... to make an end is to make a beginning.

The end is where we start from.

T.S. Eliot, *Little Gidding*

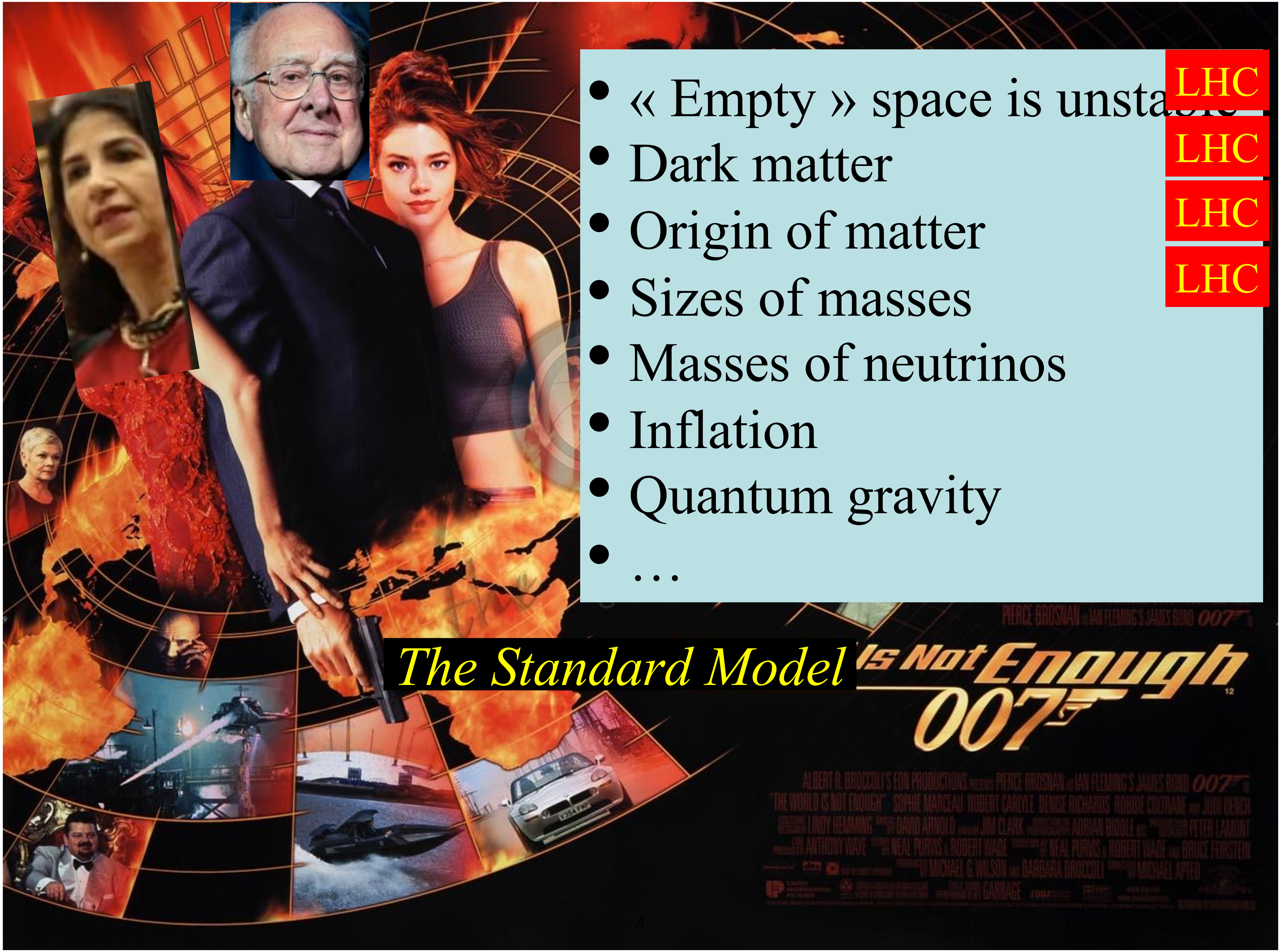
Higgstorical Summary

- Speculation
- Hypothesis
- Theory
- Search
- Discovery
- Building-block

Time to repeat?

ALBERT R. BROCCOLI'S EON PRODUCTIONS
PIERCE BROSNAN IAN FLEMING'S JAMES BOND 007
The World Is Not Enough
007
12
ALBERT R. BROCCOLI'S EON PRODUCTIONS PIERCE BROSNAN IAN FLEMING'S JAMES BOND 007
"THE WORLD IS NOT ENOUGH" SOPHIE MARCEAU ROBERT CARLYLE DENISE RICHARDS ROBBIE COLTRANE JUDI DENCH
LINDY HEMMING DAVID ARNOLD JIM CLARK ADRIAN BIDDLE PETER LAMONT
ANTHONY WAYE NEAL PURVIS ROBERT WADE NEAL PURVIS ROBERT WADE BRUCE FEIRSTEIN
MICHAEL G. WILSON BARBARA BROCCOLI MICHAEL APTED
GARBAGE

- « Empty » space is unstable — LHC
- Dark matter — LHC
- Origin of matter — LHC
- Sizes of masses — LHC
- Masses of neutrinos
- Inflation
- Quantum gravity
- …



The Standard Model

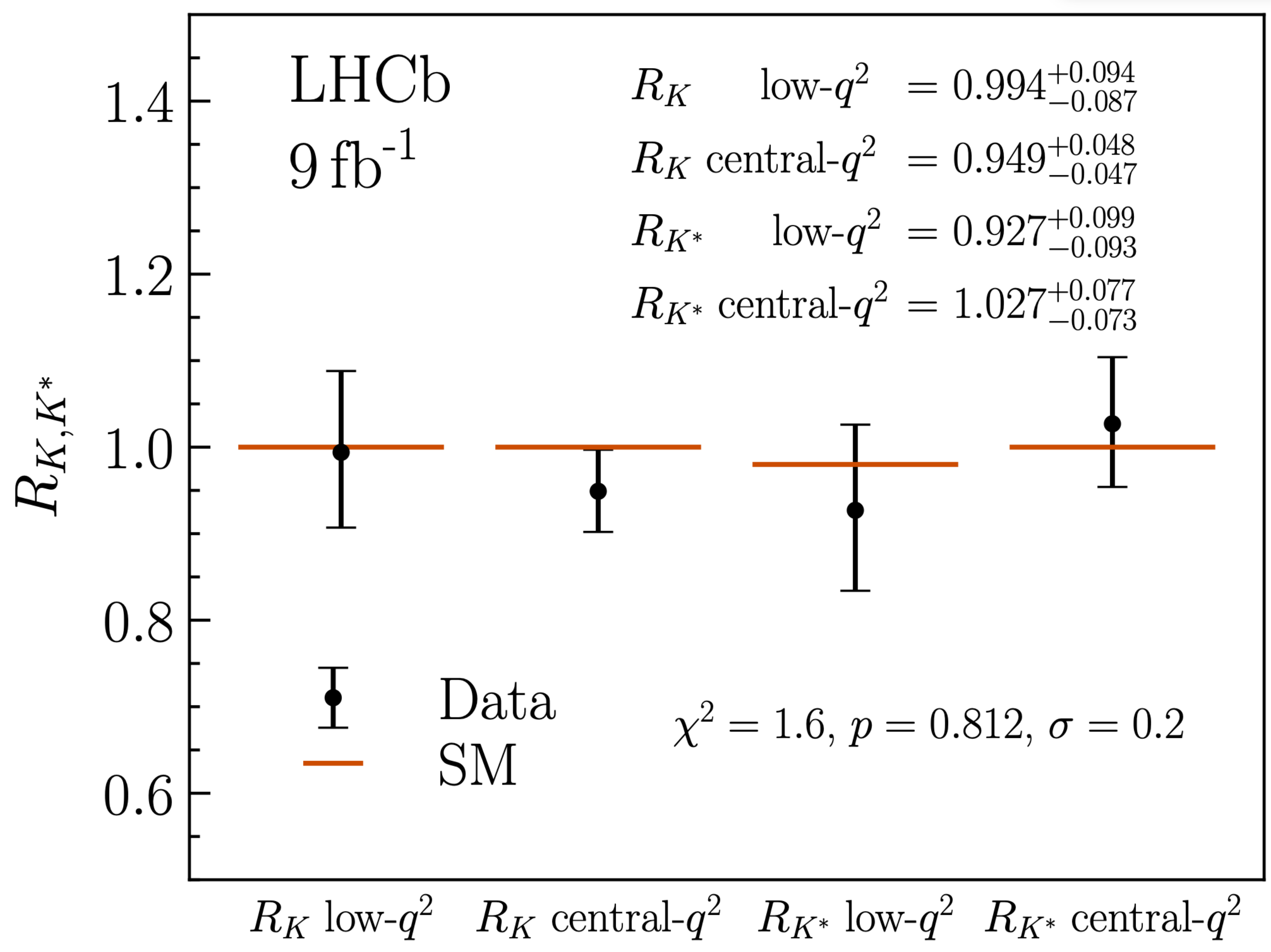
Everything about Higgs is Puzzling

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

- 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?

Sic Transit Gloria R_K Anomaliae

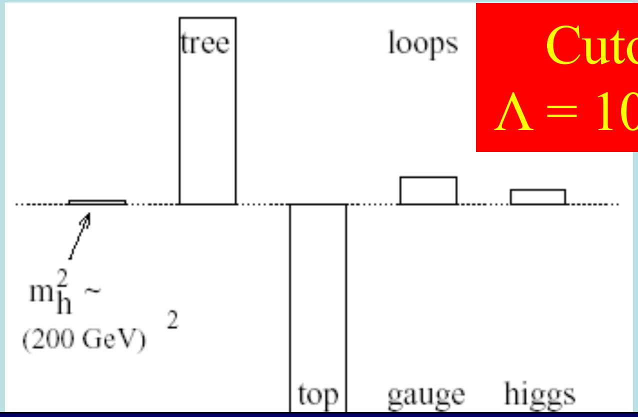


Elementary Higgs or Composite?

- Higgs field:

  $v = \langle 0|H|0\rangle \neq 0$

- Quantum loop problems
- M_h, v, other masses have quadratic divergences



Cutoff
$\Lambda = 10$ TeV

Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

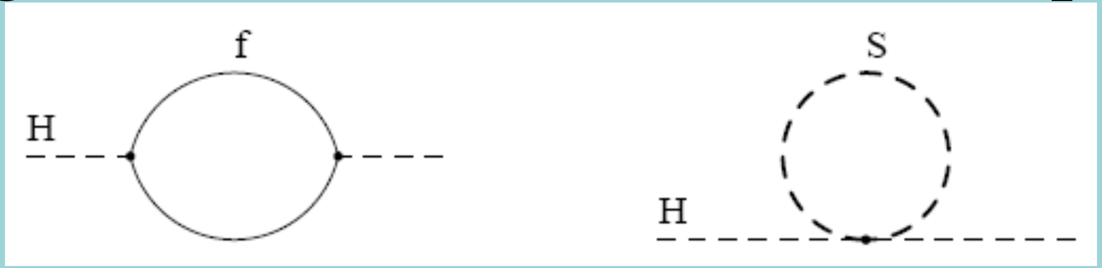
- Fermion-antifermion condensate?
- Just like π in QCD, Cooper pairs in BCS superconductivity
- Need new 'technicolour' force

- Heavy scalar resonance?
- (Problems with precision electroweak data)
- Pseudo-Nambu-Goldstone boson?

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!

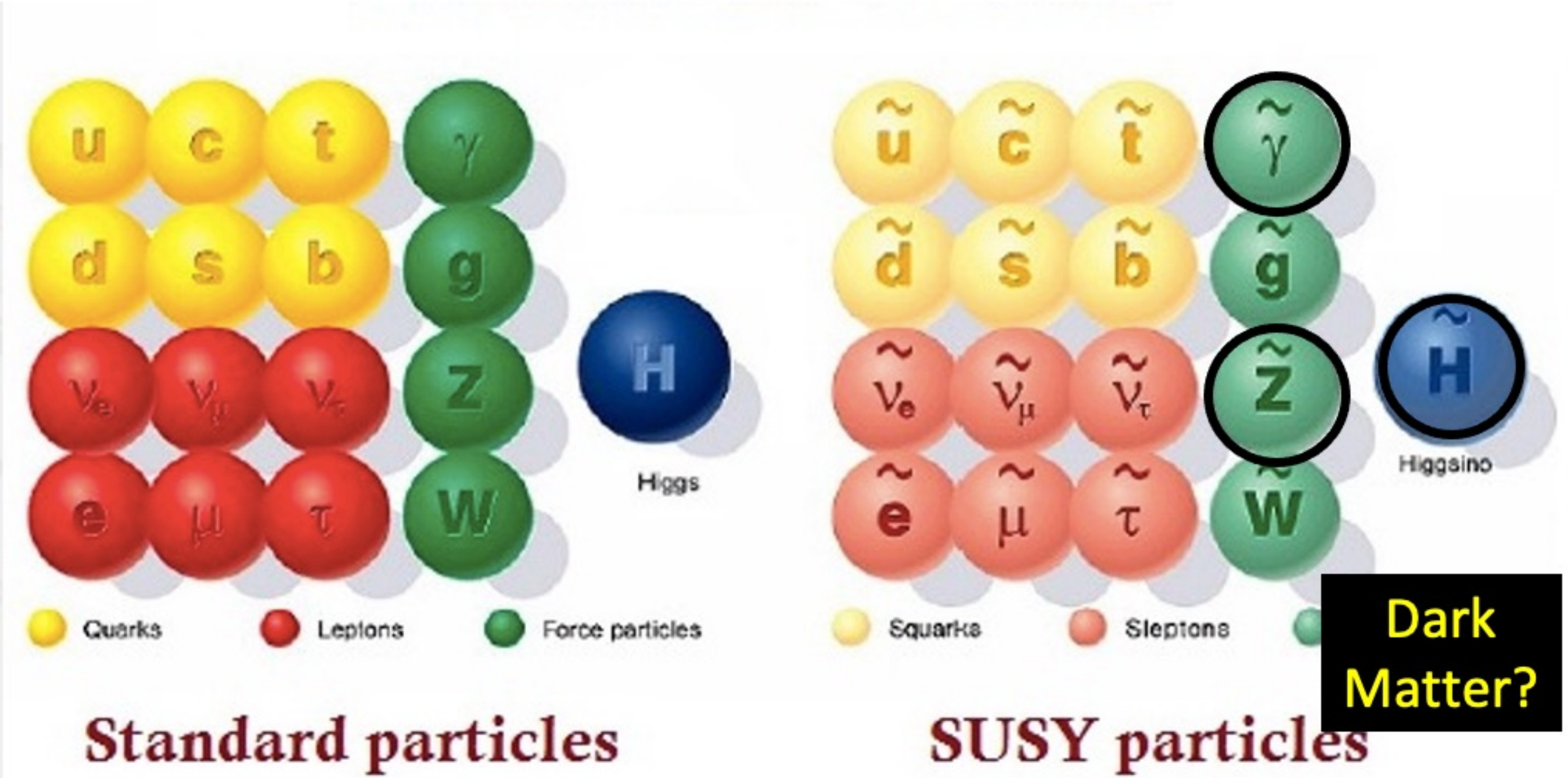
What lies beyond the Standard Model?

Supersymmetry

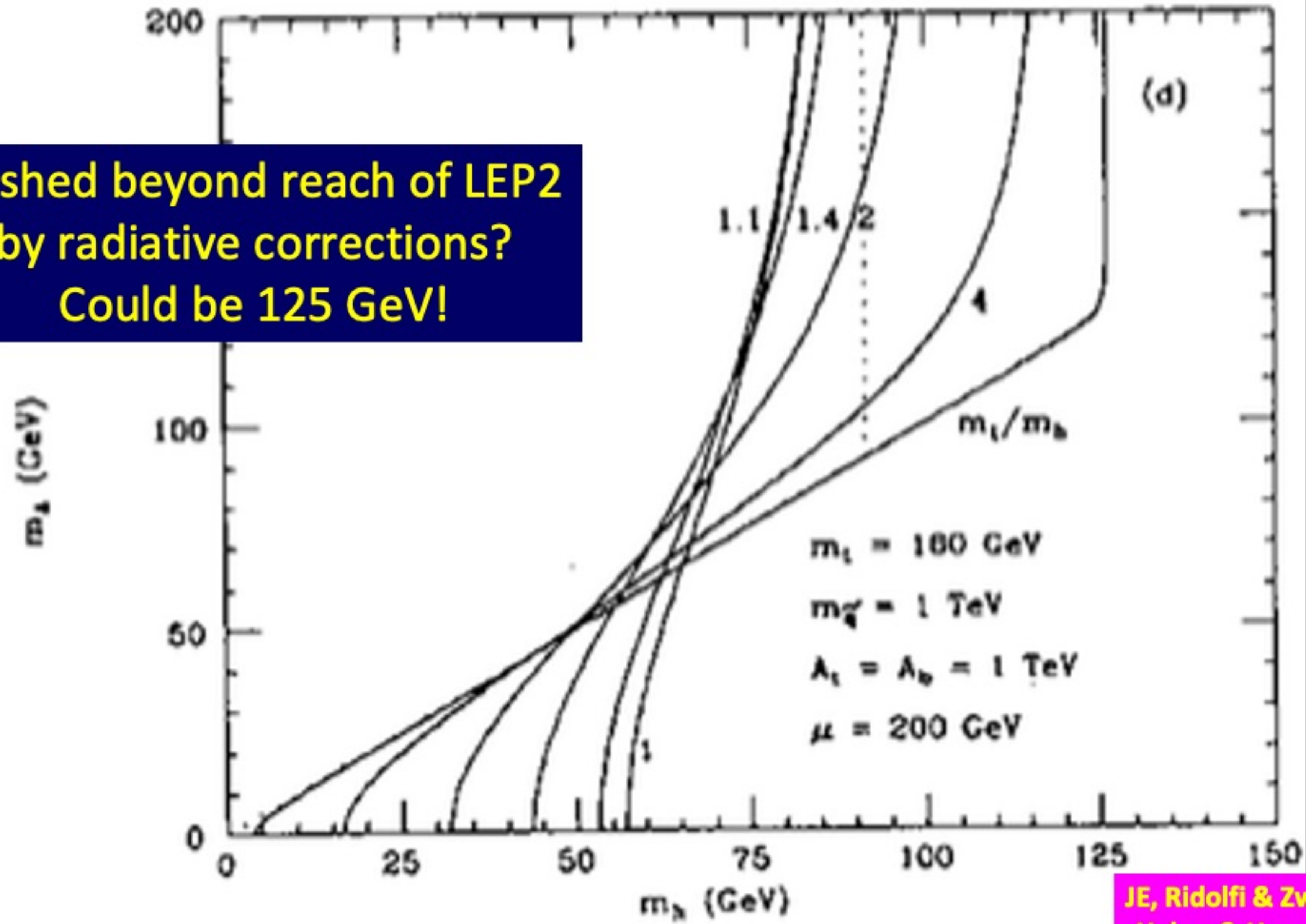
New motivations from LHC

- **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, **dark matter**, $g_\mu - 2$, ...

Minimal Supersymmetric Extension of the Standard Model



Higgs Mass in Supersymmetry



Pushed beyond reach of LEP2 by radiative corrections? Could be 125 GeV!

JE, Ridolfi & Zwirner; Haber & Hempfling

Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ 1/2 \\ 0 \end{pmatrix}$$

- At two-loop order without/**with** supersymmetry:

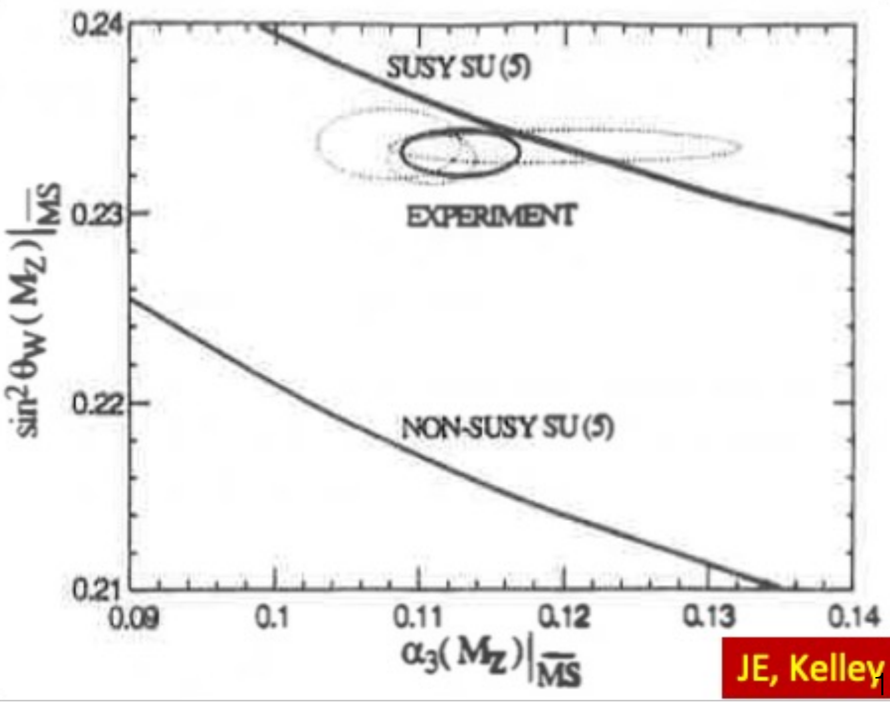
$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- At three-loop order …

1991

LEP Data Consistent with Supersymmetric Grand Unification



JE, Kelley & Nanopoulos

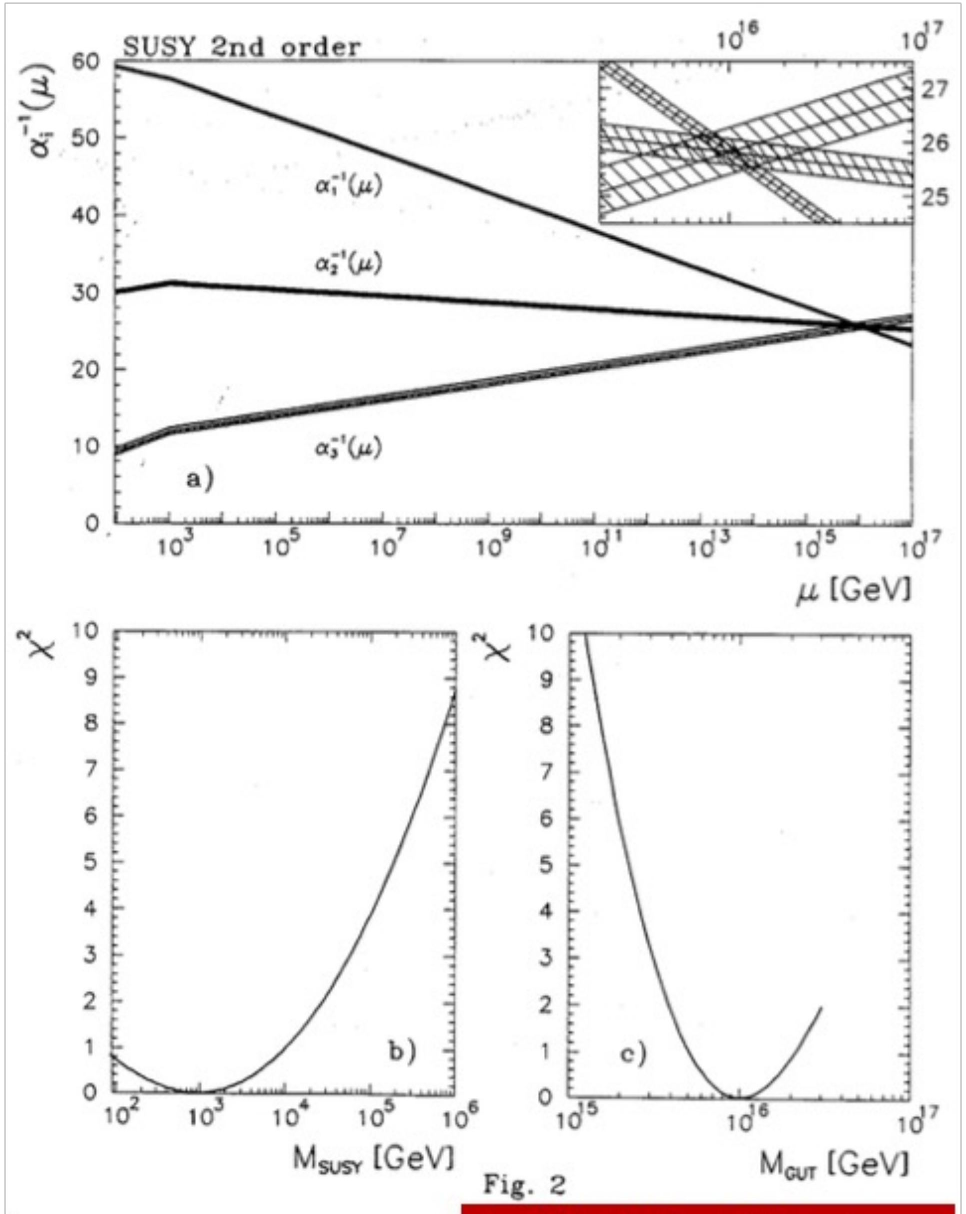


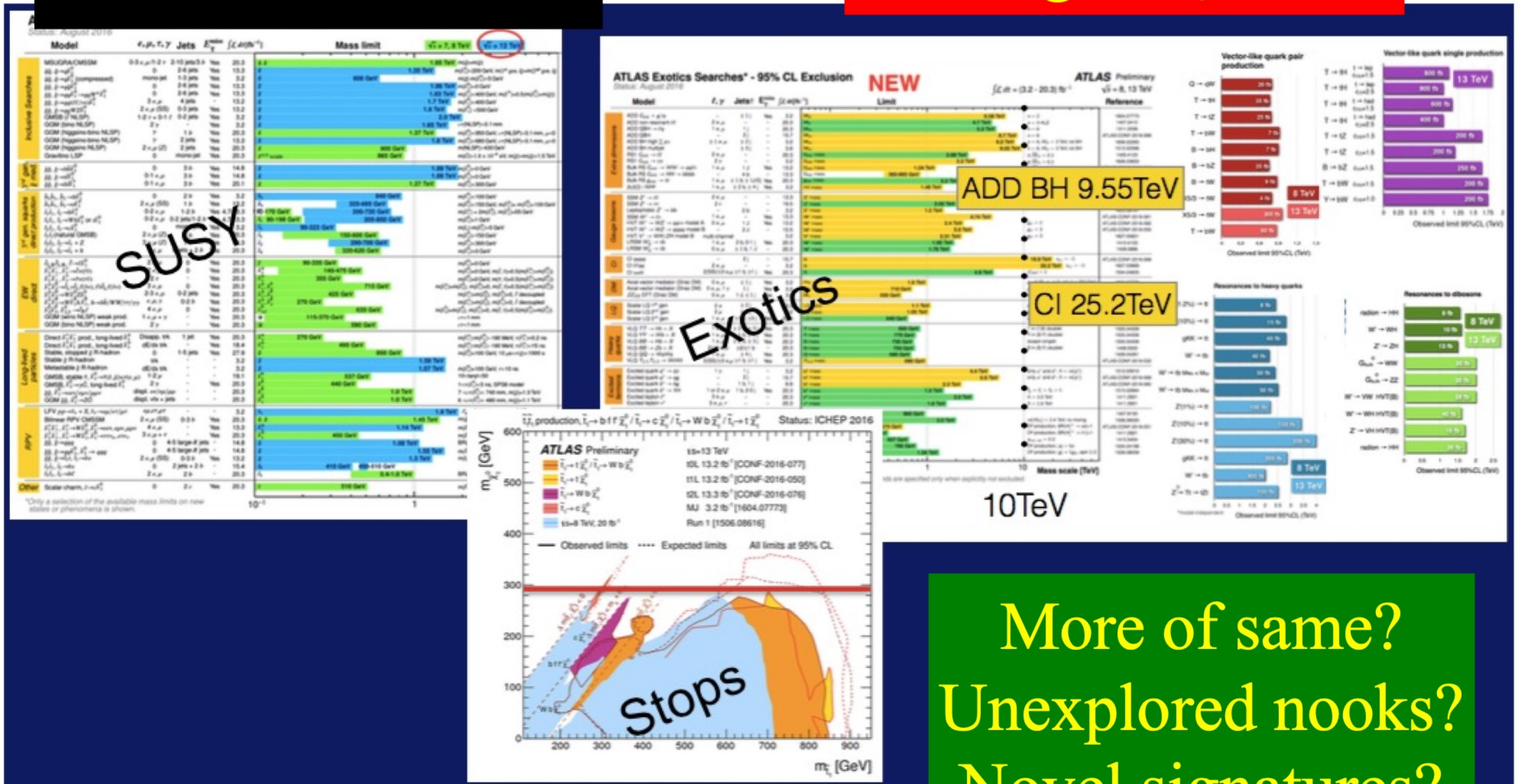
Fig. 2

Amaldi, de Boer & Furstenau

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

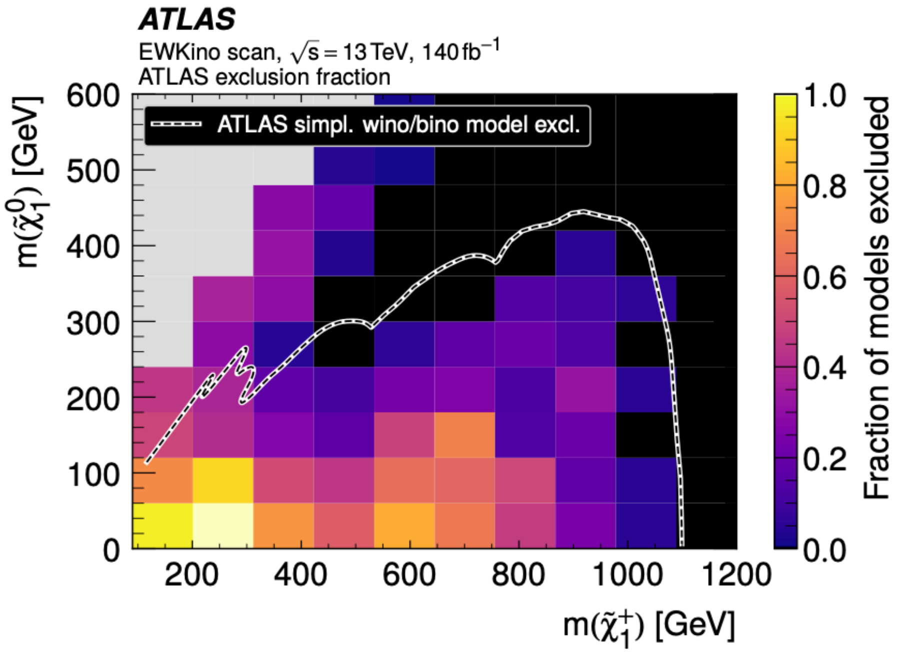
ATLAS Collaboration, arXiv:2402.01392

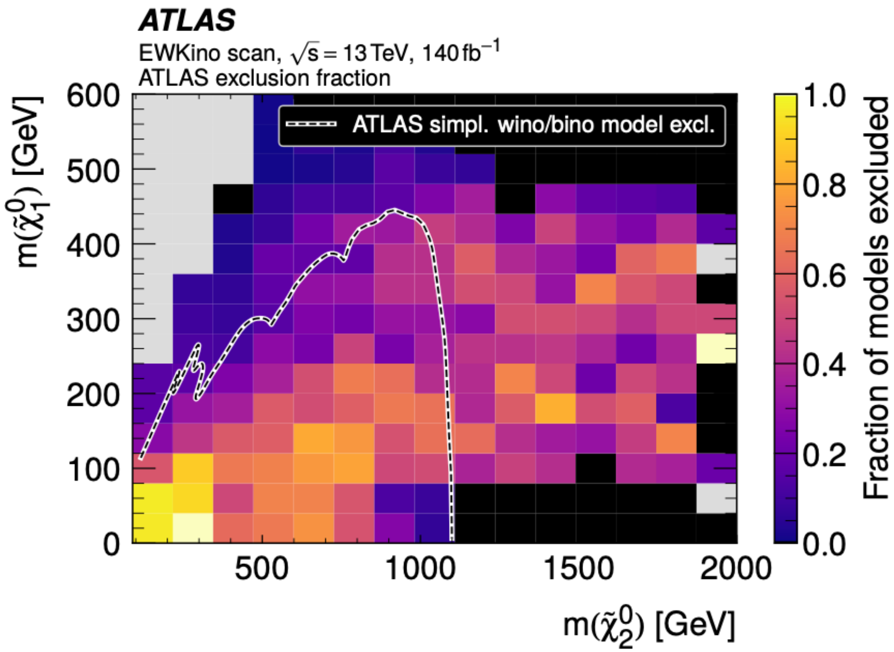
Survey of SUSY searches in pMSSM

Lines = chargino/neutralino exclusions in searches with simplifying assumptions on spectrum and decay modes

Black = < 10% of pMSSM models excluded

Cream = > 90% of pMSSM models excluded



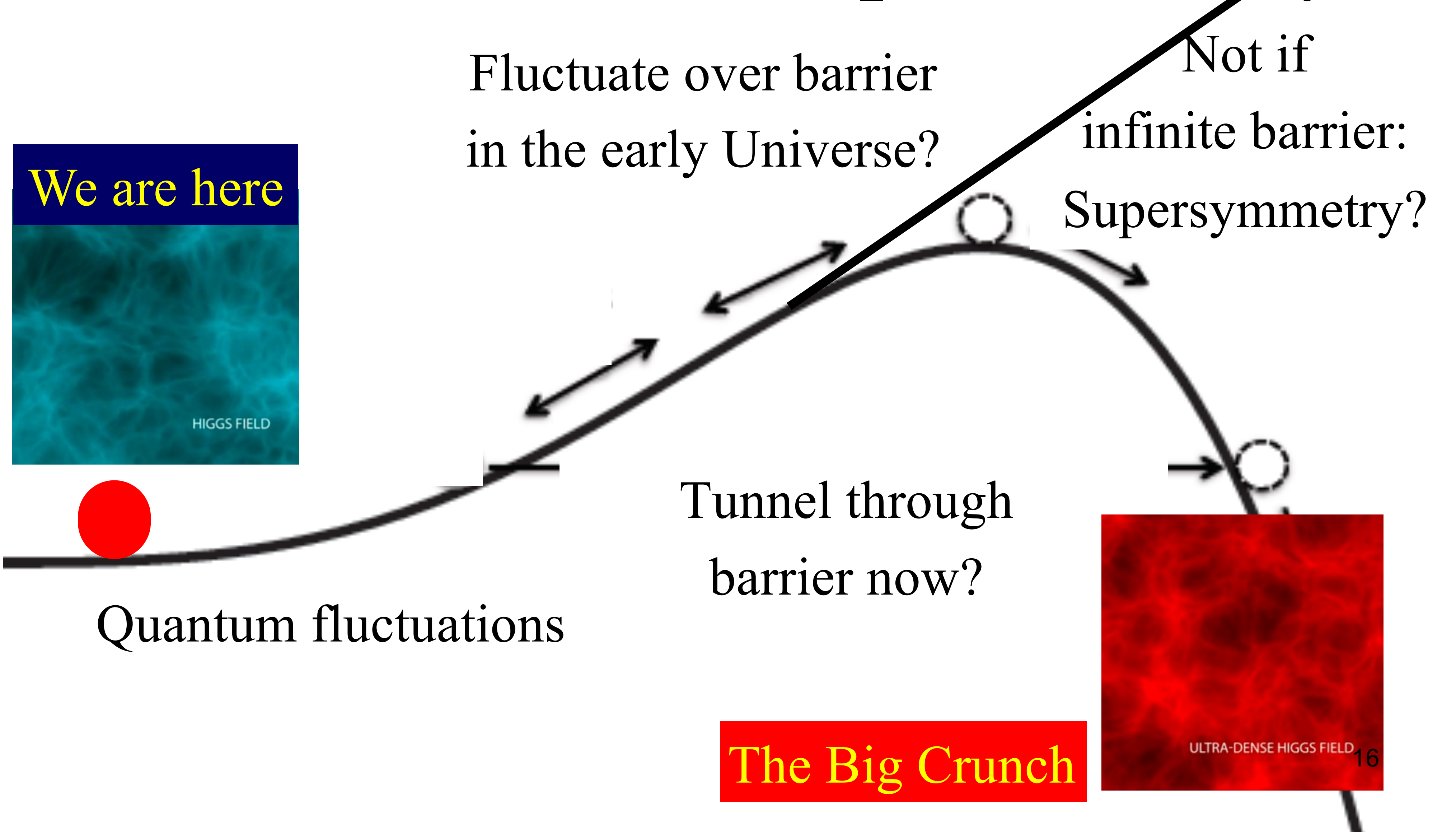


Many low-mass pMSSM models consistent with constraints

“Not dead yet”

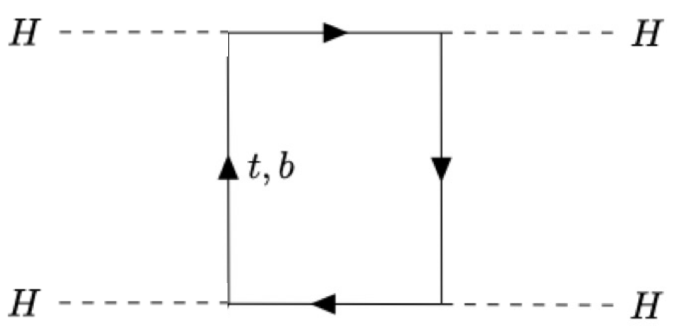
Monty Python and the Holy Grail

Will the Universe Collapse? Should it have Collapsed already?



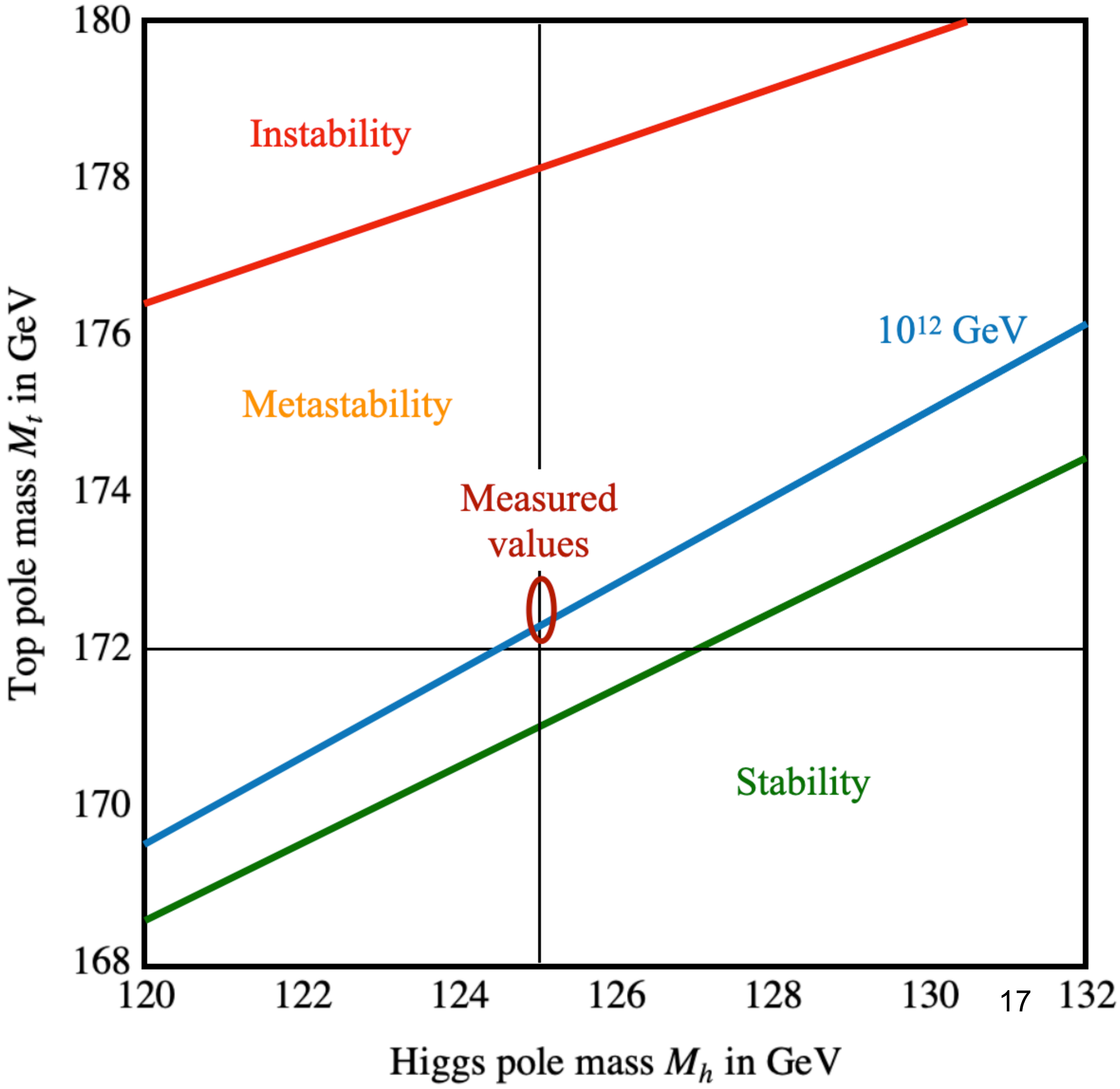
Is "Empty Space" Unstable?

Depends on masses of Higgs boson and top quark



$$16\pi^2 \frac{d\lambda}{dt} = 12(\lambda^2 + h_t^2\ \lambda - h_t^4) + \mathcal{O}(g^4, g^2\lambda$$

$$t = \log(Q^2)$$



Is “Empty Space” Unstable?

- Dependence of instability scale on masses of Higgs boson and top quark, and strong coupling:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 10.5 - 1.3\left(\frac{m_t}{\mathrm{GeV}} - 172.6\right) + 1.1\left(\frac{m_H}{\mathrm{GeV}} - 125.1)\right) + 0.6\left(\frac{\alpha_s(m_Z) - 0.1179}{0.0009}\right)$$

Buttazzo et al, arXiv:1307.3536; Franceschini et al, 2203.17197

- New CMS value of m_t : CMS Collaboration, April 2022

$$m_t = 171.77 \pm 0.38\,\mathrm{GeV}$$

- Particle Data Group values:

$$m_H = 125.25 \pm 0.17\,\mathrm{GeV}, \quad \alpha_s(m_Z) = 0.1179 \pm 0.0009$$

- Instability scale:

$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and m_t

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?"*

A Note on Units and Dimensional Analysis

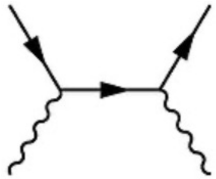
- Use “natural” units: Planck’s constant, velocity of light = 1
- Count mass dimensions: [M] = 1 = [E] = [p] = [∂]
- Consistent with Lorentz invariance: $E^2 = p^2 + m^2$
- Quantum mechanics: [x] = [t] = -1
- Action $A = \int \mathcal{L} d^4x$ has [A] = 0, so [$\mathcal{L}$] = 4

$$\mathcal{L} \ni \partial\phi\partial\phi, \psi\partial\psi, F_{\mu\nu}F^{\mu\nu}$$

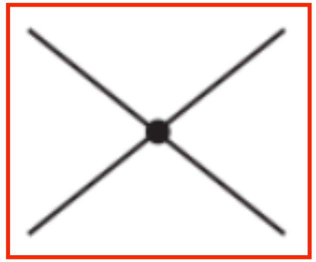
- So [ϕ] = 1, [ψ] = 3/2, [A_μ] = 1

Effective Field Theories (EFTs)
a long and glorious History

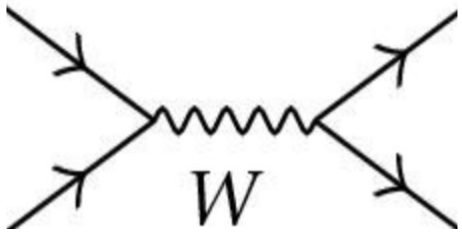
- 1930's: "Standard Model" of QED had d=4



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

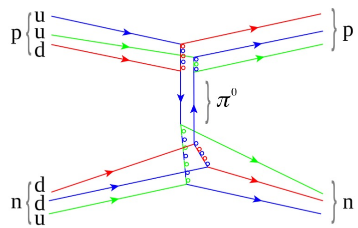


- Dimension-6 operators: form = S, P, V, A, T?
  – Due to exchanges of massive particles?



- 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?

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

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- 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		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star (H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

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

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

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

Anomalous magnetic moments

Flavour anomalies

Baryon decay

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

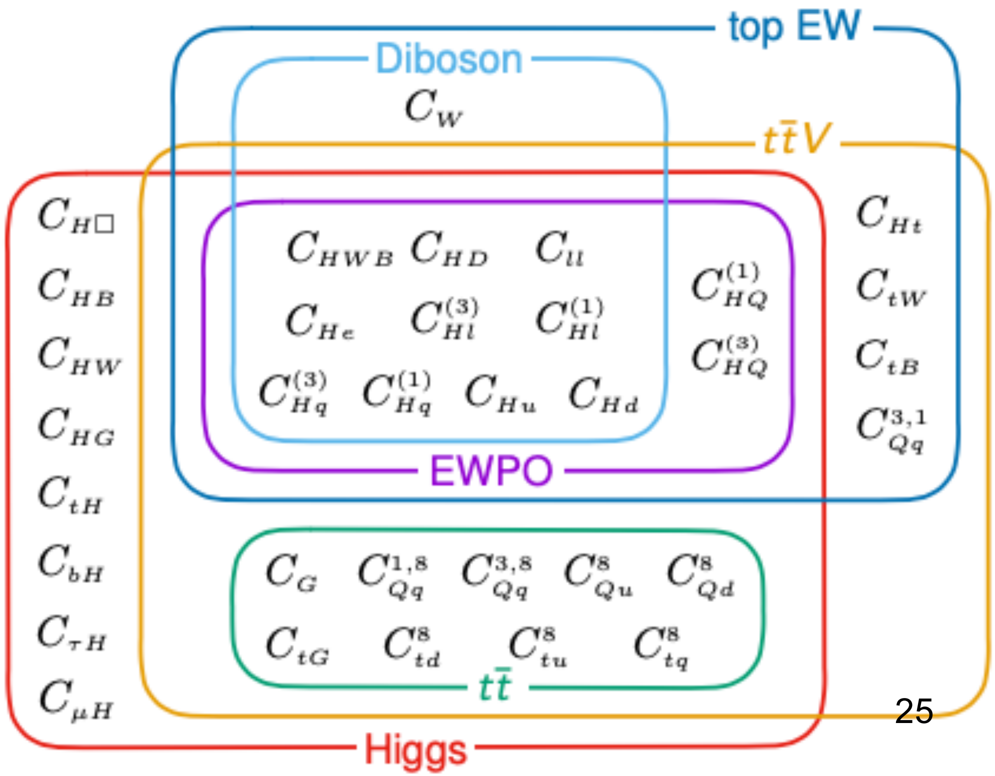
Global SMEFT Fit

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



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

Positive contributions to mw

Colours indicate which sectors constrain which operators

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

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 combinatio… 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]
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS … $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS … dilept…		
ATLA… dilept…		
ATLA… $A_C(m$…		
CMS … $\frac{d\sigma}{dm_{t\bar{t}}dy}$		
ATLA… decay.		
ATLA… f_0, f_L		
CMS … f_0, f_L		
ATLA…		
CMS …		
ATLA… $\frac{d\sigma}{dp^T}$		
CMS …		
CMS … $\frac{d\sigma}{dp^T_{t+\bar{t}}}$		
CMS … σ_t | $\sigma_{\bar{t}}$ | $\sigma_{t+\bar{t}}$ | 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 measurement…		

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. σ_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		

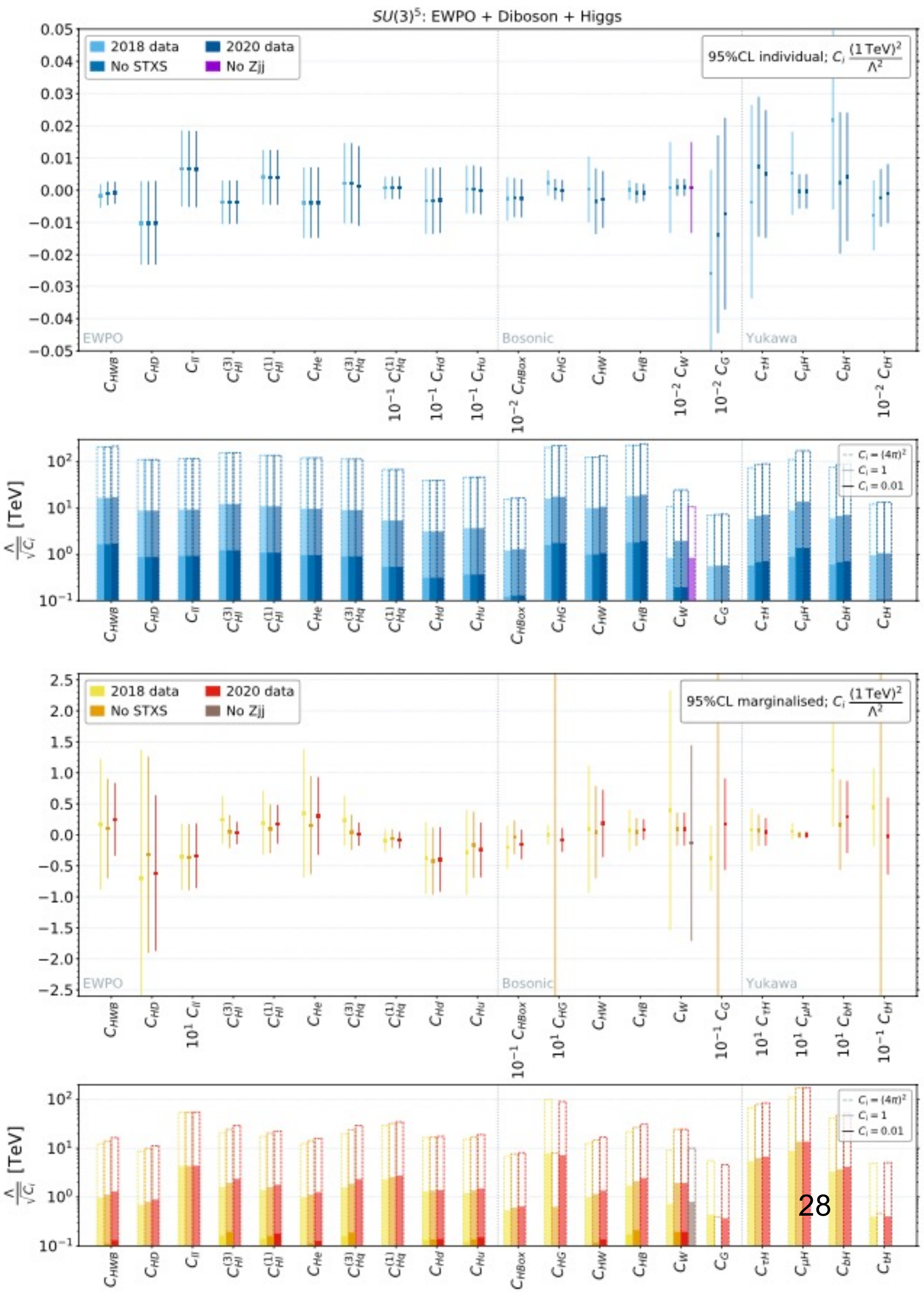
341 measurements included in global analysis

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

Single-Field Extensions of the Standard Model

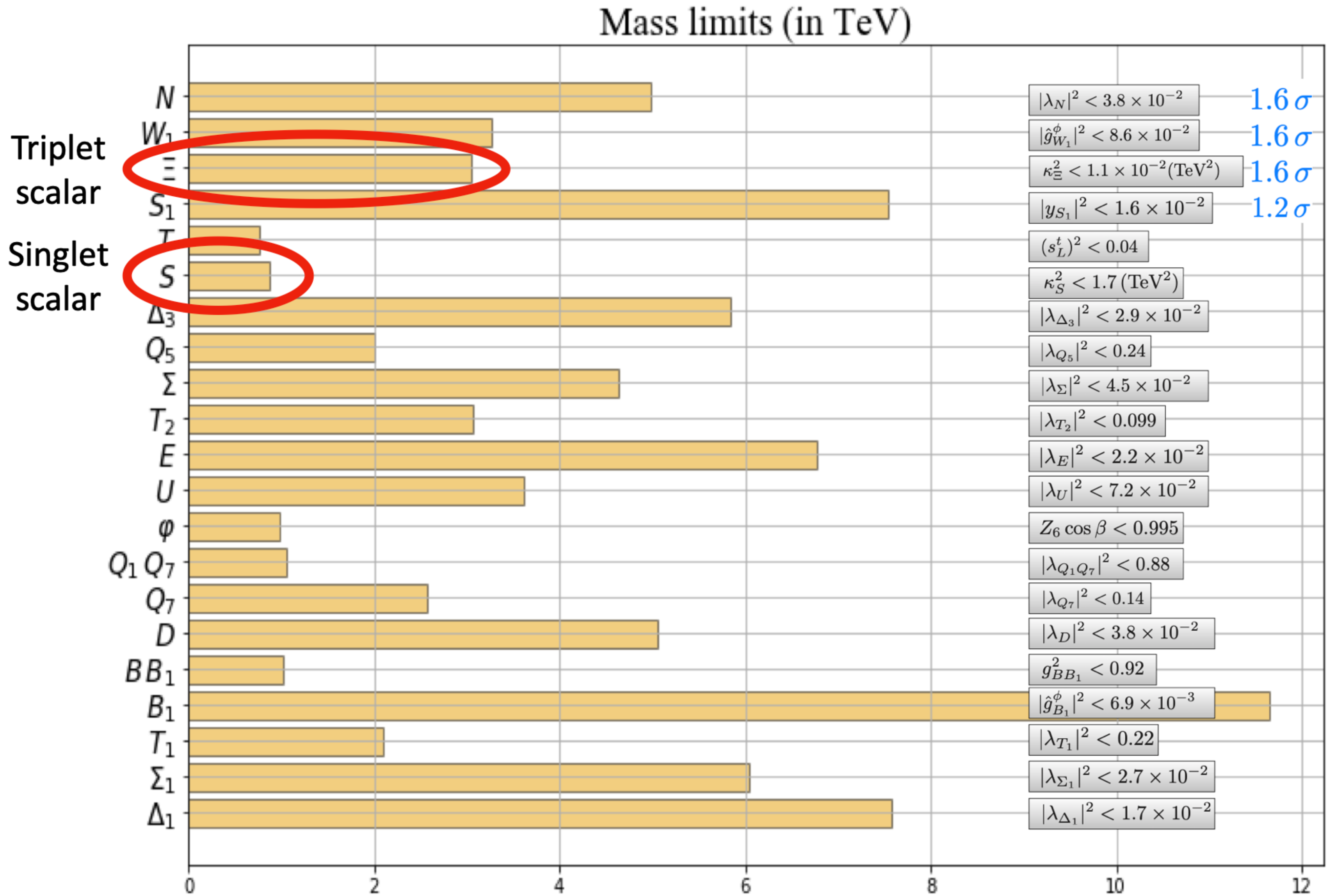
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	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

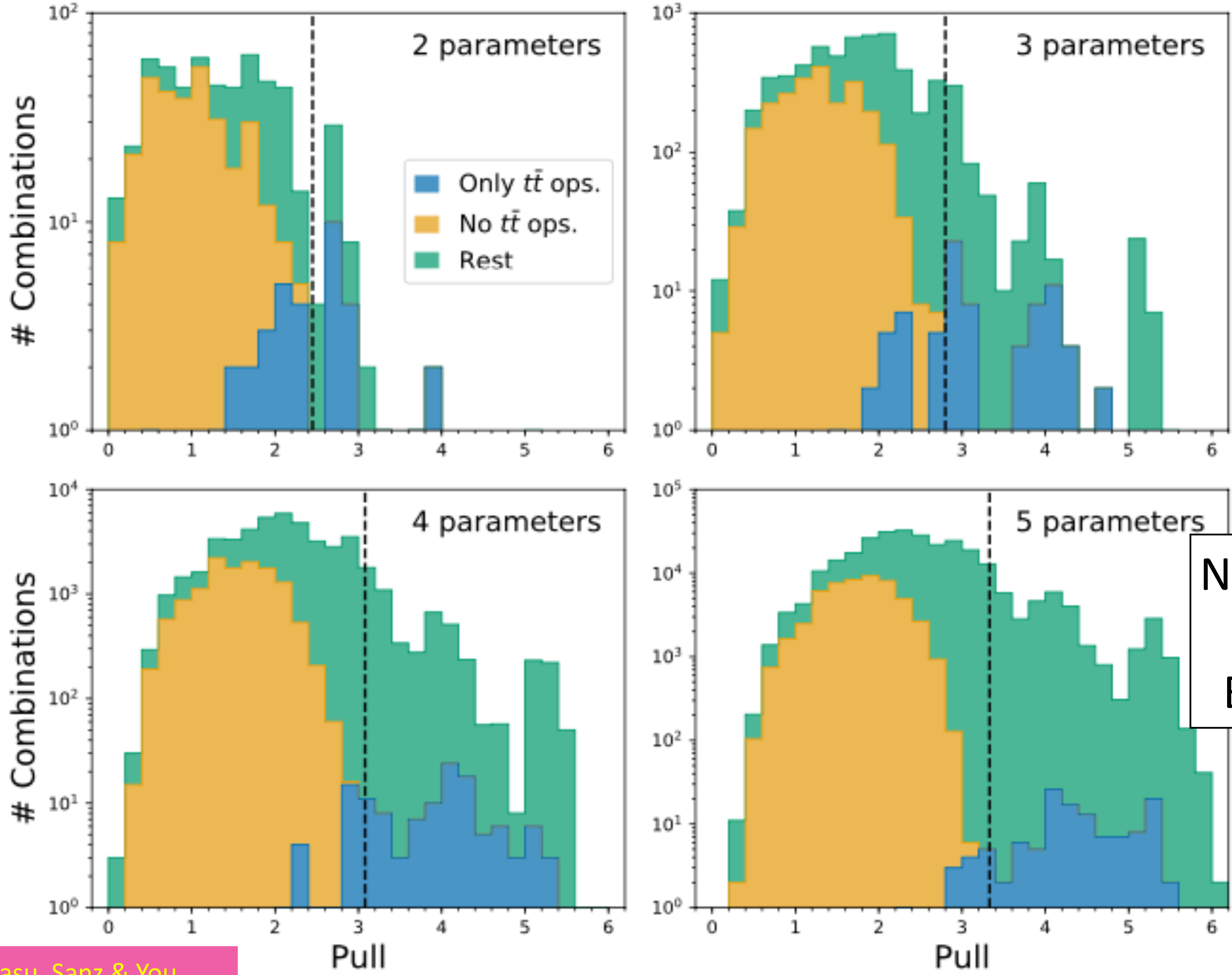
Single-Field Extensions of the Standard Model



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

Model-Independent BSM Survey

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

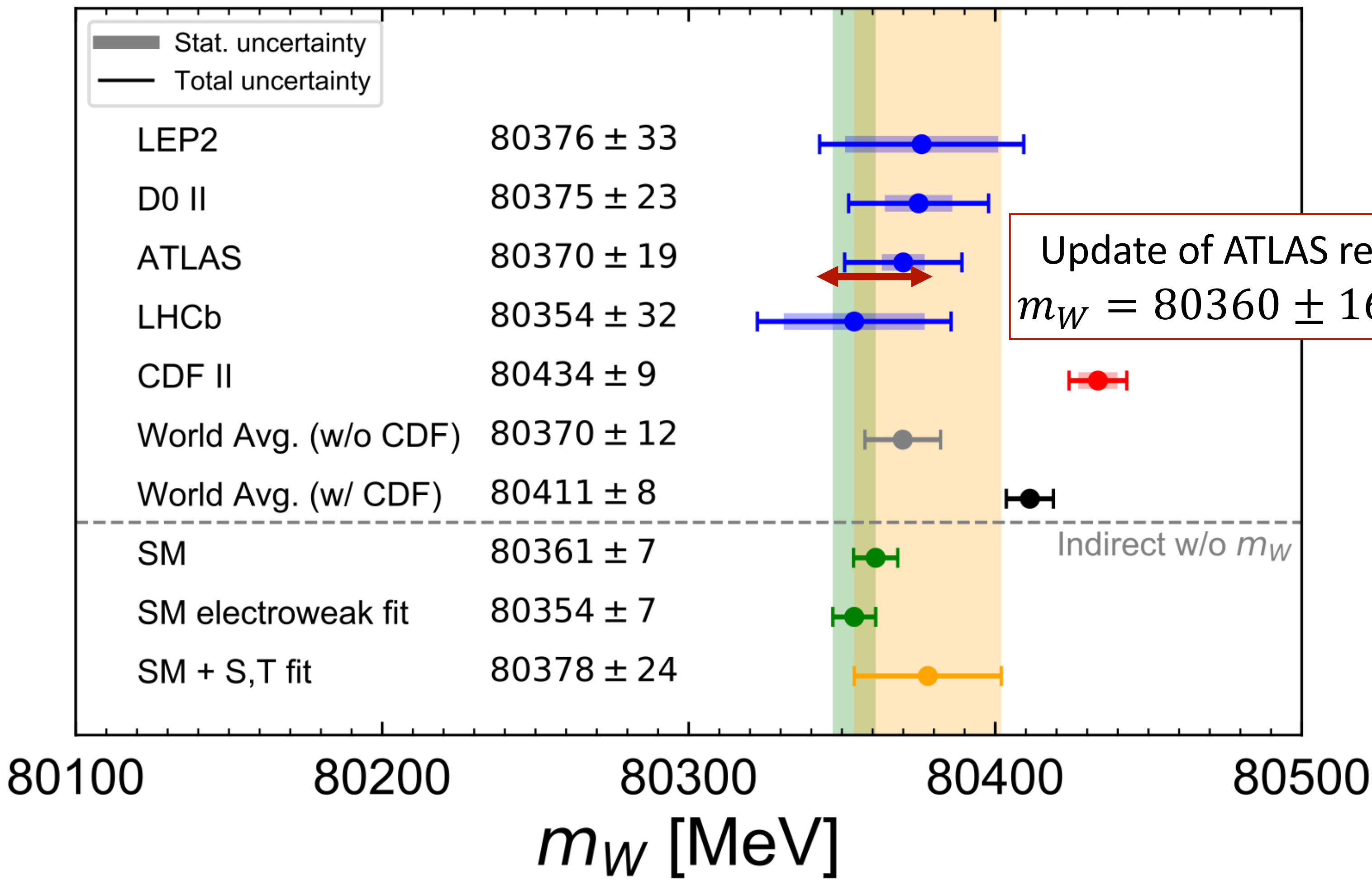


No stand-outs
Suggesting
BSM physics

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

CDF Measurement of mw

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

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

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

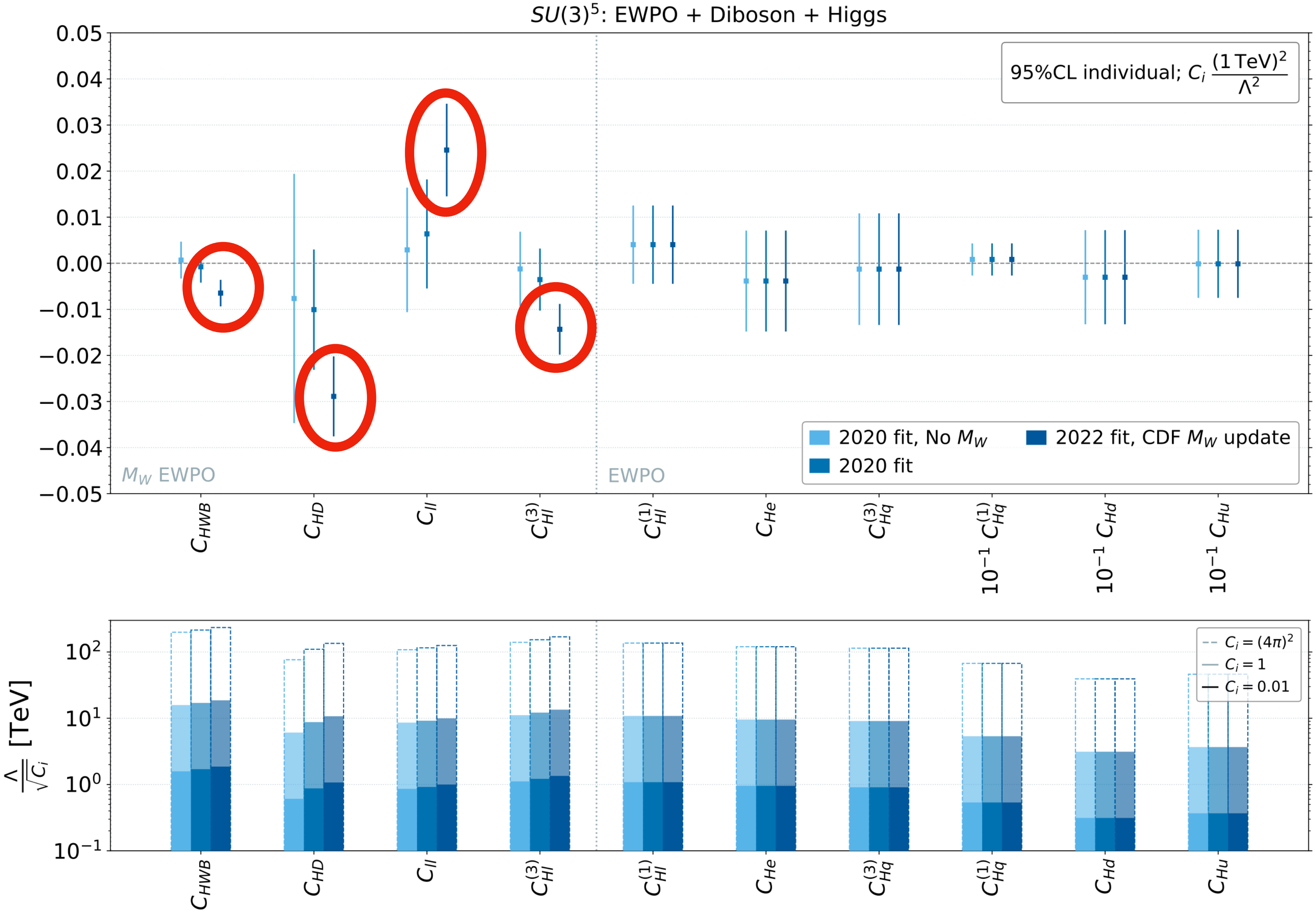
- Contributions to W mass

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

- 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	$-\frac{1}{2}$
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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					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

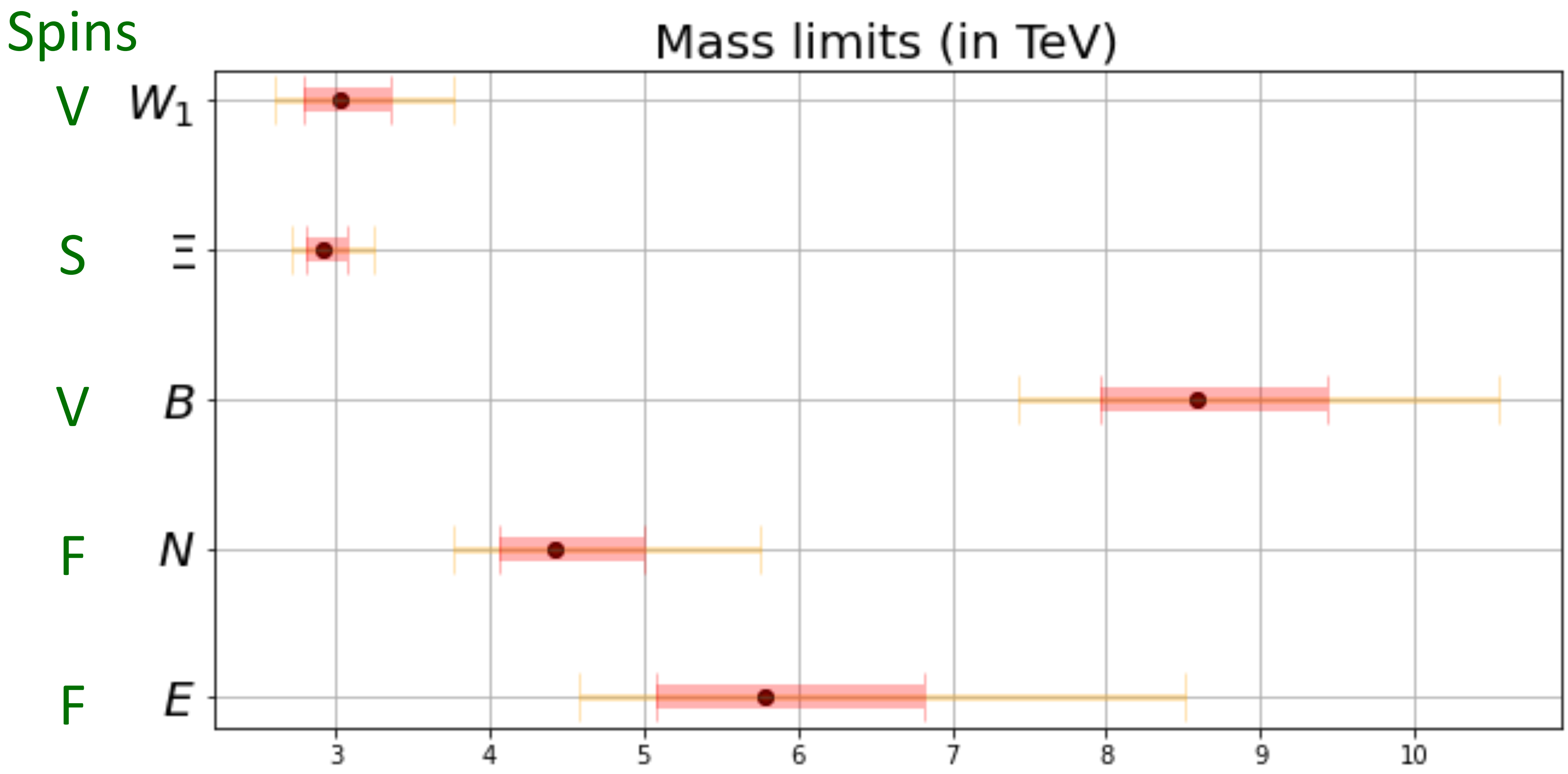
Wrong sign

Right sign

Operators contributing to m_W

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

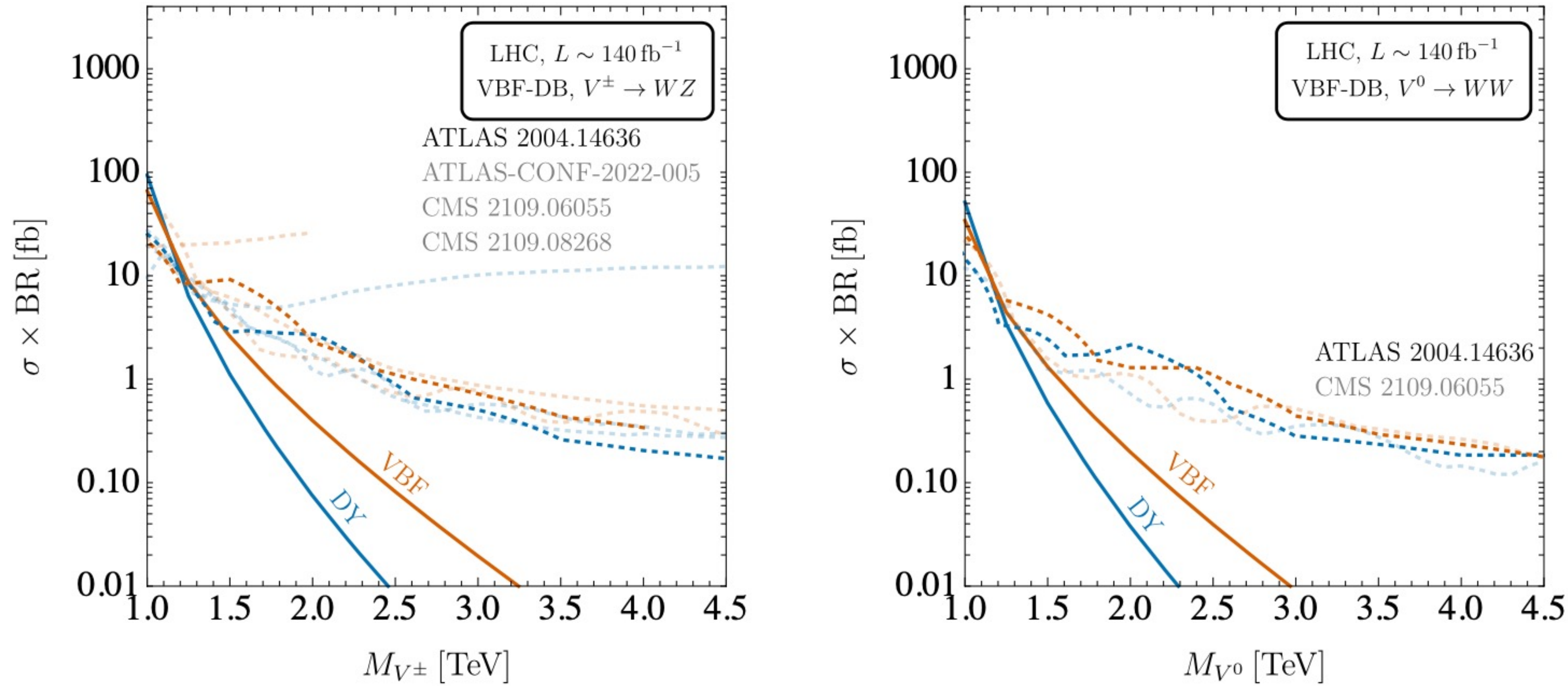
Models Fitting the Mass of the W Boson



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

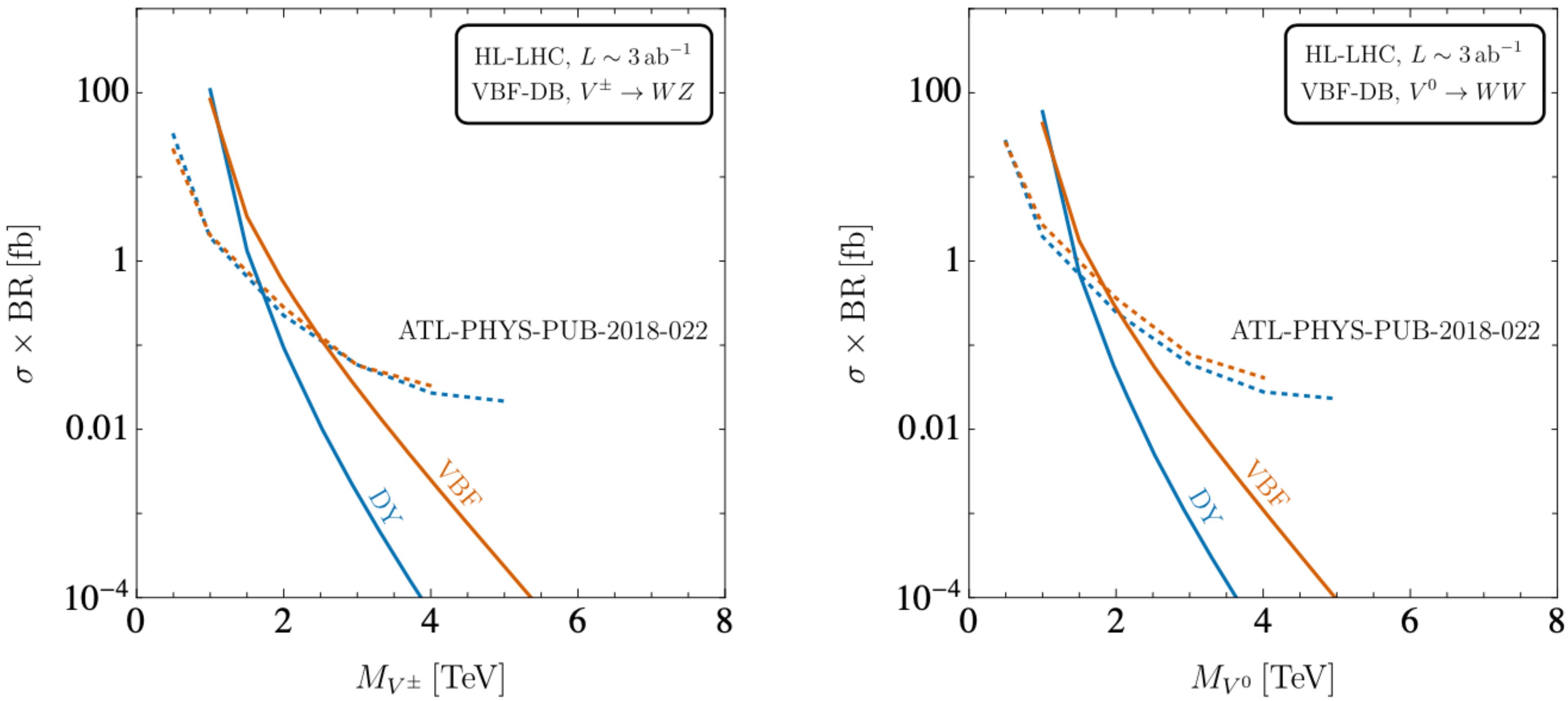
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

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

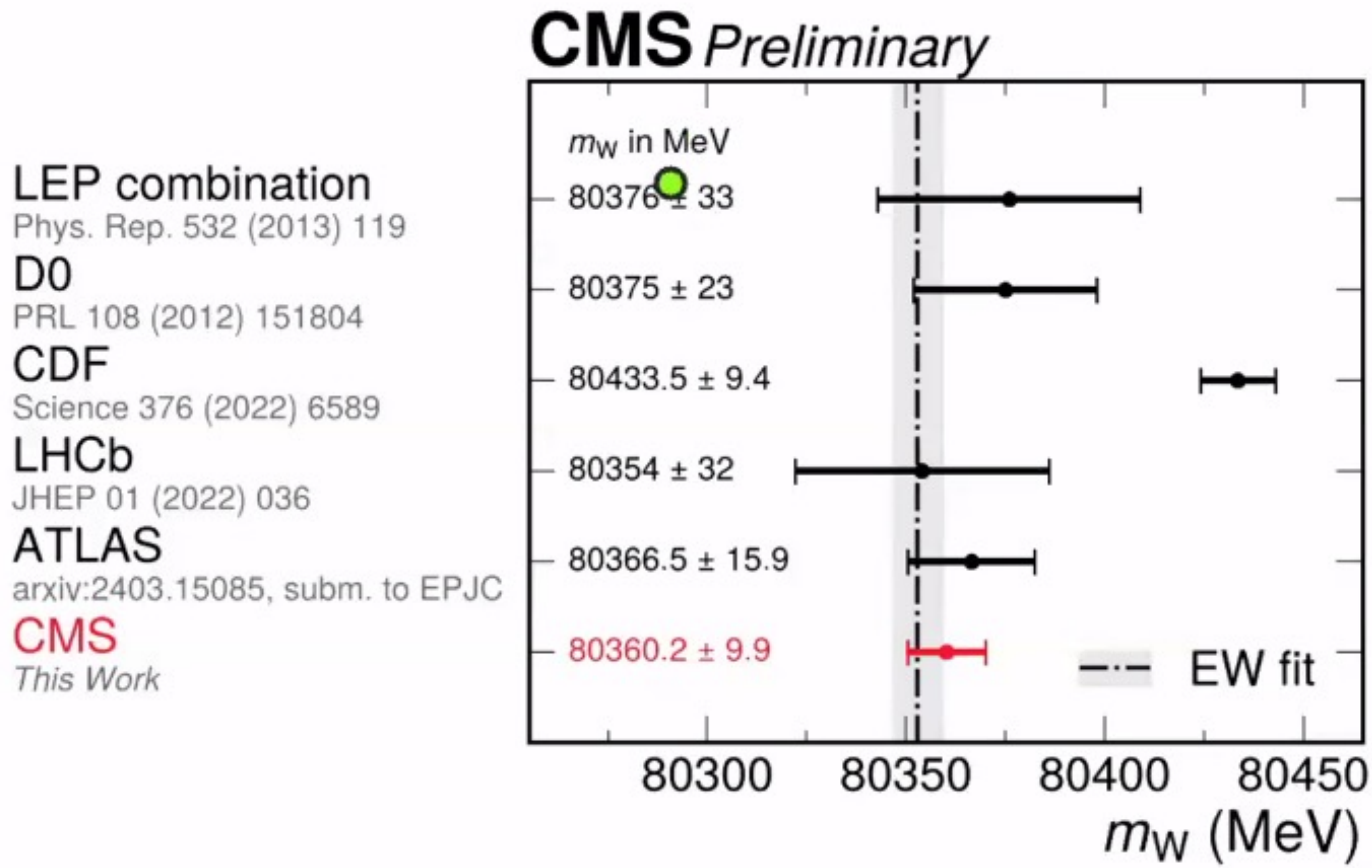
Searching for Models Fitting the Mass of the W Boson

- 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

CMS Measurement of M_W

$$m_W = 80360.2 \pm 9.9\,\text{MeV}$$



Requiem for another anomaly?

Beyond Dimension-6:

Dimension-8 Operators

- Most analyses focus on dimension-6:

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

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

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

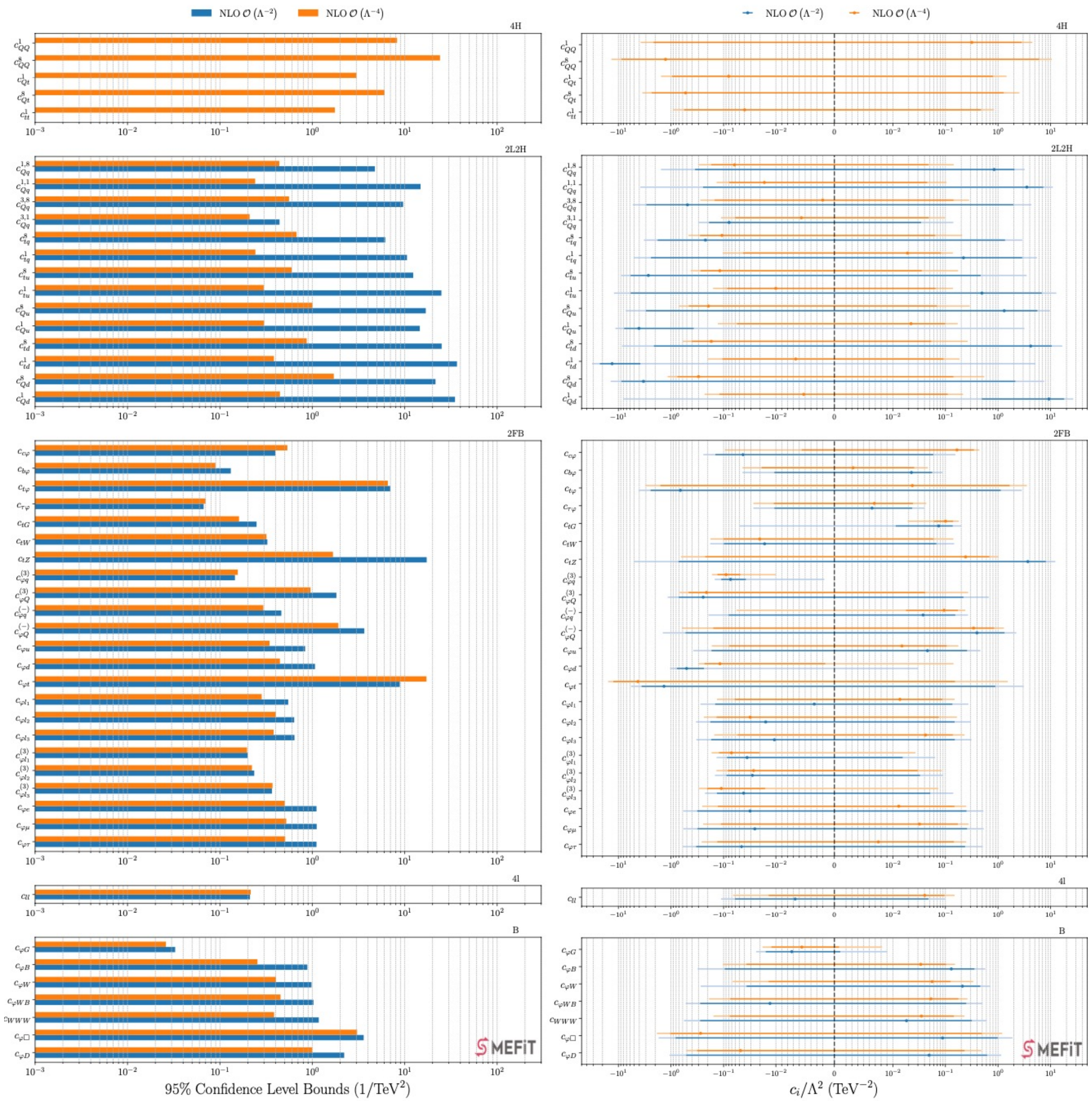
- Study corrections to dimension-6 analysis

- Or study processes without dimension-6 contributions,

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

  Neutral triple-gauge couplings (nTGCs): $\gamma\gamma^* Z, \gamma ZZ*$

SMEFiT Analysis



- Includes linear dimension-8 as well as quadratic dimension-6
- No significant evidence for non-zero operator coefficients
- Experiments, please enter the game!

Celada et al, arXiv:2004.12809

Dimension-8 Operators Contributing to On-Shell nTGCs

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

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

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

$$\mathcal{O}_{C+} = \widetilde{B}_{\mu\nu}W^{a\mu\rho}\left[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) + D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)\right]$$

$$\mathcal{O}_{C-} = \widetilde{B}_{\mu\nu}W^{a\mu\rho}\left[D_\rho(\overline{\psi_L}T^a\gamma^\nu\psi_L) - D^\nu(\overline{\psi_L}T^a\gamma_\rho\psi_L)\right]$$

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

- nTGCs generated:

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(G+)}(q_1,q_2,q_3) = -\frac{v(q_3^2 - M_Z^2)}{M_Z[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + 2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

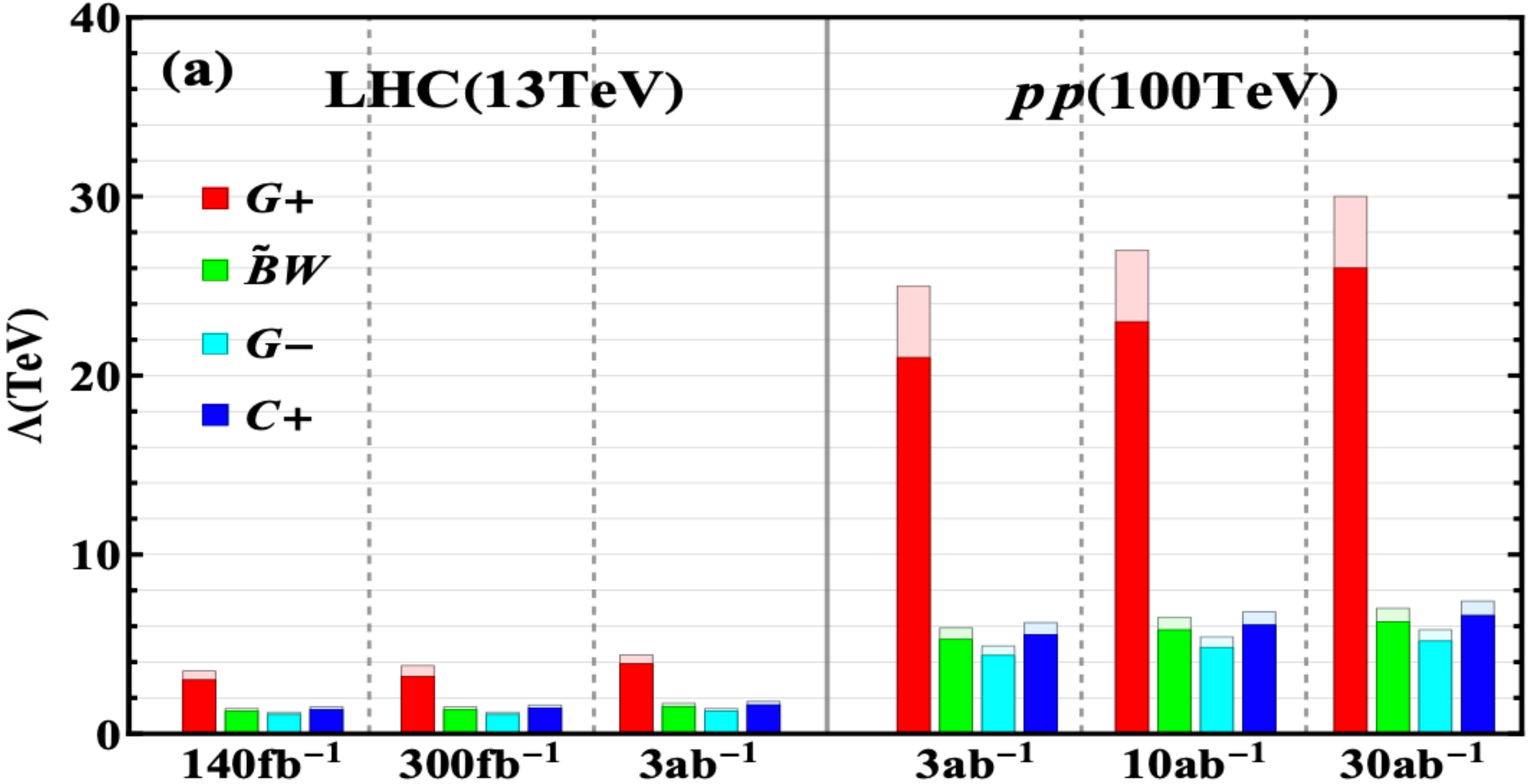
$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G+)}(q_1,q_2,q_3) = -\frac{s_W v\, q_3^2}{c_W M_Z[\Lambda^4_{G+}]}\left(q_3^2\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + 2q_2^\alpha q_{3\nu}q_{2\sigma}\epsilon^{\beta\mu\nu\sigma}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma Z^*(\widetilde{B}W)}(q_1,q_2,q_3) = \frac{v\, M_Z(q_3^2 - M_Z^2)}{[\Lambda^4_{\widetilde{B}W}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}\,,$$

$$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma^*(G-)}(q_1,q_2,q_3) = -\frac{s_W v\, M_Z}{c_W[\Lambda^4_{G-}]}\epsilon^{\alpha\beta\mu\nu}q_{2\nu}q_3^2\,.$$

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

Operator Sensitivities of pp Colliders

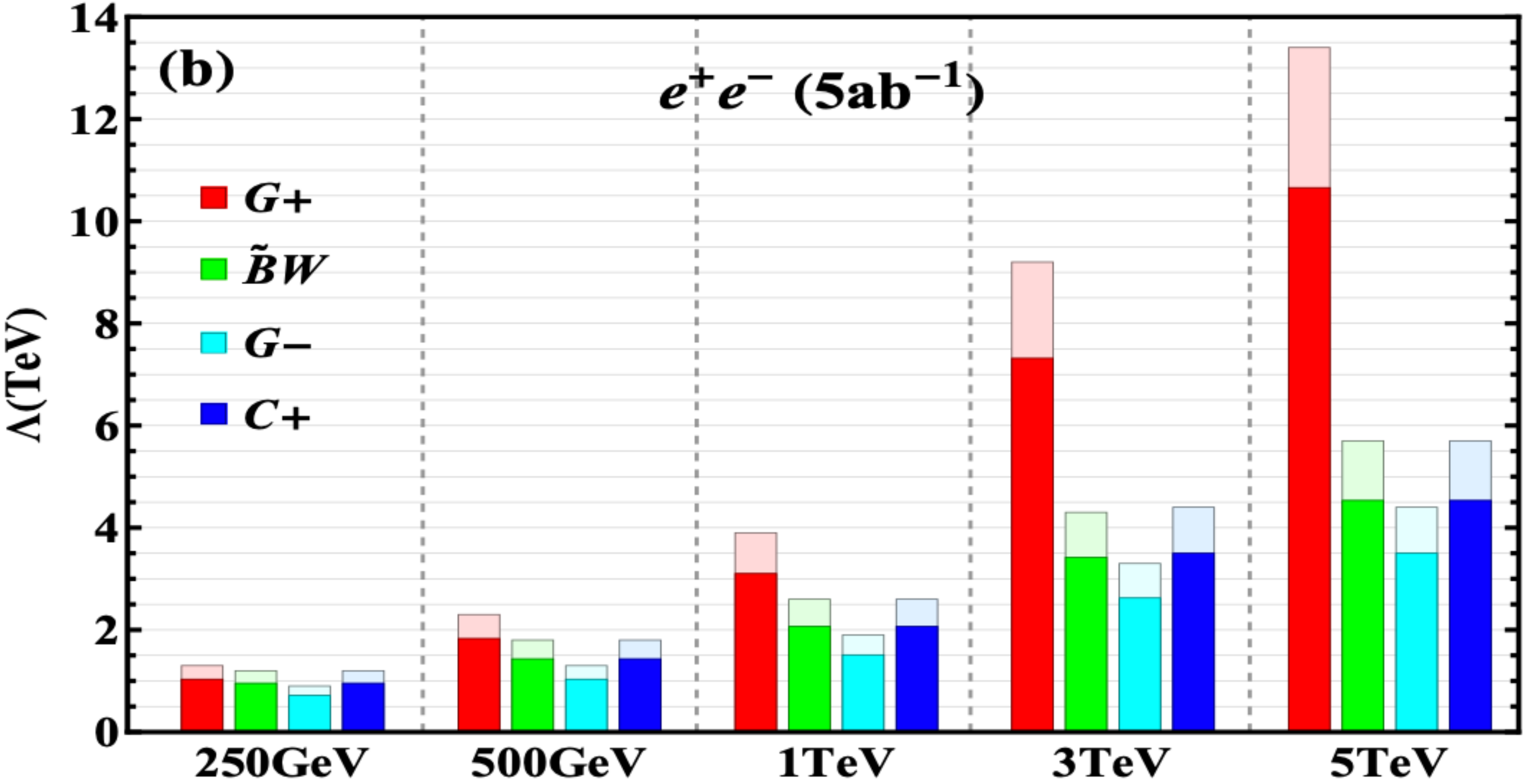


$2-\sigma$ sensitivities

$5-\sigma$ sensitivities

JE, He & Xiao, arXiv:2206.11676

Operator Sensitivities of e^+e^- Colliders



$2-\sigma$ sensitivities

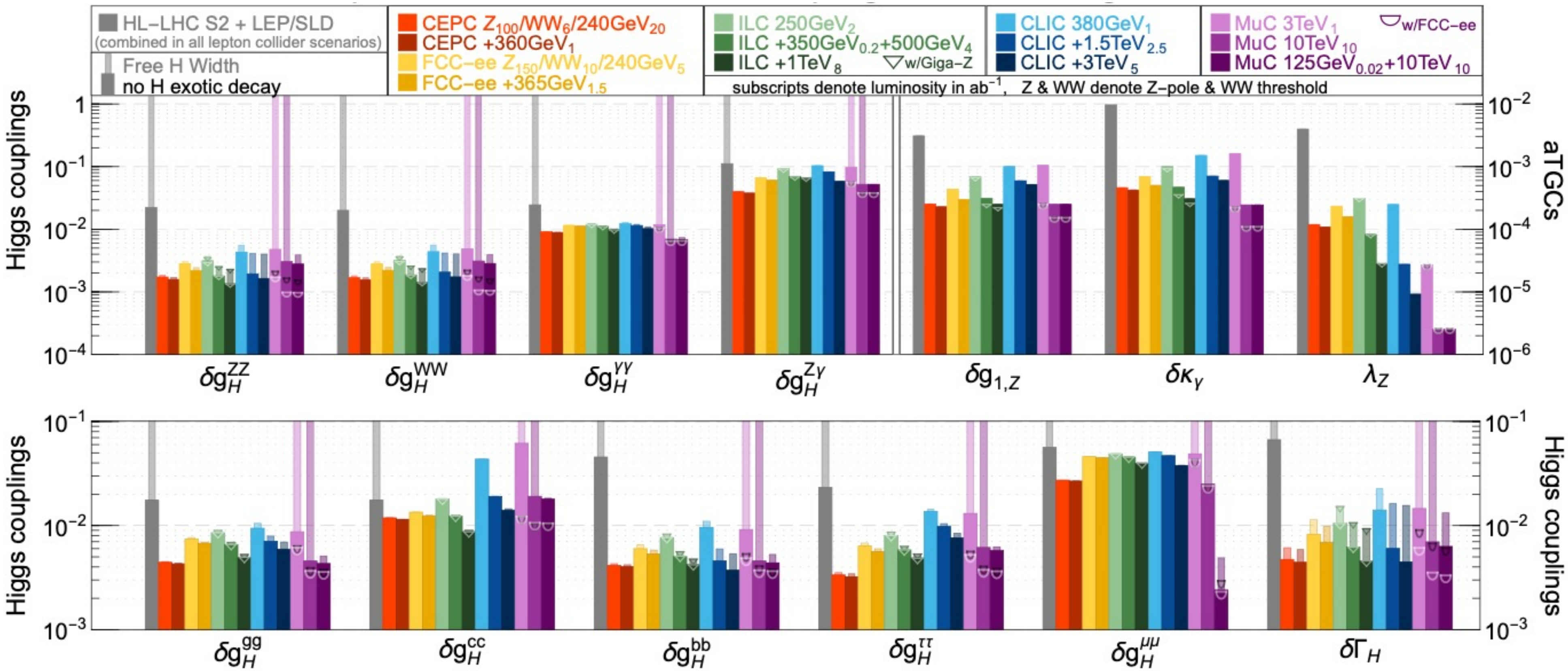
$5-\sigma$ sensitivities

JE, Ge, He & Xiao, arXiv:1902.06631

JE, He & Xiao, arXiv:2008.04298

JE, He & Xiao, arXiv:2206.11676

Future SMEFT Prospects



de Blas et al (Snowmass), arXiv:2206:08326

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