Overview of the SM

Lecture I: the SM tapestry

- Particles as Quantum Fields
- Particle zoo vs symmetry
- Gauge invariance and particle interactions
- The origin of mass: Spontaneous Symmetry breaking
- The flavour of the SM

Lecture II: the SM swiss watch

- Observables and field correlation functions
- How we calculate ? Perturbation Theory and beyond
- → Precision tests of the SM (LEP-TEVATRON-B factories)

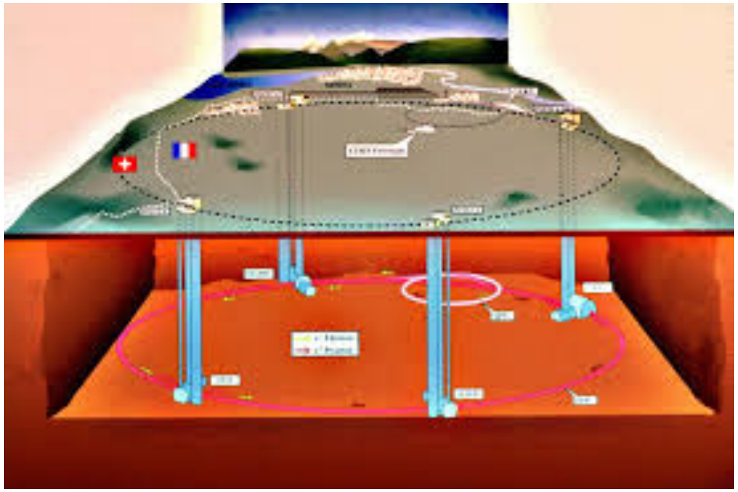
Lecture III: the open-ended SM

- The SM at the LHC: Higgs physics
- Open questions

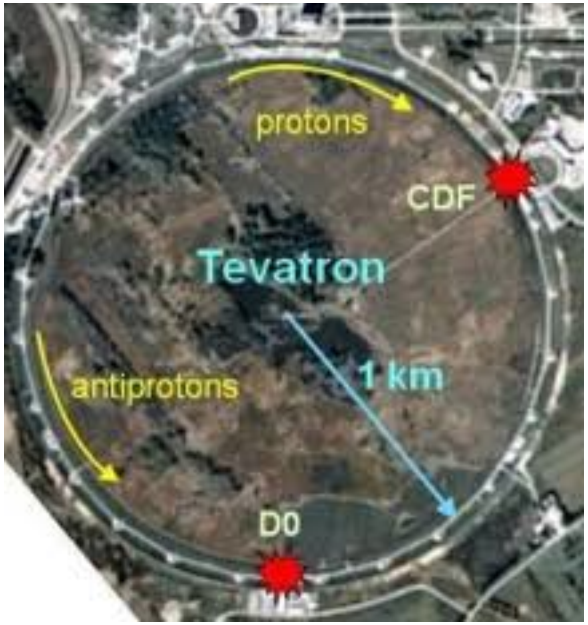
EW precision tests

In the 90's LEP/SLD and Tevatron tested the SM at few per mille level!

e+e- colliders LEP1 (s=90GeV), LEP2 (200GeV)



p pbar collider s=2 TeV



EW precision tests

Need to fix the free parameters of the SM: $g_s\,, g, g'\,, v, M_h$

$$\alpha^{-1} = 137.035999074(44)$$ -> (g-2)e

$$G_F = 1.1663787(6) \times 10^{-5}\mathrm{GeV}$$ -> Muon lifetime

$$M_Z = 91.1876(21)\mathrm{GeV}$$ -> Z-pole mass (LEP)

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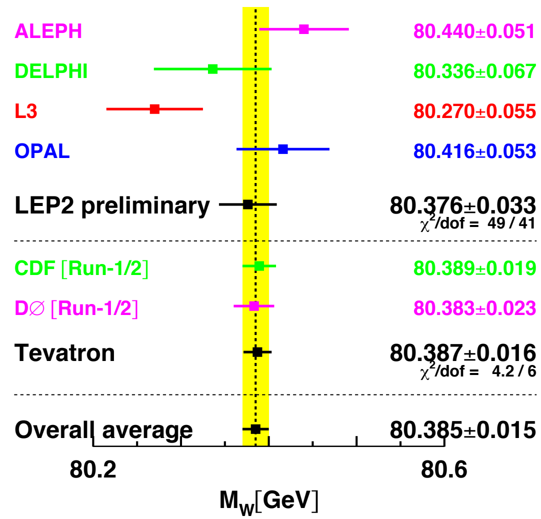
$$\left.\begin{aligned} M_W^2 \sin^2\theta_W &= \frac{\pi\alpha}{\sqrt{2}G_F} \\ \sin^2\theta_W &= 1 - \frac{M_W^2}{M_Z^2} \end{aligned}\right\} \to M_W = 80.938\ \mathrm{GeV}, \sin^2\theta_W = 0.212$$

$$|M_W(exp) - M_W(tree)| = 553(15)MeV$$



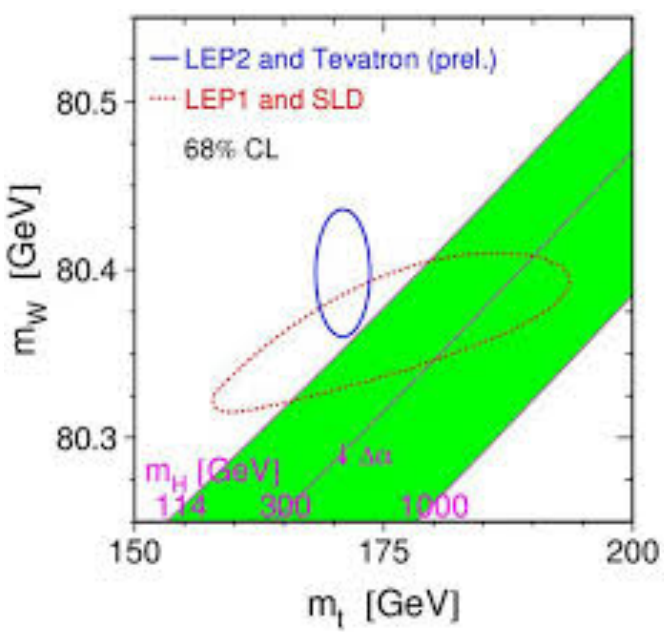
Tree level relations get modified at higher orders !

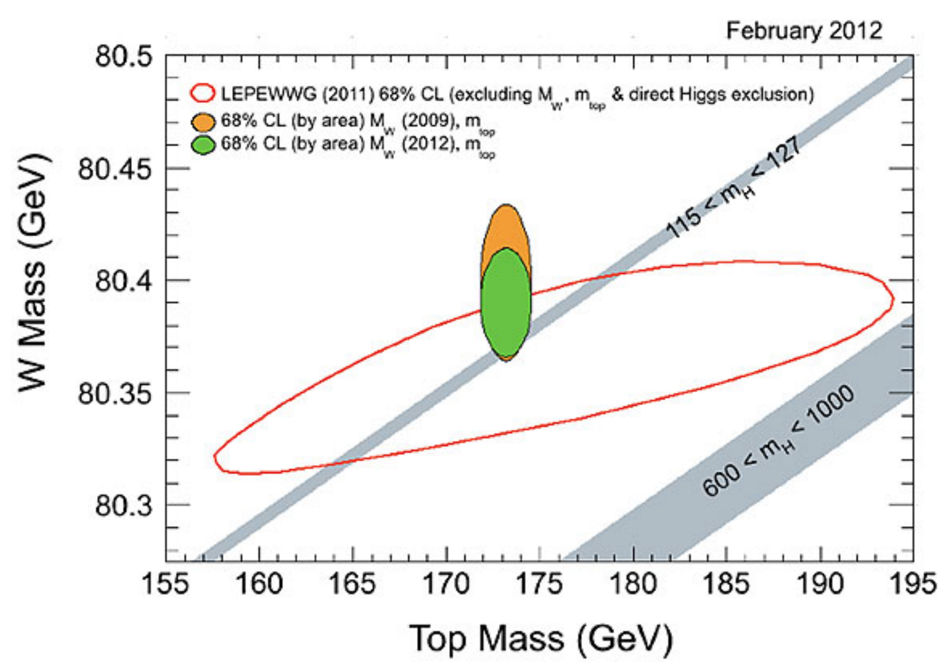
EW precision tests

Need one loop corrections: also virtual effects of heavy particles enter

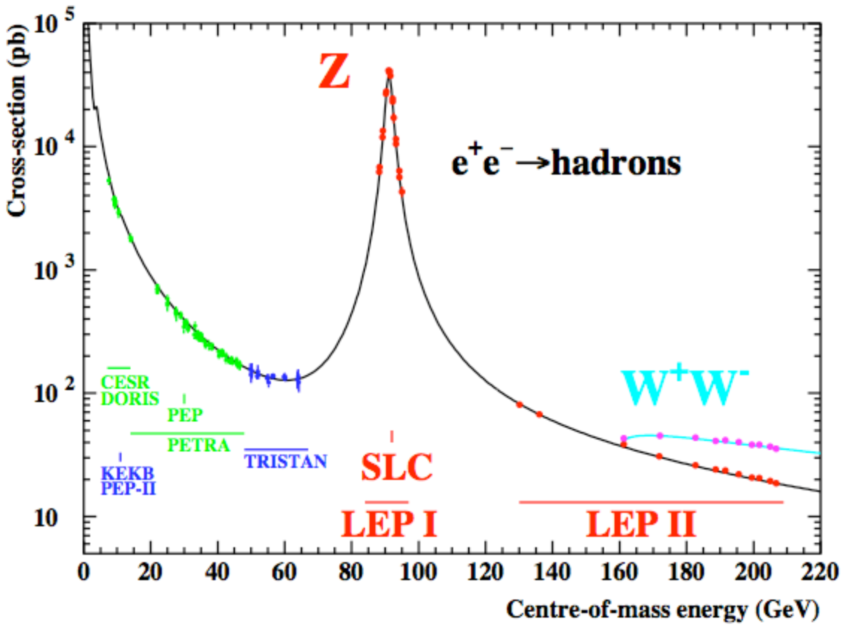
$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}(1+\Delta r)$$

$$\Delta r = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{\cos^2\theta_W}{\sin^2\theta_W} + \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\log\frac{M_h^2}{M_W^2}$$

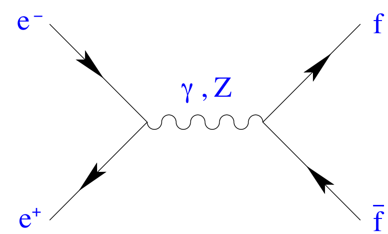


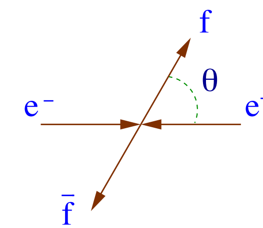


LEP



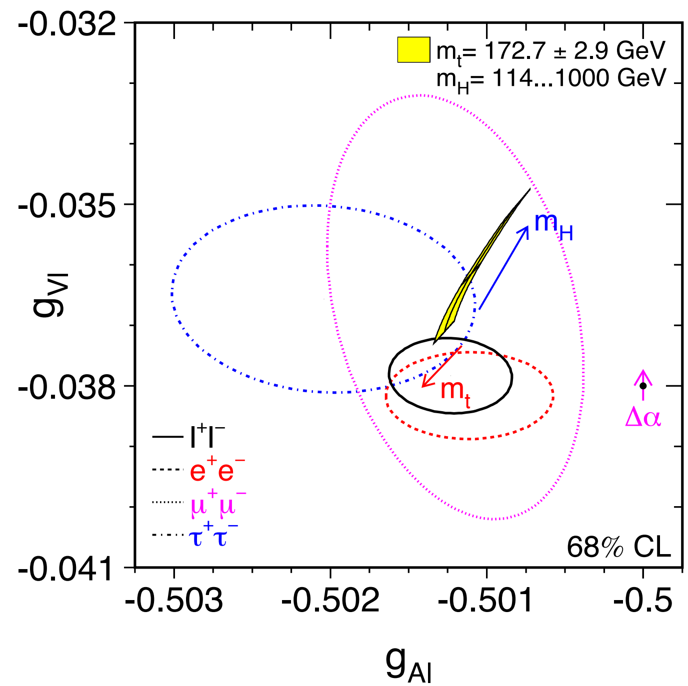
10 million Z's





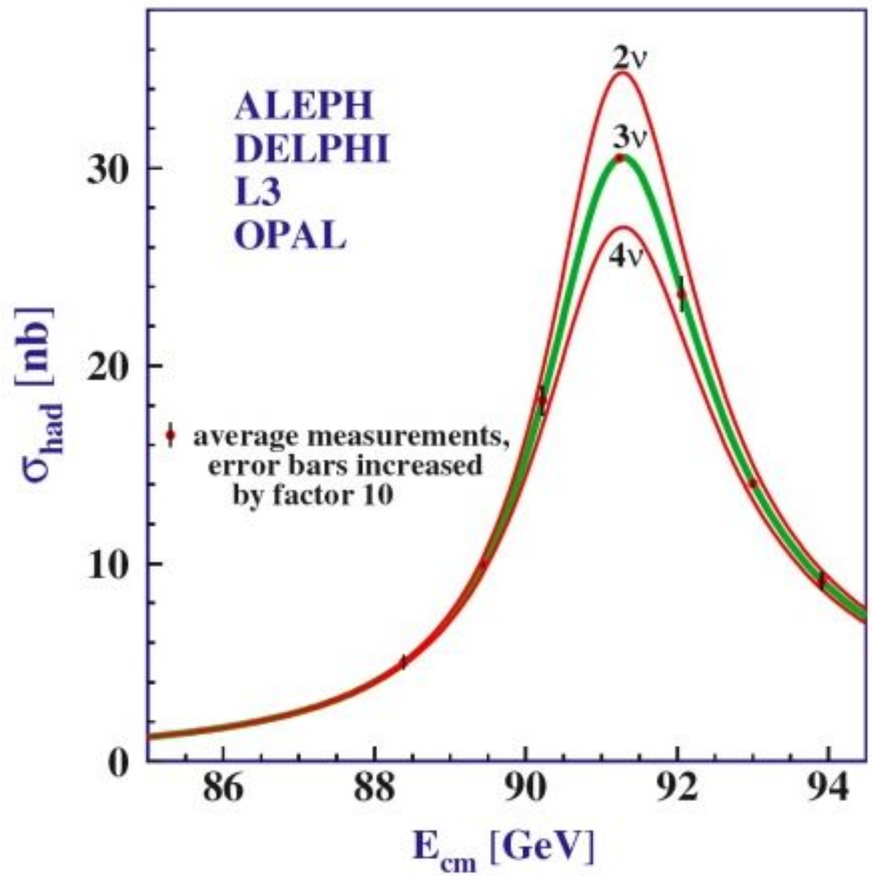
$$BR(Z \to f\bar{f}) = \frac{\Gamma_f}{\Gamma_Z}$$

$$M_Z, \Gamma_Z, \sigma_f(M_Z) = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$$



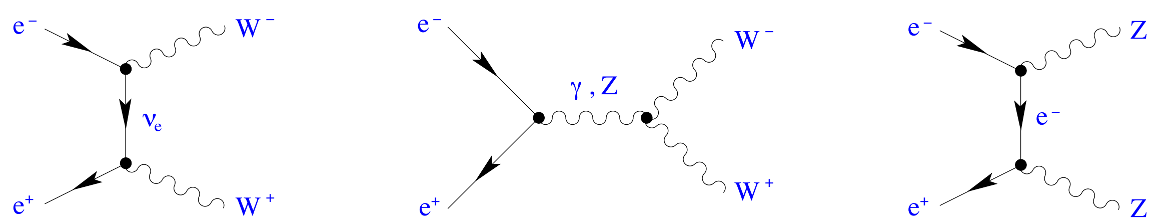
LEP: 3 flavours/families

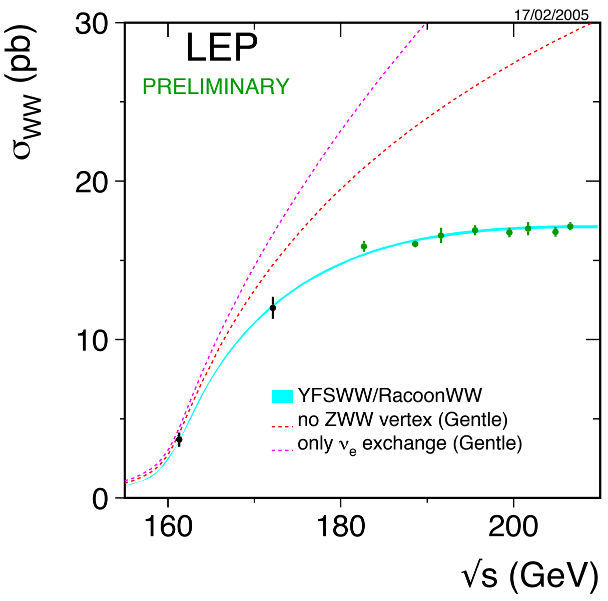
$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$$

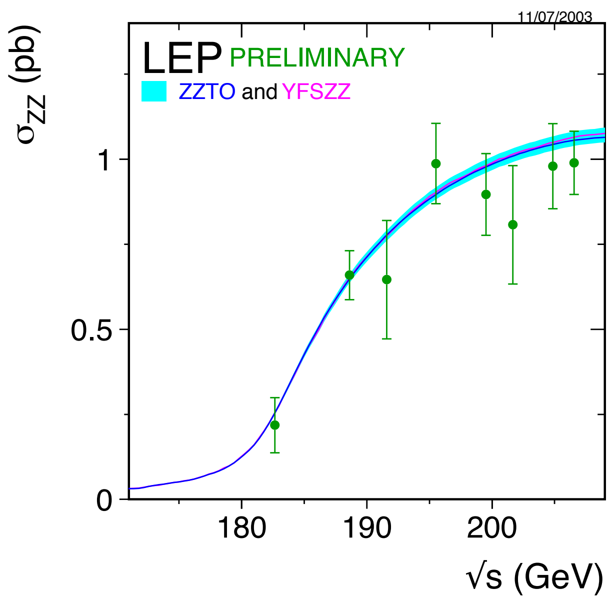


Thanks to the lightest of neutrinos we know that no new heavier families will show up

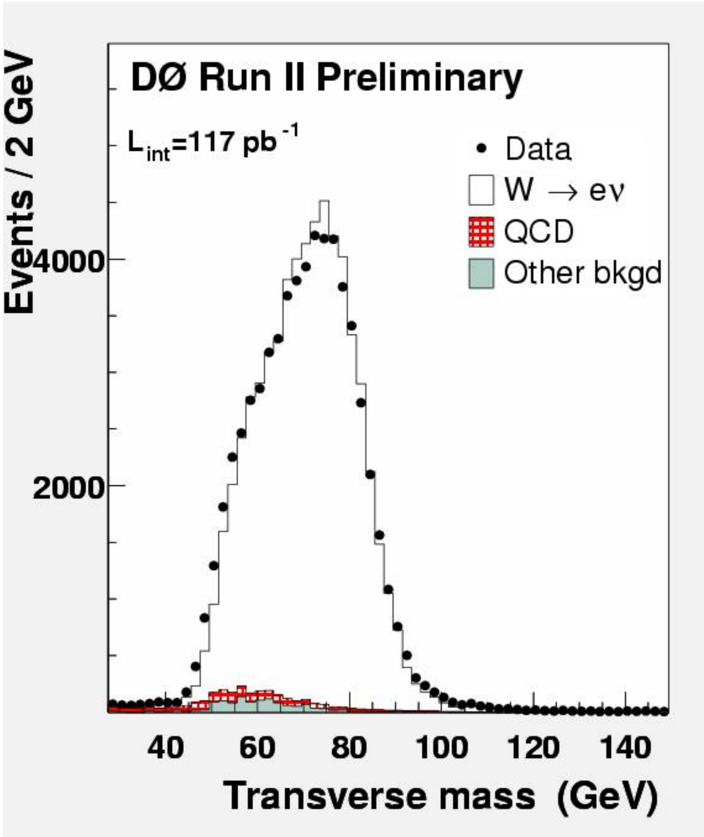
LEP: gauge boson selfcouplings



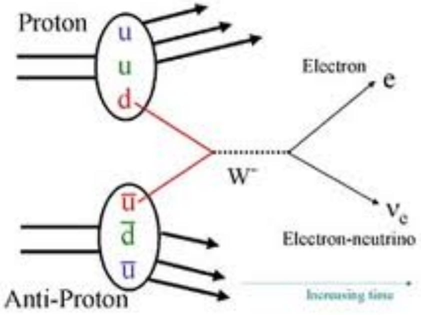


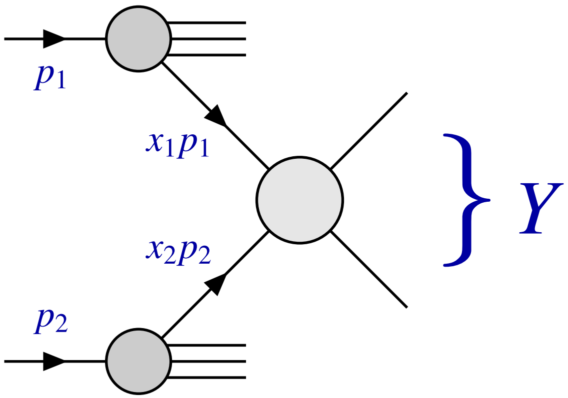


TEVATRON



O(10) million W's

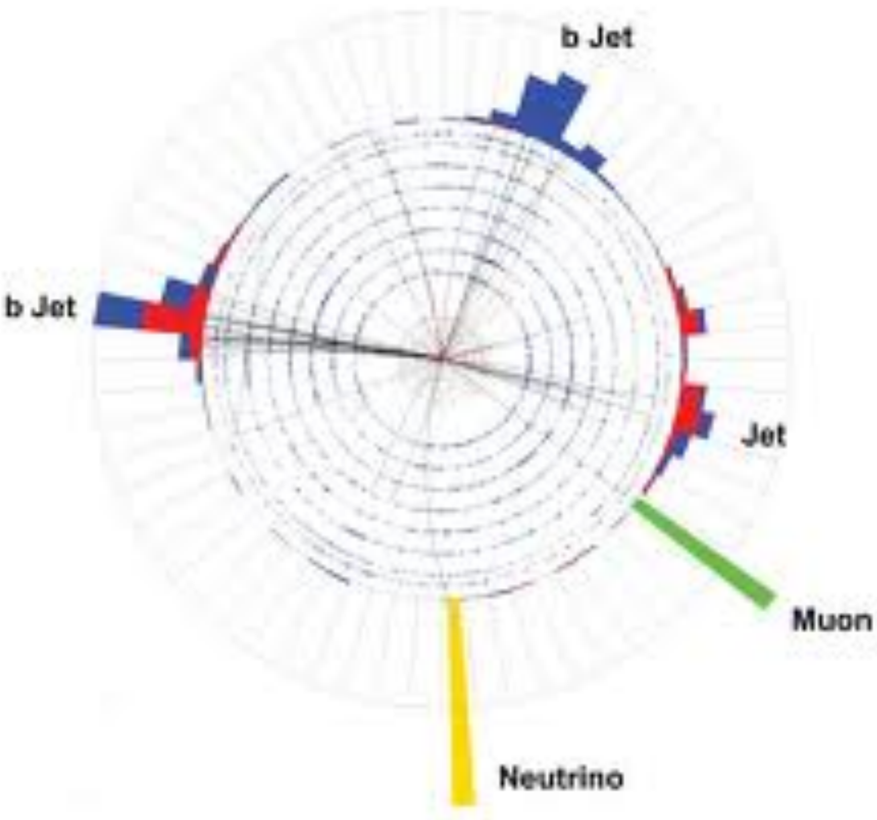


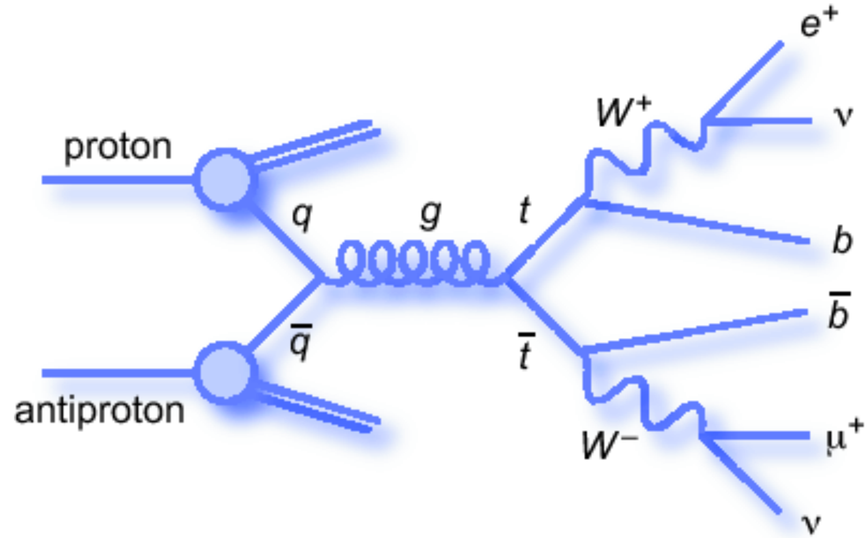


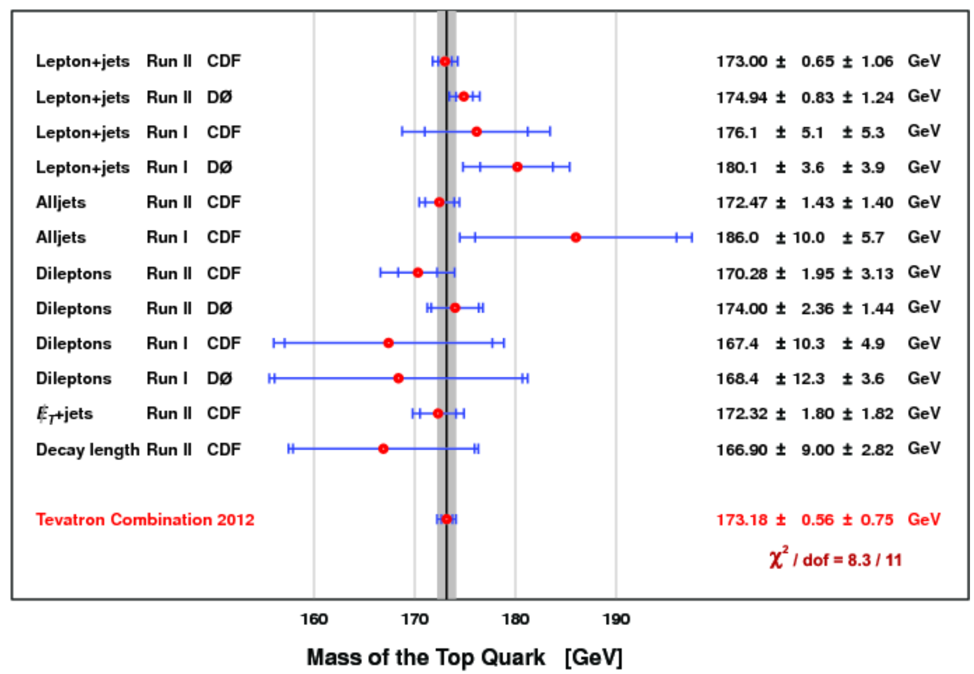
$$\sigma(h_1 + h_2 \to Y + X) = \int_{x_1} \int_{x_2} \sum_{f_1, f_2} f_{p_1}(x_1) f_{p_2}(x_2) \sigma(f_1 + f_2 \to Y)$$

$$M_W, \Gamma_W, BR's$$

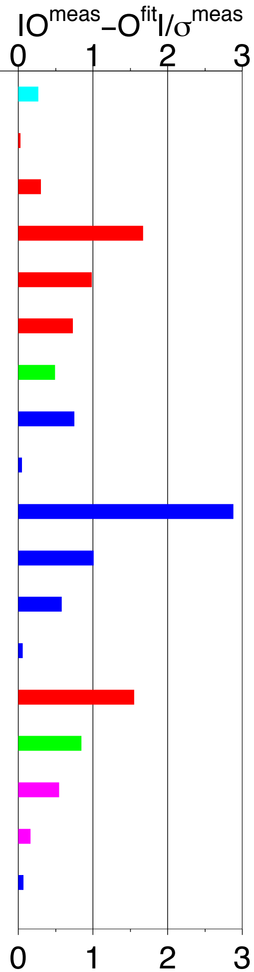
TEVATRON: top quark







	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

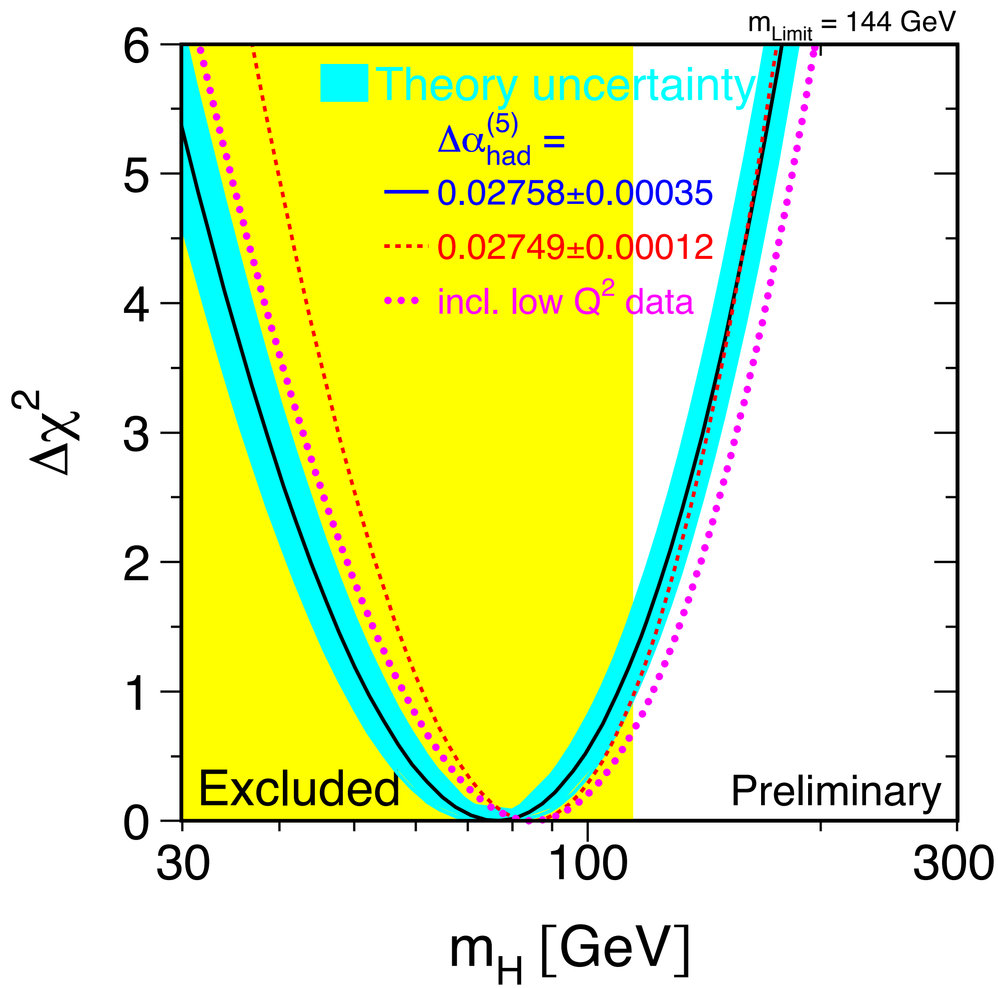


March 2012

$$\mathcal{A}^f = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$\mathcal{A}^f_{FB} = \frac{\int_0^1 d\cos\theta \frac{d\sigma_f}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\sigma_f}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\sigma_f}{d\cos\theta}}$$

Higgs mass before the discovery



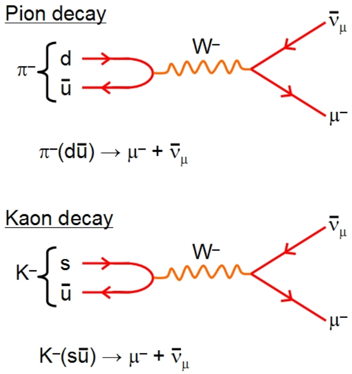
Flavour Precision Physics

$$|V_{CKM}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|^2 \\ \text{Nuclear } \beta \text{ decay} & K \to \pi l \nu,\ K, \pi \to l\nu & B \to \pi l \nu \\ & & \\ V_{cd}| & |V_{cs}| & |V_{cb}|^2 \\ D \to \pi l \nu,\ \nu d \to cX & D \to K l \nu,\ W^+ \to c\bar{s} & B \to D l \nu, b \to c l \nu \\ & & \\ |V_{td}| & |V_{ts}| & |V_{tb}| \\ \text{loops} & \text{loops} & p\bar{p} \to tb + X \end{pmatrix}$$

Extract precision physics from hadronic observables is a major achievement!

Flavour Precision Physics

One example: a precise determination of |Vus|/|Vud| comes from comparing K, pi leptonic decays:



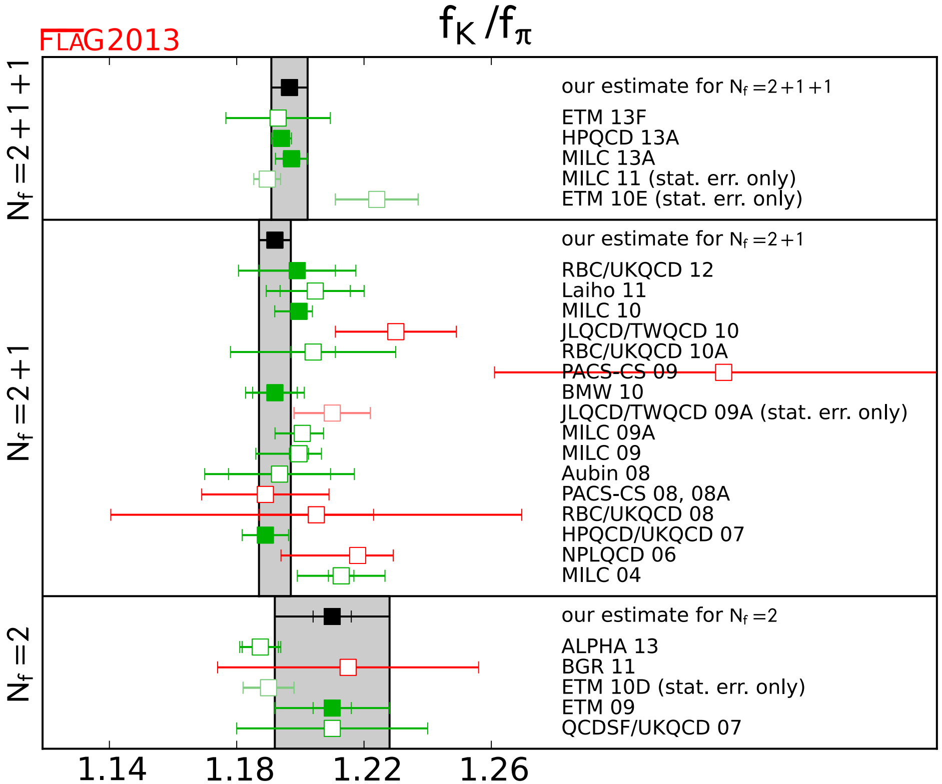
$$\mathcal{A}(M \to \mu\nu) \propto G_F \langle \mu\nu | \bar{\mu}\gamma_\mu(1-\gamma_5)\nu|0\rangle \underbrace{\langle 0|\bar{q}\gamma_\mu(1-\gamma_5)q|M(q)\rangle}_{i f_M q_\mu}$$

$$\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K(1-m_l^2/m_K^2)^2}{m_\pi(1-m_l^2/m_\pi^2)^2}(1+\delta_{EM})$$

requires a non-perturbative evaluation

Extract precision physics from hadronic observables is a major achievement!

Flavour Precision Physics



FLAG WG

Percent level non-perturbative determination

Extract precision physics from hadronic observables is a major achievement!

Flavour Precision Physics

Phases of CKM: only one for three families.

We can formulate the criterium for CP violation in the quark sector in terms of a basis independent invariant:

$$\mathrm{Im}\left\{\det[Y_u Y_u^\dagger, Y_d Y_d^\dagger]\right\} \neq 0$$

Jarkskog 85

$$\mathrm{Im}[V_{ij}V_{ik}^* V_{lk} V_{lj}^*] = \mathcal{J} \sum_{m,n} \epsilon_{ilm}\epsilon_{jkn}$$

In terms of the usual parametrization:

$$\mathcal{J} = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta$$

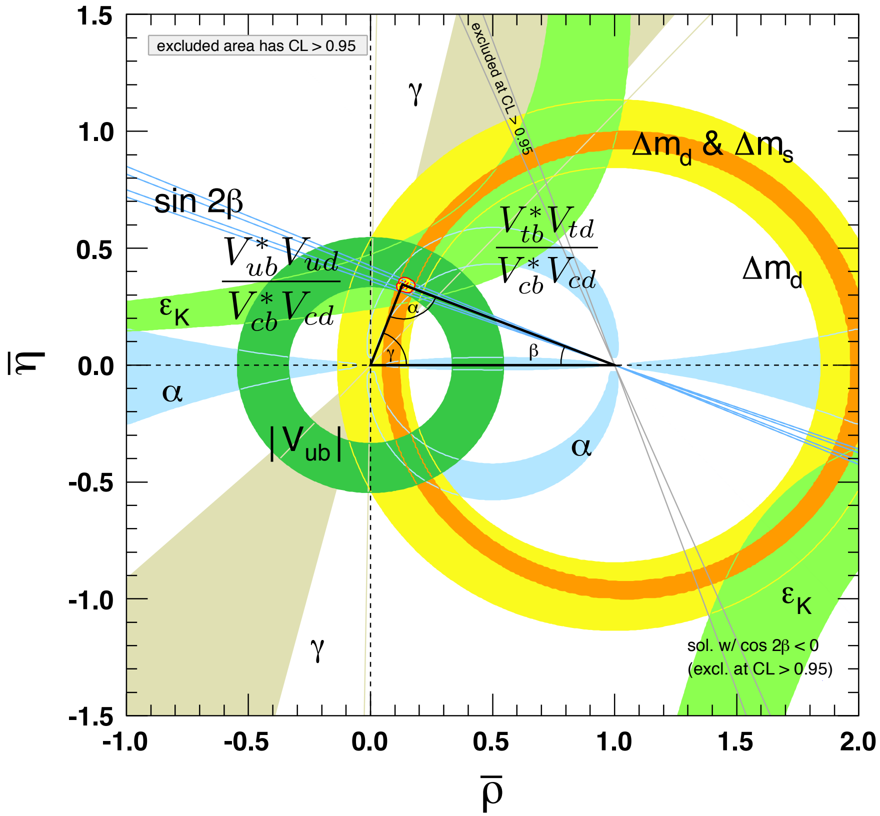
Unitarity Triangles

$$VV^\dagger = I \rightarrow \sum_k V_{ik}V^*_{jk} = 0 \quad i \neq j$$

The unitarity triangles: all have the same area J, but sides are different

$$\mathbf{V}^*_{ud}\mathbf{V}_{us} + \mathbf{V}^*_{cd}\mathbf{V}_{cs} + \mathbf{V}^*_{td}\mathbf{V}_{ts} = 0\,,$$
$$\mathbf{V}^*_{us}\mathbf{V}_{ub} + \mathbf{V}^*_{cs}\mathbf{V}_{cb} + \mathbf{V}^*_{ts}\mathbf{V}_{tb} = 0\,,$$
$$\mathbf{V}^*_{ub}\mathbf{V}_{ud} + \mathbf{V}^*_{cb}\mathbf{V}_{cd} + \mathbf{V}^*_{tb}\mathbf{V}_{td} = 0\,.$$

The last one has larger area/sides:
CP violation more significant in B sector



Angles:

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right),$$

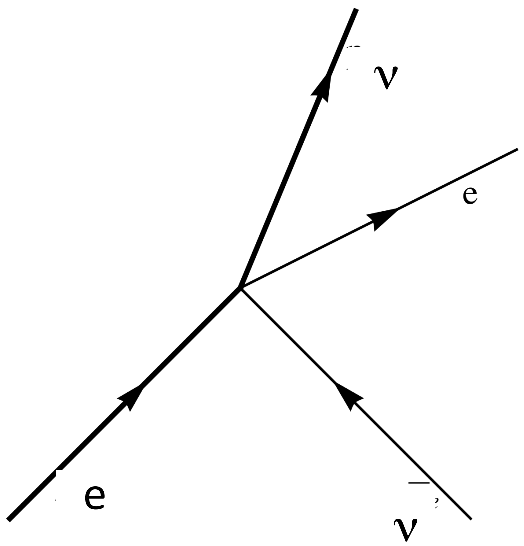
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right),$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right).$$

Lecture III: the SM open end

- The SM at the LHC: Higgs physics
- Open questions in the SM

Unitarity & effective theories



Violates unitarity at large energies:

$$\sigma(\nu e \to \nu e) = \frac{G_F^2 s}{\pi}$$

Something must pop up when we approach the unitarity bound:

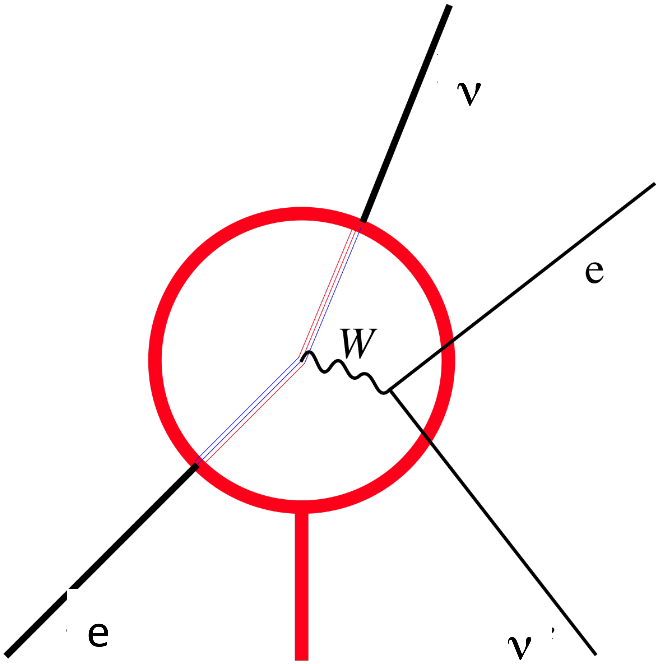
$$\sigma = \frac{16\pi}{s} \sum_l (2l+1)|a_l|^2 \qquad \sigma = \frac{1}{s} \mathrm{Im}[A(\theta=0)] = \frac{16\pi}{s} \sum_l (2l+1) \mathrm{Im}[a_l]$$

$$\mathrm{Im}[a_l] = |a_l|^2 \to \mathrm{Re}[a_l] \leq \frac{1}{2}$$

s-wave unitarity $\quad \sigma \leq \dfrac{16\pi}{s}$

$$s \geq (1\ \mathrm{TeV})^2$$

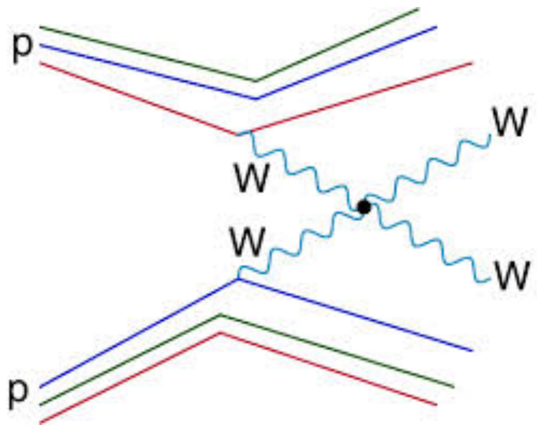
Unitarity & effective theories



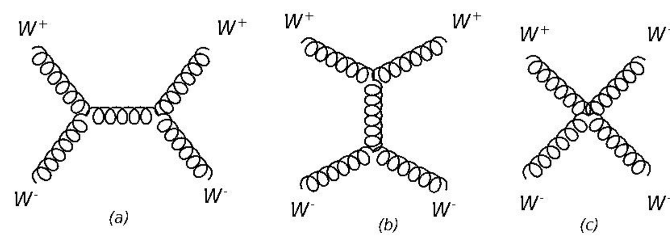
The W, Z restore unitarity:

$$\sigma_{\nu e \to \nu e} \propto G_F^2 M_W^2$$

WW scattering and Higgs mass



Without the Higgs:

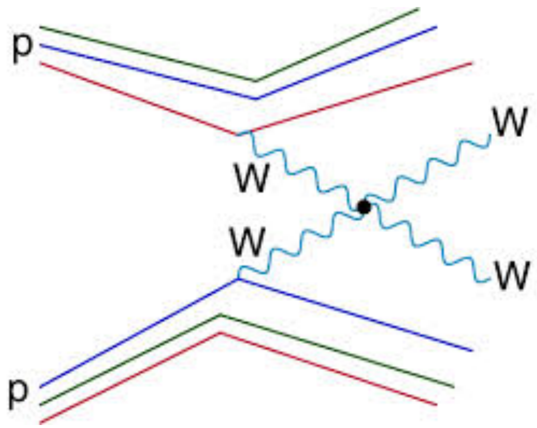


$$a_0^0 \simeq -\frac{s}{32\pi v^2}$$

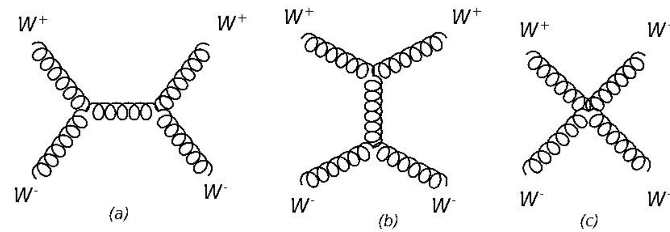
Unitarity violated

$$s \geq (1.7\ \mathrm{TeV})^2$$

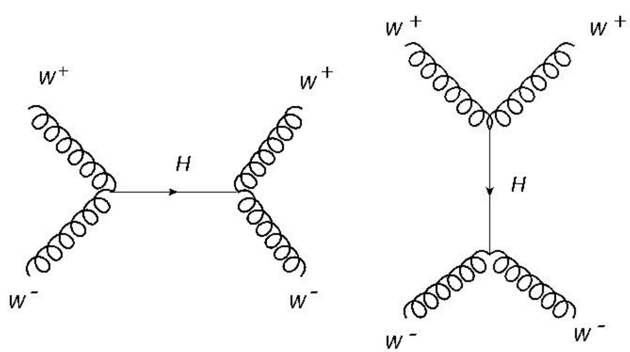
WW scattering and Higgs mass



Without the Higgs:



$$a_0^0 = -\frac{m_H^2}{8\pi v^2}$$



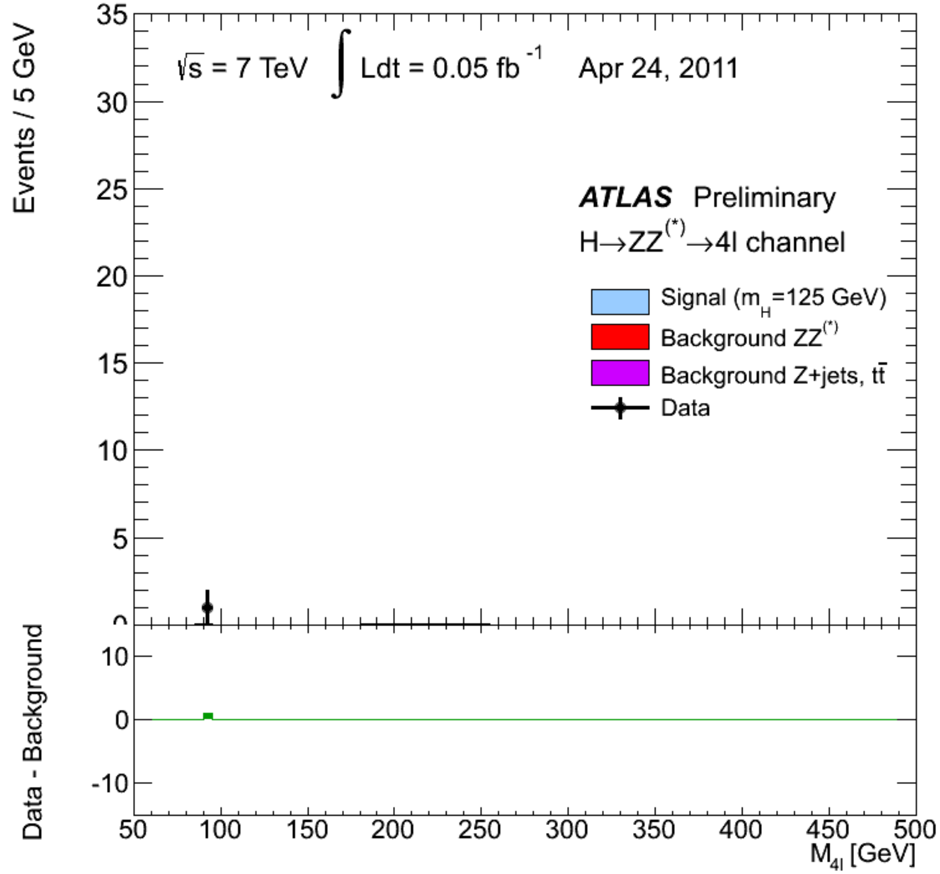
$$g_{WWH} = g M_W$$

Unitarity restored if:

$$m_H \leq 800 \text{ GeV}$$

WWH couplings exactly as in the SM!

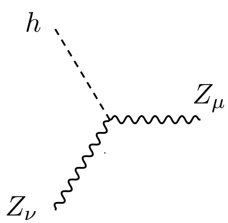
The missing piece showed up...



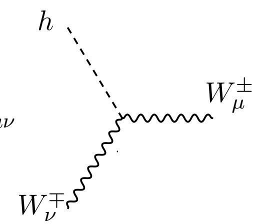
Higgs couplings

No more freedom, after the higgs mass is known all higgs couplings are fixed

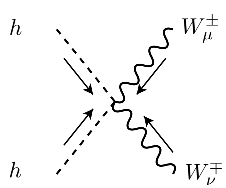
Gauge Fields



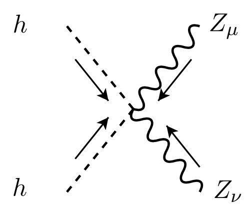
$$i\frac{g}{\cos\theta_W} m_Z\, g_{\mu\nu}$$



$$i g\, m_W\, g_{\mu\nu}$$

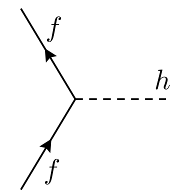


$$\frac{i}{2} g^2 g_{\mu\nu}$$



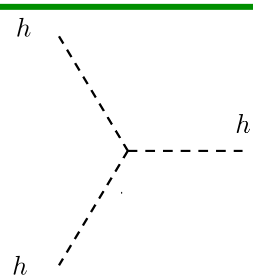
$$\frac{i}{2}\frac{g^2}{\cos^2\theta_W} g_{\mu\nu}$$

fermions

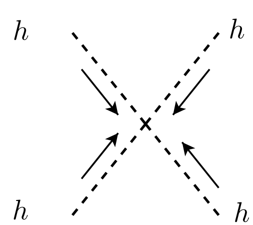


$$-i\,\frac{g}{2}\,\frac{m_f}{m_W}$$

Self-iteraction



$$-\frac{3}{2}\, i\, g \frac{m_h^2}{m_W^2}$$

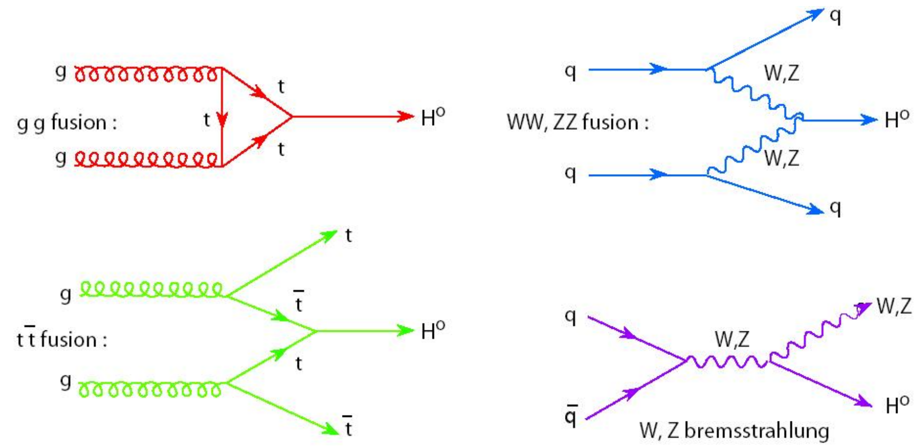


$$-\frac{3}{4}\, i\, g^2 \frac{m_h^2}{m_W^2}$$

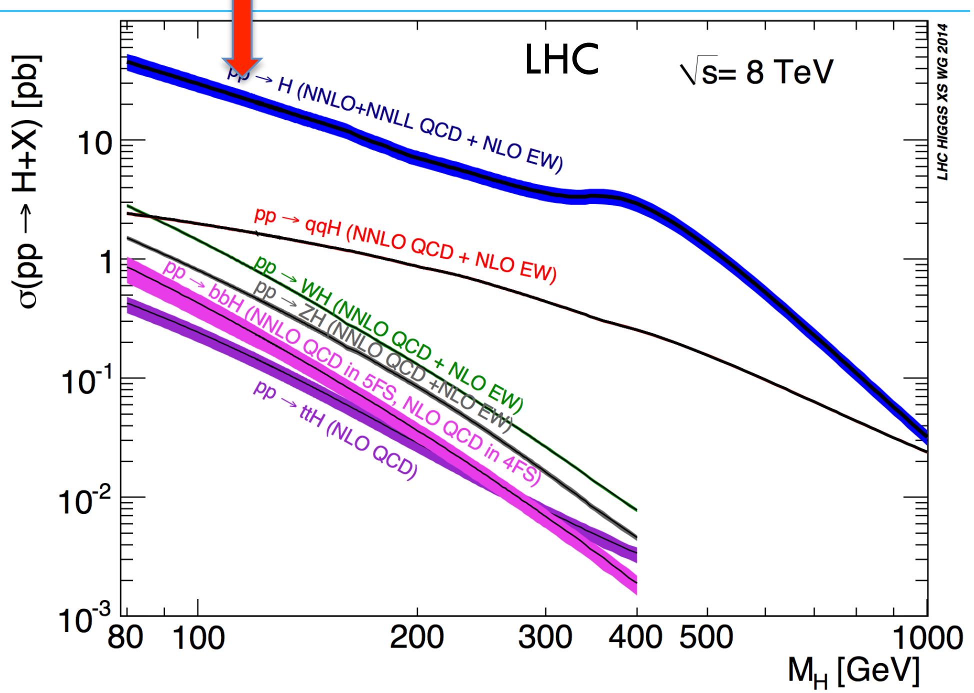
Any change would bring unitarity violations back- > New physics

Higgs @LHC

How is the H produced ?



gg fussion dominant !

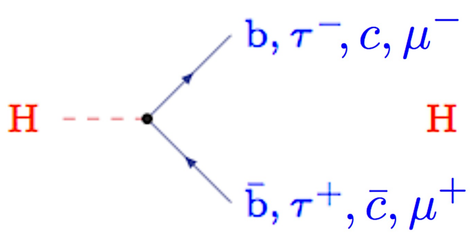


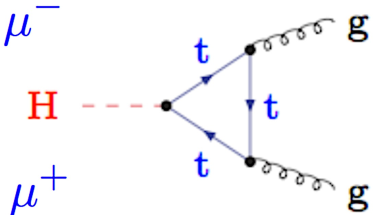
We are testing a top loop effect!

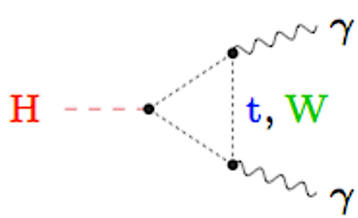
Higgs @LHC

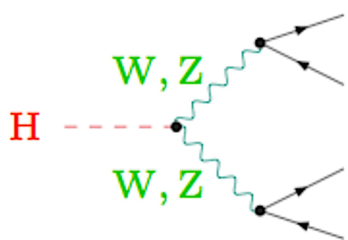
What we look for
are the decay products

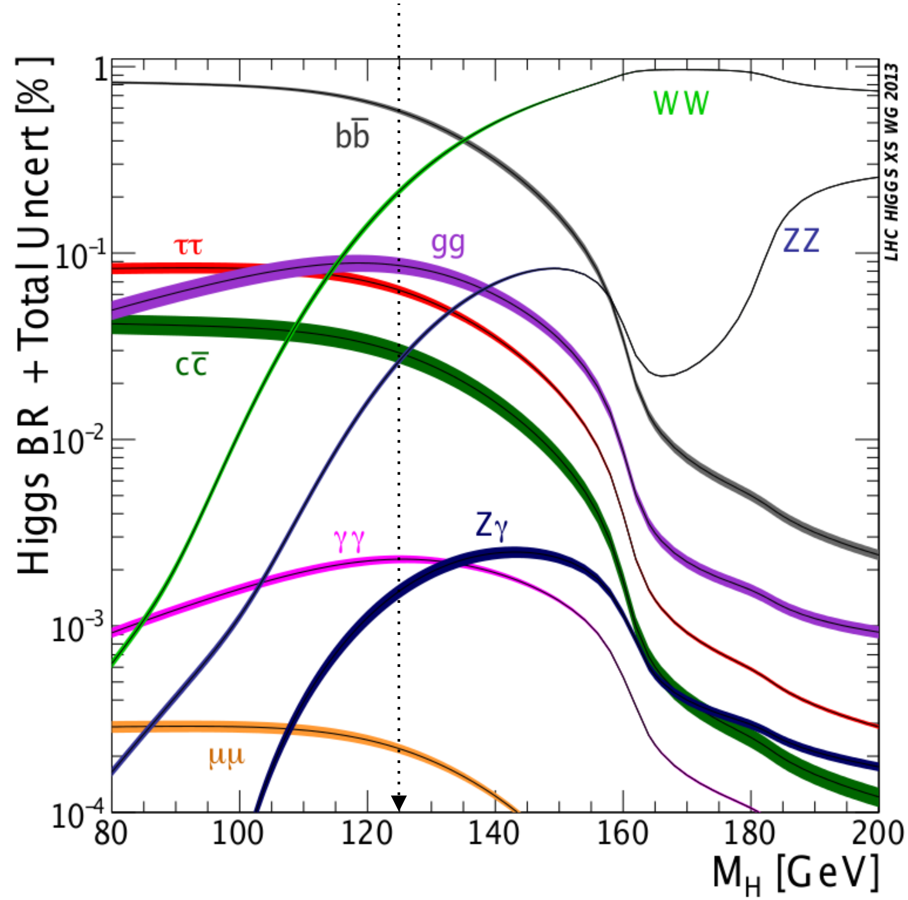
Several channels significant, various degree of difficulty



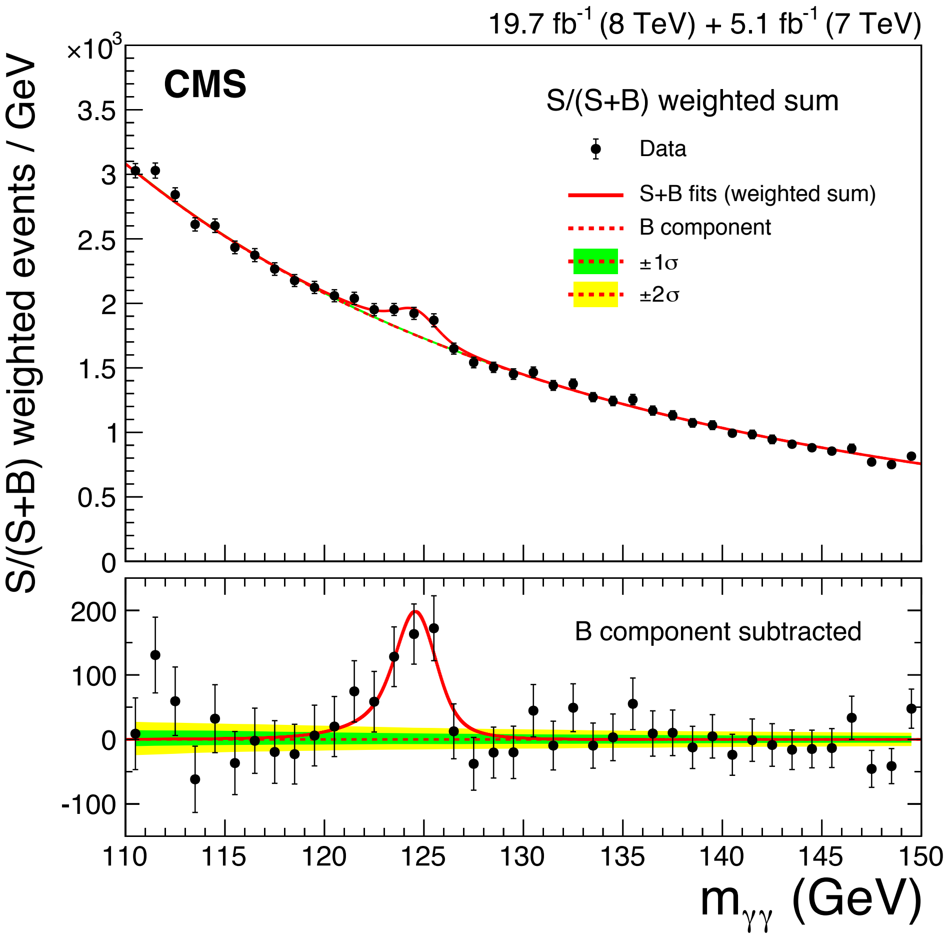


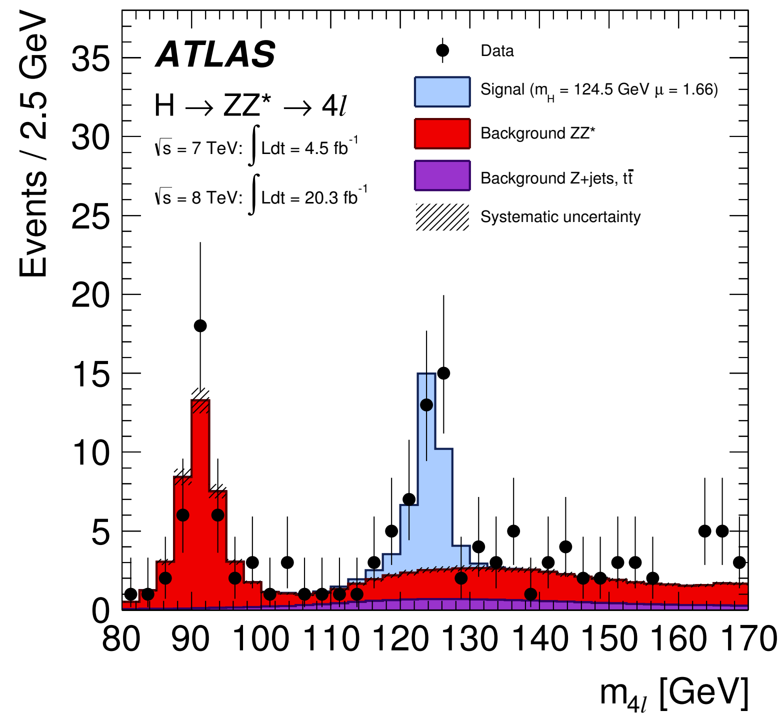




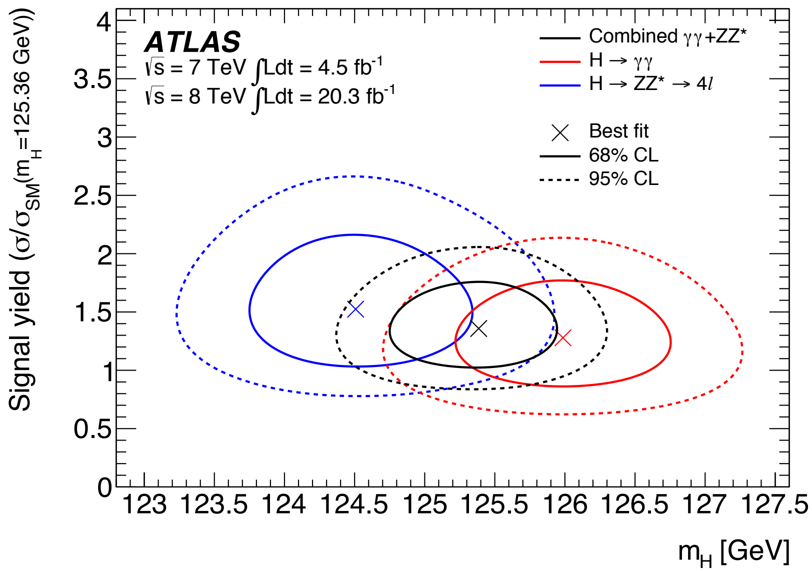


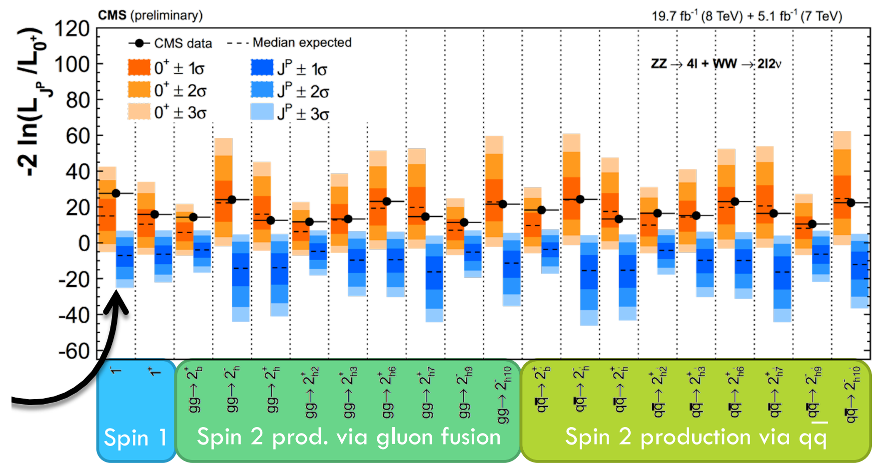
The Higgs resonance





The 0+ Higgs resonance

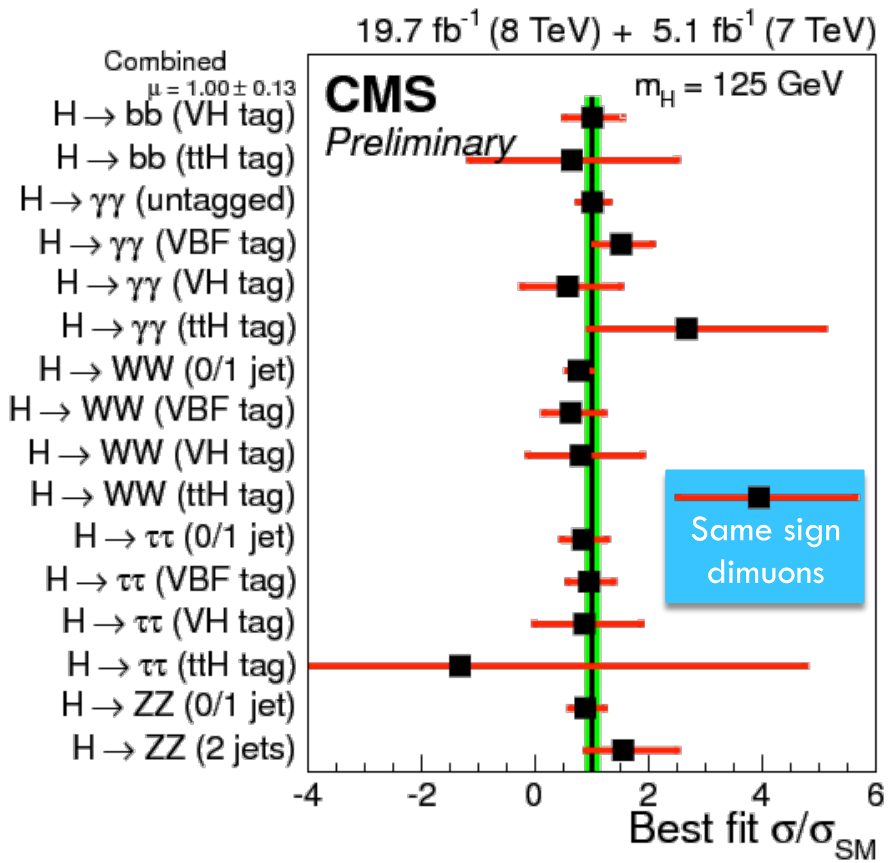


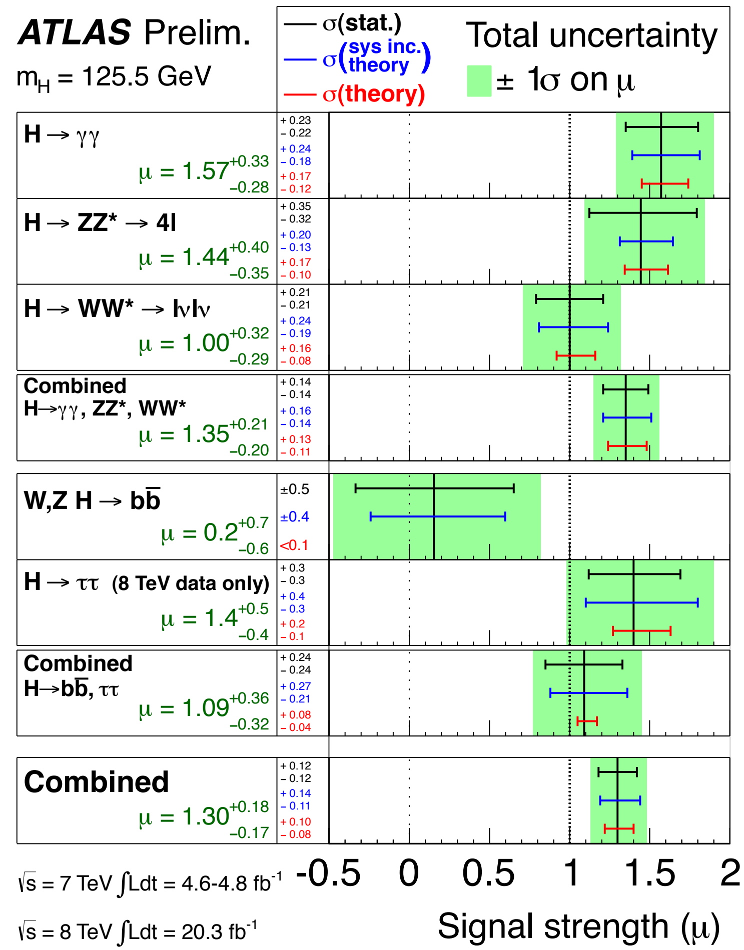


ATLAS: 125.36 +- 0.37 (stat) +-0.18 (syst)

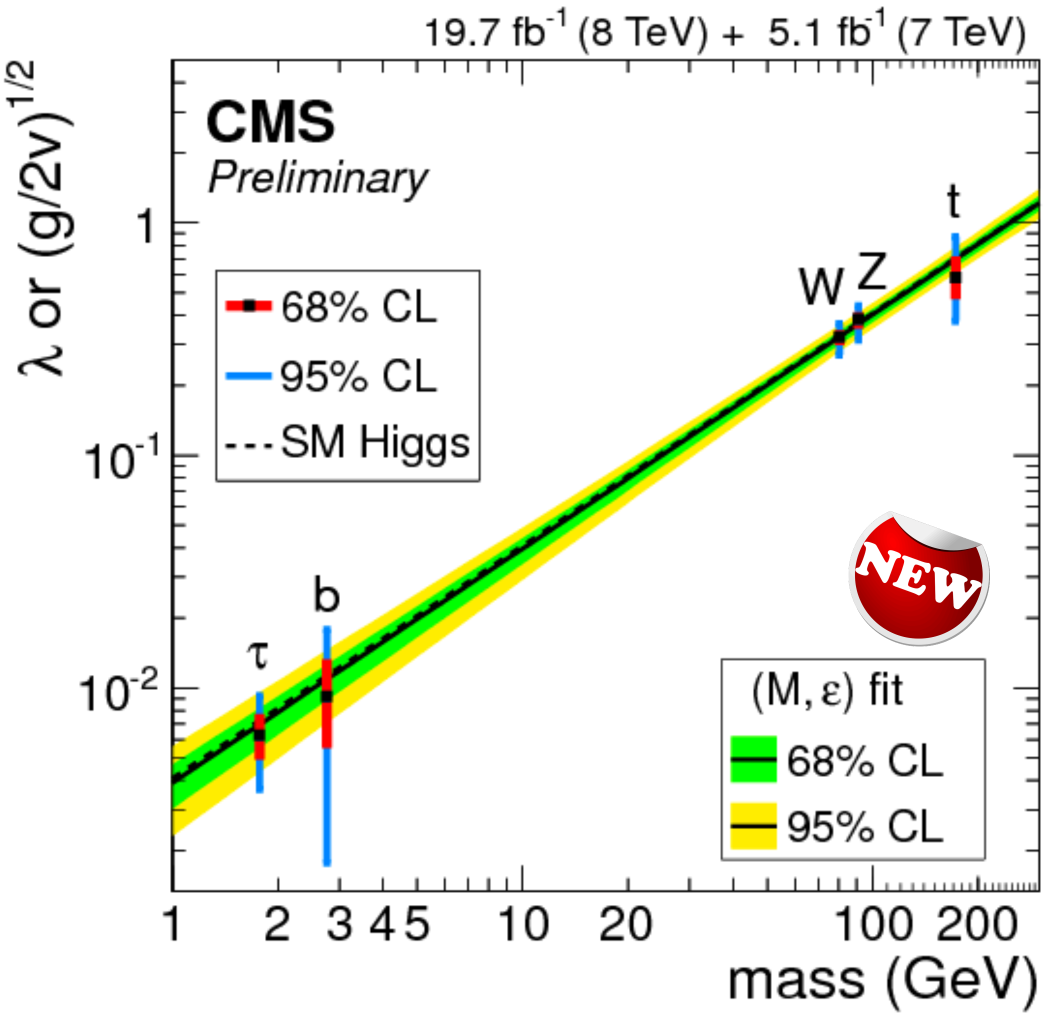
CMS: 125.03 +- 0.27 (stat) +-0.15 (syst)

Higgs couplings



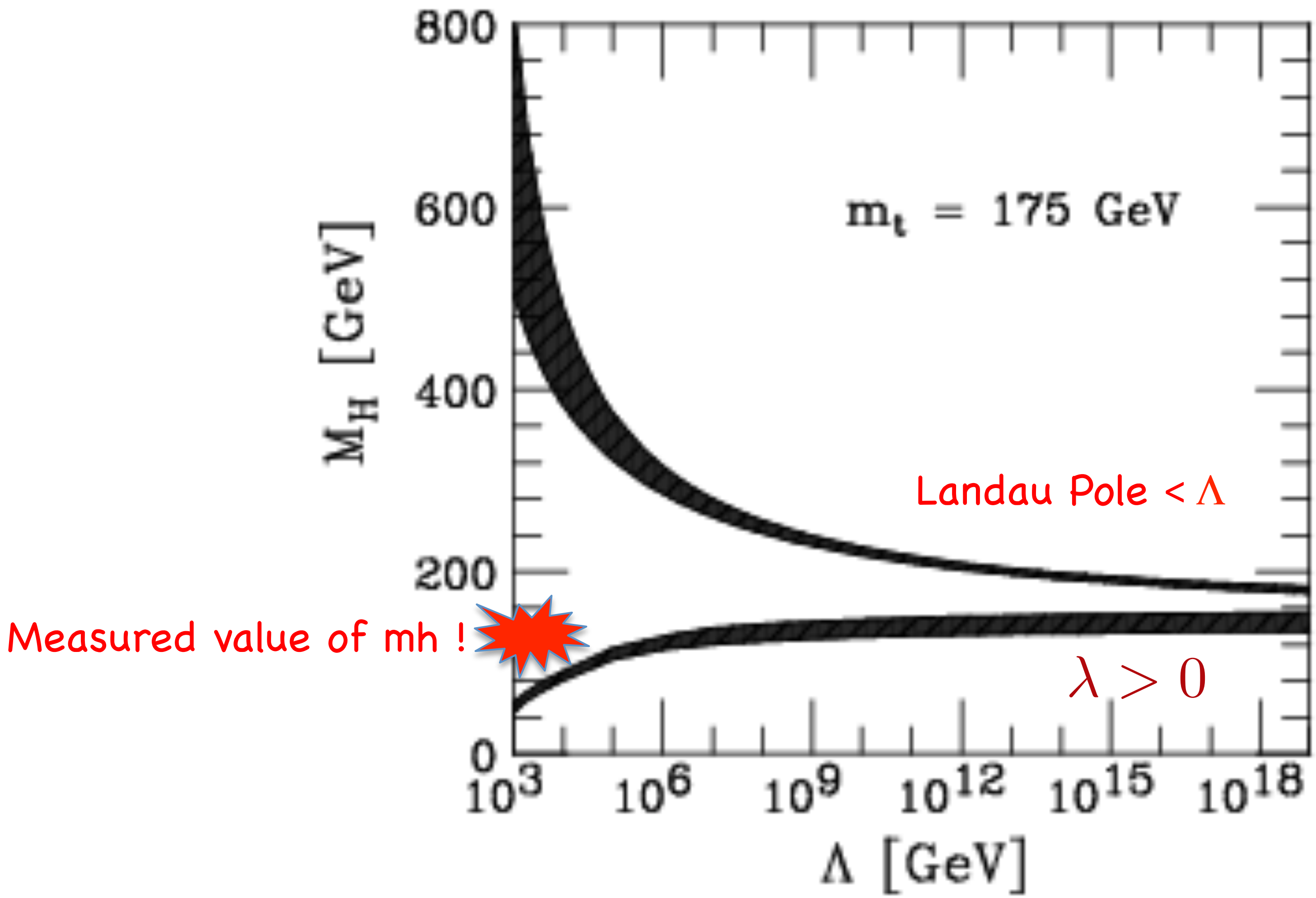


The origin of mass

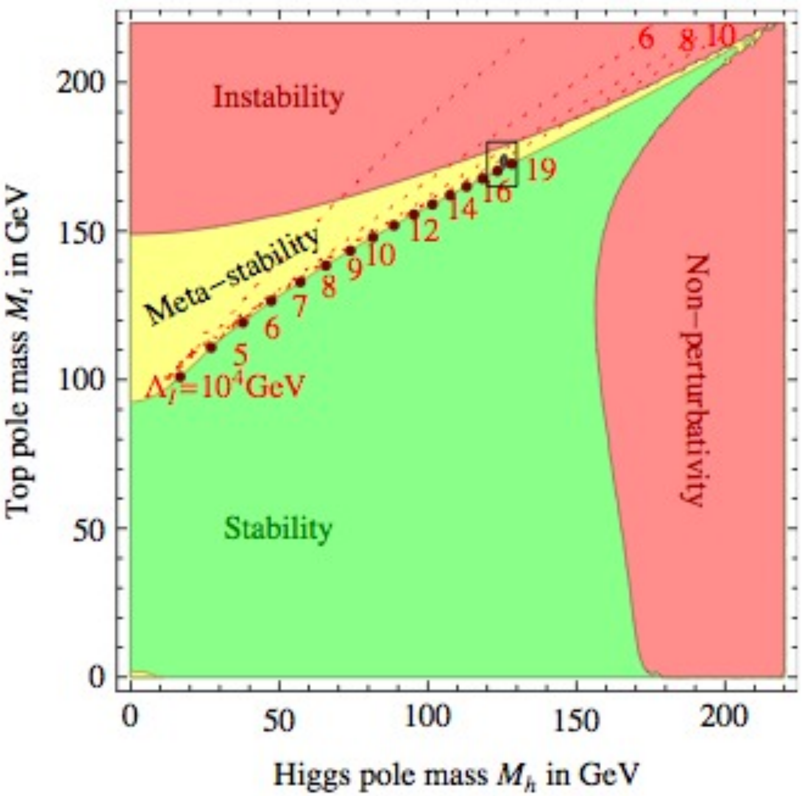


Triviality vs Stability

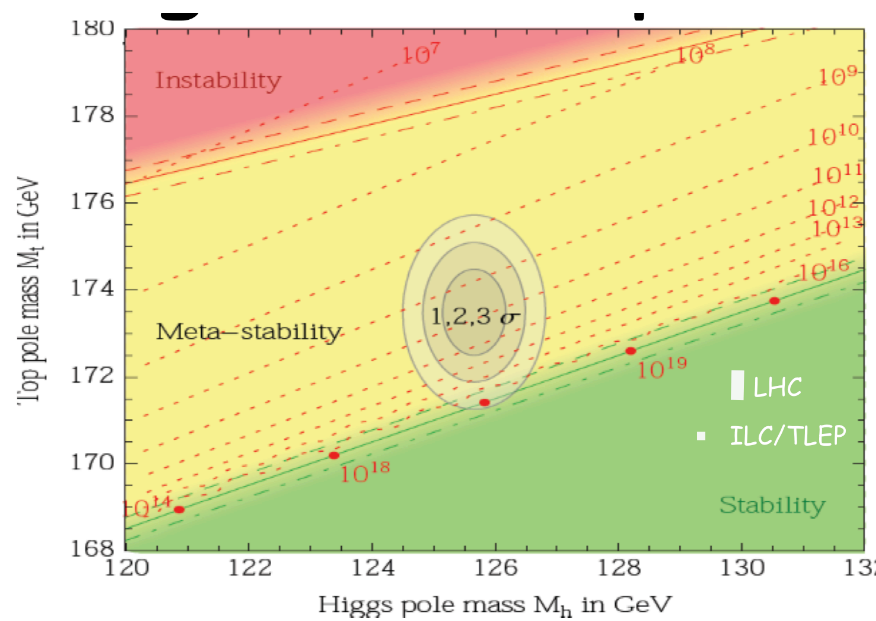
Higgs self-coupling $$16\pi^2\mu\frac{d\lambda}{d\mu} = 12\lambda^2 + 12\lambda g_t^2 - 12g_t^4 + \ldots$$



Stability



Degrassi et al



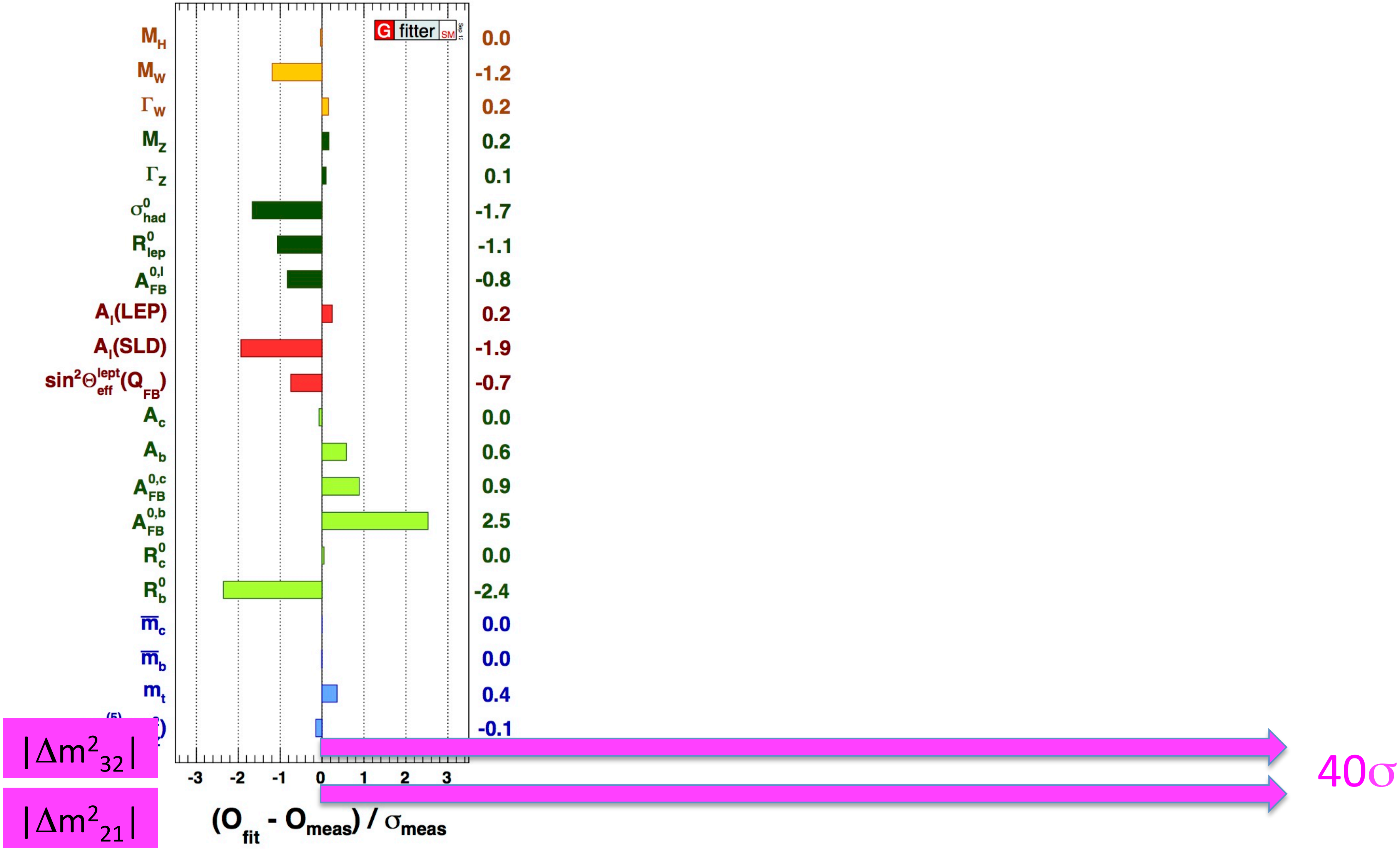
Living in a meta-stable world...

(the cutoff cannot be really taken all the way to infinity...)

SM valid theory until the Planck scale...

The SM is not complete
(experiment dixit)

- Neutrinos have a mass !!



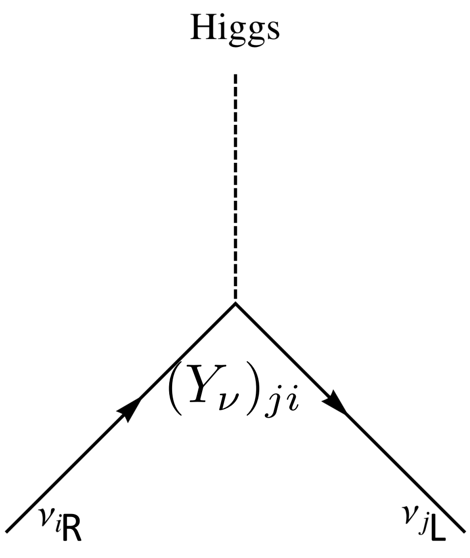
G fitter SM
M_H 0.0
M_W -1.2
Γ_W 0.2
M_Z 0.2
Γ_Z 0.1
σ⁰_had -1.7
R⁰_lep -1.1
A^{0,l}_FB -0.8
A_l(LEP) 0.2
A_l(SLD) -1.9
sin²Θ^{lept}_{eff}(Q_FB) -0.7
A_c 0.0
A_b 0.6
A^{0,c}_FB 0.9
A^{0,b}_FB 2.5
R⁰_c 0.0
R⁰_b -2.4
m̄_c 0.0
m̄_b 0.0
m_t 0.4
-0.1
-3 -2 -1 0 1 2 3
(O_fit - O_meas) / σ_meas
|Δm²₃₂|
|Δm²₂₁|
40σ

Massive Dirac neutrinos & SSB ?

$$\widetilde{\phi} \equiv \sigma_2 \phi^*, \qquad \widetilde{\phi} : (1, 2, -\frac{1}{2}), \; \left\langle \widetilde{\phi} \right\rangle = \begin{pmatrix} \frac{v}{2} \\ 0 \end{pmatrix}$$

Massive Dirac neutrino

$$-\mathcal{L}_m^{\mathrm{Dirac}} = Y_\nu \; \underbrace{\bar{L} \; \widetilde{\phi}}_{(1,1,0)} \; \underbrace{\nu_R}_{(1,1,0)} \; + h.c \rightarrow SSB \; \rightarrow Y_\nu \bar{\nu}_L \frac{v}{\sqrt{2}} \nu_R + h.c.$$



$$m_\nu = Y_\nu \frac{v}{\sqrt{2}}$$

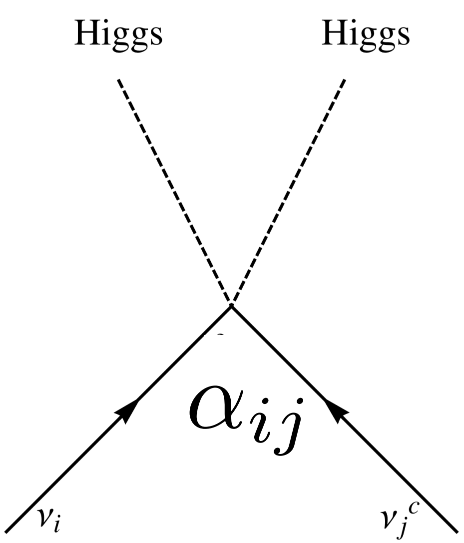
Massive Majorana neutrinos & SSB ?

$$\widetilde{\phi} \equiv \sigma_2 \phi^*, \qquad \widetilde{\phi} : (1, 2, -\frac{1}{2}), \;\; \langle \widetilde{\phi} \rangle = \begin{pmatrix} \frac{v}{2} \\ 0 \end{pmatrix}$$

Massive Majorana neutrino

$$-\mathcal{L}^{\text{Majorana}} = \alpha \bar{L} \; \widetilde{\phi} \; C \widetilde{\phi}^T \bar{L}^T + h.c. \rightarrow SSB \rightarrow \alpha \frac{v^2}{2} \bar{\nu}_L C \bar{\nu}_L^T + h.c.$$

Weinberg's operator



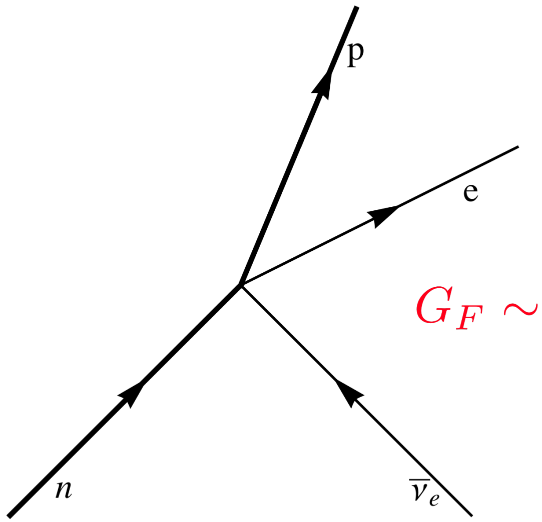
$$m_\nu = \alpha \frac{v^2}{2}$$

$$[\alpha] = -1$$

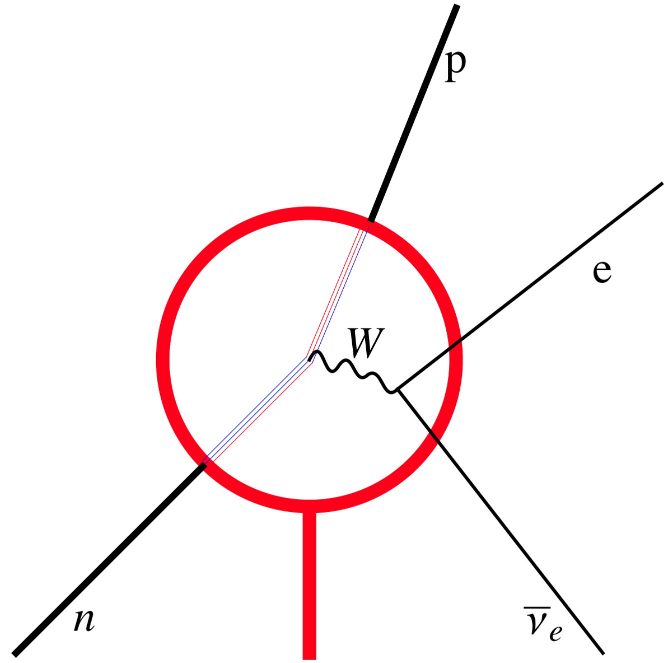
$$\alpha = \frac{Y_\nu}{\Lambda}$$

Implies the existence of a new physics scale unrelated to v !

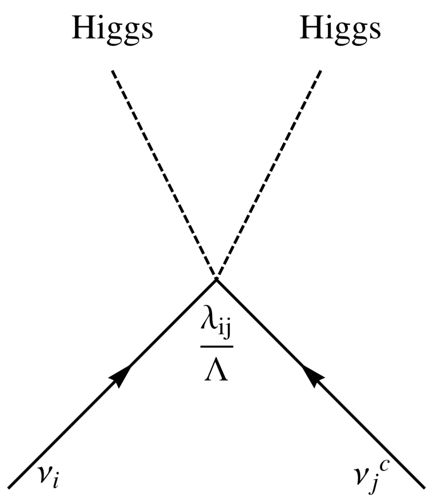
Majorana neutrinos imply a new Standard Model



$$G_F \sim \frac{1}{M_W^2}$$



SM



→ νSM ?

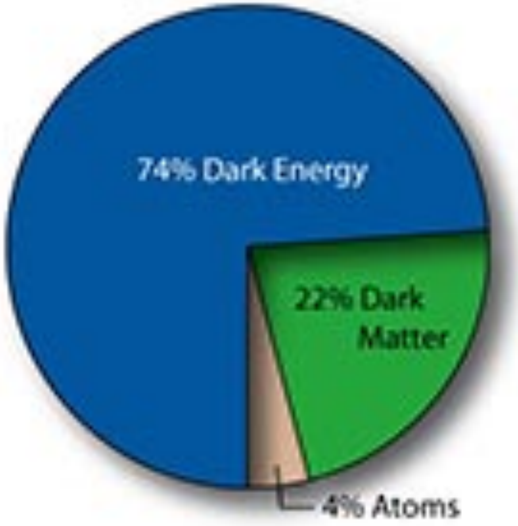
Unitarity violations!

The SM is not complete
(experiment dixit)

The SM can not complete:

- Neutrinos have a mass !!

- We cannot explain the content of the Universe!



The SM is not complete

(experiment dixit)

- Neutrinos have a mass !!
- Dark matter

  (caveat: maybe our lack of understanding of gravity)
- Baryons in the Universe

  (caveat: primordial asymmetry)

The SM can not complete

(desiderium)

- Hierarchy problem
- Gauge unification: quark/lepton symmetry, em charge quantization
- Flavour Puzzle
- Parity

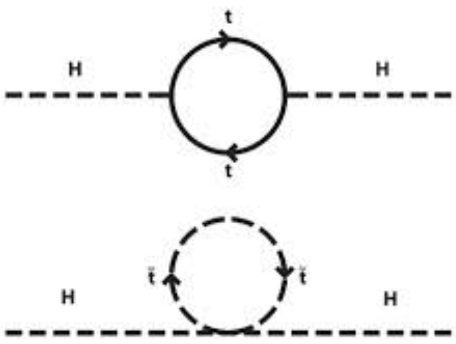
Hierarchy Problem

This is a well-defined problem if and only if there is new physics M >> v

There is a dimensionfull coupling in the SM

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

μ^2 <-> m_h^2



$$m_h^2 + c\frac{y^2}{16\pi^2} M^2 \log(M^2/Q^2)$$

$$M_H^2 = 2\lambda v^2 + \frac{2y_t^2 v^2}{(4\pi)^2} \left[2\lambda + 3\left(\lambda - y_t^2\right) \log\left(m_t^2/\mu^2\right)\right] + \cdots$$

Need to finetune the renormalized mass: not natural

The SM can not complete
(desiderata)

- Hierarchy problem
- Gauge unification: quark/lepton symmetry, em charge quantization

SM gauge group: particles

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

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

Quark/lepton symmetry ?

Parity

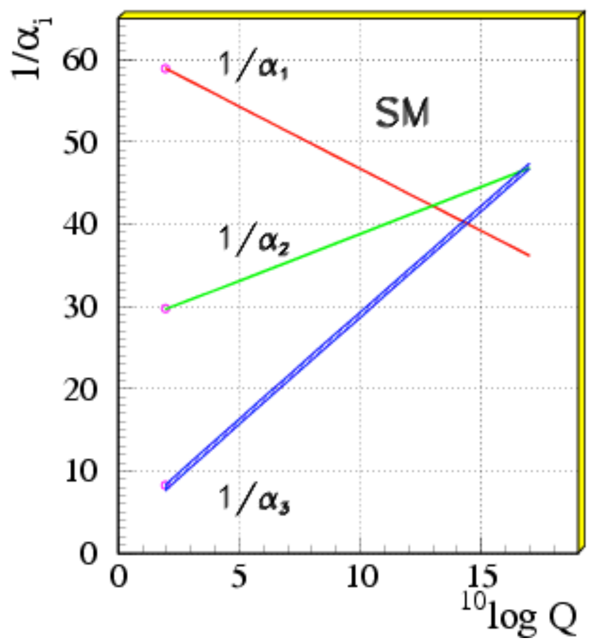
Flavour symmetry ?

SM gauge group: interactions

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

$$G_\mu^{a=1,..,8} \qquad W_\mu^{a=1,2,3} \qquad B_\mu$$

Gauge unification ?

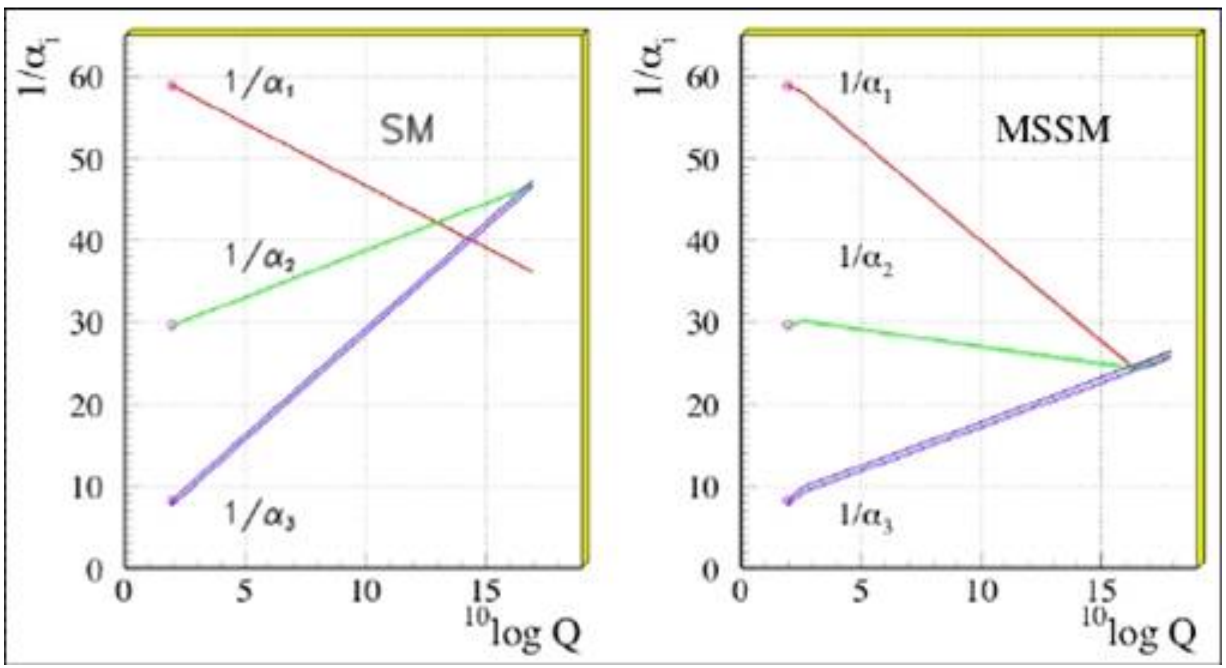


$$\alpha_i = \frac{g_i^2}{4\pi}$$

The motivation for SUSY

No quadratic corrections to the Higgs mass: cancellation between particles and SUSY partners.

Gauge unification

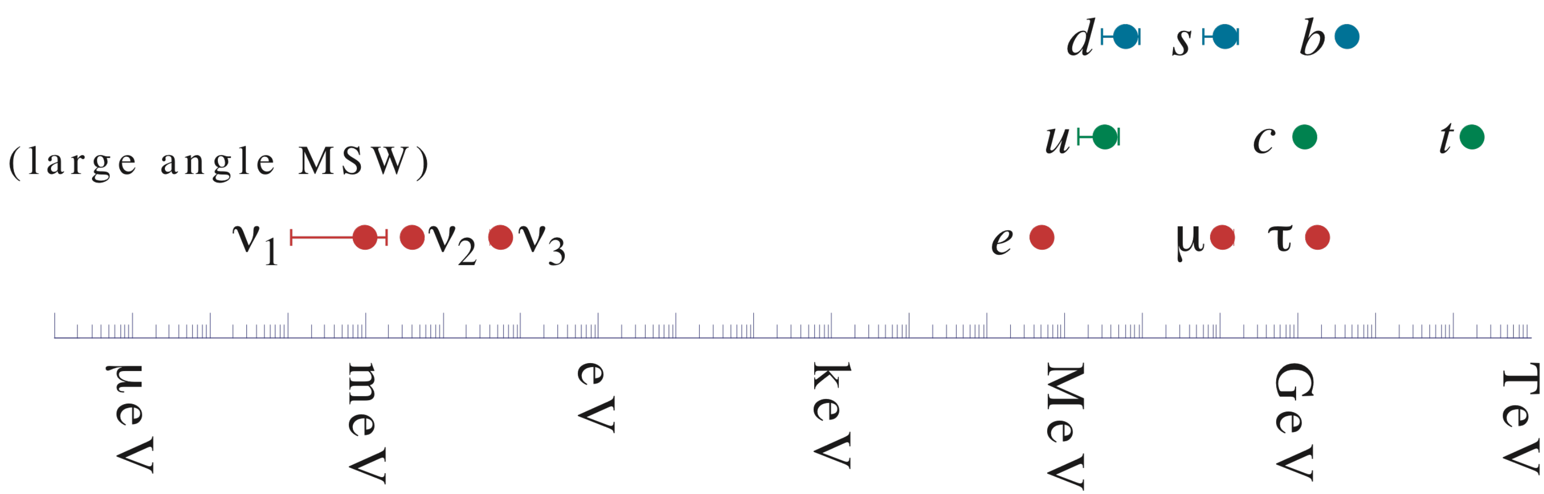


The SM can not complete
(desiderata)

- Hierarchy problem
- Gauge unification: quark/lepton symmetry
- Flavour Puzzle
- Parity

Flavour Puzzle

Where do these "random" looking numbers come from ?



$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

SM as an effective field theory

Weinberg; Buchmuller, Wyler;...

If $\Lambda >> v$ low-energy effects should be well described by an effective field theory:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} O_i^{d=6} + \ldots$$

O_i^d built from SM fields satisfying the gauge symmetries

d=5: only one: neutrino mass !
d=6: > 80 !

For α, β = O(1): $\Lambda \geq$ few TeV
$\Lambda \geq$ O(1000TeV) FCNC

SM Nobel tapestry