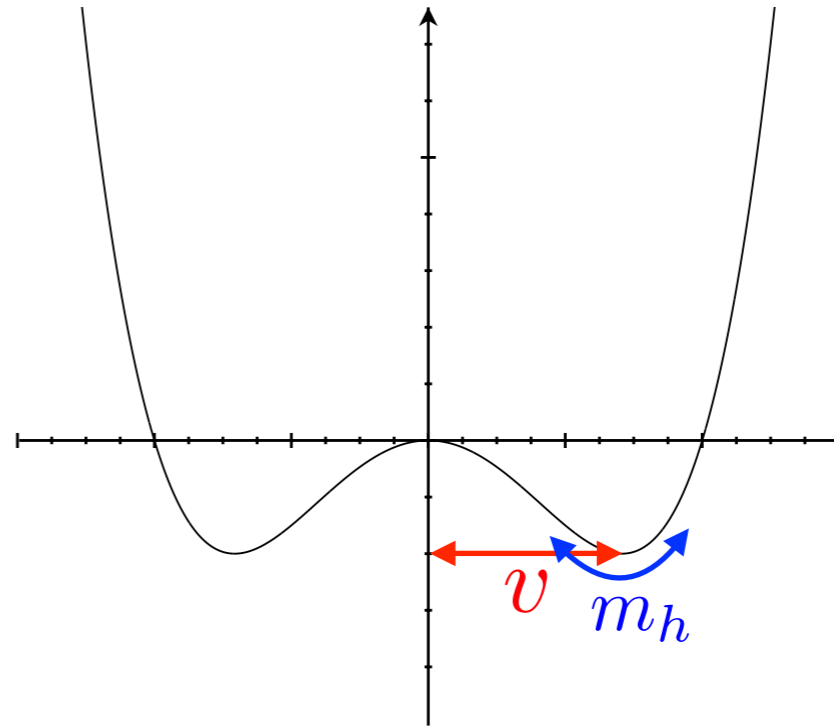


Lecture 5

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + h) \end{pmatrix}$$



Higgs VEV v

Higgs boson h

- vacuum structure
- effective potential

@high energy

- renormalization group evolution

- properties of h
- productions & decays
- Higgs coupling measurements
- > tests of mass generation & symmetry breaking

Higgs boson

The Higgs was discovered in July 2012.



$$J = 0$$

PDG2022

Mass $m = 125.25 \pm 0.17$ GeV ($S = 1.5$)
Full width $\Gamma = 3.2_{-2.2}^{+2.8}$ MeV (assumes equal
on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States = 1.13 ± 0.06

$W W^* = 1.19 \pm 0.12$

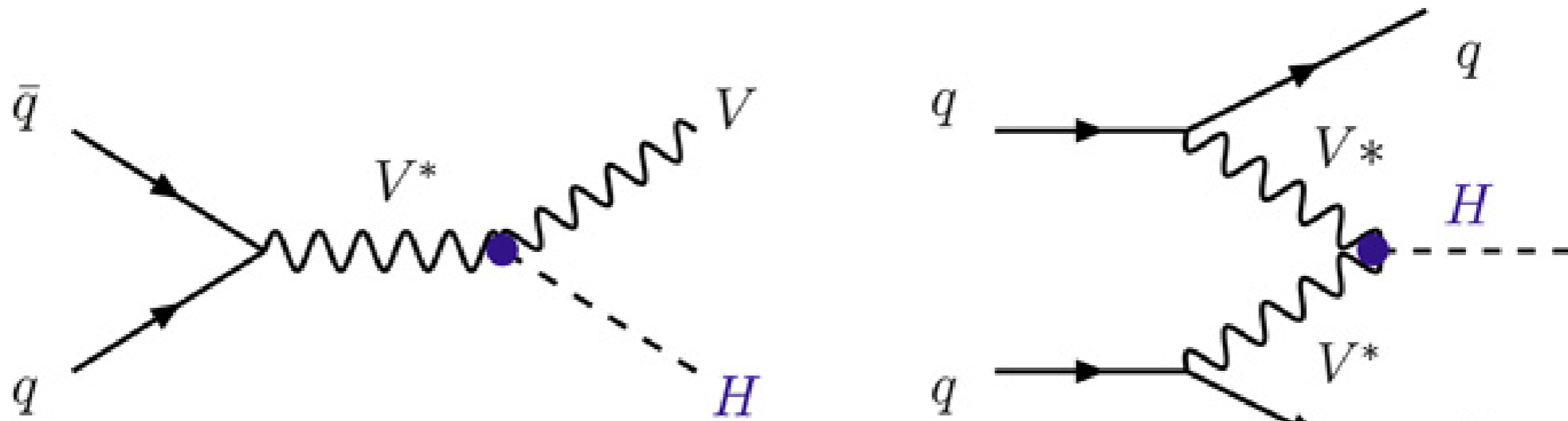
$Z Z^* = 1.06 \pm 0.09$

$\gamma\gamma = 1.11_{-0.09}^{+0.10}$

$c\bar{c}$ Final State = 37 ± 20

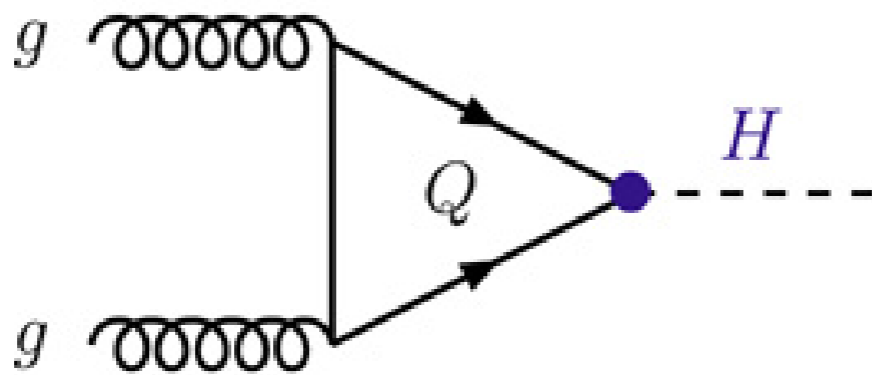
$b\bar{b} = 1.04 \pm 0.13$

Higgs productions@LHC

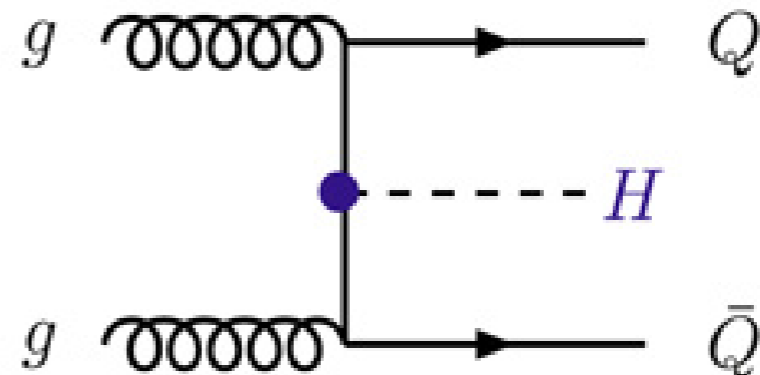


associated production (AP) w/ $V=W, Z$

vector boson fusion (VBF)



gluon fusion (ggF)



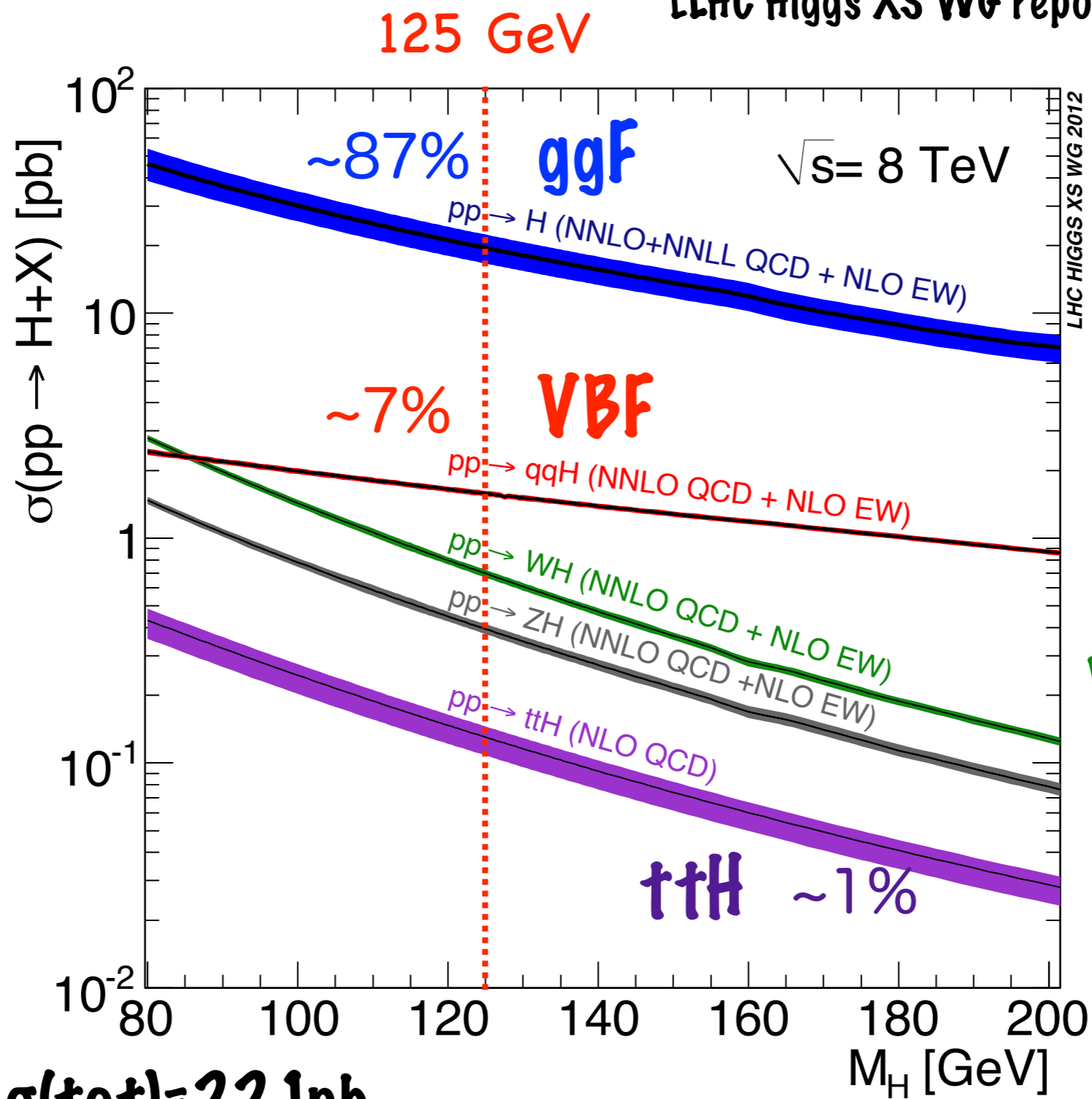
associated production w/ $Q=t, b$,

Fig. 3.1. The dominant SM Higgs boson production mechanisms in hadronic collisions.

Fig. from A. Djouadi, Phys.Rept. 457 (2008) 1

Cross sections

[LHC Higgs XS WG report, arXiv: 1307.13471]



$M_h = 125 \text{ GeV}, \sigma(\text{tot}) = 22.1 \text{ pb}$

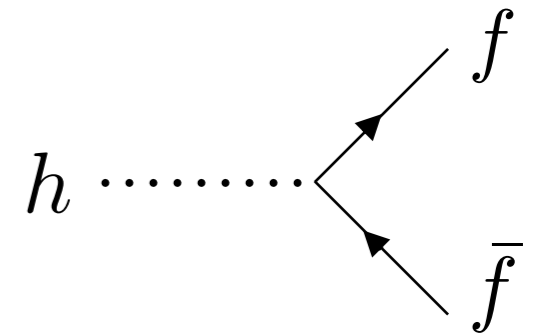
ggF: 19.3 pb, **VBF:** 1.6 pb, **WH:** 0.7 pb, **ZH:** 0.4 pb, **ttH:** 0.13 pb

Higgs decays

A. Djouadi, Phys.Rept.457 (2008) 1

$h \rightarrow f + \bar{f}$

$$\Gamma(h \rightarrow f \bar{f}) = \frac{N_C m_f^2 m_h}{8\pi v^2} \left(1 - \frac{4m_f^2}{m_h^2}\right)^{3/2}$$



For $m_h \approx 130$ GeV, the main decay mode is $h \rightarrow b + \bar{b}$.

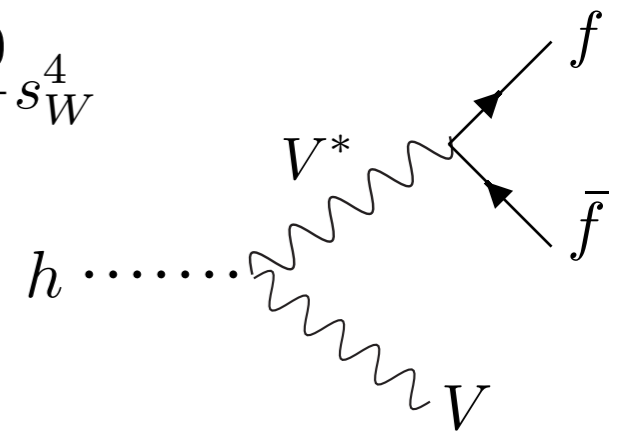
\therefore largest Yukawa coupling and color

$h \rightarrow VV^*$

$$\Gamma(h \rightarrow VV^*) = \frac{9m_h m_V^4}{32\pi^3 v^4} c_V I(x), \quad c_W = 1, \quad c_Z = \frac{7}{12} - \frac{10}{9} s_W^2 + \frac{40}{9} s_W^4$$

$$I(x) = \frac{(x^2 - 1)(2 - 13x^2 + 47x^4)}{2x^2} - 3(1 - 6x^2 + 4x^4) \ln x$$

$$+ \frac{3(1 - 8x^2 + 20x^4)}{\sqrt{4x^2 - 1}} \cos^{-1} \left(\frac{3x^2 - 1}{2x^3} \right)$$



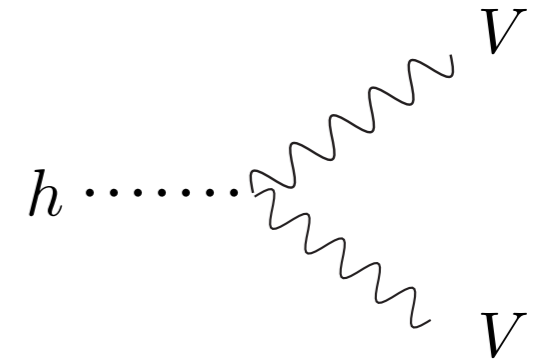
For $m_h \gtrsim 130$ GeV, WW^* starts to dominate over $h \rightarrow b + \bar{b}$. $\therefore m_b \ll m_V$

$h \rightarrow V^* V^*$ is equally important.

$h \rightarrow ZZ, WW$

$$\Gamma(h \rightarrow ZZ) = \frac{m_h^3}{32\pi v^2} \sqrt{1 - \frac{4m_Z^2}{m_h^2}} \left[1 - \frac{4m_Z^2}{m_h^2} + \frac{12m_Z^4}{m_h^4} \right],$$

$$\Gamma(h \rightarrow W^+W^-) = \frac{m_h^3}{16\pi v^2} \sqrt{1 - \frac{4m_W^2}{m_h^2}} \left[1 - \frac{4m_W^2}{m_h^2} + \frac{12m_W^4}{m_h^4} \right]$$

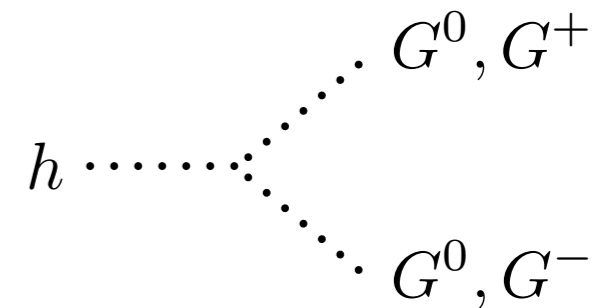


$$2^* \Gamma(h \rightarrow ZZ) \approx \Gamma(h \rightarrow WW)$$

Goldstone boson equivalence theorem

$$\Gamma(h \rightarrow G^0 G^0) = \frac{\lambda_{hG^0 G^0}^2}{32\pi m_h} = \frac{m_h^3}{32\pi v^2} \quad \lambda_{hG^0 G^0} = \frac{m_h^2}{v}$$

$$\Gamma(h \rightarrow G^+ G^-) = \frac{\lambda_{hG^+ G^-}^2}{16\pi m_h} = \frac{m_h^3}{16\pi v^2} \quad \lambda_{hG^+ G^-} = \frac{m_h^2}{v}$$



$$\Gamma(h \rightarrow ZZ) \underset{m_Z \ll m_h}{\simeq} \Gamma(h \rightarrow G^0 G^0)$$

$$\Gamma(h \rightarrow W^+ W^-) \underset{m_W \ll m_h}{\simeq} \Gamma(h \rightarrow G^+ G^-)$$

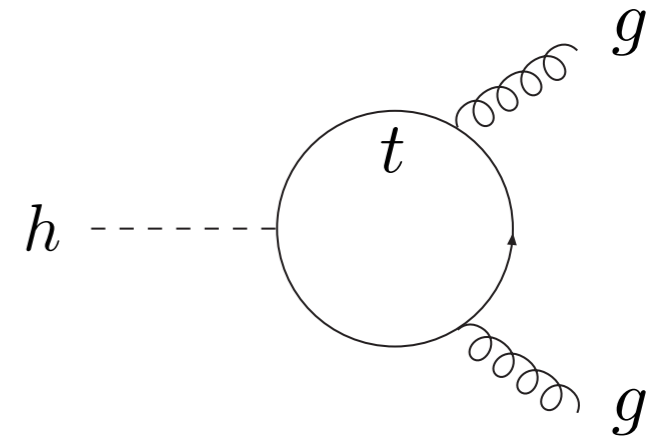
For $m_V \ll m_h$, $h \rightarrow VV$ ($V=Z, W$) is dominated by the longitudinal mode.

h → gg

1-loop induced decay is not always smaller than the tree level decay.

$$\Gamma(h \rightarrow gg)_{\text{top-loop}} = \frac{\alpha_s^2 m_h^3}{32\pi^3 v^2} \left[\tau_t^2 |1 + (1 - \tau_t) f(\tau_t)|^2 \right]$$

$$\alpha_s = \frac{g_3^2}{4\pi}, \quad \tau_t = \frac{4m_t^2}{m_h^2}$$



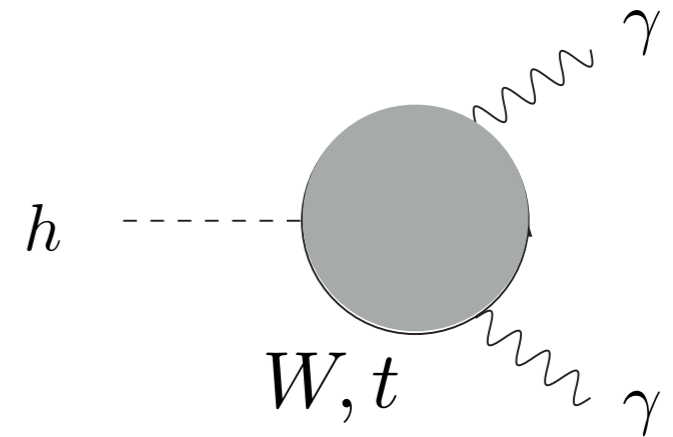
$$f(\tau_f) = -\frac{1}{2} \int_0^1 \frac{dy}{y} \ln \left[\frac{m_h^2 y(y-1) + m_f^2 - i\epsilon}{m_f^2 - i\epsilon} \right]$$

$$= \begin{cases} -\frac{1}{4} \left[\ln \left(\frac{1 + \sqrt{1 - \tau_f}}{1 - \sqrt{1 - \tau_f}} \right) - i\pi \right]^2 & \text{for } \tau_f < 1, \\ \left[\arcsin(\sqrt{1/\tau_f}) \right]^2 = \left[\arctan \left(1/\sqrt{\tau_f - 1} \right) \right]^2 & \text{for } \tau_f > 1, \\ \frac{\pi^2}{4} & \text{for } \tau_f = 1. \end{cases}$$

$h \rightarrow \gamma\gamma$

W and top give main contributions.

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha_{\text{em}}^2 m_h^3}{256\pi^3 v^2} |\mathcal{A}_W + \mathcal{A}_t|^2$$



$$\mathcal{A}_W = F_1(\tau_W), \quad \mathcal{A}_t = N_C Q_t^2 F_{1/2}(\tau_t) \quad \tau_i = \frac{4m_i^2}{m_h^2}$$

different loop functions

$$F_1(\tau) = 2 + 3\tau + 3\tau(2 - \tau)f(\tau) \xrightarrow{\tau \gg 1} 7,$$

$$F_{1/2}(\tau) = -2\tau [1 + (1 - \tau)f(\tau)] \xrightarrow{\tau \gg 1} -\frac{4}{3}$$

opposite sign

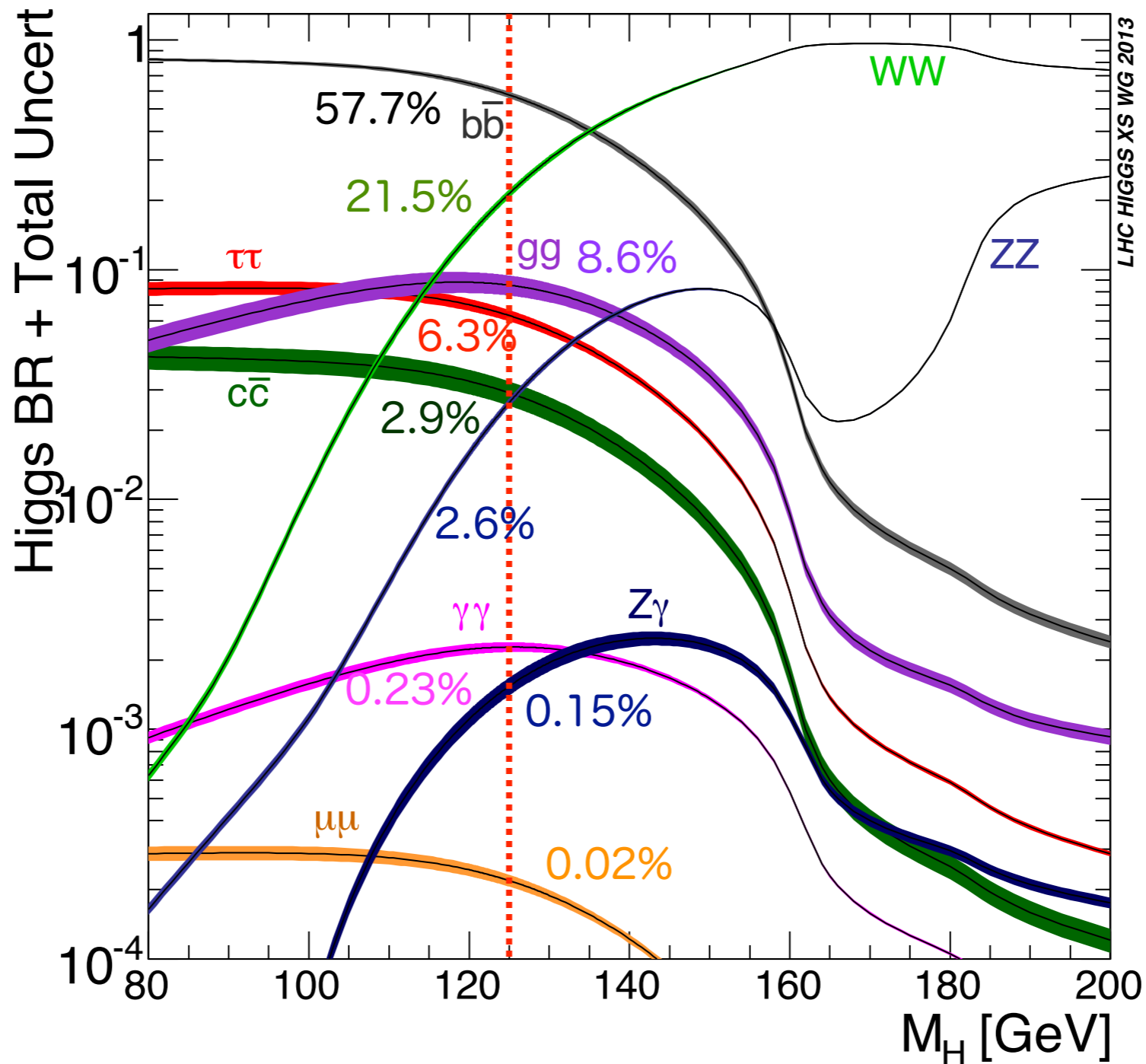
- W loop is the dominant.
- W loop and top have the opposite signs.

Branching ratios

[LHC Higgs XS WG report, arXiv: 1307.13471]

$$\Gamma(h \rightarrow f\bar{f}) \propto \frac{N_C m_f^2 m_h}{v^2}$$

125 GeV



$$\Gamma(h \rightarrow VV) \propto \frac{m_h^3}{v^2}$$

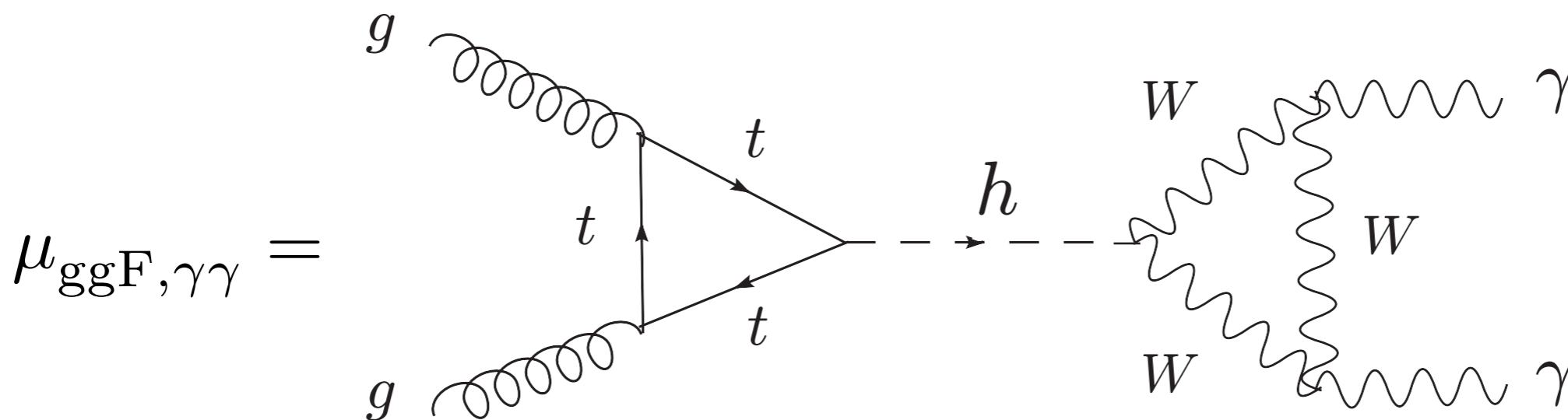
$m_h = 125 \text{ GeV}$

$b\bar{b} : 57.5\%$, $WW^* : 21.5\%$, $gg : 8.6\%$, $\tau\tau : 6.3\%$, $c\bar{c} : 2.9\%$

$ZZ^* : 2.6\%$, $\gamma\gamma : 0.23\%$, $Z\gamma : 0.15\%$, $\mu\mu : 0.02\%$

Signal strengths

$$\mu_{i,X} = \frac{\sigma_i \cdot \text{Br}(h \rightarrow X)}{\sigma_i^{\text{SM}} \cdot \text{Br}^{\text{SM}}(h \rightarrow X)} \quad \begin{array}{l} i = \text{ggF, VBF, VH, ttH,} \\ X = \gamma\gamma, VV^*, \tau\tau, b\bar{b}, \end{array}$$

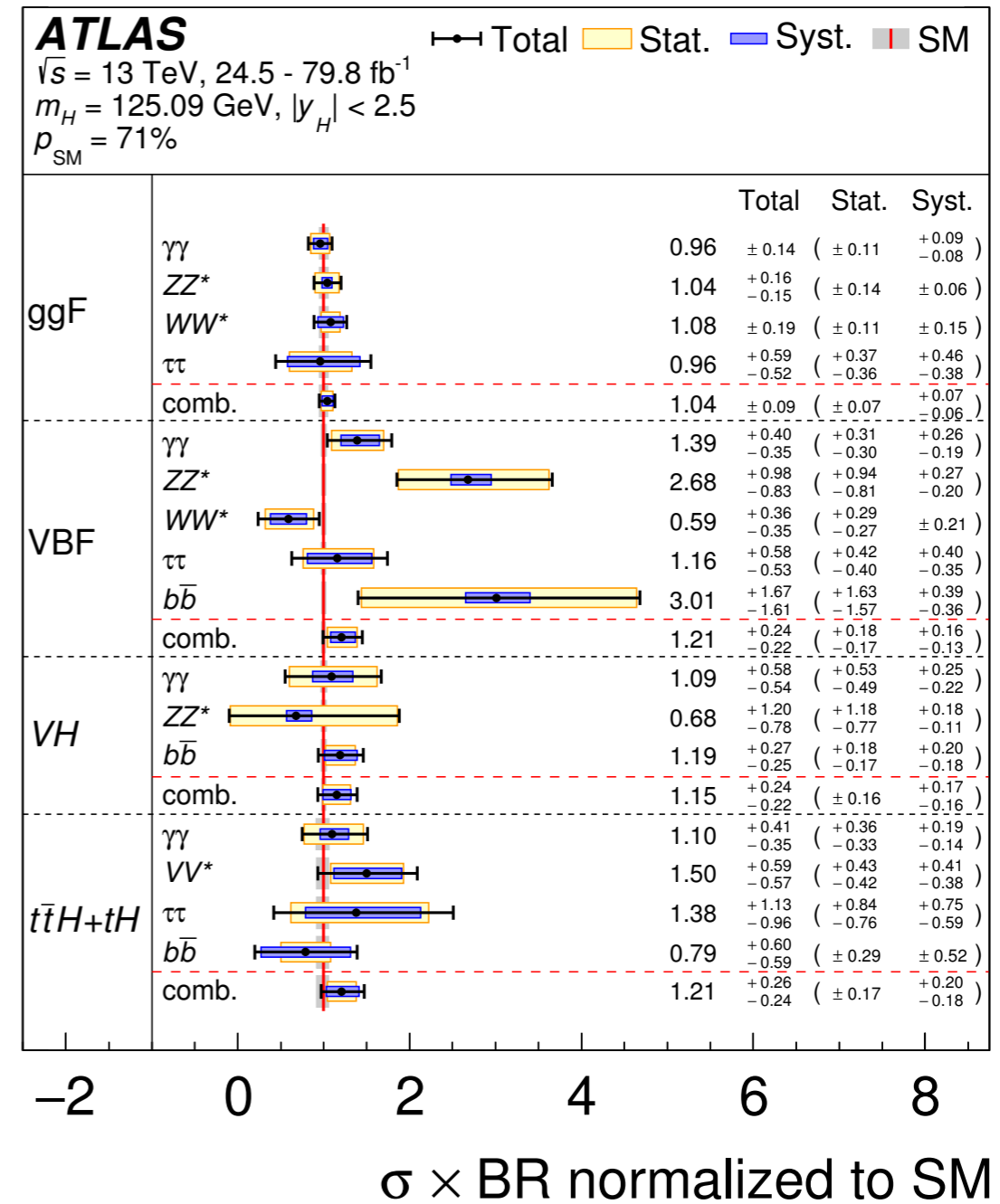
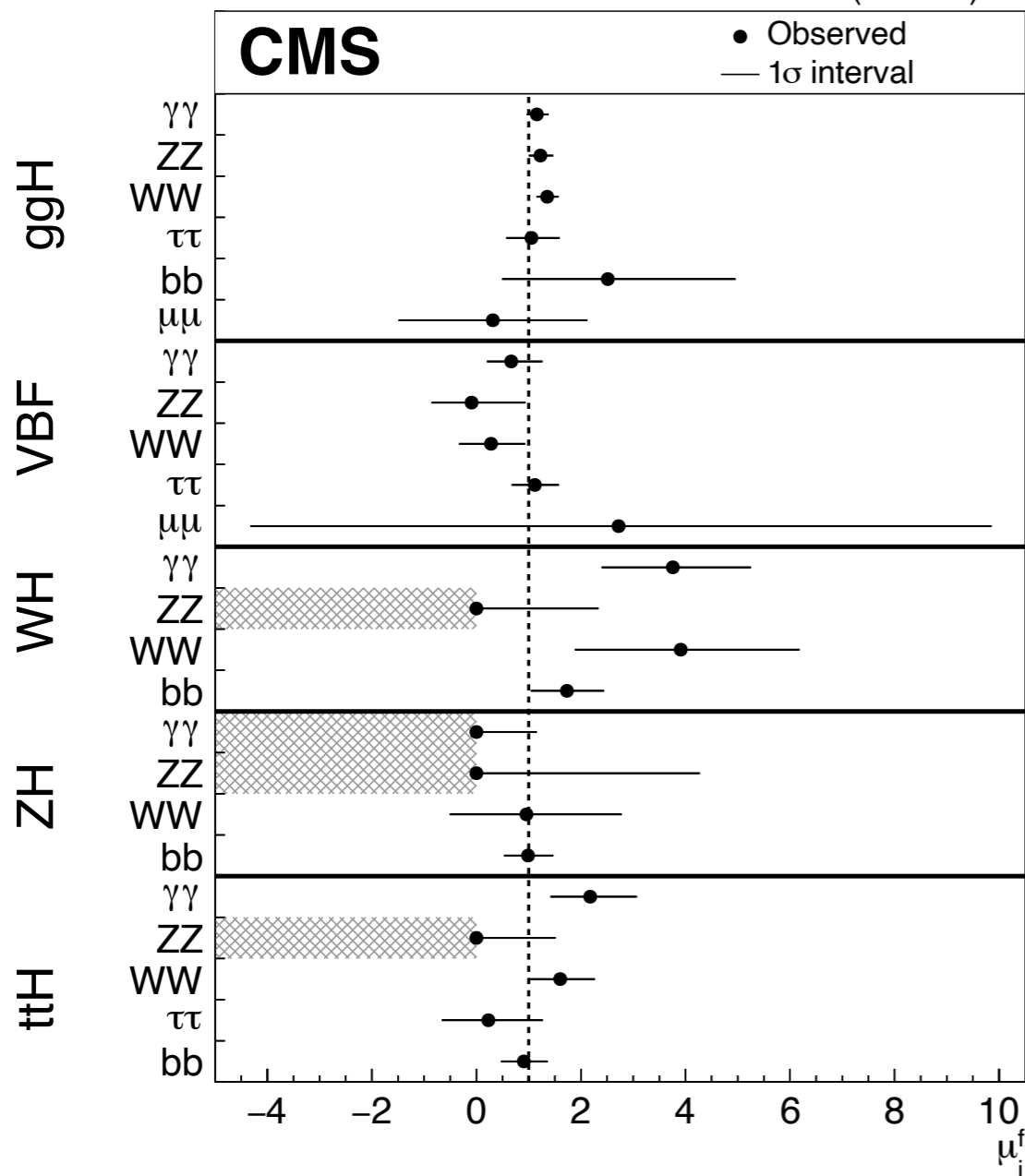


Various channels have been measured.

Current status

1809.10733
35.9 fb⁻¹ (13 TeV)

1909.02845

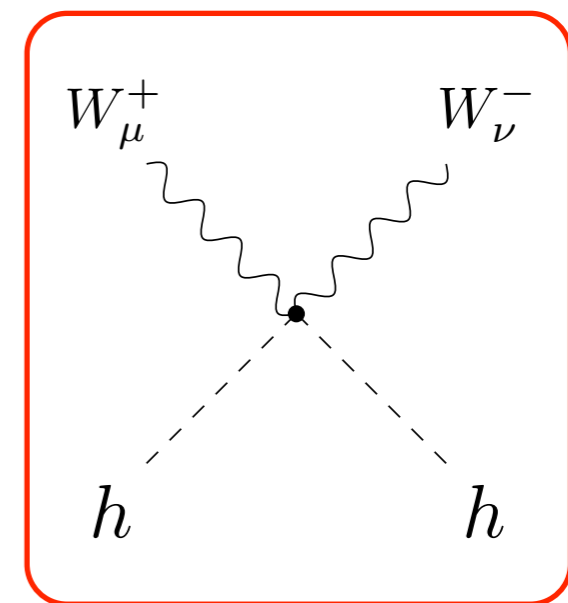
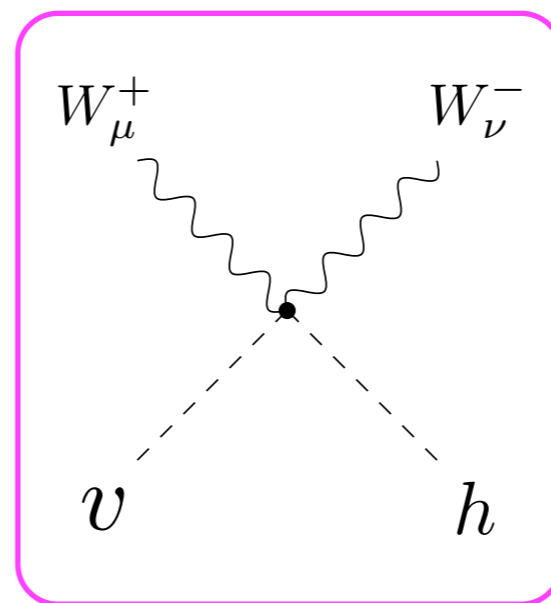
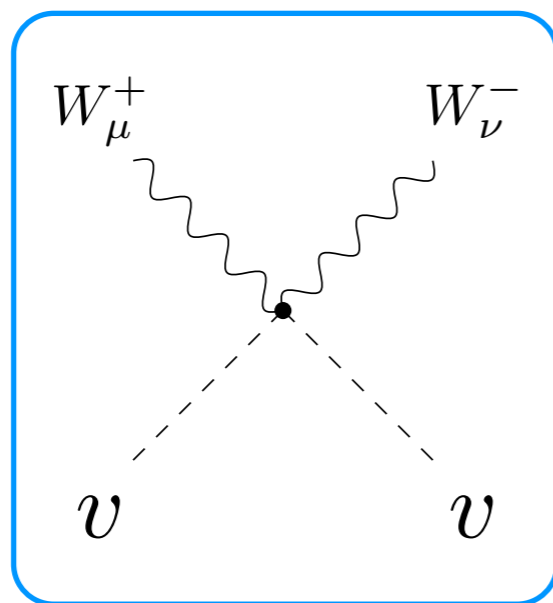


Consistent with the SM.

Higgs couplings

Since the gauge bosons get their masses from $|D\Phi|^2$, hVV coupling inevitably appears.

$$(D_\mu \Phi)^\dagger D^\mu \Phi \xrightarrow{\Phi^0 \rightarrow v+h} m_W^2 W_\mu^+ W^{-\mu} + \frac{2m_W^2}{v} h W_\mu^+ W^{-\mu} + \frac{m_W^2}{v^2} h^2 W_\mu^+ W^{-\mu} + (W \rightarrow Z)$$



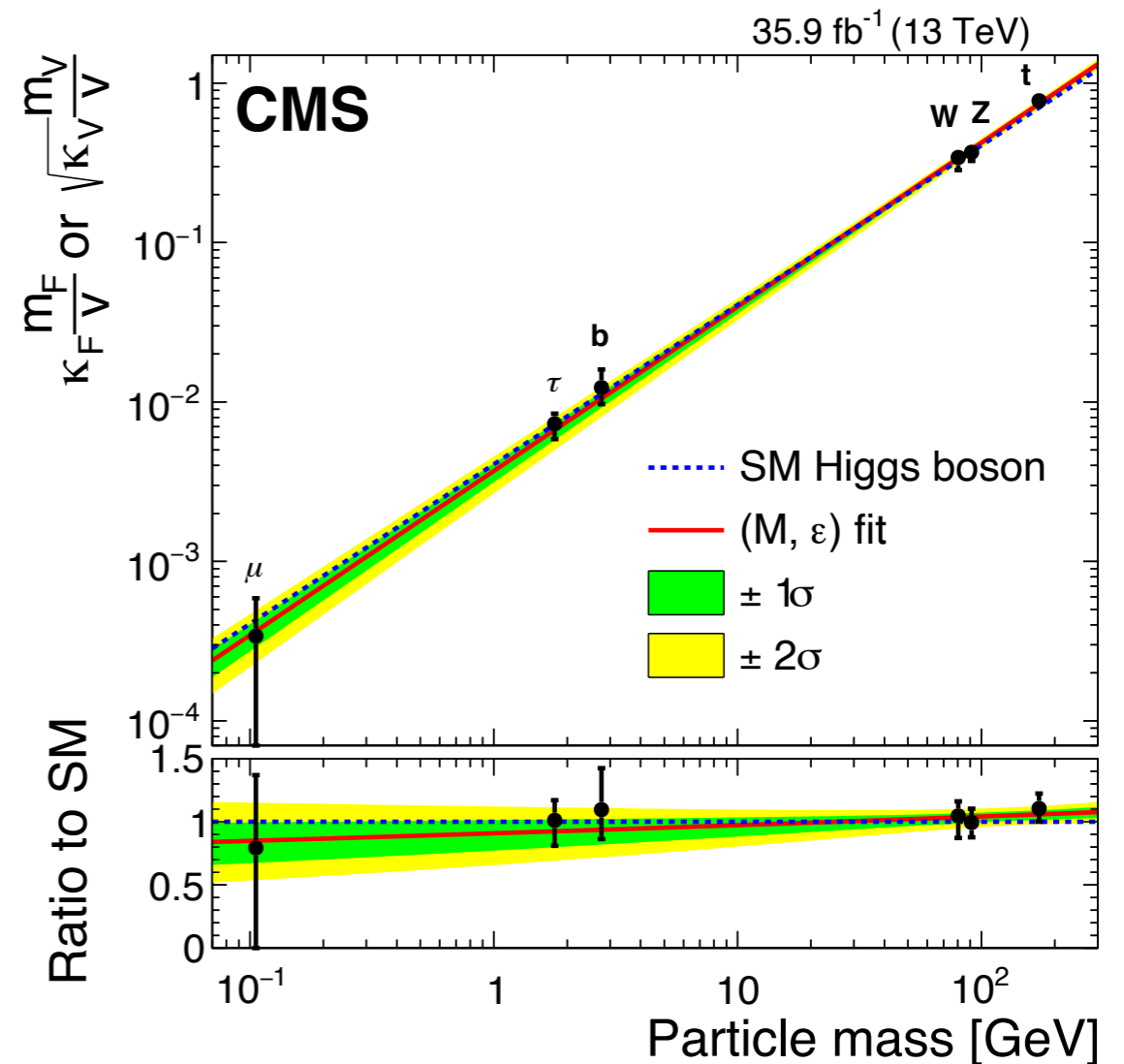
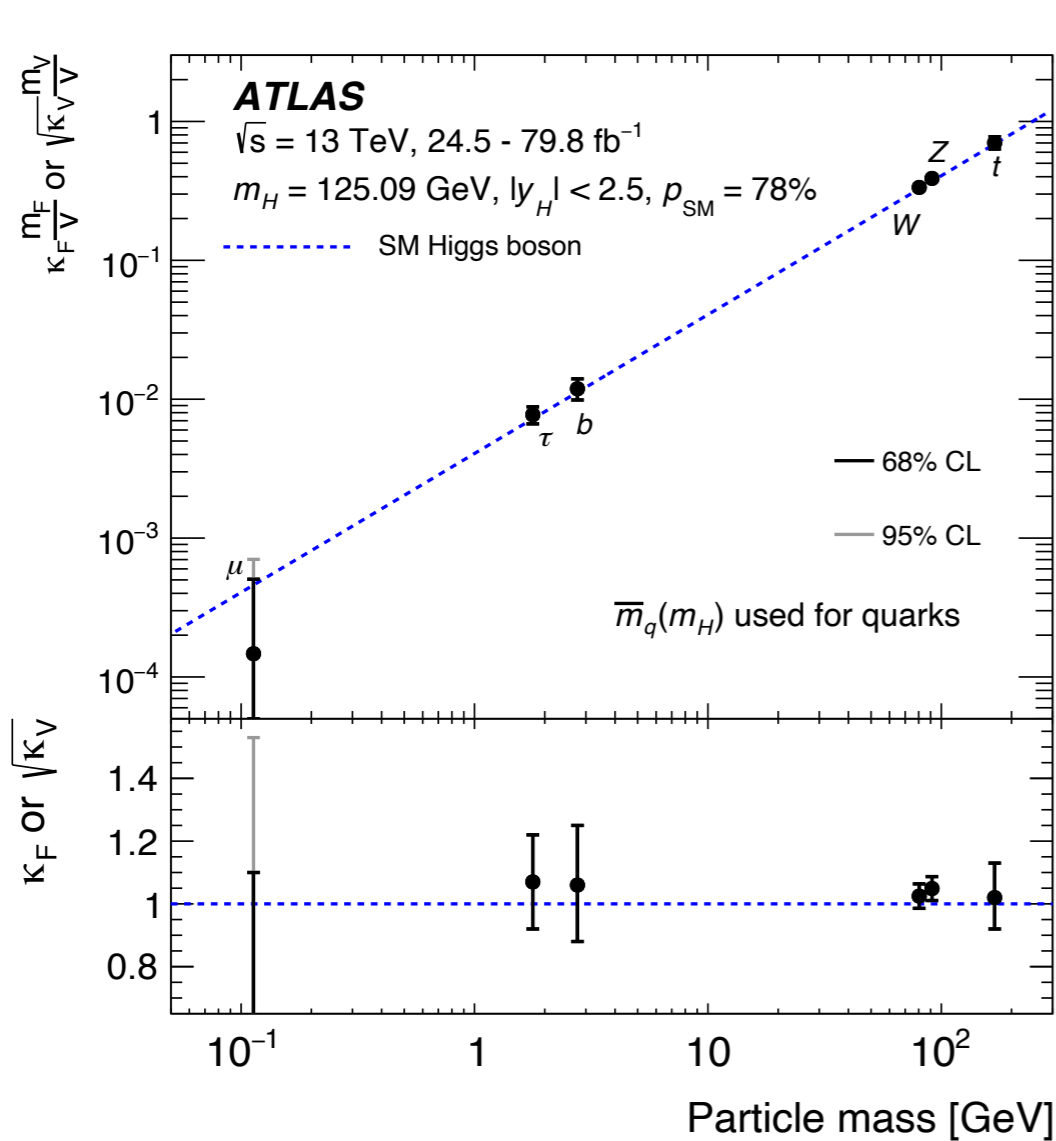
Likewise, for fermions $y_f \bar{f}_L \Phi f_R + \text{h.c.} \xrightarrow{\Phi^0 \rightarrow v+h} m_f \bar{f} f + \frac{m_f}{v} h \bar{f} f$

In the SM, coupling \propto mass.

$$g_{hVV} = m_V/v, \quad g_{h\bar{f}f} = m_f/v$$

mass vs. coupling

- Measure Higgs couplings and see the relations btw couplings and masses.



- Dotted line = SM; consistent with the SM.
- mass-coupling relations could differ in BSM models.

ρ parameter

ρ parameter is defined as $\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$

- neutral and charged current ratio
- depends on representation of Φ

SM

Φ :doublet

$$g_Z \times \frac{1}{m_Z^2} \times g_Z = \frac{4}{v^2} \quad g_Z = \sqrt{g_2^2 + g_1^2}$$

$$\rho = \frac{\text{Neutral Current Diagram}}{\text{Charged Current Diagram}} = \frac{m_W^2 g_Z^2}{m_Z^2 g_2^2} = \frac{m_W^2}{m_Z^2} \frac{1}{\cos^2 \theta_W} = 1$$

$$g_2 \times \frac{1}{m_W^2} \times g_2 = \frac{4}{v^2}$$

Experimental data

$$\rho = 1.0004_{-0.0004}^{+0.0003} \quad (95\% \text{ C.L.})$$

ρ parameter puts a constraint on representation of Φ .

m_W and m_Z depend on the representation of Higgs field.

$$\phi_{(T,Y)} = \begin{pmatrix} \vdots \\ \phi_{(T,Y)}^0 \\ \vdots \end{pmatrix}$$

↑ ↑
isospin hypercharge

$$m_W^2 = c_{T,Y} g_2^2 \sum_i \left[T_i(T_i + 1) - Y_i^2 \right] |\langle \phi_i^0 \rangle|^2,$$

$$m_Z^2 = 2(g_2^2 + g_1^2) \sum_i Y_i^2 |\langle \phi_i^0 \rangle|^2.$$

$$c_{T,Y \neq 0} = 1 \text{ and } c_{T,Y=0} = 1/2$$

- In SM $\phi_{(1/2,|1/2|)}$.
- Singlet field ($\phi_{(0,0)}$) does not contribute to m_W and m_Z .
- Fields with $Y=0$ do not contribute to m_Z .

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = \frac{c_{T,Y} \sum_i \left[T_i(T_i + 1) - Y_i^2 \right] |\langle \phi_i^0 \rangle|^2}{\sum_i 2Y_i^2 |\langle \phi_i^0 \rangle|^2},$$

If only one scalar field exists,

$\rho = 1 \longrightarrow \phi_{(T,Y)}$	with $T(T + 1) - 3Y^2 = 0$	$\phi_{(1/2, 1/2)}$	doublet
		$\phi_{(3, 2)}$	7-plet
		$\phi_{(25/2, 15/2)}$	26-plet

ρ parameter is useful for constraining new physics.

Lecture 6

Effective potential

Generating functional

$$Z[J] = e^{iW[J]} = N \int [d\phi] \exp \left[i \int d^4x \left(\mathcal{L}(\phi) + \overset{\text{external field}}{\downarrow} J(x)\phi(x) \right) \right], \quad N = Z^{-1}[J=0]$$

VEV w/ J

$$\phi_c(x) = \frac{\delta W[J]}{\delta J(x)} = N \int [d\phi] \phi(x) \exp \left[i \int d^4x \left(\mathcal{L}(\phi) + J(x)\phi(x) \right) \right] = \langle 0 | \phi(x) | 0 \rangle_J,$$

VEV w/ J=0

$$\varphi = \lim_{J \rightarrow 0} \lim_{V \rightarrow \infty} \langle 0 | \phi(x) | 0 \rangle \Big|_J \quad \leftarrow \text{constant field}$$

presumed

J=0 \rightarrow translational invariance

$$\varphi = \langle 0 | e^{iPx} \phi(0) e^{-iPx} | 0 \rangle = \langle 0 | \phi(0) | 0 \rangle$$

J=0 eventually. So, why can't we take J=0 at the beginning?

$$\varphi = N \int [d\phi] \phi(x) e^{iS[\phi]} \quad \phi(x) \rightarrow -\phi(x), \quad S[-\phi] = S[\phi], \quad [d(-\phi)] = [d\phi]$$

$$\varphi = N \int [d\phi] (-\phi(x)) e^{iS[\phi]} = -\varphi \quad \therefore \varphi = 0$$

Effective action functional Legendre trf. of $W[J]$

$$\Gamma[\phi_c] = W[J] - \int d^4x J(x)\phi_c(x), \quad \frac{\delta\Gamma[\phi_c]}{\delta\phi_c(x)} = -J(x)$$

* Generating functional for 1PI diagrams

Effective action can be expanded as

$$\Gamma[\phi_c] = \int d^4x \left[\frac{Z(\phi_c(x))}{2} (\partial_\mu \phi_c(x))^2 - V(\phi_c(x)) + \dots \right]$$

@tree level $\Gamma[\phi_c] = S[\phi_c] = \int d^4x \mathcal{L}(\phi_c)$ classical action

If $\phi_c(x)$ is a constant field φ ,

$$\Gamma[\varphi] = -V_{\text{eff}}(\varphi) \int d^4x = -V_{\text{eff}}(\varphi) (2\pi)^4 \delta^4(0)$$

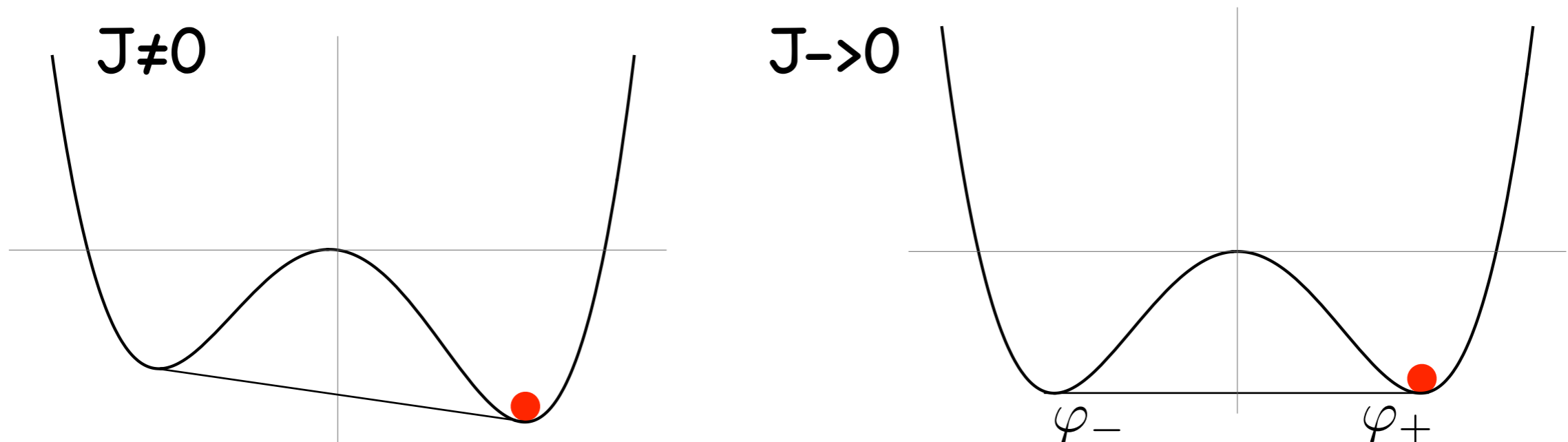
Usefulness of V_{eff}

effective potential

We can search for vacuum at quantum level by $\frac{dV_{\text{eff}}(\varphi)}{d\varphi} = 0$.

it can cope with models with radiative SSB (no SSB at tree level)

Convexity



$$\varphi = \lim_{J \rightarrow 0} \lim_{V \rightarrow \infty} \langle 0 | \phi(x) | 0 \rangle |_J$$

Legendre transformed function is mathematically convex.

- Potential with flat vacuum (convex) = genuine V_{eff} .

flatness \leftarrow mixed configuration $\varphi_{\text{mix}} = x\varphi_- + (1-x)\varphi_+$, $0 \leq x \leq 1$

- Double-well potential (we use) (*we still call it V_{eff} .)
no mixed configuration \rightarrow non-convex potential

Exercise

Show that vacuum expectation values of fields except for scalars vanish if the vacuum respect the Poincaré symmetry.

1-loop V_{eff}

After summing all 1PI diagrams and regularize them by the $\overline{\text{MS}}$ -bar scheme, one 1-loop V_{eff} as

$$V_1^{(\text{scalar})}(\varphi) = \frac{\bar{m}^4}{64\pi^2} \left(\log \frac{\bar{m}^2}{\bar{\mu}^2} - \frac{3}{2} \right) \quad \bar{m}^2 = \frac{\partial^2 V_0}{\partial \varphi^2}$$

$\bar{\mu}$: renormalization scale in the $\overline{\text{MS}}$ scheme

statistics

$$V_1^{(\text{fermion})}(\varphi) = \overset{\downarrow}{-4} \cdot \frac{\bar{m}^4}{64\pi^2} \left(\log \frac{\bar{m}^2}{\bar{\mu}^2} - \frac{3}{2} \right)$$

dof

$$V_1^{(\text{gauge})}(\varphi) = 3 \cdot \frac{\bar{m}^4}{64\pi^2} \left(\log \frac{\bar{m}^2}{\bar{\mu}^2} - \frac{5}{6} \right) \quad (\xi = 0)$$

We can obtain the Higgs mass at 1-loop level using 1-loop V_{eff} .

Higgs mass at 1-loop

$$V_{\text{eff}}(\varphi) = V_0(\varphi) + V_1(\varphi) \quad m_h^2 = \left. \frac{\partial^2 V_{\text{eff}}}{\partial \varphi^2} \right|_{\varphi=v} = 2\lambda v^2 - \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{m_t^2}{\bar{\mu}^2}$$

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{\varphi}{\sqrt{2}} \end{pmatrix}$$

However

Higgs mass obtained by the potential \neq Physical Higgs mass

$\frac{1}{p^2 - M_h^2}$ physical mass is defined by pole of the propagator

$$M_h^2 = m_h^2 + \text{Re}\bar{\Sigma}_h(M_h) - \text{Re}\bar{\Sigma}_h(0) = m_h^2 + \frac{3m_t^2 M_h^2}{4\pi^2 v^2} \left(\frac{1}{3} + \frac{1}{2} \ln \frac{m_t^2}{\bar{\mu}^2} \right)$$

↑
physical Higgs mass

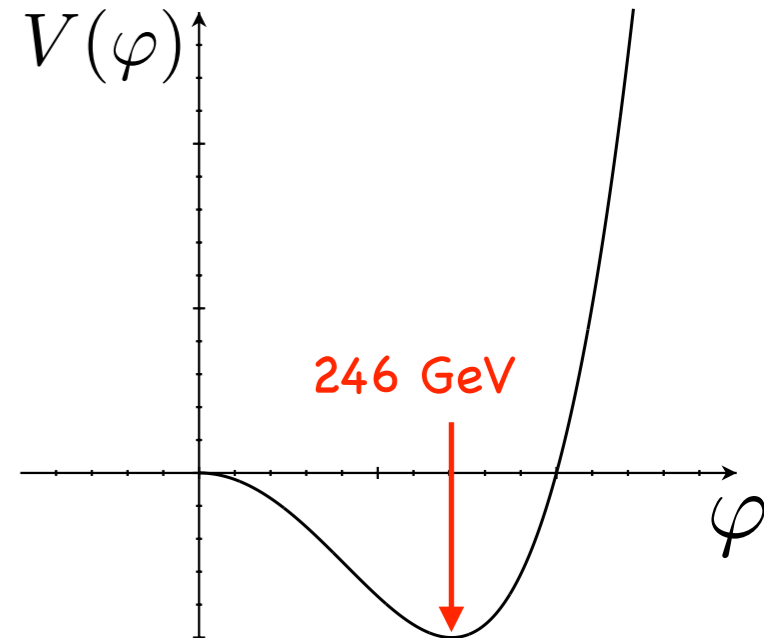
This correction is small for $\bar{\mu} = m_t$

In the SM, the Higgs mass obtained by the potential is close to the physical Higgs mass. (* this is not always true in BSM models)

Vacuum stability

- Is vacuum stable?

$$V(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4$$



- It looks stable since $\lambda = m_h^2/2v^2 > 0$.
- However, λ can change with energy. $\lambda \rightarrow \lambda(Q)$.
 $\lambda(Q) > 0$ even for high energy (large ϕ)?

$$V(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \xrightarrow{\varphi \gg v} \frac{\lambda(Q)}{4}\varphi^4$$

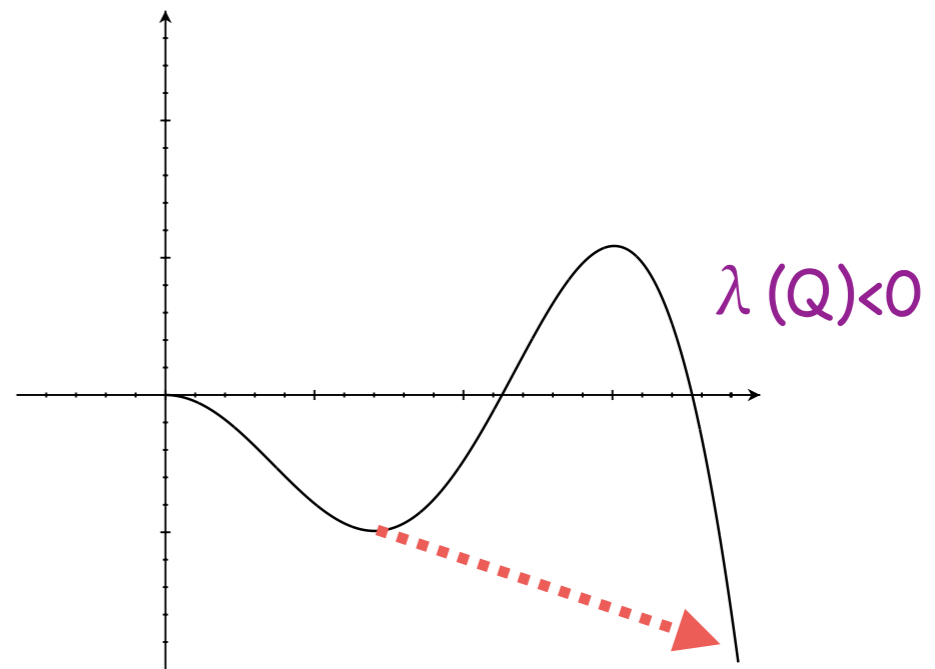
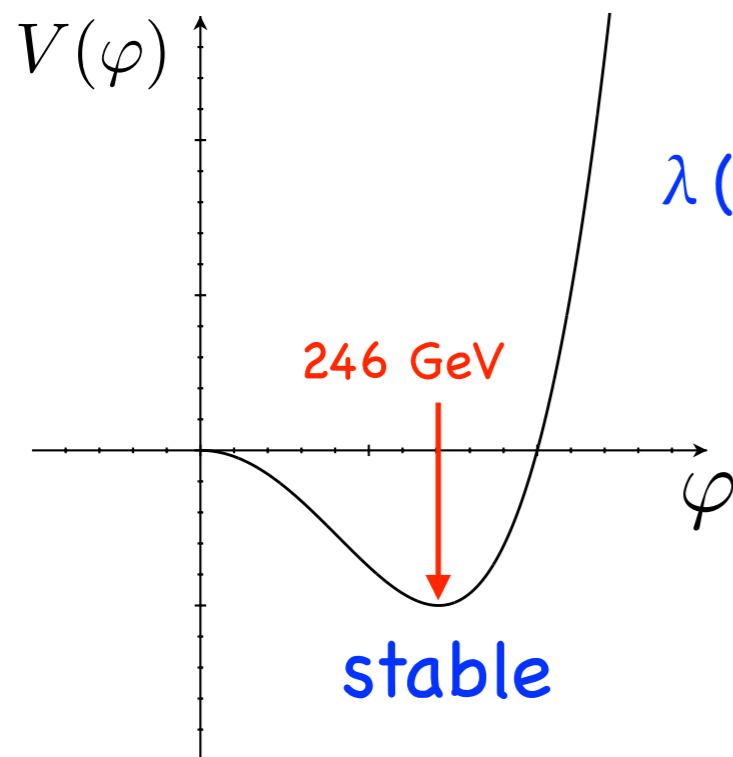
- Quadratic term can be neglected for large ϕ .

Vacuum stability

- $\lambda(Q)$ obeys renormalization group equation.

$$\frac{d\lambda(t)}{dt} = \frac{1}{16\pi^2} [24\lambda^2 - 6y_t^4 + 12\lambda y_t^2 + \dots], \quad t = \ln(Q/v)$$

- vacuum stability largely depends on λ & y_t (& α_s).



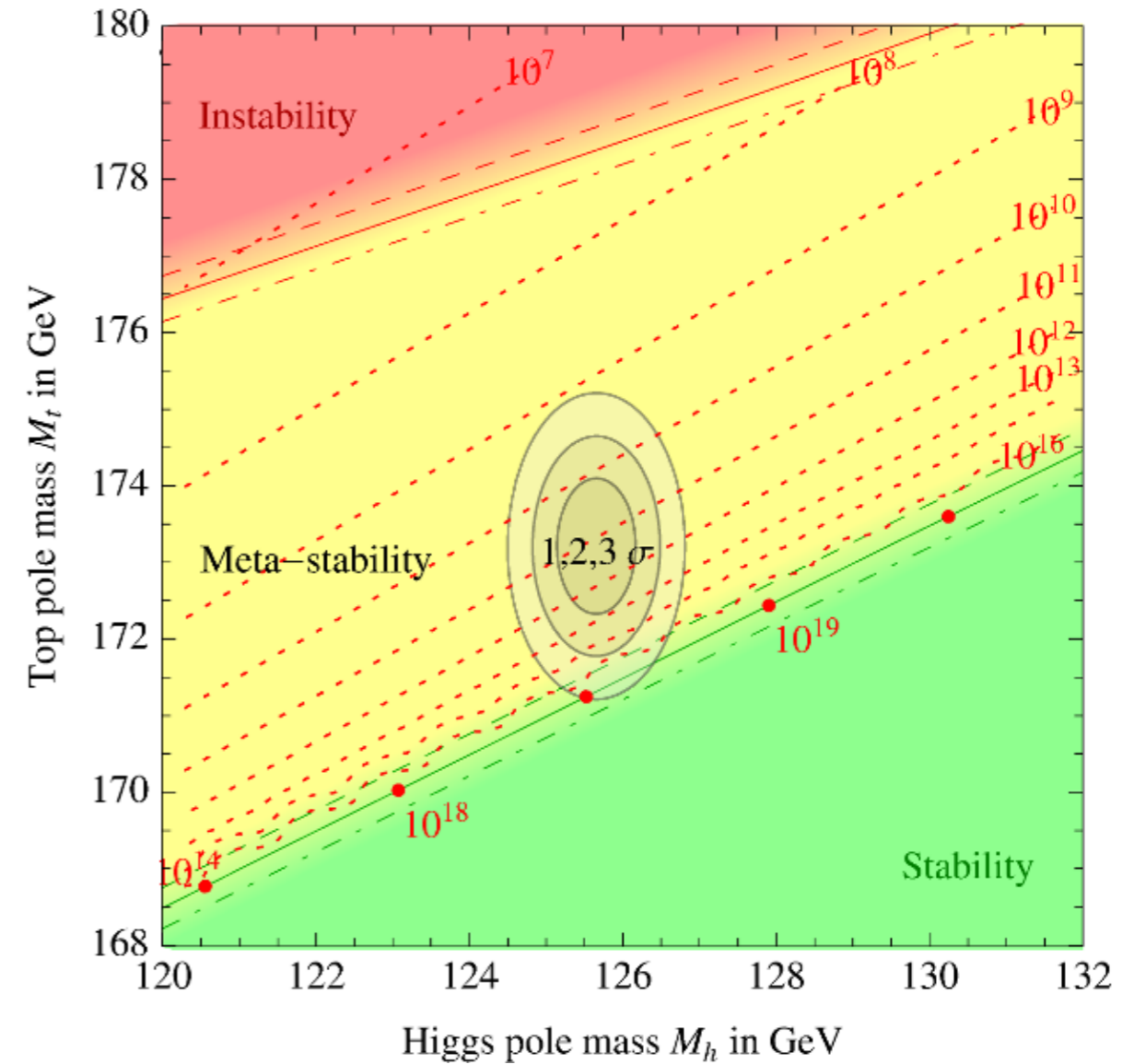
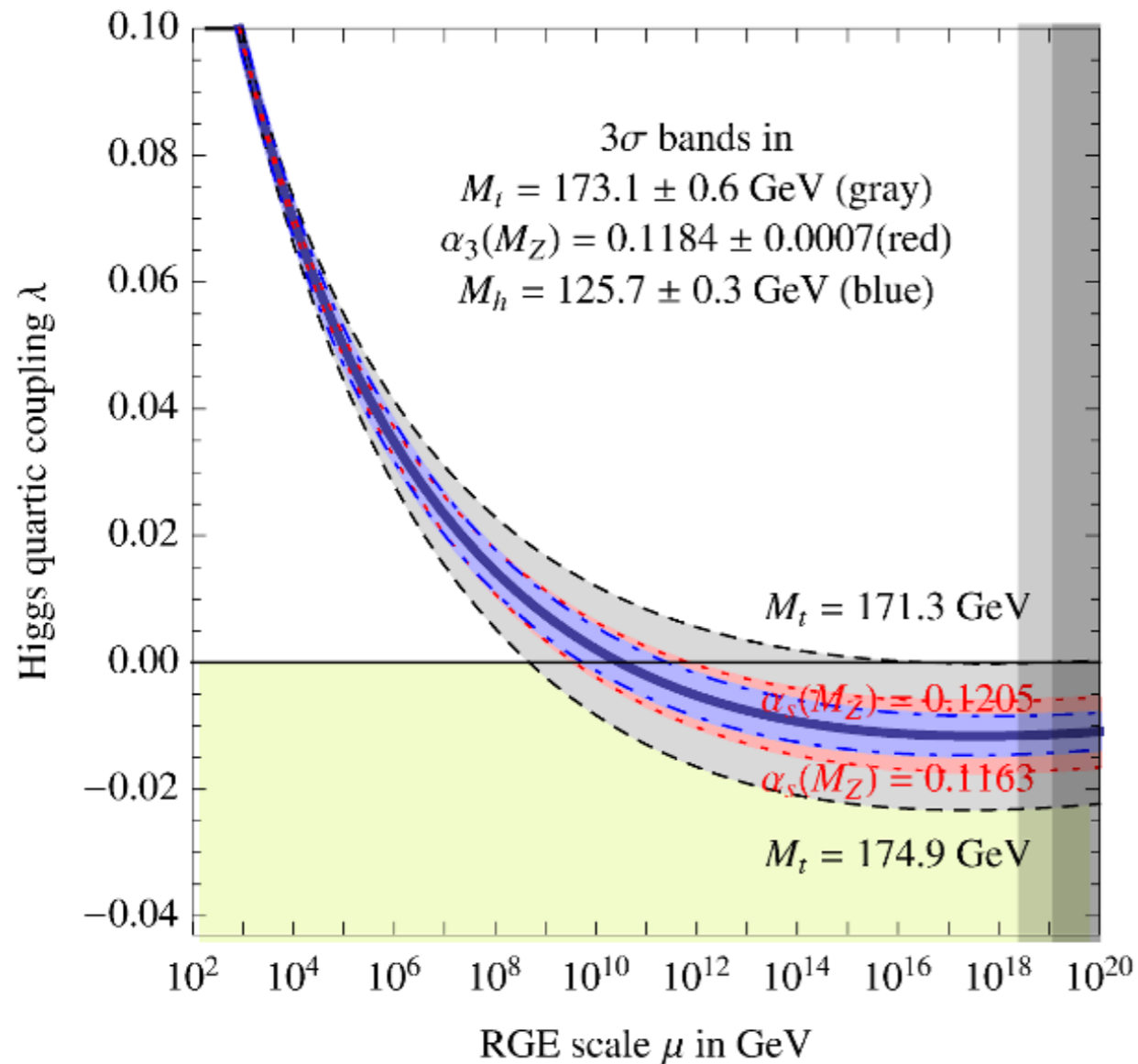
lifetime of the vacuum $>$ age of the Universe \rightarrow meta-stable.

lifetime of the vacuum $<$ age of the Universe \rightarrow unstable.

What is the current status?

Vacuum stability

JHEP12 (2013) 089 (1307.3536)



- "stable" or "meta-stable" depends on top mass.
- $\Delta m_t = 0.5$ GeV@HL-LHC, $\Delta m_t = 0.1$ GeV@ILC

Summary

Summary

- SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory.
- All elementary particles get their masses via Higgs mechanism
- All experiments so far are consistent with SM!!

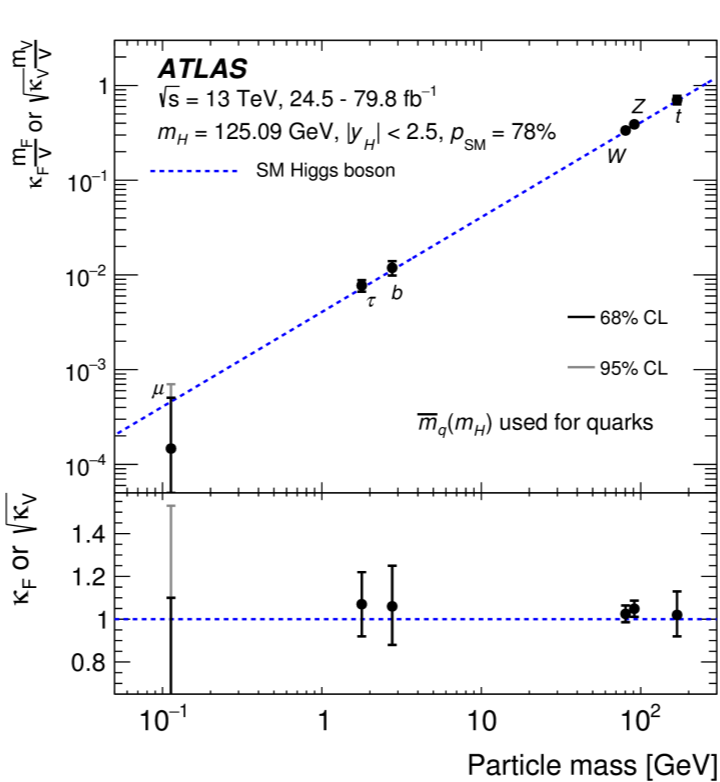
Supersymmetric particles searches at LHC

Higgs coupling measurements at LHC

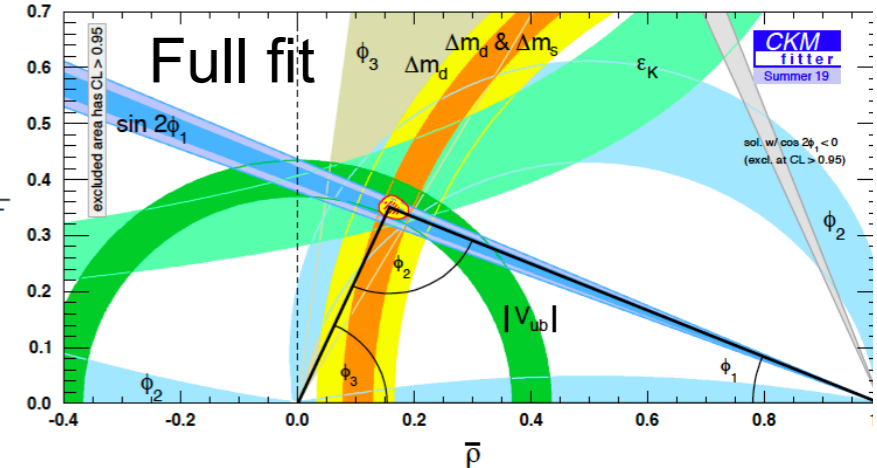
ATLAS SUSY Searches* - 95% CL Lower Limits
June 2021

Model	Signature	$\int \mathcal{L} dt$ (fb $^{-1}$)	Mass limit	Reference
Inclusive Searches	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	2-6 jets E_{T}^{miss} 139	$m(\tilde{g}) < 493$ GeV
	mono-jet	1-3 jets E_{T}^{miss} 36.1	$\tilde{\chi}_1^0$ (8x Degener.) 0.9, 1.85	$m(\tilde{g}) < 493$ GeV
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	2-6 jets E_{T}^{miss} 139	Forbidden 1.15-1.95, 2.3
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1 ϵ, μ	2-6 jets E_{T}^{miss} 139	Forbidden 1.15-1.95, 2.2
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	cc, $\mu\mu$	2 jets E_{T}^{miss} 36.1	Forbidden 1.2, 2.2
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	SS ϵ, μ	7-11 jets E_{T}^{miss} 139	Forbidden 1.15, 1.97
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	SS ϵ, μ	6 jets E_{T}^{miss} 139	Forbidden 1.25, 2.25
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0-1 ϵ, μ	3 b E_{T}^{miss} 79.8	Forbidden 1.25, 2.25
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	SS ϵ, μ	6 jets E_{T}^{miss} 139	Forbidden 1.25, 2.25
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	2 b E_{T}^{miss} 139	Forbidden 0.68, 1.255
3 γ jets, cascade decay production	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	6 b E_{T}^{miss} 139	Forbidden 0.68, 1.255
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	2 τ	2 b E_{T}^{miss} 139	Forbidden 0.13-0.85, 0.23-1.35
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0-1 ϵ, μ	≥ 1 jet E_{T}^{miss} 139	Forbidden 0.65, 1.4
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1 ϵ, μ	3 jets+1 b E_{T}^{miss} 139	Forbidden 0.55, 0.85
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1.2 τ	2 jets+1 b E_{T}^{miss} 139	Forbidden 0.55, 0.85
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	2 μ E_{T}^{miss} 36.1	Forbidden 0.55, 0.85
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	mono-jet E_{T}^{miss} 139	Forbidden 0.55, 0.85
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1-2 ϵ, μ	1-4 b E_{T}^{miss} 139	Forbidden 0.067-1.18
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	3 μ	1 b E_{T}^{miss} 139	Forbidden 0.96
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple ℓ /jets	E_{T}^{miss} 139	Forbidden 0.205, 0.96
EW direct	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple ℓ /jets	E_{T}^{miss} 139	Forbidden 0.42, 1.06
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple ℓ /jets	E_{T}^{miss} 139	Forbidden 0.16-0.3, 0.12-0.39
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	2 τ	E_{T}^{miss} 139	Forbidden 0.7, 0.7
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	2 ϵ, μ	0 jets E_{T}^{miss} 139	Forbidden 0.255, 0.29-0.88
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	cc, $\mu\mu$	≥ 1 jet E_{T}^{miss} 139	Forbidden 0.13-0.23, 0.55, 0.29-0.88
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	0 jets E_{T}^{miss} 36.1	Forbidden 0.45-0.93
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	4 ϵ, μ	0 jets E_{T}^{miss} 139	Forbidden 0.45-0.93
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 ϵ, μ	≥ 2 large jets E_{T}^{miss} 139	Forbidden 0.45-0.93
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Disapp. trk	1 jet E_{T}^{miss} 139	Forbidden 0.21, 0.66
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Stable $\tilde{\chi}_1^0$ R-hadron	Multiple	Forbidden 2.0, 2.08, 2.4
RPV	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	3 ϵ, μ	0 jets E_{T}^{miss} 139	Forbidden 0.625, 1.05
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	4 ϵ, μ	0 jets E_{T}^{miss} 139	Forbidden 0.95, 1.55
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	4-5 large jets	E_{T}^{miss} 36.1	Forbidden 1.3, 1.9
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Multiple	E_{T}^{miss} 36.1	Forbidden 0.55, 1.05
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	$\geq 4b$	E_{T}^{miss} 139	Forbidden 0.42, 0.61
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	2 jets+2 b	E_{T}^{miss} 36.1	Forbidden 0.4, 1.45
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	2 μ	2 b E_{T}^{miss} 136	Forbidden 1.0, 1.6
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1 μ	DV E_{T}^{miss} 36.1	Forbidden 0.2-0.32
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1-2 ϵ, μ	≥ 6 jets E_{T}^{miss} 139	Forbidden 0.2-0.32

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Constraints from B meson physics



Nevertheless, SM cannot be considered as final theory. Because, we know that neutrinos have masses, moreover

Beyond the SM

SM cannot explain cosmological observations.

▶ Matter-antimatter (baryon) asymmetry of the Universe

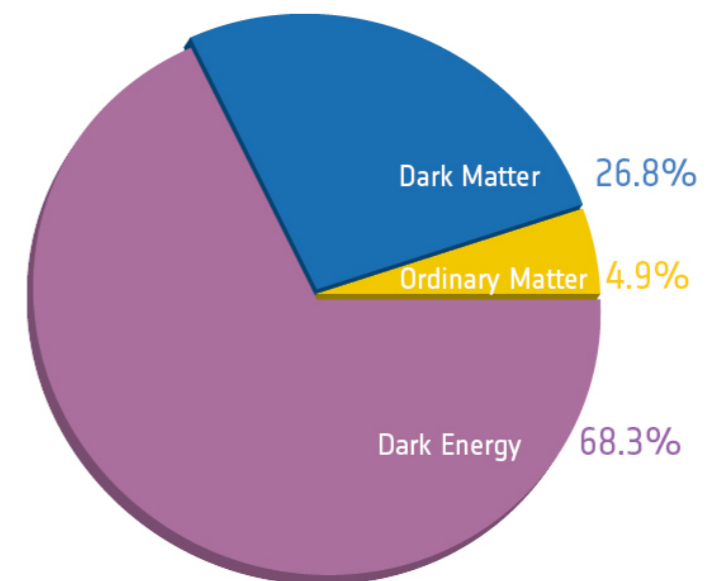
▶ Dark Matter

▶ Dark Energy

▶ Quantum gravity

▶ etc

Energy budget of the Universe



ESA and the Planck Collaboration

The Universe is NOT made of atoms but made of unknown objects.

So, SM must be extended to solve some (hopefully many) of them.