Physics Beyond the Standard Model

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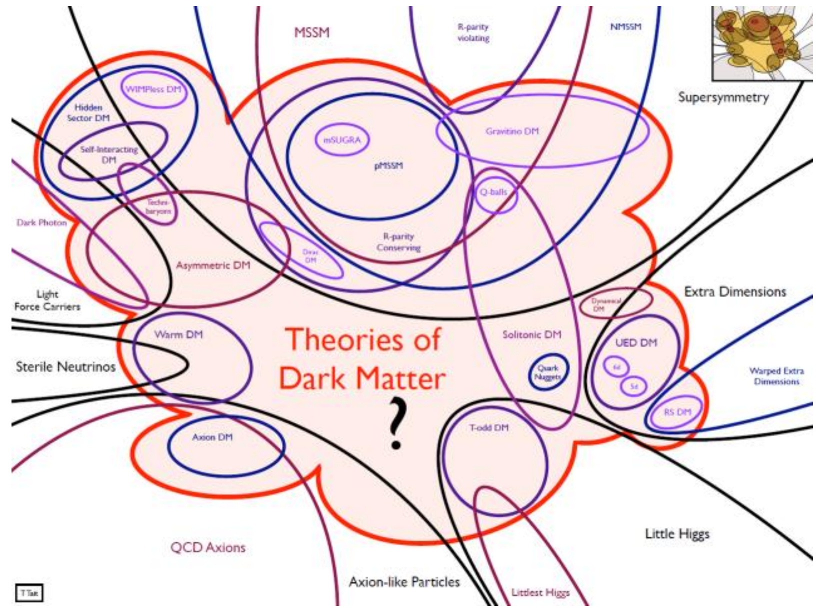


L1. Introduction. EFT (SMEFT, EFT for DM)

L2. UV complete theories (SUSY, Extra Dimensions)

L3. Simplified models. Concluding remarks

L1

Key role of Symmetries

1. Space-time symmetries (Lorenz and Poincare)

$x^\mu \to x'^\mu(x^\nu)$ $\mu,\nu = 1,2,3,4\ldots$ Classify particles according to masses and spins

2. Internal symmetries (global and local gauge invariance)

$\Psi^a(x) \to M^a{}_b\, \Psi^b(x)$, if $M^a{}_b$ is constant - global symmetry

if $M^a{}_b(x)$ is space-time dependent - local symmetry

Gauge invariance introduces interactions between matter and gauge fields, and gauge field selfinteractions

Basic blocks to construct gauge invariant Lagrangians:

Covariant derivatives

and

Gauge field strength tensors

Gauge Symmetry

$$L = \bar{\Psi}(i\partial_\mu \gamma^\mu - m)\Psi$$

$$\Psi(x) \to \Psi^U(x) = U(x)\Psi(x) \qquad U(x) = e^{i\alpha(x)^a \cdot t^a}$$

$$U(x)U(x)^+ = 1$$

$$L = \bar{\Psi}[i\partial_\mu \gamma^\mu - igA_\mu(x) - m]\Psi$$

$$L^U = \bar{\Psi}^U[i(\partial_\mu \gamma^\mu - igA_\mu^U(x)) - m]\Psi^U$$

$$A_\mu \to A_\mu^U = U(x)A_\mu(x)U(x)^+ - i/g(\partial_\mu U(x))U(x)^+$$

$$D_\mu = \partial_\mu - igA_\mu(x) \qquad D_\mu \to D_\mu^U = U(x)^+ D_\mu U(x)$$

$$U(1) \qquad U(x) = e^{ig\alpha(x)}$$

$$D_\mu = \partial_\mu - igA_\mu(x), \; A_\mu^U = A_\mu + \partial_\mu \alpha(x)$$

Well known QED gradient invariance

Gauge Symmetry

$$F_{\mu\nu} = c[D_\mu, D_\nu]$$

$$F_{\mu\nu} = c(-ig)(\partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu])$$

$$c = i/g \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$$

$$A_\mu = A_\mu^a t^a \qquad F_{\mu\nu} = F_{\mu\nu}^a t^a$$

$$[t^a, t^b] = i f^{abc} t^c$$

a = 1,2,3 for SU(2)
a = 1,…,8 for SU(3)

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

$$L_{gauge} = const \cdot Tr(F_{\mu\nu} F^{\mu\nu}) \qquad Tr(t^a t^b) = 1/2\delta^{ab}$$

$$const = -1/2$$

$$L_{gauge} = -1/2 \cdot Tr(F_{\mu\nu} F^{\mu\nu}) = -1/4 \cdot F_{\mu\nu}^a F^{\mu\nu\, a}$$

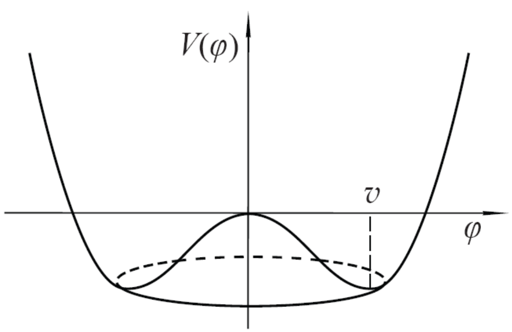
Symmetries can be hidden, spontaneously broken

The situation when the Lagrangian is invariant under some symmetry while the spectrum of the system is not invariant is very common for spontaneous symmetry breaking (for example, Ginzburg-Landau theory)

Simple illustrative example: $$L = \partial_\mu \varphi^\dagger \partial^\mu \varphi - \mu^2 \varphi^\dagger \varphi - \lambda(\varphi^\dagger \varphi)^2$$

The Lagrangian is invariant under the phase shift $\varphi \to \varphi e^{i\omega}$, *w=const*

The case $\mu^2 > 0$ is trivial and not interesting.
In the case $\mu^2 = -|\mu^2| < 0$ the potential $V(\varphi) = \mu^2 \varphi^\dagger \varphi + \lambda(\varphi^\dagger \varphi)^2$ has nontrivial minimum



$$\left.\frac{dV}{d\varphi^\dagger}\right|_{\varphi_0} = -|\mu^2|\varphi_0 + 2\lambda(\varphi_0^\dagger \varphi_0)\varphi_0 = 0 \quad \Rightarrow \quad |\varphi_0| = \sqrt{\frac{|\mu^2|}{2\lambda}} = \frac{v}{\sqrt{2}} > 0$$

$$\varphi_0 = +v/\sqrt{2}$$

A concrete vacuum solution violates the phase shift symmetry

Symmetries can be hidden, spontaneously broken

Complex scalar field can be parameterized by two real fields

$$\varphi = \frac{1}{\sqrt{2}}(v + h(x))e^{-i\xi(x)/v}$$

$$L = \partial_\mu \varphi^\dagger \partial^\mu \varphi - \mu^2 \varphi^\dagger \varphi - \lambda(\varphi^\dagger \varphi)^2$$

$$\Downarrow$$

$$\begin{aligned} L \quad = \quad & \tfrac{1}{2}\partial_\mu h \partial^\mu h - \lambda v^2 h^2 - \lambda v h^3 - \lambda h^4/4 + \\ & + \tfrac{1}{2}\partial_\mu \xi \partial^\mu \xi + \tfrac{2}{v}\partial_\mu \xi \partial^\mu \xi h + \tfrac{1}{v^2}\partial_\mu \xi \partial^\mu \xi h^2 + \lambda v^4/4 \end{aligned}$$

The Lagrangian describes the system of massive scalar field h with mass $m_h^2 = 2\lambda v^2$ interacting with massless scalar field $\xi(x)$. The field $\xi(x)$ is the Nambu-Goldstone boson field

This is a particular case of the generic Goldstone theorem.

Role of hidden symmetries

- Natural way to introduce energy scales in the theory by taking non-vanishing vevs

- Hidden symmetries allow to understand that fundamental symmetries of Nature might be much larger than the manifested symmetries at the energy range we currently able to test (SM, SUSY, grand unification, extra dimensions etc are typical examples)

Dimensions of fields and operators

Dimensions of fields and operators

$$S = \int L(x) \cdot d^4x \qquad \hbar = c = 1$$

$$[\psi] = [m]^{3/2} \qquad [V] = [\phi] = [m]^1$$

$$L(x) = \sum_{i=0} C_i \cdot O_i$$

$$[O_i] = [m]^i \qquad [C_i] = [m]^{4-i}$$

Renormalizability and unitarity $\Longrightarrow$ **In SM $i \leq 4$**

$$L = \frac{G_F}{\sqrt{2}} \bar{\mu} \gamma_\sigma (1 - \gamma_5) \nu_\mu \bar{e} \gamma_\sigma (1 - \gamma_5) \nu_e + h.e.$$

Non-renormalaizable Lagrangian

Fernando Quevedo slide

$$\mathcal{L}_{SM} = \sum_i c_i \mathcal{O}_i \,, \quad [c_i] + [\mathcal{O}_i] = 4\,.$$

- $[\mathcal{O}_i] = 0$: $c_0 = \Lambda$ $\boxed{\dfrac{\Lambda}{M_P^4} \sim 10^{-123} \ll 1 \quad \Lambda/\langle H\rangle^4 \sim 10^{-60}}$ **Cosmological constant problem**
- $[\mathcal{O}_i] = 2$: $c_2 = m^2$ $\quad H^2 = \mathcal{O}_2$ $\boxed{\dfrac{m_h}{M_P} \sim 10^{-15}}$ **Hierarchy problem**
- $[\mathcal{O}_i] = 3$: $c_3 = M^\nu$ $\nu_R \nu_R = \mathcal{O}_3$.

  Right handed neutrino mass term ?
- $[\mathcal{O}_i] = 4$: **All other terms in SM**

.

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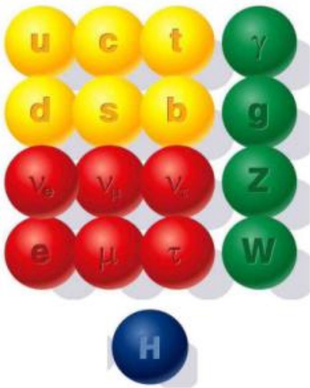
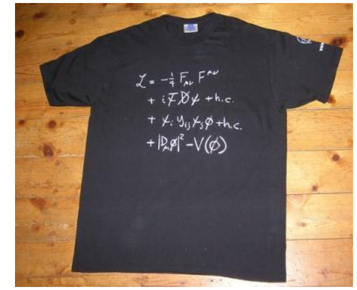
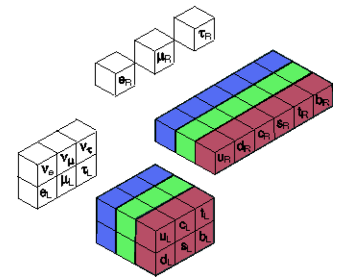
. **Higher order operators SMEFT**



Standard Model

$SU(2)_L \times U(1)_Y \times SU(3)_c$





$$L = -\tfrac{1}{4}W^i_{\mu\nu}(W^{\mu\nu})^i - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}G^a_{\mu\nu}(G^{\mu\nu})^a + $$
$$+ \sum_{f=\ell,q} \bar{\Psi}^f_L (iD^L_\mu \gamma^\mu)\Psi^\dagger_L + \sum_{f=\ell,q} \bar{\Psi}^f_R (iD^R_\mu \gamma^\mu)\Psi^\dagger_R$$
$$+ L_H$$

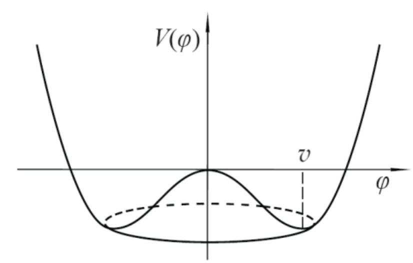
$$L_H = L_\Phi + L_{Yukawa}$$

$$L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger\Phi)^4$$

$$L_{Yukawa} = -\Gamma^{ij}_d \bar{Q'_L}^i \Phi {d'_R}^j + h.c. - \Gamma^{ij}_u \bar{Q'_L}^i \Phi^C {u'_R}^j + h.c. - \Gamma^{ij}_e \bar{L'_L}^i \Phi {e'_R}^j + h.c.$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_S f^{abc} A^b_\mu A^c_\nu \qquad W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \varepsilon^{ijk} W^j_\mu W^k_\nu$$



$$D^L_\mu = \partial_\mu - ig_2 W^i_\mu \tau^i - ig_1 B_\mu \left(\frac{Y^f_L}{2}\right) - ig_S A^a_\mu t^a$$

$$D^R_\mu = \partial_\mu - ig_1 B_\mu \left(\frac{Y^f_R}{2}\right) - ig_S A^a_\mu t^a \qquad i = 1,2,3;\ a = 1,\ldots,8,$$

$M_V,\ M_h,\ M_f \sim v$

$$Y_f = 2Q_f - 2I^3_f \quad \Rightarrow \quad Y_{L_i} = -1,\ Y_{e_{R_i}} = -2,\ Y_{Q_i} = \frac{1}{3},\ Y_{u_{R_i}} = \frac{4}{3},\ Y_{d_{R_i}} = -\frac{2}{3}$$

A very elegant theoretical construction!

$$L_{SM} = L_{Gauge} + L_{FG} + L_H$$

Kinetic terms for the gauge fields;
Interaction terms of the gauge fields

Kinetic terms for fermions;
Interactions of fermions with the gauge fields
(NC and CC currents)

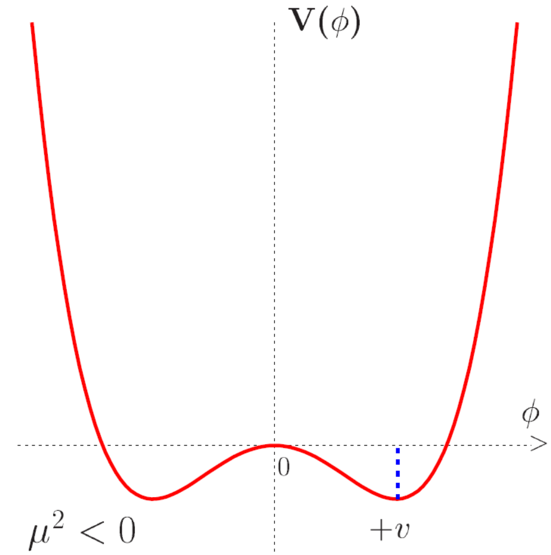
Kinetic and self-interaction terms for the higgs boson fields;
Higgs – gauge boson interaction terms;
Higgs-fermion interaction terms;
Mass terms for the gauge bosons and fermions

$$\begin{aligned} L_H \;=\; & \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2}h^2 - \frac{M_h^2}{2v}h^3 - \frac{M_h^2}{8v^2}h^4 + \\ & + \left(M_W^2 W_\mu^+ W^{-\mu} + \tfrac{1}{2}M_Z^2 Z_\mu Z^\mu\right)\left(1+\frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f \left(1+\frac{h}{v}\right) \end{aligned}$$

$$M_H^2 = 2\lambda v^2$$

CERN 10 years HIGGS boson discovery

4 July 2022
CERN

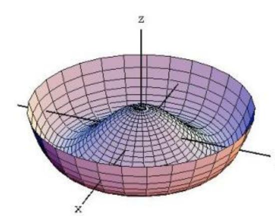


$$\mathbf{V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2}$$

$$\mathbf{\Phi \to \frac{1}{\sqrt{2}} \binom{0}{H+v}}$$

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

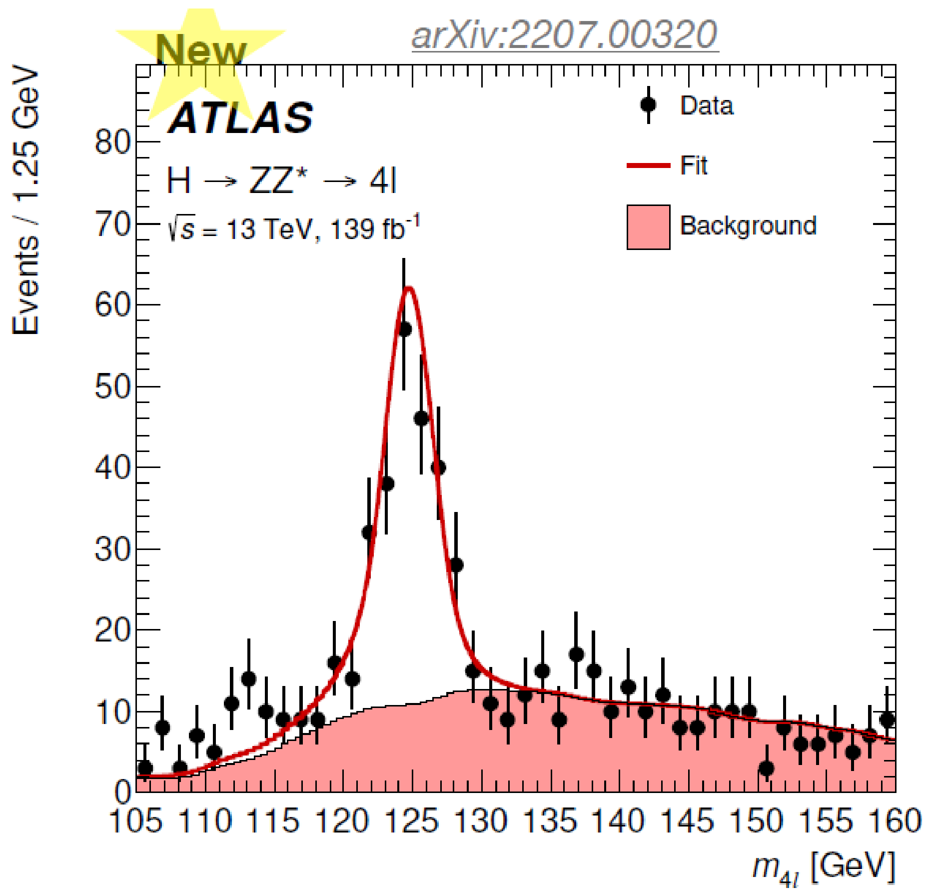
$$\mathbf{M_H^2 = 2\lambda v^2 = -2\mu^2}$$

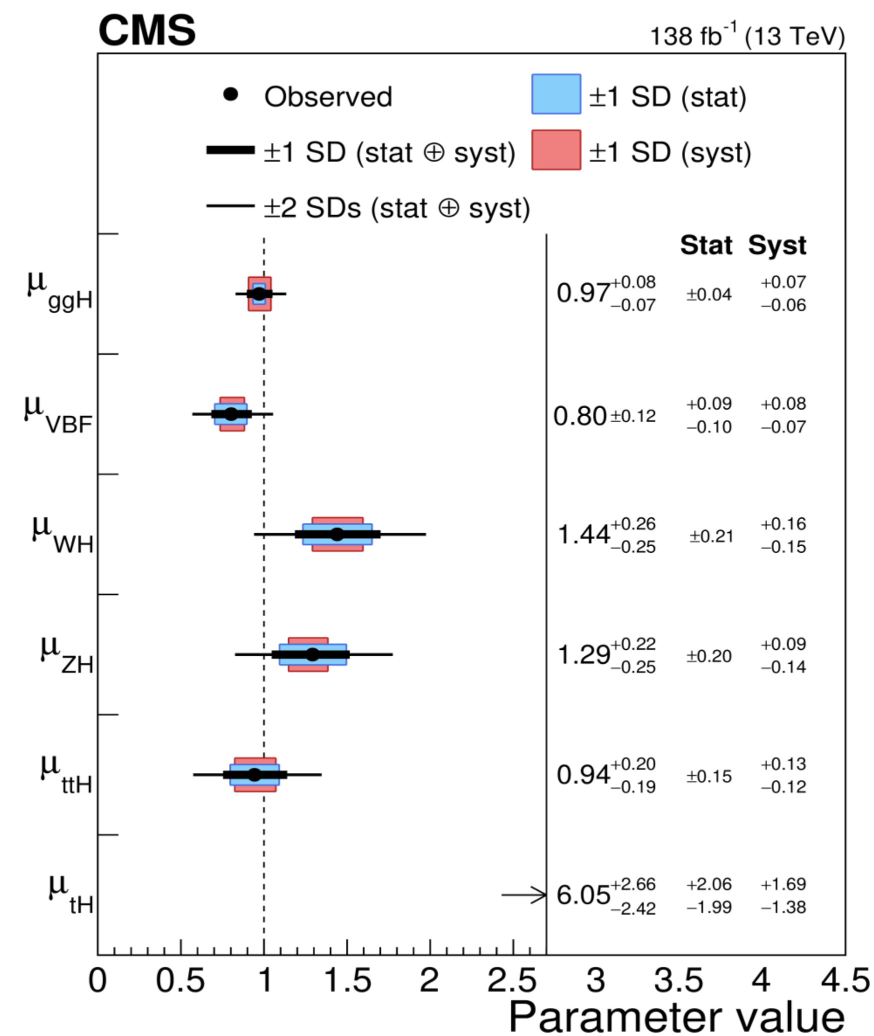


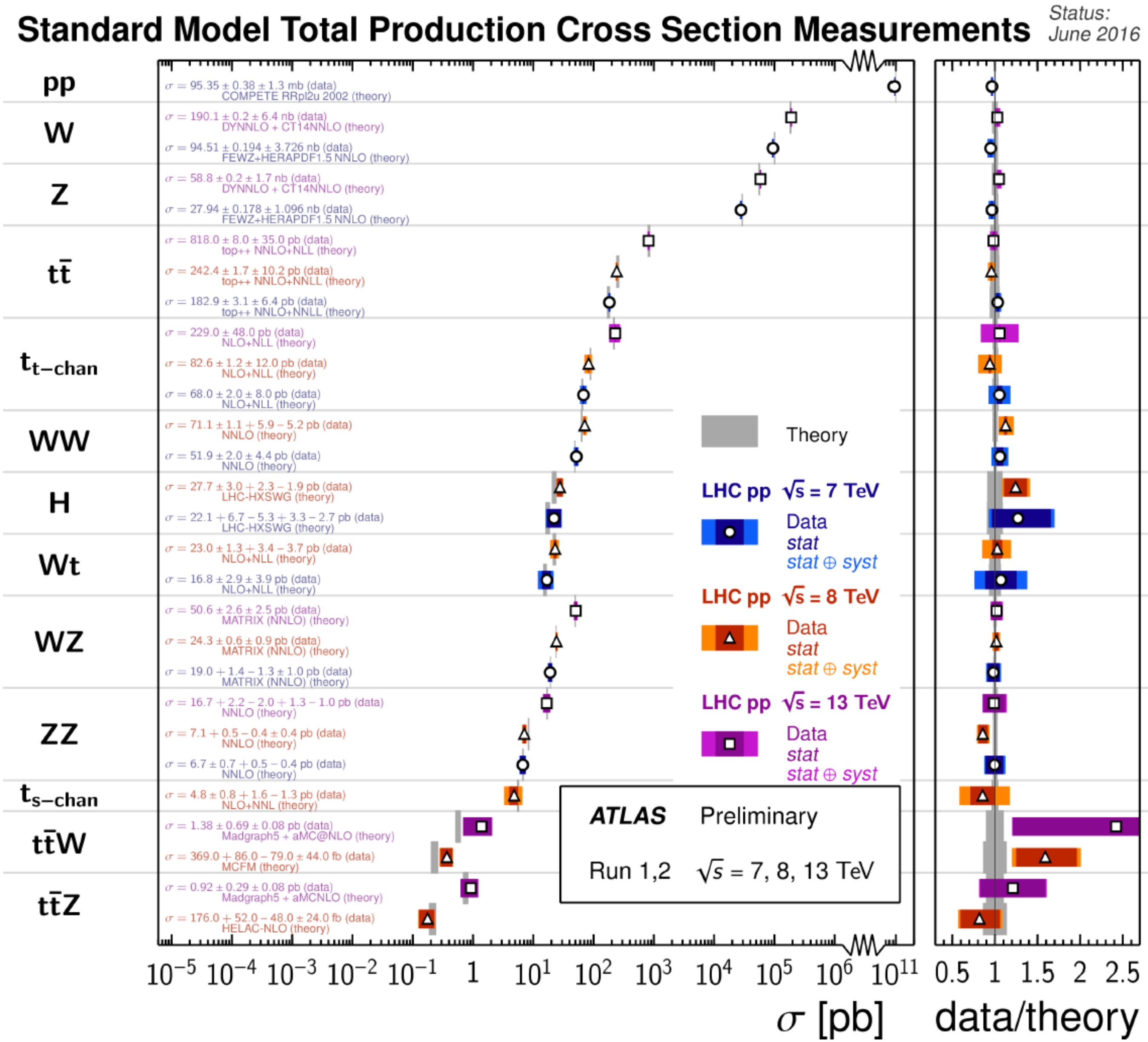
$$\lambda \cong 0.12$$

Origin of the EWSB potential → a weakly-coupled theory

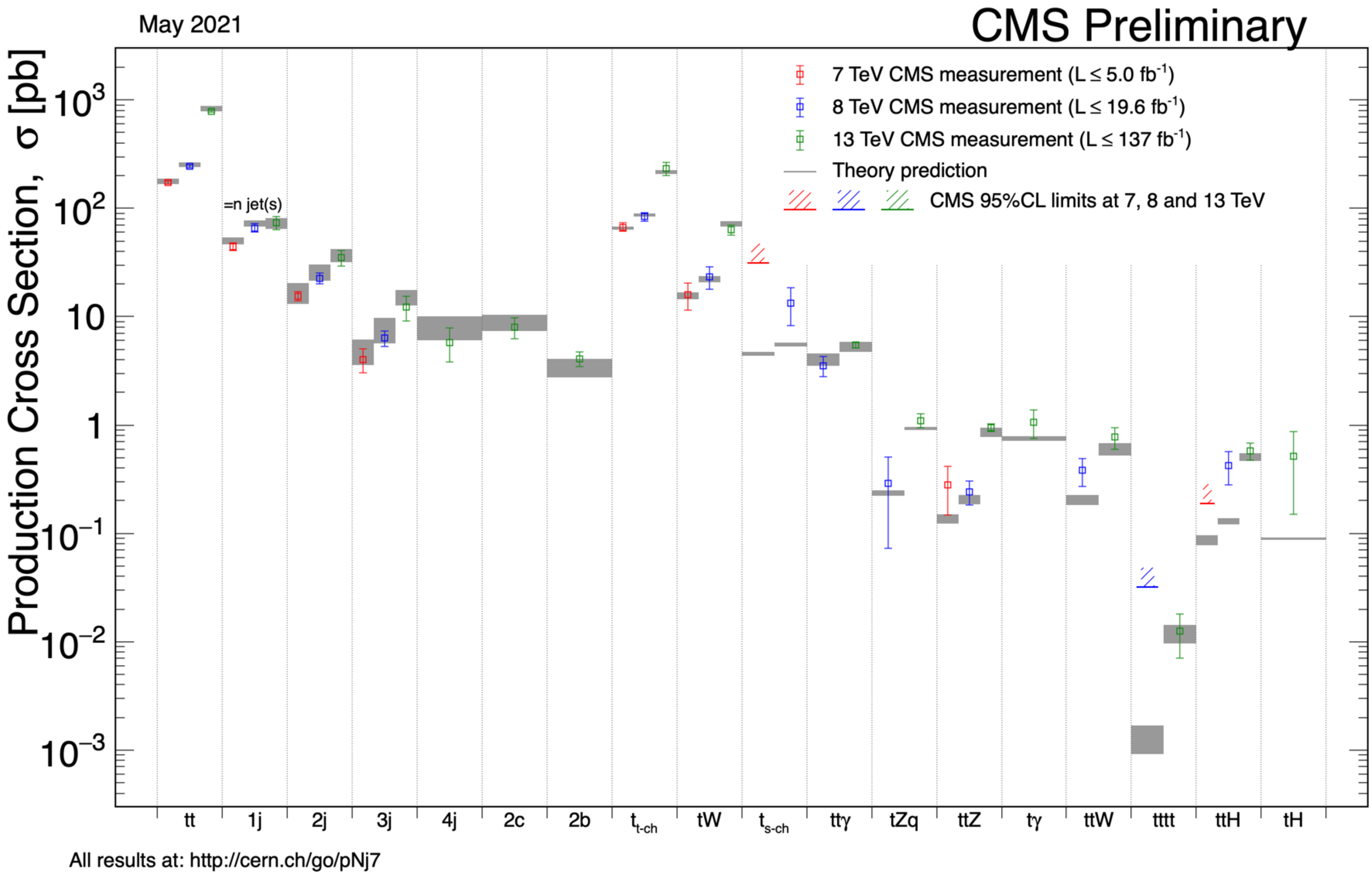
One of the latest result from RUN2

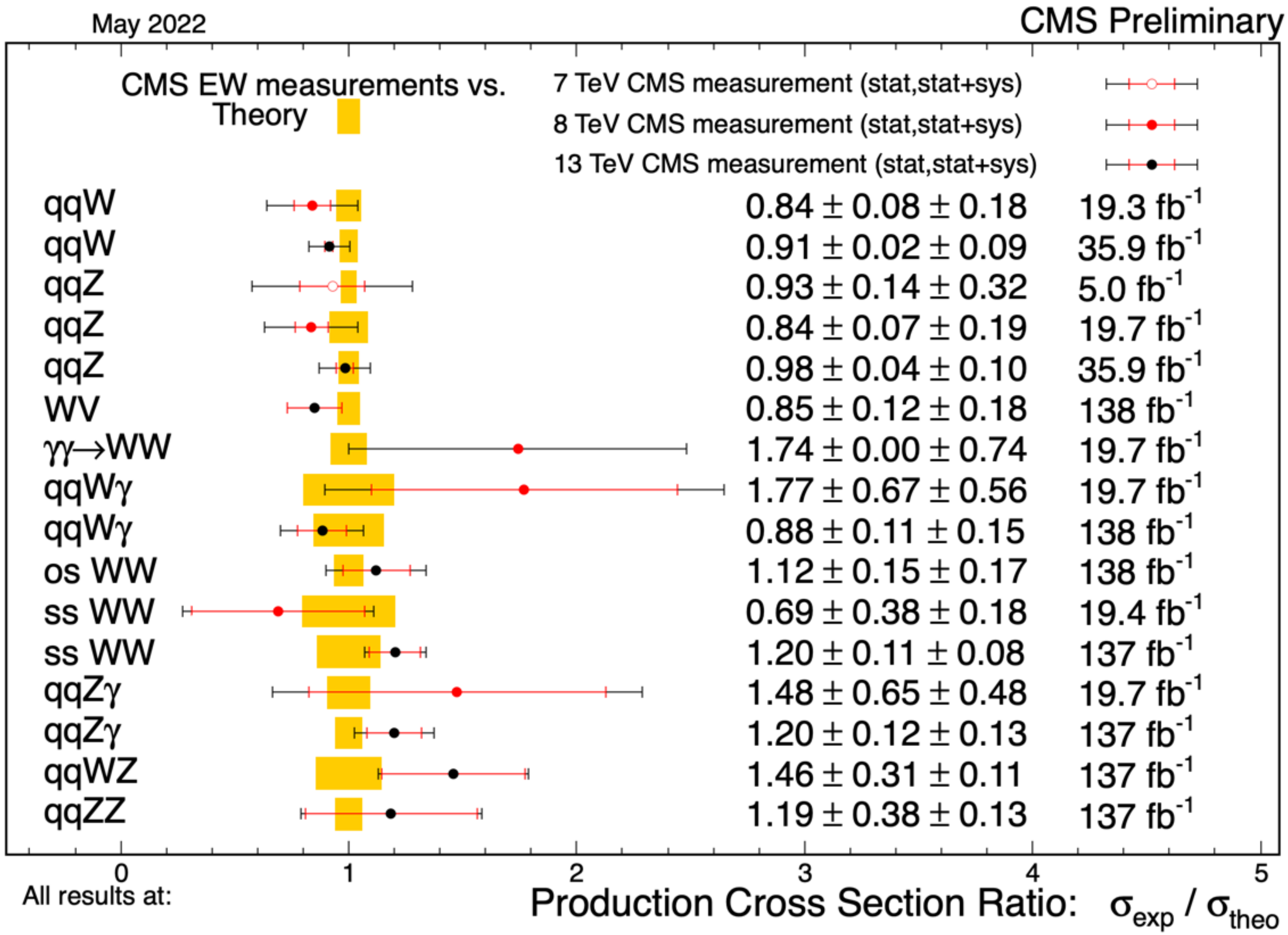


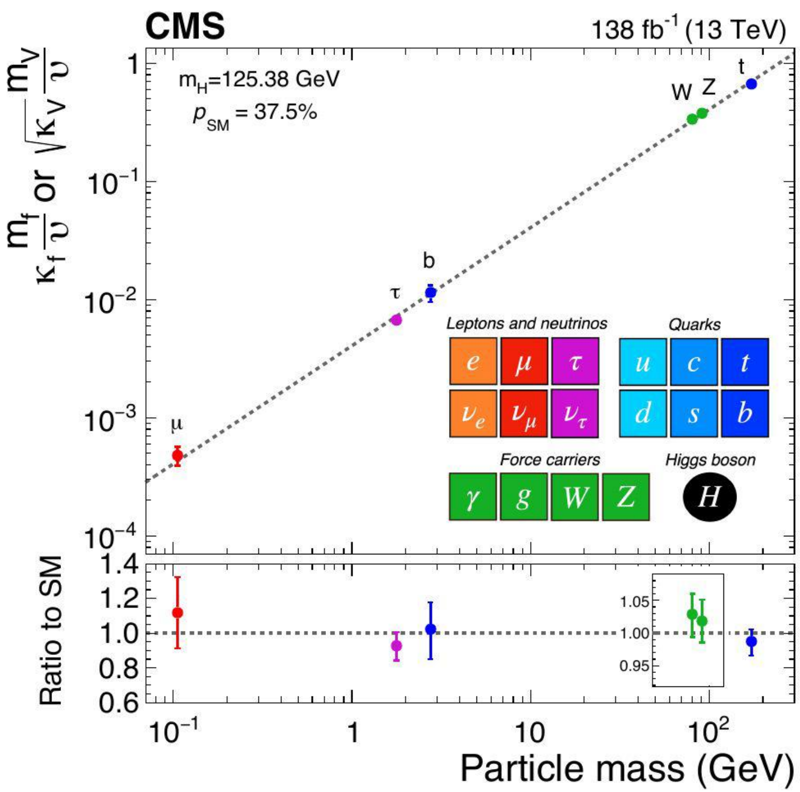


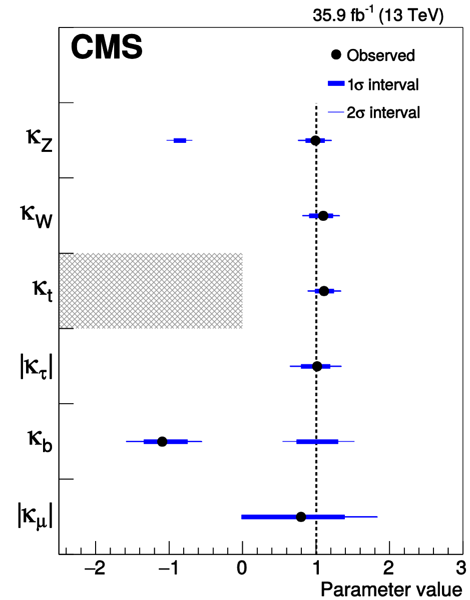


Standard Model Total Production Cross Section Measurements
Status: June 2016
pp
W
Z
tt̄
t_{t−chan}
WW
H
Wt
WZ
ZZ
t_{s−chan}
tt̄W
tt̄Z
σ = 95.35 ± 0.38 ± 1.3 mb (data) COMPETE RRpl2u 2002 (theory)
σ = 190.1 ± 0.2 ± 6.4 nb (data) DYNNLO + CT14NNLO (theory)
σ = 94.51 ± 0.194 ± 3.726 nb (data) FEWZ+HERAPDF1.5 NNLO (theory)
σ = 58.8 ± 0.2 ± 1.7 nb (data) DYNNLO + CT14NNLO (theory)
σ = 27.94 ± 0.178 ± 1.096 nb (data) FEWZ+HERAPDF1.5 NNLO (theory)
σ = 818.0 ± 8.0 ± 35.0 pb (data) top++ NNLO+NLL (theory)
σ = 242.4 ± 1.7 ± 10.2 pb (data) top++ NNLO+NNLL (theory)
σ = 182.9 ± 3.1 ± 6.4 pb (data) top++ NNLO+NNLL (theory)
σ = 229.0 ± 48.0 pb (data) NLO+NLL (theory)
σ = 82.6 ± 1.2 ± 12.0 pb (data) NLO+NLL (theory)
σ = 68.0 ± 2.0 ± 8.0 pb (data) NLO+NLL (theory)
σ = 71.1 ± 1.1 + 5.9 − 5.2 pb (data) NNLO (theory)
σ = 51.9 ± 2.0 ± 4.4 pb (data) NNLO (theory)
σ = 27.7 ± 3.0 + 2.3 − 1.9 pb (data) LHC-HXSWG (theory)
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data) LHC-HXSWG (theory)
σ = 23.0 ± 1.3 + 3.4 − 3.7 pb (data) NLO+NLL (theory)
σ = 16.8 ± 2.9 ± 3.9 pb (data) NLO+NLL (theory)
σ = 50.6 ± 2.6 ± 2.5 pb (data) MATRIX (NNLO) (theory)
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory)
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data) MATRIX (NNLO) (theory)
σ = 16.7 + 2.2 − 2.0 + 1.3 − 1.0 pb (data) NNLO (theory)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data) NNLO (theory)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory)
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data) NLO+NNL (theory)
σ = 1.38 ± 0.69 ± 0.08 pb (data) Madgraph5 + aMC@NLO (theory)
σ = 369.0 + 86.0 − 79.0 ± 44.0 fb (data) MCFM (theory)
σ = 0.92 ± 0.29 ± 0.08 pb (data) Madgraph5 + aMCNLO (theory)
σ = 176.0 + 52.0 − 48.0 ± 24.0 fb (data) HELAC-NLO (theory)
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1 1.5 2 2.5
data/theory


May 2021
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 137 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
=n jet(s)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
tt
1j
2j
3j
4j
2c
2b
$t_{t\text{-ch}}$
tW
$t_{s\text{-ch}}$
ttγ
tZq
ttZ
tγ
ttW
tttt
ttH
tH
All results at: http://cern.ch/go/pNj7

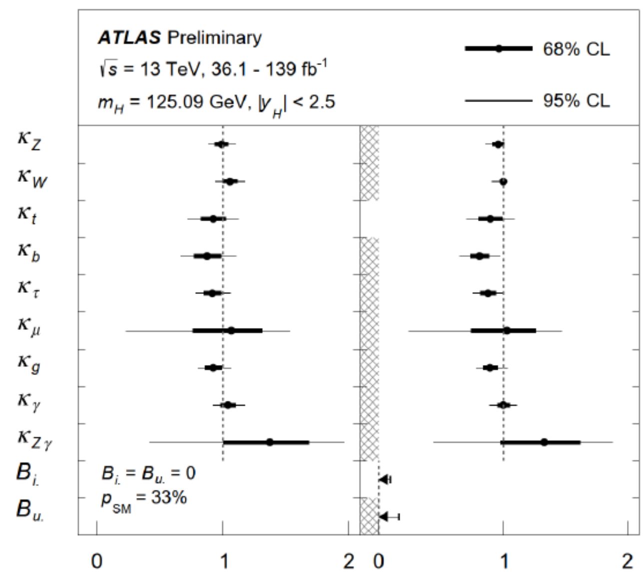

May 2022
CMS Preliminary
CMS EW measurements vs. Theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
qqW 0.84 ± 0.08 ± 0.18 19.3 fb^{-1}
qqW 0.91 ± 0.02 ± 0.09 35.9 fb^{-1}
qqZ 0.93 ± 0.14 ± 0.32 5.0 fb^{-1}
qqZ 0.84 ± 0.07 ± 0.19 19.7 fb^{-1}
qqZ 0.98 ± 0.04 ± 0.10 35.9 fb^{-1}
WV 0.85 ± 0.12 ± 0.18 138 fb^{-1}
γγ→WW 1.74 ± 0.00 ± 0.74 19.7 fb^{-1}
qqWγ 1.77 ± 0.67 ± 0.56 19.7 fb^{-1}
qqWγ 0.88 ± 0.11 ± 0.15 138 fb^{-1}
os WW 1.12 ± 0.15 ± 0.17 138 fb^{-1}
ss WW 0.69 ± 0.38 ± 0.18 19.4 fb^{-1}
ss WW 1.20 ± 0.11 ± 0.08 137 fb^{-1}
qqZγ 1.48 ± 0.65 ± 0.48 19.7 fb^{-1}
qqZγ 1.20 ± 0.12 ± 0.13 137 fb^{-1}
qqWZ 1.46 ± 0.31 ± 0.11 137 fb^{-1}
qqZZ 1.19 ± 0.38 ± 0.13 137 fb^{-1}
0 1 2 3 4 5
All results at:
Production Cross Section Ratio: σ_{exp} / σ_{theo}





$$\mathcal{L}_\kappa = -\sum_\psi \kappa_\psi \frac{\sqrt{2}M_\psi}{\hat{v}}\bar{\psi}\psi h + \kappa_Z \frac{M_Z^2}{\hat{v}} Z_\mu Z^\mu h + \kappa_W \frac{2M_W^2}{\hat{v}} W_\mu^+ W^{-\mu} h,$$
$$+ \kappa_{g,c}\frac{g_3^2}{16\pi^2\hat{v}} G_{\mu\nu}G^{\mu\nu}h + \kappa_{\gamma,c}\frac{e^2}{16\pi^2\hat{v}} F_{\mu\nu}F^{\mu\nu}h + \kappa_{Z\gamma,c}\frac{e^2}{16\pi^2 c_{\hat{\theta}}\hat{v}} Z_{\mu\nu}F^{\mu\nu}h$$

$$\kappa_g^2(\kappa_t,\kappa_b) = \frac{\kappa_t^2\,\sigma_{ggH}^{tt} + \kappa_b^2\,\sigma_{ggH}^{bb} + \kappa_t\kappa_b\,\sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$



invisible $B_{\rm i} < 0.09$ at 95% CL

undetected $B_{\rm u} < 0.16$ at 95% CL

Standard Model

1. Standard Model is the renormalizable anomaly free gauge quantum field theory with spontaneously broken electroweak symmetry. Remarkable agreement with many experimental measurements.

2. All SM leptons, quarks, gauge bosons, and, finally, the Higgs boson have been discovered

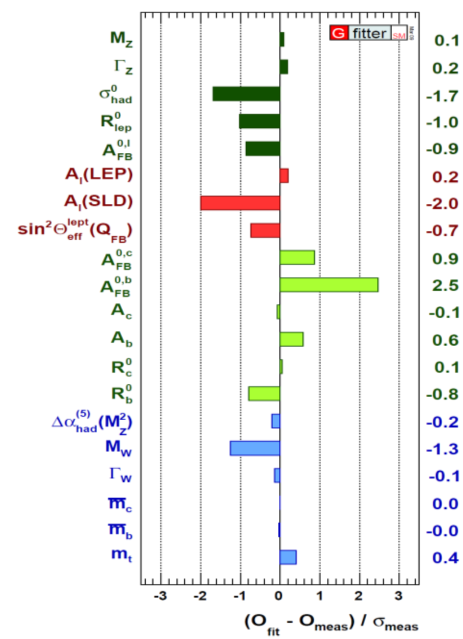
3. SM predicts the structure of all interactions: fermion-gauge, gauge self couplings, Higgs-gauge, Higgs-fermion, Higgs self couplings (but not all couplings were tested yet experimentally)

4. The EW SM has 17 parameters (from experiments) gauge-Higgs sector contains 4 parameters: g_1, g_2, μ^2, λ $\longrightarrow$ best measured α_{em}, G_F, M_Z (or α_{em}, s_W, M_W) plus M_H

   In addition, 6 quarks masses, 3 lepton masses, 3 mixing angles and one phase of the CKM matrix

   plus α_{QCD} $\Longrightarrow$ 18 SM parameters

(+ masses and mixing parameters from the neutrino sector)



Facts which can not be understood in SM

- EW symmetry is broken – photon is massless, W and Z are massive particles
Fermions have very much unnaturally different masses
(Mtop ≈ 172 GeV, Me ≈ 0.5 MeV, ΔMν ≈ 10^{-3} eV)

- Dark Matter in the Universe

- Particle – antiparticle asymmetry in the Universe, CP violation CKM phase – too small efect

baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

- Neutrino masses, mixing, oscillations

- Very small cosmological constant. Very weak gravity interaction

- Muon $(g-2)_\mu$ anomaly (about 3.5 σ → 4.2 σ BNL)

- B-anomalies (about 4.5 σ)

- CDF W-mass anomaly (about 7 σ)

In addition to mentioned problems (naturalness/hierarchy, dark matter content, CP violation) SM does not give answers to many questions

What is a generation? Why there are only 3 generations?

How quarks and leptons related to each other, what is a nature of quark-lepton analogy?

What is responsible for gauge symmetries, why charges are quantize? Are there additional gauge symmetries?

What is responsible for a formation of the Higgs potential?

To which accuracy the CPT symmetry is exact?

Why gravity is so weak comparing to other interactions?

………

What is a scale for New physics?

Before the LHC start we knew a scale ~1 TeV from

No lose theorem!

From the unitariry of VV->VV (V: W,Z) amplitudes $\left|\mathrm{Re}(a_l)\right| \leq \frac{1}{2}$

Either light Higgs $M_H \lesssim 710\ \mathrm{GeV}$

or

New Physics at $\sqrt{s} \lesssim 1.2\ \mathrm{TeV}$

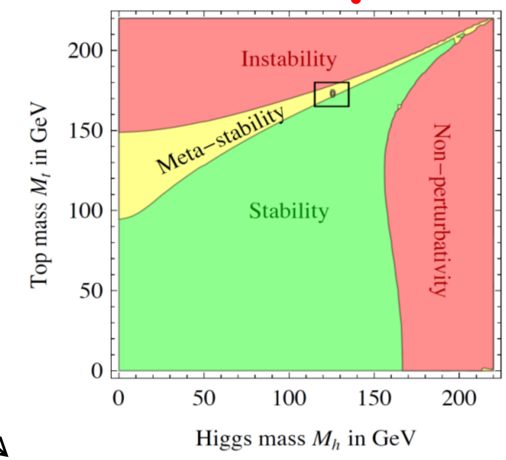
The Higgs boson was found !

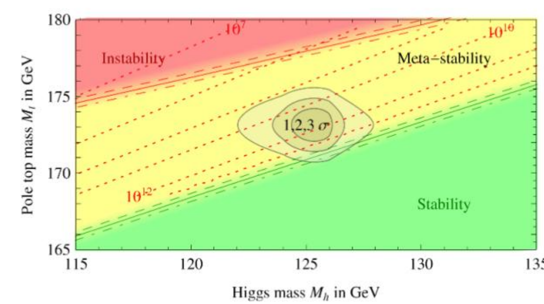
We do not have solid arguments for a new scale

We do not know if a new scale (if exists) would be accessible at the LHC/FCC energies

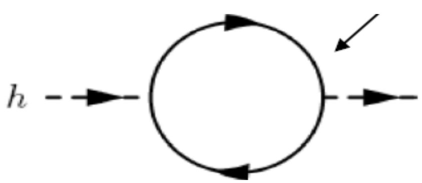
SM itself is a renormalizable theory !

SM by itself consistent up to very high energies





Correction to the Higgs mass from a loop contaning new particle



$$|M^2_H(\Lambda) - M^2_H(v)| \sim 3/(8\pi^2)\, y_f^2\, M_f^2 \ln(\Lambda^2/v^2) + \ldots$$

Correction is large for $M_f^2 \sim \Lambda^2$ if the coupling constant y_f is large

But a new fermion may have a very small coupling to the SM Higgs boson

No solid arguments for a new scale

Scales

Plank Mass ~ 10^{19} GeV

Grand Unification scale ~10^{15} - 10^{16} GeV ?

Neutrino physics (see-saw) scale ~10^{12} - 10^{15} GeV ?

SM vacuum metastablity scale ~10^{10} - 10^{11} GeV ?

Some BSM models, some SUSY scenarios ~ 10^{3} - 10^{4} GeV ?

EW scale (v_{SM}) ~10^{2} GeV

QCD scale ~ 0.2 – 1 GeV

- More symmetries

- Larger scales

- More Higgses

Main directions beyond the Standard Model

Supersymmetry
(MSSM, NMSSM...)

Extra space-time dimensions
(ADD, RS, UED ...)

Compositeness, new strong dynamics
(latest technicolor variants, Little Higgs...)

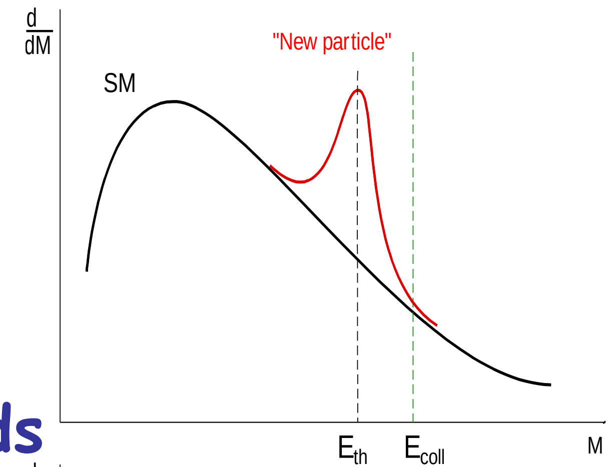
Grand unification

Strings and string motivated extensions

Two possibilities to search for BSM

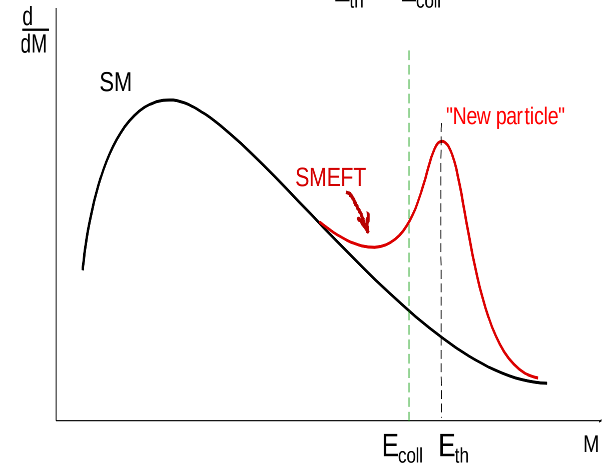
Collision energy E > production thresholds

⇒New particles, new resonances



Z', W', π_T, ρ_T , KK states, squarks, sleptons,
vector like fermions, excited states...

Collision energy E < production thresholds



⇒New effective anomalous interactions of SM particles

⇒New particle contributions via quantum loops

(modification of SM decay widths,
production cross sections, kinematical distributions)

- Effective field theories
- UV complete theories
- Simplified models

Searches below threshold

Precision physics

SM Effective Field Theory (SMEFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4} O_j^{(8)} + \ldots$$

c_i - dimensionless coefficients
O_i – operators constructed from SM fields preserving SM gauge invariance, and (optionally) other symmetries

S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979)

W. Buchmuller and D. Wyler, Nucl. Phys. B268, 621 (1986)

Operator basis

Operator basis, all operators allowed by the symmetries and then reduced using equations of motion, integration by parts identities, and Fierz transformations

At dimension-5 there exists only a single, lepton number violating operator (Weinberg operator), whose Wilson coefficient is heavily suppressed

$$\left(\overline{L^c_{L\alpha}}\widetilde{H}^*\right)\left(\widetilde{H}^\dagger L_{L\beta}\right) + \text{h.c.}$$

$$L_L = (\nu_L, \ell_L)^T \quad \widetilde{H} = i\sigma_2 H^*$$

S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979)

At dimension-6 there are 59 (Warsaw basis) independent operators for one generation of fermions excluding baryon number violating operators (There are about 80 operators in the original Buchmuller-Wyler basis)

B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, JHEP 10 (2010) 085

2499 dimension-6 operators for three generations.
Global SMEFT fit will have to explore a huge parameter space with potentially a large number of flat directions.

R. Alonso, E. E. Jenkins, A. V. Manohar, and M. Trott, JHEP 04 (2014) 159

Several issues

Operator basis ?

Squared terms $(1/\Lambda^2)^2$?

NLO corrections ?

Unitarity?

Simultaneous analysis of different signatures (processes) ?

Proper modeling and strategy to get limits from exp. data ?

etc.

Warsaw Basis (WB)

$1: X^3$	
O_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$O_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
O_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$O_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
O_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
O_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
O_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
O_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
O_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
O_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
O_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
O_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$O_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
O_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
O_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
O_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
O_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
O_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
O_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
O_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
O_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$O_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$O_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
O_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$O_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$O_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
O_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
O_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
O_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
O_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$O_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$O_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$O_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$O_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
O_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
O_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
O_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
O_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
O_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$O_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$O_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
O_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
O_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
O_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
O_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$O_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$O_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$O_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$O_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
O_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$O_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$O_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
$O_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$O_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Squired terms $(1/\Lambda^2)^2$

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

$$\sigma = \sigma^{\rm SM} + \sum_i \left(\frac{c_i^{(6)}}{\Lambda^2}\sigma_i^{(6\times{\rm SM})} + {\rm h.c.}\right) + \sum_{ij}\frac{c_i^{(6)}c_j^{(6)*}}{\Lambda^4}\sigma_{ij}^{(6\times 6)} + \sum_j \left(\frac{c_j^{(8)}}{\Lambda^4}\sigma_j^{(8\times{\rm SM})} + {\rm h.c.}\right) + \dots$$

1. Without an operator basis at dimension eight for the higher-dimensional contribution, it is not possible to calculate the full term of $1/\Lambda^4$, and it should thus be treated as an uncertainty.

2. In some cases, the interference between SM amplitudes and EFT ones could be suppressed (for instance, for certain helicities) or even vanishingly small (for instance, in the case of FCNCs). The dominant contribution could then arise at the quadratic level.

3. Repeat this procedure twice, with and without including the quadratic EFT contributions. The comparison between those two sets of results can explicitly establish where quadratic dimension-six EFT contributions are subleading compared to linear ones.

But the problem is even more involved since the SMEFT contributions come from production, from decay, and from the width in Breit-Wiegner denominator

SMEFT in the TOP sector

1802.07237

28 operators are involved directly to the top sector

2-Quark Operators (9)

$$^{\ddagger}O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$^{\ddagger}O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$^{\ddagger}O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu},$$
$$^{\ddagger}O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu},$$
$$^{\ddagger}O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\quad\tilde{\varphi}B_{\mu\nu},$$
$$^{\ddagger}O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu},$$

4-Quark Operators (11)

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$^{\ddagger}O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$^{\ddagger}O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

2-Quark-2-Lepton Operators (8)

$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$^{\ddagger}O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$^{\ddagger}O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$^{\ddagger}O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

Notations

$$\mathcal{L} = \sum_a \left(\frac{C_a}{\Lambda^2}{}^{\ddagger}O_a + \mathrm{h.c.}\right) + \sum_b \frac{C_b}{\Lambda^2}O_b$$

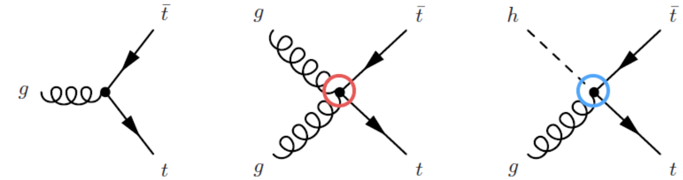
In addition 5 baryon- and lepton-number-violating operators:

$$^{\ddagger}O_{duq}^{(ijkl)} = (\overline{d^c}_{i\alpha}u_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqu}^{(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{u^c}_{k\gamma}e_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqq}^{1(ijkl)} = (\overline{q^c}_{i\alpha}\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{qqq}^{3(ijkl)} = (\overline{q^c}_{i\alpha}\tau^I\varepsilon q_{j\beta})(\overline{q^c}_{k\gamma}\tau^I\varepsilon l_l)\,\epsilon^{\alpha\beta\gamma},$$
$$^{\ddagger}O_{duu}^{(ijkl)} = (\overline{d^c}_{i\alpha}u_{j\beta})(\overline{u^c}_{k\gamma}e_l)\,\epsilon^{\alpha\beta\gamma},$$

SMEFT operators lead to additional vertexes (i=j=3)

$$\mathcal{L}_{gtt} = -g_s \bar{t}\,\frac{\lambda^a}{2}\gamma^\mu t\, G^a_\mu - g_s \bar{t}\,\lambda^a \frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d^g_V + i d^g_A \gamma_5\right) t\, G^a_\mu$$

$$^\ddagger O^{(ij)}_{uG} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi} G^A_{\mu\nu}$$



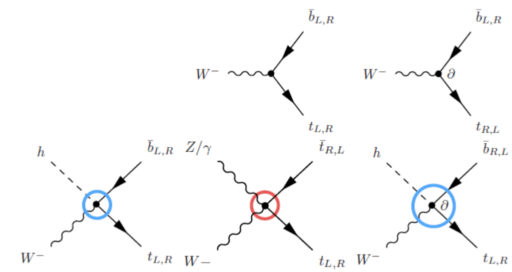
$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^\mu\left(f^{\mathrm{L}}_{\mathrm{V}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{V}} P_{\mathrm{R}}\right)\mathrm{t}W^-_\mu - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_\nu W^-_\mu}{M_{\mathrm{W}}}\left(f^{\mathrm{L}}_{\mathrm{T}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathrm{T}} P_{\mathrm{R}}\right)\mathrm{t} + \mathrm{h.c.}$$

$$^\ddagger O^{(ij)}_{u\varphi} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger \varphi),$$

$$^\ddagger O^{(ij)}_{\varphi ud} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j),$$

$$^\ddagger O^{(ij)}_{uW} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi} W^I_{\mu\nu}$$

$$^\ddagger O^{(ij)}_{dW} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\,\varphi W^I_{\mu\nu}$$



$$\begin{aligned}\mathcal{L}_{Ztt} &= -\frac{g}{2c_W}\bar{t}\gamma^\mu\left(X^L_{tt}P_L + X^R_{tt}P_R - 2s^2_W Q_t\right) t\, Z_\mu \\ &\quad -\frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d^Z_V + i d^Z_A\gamma_5\right) t\, Z_\mu\,,\end{aligned}$$

$$\mathcal{L}_{\gamma tt} = -eQ_t \bar{t}\gamma^\mu t\, A_\mu - e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d^\gamma_V + i d^\gamma_A \gamma_5\right) t\, A_\mu$$

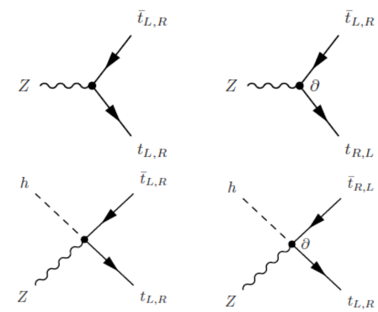
$$O^{1(ij)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),$$

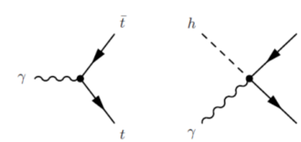
$$O^{3(ij)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),$$

$$O^{(ij)}_{\varphi u} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),$$

$$^\ddagger O^{(ij)}_{uW} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi} W^I_{\mu\nu},$$

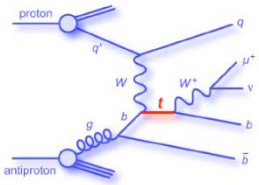
$$^\ddagger O^{(ij)}_{uB} = (\bar{q}_i \sigma^{\mu\nu} u_j)\quad \tilde{\varphi} B_{\mu\nu}$$





Anomalous Wtb couplings

Operators contributing to tWb interactions



E.B., Dubinin, Sachwitz, Schreiber 0001048;
Aguilar-Saavedra 0811.3842

$$O_{\phi q}^{(3,33)} = \frac{i}{2}\left[\phi^\dagger \tau^I (D_\mu \phi) - (D_\mu \phi^\dagger)\tau^I \phi\right](\bar{q}_{L3}\gamma^\mu \tau^I q_{L3}),$$

$$O_{\phi ud}^{(33)} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R),$$

$$O_{dW}^{(33)} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I b_R)\phi W_{\mu\nu}^I,$$

$$O_{uW}^{(33)} = (\bar{q}_{L3}\sigma^{\mu\nu}\tau^I t_R)\tilde{\phi} W_{\mu\nu}^I$$

Connection to notations of WB

$$O_{Hq}^{(3)} \equiv O_{\phi q}^{(3,33)}, O_{Hu} \equiv O_{\phi ud}^{(33)}, O_{dW} \equiv O_{dW}^{(33)}, O_{uW} \equiv O_{uW}^{(33)}$$

Kane, Ladinski, Yaun

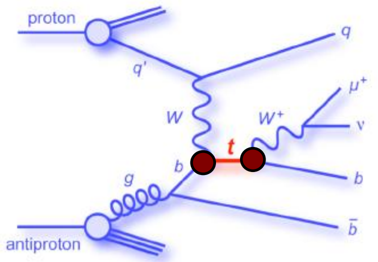
$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^\mu\left(f_\mathrm{V}^\mathrm{L} P_\mathrm{L} + f_\mathrm{V}^\mathrm{R} P_\mathrm{R}\right)\mathrm{t}W_\mu^- - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{\sigma^{\mu\nu}\partial_\nu W_\mu^-}{M_\mathrm{W}}\left(f_\mathrm{T}^\mathrm{L} P_\mathrm{L} + f_\mathrm{T}^\mathrm{R} P_\mathrm{R}\right)\mathrm{t} + \mathrm{h.c.}$$

$$f_{LV} = V_{tb} + C_{\phi q}^{(3,33)}\frac{v^2}{\Lambda^2}, \quad f_{RV} = \frac{1}{2}C_{\phi ud}^{(33)}\frac{v^2}{\Lambda^2}, \quad f_{LT} = \sqrt{2}C_{dW}^{(33)}\frac{v^2}{\Lambda^2}, \quad f_{RT} = \sqrt{2}C_{uW}^{(33)}\frac{v^2}{\Lambda^2}$$

CM: f_1^L = Vtb, f_1^R = 0, $f_2^{L,R}$ = 0

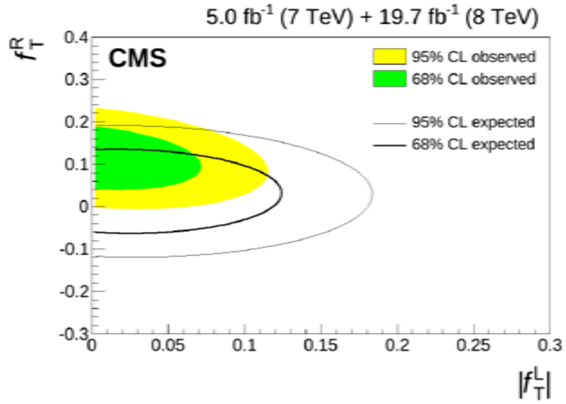
Natural size $|1-f_L^V|$, $f_R^V \sim v^2/\Lambda^2$

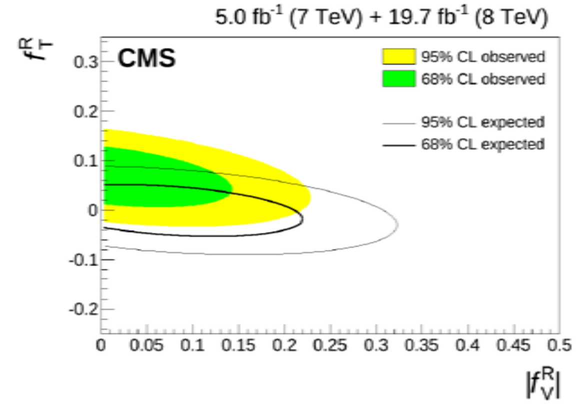
Natural size f_L^T, $f_R^T \sim v^2/\Lambda^2$



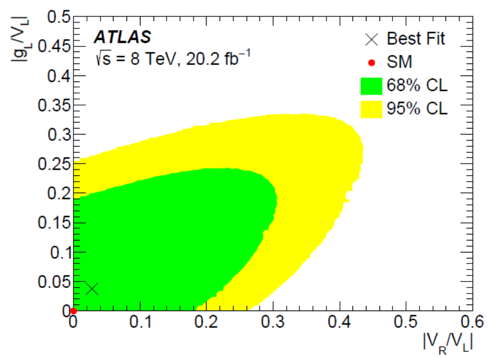
Anomalous Wtb couplings

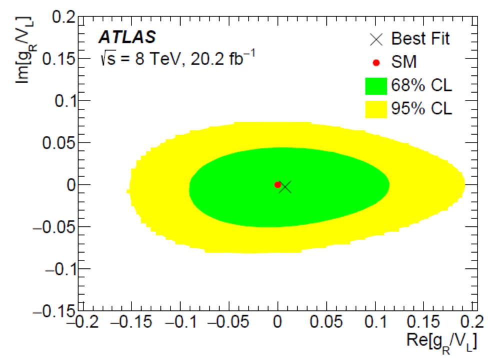
CMS limits



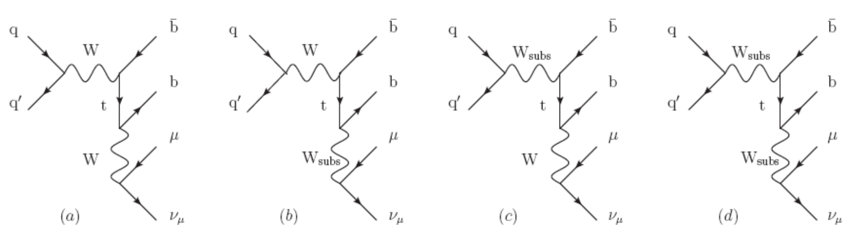


ATLAS limits





New method of modeling with subsidiary vector fields corresponding to each anomalous couplings



E.B., Bunichev, Dudko, Perfilov
Int. J. Mod. Phys. A 32, 1750008 (2016)

tttt in SMEFT

Alwall et al.,1405.0301

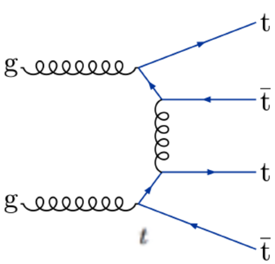
Relevant set of 4 top operators

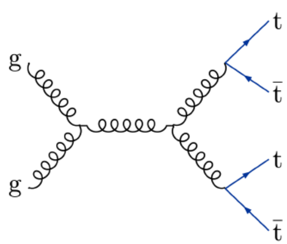
$$\mathcal{O}^1_{\mathrm{tt}} = \left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma^\mu \mathrm{t}_{\mathrm{R}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu \mathrm{t}_{\mathrm{R}}\right),$$

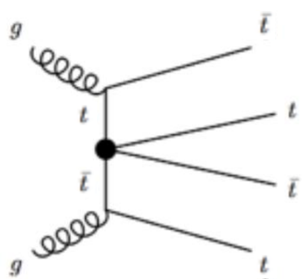
$$\mathcal{O}^1_{\mathrm{QQ}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma_\mu \mathrm{Q}_{\mathrm{L}}\right),$$

$$\mathcal{O}^1_{\mathrm{Qt}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu \mathrm{t}_{\mathrm{R}}\right),$$

$$\mathcal{O}^8_{\mathrm{Qt}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu T^A \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu T^A \mathrm{t}_{\mathrm{R}}\right)$$







NLO cross section $\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}t\bar{t}}} = 9.2\ \mathrm{fb}$

CMS, 1906.02805

$$\sigma_{\mathrm{t\bar{t}t\bar{t}}} = \sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}t\bar{t}}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma^{(1)}_k + \frac{1}{\Lambda^4}\sum_{j\le k} C_j C_k \sigma^{(2)}_{j,k}$$

Operator	$\sigma^{(1)}_k$ (fb TeV^2)	$\sigma^{(2)}_{j,k}$ (fb TeV^4) $\mathcal{O}^1_{\mathrm{tt}}$	$\mathcal{O}^1_{\mathrm{QQ}}$	$\mathcal{O}^1_{\mathrm{Qt}}$	$\mathcal{O}^8_{\mathrm{Qt}}$
$\mathcal{O}^1_{\mathrm{tt}}$	0.39	5.59	0.36	−0.39	0.3
$\mathcal{O}^1_{\mathrm{QQ}}$	0.47		5.49	−0.45	0.13
$\mathcal{O}^1_{\mathrm{Qt}}$	0.03			1.9	−0.08
$\mathcal{O}^8_{\mathrm{Qt}}$	0.28				0.45

95% CL intervals for Wilson coefficients

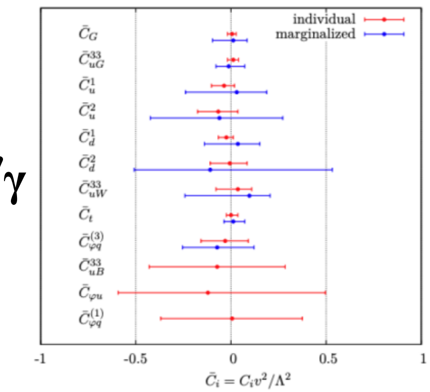
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	[−2.0, 1.8]	[−2.1, 2.0]
$\mathcal{O}^1_{\mathrm{QQ}}$	[−2.0, 1.8]	[−2.2, 2.0]
$\mathcal{O}^1_{\mathrm{Qt}}$	[−3.3, 3.2]	[−3.5, 3.5]
$\mathcal{O}^8_{\mathrm{Qt}}$	[−7.3, 6.1]	[−7.9, 6.6]

Towards global fits in SMEFT

TopFitter

Buckley, Englert, Ferrando, Miller, Moore, Russell, White, 1512.03360

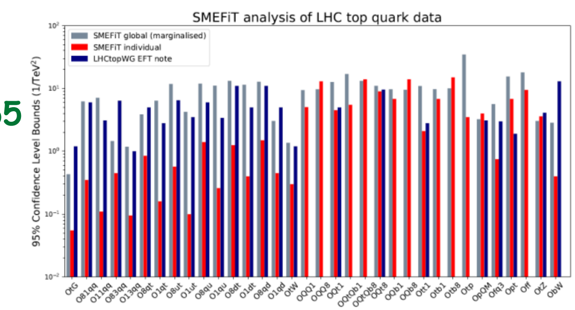
Top pair, single-top production, ttZ/γ from the LHC run I and II and Tevatron

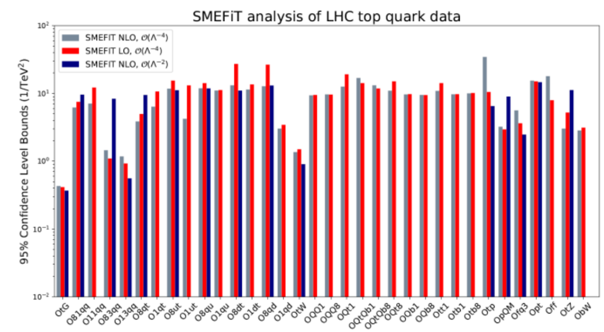


Global fits to the SMEFT from the top sector.

SMEFiT

Hartland, *Maltoni, Nocera, Rojo,* Slade, Vryonidou, Zhang, 1901.05965

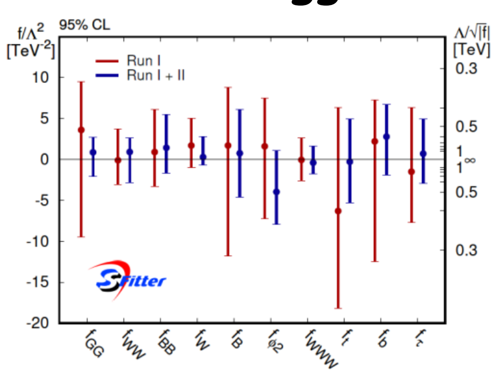




Sfitter

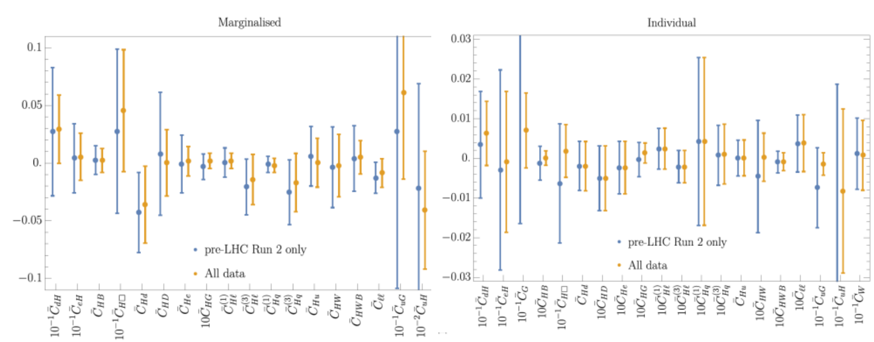
Biekoetter, Corbett, Plehn,1812.07587

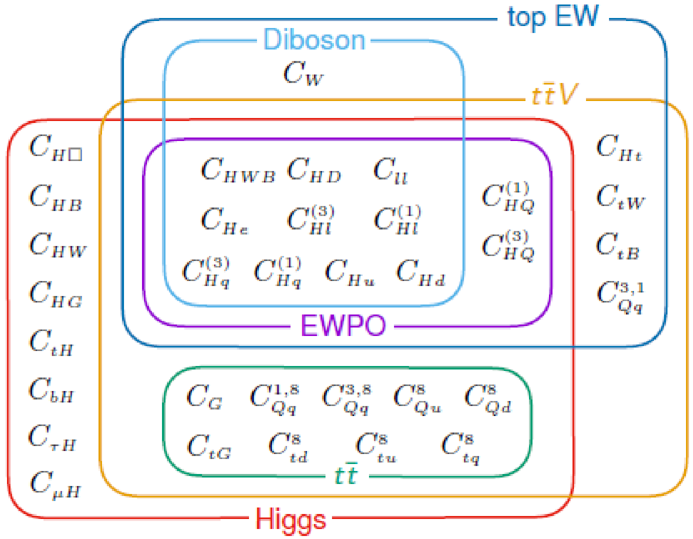
Global fits to the SMEFT from the Higgs sector.



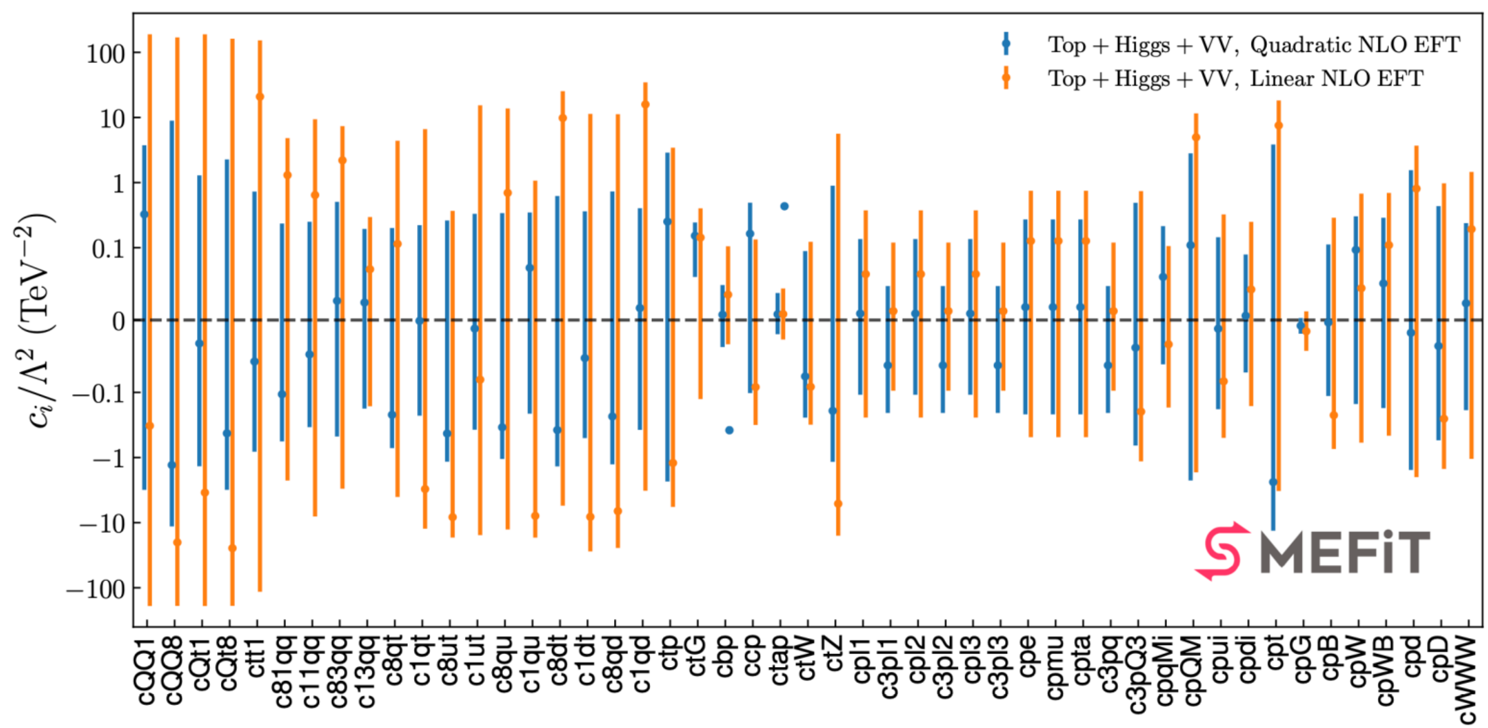
Global SMEFT Fit to Higgs, Diboson and Electroweak Data

Ellisa, Murphyc, Sanzd, Youe, 1803.03252





Ellis et al. [arXiv:2012.02779]



New M_W measurement by CDF, SMEFT

ATLAS:80370 ± 7stat ± 11exp ± 14mod MeV

LHCb:80354 ± 23stat ± 10exp ± 17th ± 9PDF MeV

CDF: 80433.5 ± 6.4stat ± 6.9syst MeV

SMEFT operators shifting W mass at linear order

Bagnaschi, Ellis et al 2204.05260

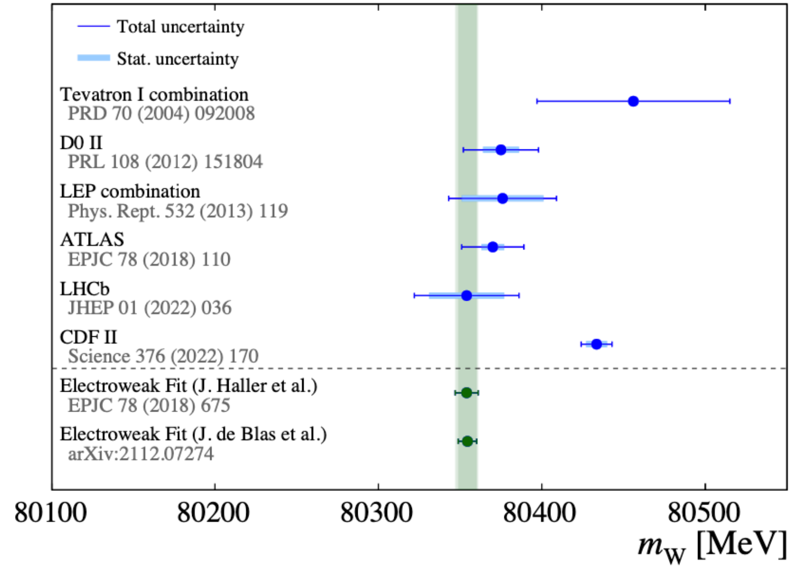
$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H \, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

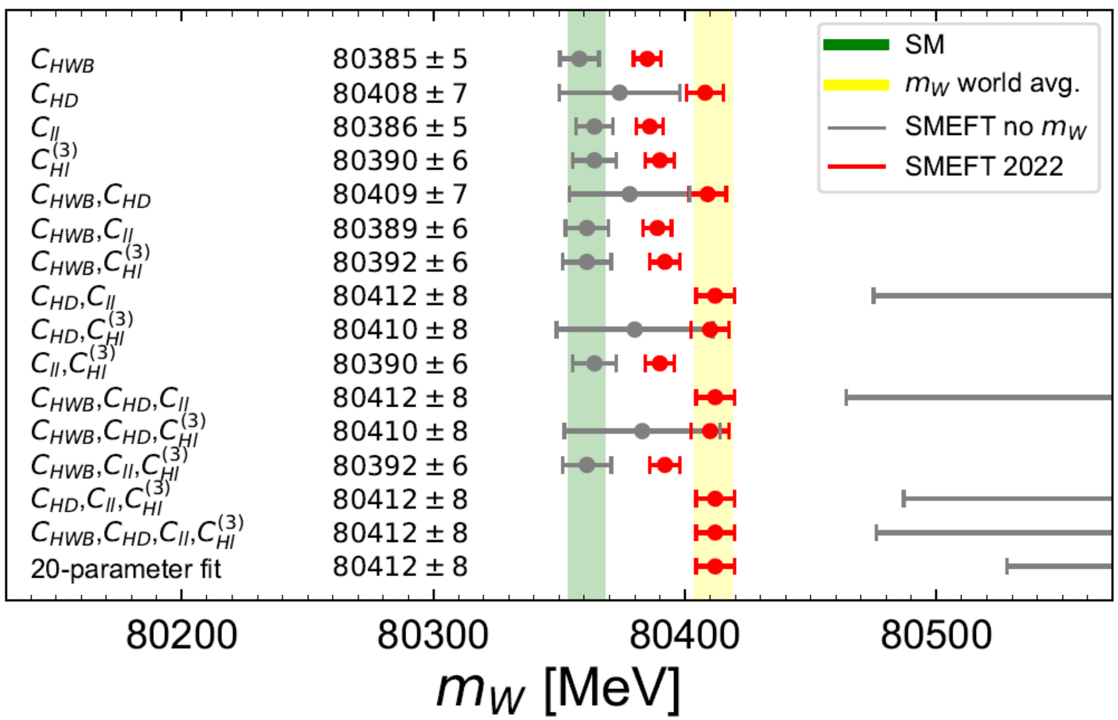
$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

Pole mass shift

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

LHCB-FIGURE-2022-003





EFT for Dark Matter

$$L_{DMEFT} \sim O_{SM} \cdot O_{DM}$$

EFT (a mediator is very heavy)

Operators coupling DM particles to the SM particles

J.Goodman, M.Ibe, A.Rajaraman, W.Shepherd, T.Tait, H.-B. Yu 1008.1783

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

$$\mu_{n\chi} = m_n m_{\rm DM}/(m_n + m_{\rm DM})$$

$$\begin{aligned}
\sigma_0^{D1} &= 1.60\times10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{20\mathrm{GeV}}{M_*}\right)^6,\\
\sigma_0^{D5,C3} &= 1.38\times10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{300\mathrm{GeV}}{M_*}\right)^4,\\
\sigma_0^{D8,D9} &= 9.18\times10^{-40}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{300\mathrm{GeV}}{M_*}\right)^4,\\
\sigma_0^{D11} &= 3.83\times10^{-41}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{100\mathrm{GeV}}{M_*}\right)^6,\\
\sigma_0^{C1,R1} &= 2.56\times10^{-36}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{10\mathrm{GeV}}{M_*}\right)^4\\
\sigma_0^{C5,R3} &= 7.40\times10^{-39}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{10\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{60\mathrm{GeV}}{M_*}\right)^4
\end{aligned}$$

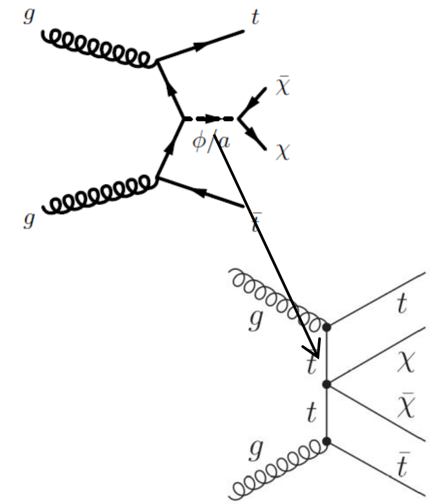
CMS:1504.03198

EFT (a mediator is very heavy)

$$L_{\rm int} = \frac{m_{\rm q}}{M_*^3}\bar{q}q\bar{\chi}\chi$$ couplings to light quarks are suppressed

Signal

Signature: tt+MET

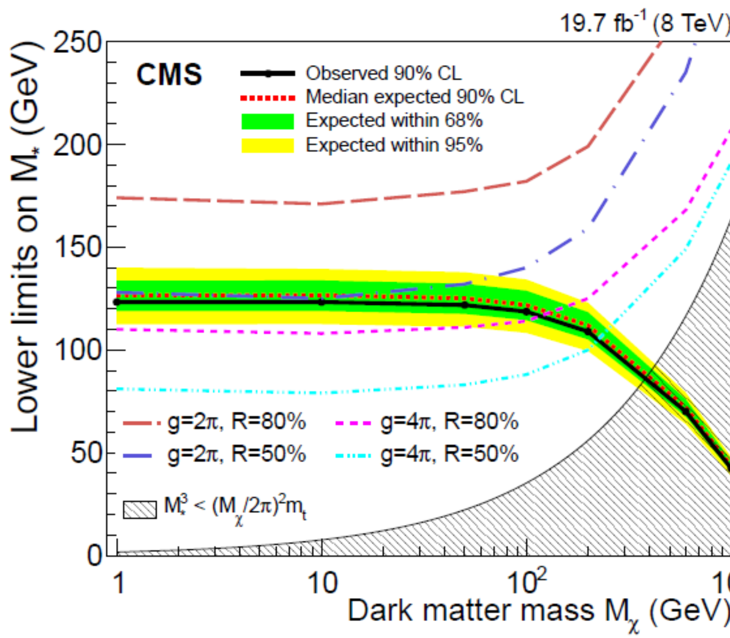


perturbative limit $g \equiv \sqrt{g_\chi g_{\rm t}} = 4\pi$ ($m_t/M_*^3 = g^2/M^2$, $M>2M_{\chi\chi}$)

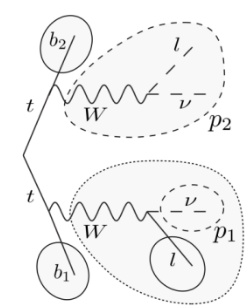
EFT approximation is valid if $M_{\chi\bar{\chi}} < g\sqrt{M_*^3/m_{\rm t}}$

Requirement R – number of events with $M_{\chi\bar{\chi}} < g\sqrt{M_*^3/m_{\rm t}}$

Source	Yield (±stat ±syst)
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell–Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Data	18



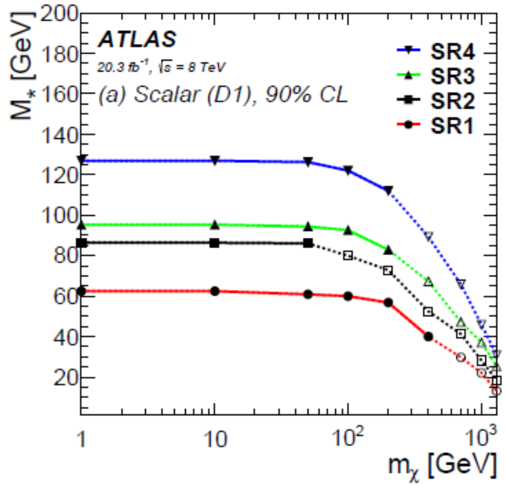
Dominating background

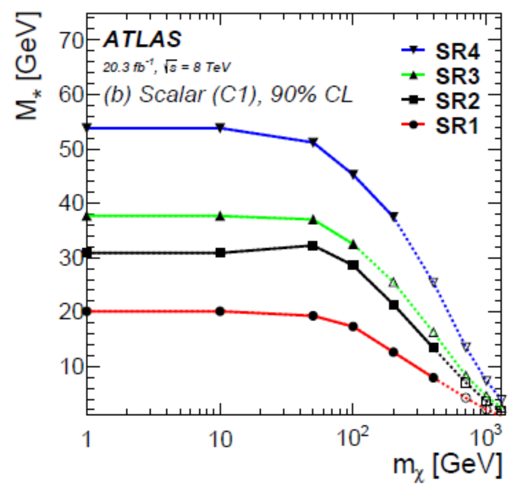


Observed exclusion limits, the region below the solid curve is excluded at a 90% CL.

ATLAS:1410.4031

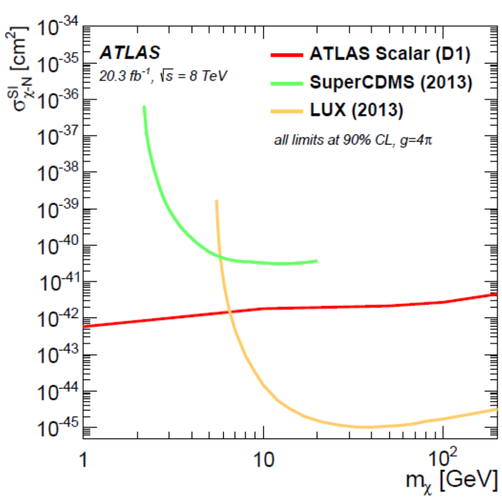
$$\mathcal{O}_{\rm scalar} = \sum_q \frac{m_q}{M_*^N}\bar{q}q\bar{\chi}\chi$$ N=3 for D1, N=2 for C1

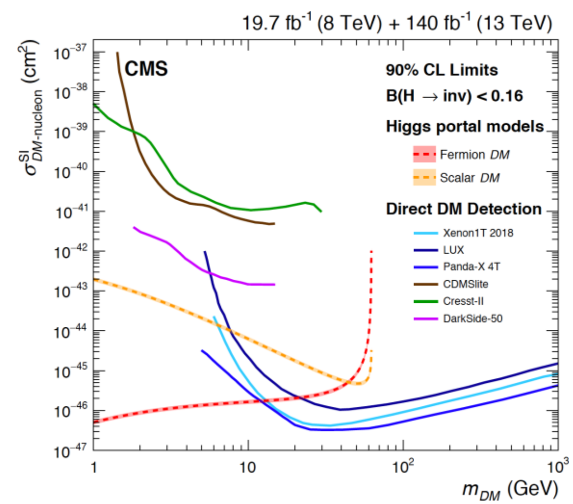




Lower limits on M* at 90% CL for verious signal regions as a function of m_χ for the operators D1 (Dirac fermion) and C1 (complex scalar)

Comparison with direct detection for D1





BACKUP SLIDES