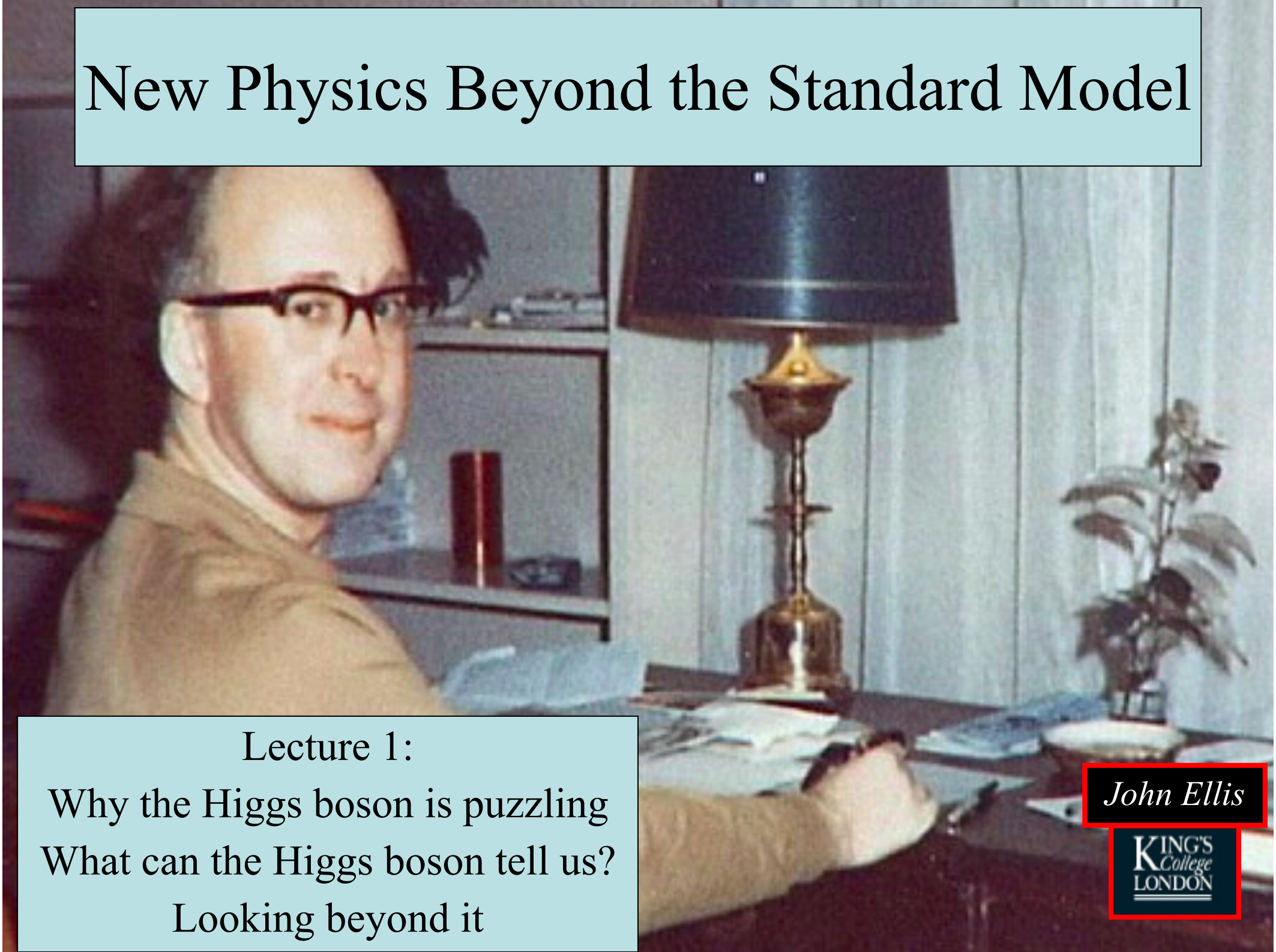
New Physics Beyond the Standard Model



Lecture 1:

Why the Higgs boson is puzzling

What can the Higgs boson tell us?

Looking beyond it

John Ellis

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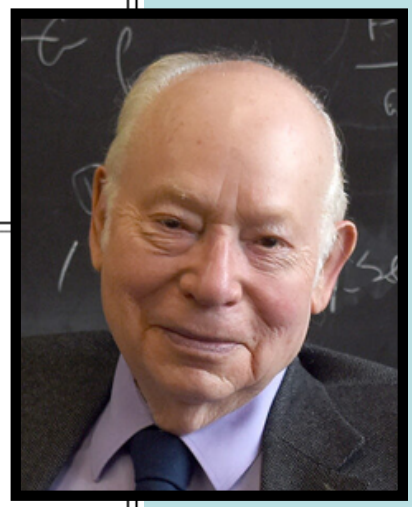
Where are we?

Summary of the Standard Model

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

L_L	$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	e_R^-, μ_R^-, τ_R^-	$(\mathbf{1},\mathbf{1},-2)$
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	$(\mathbf{3},\mathbf{1},-2/3)$

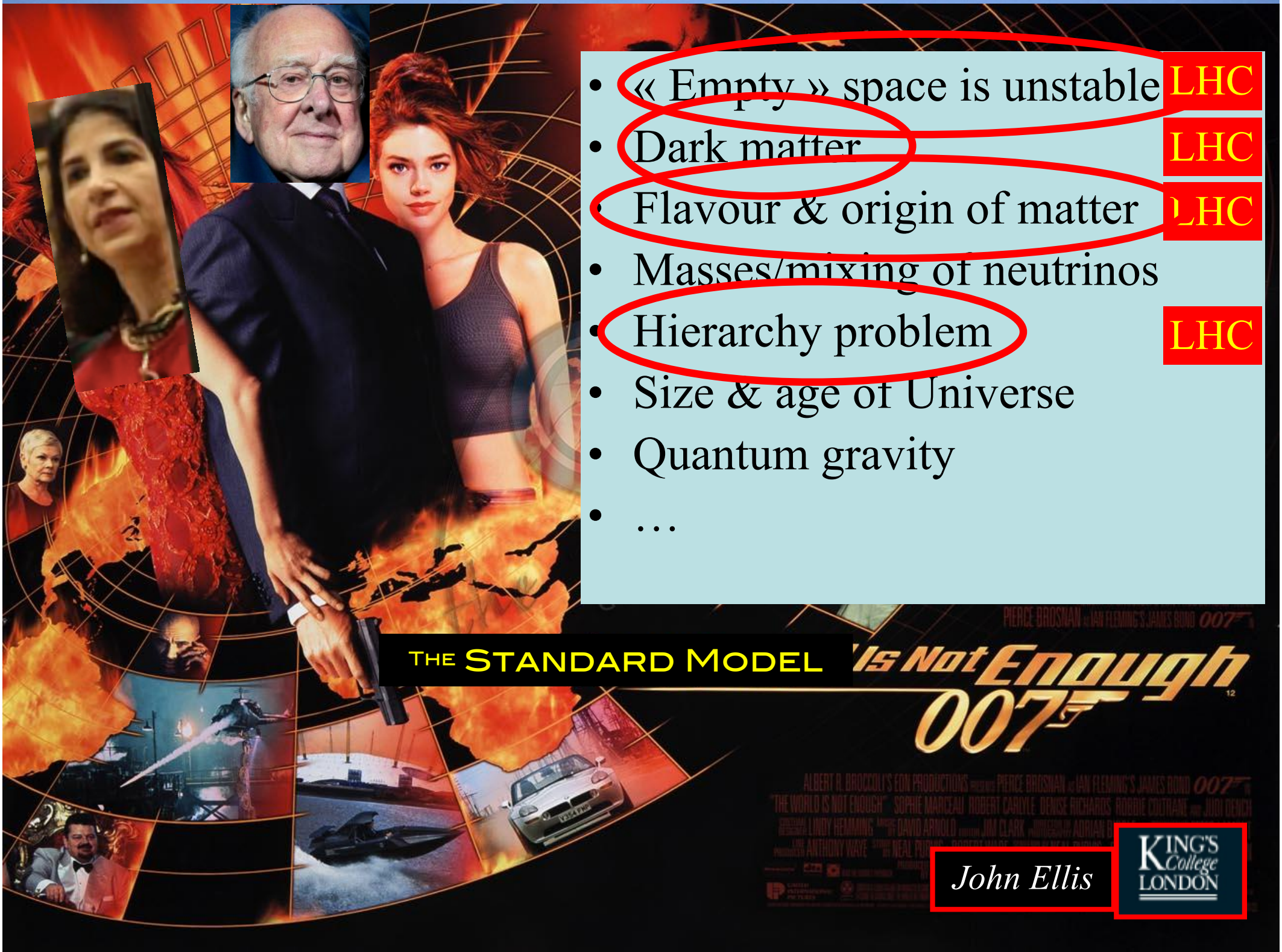


- Lagrangian:

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

Tested < 0.1% before LHC

Testing now in progress



- « Empty » space is unstable LHC
- Dark matter LHC
- Flavour & origin of matter LHC
- Masses/mixing of neutrinos
- Hierarchy problem LHC
- Size & age of Universe
- Quantum gravity
- …

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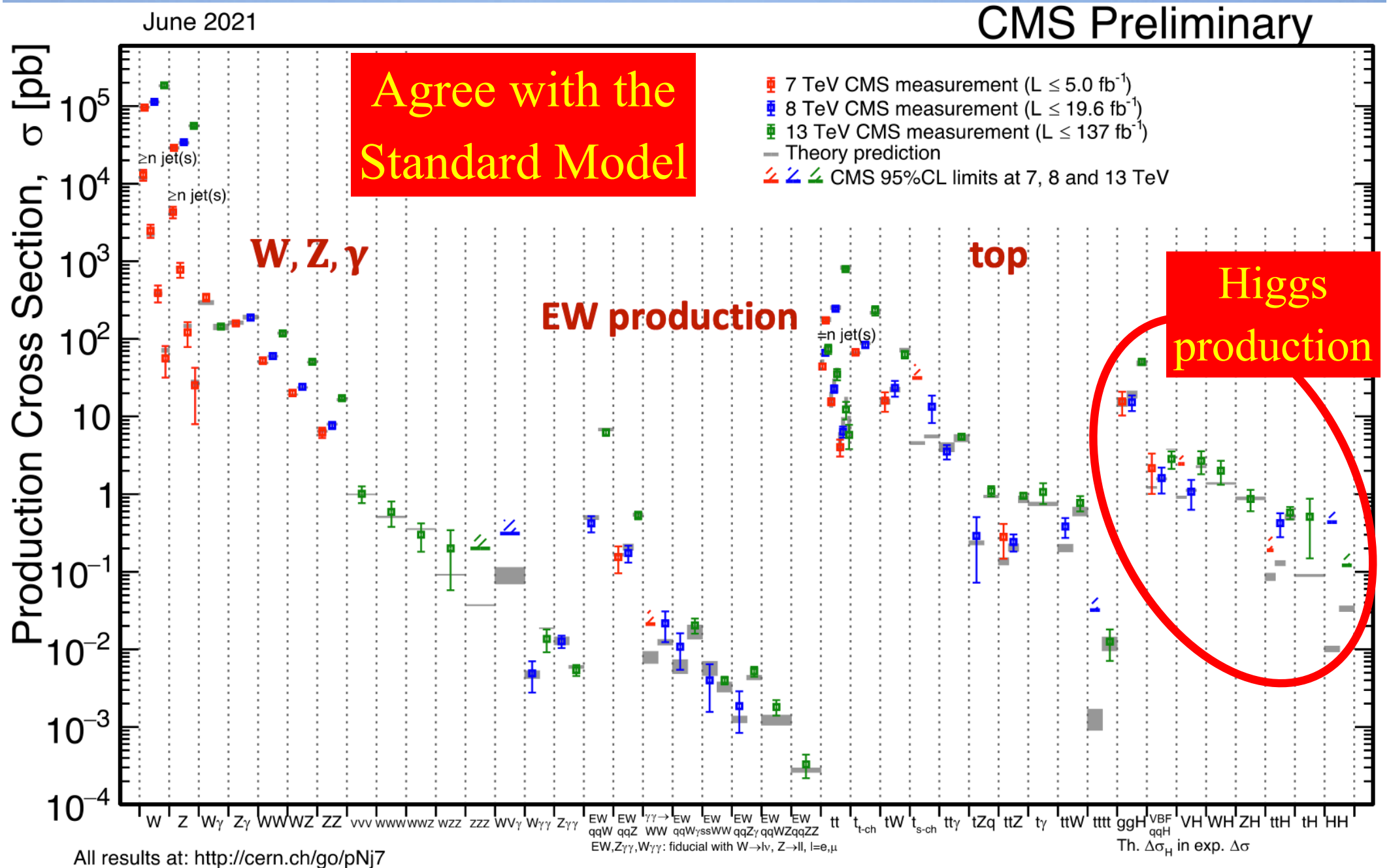
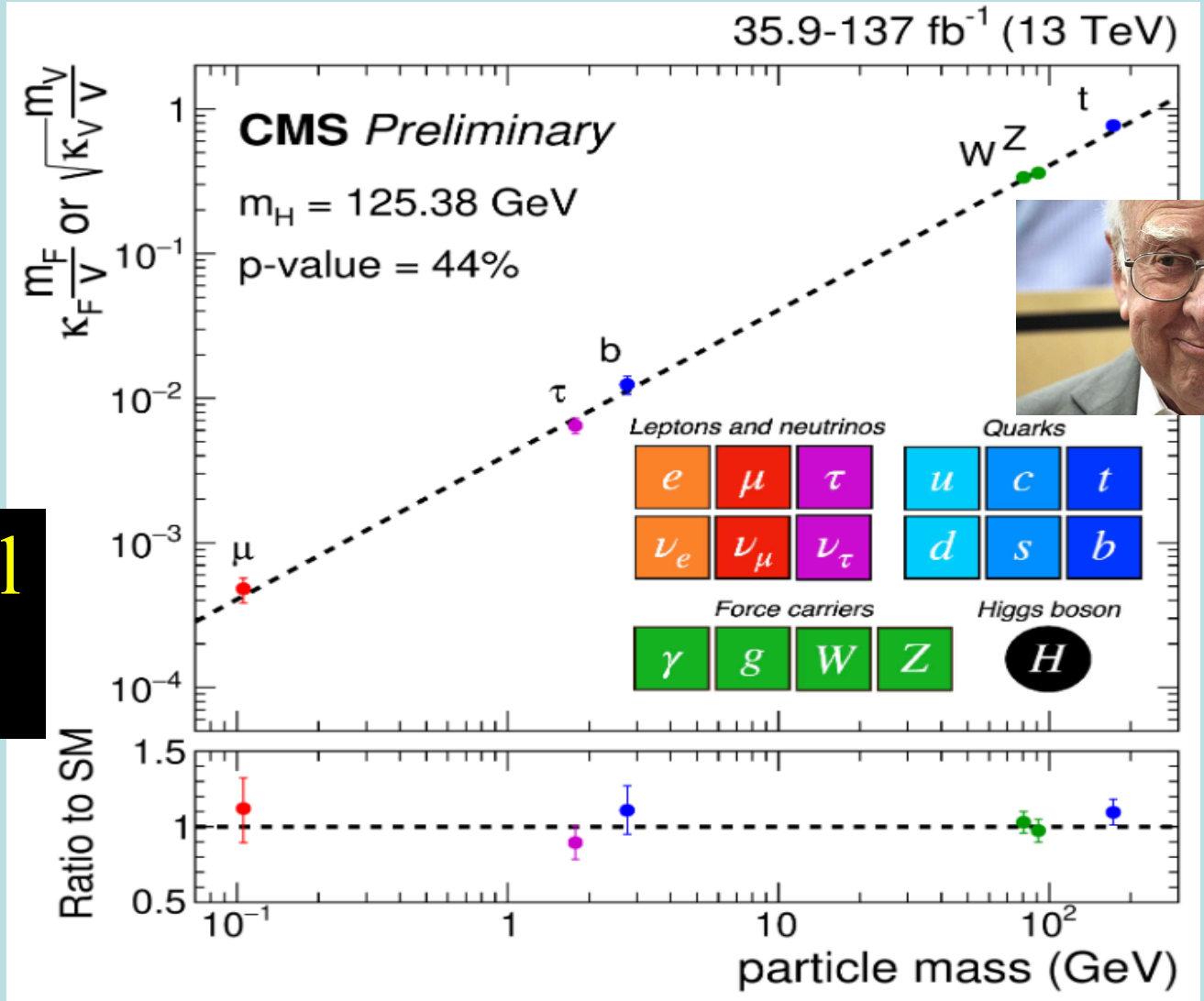
LHC Measurements

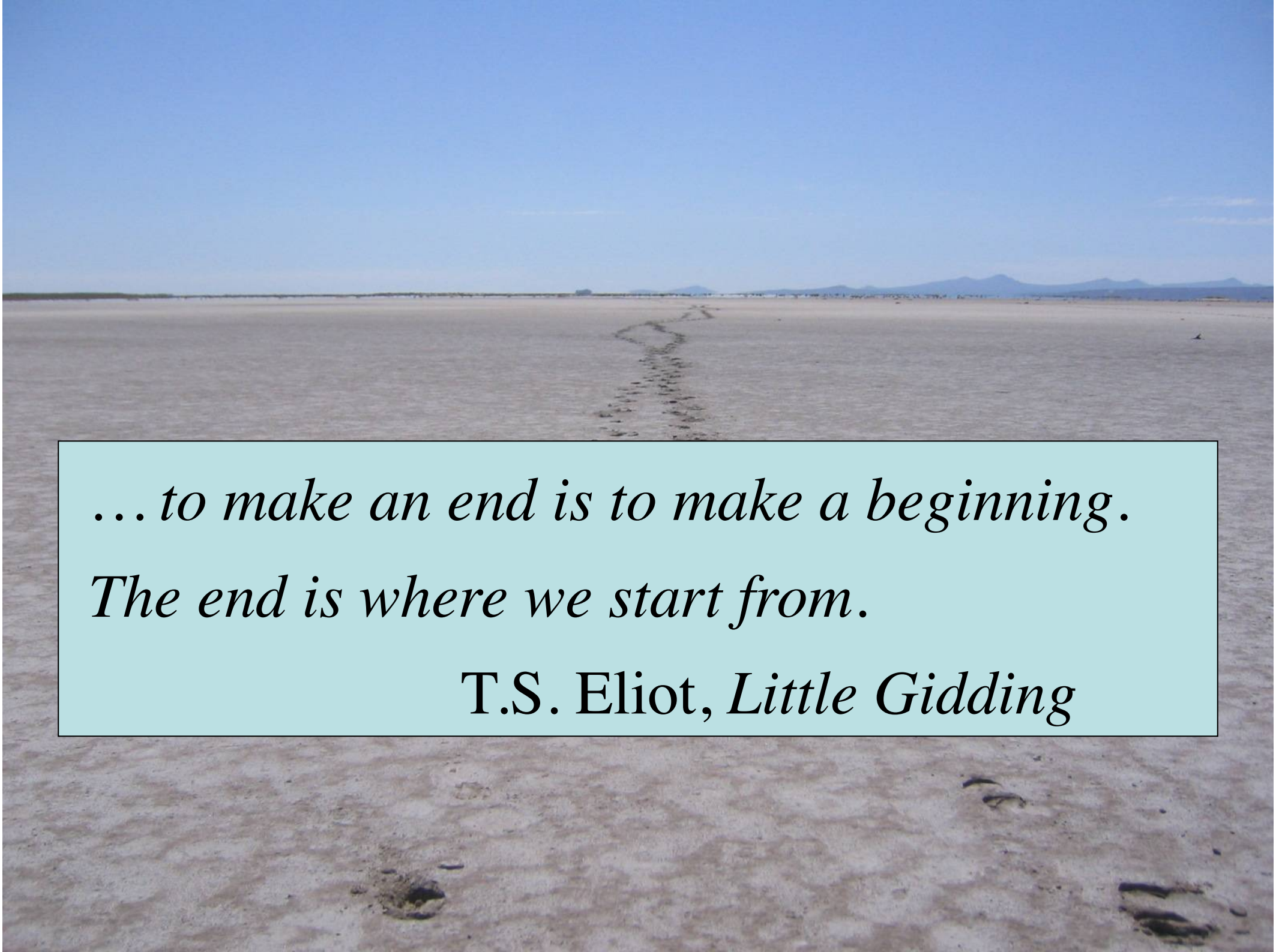


It Walks and Quacks like a Higgs

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

Global fit





…to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*

Everything about Higgs is Puzzling

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

- 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?

Parameters of the Standard Model

- Gauge sector:
  - 3 gauge couplings: g_3, g_2, g'
  - 1 strong CP-violating phase
- Yukawa interactions:
  - 3 charged-lepton masses
  - 6 quark masses
  - 4 CKM angles and phase
- Higgs sector:
  - 2 parameters: μ, λ
- **Total: 19 parameters**

Unification?

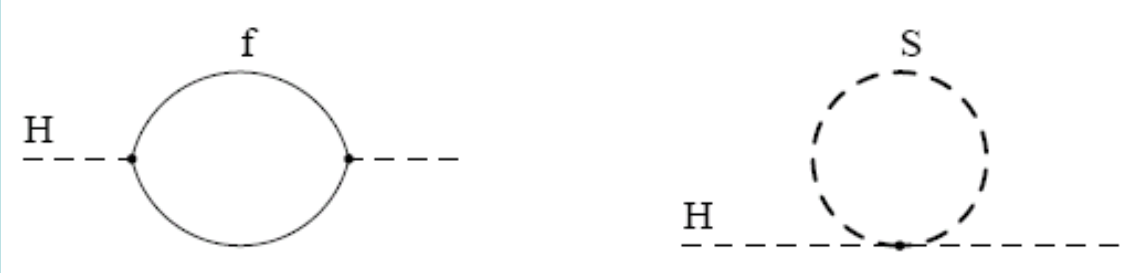
Flavour?

Mass?

Naturalness of hierarchy of mass scales

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{{y_f}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \text{ x } 2$$

Supersymmetry!

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, inflation, **dark matter**, ..

Should it have Collapsed already?

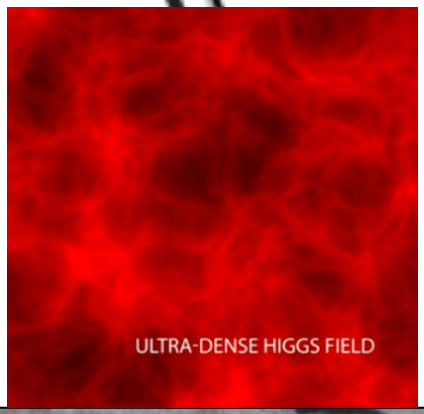
Fluctuate over barrier
in the early Universe?

Not if
infinite wall:
Supersymmetry?

We are here

Tunnel through
barrier now?

Quantum fluctuations



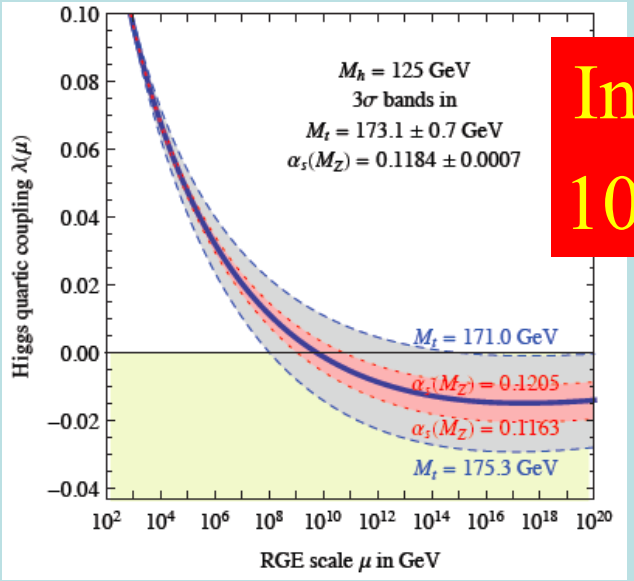
The Big Crunch

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization

$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\log\frac{Q^2}{v^2}} \qquad \lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4}\log\frac{Q}{v}$$

- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable

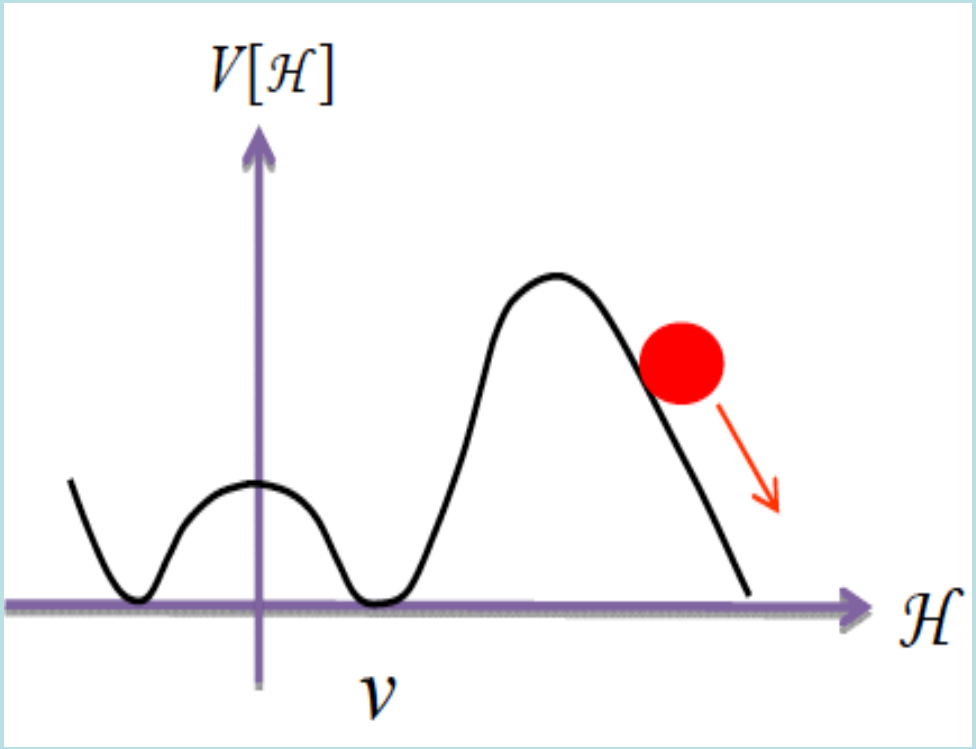


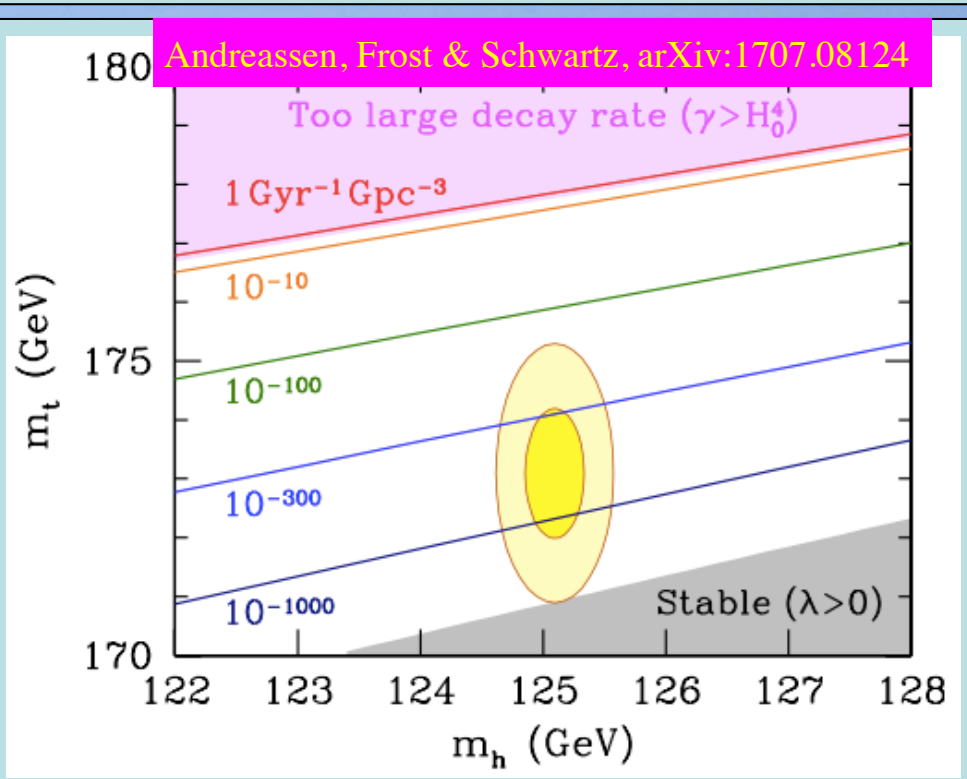
Instability @ $10^{11.4\pm0.8}$ GeV

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Vacuum could be stabilized by **Supersymmetry**

Vacuum Instability in the Standard Model





- Sensitive to α_s as well as m_t and M_H
- Instability scale:

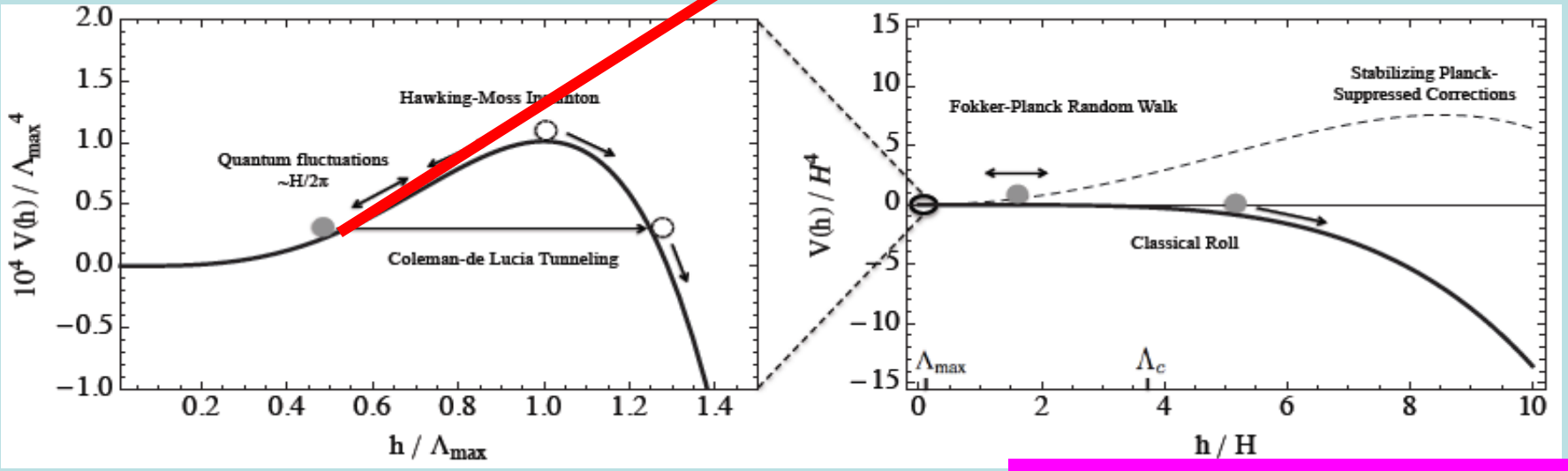
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

$$\log_{10}\frac{\Lambda_I}{\mathrm{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\mathrm{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\mathrm{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 172.47 \pm 0.35$ GeV → $\log_{10}(\Lambda/\mathrm{GeV}) = 11.4 \pm 0.8$

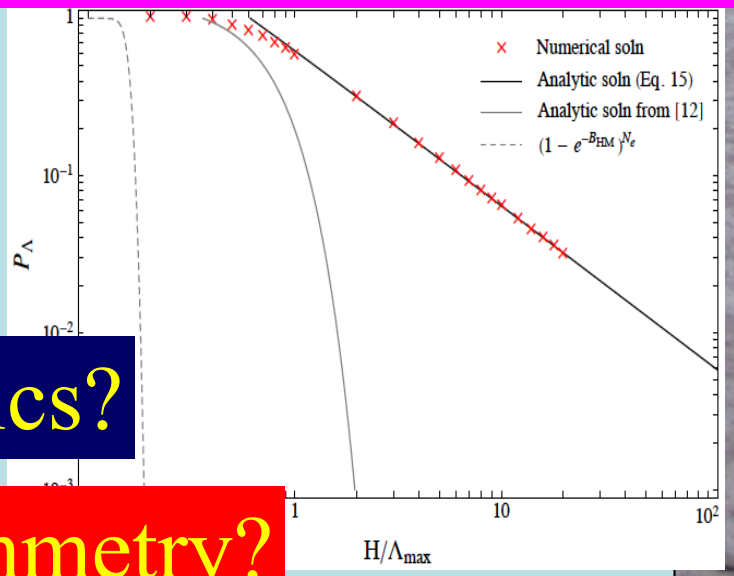
Instability during Inflation?

- Do inflation fluctuations drive us over the hill?



- Then Fokker-Planck evolution
- Big Crunch probably eats us!
  - Disaster if so

Hook, Kearney, Shakya & Zurek: arXiv:1404.5953



Stabilize vacuum with BSM physics?

"Build a wall" with supersymmetry?

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, *The Art of War*

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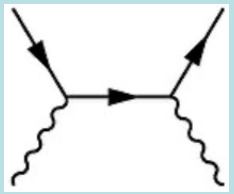
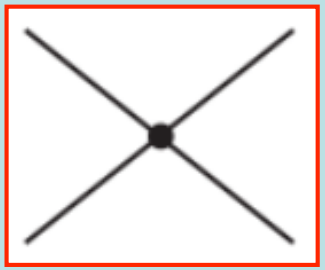
Effective Field Theories (EFTs)
a long and glorious History

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

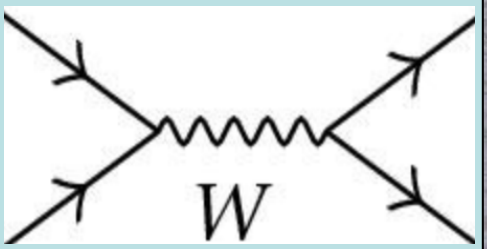


- **Fermi's four-fermion theory of the weak force**

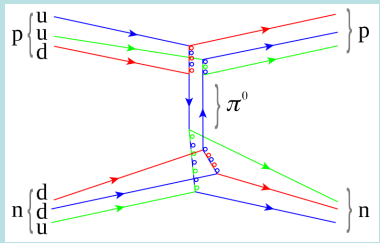


- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?

- 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**: $(\partial\pi\partial\pi)\pi\pi$ 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

Summarize Analysis Framework

- Include all leading dimension-6 operators?

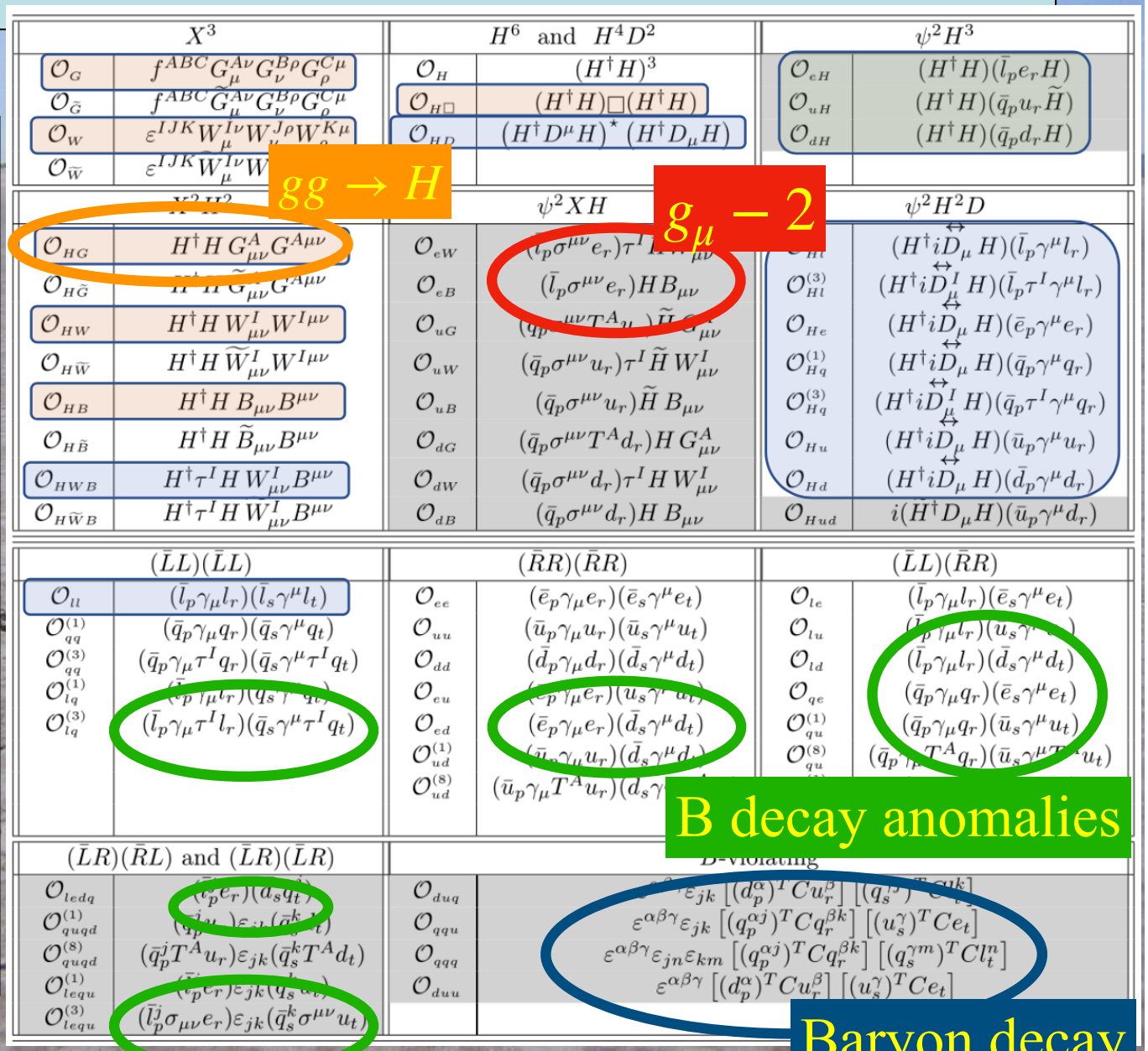
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions

  (maybe there is something special about top quark?)
- 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 Operators in Detail

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



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

Operators included in Global Fit

- 20 operators in flavour-universal $SU(3)^5$ fit

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

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

- 34 operators in top-specific $SU(2)^2$ x $SU(3)^3$ fit

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

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

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

Top 2F: $\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$

Top 4F: $\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$ (2.12)

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

Search for BSM

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	1	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_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
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					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Model	C_{HG}	C_{Hq}^3	C_{Hq}^1	$(C_{Hq}^3)_{33}$	$(C_{Hq}^1)_{33}$	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	$-\frac{M_T^2}{v^2}\frac{\alpha_s(0.02)}{8\pi}$			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$	

Spin zero

Spin zero

Vector

Spin zero

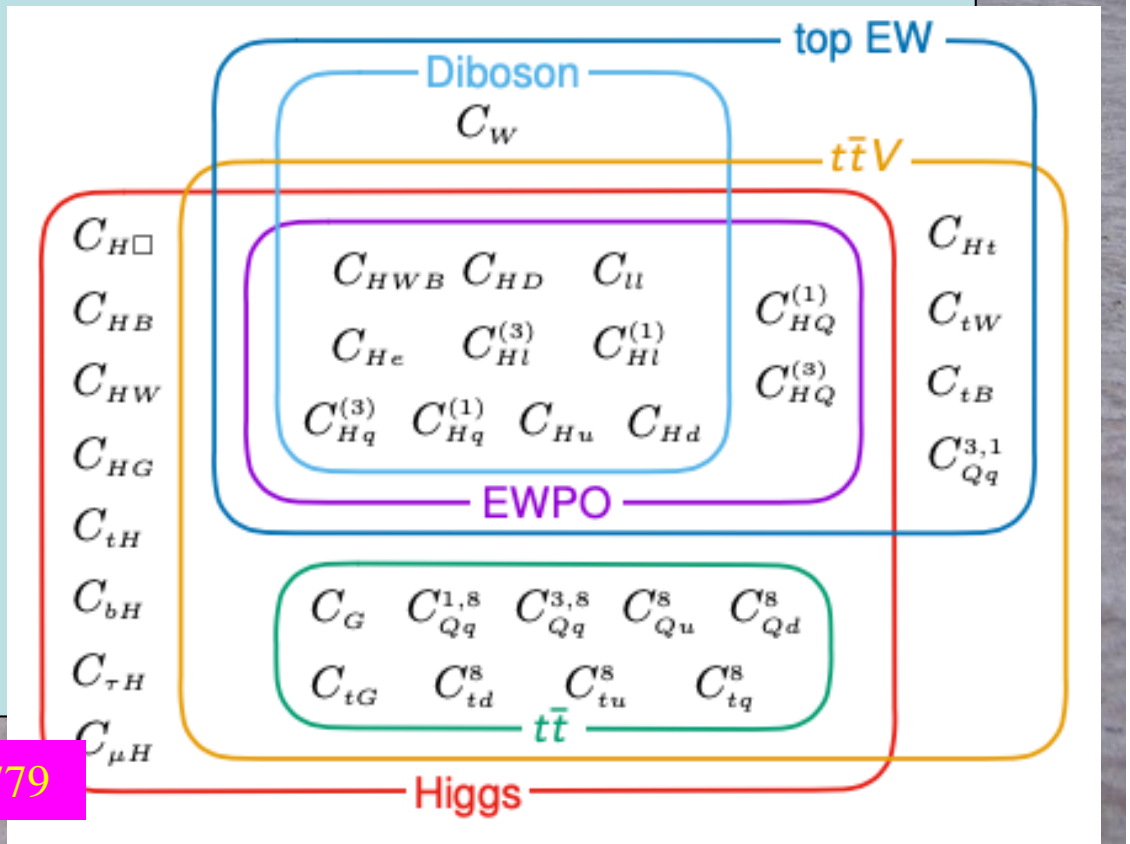
Vector

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 & 2

- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level
  - **Supersymmetry**



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

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 measu

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 p
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]

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 $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	2	[39]
CMS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}\|\sigma_{t\bar{t}Z}$	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. $\sigma_t \,\|\, \sigma_{\bar{t}} \,\|\, \sigma_{t+\bar{t}} \,\|\, R_t$.	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		
$\sigma_t \,\|\, \sigma_{\bar{t}} \,\|\, \sigma_{t+\bar{t}} \,\|\, R_t$.		
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 measurement		

328 measurements included in global analysis

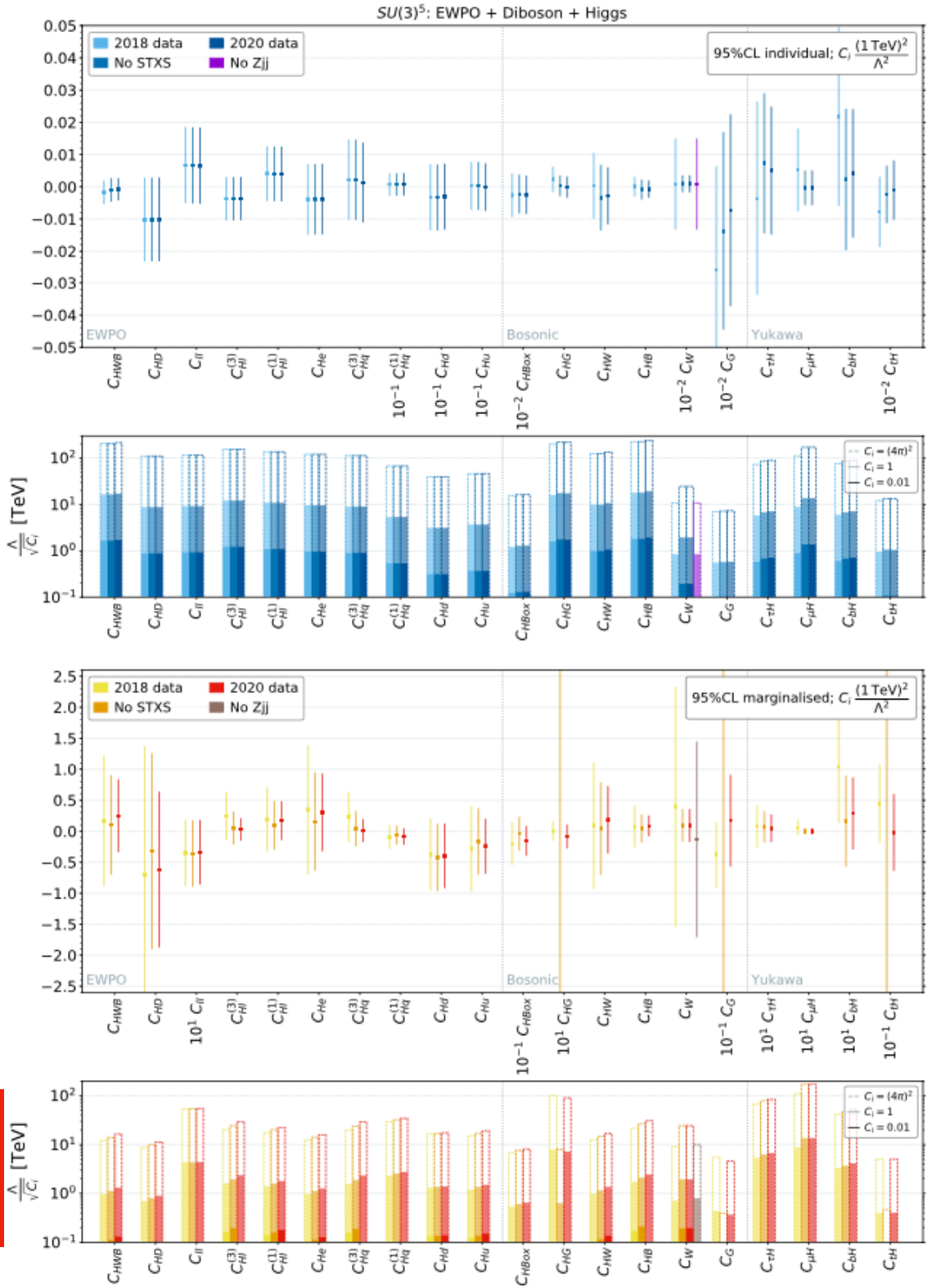
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

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

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

No significant deviations from SM

JE, Madigan, Min
arXiv:2012.02779

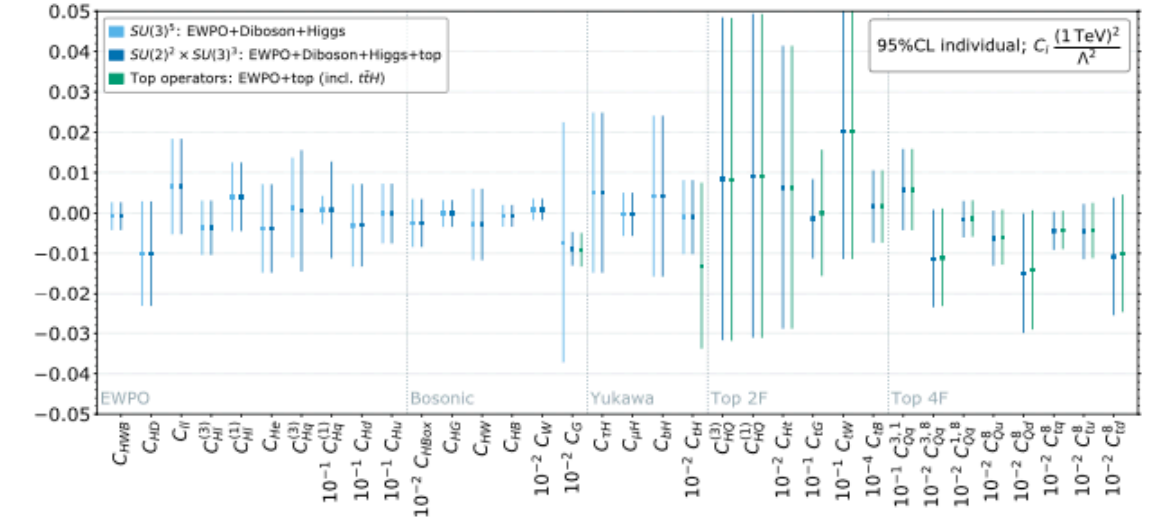


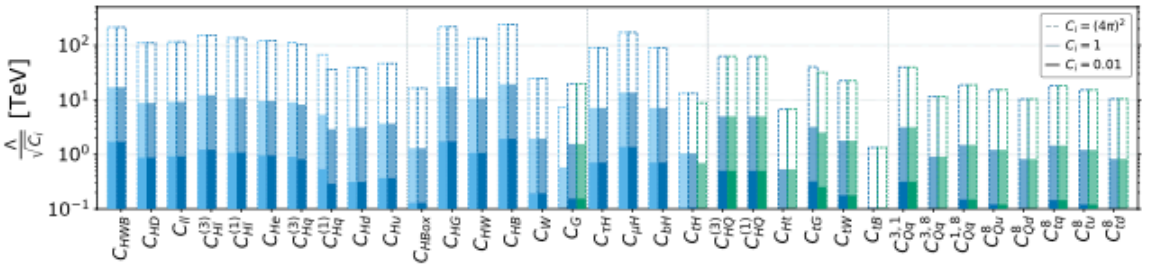
Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

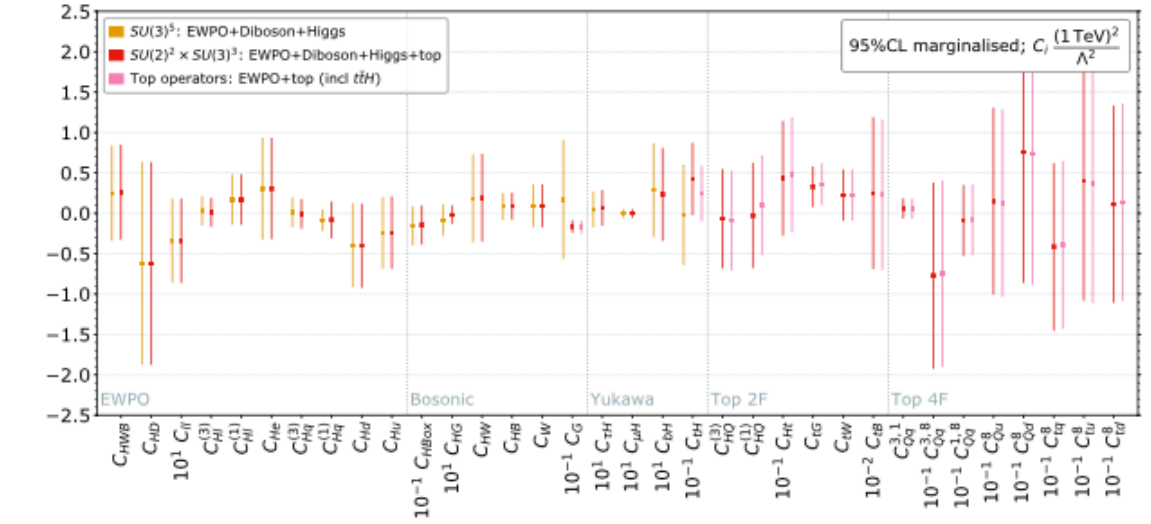
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

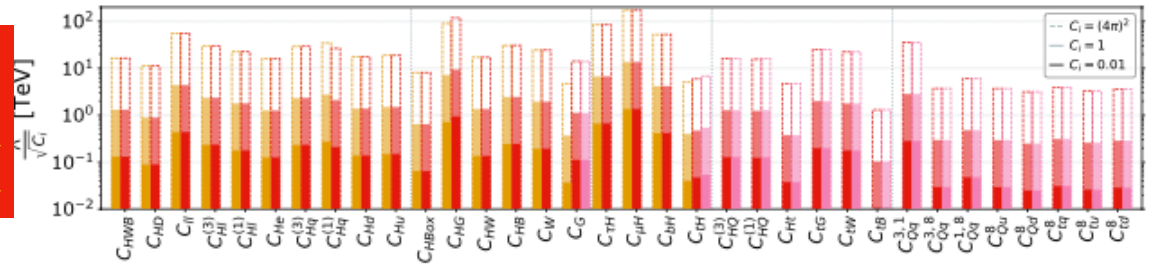
No significant deviations from SM

JE, Madigan, Min
arXiv:2012.02779



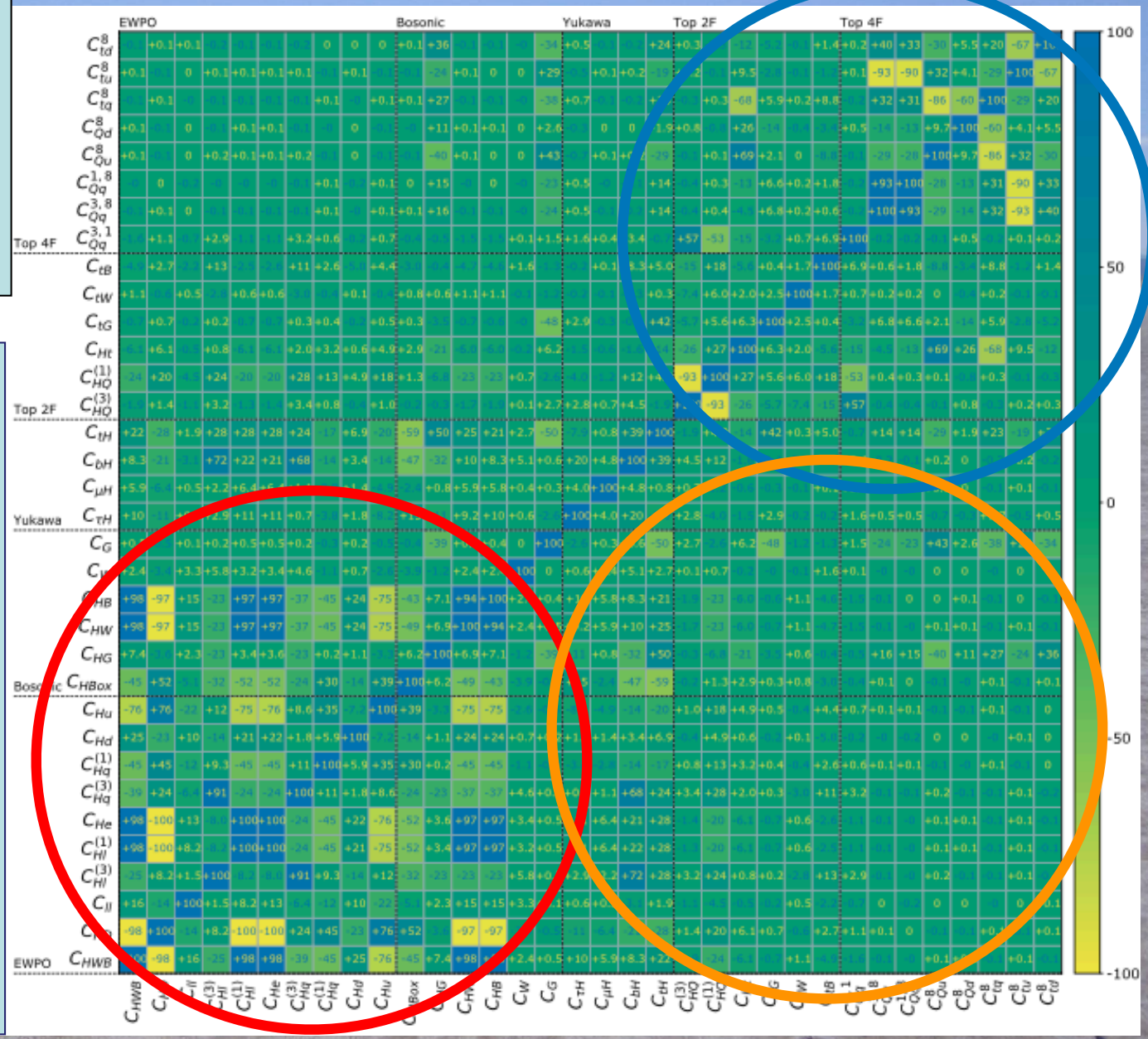






Correlation Analysis

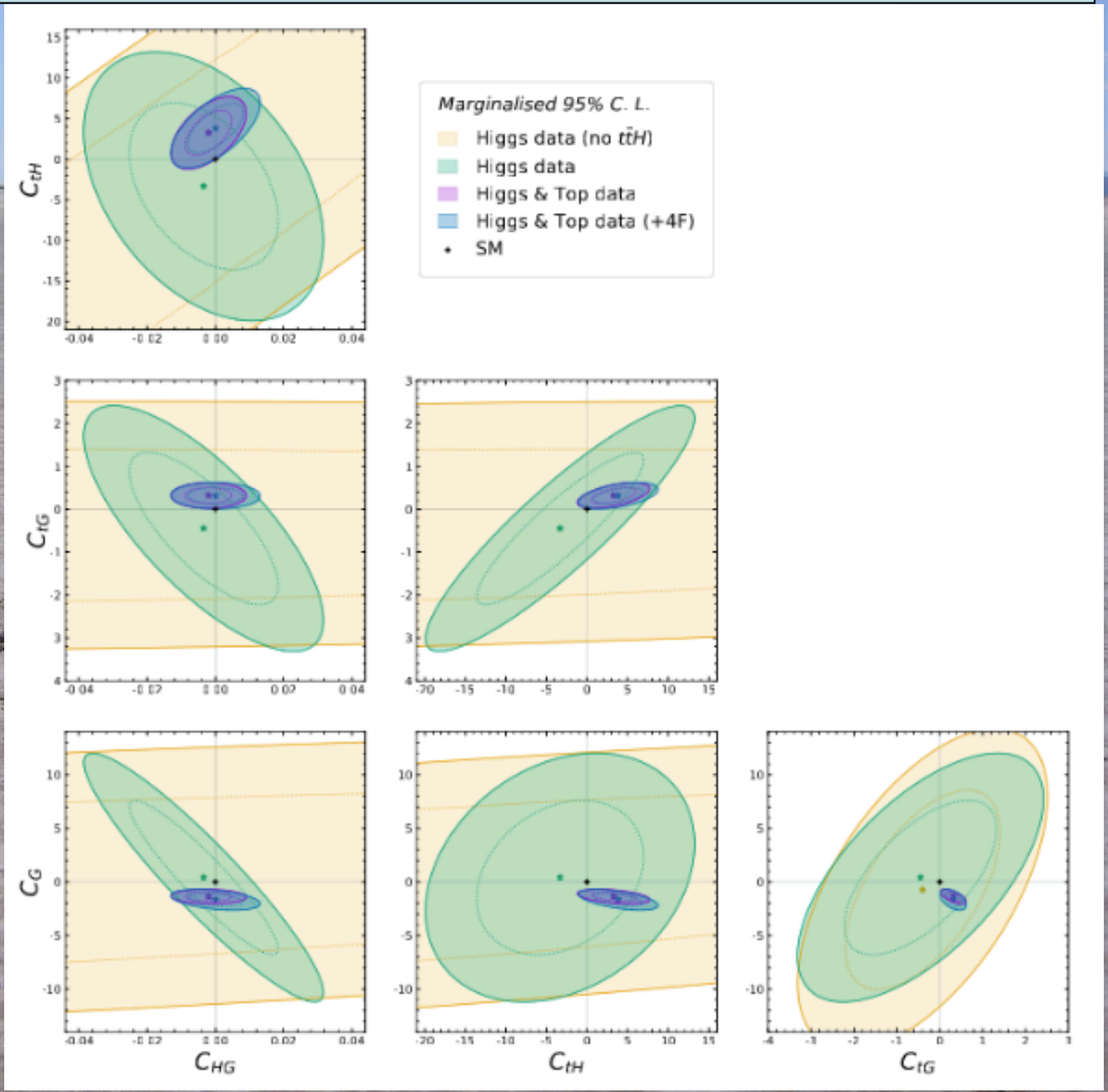
- **EWPO and boson sectors correlated**
- **Also within top sector**
- **Weaker correlations between sectors**



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

Example of Interplay between Data Sets

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



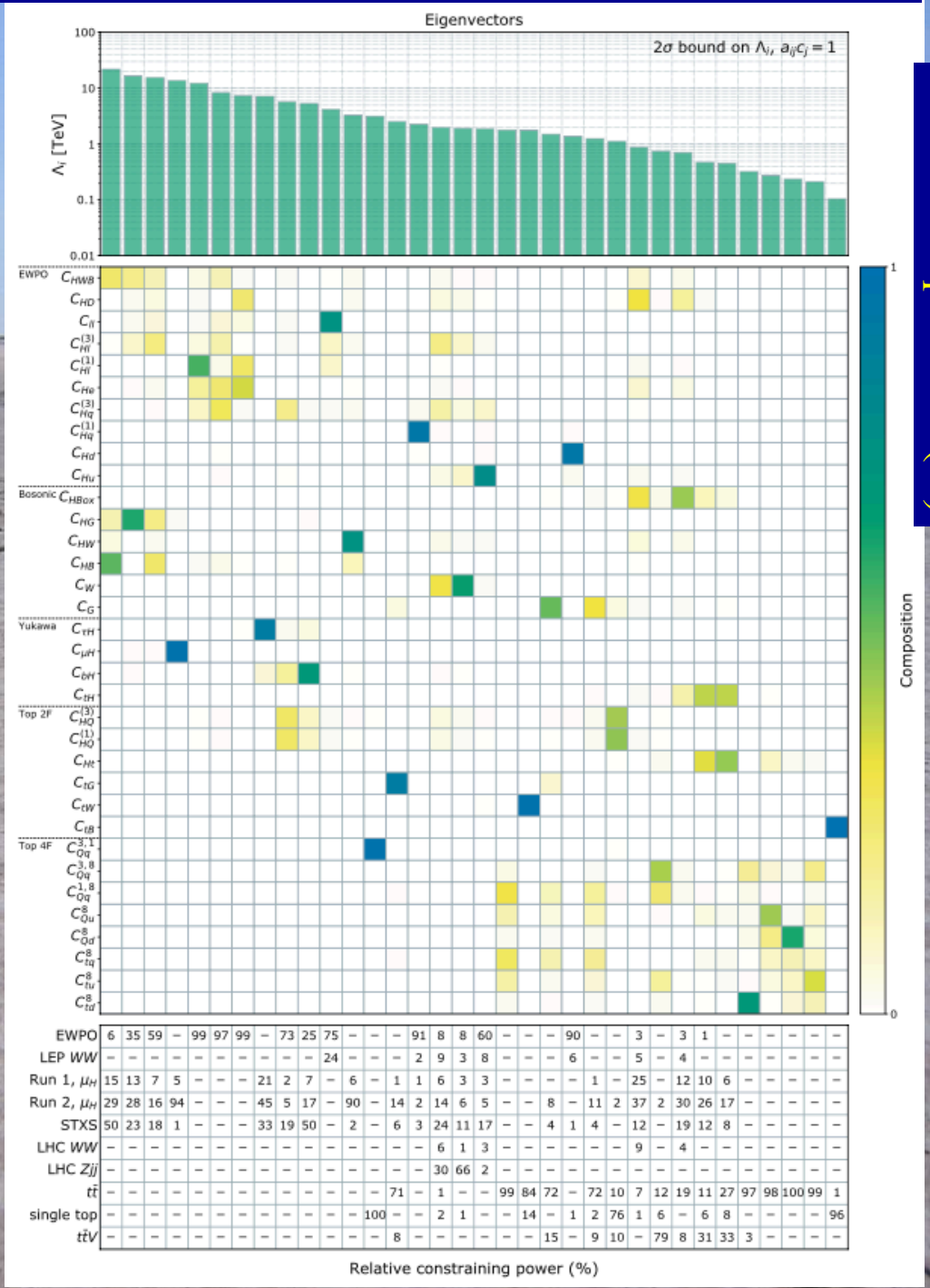
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Principal Component Analysis

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

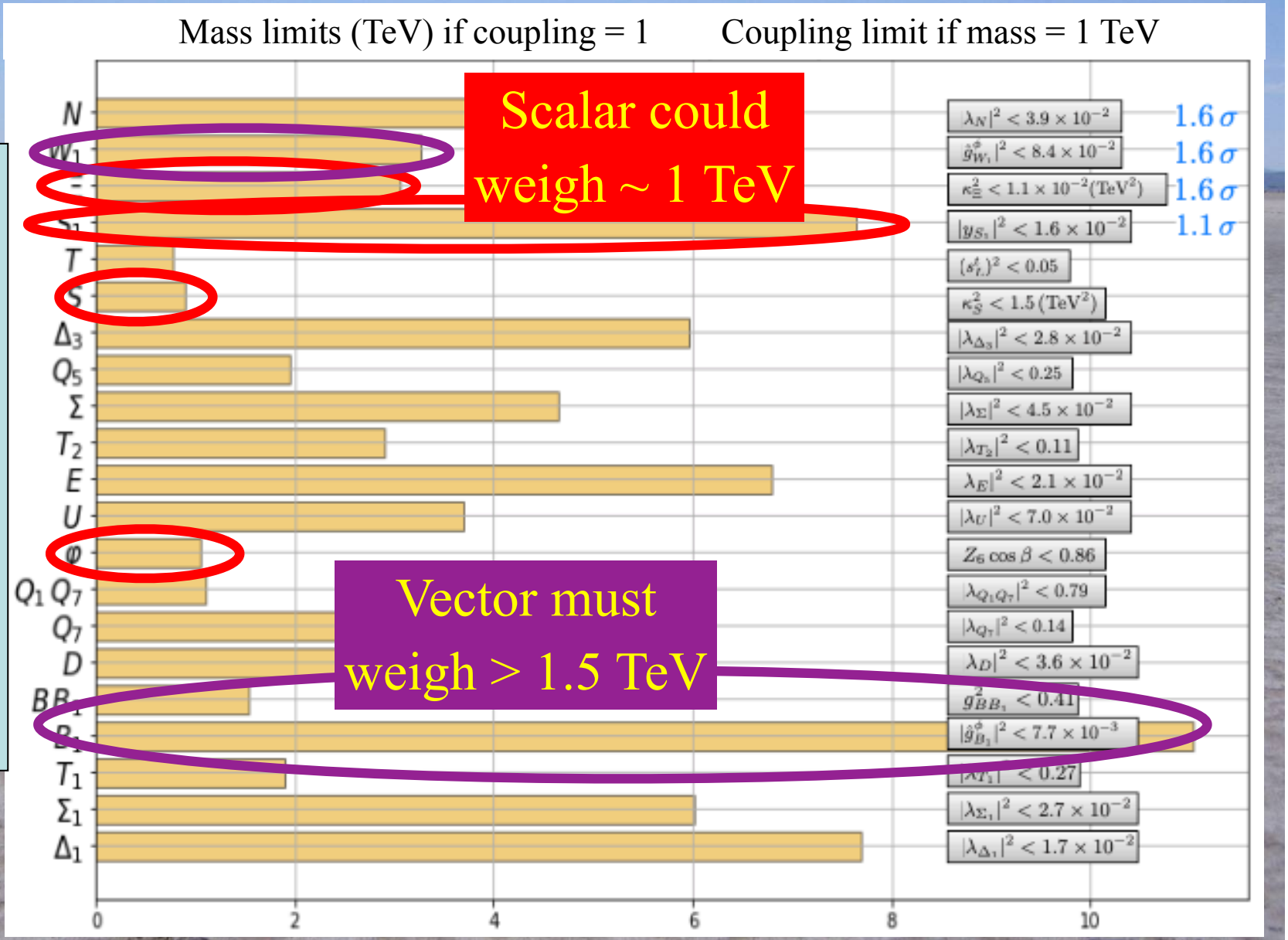
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Less constrained operator combinations ➔



Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 800 GeV if coupling = 1



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

SMEFT Constraints on Light Stops

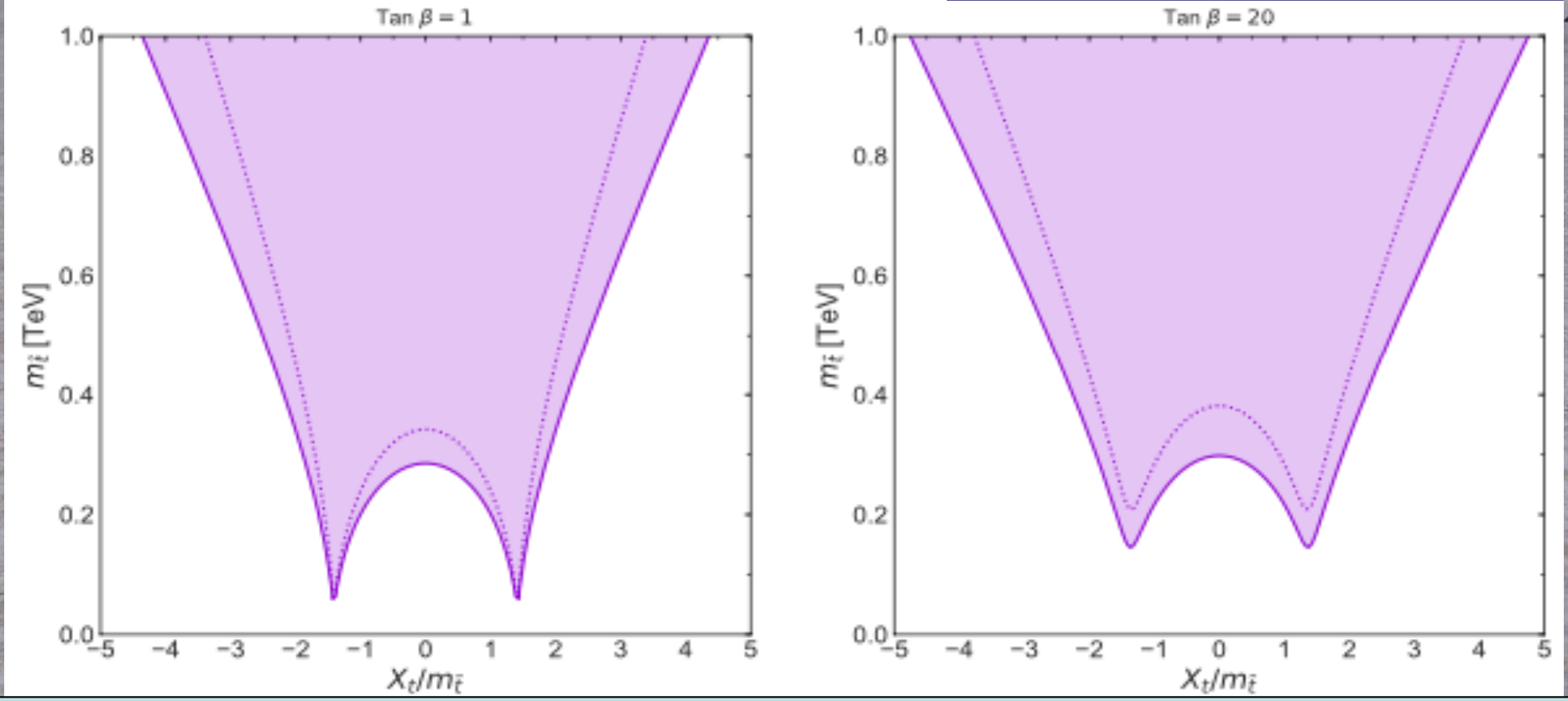
From quantum loop corrections:

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

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

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

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

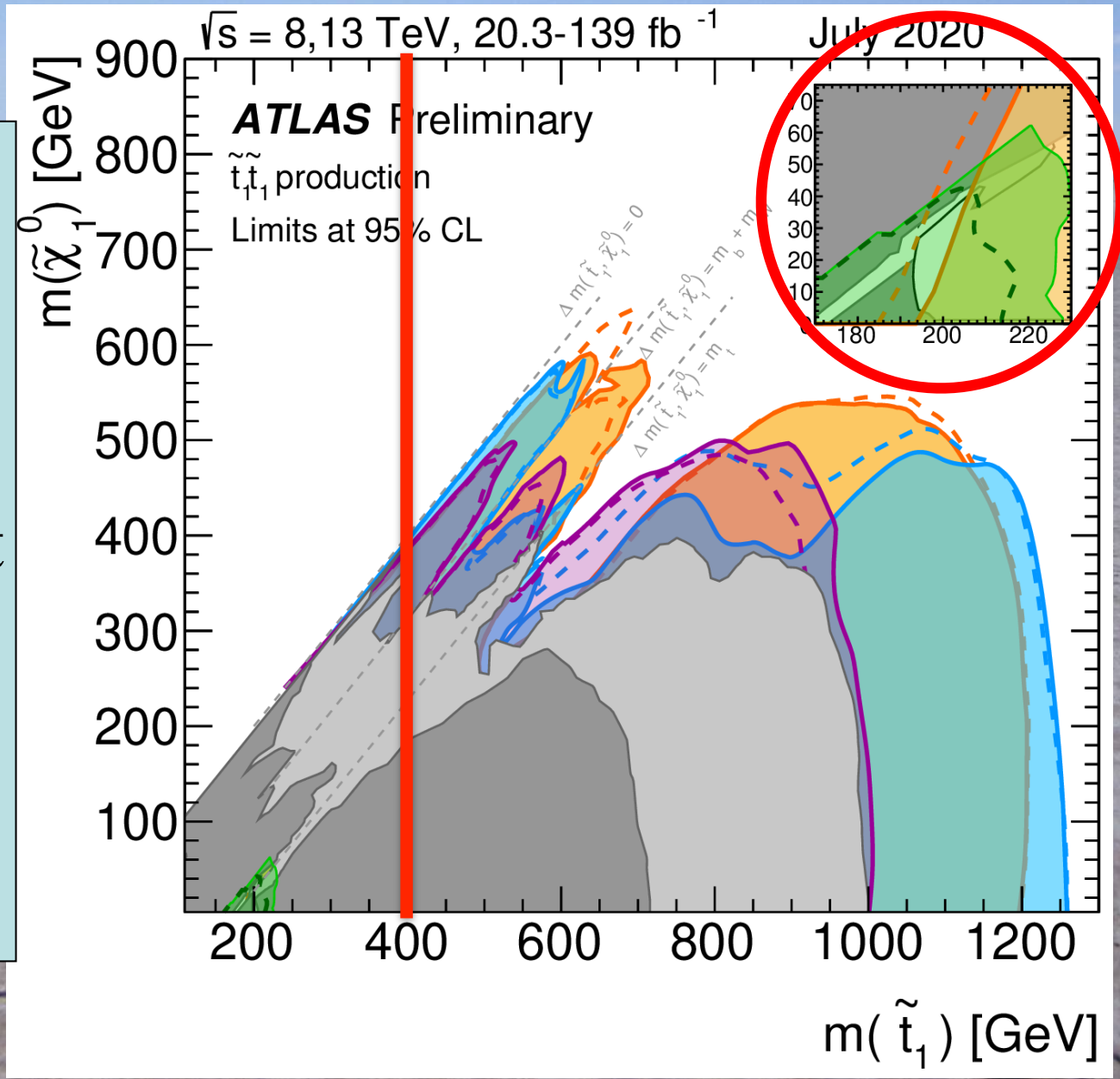


(Almost) model-independent lower limit on stop squark mass

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

Direct Search Constraints on Light Stops

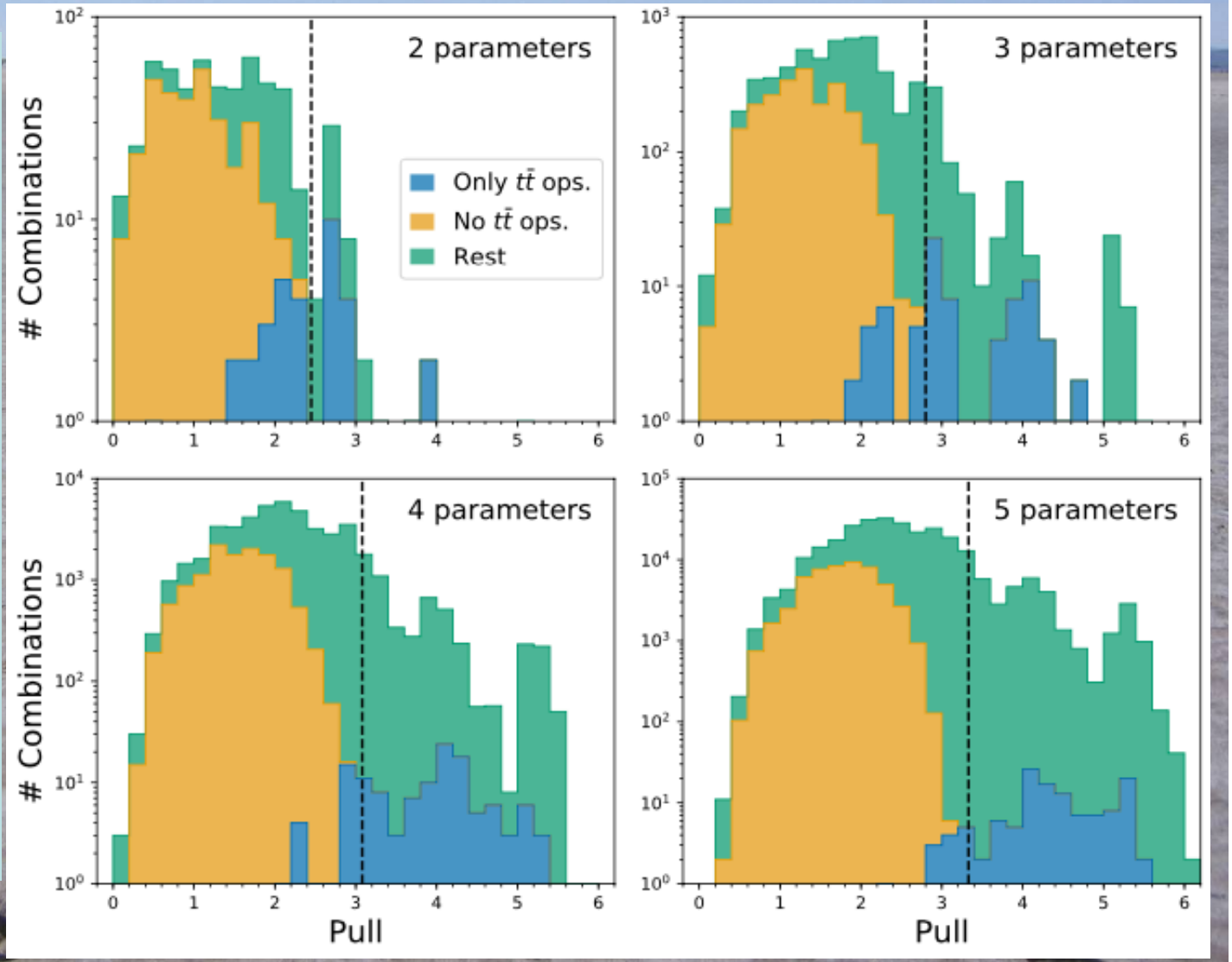
- Patchwork of many model-dependent searches
- Indirect constraint excludes low-mass region (almost) model-independently



Model-Independent BSM Survey

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

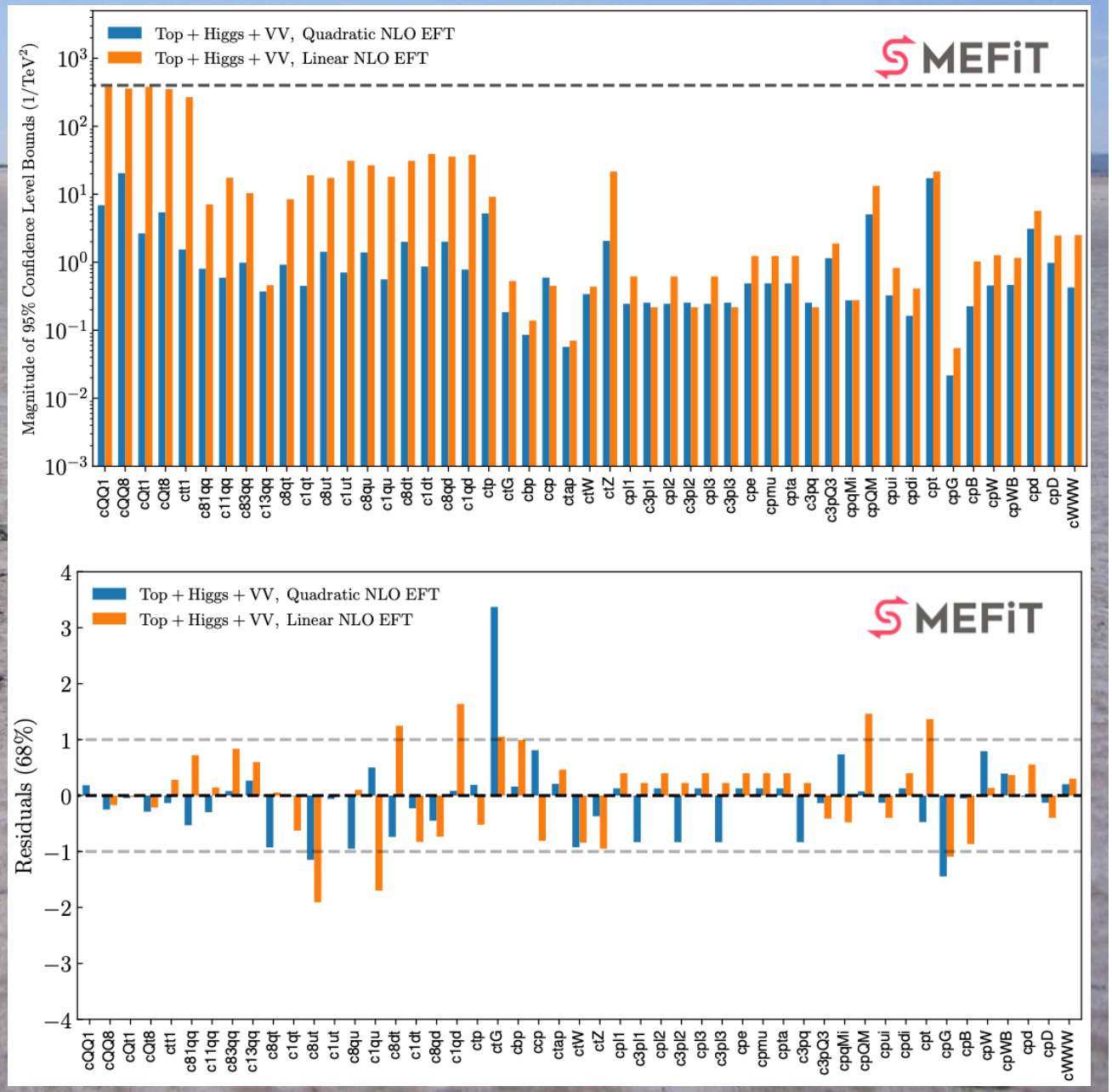
- **Top-less sector fits SM very well**
- **Top sector does not fit so well**
- **Mixed set intermediate**
- Overall, pulls not excessive
- **No hint of BSM**



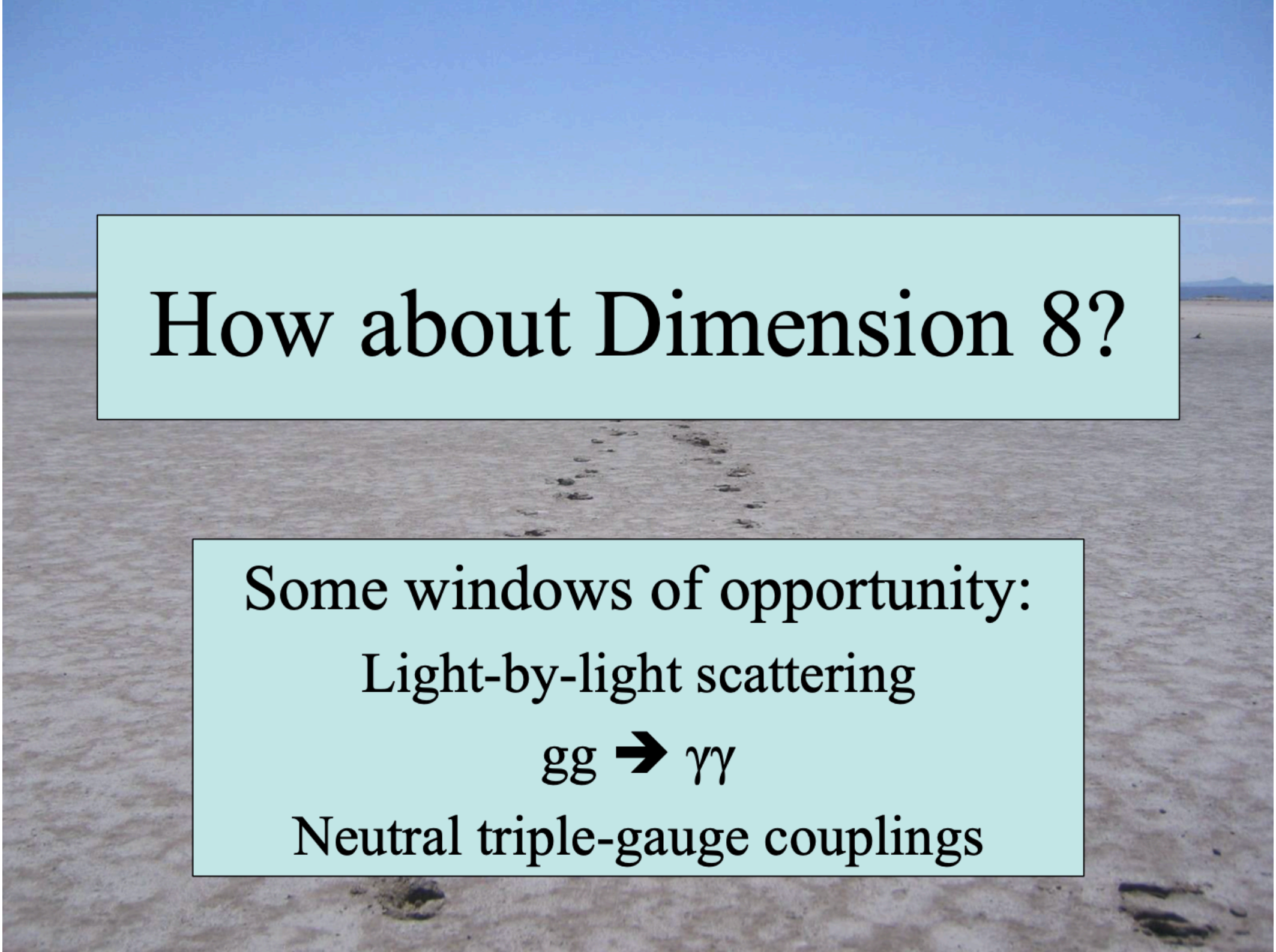
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Comparison of Linear and Quadratic Fits

- Quadratic fit assuming EW data = Standard Model
- Tighter constraints in general
- What about dimension 8, also contribute at $\mathcal{O}(1/\Lambda^4)$?
- Fitting process slower, difficult to make broad BSM survey

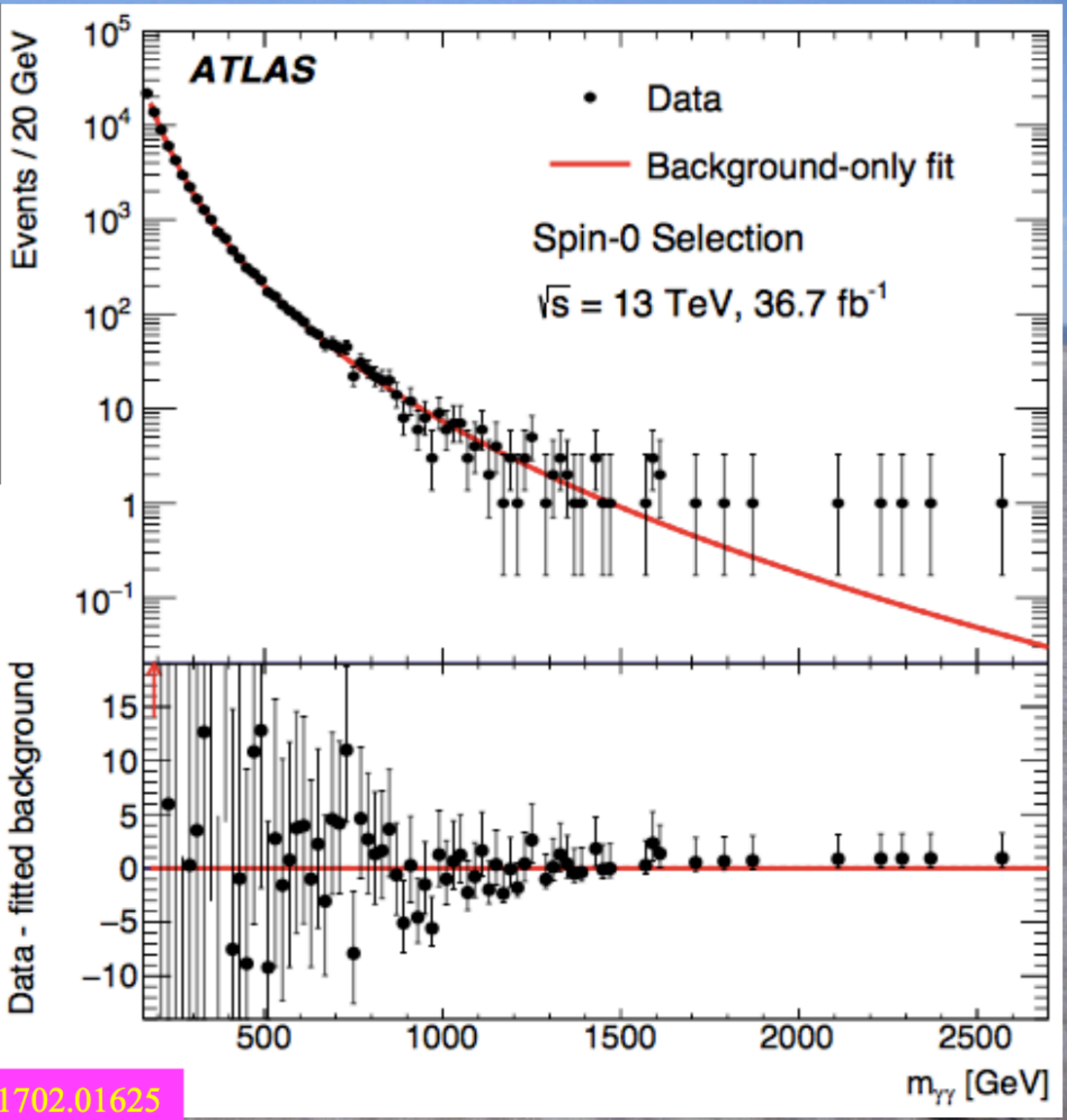


Ethier et al., arXiv:2105.00006


How about Dimension 8?
Some windows of opportunity:
Light-by-light scattering
gg ➔ γγ
Neutral triple-gauge couplings

Production of Isolated γγ at LHC

- Data agree with SM
- Can be used to constrain dimension-8 ggγγ operators

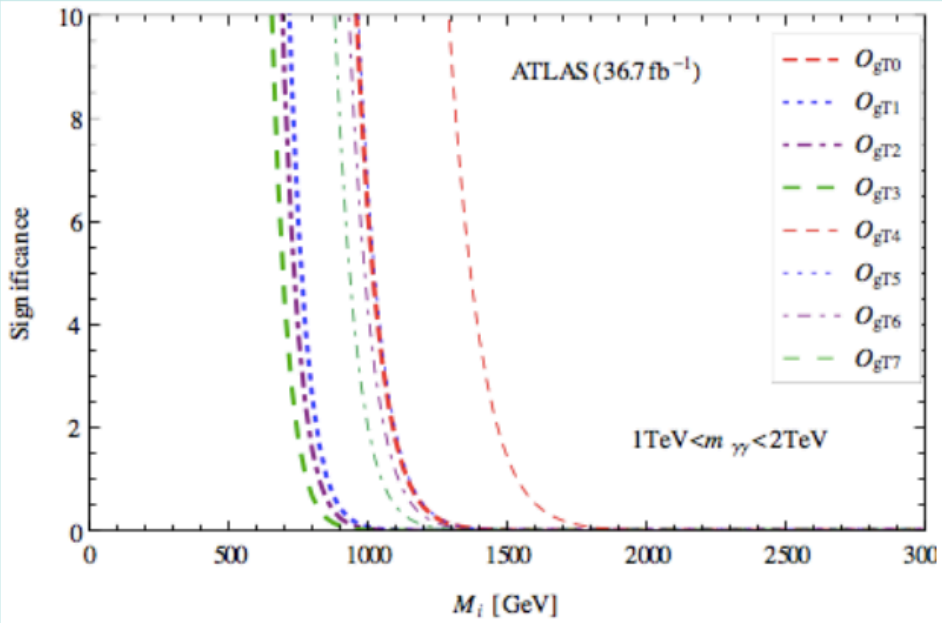


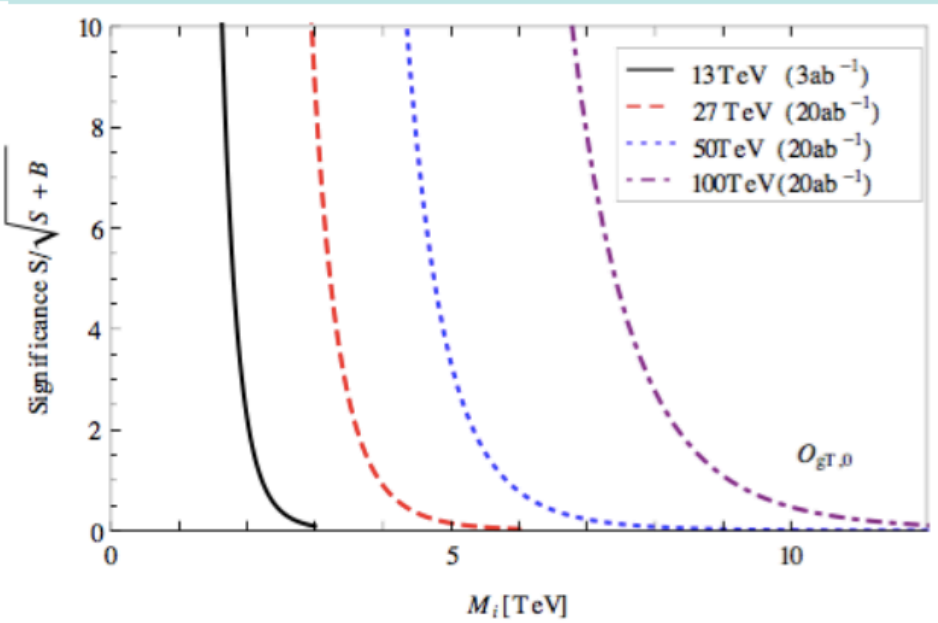
ATLAS Collaboration, arXiv:1702.01625

JE & Ge, arXiv:1802.02416

Constraints from Collider Data

- ATLAS: 95% CL lower limits in TeV range

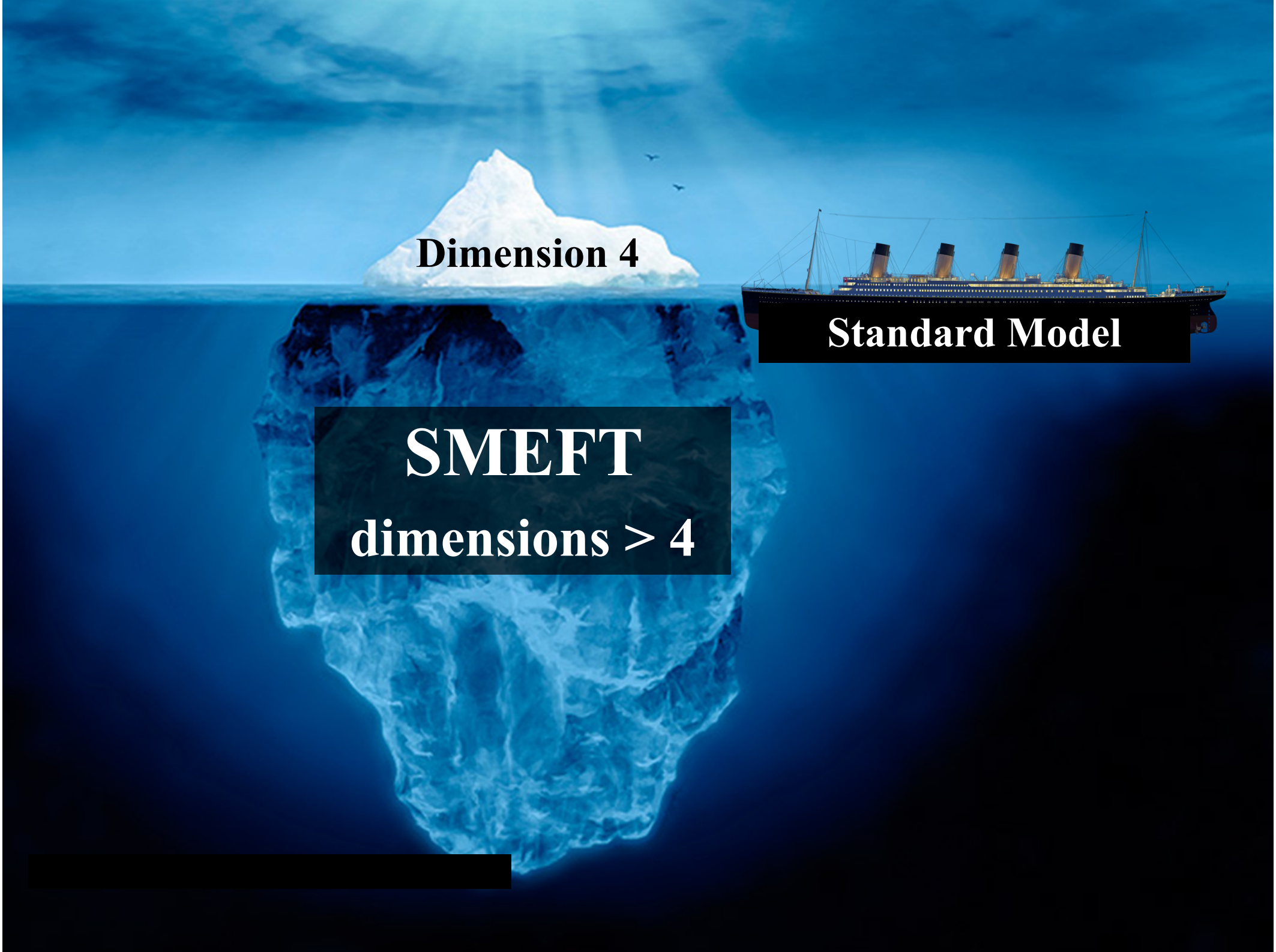




- Prospective sensitivities of future colliders in multi-TeV range
- **Unique window on dimension-8 physics**

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