.8	0.2		١							
c_{Qd}^1		0.4	13.8								10.2		0.0		(C_{φ}	t					3.6		1.5	D.1										
$c_{c\varphi}$															0		1	12	5	0.0		28.7	, ,	07 0		0.1				78.8	21.1		-	60	
$c_{b\varphi}$															C	φl	1	42.	5	0.0	· ·	20.7	-	2		16.9				58.6	29.1				$\overline{}$
$c_{\tau\varphi}$															c	Col	<u>,</u>	78.	1			15.6	5	1.7		0.0				78.7	21.2				or
c_{tG}		1.8	1.3	0.1	0.0	0.1			0.0		0.0	0.0	0.1			τ.	² -	01							04	39.9				25.4	11.9				ma
c_{tW}				0.0		0.0	0.0	0.0	0.0	0.0		1.9			C	φl	3	81.	4			13.9	,	1.5		4 8				26.1	10.9		-		lize
C_{tZ} (3)	3.2			0.0	0.0	0.0	0.0	0.0		0.0					C	(3))	3.1	1	4.2		79.6	5 1	2.9		44.6	0.5	84.8	3.4	27.9	11.				ed
$c_{\varphi q}^{(3)}$	1.8				0.0	0.0	0.0	0.0	0.0	0.0					C	φl	1									0.0	0.0	98.1	0.4	0.0	0.0				\sim a
$c^{\varphi Q}_{\varphi q} = c^{(-)}_{\varphi q}$	1.5					0.0				0.0					С	() Col)	1.1	1	5.1	8	82.5	5 1	1.2	2	0.3	0.0	82.2		14.5	1.5				lue
$c_{\varphi Q}^{(-)}$	1.5					0.0				0.0						(3)	$\frac{2}{3}$	68.	5	6.7	, .	16.2	2	6.3		0.0	0.0	80.7		16.1	1.6			40	
$c_{\varphi u}$	3.8					0.0									C	φl	3 -									1.1	0.0	95.1		0.0	0.0				
$c_{arphi d}$	4.5					0.0				0.1					0	c_{φ}	e	31.	0	0.0) 4	41.5	5 2	25.9		0.2 6.2	0.0	95.2		0.0	0.0				
$c_{\varphi l_1}$	1.6																1	78	6			154		17	T	0.0	0.0	42.5	0.0	28.7	27.2				
$c_{\varphi l_2}$	4.6														C	φ	l I	/0.	Ŭ			10.1			-	0.0	0.0	78.1		15.6	1.7				
$c_{\varphi l_3}$	3.1														(τ	81.	7			13.3	3	1.5		0.0	0.0	81.4		13.9	1.5				
$c^{(3)}_{\varphi l_1}$ (3)	0.1			0.0	0.0	0.0	0.0	0.0	0.0	0.0						r	. 1	0.1		25		52.0				0.0	0.0	3.1	4.2	79.6	12.9				
$c^{(0)}_{arphi l_2} \ c^{(3)}$	2.4			0.0	0.0	0.0	0.0	0.0	0.0	0.0						c_l	l	0.	·	2.5	· ·	52.9	, 4	4.5		0.0	0.0	68.5	6.7	16.2	6.3				
$c_{arphi l_3} \ c_{arphi e}$	1.5														c	$\sim C$	r				ę	58.7	2	27.6	;	0.0	0.0	31.0	0.0	41.5	25.9			20	
$c_{arphi\mu}$	4.3														Ū	φc	* -									0.0	0.0	78.6		15.4	1.7		F	20	
$c_{\varphi\tau}$	3.5														c	φI	3				2	28.6	5 1	1.7	ĺ	0.0	0.0	81.7		13.3	1.5				
c_{ll}	0.0			0.0	0.0	0.0	0.0	0.0	0.0	0.0					c	тт	., 1				4	46.4	2	27.3		0.0	0.0	0.1	2.5	52.9	44.5				
$c_{\varphi G}$															\mathcal{C}_{ζ}	ρИ	/ -				-					44.1				28.6	11.7				
$c_{\varphi W}$														c	φV	V E	3	0.0	D	0.0	8	38.6	6 1	1.1		19.4				46.4	27.3		F		
$c_{\varphi WB}$	0.0			0.0		0.0				0.0				-	, · ·		1			0.0		62.4		21.4		0.1	0.0	0.0	0.0	88.6	11.1				
WWW	0.2									0.0				c_{W}	VИ	VИ	V			0.0		55.4		1.4			4.8		0.0	63.4	31.4				
$c_{\varphi \square}$	0.1			0.0		0.0				0.0					c	wГ	ן ר					75.2	2 2	24.5		0.2	0.0	0.1	0.0	75.2	24.5				
$c_{\varphi D}$				0.0		0.0				0.0						Υ∟	- +									0.0	0.0	-0.1	0.0		11:0			0	
															\mathcal{C}	φL)	0.1	1	0.0		38.8	5 1	1.0											

 c_{WW}



Impact of quadratics

Ratio of Uncertainties to HL - LHC + FCC - ee, $\mathcal{O}(\Lambda^{-2})$, Marginalised







Conclusion and outlook

- ► quadratic corrections
- LHC datasets, as well as through future colliders
- The FCC-ee offers an **unprecedented indirect mass reach** on new heavy particles ►
- RGE effects are crucial to include to connect experiments at widely separated scales ►
- Outlook: the inclusion of other proposed future colliders ►

Presented SMEFIT3.0, a global fit of 50 Wilson coefficients to Higgs, top, diboson and EWPOs, including

We are becoming increasingly sensitive to possible new physics effects, both through (still) expanding



Conclusion and outlook

- ► quadratic corrections
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Contact: jaco.ter.hoeve@ed.ac.uk

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Thanks for your attention!



SM predictions

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Jaco ter Hoeve

Category	Process	\mathbf{SM}	$\operatorname{Code}/\operatorname{Ref}$	SMEFT
	$t\bar{t}$ (incl)	NNLO QCD	MG5_aMC NLO + NNLO K -fact	NLO QCD
	$t\bar{t} + V$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K -fact
Top quark production	single- t (incl)	NNLO QCD	MG5_aMC NLO + NNLO K -fact	NLO QCD
	t + V	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K -fact
	$t\bar{t}t\bar{t}$, $t\bar{b}t\bar{b}$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K -fact
	gg ightarrow h	NNLO QCD + NLO EW	HXSWG	NLO QCD
	VBF	NNLO QCD + NLO EW	HXSWG	LO QCD
Higgs production and decay	h + V	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$htar{t}$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$h \to X$	NNLO QCD + NLO EW	HXSWG	NLO QCD $(X = b\bar{b})$ LO QCD $(X \neq b\bar{b})$
Diboson	$e^+e^- \rightarrow W^+W^-$	NNLO QCD + NLO EW	LEP EWWG	LO QCD
production	$pp \to VV'$	NNLO QCD	MATRIX	NLO QCD



.

HL-LHC projected datasets

Dataset	\mathcal{L} (fb ⁻¹)	Info	Observables	$n_{ m dat}$	Ref.
ATLAS_STXS_RunII_13TeV_2022	139	ggF , VBF, Vh , $t\bar{t}h$, th	$egin{array}{c} d\sigma/dp^h_T \ d\sigma/dm_{jj} \ d\sigma/dp^V_T \end{array}$	36	[<mark>55</mark>]
CMS_ggF_aa_13TeV	77.4	$ggF, h \rightarrow \gamma\gamma$	$\sigma_{gg\mathrm{F}}(p_T^h, N_{\mathrm{jets}})$	6	[<mark>83</mark>]
ATLAS_ggF_ZZ_13TeV	79.8	$ggF, h \rightarrow ZZ$	$\sigma_{ggF}(p_T^h, N_{\rm jets})$	6	[84]
ATLAS_ggF_13TeV_2015	36.1	$ggF, h \rightarrow ZZ, h \rightarrow \gamma\gamma$	$d\sigma(ggF)/dp_T^h$	9	[85]
ATLAS_WH_Hbb_13TeV	79.8	$Wh, h ightarrow bar{b}$	$d\sigma^{(\text{fid})}/dp_T^W$ (stage 1 STXS)	2	[<mark>86</mark>]
ATLAS_ZH_Hbb_13TeV	79.8	$Zh, h ightarrow bar{b}$	$d\sigma^{(\rm fid)}/dp_T^Z$ (stage 1 STXS)	2	[<mark>86</mark>]
CMS_H_13TeV_2015_pTH	35.9	$\label{eq:holdstress} h \to b\bar{b}, h \to \gamma\gamma, h \to ZZ$	$d\sigma/dp_T^h$	9	[<mark>87</mark>]
ATLAS_WW_13TeV_2016_memu	36.1	fully leptonic	$d\sigma^{({ m fid})}/dm_{e\mu}$	13	[88]
ATLAS_WZ_13TeV_2016_mTWZ	36.1	fully leptonic	$d\sigma^{({ m fid})}/dm_T^{WZ}$	6	[<mark>89</mark>]
CMS_WZ_13TeV_2016_pTZ	35.9	fully leptonic	$d\sigma^{({ m fid})}/dp_T^Z$	11	[<mark>90</mark>]
CMS_WZ_13TeV_2022_pTZ	137	fully leptonic	$d\sigma/dp_T^Z$	11	[<mark>56</mark>]



	Dataset	$\mathcal{L}(fb^{-1})$	Info	Observables	$n_{ m dat}$	Ref.	
	ATLAS_tt_13TeV_ljets_2016_Mtt	36.1	ℓ+jets	$d\sigma/dm_{t\bar{t}}$	7	[91]	
	CMS_tt_13TeV_dilep_2016_Mtt	35.9	dilepton	$d\sigma/dm_{t\bar{t}}$	7	[<mark>92</mark>]	
• • • • • • • • • • • • • • • • • • • •	CMS_tt_13TeV_Mtt	137	ℓ+jets	$1/\sigma d\sigma/dm_{t\bar{t}}$	14	[57]	
	CMS_tt_13TeV_ljets_inc	137	ℓ +jets	$\sigma(t\bar{t})$	1	[57]	
	ATLAS_tt_13TeV_asy_2022	139	ℓ + jets	Ac	5	[59]	
	CMS_tt_13TeV_asy	138	ℓ + jets	A_C	3	[58]	
	ATLAS_Whel_13TeV	139	W-helicity fraction	F_0, F_L	2	[<mark>60</mark>]	
	ATLAS_ttbb_13TeV_2016	36.1	lepton + jets	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[<mark>93</mark>]	
	CMS_ttbb_13TeV_2016	35.9	all-jets	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[94]	
	CMS_ttbb_13TeV_dilepton_inc	35.9	dilepton	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[<mark>68</mark>]	
	CMS_ttbb_13TeV_ljets_inc	35.9	lepton + jets	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[<mark>68</mark>]	
	ATLAS_tttt_13TeV_run2	139	multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[95]	
	CMS_tttt_13TeV_run2	137	same-sign or multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[<mark>96</mark>]	
	ATLAS_tttt_13TeV_slep_inc	139	single-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[64]	
	CMS_tttt_13TeV_slep_inc	35.8	single-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[<mark>65</mark>]	
	ATLAS_tttt_13TeV_2023	139	multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[<mark>66</mark>]	
	CMS_tttt_13TeV_2023	139	same-sign or multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[<mark>67</mark>]	
	CMS_ttZ_13TeV_pTZ	77.5	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[<mark>97</mark>]	
	ATLAS_ttZ_13TeV_pTZ	139	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	7	[<mark>61</mark>]	
	ATLAS_ttW_13TeV_2016	36.1	$t\bar{t}W$	$\sigma_{tot}(t\bar{t}W)$	1	[98]	
	CMS_ttW_13TeV	35.9	$t\bar{t}W$	$\sigma_{tot}(t\bar{t}W)$	1	[<mark>99</mark>]	
	ATLAS_t_tch_13TeV_inc	3.2	t-channel	$\sigma_{\rm tot}(tq), \sigma_{\rm tot}(\bar{t}q)$	2	[100]	
	CMS_t_tch_13TeV_2019_diff_Yt	35.9	t-channel	$d\sigma/d y_t $	5	[101]	
	ATLAS_t_sch_13TeV_inc	139	s-channel	$\sigma(t + \bar{t})$	1	[<mark>69</mark>]	
	ATLAS_tW_13TeV_inc	3.2	multi-lepton	$\sigma_{tot}(tW)$	1	[102]	
	CMS_tW_13TeV_inc	35.9	multi-lepton	$\sigma_{tot}(tW)$	1	[103]	
	CMS_tW_13TeV_slep_inc	36	single-lepton	$\sigma_{\rm tot}(tW)$	1	[71]	
	ATLAS_tZ_13TeV_run2_inc	139	multi-lepton + jets	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[104]	
Jaco ter Hoeve	CMS_tZ_13TeV_pTt	138	multi-lepton + jets	$d\sigma_{\rm fid}(tZj)/dp_T^t$	3	[70]	



FCC-ee and CEPC datasets

EWPOs

	-pole EWPOs ($\sqrt{s} = 91.2$	$2 \mathrm{GeV})$
0	δ / Δ	\mathcal{O}_i
	FCC-ee	CEPC
$lpha(m_Z)^{-1}(imes 10^3)$	$\Delta=2.7~(1.2)$	$\Delta = 17.8$
$\Gamma_W ~({ m MeV})$	$\Delta=0.85~(0.3)$	$\Delta = 1.8~(0.9)$
$\Gamma_Z ~({ m MeV})$	$\Delta = 0.0028~(0.025)$	$\Delta = 0.005~(0.025)$
$A_e \left(imes 10^5 ight)$	$\Delta=0.5~(2)$	$\Delta = 1.5$
A_{μ} (×10 ⁵)	$\Delta = 1.6~(2.2)$	$\Delta=3.0~(1.8)$
$A_{ au} \left(imes 10^5 ight)$	$\Delta=0.35~(20)$	$\Delta = 1.2 \ (6.9)$
$A_b \left(imes 10^5 ight)$	$\Delta = 1.7 \ (21)$	$\Delta = 3~(21)$
$A_c (imes 10^5)$	$\Delta = 14 \ (15)$	$\Delta=6~(30)$
$\sigma_{ m had}^0~({ m pb})$	$\Delta=0.025~(4)$	$\Delta=0.05~(2)$
$R_e (imes 10^3)$	$\delta = 0.0028~(0.3)$	$\delta = 0.003 \; (0.2)$
$R_{\mu}~(imes 10^3)$	$\delta = 0.0021 \; (0.05)$	$\delta = 0.003 \; (0.1)$
$R_{ au} (imes 10^3)$	$\delta = 0.0021 \ (0.1)$	$\delta = 0.003 \ (0.1)$
$R_b (imes 10^3)$	$\delta = 0.001 \; (0.3)$	$\delta = 0.005 \; (0.2)$
$R_c (imes 10^3)$	$\delta = 0.011 \; (1.5)$	$\delta = 0.02 \; (1)$



Zh and VBF ($h\nu\nu$)

		$e^+e^- \to Zh$		
	$\sqrt{s} = 24$	$40 { m GeV}$	$\sqrt{s} = 36$	$35 { m GeV}$
O_i	$\delta_{\exp} \mathcal{O}_i$ (FCC-ee)	$\delta_{\exp} \mathcal{O}_i$ (CEPC)	$\delta_{\exp} \mathcal{O}_i$ (FCC-ee)	$\delta_{ ext{exp}}\mathcal{O}_i ext{ (CEPC)}$
σ_{Zh}	0.0035	0.0026	0.0064	0.014
$\sigma_{Zh} imes \mathrm{BR}_{b\bar{b}}$	0.0021	0.0014	0.0035	0.009
$\sigma_{Zh} imes \mathrm{BR}_{c\bar{c}}$	0.0156	0.0202	0.046	0.088
$\sigma_{Zh} \times \mathrm{BR}_{gg}$	0.0134	0.0081	0.0247	0.034
$\sigma_{Zh} imes \mathrm{BR}_{ZZ}$	0.0311	0.0417	0.0849	0.2
$\sigma_{Zh} imes \mathrm{BR}_{WW}$	0.0085	0.0053	0.0184	0.028
$\sigma_{Zh} imes \mathrm{BR}_{ au^+ au^-}$	0.0064	0.0042	0.0127	0.021
$\sigma_{Zh} imes \mathrm{BR}_{\gamma\gamma}$	0.0636	0.0302	0.127	0.11
$\sigma_{Zh} imes \mathrm{BR}_{\gamma Z}$	0.12	0.085	-	-
		$e^+e^- \to h \nu \nu$		
	$\sqrt{s} = 24$	$40 { m GeV}$	$\sqrt{s} = 36$	$35 { m GeV}$
\mathcal{O}_i	$\delta_{\exp} \mathcal{O}_i$ (FCC-ee)	$\delta_{ ext{exp}}\mathcal{O}_i ext{ (CEPC)}$	$\delta_{\exp} \mathcal{O}_i$ (FCC-ee)	$\delta_{ ext{exp}}\mathcal{O}_i ext{ (CEPC)}$
$\sigma_{h\nu\nu} \times \mathrm{BR}_{b\bar{b}}$	0.0219	0.0159	0.0064	0.011
$\sigma_{h\nu\nu} imes \mathrm{BR}_{c\bar{c}}$	-	-	0.0707	0.16
$\sigma_{h\nu\nu} imes \mathrm{BR}_{gg}$	-	-	0.0318	0.045
$\sigma_{h\nu\nu} \times \mathrm{BR}_{ZZ}$	-	-	0.0707	0.21
$\sigma_{h\nu\nu} \times \mathrm{BR}_{WW}$	-	-	0.0255	0.044
$\sigma_{h u u} imes \mathrm{BR}_{ au^+ au^-}$	-	-	0.0566	0.042
$\sigma_{h\nu\nu} \times \mathrm{BR}_{\gamma\gamma}$	-	-	0.156	0.16



FCC-ee and CEPC datasets

					$e^+e^- \rightarrow f\bar{f}$				<u> </u>
			$\sqrt{s} = 24$	40 G	eV	\sqrt{s}	= 36	$5~{ m GeV}$	
${\cal O}_i$		$\Big \ \Delta_{ ext{exp}} \mathcal{O}_i$	(FCC-ee)	$ \Delta_{\rm e} $	$_{\mathrm{xp}}\mathcal{O}_{i} \; (\mathrm{CEPC}) \; \Big $	$\Delta_{\exp} \mathcal{O}_i$ (FCC-	-ee)	$\Delta_{\exp}\mathcal{O}_i$ (CEPC)
$\sigma_{ m tot}(e^+e^-)$	[fb]	2.29		1.6	52	2.74		4.68	
$A_{ m FB}(e^+e^-)$)	$9.79 \cdot 10$	-6	6.9	$2 \cdot 10^{-6}$	$2.83\cdot 10^{-5}$		$4.83 \cdot 10^{-1}$	-5
$\sigma_{ m tot}(\mu^+\mu^-)$) [fb]	0.405		0.2	287	0.48		0.82	
$A_{ m FB}(\mu^+\mu^-$	·)	$1.98 \cdot 10$	-4	1.3	$97 \cdot 10^{-4}$	$5.69\cdot 10^{-4}$		$9.7 \cdot 10^{-4}$	-
$\sigma_{ m tot}(au^+ au^-)$) [fb]	0.374		0.2	264	0.443		0.756	
$A_{ m FB}(au^+ au^-)$)	$2.17 \cdot 10$	-4	1.5	$53 \cdot 10^{-4}$	$6.24\cdot 10^{-4}$		0.00106	
$\sigma_{ m tot}(car{c})~[{ m fb}$)	0.088		0.0	62	0.102		0.175	
$A_{ m FB}(car{c})$		0.000813	3	5.7	$4 \cdot 10^{-4}$	0.00238		0.00405	
$\sigma_{ m tot}(bar{b})$ [fb	•]	0.151		0.1	.07	0.171		0.29	
$A_{ m FB}(bar{b})$		$4.86 \cdot 10$	-4	3.4	$4 \cdot 10^{-4}$	0.00142		0.00243	
					$e^+e^- \rightarrow W^+W$	·			
0.		$\sqrt{s} = 16$	$61~{ m GeV}$		$\sqrt{s} = 24$	40 GeV		$\sqrt{s} = 36$	$65~{ m GeV}$
	$\delta_{ m exp}$ ((FCC-ee)	δ_{exp} (CEP	PC)	δ_{exp} (FCC-ee)	δ_{exp} (CEPC)	$\delta_{ m exp}$	(FCC-ee)	$\delta_{\rm exp}$ (CE
σ_{WW}	1.36	$6\cdot 10^{-4}$	$2.48\cdot 10^{-1}$	-4	$1.22\cdot 10^{-4}$	$8.63\cdot 10^{-5}$	2.8	$1\cdot 10^{-4}$	$4.87 \cdot 10^{-10}$
$BR_{W \to \ell_i \nu_i}$	2.72	$2 \cdot 10^{-4}$	$4.95 \cdot 10^{-1}$	-4	$2.44\cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	5.6	$3\cdot 10^{-4}$	9.75 \cdot 10

					$e^+e^- \rightarrow f\bar{f}$				
			$\sqrt{s} = 24$	0 G	eV	\sqrt{s}	= 36	$55 { m GeV}$	
${\cal O}_i$		$\Delta_{ ext{exp}}\mathcal{O}_i$	(FCC-ee)	$\Delta_{ m e}$	$_{\mathrm{xp}}\mathcal{O}_i \; (\mathrm{CEPC}) \; \Big $	$\Delta_{\exp} \mathcal{O}_i$ (FCC	-ee)	$\Delta_{\exp}\mathcal{O}_i$ (CEPC)
$\sigma_{ m tot}(e^+e^-)$	[fb]	2.29		1.6	2	2.74		4.68	
$A_{ m FB}(e^+e^-)$		$9.79\cdot 10^{\circ}$	-6	6.9	$2 \cdot 10^{-6}$	$2.83\cdot 10^{-5}$		$4.83 \cdot 10^{-1}$.5
$\sigma_{ m tot}(\mu^+\mu^-)$	[fb]	0.405		0.2	87	0.48		0.82	
$A_{ m FB}(\mu^+\mu^-)$)	$1.98 \cdot 10^{-1}$	-4	1.3	$97 \cdot 10^{-4}$	$5.69\cdot 10^{-4}$		$9.7\cdot 10^{-4}$	
$ au_{ m tot}(au^+ au^-)$	[fb]	0.374		0.2	64	0.443		0.756	
$A_{ m FB}(au^+ au^-)$)	$2.17 \cdot 10^{\circ}$	-4	1.5	$3 \cdot 10^{-4}$	$6.24\cdot 10^{-4}$		0.00106	
$\sigma_{ m tot}(car{c})$ [fb]	0.088		0.0	62	0.102		0.175	
$A_{ m FB}(car{c})$		0.000813	3	5.7	$4 \cdot 10^{-4}$	0.00238		0.00405	
${ m tot}(bar{b})$ [fb]	0.151		0.1	07	0.171		0.29	
$A_{ m FB}(bar{b})$		$4.86 \cdot 10^{-10}$	-4	3.4	$4 \cdot 10^{-4}$	0.00142		0.00243	
					$e^+e^- \rightarrow W^+W$	·			
n.		$\sqrt{s} = 16$	$61 { m GeV}$		$\sqrt{s}=24$	$40 { m GeV}$		$\sqrt{s} = 36$	$65~{ m GeV}$
	$\delta_{ m exp}$ ((FCC-ee)	δ_{exp} (CEP	C)	δ_{exp} (FCC-ee)	δ_{exp} (CEPC)	$\delta_{ m exp}$	(FCC-ee)	$\delta_{\rm exp}$ (CE
WW	1.36	$5\cdot 10^{-4}$	$2.48\cdot 10^{-1}$	-4	$1.22\cdot 10^{-4}$	$8.63\cdot 10^{-5}$	2.8	$81 \cdot 10^{-4}$	$4.87 \cdot 10$
$\mathbf{R}_{W \to \ell_i \nu_i}$	2.72	$2 \cdot 10^{-4}$	$4.95\cdot 10^{-1}$	-4	$2.44\cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	5.6	$33\cdot10^{-4}$	$9.75\cdot 10$



HL-LHC projections

The central values of the pseudo data are fluctuated ► around the SM

$$\mathcal{O}_i^{(\text{exp})} = \mathcal{O}_i^{(\text{th})} \left(1 + r_i \delta_i^{(\text{stat})} + \sum_{k=1}^{n_{\text{sys}}} r_{k,i} \delta_i \right)$$

Statistical uncertainties we rescale according to the improved luminosity

$$\delta_i^{(\text{stat})} = \tilde{\delta}_i^{(\text{stat})} \sqrt{\frac{\mathcal{L}_{\text{Run2}}}{\mathcal{L}_{\text{HLLHC}}}}$$

$$\delta_{k,i}^{(\mathrm{sys})} = \tilde{\delta}_{k,i}^{(\mathrm{sys})} \times f_{\mathrm{red}}^{(k)}$$

While systematics are rescaled by an overall factor, namely 1/2 for all datasets







FCC-ee and CEPC

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}(\Lambda^{-2})$, Marginalised





1-loop & multi-particle matching

 T_1 (tree)



Jaco ter Hoeve

 $|(\lambda_{T_1})_3|$

