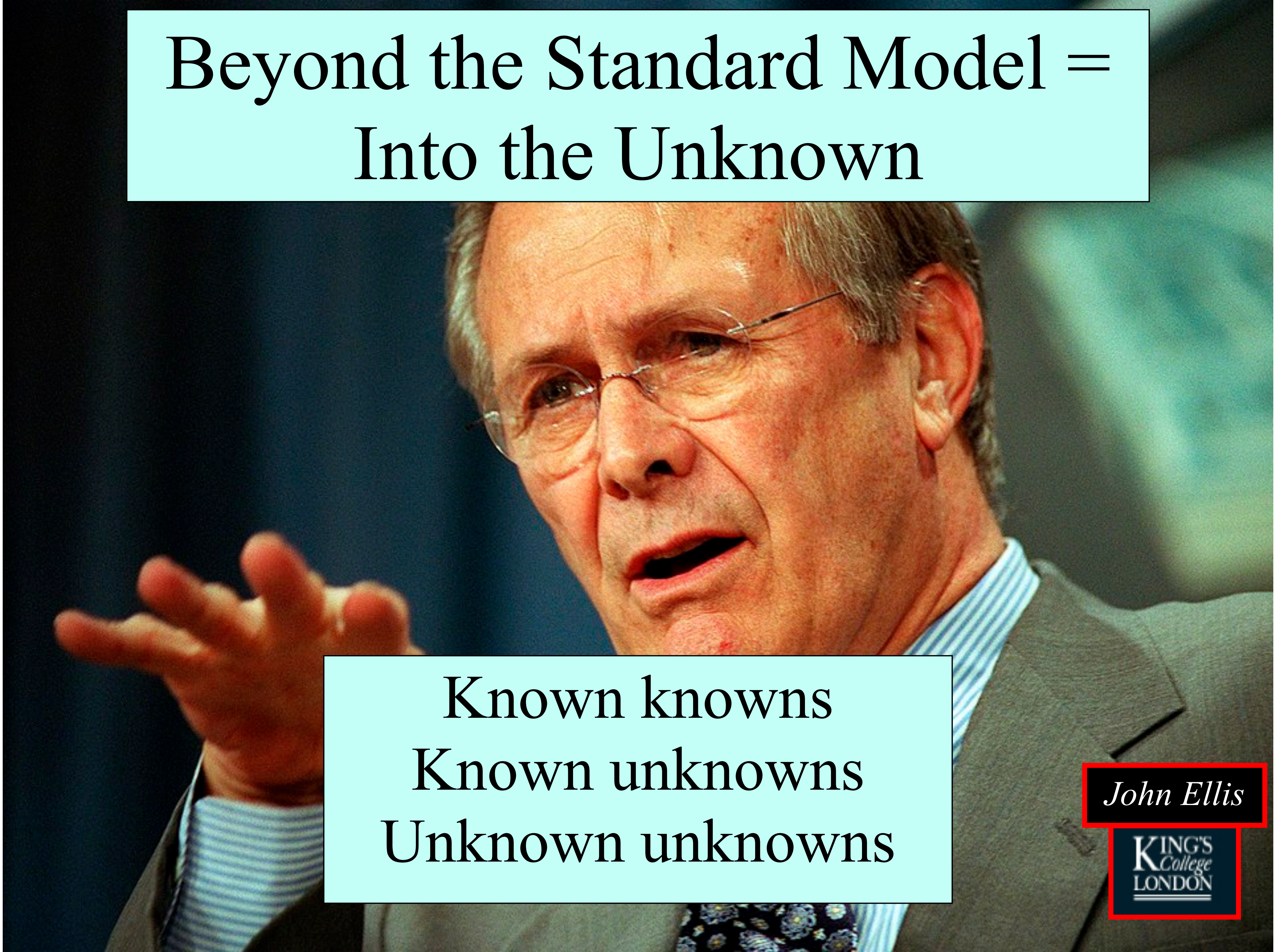
Beyond the Standard Model = Into the Unknown



Known knowns
Known unknowns
Unknown unknowns

John Ellis
KING'S College LONDON

The Standard Model & its Current Status

Why the Higgs boson?

What can the Higgs boson tell us?

Looking beyond it

Fundamental Particle Interactions

- Strong, weak and electromagnetic
- Three separate gauge group factors:
  - $SU(3) \times SU(2) \times U(1)$
- Three different gauge couplings:
  - g_3, g_2, g'
- Similar structures, important difference
- The carrier particles of the weak interactions are massive: $m_W \sim 80$ GeV, $m_Z \sim 91$ GeV
- What is the origin of these masses (also electron, …)

Is the Higgs Boson the answer?

To Higgs or not to Higgs?

- Need to discriminate between different types of particles:
  - Some have masses, some do not
  - Masses of different particles are different
- In mathematical jargon, symmetry must be broken: how?
  - Break symmetry in equations? **Inconsistencies …**
  - **Or in solutions to symmetric equations?**
- Latter is the route proposed by Higgs (et al.)
  - **Is there any other way?**

Where to Break the Symmetry?

- Throughout all space?
  - Route proposed by Higgs et al
  - Universal scalar field breaks symmetry
- Or at the edge of space?
  - **Break symmetry at the boundary?**
- Not possible in 3-dimensional space
  - No boundaries
  - **Postulate extra dimensions of space**
- Different particles behave differently in the extra dimension(s)

1964

The Founding Fathers

1964

The (G)AEBHGHKMP'tH Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTER

BROKEN SYMMETRIES AND THE MASSES OF GAU

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh,
(Received 31 August 1964)

The only one
who mentioned a
massive scalar boson

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

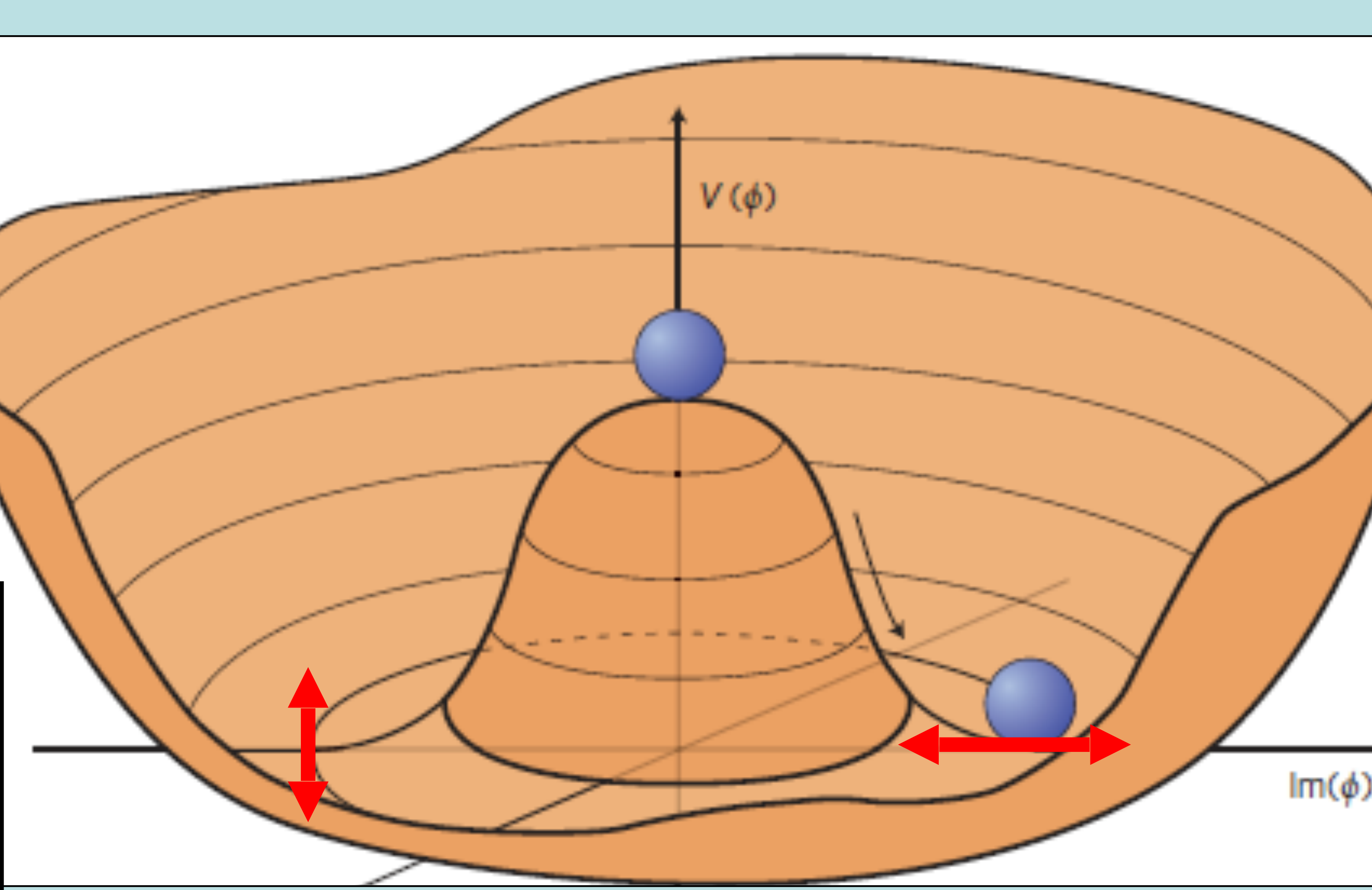
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

A. A. MIGDAL

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl.

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

Nambu, **EB, H, GHK & Higgs**



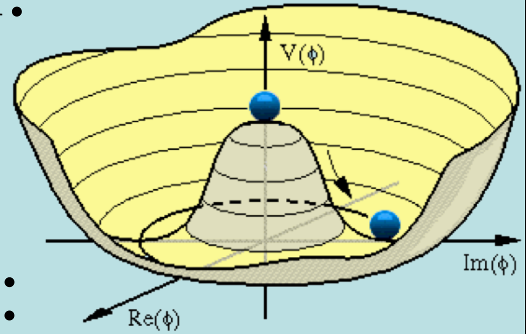
Spontaneous symmetry breaking: massless Nambu-Goldstone boson **'eaten' by massless gauge boson**

Accompanied by massive particle

The Nambu-Goldstone Mechanism

- Postulated effective scalar potential:

$$V[\phi] = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$



- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Components of scalar field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive:

$$m_H^2 = 2\mu^2 = 2\lambda v$$

Abelian EBH Mechanism

- Lagrangian

$$\mathcal{L} = (D_\mu \phi)^+ (D^\mu \phi) - V(|\phi|) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \quad D_\mu = \partial_\mu - ieA_\mu$$

- Gauge transformation

$$\phi'(x) = e^{i\alpha(x)} \phi(x) = e^{i\alpha(x)} e^{i\theta(x)} \eta(x)$$

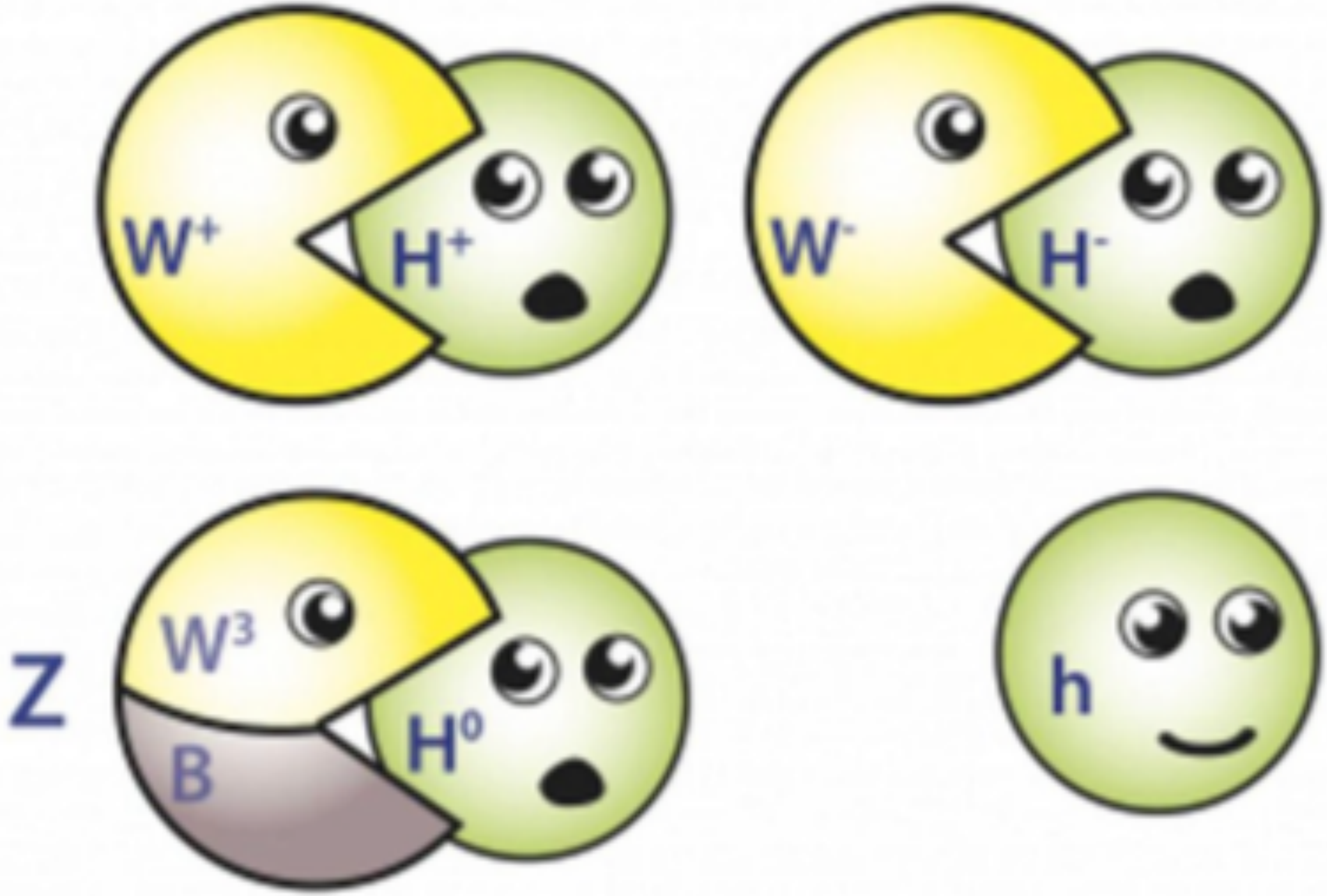
$$A'_\mu(x) = A_\mu(x) + \frac{1}{e} \partial_\mu \alpha(x)$$

- Choose $\alpha(x) = -\theta(x)$: $\quad \phi'(x) = \eta(x)$
- Rewrite Lagrangian: $\mathcal{L} = |(\partial - ieA'_\mu)\eta|^2 - V(\eta) - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu}$

$$\mathcal{L} = |(\partial_\mu - ieA'_\mu)(v + \tfrac{1}{\sqrt{2}} H)|^2 - \tfrac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - V$$

$$= \underbrace{-\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + v^2 e^2 A'_\mu A'^\mu}_{\text{massive A-field, } m_A \sim ev} + \underbrace{\frac{1}{2} [(\partial_\mu H)^2 - m_H^2 H^2]}_{\text{neutral scalar, } m_H \neq 0} + \cdots$$

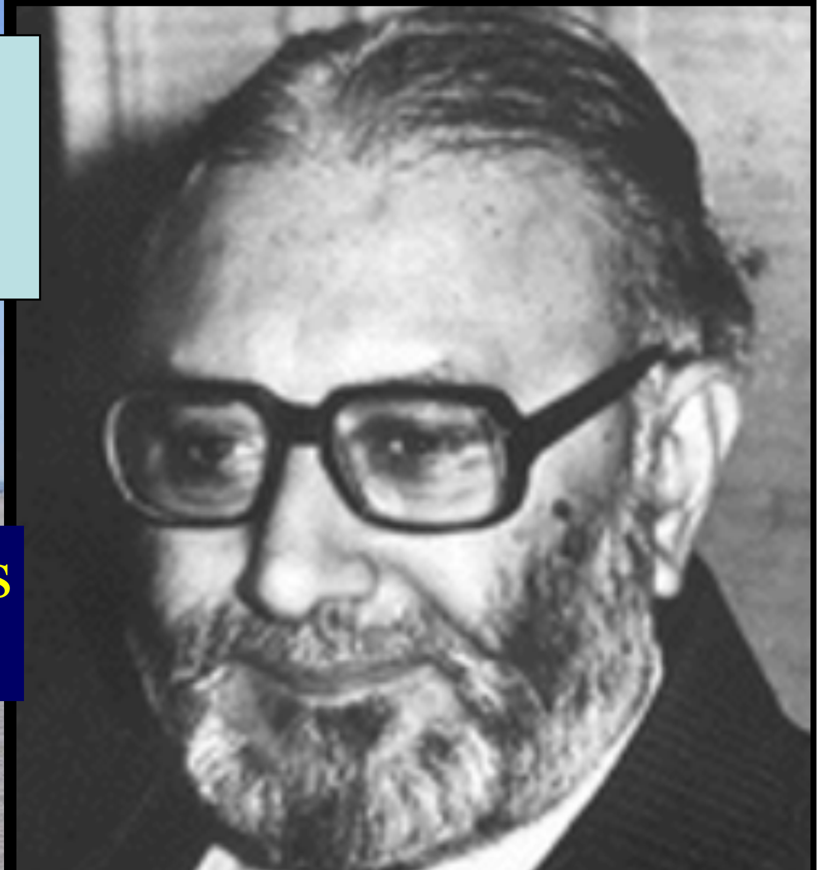
Hungry Higgs



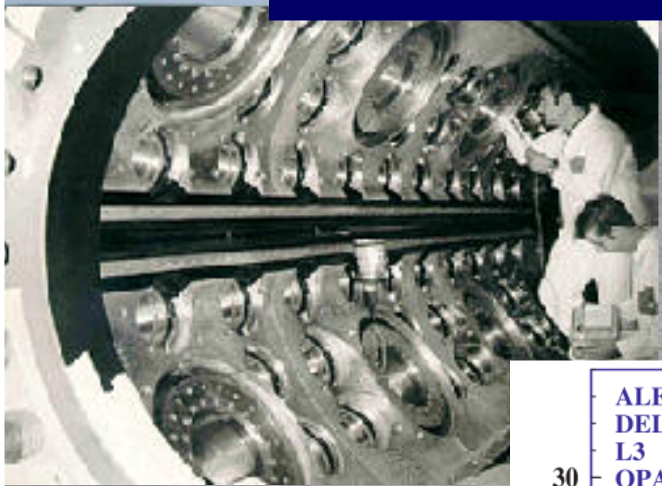
(FLIP TANEDO / QUANTUM DIARIES)

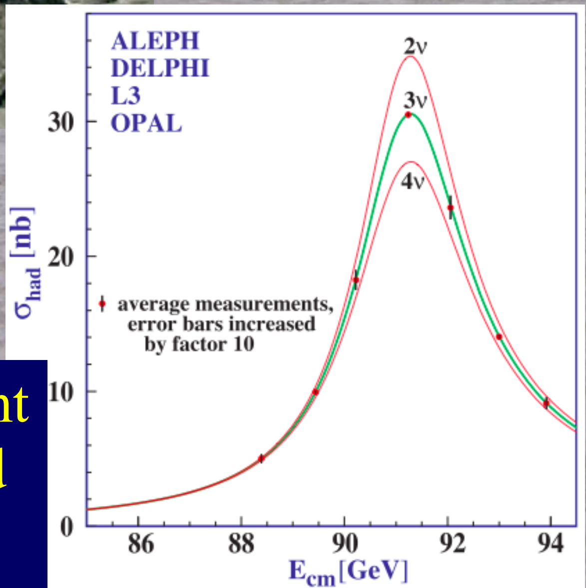
The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg



Tested by experiments at CERN





Perfect (?) agreement between theory and experiments in all laboratories

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?

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 , μ^-_R , τ^-_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

The Standard Model Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_y \qquad ,$$

$$\mathcal{L}_m = \bar{Q}_L i\gamma^\mu D^L_\mu Q_L + \bar{q}_R i\gamma^\mu D^R_\mu q_R + \bar{L}_L i\gamma^\mu D^L_\mu L_L + \bar{l}_R i\gamma^\mu D^R_\mu l_R$$

$$\mathcal{L}_G = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu}$$

✓ Experiment: accuracy < %

$$\mathcal{L}_H = (D^L_\mu \phi)^\dagger (D^{L\mu} \phi) - V(\phi)$$

$$\mathcal{L}_Y = y_d \bar{Q}_L \phi q^d_R + y_u \bar{Q}_L \phi^c q^u_R + y_L \bar{L}_L \phi l_R +$$

No direct evidence until July 4, 2012

$$D^L_\mu = \partial_\mu - igW^a_\mu T^a - iYg' B_\mu \quad , \quad D^R_\mu = \partial_\mu - iYg' B_\mu$$

$$V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4 \qquad .$$

Masses for SM Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + i g \epsilon_{ijk} W^j_\mu W^k_\nu$ $\quad F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

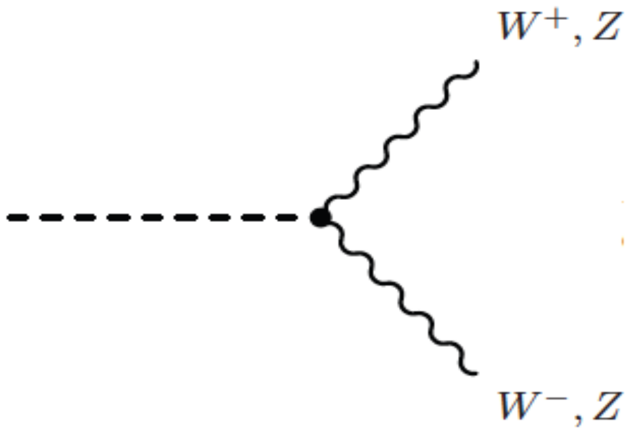
- Expanding around vacuum: $\phi = <0|\phi|0> + \hat{\phi}$

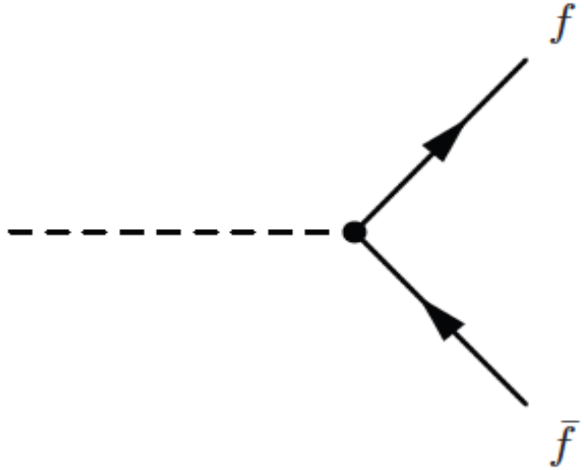
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\ W^+_\mu\ W^{\mu -} - g'^2\ \frac{v^2}{2}\ B_\mu\ B^\mu + g\ g' v^2\ B_\mu\ W^{\mu 3} - g^2\ \frac{v^2}{2}\ W^3_\mu\ W^{\mu 3}$$

- Boson masses: 

$$m_{W^\pm} = \frac{gv}{2} \qquad Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}}\ :\ m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v\ ;\ \ A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}}\ :\ m_A = 0$$

Higgs Boson Couplings





$$g_2 M_W\,, \quad g_2 \frac{M_Z}{c_W}$$

$$\frac{m_f}{v} = \frac{g_2\, m_f}{2M_W}$$

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

1975

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.

2011

Status of the Standard Model before the LHC

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a Higgs boson*
- Agreement seems to require *a relatively light Higgs boson* weighing < ~ 180 GeV
- Raises many unanswered questions:

mass? flavour? unification?

Constraints on Higgs Mass

- Electroweak observables sensitive via quantum loop corrections:

$$m_W^2 \sin^2\theta_W = m_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Sensitivity to top, Higgs masses:

$$\frac{3G_F}{8\pi^2\sqrt{2}} m_t^2 \qquad \frac{\sqrt{2}G_F}{16\pi^2} m_W^2 \left(\frac{11}{3}\ln\frac{M_H^2}{m_Z^2} + \ldots\right),\ M_H >> m_W$$

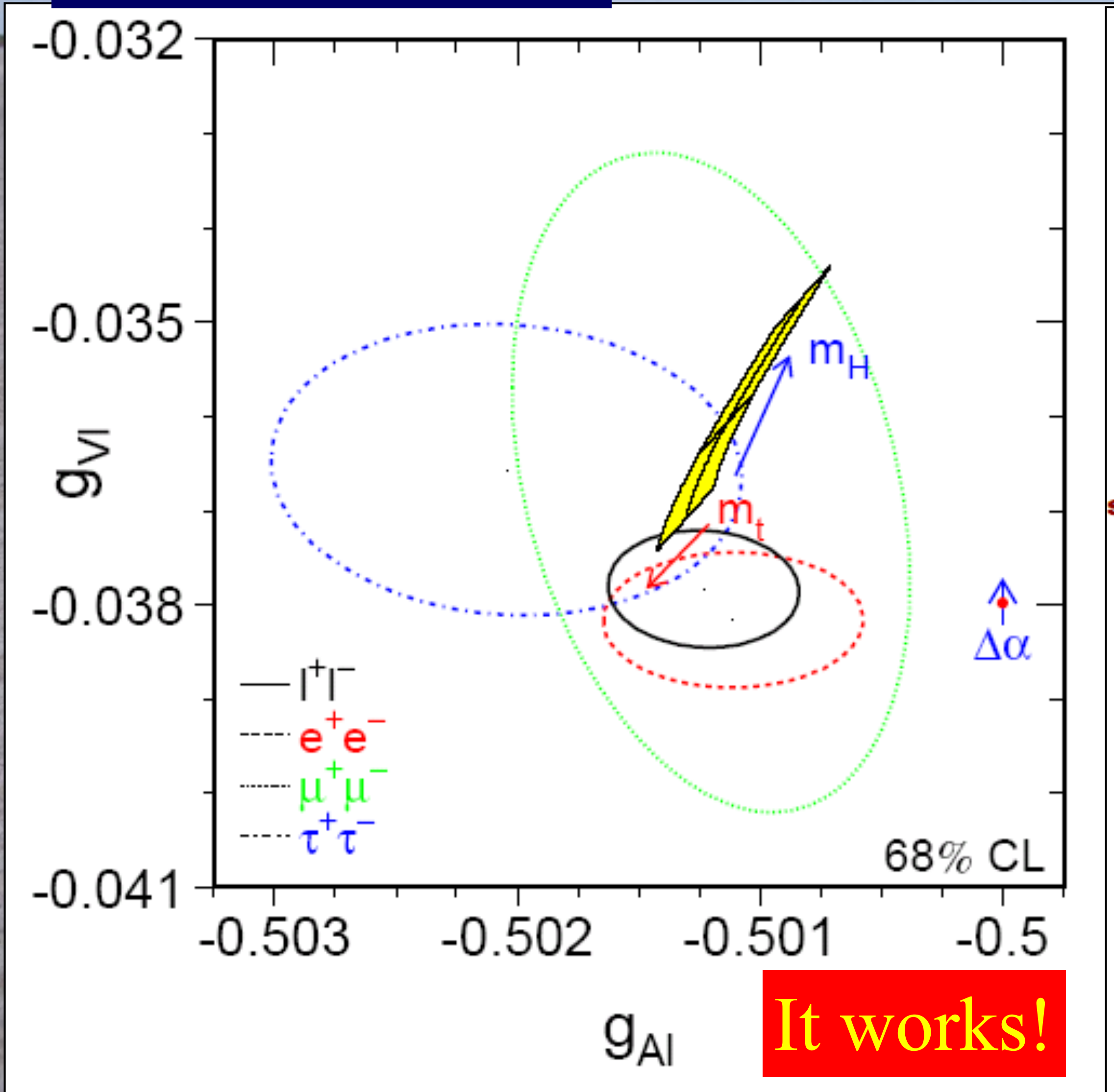
- Preferred Higgs mass: **$m_H \sim 100 \pm 30$ GeV**
- Compare with lower limit from direct search at LEP:

$m_H > 114$ GeV

and exclusion around **(160, 170 GeV)** at TeVatron

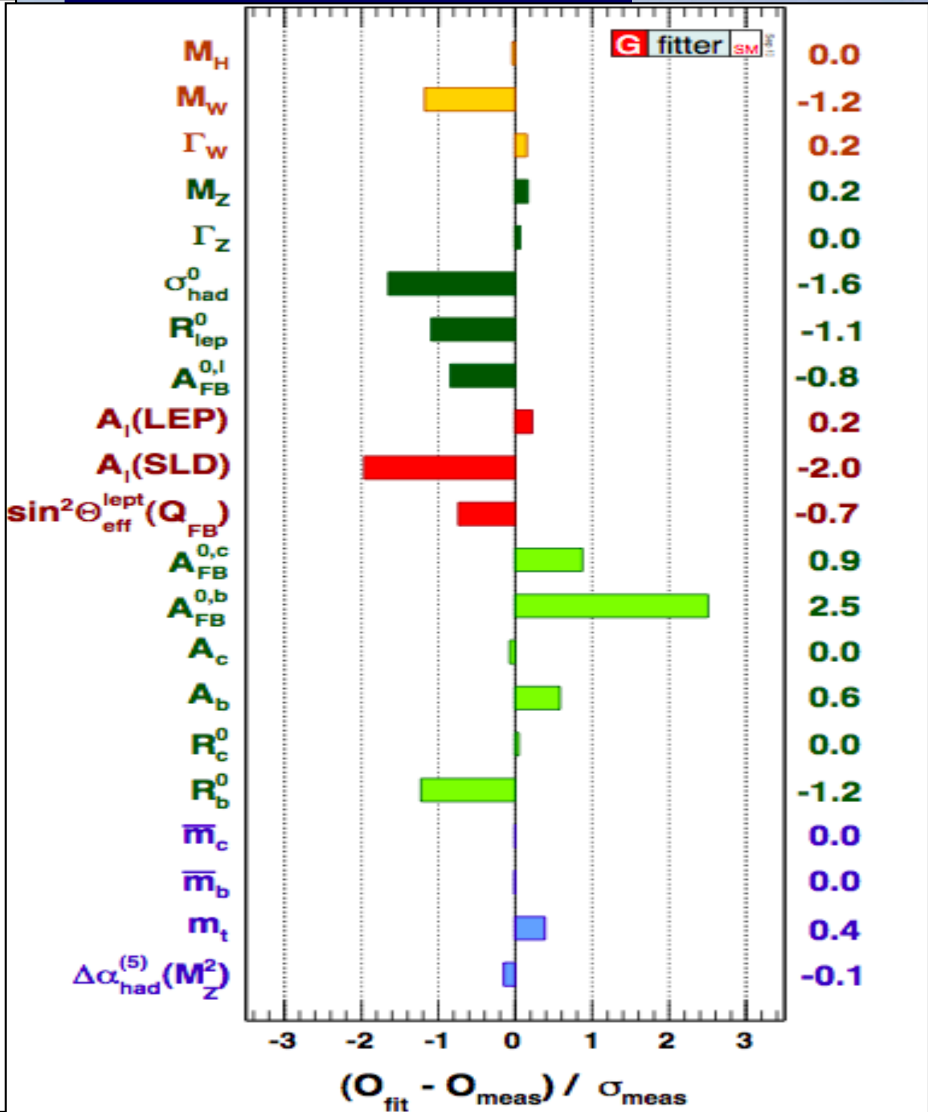
Precision Tests of the Standard Model

Lepton couplings



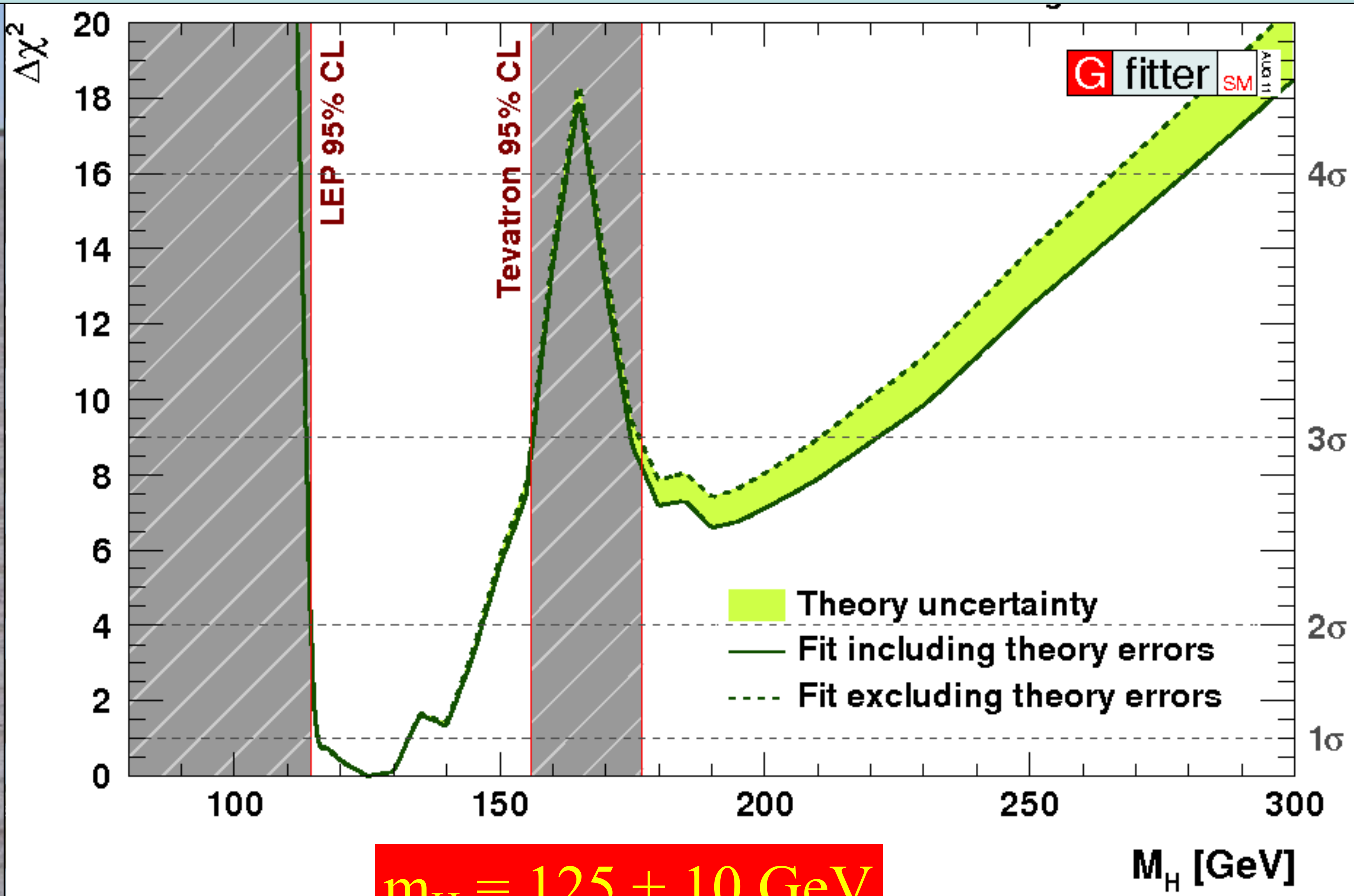
It works!

Pulls in global fit



2011

Combining Information from Previous Direct Searches and Indirect Data

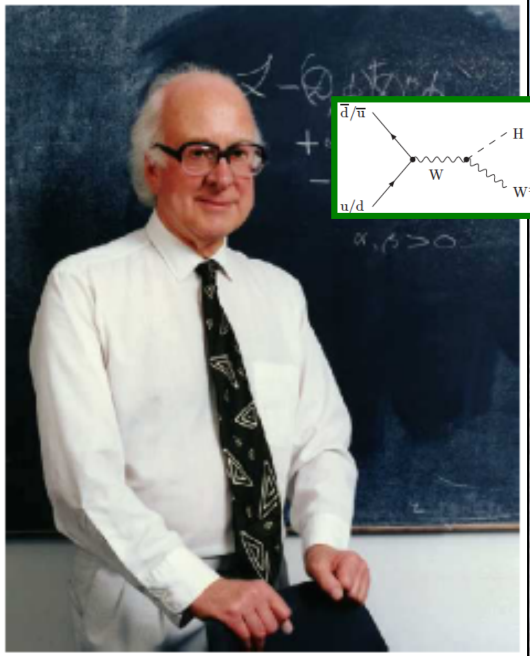


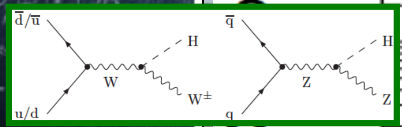
$m_H = 125 \pm 10$ GeV

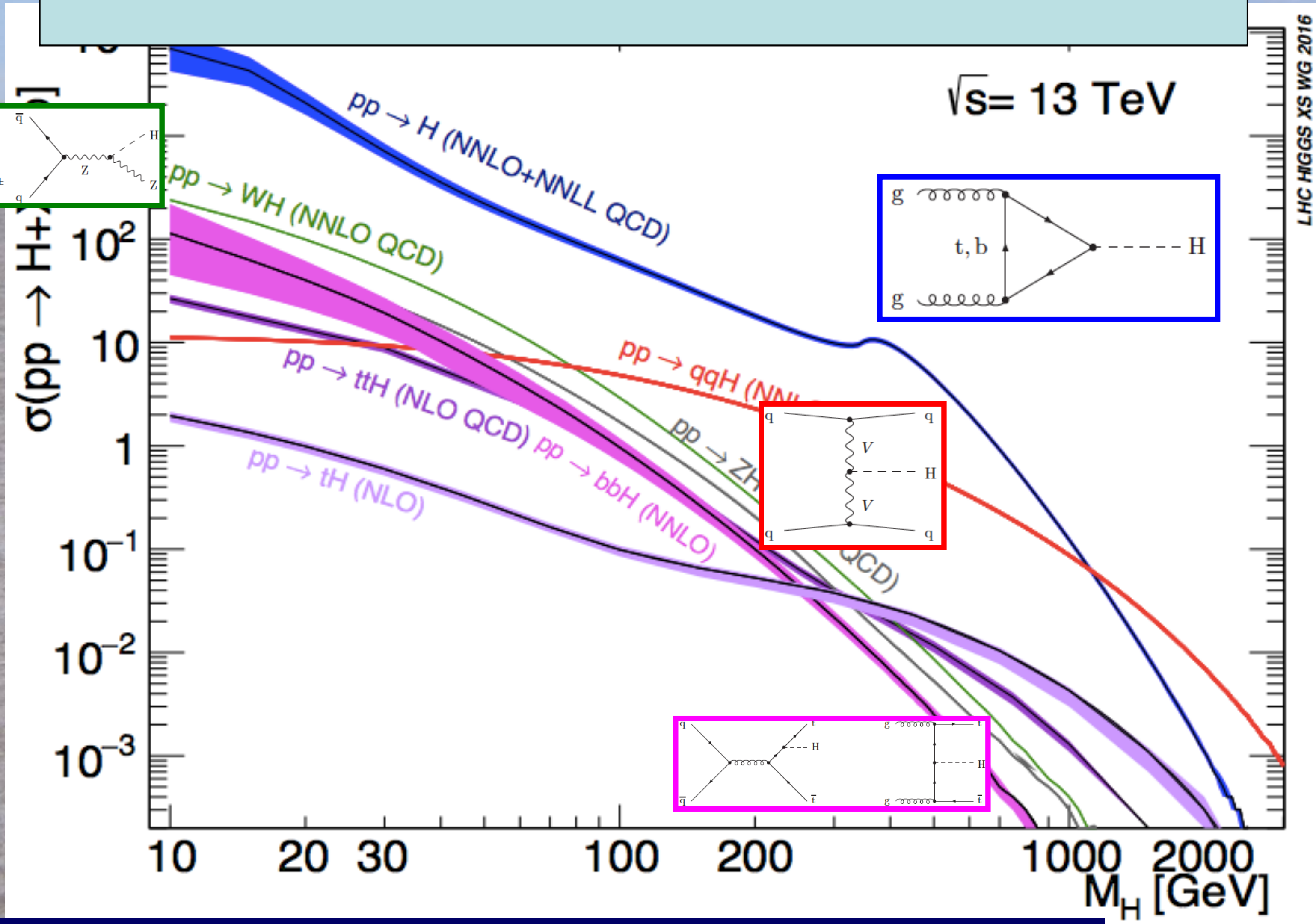
Gfitter collaboration

A la recherche du Higgs perdu …

Higgs Production at the LHC





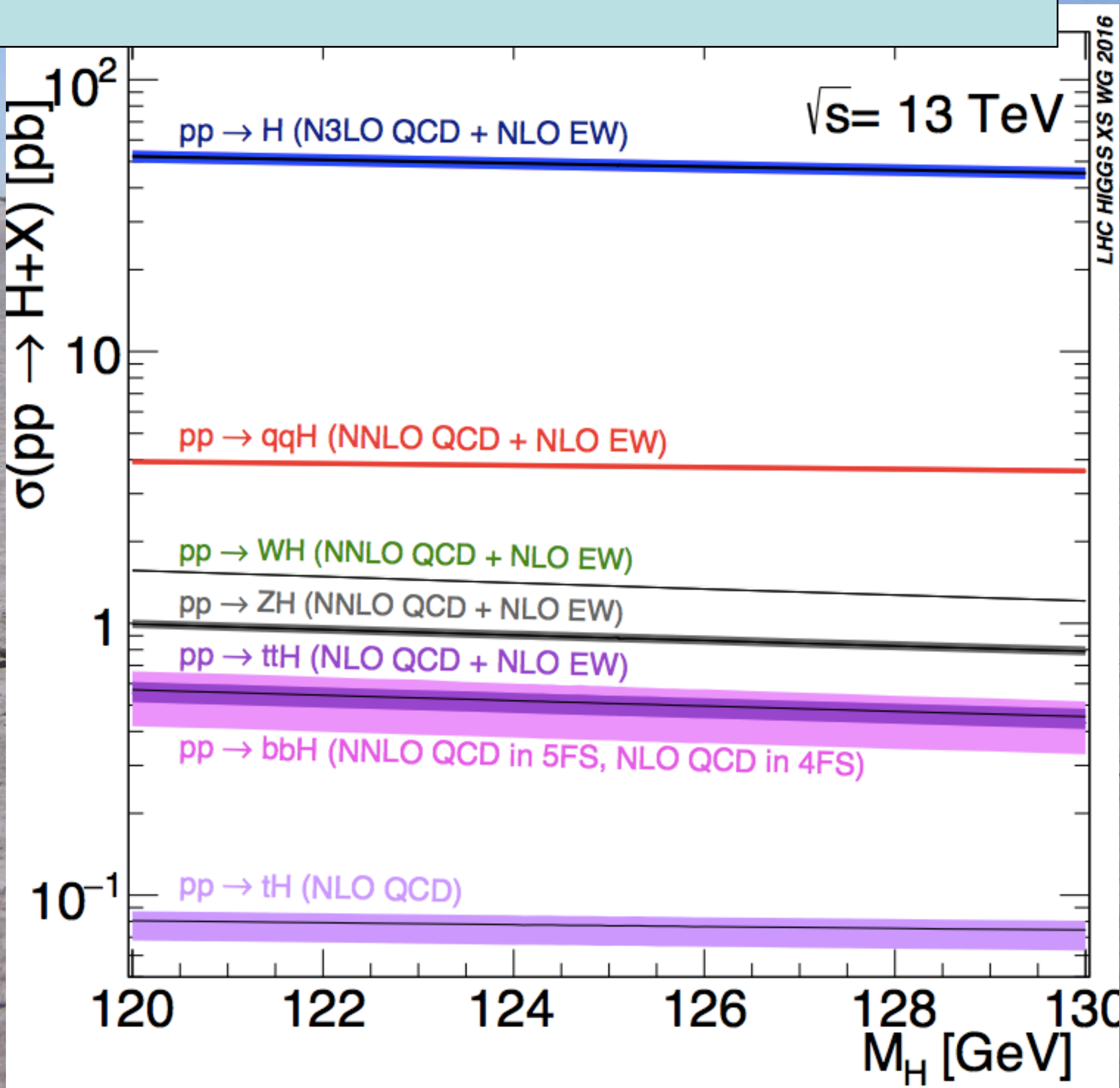


LHC Higgs Cross-Section Working Group (LHXSWG)

Many production modes measurable if $M_h \sim 125$ GeV

Higgs Production at the LHC

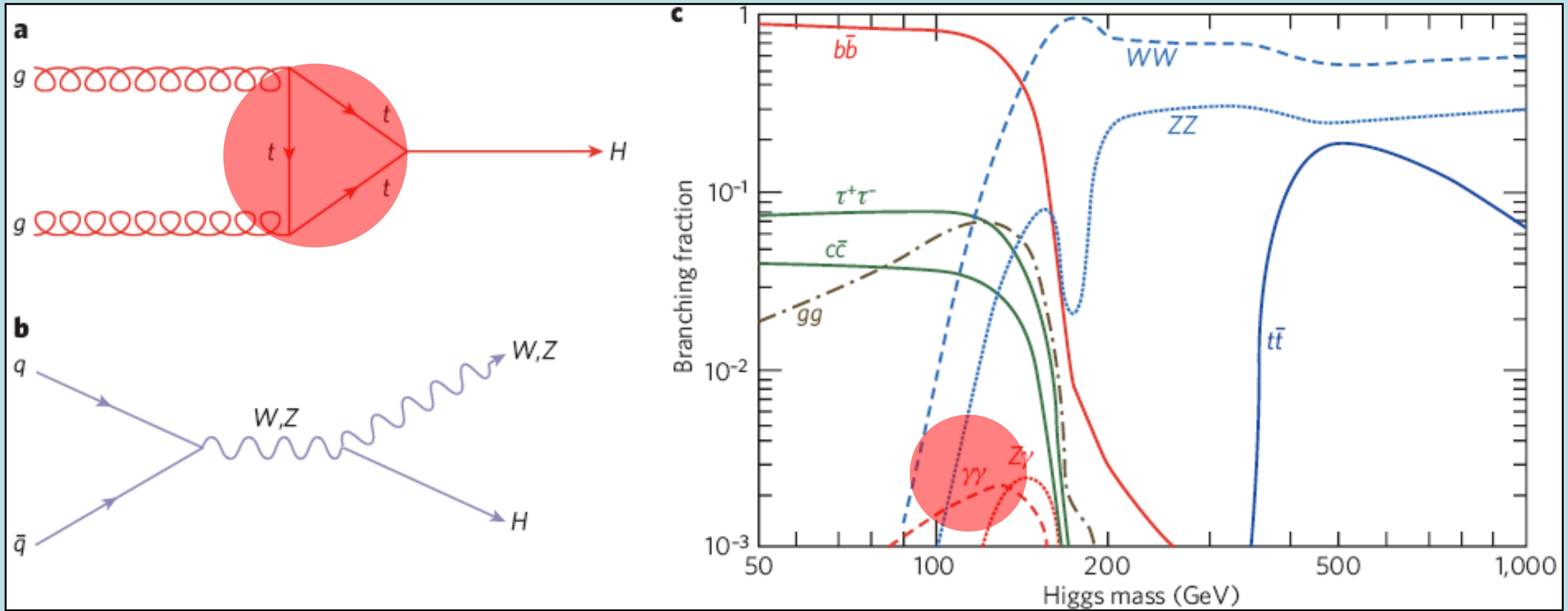
Cross sections for Higgs mass near 125 GeV



LHC Higgs Cross-Section Working Group (LHXSWG)

Higgs Decay Branching Ratios

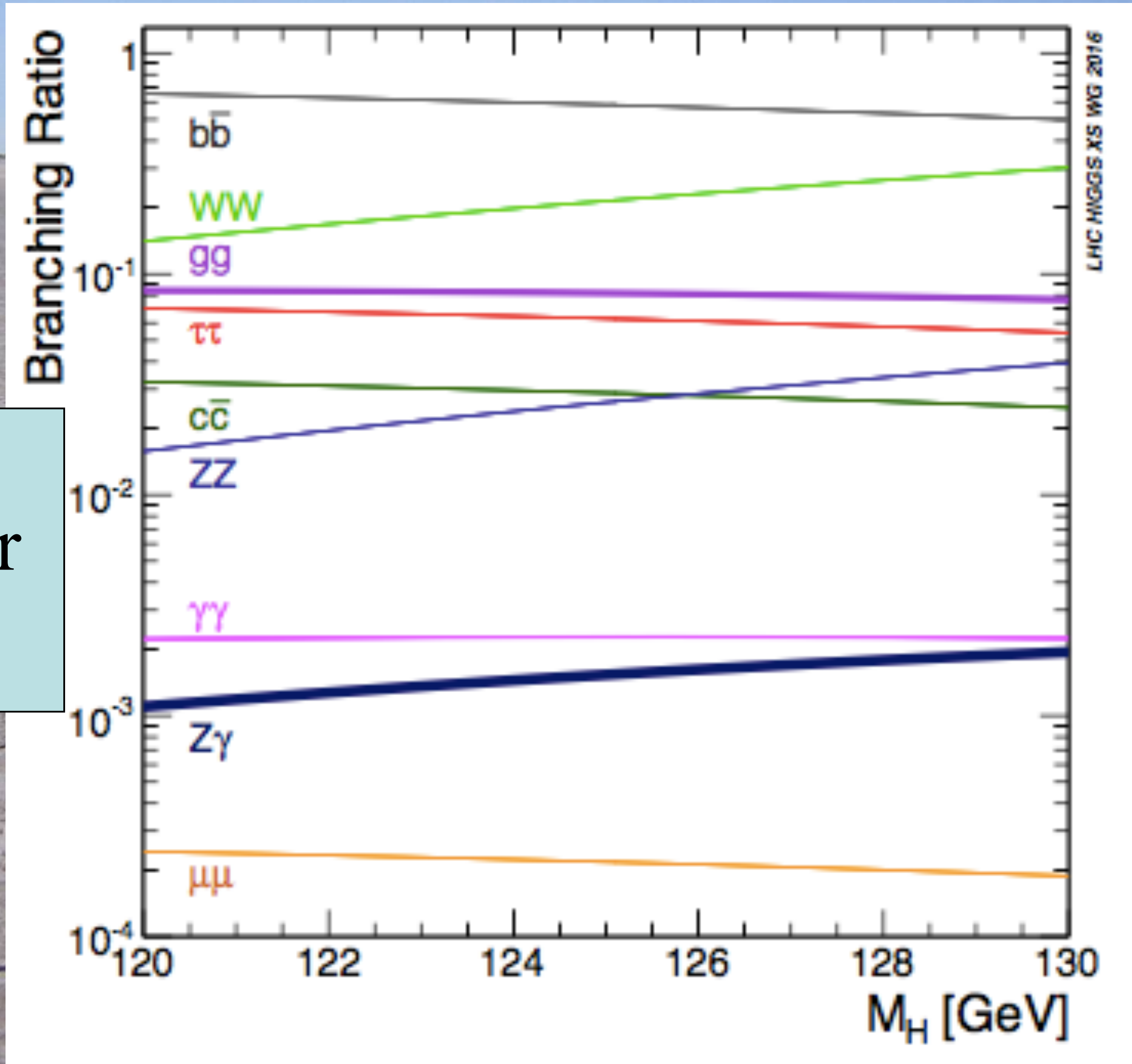
- Couplings proportional to masses (?)



- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if $M_h \sim 125$ GeV

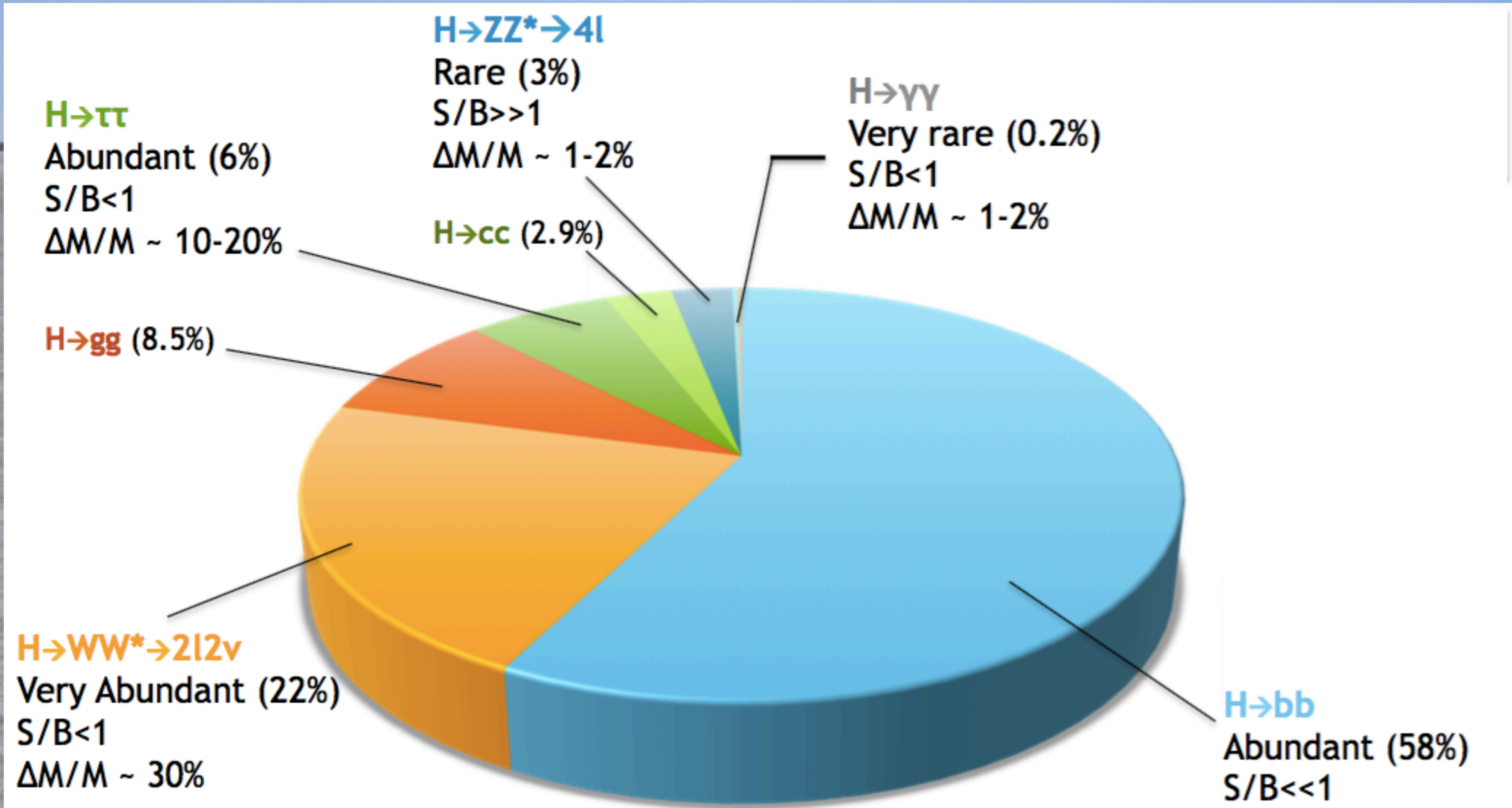
Higgs Decay Branching Ratios



Dominant decay branching ratios for $m_H \sim 125$ GeV

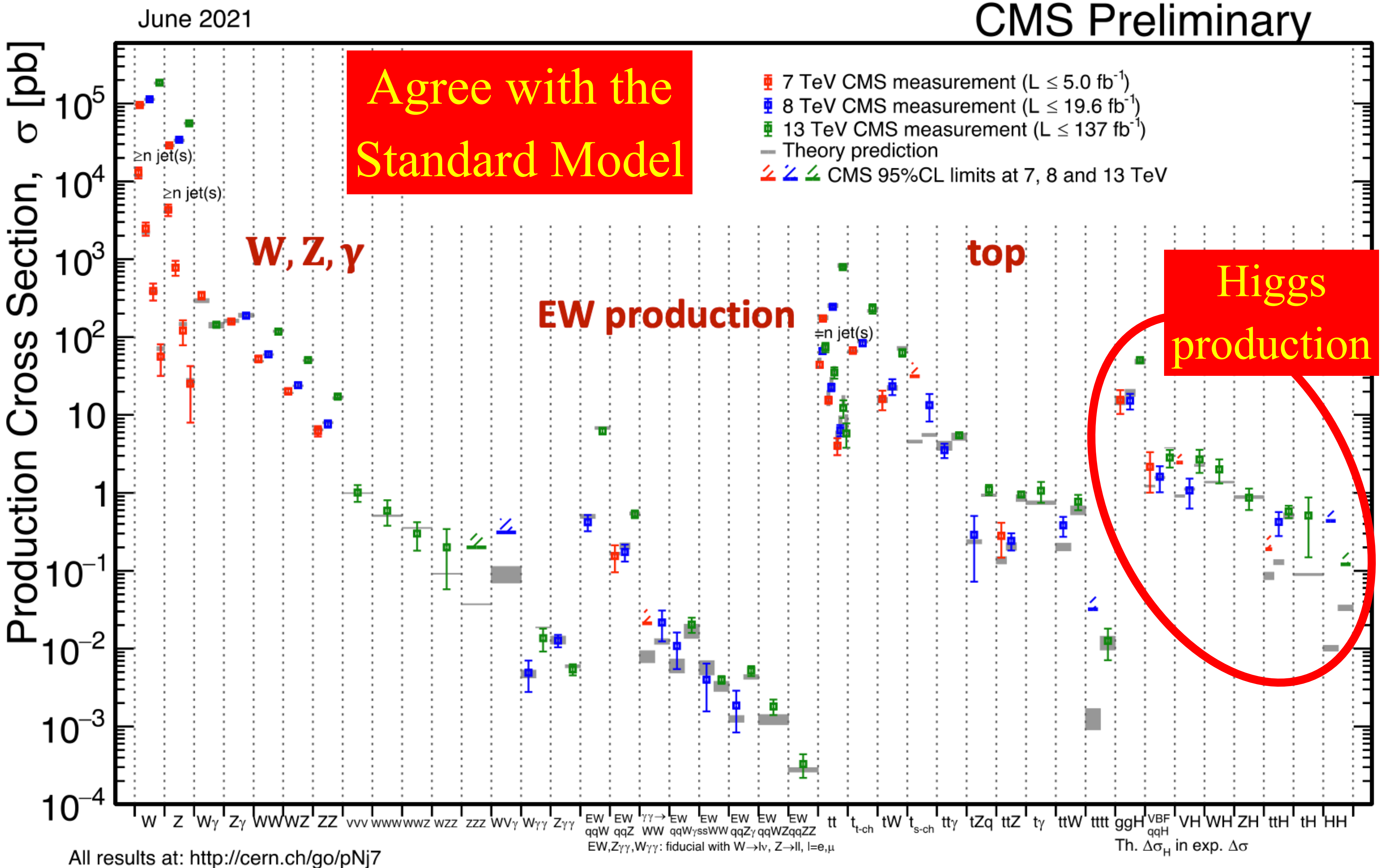
LHC Higgs Cross-Section Working Group (LHXSWG)

What was Expected

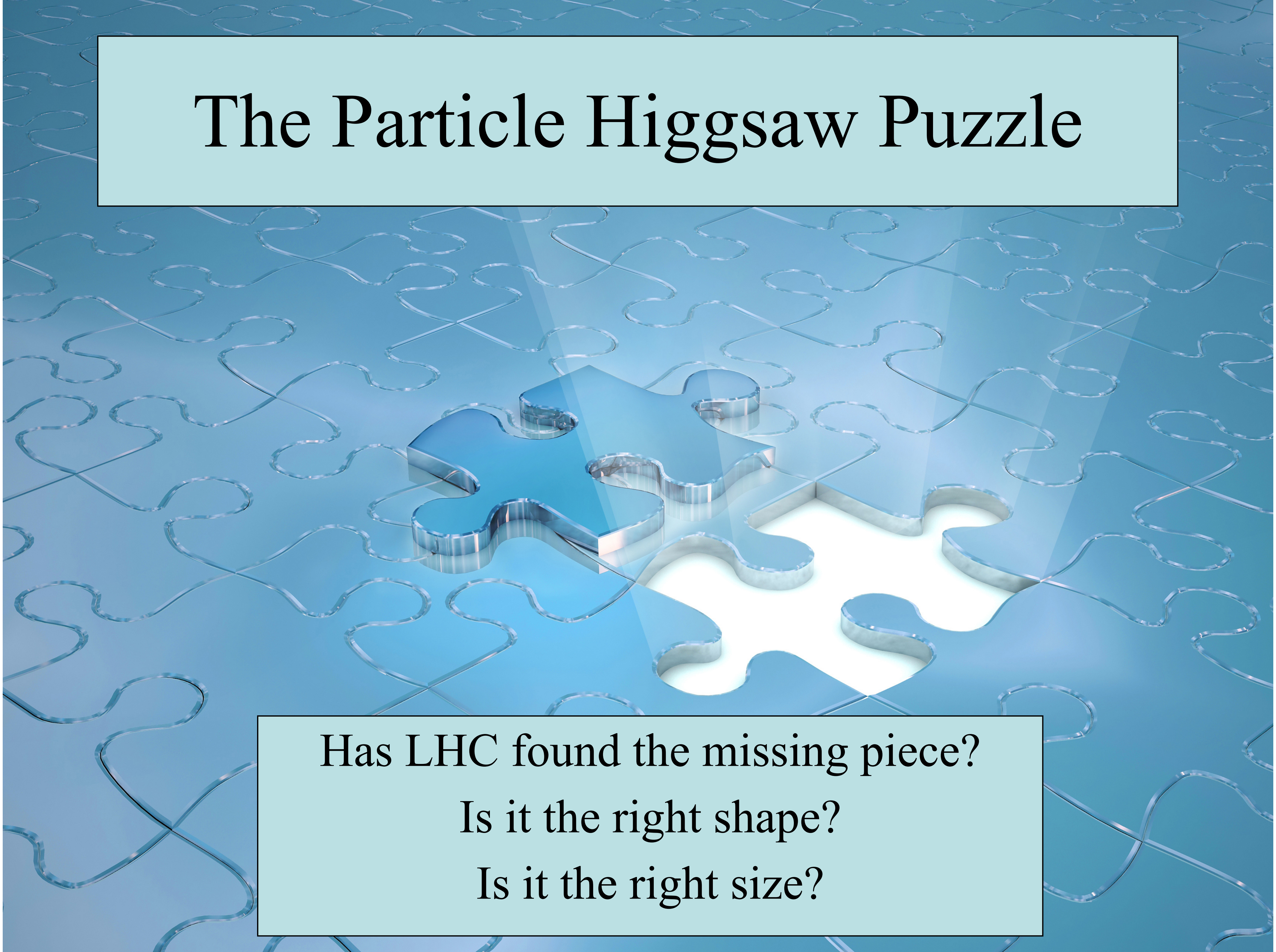


What do we know?

LHC Measurements



The Particle Higgsaw Puzzle



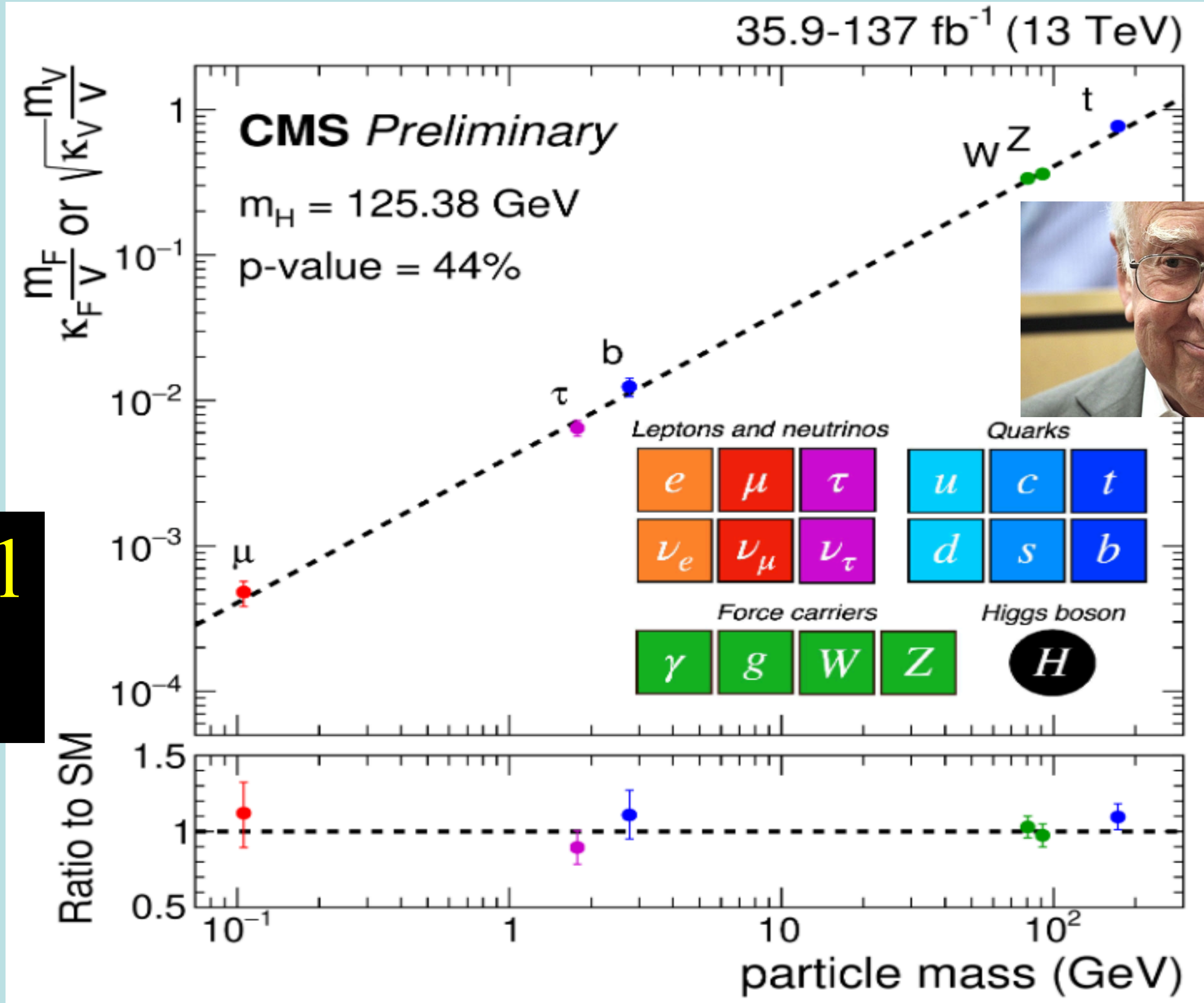
Has LHC found the missing piece?

Is it the right shape?

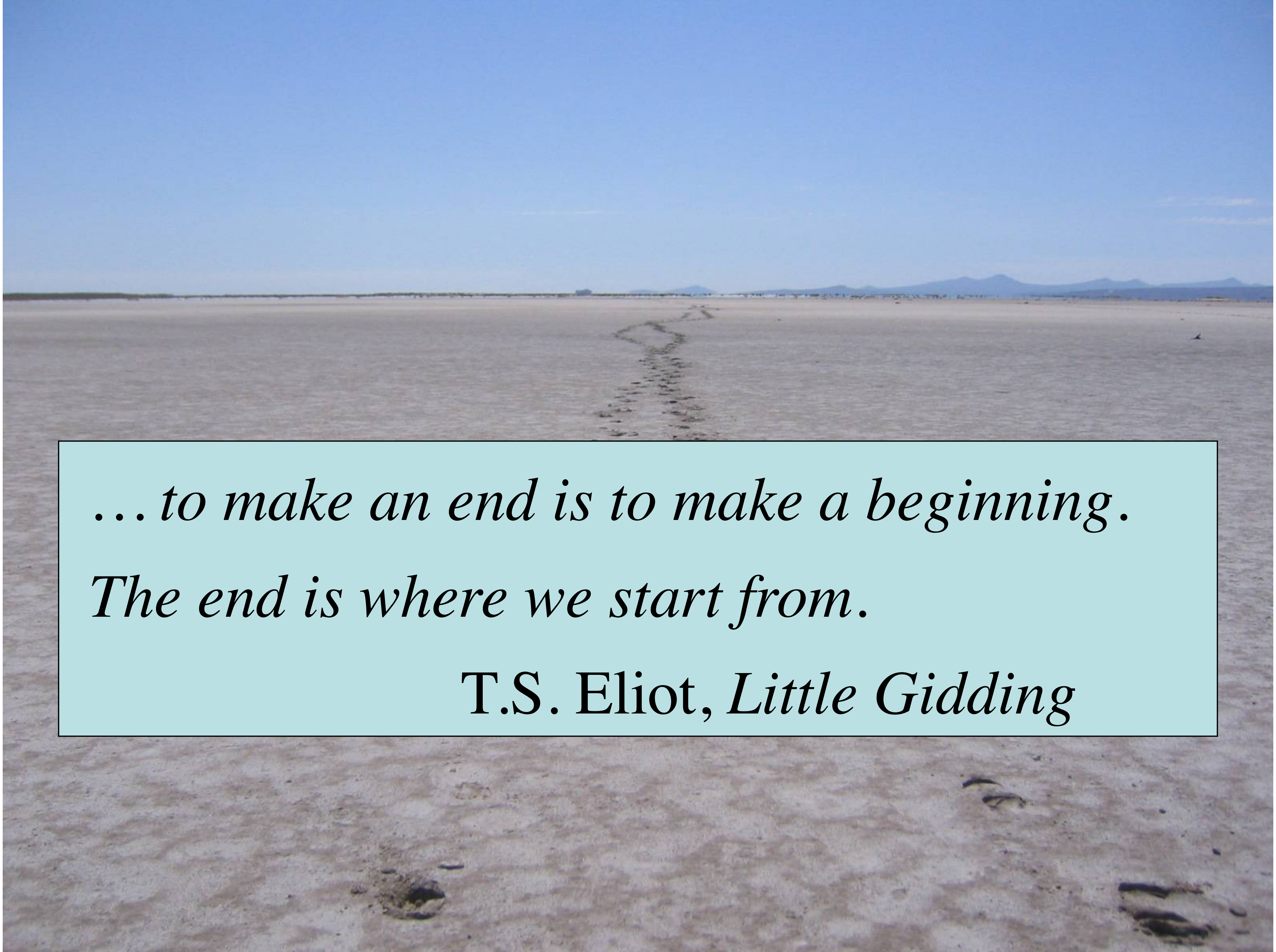
Is it the right size?

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?

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?"

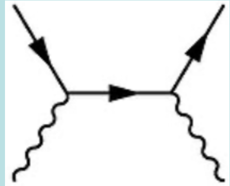
Sun Tzu, *The Art of War*

John Ellis

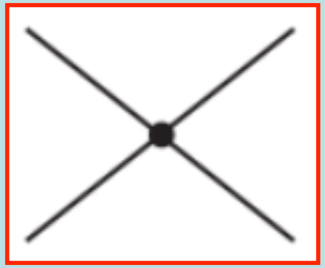
King's College London

Effective Field Theories (EFTs)
a long and glorious History

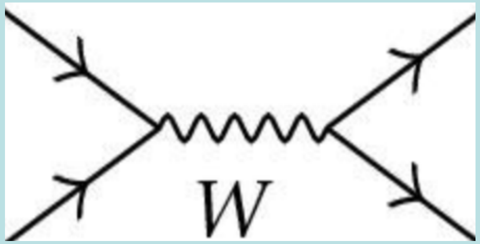
- 1930's: "Standard Model" of QED had d=4



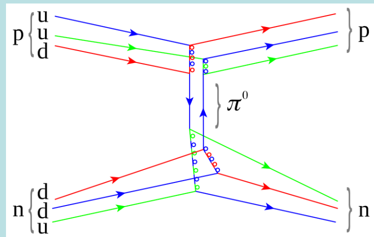
- **Fermi's four-fermion theory of the weak force**



- 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?

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

- 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 Operators in Detail

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

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

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

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$\mathcal{O}^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$		

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)

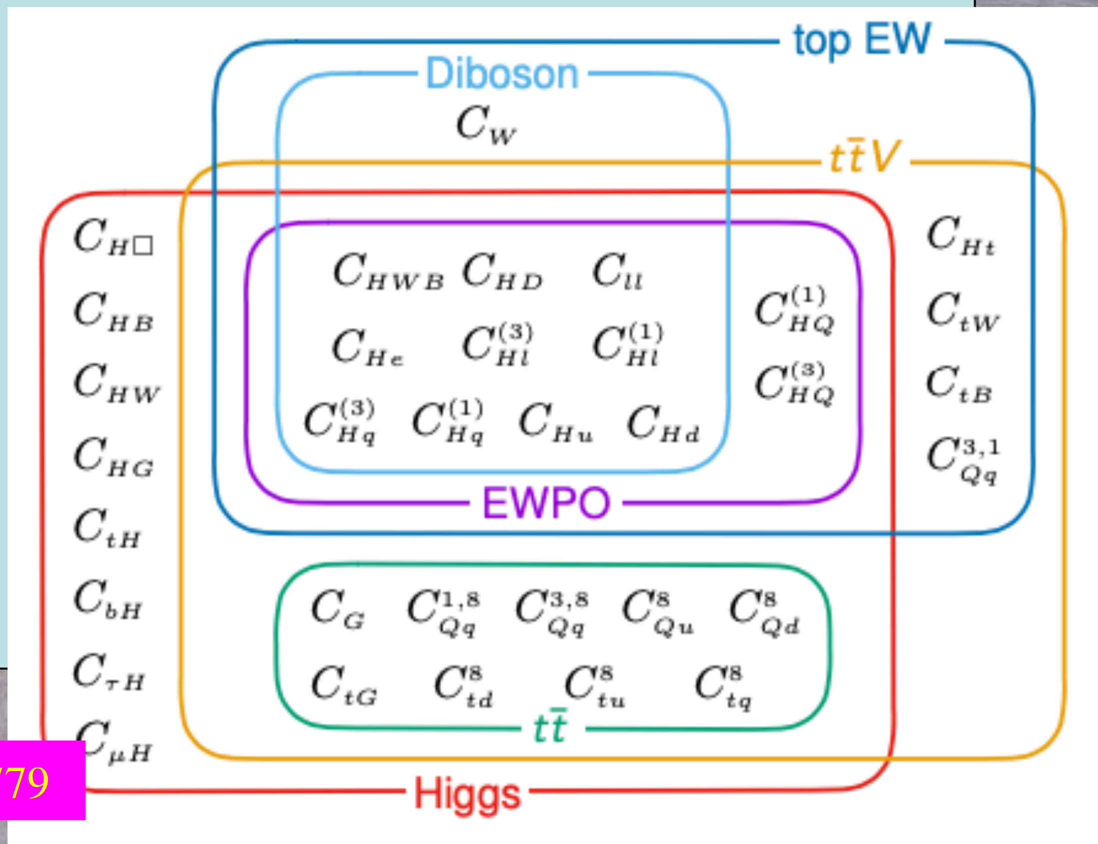
JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

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



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

Data included in Global Fit

EW precision observables

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

Diboson LEP & LHC

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

LHC Run 1 Higgs

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

LHC Run 2 Higgs

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

Tevatron & Run 1 top	n_{obs}	Ref.
Tevatron combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$.	4	[7]
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
ATLA… $\frac{d\sigma}{dm_{t\bar{t}}}$		
CMS… $\frac{d\sigma}{dm_{t\bar{t}}}$		
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… $\frac{d\sigma}{dp^T_t}$		
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.	1	[33]
ATLAS tW cross section measurement in the single lepton channel	1	[34]
ATLAS tW cross section measuremen…		

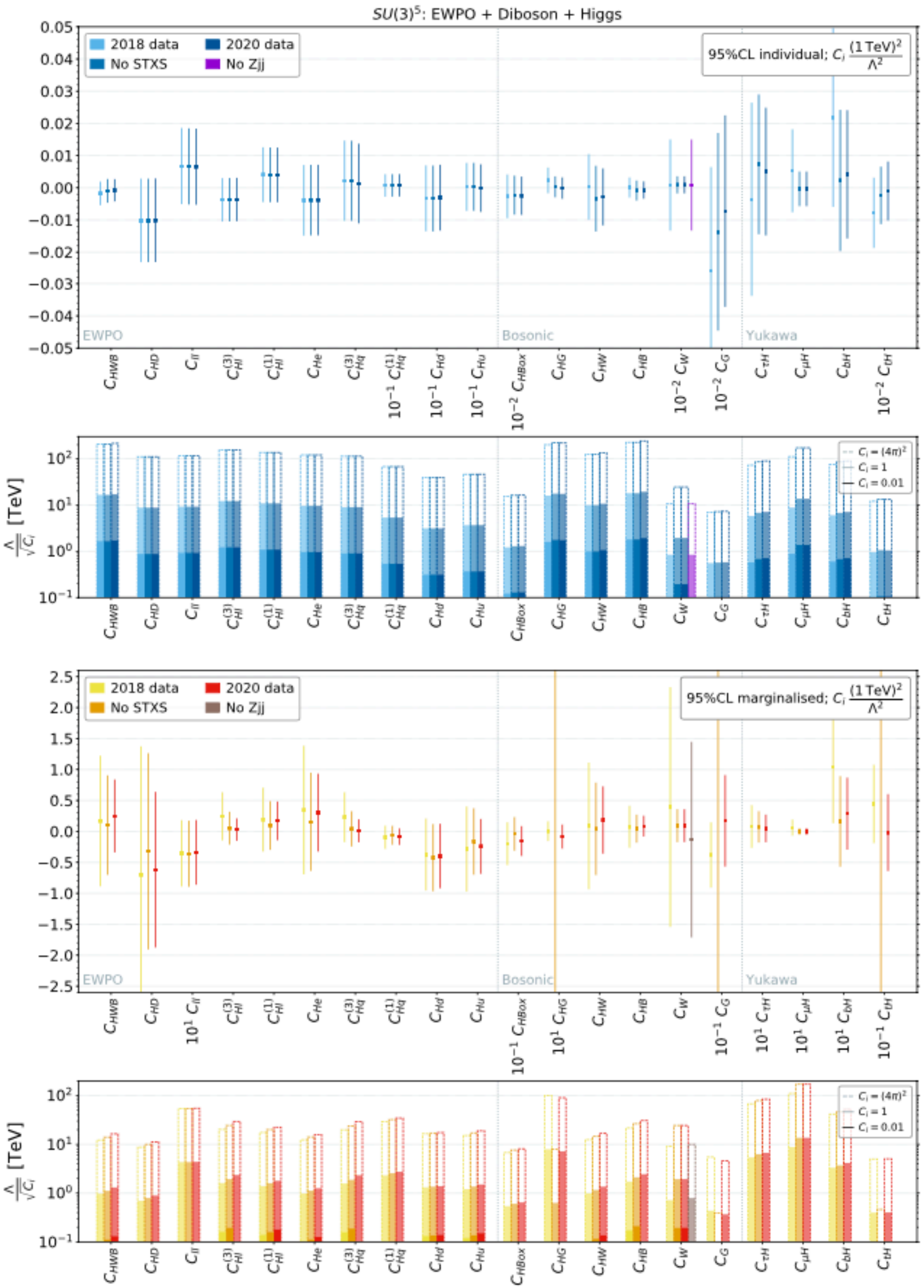
Run 2 top	n_{obs}	Ref.
CMS $t\bar{t}$ differential distributions in the dilepton channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	6	[36, 231]
CMS $t\bar{t}$ differential distributions in the ℓ+jets channel. $\frac{d\sigma}{dm_{t\bar{t}}}$	10	[37]
ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$.	5	[38]
ATLAS $t\bar{t}W$ & $t\bar{t}Z$ cross section measurements. $\sigma_{t\bar{t}W}$ | $\sigma_{t\bar{t}Z}$	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		

328 measurements included in global analysis

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

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

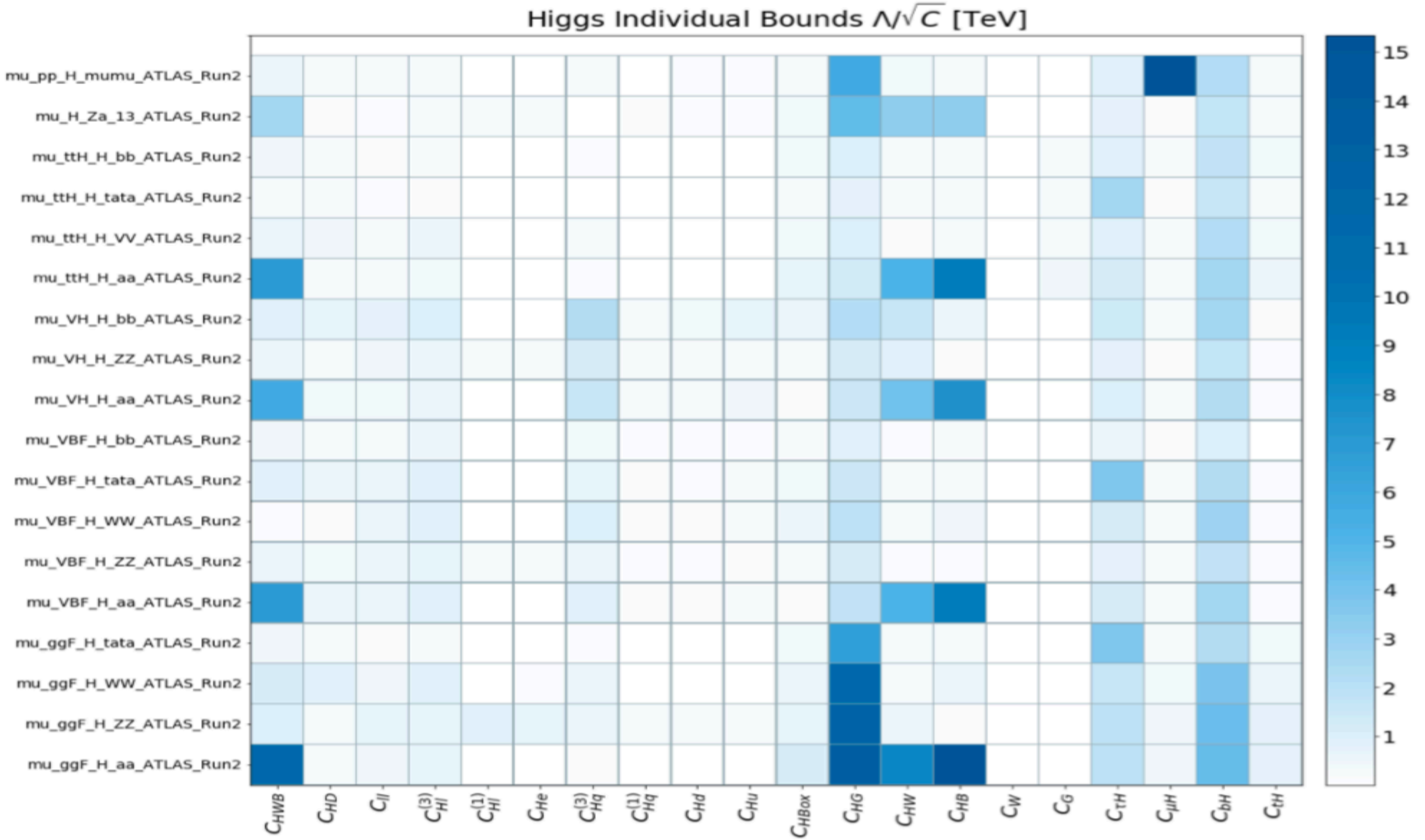
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**



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

Impacts of Measurements

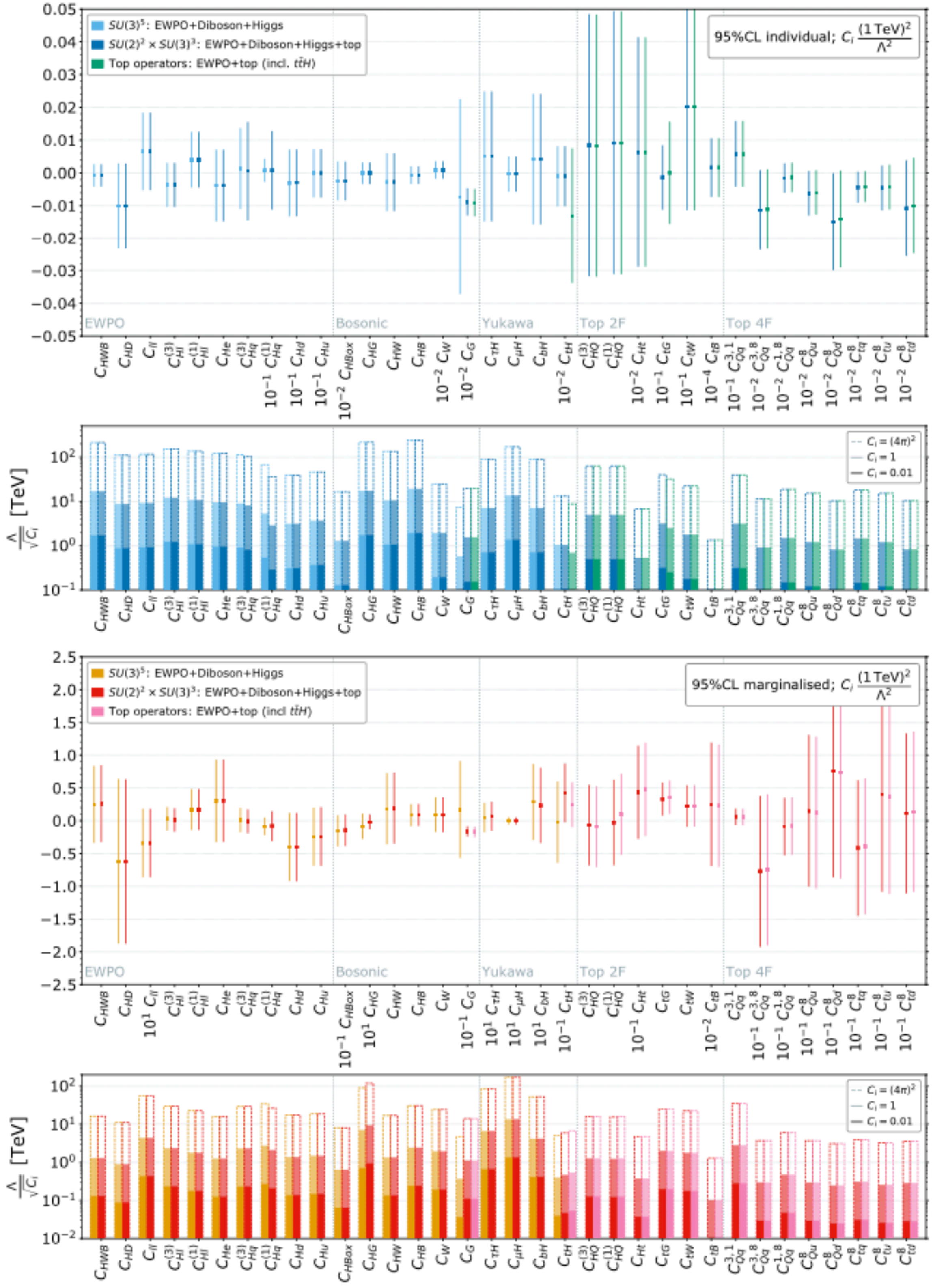
$$\frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



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

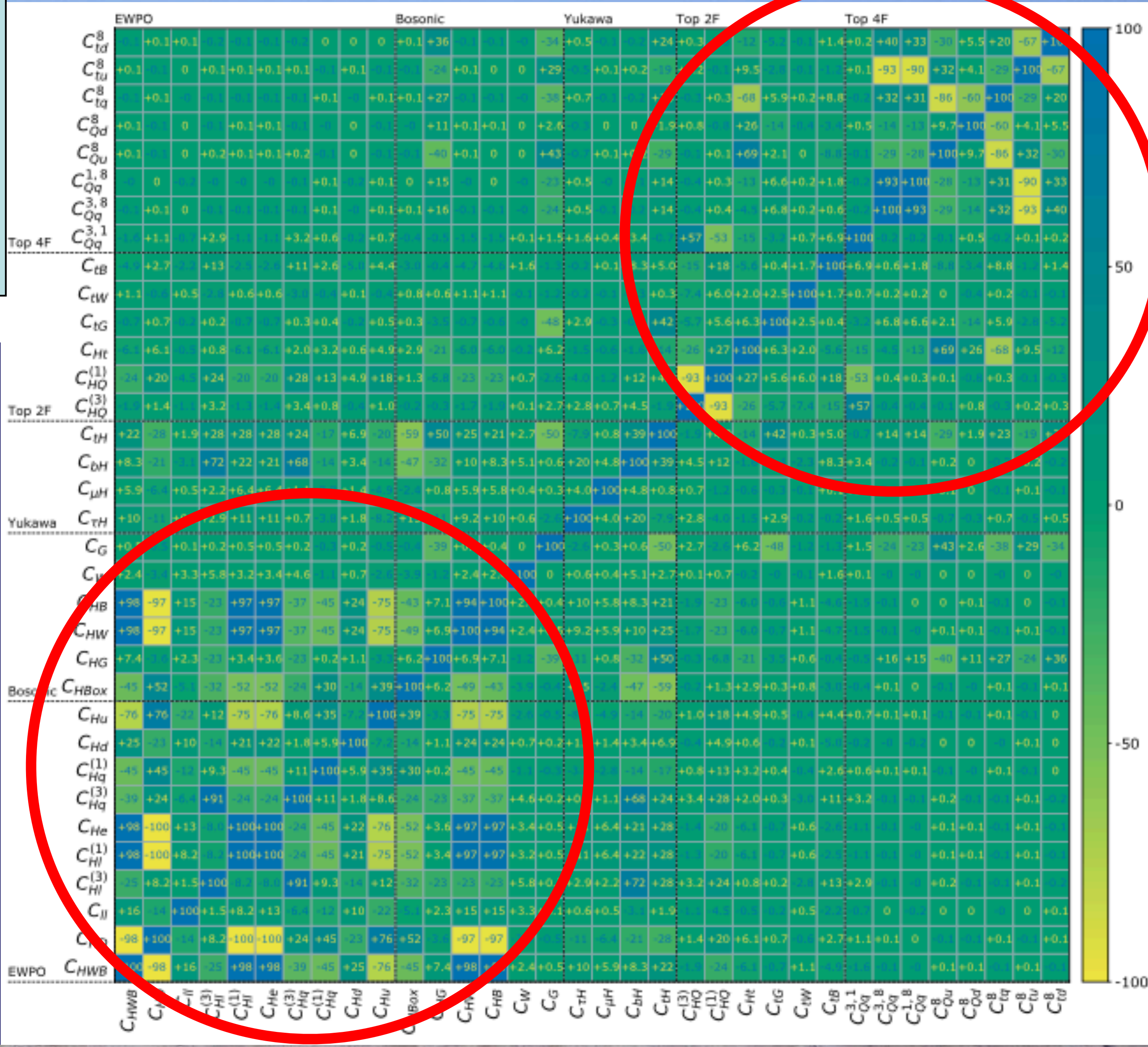
- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

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



Correlation Analysis

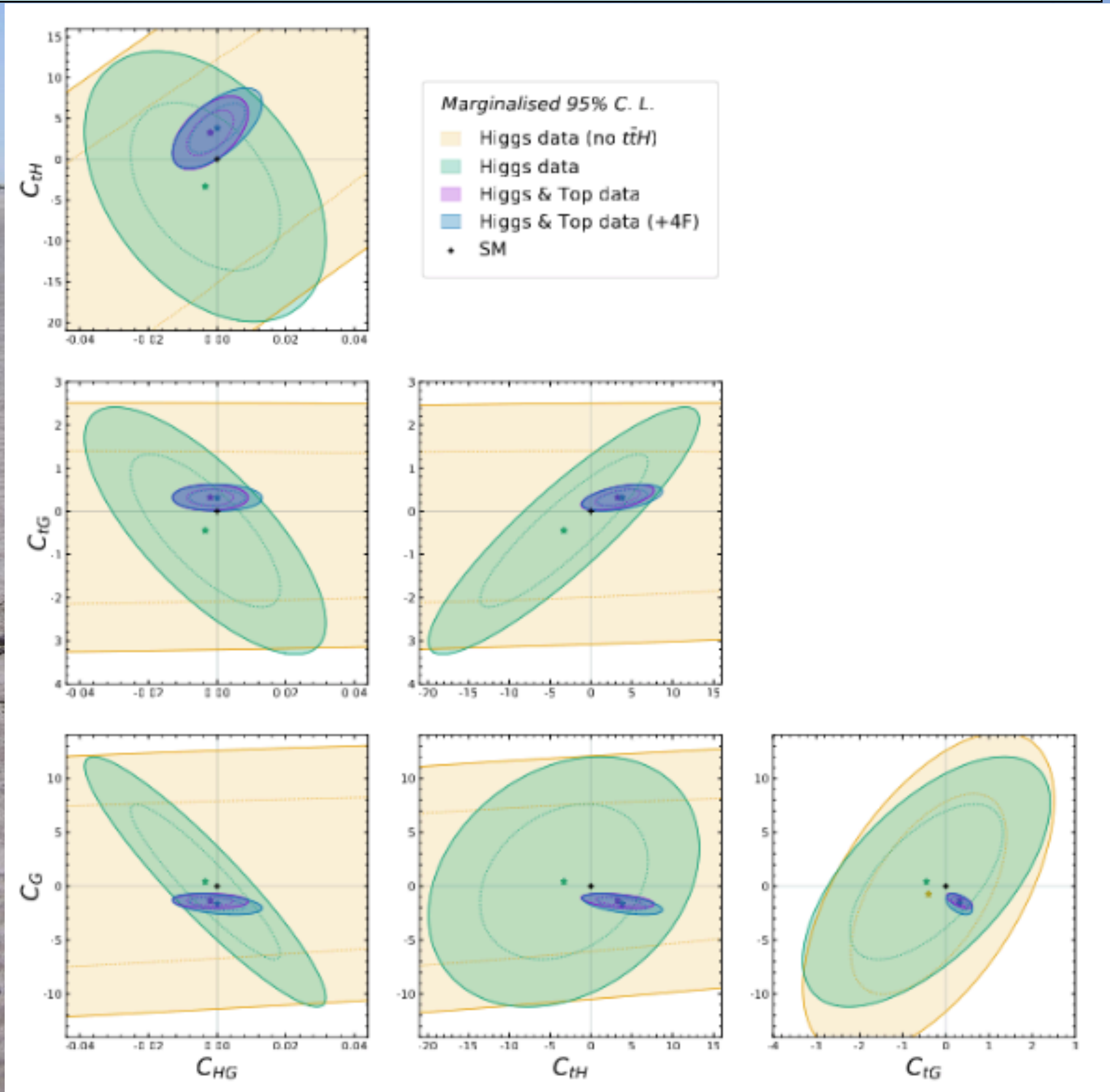
- EWPO and boson sectors correlated
- Also within top sector
- Weaker correlations between sectors



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

Example of Interplay between Data Sets

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

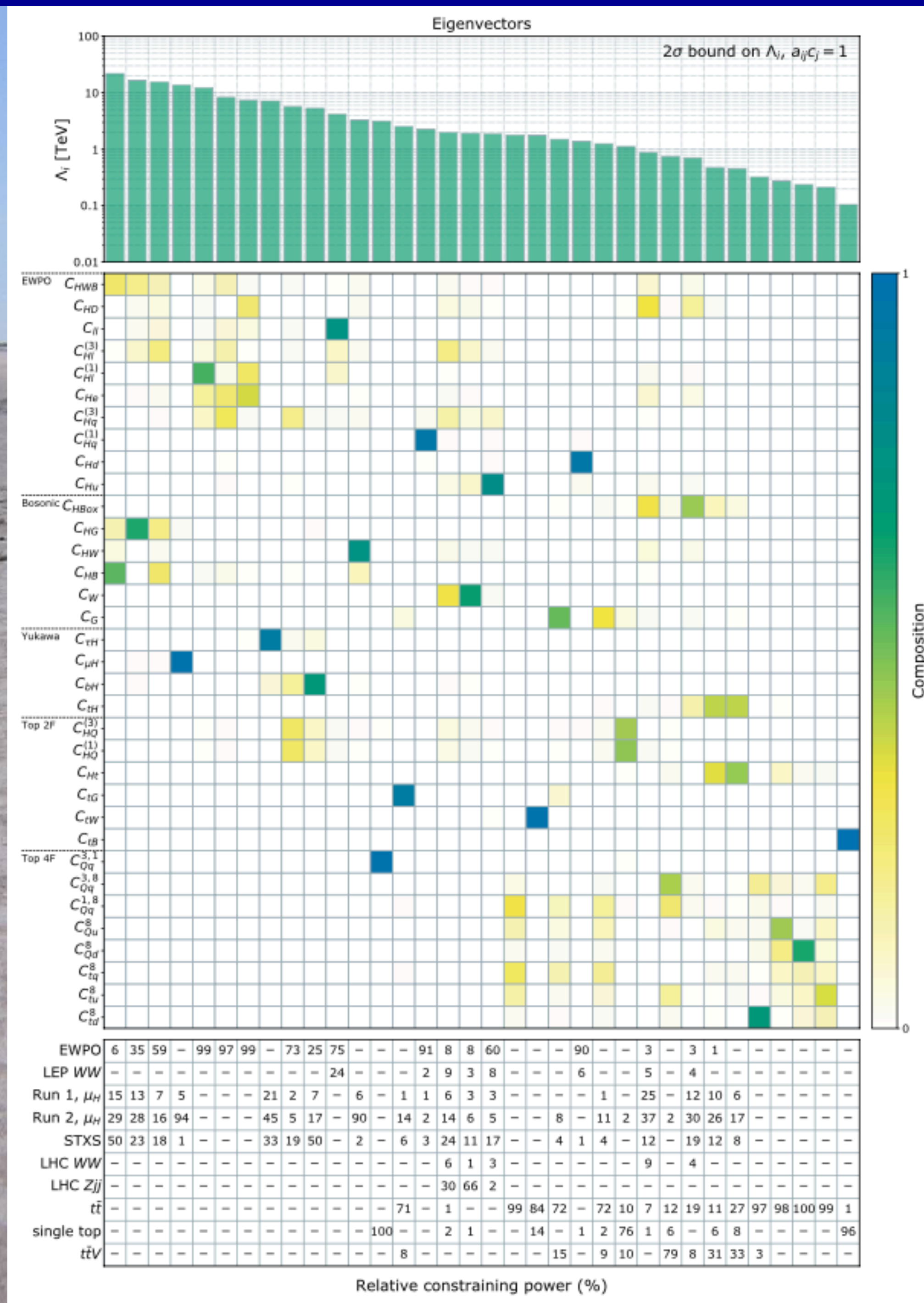


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

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 (%)

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

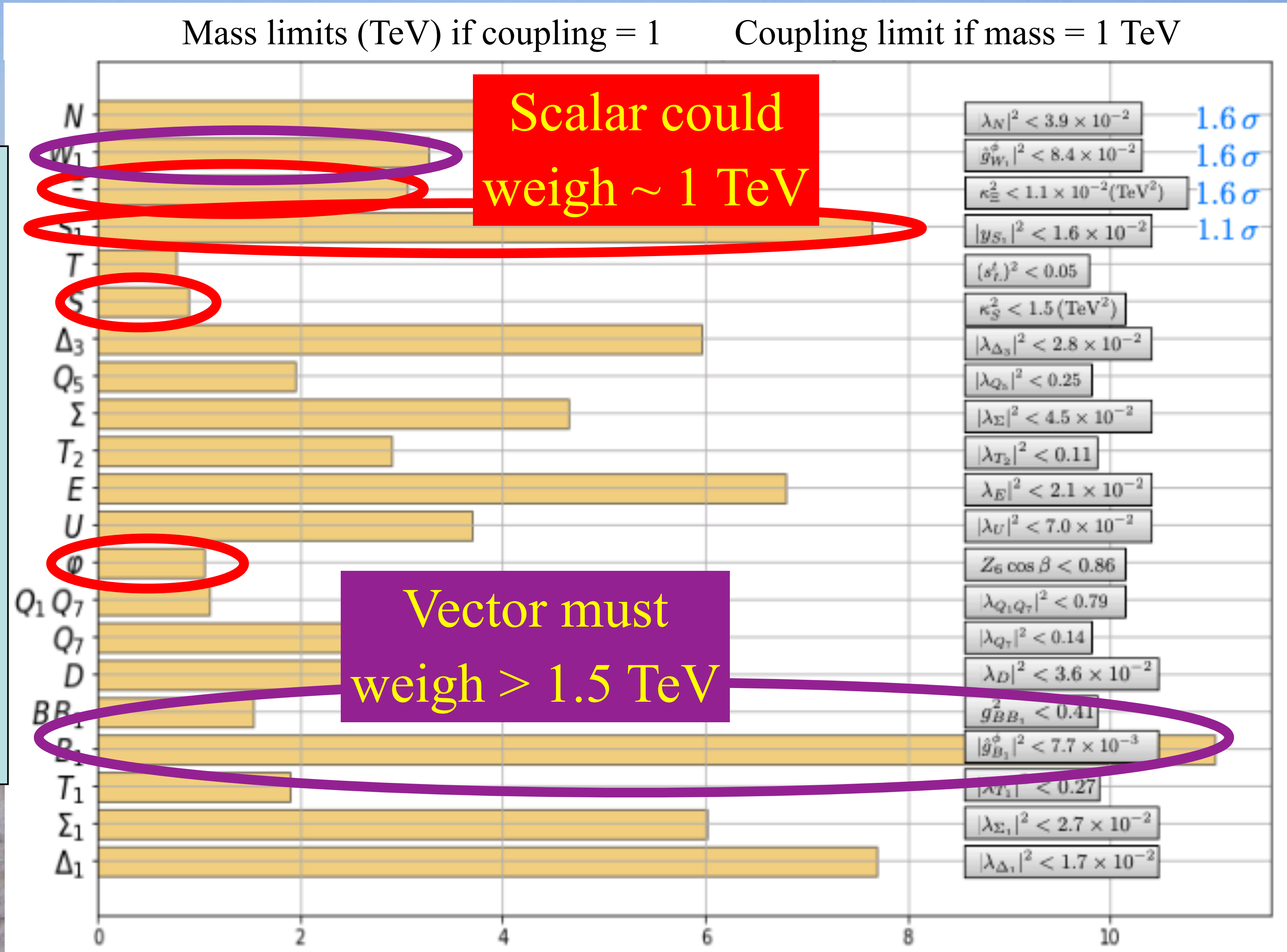
Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
Spin zero S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
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 > 800 GeV if coupling = 1

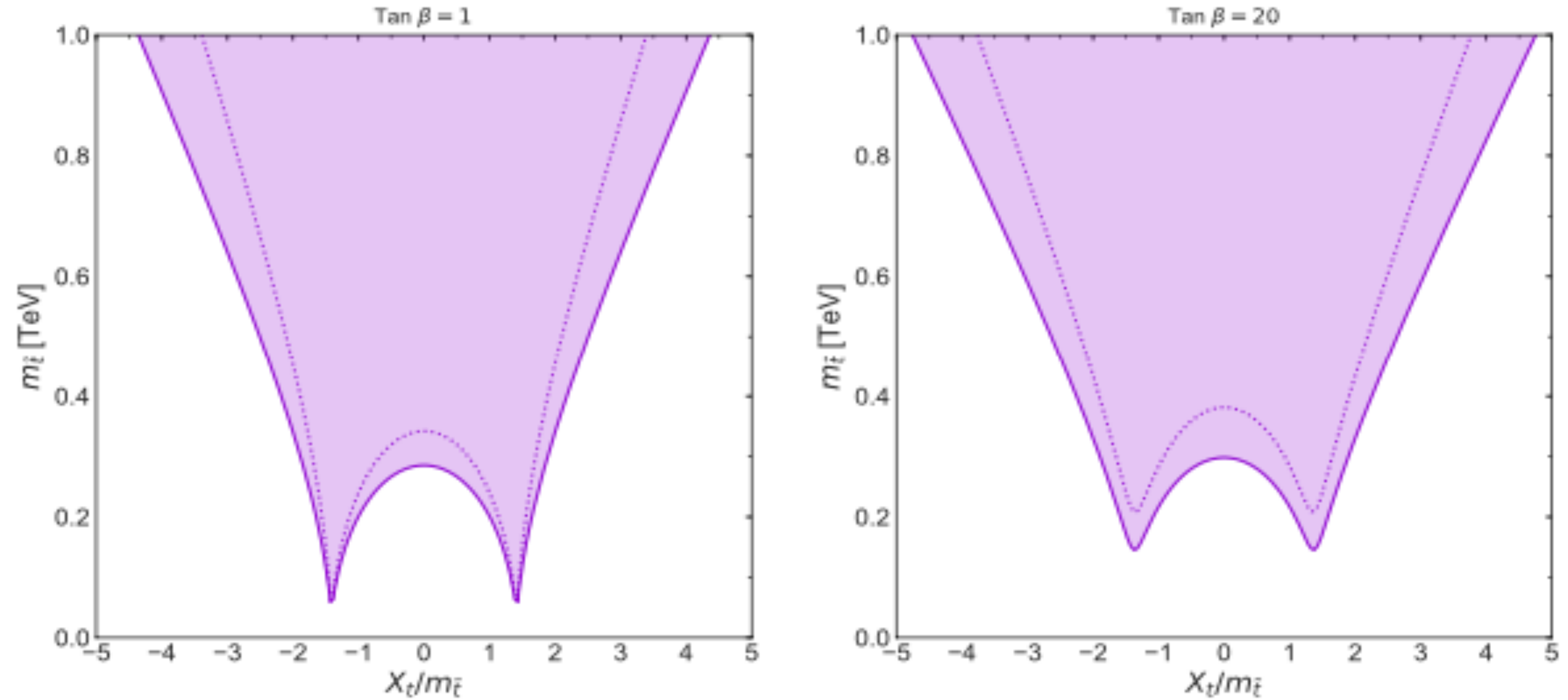


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

SMEFT Constraints on Light Stops

From quantum loop corrections:

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

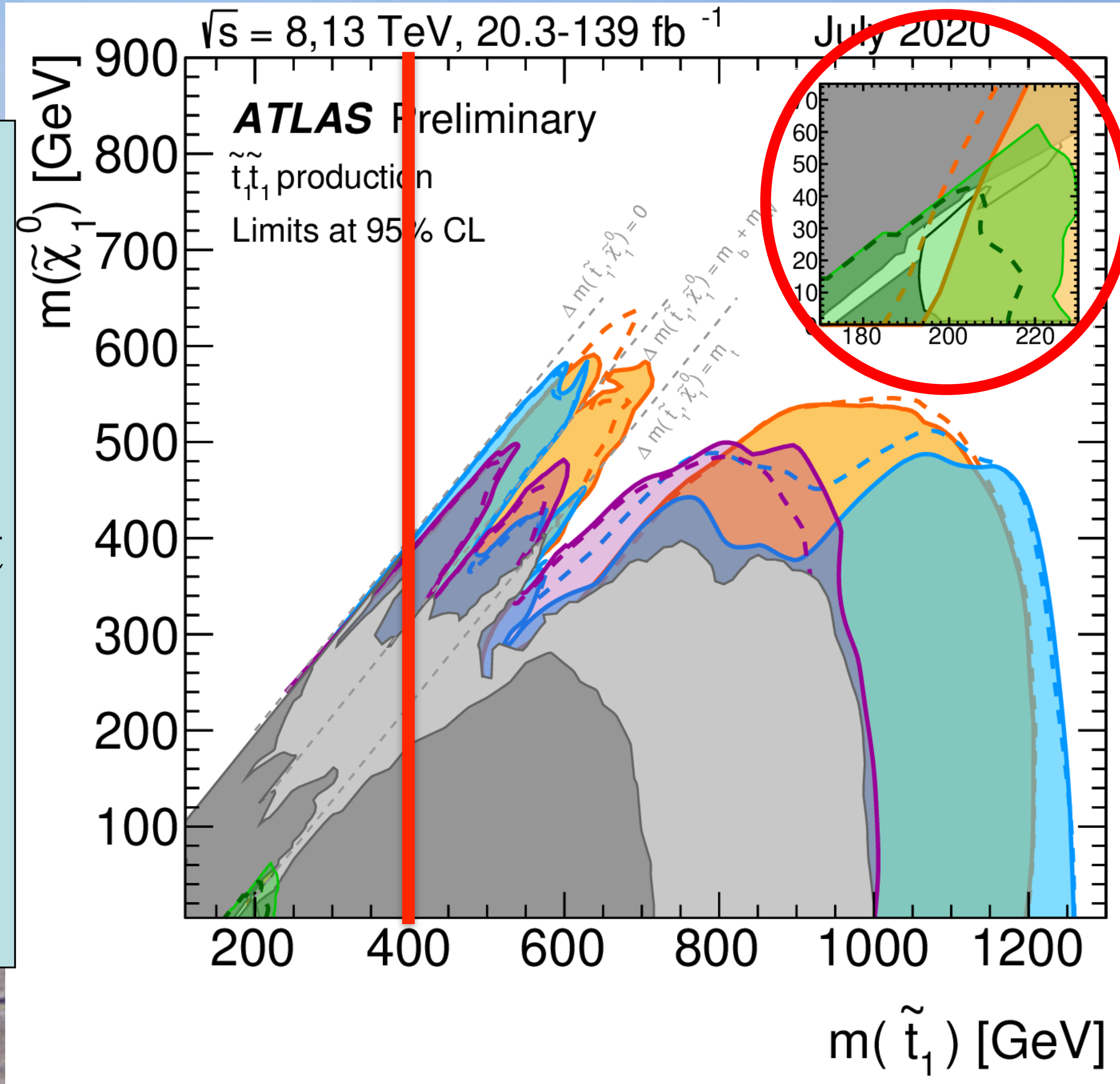


(Almost) model-independent lower limit on stop squark mass

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

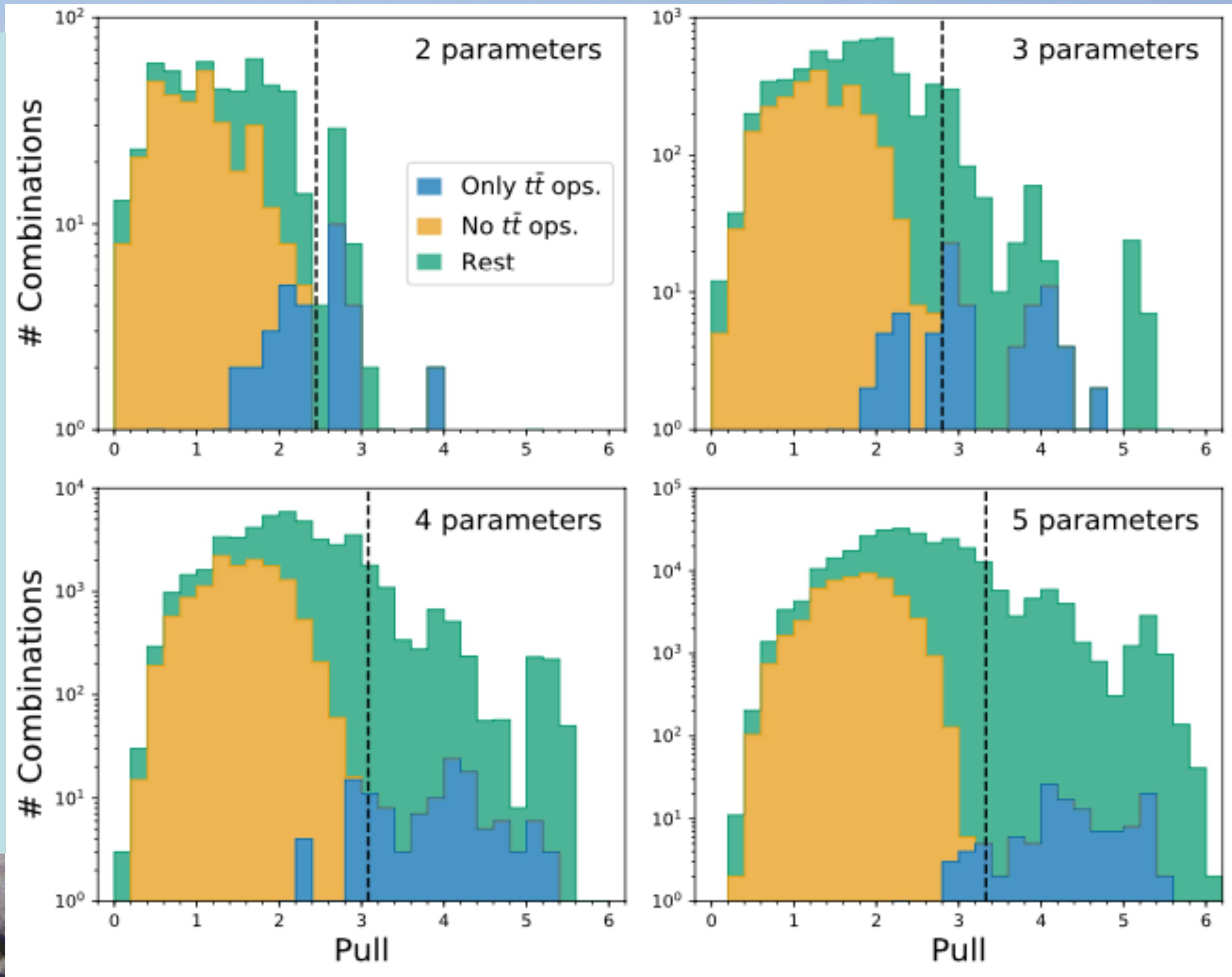
Direct Search Constraints on Light Stops

- 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**

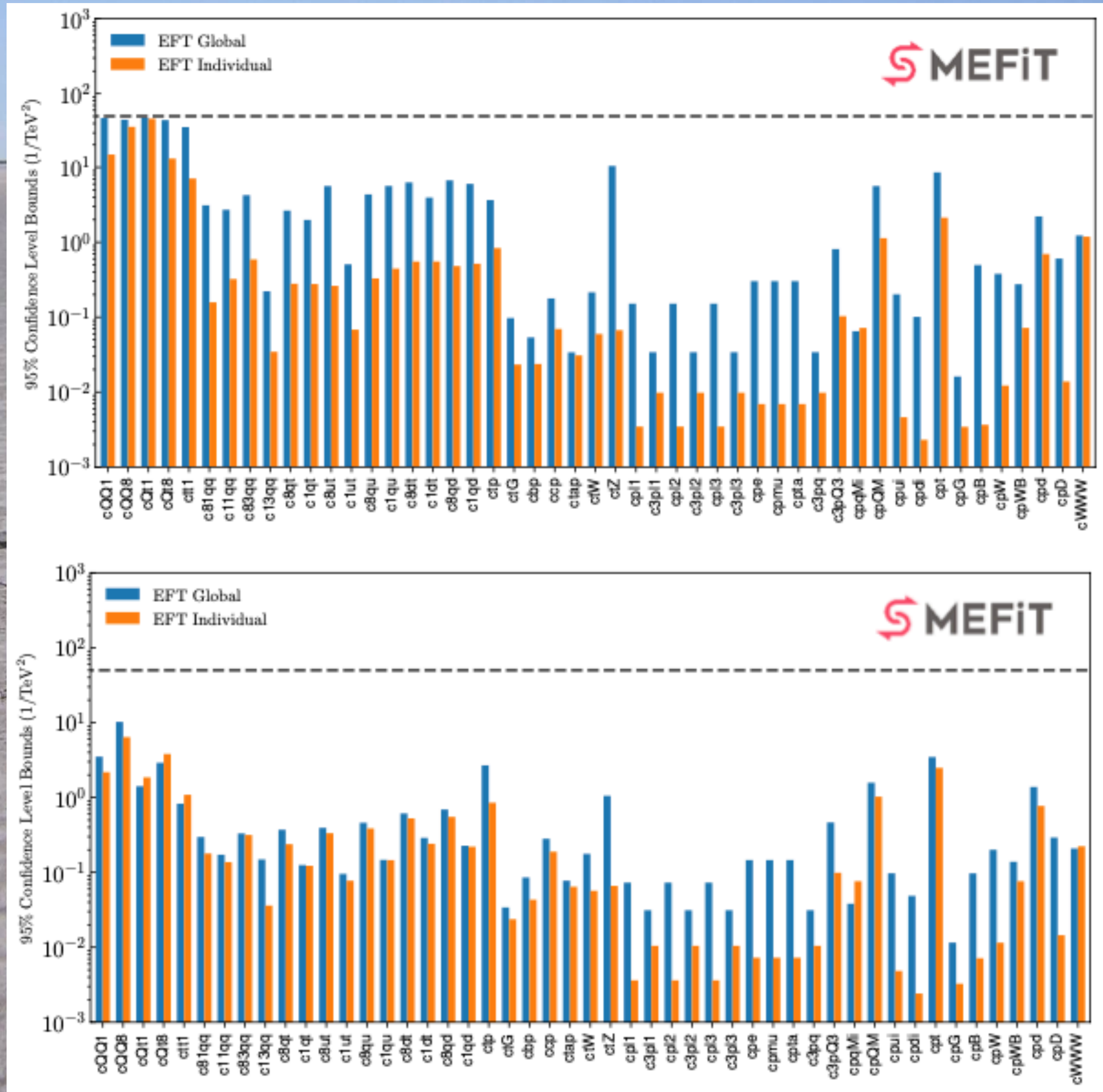


JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

Comparison of Linear and Quadratic Fits

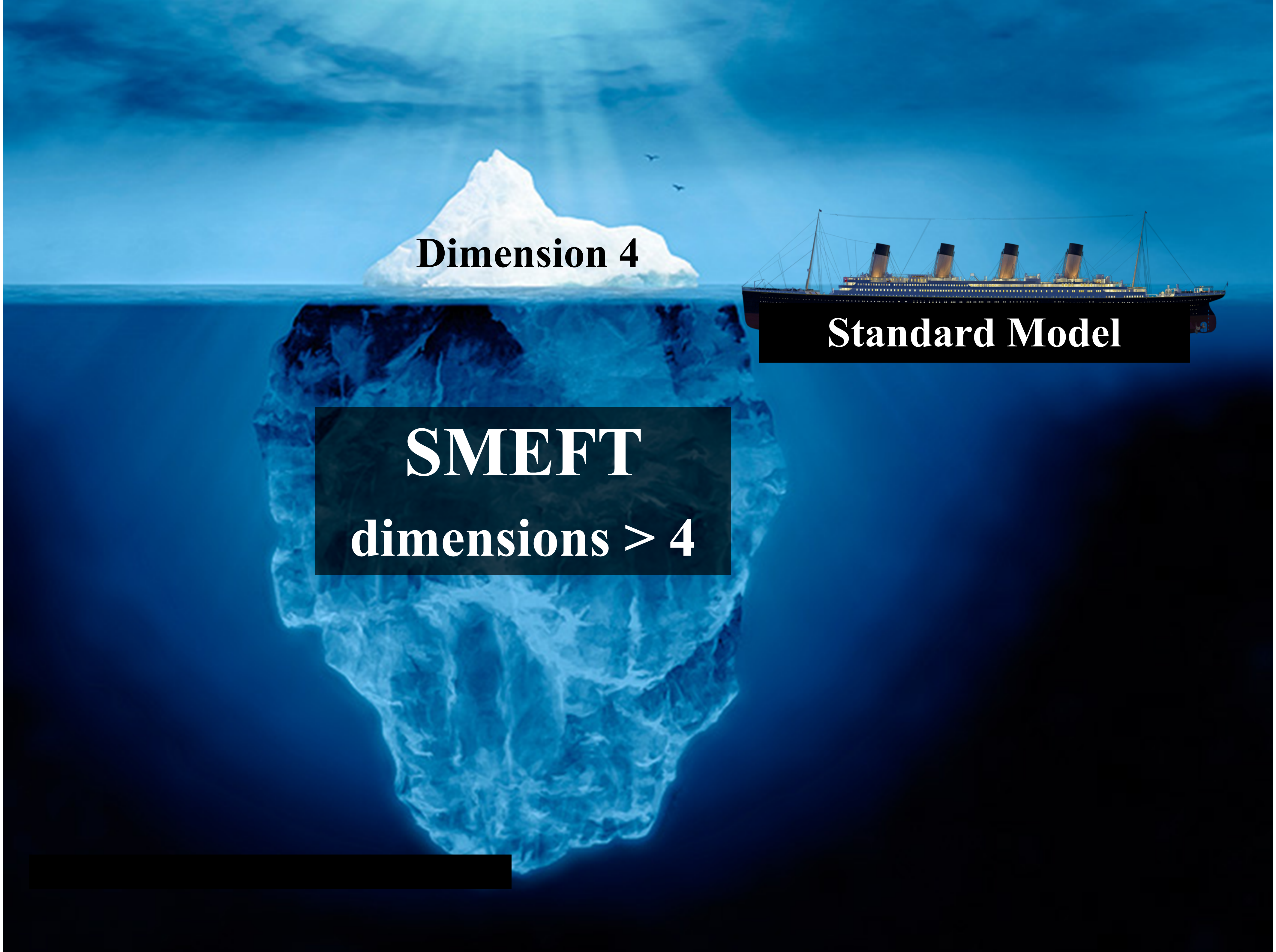
- Quadratic fit assuming EW data = Standard Model
- Tighter constraints in general
- What about dimension 8, also contribute at $\mathcal{O}(1/\Lambda^4)$?
- Fitting process slower, difficult to make broad BSM survey

Ethier et al., arXiv:2105.00006



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]