SMEFT Constraints on New Physics Beyond the Standard Model

"...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, *The Art of War*

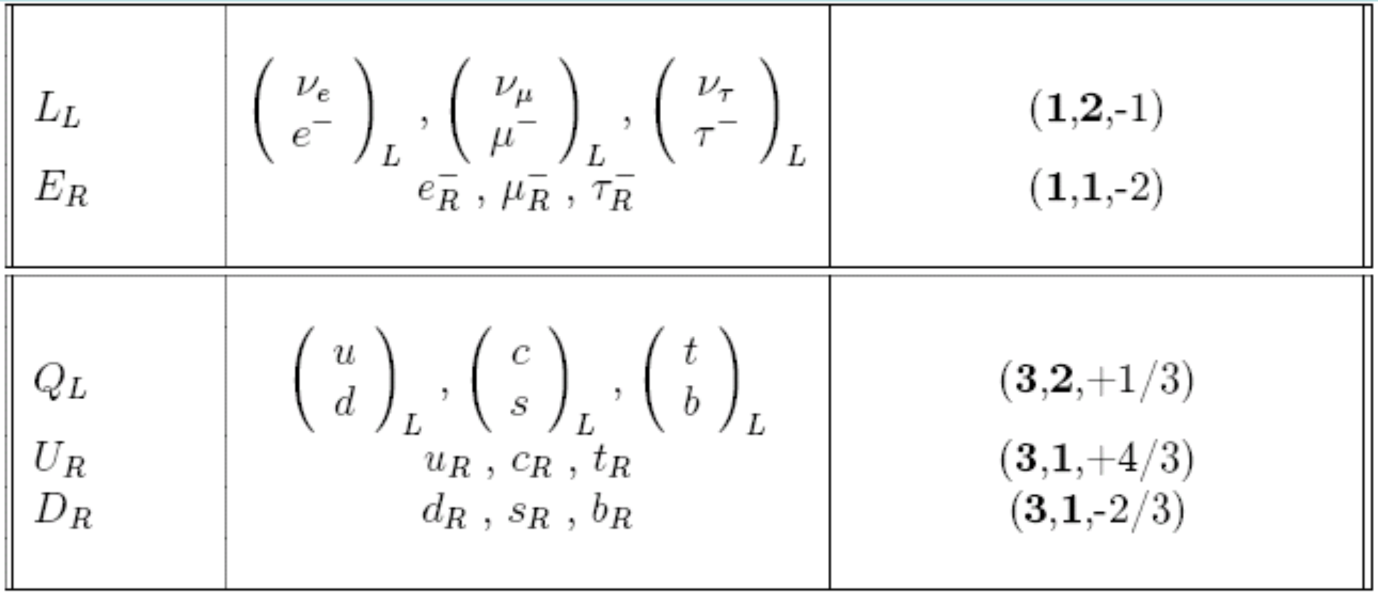
John Ellis

KING'S College LONDON

Where are we?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:



L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},\text{-}1)$
E_R	$e^-_R , \mu^-_R , \tau^-_R$	$(\mathbf{1},\mathbf{1},\text{-}2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},\text{-}2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} \\ &+ i\bar{\psi}\, \not{D} \psi + h.c. \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

gauge interactions

matter fermions

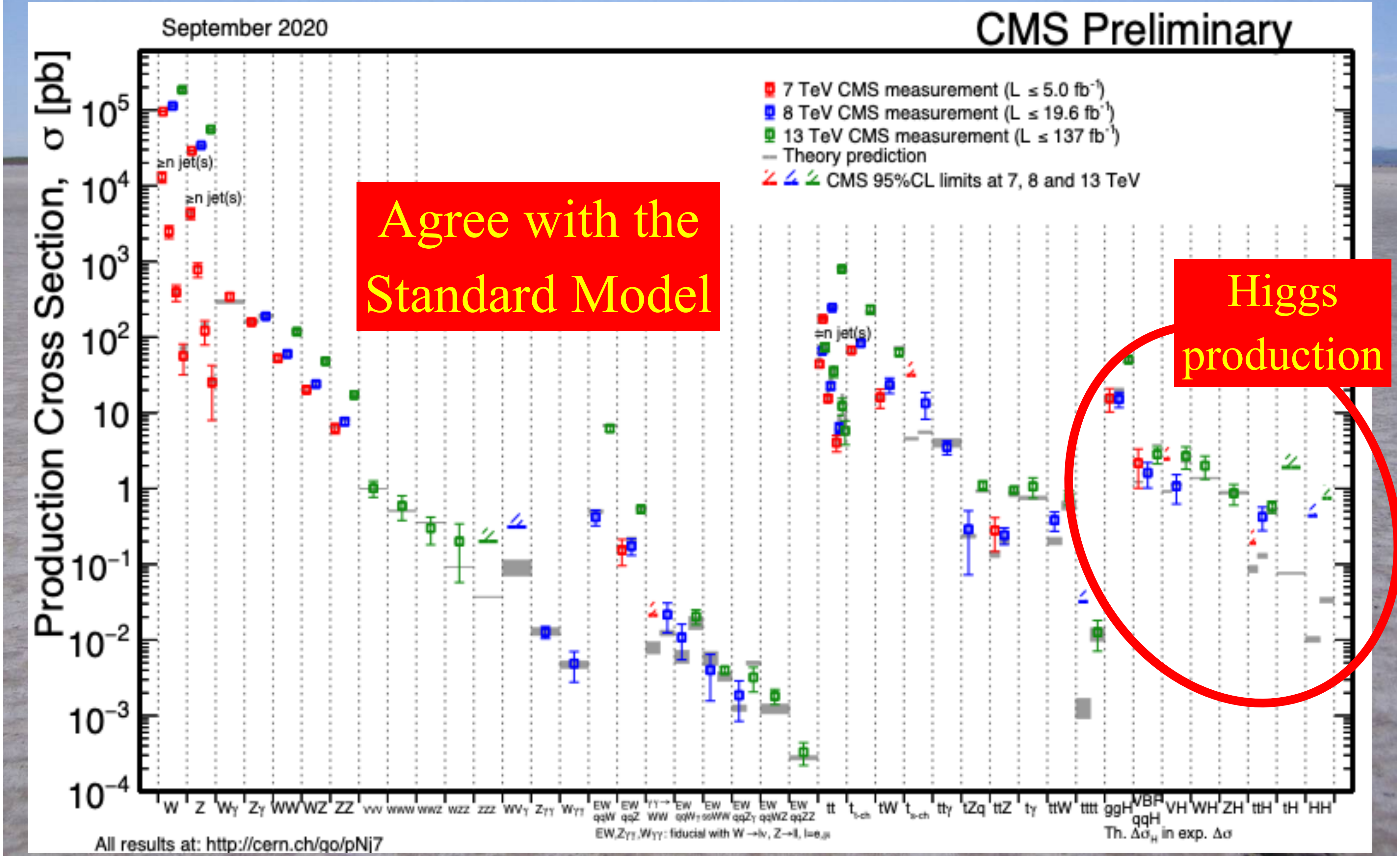
Yukawa interactions

Higgs potential

Tested < 0.1% before LHC

Testing now in progress

LHC Measurements



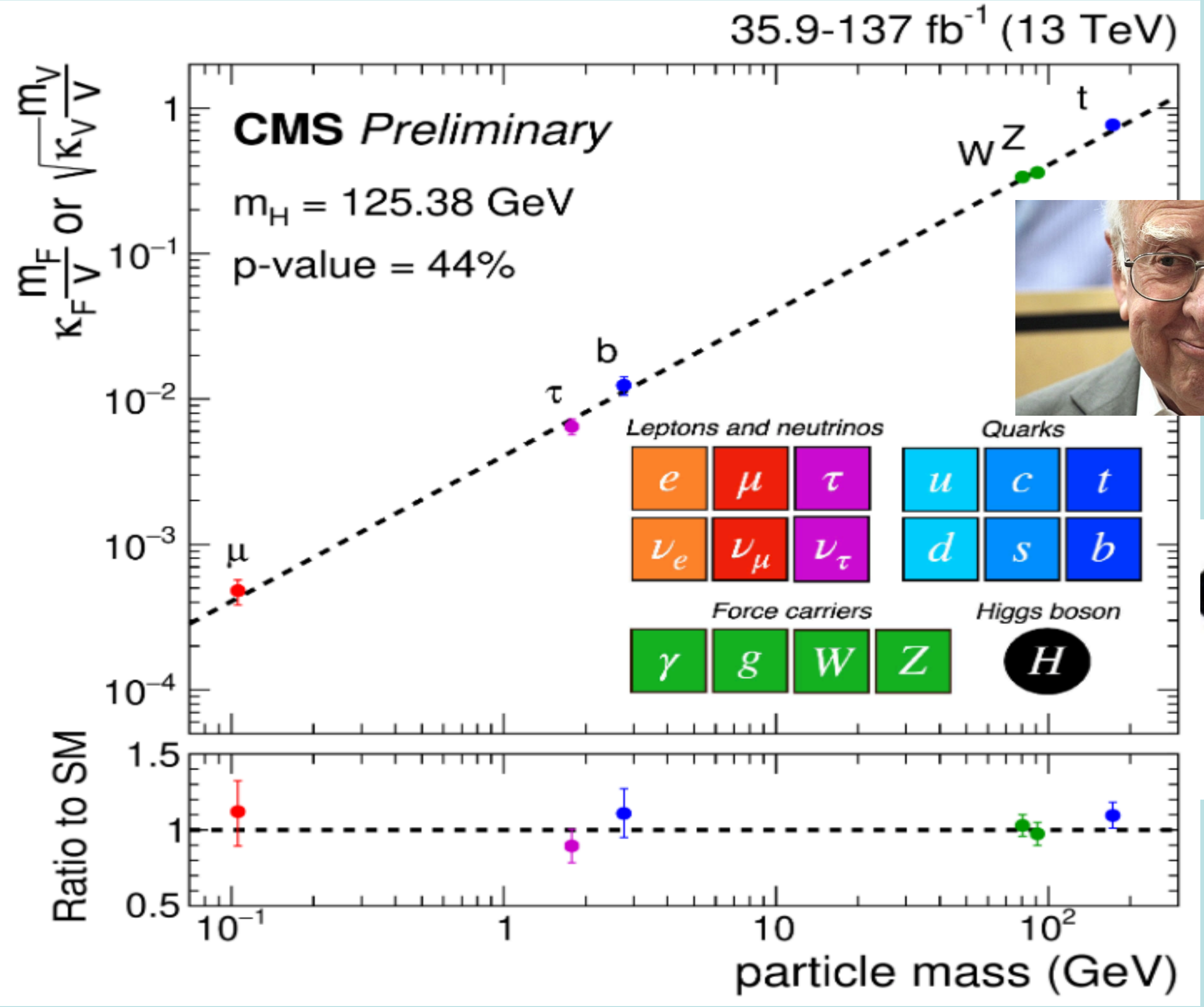
Agree with the Standard Model

Higgs production

It Walks and Quacks like a Higgs

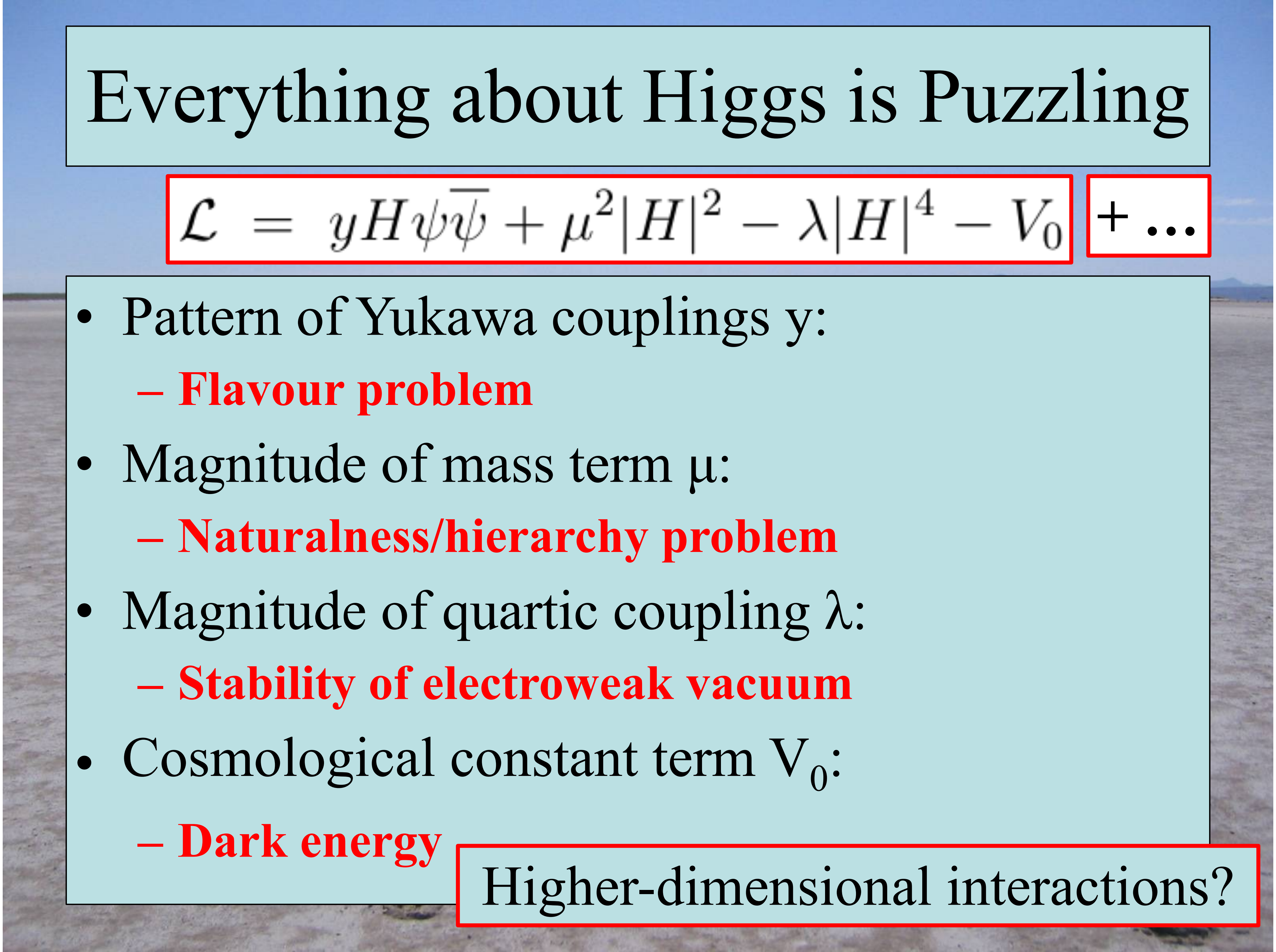
- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V$$



Gl

- **Red li**



Everything about Higgs is Puzzling

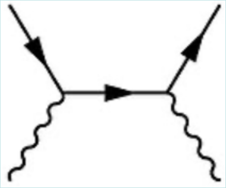
$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0$$ + …

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

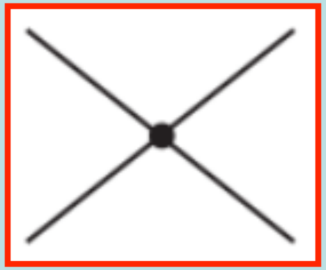
Higher-dimensional interactions?

Effective Field Theories (EFTs)
a long and glorious History

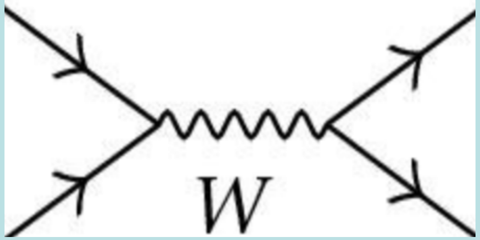
- 1930's: "Standard Model" of QED had d=4



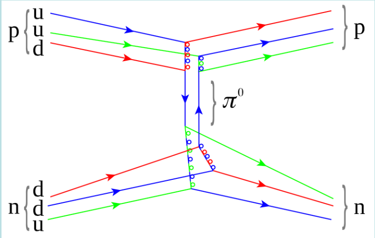
- **Fermi's four-fermion theory of the weak force**



- 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
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other data
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

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

Summarize Analysis Framework

- Include all leading dimension-6 operators?

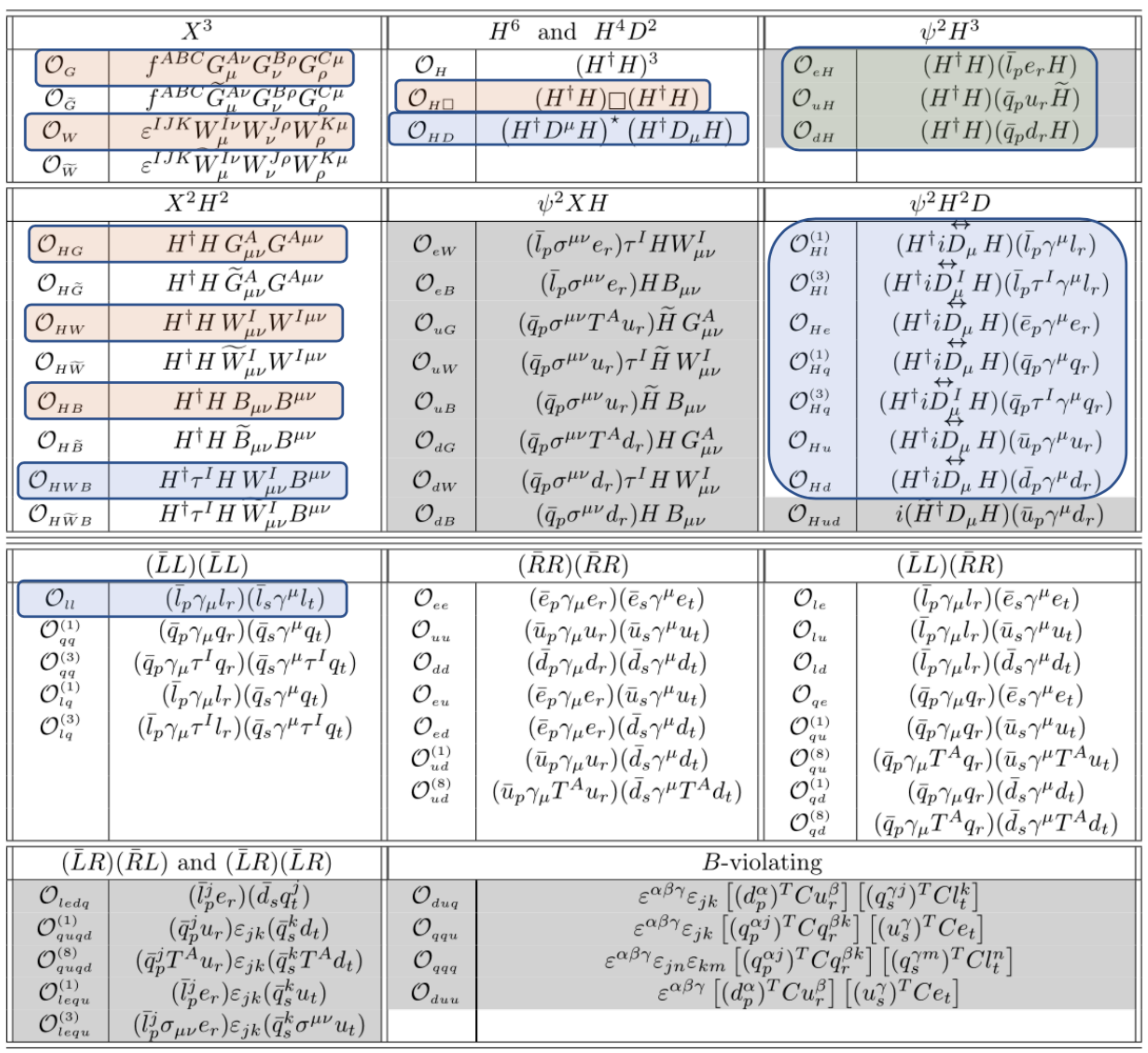
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients
- Use G_F, M_Z, α as input parameters

Dimension-6 Operators in Detail

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

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



X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

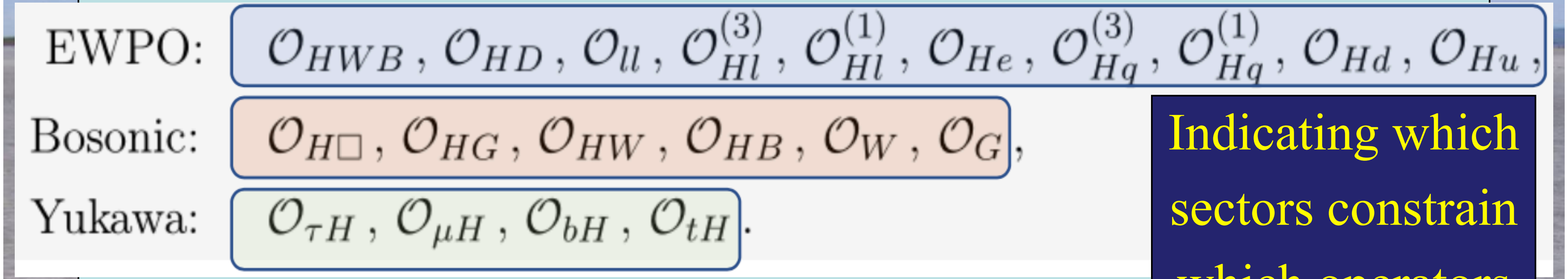
X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

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

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

Operators included in Global Fit

- Operators in flavour-universal SU(3)^5 fit



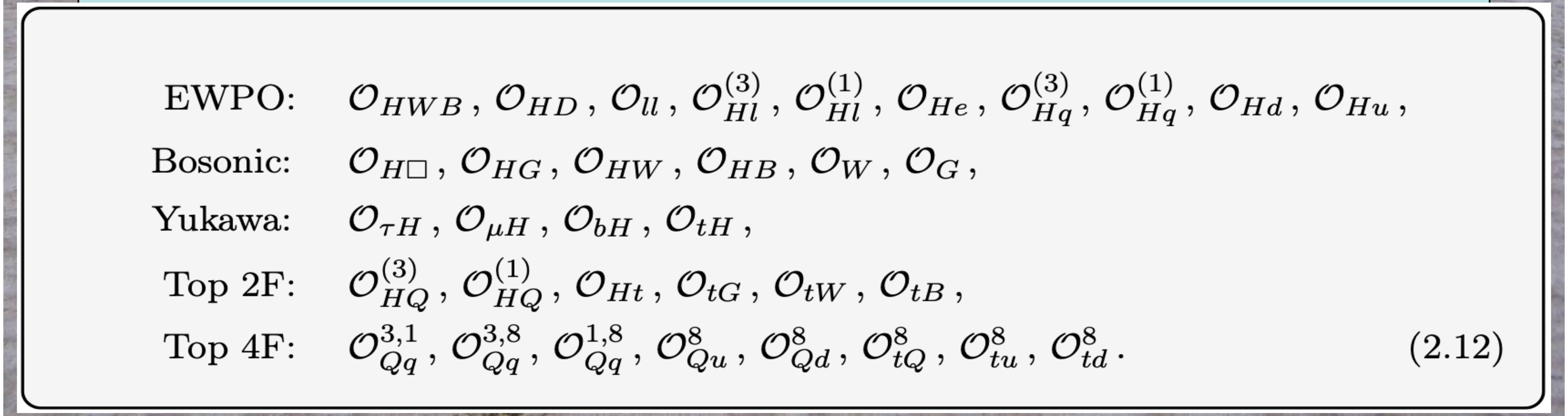
EWPO: $\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}^{(3)}_{Hl}\,,\ \mathcal{O}^{(1)}_{Hl}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}^{(3)}_{Hq}\,,\ \mathcal{O}^{(1)}_{Hq}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$

Bosonic: $\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$

Yukawa: $\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,.$

Indicating which sectors constrain which operators

- Operators in top-specific SU(2)^2 x SU(3)^3 fit

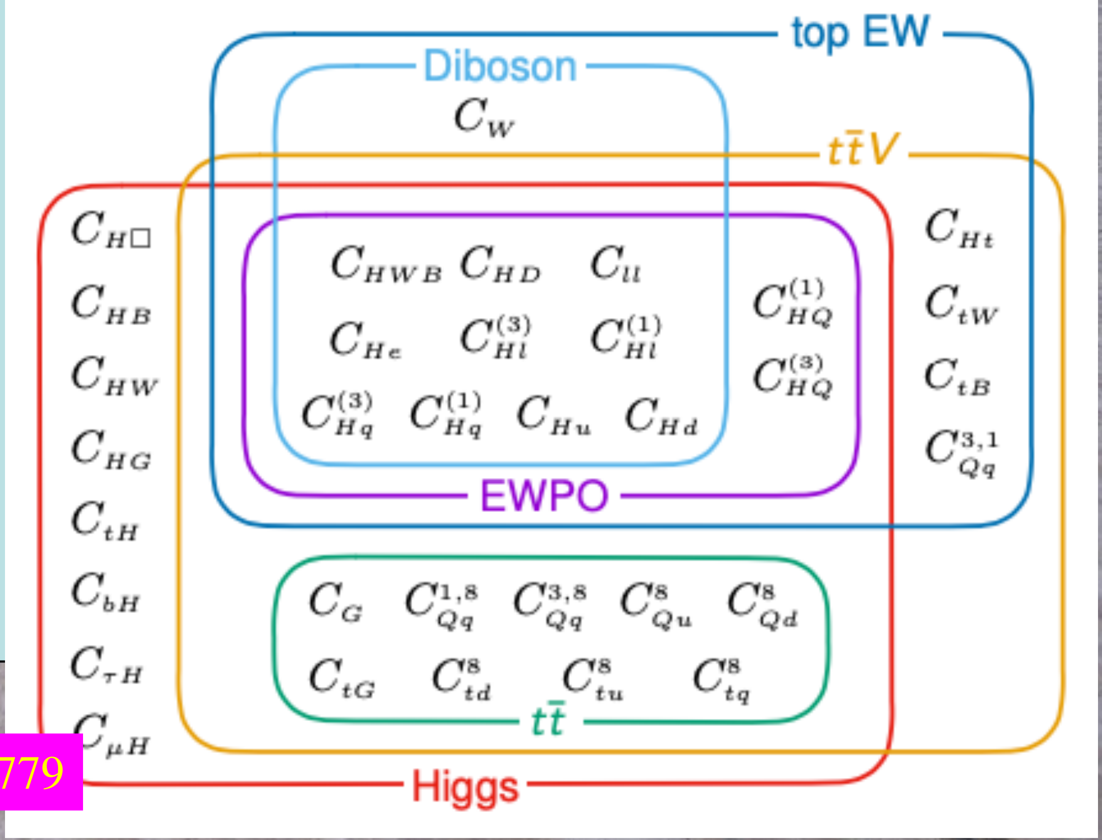


$$\begin{array}{ll}
\text{EWPO:} & \mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}^{(3)}_{Hl}\,,\ \mathcal{O}^{(1)}_{Hl}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}^{(3)}_{Hq}\,,\ \mathcal{O}^{(1)}_{Hq}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,\\
\text{Bosonic:} & \mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,\\
\text{Yukawa:} & \mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,\\
\text{Top 2F:} & \mathcal{O}^{(3)}_{HQ}\,,\ \mathcal{O}^{(1)}_{HQ}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,\\
\text{Top 4F:} & \mathcal{O}^{3,1}_{Qq}\,,\ \mathcal{O}^{3,8}_{Qq}\,,\ \mathcal{O}^{1,8}_{Qq}\,,\ \mathcal{O}^{8}_{Qu}\,,\ \mathcal{O}^{8}_{Qd}\,,\ \mathcal{O}^{8}_{tQ}\,,\ \mathcal{O}^{8}_{tu}\,,\ \mathcal{O}^{8}_{td}\,.
\end{array} \tag{2.12}$$

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

Global SMEFT Fit
to Top, Higgs, Diboson, Electroweak Data

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



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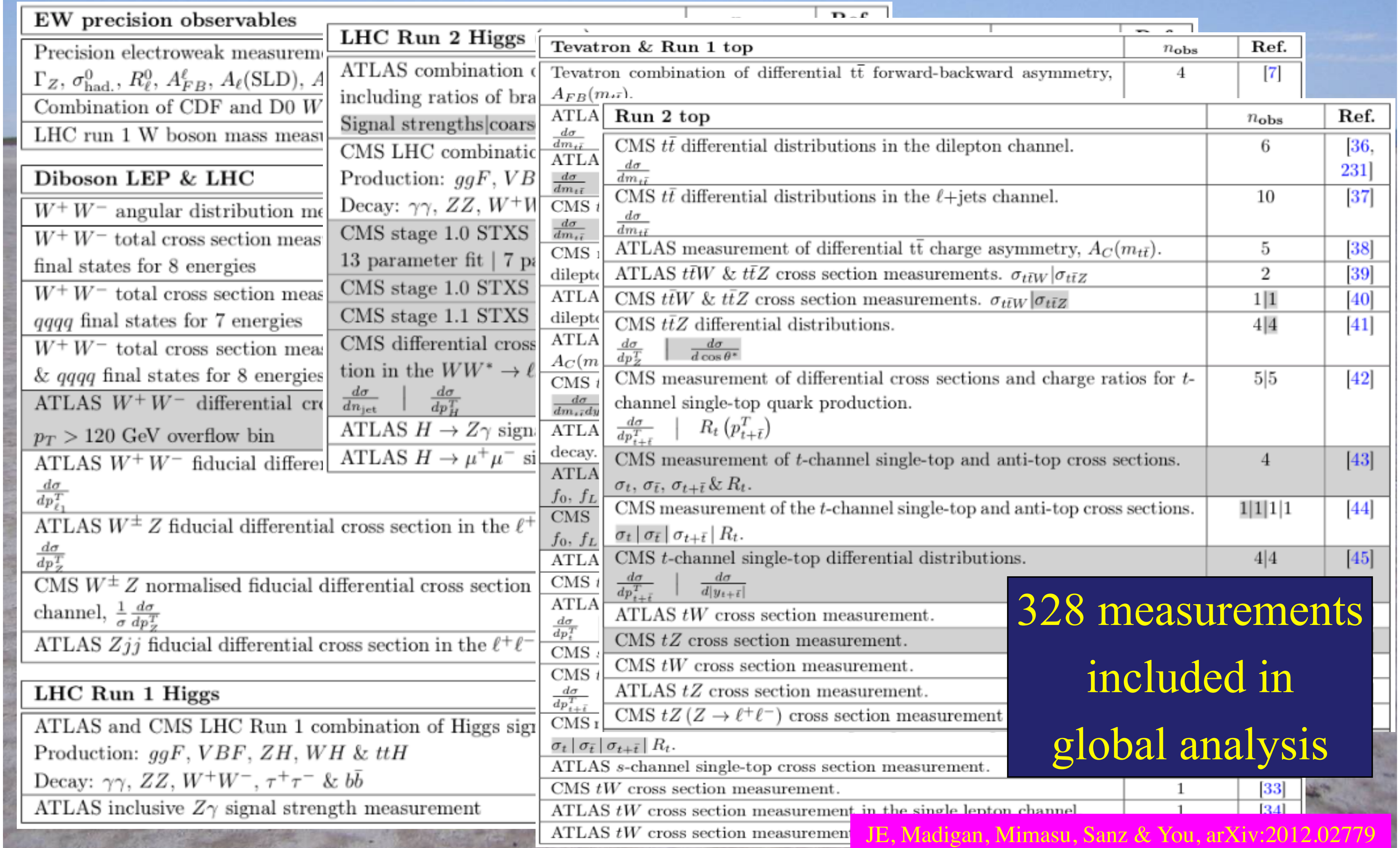
Data included in Global Fit



EW precision observables

Precision electroweak measurem

Γ_Z, $\sigma^0_{\rm had.}$, 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 combinatic 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 $WW^* \to \ell$ $\frac{d\sigma}{dn_{\rm jet}}$ | $\frac{d\sigma}{dp^T_H}$

ATLAS $H \to Z\gamma$ sign

ATLAS $H \to \mu^+\mu^-$ si

Tevatron & Run 1 top	$n_{\rm obs}$	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 dilepto

ATLA dilepto

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

CMS t $\frac{d\sigma}{dp^T_{t+\bar t}}$

CMS

$\sigma_t\,|\,\sigma_{\bar t}\,|\,\sigma_{t+\bar t}\,|\,R_t$.

ATLAS s-channel single-top cross section measurement.

CMS tW cross section measurement.	1	[33]
ATLAS tW cross section measurement in the single lepton channel	1	[34]
ATLAS tW cross section measuremen		

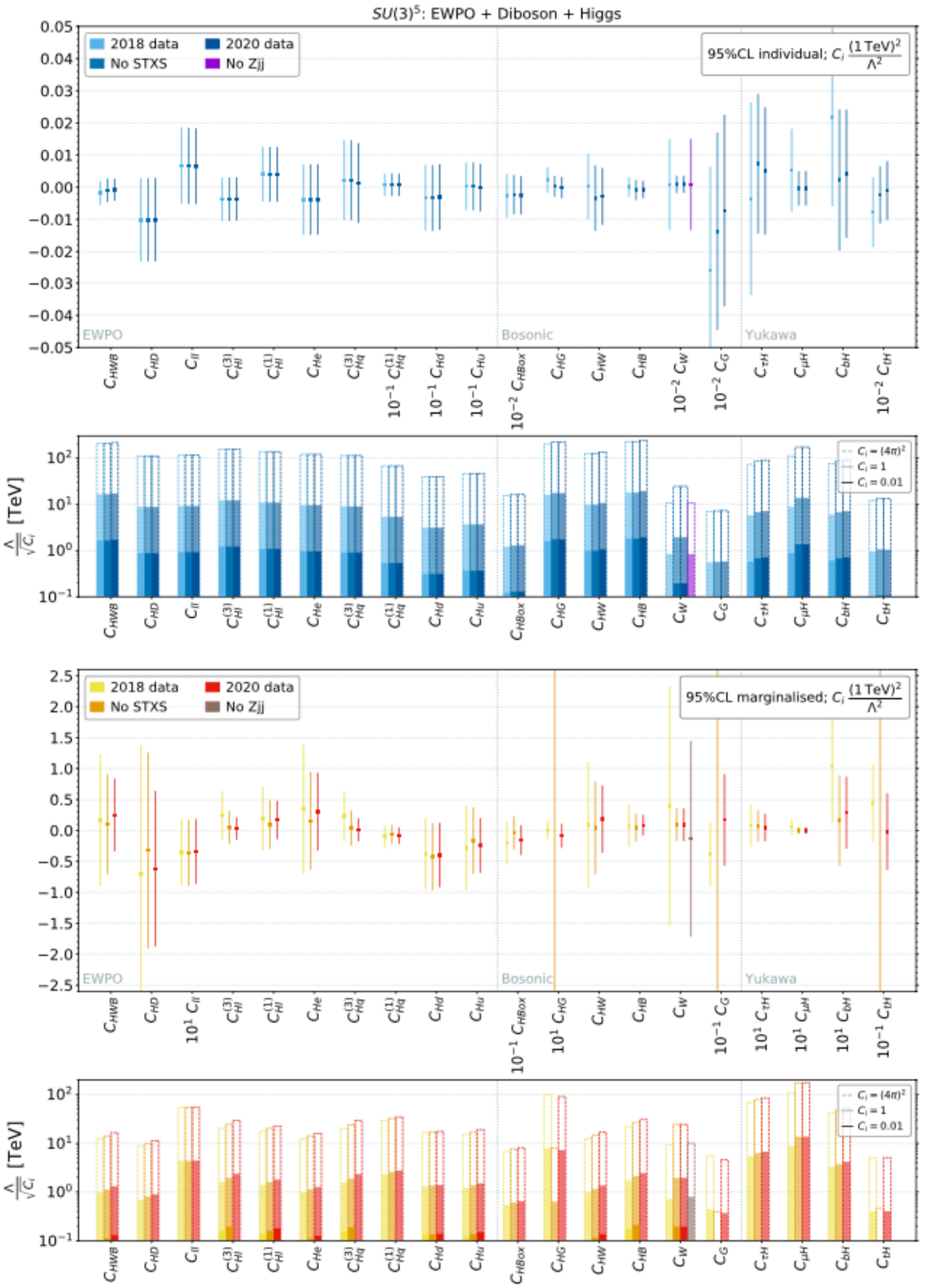
Run 2 top	$n_{\rm obs}$	Ref.
CMS $t\bar t$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar t}}$	6	[36, 231]
CMS $t\bar t$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar t}}$	10	[37]
ATLAS measurement of differential $t\bar t$ charge asymmetry, $A_C(m_{t\bar t})$.	5	[38]
ATLAS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW}\,|\,\sigma_{t\bar tZ}$	2	[39]
CMS $t\bar tW$ & $t\bar tZ$ cross section measurements. $\sigma_{t\bar tW}\,|\,\sigma_{t\bar tZ}$	1|1	[40]
CMS $t\bar tZ$ 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. $\sigma_t\,|\,\sigma_{\bar t}\,|\,\sigma_{t+\bar t}\,|\,R_t$.	1|1|1|1	[44]
CMS t-channel single-top differential distributions. $\frac{d\sigma}{dp^T_{t+\bar t}}$ | $\frac{d\sigma}{d\|y_{t+\bar t}\|}$	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		

328 measurements included in global analysis

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

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

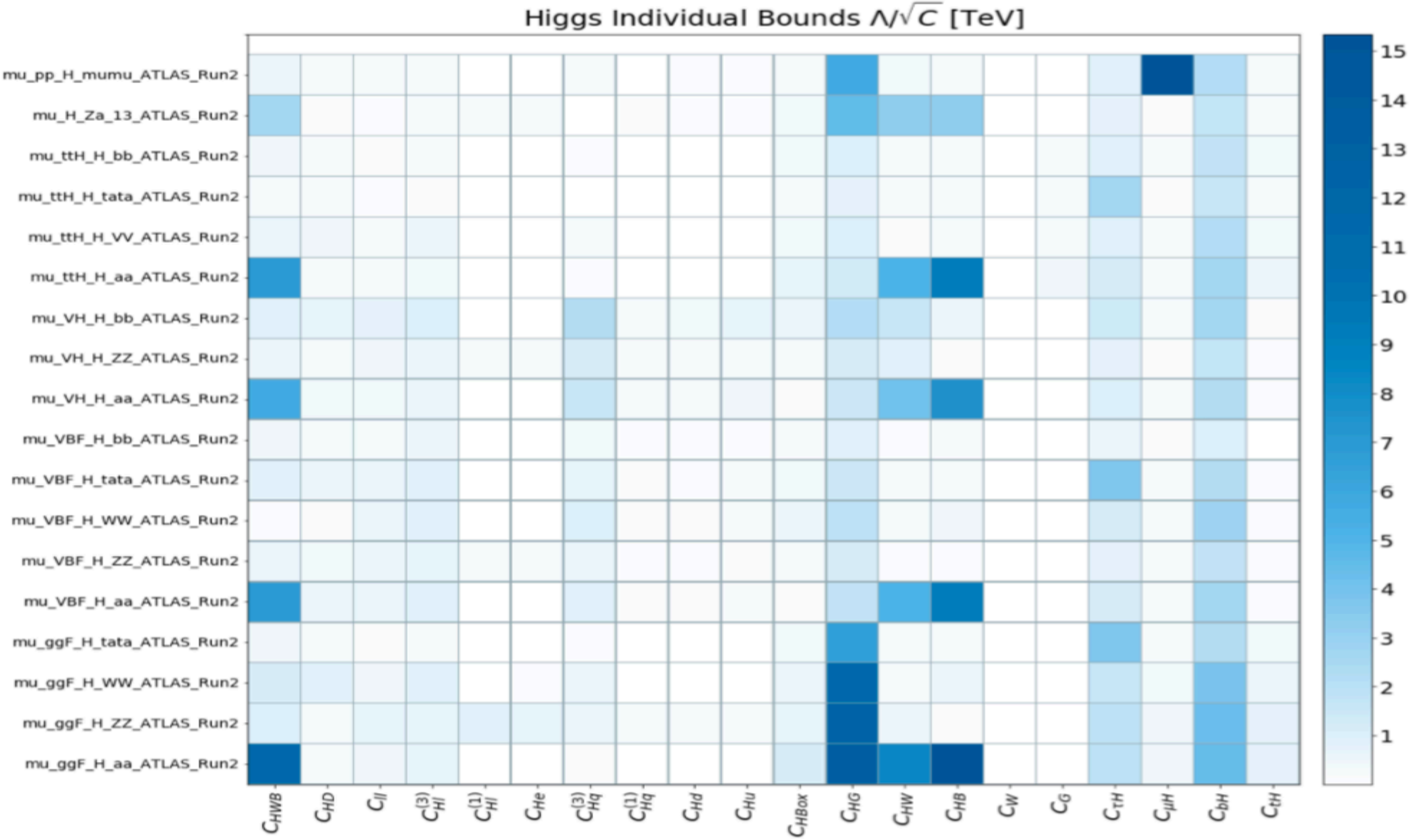
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

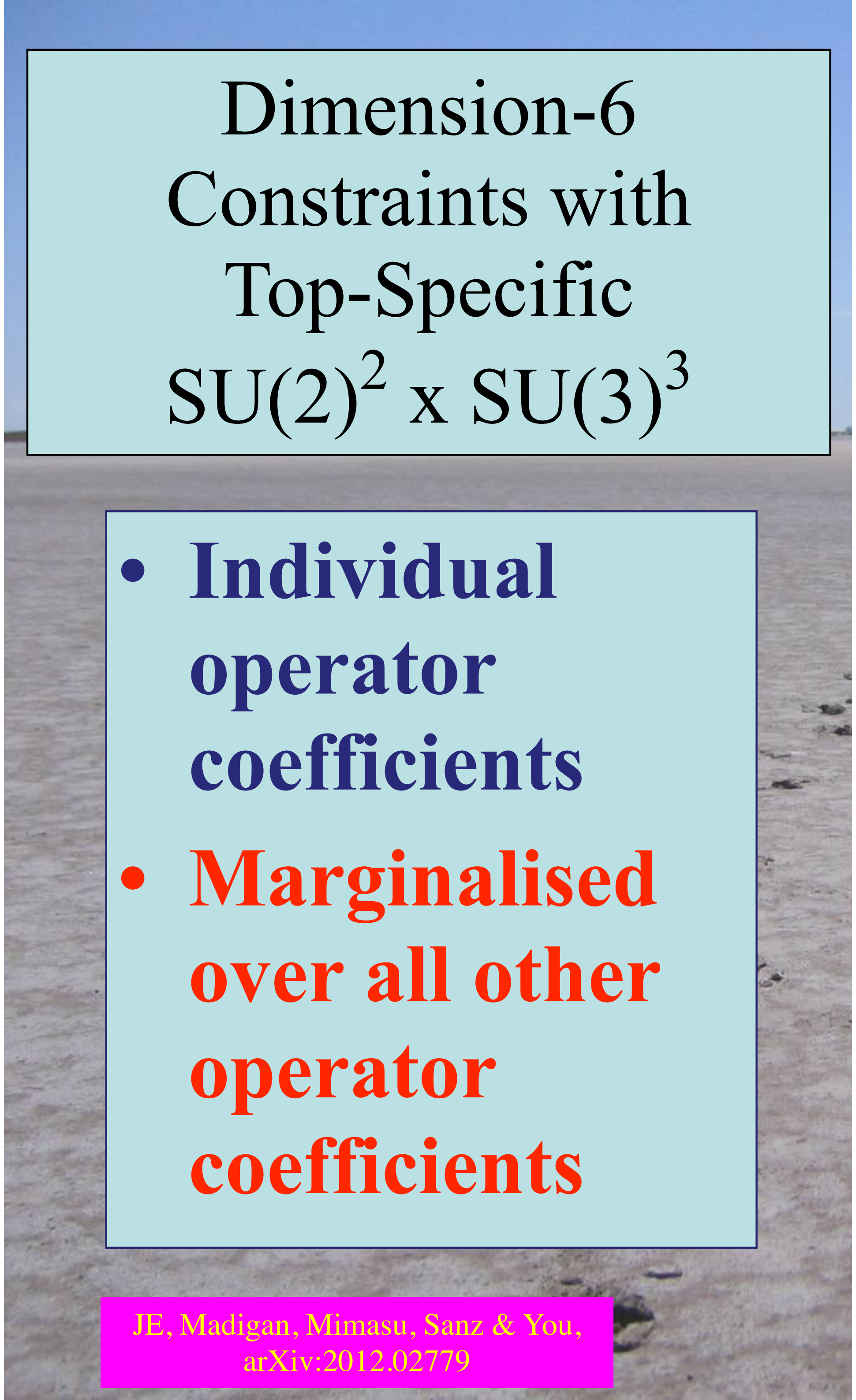


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Impacts of Measurements

$$\frac{X}{X_{SM}} = 1 + \sum_i \boxed{a_i^X} \frac{C_i}{\Lambda^2} + \cancel{\mathcal{O}\left(\frac{1}{\Lambda^4}\right)}$$

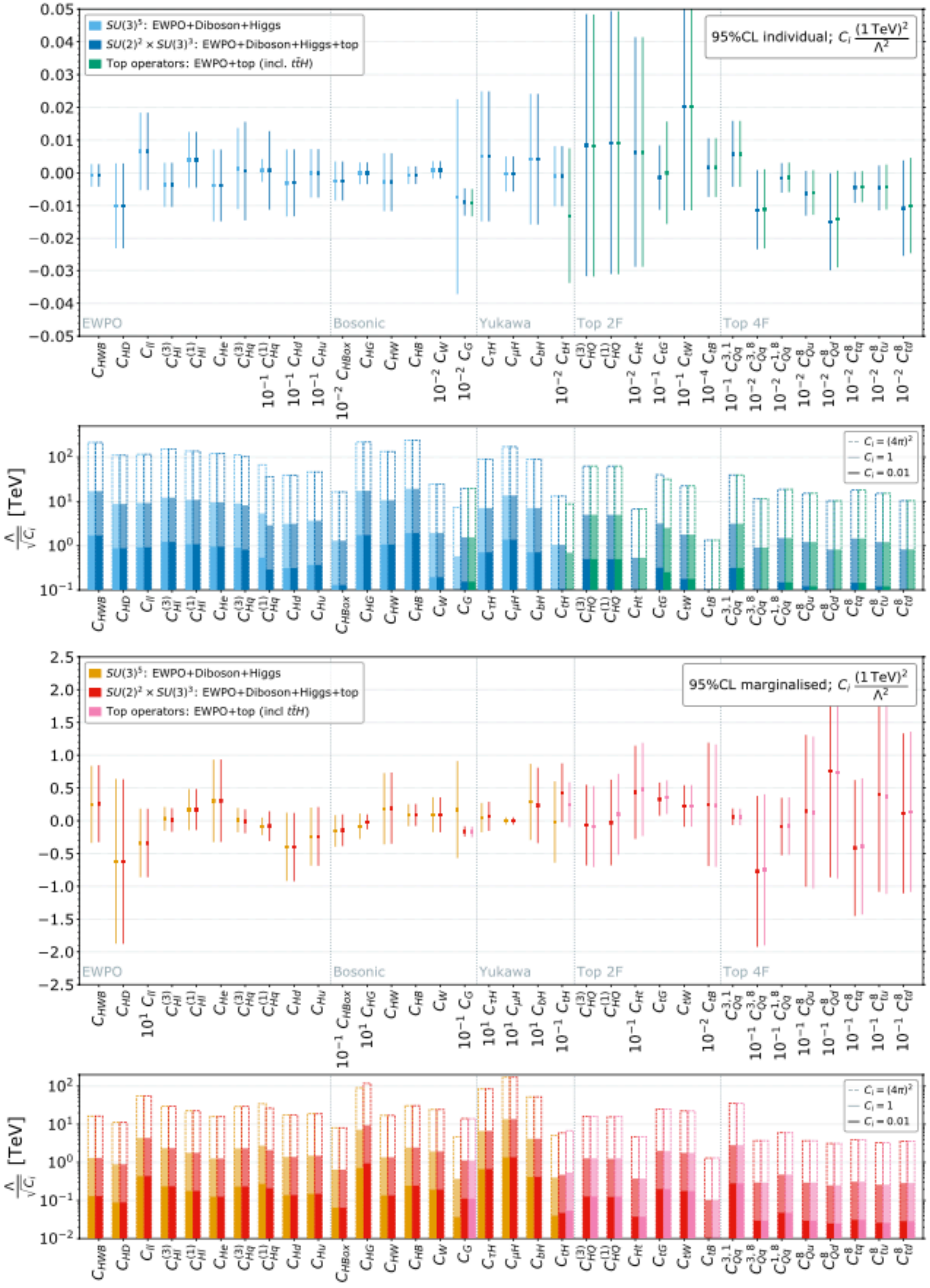




Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

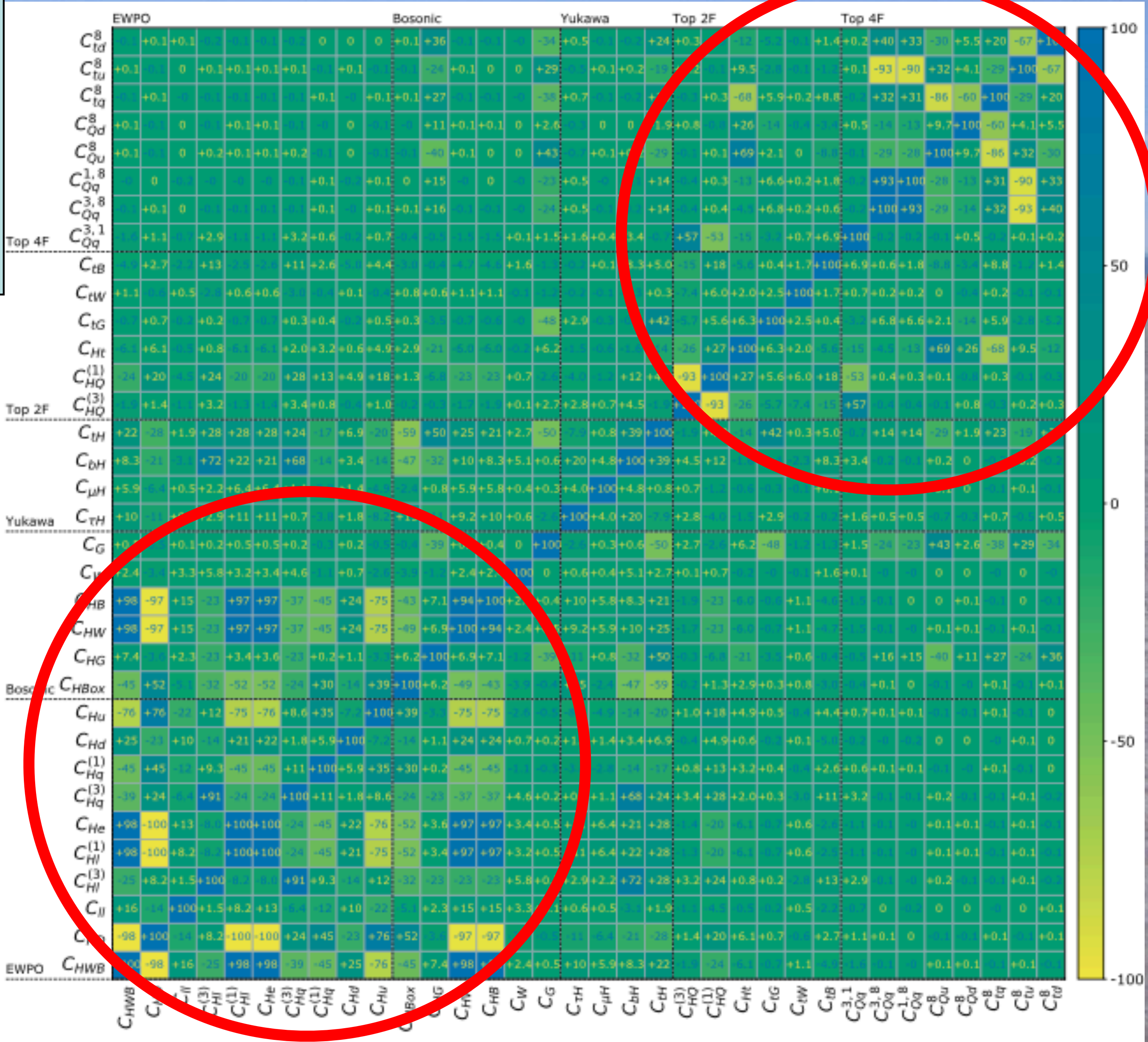
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

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



Correlation Analysis

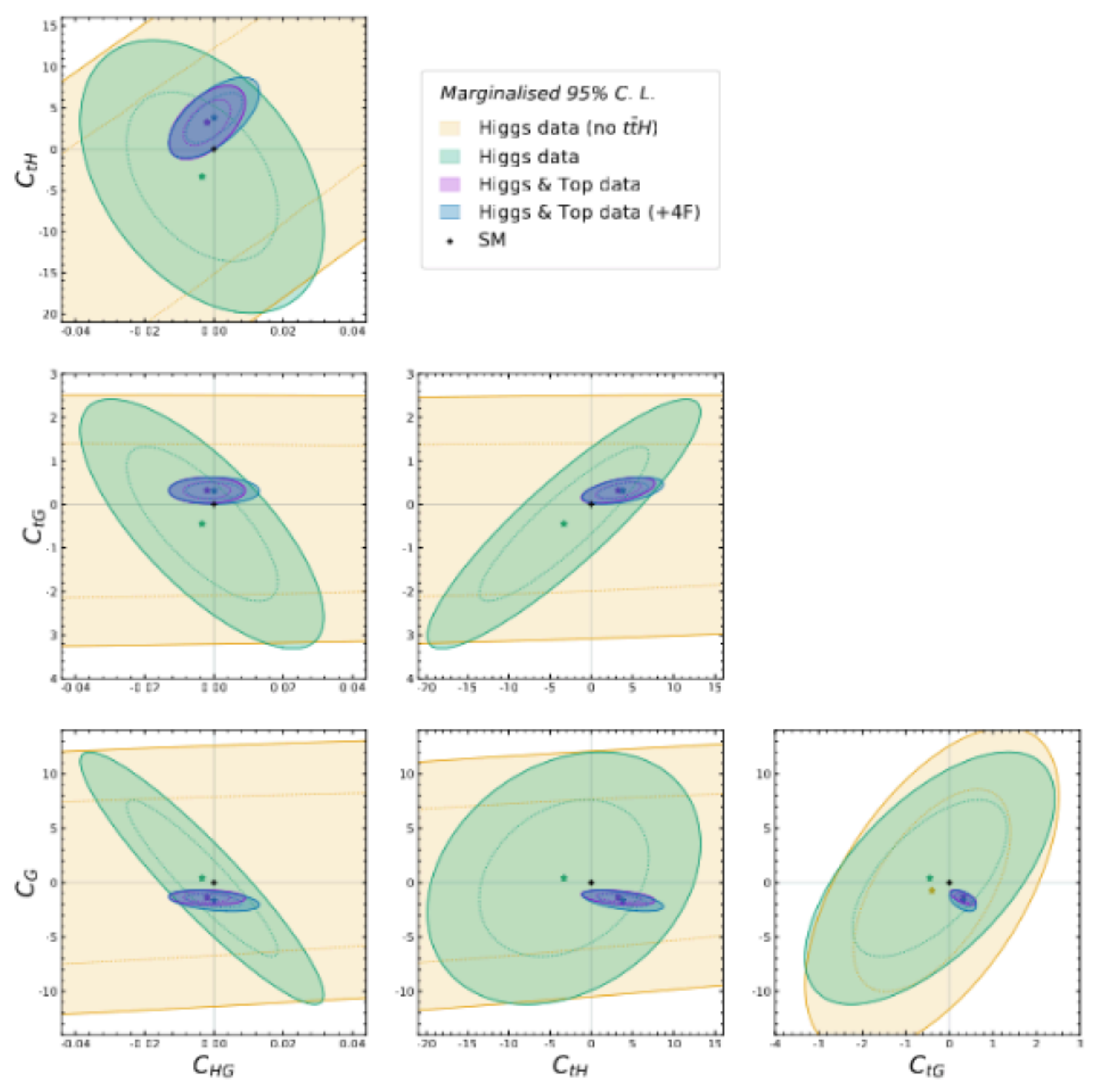
- EWPO and boson sectors correlated
- Also within top sector
- Weaker correlations between sectors



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

Example of Interplay between Data Sets

- **Higgs data**
- Include ttH
- Include top data
- Global analysis



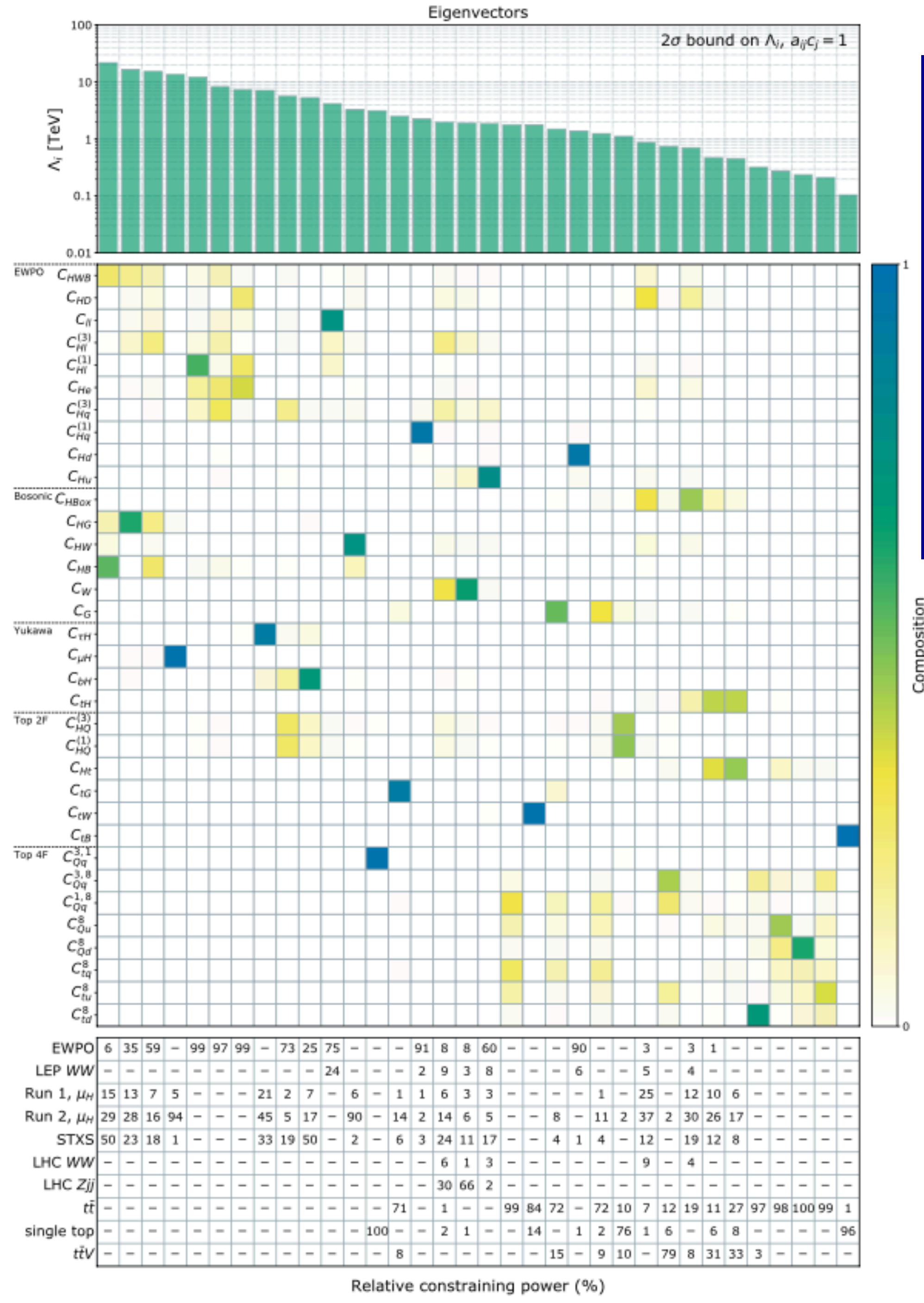
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Principal Component Analysis

- Diagonalise correlation matrix
- Analyze eigenvectors and eigenvalues
- Scales from 20 TeV to 100 GeV
- Strongest constraints from Electroweak, H

Less constrained operator combinations ➔

Relative importance (%)



EWPO	6	35	59	–	99	97	99	–	73	25	75	–	–	–	91	8	8	60	–	–	–	90	–	–	3	–	3	1	–	–	–	–	–	–
LEP WW	–	–	–	–	–	–	–	–	–	–	24	–	–	–	2	9	3	8	–	–	–	6	–	–	5	–	4	–	–	–	–	–	–	–
Run 1, μ_H	15	13	7	5	–	–	–	21	2	7	–	6	–	1	1	6	3	3	–	–	–	–	1	–	25	–	12	10	6	–	–	–	–	–
Run 2, μ_H	29	28	16	94	–	–	–	45	5	17	–	90	–	14	2	14	6	5	–	–	8	–	11	2	37	2	30	26	17	–	–	–	–	–
STXS	50	23	18	1	–	–	–	33	19	50	–	2	–	6	3	24	11	17	–	–	4	1	4	–	12	–	19	12	8	–	–	–	–	–
LHC WW	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	1	3	–	–	–	–	–	–	9	–	4	–	–	–	–	–	–	–
LHC Zjj	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	30	66	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$t\bar{t}$	–	–	–	–	–	–	–	–	–	–	–	–	–	71	–	1	–	–	99	84	72	–	72	10	7	12	19	11	27	97	98	100	99	1
single top	–	–	–	–	–	–	–	–	–	–	–	–	100	–	–	2	1	–	–	14	–	1	2	76	1	6	–	6	8	–	–	–	–	96
$t\bar{t}V$	–	–	–	–	–	–	–	–	–	–	–	–	–	8	–	–	–	–	–	–	15	–	9	10	–	79	8	31	33	3	–	–	–	–

Relative constraining power (%)

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

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

Contributions to SMEFT Coefficients

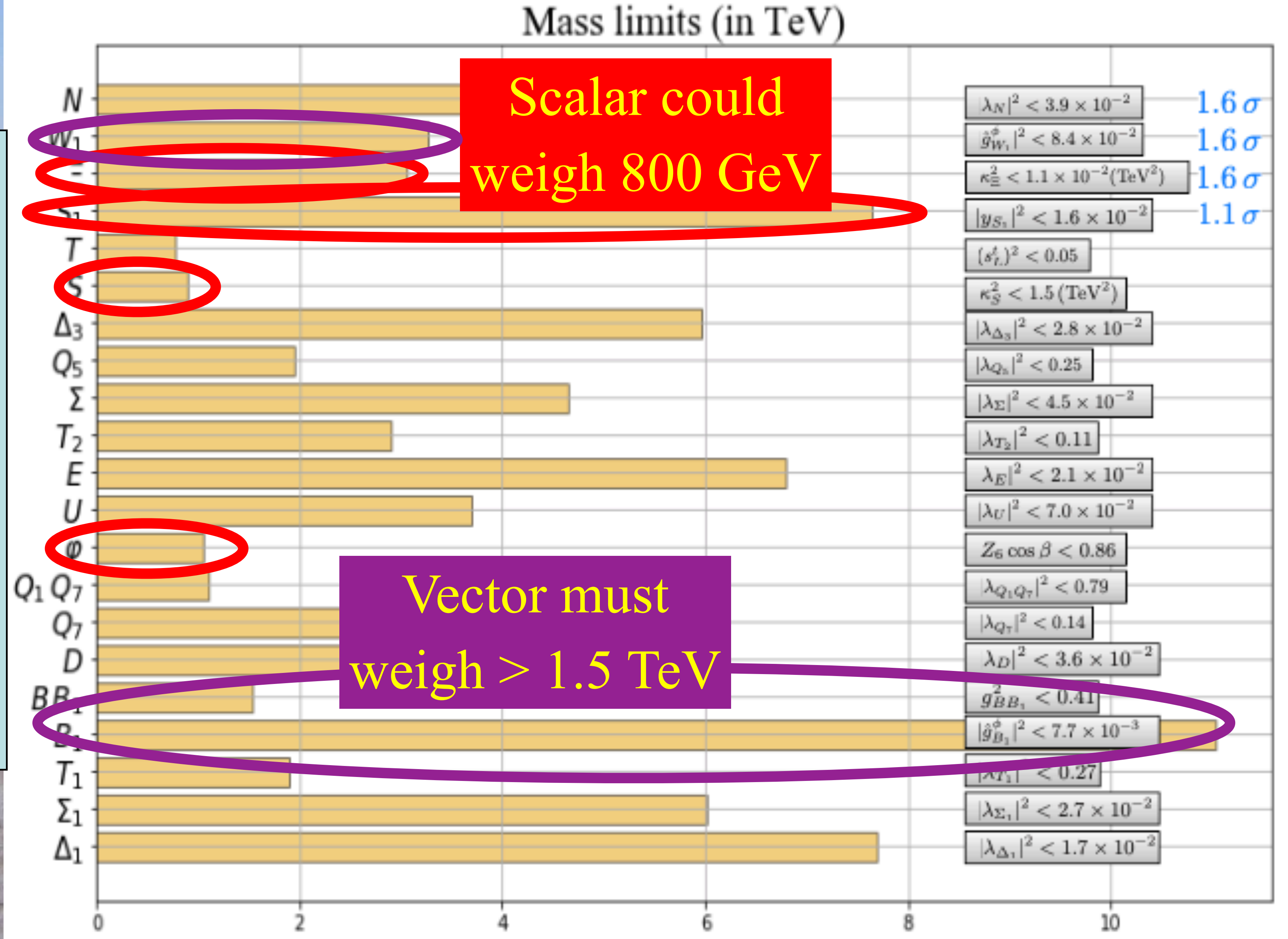
Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
Spin zero S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Spin zero Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1 Vector	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
Spin zero φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$ Vector						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Model	C_{HG}	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}
U		$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$	
D		$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$
Q_5							$-\frac{1}{2}$		$\frac{y_b}{2}$
Q_7						$\frac{1}{2}$		$\frac{y_t}{2}$	
T_1		$-\frac{5}{8}$	$-\frac{3}{16}$	$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$
T_2		$-\frac{5}{8}$	$\frac{3}{16}$	$-\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$
T	$-\frac{M_T^2}{v^2}\frac{\alpha_s(0.02)}{8\pi}$			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$	

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

Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 400 GeV if coupling = 1



Scalar could weigh 800 GeV

Vector must weigh > 1.5 TeV

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

SMEFT Constraints on Light Stops

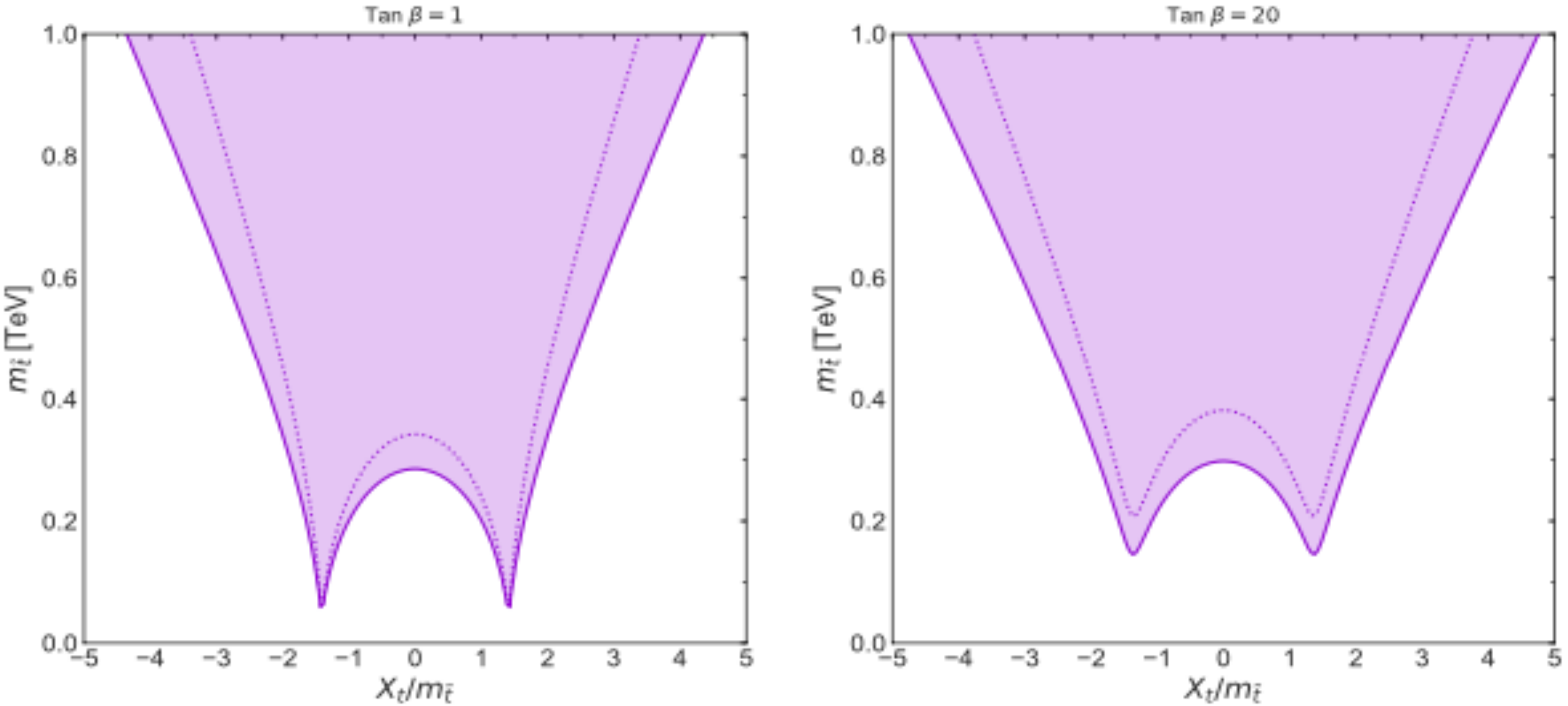
From quantum loop corrections:

$$C_{HG} = \frac{g_s^2}{12}\frac{h_t^2}{(4\pi)^2}\left[\left(1 + \frac{1}{12}\frac{c_{2\beta}g'^2}{h_t^2}\right) - \frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HB} = \frac{17g'^2}{144}\frac{h_t^2}{(4\pi)^2}\left[\left(1 + \frac{31}{102}\frac{c_{2\beta}g'^2}{h_t^2}\right) - \frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HW} = \frac{g^2}{16}\frac{h_t^2}{(4\pi)^2}\left[\left(1 - \frac{1}{6}\frac{c_{2\beta}g'^2}{h_t^2}\right) - \frac{2}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

$$C_{HWB} = -\frac{gg'}{24}\frac{h_t^2}{(4\pi)^2}\left[\left(1 + \frac{1}{2}\frac{c_{2\beta}g^2}{h_t^2}\right) - \frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right],$$

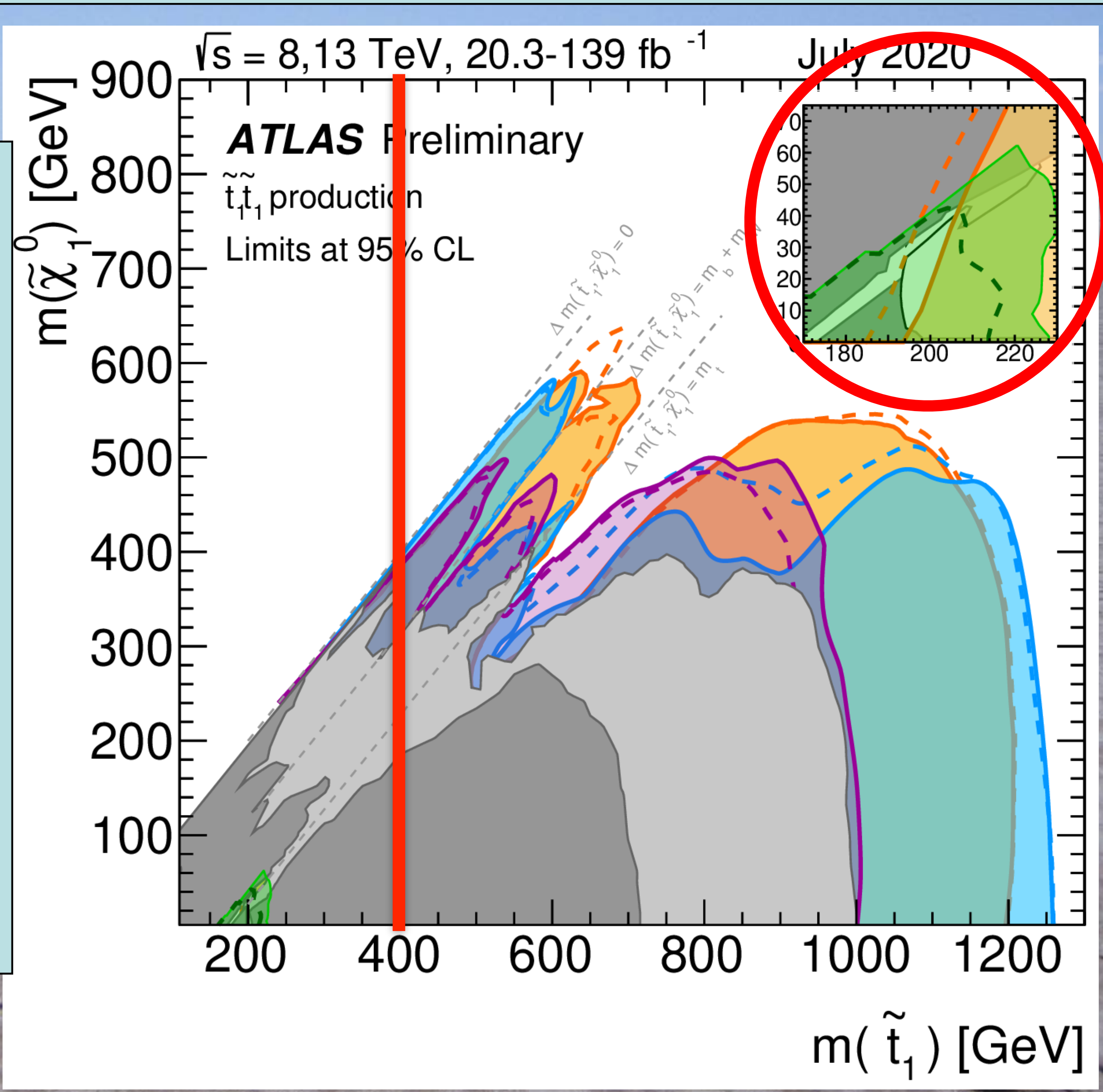


(Almost) model-independent lower limit on stop squark mass

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

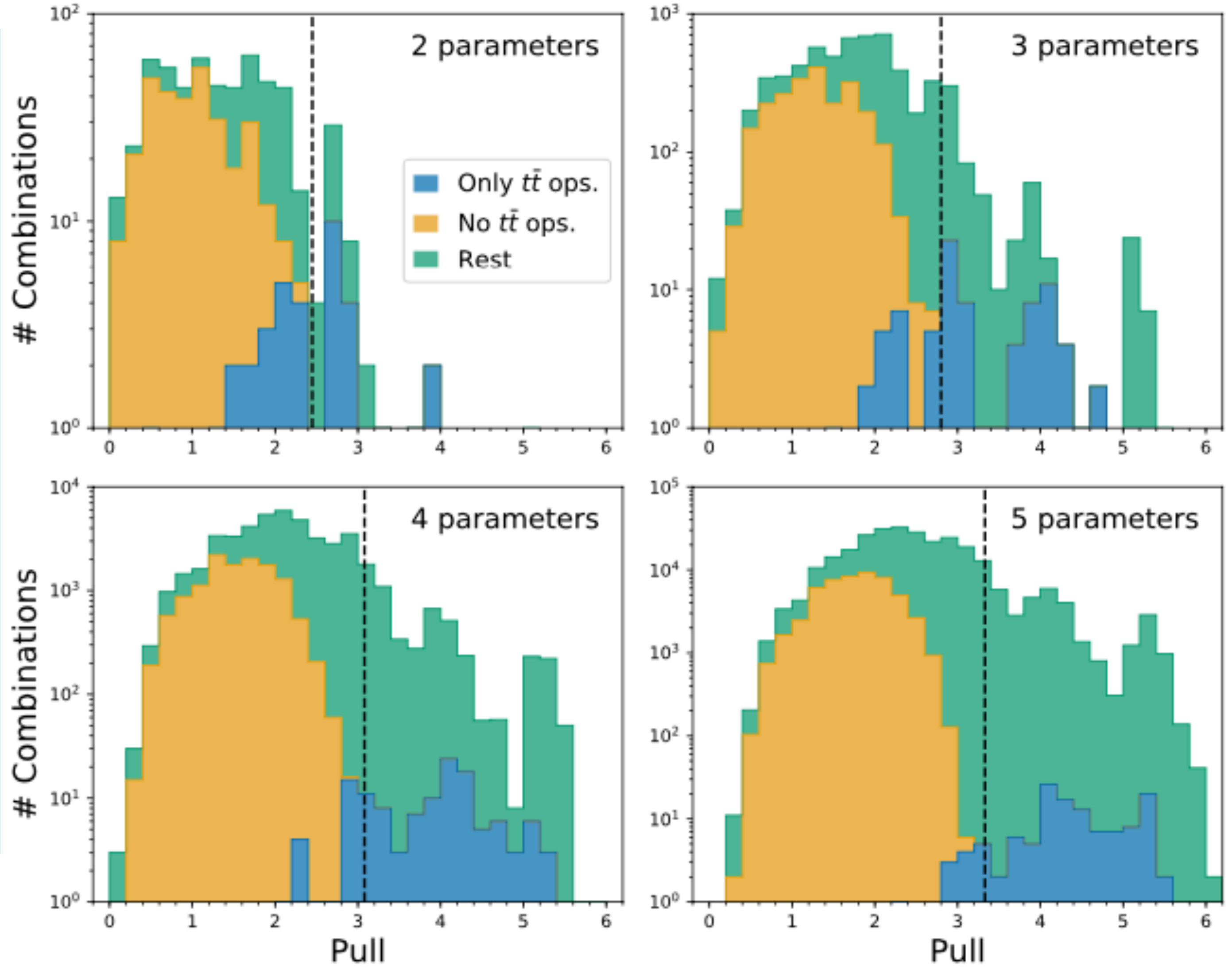
Direct Search Constraints on Light Stops

- Patchwork of many model-dependent searches
- Indirect constraint excludes low-mass region (almost) model-independently



Model-Independent BSM Survey

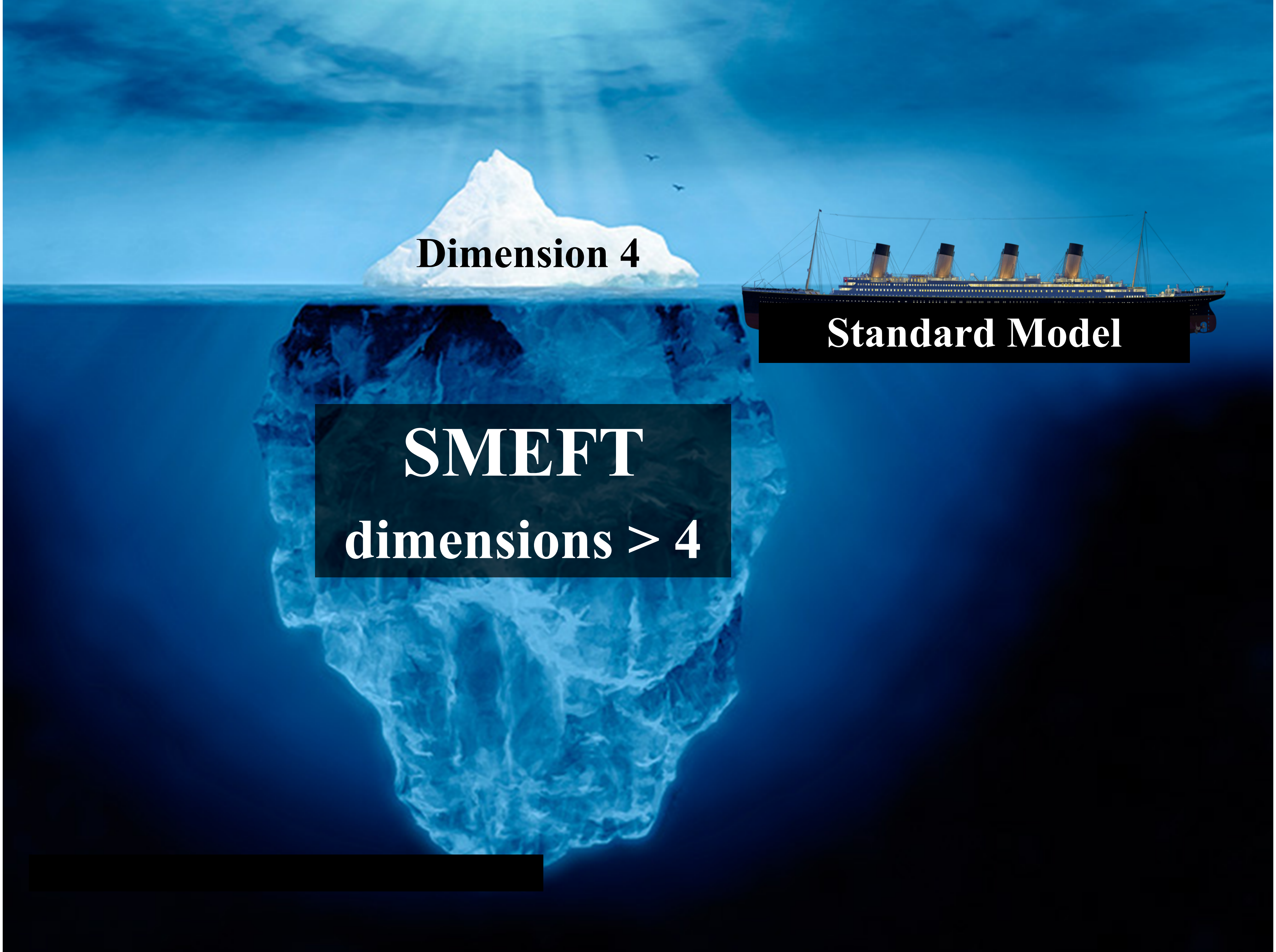
- **Top-less sector fits SM very well**
- Top sector does not fit so well
- Overall, pulls not excessive
- **No hint of BSM**



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

Summary

- **Remember Sun Tzu:** search for new physics indirectly as well as directly
- SMEFT is an effective, model-independent tool for probing indirectly possible physics beyond the SM
- It can be used to analyze jointly precision electroweak, diboson and top quark data from LHC and elsewhere
- Our current analysis indicates that the scale of new physics is probably > TeV
- Useful for assessing sensitivities of proposed future accelerators



Dimension 4

Standard Model

SMEFT

dimensions > 4

[redacted]