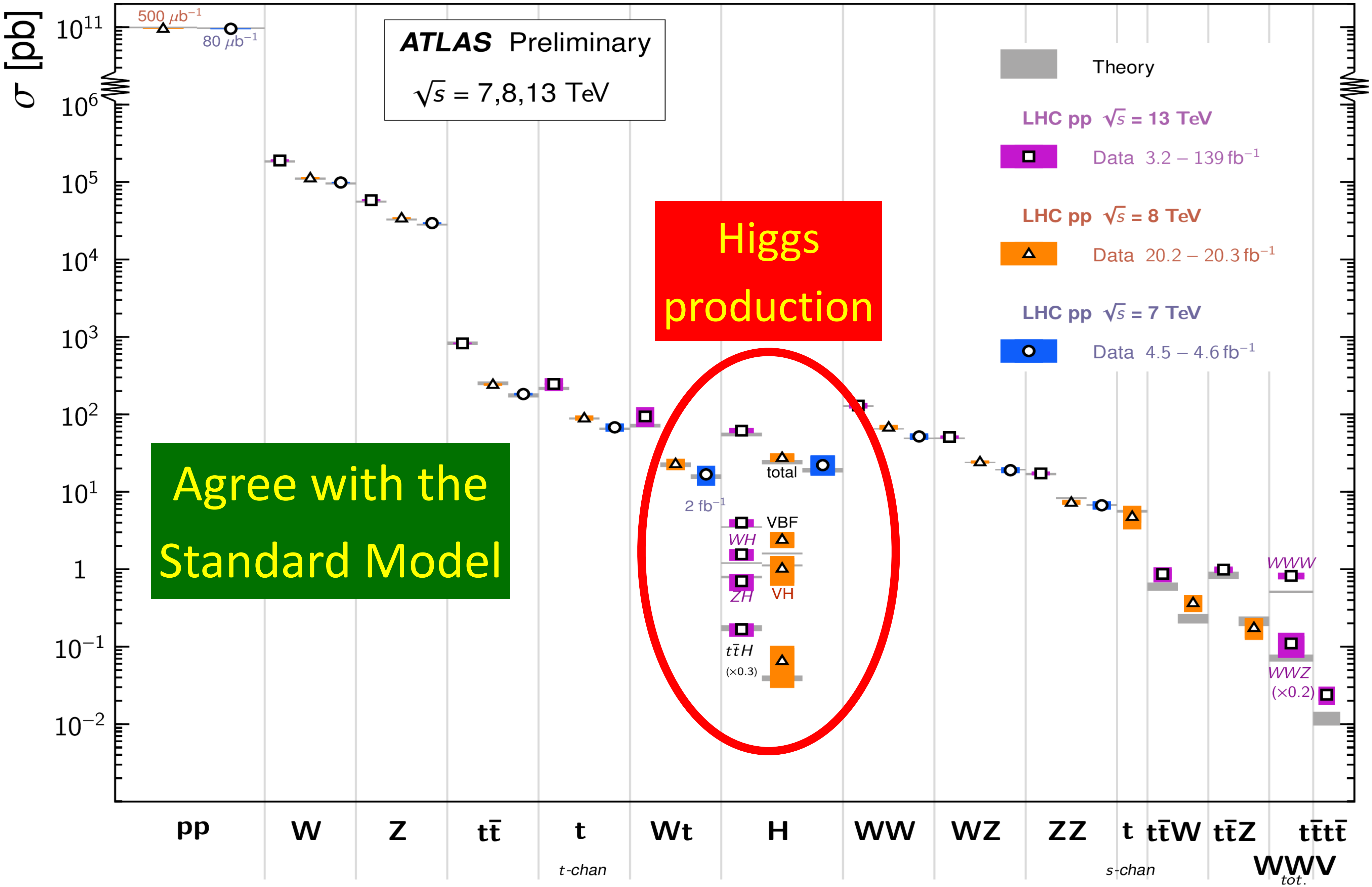
Particle Physics Today

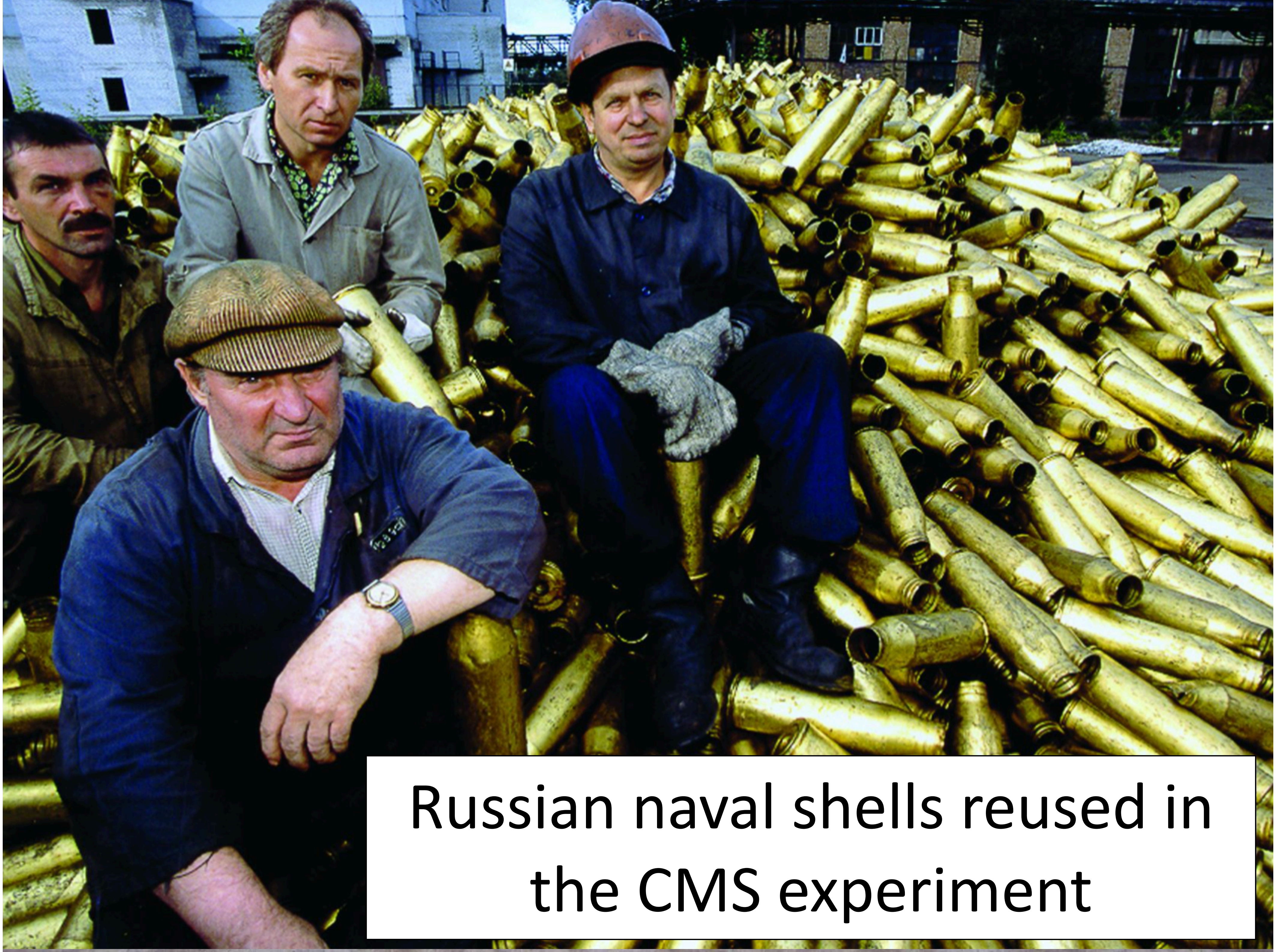
LHC measurements and the Higgs boson
Many Higgs puzzles: supersymmetry?
Beyond Standard Model with Effective Field Theory?
M_W ?

John Ellis

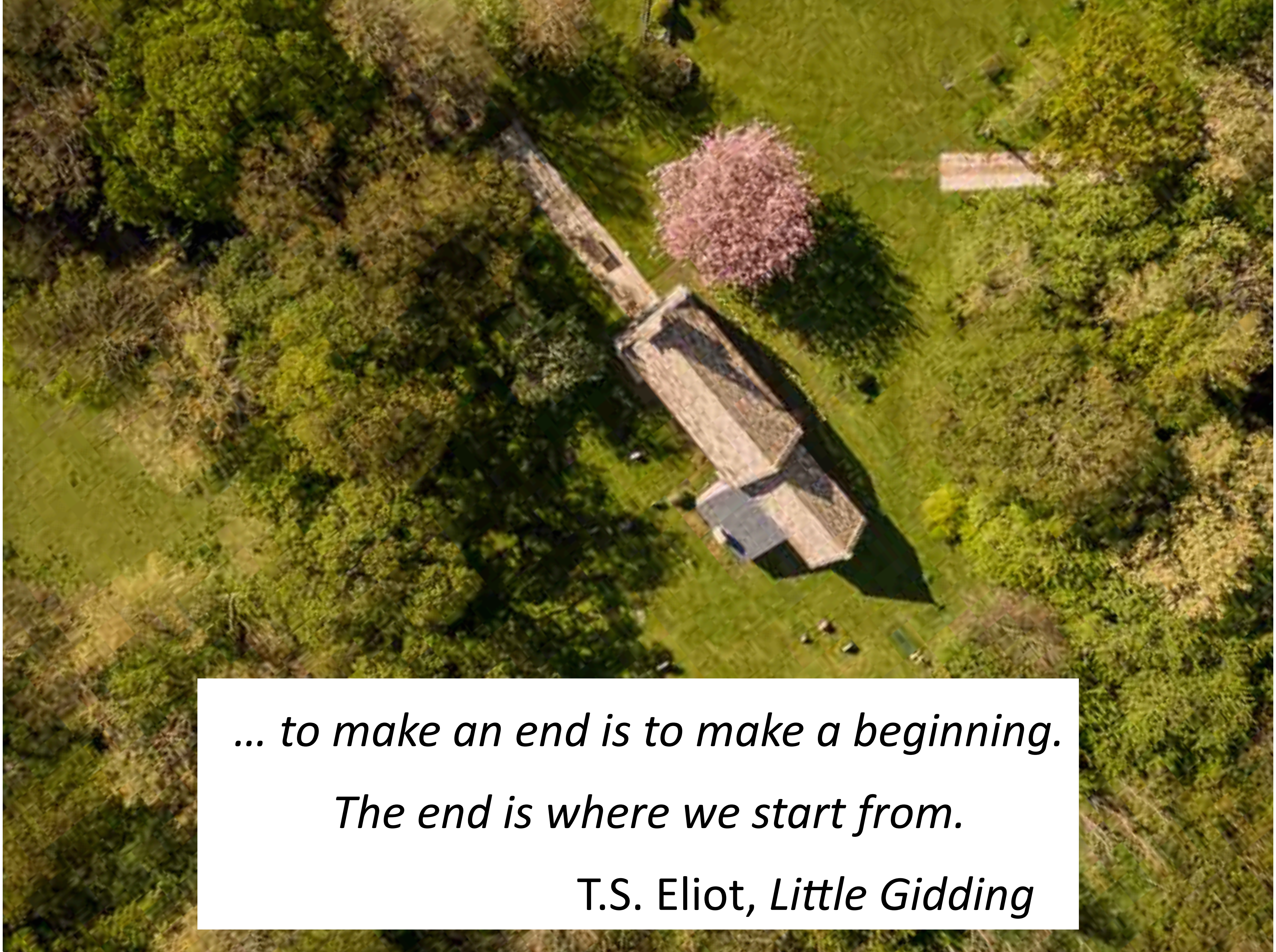
KING'S College LONDON

LHC Measurements





Russian naval shells reused in the CMS experiment



… to make an end is to make a beginning.

The end is where we start from.

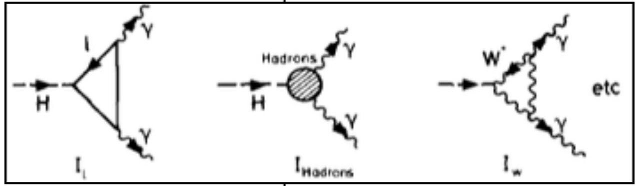
T.S. Eliot, *Little Gidding*

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva



Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Everything about Higgs is Puzzling

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

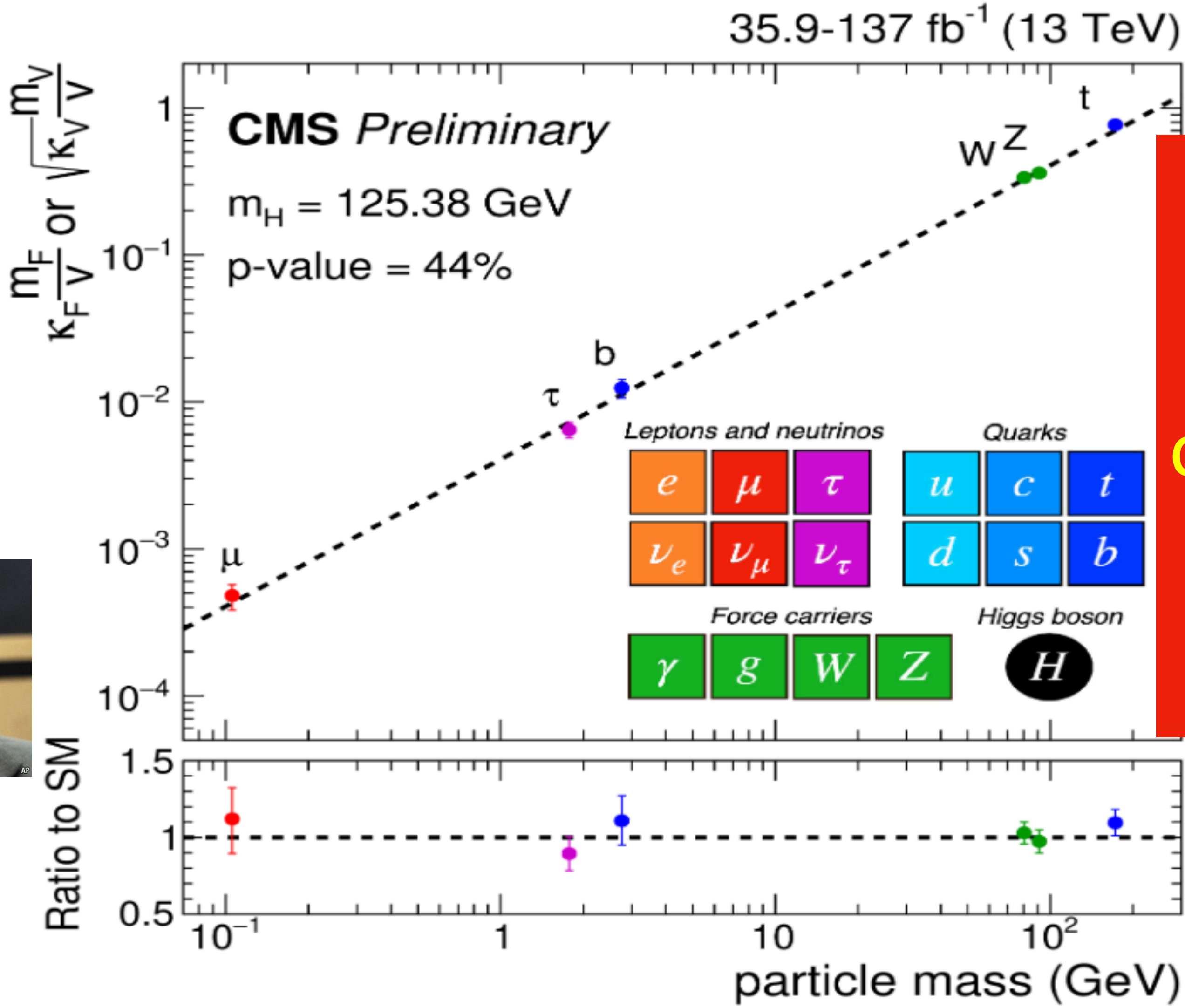
- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional terms due to heavy particles?

It Walks and Quacks like a Higgs

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

Global fit

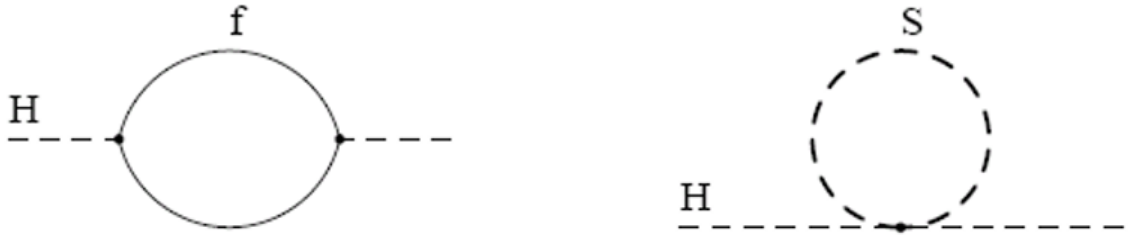


But what is origin of hierarchy of masses & mixing?

Naturalness of electroweak mass scale?

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



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

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

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

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \times 2$$

Supersymmetry!

What lies beyond the Standard Model?

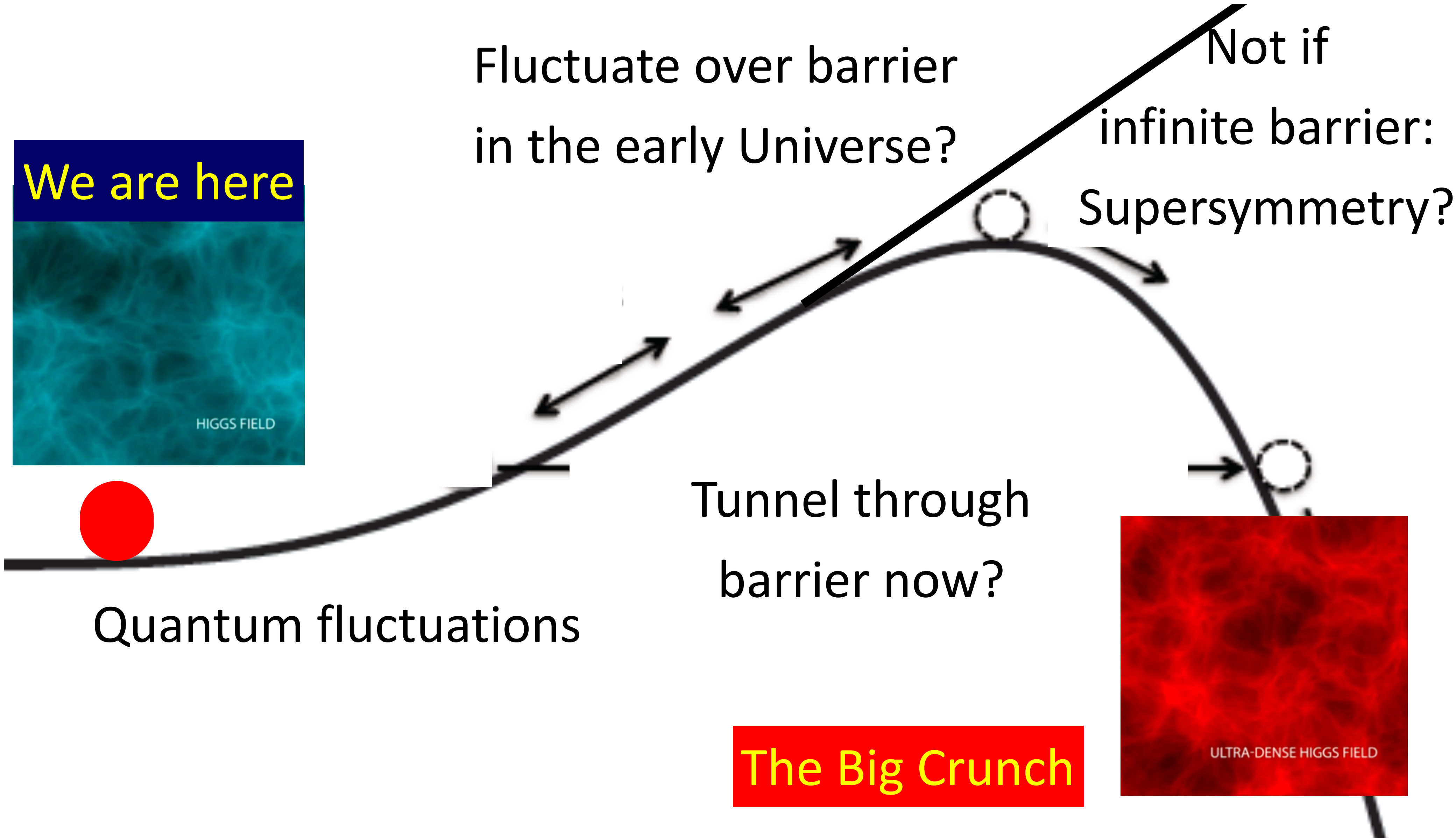
Supersymmetry

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, $g_\mu - 2$, …

Will the Universe Collapse?

Should it have Collapsed already?



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

- Particle Data Group values:

$$m_t = 172.69 \pm 0.30\,\mathrm{GeV}$$

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

- Instability scale:

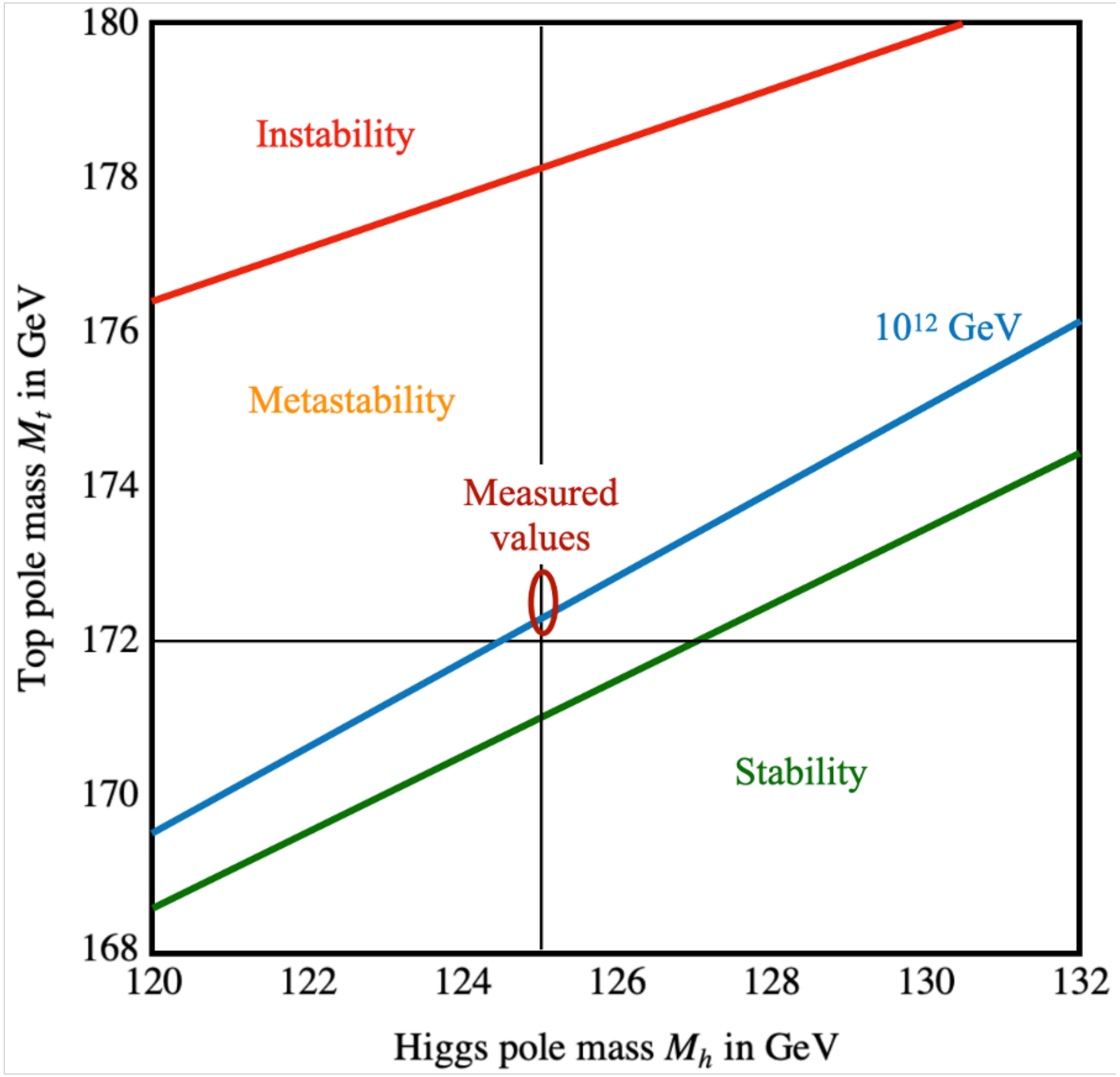
$$\mathrm{Log}_{10}\frac{\Lambda}{\mathrm{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties that in α_s and then m_t

Is "Empty Space" Unstable?

Depends on masses of Higgs boson and top quark

Are we in metastable region of parameters?



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…."

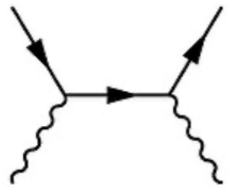
Who can exhaust the possibilities of their combination?"

Sun Tzu

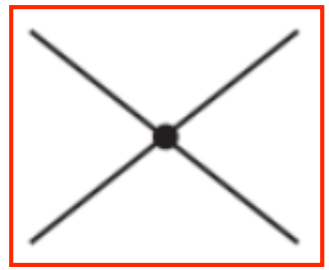
Effective Field Theories (EFTs)

a long and glorious History

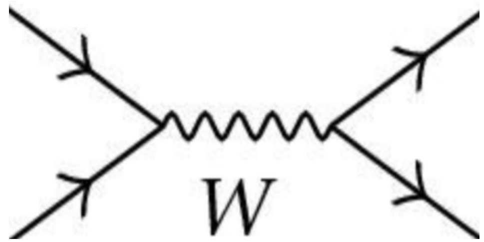
- 1930's: "Standard Model" of QED had d=4



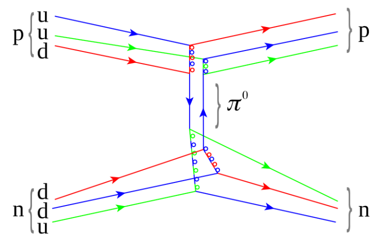
- **Fermi's four-fermion theory of the weak force**



- 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?

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

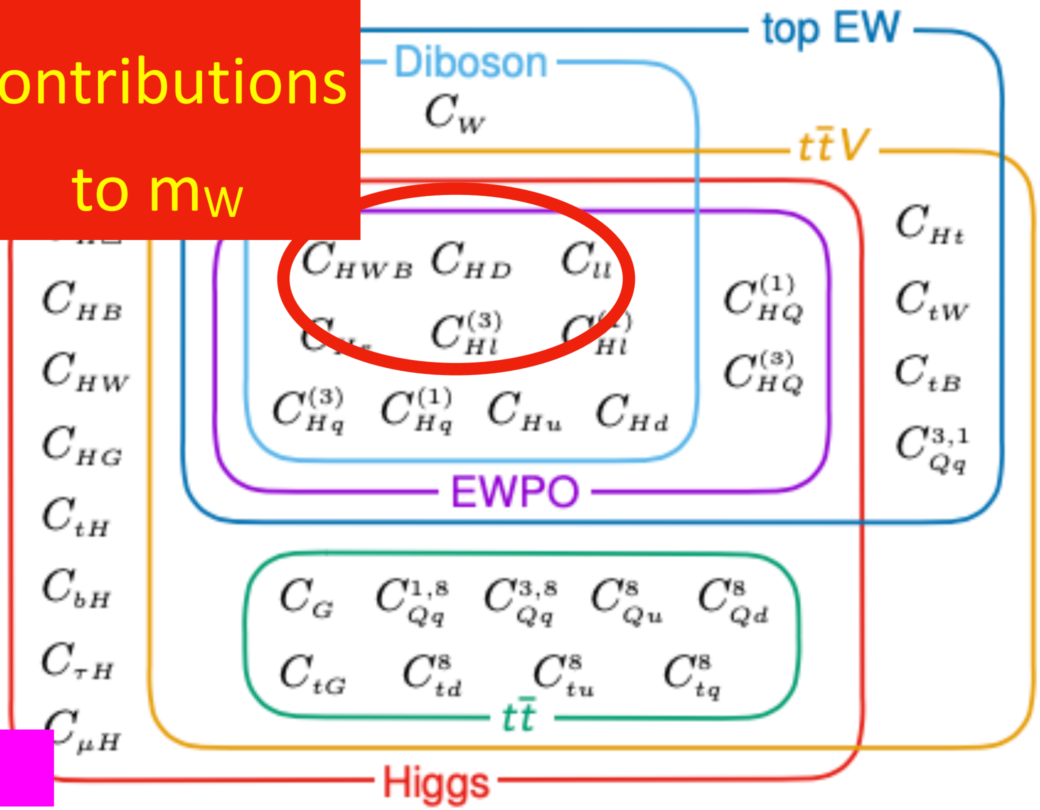
- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

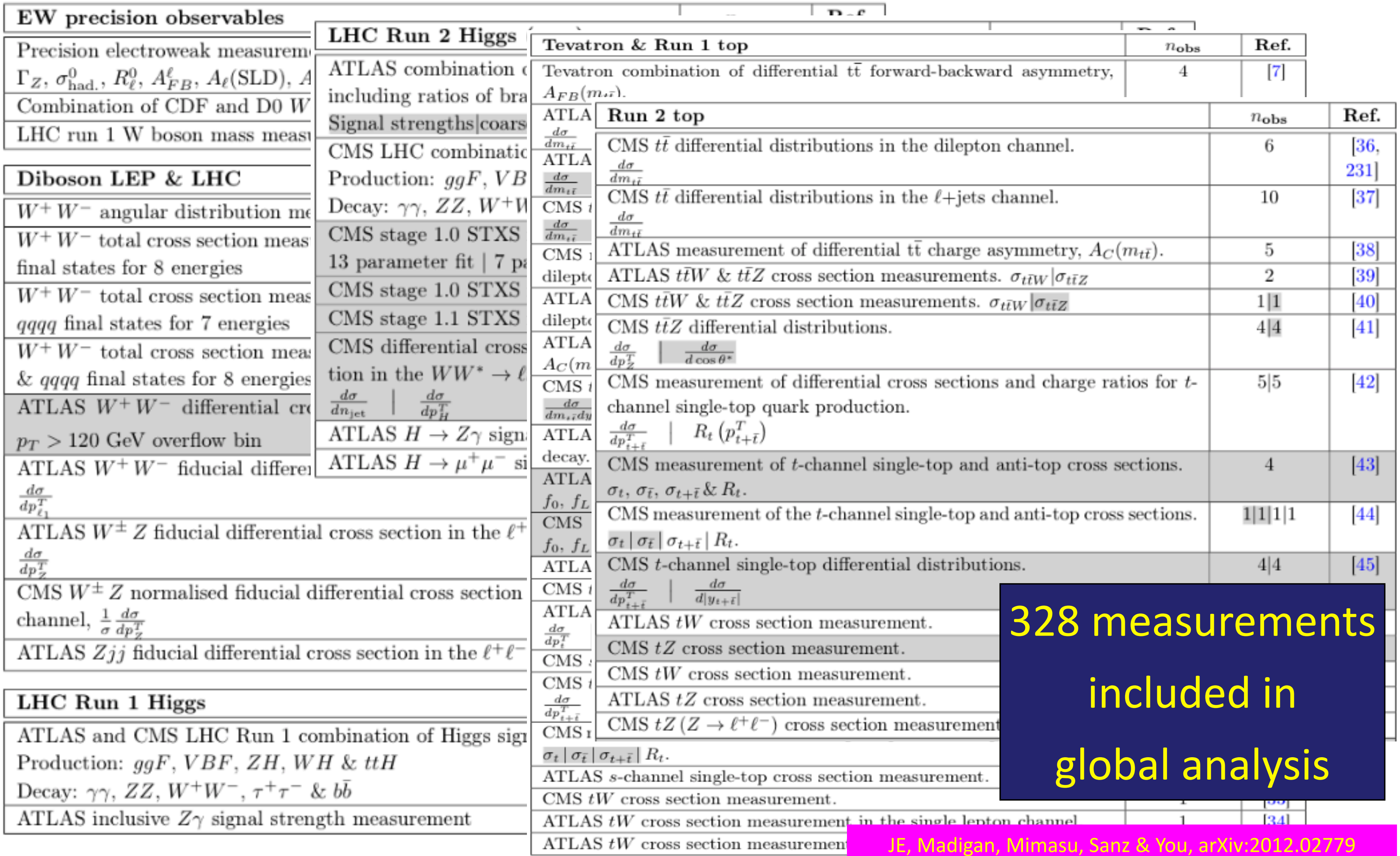
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

Positive contributions to m_W



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

Data included in Global Fit

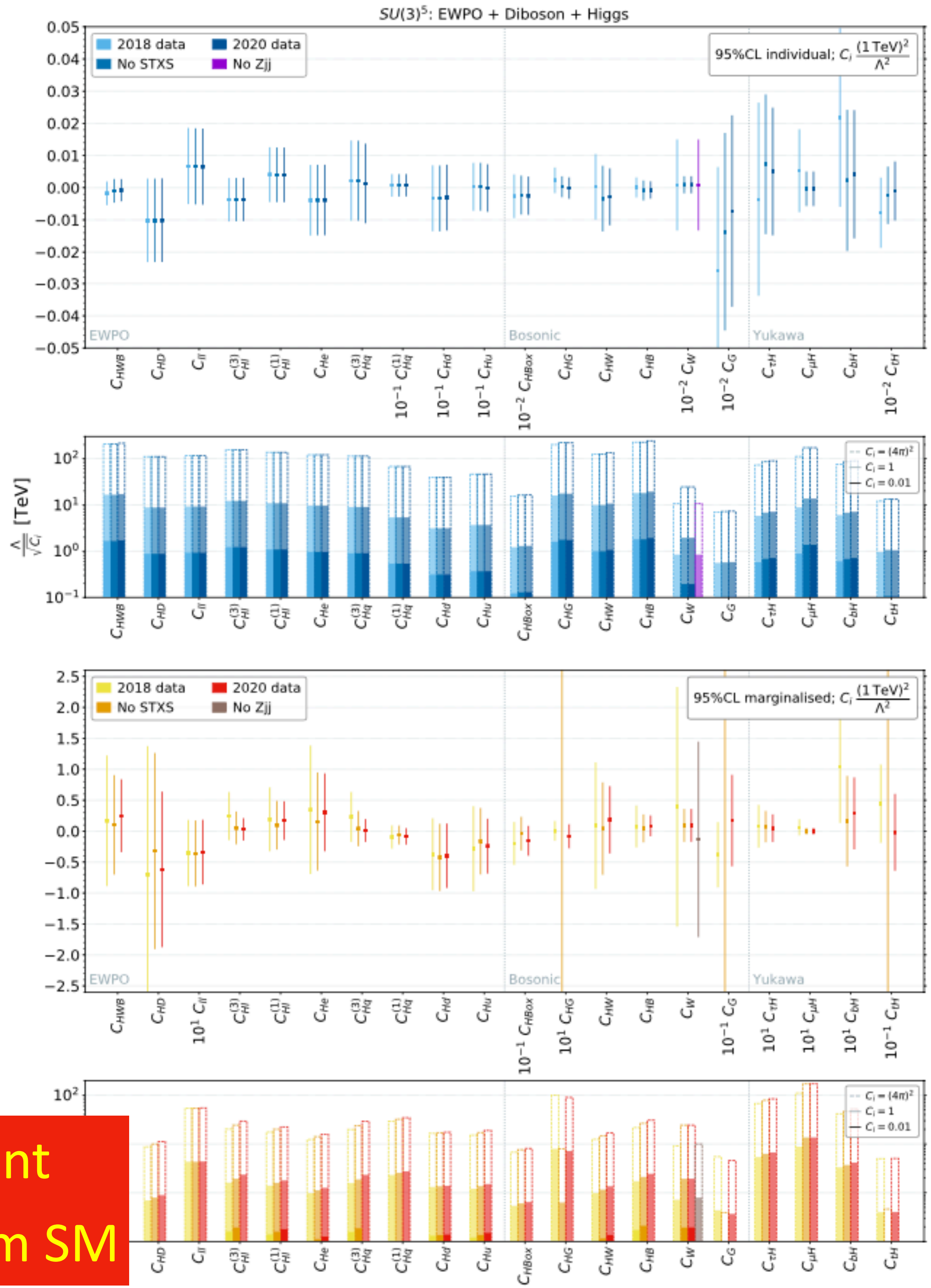


328 measurements included in global analysis

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**



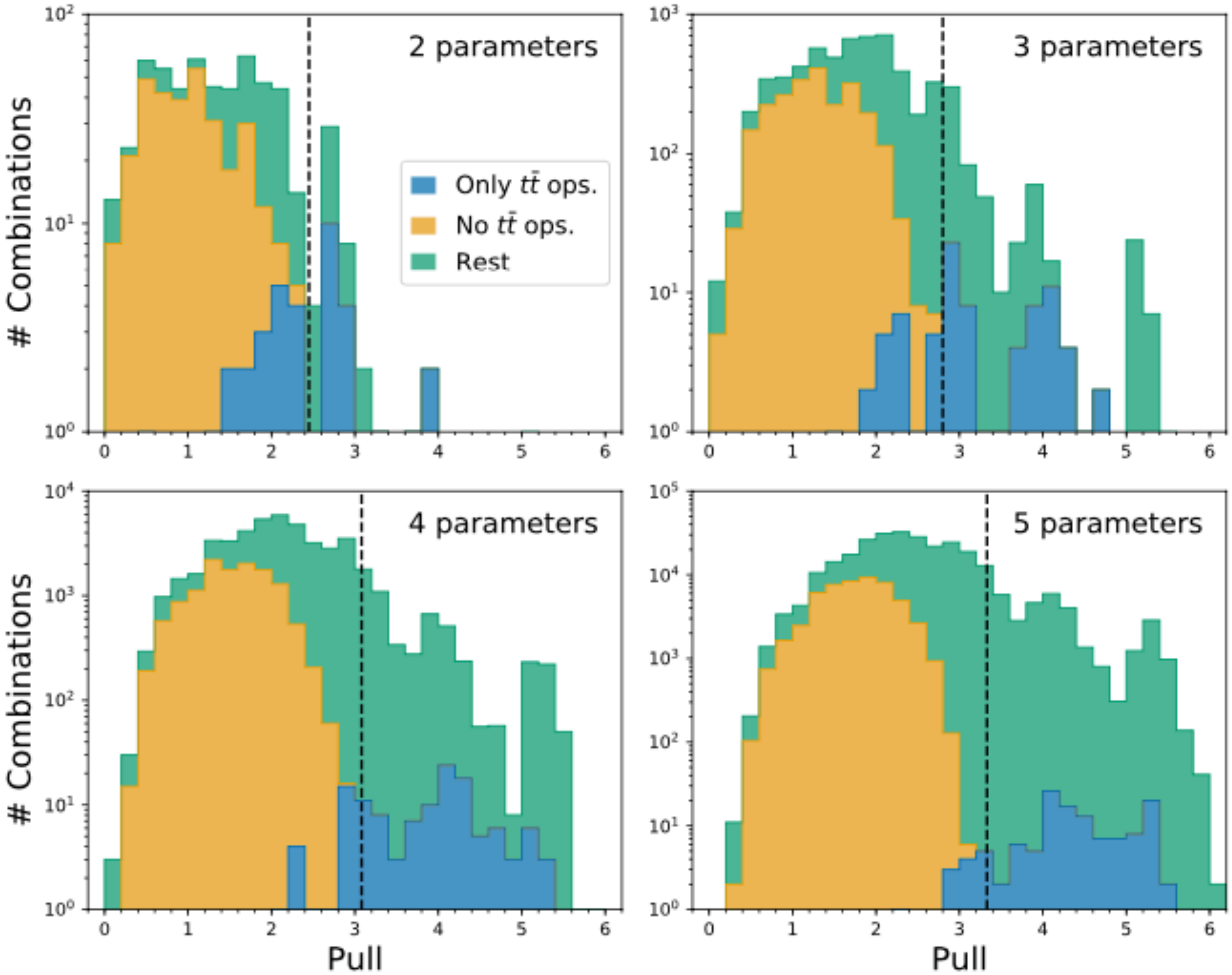
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

No significant deviations from SM

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**

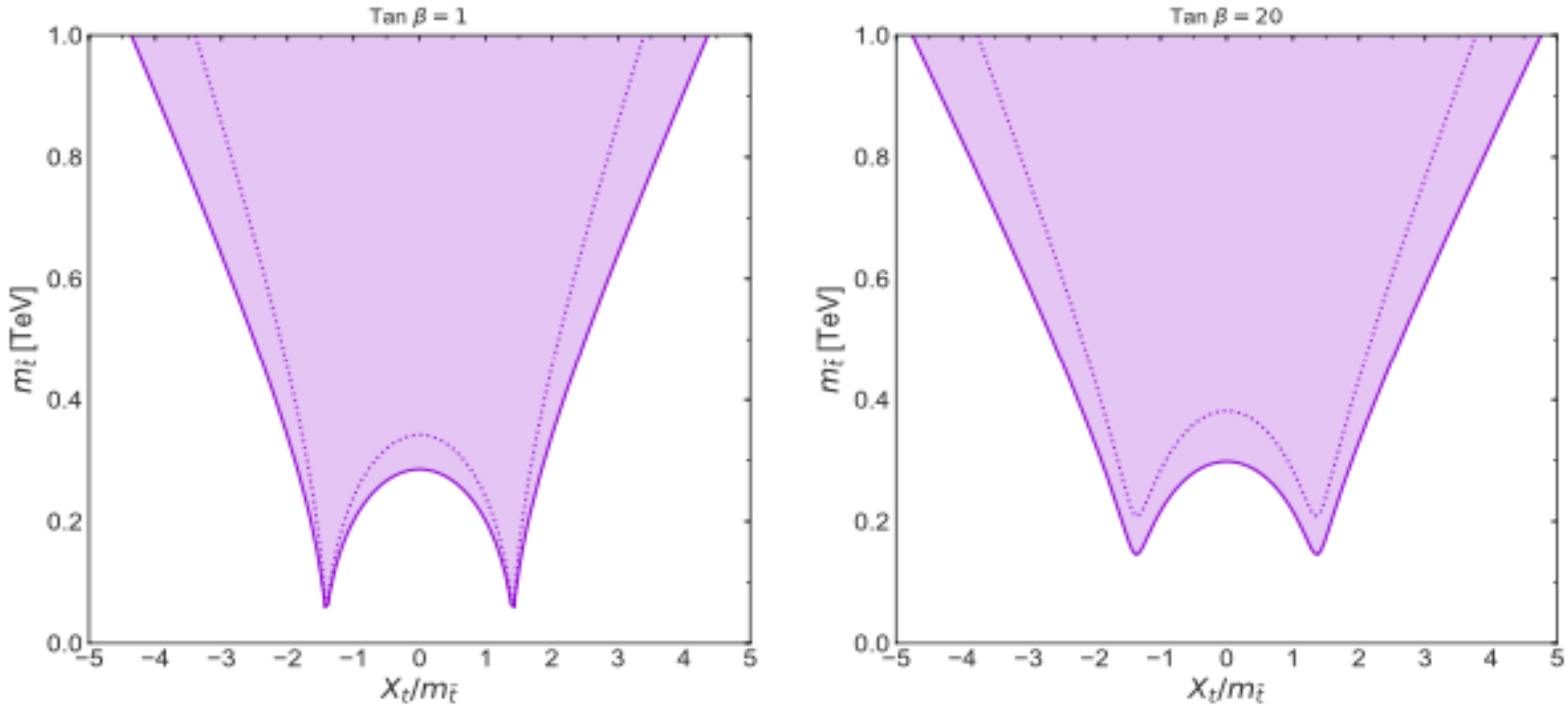


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Constraints on Light Stops

$$C_{HG} = \frac{g_s^2}{12}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{1}{12}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{1}{2}\frac{X_t^2}{m_{\tilde t}^2}\Big],$$
$$C_{HB} = \frac{17g'^2}{144}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{31}{102}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{38}{85}\frac{X_t^2}{m_{\tilde t}^2}\Big],$$
$$C_{HW} = \frac{g^2}{16}\frac{h_t^2}{(4\pi)^2}\Big[(1-\frac{1}{6}\frac{c_{2\beta}g'^2}{h_t^2}) - \frac{2}{5}\frac{X_t^2}{m_{\tilde t}^2}\Big],$$
$$C_{HWB} = -\frac{gg'}{24}\frac{h_t^2}{(4\pi)^2}\Big[(1+\frac{1}{2}\frac{c_{2\beta}g^2}{h_t^2}) - \frac{4}{5}\frac{X_t^2}{m_{\tilde t}^2}\Big],$$

From quantum loop corrections:

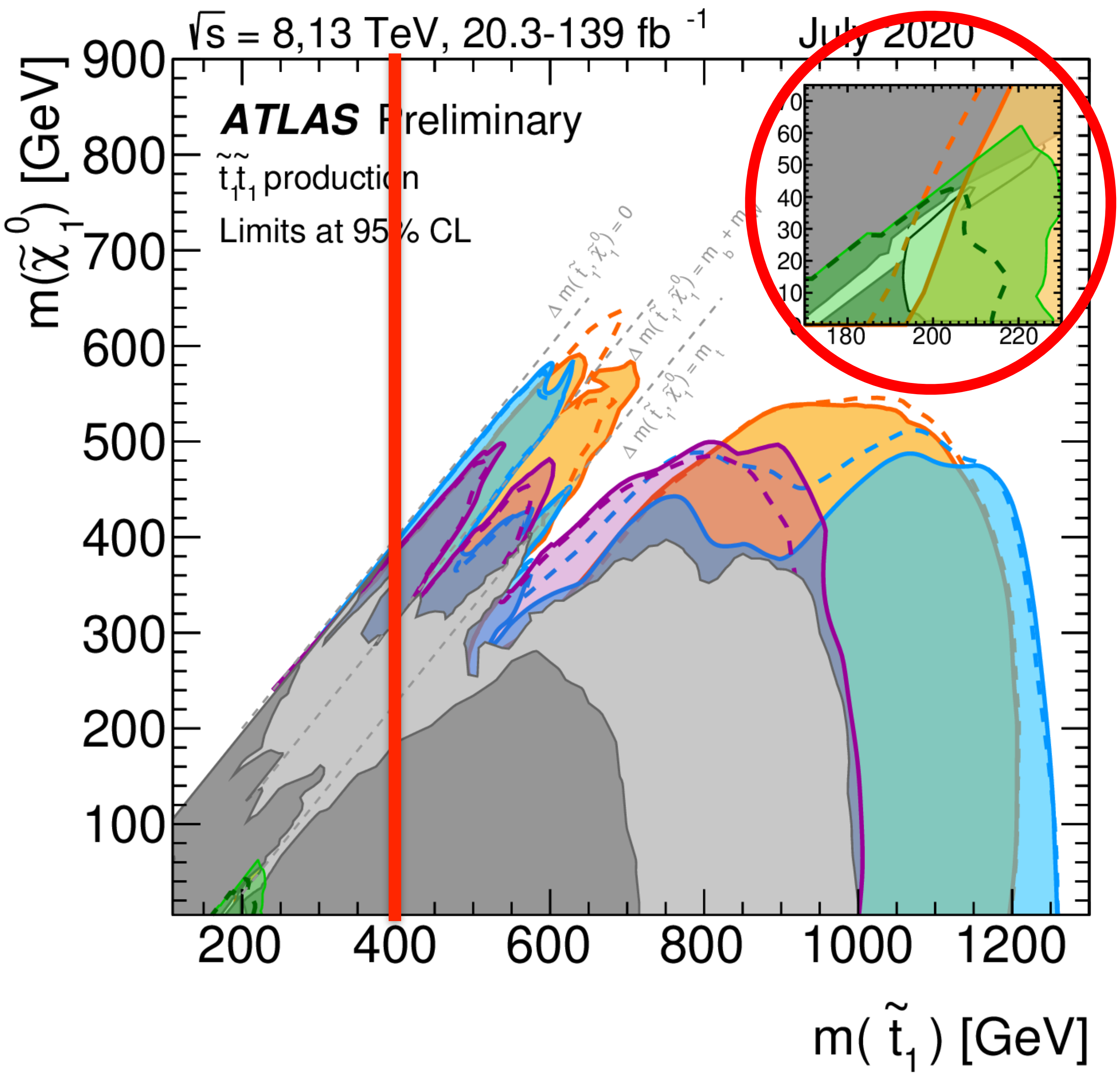


(Almost) model-independent lower limit on stop squark mass

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

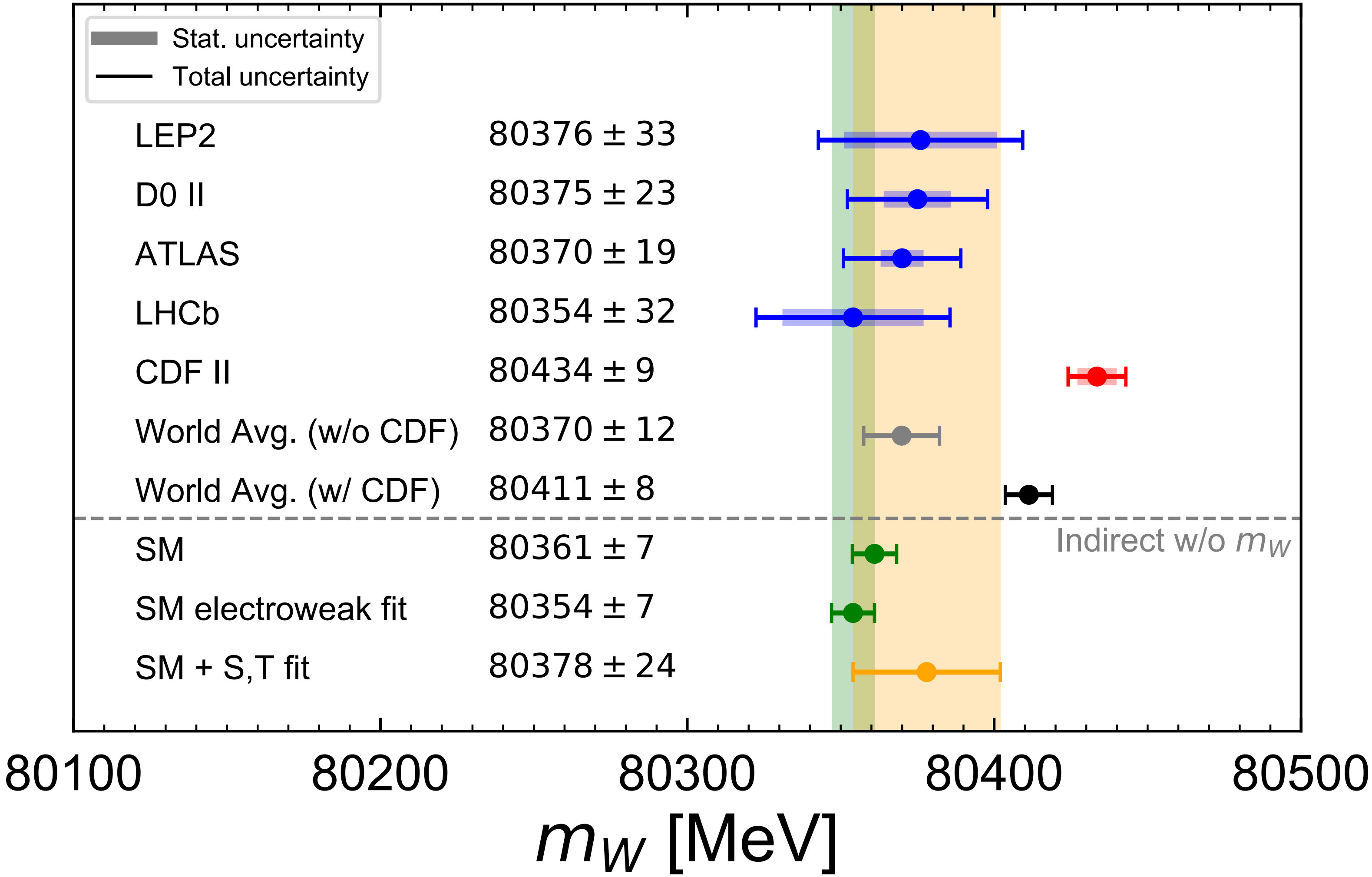
Direct Search Constraints on Light Stops

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



CDF Measurement of m_W

compared with previous measurements



Tension: 7-σ discrepancy with Standard Model?

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

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

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

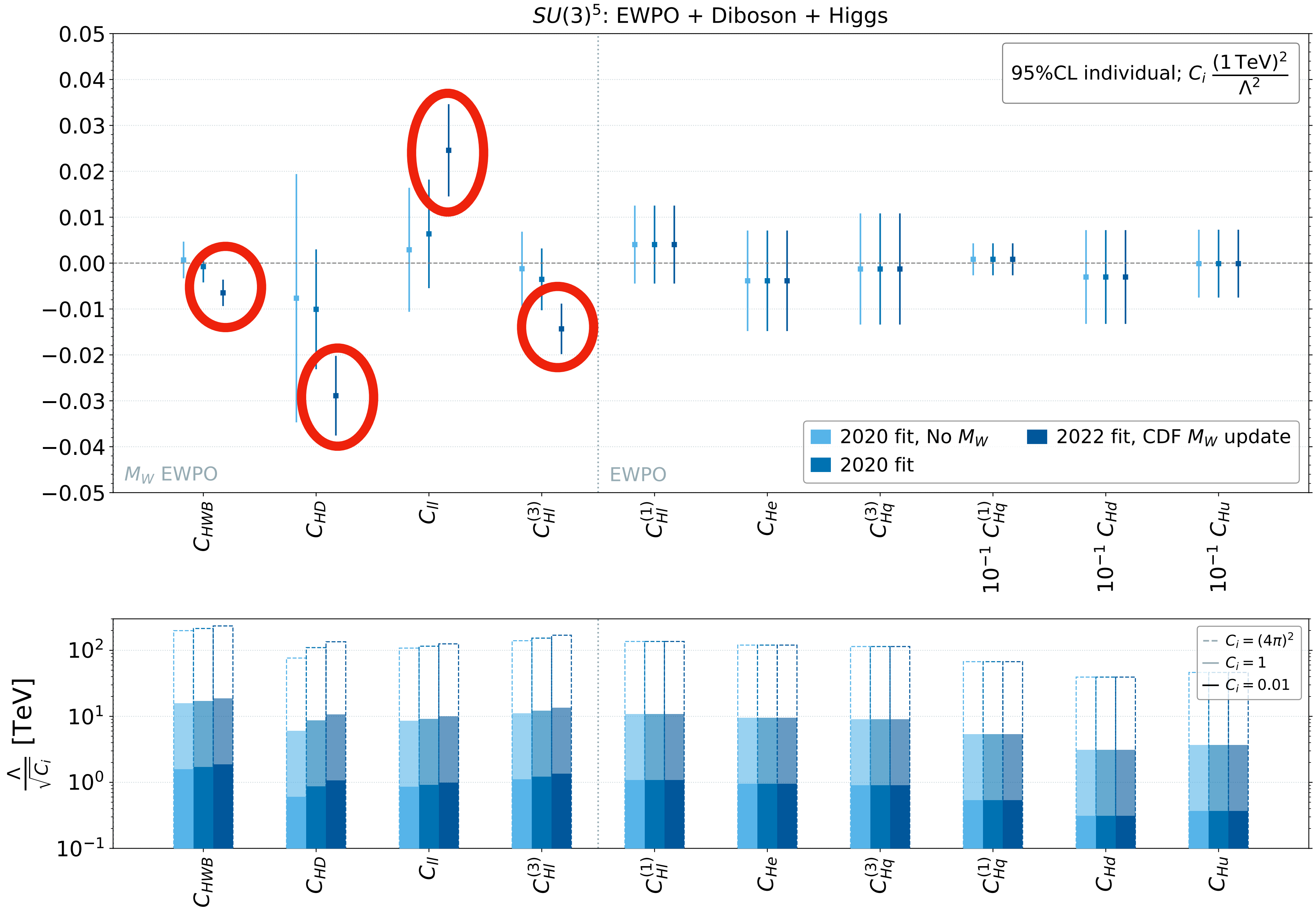
- Contributions to W mass

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

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

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

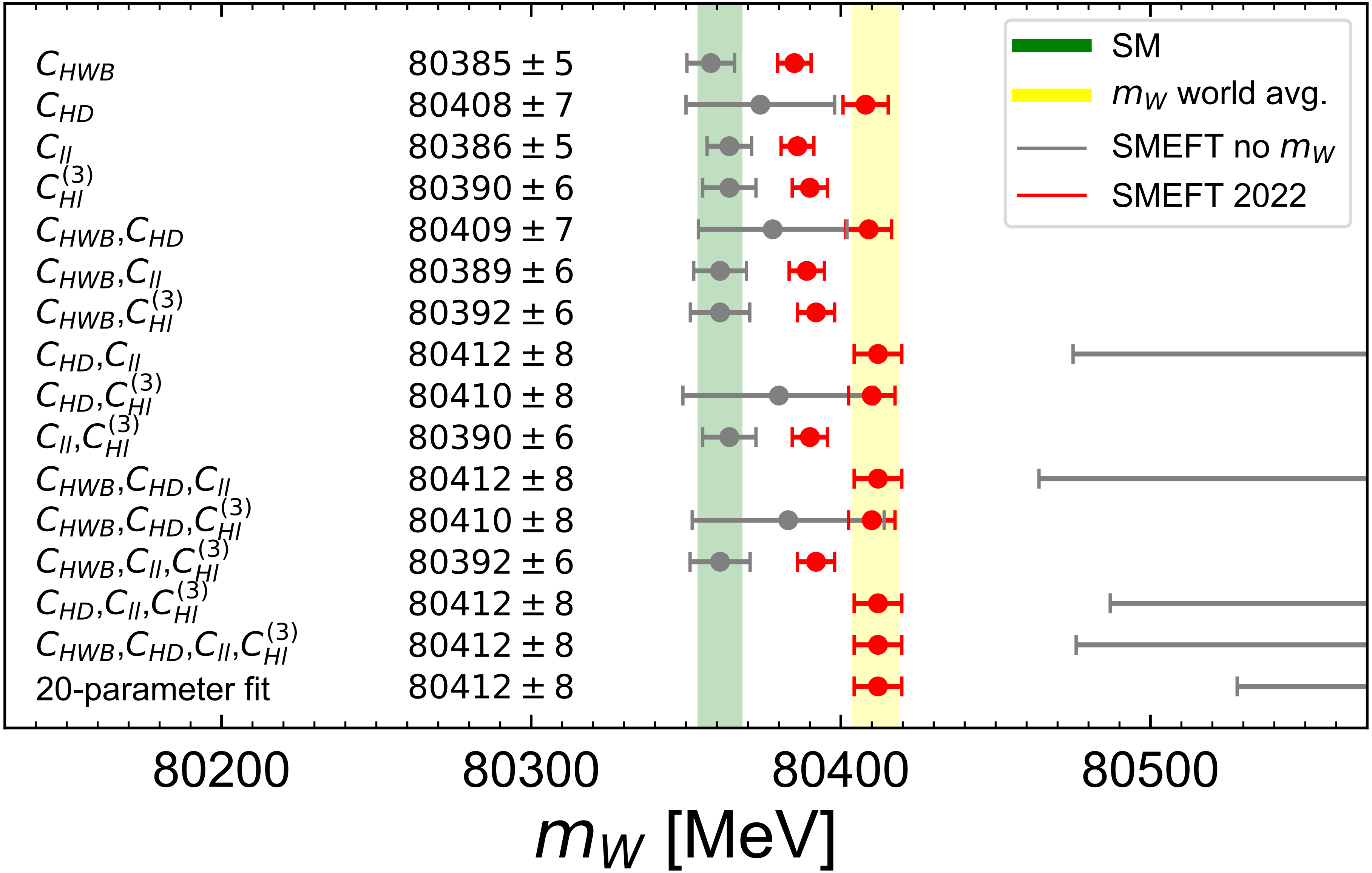
SMEFT Fits with the Mass of the W Boson



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

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

SMEFT Fits with the Mass of the W Boson



Subsets 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 1							
Σ			X $\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X $\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X 1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
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 $\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Wrong sign

Right sign

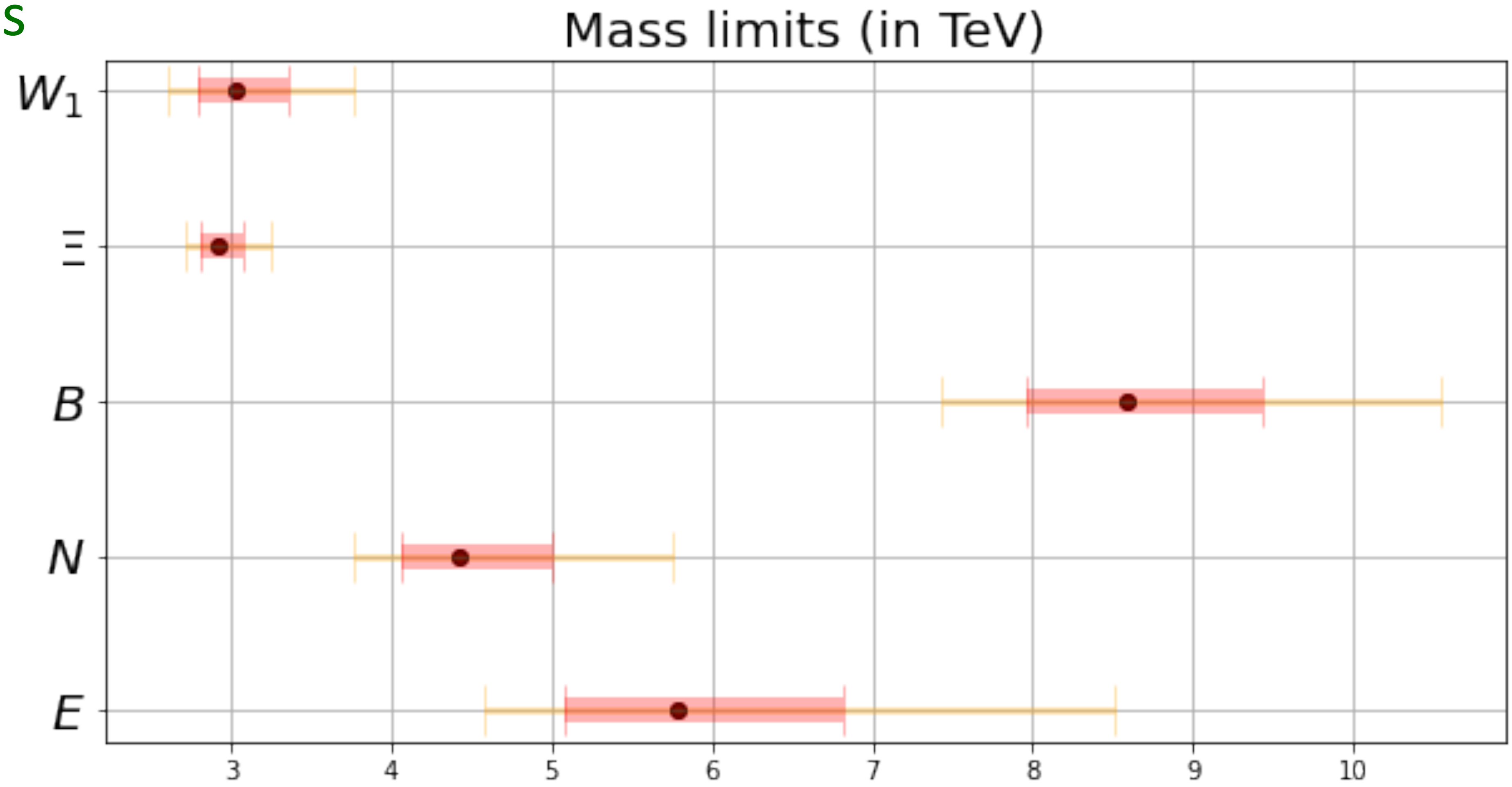
Operators contributing to m_W

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

Models Fitting the Mass of the W Boson

Spins

V
S
V
F
F



68 and 95% CL ranges of masses assuming unit couplings

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

Models Fitting Mass of the W Boson

Spins	Model	Pull	Best-fit mass (TeV)	1-σ mass range (TeV)	2-σ mass range (TeV)	1-σ coupling^2 range
V	W_1	6.4	3.0	[2.8, 3.6]	[2.6, 3.8]	[0.09, 0.13]
S	B	6.4	8.6	[8.0, 9.4]	[7.4, 10.6]	[0.011, 0.016]
V	Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.016]
F	N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
F	E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

Best-fit, 68 and 95% CL ranges of masses assuming unit couplings

68% CL ranges of couplings for 1 TeV

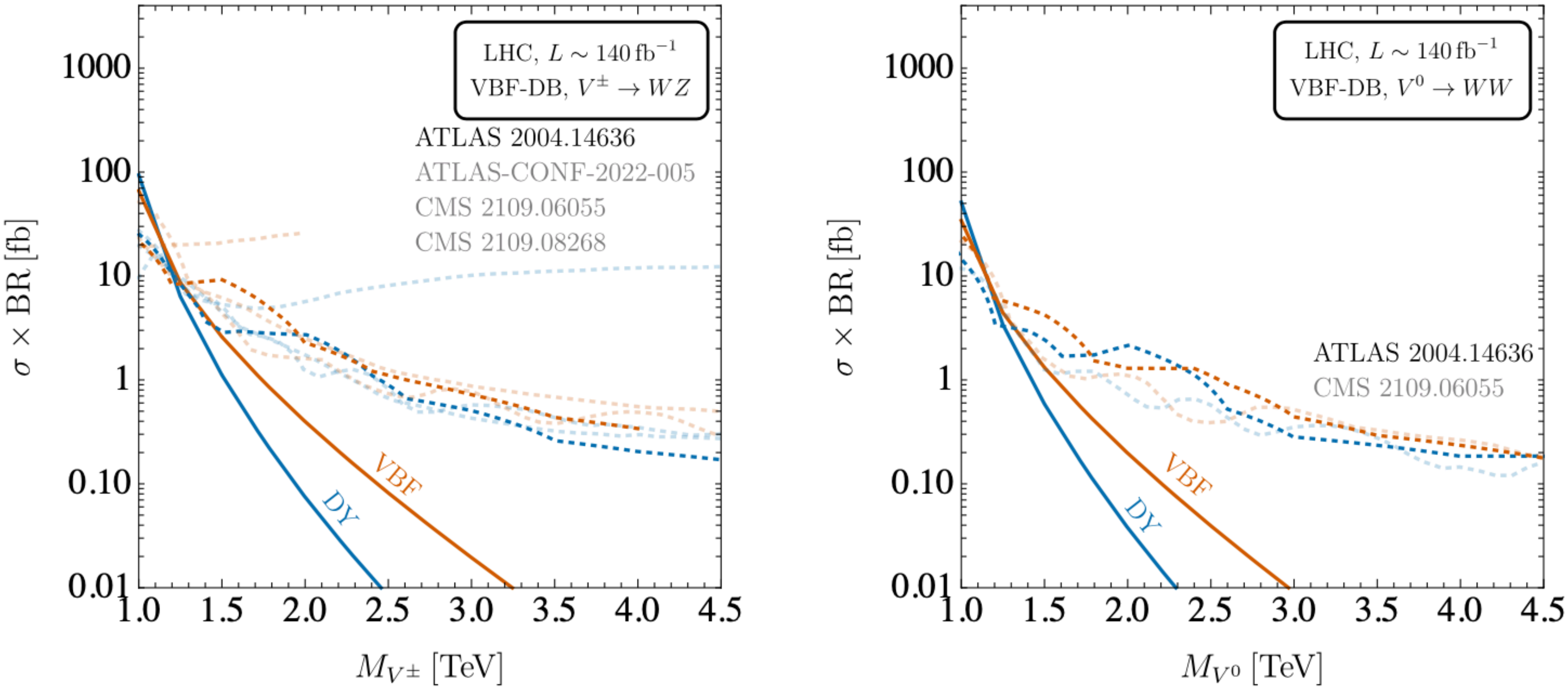
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

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

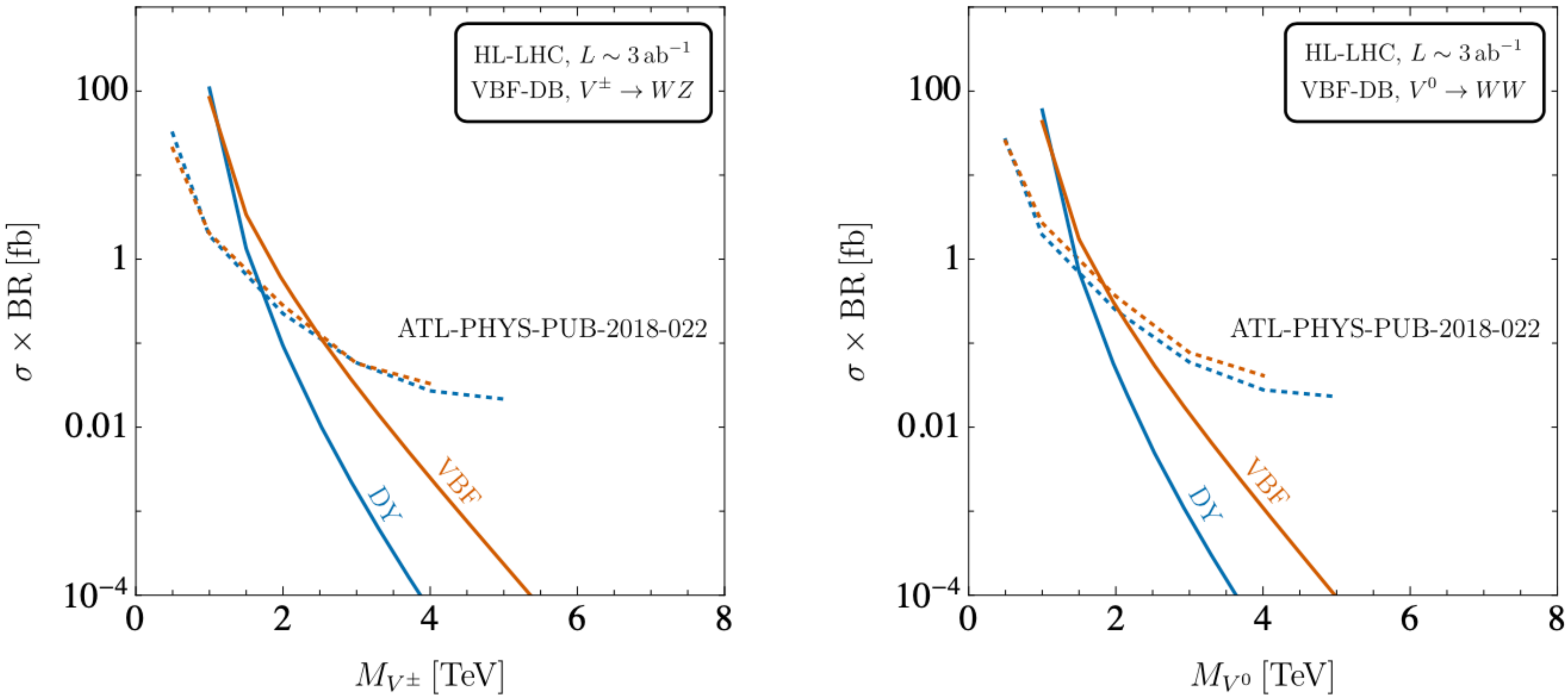
Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

LHC Search for Triplet Vector Boson



Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

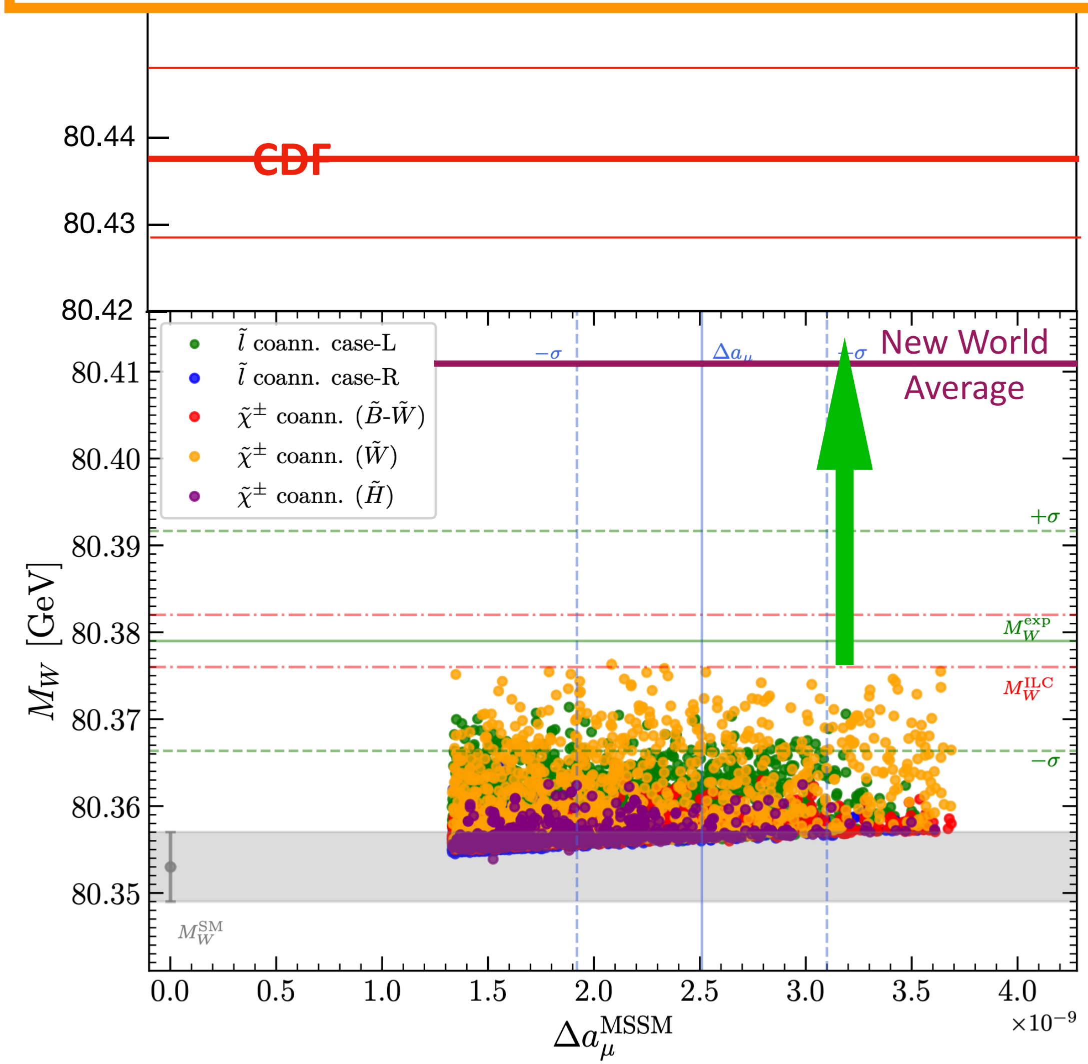
HL-LHC Search for Triplet Vector Boson



Baker, Martonhelyi, Thamm & Torre, arXiv:2207.05091

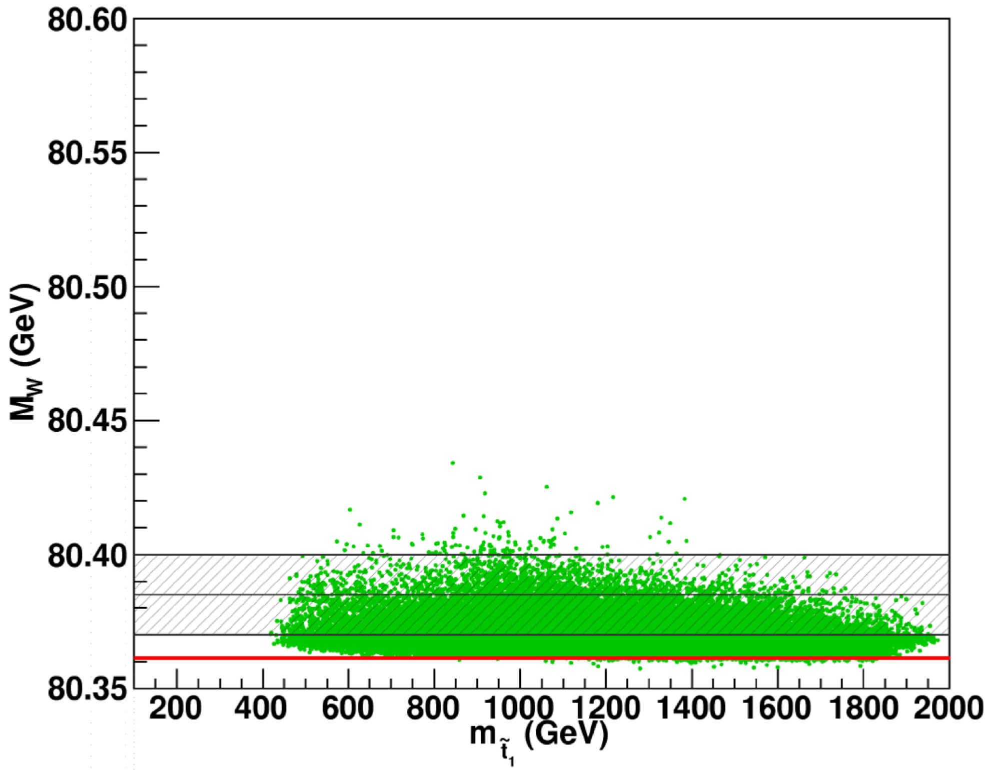
W Mass in Supersymmetry?

Electroweak particles reach old world average, but not CDF or new world average



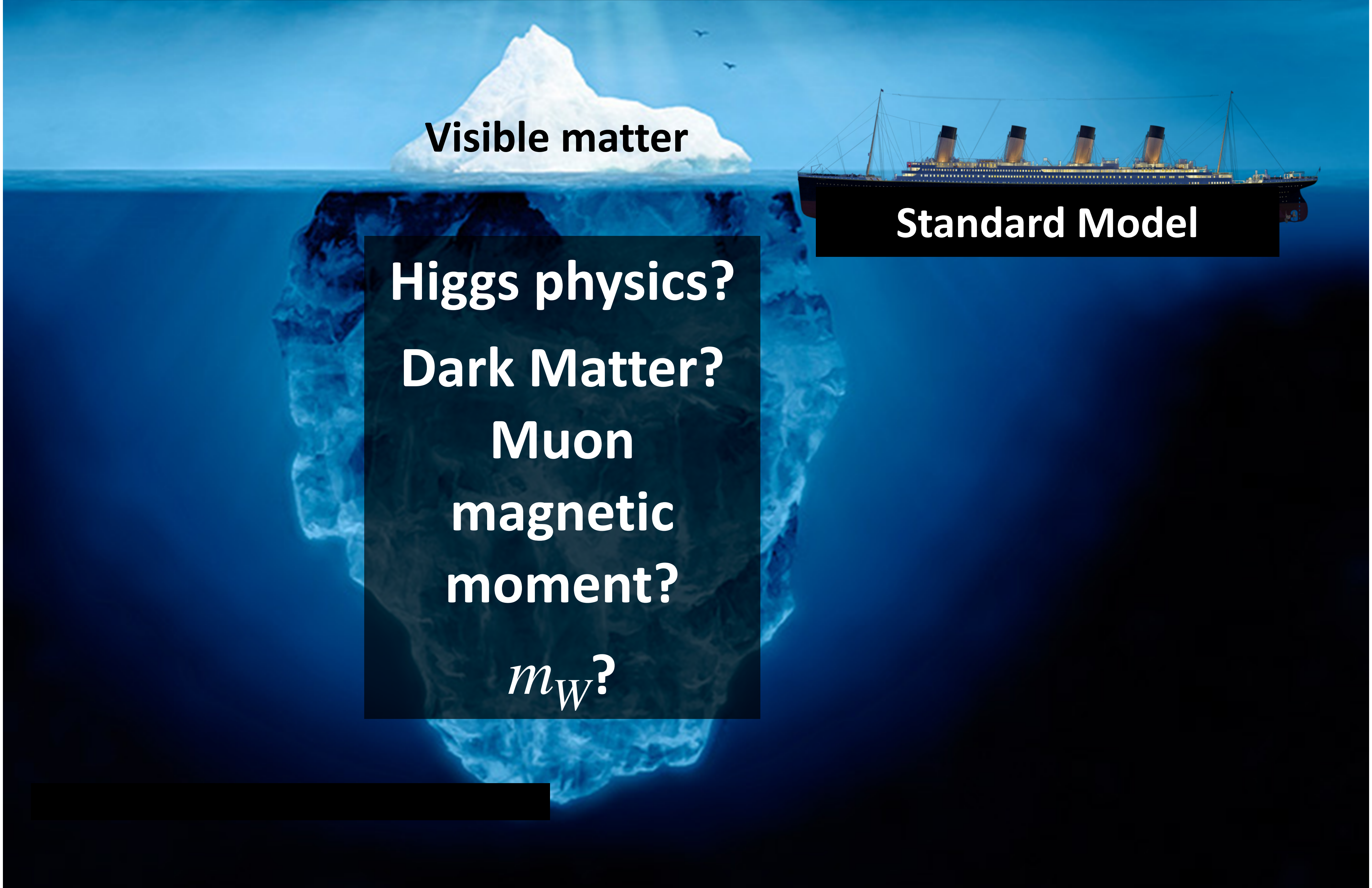
Bagnaschi, Chakraborti, Heinemeyer, Saha & Weiglein, arXiv:2203.15710

Contribution from stops?



Heinemeyer, Hollik, Weiglein & Zeune, 2013

Summary



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