Electroweak and Higgs Physics

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- **The Standard Model**
- **EW Physics at the LHC**
- **EWSB in the SM**
- **Higgs decays**
- **The Higgs at the LHC**
- **Measurement of Higgs properties**
- **EWSB in SUSY**
- **SUSY Higgsses at the LHC**

1. The Standard Model

The SM of the electromagnetic, weak and strong interactions is:

- **a relativistic quantum field theory,**
- **based on local gauge symmetry: invariance under symmetry group,**
- **more or less a carbon–copy of QED, the theory of electromagnetism.**

QED: invariance under local transformations of the abelian group U(1)$_{\rm Q}$

– transformation of electron field: $\Psi(x) \rightarrow \Psi'(x) = e^{ie\alpha(x)}\Psi(x)$

– transformation of photon field: $A_\mu(x) \rightarrow A'_\mu(x) = A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$

The Lagrangian density is invariant under above field transformations

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\,D_\mu\gamma^\mu\Psi \;\; - m_e\bar{\Psi}\Psi$$

field strength $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ **and cov. derivative** $D_\mu = \partial_\mu - ieA_\mu$

Very simple and extremely successful theory!

– minimal coupling: the interactions/couplings uniquely determined,

– renormalisable, perturbative, unitary (predictive), very well tested...

1. The Standard Model: brief introduction

The SM is based on the local gauge symmetry group

$$\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- The group $\mathrm{SU(3)_C}$ describes the strong force:

– interaction between quarks which are SU(3) triplets: q, q , q

– mediated by 8 gluons, $\mathbf{G^a_\mu}$ corresponding to 8 generators of $\mathbf{SU(3)_C}$

Gell-Man 3×3 matrices: $\mathbf{[T^a, T^b] = if^{abc}T_c}$ with $\mathbf{Tr[T^aT^b] = \frac{1}{2}\delta_{ab}}$

– asymptotic freedom: interaction “weak” at high energy, $\alpha_\mathbf{s} = \frac{\mathbf{g_s^2}}{\mathbf{4\pi}} \ll \mathbf{1}$

The Lagrangian of the theory is given by:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}\mathbf{G^a_{\mu\nu}G^{\mu\nu}_a + i\sum_i \bar{q}_i(\partial_\mu - ig_s T_a G^a_\mu)\gamma^\mu q_i} \;\; \mathbf{(-\sum_i m_i \bar{q}_i q_i)}$$

$$\text{with } \mathbf{G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s\, f^{abc} G^b_\mu G^c_\nu}$$

The interactions/couplings are then uniquely determined:

– fermion gauge boson couplings : $\mathbf{-g_i \overline{\psi} V_\mu \gamma^\mu \psi}$

– V self-couplings : $\mathbf{ig_i {\rm Tr}(\partial_\nu V_\mu - \partial_\mu V_\nu)[V_\mu, V_\nu] + \frac{1}{2} g_i^2\, {\rm Tr}[V_\mu, V_\nu]^2}$

1. The SM: brief introduction

• $\mathrm{SU(2)_L \times U(1)_Y}$ **describes the electroweak interaction:**

– between the three families of quarks and leptons: $\mathbf{f_{L/R} = \frac{1}{2}(1 \mp \gamma_5)f}$

$$\mathbf{I_f^{3L,3R} = \pm\frac{1}{2}, 0 \;\; \Rightarrow \;\; L = \binom{\nu_e}{e^-}_L, \; R = e_R^-, \; Q = \binom{u}{d}_L, \; u_R, \; d_R}$$

$$\mathbf{Y_f = 2Q_f - 2I_f^3 \Rightarrow Y_L = -1, Y_R = -2, Y_Q = \frac{1}{3}, Y_{u_R} = \frac{4}{3}, Y_{d_R} = -\frac{2}{3}}$$

Same holds for the two other generations: $\mu, \nu_\mu, \mathbf{c}, \mathbf{s}; \; \tau, \nu_\tau, \mathbf{t}, \mathbf{b}$.

There is no ν_{R} **(and neutrinos are and stay exactly massless)**

– mediated by the $\mathrm{W}_\mu^{\mathrm{i}}$ **(isospin) and** B_μ **(hypercharge) gauge bosons**

the gauge bosons, corresp. to generators, are exactly massless

$$\mathbf{T^a = \frac{1}{2}\tau^a ; \quad [T^a, T^b] = i\epsilon^{abc}T_c \;\; \text{and} \;\; [Y, Y] = 0}$$

Lagrangian simple: with fields strengths and covariant derivatives

$$\mathbf{W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu, \; B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu}$$

$$\mathbf{D_\mu \psi = \left(\partial_\mu - igT_a W^a_\mu - ig' \frac{Y}{2} B_\mu\right) \psi \, , \;\; T^a = \frac{1}{2}\tau^a}$$

$$\mathcal{L}_{\mathrm{SM}} = \mathbf{-\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{F}_{Li}\, iD_\mu \gamma^\mu \, F_{Li} + \bar{f}_{Ri}\, iD_\mu \gamma^\mu \, f_{R_i}}$$

1. The SM: brief introduction

But if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

$\frac{1}{2}{\rm M_V^2 V^\mu V_\mu}$ **and/or** ${\rm m_f \bar{f} f}$ **terms: breaking of gauge symmetry.**

This statement can be visualized by taking the example of QED where

the photon is massless because of the local $\rm U(1)_Q$ local symmetry:

$$\Psi(\mathbf{x}) \to \Psi'(\mathbf{x}) = \mathbf{e}^{\mathbf{ie}\alpha(\mathbf{x})}\Psi(\mathbf{x})\ ,\ \mathbf{A}_\mu(\mathbf{x}) \to \mathbf{A}'_\mu(\mathbf{x}) = \mathbf{A}_\mu(\mathbf{x}) - \frac{\mathbf{1}}{\mathbf{e}}\partial_\mu\alpha(\mathbf{x})$$

- **For the photon (or B field for instance) mass we would have:**

$$\frac{\mathbf{1}}{\mathbf{2}}\mathbf{M_A^2 A}_\mu \mathbf{A}^\mu \to \frac{\mathbf{1}}{\mathbf{2}}\mathbf{M_A^2}(\mathbf{A}_\mu - \frac{\mathbf{1}}{\mathbf{e}}\partial_\mu\alpha)(\mathbf{A}^\mu - \frac{\mathbf{1}}{\mathbf{e}}\partial^\mu\alpha) \neq \frac{\mathbf{1}}{\mathbf{2}}\mathbf{M_A^2 A}_\mu \mathbf{A}^\mu$$

and thus, gauge invariance is violated with a photon mass.

- **For the fermion masses, we would have (e.g. for the electron):**

$$\mathbf{m_e \bar{e} e} = \mathbf{m_e \bar{e}}\left(\frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1}-\gamma_\mathbf{5}) + \frac{\mathbf{1}}{\mathbf{2}}(\mathbf{1}+\gamma_\mathbf{5})\right)\mathbf{e} = \mathbf{m_e}(\mathbf{\bar{e}_R e_L} + \mathbf{\bar{e}_L e_R})$$

manifestly non–invariant under SU(2) isospin symmetry transformations.

We need a less "brutal" way to generate particle masses in the SM:

$\Rightarrow$ **The Higgs mechanism for EWSB** $\Rightarrow$ **the Higgs particle H.**

1. The SM: precision tests

Parameters of the SM: 18 free parameters (+$\theta_{QCD}+$ neutrino sector):

- **9 fermions masses, 4 CKM parameters (see below for details).**
- **3 coupling g_s, g_2, g_1 and 2 parameters from EWSB scalar potential.**

More precise inputs, $\alpha_s, \alpha(M_Z^2), G_F, M_Z$ and M_H (unknown)

Weak interactions of fermions with gauge bosons

$$\mathcal{L}_{NC} = eJ_\mu^A A^\mu + \frac{g_2}{\cos\theta_W} J_\mu^Z Z^\mu \;,\;\; \mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}}(J_\mu^+ W^{+\mu} + J_\mu^- W^{-\mu})$$

$$J_\mu^A = Q_f \bar{f}\gamma_\mu f \;,\; J_\mu^Z = \frac{1}{4}\bar{f}\gamma_\mu[\hat{v}_f - \gamma_5 \hat{a}_f]f \;,\; J_\mu^+ = \frac{1}{2}\bar{f}_u\gamma_\mu(1-\gamma_5)f_d$$

with $v_f = \frac{\hat{v}_f}{4s_W c_W} = \frac{2I_f^3 - 4Q_f s_W^2}{4s_W c_W} \;,\; a_f = \frac{\hat{a}_f}{4s_W c_W} = \frac{2I_f^3}{4s_W c_W}$

3–families: complication in CC as current eigenstates $\neq$ mass eigenstates

connected by a unitary transformation: $(d', s', b') = V_{CKM}(d, s, b)$

$V_{CKM} \equiv 3\times 3$ **unitarity matrix parametrized by 3 angles and 1 CPV phase**

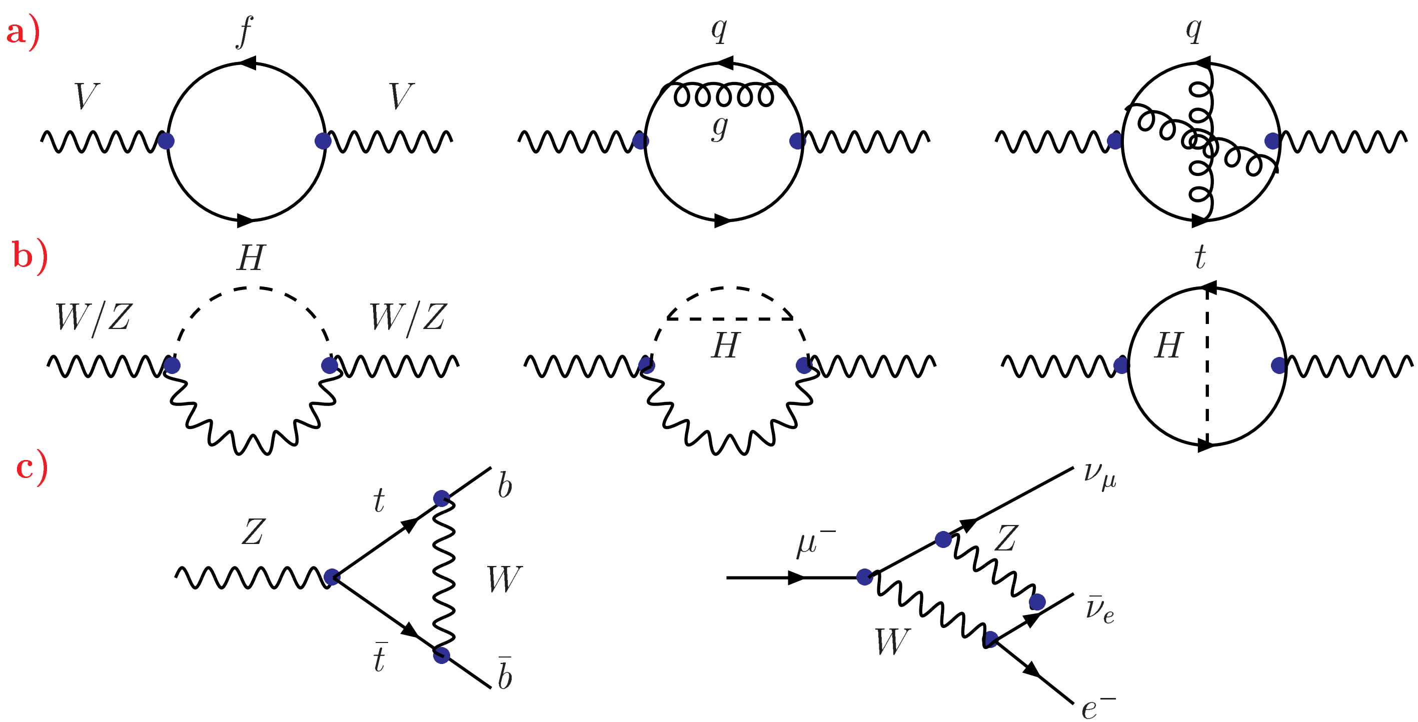
Beautiful tests at B–factories and further tests at Tevatron and LHC(b).

1. The SM: precision tests

$\mathbf{M_W}$ **and** $\sin^2\theta_W$ **predicted**: $\frac{\mathbf{G_F}}{\sqrt{2}} = \frac{\pi\alpha(\mathbf{M_Z^2})}{\mathbf{2M_W^2(1{-}M_W^2/M_Z^2)}}$; $\sin^2\theta_W = \mathbf{1} - \frac{\mathbf{M_W^2}}{\mathbf{M_Z^2}}$

In fact, they are related by $\rho = \frac{\mathbf{M_W^2}}{\cos^2\theta_W \mathbf{M_Z^2}} \equiv 1$ **at tree–level in the SM.**

To have very precise predictions, include the radiative corrections:



The dominant correction, besides $\Delta\alpha$**, is the one to the** ρ **parameter:**

$$\rho = \frac{\mathbf{1}}{\mathbf{1-\Delta}\rho}\ ,\ \mathbf{\Delta}\rho = \frac{\mathbf{\Pi_{WW}(0)}}{\mathbf{M_W^2}} - \frac{\mathbf{\Pi_{ZZ}(0)}}{\mathbf{M_Z^2}} = \frac{\mathbf{3G_\mu m_t^2}}{\mathbf{8\sqrt{2}\pi^2}} - \frac{\mathbf{G_\mu M_W^2}}{\mathbf{8\sqrt{2}\pi^2}} \log\frac{\mathbf{M_H^2}}{\mathbf{M_W^2}} + \cdots$$

1. The SM: precision tests

- **Z boson lineshape parameters at LEP1 ($\sqrt{s} \sim M_Z$):**

$$\mathbf{M_Z, \Gamma_Z, \sigma(e^+e^- \to hadrons)}$$

- **Partial decay widths and asymmetries in Z decays at LEP1:**

$$\mathbf{\Gamma(Z \to f\bar{f}) = \frac{2\alpha}{3} N_c M_Z (v_f^2 + a_f^2)\ ,\ A_{FB}^f = \frac{3}{4} \frac{2a_e v_e}{v_e^2 + a_e^2} \frac{2a_f v_f}{v_f^2 + a_f^2}}$$

- **Left–right polarized asymmetries in Z decays at SLC:**

$$\mathbf{A_{LR} = \frac{2a_e v_e}{v_e^2 + a_e^2}\ ,\ A_{LR/FB}^f = \frac{3}{4} \frac{2a_f v_f}{v_f^2 + a_f^2}}$$

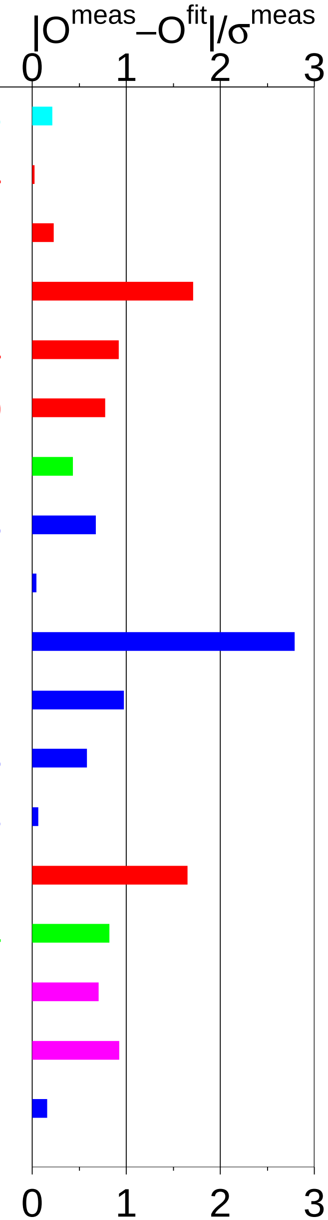
- **W boson parameters: $\mathbf{M_W}$ and $\mathbf{\Gamma_W}$ at LEP2 and Tevatron.**
- **Other observables at low–energy: ν_e DIS, PV in Cs and Th ...**
- **Use top quark mass value from Tevatron $\mathbf{m_t = 172 \pm 2}$ GeV**
- **Use value of α_s from LEP and elsewhere: $\mathbf{\alpha_s = 0.117 \pm 0.002}$**
- **Use $\alpha(M_Z)$ with $\mathbf{\Delta\alpha = 0.028 \pm 0.00036}$ from low–energy data**

$\Rightarrow$ **Very high precision tests of the SM at the quantum level: 1%–0.1%**

The SM describes precisely (almost) all available experimental data!

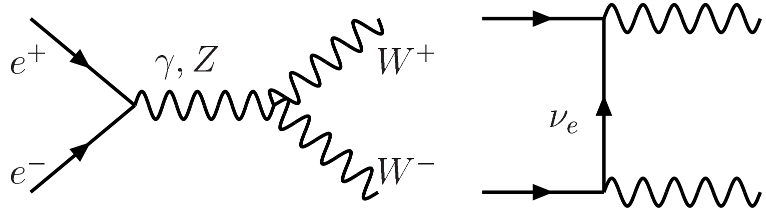
1. The SM: precision tests

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



1. The SM: precision tests

WW production at LEP2:



General CPC WWV coupling given by:

$$\mathcal{L}_{\rm eff}^{WWV} \propto g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu}$$

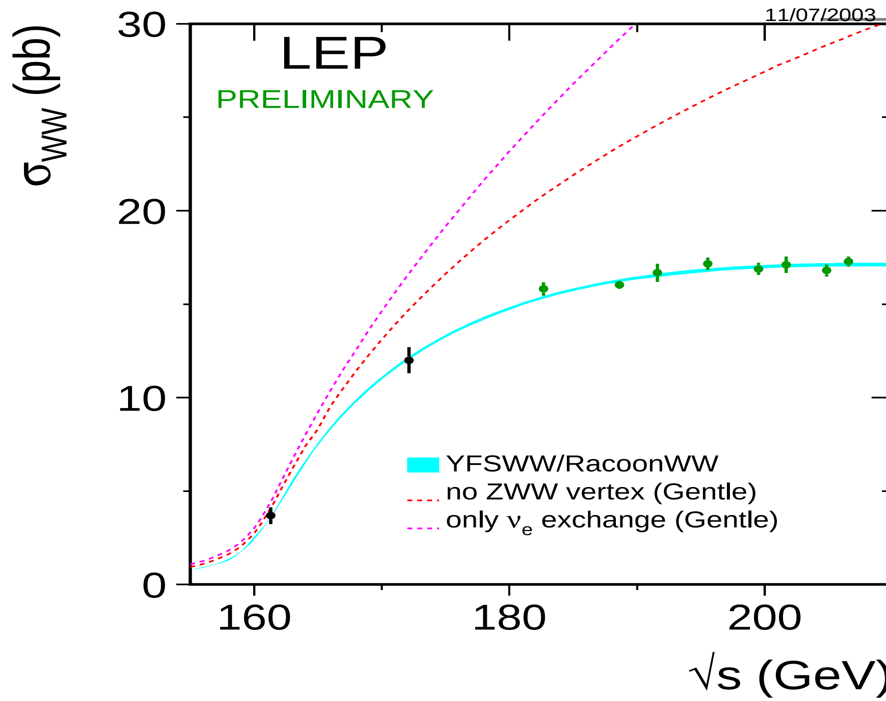
In SM: $g_1^V = 1, \kappa_V = 1, \lambda_V = 0$

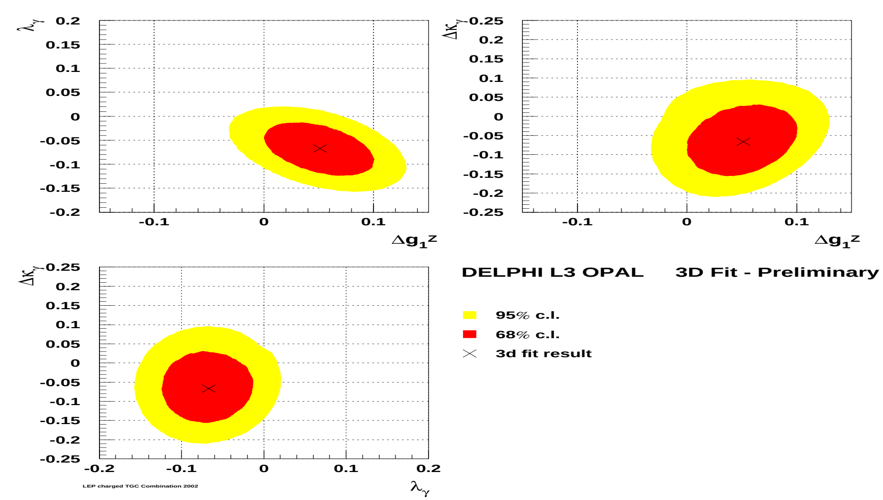
$\mathbf{SU(2)_L \times U(1)_Y}$ gauge structure checked rather precisely at LEP2

Note: QCD also very precisely tested!

– running of α_s from m_τ to LEP2.

– 3 gluon vertex determined at LEP1.





2. EW Physics at the LHC

Physics at the LHC: some generalities

LHC: pp collider $\sqrt{s}=7+7=14 \;\; \mathrm{TeV} \Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \;\; \sim \;\; 5 \;\; \mathrm{TeV}$

$\mathcal{L} \sim 10\,\mathrm{fb}^{-1}$ first years and $100\,\mathrm{fb}^{-1}$ later (we hope!)

- **Huge cross sections for QCD processes.**
- **Small cross sections for EW (and H) signals**

  S/B $\gtrsim 10^{10} \Rightarrow$ **a needle in a haystack!**
- **Need some strong selection criteria:**

Trigger: get rid of uninteresting events...

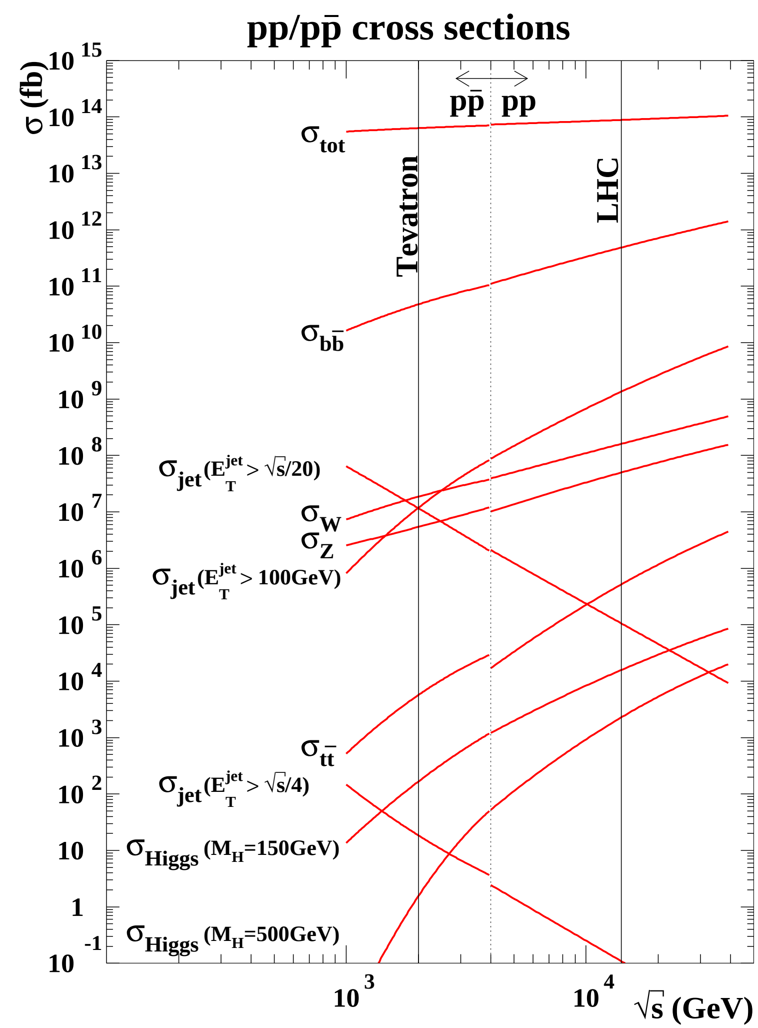
Select clean channels: $\mathrm{H} \to \gamma\gamma, \mathrm{V} \to \ell$.

Use different kinematic features for signal.

Combine different decay/production channels.

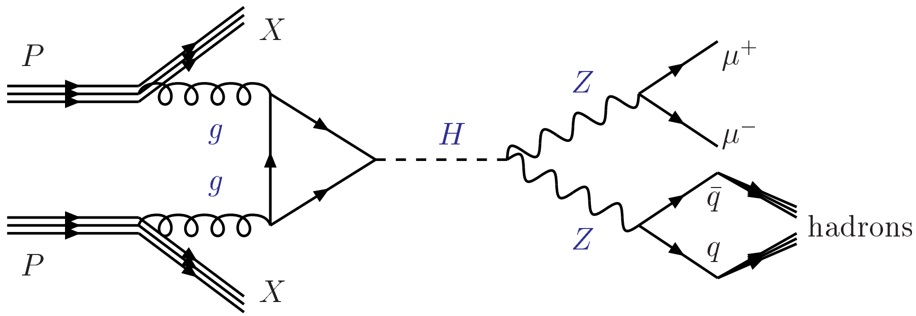
Have a precise knowledge of S and B rates.

- **Gigantic experimental (+theoretical) efforts!**



2. EW Physics at the LHC: generalities

Example of process at LHC to see how things work: $\mathrm{gg} \to \mathrm{H}$



$$\mathrm{N_{ev}} = \mathcal{L} \times \mathrm{P(g/p)} \times \hat{\sigma}(\mathrm{gg} \to \mathrm{H}) \times \mathrm{B(H \to ZZ)} \times \mathrm{B}(\mathrm{Z} \to \mu\mu) \times \mathrm{BR(Z \to qq)}$$

For a large number of events, all these numbers should be large!

Two ingredients: hard process (σ, B) and soft process (PDF, hadr).

Factorization theorem! Here discuss production/decay process.

The partonic cross section of the subprocess, $\mathrm{gg} \to \mathrm{H}$, is:

$$\hat{\sigma}(\mathbf{gg} \to \mathbf{H}) = \int \frac{\mathbf{1}}{\mathbf{2\hat{s}}} \times \frac{\mathbf{1}}{\mathbf{2 \cdot 8}} \times \frac{\mathbf{1}}{\mathbf{2 \cdot 8}} |\mathcal{M}_{\mathbf{Hgg}}|^{\mathbf{2}} \frac{\mathrm{d}^{\mathbf{3}}\mathbf{p_H}}{(\mathbf{2}\pi)^{\mathbf{3}}\mathbf{2E_H}} (\mathbf{2}\pi^{\mathbf{4}}) \delta^{\mathbf{4}} (\mathbf{q} - \mathbf{p_H})$$

Flux factor, color/spin average, matrix element squared, phase space.

Convolute with gluon densities to obtain total hadronic cross section

$$\sigma = \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_1} \int_{\mathbf{0}}^{\mathbf{1}} \mathrm{d}\mathbf{x_2} \frac{\pi^{\mathbf{2}}\mathbf{M_H}}{\mathbf{8\hat{s}}} \, \mathbf{\Gamma}(\mathbf{H} \to \mathbf{gg}) \mathbf{g}(\mathbf{x_1}) \mathbf{g}(\mathbf{x_2}) \delta(\mathbf{\hat{s}} - \mathbf{M_H^2})$$

2. EW Physics at the LHC: generalities

The calculation of $\sigma_{\rm born}$ is not enough in general at pp colliders:

need to include higher order radiative corrections which introduce terms of order $\alpha_{\bf s}^{\bf n} \log^{\bf m}({\bf Q}/{\bf M_W})$ where Q is either large or small...

- **Since α_s is large, these corrections are in general very important.**
- **Choose a (natural scale) which absorbs/resums the large logs.**

Since we truncate pert. series: only NLO/NNLO corrections available.

- **The (hopefully) not known HO corrections induce a theoretical error.**
- **The scale variation is a (naive) measure of the HO: must be small.**

Also, precise knowledge of σ is not enough: need to calculate some kinematical distributions (e.g. ${\bf p_T}, \eta, \frac{\bf d\sigma}{\bf dM}$) to distinguish S from B.

In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{\rm N_S}{\sqrt{\rm N_{bjg}}}$

$\Rightarrow$ a lot of theoretical work is needed!

But most complicated thing is to actually see the signal for S/B$\ll$1!

2. EW Physics at the LHC: generalities

Tests of the SM and background calibration for New Physics searches

- **The physics of the bottom quarks:**

– Study of QCD.

– Further tests of CKM matrix and of CP violation (mainly LHCb).

- **The physics of the top quark:**

– plays a key role origin of EWSB and clue to SM flavour problem?

– since lifetime shorter than hadronisation scale, QCD laboratory,

– single top production allows for further tests of the CKM matrix.

- **The physics of W,Z bosons:**

– W,Z production allow to measure precisely $\mathrm{M_W}$ and Γ_W,

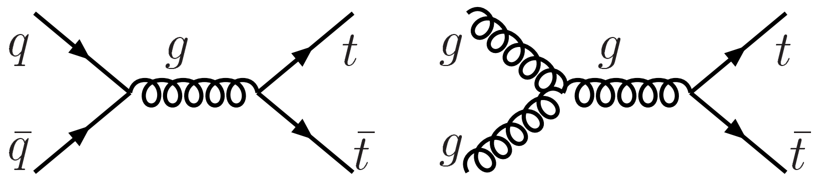
– the WW, WZ(γ),ZZ(γ) processes allow to measure the TGC,

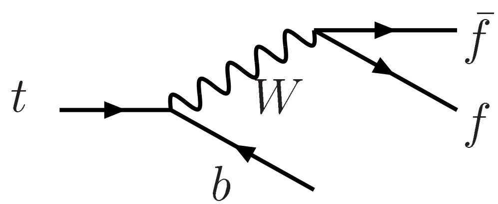
– VV and VV $\rightarrow$VV allow to test a strongly interacting sector.

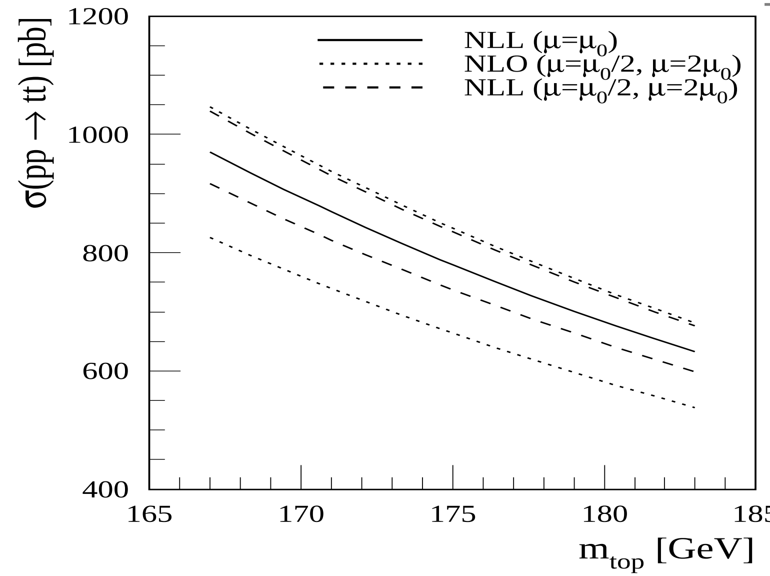
The discovery of the Higgs boson is the ultimate test of the SM!

2. EW Physics at the LHC: the top quark

Top quark pair production: $\mathbf{pp \to t\bar{t}}$

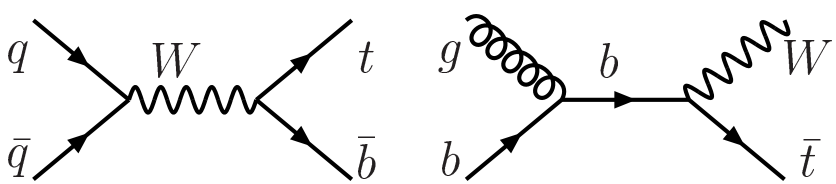


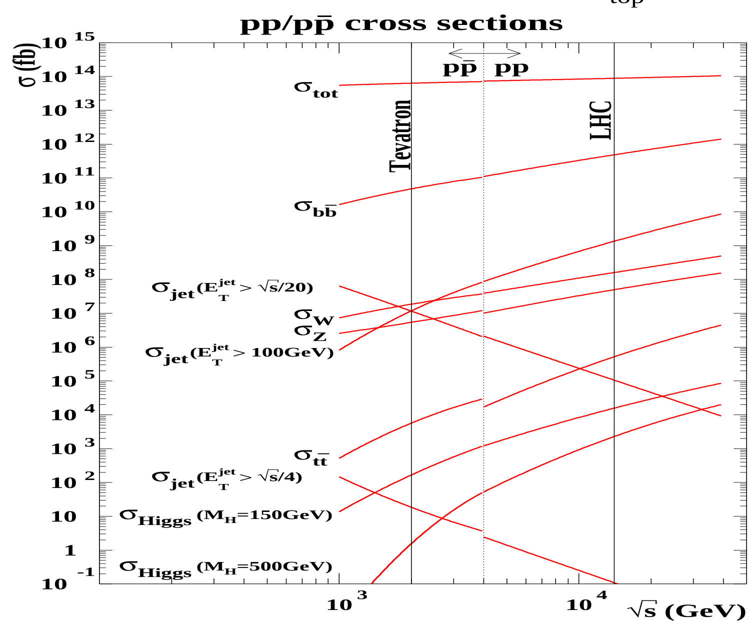




M_t measurement: $\Delta M_t \sim \pm 1$ GeV

Single top production: $\mathbf{pp \to t + X}$

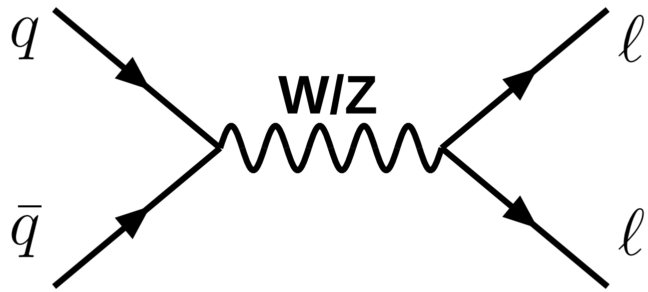




Much smaller rates by enough events for precise $V_{bt}^{\rm CKM}$ measurement....

2. EW Physics at the LHC: the W/Z bosons

Single W/Z production: $\mathrm{pp} \to \mathrm{q\bar{q}} \to \mathrm{V}$



Very large number of events $\sim 10^9$:

Include RC: $\mathrm{K_V} = \sigma_{\mathrm{NNL0}}/\sigma_{\mathrm{LO}} \sim 1.4$

Systematical errors ($\mathcal{L}$, PDF's, etc..)

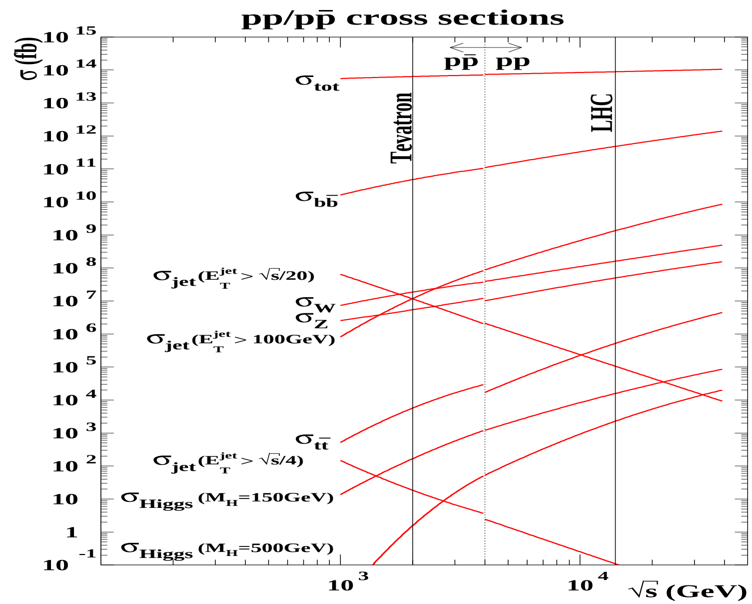
cancell in the ratio $\sigma(\mathrm{W})/\sigma(\mathrm{Z})$

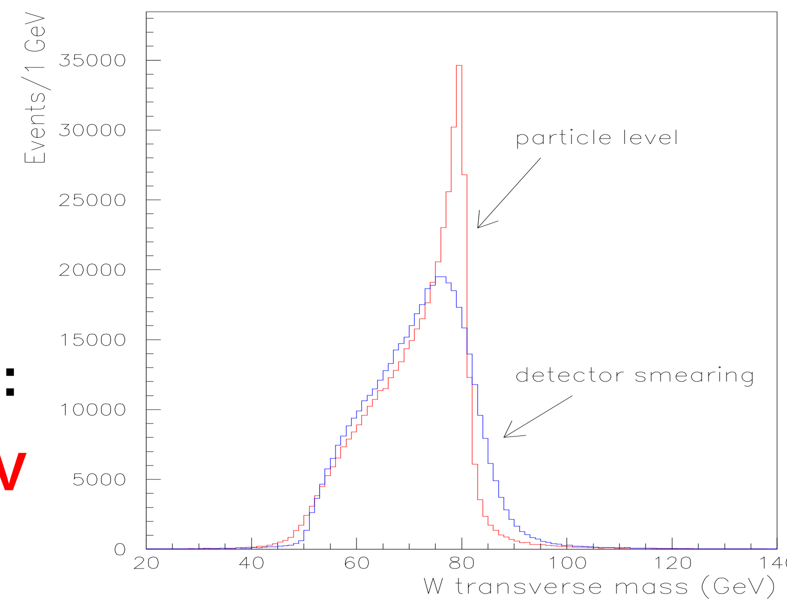
Use Z parameters from LEP1/SLC

Precise measurements of W parameters:

ATLAS+CMS@10 fb^{-1}: $\Delta \mathrm{M_W} \approx 15$ MeV

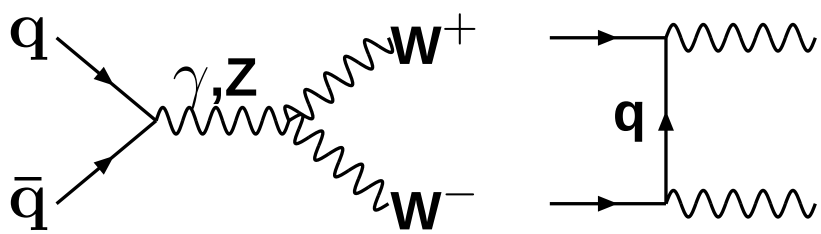
Now at CDF/D0: $\Delta \mathrm{M_W} \approx 30$ MeV

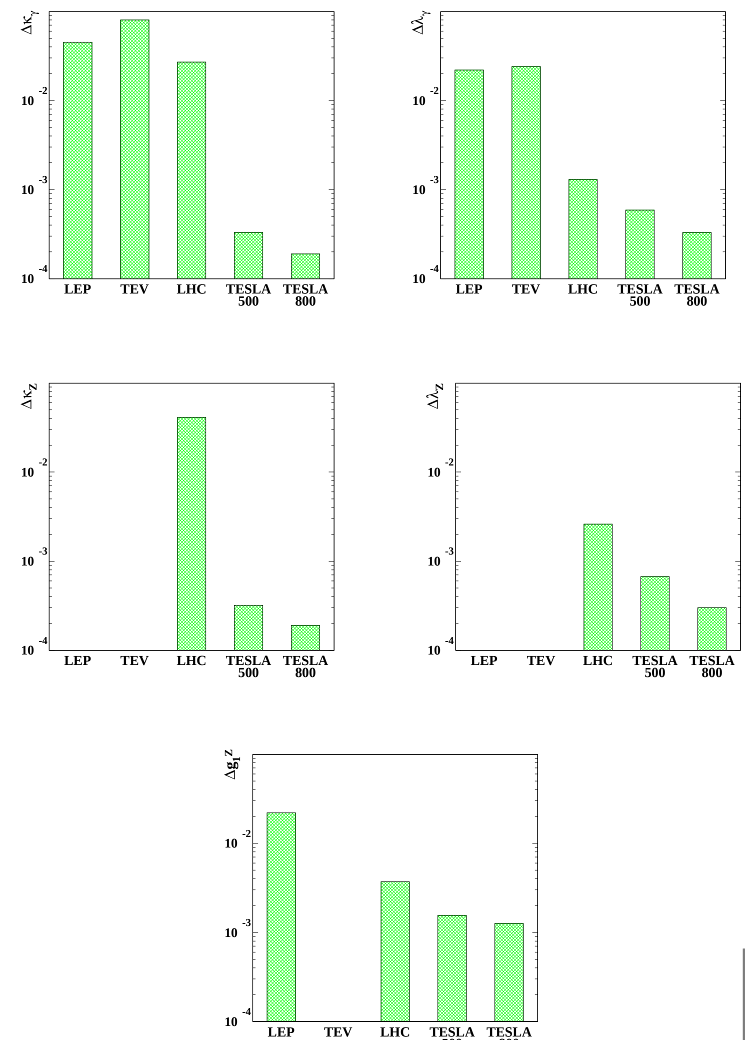




2. EW Physics at the LHC: VV production

WW/ZZ/Zγ production important to check SM gauge structure (as at LEP)





General form of the trilinear couplings

$$\mathcal{L}_{\rm eff}^{\rm WWV} = {\rm i}g_{\rm WWV}\Big[g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu} \right)$$

$$+\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}$$

$$+{\rm i}g_5^V \varepsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu}) \right) V^\sigma$$

$$+{\rm i}g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$$

$$-\frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}{}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \Big]$$

overall couplings $g_{WW\gamma} = e, g_{WWZ} = e\cot\theta_W$

In practice: deviations from SM values

$$\Delta g_1^Z \equiv (g_1^Z - 1), \Delta\kappa_\gamma \equiv (\kappa_\gamma - 1), \Delta\kappa_Z \equiv (\kappa_Z - 1)$$

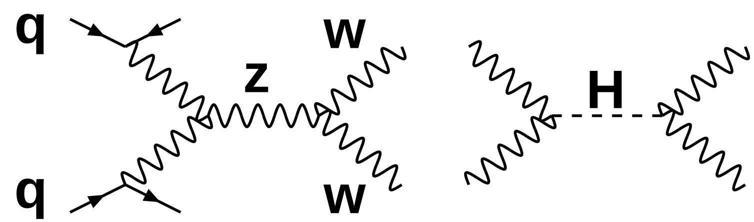
2. EW Physics at the LHC: strong W/Z sector

WW/ZZ/WZ scattering: important if the Higgs is too heavy or absent!

SM with Higgs field integrated out,

$\Rightarrow$ non–linear realisation of EWSB.

$\mathcal{L}_{\rm SM}^{\rm eff}$ below $\Lambda_{\rm ewsb} = 4\pi v \approx 3\,{\rm TeV}$:



$$L_1 = \frac{\alpha_1}{16\pi^2}\frac{gg'}{2} B_{\mu\nu}\,{\rm tr}\left(\sigma_3 W^{\mu\nu}\right)$$

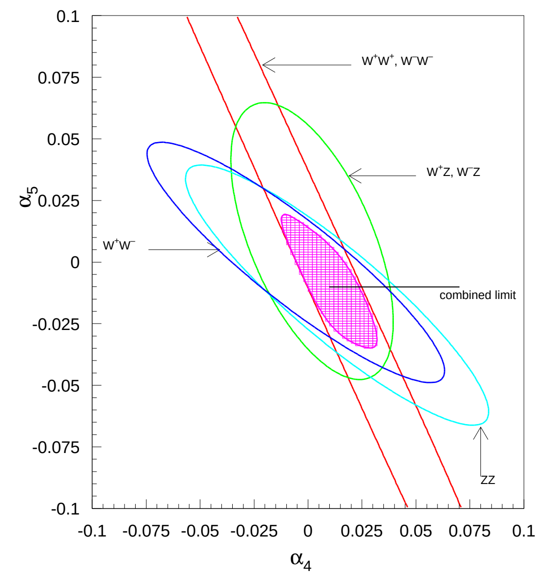
$$L_2 = \frac{\alpha_2}{16\pi^2}\, ig' B_{\mu\nu}\,{\rm tr}\left(\sigma_3 V^\mu V^\nu\right)$$

$$L_3 = \frac{\alpha_3}{16\pi^2}\, 2ig\,{\rm tr}\left(W_{\mu\nu} V^\mu V^\nu\right)$$

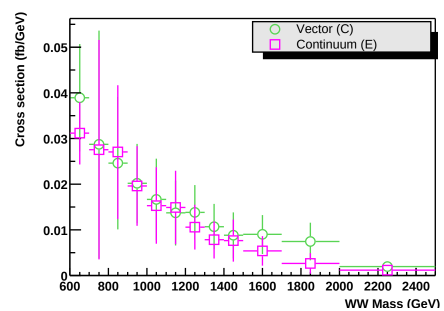
$$L_4 = \frac{\alpha_4}{16\pi^2}\,{\rm tr}\left(V_\mu V_\nu\right){\rm tr}\left(V^\mu V^\nu\right)$$

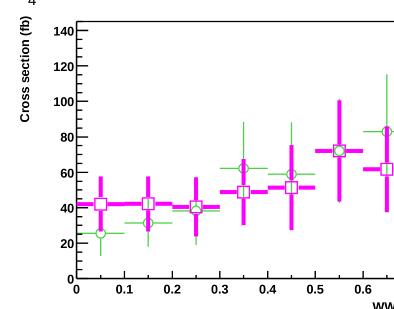
$$L_5 = \frac{\alpha_5}{16\pi^2}\,{\rm tr}\left(V_\mu V^\mu\right){\rm tr}\left(V_\nu V^\nu\right)$$

$$L_{6,7,8,9,10}({\rm C/P\ non-conserving})$$



- α_i **related to** Λ_i^* **by** $\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$
- $L_{1,2,.}$ **enter precisison data ($\triangle\rho$).**
- $L_{1,2,3}$ **contribute to TGC; qq$\to$ VV**
- $L_{3,4,5}$ **parametrize strong EWSB**





3. EWSB in the SM

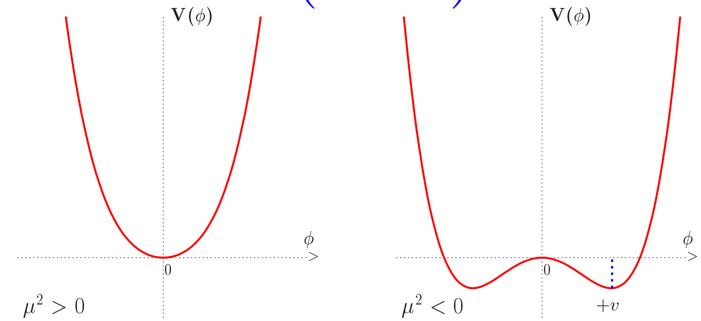
In the SM, if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

breaking of gauge symmetry $\Rightarrow$ spontaneous EW symmetry breaking

$\Rightarrow$ **introduce a doublet of complex scalar fields:** $\mathbf{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^{\mathbf{0}} \end{pmatrix}$, $\mathbf{Y_\Phi = +1}$

with a Lagrangian that is invariant under $\mathbf{SU(2)_L \times U(1)_Y}$

$$\mathcal{L}_{\mathbf{S}} = (\mathbf{D}^\mu \mathbf{\Phi})^\dagger (\mathbf{D}_\mu \mathbf{\Phi}) - \mu^{\mathbf{2}} \mathbf{\Phi}^\dagger \mathbf{\Phi} - \lambda (\mathbf{\Phi}^\dagger \mathbf{\Phi})^{\mathbf{2}}$$

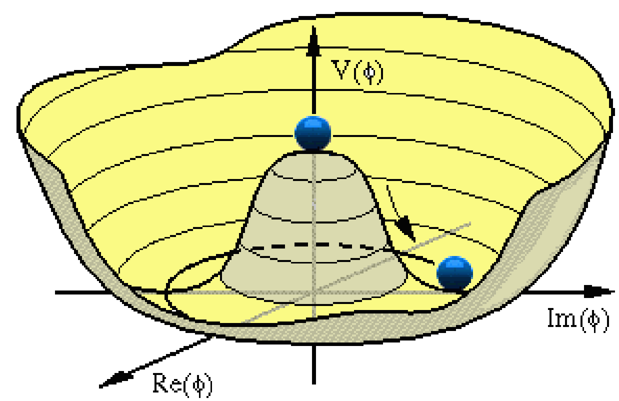


$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

$$\langle \mathbf{0} | \mathbf{\Phi} | \mathbf{0} \rangle = \begin{pmatrix} \mathbf{0} \\ \mathbf{v}/\sqrt{\mathbf{2}} \end{pmatrix}$$

$$\textbf{with vev} \equiv \mathbf{v} = (-\mu^{\mathbf{2}}/\lambda)^{\frac{\mathbf{1}}{\mathbf{2}}}$$



To obtain the physical states,

write $\mathcal{L}_{\rm S}$ with the true vacuum:

3. EWSB in SM: mass generation

- Rewrite: $\Phi(x) = \frac{1}{\sqrt{2}}\binom{\theta_2+i\theta_1}{v+H-i\theta_3} \simeq e^{i\theta_a(x)\tau^a(x)/v}\,\frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$
- Gauge transf. (unitary gauge): $\Phi \to e^{-i\theta_a(x)\tau^a(x)}\Phi = \frac{1}{\sqrt{2}}\binom{0}{v+H(x)}$
- Develop covariant derivative: $|D_\mu\Phi|^2 = \left|\left(\partial_\mu - ig_2\frac{\tau_a}{2}W^a_\mu - i\frac{g_1}{2}B_\mu\right)\Phi\right|^2$
- Define: $W^\pm = \frac{W^1_\mu \mp iW^2_\mu}{\sqrt{2}}\ ,\ Z_\mu = \frac{g_2W^3_\mu - g_1B_\mu}{\sqrt{g_2^2+g_1^2}}\ ,\ A_\mu = \frac{g_2W^3_\mu + g_1B_\mu}{\sqrt{g_2^2+g_1^2}}$
- And pick up terms bilinear in the fields $W^\pm, Z, A$ (i.e. $M_V^2 V^+_\mu V^{-\mu}$)

$\Rightarrow$ 3 degrees of freedom for $W^\pm_L, Z_L$ and thus $M_{W^\pm}, M_Z$:

$$M_W = \frac{1}{2}vg_2\ ,\ M_Z = \frac{1}{2}v\sqrt{g_2^2+g_1^2}\ ,\ M_A = 0\ ,$$

with the value of the vev given by $v = 1/(\sqrt{2}G_F)^{1/2} \sim 246\ \mathrm{GeV}$.

$\Rightarrow$ The photon stays massless and thus $U(1)_{QED}$ is preserved.

- For fermion masses, use <u>same</u> doublet field Φ and its <u>conjugate</u> field $\tilde{\Phi} = i\tau_2\Phi^*$ and introduce $\mathcal{L}_{\rm Yuk}$ which is invariant under SU(2)xU(1):

$$\mathcal{L}_{\rm Yuk} = -f_e(\bar{e},\bar{\nu})_L\Phi e_R - f_d(\bar{u},\bar{d})_L\Phi d_R - f_u(\bar{u},\bar{d})_L\tilde{\Phi}u_R + \cdots$$

$$\Phi \to \frac{1}{\sqrt{2}}\binom{0}{H+v} \Rightarrow m_e = \frac{f_e\,v}{\sqrt{2}},\ m_u = \frac{f_u\,v}{\sqrt{2}},\ m_d = \frac{f_d\,v}{\sqrt{2}}$$

3. EWSB in SM: the Higgs boson

With same Φ, we have generated gauge boson and fermion masses, while preserving SU(2)xU(1) gauge symmetry (which is now hidden)!

What about the residual degree of freedom?

It will correspond to the physical spin–zero scalar Higgs particle, H.

The kinetic part of H field, $\frac{1}{2}(\partial_\mu \mathrm{H})^2$, comes from $|\mathrm{D}_\mu \Phi)|^2$ term.

Mass and self-interaction part from $\mathrm{V}(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$:

with $\Phi \rightarrow \frac{1}{\sqrt{2}} \binom{0}{\mathrm{H+v}}$ the Lagrangian containing the H field becomes,

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

- **The Higgs boson mass is given by:** $\mathrm{M_H^2} = 2\lambda \mathrm{v}^2 = -2\mu^2$.
- **The self–couplings are:** $\mathrm{g_{H^3}} = 3\mathrm{i}\, \mathrm{M_H^2/v}\,,\ \mathrm{g_{H^4}} = 3\mathrm{i}\mathrm{M_H^2/v^2}$
- **Higgs couplings to gauge bosons and fermions almost derived:**

$$\mathcal{L}_{\mathrm{M_V}} \sim \mathrm{M_V^2}(1 + \mathrm{H/v})^2\ ,\ \mathcal{L}_{\mathrm{m_f}} \sim -\mathrm{m_f}(1 + \mathrm{H/v})$$

$$\Rightarrow \mathrm{g_{Hff}} = \mathrm{i m_f/v}\,,\ \mathrm{g_{HVV}} = -2\mathrm{i}\mathrm{M_V^2/v}\,,\ \mathrm{g_{HHVV}} = -2\mathrm{i}\mathrm{M_V^2/v^2}$$

Since v is known, the only free parameter in the SM is $\mathrm{M_H}$ (or λ).

3. EWSB in SM: W/Z/H at high energies

Propagators of gauge and Goldstone bosons in a general ζ gauge:

$\longrightarrow q$ $\quad \frac{-i}{q^2-M_V^2+i\epsilon}\left[g_{\mu\nu}+(\zeta-1)\frac{q_\mu q_\nu}{q^2-\zeta M_V^2}\right]$

$\zeta=\infty$: **Landau gauge**

$\zeta=1$: **'t Hooft-Feynman**

$\omega^\pm, \omega^0$:

$\longrightarrow q$ $\quad \frac{-i}{q^2-\zeta M_V^2+i\epsilon}$

- **In unitary gauge, Goldstones do not propagate and gauge bosons have usual propagators of massive spin–1 particles (old IVB theory).**
- **At very high energies, $\mathbf{s \gg M_V^2}$, an approximation is $\mathbf{M_V \sim 0}$. The $\mathbf{V_L}$ components of V can be replaced by the Goldstones, $\mathbf{V_L \to w}$.**
- **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones. In VV scattering e.g.**

$$\mathbf{A(V_L^1 \cdots V_L^n \to V_L^1 \cdots V_L^{n'}) = (i)^n(-i)^{n'} A(w^1 \cdots w^n \to w^1 \cdots w^{n'})}$$

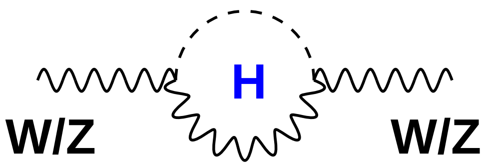
Thus, we simply replace V by w in the scalar potential and use w:

$$\mathbf{V = \frac{M_H^2}{2v}(H^2+w_0^2+2w^+w^-)H + \frac{M_H^2}{8v^2}(H^2+w_0^2+2w^+w^-)^2}$$

3. EWSB in SM: constraints on M_H

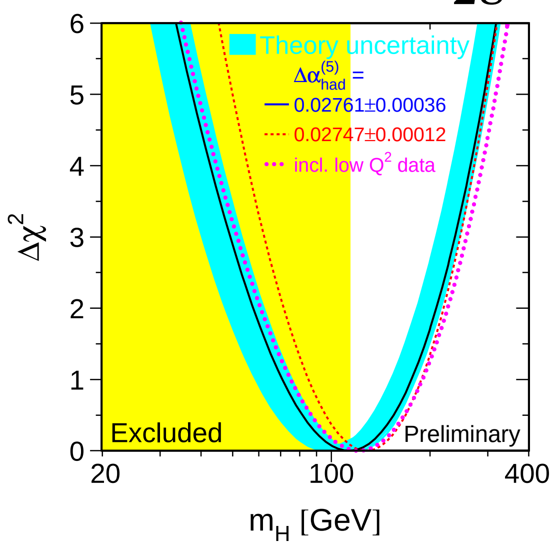
Indirect Higgs searches:

H contributes to RC to W/Z masses:



Fit the EW precision measurements:

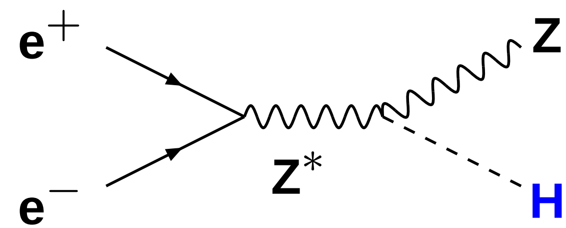
we obtain $M_H = 85^{+39}_{-28}$ GeV, or



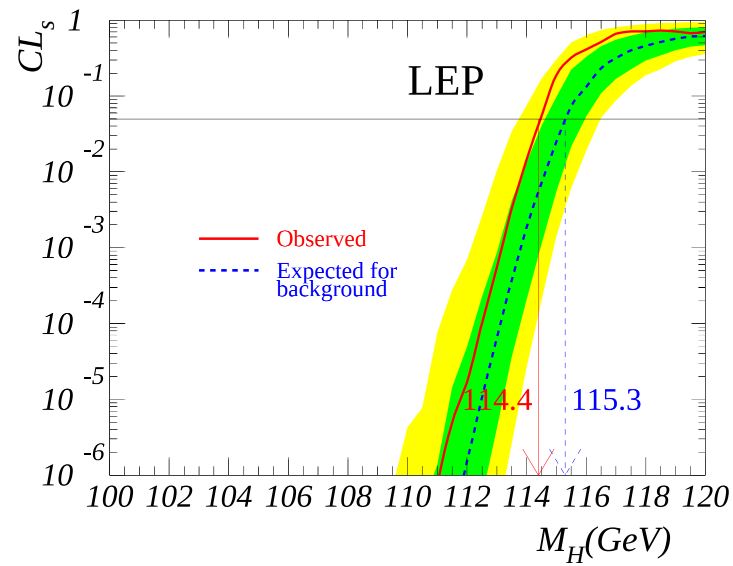
$M_H \lesssim 180$ **GeV at 95% CL**

Direct searches at colliders:

H looked for in $e^+e^- \to ZH$



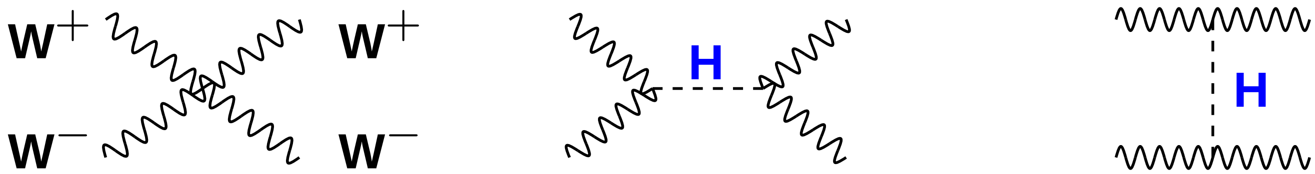
$M_H > 114.4$ **GeV** $@95\%$**CL**



Tevatron $M_H \neq 160-170$ GeV

3. EWSB in SM: constraints from perturbative unitarity

Scattering of massive gauge bosons $V_L V_L \to V_L V_L$ at high-energy



Because w interactions increase with energy (q^μ terms in V propagator),

$s \gg M_W^2 \Rightarrow \sigma(w^+w^- \to w^+w^-) \propto s$: $\Rightarrow$ **unitarity violation possible!**

Decomposition into partial waves and choose J=0 for $s \gg M_W^2$:

$$a_0 = -\frac{M_H^2}{8\pi v^2}\left[1 + \frac{M_H^2}{s-M_H^2} + \frac{M_H^2}{s}\log\left(1+\frac{s}{M_H^2}\right)\right]$$

For unitarity to be fullfiled, we need the condition $|\mathrm{Re}(a_0)| < 1/2$.

- At high energies, $s \gg M_H^2, M_W^2$, we have: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$

$$\text{unitarity} \Rightarrow M_H \lesssim 870\ \text{GeV} \ \ (M_H \lesssim 710\ \text{GeV})$$

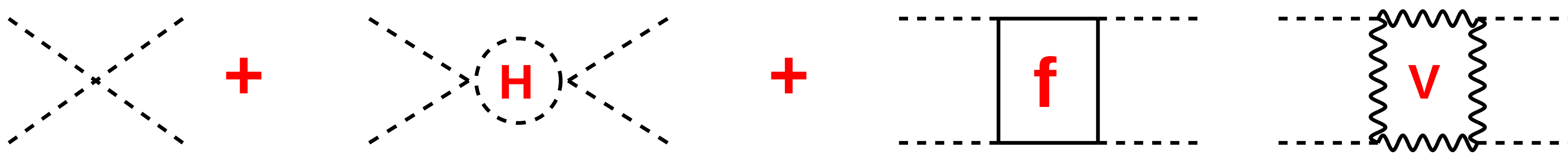
- For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7\ \text{TeV} \ \ (\sqrt{s} \lesssim 1.2\ \text{TeV})$$

Otherwise (strong?) New Physics should appear to restore unitarity.

3. EWSB in SM: constraints from triviality+stability

The quartic coupling of the Higgs boson $\lambda \propto M_H^2$ increases with energy.



Heavy H: H contributions dominant

RGE: $\frac{d\lambda(Q^2)}{dQ^2} = \frac{3}{4\pi^2}\,\lambda^2(Q^2) \Rightarrow$

$\lambda(Q^2) = \lambda(v^2)/[1 - \frac{3}{4\pi^2}\log\frac{Q^2}{v^2}]$

- $Q^2 \ll v^2;\ \lambda \rightarrow 0_+$: **triviality**
- $Q^2 \gg v^2\ :\ \lambda \rightarrow \infty$: **Landau pole**

SM only valid before $\lambda \lesssim 4\pi \ll \infty$

$\Lambda_C = M_H \Rightarrow M_H \lesssim 650$ GeV

(Comparable to results on lattice!)

Light H: t/W/Z contributions dominant

$\frac{\lambda(Q^2)}{\lambda(v^2)} = 1 + 3\,\frac{2M_W^4 + M_Z^4 - 4m_t^4}{16\pi^2 v^4}\log\frac{Q^2}{v^2}$

If λ is small, i.e. if the H is too light:

top loops might lead to $\lambda(0) < \lambda(v)$:

v not minimum / EW vacuum unstable

The SM is valid only if $\lambda(Q^2) > 0$

$\Rightarrow M_H^2 > \frac{3(2M_W^4 + M_Z^4 - 4m_t^4)}{8\pi^2 v^2}\log\frac{Q^2}{v^2}$

Strong lower bound on the H mass:

$Q = \Lambda_C \sim 1$ TeV $\Rightarrow M_H \gtrsim 70$ GeV

3. EWSB in SM: constraints from triviality+stability

Combine trivilaity+stability constraints and include all possible effects:

$\Lambda_C \sim 10^3$ GeV $\Rightarrow$

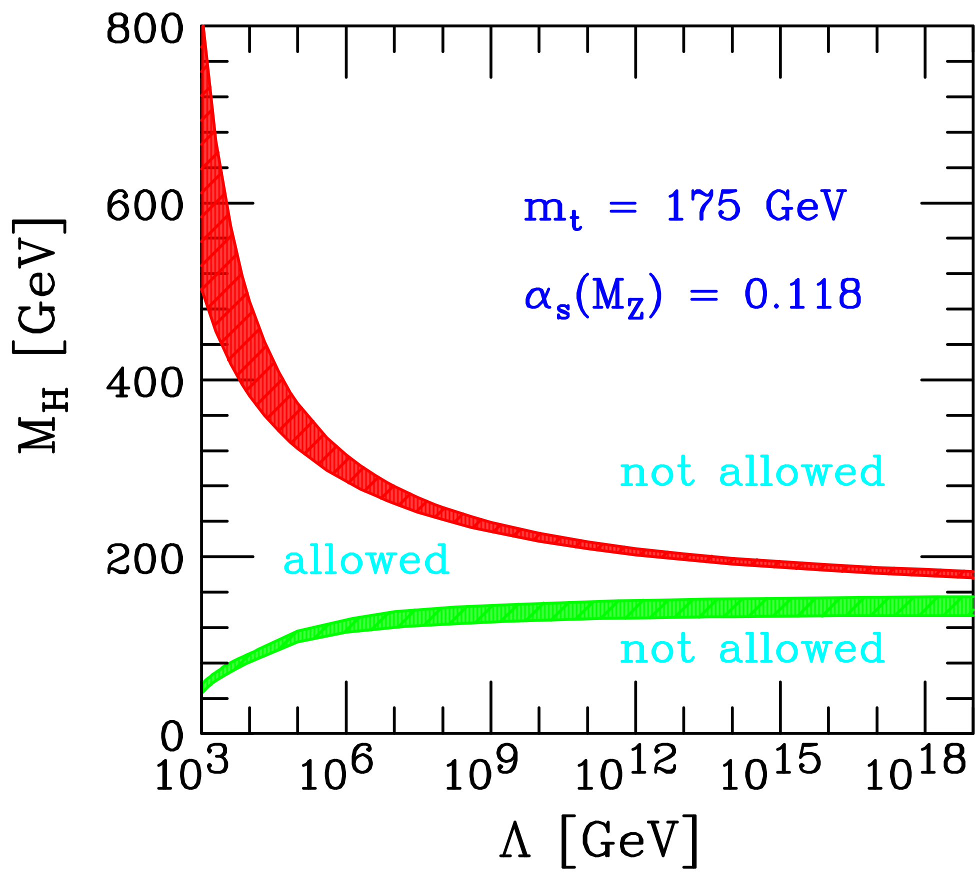
$70\ \mathrm{GeV} \lesssim M_H \lesssim 700\ \mathrm{GeV}$

$\Lambda_C \sim 10^{16}$ GeV $\Rightarrow$

$130\ \mathrm{GeV} \lesssim M_H \lesssim 180\ \mathrm{GeV}$

Very close to experimental limit

The Higgs is arround the corner!

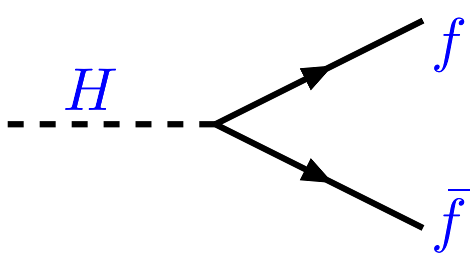


4. Higgs decays

Higgs couplings proportional to particle masses: once $\mathrm{M_H}$ is fixed,

- the profile of the Higgs boson is determined and its decays fixed,
- the Higgs has tendancy to decay into heaviest available particle.

Higgs decays into fermions:



$$\Gamma_{\rm Born}(\mathrm{H \to f\bar{f}}) = \frac{\mathrm{G_\mu N_c}}{4\sqrt{2}\pi}\,\mathrm{M_H\, m_f^2}\, \beta_{\rm f}^3$$

$$\beta_{\rm f} = \sqrt{1-4\mathrm{m_f^2/M_H^2}}\ :\ \mathrm{f\ velocity}$$

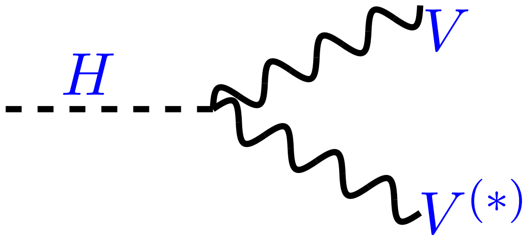
$$\mathrm{N_c = color\ number}$$

- Only $\mathrm{b\bar{b}, c\bar{c}}, \tau^+\tau^-, \mu^+\mu^-$ for $\mathrm{M_H} < 350$ GeV, also $\mathrm{t\bar{t}}$ beyond.
- $\Gamma \propto \beta^3$: H is CP–even scalar particle ($\propto \beta$ for pseudoscalar H).
- Decay width grows as $\mathrm{M_H}$: moderate growth....
- QCD RC: $\Gamma \propto \Gamma_0[1 - \frac{\alpha_s}{\pi}\log\frac{\mathrm{M_H^2}}{\mathrm{m_q^2}}] \Rightarrow$ very large: absorbed/summed

using running masses at scale $\mathrm{M_H}\ :\ \mathrm{m_b(M_H^2)} \sim \frac{2}{3}\mathrm{m_b^{pole}} \sim 3\,\mathrm{GeV}$.

- Include also direct QCD corrections (3 loops) and EW (one-loop).

4. Higgs decays: decays into gauge bosons



$$\Gamma(\mathrm{H} \to \mathrm{VV}) = \frac{\mathrm{G}_\mu \mathrm{M}_\mathrm{H}^3}{16\sqrt{2}\pi} \delta_\mathrm{V} \beta_\mathrm{V} \left(1 - 4\mathrm{x} + 12\mathrm{x}^2\right)$$

$$\mathrm{x} = \mathrm{M}_\mathrm{V}^2/\mathrm{M}_\mathrm{H}^2, \; \beta_\mathrm{V} = \sqrt{1 - 4\mathrm{x}}$$

$$\delta_\mathrm{W} = 2, \; \delta_\mathrm{Z} = 1$$

- **For a very heavy Higgs boson:**

$\Gamma(\mathrm{H} \to \mathrm{WW}) = 2 \times \Gamma(\mathrm{H} \to \mathrm{ZZ}); \Rightarrow \mathrm{BR}(\mathrm{WW}) \sim \frac{2}{3}, \mathrm{BR}(\mathrm{ZZ}) \sim \frac{1}{3}$

$\Gamma(\mathrm{H} \to \mathrm{WW} + \mathrm{ZZ}) \propto \frac{1}{2} \frac{\mathrm{M}_\mathrm{H}^3}{(1\ \mathrm{TeV})^3}$ **because of contributions of $\mathrm{V_L}$:**

heavy Higgs is obese: width very large, comparable to $\mathrm{M_H}$ at 1 TeV.

EW radiative corrections from scalars large because $\propto \lambda = \frac{\mathrm{M}_\mathrm{H}^2}{2\mathrm{v}^2}$.

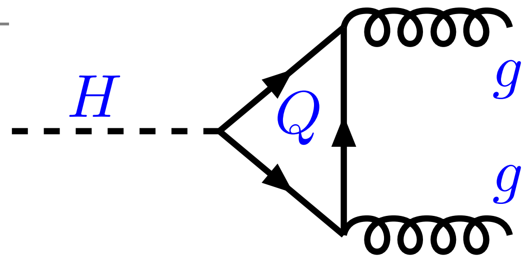
- **For a light Higgs boson:**

$\mathrm{M_H} < 2\mathrm{M_V}$**: possibility of off–shell V decays, $\mathrm{H} \to \mathrm{VV}^* \to \mathrm{Vf\bar{f}}$.**

Virtuality and addition EW cplg compensated by large $\mathrm{g_{HVV}}$ vs $\mathrm{g_{Hbb}}$.

In fact: for $\mathrm{M_H} \gtrsim$ 130 GeV, $\mathrm{H} \to \mathrm{WW}^*$ dominates over $\mathrm{H} \to \mathrm{b\bar{b}}$

4. Higgs decays: decays into gluons



$$\Gamma\,(\mathrm{H}\to\mathrm{gg}) = \frac{G_\mu\,\alpha_s^2\,M_H^3}{36\,\sqrt{2}\,\pi^3}\left|\frac{3}{4}\sum_Q A_{1/2}^H(\tau_Q)\right|^2$$

$$A_{1/2}^H(\tau) = 2[\tau + (\tau-1)f(\tau)]\,\tau^{-2}$$

$$f(\tau) = \arcsin^2\sqrt{\tau} \text{ for } \tau = M_H^2/4m_Q^2 \leq 1$$

- Gluons massless and Higgs has no color: must be a loop decay.
- For $m_Q \to \infty, \tau_Q \sim 0 \Rightarrow A_{1/2} = \frac{4}{3} =$ constant and Γ is finite!

Width counts the number of strong inter. particles coupling to Higgs!

- In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.
- Loop decay but QCD and top couplings: comparable to cc, $\tau\tau$.
- Approximation $m_Q \to \infty/\tau_Q = 1$ valid for $M_H \lesssim 2m_t = 350$ GeV.

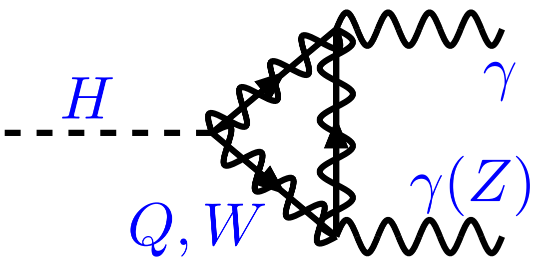
Good approximation in decay: include only t–loop with $m_Q \to \infty$. But:

- Very large QCD RC: the two– and three–loops have to be included:

$$\Gamma = \Gamma_0[1 + 18\tfrac{\alpha_s}{\pi} + 156\tfrac{\alpha_s^2}{\pi^2}] \sim \Gamma_0[1+0.7+0.3] \sim 2\Gamma_0$$

- Reverse process $\mathrm{gg}\to\mathrm{H}$ very important for Higgs production in pp!

4. Higgs decays: decays into photons



$$\Gamma = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c e_f^2 A^H_{\frac{1}{2}}(\tau_f) + A^H_1(\tau_W) \right|^2$$

$$A^H_{1/2}(\tau) = 2[\tau + (\tau - 1)f(\tau)]\,\tau^{-2}$$

$$A^H_1(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]\,\tau^{-2}$$

- **Photon massless and Higgs has no charge: must be a loop decay.**
- **In SM: only W–loop and top-loop are relevant (b–loop too small).**
- **For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: W loop dominating!**

(approximation $\tau_W \to 0$ valid only for $M_H \lesssim 2M_W$: relevant here!).

$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

- **Loop decay but EW couplings: very small compared to $H \to gg$.**
- **Rather small QCD (and EW) corrections: only of order $\frac{\alpha_s}{\pi} \sim 5\%$.**
- **Reverse process $\gamma\gamma \to H$ important for H production in $\gamma\gamma$.**
- **Same discussions hold qualitatively for loop decay $H \to Z\gamma$.**

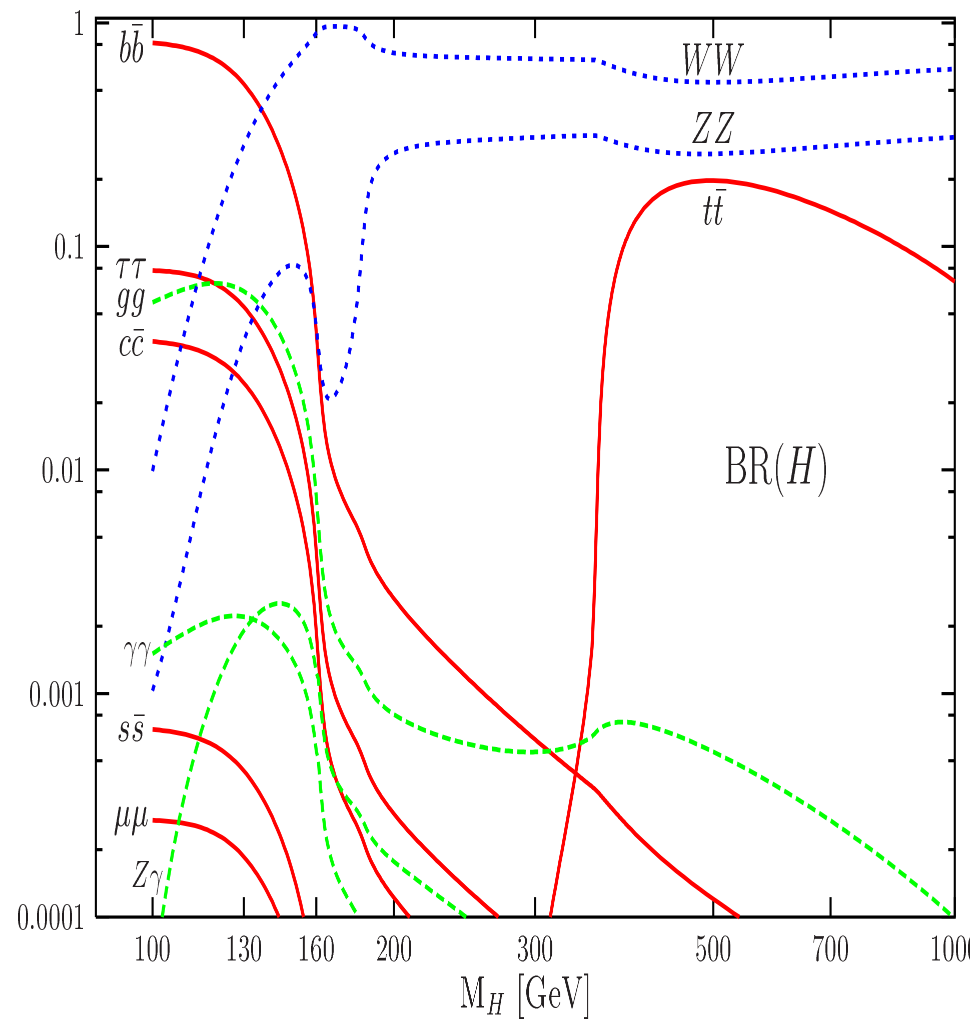
4. Higgs decays: branching ratios

Branching ratios: $\mathrm{BR}(\mathrm{H} \rightarrow \mathbf{X}) \equiv \frac{\Gamma(\mathbf{H} \rightarrow \mathbf{X})}{\Gamma(\mathbf{H} \rightarrow \mathbf{all})}$

- **'Low mass range', $\mathrm{M_H} \lesssim 130$ GeV:**
- – $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ **dominant, BR = 60–90%**
- – $\mathrm{H} \rightarrow \tau^+\tau^-, \mathrm{c\bar{c}}, \mathrm{gg}$ **BR= a few %**
- – $\mathrm{H} \rightarrow \gamma\gamma, \gamma\mathrm{Z}$**, BR = a few permille.**

- **'High mass range', $\mathrm{M_H} \gtrsim 130$ GeV:**
- – $\mathrm{H} \rightarrow \mathbf{WW^*}, \mathbf{ZZ^*}$ **up to** $\gtrsim 2\mathrm{M_W}$
- – $\mathrm{H} \rightarrow \mathbf{WW}, \mathbf{ZZ}$ **above (BR** $\rightarrow \frac{2}{3}, \frac{1}{3}$**)**
- – $\mathrm{H} \rightarrow \mathrm{t\bar{t}}$ **for high** $\mathrm{M_H}$**; BR** $\lesssim 20\%$.

- **Total Higgs decay width:**
- – $\mathcal{O}$**(MeV) for** $\mathrm{M_H} \sim 100$ **GeV (small)**
- – $\mathcal{O}$**(TeV) for** $\mathrm{M_H} \sim 1$ **TeV (obese).**



4. Higgs decays: total width

Total decay width: $\Gamma_{\rm H} \equiv \sum_{\rm X} \Gamma({\rm H} \to {\rm X})$

- **'Low mass range', $\rm M_H \lesssim 130$ GeV:**

– $\rm H \to b\bar{b}$ **dominant, BR = 60–90%**

– $\rm H \to \tau^+\tau^-, c\bar{c}, gg$ **BR= a few %**

– $\rm H \to \gamma\gamma, \gamma Z$**, BR = a few permille.**

- **'High mass range', $\rm M_H \gtrsim 130$ GeV:**

– $\rm H \to WW^*, ZZ^*$ **up to** $\gtrsim 2M_W$

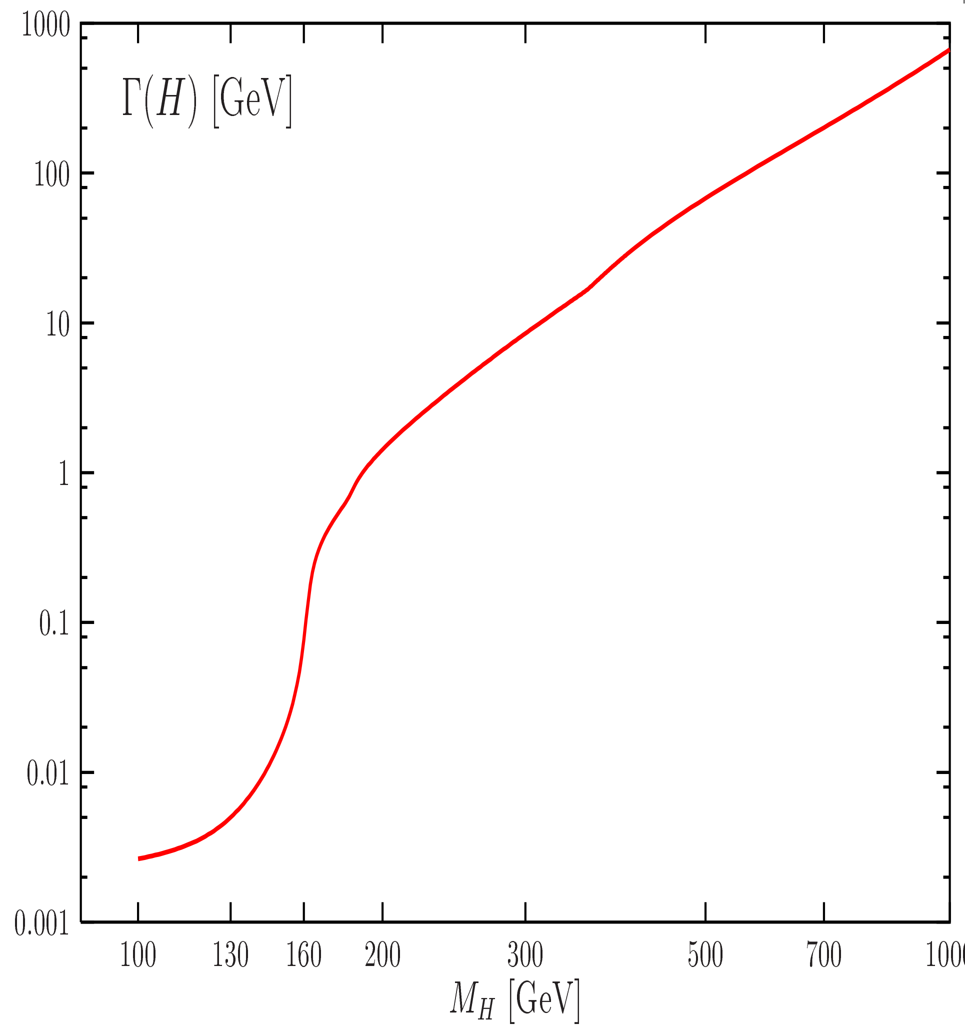
– $\rm H \to WW, ZZ$ **above (BR** $\to \frac{2}{3}, \frac{1}{3}$**)**

– $\rm H \to t\bar{t}$ **for high $\rm M_H$; BR** $\lesssim 20\%$**.**

- **Total Higgs decay width:**

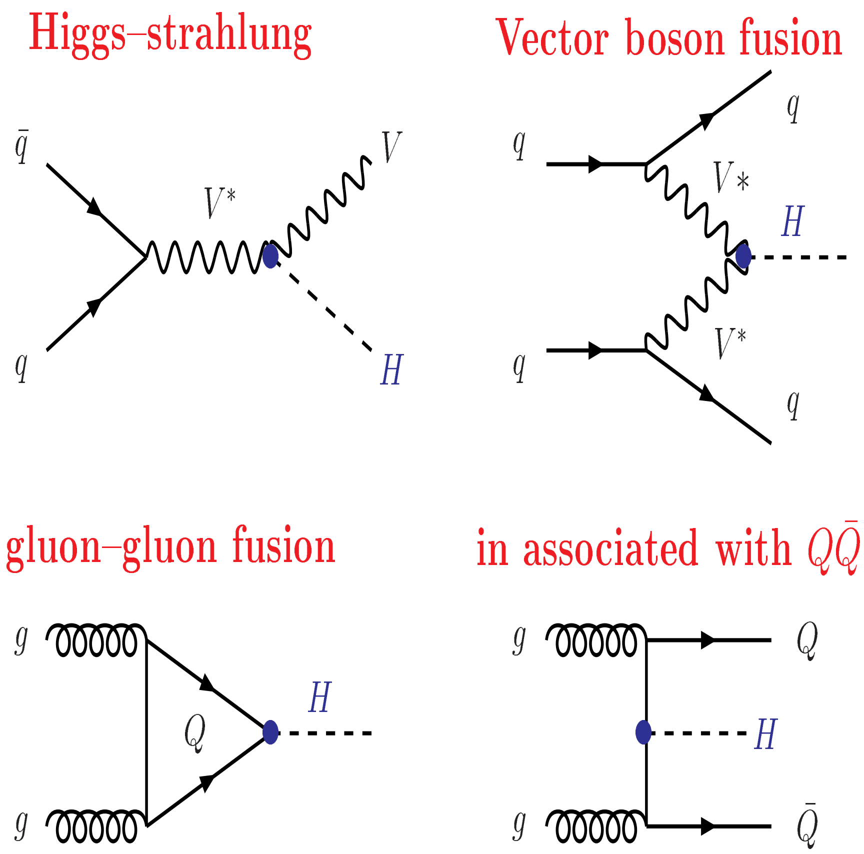
– $\mathcal{O}$**(MeV) for $\rm M_H \sim 100$ GeV (small)**

– $\mathcal{O}$**(TeV) for $\rm M_H \sim 1$ TeV (obese).**

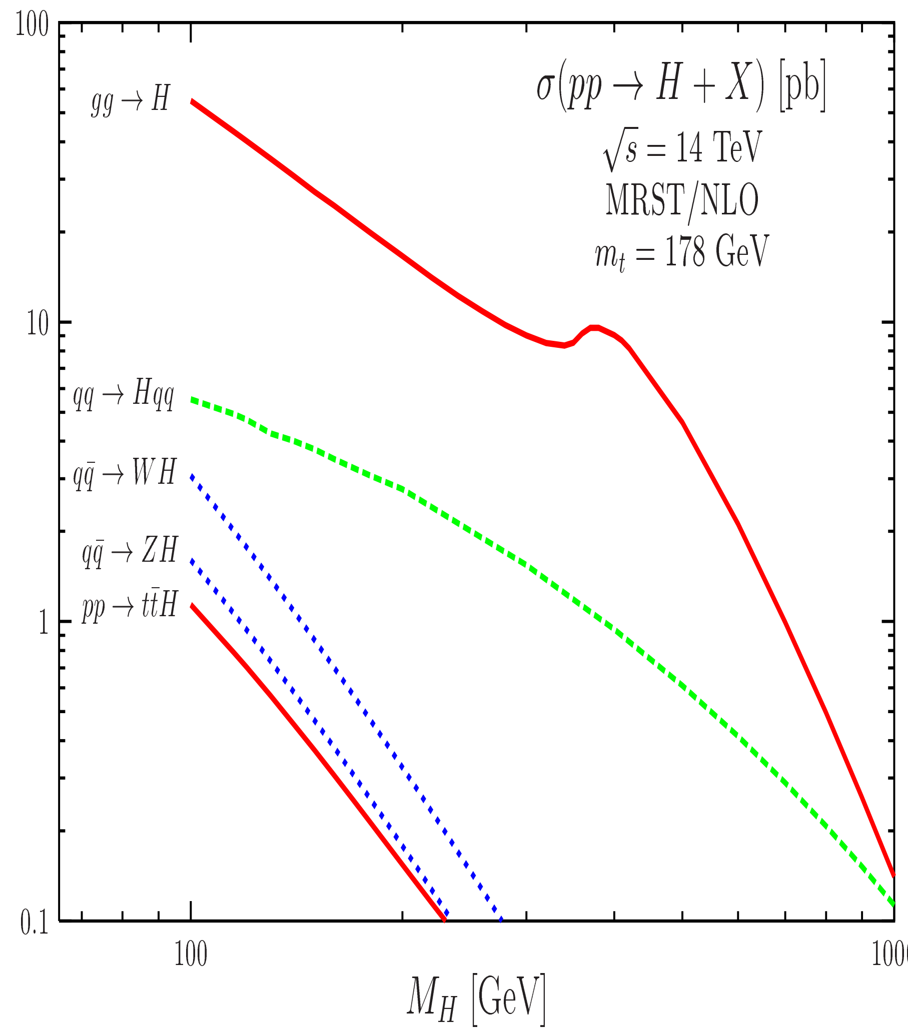


5. The Higgs at the LHC

Production mechanisms



Cross sections at the LHC

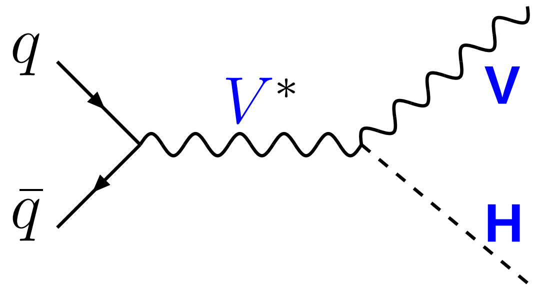


There are also subleading processes, $gg \to HH$, etc...

5. Higgs at the LHC: associated HV

Let us look at all the main Higgs production channels at the LHC:

The associated HV production:



$$\hat{\sigma}_{\rm LO}(\mathbf{q\bar{q}} \to \mathbf{VH}) = \frac{\mathbf{G_\mu^2 M_V^4}}{\mathbf{288\pi\hat{s}}}$$

$$\times (\hat{\mathbf{v}}_\mathbf{q}^\mathbf{2} + \hat{\mathbf{a}}_\mathbf{q}^\mathbf{2}) \lambda^{\mathbf{1/2}} \frac{\lambda + \mathbf{12 M_V^2/\hat{s}}}{(\mathbf{1} - \mathbf{M_V^2/\hat{s}})^\mathbf{2}}$$

Similar to $\mathrm{e^+e^-} \to \mathrm{HZ}$ process used for Higgs searches at LEP2.

Cross section $\propto \hat{\mathrm{s}}^{-1}$ sizable only for low $\mathrm{M_H} \lesssim 200$ GeV values.

Cross section for $\mathrm{W^\pm H}$ approximately 2 times larger than ZH.

In fact, simply Drell–Yan production of virtual boson with $\mathrm{q^2} \neq \mathrm{M_V^2}$

$$\hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{HV}) = \hat{\sigma}(\mathbf{q\bar{q}} \to \mathbf{V^*}) \times \frac{\mathbf{d\Gamma}}{\mathbf{dq^2}} (\mathbf{V^*} \to \mathbf{HV})$$

$\Rightarrow$ radiative corrections are mainly those of the known DY process

(at 2-loop, need to consider also $\mathrm{gg} \to \mathrm{HZ}$ through box which is $\neq$).

5. Higgs at the LHC: associated HV

Radiative corrections needed:

– for precise determination of σ

– stability against scale variation

HO also needed to fix scales:

– renormalization μ_R for α_s

– factorization μ_F for matching.

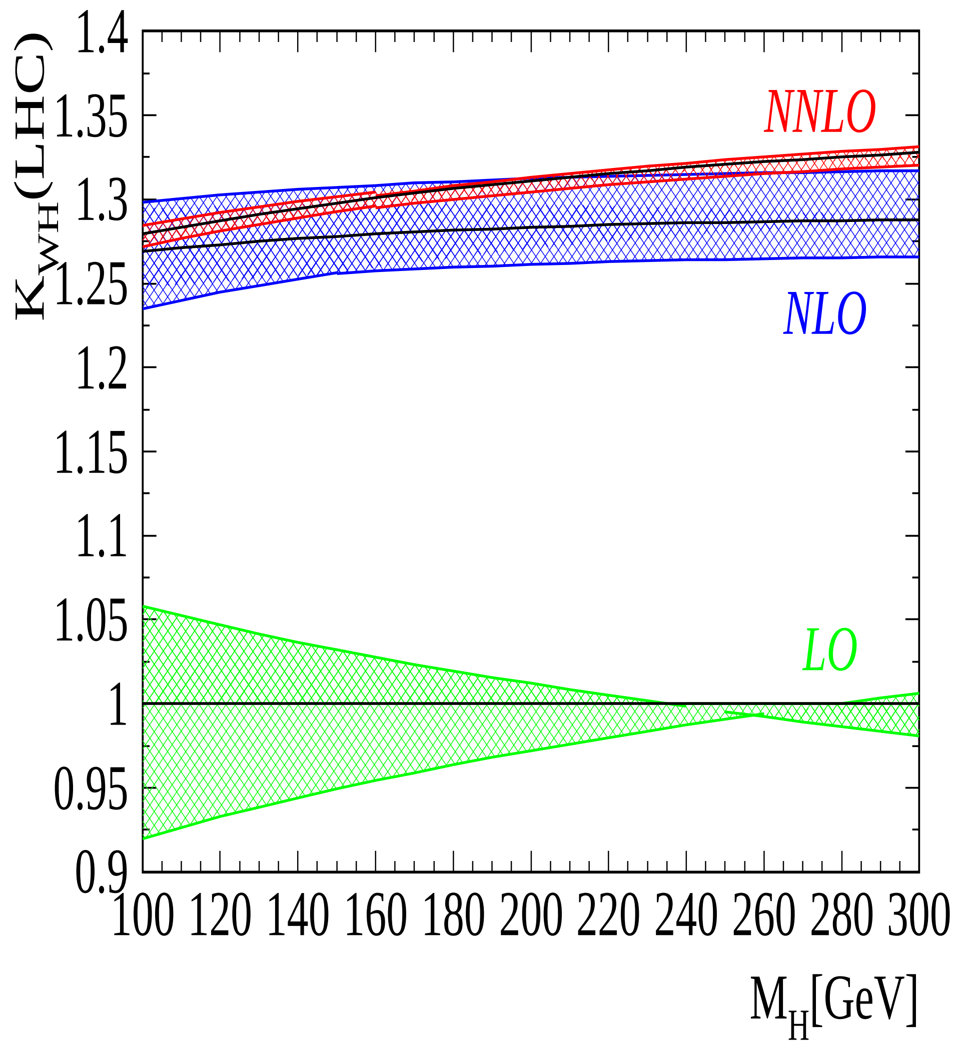
RC parameterized by K–factor:

$$\mathbf{K} = \frac{\sigma_{\rm HO}(\mathbf{pp\to H+X})}{\sigma_{\rm LO}(\mathbf{pp\to H+X})}$$

Can also define K-factor at LO.

QCD RC known up to NNLO.

EW RC known at $\mathcal{O}(\alpha)$: small.



5. Higgs at the LHC: associated HV

Up-to-now, it only plays a marginal role at the LHC (small rates etc...).

Interesting final states are: $\mathrm{WH} \to \gamma\gamma\ell, \mathrm{b\bar{b}}\ell, 3\ell$ and $\mathrm{ZH} \to \mathrm{q\bar{q}}\nu\nu$.

Analyses by ATLAS+CMS: 5σ discovery possible with $\mathcal{L} \gtrsim 100$ fb.

But very clean channel when normalized to $\mathrm{pp} \to \mathrm{Z}$. Measurements!

However: WH channel is the

most important at Tevatron:

$\mathrm{M_H} \lesssim 130\,\mathrm{GeV} : \mathrm{H} \to \mathrm{bb}$:

$\Rightarrow \ell\nu\mathrm{b\bar{b}},\ \nu\bar{\nu}\mathrm{b\bar{b}},\ \ell^+\ell^-\mathrm{b\bar{b}}$

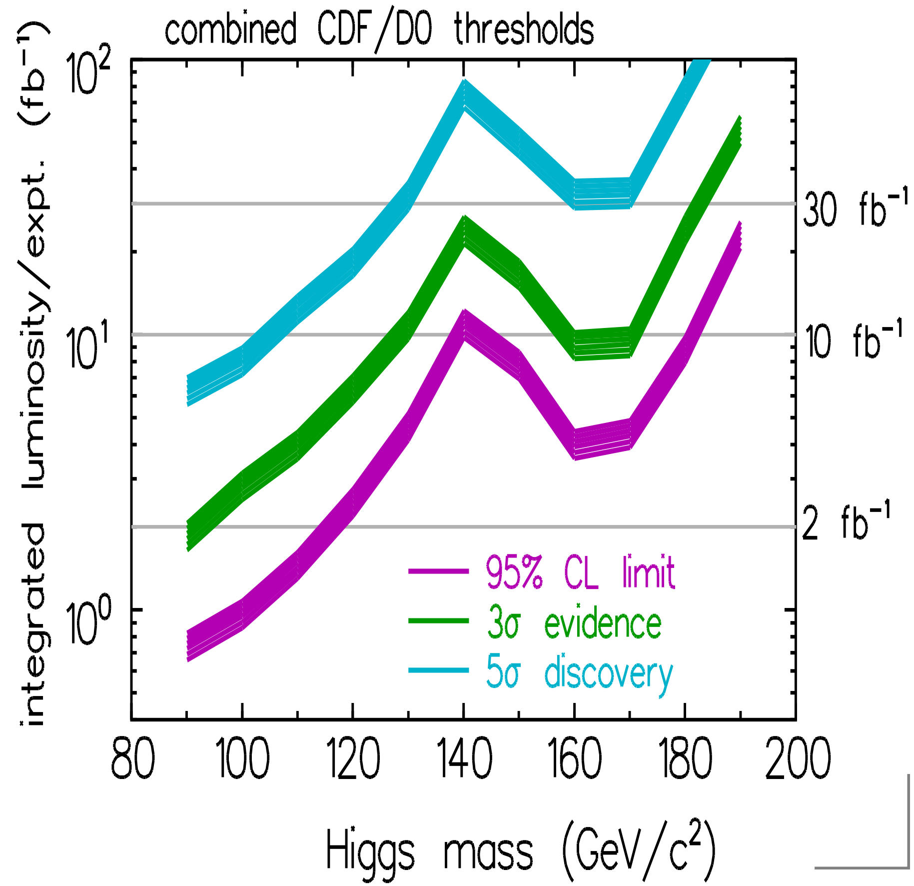
$\mathrm{M_H} \gtrsim 130\,\mathrm{GeV} : \mathrm{H} \to \mathrm{WW}^*$

$\Rightarrow \ell^\pm\ell^\pm\mathrm{jj},\ 3\ell^\pm$

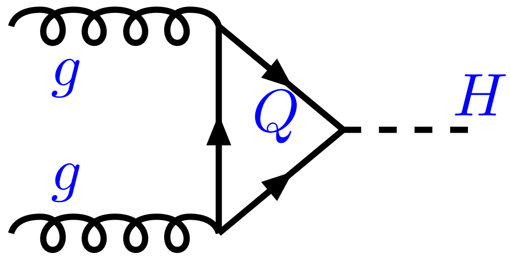
(report of Tevatron Higgs WG)

CDF/D0 are getting very close!

(included in 160–170 GeV excl.)



5. Higgs at the LHC: gg fusion



$$\hat{\sigma}_{\rm LO}(\mathbf{gg \to H}) = \frac{\pi^2}{8\mathbf{M_H}}\Gamma_{\rm LO}(\mathbf{H \to gg})\delta(\hat{\mathbf{s}} - \mathbf{M_H^2})$$

$$\sigma_0^{\mathbf{H}} = \frac{\mathbf{G}_\mu \alpha_{\mathbf{s}}^2(\mu_{\mathbf{R}}^2)}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_{\mathbf{q}} \mathbf{A}_{1/2}^{\mathbf{H}}(\tau_{\mathbf{Q}}) \right|^2$$

Related to the Higgs decay width into gluons discussed previously.

- **In SM: only top quark loop relevant, b–loop contribution $\lesssim 5\%$.**
- **For $\mathrm{m_Q} \to \infty, \tau_{\mathbf{Q}} \sim 0 \Rightarrow \mathbf{A_{1/2}} = \frac{4}{3} =$ constant and $\hat{\sigma}$ finite.**
- **Approximation $\mathrm{m_Q} \to \infty$ valid for $\mathrm{M_H} \lesssim 2\mathrm{m_t} = 350$ GeV.**

Gluon luminosities large at high energy+strong QCD and Htt couplings

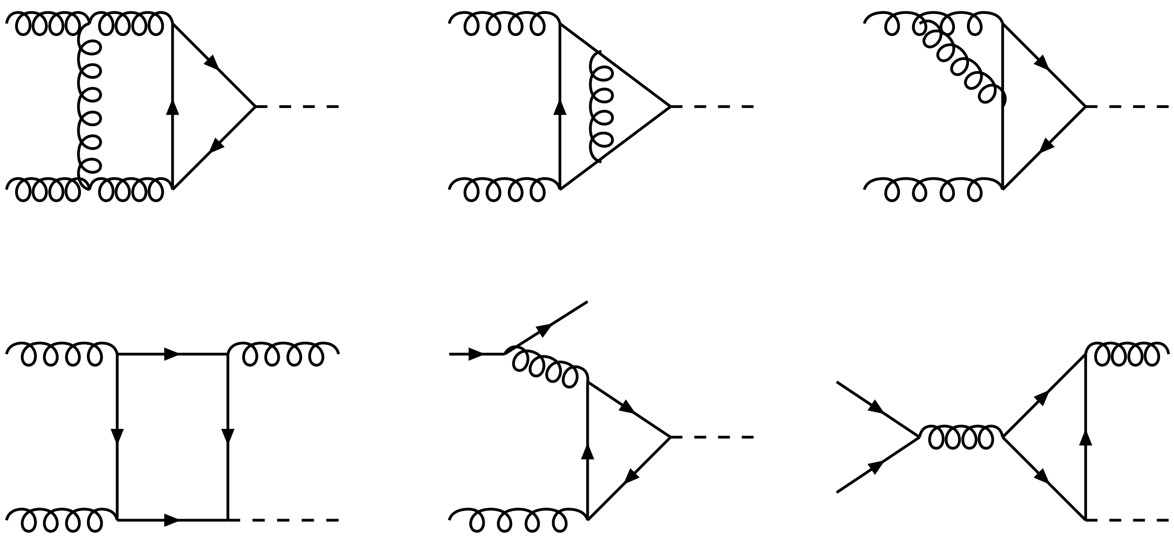
$gg \to H$ **is the leading production process at the LHC.**

- **Very large QCD RC: the two– and three–loops have to be included.**
- **Also the Higgs $\mathrm{P_T}$ is zero at LO, must generated at NLO.**

5. Higgs at the LHC: gg fusion

QCD radiative corrections to $\mathrm{gg} \to \mathrm{H}$: NLO case

Typical diagrams for virtual and real QCD corrections to $gg \to H$ at NLO:



- **Regularization of UV divergences from virtual and IR+collinear divergences from real corrections in dimensional regularization.**
- **UV divergences cancelled by corresponding counterterms.**
- **IR divergences cancel in sum of virtual+real corrections.**
- **Collinear singularities are left: absorbed in PDF renormalization.**

5. Higgs at the LHC: gg fusion

- **Corrections known exactly, i.e. for finite $\mathrm{m_t}$ and $\mathrm{M_H}$, at NLO:**

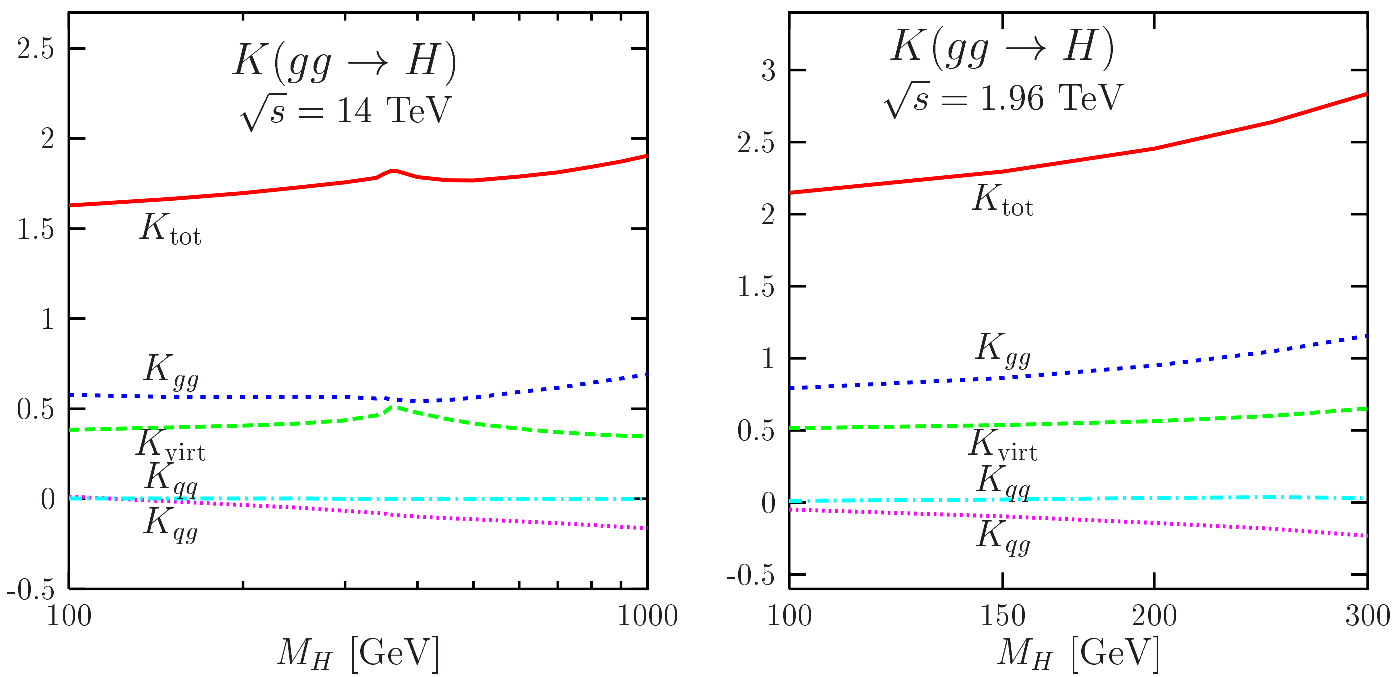
– quark mass effects are important for $\mathrm{M_H} \gtrsim 2\mathrm{m_t}$.

– $\mathrm{m_t} \to \infty$ is still a good approximation for masses below 300 GeV.

– corrections are large, increase cross section by a factor 1.6–1.9.

Note 1: NLO corrections to P_T, η distributions are also known.

Note 2: NLO EW corrections are also available, they are rather small.



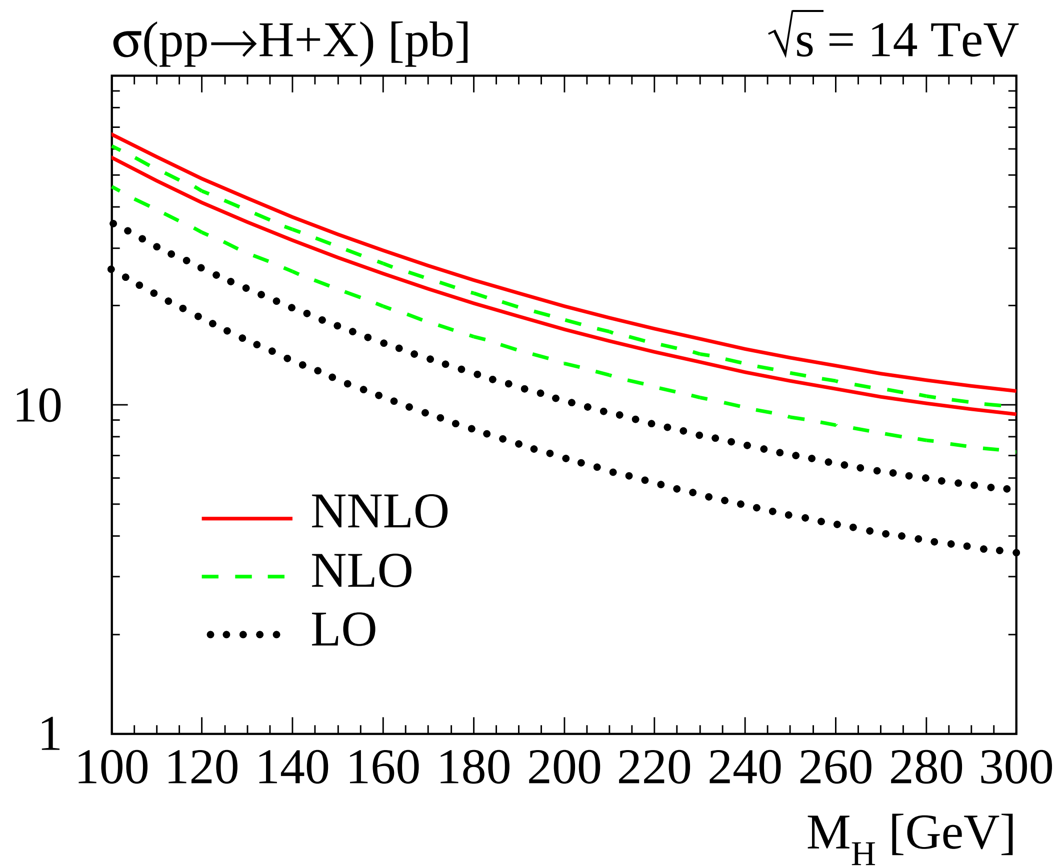
5. Higgs at the LHC: gg fusion

- **Corrections have been calculated in $\mathrm{m_t} \to \infty$ limit at NNLO.**

– moderate increase of cross section by 30% (good behavior of PT!).

– large stabilization with renormalization and factorization scales.

– soft–gluon resummation performed up to NNLL: $\sim 5\%$ effects.



5. Higgs at the LHC: gg fusion

Relevant detection signals

- $\mathrm{H} \to b\bar{b}, \tau^+\tau^-, t\bar{t}$: hopeless.
- $\mathrm{H} \to \gamma\gamma$ for $M_H \lesssim 150$ GeV:

– large σ and small BR: many events left.

– huge irreducibe bkgs from jets: 10^6 rejection.

– large physics bkg from $q\bar{q}/gg \to \gamma\gamma + X$.

– measure $d\sigma/dM_{\gamma\gamma}$ on both sides of peak.

– $S/B = 1/30$ for $M_{\gamma\gamma} \sim 2$ GeV (good $\gamma\gamma$ res.).

- $\mathrm{H} \to WW \to \ell\ell\nu\nu$ for $M_H \sim$130–200 GeV:

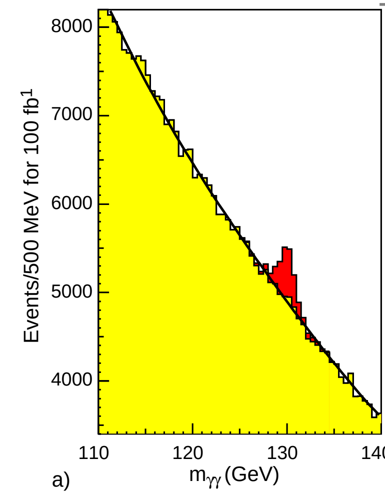
– large $\sigma \times \mathrm{BR}$ in this range but no M_H^{recons}

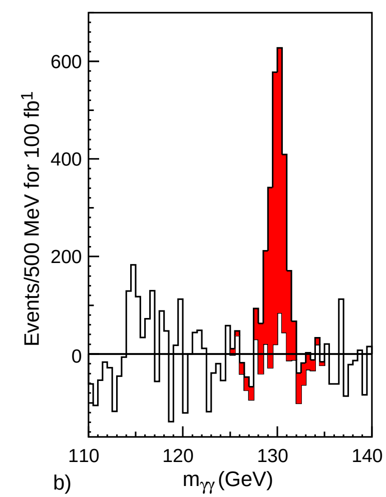
– large bkg from WW/tt but use spin-correlations!

- $\mathrm{H} \to ZZ \to 4\ell^\pm$ for $M_H \gtrsim$ 180–500 GeV:

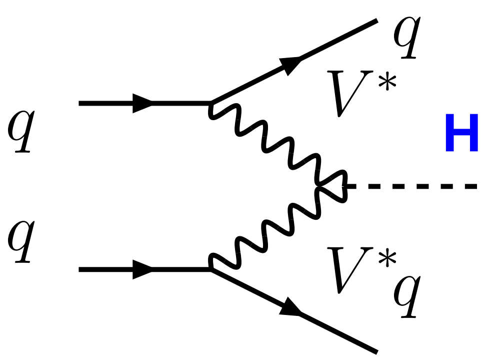
– gold plated mode, clean and small/measurable ZZ bkg.

- $\mathrm{H} \to ZZ \to \ell\ell jj, \ell\ell\nu\nu, WW \to \ell\nu jj$ for M_H=0.5–1 TeV.





5. Higgs at the LHC: WW fusion



$$\hat{\sigma}_{\rm LO} = \frac{\mathbf{16\pi^2}}{\mathbf{M_H^3}}\Gamma(\mathbf{H \to V_L V_L})\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}}$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{\mathbf{V_L V_L/qq}} \sim \frac{\alpha}{\mathbf{4\pi^3}}(\mathbf{v_q^2} + \mathbf{a_q^2})^{\mathbf{2}} \log\left(\frac{\hat{\mathrm{s}}}{\mathbf{M_H^2}}\right)$$

Three–body final state: analytical expression rather complicated...

Simple form in LVBA: σ related to $\Gamma(\mathbf{H \to VV})$ and $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\tau}\Big|_{V_L V_L/qq}$

Not too bad approximation at $\sqrt{\hat{\mathrm{s}}} \gg \mathrm{M_H}$: a factor 2 accurate.

Large cross section: in particular for small $\mathrm{M_H}$ and large c.m. energy:

$\Rightarrow$ most important process at the LHC after $\mathrm{gg \to H}$.

QCD radiative corrections small: order 10% (also for distributions).

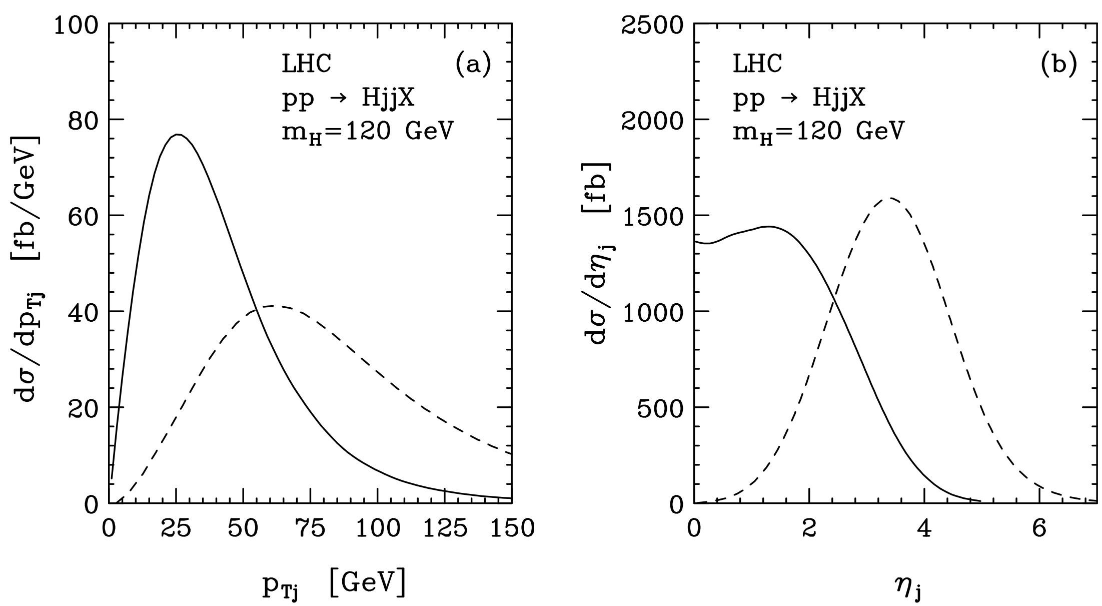
In fact: at LO in/out quarks are in color singlets and at NLO: no gluons are exchanged between first/second incoming (outgoing) quarks: QCD corrections only consist of known corrections to the PDFs!

5. Higgs at the LHC: WW fusion

Kinematics of the process: a very specific kinematics indeed....

- Forward jet tagging: the two final jets are very forward peaked.
- They have large energies of $\mathcal{O}$(1 TeV) and sizeable P_T of $\mathcal{O}(\mathrm{M_V})$.
- Central jet vetoing: Higgs decay products are central and isotropic.
- Small hadronic activity in the central region no QCD (trigger uppon).

Allow to suppress the background to the level of H signal: $\mathrm{S/B} \sim 1$.



——— lowest/central jet – – – – highest/central jet

5. Higgs at the LHC: WW fusion

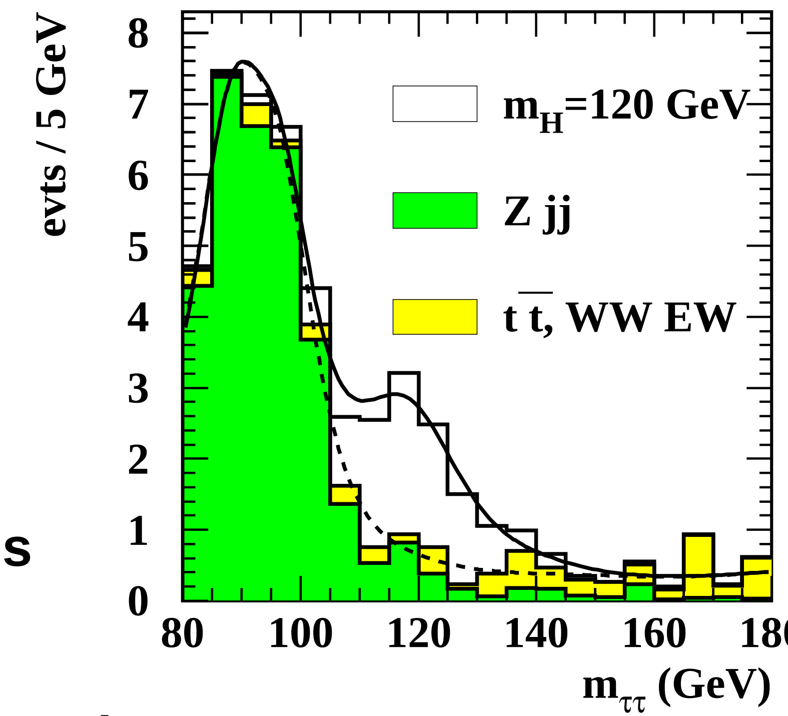
Relevant detection signals

• $\mathrm{H} \to \tau^+\tau^-$ **for** $\mathrm{M_H} \lesssim 150$ **GeV:**

first to be established: needs $\mathcal{L} \sim 30\mathrm{fb}^{-1}$

$\mathrm{M}_{\tau^+\tau^-}^{\mathrm{recons.}}$ **against WW/tt/Zjj bkg.**

τ **polarization usefull against** $\mathrm{Z} \to \tau^+\tau^-$



• $\mathrm{H} \to \gamma\gamma$ **for** $\mathrm{M_H} \lesssim 150$ **GeV:**

very clean with small/measurable bkgs

rare/needs $\mathcal{L}$**+combine with other channels**

• $\mathrm{H} \to \mathrm{WW} \to \ell\ell\nu\nu$

very difficult as you need to know background.

but feasible at low $\mathrm{M_H}$ **and efficient at high** $\mathrm{M_H}$**.**

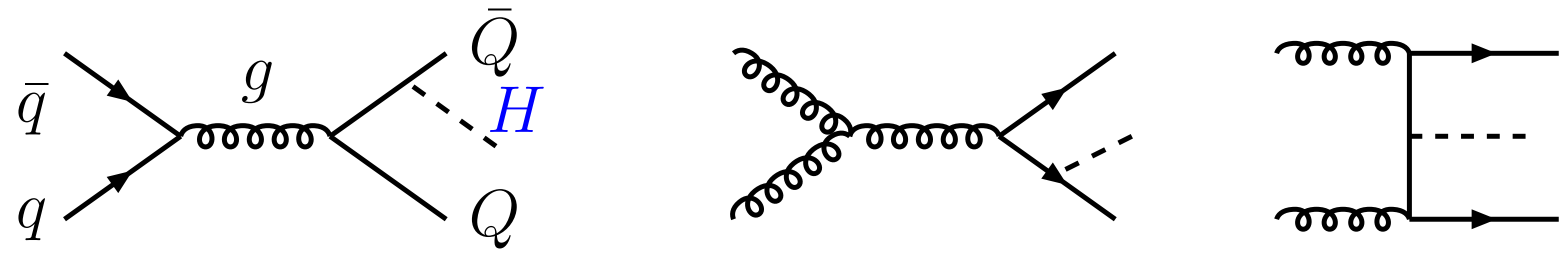
• $\mathrm{H} \to \mathrm{ZZ} \to \ell\ell\nu\nu, \ell\ell\mathrm{jj}$**: have large bkg**

need high $\mathcal{L}$**, usefull at high masses in combination.**

• $\mathrm{H} \to \mathrm{b\bar{b}}, \mathrm{t\bar{t}}$ **very difficult and** $\mathrm{H} \to \mu^+\mu^-$ **needs high** $\mathcal{L}$**.**

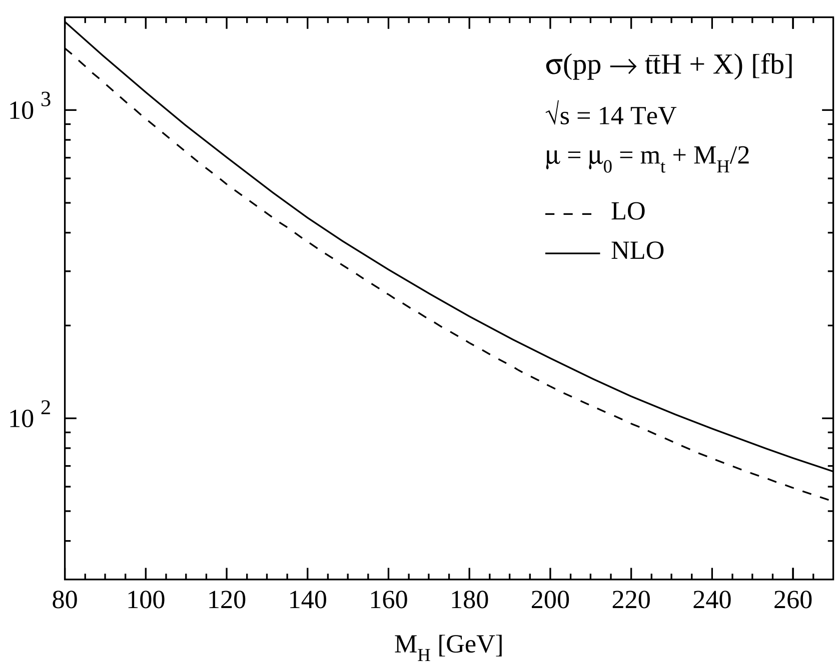
5. Higgs at the LHC: Htt production

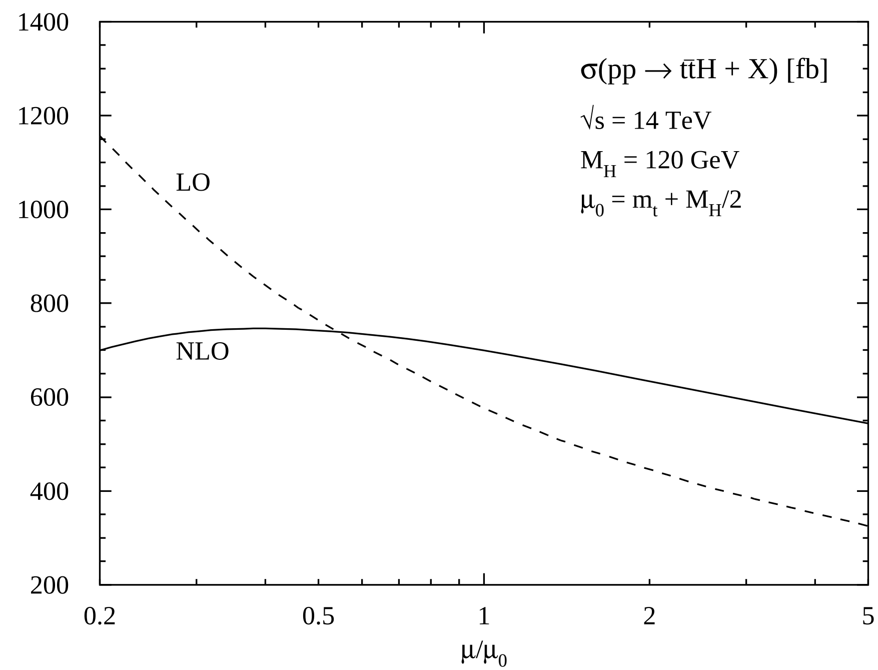
Most complicated process for Higgs production in pp: many channels:



NLO corrections calculateda fewyears ago (at last!):

small K–factors (~ 1.2) **but strong reduction of scale variation!**





5. Higgs at the LHC: Htt production

Small corrections to kinematical distributions (e.g: $\mathrm{p_T^{top}}, \mathrm{P_T^H}$), etc...

- **Rather tiny uncertainties from higher orders, PDFs.**
- **Other possible processes involving heavy quarks work only in BSM:**

– Single top+Higgs production: $\mathrm{pp \to tH + X}$.

– Associated production with bottom quarks: $\mathrm{pp \to bbH}$.

Interesting signals at the LHC for this process are:

- $\mathrm{pp \to Htt \to \gamma\gamma\ell^\pm}$**: clean but rather small rates.**
- $\mathrm{pp \to Htt \to b\bar{b}\ell^\pm}$**: needs efficent b tagging; large jet bkg!**
- $\mathrm{pp \to Htt \to \ell^\mp\ell^\pm\nu\nu}$**: large bckgs from ttWjj, etc...**

Possibility for a 3–5 signal at $\mathrm{M_H \lesssim 140}$ GeV with high luminosity.

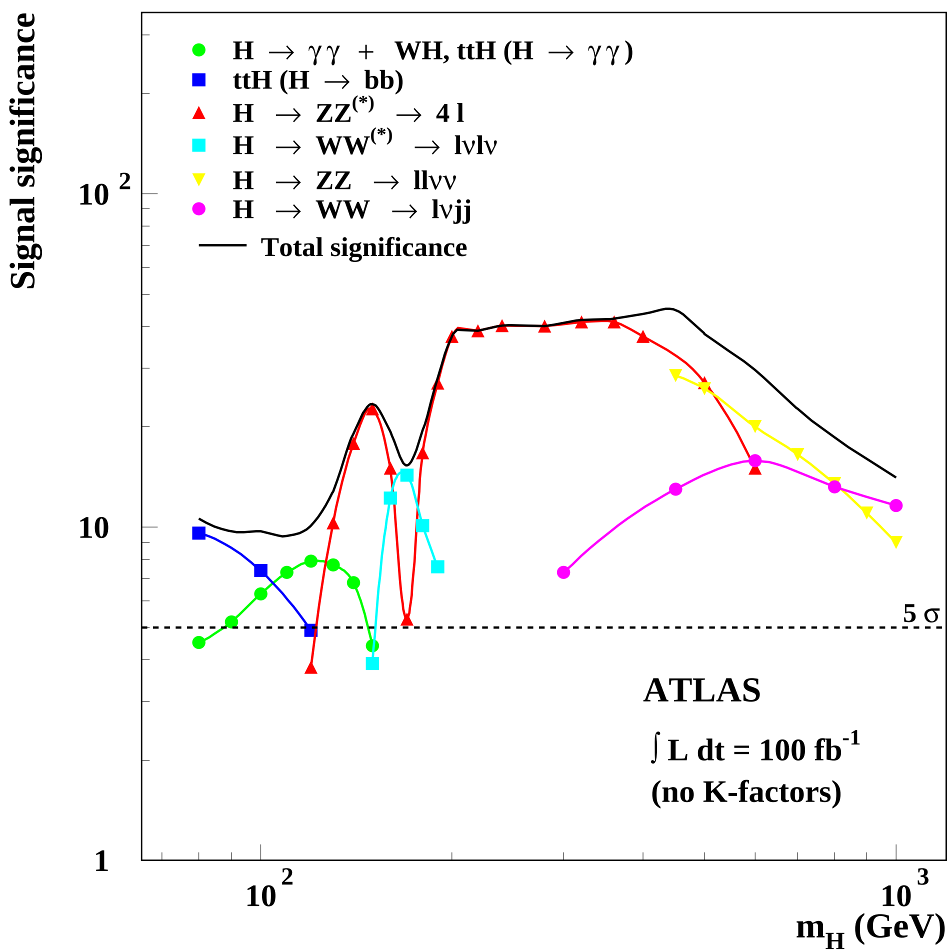
Needs to be combined with similar channels and topologies (eg:

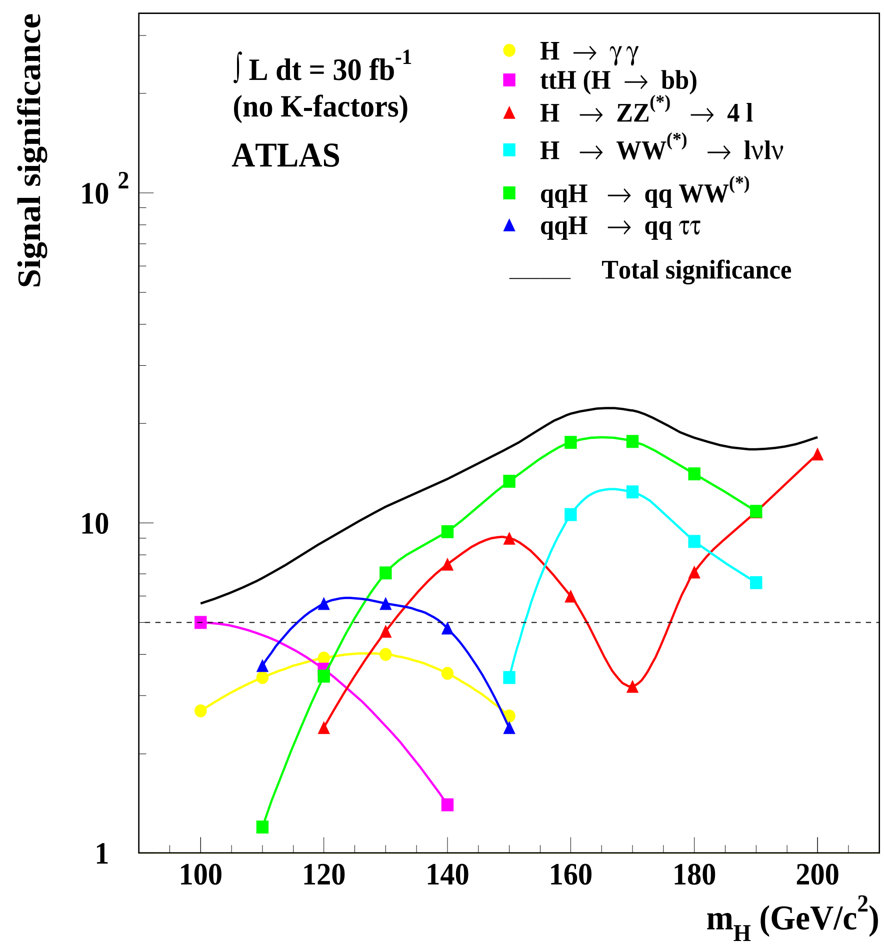
$\mathrm{pp \to WH \to \ell\gamma\gamma, \ell b\bar{b}}$**) to increase total signal significance.**

But process very important for measurement of Htt Yukawa coupling!

5. Higgs at the LHC: summary

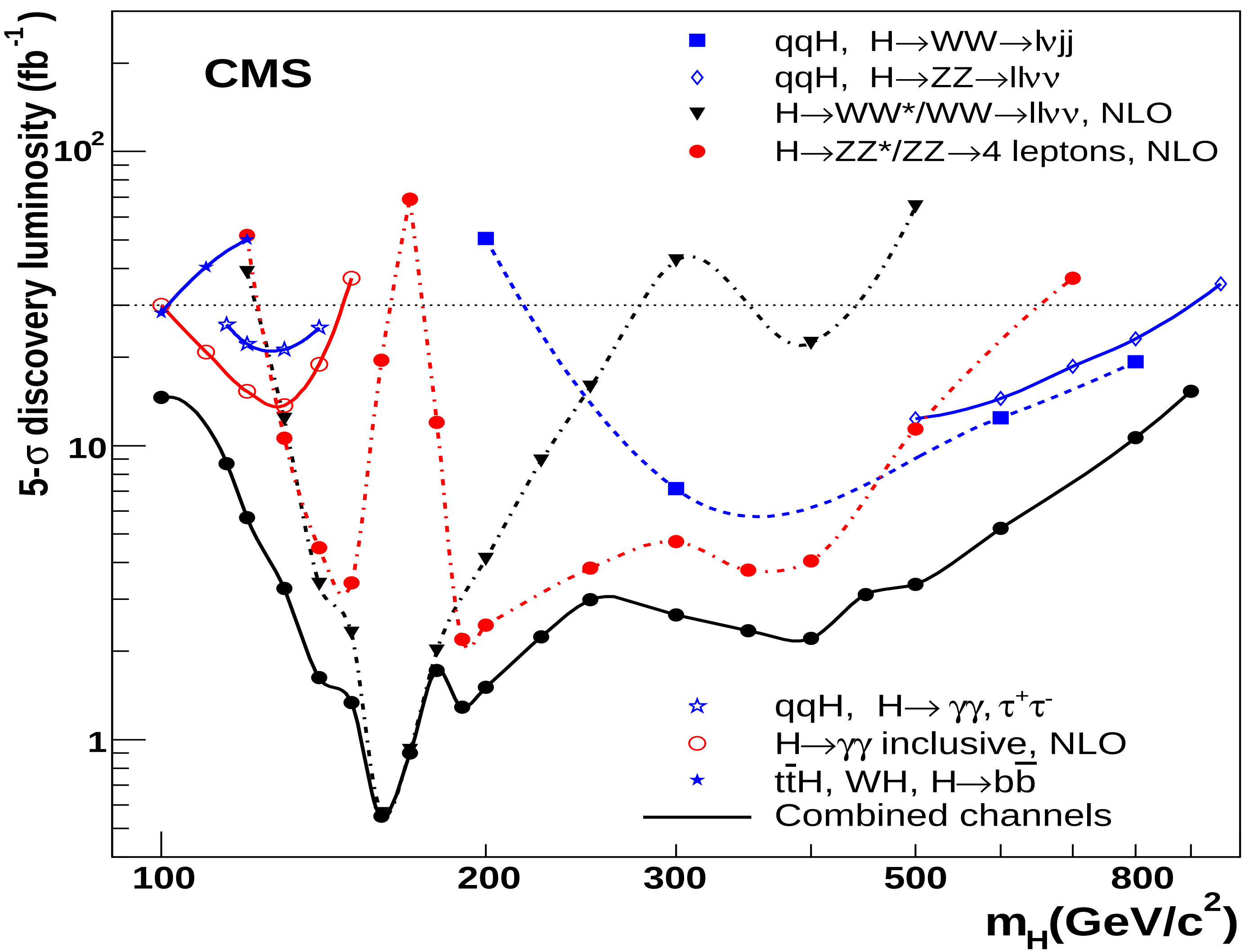
All in all, when you do the hard experimental work, you will get:



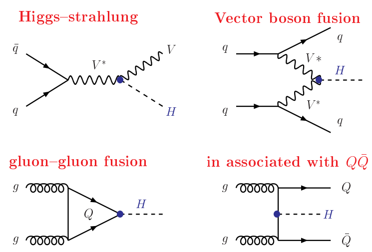


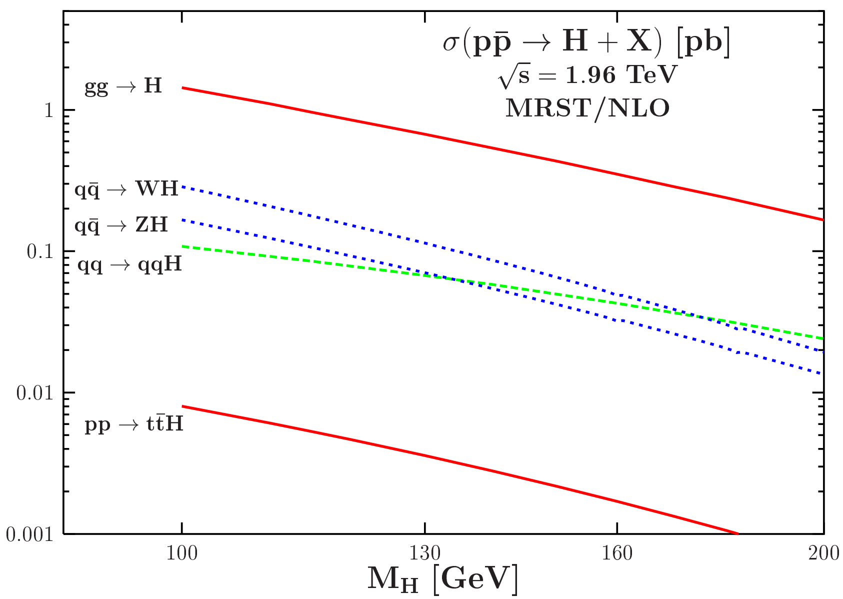
5. Higgs at the LHC: summary

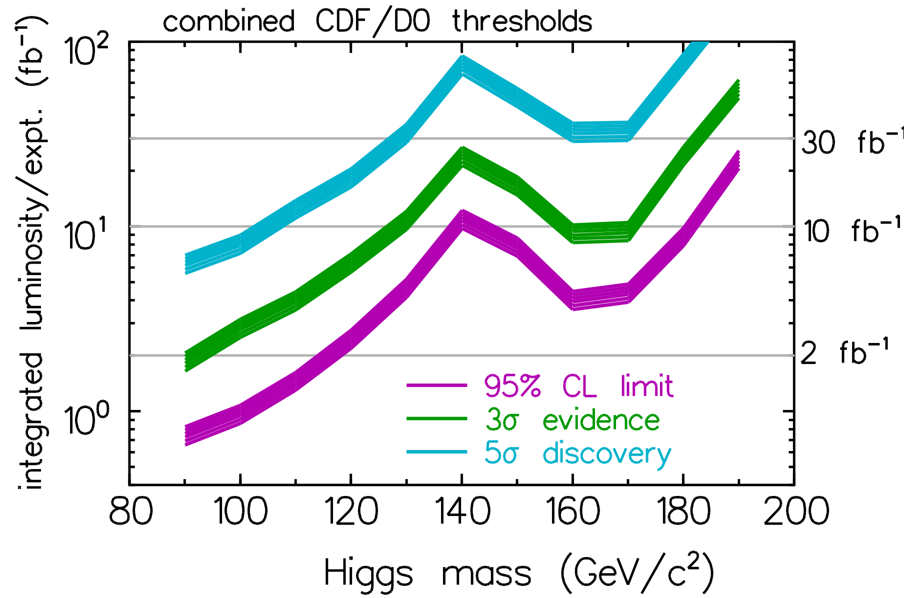
Another way too summarize the expections: in terms of luminosity

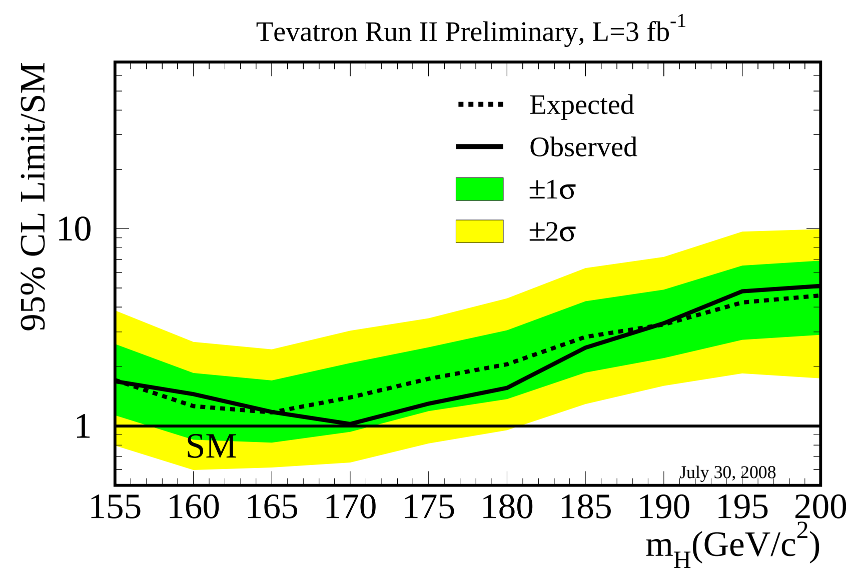


5. Higgs at LHC: production at the Tevatron









Relevant two main processes:

$$pp \to WH/ZH \to \ell\nu b\bar{b}/\nu\bar{\nu}b\bar{b}$$

$$gg \to H \to W^*W \to \ell\nu\ell\nu$$

6. Measurement of Higgs properties

So in 1–2 years from now we will find the Higgs (and maybe nothing else):

we celebrate, shake hands, drink champagne, take care of our bets, ...

and should we declare Particle Physics closed and go home or fishing?

No! We need to check that it is indeed responsible of spontaneous EWSB!

Measure its fundamental properties in the most precise way:

- **its mass and total decay width,**
- **its spin–parity quantum numbers and chek $\mathrm{J^{PC}} = 0^{++}$,**
- **its couplings to fermions and gauge bosons and check that they are indeed proportional to the particle masses (fundamental prediction!),**
- **its self–couplings to reconstruct the potential $\mathrm{V_H}$ that makes EWSB.**

A very ambitious and challenging program!

which is even more difficult to achieve than the Higgs discovery itself...

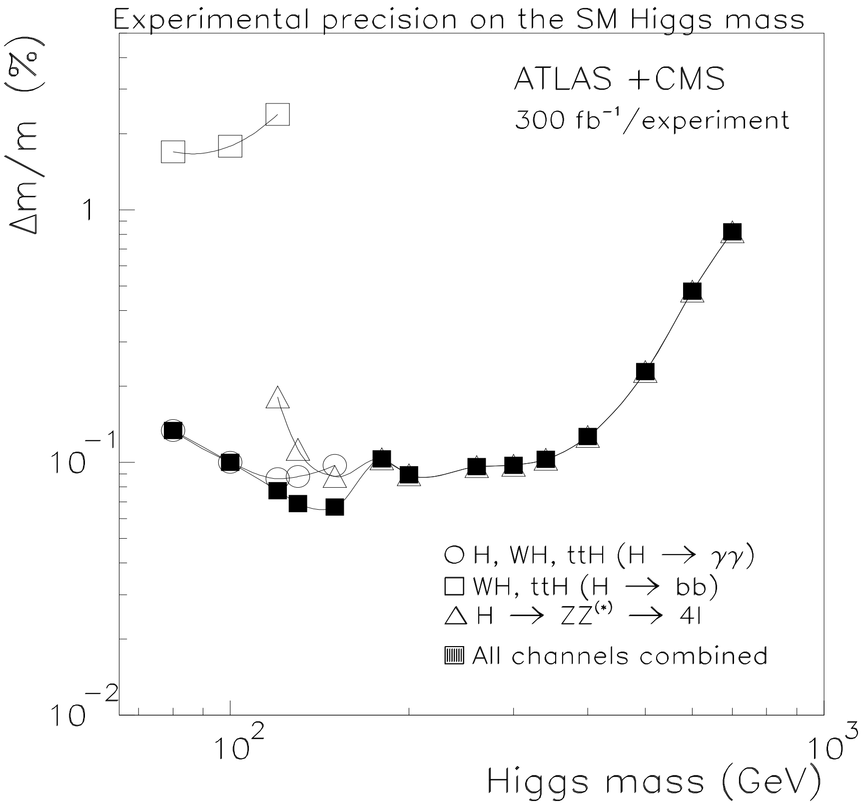
6. Higgs properties: mass and width

Higgs boson mass from:

– $H \to \gamma\gamma$ **for** $M_H \lesssim 130$ **GeV**

– $H \to ZZ \to 4\ell^{\pm}$ **beyond**

Final $\Delta M_H/M_H \sim 0.1\%$ to 1%.

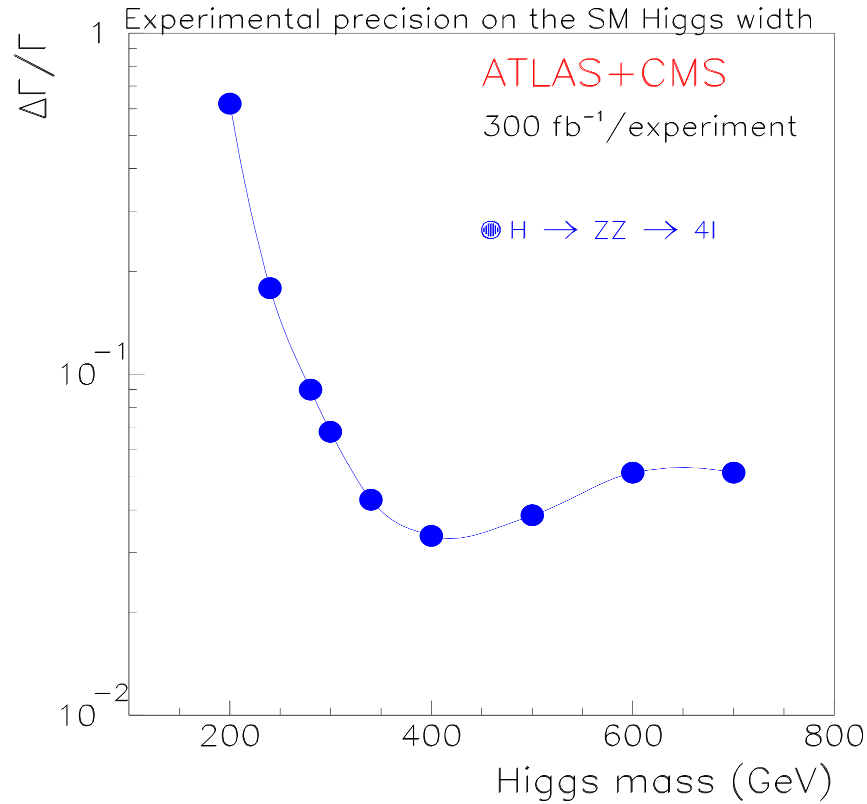


Higgs boson total width:

– **Too small for** $M_H \lesssim 2M_Z$

– $H \to ZZ \to 4\ell^{\pm}$ **beyond**

Final $\Delta\Gamma_H/\Gamma_H \sim$ **a few %**



However: for large M_H effects from large width are important!

6. Higgs properties: $\mathrm{J^{PC}}$ numbers

- **Higgs spin:**

Higgs can be observed in $\mathrm{H} \to \gamma\gamma$ decays: rules out J=1 and fixes C=+,

– argument not generalizable to $\mathrm{H} \leftrightarrow \mathrm{gg}$ since no g/q distinction,

– other particle spin–assignements might be possible J=2 (radion), etc.

- **Higgs parity:**

– Higgs can be observed in $\mathrm{H} \to \mathrm{ZZ} \to 4\ell^{\pm}$ rules out CP–odd state.

– Higgs spin–correlations in $\mathrm{gg} \to \mathrm{H} \to \mathrm{WW}^*$ also useful here...

But we need to check that H is pure CP–even with no CP–odd mixture:

– it becomes then a challenging high–precision measurement,

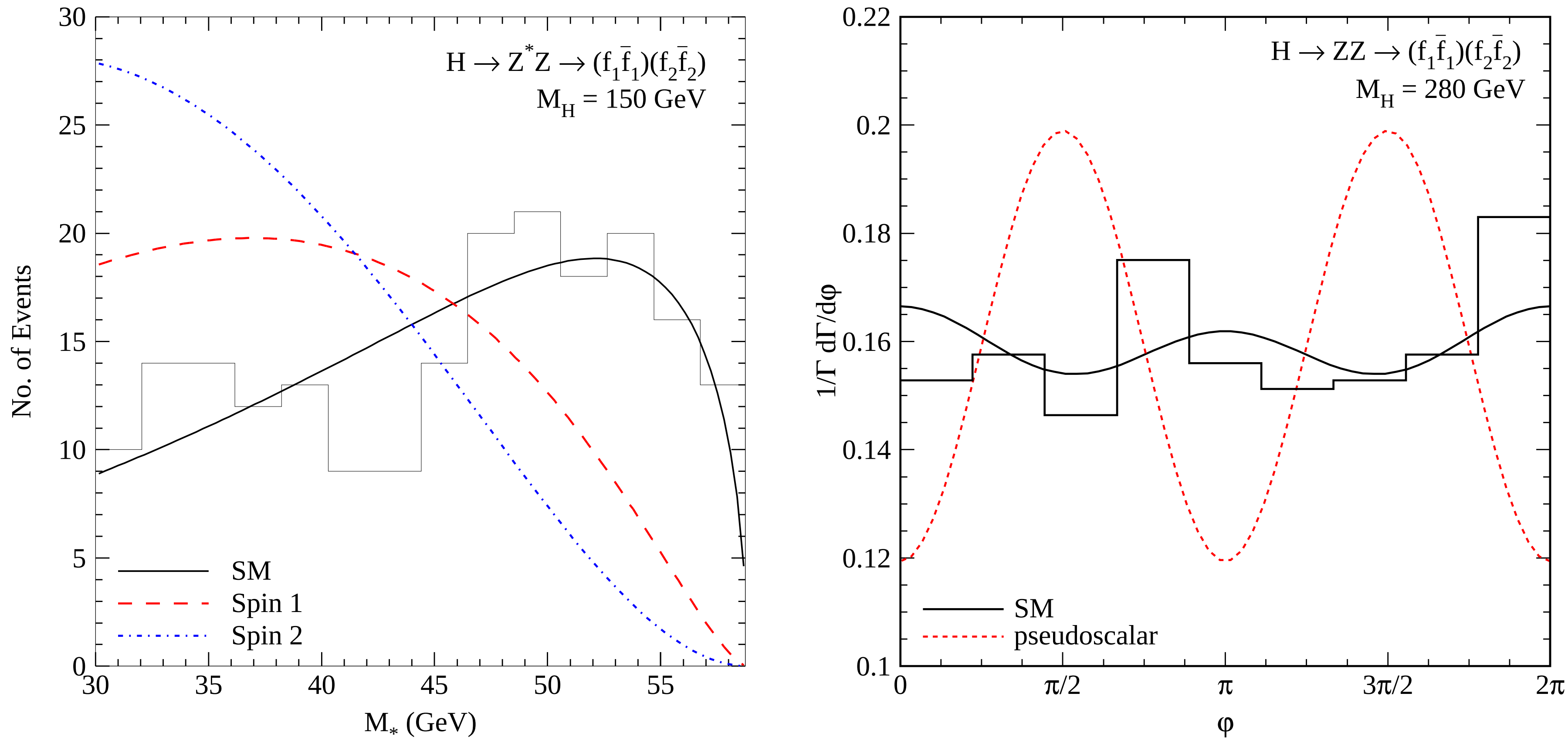
– can be done roughly by looking at correlations in $\mathrm{H} \to \mathrm{ZZ}, \mathrm{WW}$.

Drawback: If H is mostly CP–even, rates for $\mathrm{A} \to \mathrm{VV}$ too small...

More convincing to look at more democratic Higgs-fermion couplings.

Possible channels: $\mathrm{H} \to \tau^+\tau^-$ or $\mathrm{pp} \to \mathrm{t\bar{t}H}$: very challenging!!

6. Higgs properties: J^{PC} numbers



left: threshold behavior of $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ}^*)/\mathrm{dM}_*$ distribution for J=0,1,2

right: azimuthal distributions $\mathrm{d}\Gamma(\mathrm{H} \to \mathrm{ZZ})/\mathrm{d}\phi$ for SM and CP-odd A

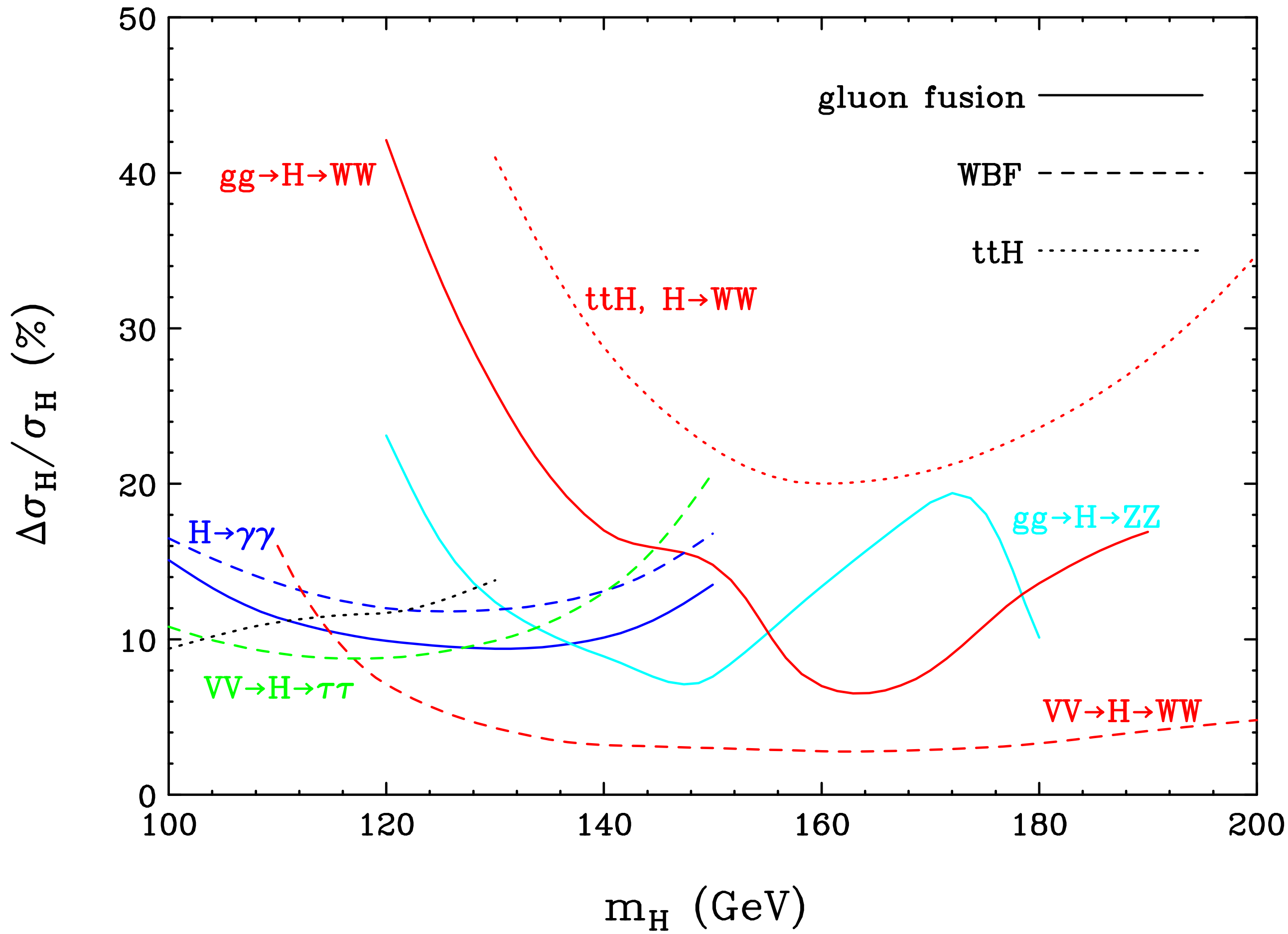
ATLAS simulation including bkgs with $\int \mathcal{L}\mathrm{dt} = 300\,\mathrm{fb}^{-1}$ at the LHC

6. Higgs properties: Higgs couplings

Higgs couplings can be determined by looking at various Higgs production and decay channels and measuring $\mathrm{N_{ev}} = \sigma \times \mathrm{BR}$.

LHC with $\mathcal{L} = 300$fb^{-1}.

Only statistical errors.



6. Higgs properties: Higgs couplings

The errors are in general rather large unfortunately:

- **experimental errors: statistics, systematics, parton luminosity,...**
- **theoretical errors: PDFs, HO+scale variation, model dependence...**

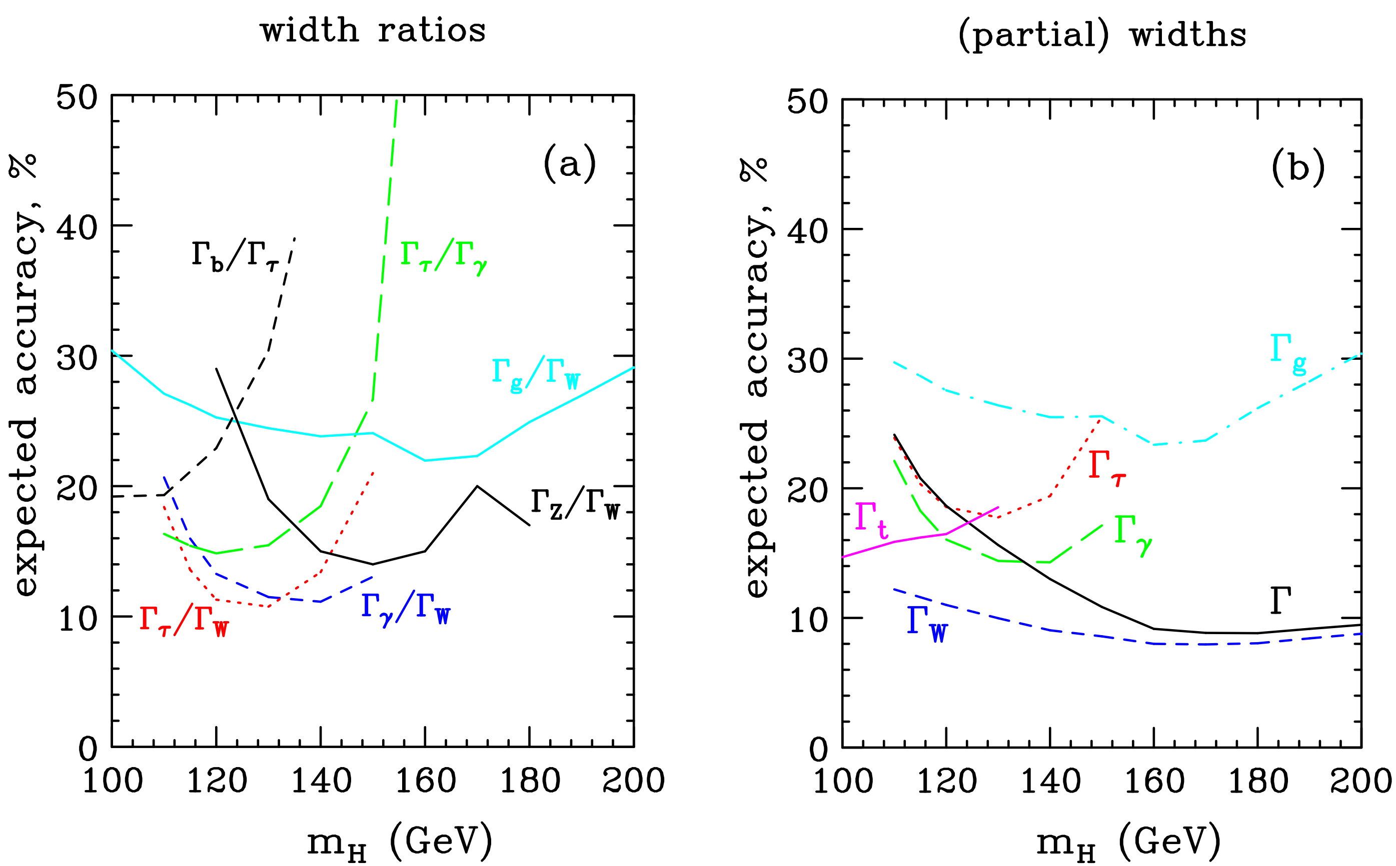
$\Rightarrow$ **ratios of $\sigma \times \mathrm{BR}$: many errors drop out!**

Process	Measurement quantity	Error	Mass range
$\frac{(t\bar{t}H+WH)\to\gamma\gamma+X}{(t\bar{t}H+WH)\to b\bar{b}+X}$	$\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to b\bar{b})}$	$\sim 15\%$	$80-120$ GeV
$\frac{H\to\gamma\gamma}{H\to 4\ell^{+}}$	$\frac{\mathrm{BR}(H\to\gamma\gamma)}{\mathrm{BR}(H\to ZZ^*)}$	$\sim 7\%$	$120-150$ GeV
$\frac{t\bar{t}H\to\gamma\gamma,b\bar{b}}{WH\to\gamma\gamma,b\bar{b}}$	$\left(g_{Htt}/g_{HWW}\right)^2$	$\sim 15\%$	$80-120$ GeV
$\frac{H\to ZZ^*\to 4\ell^{+}}{H\to WW^*\to 2\ell^{\pm}2\nu}$	$\left(g_{HZZ}/g_{HWW}\right)^2$	$\sim 10\%$	$130-190$ GeV

Note: for $\mathrm{M_H} \gtrsim 2\mathrm{M_Z}$ only few processes accessible: $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ}$.
while $\sigma(\mathrm{gg} \to \mathrm{H})$ provides $\mathrm{g_{Htt}}$ but indirectly since loop mediated.

6. Higgs properties: Higgs couplings

- **Then translate into partial widths $\propto$ Higgs coupling squared.**
- **Precision on coupling measurement is: $\Delta g_{HXX} = \frac{1}{2}\frac{(\Delta^{\exp}\Gamma + \Delta^{th}\Gamma)}{\Gamma}$**
- **Some theoretical assumptions (no invisible, SU(2) invariance, some couplings are known, etc..) allow to extract additional couplings....**

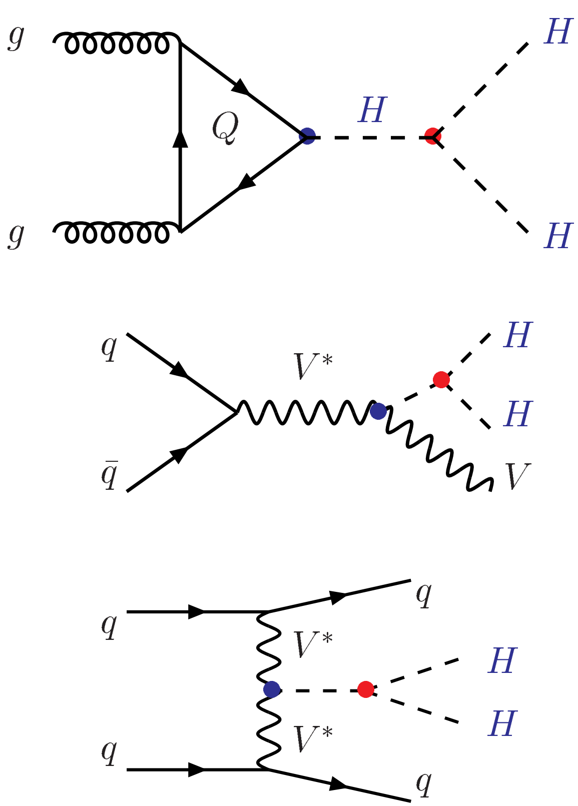


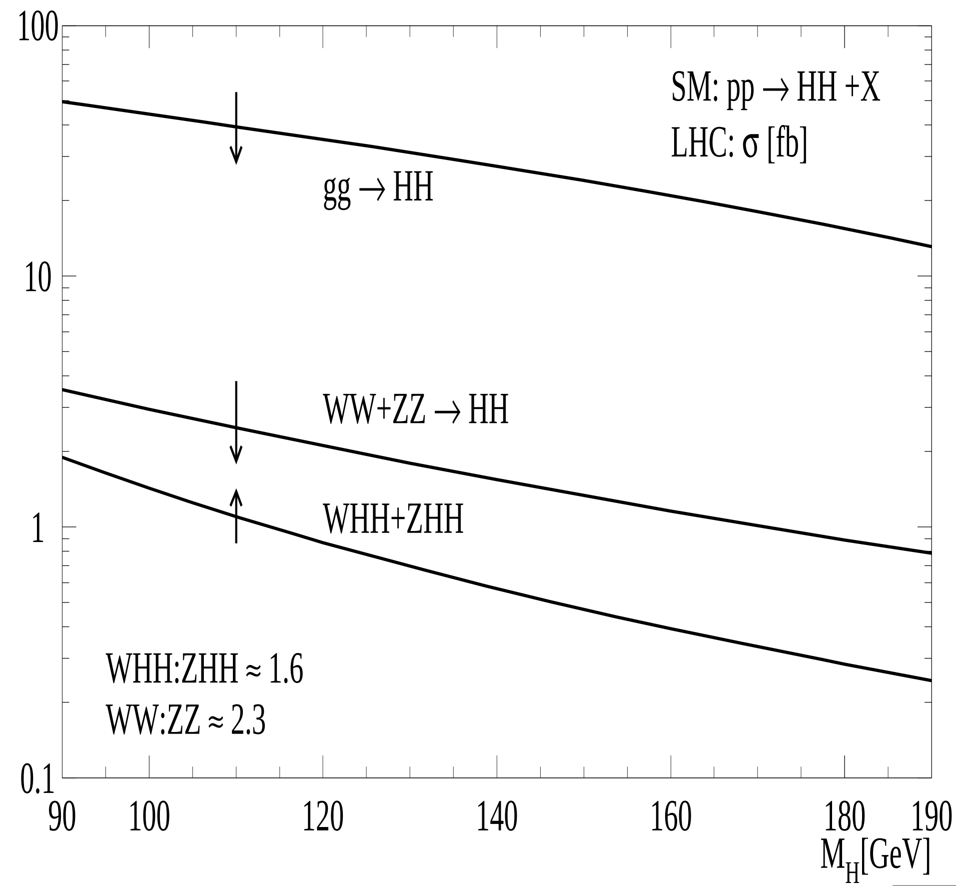
6. Higgs properties: Higgs self-couplings

Important couplings to be measured: $g_{H^3}, g_{H^4} \Rightarrow$ access to V_H.

- **g_{H^3} is accessible in double Higgs production: $pp \to HH + X$**
- **g_{H^4} is hopeless to measure, needs pp$\to$HHH+X with too low rates.**

Relevant processes for HH prod:





6. Higgs properties: Higgs self-couplings

Cross sections small, except maybe for gg→HH at $M_H \lesssim 200$ GeV:

- $\mathrm{H} \to \gamma\gamma$ **decay too rare,**
- $\mathrm{H} \to \mathrm{b\bar{b}}$ **decay not clean**
- $\mathrm{H} \to \mathrm{WW}$ **at low $\mathrm{M_H}$?**

Yes, it has been tried:

– parton level analysis...

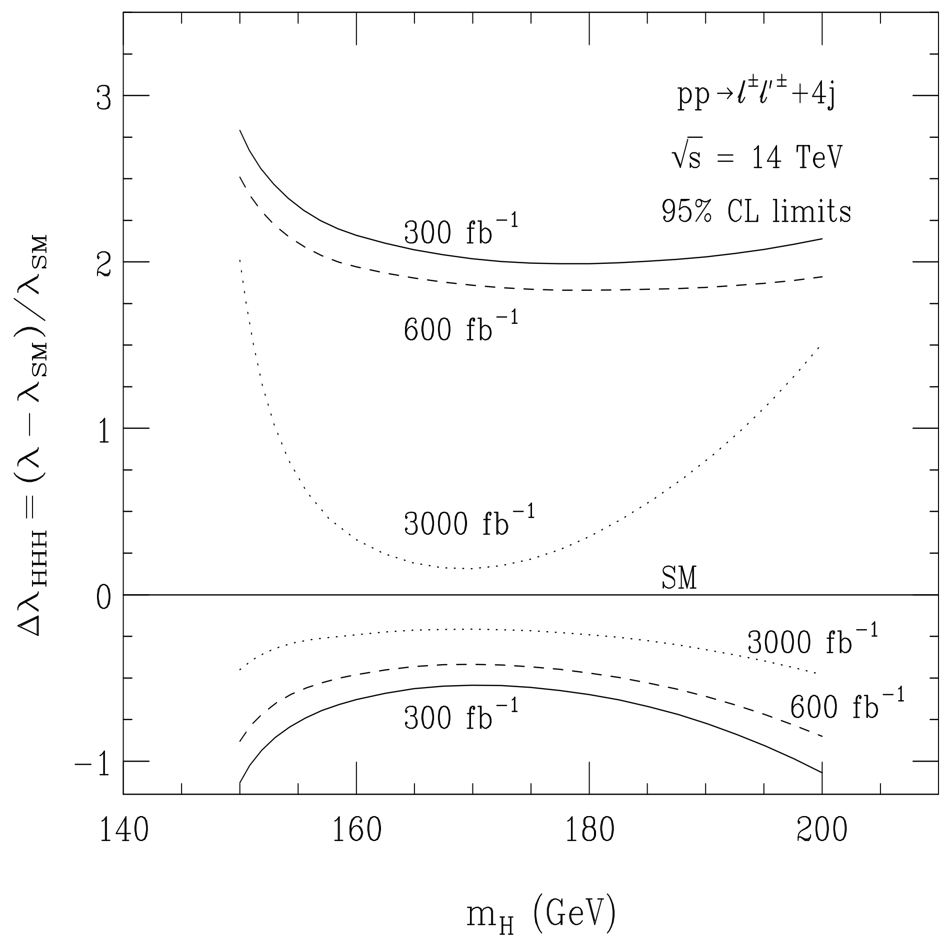
– look for $2\ell^{\pm}, 3\ell^{\pm} + \nu$+jets+

– look at IM distributions

– use large luminosity.

Some hope to set limits....

Needs to go to SLHC...



7. EWSB in SUSY

The SM has many attractive theoretical/experimental features:

- Based on gauge principle, unitary, perturbative, renormalisable $\cdots$
- Once $\mathrm{M_H}$ fixed: everything is predictible with great accuracy.
- And has passed all experimental tests up to now.

But the model has too many shortcomings:

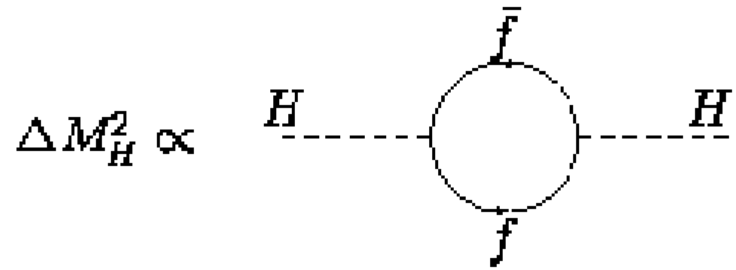
- Too many free parameters (19!) in the model, put by hand...
- Does not include the fourth fundamental force, gravity, ..
- Does not say anything about the masses of the neutrinos.
- No real unification of the three gauge interactions.
- Does not explain the baryon asymmetry in the universe.
- There is no stable, weak, massive particle for dark matter.
- No satisfactory explanation for $\mu^2 < 0$ (put ad hoc).

And above all that, there is the hierarchy or naturalness problem.

7. EWSB in SUSY: the SM hierarchy problem

- **Radiative corrections to $\mathrm{M_H^2}$ in SM**

with a cut–off $\Lambda = \mathrm{M_{NP}} = \mathrm{M_{GUT}}$



$$\mathbf{\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2] + \mathcal{O}(1/\Lambda^2)}$$

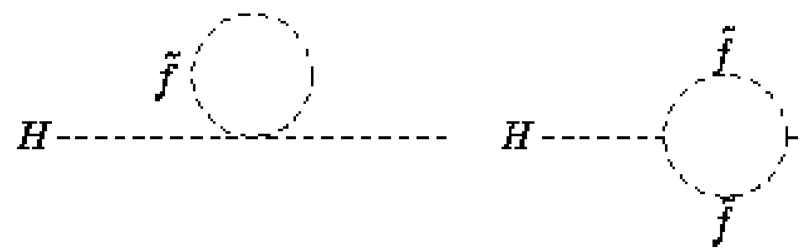
$\mathrm{M_H}$ prefers to be close to the high scale than to the EWSB scale,

unless an extreme parameter fine tunning is made (also problematic).

$\Rightarrow$ there is no symmetry to protect $\mathrm{M_H}$ in the SM ($\neq$ fermions, photon, ..).

- **Add scalar partner contribution:**

$$\mathrm{N_S = N_f,\ \lambda_f^2 = -\lambda_S,\ m_1 = m_2 = m_S}$$



$$\mathbf{\Delta M_H^2|^{tot} = \frac{\lambda_f^2 N_f}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S}) + 3m_f^2 \log(\frac{m_S}{m_f})]}$$

$\Rightarrow$ Symmetry between fermions–scalars $\Rightarrow$ no divergence in Λ^2

“Supersymmetry” no divergences at all: $\mathrm{M_H}$ is protected!

Note that if $\mathrm{m_S} \gg \mathrm{m_f}$ ($\gtrsim$ 1 TeV) the fine tunning problem is back!!!

7. EWSB in SUSY: SUSY and the MSSM

Supersymmetry: symmetry relating fermions s=$\frac{1}{2}$ and bosons s=0,1

– a new sparticle for each SM particle, with spin different by unit $\frac{1}{2}$

– beautiful: most general, link to gravity and superstrings,....

– however, SUSY must be broken $\Rightarrow$ effective way at low energy?

– solves SM pbs: hierarchy, unification, dark matter (+$\not{P}$,m$_\nu$,Bgenesis ...)

Focus on: Minimal Supersymmetric Standard Model (MSSM):

- **minimal gauge group: SU(3)$\times$SU(2)$\times$U(1),**
- **minimal particle content: 3 fermion families and 2 Φ doublets,**
- **R=$(-1)^{(2s+L+3B)}$ parity is conserved,**
- **minimal set of terms (masses, couplings) breaking “softly” SUSY.**

To reduce the number of the (too many in general) free parameters:

– impose phenomenological constraints: O(20) free parameters,

– in general sparticles assumed to be heavy: decouple from Higgs.

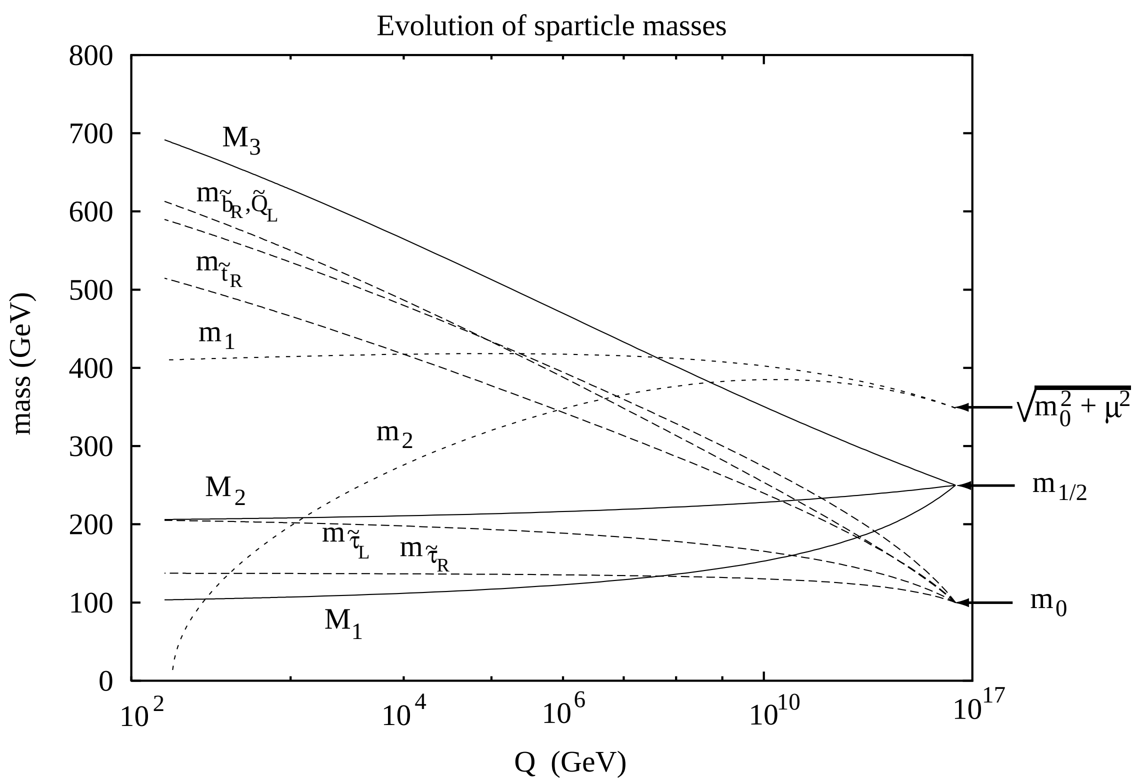
– constrained models with universal boundaries, very few parameters

7. EWSB in SUSY: symmetry breaking

mSUGRA: Only 4.5 param: $\tan\beta\ ,\ \mathbf{m_{1/2}}\ ,\ \mathbf{m_0}\ ,\ \mathbf{A_0}\ ,\ \mathrm{sign}(\mu)$

All soft breaking parameters at M_S are obtained through RGEs.

With $\mathrm{M_{GUT}} \sim \mathbf{2 \cdot 10^{16}}$ GeV and $\mathrm{M_{SUSY}} \sim \sqrt{\mathbf{m_{\tilde{t}_L} m_{\tilde{t}_R}}}$:



Radiative EWSB occurs since $\mathrm{M^2_{H_2}} < \mathbf{0}$ at scale $\mathrm{M_Z}$ $(\mathbf{t}/\tilde{\mathbf{t}}\ \mathbf{loops})$

$\Rightarrow$ EWSB more natural in MSSM ($\mu^2 < 0$ from RGEs) than in SM!

7. EWSB in SUSY: MSSM Higgs sector

In MSSM with two Higgs doublets: $\mathbf{H_1} = \begin{pmatrix} \mathbf{H_1^0} \\ \mathbf{H_1^-} \end{pmatrix}$ and $\mathbf{H_2} = \begin{pmatrix} \mathbf{H_2^+} \\ \mathbf{H_2^0} \end{pmatrix}$,

- to cancel the chiral anomalies introduced by the new $\tilde{\mathrm{h}}$ field,
- give separately masses to d and u fermions in SUSY invariant way.

After EWSB (which can be made radiative: more elegant than in SM):

Three dof to make $\mathbf{W_L^\pm}, \mathbf{Z_L} \Rightarrow$ 5 physical states left out: $\mathbf{h}, \mathbf{H}, \mathbf{A}, \mathbf{H^\pm}$

Only two free parameters at the tree level: $\tan\beta, \mathbf{M_A}$; others are:

$$\mathbf{M^2_{h,H}} = \frac{1}{2}\left[\mathbf{M_A^2} + \mathbf{M_Z^2} \mp \sqrt{(\mathbf{M_A^2}+\mathbf{M_Z^2})^2 - 4\mathbf{M_A^2}\mathbf{M_Z^2}\cos^2 2\beta}\right]$$

$$\mathbf{M^2_{H^\pm}} = \mathbf{M_A^2} + \mathbf{M_W^2}$$

$$\tan 2\alpha = \tan 2\beta\,(\mathbf{M_A^2}+\mathbf{M_Z^2})/(\mathbf{M_A^2}-\mathbf{M_Z^2})$$

We have important constraint on the MSSM Higgs boson masses:

$$\mathbf{M_h} \leq \min(\mathbf{M_A}, \mathbf{M_Z}) \cdot |\cos 2\beta| \leq \mathbf{M_Z},\ \mathbf{M_{H^\pm}} > \mathbf{M_W}, \mathbf{M_H} > \mathbf{M_A} \ldots$$

$\mathbf{M_A} \gg \mathbf{M_Z}$: decoupling regime, all Higgses heavy except for h.

$$\mathbf{M_h} \sim \mathbf{M_Z}|\cos 2\beta| \leq \mathbf{M_Z}!\ ,\ \mathbf{M_H} \sim \mathbf{M_{H^\pm}} \sim \mathbf{M_A}\ ,\ \alpha \sim \frac{\pi}{2} - \beta$$

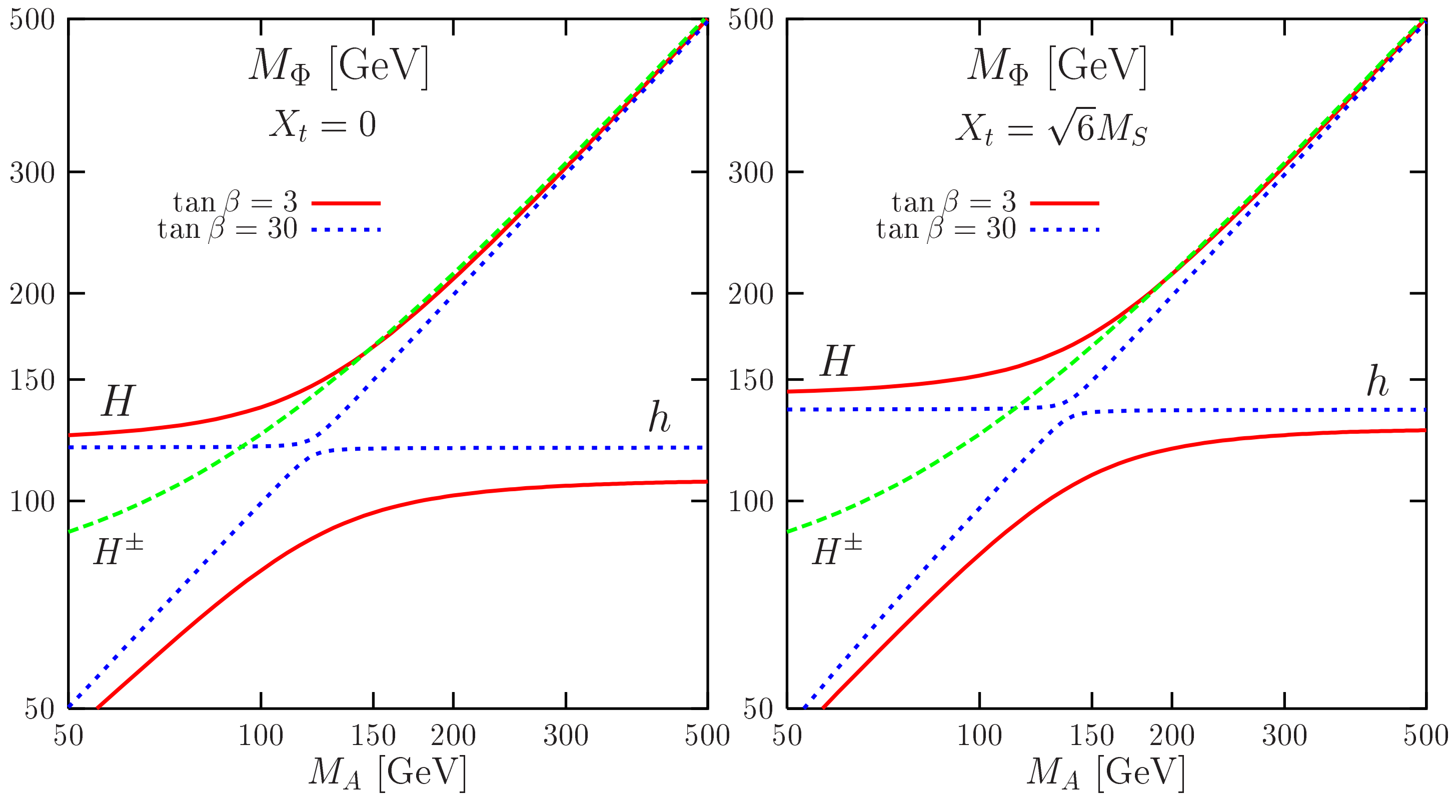
7. EWSB in SUSY: Higgs masses

Radiative corrections very important in the MSSM Higgs sector.

- **Dominant corrections are due to top (s)quark at one-loop level**

$$\Delta M_h^2 = \frac{3g^2}{2\pi^2}\frac{m_t^4}{M_W^2}\log\frac{m_{\tilde{t}}^2}{m_t^2} \text{ large: } \xrightarrow{M_h^{max} \to M_Z + 40\,\mathrm{GeV}} \gtrsim 115\,\mathrm{GeV}$$

- **Full one–loop corrections + approximate two–loop important.**
- **After RC: $M_h^{max} \approx 110 - 140\,\mathrm{GeV}$ depending on $\tan\beta$ and A_t**



7. EWSB in SUSY: Higgs couplings

Higgs decays and cross sections strongly depend on couplings.

Couplings in terms of $\mathrm{H_{SM}}$ and their values in decoupling limit:

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\frac{\sin\alpha}{\sin\beta} \rightarrow 1/\tan\beta$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\cos(\beta-\alpha) \rightarrow 0$
A	$1/\tan\beta$	$\tan\beta$	0

– **The couplings of $\mathrm{H^\pm}$ have the same intensity as those of A.**

– **Couplings of $\mathrm{h, H}$ to VV are suppressed; no AVV couplings (CP)**

– **For $\tan\beta > 1$: couplings to d enhanced, couplings to u suppressed.**

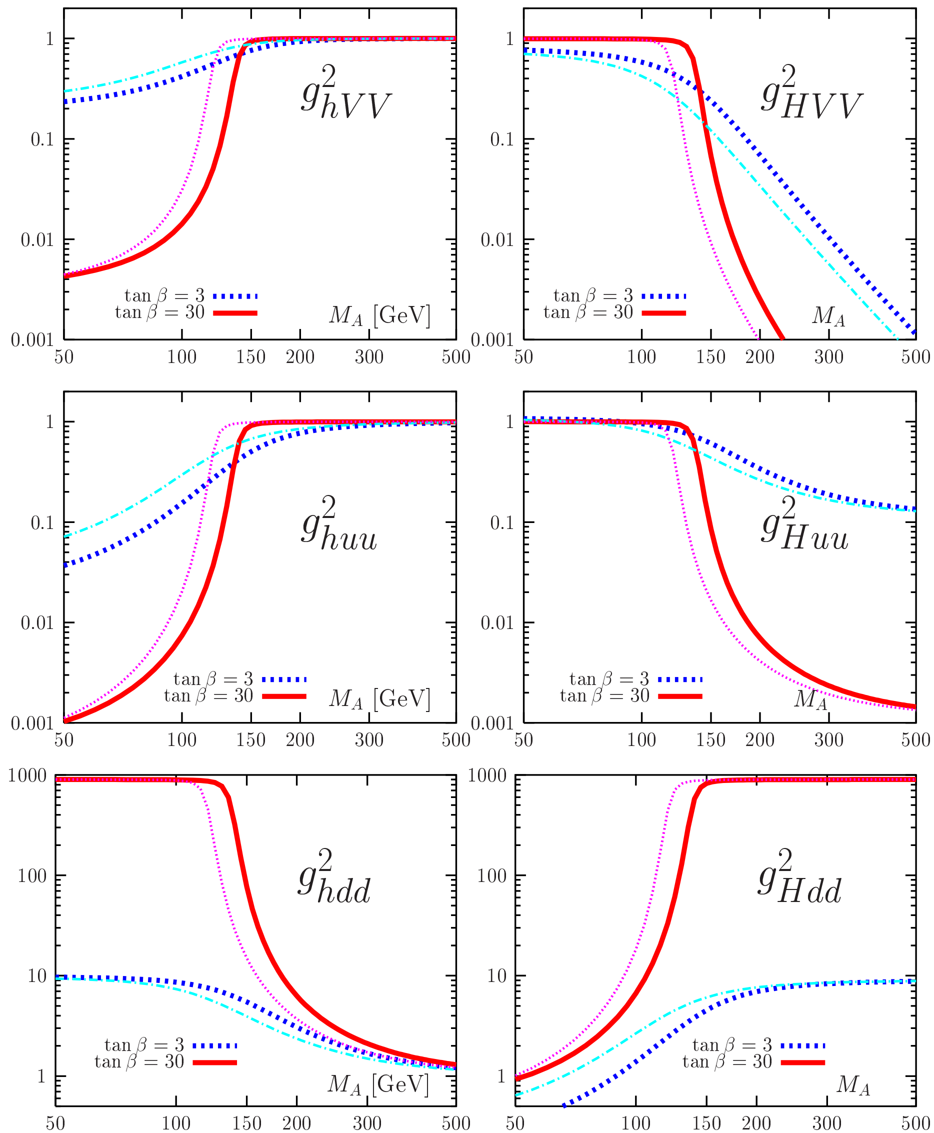
– **For $\tan\beta \gg 1$: couplings to b quarks ($\mathrm{m_b}\tan\beta$) very strong.**

– **For $\mathrm{M_A} \gg \mathrm{M_Z}$: h couples like the SM Higgs boson and H like A.**

In decoupling limit: MSSM reduces to SM but with a light Higgs.

7. Higgs decays: SUSY Higgs couplings

Including radiative corrections just as in the case of the Higgs masses:



7. EWSB in SUSY: beyond the conventional MSSM

Giving up some assumptions: the example of the CP–violating MSSM

We can allow for some amount of CP–violation in eg. M_i, μ and A_f

Higgs sector: CP–conserving at tree level $\Rightarrow$ CP–violating at one–loop

(good to address the issue of baryogenesis at the electroweak scale....)

$\Rightarrow$ h, H,A are not CP definite states: h_1, h_2, h_3 are CP mixtures

determination of Higgs spectrum slightly more complicated than usual

Additional Higgs representations: the example of the NMSSM

MSSM problem: μ is SUSY-preserving but $\mathcal{O}(M_Z)$; a priori no reason

Solution, μ related to the vev of additional singlet field, $\langle S \rangle \propto \mu$

NMSSM: introduce a gauge singlet in Superpotential: $\lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{1}{3}\hat{S}$

$\Rightarrow$ SUSY spectrum extended by χ_5^0 and two neutral Higgs particles h_3, a_2

less fine-tuning, richer phenomenology, interesting constrained version, ..

Both lead to a possibly very light Higgs that has escaped detection!

8. SUSY Higgses at the LHC

Higgs decays in the MSSM:

General features:

- **h: same as $\mathrm{H_{SM}}$ in general**

(in particular in decoupling limit)

$\mathrm{h} \to \mathrm{b\bar{b}}$ and $\tau^+\tau^-$ same or enhanced

- **A: only $\mathrm{b\bar{b}}, \tau^+\tau^-$ and $\mathrm{t\bar{t}}$ decays**

(no VV decays, hZ suppressed).

- **H: same as A in general**

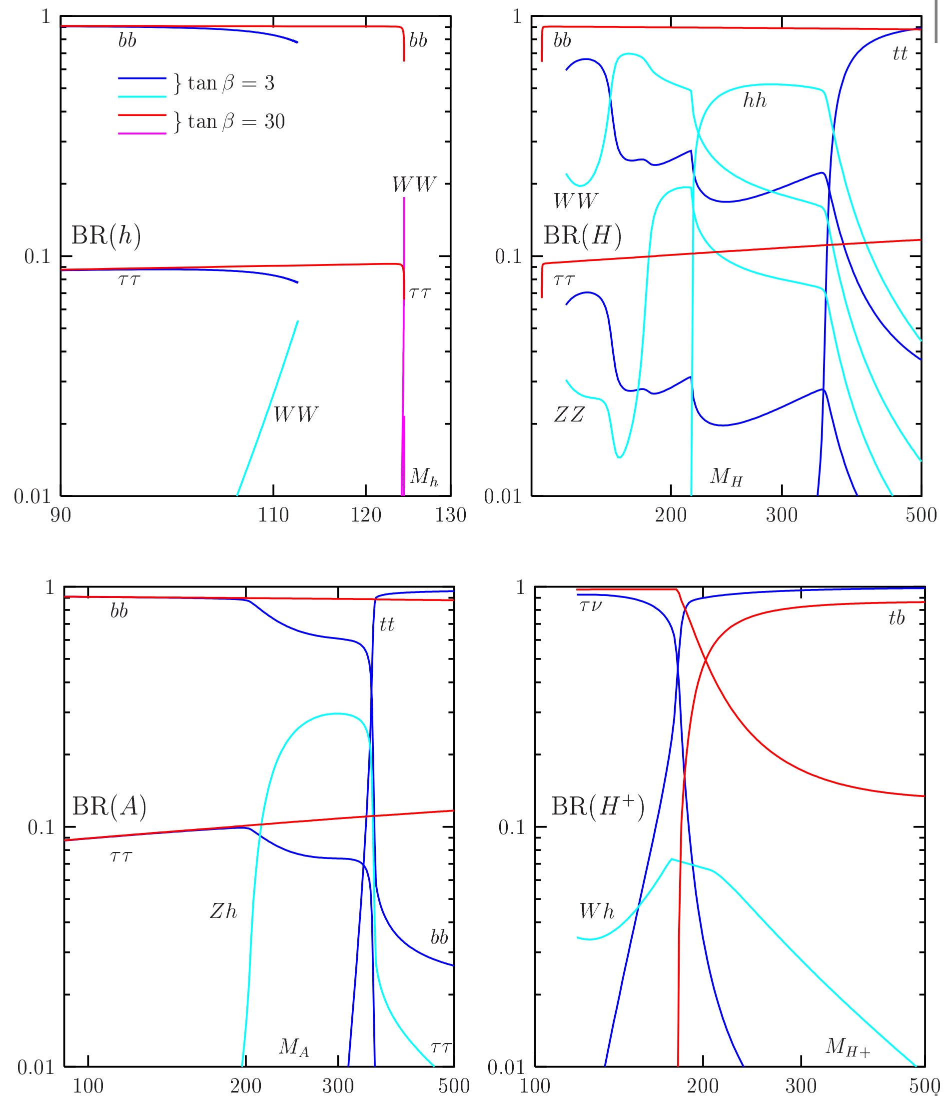
$(\mathrm{WW}, \mathrm{ZZ}, \mathrm{hh}$ decays suppressed).

- **$\mathrm{H}^\pm$: $\tau\nu$ and tb decays**

(depending if $\mathrm{M_{H^\pm}} < $ or $>$ $\mathrm{m_t}$).

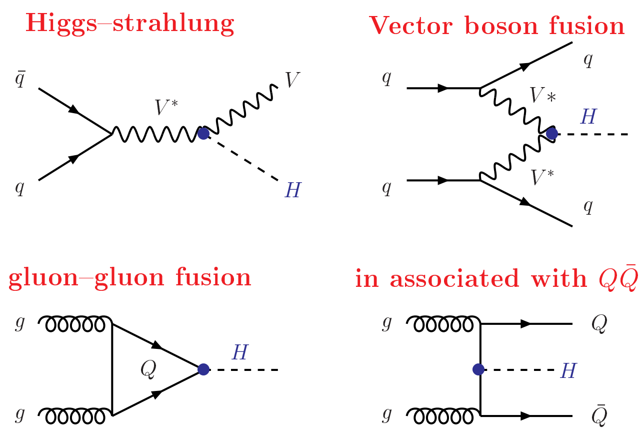
Possible new effects from SUSY

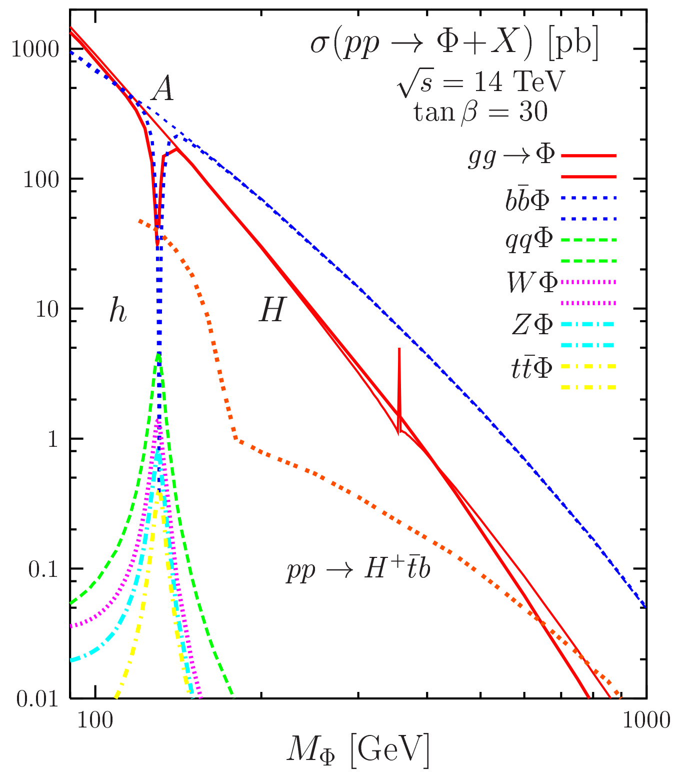
Note: total decay widths small....



8. SUSY Higgses at the LHC: production rates

SM production mechanisms





What is different in MSSM

- **All work for CP–even h,H bosons.**

– in ΦV, $qq\Phi$ h/H complementary

– $\sigma(\mathrm{h}) + \sigma(\mathrm{H}) = \sigma(\mathrm{H_{SM}})$

– additional mechanism: qq $\to$ A+h/H

- **For $\mathrm{gg} \to \Phi$ and $\mathrm{pp} \to \mathrm{tt}\Phi$**

– include the contr. of b–quarks

– dominant contr. at high tanβ!

- **For pseudoscalar A boson:**

– CP: no ΦA and qqA processes

– $\mathrm{gg} \to \mathrm{A}$ and $\mathrm{pp} \to \mathrm{bbA}$ dominant.

- **For charged Higgs boson:**

– $\mathrm{M_H} \lesssim \mathrm{m_t}$: $\mathrm{pp} \to \mathrm{t\bar{t}}$ with $\mathrm{t} \to \mathrm{H^+b}$

– $\mathrm{M_H} \gtrsim \mathrm{m_t}$: continuum $\mathrm{pp} \to \mathrm{t\bar{b}H^-}$

8. SUSY Higgses at the LHC: higher orders

Summary of higher order calculations in MSSM (for SM see earlier)

For h/H: same processes as for SM Higgs (esp. for $\mathrm{M_A} \gg \mathrm{M_Z}$) but:

- Include b–loop contributions to $\mathrm{gg} \to \mathrm{h/H}$ and new $\mathrm{gg} \to \mathrm{A}$

K–factors only at NLO ($\sim$ 1.5–2)

- Include b–final states in $\mathrm{pp} \to \mathrm{b\bar{b}} + \mathrm{h/H}$ (dominant at high $\tan\beta$)

large K–factors at NLO (50%)

- Additional SUSY–QCD corrections in $\mathrm{pp} \to \mathrm{V+h/H;qq+h/H}$:

rather small at NLO (a few %) for heavy $\tilde{\mathrm{q}}/\tilde{\mathrm{g}}$

For A: rates including K–factors approx the same as above for h/H

For $\mathrm{H^\pm}$: main process is $\mathrm{pp} \to \mathrm{tt^{(*)}} \to \mathrm{tbH^\pm}$ in general

relevant corrections known exactly at NLO

h,H,A,$\mathrm{H^\pm}$ decays: well under control including SUSY+NL0 corrections

summarized in the program HDECAY

8. SUSY Higgses at the LHC: detection

The lighter Higgs boson:

same as in the SM for $\mathrm{M_h} \lesssim 140$ GeV

(in particular in the decoupling regime)

$$\mathrm{gg \to h \to \gamma\gamma, WW^*}$$

$$\mathrm{pp \to hqq \to qq\gamma\gamma, qq\tau\tau, qqWW^*}$$

The heavier neutral Higgses:

same production/decays for H/A in general

$$\mathrm{pp \to b\bar{b} + H/A \to b\bar{b} + \tau\tau/\mu\mu}$$

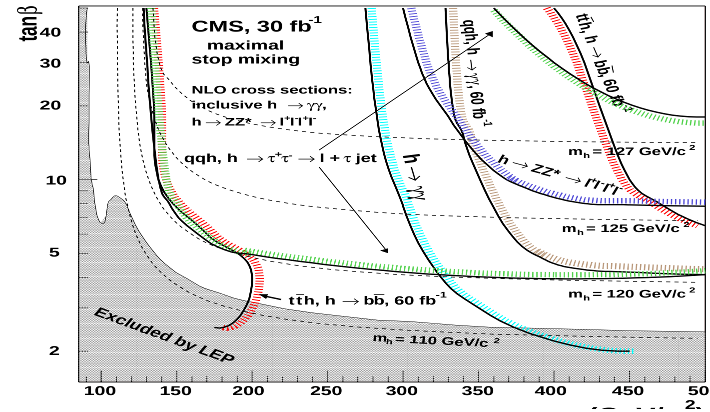
(as in SM for H in anti-decoupling regime).

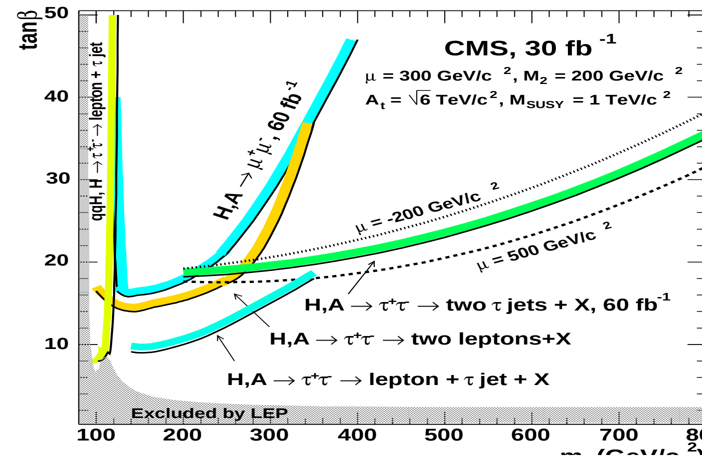
The charged Higgs:

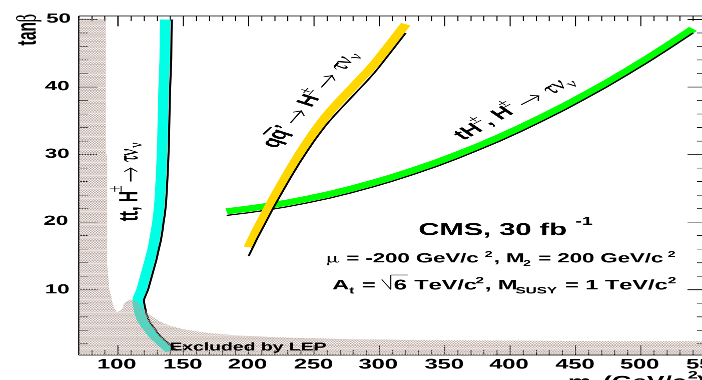
$$\mathrm{t \to bH^- \to b\tau\nu \ for\ M_H \lesssim m_t}$$

$$\mathrm{gb \to tH^+ \to t\tau\nu \ for\ M_H \gtrsim m_t}$$

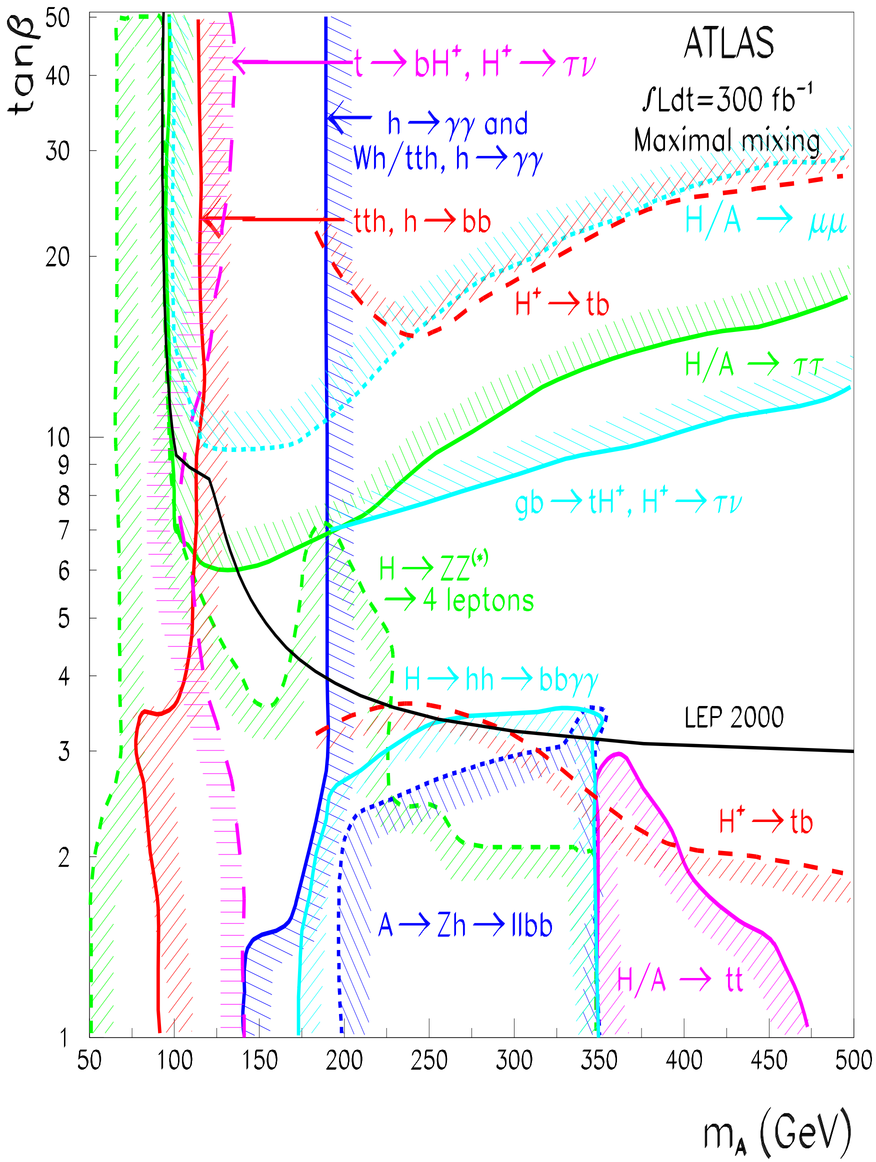
reach depends on $\mathrm{M_A}$ and tanβ

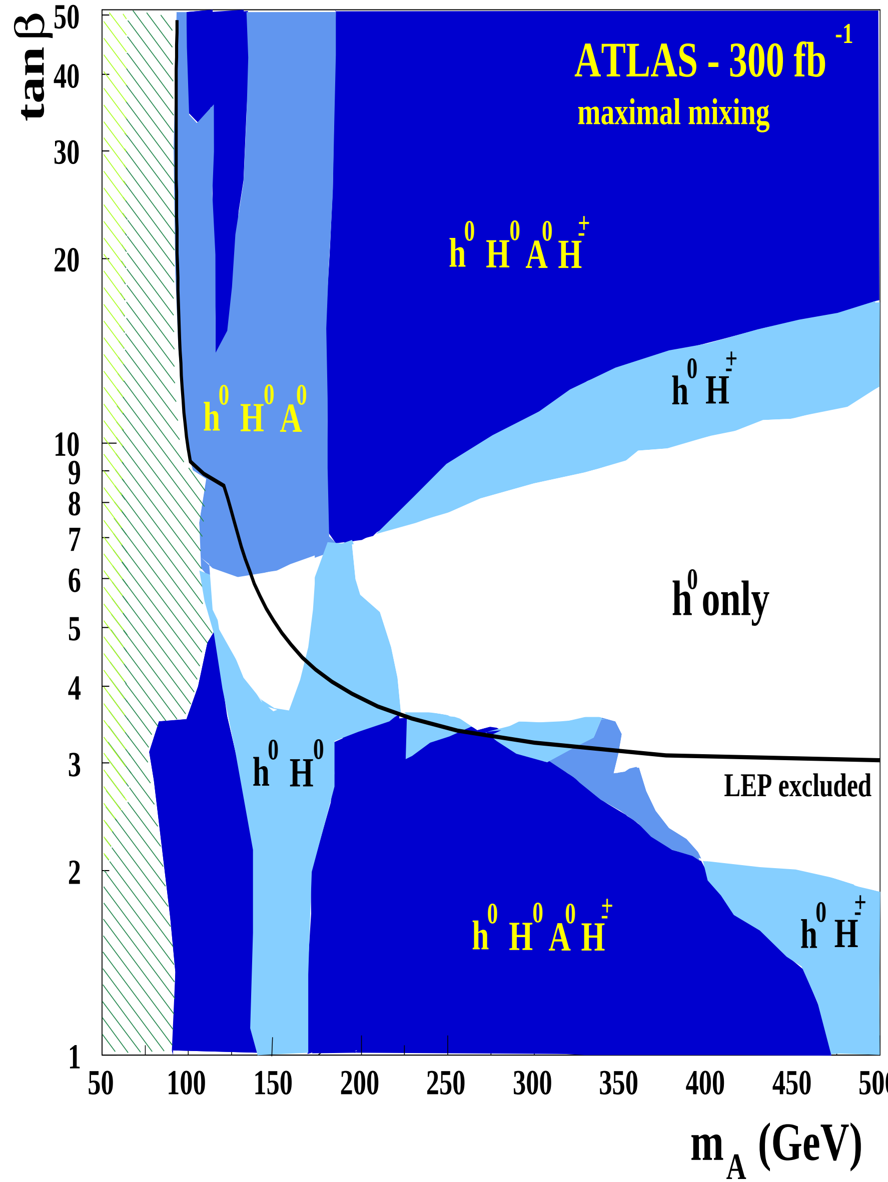






8. SUSY Higgses at the LHC: detection





8. SUSY Higgses at the LHC: measurements

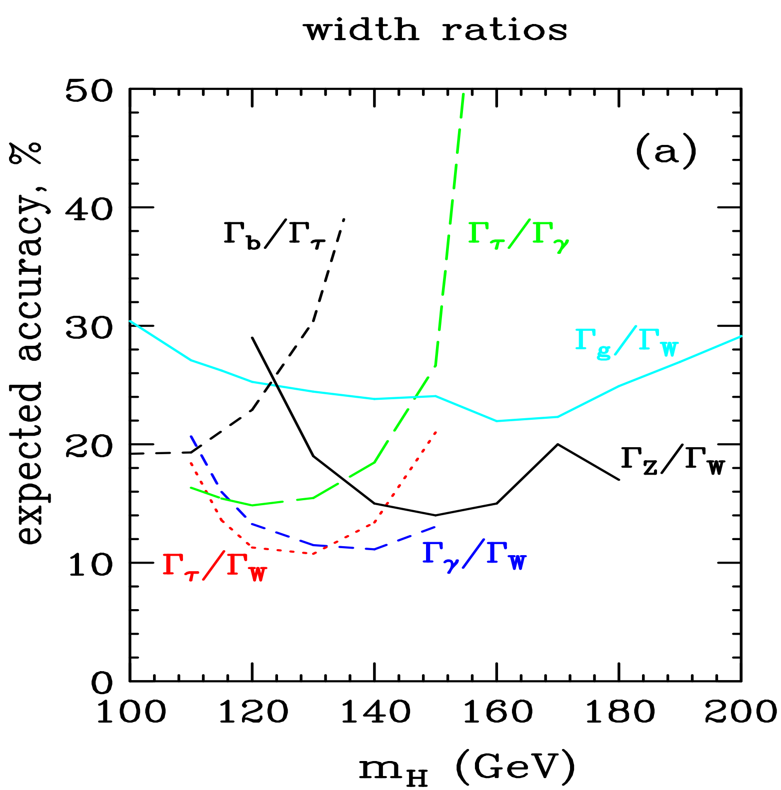
Lightest Higgs: as in SM

Higgs mass $\mathrm{h} \to \gamma\gamma, \mathrm{ZZ}^*$

Higgs couplings from $\sigma\times$ BR

Higgs spin+CP numbers: hard

Higgs self-couplings hopeless...

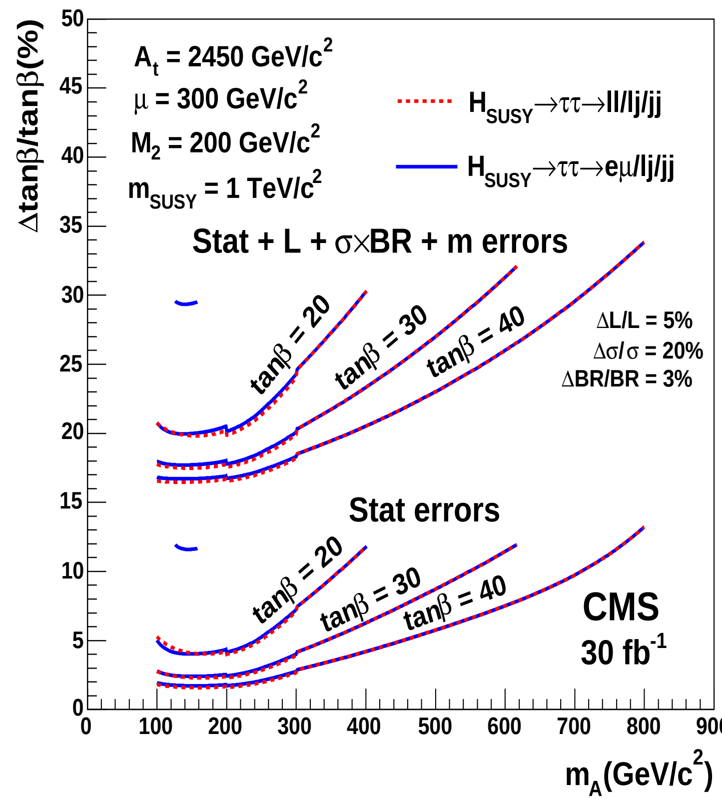


The heavy Higgsses

Masses from $\mathrm{H/A} \to \mu^+\mu^-$

$\tan\beta$ in $\mathrm{pp} \to \mathrm{H/A} + \mathrm{b\bar{b}}$

H/A separation difficult



3. SUSY Higgses at the LHC: difficult scenarios in the MSSM

However: life can be much more complicated even in this MSSM

- **There is the "bad luck" scenario in which only h is observed:**

– looks SM–like at the 10% level (and $M_{SUSY} \gtrsim 3$ TeV...): SM

- **There are scenarii where searches are different from standard case:**

– The intense coupling regime: h,H,A almost mass degenerate....

- **SUSY particles might play an important role in production/decay:**

– light $\tilde{t}$ loops might make $\sigma(gg \to h \to \gamma\gamma)$ smaller than in SM.

– Higgses can be produced with sparticles ($pp \to \tilde{t}\tilde{t}^* h$,..).

– Cascade decays of SUSY particles into Higgs bosons....

- **SUSY decays, if allowed, might alter the search strategies:**

– $h \to \chi_1^0 \chi_1^0, \tilde{\nu}\tilde{\nu}$ are still possible in non universal models...

– Decays of $A, H, H^\pm$ into $\chi_i^\pm, \chi_i^0$ are possible but can be useful...

Life can be even more complicated in extensions of the MSSM

8. SUSY Higgses at the LHC: the CP–violating MSSM

h, H,A are not CP definite states and h_1, h_2, h_3 are CP–mixed states

The relation for the Higgs masses and couplings different from MSSM.

There is the possibility of a light Higgs which has escaped detection.

An example is the CPX scenario

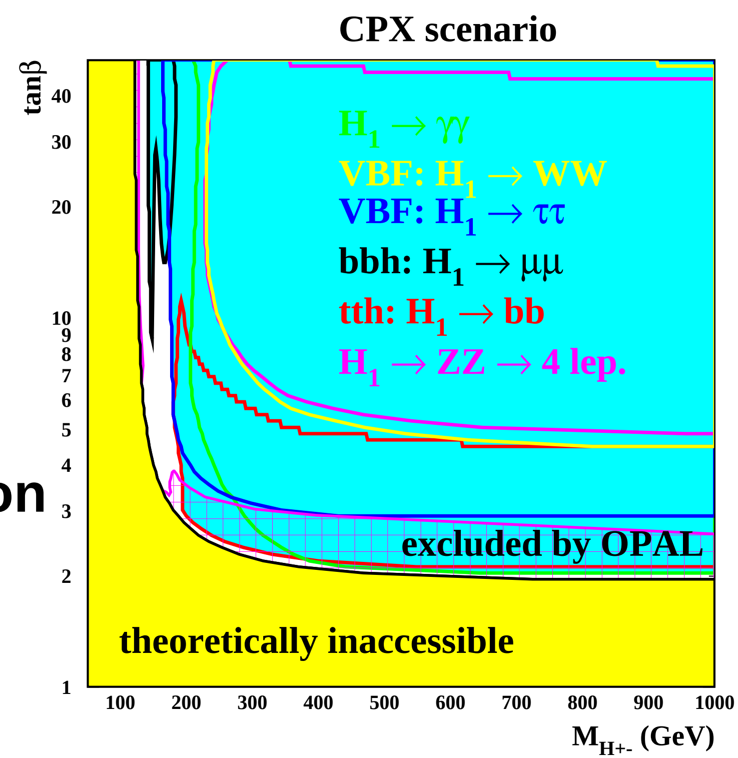
- **h_1 light but weak cplgs to W,Z**
- **$h_2 \to h_1 h_1$ decays allowed**
- **h_3 couplings to VV reduced...**

All neutral Higgses escape detection:

only (SM-like) h_2 has large cross section

$h_2 \to h_1 h_1 \to 4b, 4\tau$ unobservable.

Still, one has $t \to H^+ b \to b + hW^*$



8. SUSY Higgses at the LHC: the NMSSM

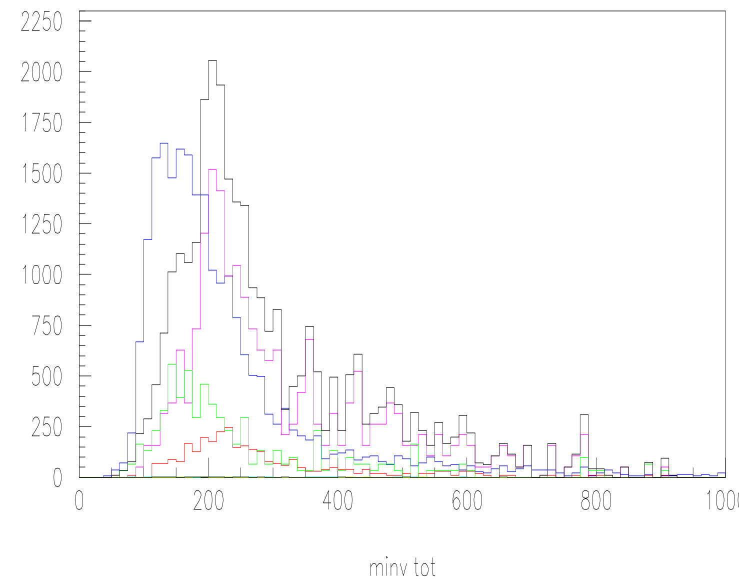
In the NMSSM with $h_{1,2,3}, a_{1,2}, h^{\pm}$ one can have Higgs to Higgs decays:
then the possibility of missing all Higgs bosons is not yet ruled out!

Higgs → Higgs+Higgs $\to 4b, 2b2\tau$

searches very difficult at the LHC:

$$pp \to qq \to\to W^*W^*qq \to h_1 qq$$

$$h_1 \to a_1 a_1 \to b\bar{b}\tau\tau \times 500$$

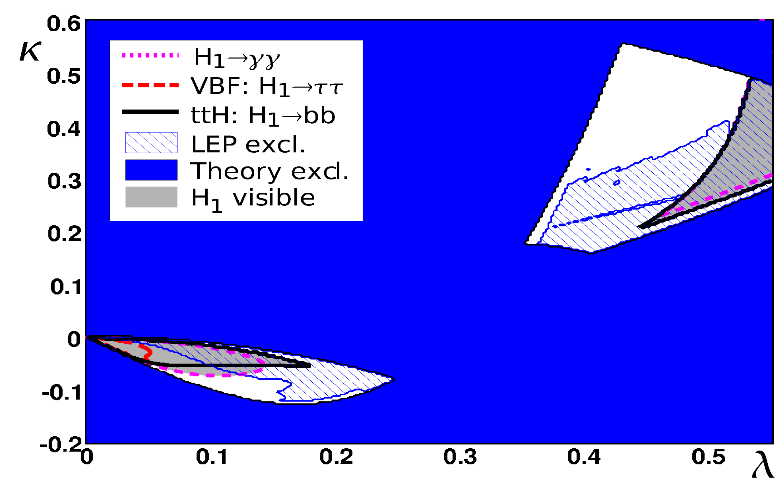


Higgs → Higgs+Higgs $\to 4\tau \to 4\ell X$

also difficult but detection possible

using VBF + all h_1 decay channels

(same for all Higgses can be done)



8. SUSY Higgses at the LHC: invisible Higgs?

There are many scenarios in which a Higgs boson would decay invisibly

- **In MSSM, Higgs $\rightarrow \chi_1^0\chi_1^0, \tilde{\nu}\tilde{\nu}$, etc.. as already discussed.**
- **In MSSM with $\mathrm{R\!\!\!/_p}$: Higgs $\rightarrow \mathrm{JJ}$ could be dominant.**
- **The SM when minimally extended to contain a singlet scalar field (which decouples from f/V), $\mathrm{H} \rightarrow \mathrm{SS}$ can be dominant**
- **In large extra dimensions H mixing with graviscalars.**

... or very different couplings to fermions and bosons...

- **Radion mixing in warped extra dimension models: suppressed f/V couplings and Higgs decays to radions**
- **Presence of new quarks which alter production**
- **Composite light Higgs boson**

... Many possible surprises/difficult scenarios......

Conclusion: the LHC will tell!