

Physics Overview

The Standard Model

Motivations for physics beyond

Many Higgs puzzles

Effective Field Theory: a tool for looking beyond

Experimental anomalies: $M_W, g_\mu - 2$?

Cosmology: dark matter & origin of matter

Summary of the Standard Model

- Particles and $SU(3) \times SU(2) \times U(1)$ quantum numbers:

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

- Lagrangian:

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

gauge interactions

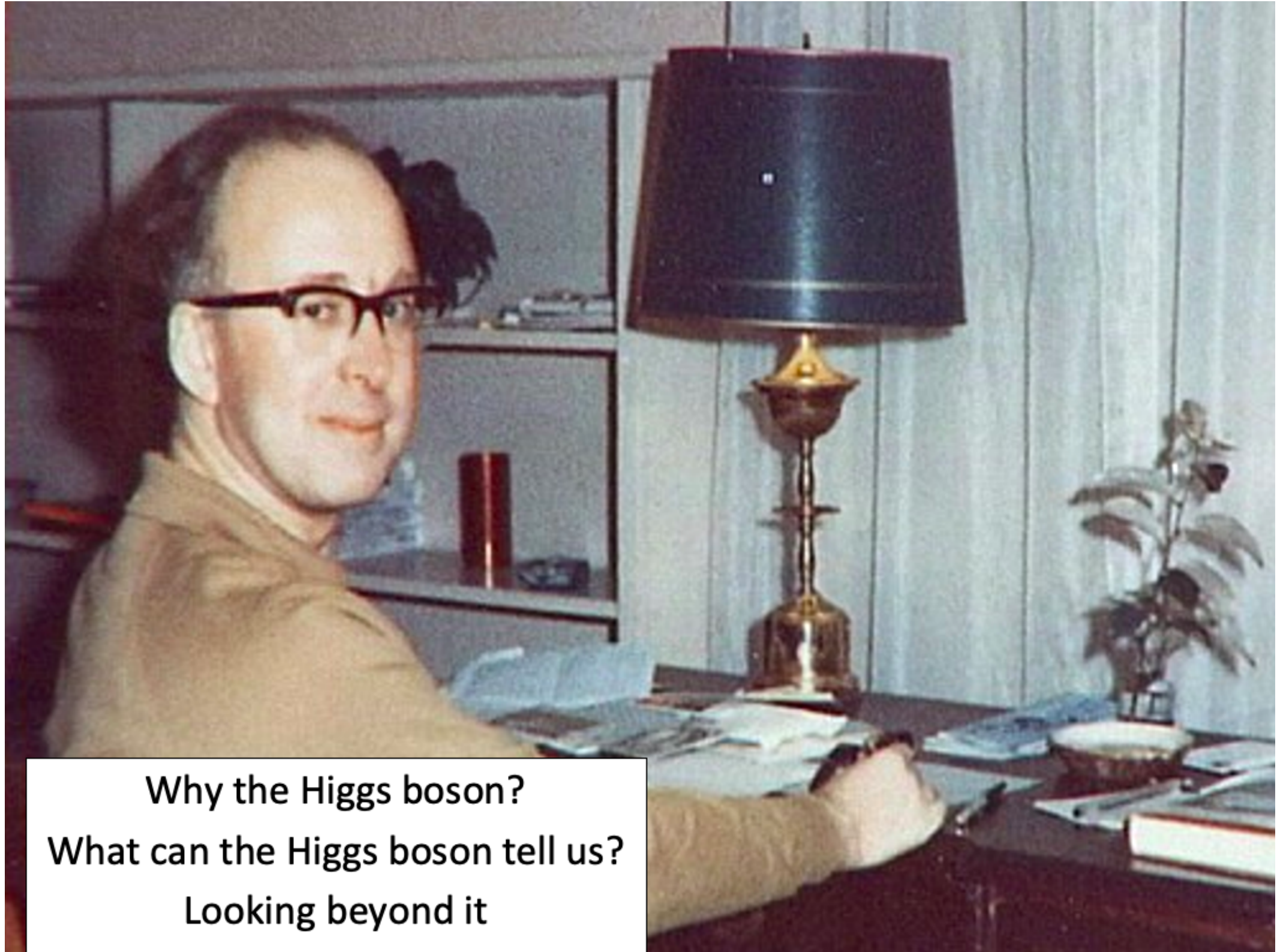
matter fermions

Yukawa interactions

Higgs potential

Tested < 0.1%
before LHC

Testing now
in progress



Why the Higgs boson?
What can the Higgs boson tell us?
Looking beyond it

A Phenomenological Profile of the Higgs Boson

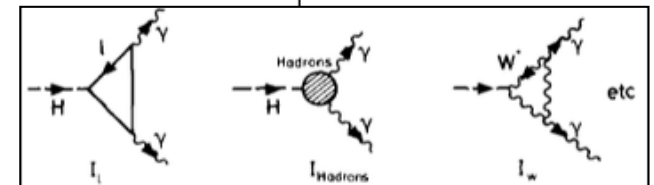
- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD ^{*} and D.V. NANOPOULOS ^{**}

CERN, Geneva

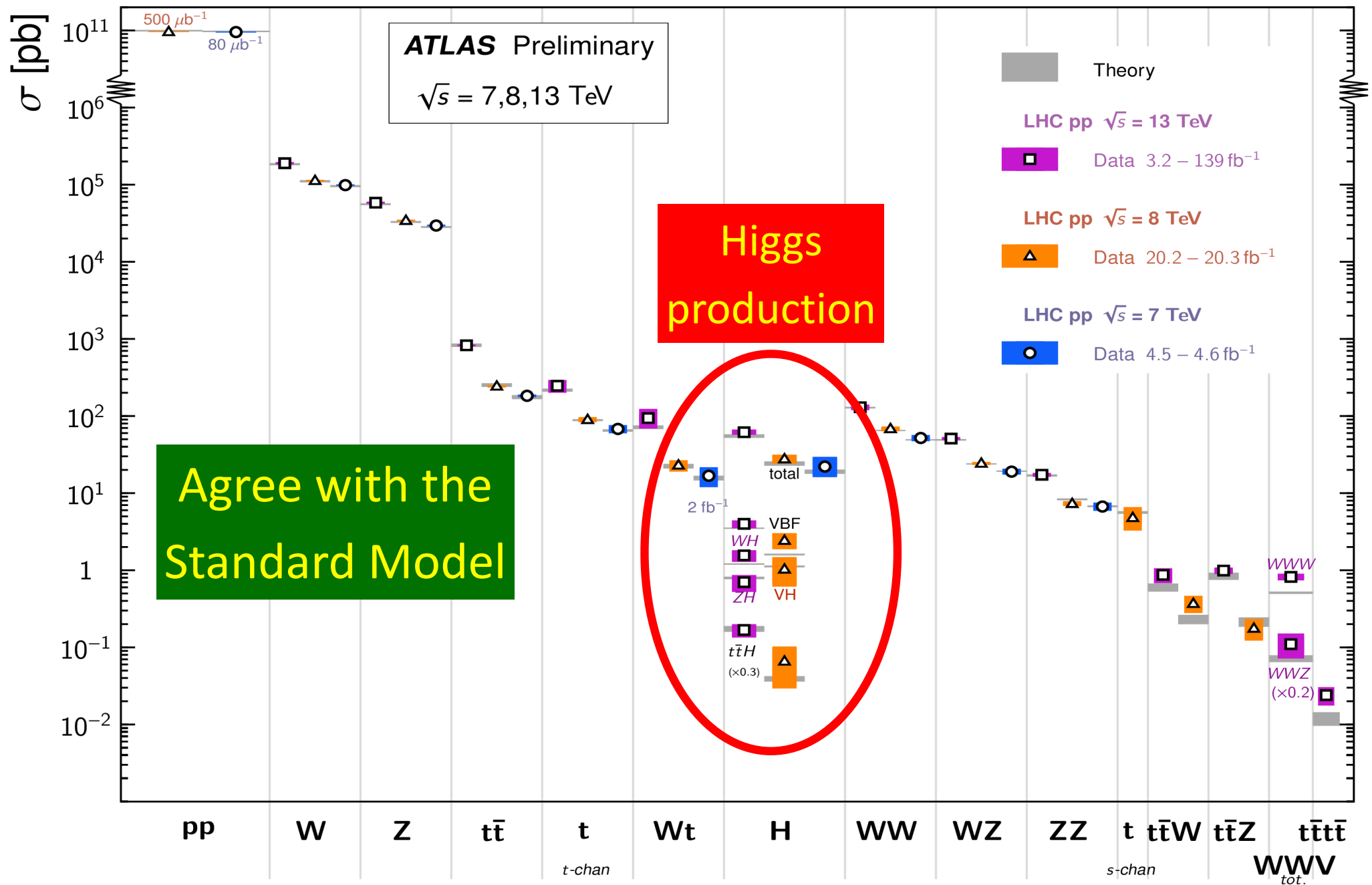
Received 7 November 1975

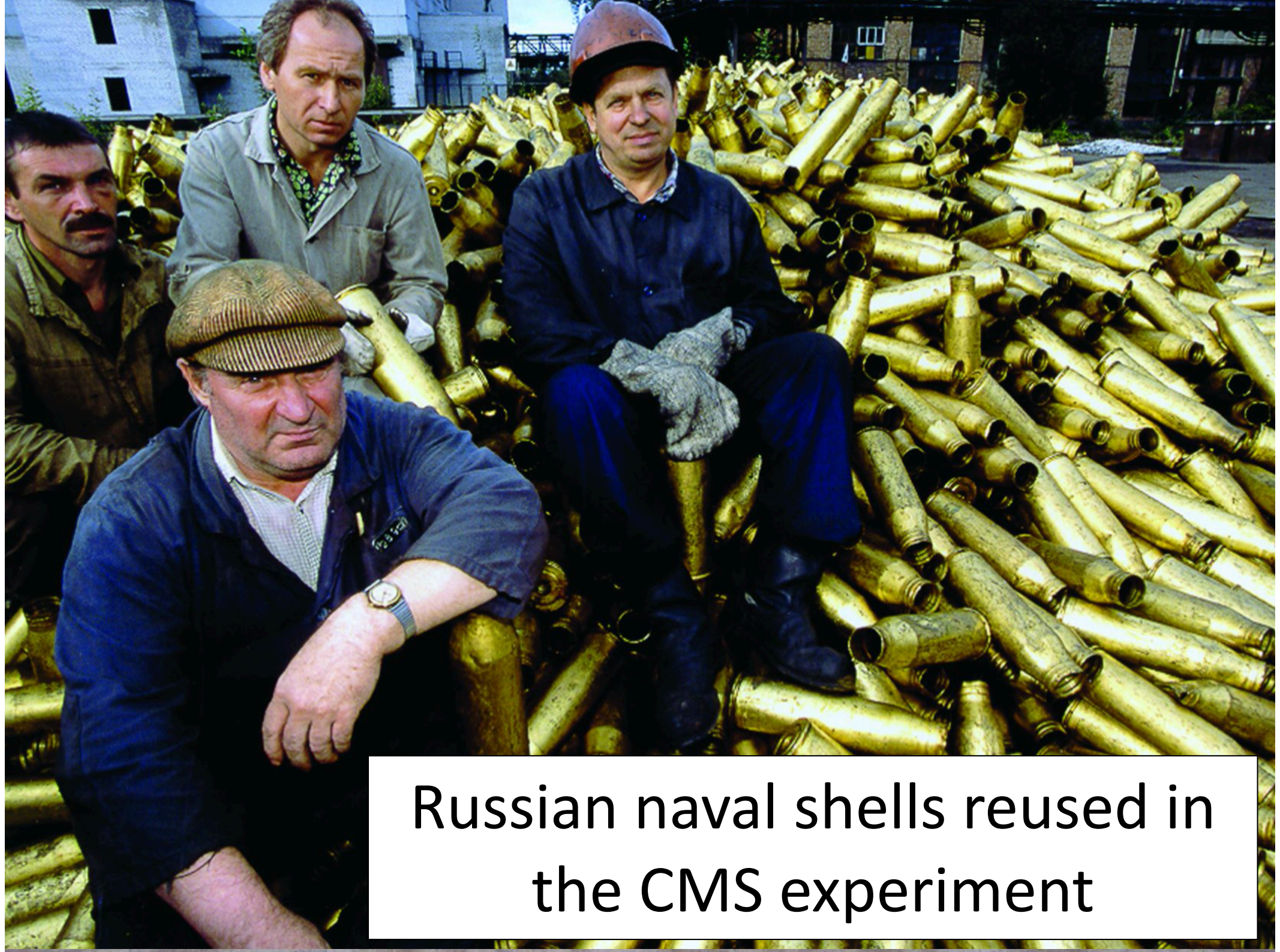


A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

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.

LHC Measurements



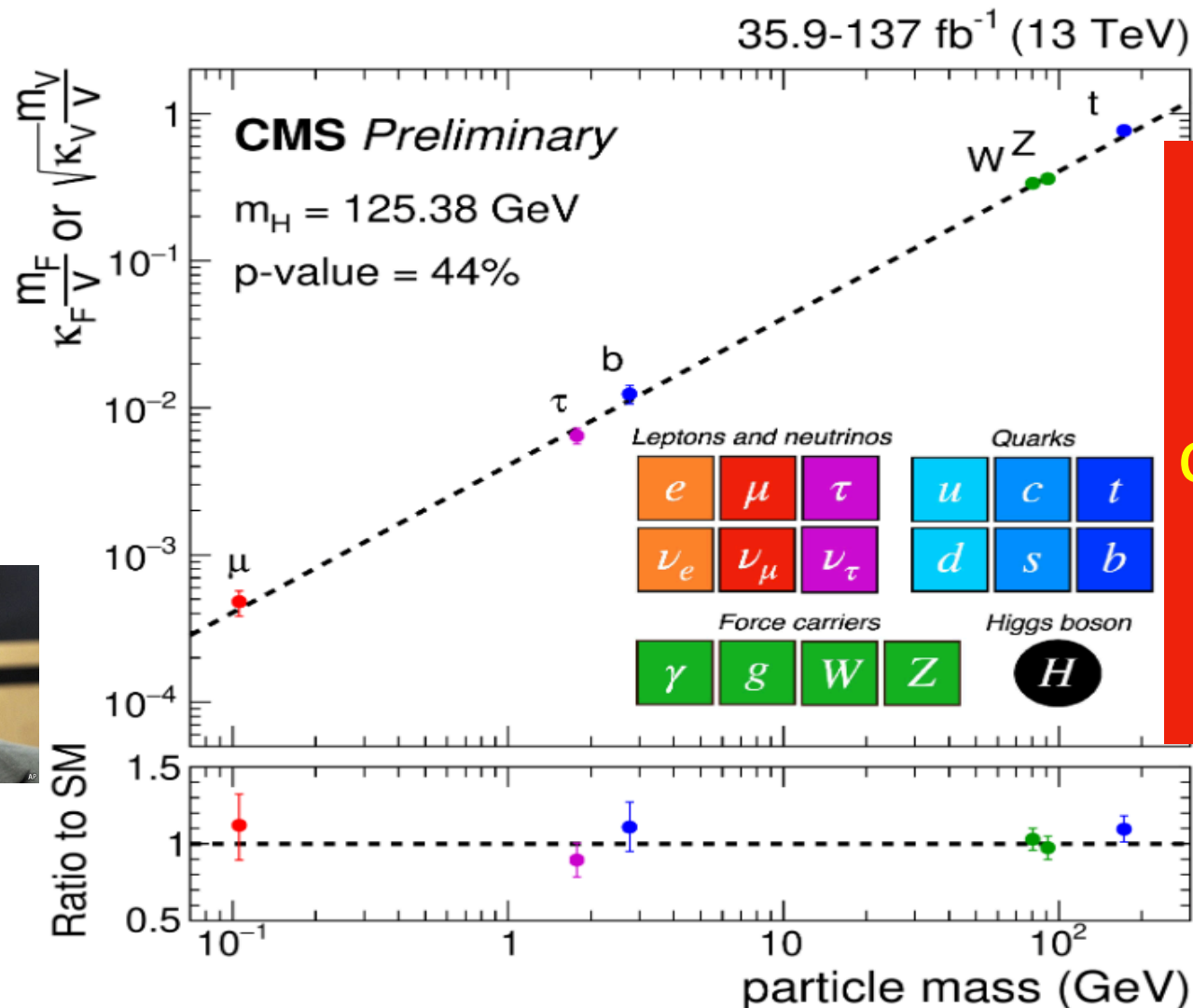


Russian naval shells reused in
the CMS experiment

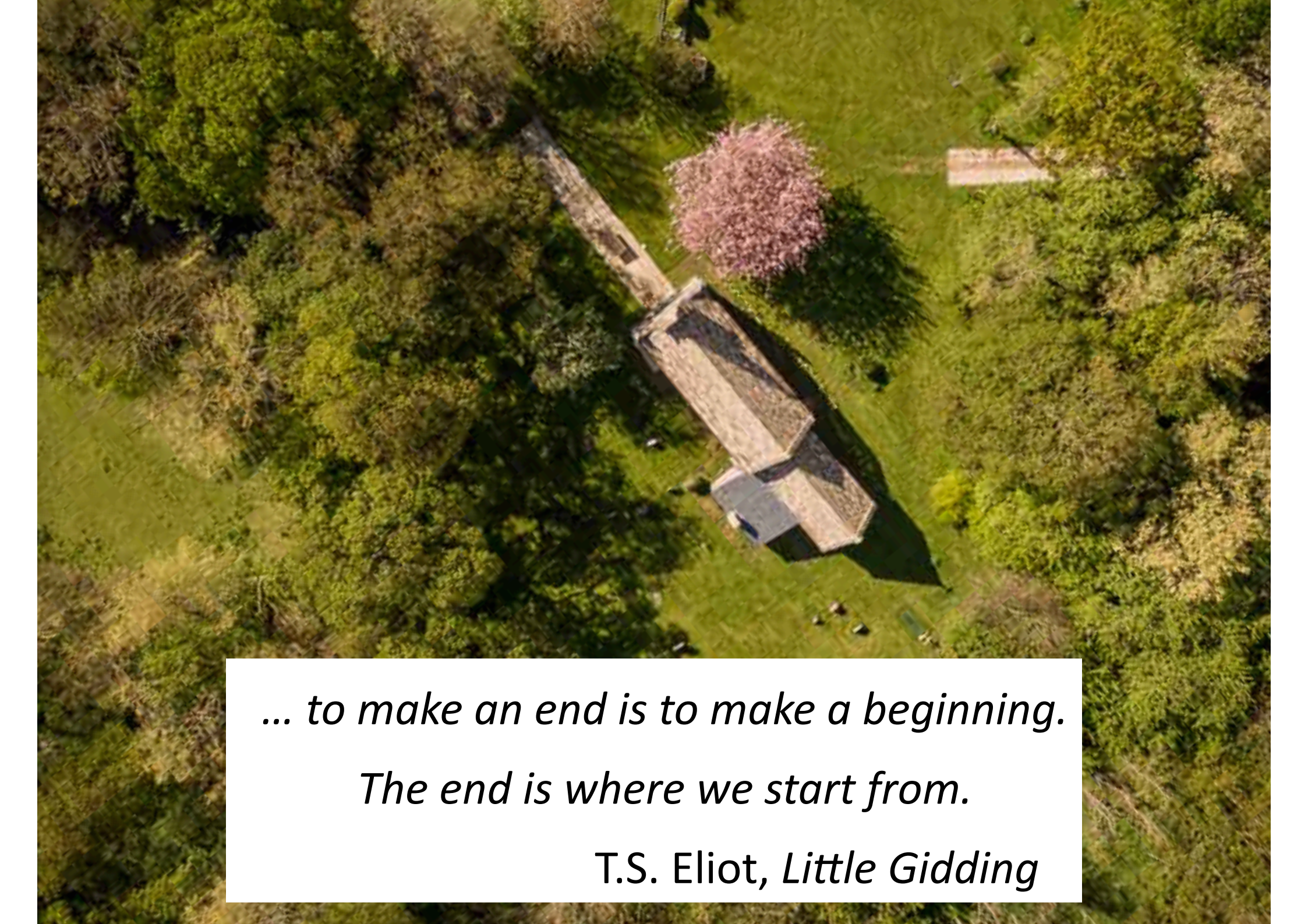
It Walks and Quacks like a Higgs

- Do couplings scale \sim mass? With scale = v ?

Global
fit

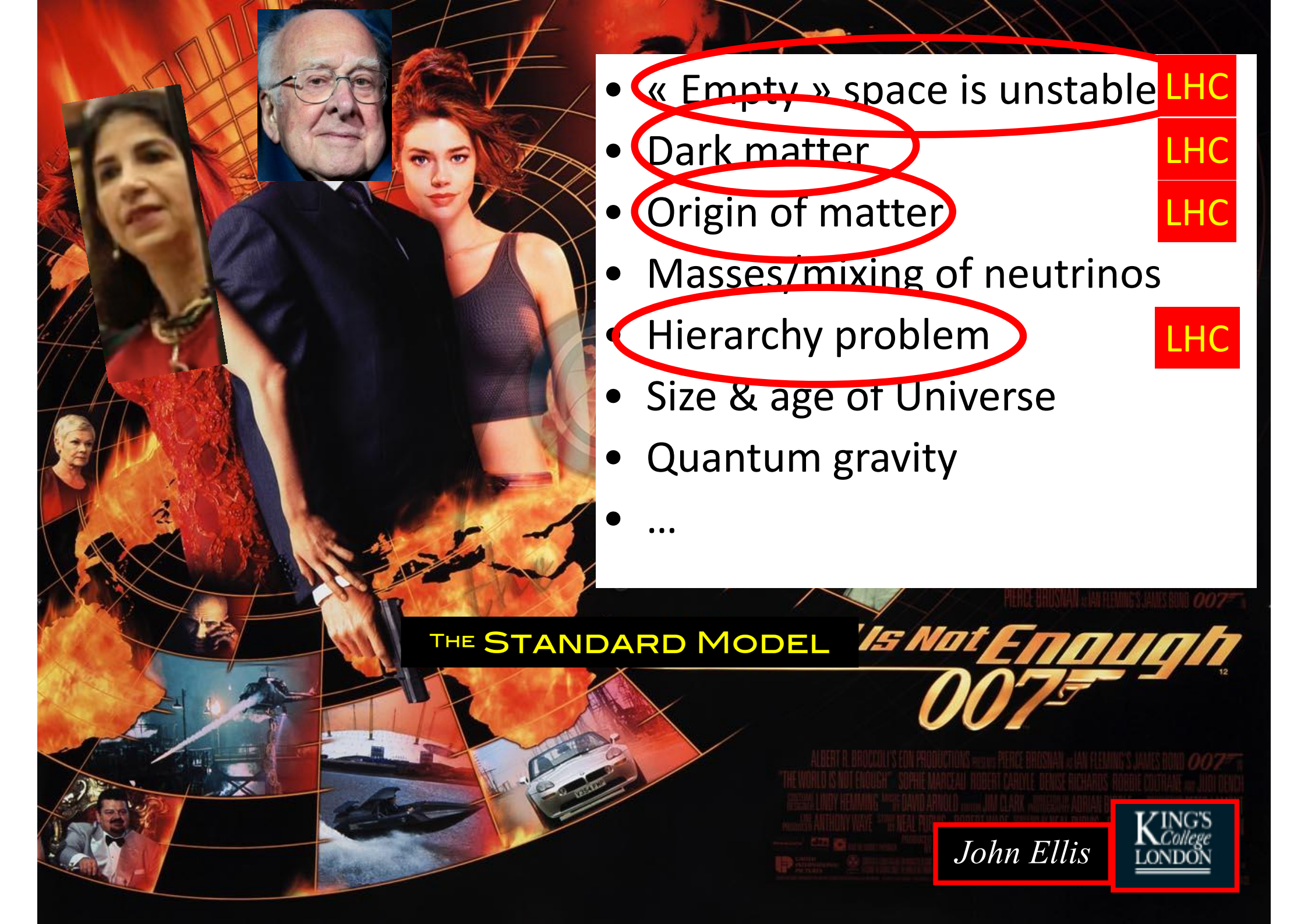


But what
is origin
of hierarchy
of masses
& mixing?



*... to make an end is to make a beginning.
The end is where we start from.*

T.S. Eliot, Little Gidding

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

THE STANDARD MODEL

'Is Not Enough'
007

John Ellis

KING'S
College
LONDON

Everything about Higgs is Puzzling

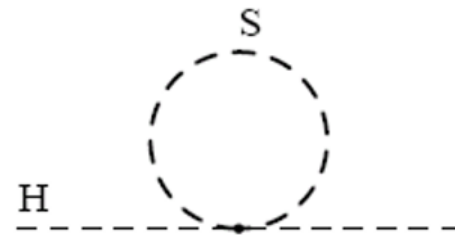
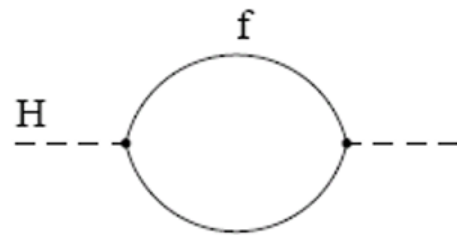
$$\mathcal{L} = yH\psi\bar{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 + \dots$$

- 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?

Loop Corrections to Higgs Mass²

- Consider generic fermion and boson loops:



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

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

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

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \times 2 \quad \text{Supersymmetry!}$$

What lies beyond the Standard Model?

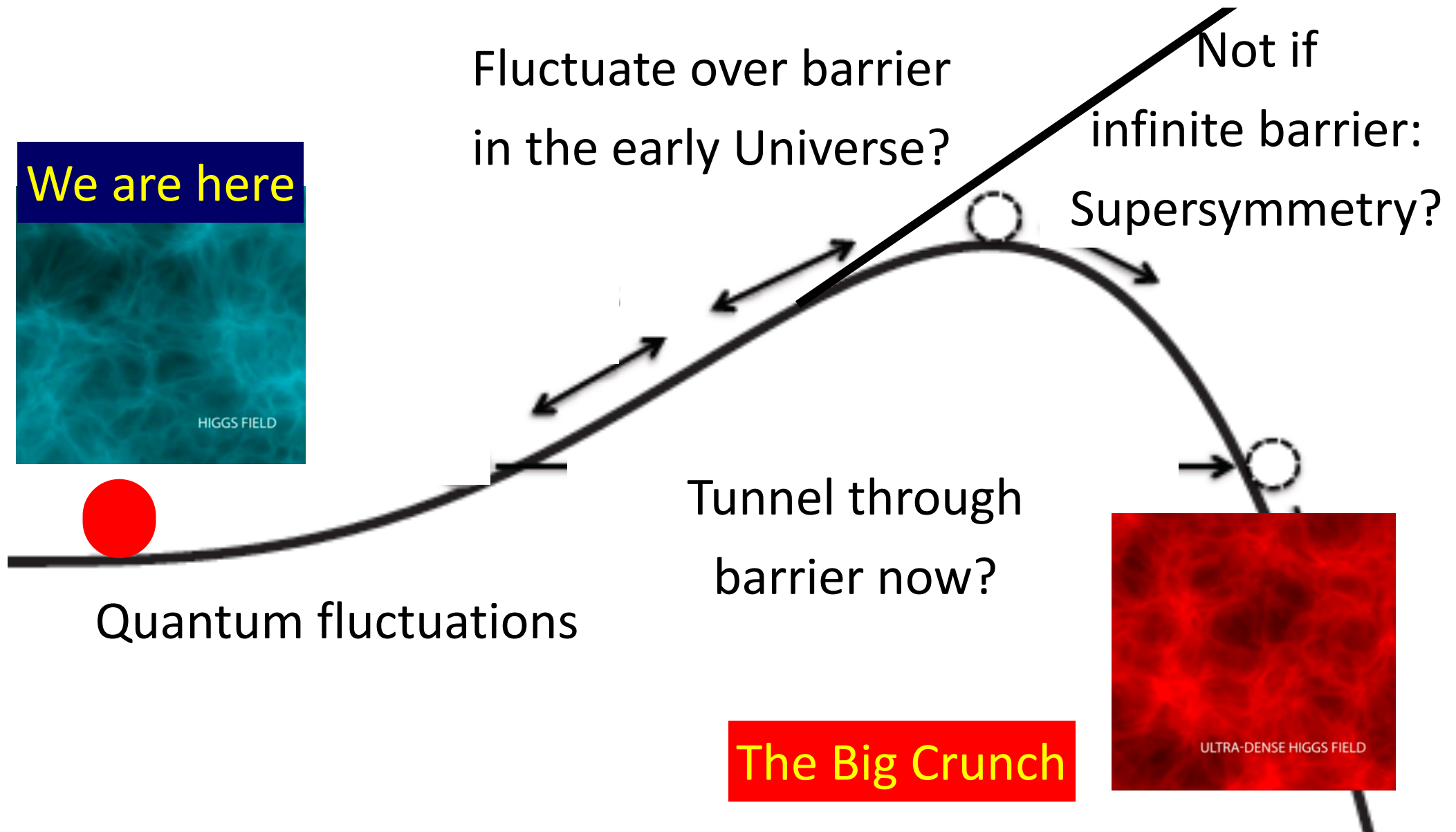
Supersymmetry

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?

- Instability scale depends on masses of Higgs boson and top quark, and strong coupling:

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

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

- Particle Data Group values:

$$m_t = 172.69 \pm 0.30 \text{ GeV}$$

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

- Instability scale:

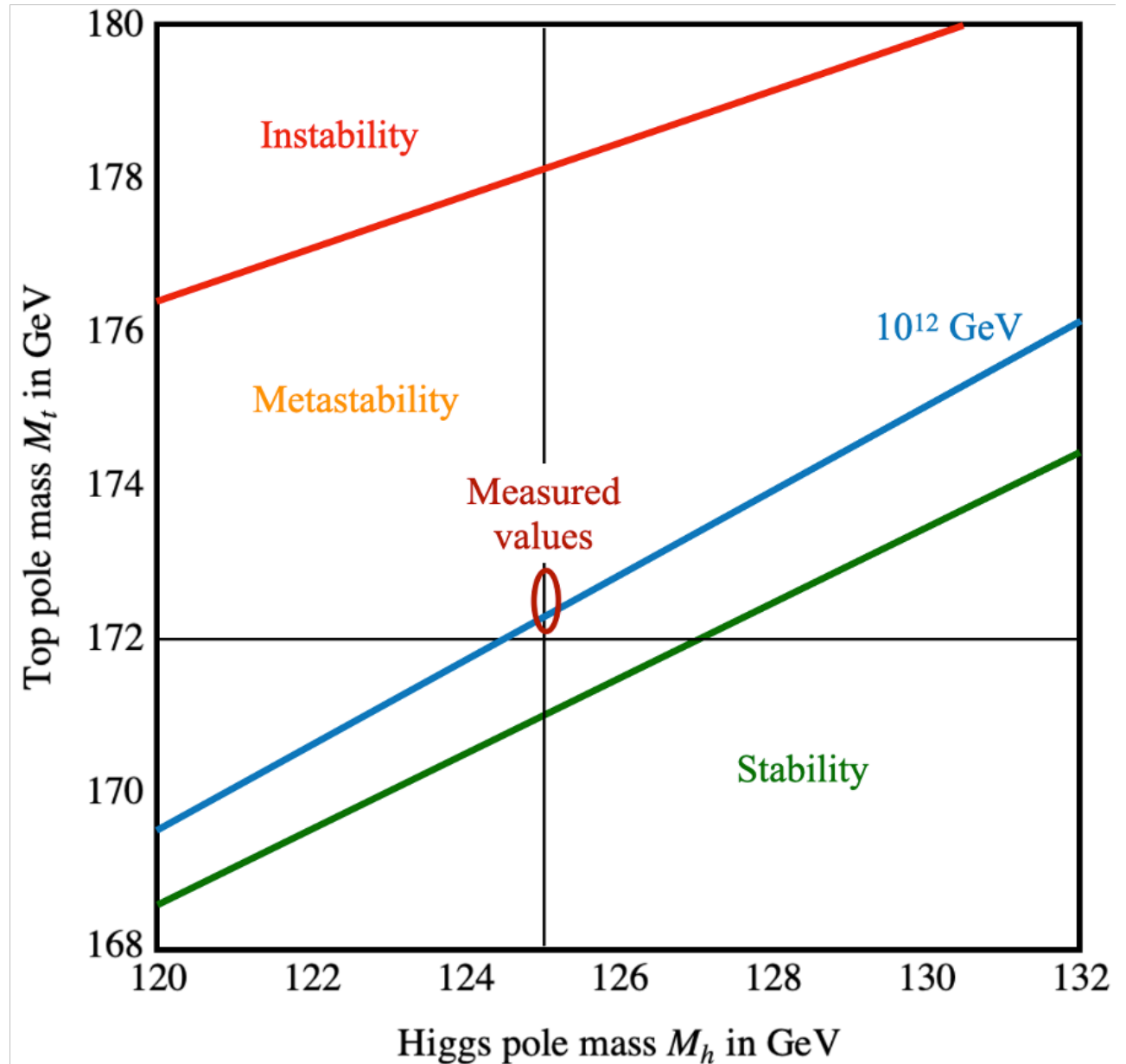
$$\text{Log}_{10} \frac{\Lambda}{\text{GeV}} = 11.7 \pm 0.8$$

- Dominant uncertainties those in α_s and 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

France

“...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....”

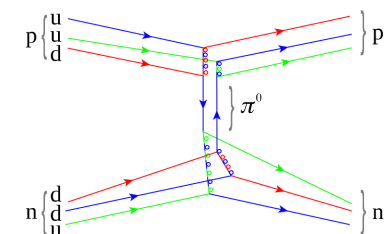
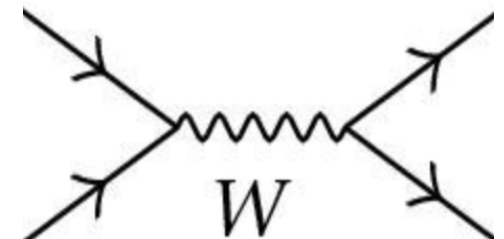
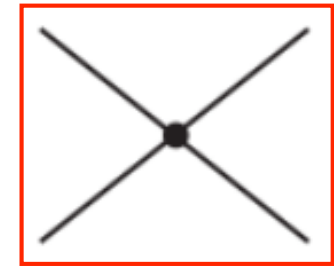
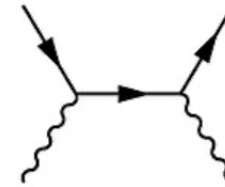
Who can exhaust the possibilities of their combination?”

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 \rightarrow massive vector bosons \rightarrow gauge theory
- Yukawa's meson theory of the strong N-N force
 - Due to exchanges of mesons? \rightarrow pions
- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue \rightarrow 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)**

Summary of Analysis Framework

- Include all leading dimension-6 operators?

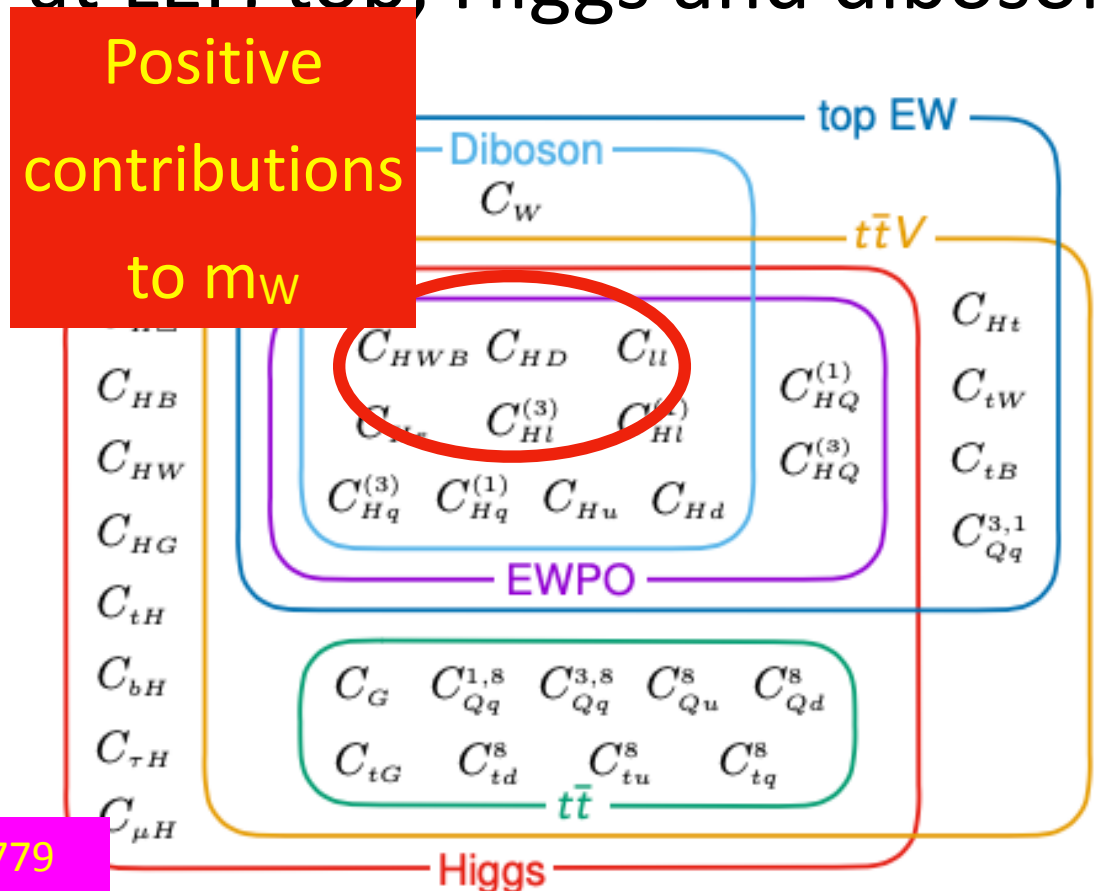
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $\text{SU}(3)^5$ or $\text{SU}(2)^2 \times \text{SU}(3)^3$ 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

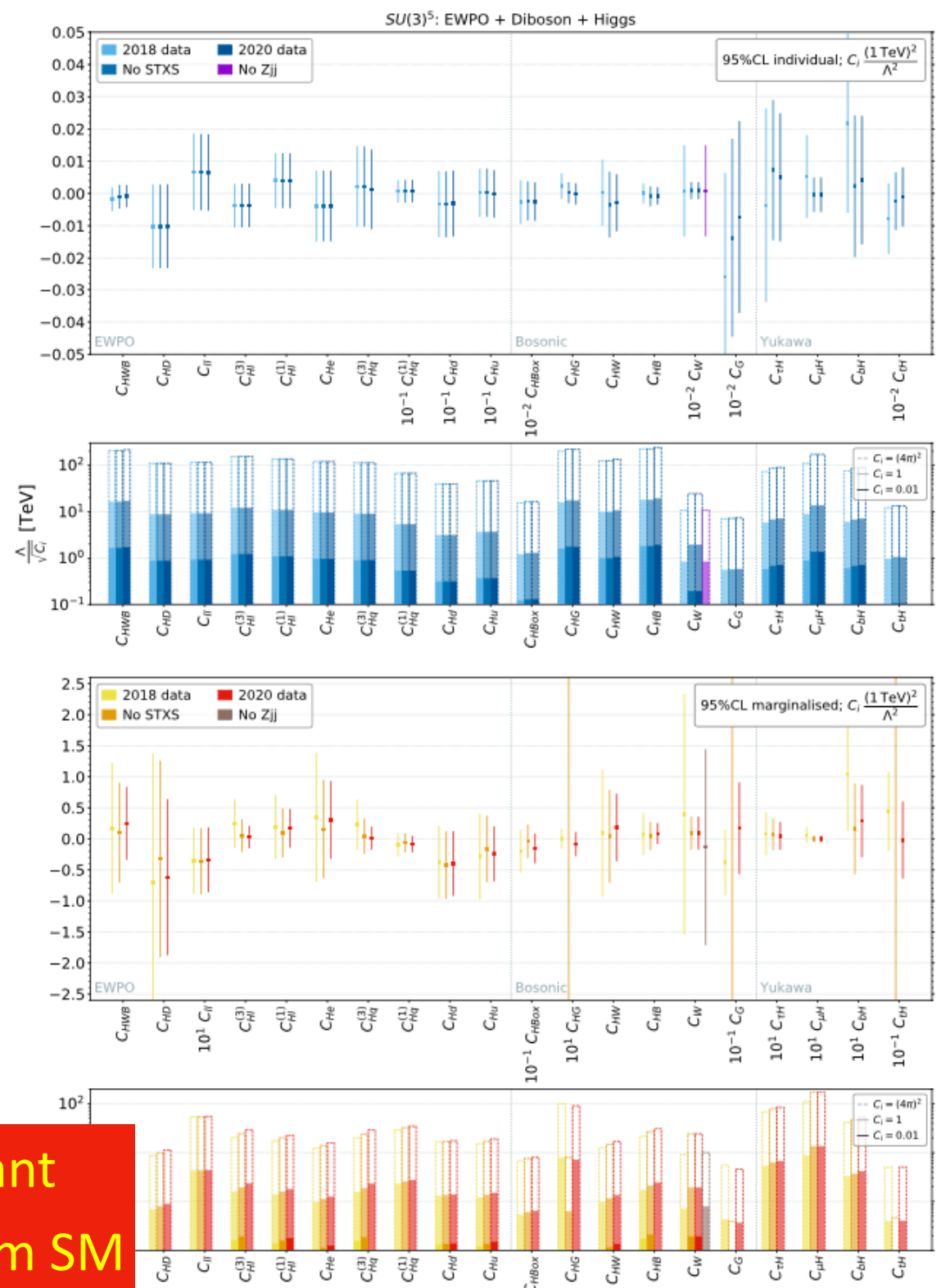
- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
 - At tree level
 - At loop level



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

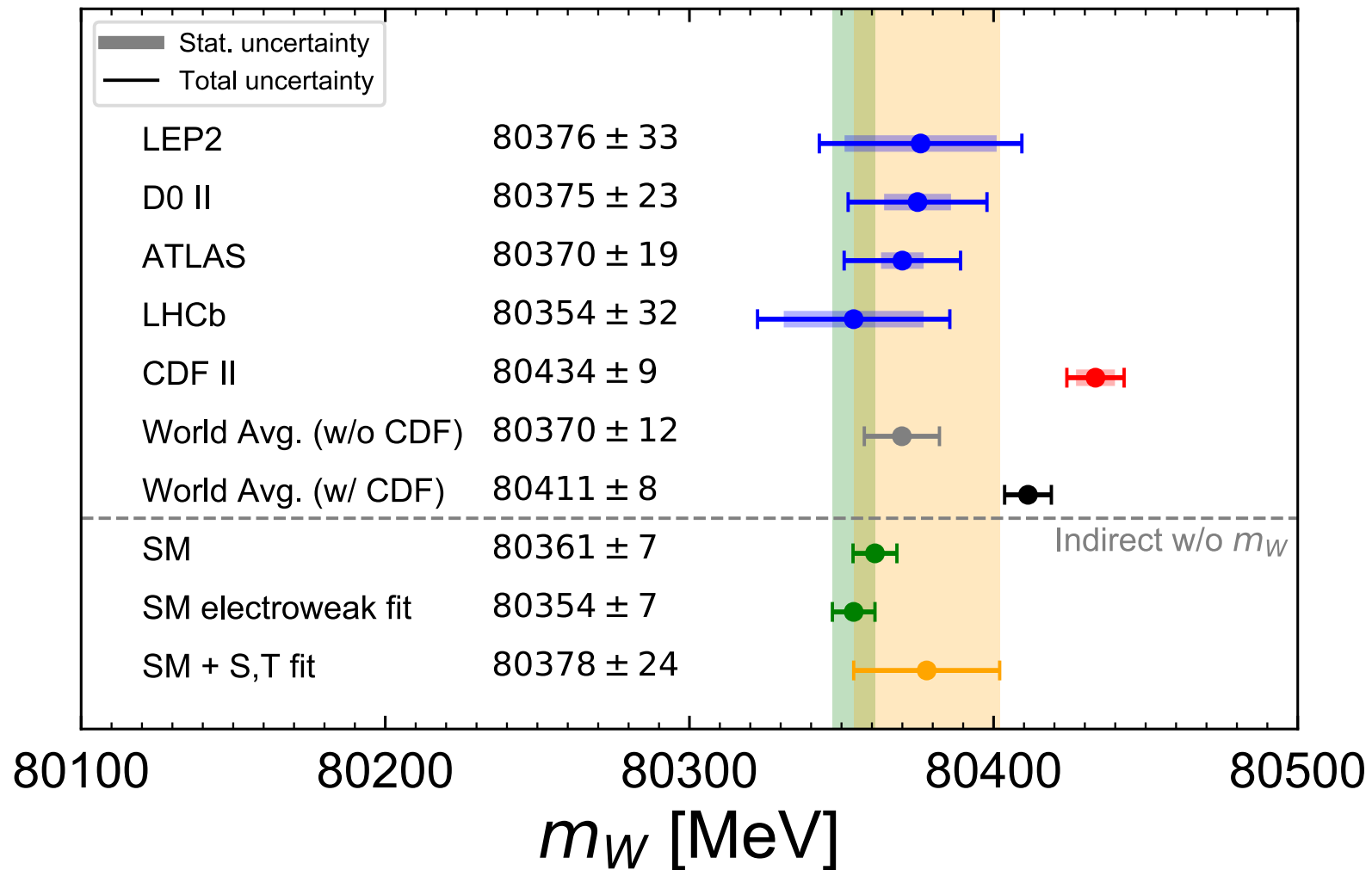
- Individual operator coefficients
- Marginalised over all other operator coefficients

No significant
deviations from SM



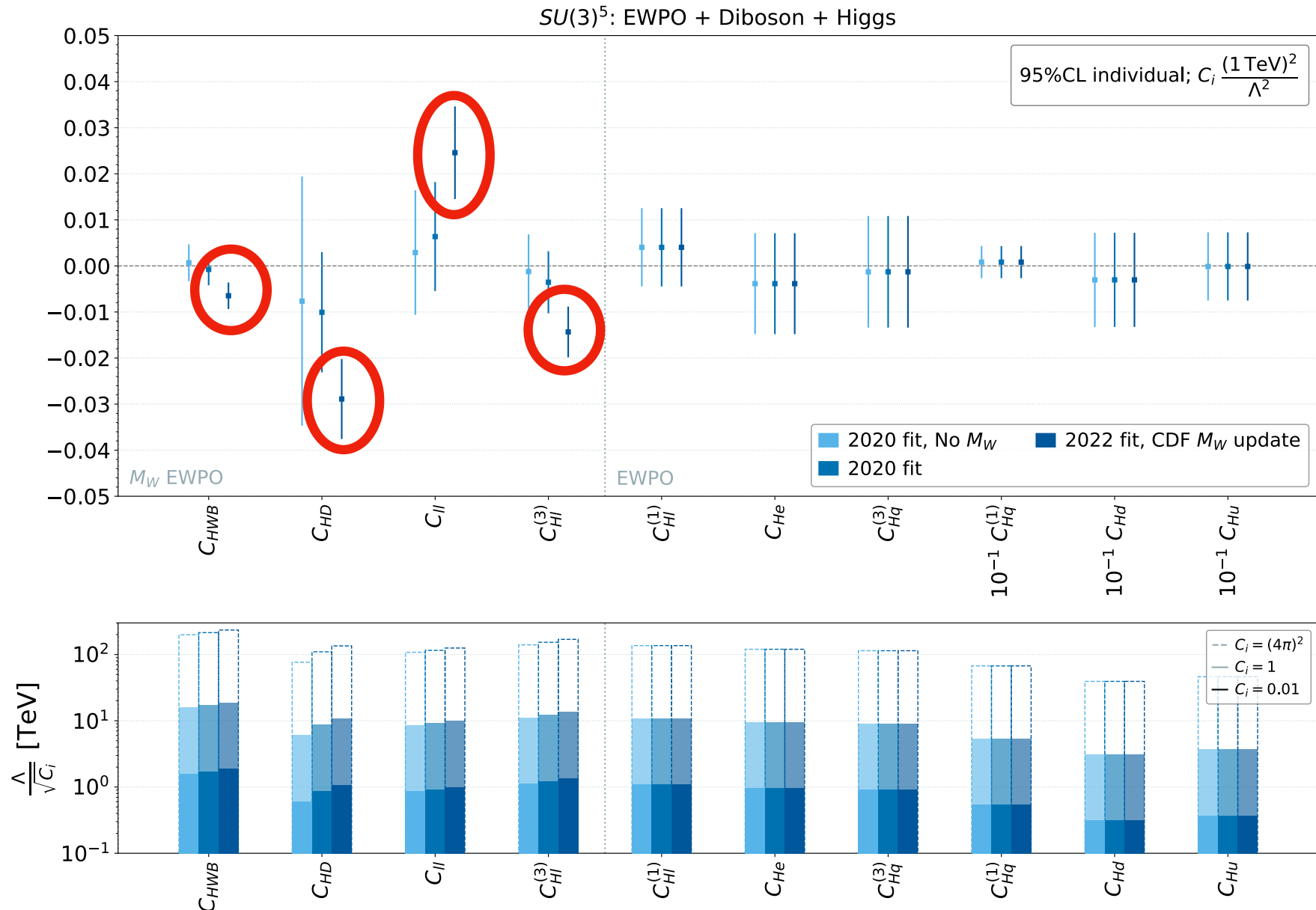
CDF Measurement of m_W

compared with previous measurements



Tension: 7- σ discrepancy with Standard Model?

SMEFT Fits with the Mass of the W Boson



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

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	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

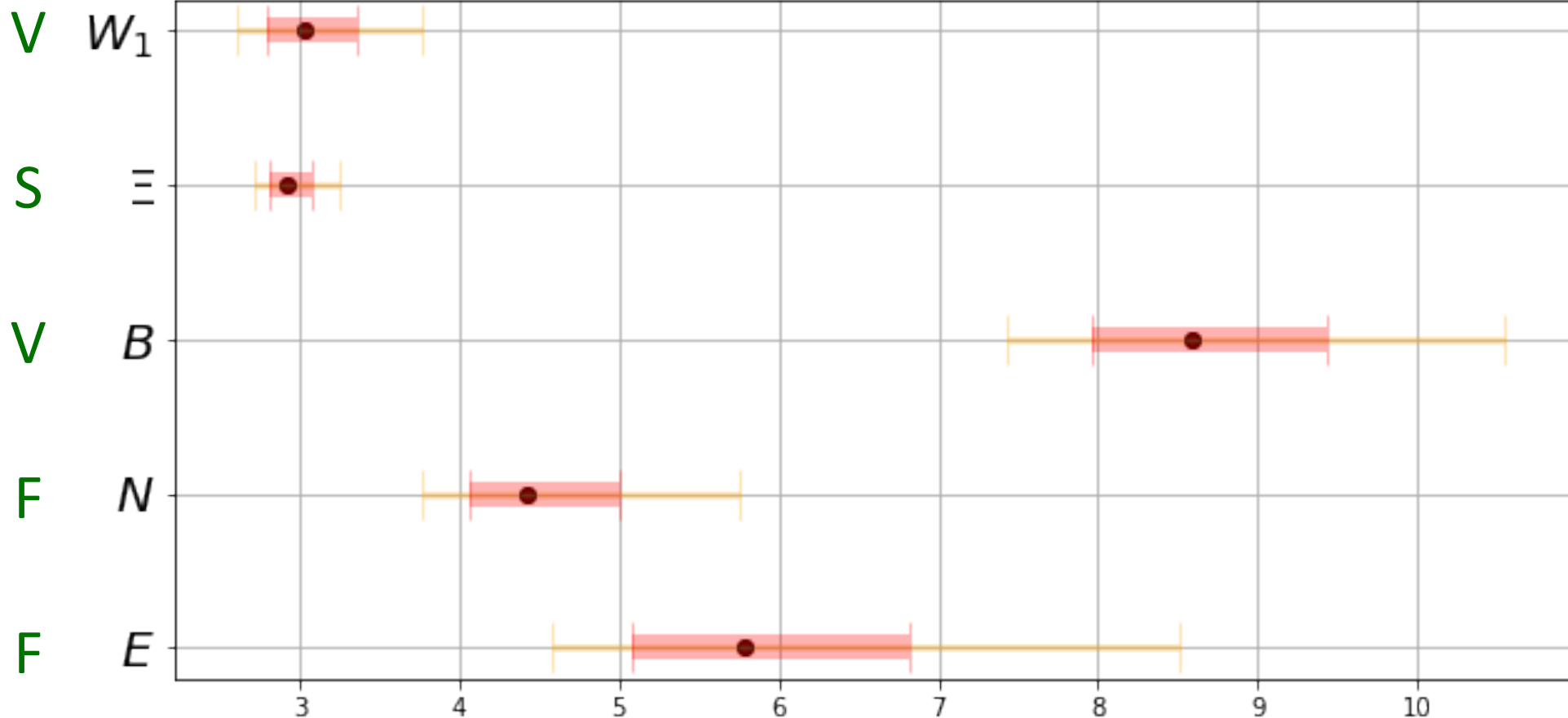
Single-Field Models that can Contribute to W Mass

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

Operators
contributing to m_W

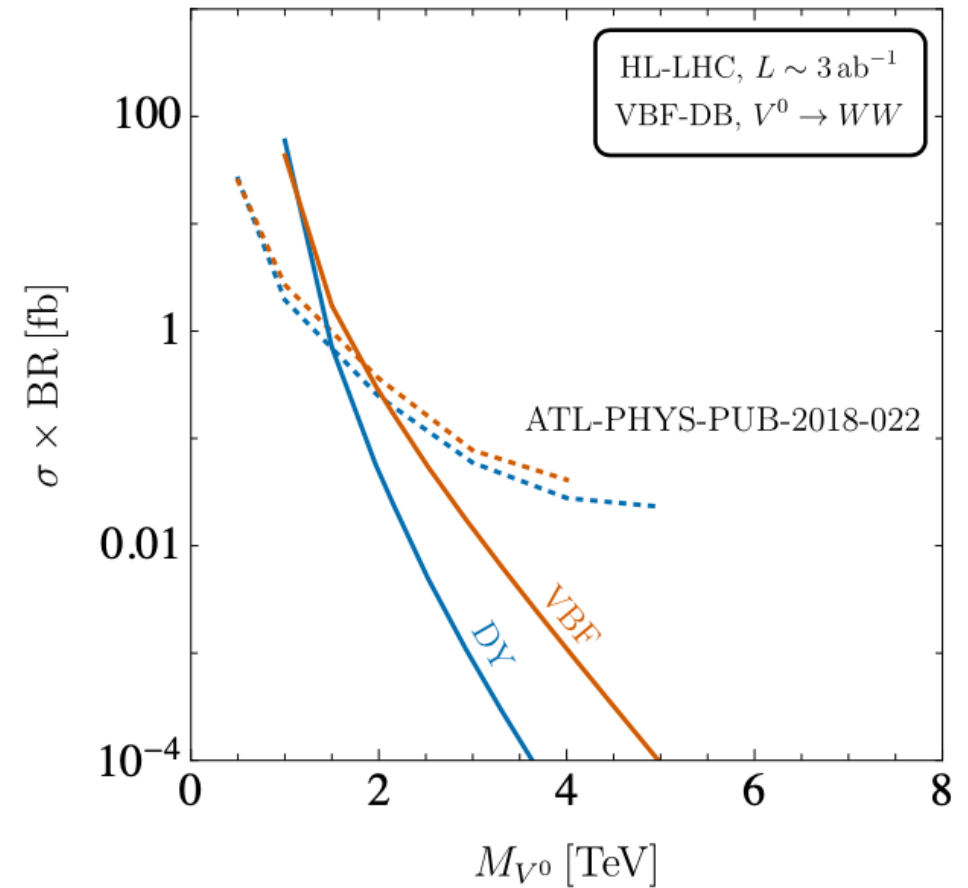
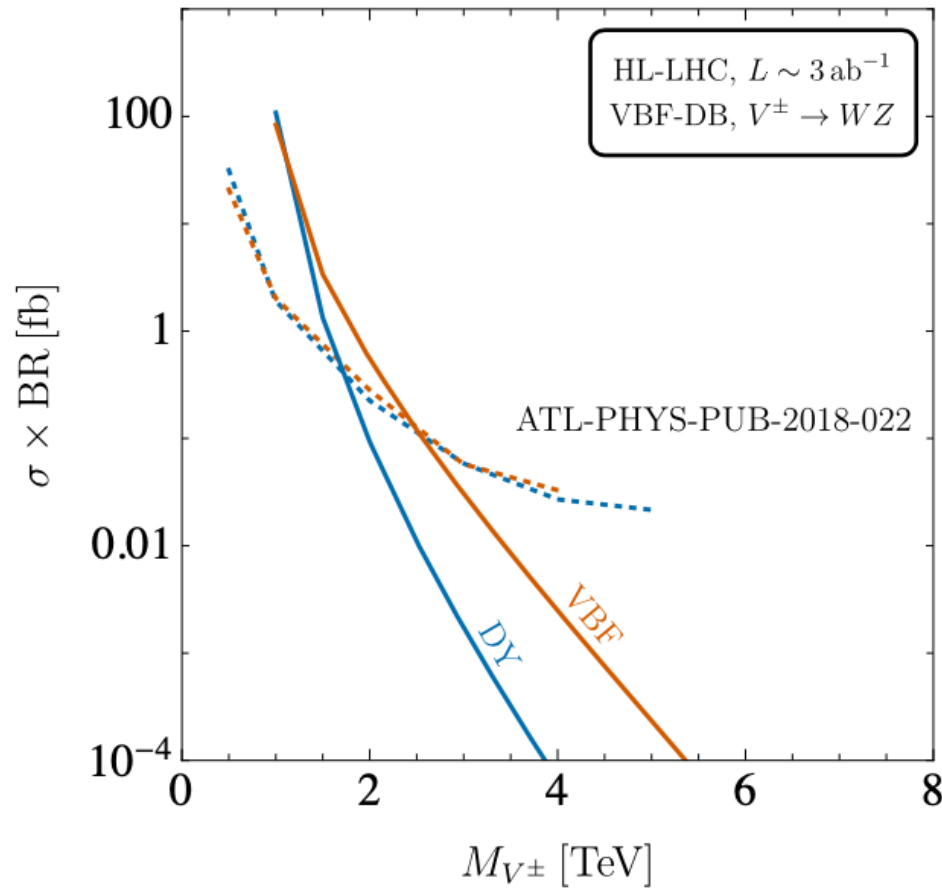
Models Fitting the Mass of the W Boson

Spins



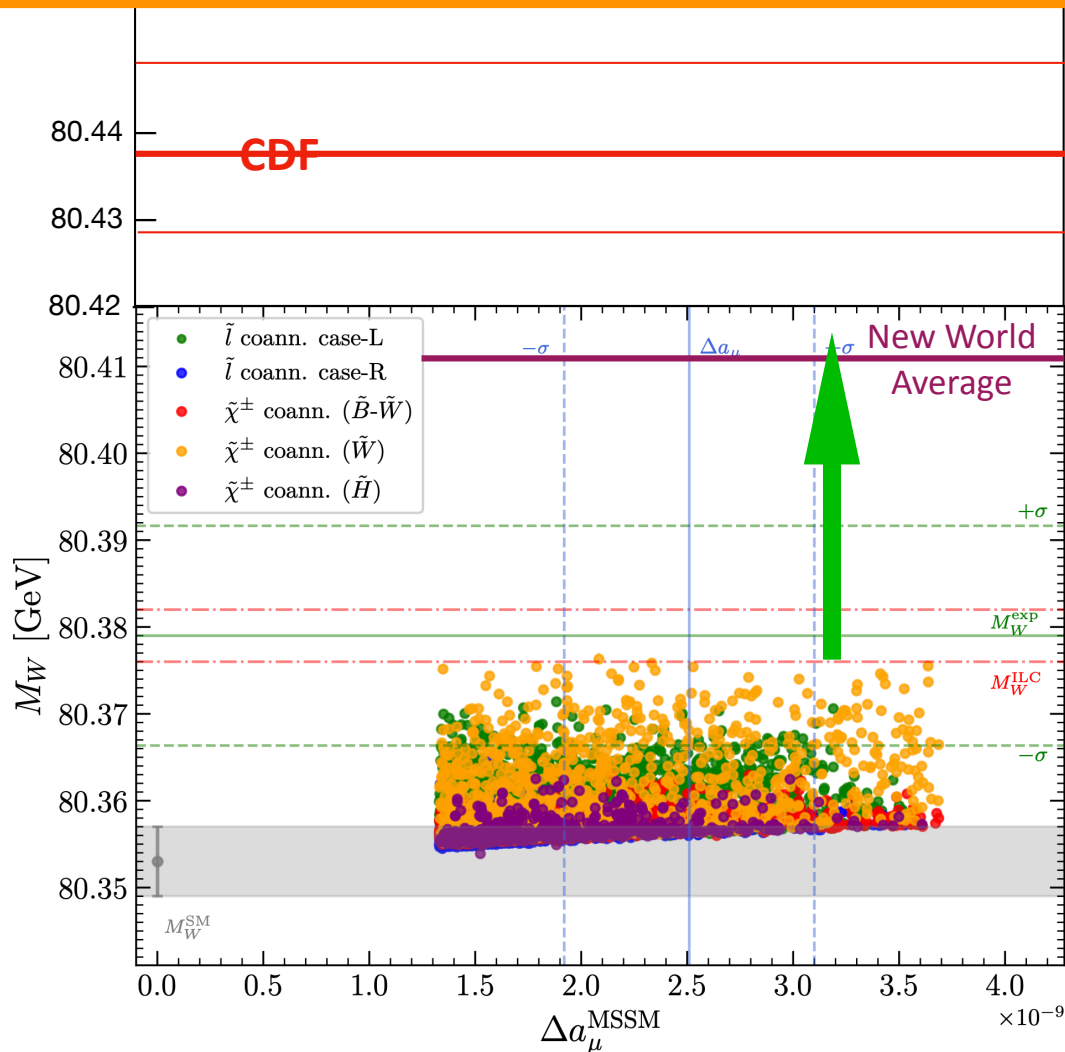
68 and 95% CL ranges of masses assuming unit couplings

HL-LHC Search for Triplet Vector Boson

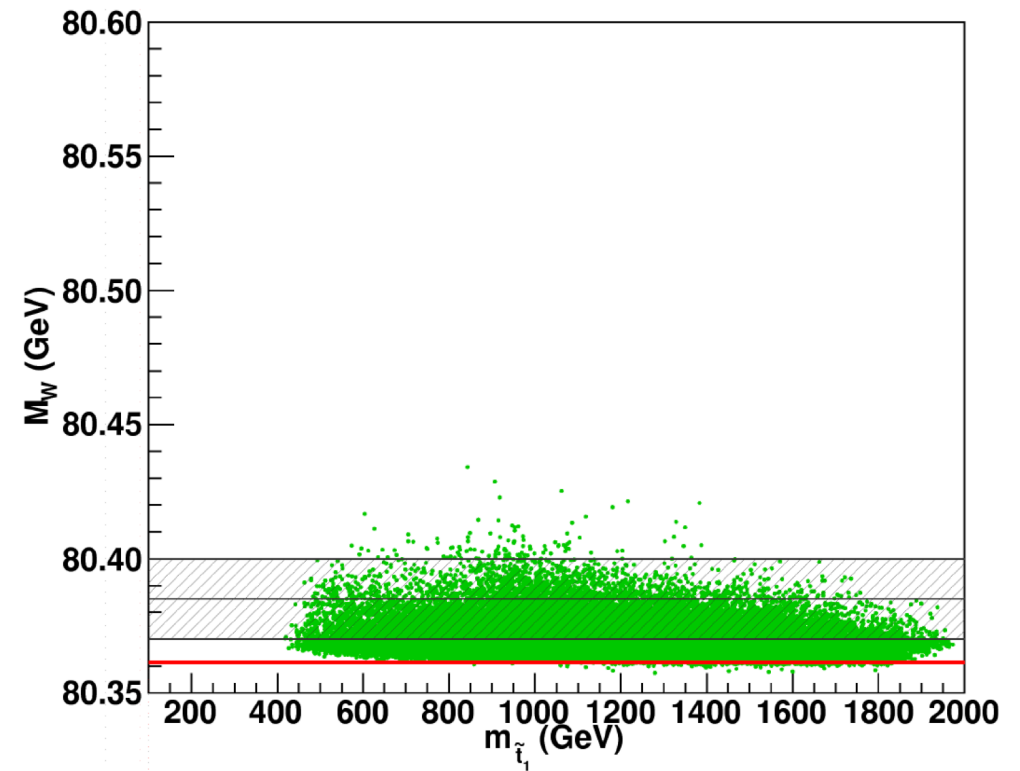


W Mass in Supersymmetry?

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

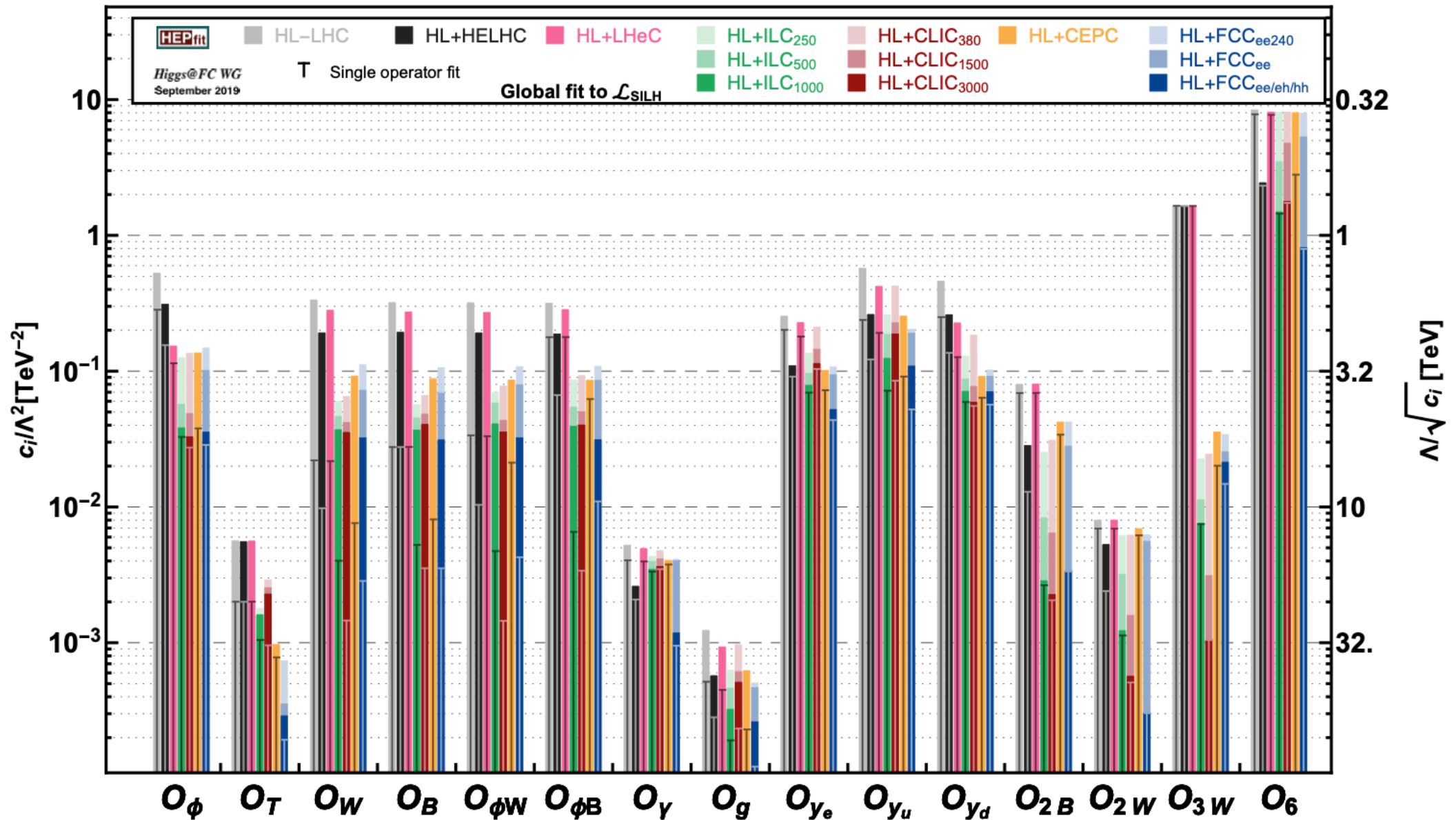


Contribution from stops?



Heinemeyer, Hollik, Weiglein & Zeune, 2013

SMEFT Analysis of Future Colliders



$g_\mu - 2$:
dawn of new physics or its sunset?



$g_\mu - 2$ in Supersymmetry

Volume 116B, number 4

PHYSICS LETTERS

(1982)

SPIN-ZERO LEPTONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

John ELLIS, John HAGELIN and D.V. NANOPOULOS

CERN, Geneva, Switzerland

Received 14 June 1982

The anomalous magnetic moment of the muon $(g - 2)_\mu$ imposes constraints on the masses and mixing of spin-zero leptons (sleptons). We develop the predictions of models of spontaneous supersymmetry breaking for the slepton mass matrix, and show that they are comfortably consistent with the $(g - 2)_\mu$ constraints.

During the present resurgence of interest in supersymmetry broken at low energies [1] new significance is attached to the classical phenomenological playgrounds of gauge theories such as the anomalous magnetic moments of the electron and muon [2], flavour-changing neutral interactions [3,5] parity [6] and CP violation [7,8] in the strong interactions. The three latter phenomena make life rather difficult [3,7] for the most general form of soft supersymmetry breaking, whereas simple models [9–11] of spontaneously broken supersymmetry naturally [3,4,7] respect the $\Delta F \neq 0$, P and CP violation constraints. As for the anomalous magnetic moments of the leptons, it has long been known that they vanish in an exactly supersymmetric theory [12], and Fayet [2] showed that in his model of supersymmetry breaking $(g - 2)_\mu$ would be compatible with experiment if the spin-zero muon (smuon) masses were heavier than 15 GeV. Direct experimental searches [13] now exclude the existence of lighter smuons. Fayet's analysis [2] was in the context of a model with a very light photino $\tilde{\gamma}$ (see fig. 1a), and Grifols and Méndez [14] have recently made the interesting observation that his analysis is significantly altered for massive gauginos (see figs. 1b, 1c). They show that there are potentially nontrivial constraints on the smuon masses in models of broken supersymmetry.

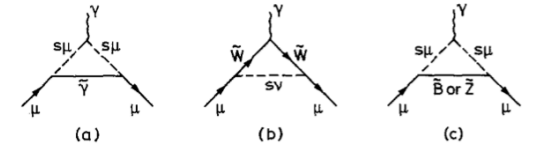


Fig. 1. One-loop diagrams contributing to $(g - 2)_\mu$: (a) essentially massless photino ($\tilde{\gamma}$) exchange, (b) \tilde{W} and sneutrino ($\tilde{\nu}$) exchange, and (c) \tilde{B} or \tilde{Z} exchange.

right transition operator there is a GIM [15]-like cancellation between the smuon mass eigenstates in fig. 1c which provides a potential suppression mechanism. We analyze recent models [10,11] of spontaneous supersymmetry breaking originating in the D and F sectors, respectively. We show that in the former case $(g - 2)_\mu$ is suppressed by near degeneracy between the smuon mass eigenstates, while in the latter case $(g - 2)_\mu$ is suppressed by small mixing angles between the left- and right-handed smuons. We close with some remarks about $(g - 2)_e$ and about parity violation in the strong interactions.

When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the \tilde{W} diagram of fig. 1b as compared to the massive \tilde{B} or \tilde{Z} diagram of fig. 1c. The

- One-loop contribution from smuon/neutralino loop

$$\Delta(g - 2)_\mu = -ab(\cos \alpha \sin \alpha / 4\pi^2)(m_\mu / m_{\tilde{G}})$$

$$\times \{1/(1 - \eta_1) + 2\eta_1/(1 - \eta_1)^2$$

$$+ [2\eta_1/(1 - \eta_1)^3] \log \eta_1 - (\eta_1 \leftrightarrow \eta_2)\},$$

- where $\eta_i \equiv (m_{s\mu_i}^2 / m_{\tilde{G}}^2)$

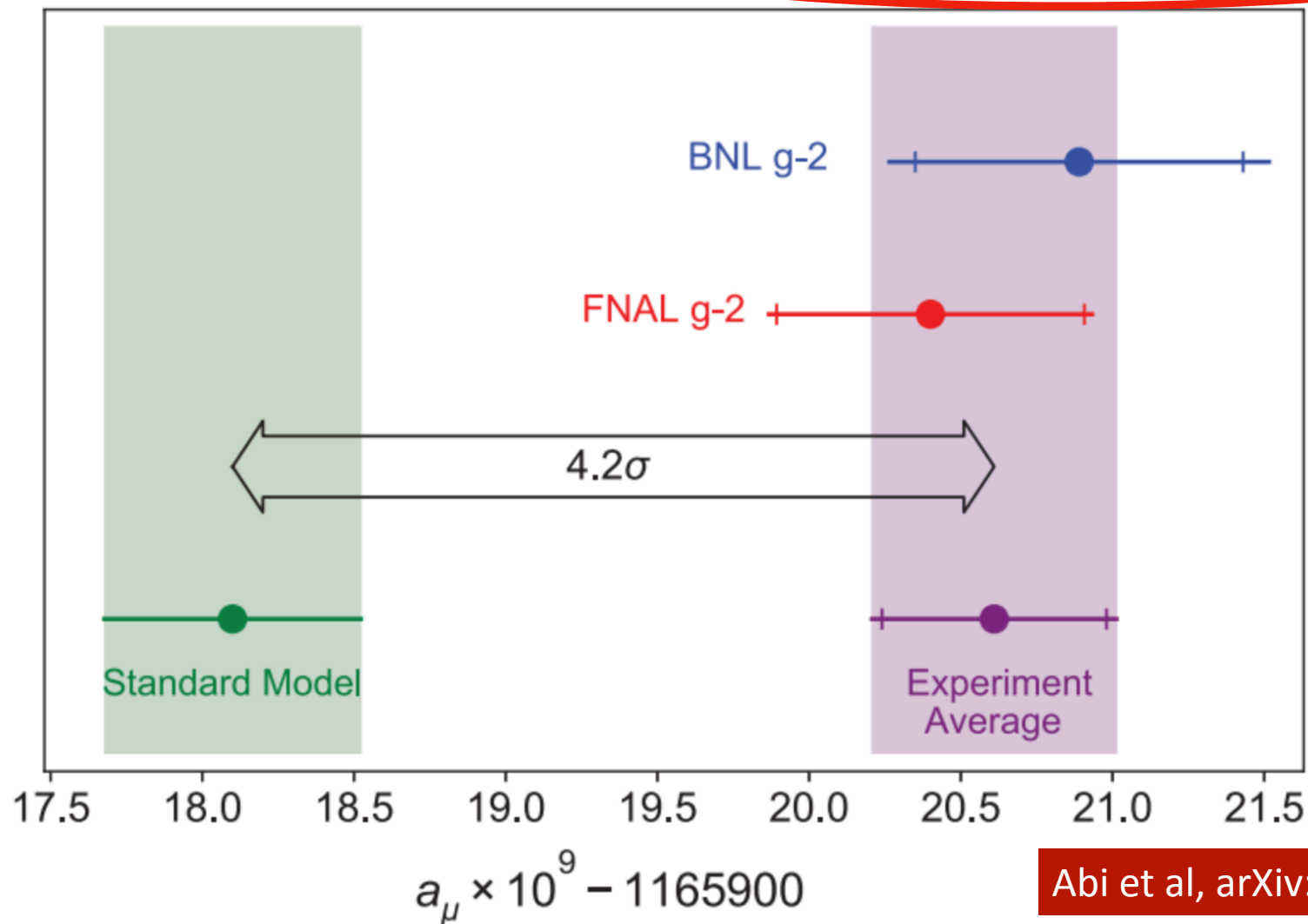
- and $\mathcal{L} = a\sqrt{2} s_\mu \bar{\mu}_L \tilde{G} + b\sqrt{2} t_\mu \bar{\mu}_R \tilde{G}$

Fermilab Measurement

FNAL result: $a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11}$ (0.46 ppm)

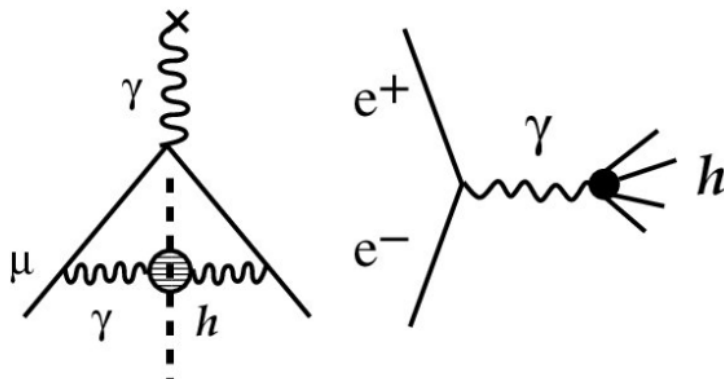
Combined result: $a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11}$ (0.35 ppm)

Difference from Standard Model: $a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$



Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822



The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama^{1,2,3}, N. Asmussen⁴, M. Benayoun⁵, J. Bijnens⁶, T. Blum^{7,8}, M. Bruno⁹, I. Caprini¹⁰, C.M. Carloni Calame¹¹, M. Cè^{9,12,13}, G. Colangelo^{14,*}, F. Curciarello^{15,16}, H. Czyż¹⁷, I. Danilkin¹², M. Davier^{18,*}, C.T.H. Davies¹⁹, M. Della Morte²⁰, S.I. Eidelman^{21,22,*}, A.X. El-Khadra^{23,24,*}, A. Gérardin²⁵, D. Giusti^{26,27}, M. Golterman²⁸, Steven Gottlieb²⁹, V. Gülpers³⁰, F. Hagelstein¹⁴, M. Hayakawa^{31,2}, G. Herdoíza³², D.W. Hertzog³³, A. Hoecker³⁴, M. Hoferichter^{14,35,*}, B.-L. Hoid³⁶, R.J. Hudspith^{12,13}, F. Ignatov²¹, T. Izubuchi^{37,8}, F. Jegerlehner³⁸, L. Jin^{7,8}, A. Keshavarzi³⁹, T. Kinoshita^{40,41}, B. Kubis³⁶, A. Kupich²¹, A. Kupś^{42,43}, L. Laub¹⁴, C. Lehner^{26,37,*}, L. Lellouch²⁵, I. Logashenko²¹, B. Malaescu⁵, K. Maltman^{44,45}, M.K. Marinković^{46,47}, P. Masjuan^{48,49}, A.S. Meyer³⁷, H.B. Meyer^{12,13}, T. Mibe^{1,*}, K. Miura^{12,13,3}, S.E. Müller⁵⁰, M. Nio^{2,51}, D. Nomura^{52,53}, A. Nyffeler^{12,*}, V. Pascalutsa¹², M. Passera⁵⁴, E. Perez del Rio⁵⁵, S. Peris^{48,49}, A. Portelli³⁰, M. Procura⁵⁶, C.F. Redmer¹², B.L. Roberts^{57,*}, P. Sánchez-Puertas⁴⁹, S. Serednyakov²¹, B. Shwartz²¹, S. Simula²⁷, D. Stöckinger⁵⁸, H. Stöckinger-Kim⁵⁸, P. Stoffer⁵⁹, T. Teubner^{60,*}, R. Van de Water²⁴, M. Vanderhaeghen^{12,13}, G. Venanzoni⁶¹, G. von Hippel¹², H. Wittig^{12,13}, Z. Zhang¹⁸, M.N. Achasov²¹, A. Bashir⁶², N. Cardoso⁴⁷, B. Chakraborty⁶³, E.-H. Chao¹², J. Charles²⁵, A. Crivellin^{64,65}, O. Deineka¹², A. Denig^{12,13}, C. DeTar⁶⁶, C.A. Dominguez⁶⁷, A.E. Dorokhov⁶⁸, V.P. Druzhinin²¹, G. Eichmann^{69,47}, M. Fael⁷⁰, C.S. Fischer⁷¹, E. Gámiz⁷², Z. Gelzer²³, J.R. Green⁹, S. Guellati-Khelifa⁷³, D. Hatton¹⁹, N. Hermansson-Truedsson¹⁴, S. Holz³⁶, B. Hörz⁷⁴, M. Knecht²⁵, J. Koponen¹, A.S. Kronfeld²⁴, J. Laiho⁷⁵, S. Leupold⁴², P.B. Mackenzie²⁴, W.J. Marciano³⁷, C. McNeile⁷⁶, D. Mohler^{12,13}, J. Monnard¹⁴, E.T. Neil⁷⁷, A.V. Nesterenko⁶⁸, K. Ottnad¹², V. Pauk¹², A.E. Radzhabov⁷⁸, E. de Rafael²⁵, K. Raya⁷⁹, A. Risch¹², A. Rodríguez-Sánchez⁶, P. Roig⁸⁰, T. San José^{12,13}, E.P. Solodov²¹, R. Sugar⁸¹, K. Yu. Todyshev²¹, A. Vainshtein⁸², A. Vaquero Avilés-Casco⁶⁶, E. Weil⁷¹, J. Wilhelm¹², R. Williams⁷¹, A.S. Zhevlakov⁷⁸

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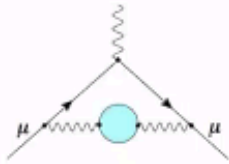
⁴ School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom

⁵ LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France

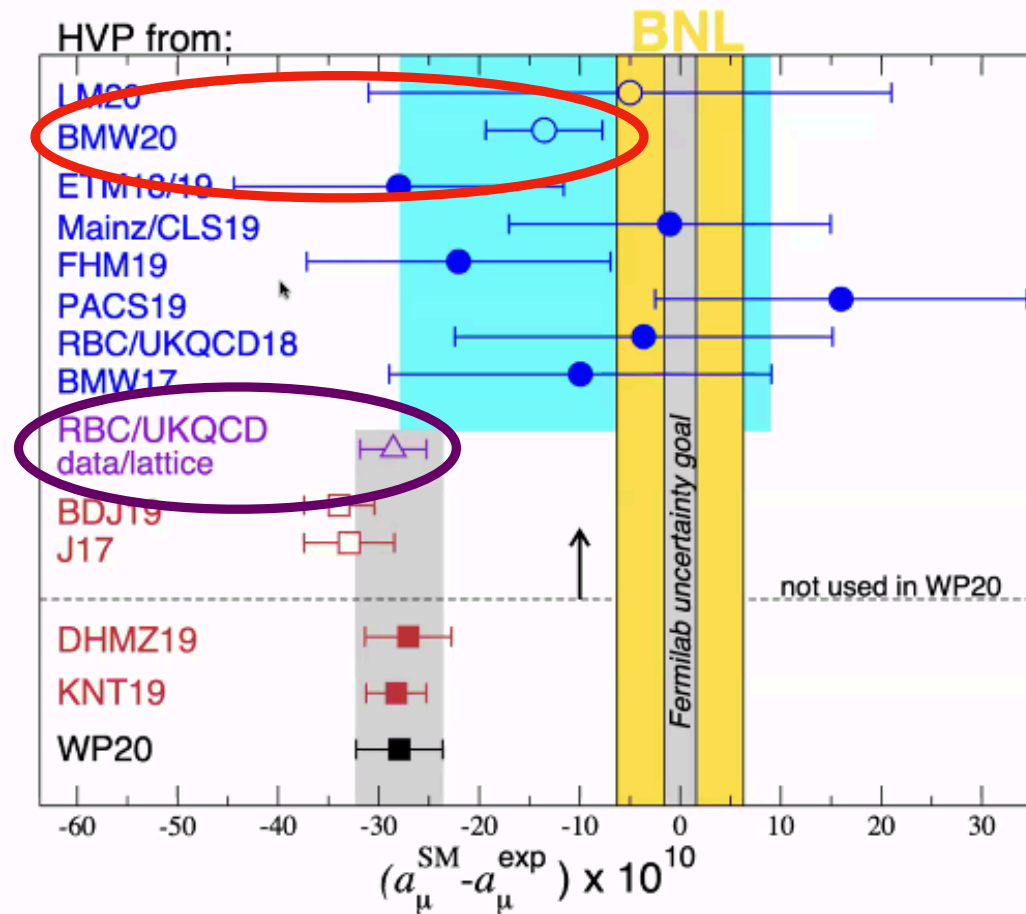
* Corresponding authors.

E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

Comparison of Calculations of Hadronic Vacuum Polarization



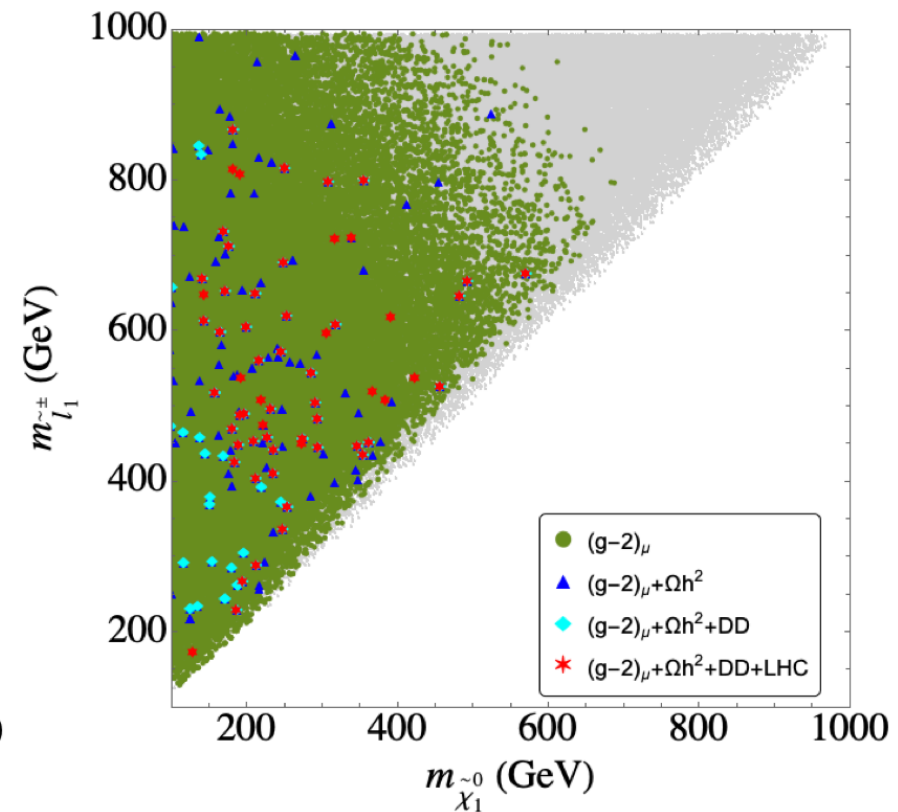
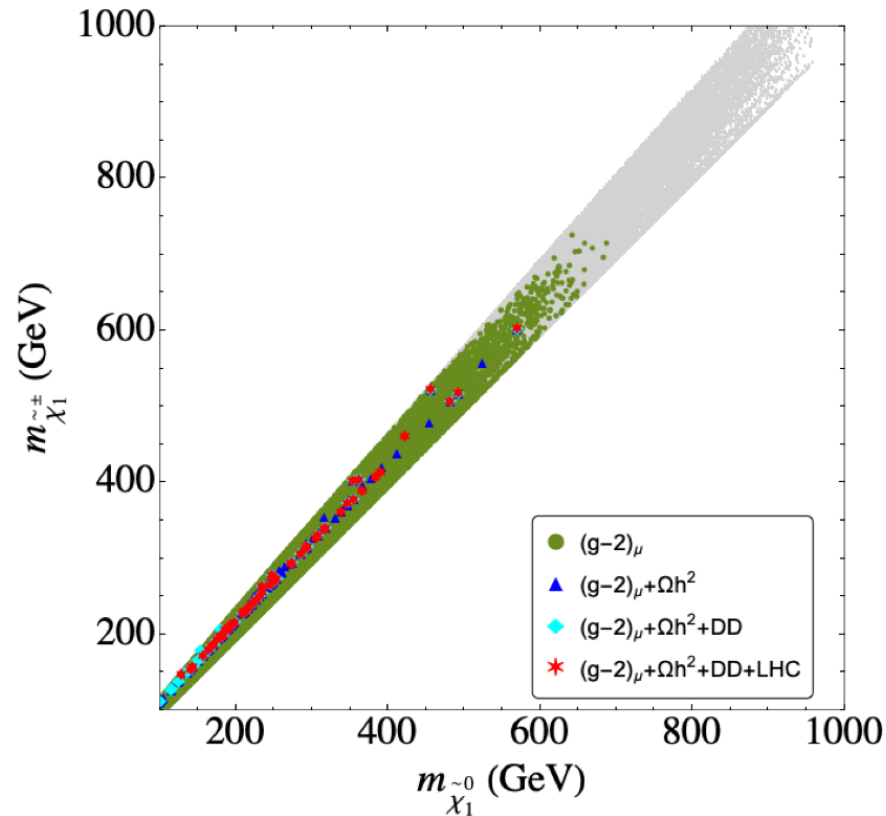
$$a_{\mu}^{\text{HVP}} + [a_{\mu}^{\text{QED}} + a_{\mu}^{\text{Weak}} + a_{\mu}^{\text{HLbL}}] \rightarrow a_{\mu}^{\text{SM}}$$



Not such a big problem according to (some) lattice calculations

Supersymmetry

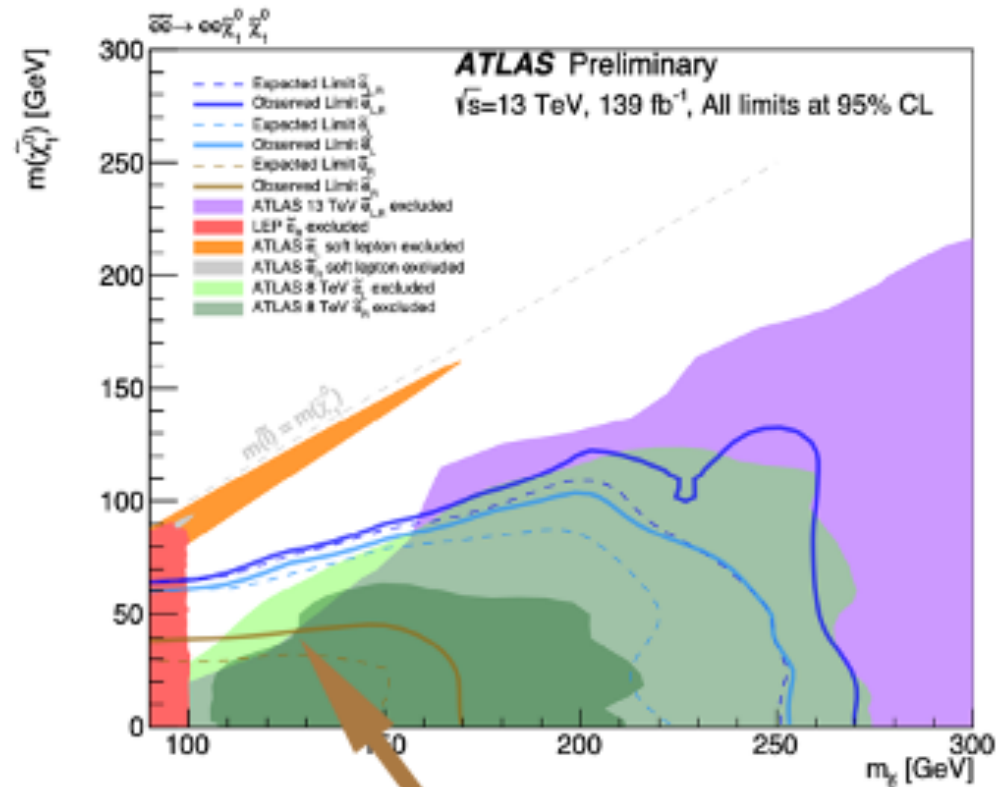
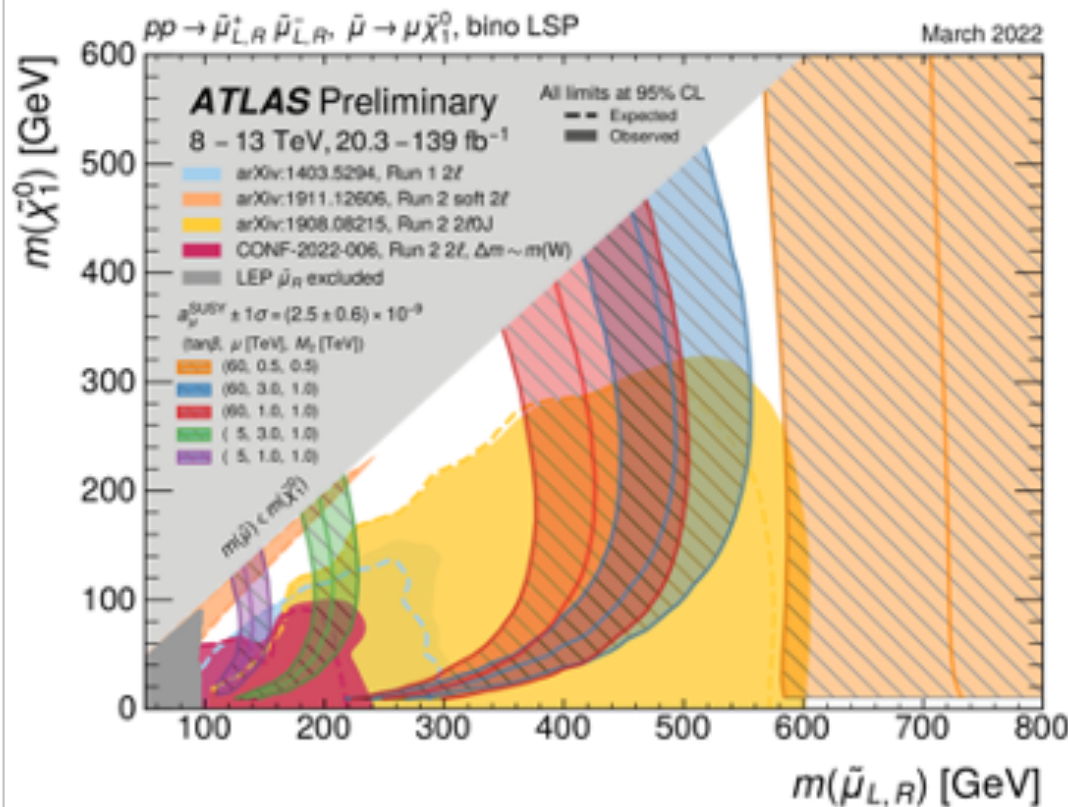
- g_μ – 2-friendly scenario with light neutralino, chargino & slepton



- Red star points include all relevant LHC and direct scattering constraints
- Prospects for the ILC

LHC vs Supersymmetry

- LHC favours squarks & gluinos > 2 TeV (but loopholes)
- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons



- Most models have $m_{\tilde{\mu}_L}^- > m_{\tilde{\mu}_R}^-$ but $m_{\tilde{\mu}_R}^- \simeq m_{\tilde{e}_R}^-$: **relevant constraint**

How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter

observed in the laboratory

- Need interactions able to create matter

predicted by theories

not yet seen by experiment

- Need the expansion of the Universe

a role for the Higgs boson?

Decays of heavy neutrinos?



Will we be able to calculate using laboratory data?

Example of Baryogenesis Model Testable at LHC

Simplest extension of the Standard Model: singlet scalar

$$V_0(H, s) = -\mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2 - \frac{1}{2} \mu_s^2 s^2 + \frac{1}{4} \lambda_s s^4 + \frac{1}{2} \lambda_{hs} H^\dagger H s^2 + \mu_{hs} H^\dagger H s - \frac{1}{3} \mu_3 s^3$$

Exhibits first-order cosmological phase transition
Introduce dimension-5 term breaking CP, Z_2 symmetry

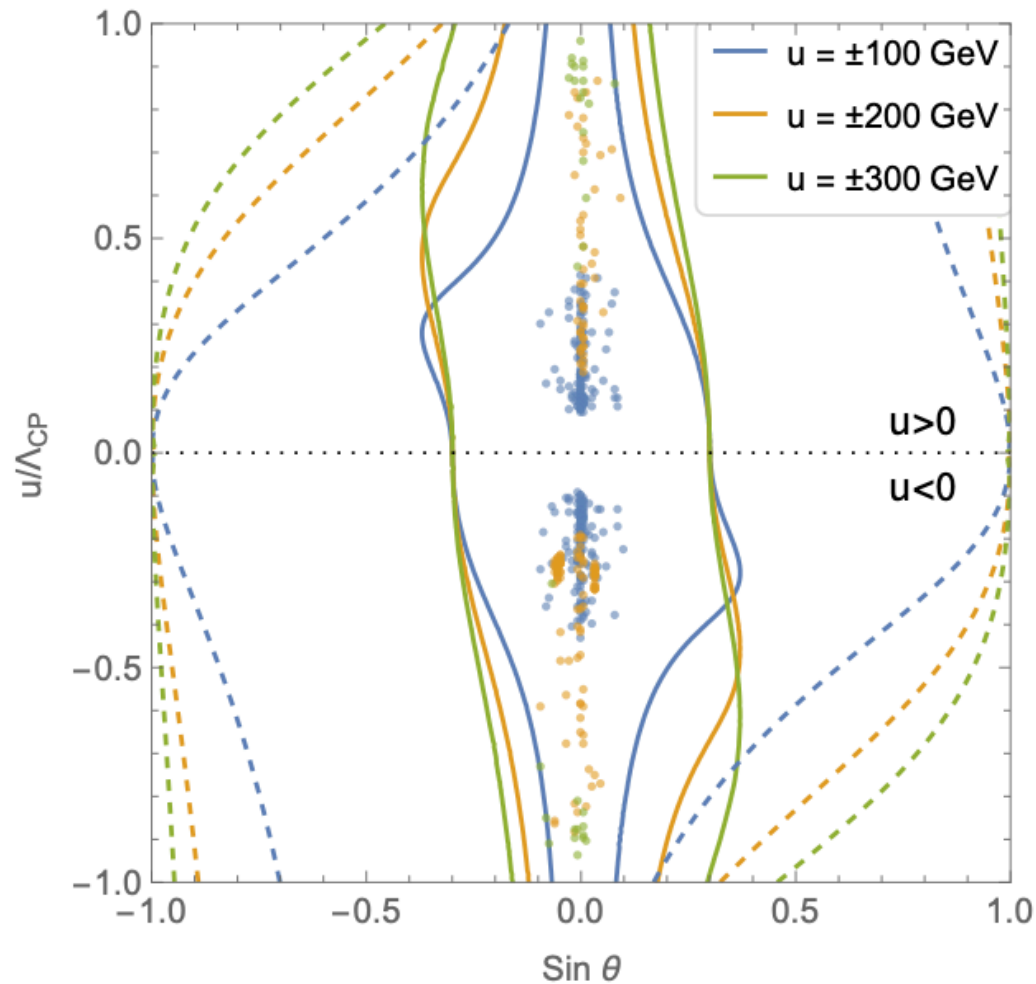
$$\mathcal{L} \supseteq y_t \bar{Q} \tilde{\Phi} t_R \left(i \frac{s}{\Lambda_{CP}} \right) + \text{h.c.}$$

Constrain with LEP and LHC measurements

Phenomenological Constraints

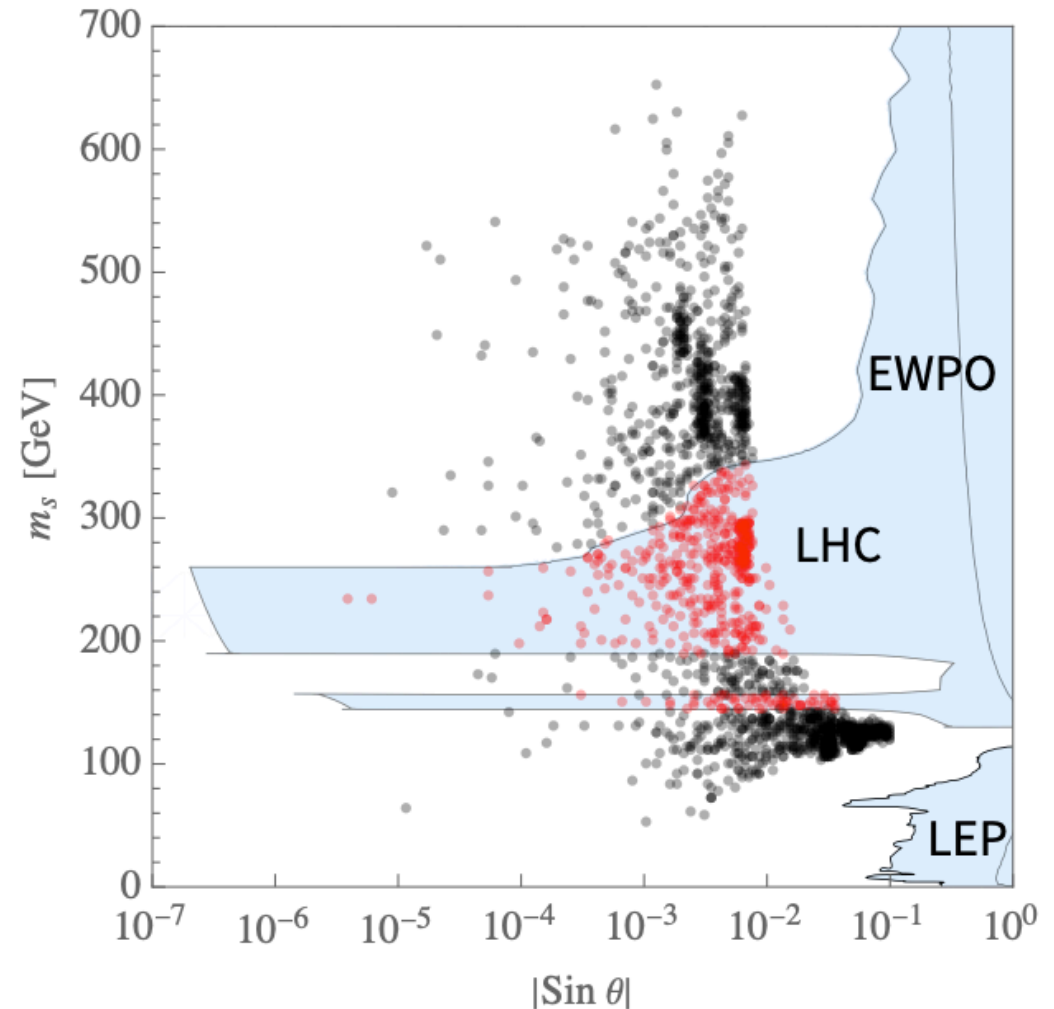
on mass and mixing of singlet boson

From top-Higgs measurements



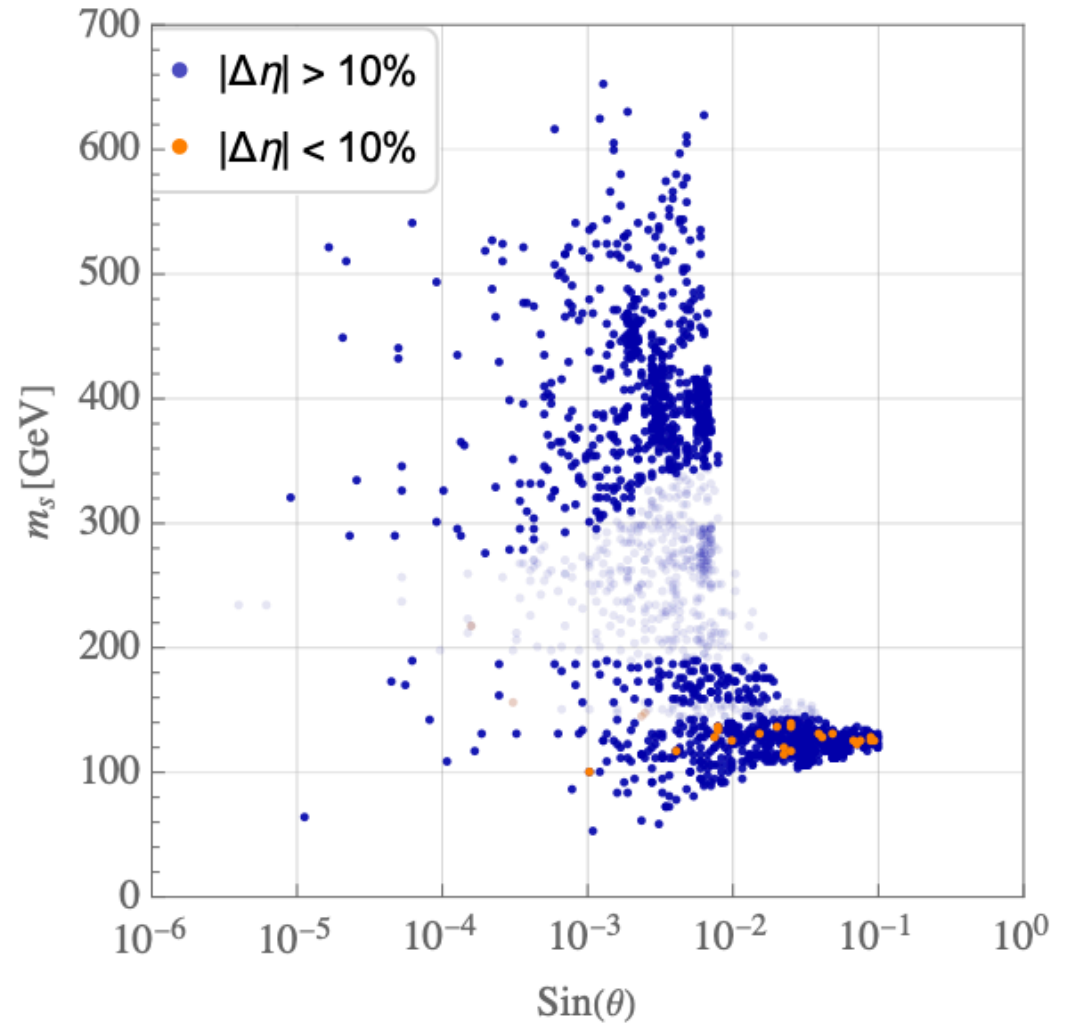
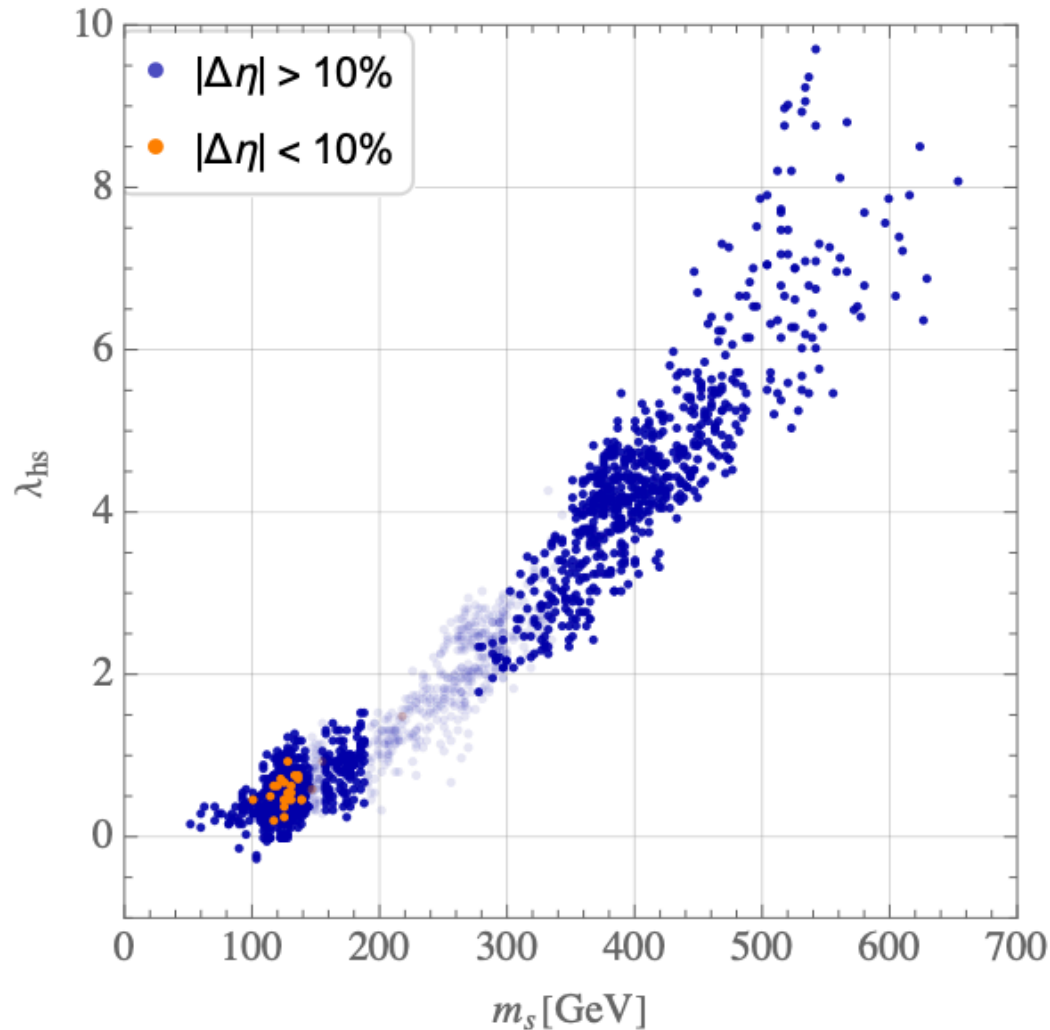
—— Higgs signal strength
 --- Limit on CP-violation

From other measurements



Electroweak measurements
 LHC and LEP searches

Results for Baryon Asymmetry



Orange points within 10% of η measurement
Can be probed with LHC data

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**



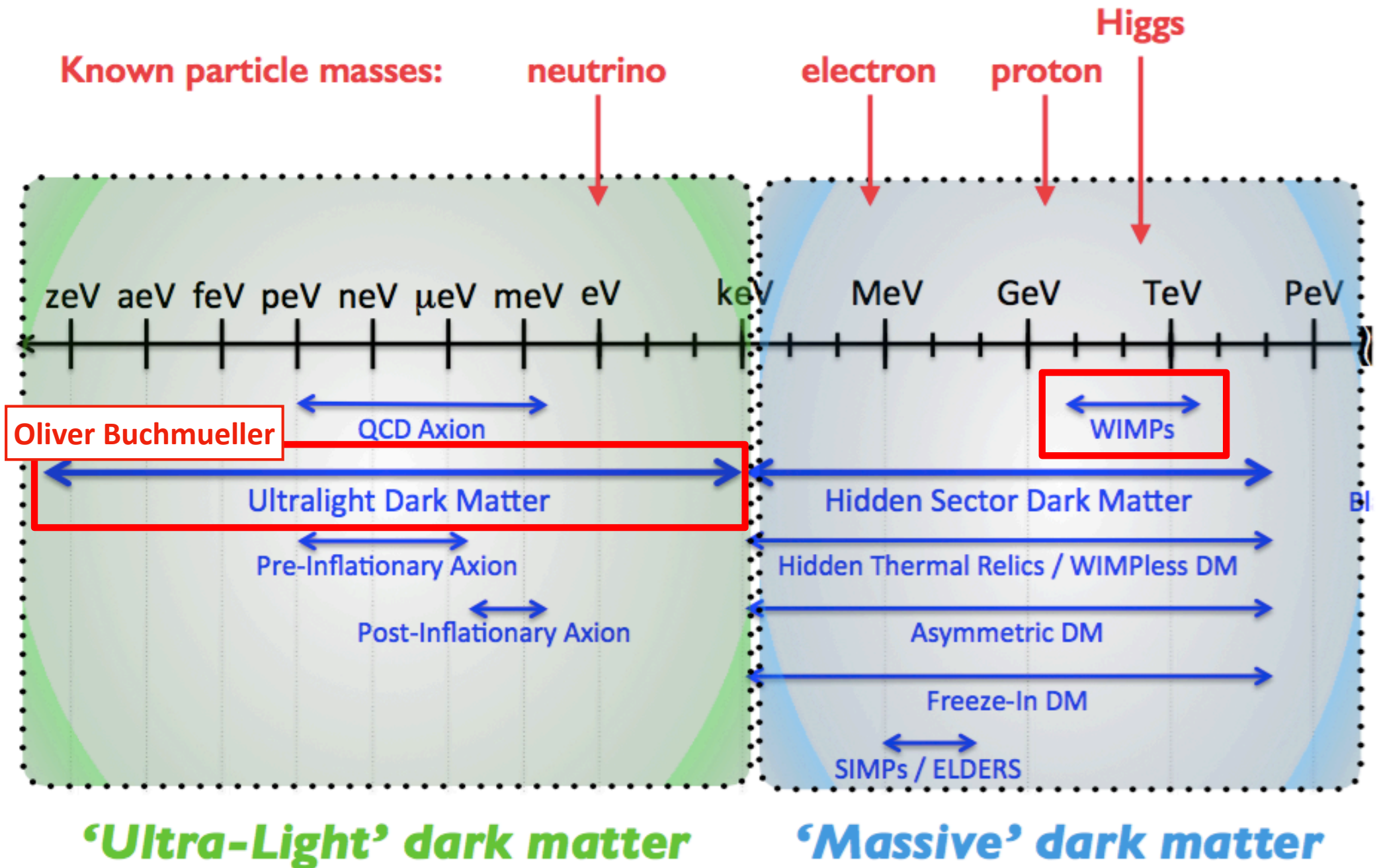
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit 'too quickly'
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**
- Also:
 - Structure formation, cosmic background radiation,
...

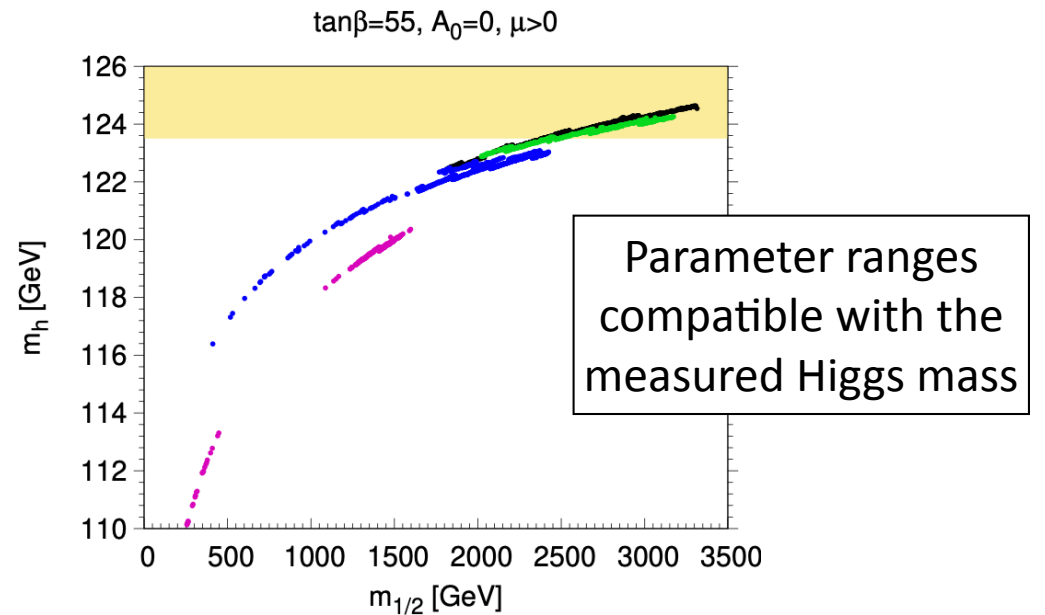
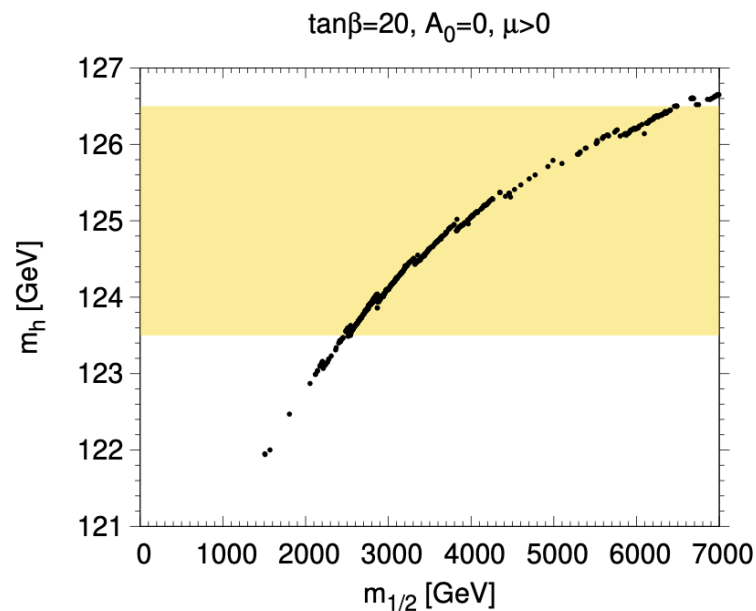
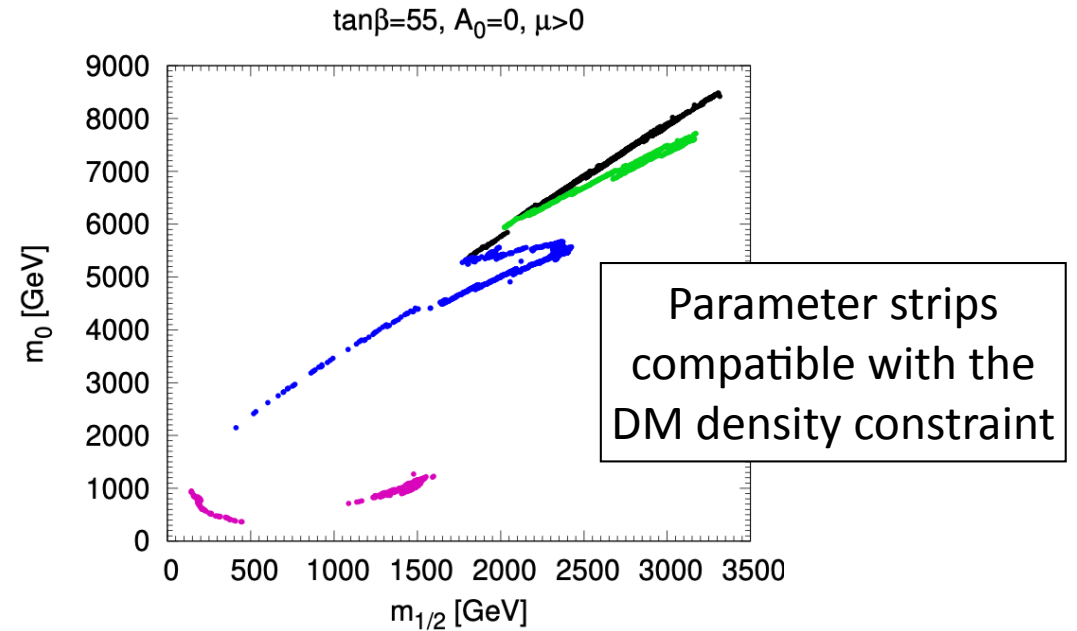
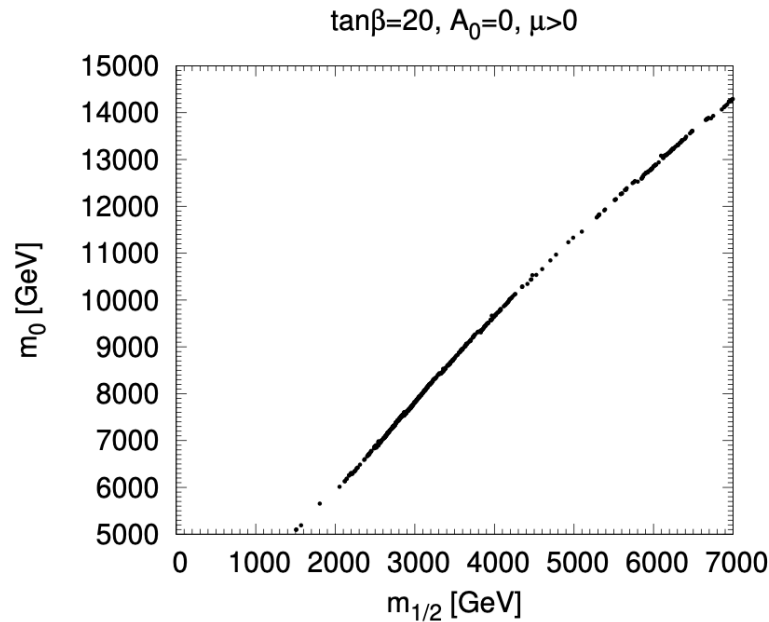


Scanned at the American
Institute of Physics

Searches for Dark Matter Particles



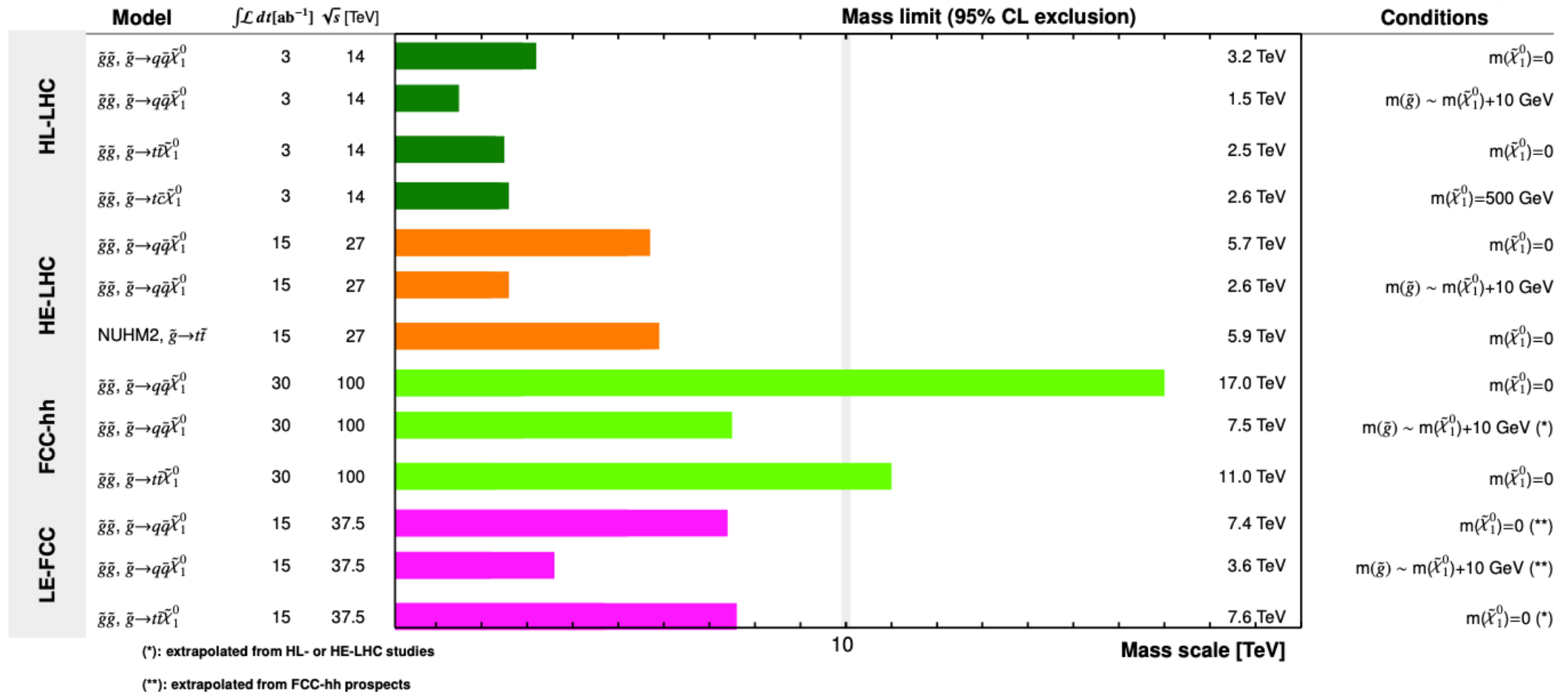
Quo Vadis Supersymmetry?



Quo Vadis Supersymmetry?

Hadron Colliders: gluino projections

(R-parity conserving SUSY, prompt searches)



Dark Matter strips can be explored by FCC-hh

Summary

Visible matter

Standard Model

Higgs physics?

$m_W, g_\mu - 2?$

Dark Matter?