SMEFT at the FCC

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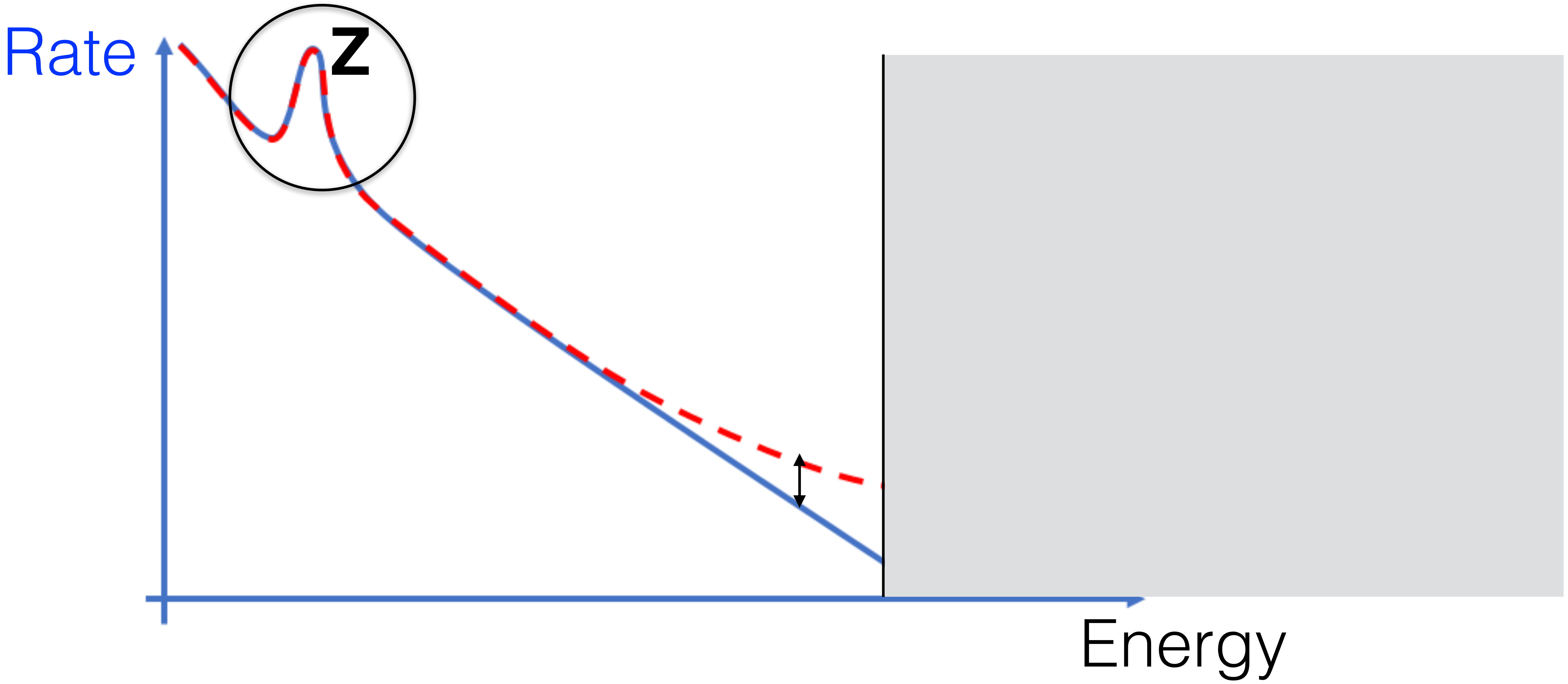
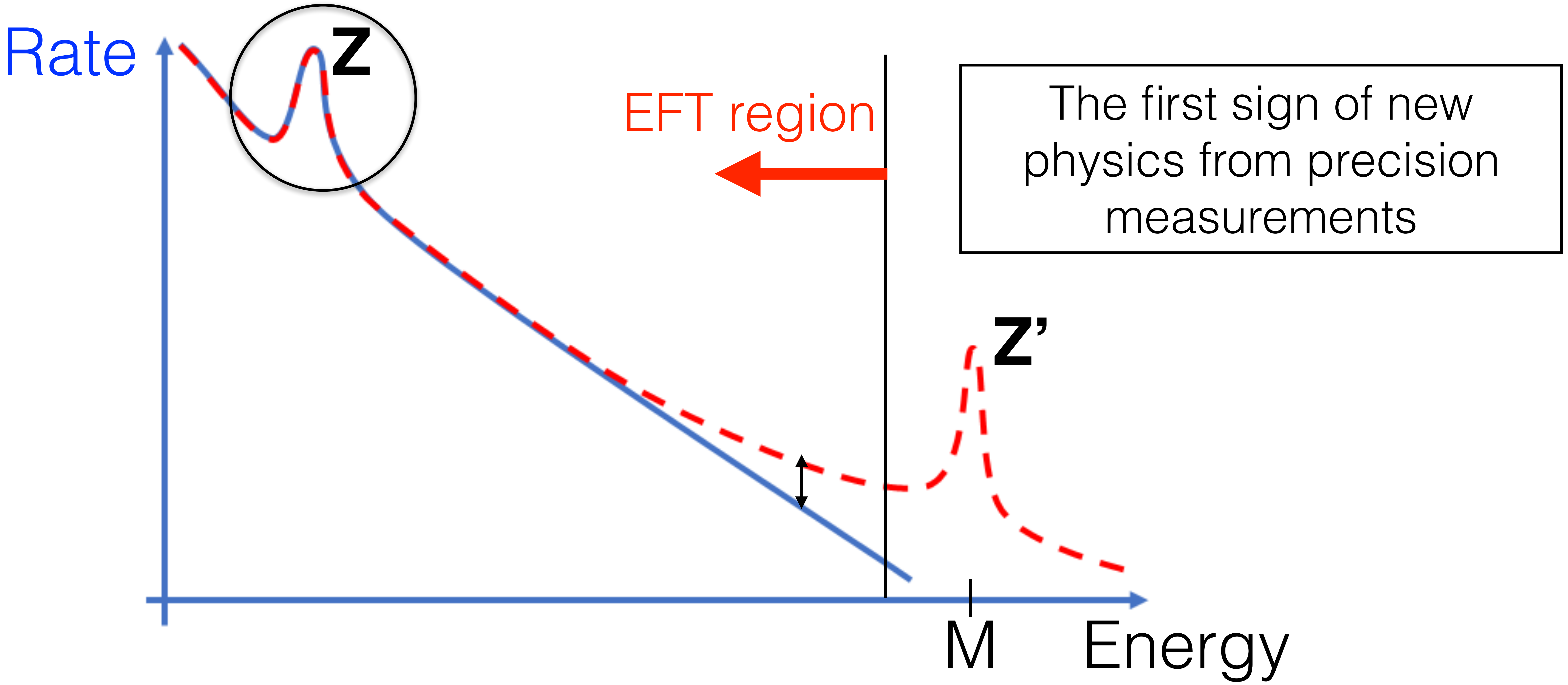
SMEFT basics



The way to probe New Physics in the absence of light states

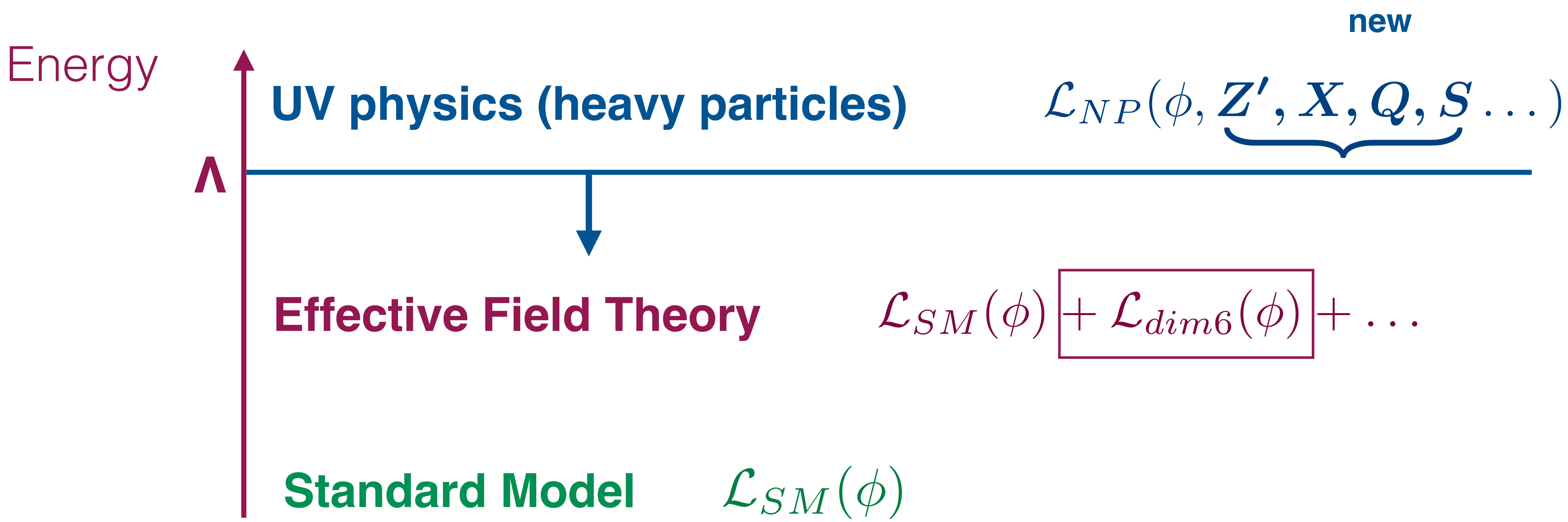
SMEFT basics



The first sign of new physics from precision measurements

The way to probe New Physics in the absence of light states

SMEFT: What is it all about?



Energy

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

Λ

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.

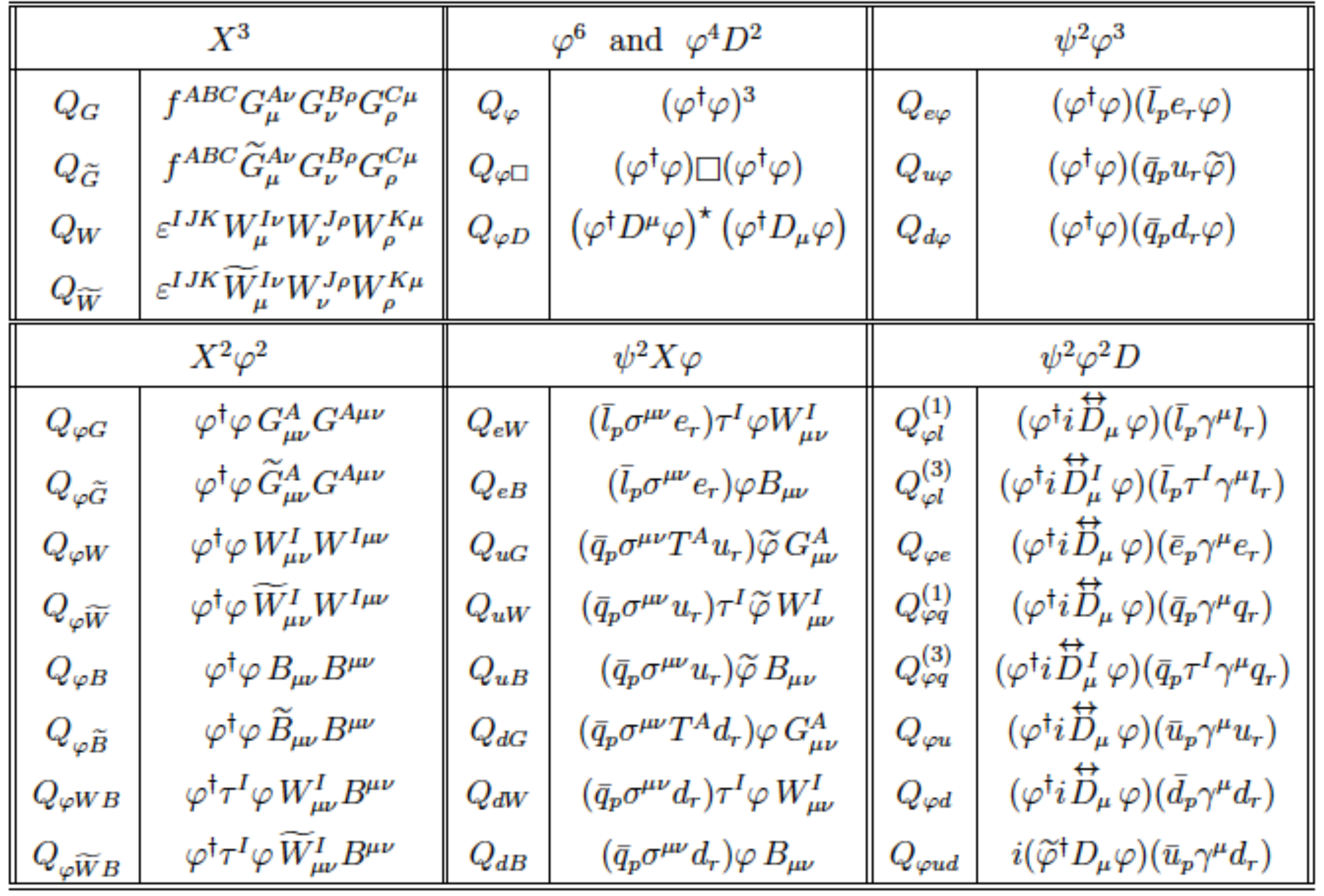
SMEFT@dim-6

New Physics: → New Interactions of SM particles

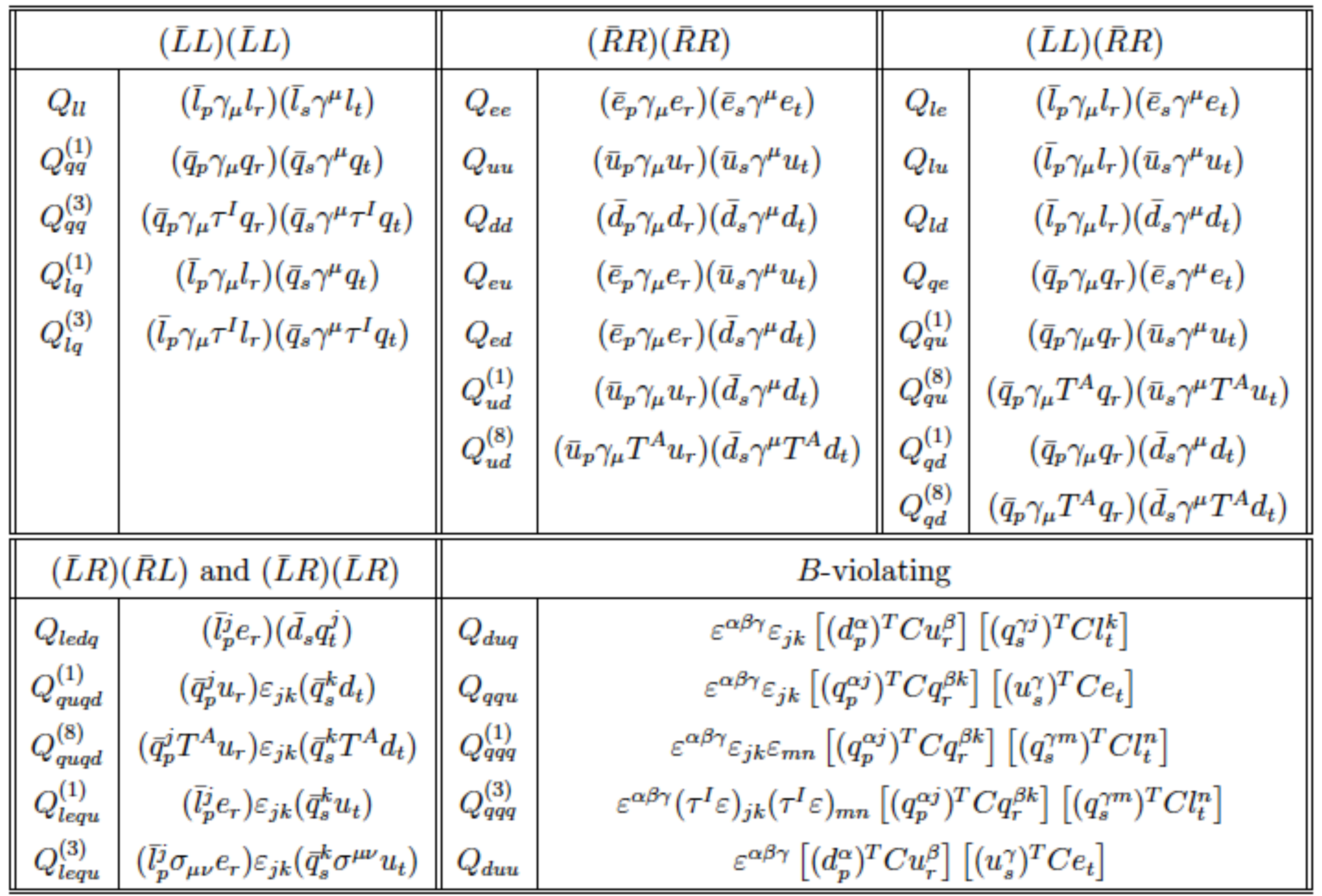
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arXiv:1008.4884



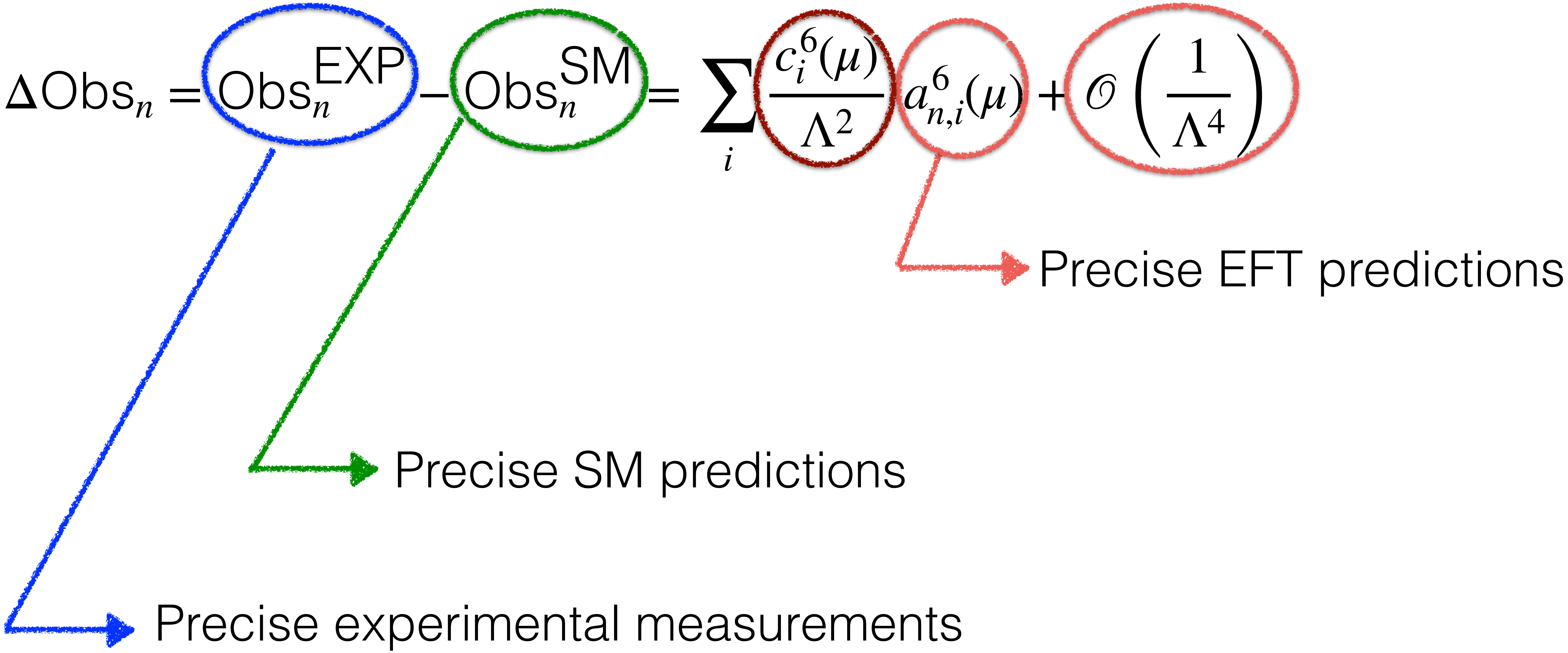
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

SMEFT@colliders in practice



$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Precise EFT predictions

Precise SM predictions

Precise experimental measurements

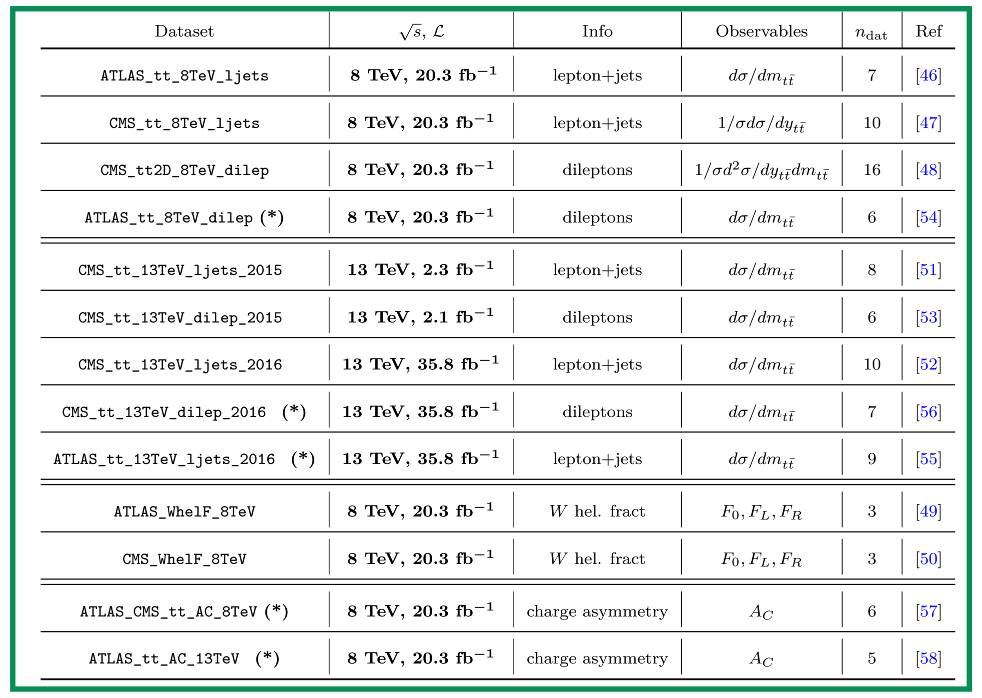
SMEFT@colliders in practice

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

LHC observables

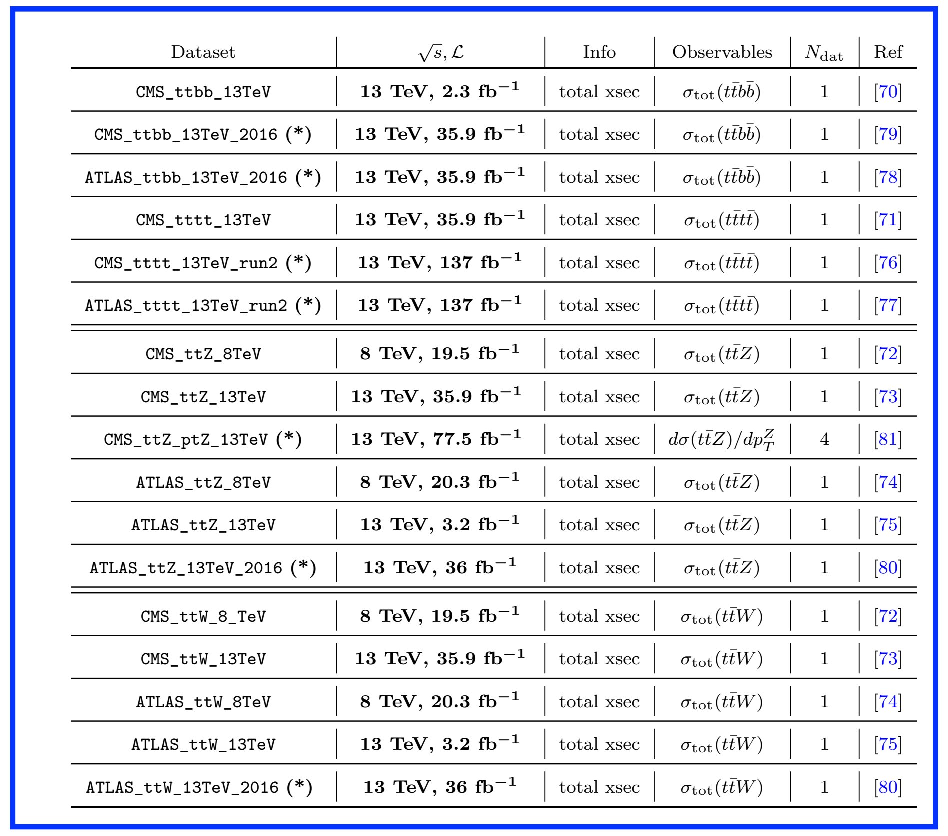
Data

Top-pair production W-helicities, asymmetry

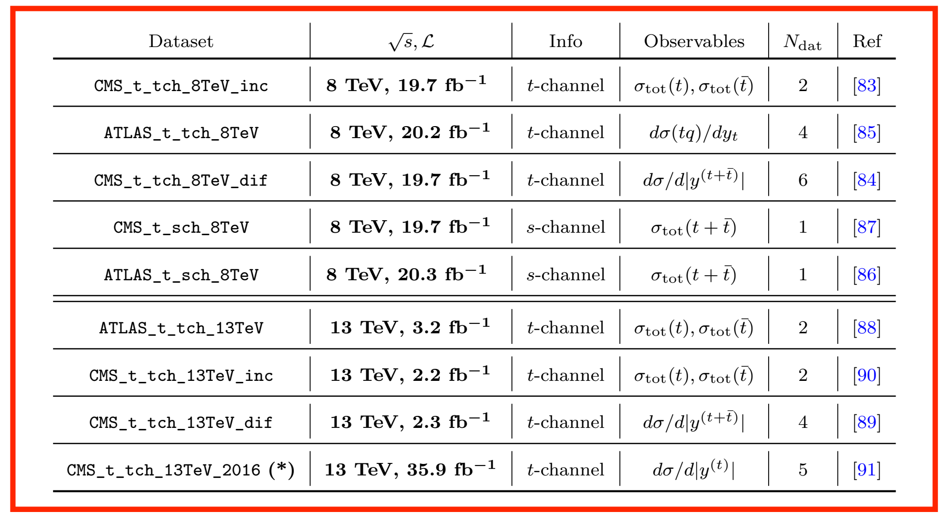


Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	5	[58]

4 tops, ttbb, top-pair associated production

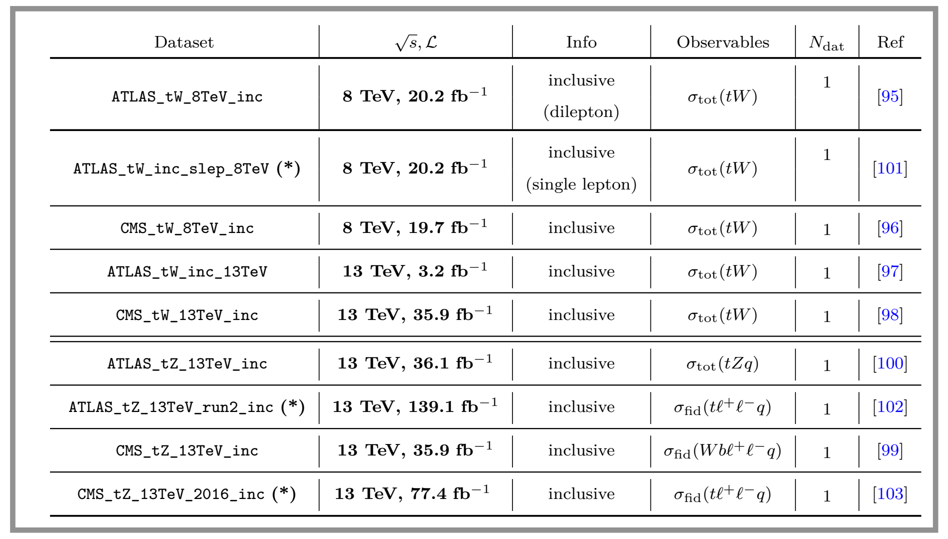


Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]



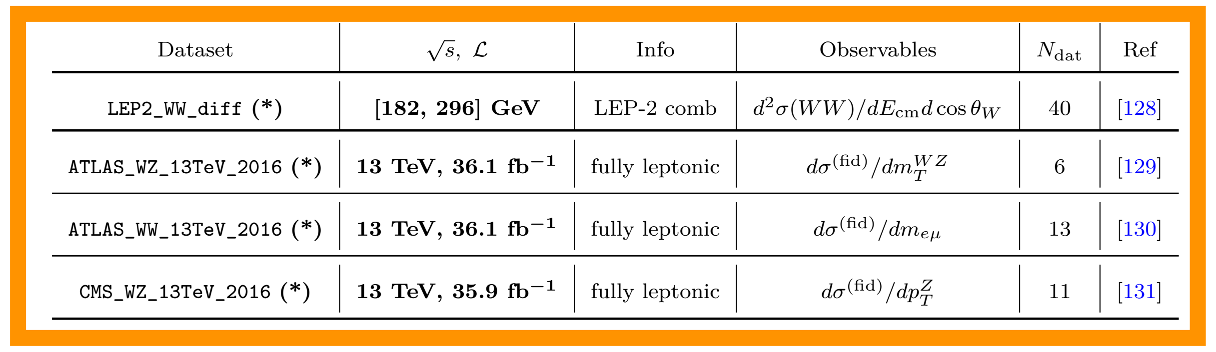
Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\vert y^{(t+\bar{t})}\vert$	6	[84]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\vert y^{(t+\bar{t})}\vert$	4	[89]
CMS_t_tch_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\vert y^{(t)}\vert$	5	[91]

Single top t-, s-channel



Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tW_8TeV_inc	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[101]
CMS_tW_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[97]
CMS_tW_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[103]

tW, tZ



Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff (*)	**[182, 296] GeV**	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dp_T^Z$	11	[131]

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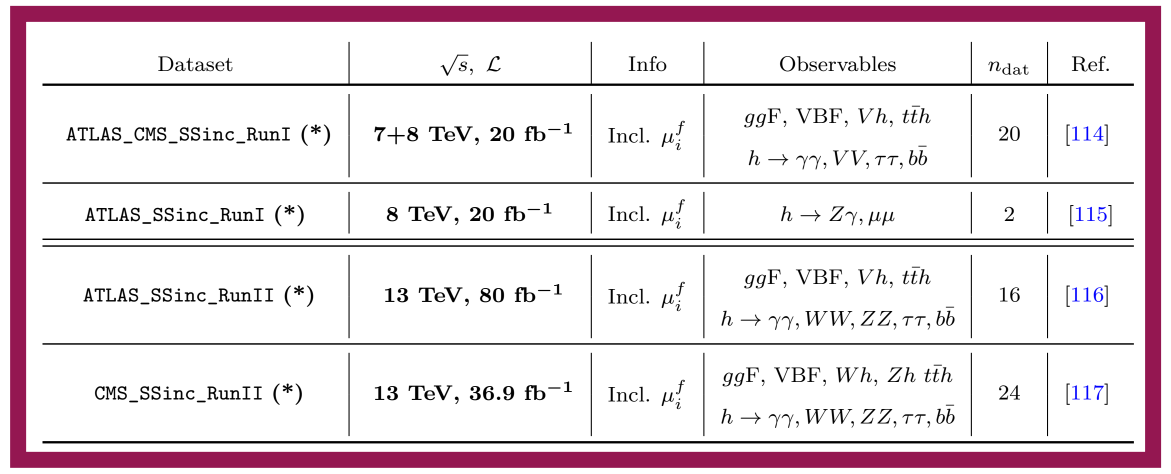
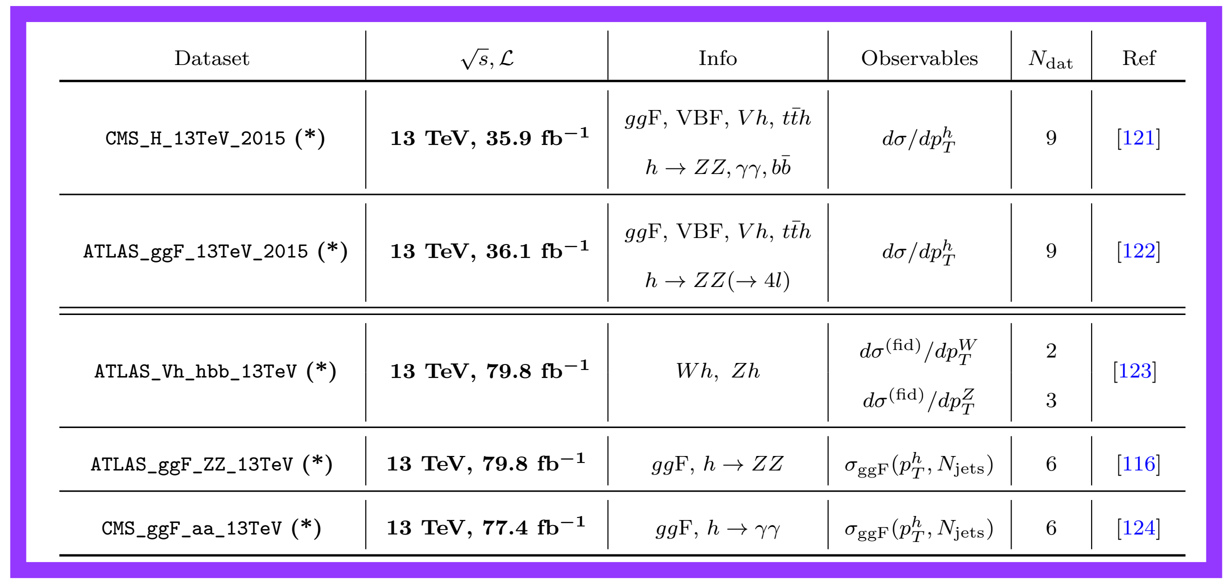


Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	**8 TeV, 20 fb^{-1}**	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]

Higgs signal strengths



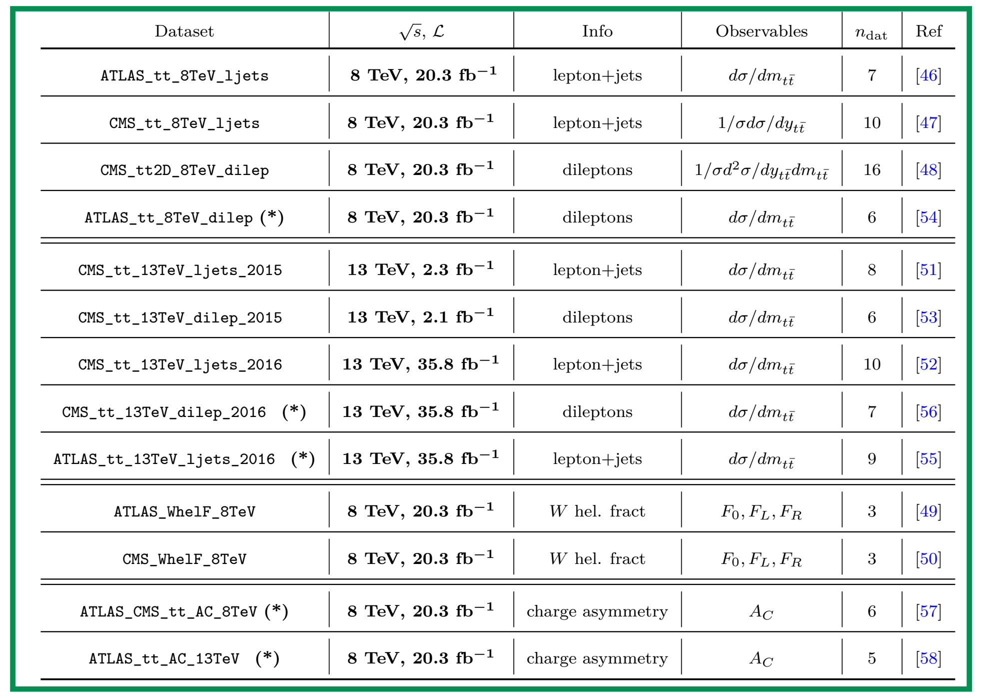
Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_H_13TeV_2015 (*)	**13 TeV, 35.9 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	**13 TeV, 36.1 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	Wh, Zh	$d\sigma^{(\rm fid)}/dp_T^W$ $d\sigma^{(\rm fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	**13 TeV, 77.4 fb^{-1}**	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

Higgs differential

LHC observables

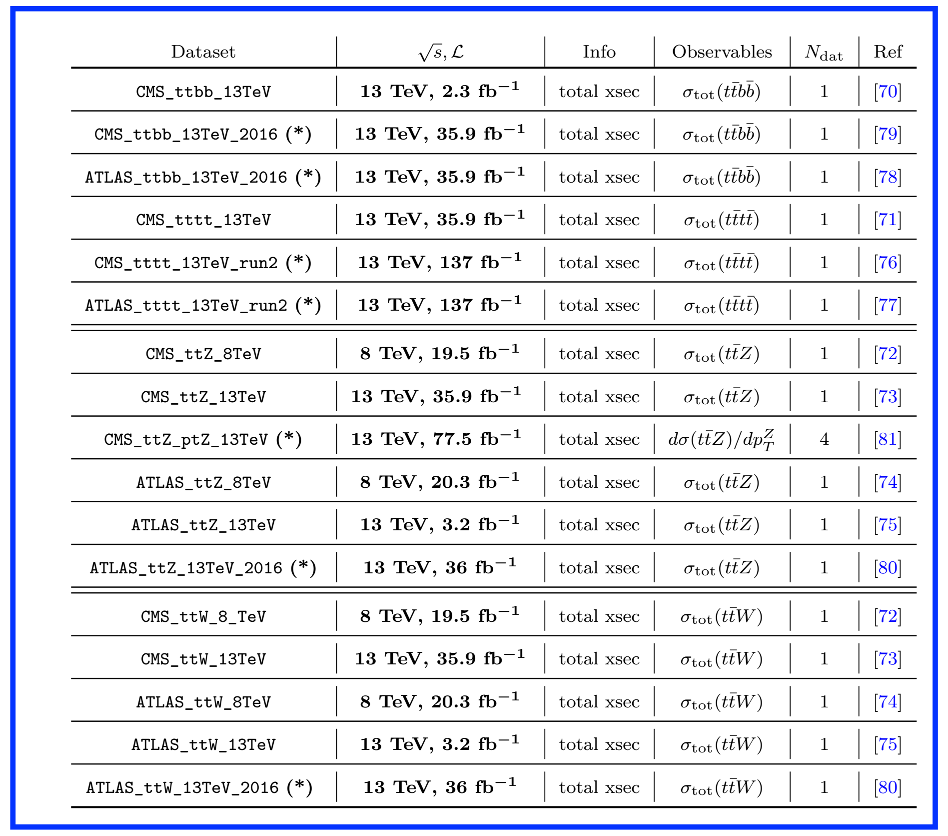
Data

Top-pair production W-helicities, asymmetry

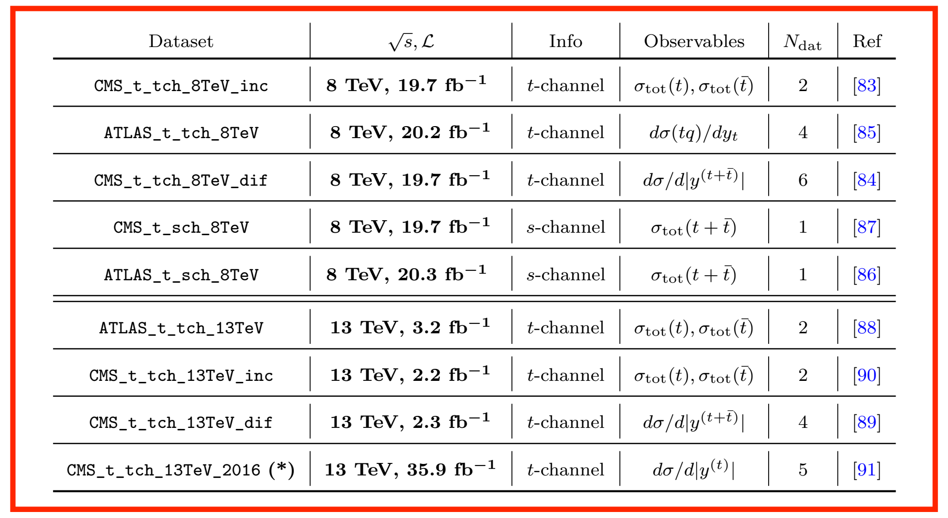


Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref
ATLAS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[46]
CMS_tt_8TeV_ljets	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[47]
CMS_tt2D_8TeV_dilep	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[48]
ATLAS_tt_8TeV_dilep (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[54]
CMS_tt_13TeV_ljets_2015	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[51]
CMS_tt_13TeV_dilep_2015	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[53]
CMS_tt_13TeV_ljets_2016	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[52]
CMS_tt_13TeV_dilep_2016 (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[56]
ATLAS_tt_13TeV_ljets_2016 (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[55]
ATLAS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[49]
CMS_WhelF_8TeV	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[50]
ATLAS_CMS_tt_AC_8TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[57]
ATLAS_tt_AC_13TeV (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	5	[58]

4 tops, ttbb, top-pair associated production

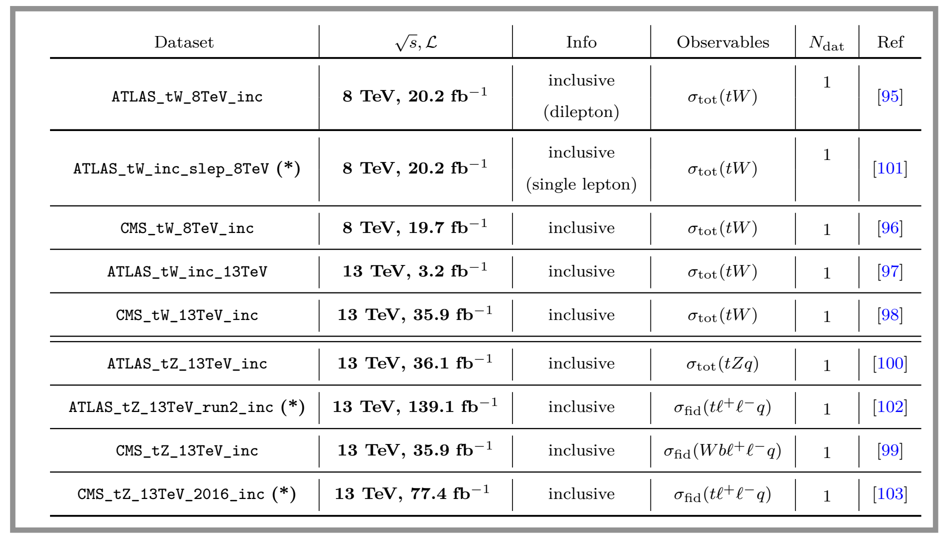


Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_ttbb_13TeV	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[70]
CMS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[79]
ATLAS_ttbb_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[78]
CMS_tttt_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[71]
CMS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[76]
ATLAS_tttt_13TeV_run2 (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[77]
CMS_ttZ_8TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[72]
CMS_ttZ_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[73]
CMS_ttZ_ptZ_13TeV (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[81]
ATLAS_ttZ_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[74]
ATLAS_ttZ_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[75]
ATLAS_ttZ_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
CMS_ttW_8_TeV	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[72]
CMS_ttW_13TeV	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[73]
ATLAS_ttW_8TeV	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[74]
ATLAS_ttW_13TeV	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[75]
ATLAS_ttW_13TeV_2016 (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]



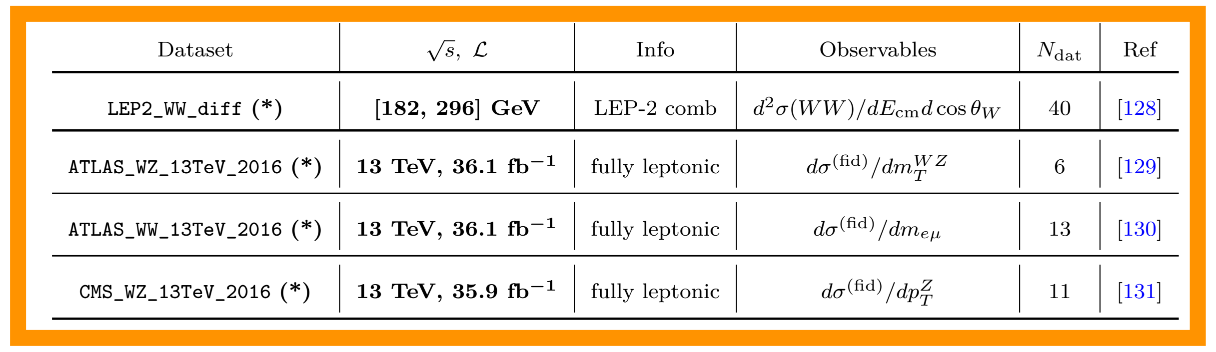
Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_t_tch_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[83]
ATLAS_t_tch_8TeV	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[85]
CMS_t_tch_8TeV_dif	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	6	[84]
CMS_t_sch_8TeV	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[87]
ATLAS_t_sch_8TeV	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[86]
ATLAS_t_tch_13TeV	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[88]
CMS_t_tch_13TeV_inc	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
CMS_t_tch_13TeV_dif	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t+\bar{t})}\|$	4	[89]
CMS_t_tch_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\|y^{(t)}\|$	5	[91]

Single top t-, s-channel



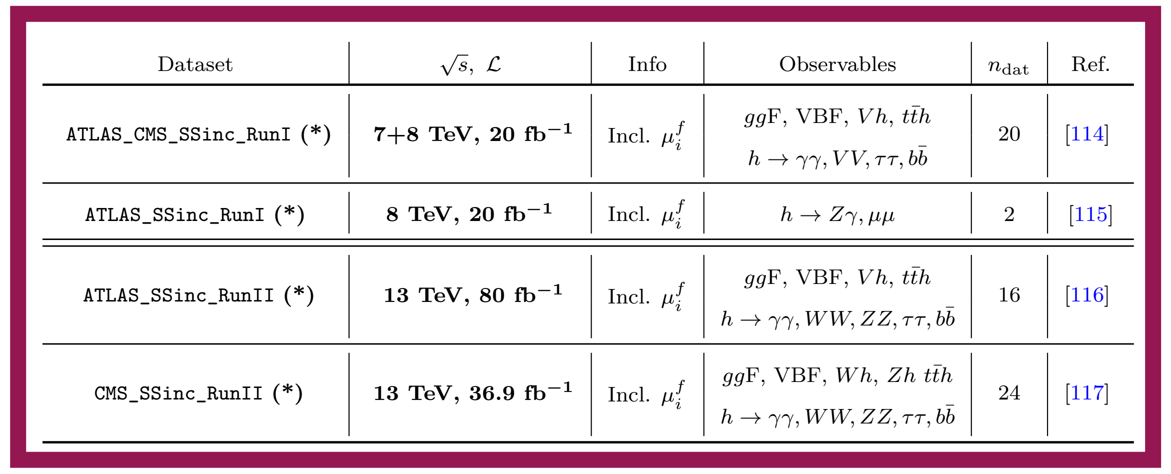
Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
ATLAS_tW_8TeV_inc	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[95]
ATLAS_tW_inc_slep_8TeV (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[101]
CMS_tW_8TeV_inc	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[96]
ATLAS_tW_inc_13TeV	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[97]
CMS_tW_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[98]
ATLAS_tZ_13TeV_inc	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[100]
ATLAS_tZ_13TeV_run2_inc (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[102]
CMS_tZ_13TeV_inc	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^-q)$	1	[99]
CMS_tZ_13TeV_2016_inc (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[103]

tW, tZ



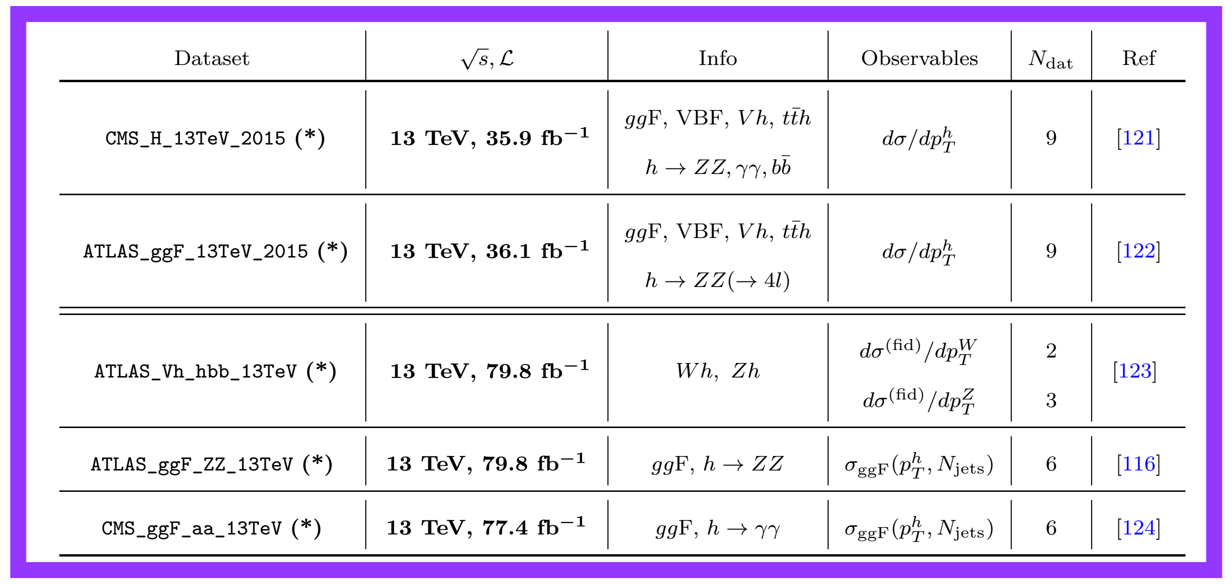
Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
LEP2_WW_diff (*)	**[182, 296] GeV**	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dp_T^Z$	11	[131]

Diboson



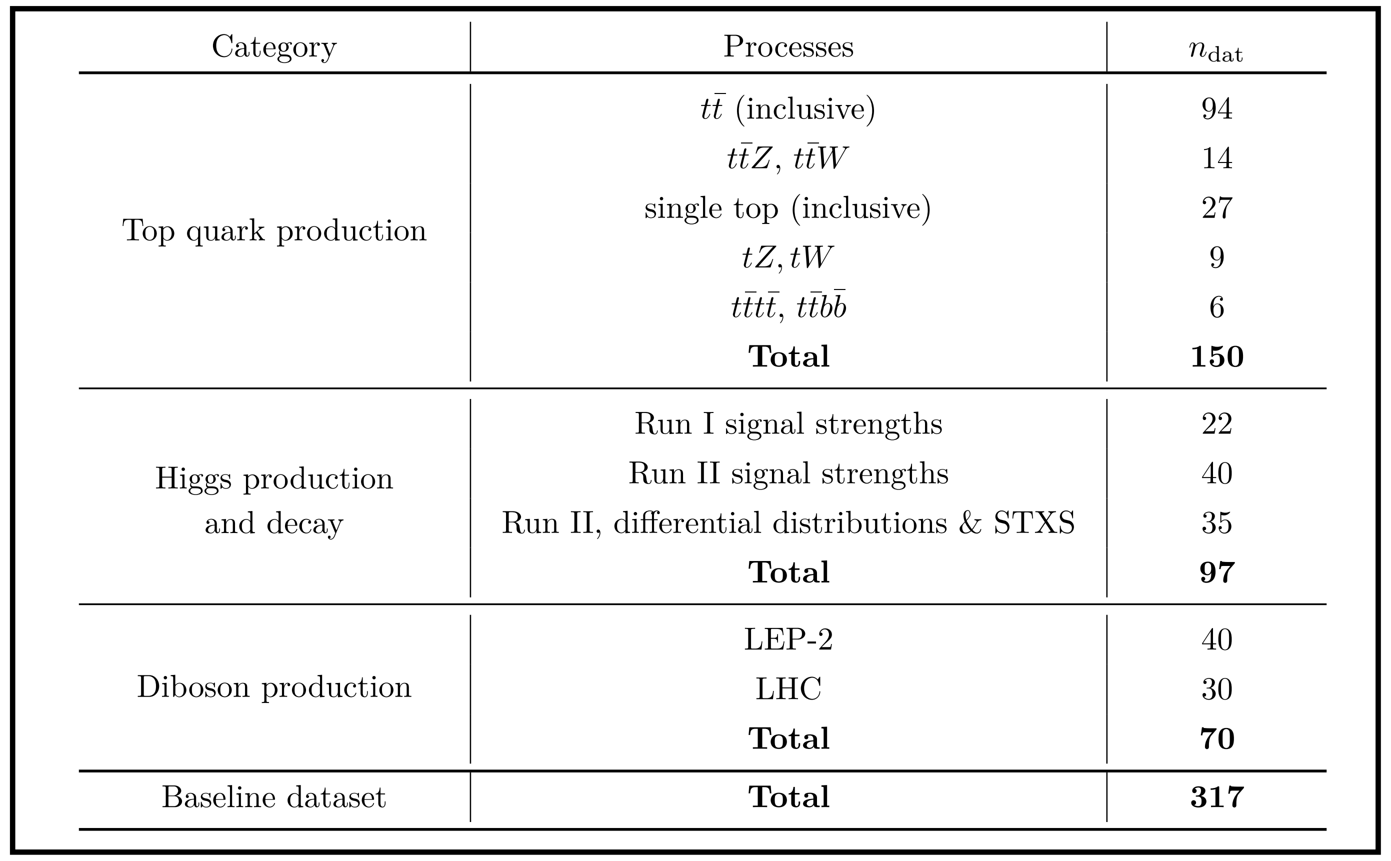
Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_CMS_SSinc_RunI (*)	**7+8 TeV, 20 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}$	20	[114]
ATLAS_SSinc_RunI (*)	**8 TeV, 20 fb^{-1}**	Incl. μ_i^f	$h \to Z\gamma, \mu\mu$	2	[115]
ATLAS_SSinc_RunII (*)	**13 TeV, 80 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Vh, $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	16	[116]
CMS_SSinc_RunII (*)	**13 TeV, 36.9 fb^{-1}**	Incl. μ_i^f	ggF, VBF, Wh, Zh $t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	24	[117]

Higgs signal strengths



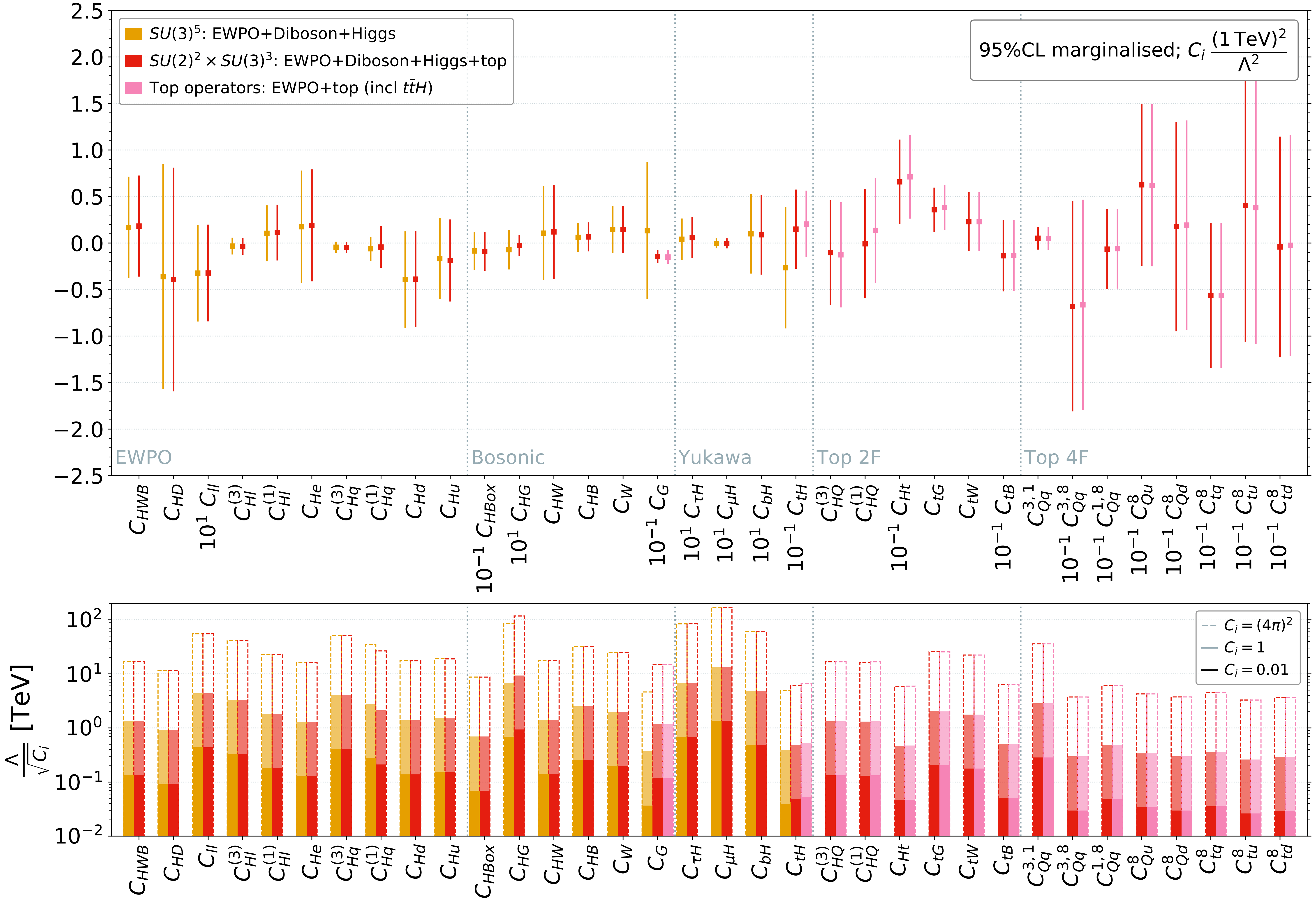
Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref
CMS_H_13TeV_2015 (*)	**13 TeV, 35.9 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	[121]
ATLAS_ggF_13TeV_2015 (*)	**13 TeV, 36.1 fb^{-1}**	ggF, VBF, Vh, $t\bar{t}h$ $h \to ZZ(\to 4l)$	$d\sigma/dp_T^h$	9	[122]
ATLAS_Vh_hbb_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	Wh, Zh	$d\sigma^{(\rm fid)}/dp_T^W$ $d\sigma^{(\rm fid)}/dp_T^Z$	2 3	[123]
ATLAS_ggF_ZZ_13TeV (*)	**13 TeV, 79.8 fb^{-1}**	ggF, $h \to ZZ$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[116]
CMS_ggF_aa_13TeV (*)	**13 TeV, 77.4 fb^{-1}**	ggF, $h \to \gamma\gamma$	$\sigma_{\rm ggF}(p_T^h, N_{\rm jets})$	6	[124]

Higgs differential



Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

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???**

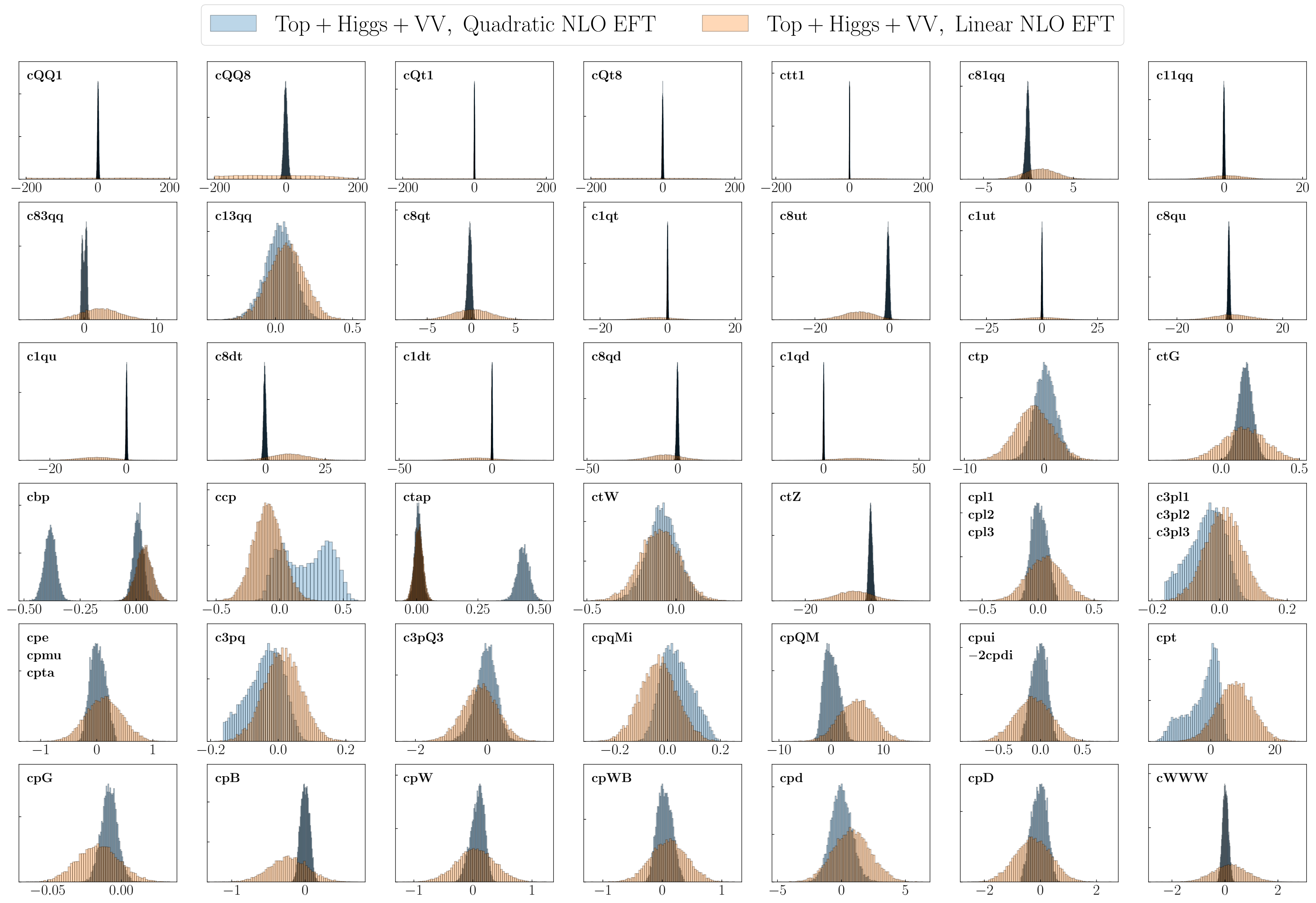
↓ Strongly coupled

Weakly coupled

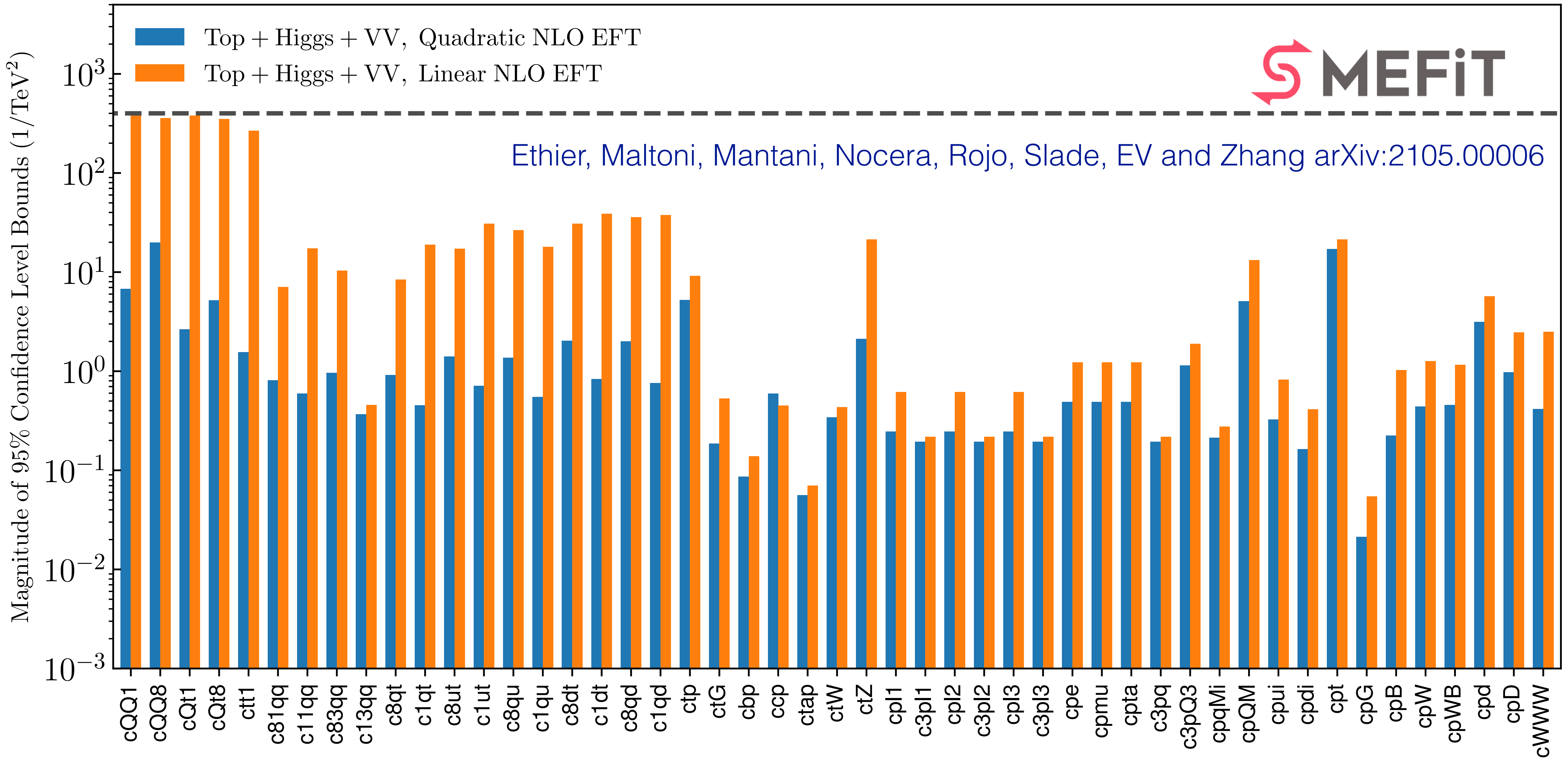
$$\frac{c_i^6(\mu)}{\Lambda^2}$$

LHC global EFT fit: marginalised (2)

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



Posterior distributions

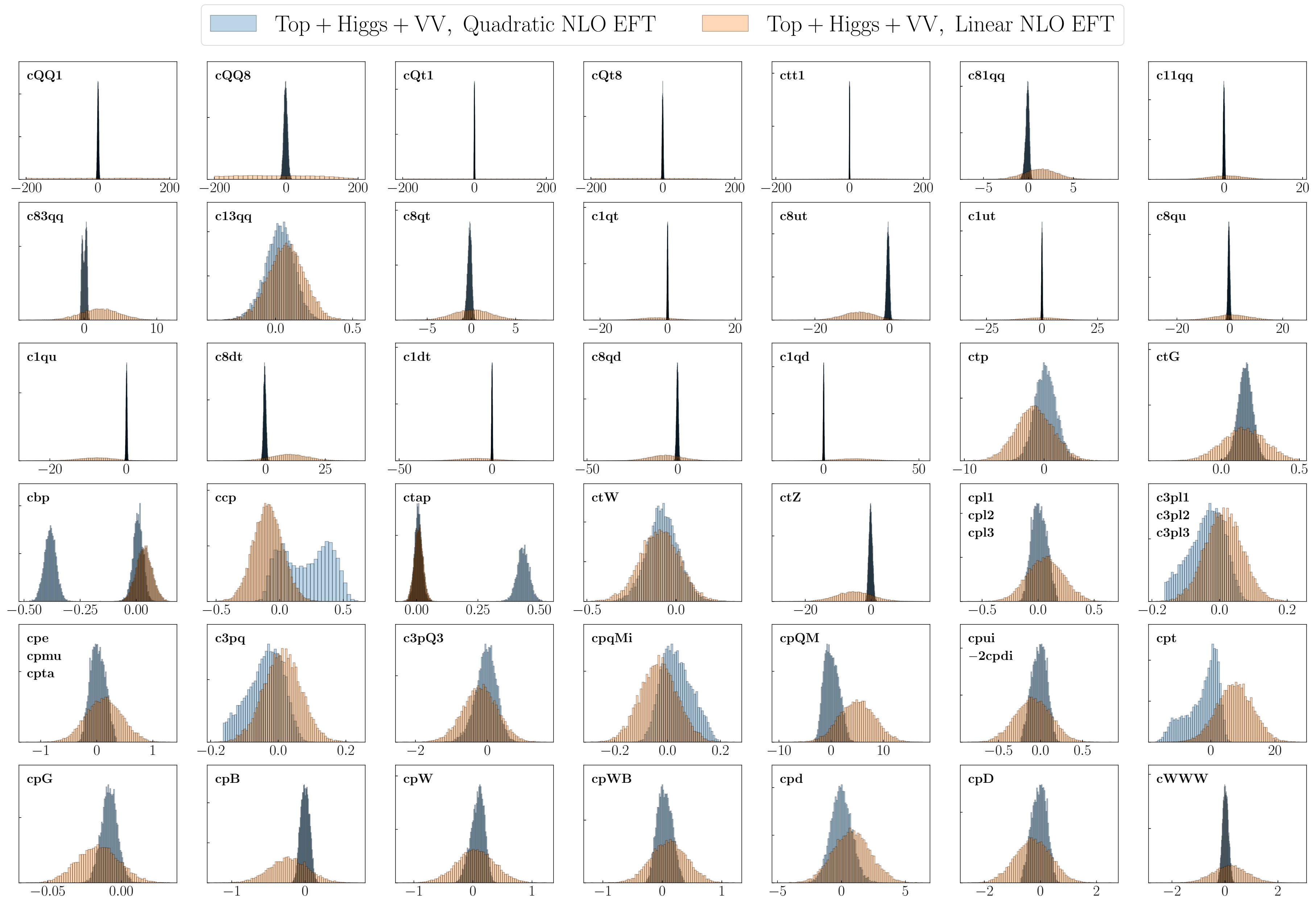


Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, EV and Zhang arXiv:2105.00006

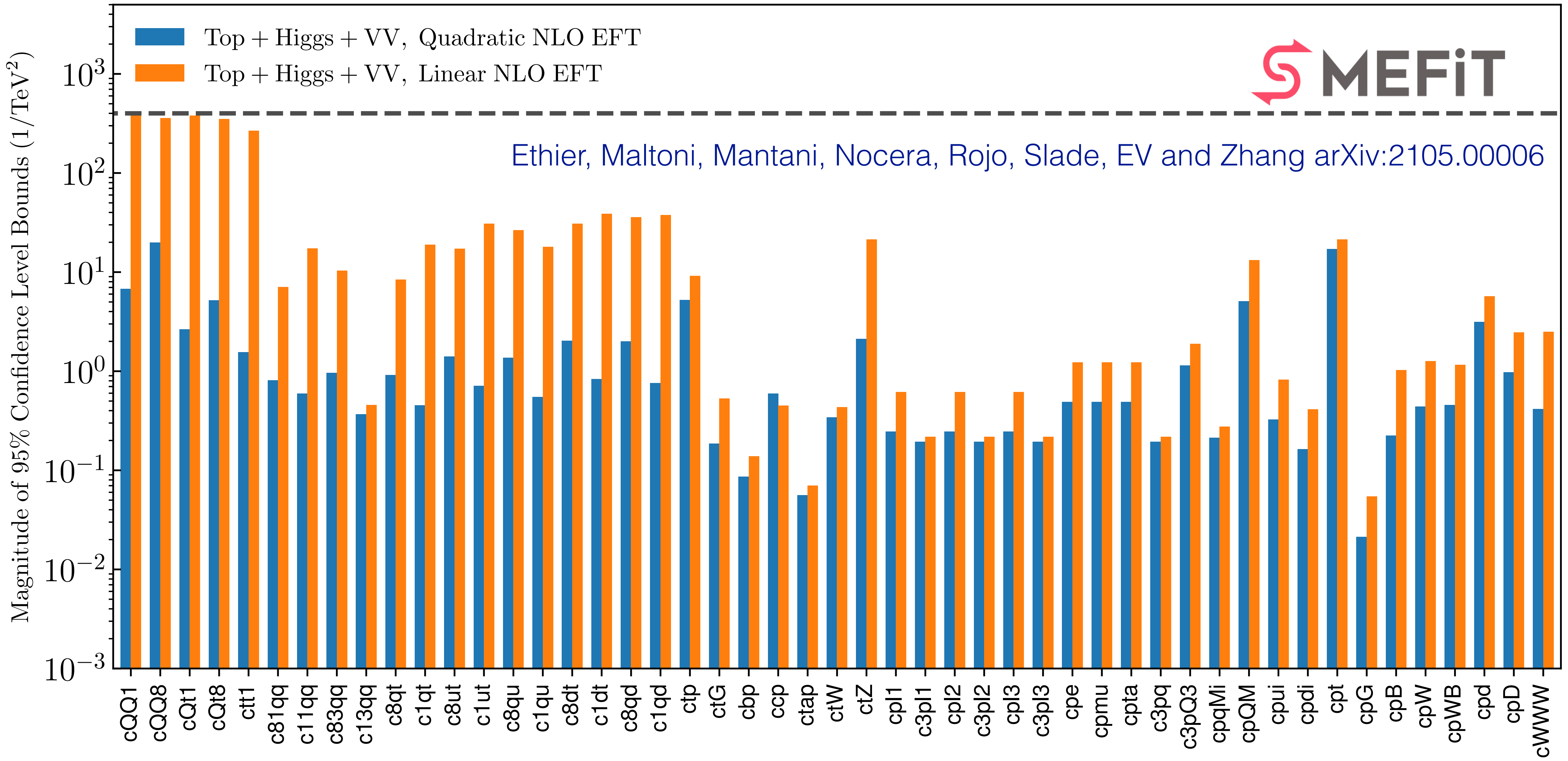
Significant impact for most operators
in particular 4-fermion operators

LHC global EFT fit: marginalised (2)

- Higher Orders in $1/\Lambda^4$
  - 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

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

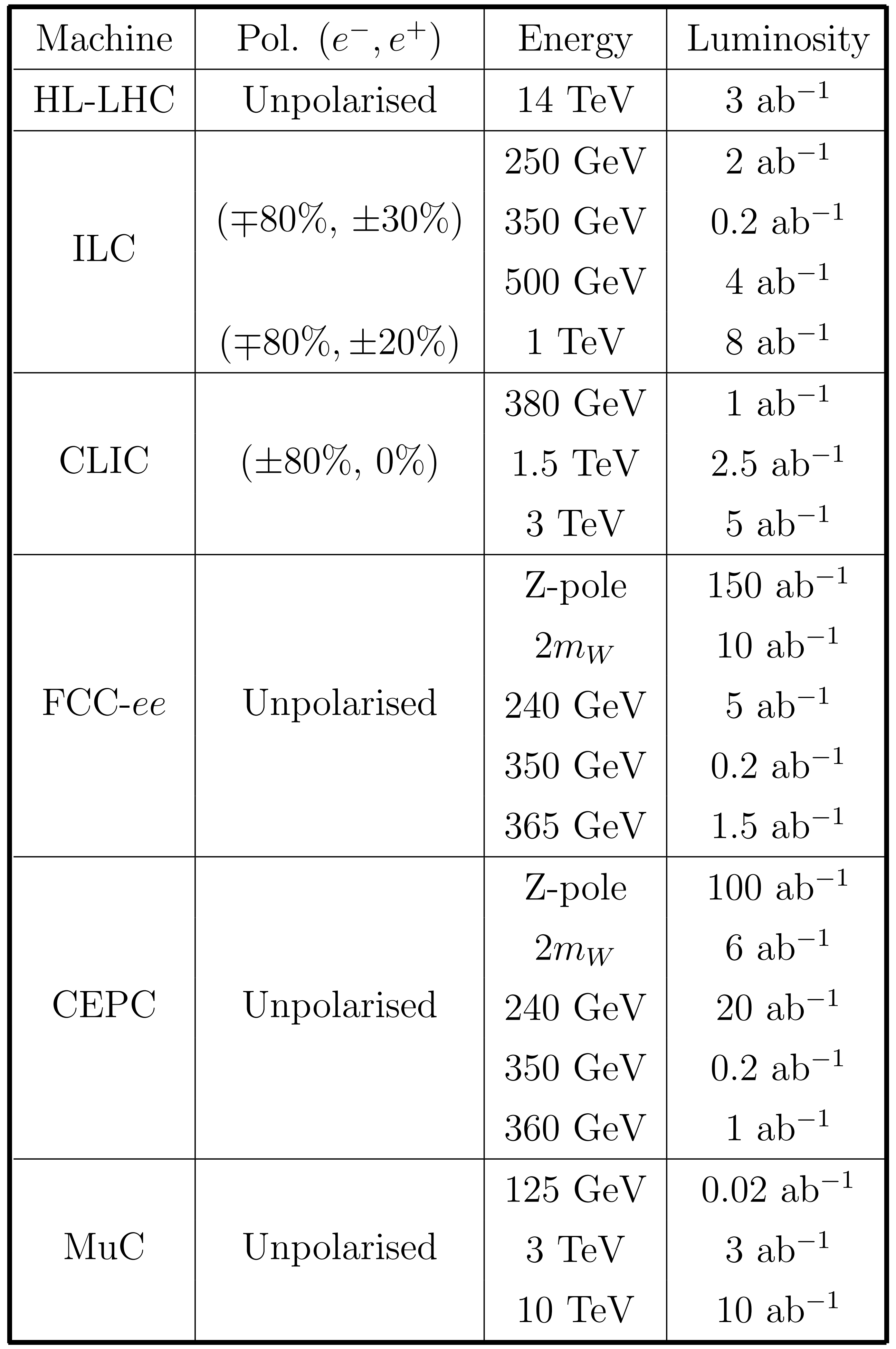
4-quark, 2-fermion, pure gauge, Higgs-gauge, top operators, 4-heavy operators

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:

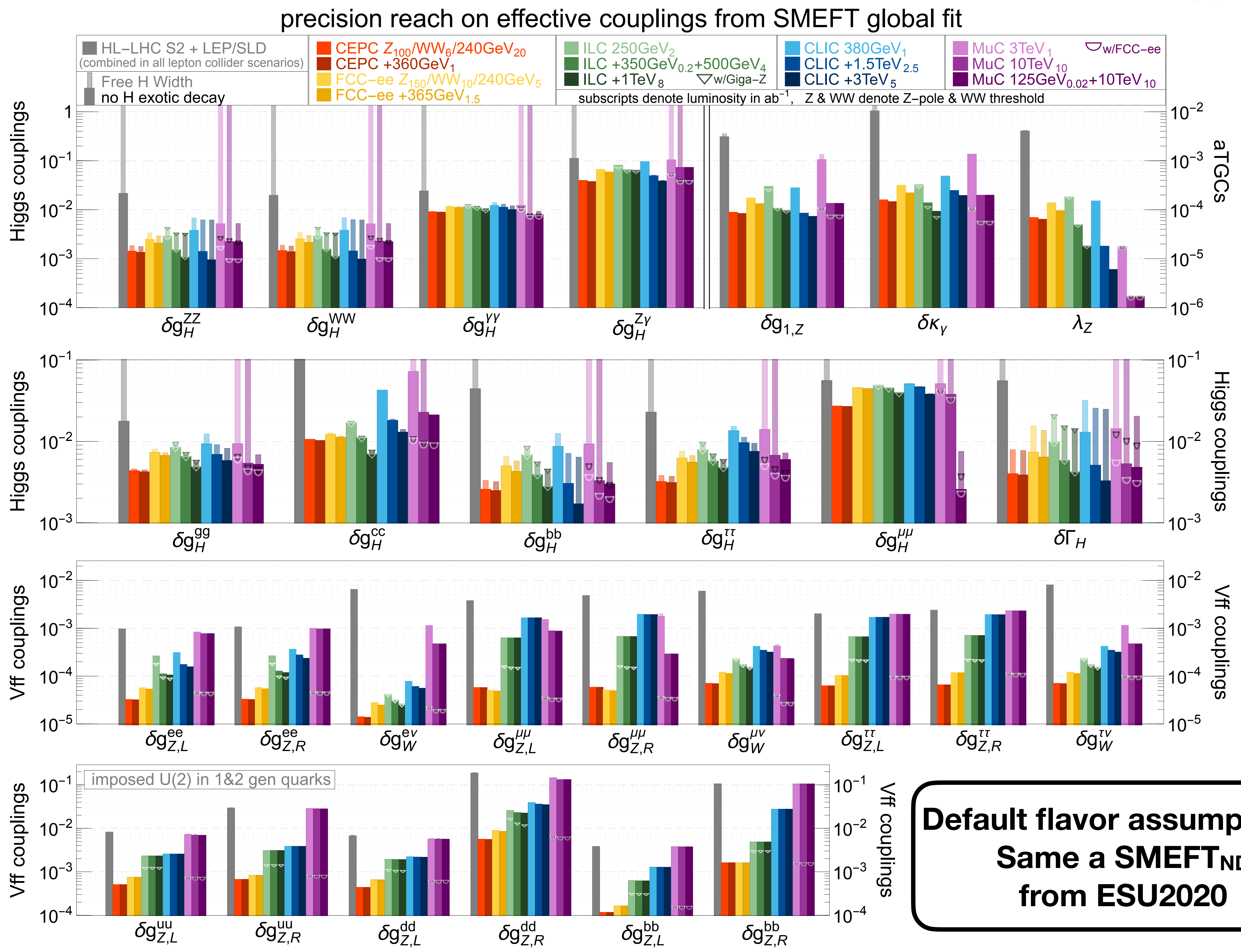
SMEFT truncated at linear level

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:

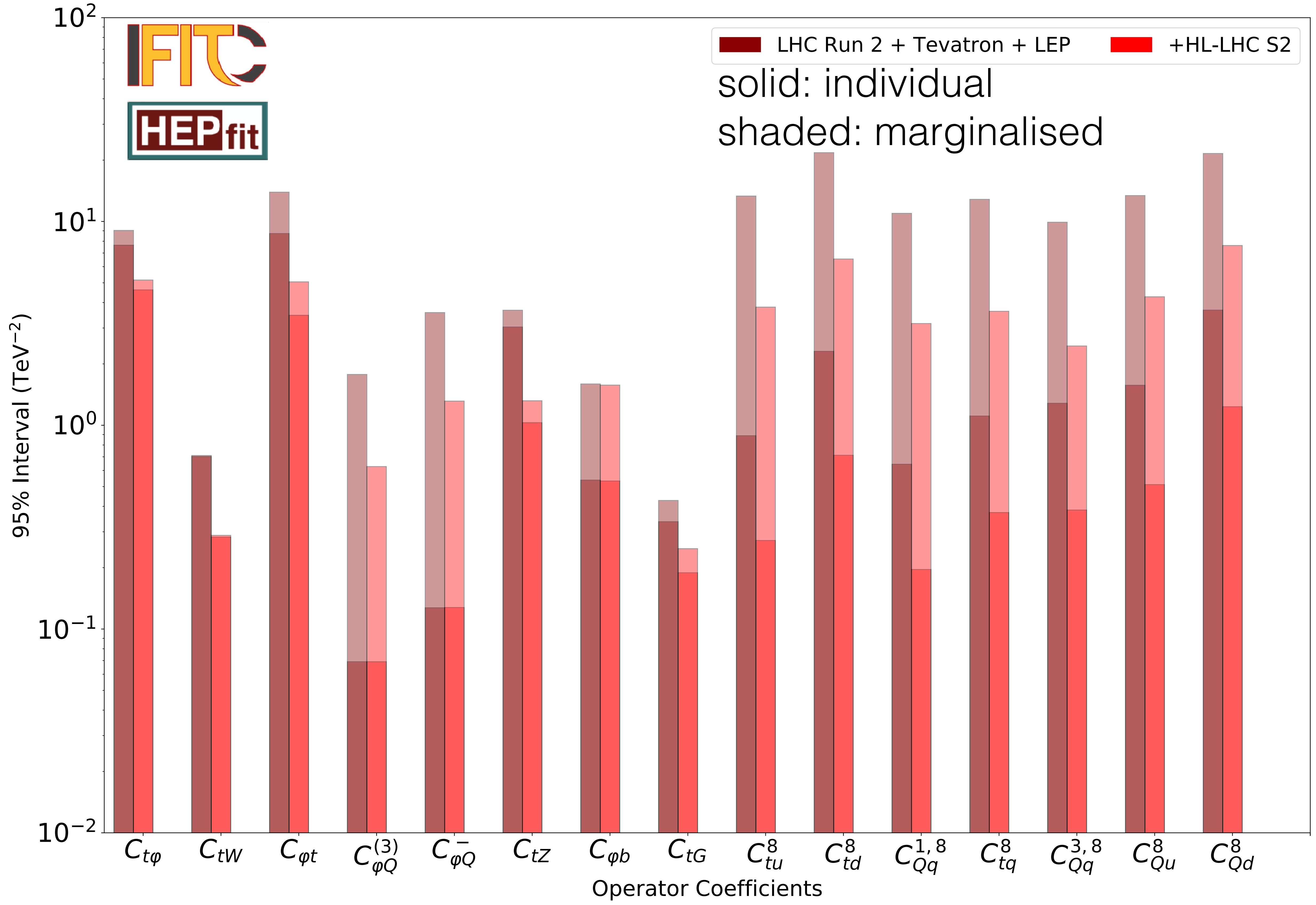
- Explore HL-LHC prospects
- Explore future collider prospects
- Do this in some some unified fit setup, with reasonable uncertainty assumptions

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



arXiv:2205.02140

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

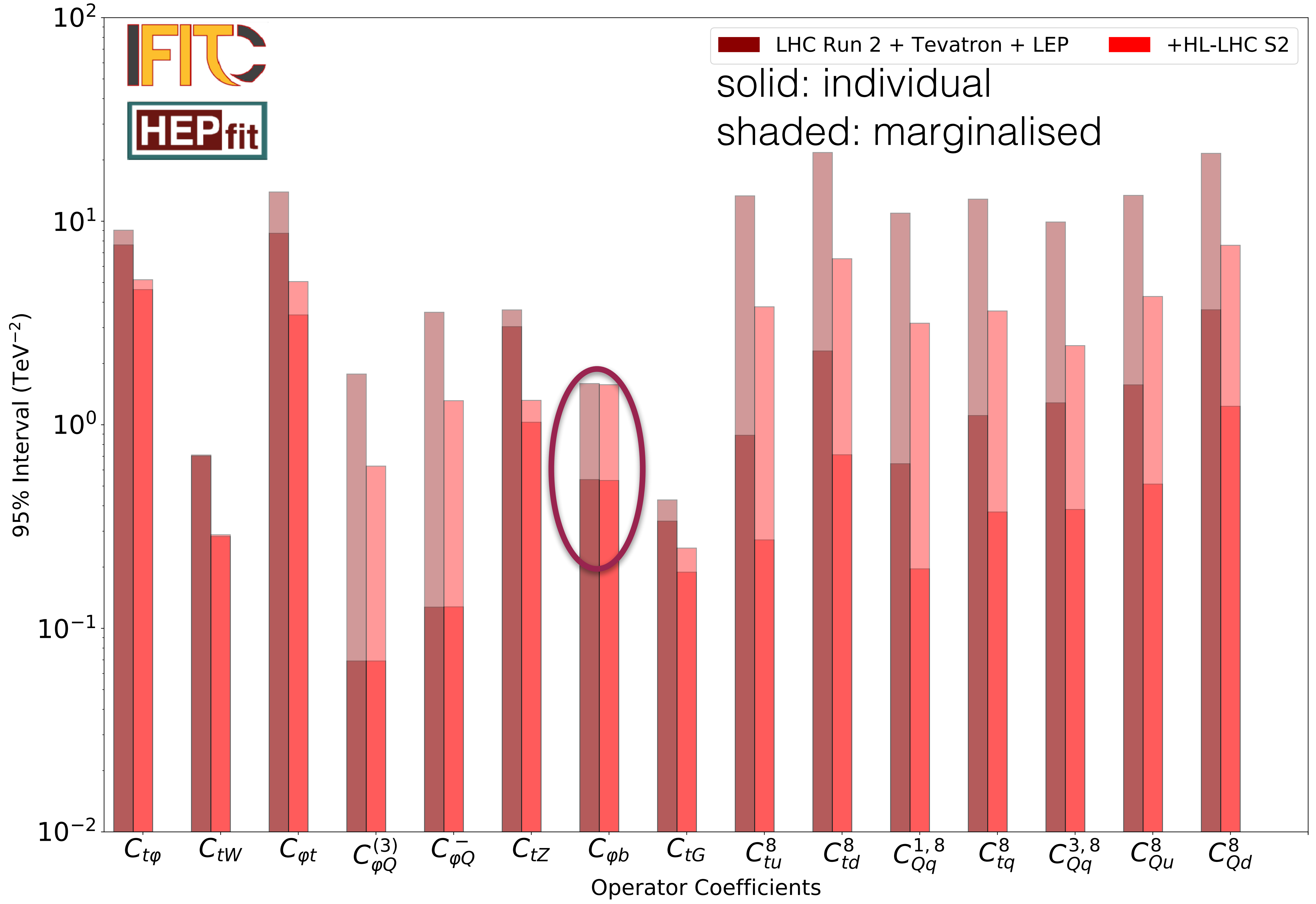
Not much improvement $C_{\phi Q}^{-}$ and $C_{\phi Q}^{3}$ (dominated by b at LEP but better at FCC)

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



arXiv:2205.02140

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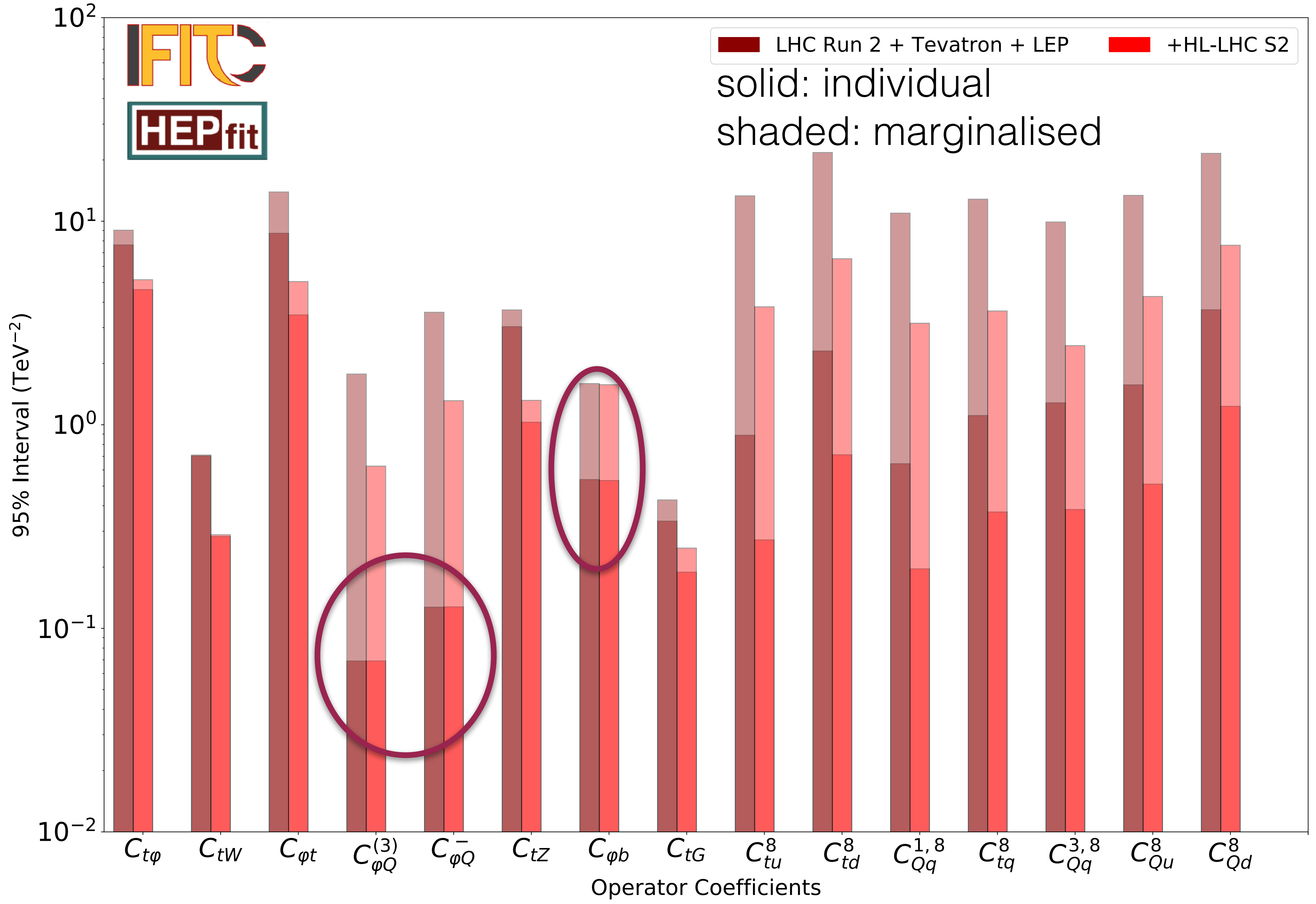

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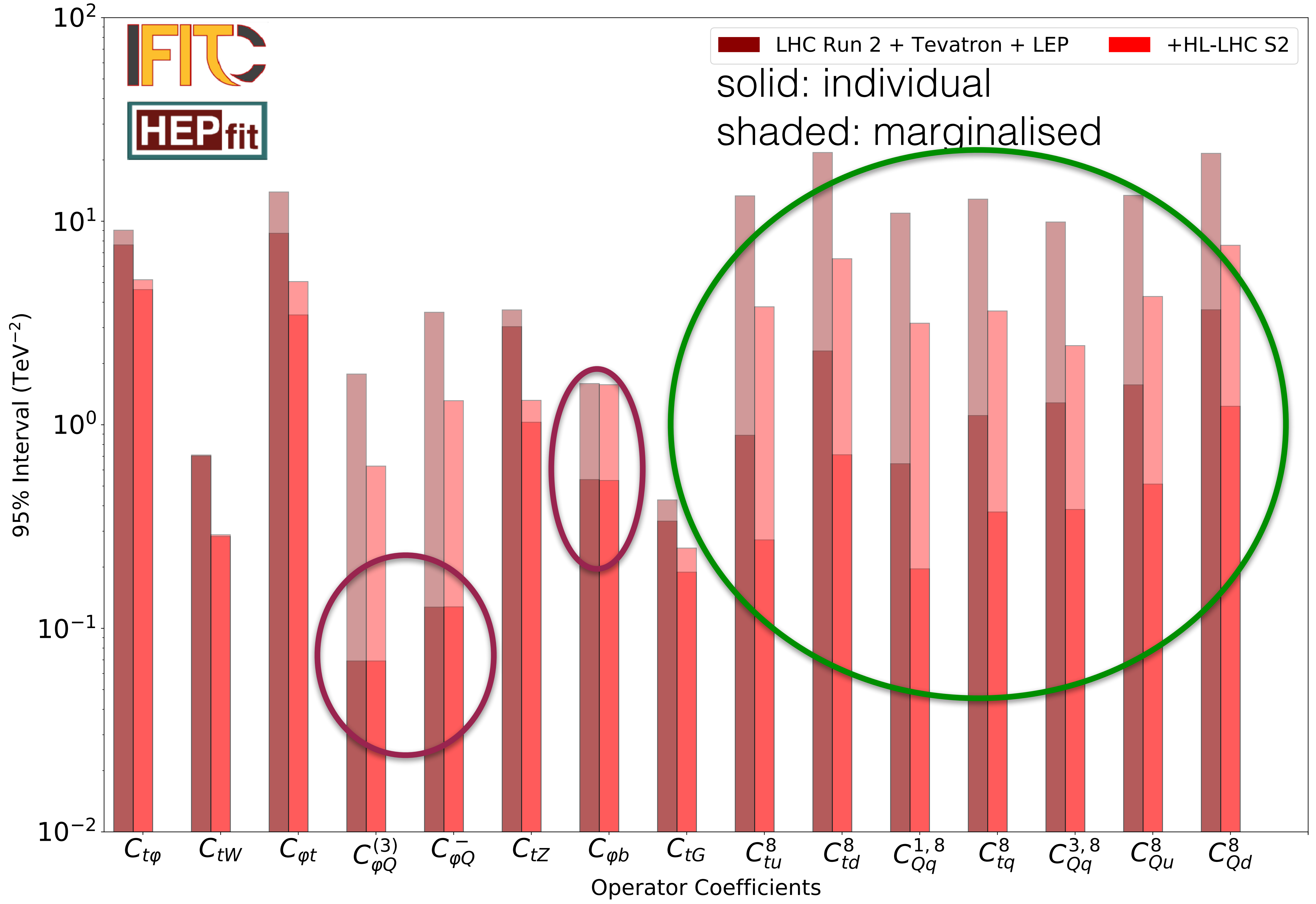

arXiv:2205.02140

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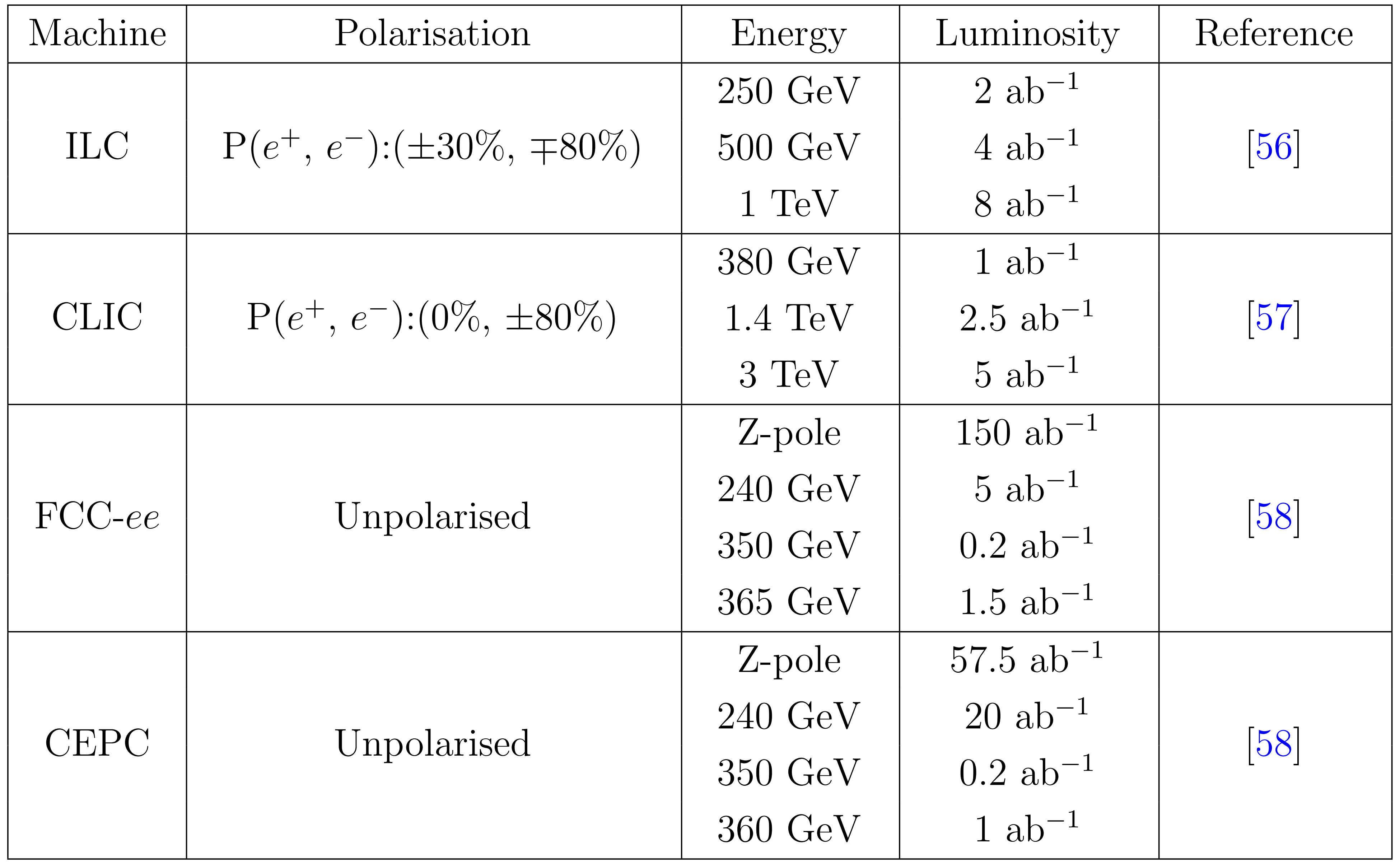
Difference in individual and marginalised limits persists at HL for 4-fermion operators

Top quarks at future lepton colliders

Scenarios considered:



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

Observables:

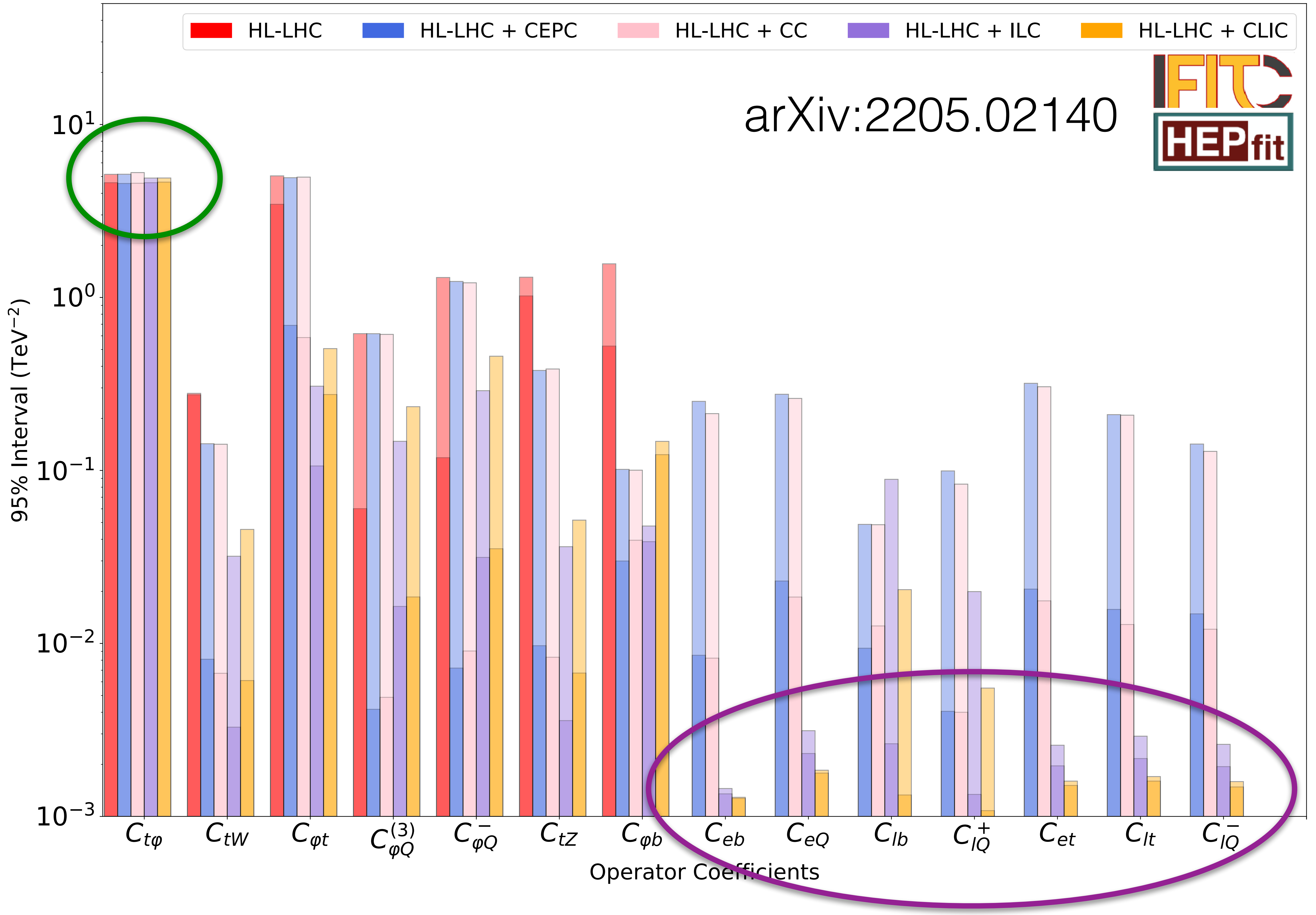
$e^+e^- \to b\bar{b}$: σ_b, A_{FB}^b
$e^+e^- \to t\bar{t}$: optimal observable constraints from arXiv:1807.02121 for ILC, CLIC, FCC-ee, CEPC

Optimal observables based on $WbWb$ distribution

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



No improvement for top Yukawa due to missing ttH (expect factor of two improvement for ILC1000)

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 ILC and CLIC (10^{-3})

Pushing the energy frontier

How about top quarks at the FCC-hh?

No full study but expect much better sensitivity:

LHC14

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

FCC-hh

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

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

Pushing the energy frontier

How about top quarks at the FCC-hh?

No full study but expect much better sensitivity:

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

FCC-hh

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

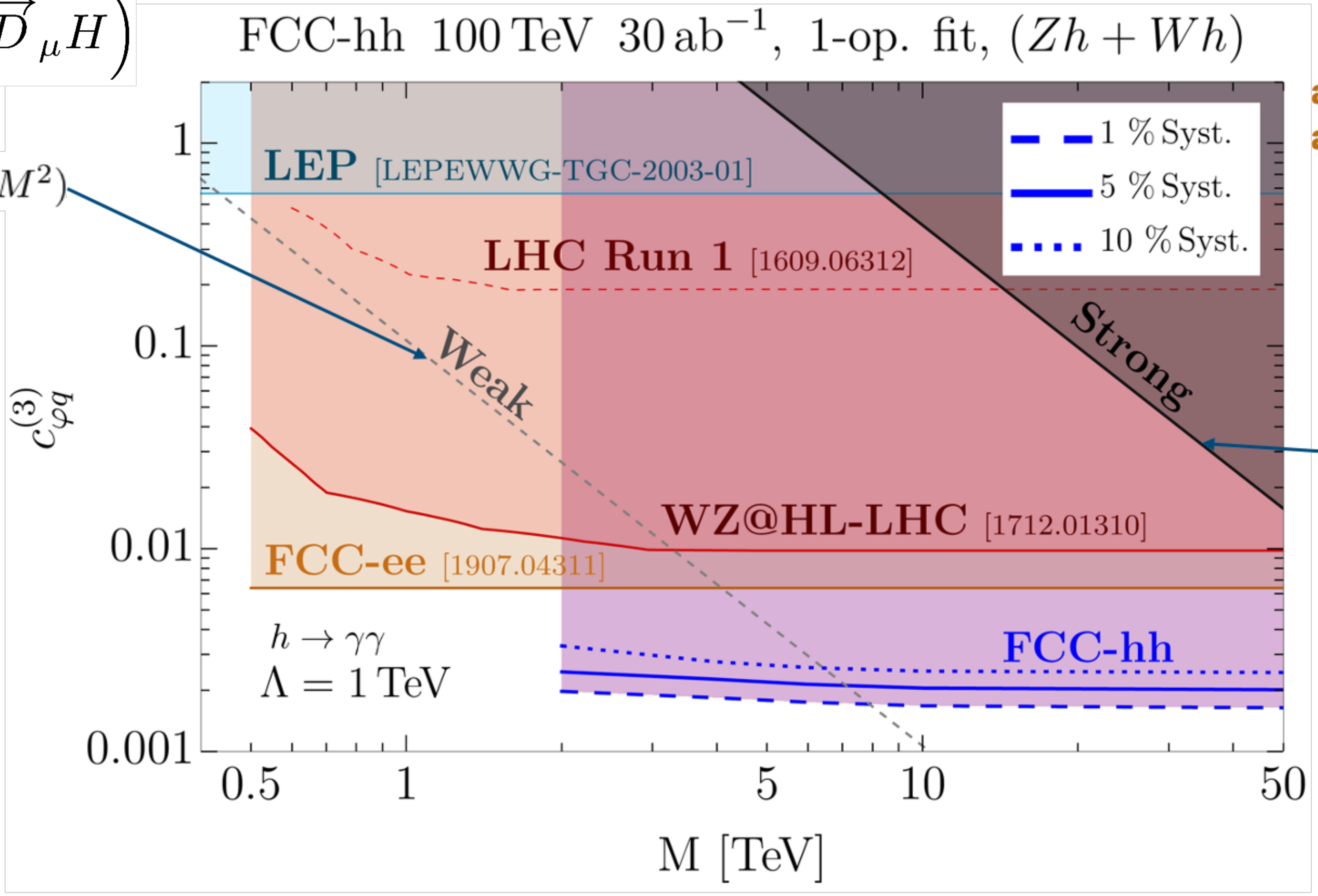
Expect bounds to improve from $\mathcal{O}(1\text{TeV}^{-2})$ down to $\mathcal{O}(0.1\text{TeV}^{-2})$

Where can the FCC-hh help?

Example 1: Vff and HVV couplings

Higgs+vector boson associated production:

$$\frac{c_{\varphi q}^{(3)}}{\Lambda^2}\left(\overline{Q}_L \sigma^a \gamma^\mu Q_L\right)\left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)$$



$c_{\varphi q}^{(3)} \sim g^2/(4M^2)$

$c_{\varphi q}^{(3)} \sim (4\pi)^2/(4M^2)$

arXiv 2004.06122
arXiv 2011.13941

Thanks to A. Rossia

Summary of bounds from Vh(→γγ)

$$\frac{c_{\varphi q}^{(3)}}{\Lambda^2}\left(\overline{Q}_L\sigma^a\gamma^\mu Q_L\right)\left(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H\right)$$

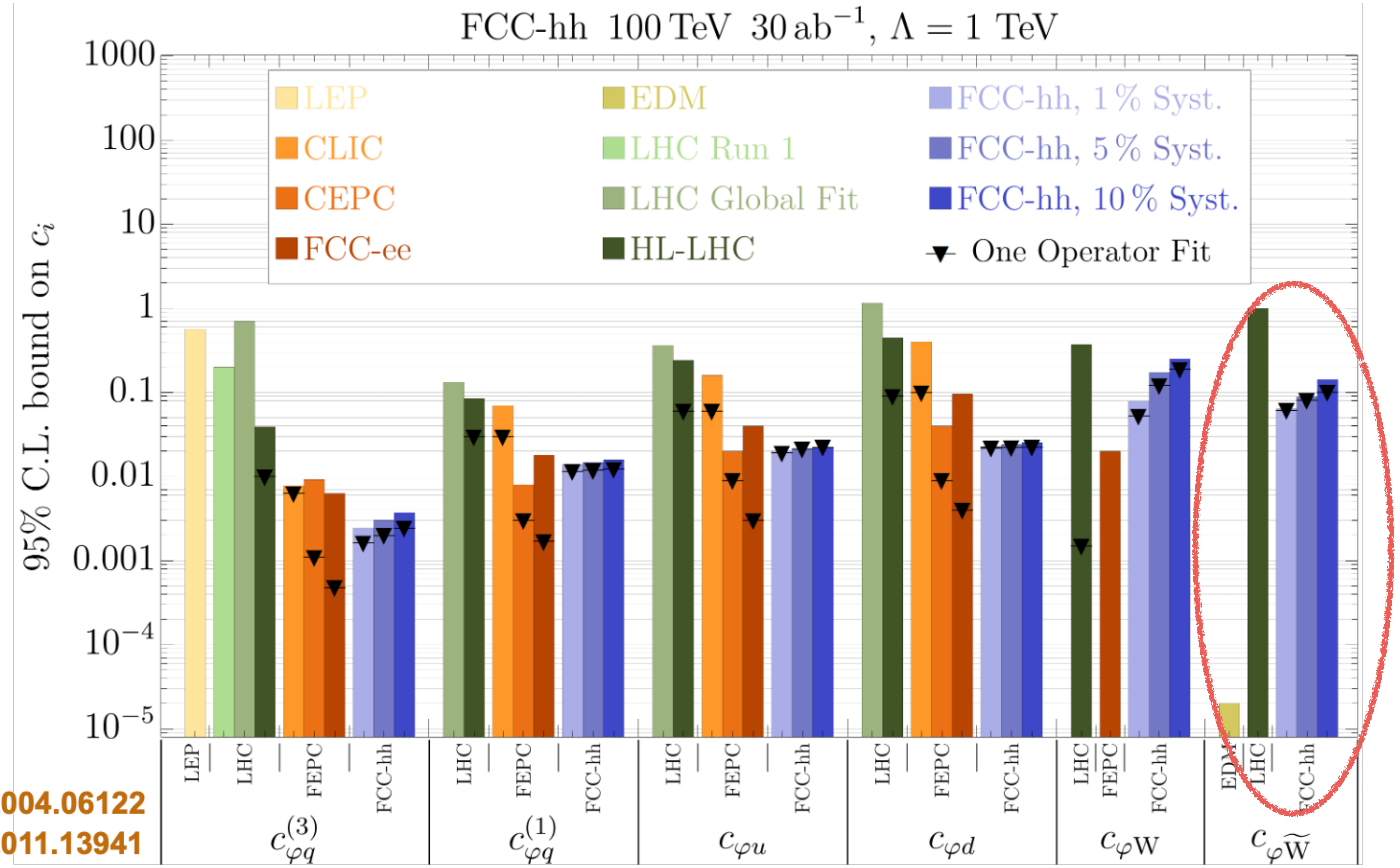
$$\frac{c_{\varphi q}^{(1)}}{\Lambda^2}\left(\overline{Q}_L\gamma^\mu Q_L\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi u}}{\Lambda^2}\left(\overline{u}_R\gamma^\mu u_R\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi d}}{\Lambda^2}\left(\overline{d}_R\gamma^\mu d_R\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right)$$

$$\frac{c_{\varphi \mathrm{W}}}{\Lambda^2}H^\dagger H\, W^{a,\mu\nu}W^a_{\mu\nu}$$

$$\frac{c_{\varphi \widetilde{\mathrm{W}}}}{\Lambda^2}H^\dagger H\, W^{a,\mu\nu}\widetilde{W}^a_{\mu\nu}$$



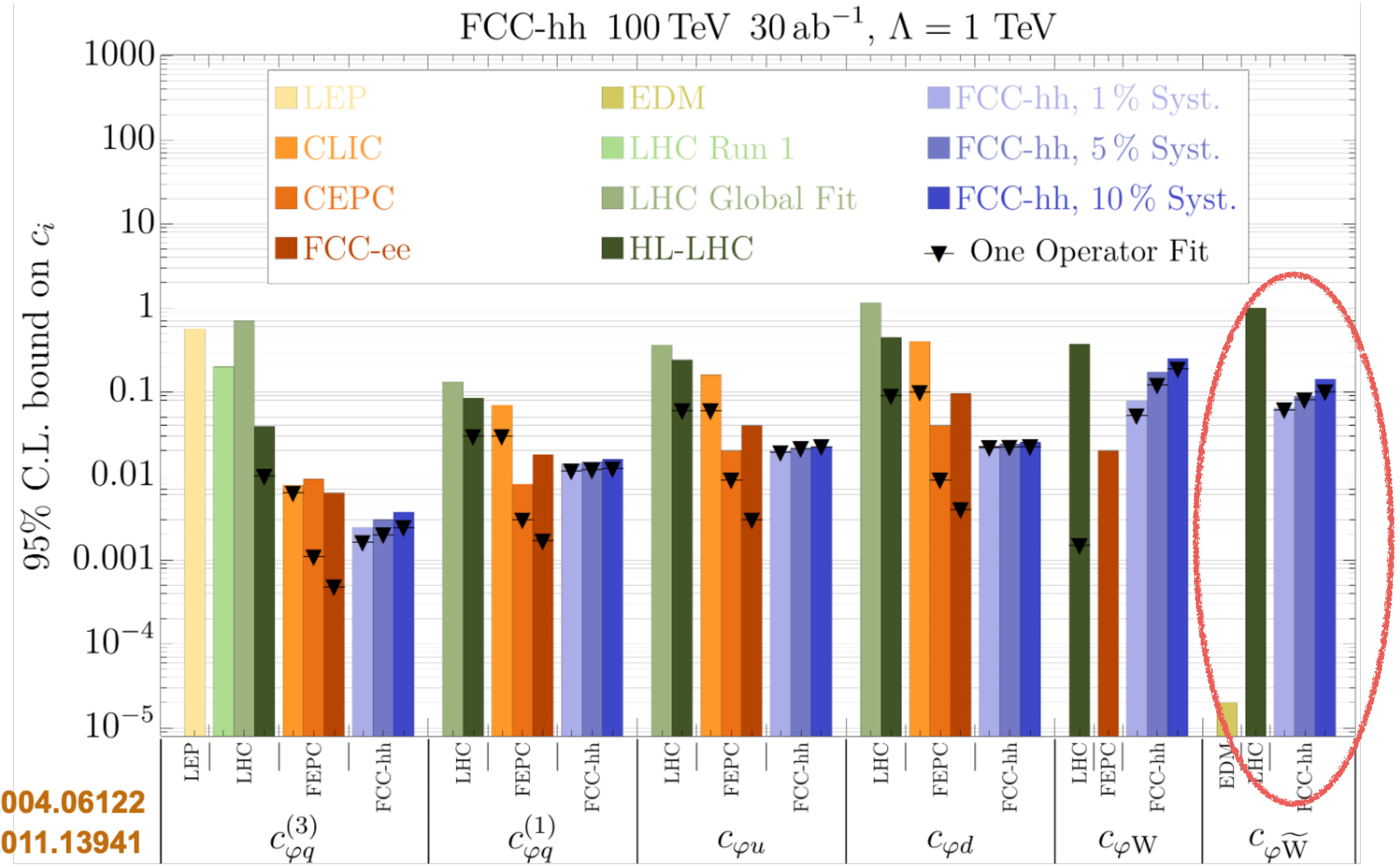
arXiv 2004.06122
arXiv 2011.13941

CP-violating:

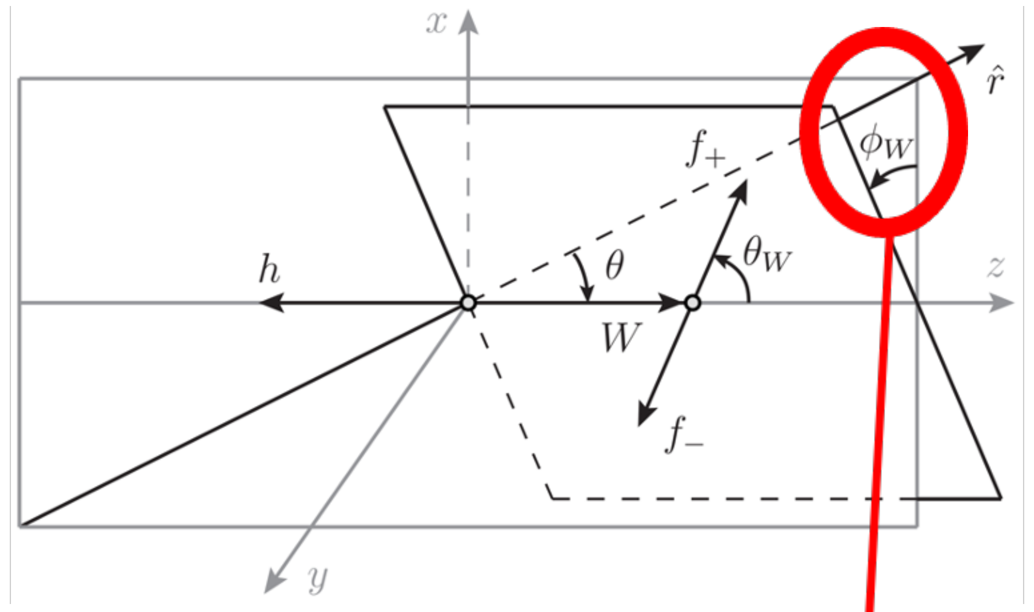
FCC can significantly improve HL-LHC bound!

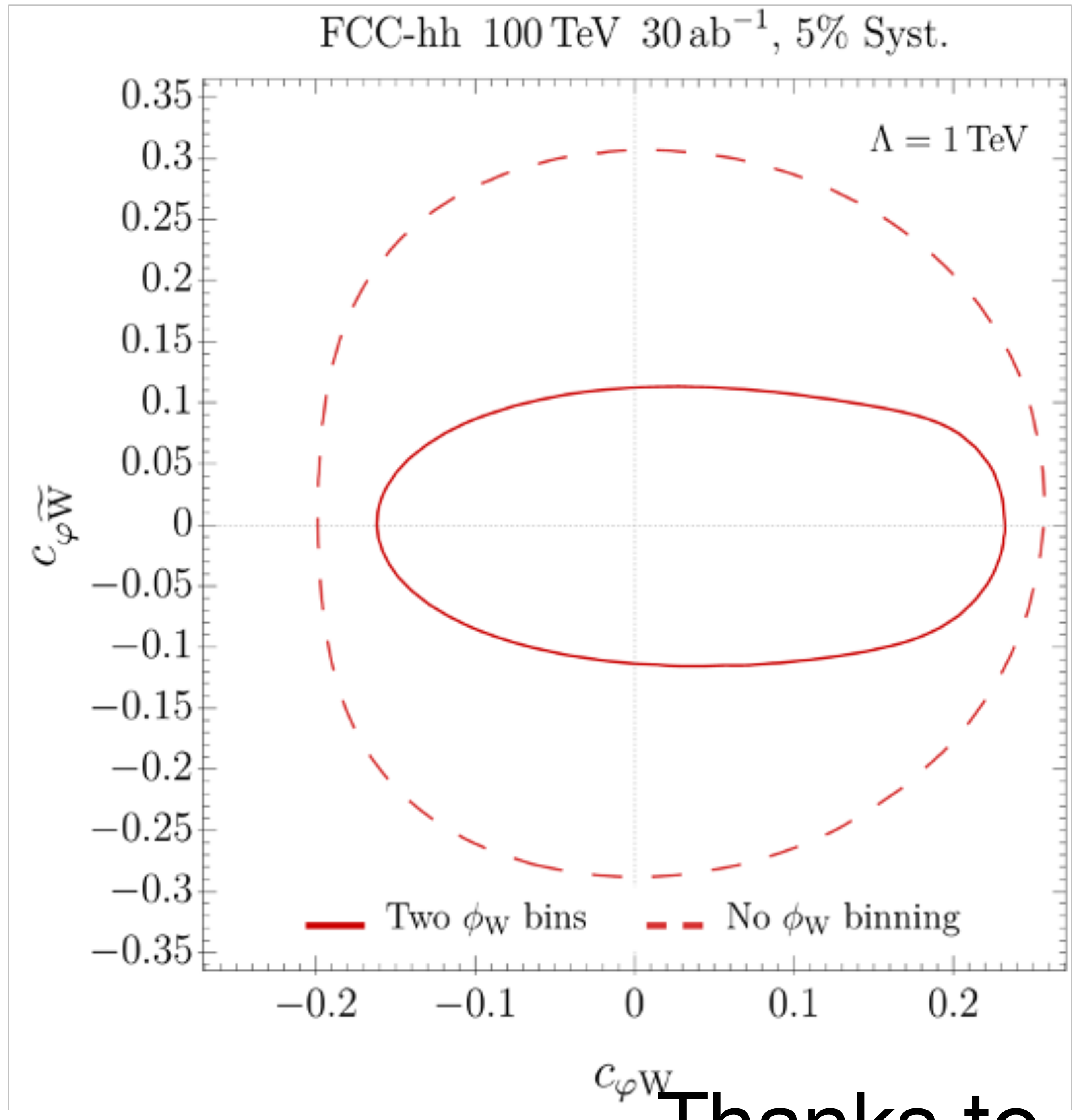
Thanks to A. Rossia

Angular binning probes CP-odd operators



arXiv 2004.06122
arXiv 2011.13941

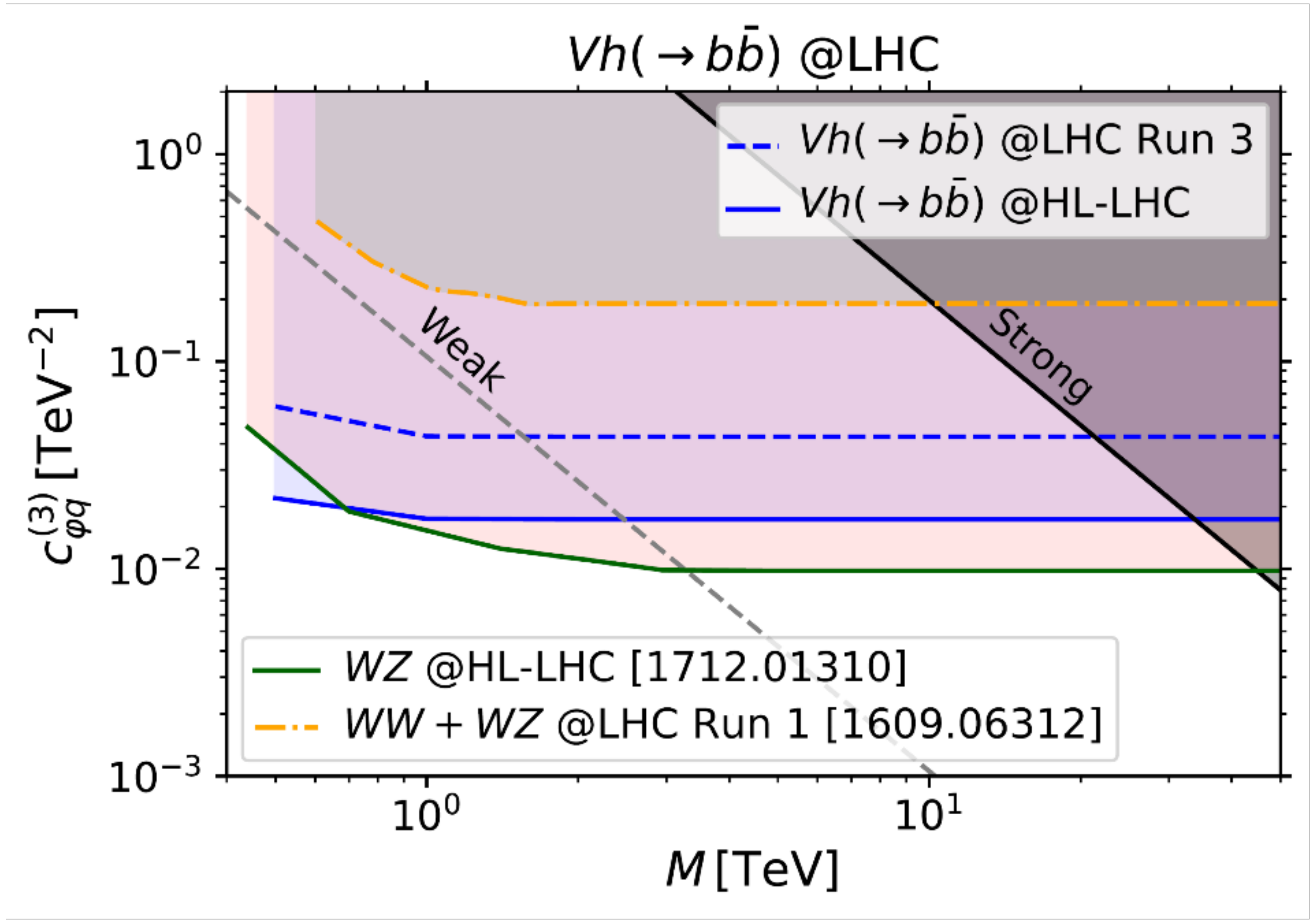


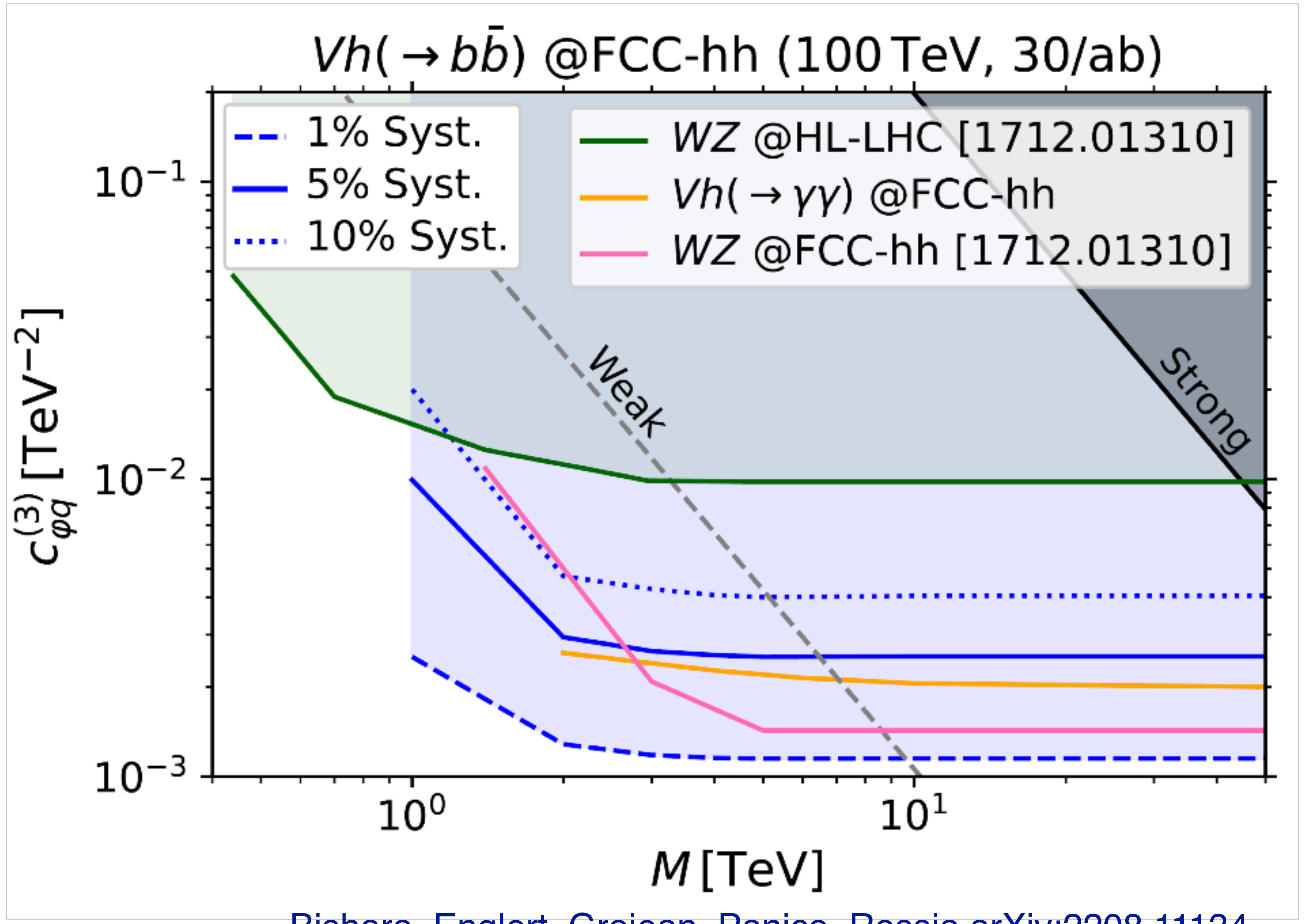


Thanks to A. Rossia

Combining different channels

$Vh(h \to b\bar{b})$ allows for a fairer LHC vs FCC-hh comparison





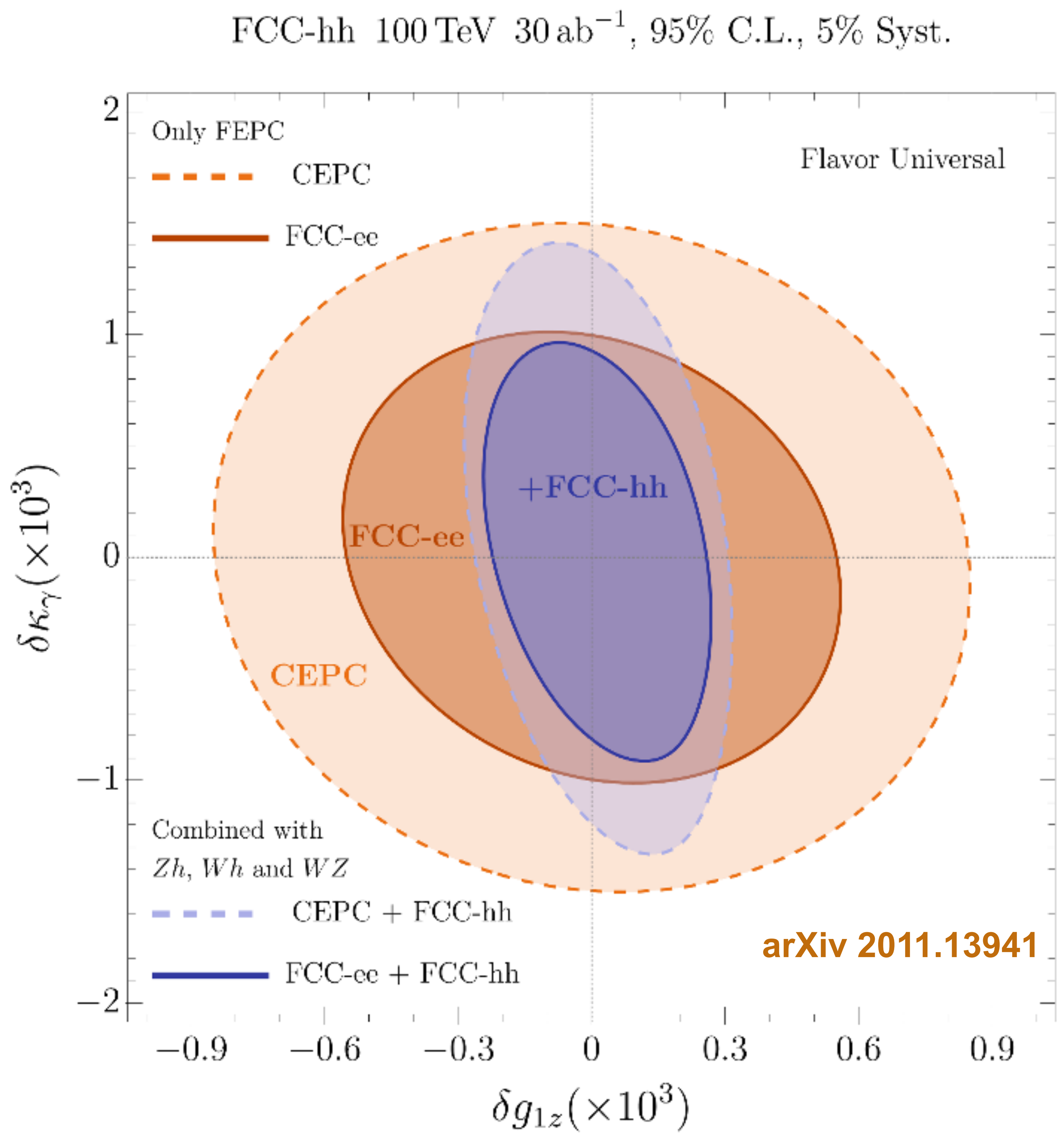
Bishara, Englert, Grojean, Panico, Rossia arXiv:2208.11134

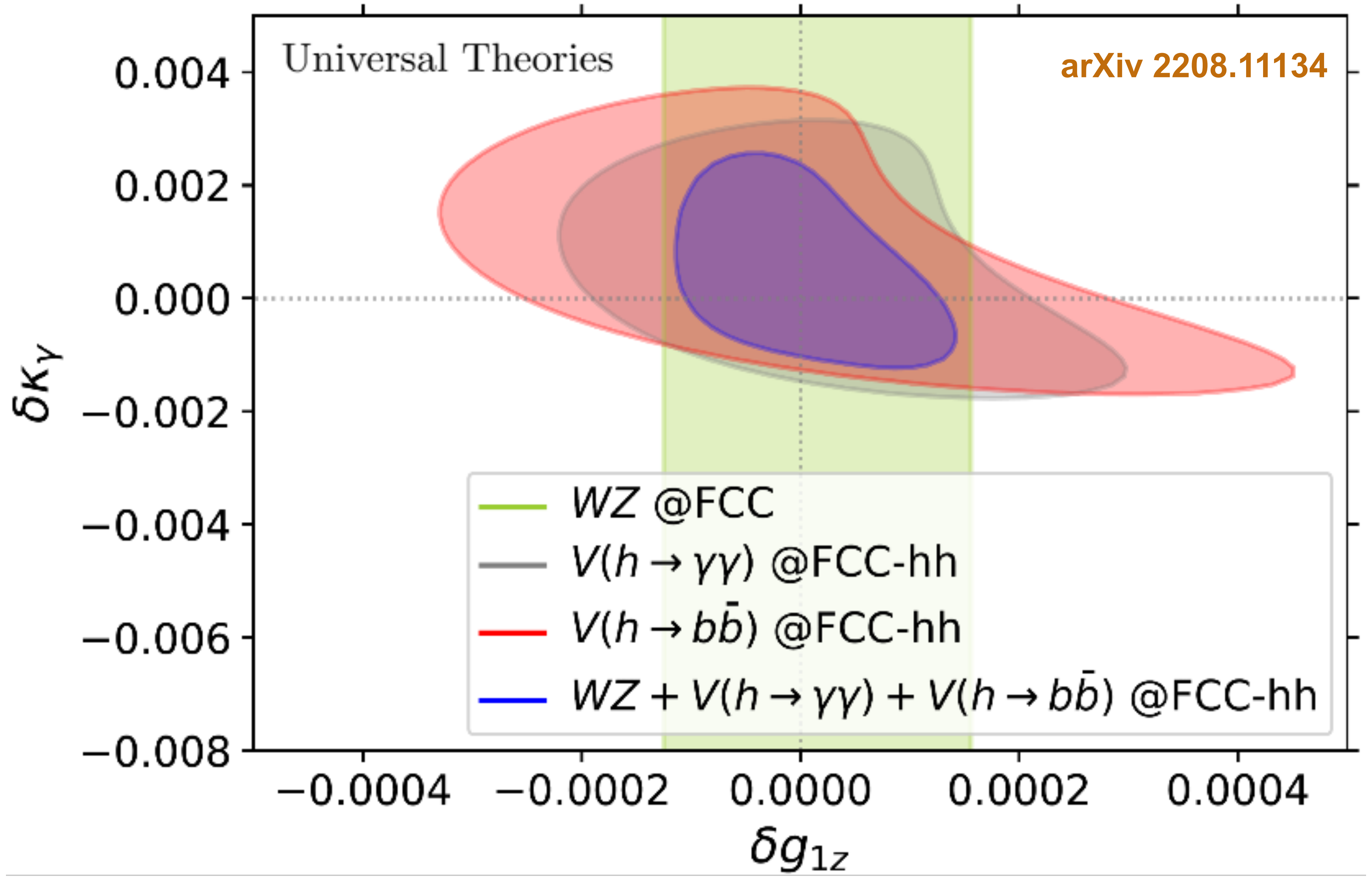
FCC-hh improves HL-LHC by a factor of 10

$h \to \gamma\gamma \approx h \to b\bar{b}$ @FCC-hh (syst. dependent)

Thanks to A. Rossia

Prospects for aTGC





FCC-(ee+hh) complementarity

Combining different channels is crucial

Where else can the FCC-hh help?

Example 2:4-heavy operators

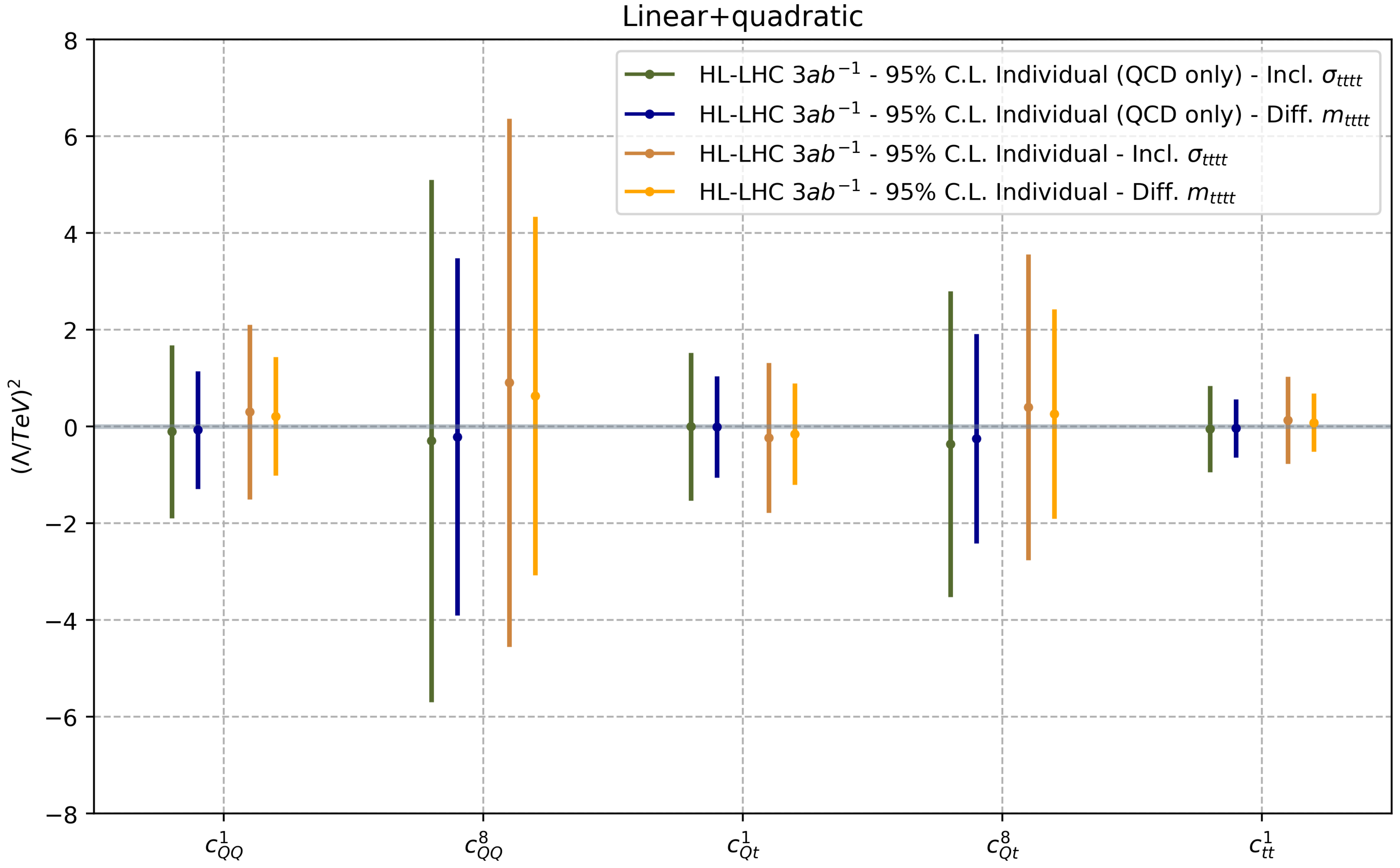
$$\mathcal{O}^{8}_{QQ} = (\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{Q}\gamma_{\mu}T^{A}Q)$$

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

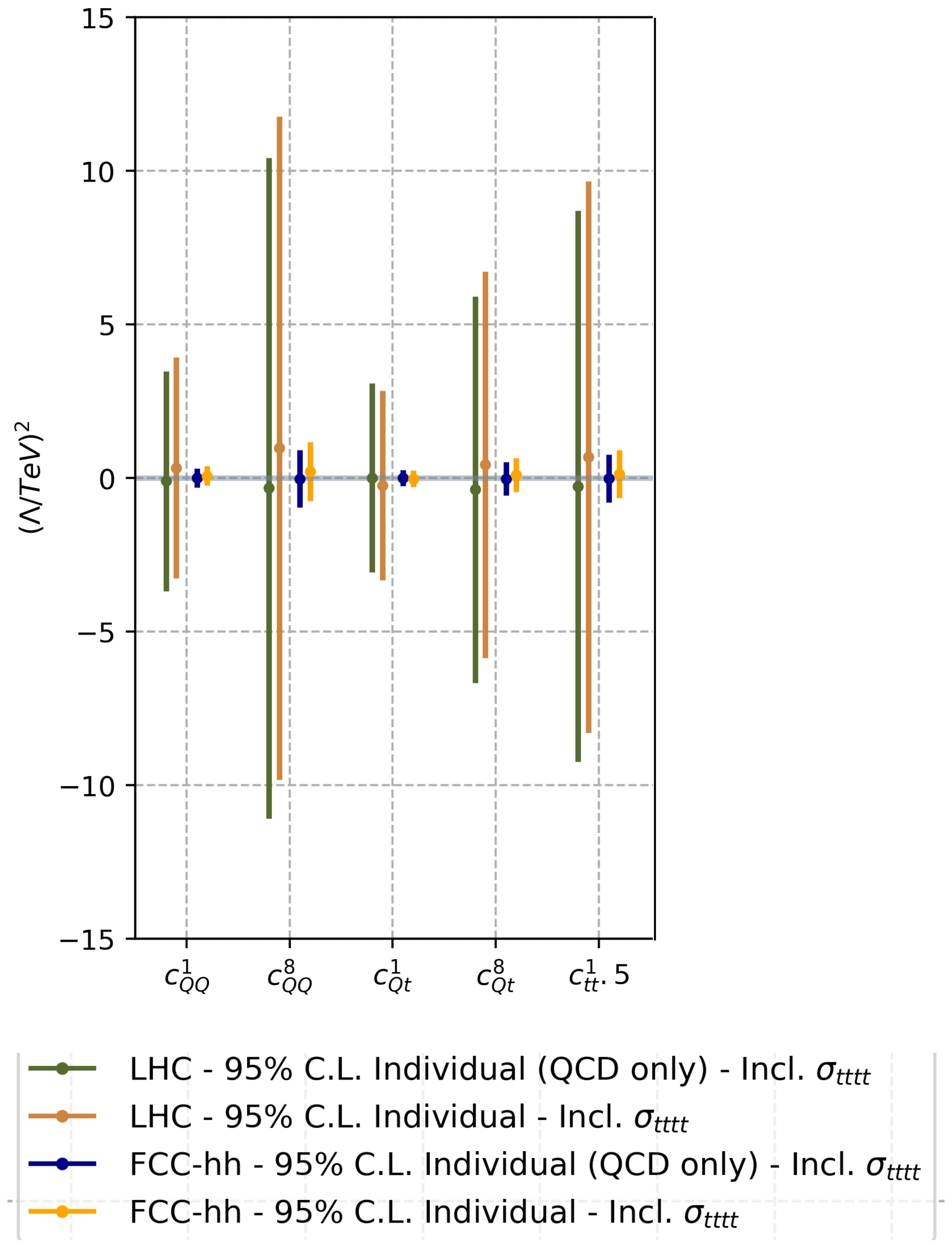
$$\mathcal{O}^{8}_{Qt} = (\bar{Q}\gamma^{\mu}T^{A}Q)(\bar{t}\gamma_{\mu}T^{A}t)$$

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

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



Aoude, El Faham, Maltoni, EV arXiv:2208.04962



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

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
- More studies and combinations very welcome