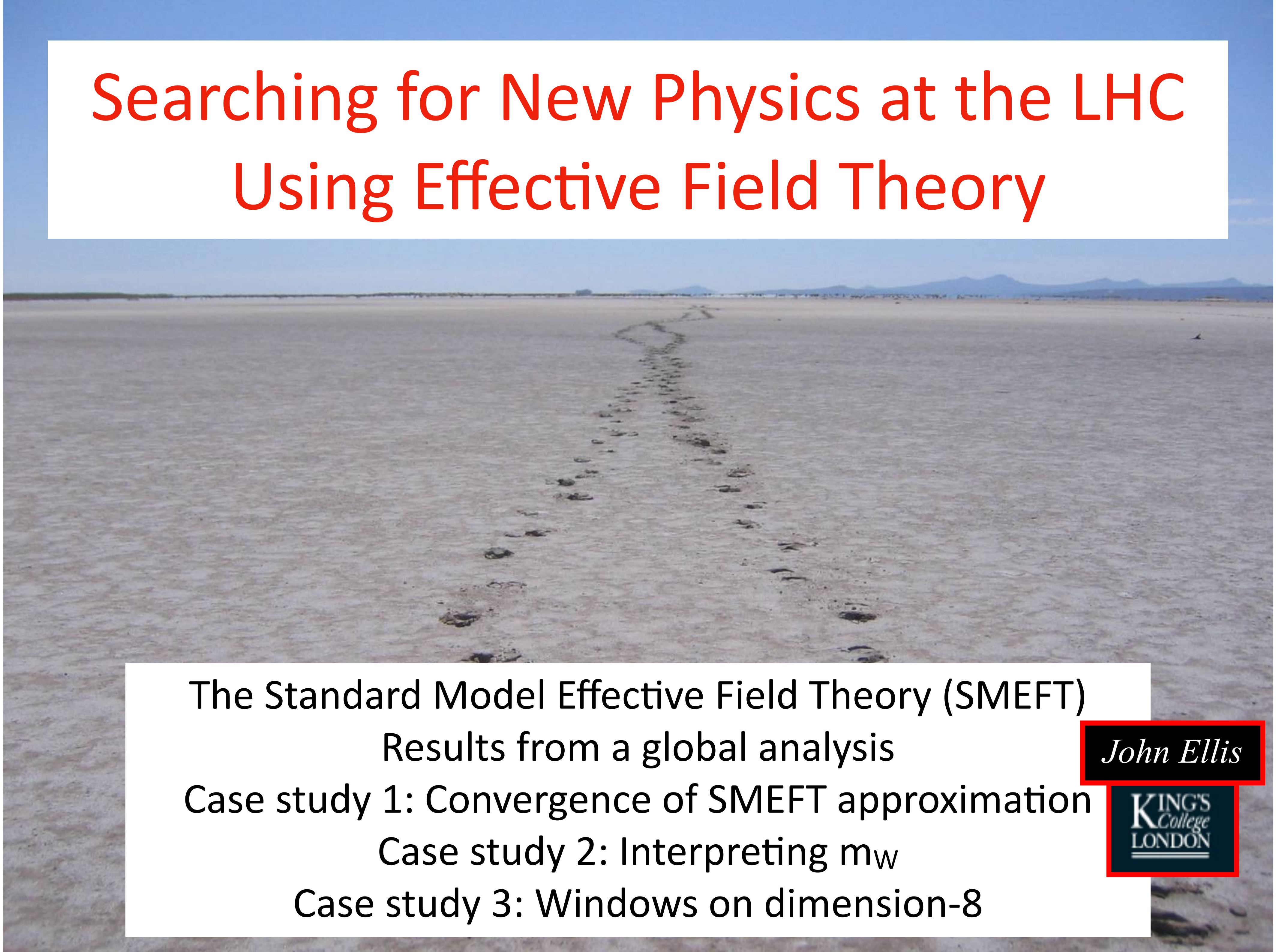
Searching for New Physics at the LHC Using Effective Field Theory



The Standard Model Effective Field Theory (SMEFT)
Results from a global analysis
Case study 1: Convergence of SMEFT approximation
Case study 2: Interpreting m_W
Case study 3: Windows on dimension-8

John Ellis
King's College London

Looking Beyond the Standard Model with the SMEFT

"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

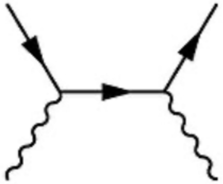
Who can exhaust the possibilities of their combination?"

Sun Tzu

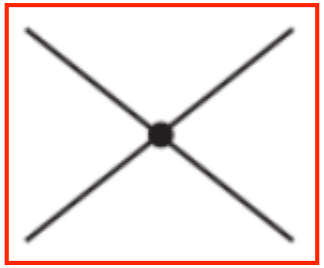
Effective Field Theories (EFTs)

a long and glorious History

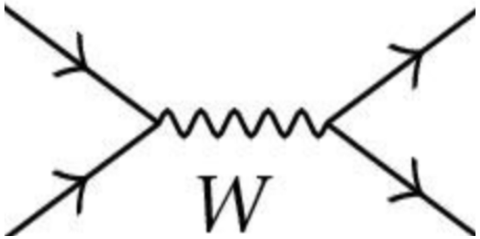
- 1930's: "Standard Model" of QED had d=4



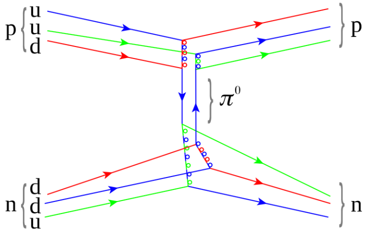
- **Fermi's four-fermion theory of the weak force**



- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?
- V-A ➔ massive vector bosons ➔ gauge theory



- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: (∂π∂π)ππ clue ➔ QCD

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Summary of Analysis Framework

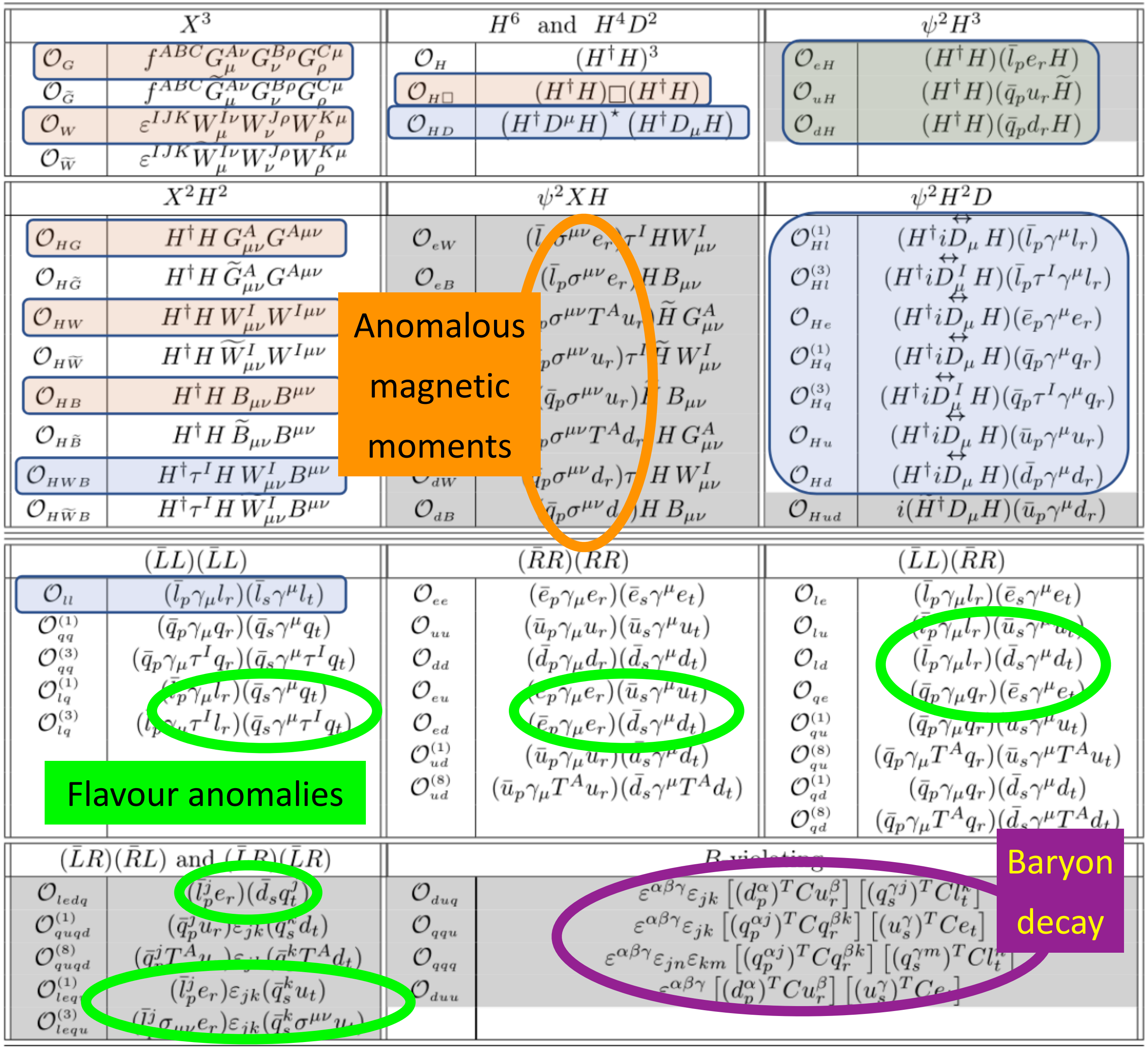
- Include all leading dimension-6 operators?

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2$ X $SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate SU(3)^5 symmetry
- Important when including top observables



X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$		$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$		$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$		$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$		
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$		
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$		
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$				

Anomalous magnetic moments

Flavour anomalies

Baryon decay

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

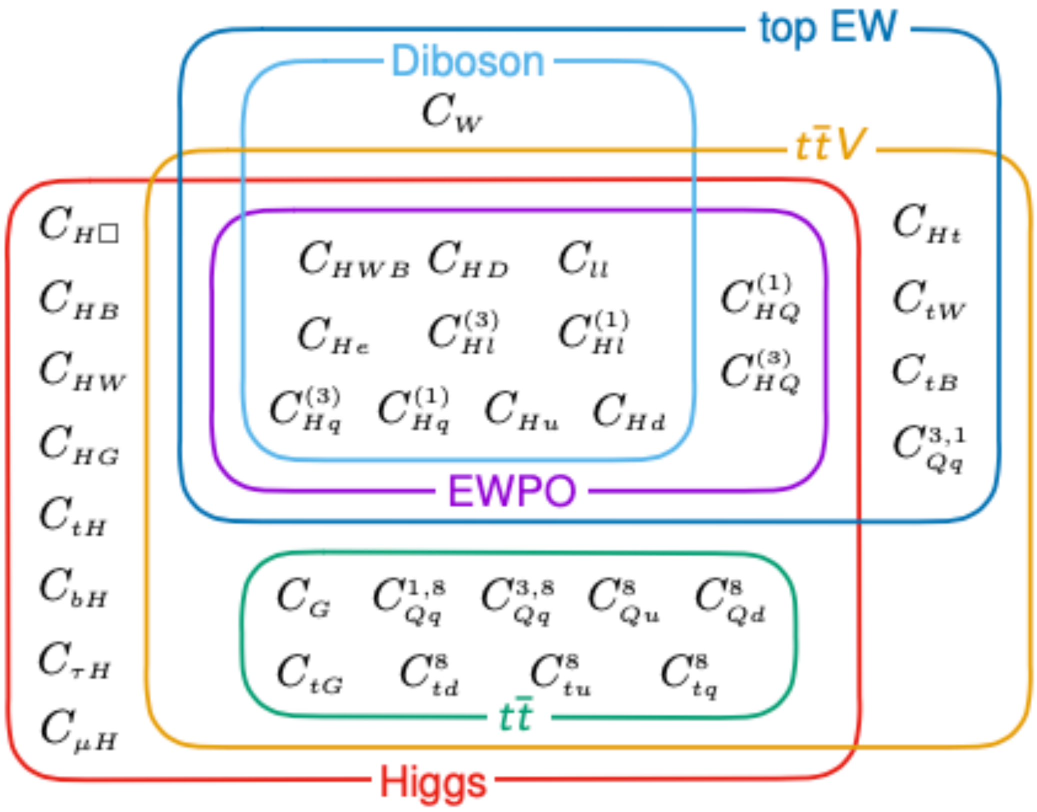
Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

341 measurements included in global analysis



top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

EWPO

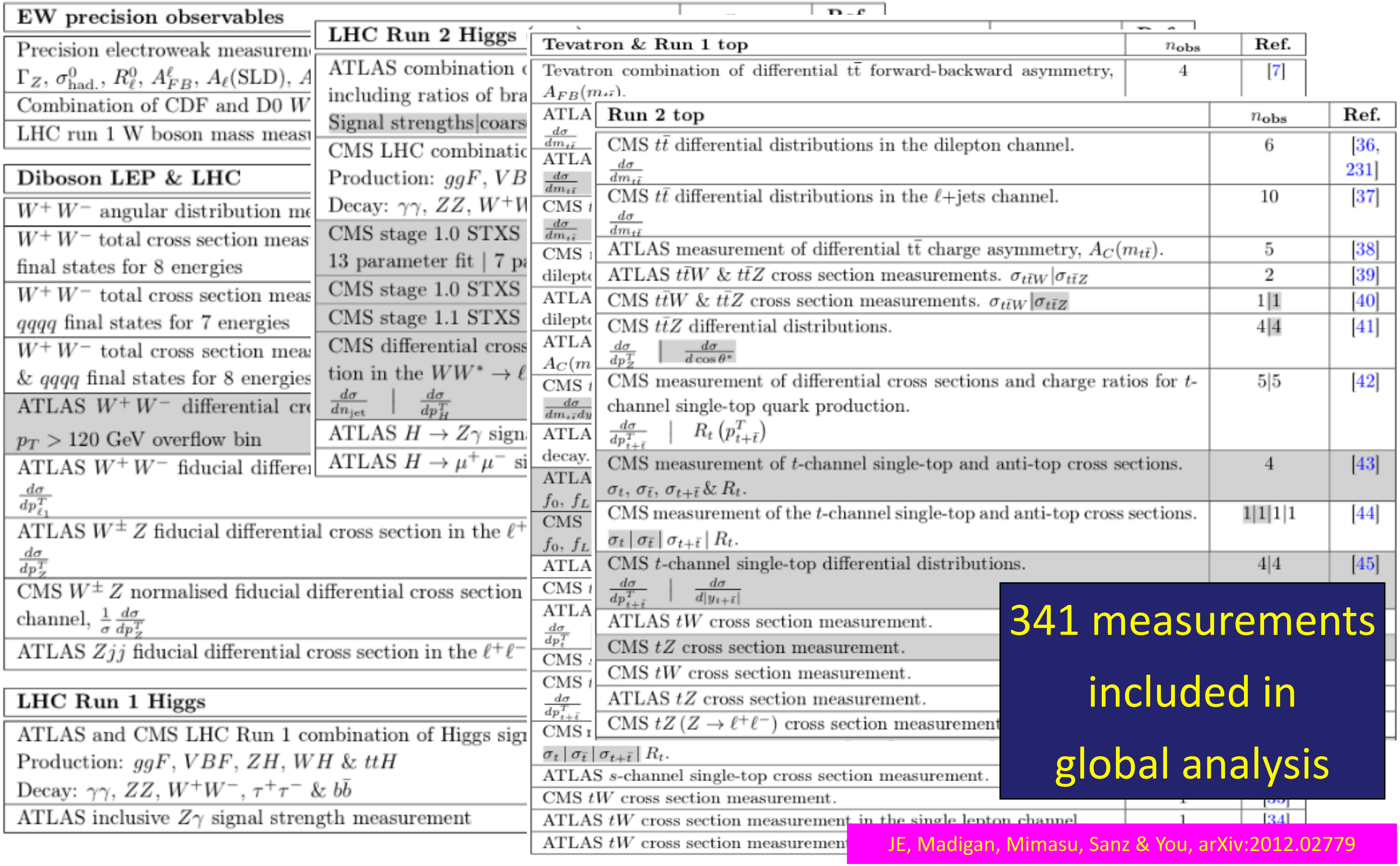
C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

$t\bar{t}$

Higgs

Data included in Global Fit



EW precision observables

Precision electroweak measurem
Γ_Z, $\sigma^0_{\mathrm{had.}}$, R^0_ℓ, A^ℓ_{FB}, A_ℓ(SLD), A
Combination of CDF and D0 W
LHC run 1 W boson mass meas

Diboson LEP & LHC

W^+W^- angular distribution me
W^+W^- total cross section meas
final states for 8 energies
W^+W^- total cross section meas
$qqqq$ final states for 7 energies
W^+W^- total cross section mea
& $qqqq$ final states for 8 energies
ATLAS W^+W^- differential cr
$p_T > 120$ GeV overflow bin
ATLAS W^+W^- fiducial differe
$\frac{d\sigma}{dp^T_{\ell_1}}$
ATLAS $W^\pm Z$ fiducial differential cross section in the ℓ^+
$\frac{d\sigma}{dp^T_Z}$
CMS $W^\pm Z$ normalised fiducial differential cross section
channel, $\frac{1}{\sigma}\frac{d\sigma}{dp^T_Z}$
ATLAS Zjj fiducial differential cross section in the $\ell^+\ell^-$

LHC Run 1 Higgs

ATLAS and CMS LHC Run 1 combination of Higgs sig
Production: ggF, VBF, ZH, WH & ttH
Decay: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ & $b\bar{b}$
ATLAS inclusive $Z\gamma$ signal strength measurement

LHC Run 2 Higgs

ATLAS combination
including ratios of bra
Signal strengths|coars
CMS LHC combinatio
Production: ggF, VB
Decay: $\gamma\gamma$, ZZ, W^+W
CMS stage 1.0 STXS
13 parameter fit | 7 pa
CMS stage 1.0 STXS
CMS stage 1.1 STXS
CMS differential cross
tion in the $WW^* \to \ell$
$\frac{d\sigma}{dn_{\mathrm{jet}}}$ | $\frac{d\sigma}{dp^T_H}$
ATLAS $H \to Z\gamma$ sign
ATLAS $H \to \mu^+\mu^-$ si

Tevatron & Run 1 top	n_{obs}	**Ref.**
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLA $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS t $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS dilept		
ATLA dilept		
ATLA $A_C(m$		
CMS t $\frac{d\sigma}{dm_{t\bar{t}}dy}$		
ATLA decay.		
ATLA f_0, f_L		
CMS f_0, f_L		
ATLA		
CMS t		
ATLA $\frac{d\sigma}{dp^T_t}$		
CMS s		
CMS t $\frac{d\sigma}{dp^T_{t+\bar{t}}}$		
CMS $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.		
ATLAS s-channel single-top cross section measurement.		
CMS tW cross section measurement.		
ATLAS tW cross section measurement in the single lepton channel.	1	[34]
ATLAS tW cross section measuremen		

Run 2 top	n_{obs}	**Ref.**
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W} \mid \sigma_{t\bar{t}Z}$	1|1	[40]
CMS $t\bar{t}Z$ differential distributions. $\frac{d\sigma}{dp^T_Z}$ | $\frac{d\sigma}{d\cos\theta^*}$	4|4	[41]
CMS measurement of differential cross sections and charge ratios for t-channel single-top quark production. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $R_t\,(p^T_{t+\bar{t}})$	5|5	[42]
CMS measurement of t-channel single-top and anti-top cross sections. σ_t, $\sigma_{\bar{t}}$, $\sigma_{t+\bar{t}}$ & R_t.	4	[43]
CMS measurement of the t-channel single-top and anti-top cross sections. $\sigma_t \mid \sigma_{\bar{t}} \mid \sigma_{t+\bar{t}} \mid R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar{t}}}$ | $\frac{d\sigma}{d\lvert y_{t+\bar{t}}\rvert}$	4|4	[45]
ATLAS tW cross section measurement.		
CMS tZ cross section measurement.		
CMS tW cross section measurement.		
ATLAS tZ cross section measurement.		
CMS $tZ\,(Z \to \ell^+\ell^-)$ cross section measurement		

341 measurements included in global analysis

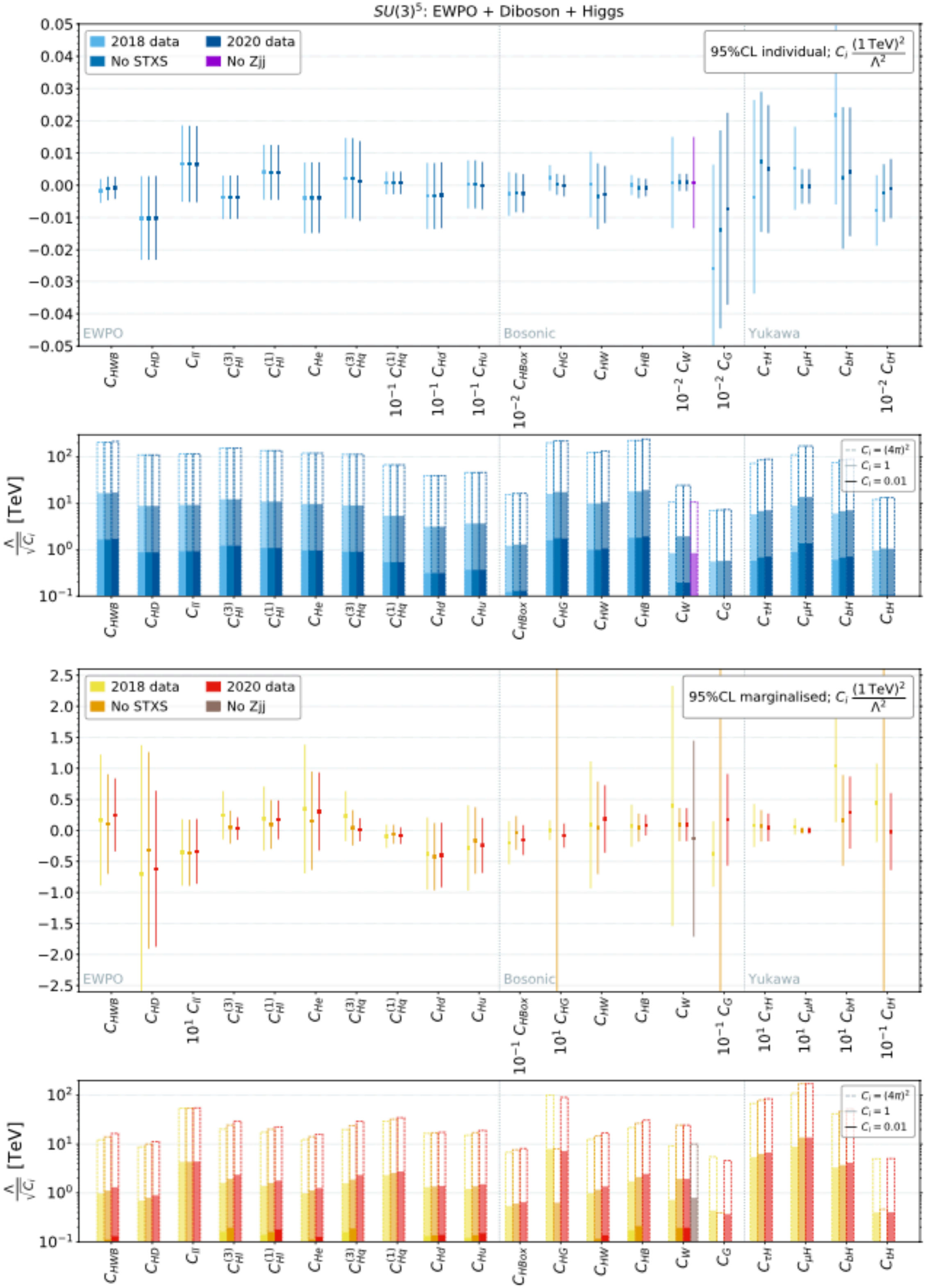
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

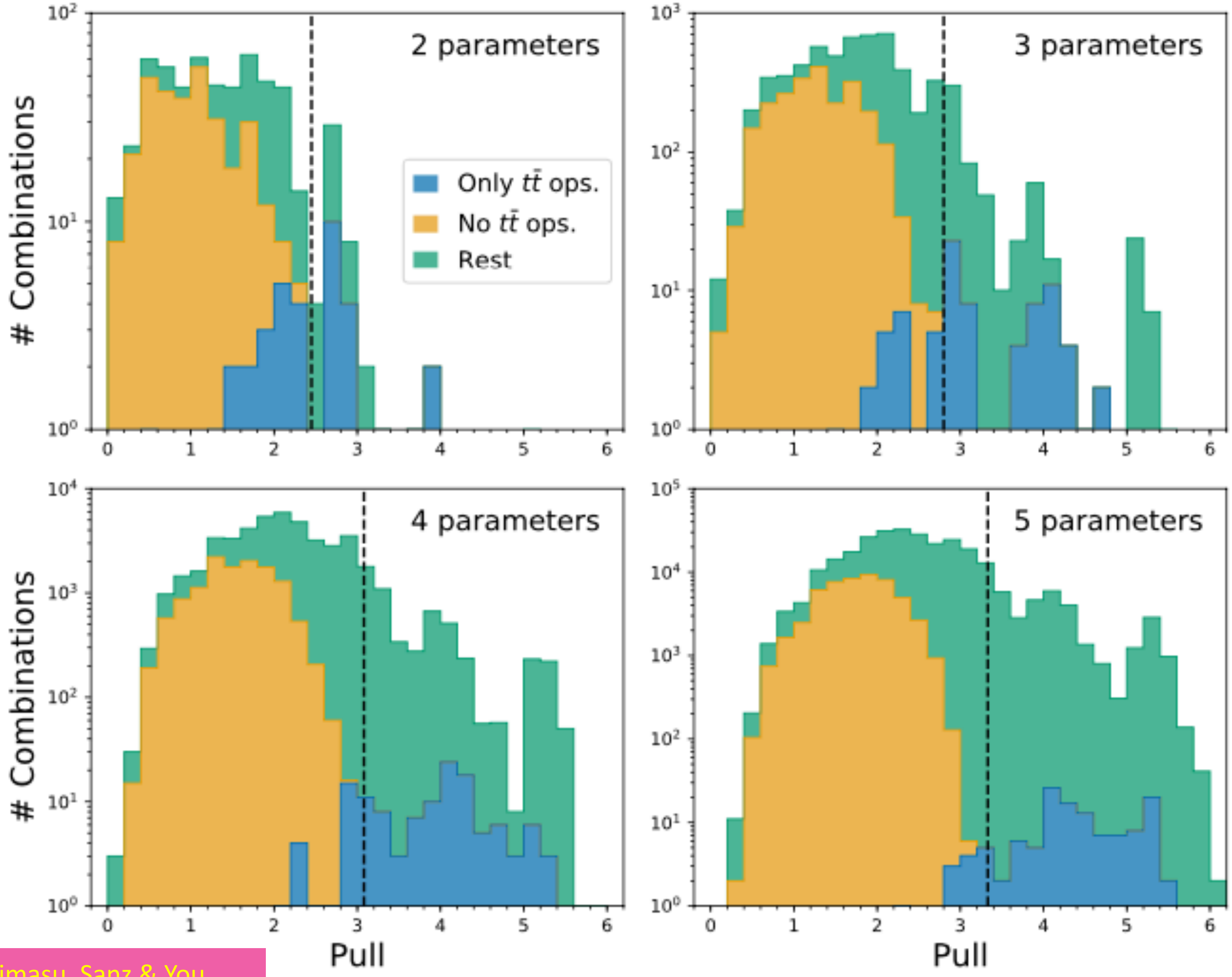
No significant deviations from SM

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779



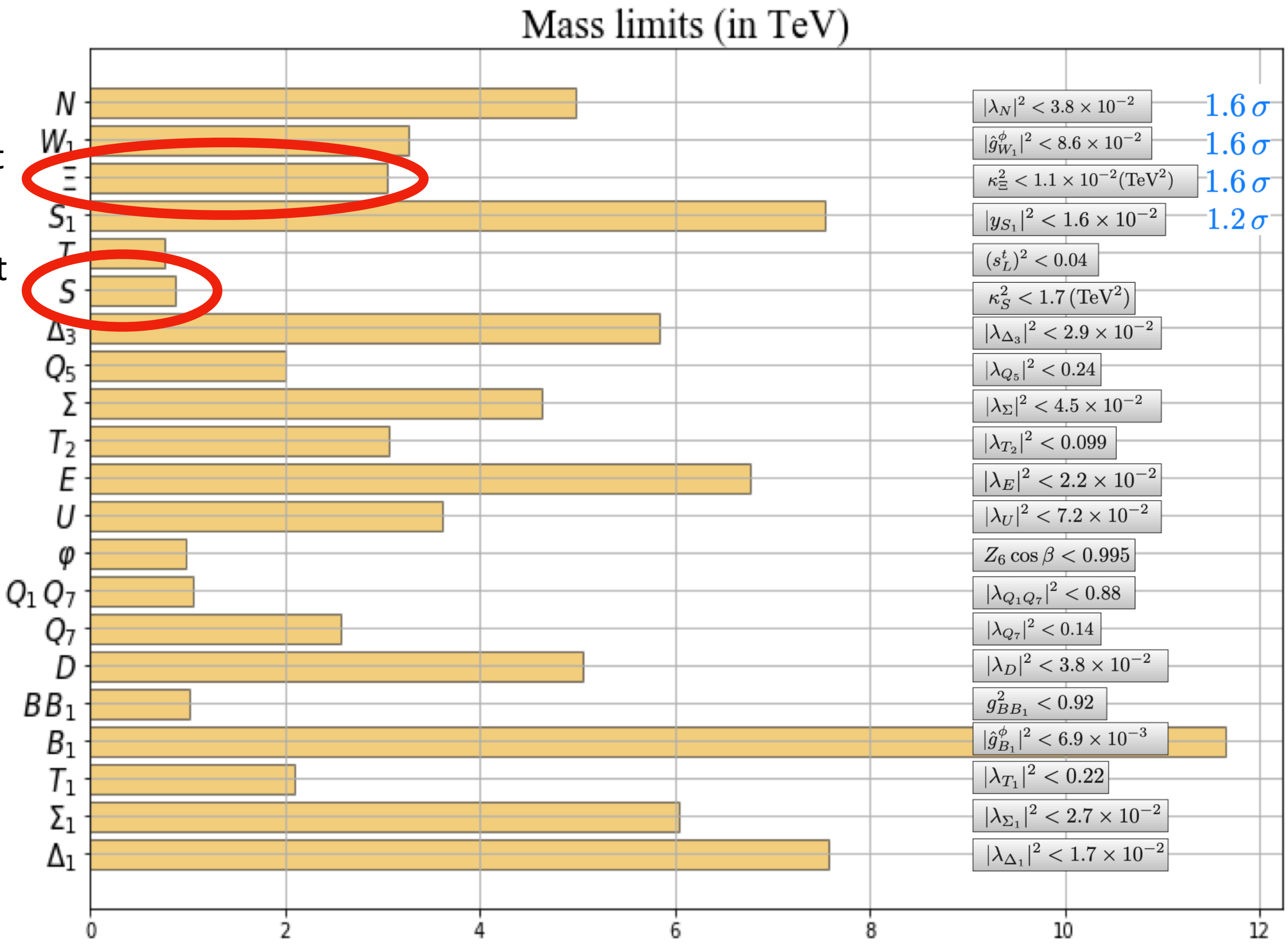
Model-Independent BSM Survey

Switch on random subsets of 2, 3, 4 or 5 operators



JE, Madigan, Mimasu, Sanz & You,
arXiv:2012.02779

Single-Field Extensions of the Standard Model



Triplet scalar

Singlet scalar

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

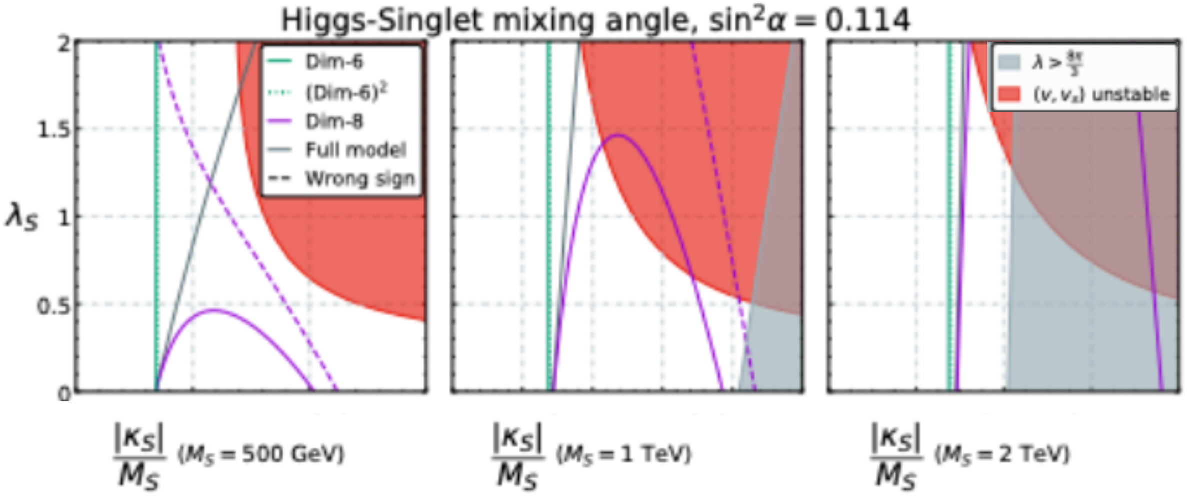
Check on Reliability of SMEFT

Singlet Scalar Field:

dimension-6, -8 and full model

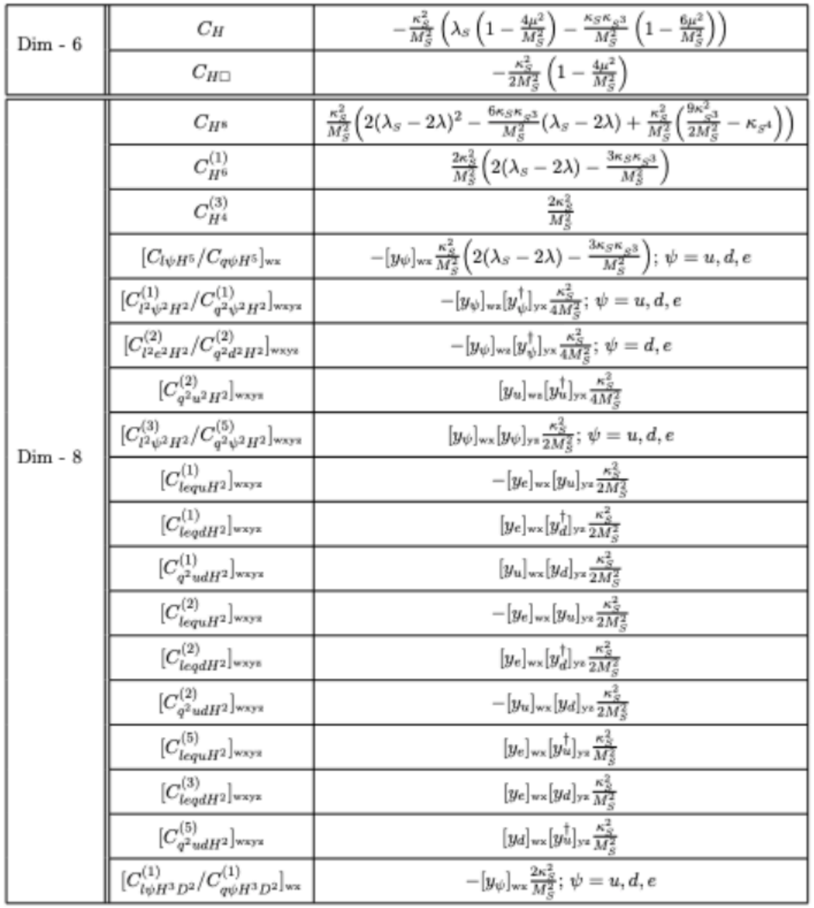
$$\mathcal{L}_s = \frac{1}{2}(D_\mu S)(D^\mu S) - \frac{1}{2}M_S^2 SS - (\kappa_s)SH^\dagger H - (\lambda_s)SSH^\dagger H - \kappa_{S^3}SSS - (\kappa_{S^4})SSSS$$

Main effect via singlet mixing with Higgs:
good convergence for $M_S > 500\text{GeV}$


Higgs-Singlet mixing angle, $\sin^2\alpha = 0.114$

JE, Mimasu & Zampedri, arXiv:2304.06663

SMEFT at dimension-6, -8



Dim - 6	C_H	$-\frac{\kappa_S^2}{M_S^2}\left(\lambda_S\left(1-\frac{4\mu^2}{M_S^2}\right)-\frac{\kappa_S\kappa_{S^3}}{M_S^2}\left(1-\frac{6\mu^2}{M_S^2}\right)\right)$
	$C_{H\Box}$	$-\frac{\kappa_S^2}{2M_S^2}\left(1-\frac{4\mu^2}{M_S^2}\right)$
Dim - 8	C_{H^8}	$\frac{\kappa_S^2}{M_S^2}\left(2(\lambda_S-2\lambda)^2-\frac{6\kappa_S\kappa_{S^3}}{M_S^2}(\lambda_S-2\lambda)+\frac{\kappa_S^2}{M_S^2}\left(\frac{9\kappa_{S^3}^2}{2M_S^2}-\kappa_{S^4}\right)\right)$
	$C_{H^6}^{(1)}$	$\frac{2\kappa_S^2}{M_S^2}\left(2(\lambda_S-2\lambda)-\frac{3\kappa_S\kappa_{S^3}}{M_S^2}\right)$
	$C_{H^4}^{(3)}$	$\frac{2\kappa_S^2}{M_S^2}$
	$[C_{l\psi H^5}/C_{q\psi H^5}]_{\rm wx}$	$-[y_\psi]_{\rm wx}\frac{\kappa_S^2}{M_S^2}\left(2(\lambda_S-2\lambda)-\frac{3\kappa_S\kappa_{S^3}}{M_S^2}\right);\ \psi=u,d,e$
	$[C_{l^2\psi^2H^2}^{(1)}/C_{q^2\psi^2H^2}^{(1)}]_{\rm wxyz}$	$-[y_\psi]_{\rm wx}[y_\psi^\dagger]_{\rm yx}\frac{\kappa_S^2}{4M_S^2};\ \psi=u,d,e$
	$[C_{l^2e^2H^2}^{(2)}/C_{q^2d^2H^2}^{(2)}]_{\rm wxyz}$	$-[y_\psi]_{\rm wz}[y_\psi^\dagger]_{\rm yx}\frac{\kappa_S^2}{4M_S^2};\ \psi=d,e$
	$[C_{q^2u^2H^2}^{(2)}]_{\rm wxyz}$	$[y_{\rm u}]_{\rm wz}[y_{\rm u}^\dagger]_{\rm yx}\frac{\kappa_S^2}{4M_S^2}$
	$[C_{l^2\psi^2H^2}^{(3)}/C_{q^2\psi^2H^2}^{(5)}]_{\rm wxyz}$	$[y_\psi]_{\rm wx}[y_\psi]_{\rm yz}\frac{\kappa_S^2}{2M_S^2};\ \psi=u,d,e$
	$[C_{lequH^2}^{(1)}]_{\rm wxyz}$	$-[y_e]_{\rm wx}[y_{\rm u}]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{leqdH^2}^{(1)}]_{\rm wxyz}$	$[y_e]_{\rm wx}[y_d^\dagger]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{q^2udH^2}^{(1)}]_{\rm wxyz}$	$[y_{\rm u}]_{\rm wx}[y_d]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{lequH^2}^{(2)}]_{\rm wxyz}$	$-[y_e]_{\rm wx}[y_{\rm u}]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{leqdH^2}^{(2)}]_{\rm wxyz}$	$[y_e]_{\rm wx}[y_d^\dagger]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{q^2udH^2}^{(2)}]_{\rm wxyz}$	$-[y_{\rm u}]_{\rm wx}[y_d]_{\rm yz}\frac{\kappa_S^2}{2M_S^2}$
	$[C_{lequH^2}^{(5)}]_{\rm wxyz}$	$[y_e]_{\rm wx}[y_{\rm u}^\dagger]_{\rm yz}\frac{\kappa_S^2}{M_S^2}$
	$[C_{leqdH^2}^{(3)}]_{\rm wxyz}$	$[y_e]_{\rm wx}[y_d]_{\rm yz}\frac{\kappa_S^2}{M_S^2}$
	$[C_{q^2udH^2}^{(5)}]_{\rm wxyz}$	$[y_d]_{\rm wx}[y_{\rm u}^\dagger]_{\rm yz}\frac{\kappa_S^2}{M_S^2}$
	$[C_{l\psi H^3D^2}^{(1)}/C_{q\psi H^3D^2}^{(1)}]_{\rm wx}$	$-[y_\psi]_{\rm wx}\frac{2\kappa_S^2}{M_S^2};\ \psi=u,d,e$

Check on Reliability of SMEFT

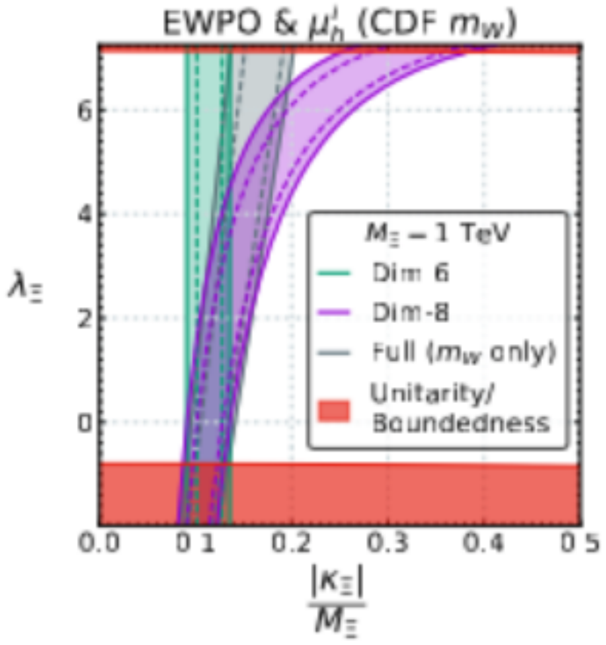
Triplet Scalar Field:

dimension-6, -8 and full model

$$\mathcal{L}_\Xi = \frac{1}{2}(D_\mu \Xi^a)(D^\mu \Xi^a) - \frac{1}{2}M_\Xi^2(\Xi^a\Xi^a) - \kappa_\Xi H^\dagger \Xi^a \sigma^a H + \\ - \lambda_\Xi (\Xi^a\Xi^a)(H^\dagger H) - \frac{1}{4}\eta_\Xi (\Xi^a\Xi^a)^2 \,,$$

Constrained by EWPOs: could modify M_W

Good convergence for $M_\Xi = 1\,\mathrm{TeV}$

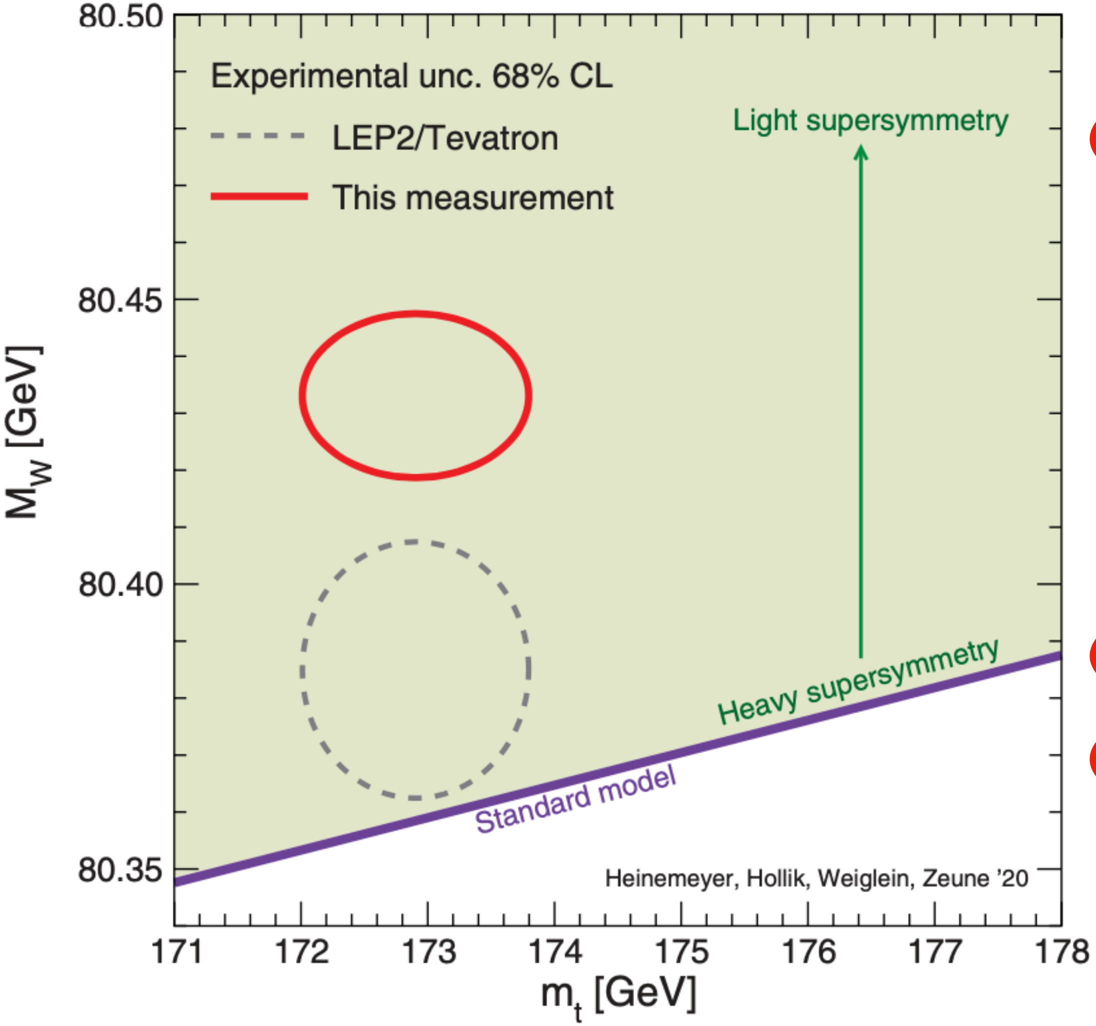


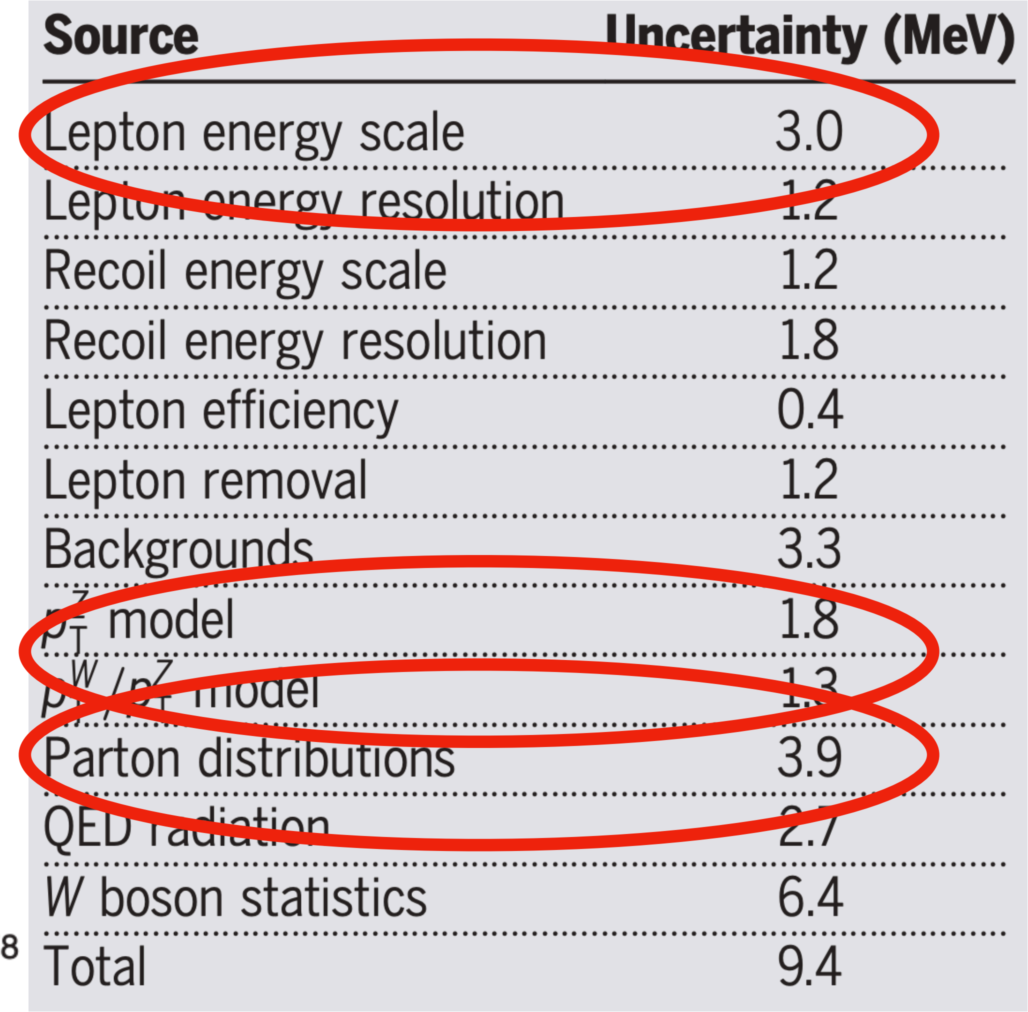
SMEFT at dimension-6, -8

Dim - 6	C_H	$\frac{\kappa_\Xi^2}{M_\Xi^2}\left((4\lambda-\lambda_\Xi)\left(1-\frac{4\mu^2}{M_\Xi^2}\right)-\frac{5\mu^2\kappa_\Xi^2}{M_\Xi^6}\right)$
	C_{HD}	$-\frac{2\kappa_\Xi^2}{M_\Xi^2}\left(1-\frac{4\mu^2}{M_\Xi^2}\right)$
	$C_{H\Box}$	$\frac{\kappa_\Xi^2}{2M_\Xi^2}\left(1-\frac{4\mu^2}{M_\Xi^2}\right)$
	$[C_{\psi H}]_{\rm wx}$	$[y_\psi]_{\rm wx}\frac{\kappa_\Xi^2}{M_\Xi^2}\left(1-\frac{4\mu^2}{M_\Xi^2}\right);\ \psi=u,d,e$
Dim - 8	C_{H^8}	$\frac{2\kappa_\Xi^2}{M_\Xi^2}\left((2\lambda-\lambda_\Xi)^2+\frac{\kappa_\Xi^2}{M_\Xi^2}(3\lambda_\Xi-5\lambda-\frac{\eta_\Xi}{8})\right)$
	$C^{(1)}_{H^6}$	$-\frac{\kappa_\Xi^4}{M_\Xi^4}$
	$C^{(2)}_{H^6}$	$\frac{4\kappa_\Xi^2}{M_\Xi^2}\left(\lambda_\Xi-2\lambda+\frac{\kappa_\Xi^2}{M_\Xi^2}\right)$
	$C^{(1)}_{H^4}$	$\frac{4\kappa_\Xi^2}{M_\Xi^2}$
	$C^{(3)}_{H^4}$	$-\frac{2\kappa_\Xi^2}{M_\Xi^2}$
	$[C_{l\psi H^5}/C_{q\psi H^5}]_{\rm wx}$	$-[y_\psi]_{\rm wx}\frac{2\kappa_\Xi^2}{M_\Xi^2}\left(\lambda_\Xi-2\lambda+\frac{\kappa_\Xi^2}{2M_\Xi^2}\right);\ \psi=u,d,e$
	$[C^{(1)}_{l^2\psi^2H^2}/C^{(1)}_{q^2\psi^2H^2}]_{\rm wxyz}$	$-[y_\psi]_{\rm wz}[y_\psi^\dagger]_{\rm yx}\frac{3\kappa_\Xi^2}{4M_\Xi^2};\ \psi=u,d,e$
	$[C^{(2)}_{l^2e^2H^2}/C^{(2)}_{q^2d^2H^2}]_{\rm wxyz}$	$[y_\psi]_{\rm wz}[y_\psi^\dagger]_{\rm yx}\frac{\kappa_\Xi^2}{4M_\Xi^2};\ \psi=d,e$
	$[C^{(2)}_{q^2u^2H^2}]_{\rm wxyz}$	$-[y_{\rm u}]_{\rm wz}[y_{\rm u}^\dagger]_{\rm yx}\frac{\kappa_\Xi^2}{4M_\Xi^2}$
	$[C^{(3)}_{l^2\psi^2H^2}/C^{(5)}_{q^2\psi^2H^2}]_{\rm wxyz}$	$[y_\psi]_{\rm wx}[y_\psi]_{\rm yz}\frac{\kappa_\Xi^2}{2M_\Xi^2};\ \psi=u,d,e$
	$[C^{(1)}_{lequH^2}]_{\rm wxyz}$	$[y_{\rm e}]_{\rm wx}[y_{\rm u}]_{\rm yz}\frac{5\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(1)}_{leqdH^2}]_{\rm wxyz}$	$[y_{\rm e}]_{\rm wx}[y_{\rm d}^\dagger]_{\rm yz}\frac{5\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(1)}_{q^2udH^2}]_{\rm wxyz}$	$-[y_{\rm u}]_{\rm wx}[y_{\rm d}]_{\rm yz}\frac{5\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(2)}_{lequH^2}]_{\rm wxyz}$	$[y_{\rm e}]_{\rm wx}[y_{\rm u}]_{\rm yz}\frac{\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(2)}_{leqdH^2}]_{\rm wxyz}$	$-[y_{\rm e}]_{\rm wx}[y_{\rm d}^\dagger]_{\rm yz}\frac{\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(2)}_{q^2udH^2}]_{\rm wxyz}$	$[y_{\rm u}]_{\rm wx}[y_{\rm d}]_{\rm yz}\frac{\kappa_\Xi^2}{2M_\Xi^2}$
	$[C^{(5)}_{lequH^2}]_{\rm wxyz}$	$[y_{\rm e}]_{\rm wx}[y_{\rm u}^\dagger]_{\rm yz}\frac{\kappa_\Xi^2}{M_\Xi^2}$
	$[C^{(3)}_{leqdH^2}]_{\rm wxyz}$	$[y_{\rm e}]_{\rm wx}[y_{\rm d}]_{\rm yz}\frac{\kappa_\Xi^2}{M_\Xi^2}$
	$[C^{(5)}_{q^2udH^2}]_{\rm wxyz}$	$[y_{\rm d}]_{\rm wx}[y_{\rm u}^\dagger]_{\rm yz}\frac{\kappa_\Xi^2}{M_\Xi^2}$
	$[C^{(2)}_{l\psi H^3D^2}/C^{(2)}_{q\psi H^3D^2}]_{\rm wx}$	$-[y_\psi]_{\rm wx}\frac{4\kappa_\Xi^2}{M_\Xi^2};\ \psi=u,d,e$

JE, Mimasu & Zampedri, arXiv:2304.06663

CDF Measurement of the Mass of the W Boson





Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

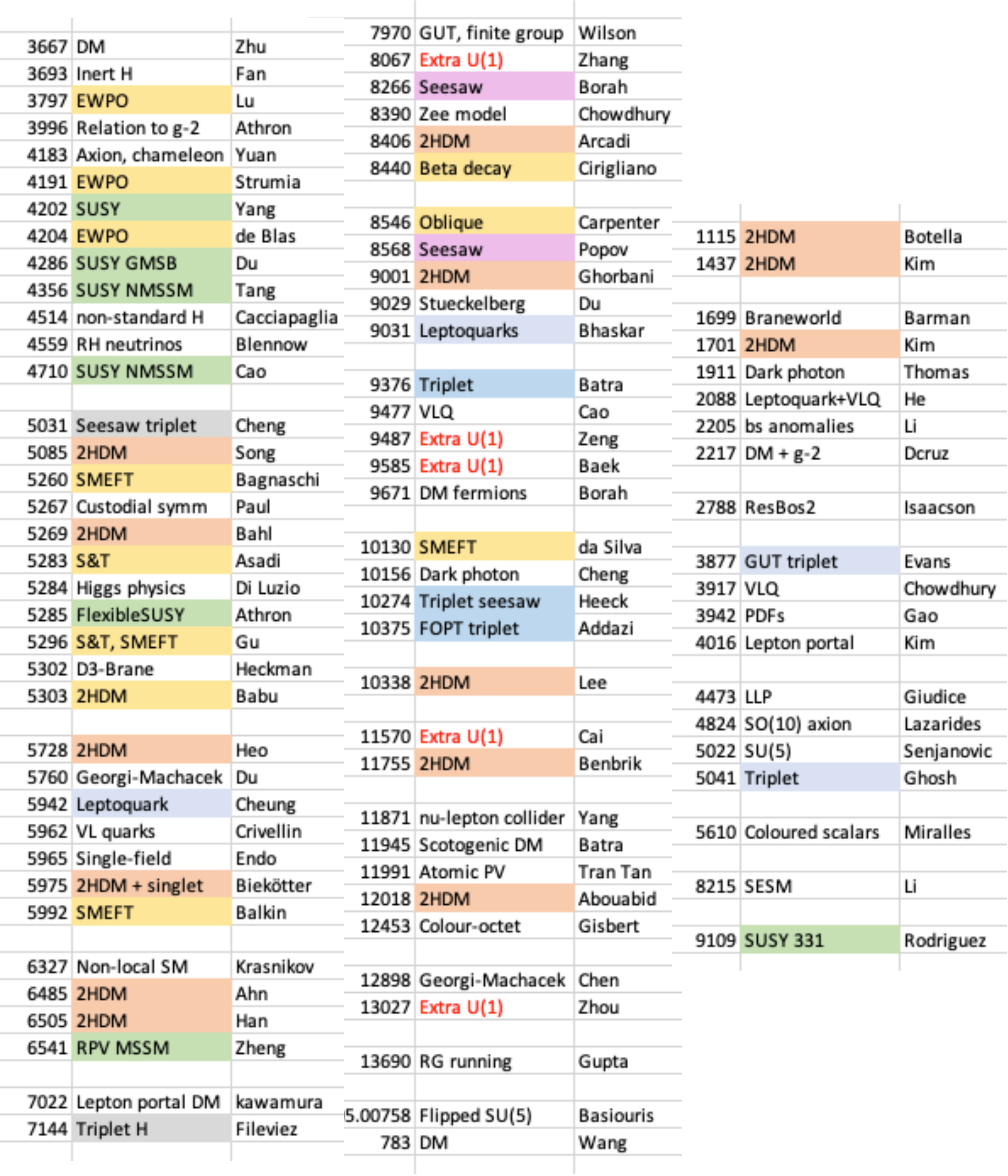
Biggest uncertainties: lepton energy, p_T model, parton distributions, backgrounds

CDF Collaboration, Science 376 (2022) p170

Theoretical Interpretations of W Mass

taking CDF
measurement
at face value

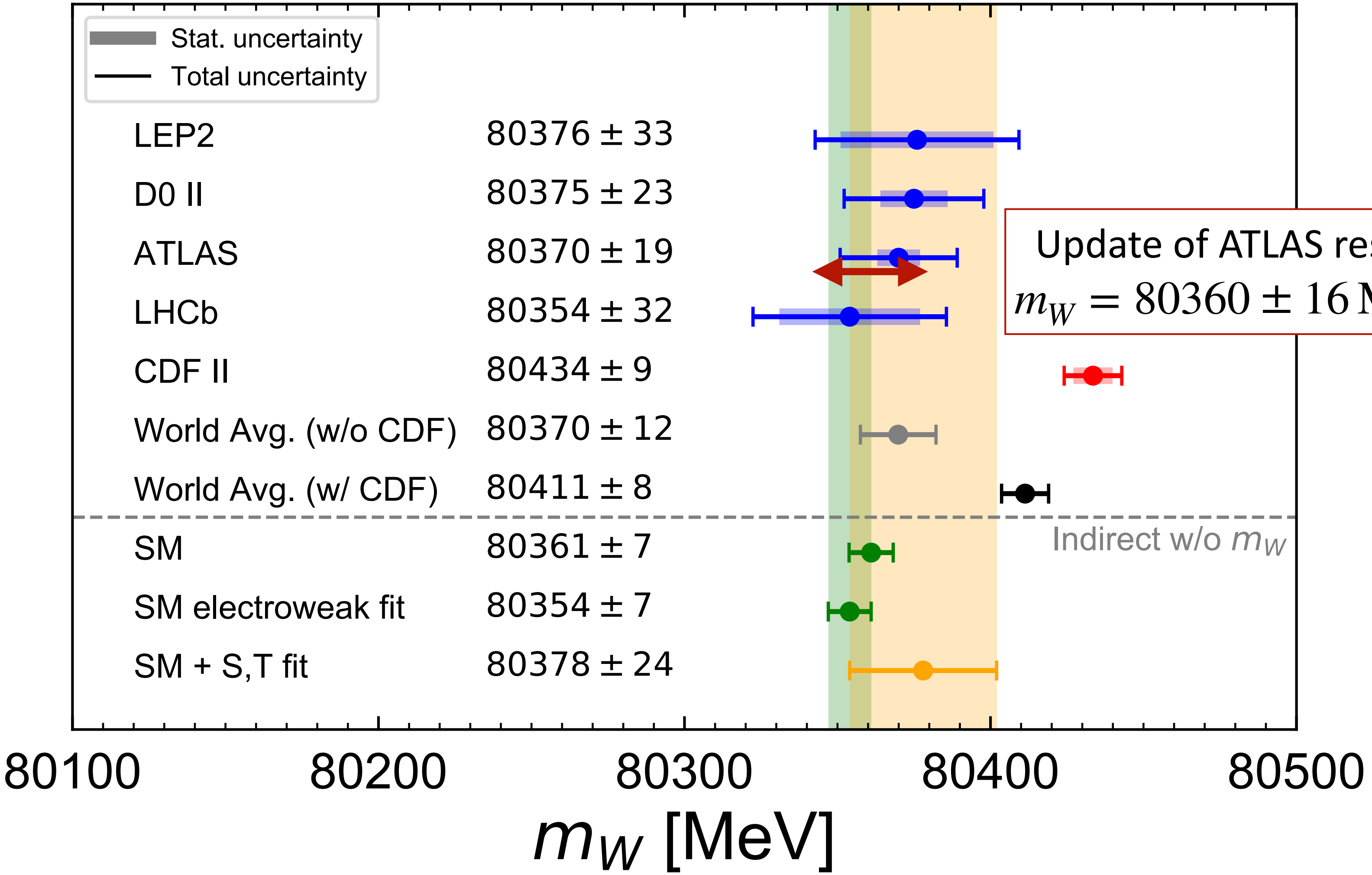
90 papers and counting!



3667	DM	Zhu
3693	Inert H	Fan
3797	EWPO	Lu
3996	Relation to g-2	Athron
4183	Axion, chameleon	Yuan
4191	EWPO	Strumia
4202	SUSY	Yang
4204	EWPO	de Blas
4286	SUSY GMSB	Du
4356	SUSY NMSSM	Tang
4514	non-standard H	Cacciapaglia
4559	RH neutrinos	Blennow
4710	SUSY NMSSM	Cao
5031	Seesaw triplet	Cheng
5085	2HDM	Song
5260	SMEFT	Bagnaschi
5267	Custodial symm	Paul
5269	2HDM	Bahl
5283	S&T	Asadi
5284	Higgs physics	Di Luzio
5285	FlexibleSUSY	Athron
5296	S&T, SMEFT	Gu
5302	D3-Brane	Heckman
5303	2HDM	Babu
5728	2HDM	Heo
5760	Georgi-Machacek	Du
5942	Leptoquark	Cheung
5962	VL quarks	Crivellin
5965	Single-field	Endo
5975	2HDM + singlet	Biekötter
5992	SMEFT	Balkin
6327	Non-local SM	Krasnikov
6485	2HDM	Ahn
6505	2HDM	Han
6541	RPV MSSM	Zheng
7022	Lepton portal DM	kawamura
7144	Triplet H	Fileviez
7970	GUT, finite group	Wilson
8067	Extra U(1)	Zhang
8266	Seesaw	Borah
8390	Zee model	Chowdhury
8406	2HDM	Arcadi
8440	Beta decay	Cirigliano
8546	Oblique	Carpenter
8568	Seesaw	Popov
9001	2HDM	Ghorbani
9029	Stueckelberg	Du
9031	Leptoquarks	Bhaskar
9376	Triplet	Batra
9477	VLQ	Cao
9487	Extra U(1)	Zeng
9585	Extra U(1)	Baek
9671	DM fermions	Borah
10130	SMEFT	da Silva
10156	Dark photon	Cheng
10274	Triplet seesaw	Heeck
10375	FOPT triplet	Addazi
10338	2HDM	Lee
11570	Extra U(1)	Cai
11755	2HDM	Benbrik
11871	nu-lepton collider	Yang
11945	Scotogenic DM	Batra
11991	Atomic PV	Tran Tan
12018	2HDM	Abouabid
12453	Colour-octet	Gisbert
12898	Georgi-Machacek	Chen
13027	Extra U(1)	Zhou
13690	RG running	Gupta
5.00758	Flipped SU(5)	Basiouris
783	DM	Wang
1115	2HDM	Botella
1437	2HDM	Kim
1699	Braneworld	Barman
1701	2HDM	Kim
1911	Dark photon	Thomas
2088	Leptoquark+VLQ	He
2205	bs anomalies	Li
2217	DM + g-2	Dcruz
2788	ResBos2	Isaacson
3877	GUT triplet	Evans
3917	VLQ	Chowdhury
3942	PDFs	Gao
4016	Lepton portal	Kim
4473	LLP	Giudice
4824	SO(10) axion	Lazarides
5022	SU(5)	Senjanovic
5041	Triplet	Ghosh
5610	Coloured scalars	Miralles
8215	SESM	Li
9109	SUSY 331	Rodriguez

CDF Measurement of m_W

compared with other measurements



Update of ATLAS result
$m_W = 80360 \pm 16\,\text{MeV}$

Tension: 7-σ discrepancy with Standard Model?

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H \, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

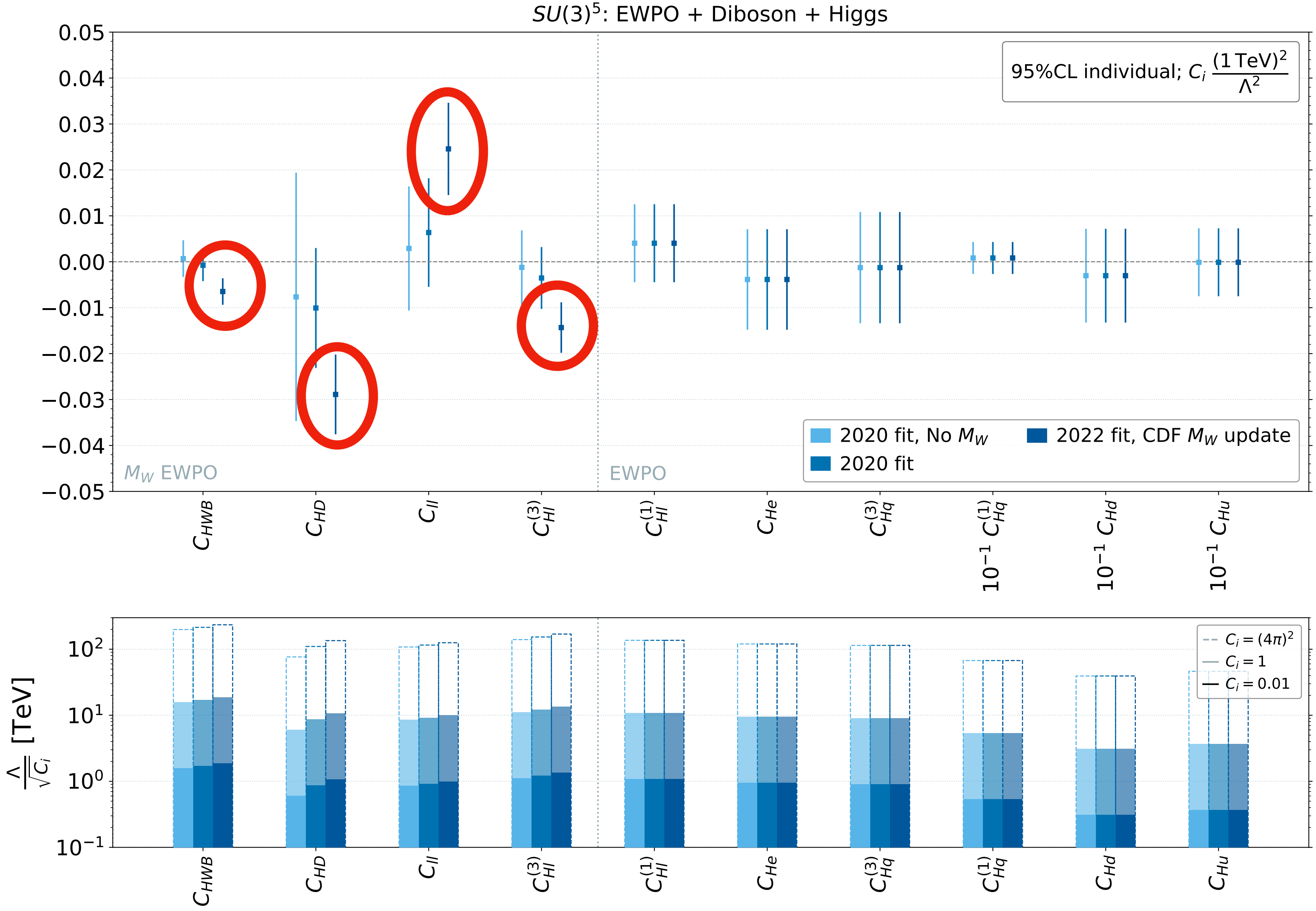
- Contributions to W mass

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w} \frac{v^2}{4\Lambda^2} \left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w} \left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB} \right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

SMEFT Fit with the Mass of the W Boson



Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Extensions of the Standard Model

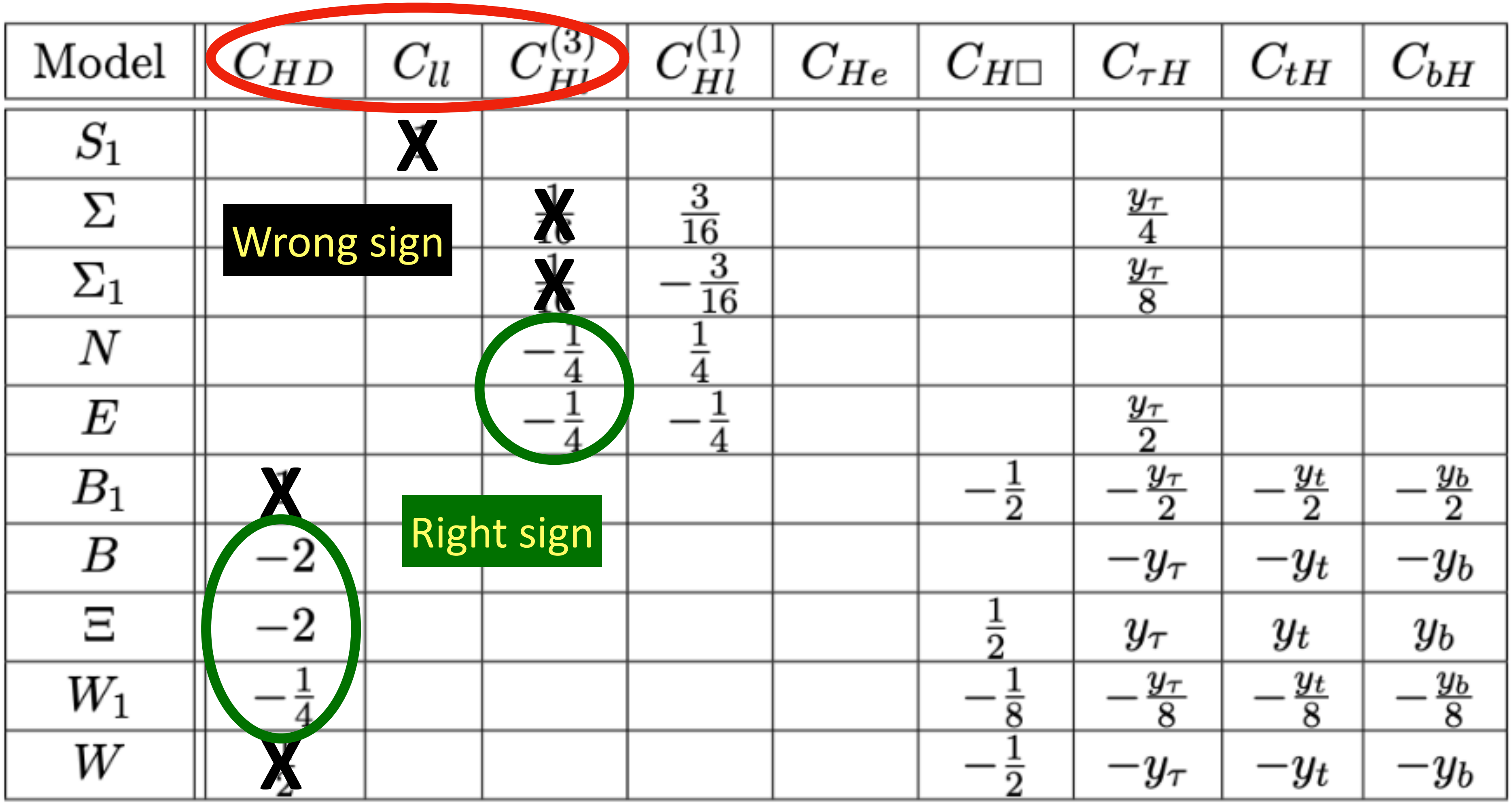
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Single-Field Models that can Contribute to W Mass



Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		X							
Σ			X	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Wrong sign

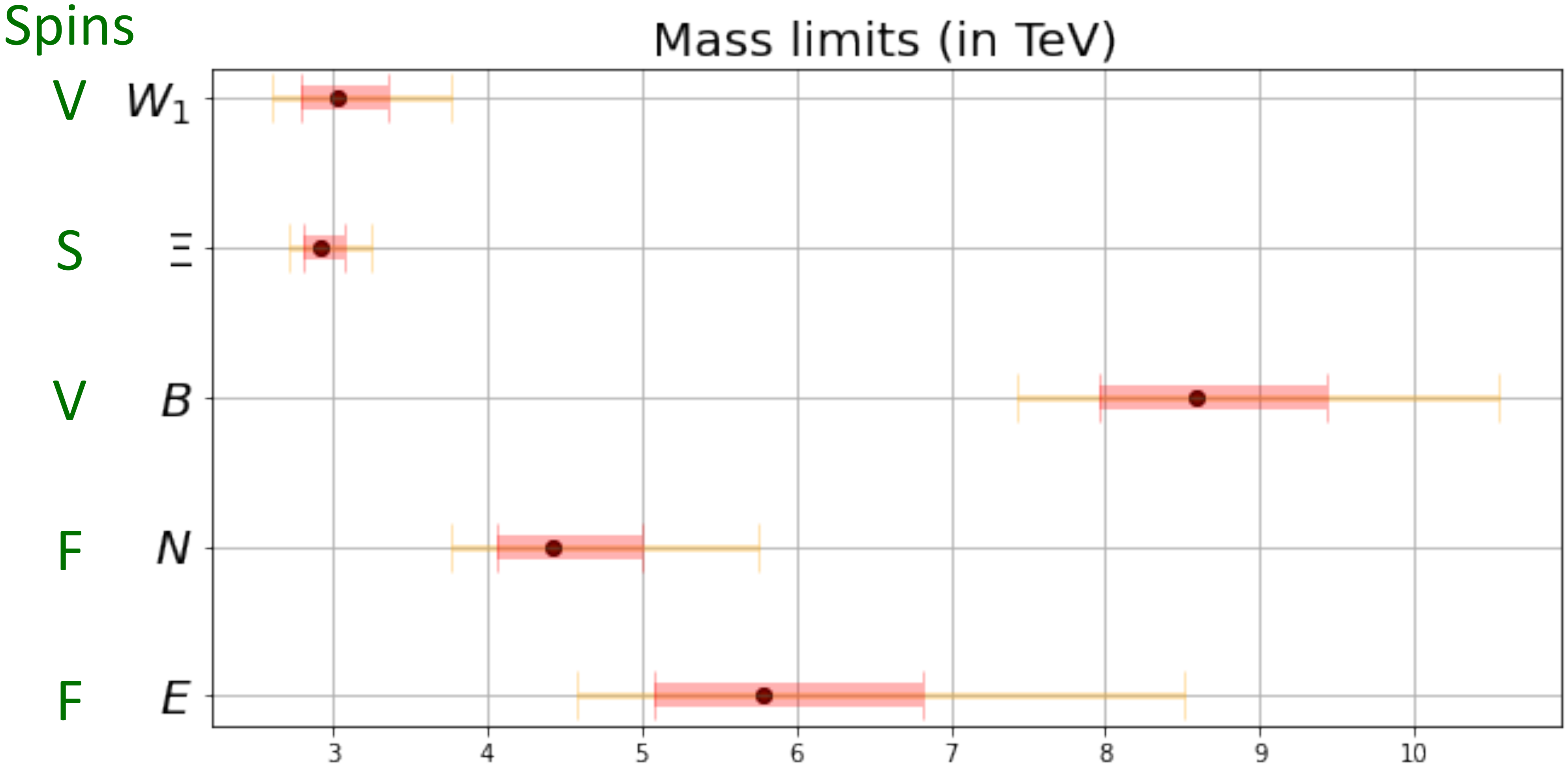
Right sign

Operators

contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson



68 and 95% CL ranges of masses assuming unit couplings, mass range proportional to coupling

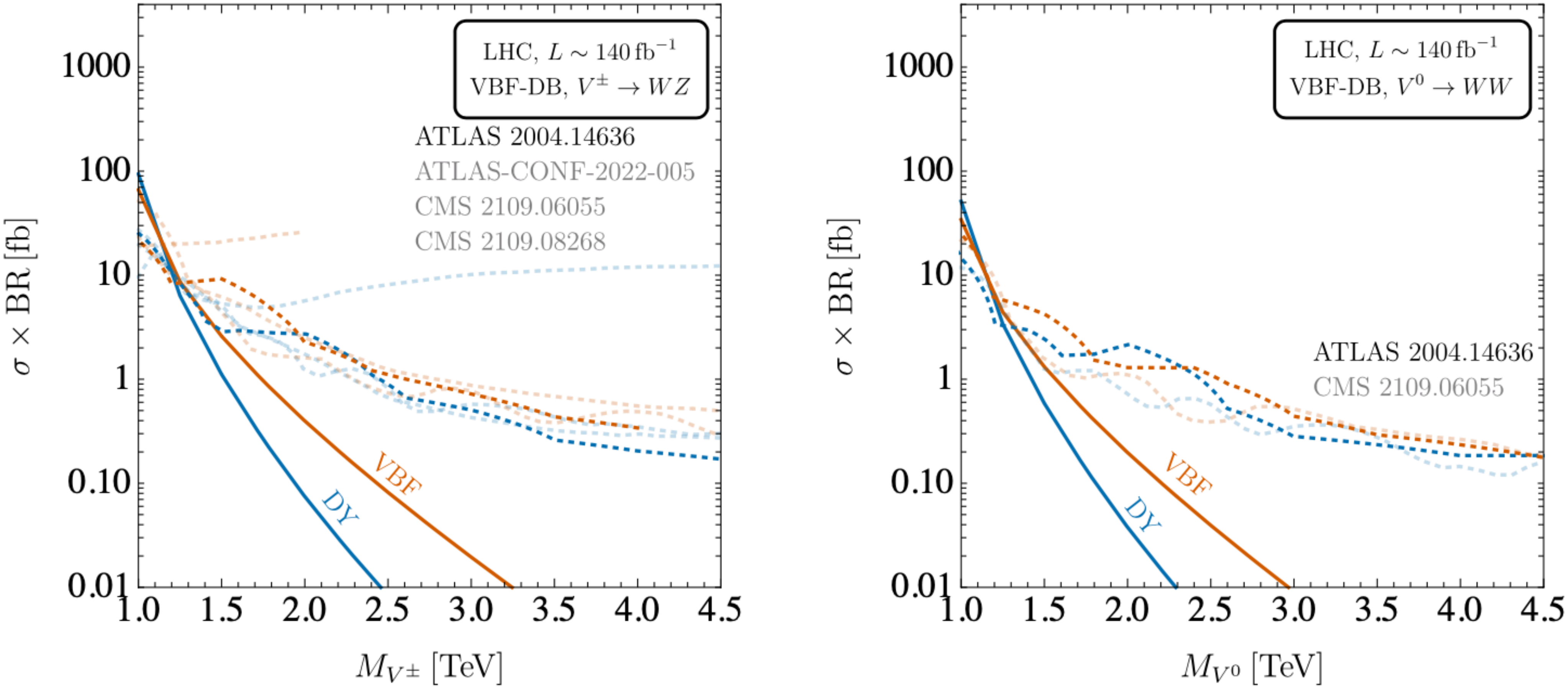
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Searching for Models Fitting the Mass of the W Boson

- W: Isotriplet vector boson, mass ~ 3 TeV x coupling, electroweak production, accessible at LHC?
- B: Singlet vector boson, mass ~ 8 TeV x coupling, phenomenology depends on fermion couplings, too heavy for LHC?
- Ξ: Isotriplet scalar boson, mass ~ 3 TeV x coupling, detectable in LHC searches for heavy Higgs bosons?
- N: Isosinglet neutral fermion, mass ~ 4 TeV x coupling, similar to (right-handed) singlet neutrino
- E: Isosinglet charged fermion, mass ~ 6 TeV x coupling, similar to (right-handed) singlet electron

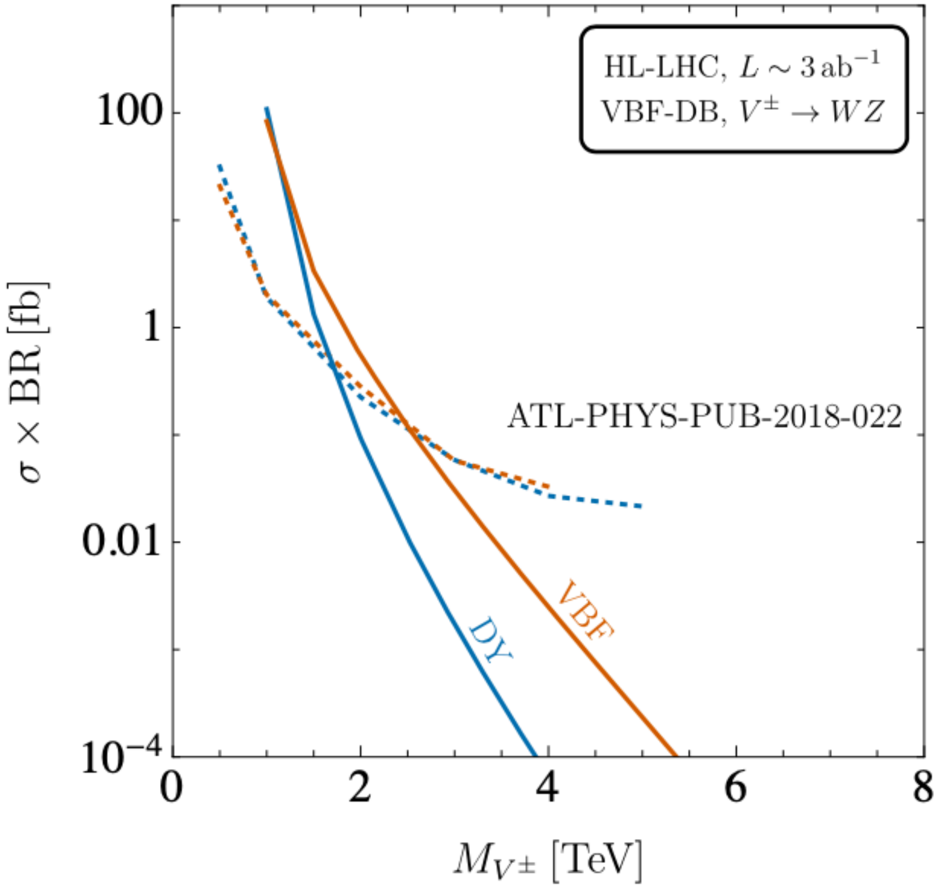
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

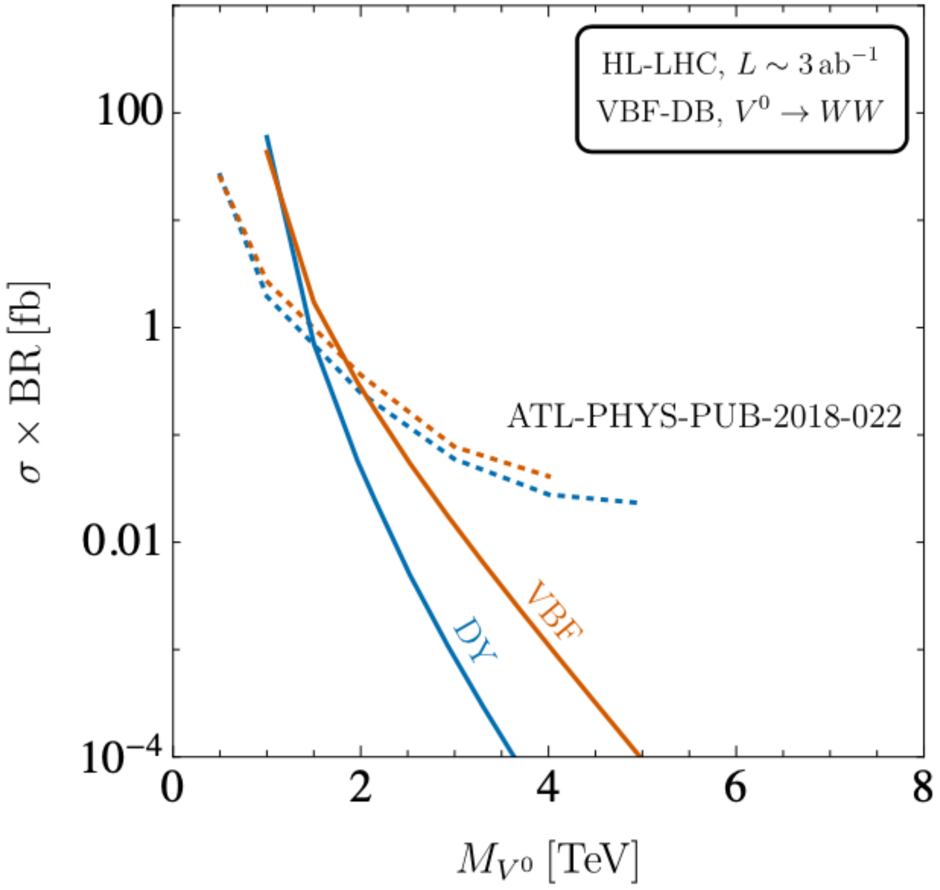
LHC Search for Triplet Vector Boson



Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

HL-LHC Search for Triplet Vector Boson





Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

Quo Vadis m_W?

- The jury is still out concerning the experimental measurement
    - Tension with SM, previous measurements

“Extraordinary claims require extraordinary evidence”

- Nevertheless, much theoretical speculation (> 90 papers!)
- 4 SMEFT operators can increase m_W
- 3 SMEFT operators generated by single field extensions of the SM at tree level
    - Vector bosons W or B, scalar boson Ξ, fermions N, E
- Prospects for the LHC?

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Beyond Dimension-6:

Dimension-8 Operators

- Most analyses focus on dimension-6:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Dimension-8 contributions scaled by quartic power of new physics scale:

$$\Delta\mathcal{L}(\text{dim-8}) = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4} \mathcal{O}_j = \sum_j \frac{\mathrm{sign}(\tilde{c}_j)}{\Lambda_j^4} \mathcal{O}_j$$

- Study processes without dimension-6 contributions,

e.g., light-by-light scattering, $gg \to \gamma\gamma, Z\gamma, \ldots$

- Neutral triple-gauge couplings (nTGCs): $\gamma\gamma^* Z, \gamma Z Z^*$
- Now also off-shell nTGCs: $Z/\gamma^* \gamma Z^*$

JE, Mavromatos & You, arXiv:1703.08450

JE, Mavromatos, Roloff & You, arXiv:2203.17311

JE & Ge, arXiv:1802.02146

JE, Ge & Ma, arXiv:2112.06729

JE, Ge, He & Xiao, arXiv:1902.06631

JE, He & Xiao, arXiv:2008.04298

JE, He & Xiao, arXiv:2206.11676

JE, He & Xiao, arXiv:2308.16887

Dimension-8 Operators Contributing to On-Shell nTGCs

$$\begin{aligned}
g\mathcal{O}_{G+} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda}+D^\nu D^\lambda W^a_{\lambda\rho}),\\
g\mathcal{O}_{G-} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda}-D^\nu D^\lambda W^a_{\lambda\rho}),\\
\mathcal{O}_{\widetilde{B}W} &= \mathrm{i}\,H^\dagger \widetilde{B}_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}H+\text{h.c.},\\
\mathcal{O}_{C+} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}\left[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L)+D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)\right]\\
\mathcal{O}_{C-} &= \widetilde{B}_{\mu\nu}W^{a\mu\rho}\left[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L)-D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)\right]
\end{aligned}$$

- $\mathcal{O}_{C+,C-}$ related to $\mathcal{O}_{G+,G-,\tilde{B}W}$ by equations of motion:

$$\begin{aligned}
\mathcal{O}_{C+} &= \mathcal{O}_{G-}-\mathcal{O}_{\widetilde{B}W}\,,\\
\mathcal{O}_{C-} &= \mathcal{O}_{G+}-\{\,\mathrm{i}H^\dagger\widetilde{B}_{\mu\nu}W^{\mu\rho}[D_\rho, D^\nu]H+\mathrm{i}\,2(D_\rho H)^\dagger\widetilde{B}_{\mu\nu}W^{\mu\rho}D^\nu H+\text{h.c.}\}
\end{aligned}$$

- nTGCs generated:

$$\begin{aligned}
\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(G+)}(q_1,q_2,q_3) &= -\frac{v(q_3^2-M_Z^2)}{M_Z[\Lambda^4_{G+}]}\left(q_3^2\,q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),\\
\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G+)}(q_1,q_2,q_3) &= -\frac{s_W v\,q_3^2}{c_W M_Z[\Lambda^4_{G+}]}\left(q_3^2\,q_{2\nu}\epsilon^{\alpha\beta\mu\nu}+2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),\\
\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(\widetilde{B}W)}(q_1,q_2,q_3) &= \frac{v\,M_Z(q_3^2-M_Z^2)}{[\Lambda^4_{\widetilde{B}W}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}\,,\\
\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G-)}(q_1,q_2,q_3) &= -\frac{s_W v\,M_Z}{c_W[\Lambda^4_{G-}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}q_3^2\,.
\end{aligned}$$

JE, Ge, He & Xiao, arXiv:1902.06631
JE, He & Xiao, arXiv:2008.04298
JE, He & Xiao, arXiv:2206.11676

Dimension-8 Operators Contributing to **Off-Shell and CP-violating** nTGCs

- Off-shell vertex: $V^* \gamma Z^*$ needed to analyze $(Z^* \to \bar{\nu}\nu) + \gamma$ final states at pp colliders because no kinematic constraint on $m_{\bar{\nu}\nu}$:

- Higgs operators:

$$\text{CPC:} \quad \mathcal{O}_{\widetilde{B}W} = \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPC:} \quad \mathcal{O}_{\widetilde{BW}} = \mathrm{i}\, H^\dagger (D_\sigma \widetilde{W}^a_{\mu\nu} W^{a\mu\sigma} + D_\sigma \widetilde{B}_{\mu\nu} B^{\mu\sigma}) D^\nu H + \text{h.c.}$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{BW} = \mathrm{i}\, H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{WW} = \mathrm{i}\, H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{BB} = \mathrm{i}\, H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

- Gauge operators:

$$\text{CPC:} \quad g\mathcal{O}_{G+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho})$$

$$\text{CPC:} \quad g\mathcal{O}_{G-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho})$$

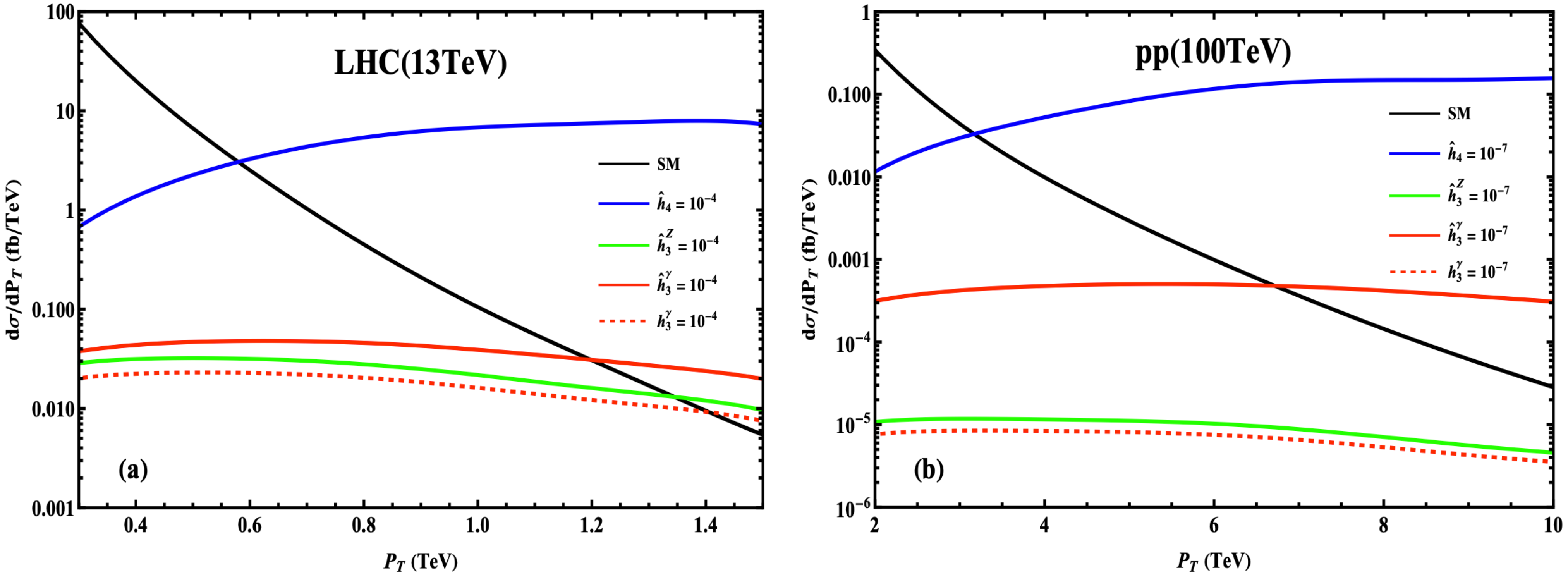
$$\text{CPV:} \quad g\widetilde{\mathcal{O}}_{G+} = B_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho})$$

$$\text{CPV:} \quad g\widetilde{\mathcal{O}}_{G-} = B_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho})$$

JE, He & Xiao, arXiv:2308.16887

Probing nTGCs with $Z^*(\to \nu\bar{\nu})\gamma$ Production at Hadron Colliders

- Cannot determine whether Z is on-shell: primary observable is p_T^γ



- Sample differential cross-sections for illustrative values of the SU(2)⊗U(1) form factors rise above Standard Model cross-section for values < unitarity limit

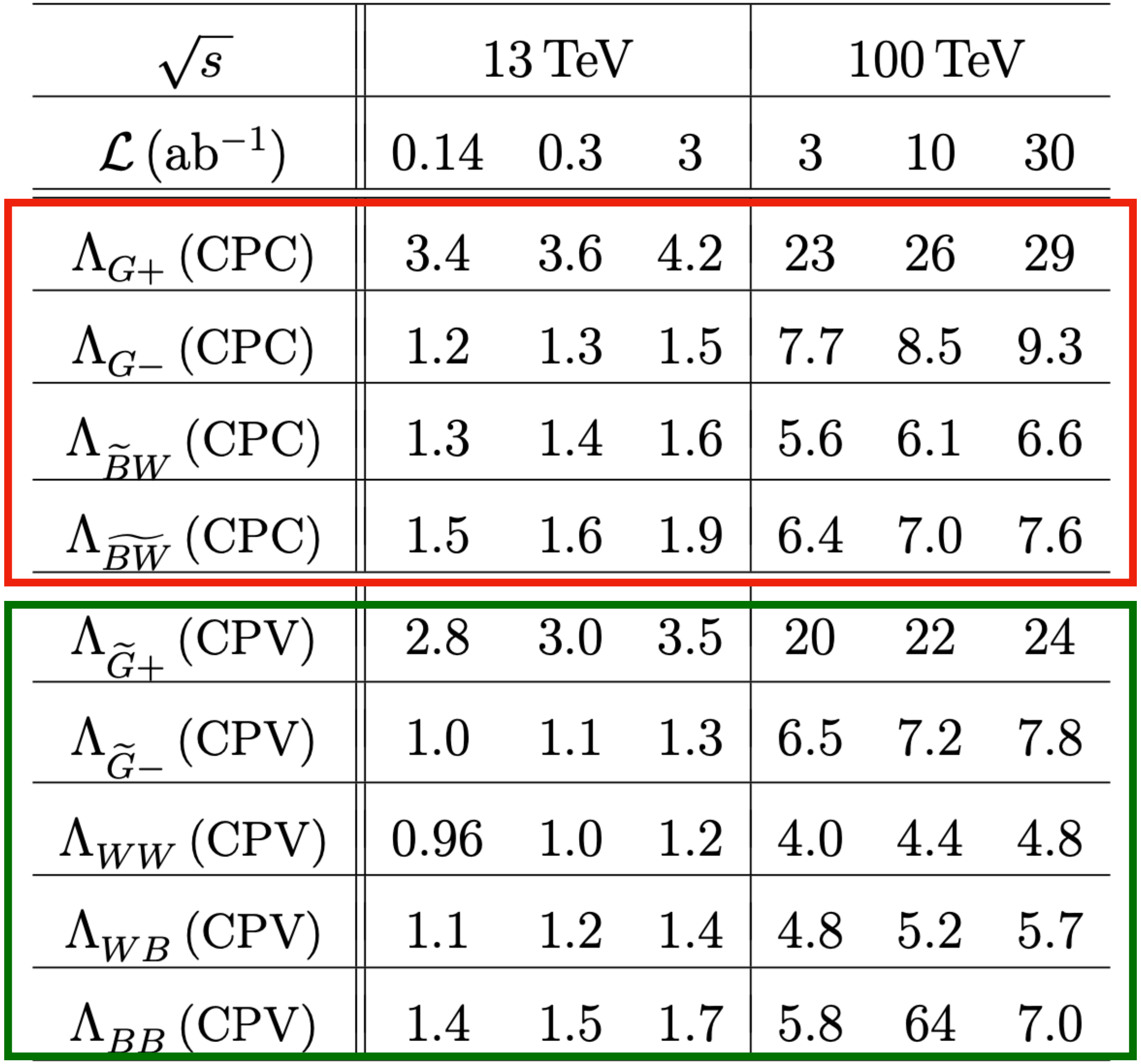
JE, He & Xiao, arXiv:2308.16887

Combined Sensitivities to SU(2)⊗U(1)-Invariant Mass Scales

Sensitivities using
$Z \to \ell^+\ell^-, \bar{\nu}\nu$ decays

CPC and **CPV** operators

JE, He & Xiao, arXiv:2308.16887



$\sqrt{s}$	13 TeV			100 TeV		
$\mathcal{L}\,(\mathrm{ab}^{-1})$	0.14	0.3	3	3	10	30
Λ_{G+} (CPC)	3.4	3.6	4.2	23	26	29
Λ_{G-} (CPC)	1.2	1.3	1.5	7.7	8.5	9.3
$\Lambda_{\widetilde{B}W}$ (CPC)	1.3	1.4	1.6	5.6	6.1	6.6
$\Lambda_{\widetilde{BW}}$ (CPC)	1.5	1.6	1.9	6.4	7.0	7.6
$\Lambda_{\widetilde{G}+}$ (CPV)	2.8	3.0	3.5	20	22	24
$\Lambda_{\widetilde{G}-}$ (CPV)	1.0	1.1	1.3	6.5	7.2	7.8
Λ_{WW} (CPV)	0.96	1.0	1.2	4.0	4.4	4.8
Λ_{WB} (CPV)	1.1	1.2	1.4	4.8	5.2	5.7
Λ_{BB} (CPV)	1.4	1.5	1.7	5.8	64	7.0

Quo Vadis SMEFT?

- Powerful framework for global analyses of LHC and other data
- Systematic way to search for BSM physics
- Can be used in principle to identify "interesting" BSM scenarios
- Dimension-6 operators are a first approximation
- Important to check lesser importance of dimension-8, convergence towards ultraviolet-complete model
- Interesting direct windows on dimension-8 operators

Looking Beyond the Standard Model with the SMEFT

“...the direct method may be used...but indirect methods will be needed in order to secure victory....”

“The direct and the indirect lead on to each other in turn. It is like moving in a circle....”

Who can exhaust the possibilities of their combination?”

Sun Tzu