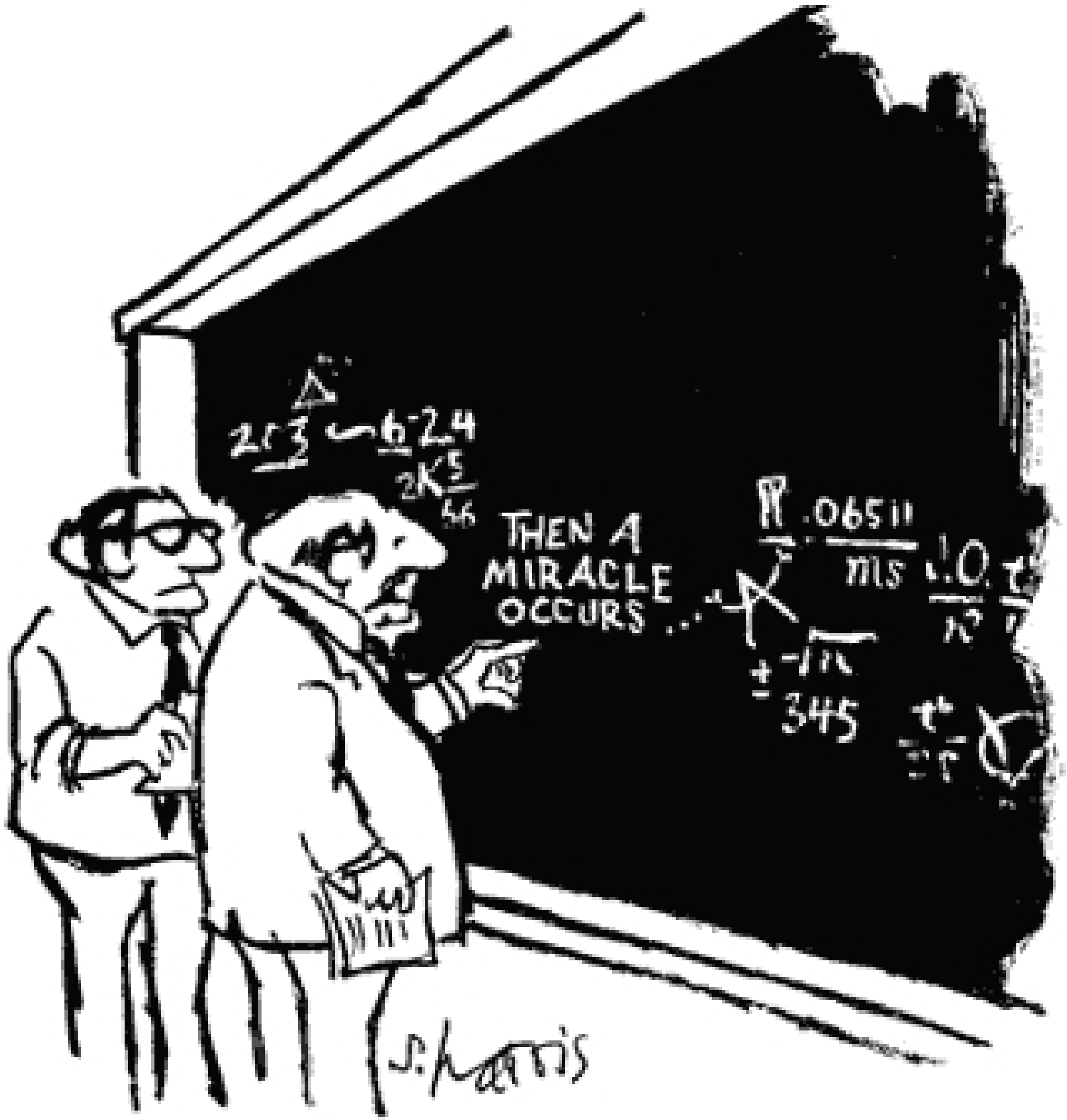
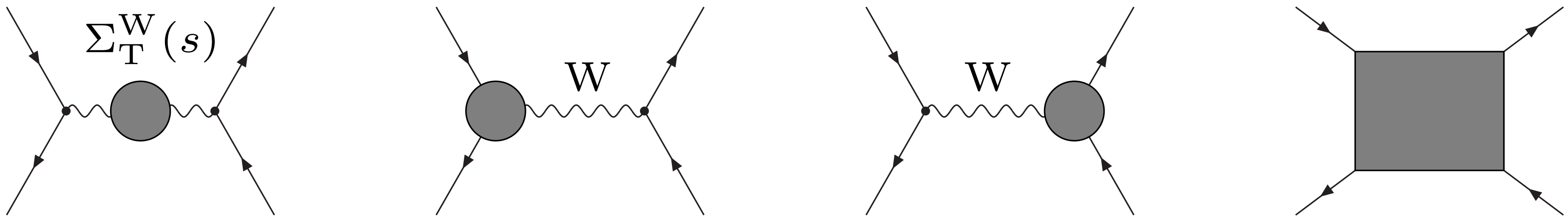
# precise experiments need precise calculations

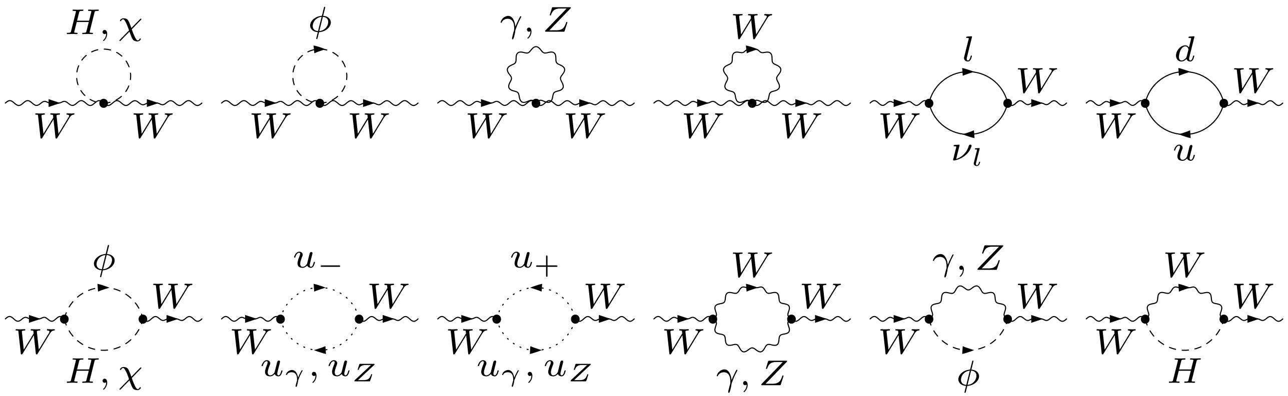


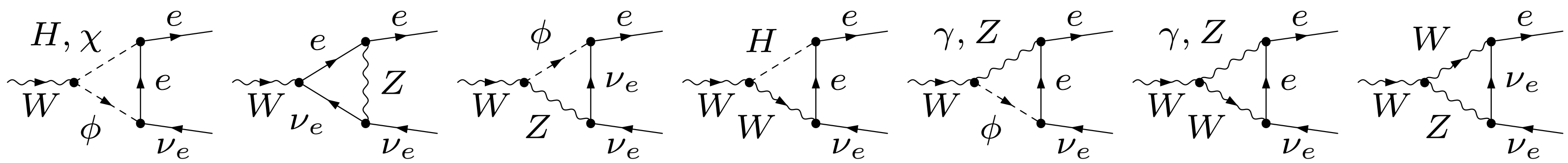

"I think you should be more explicit here in step two."

# example: 1-loop diagrams for $\mu$ decay amplitude

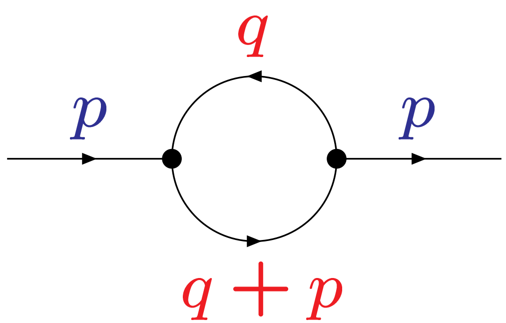



W self-energy    $Wl\nu_l$ vertex correction    box diagrams



Example of loop integral:




$$\sim \int d^4q \frac{1}{(q^2 - m_1^2)\left[(q+p)^2 - m_2^2\right]}$$

$$q \to \infty : \quad \sim \int^{\infty} \frac{q^3 dq}{q^4} = \int^{\infty} \frac{dq}{q} \quad \to \infty$$

$\Rightarrow$ integral diverges for large $q$

$\Rightarrow$ theory in this form not physically meaningful

needs (i) regularization

(ii) renormalization

## Regularization:

theory modified such that expressions become mathematically meaningful

$\Rightarrow$ "regulator" introduced, removed at the end

e.g. cut-off in loop integral

$$\int_0^{\infty} d^4q \;\to \int_0^{\Lambda} d^4q; \quad \Lambda \to \infty \text{ at the end}$$

technically more convenient: dimensional regularization

$$\int d^4q \;\to \int d^Dq, \quad D = 4 - \varepsilon; \quad D \to 4 \text{ at the end}$$

# Renormalization:

- absorption of divergencies
- determination of physical meaning of parameters order by order in perturbation theory

add counterterms that absorb divergent parts

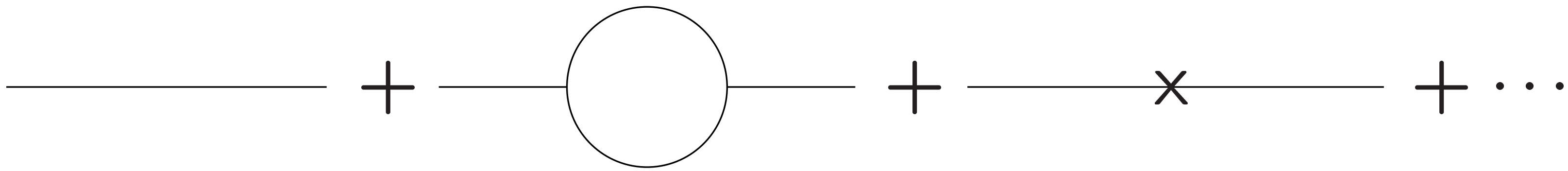
- parameters in $\mathcal{L}$ are formal, "bare parameters"

  $g_0 = g + \delta g$ *for a coupling,* $m_0 = m + \delta m$ *for a mass*

- $g, \; m$ are "physical", *i.e.* measurable mass renormalization, $m_0^2 = m^2 + \delta m^2$

Physical mass: pole of propagator

inverse propagator up to 1-loop order:

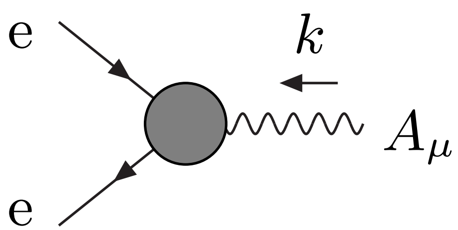


$p^2 - m^2 \qquad \Sigma(p^2) \qquad -\,\delta m^2$

**on-shell renormalization**: $\delta m^2 = \mathrm{Re}\,\Sigma(m^2)$

# charge renormalization: $e_0 = e + \delta e$

$\delta e$ *cancels loop contributions to* $ee\gamma$ *vertex in the Thomson limit*




$\xrightarrow{k \to 0}$ $\mathrm{i}e\gamma_\mu$ for on-shell electrons

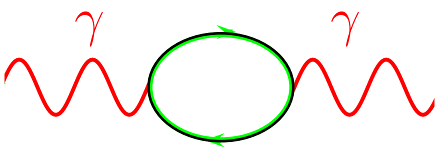
$\Rightarrow$ $e =$ elementary charge of classical electrodynamics

fine-structure constant $\alpha(0) = \dfrac{e^2}{4\pi} = 1/137.03599976$

$\delta e$ *contains photon vacuum polarization* $\Pi^\gamma(k^2 = 0)$ :

$$\Pi^\gamma(0) \;=\; \underbrace{\Pi^\gamma(0) - \Pi^\gamma(M_Z^2)}_{\textit{non-perturbative}} + \underbrace{\Pi^\gamma(M_Z^2)}_{\textit{perturbative}}$$

## photon vacuum polarization



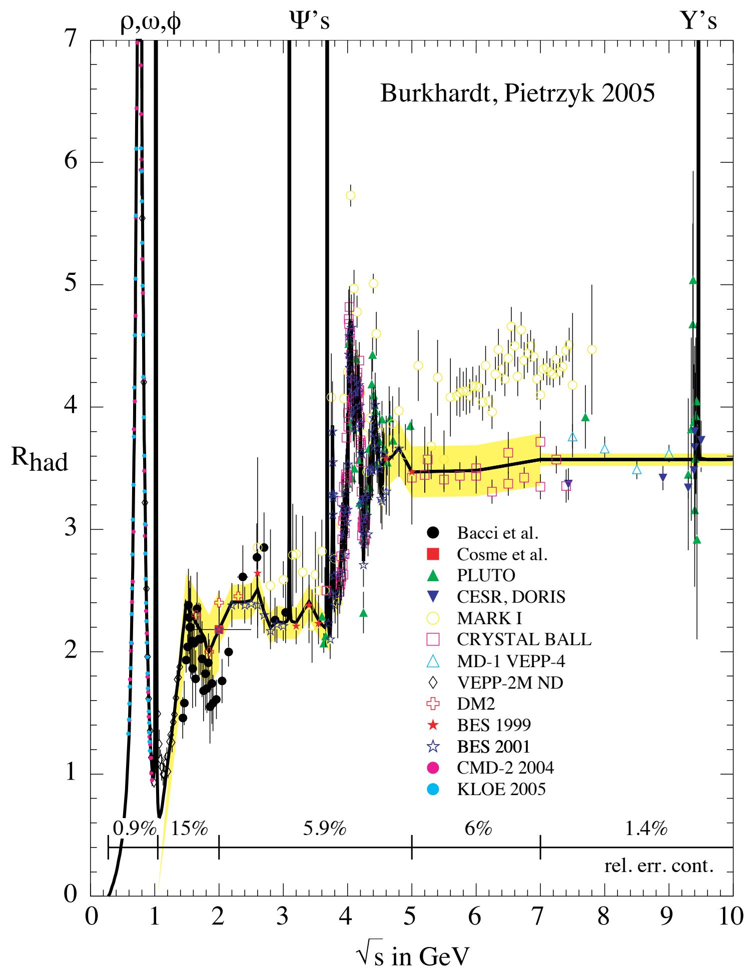

$$\Pi^\gamma(M_Z^2) - \Pi^\gamma(0) \equiv \Delta\alpha \quad \rightarrow \quad \alpha(M_Z) = \frac{\alpha}{1-\Delta\alpha} \simeq \frac{1}{129}$$

$$\begin{aligned}
\Delta\alpha &= \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{had}}, \\
\Delta\alpha_{\text{lept}} &= 0.031498 \quad (3-\text{loop}) \\
\Delta\alpha_{\text{had}} &= 0.02750 \pm 0.00033 \\
&= 0.02757 \pm 0.00010
\end{aligned}$$

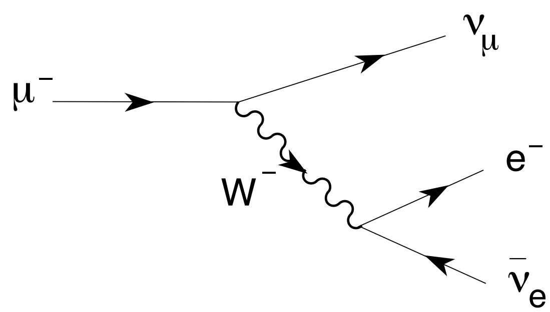
*arXiv:1010.4180*

$$\Delta\alpha_{\rm had} = -\frac{\alpha}{3\pi} M_Z^2 \,\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds' \,\frac{R_{\rm had}(s')}{s'(s' - M_Z^2 - i\epsilon)}$$

$$R_{\rm had} = \frac{\sigma(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

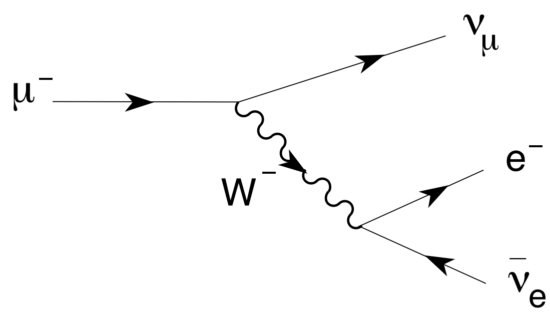


# $M_W - M_Z$ correlation




$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\left(1 - M_W^2/M_Z^2\right)}$$

# $M_W - M_Z$ correlation




$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\left(1 - M_W^2/M_Z^2\right)}$$

$M_W = 80.939 \pm 0.002\,\mathrm{GeV}$ *from* $G_F,\ \alpha,\ M_Z$

$M_W = 79.965 \pm 0.005\,\mathrm{GeV}$ *with* $\alpha \to \alpha(M_Z)$

$M_W = 80.385 \pm 0.015\,\mathrm{GeV}$ *exp.* $37\sigma\,/\,28\,\sigma$

**with loop contributions**

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\left(1 - M_W^2/M_Z^2\right)} \cdot (1 + \Delta r)$$

$\Delta r$ :  quantum correction

$$\Delta r = \Delta r(m_t, M_H)$$

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \cdots$$

$$\Delta\rho \sim \frac{m_t^2}{M_W^2}$$

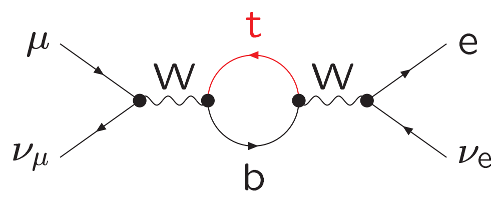
determines W mass

$$M_W = M_W(\alpha, G_F, M_Z, m_t, M_H)$$

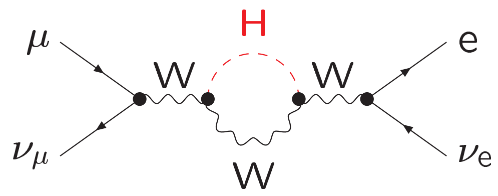
complete at 2-loop order

*1-loop examples*

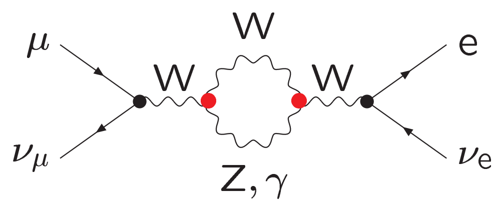
- top quark



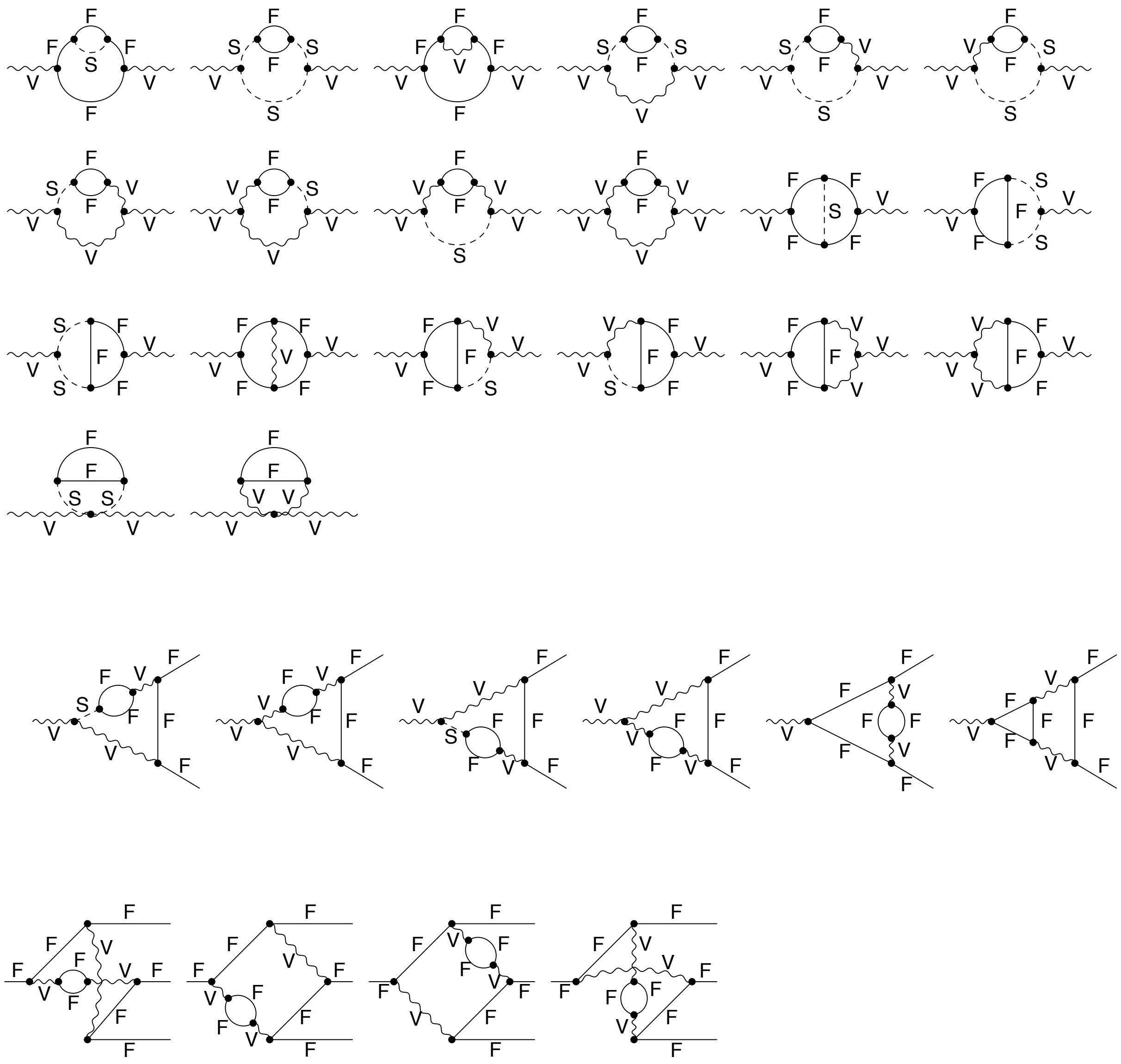

- Higgs boson




- gauge-boson self-couplings

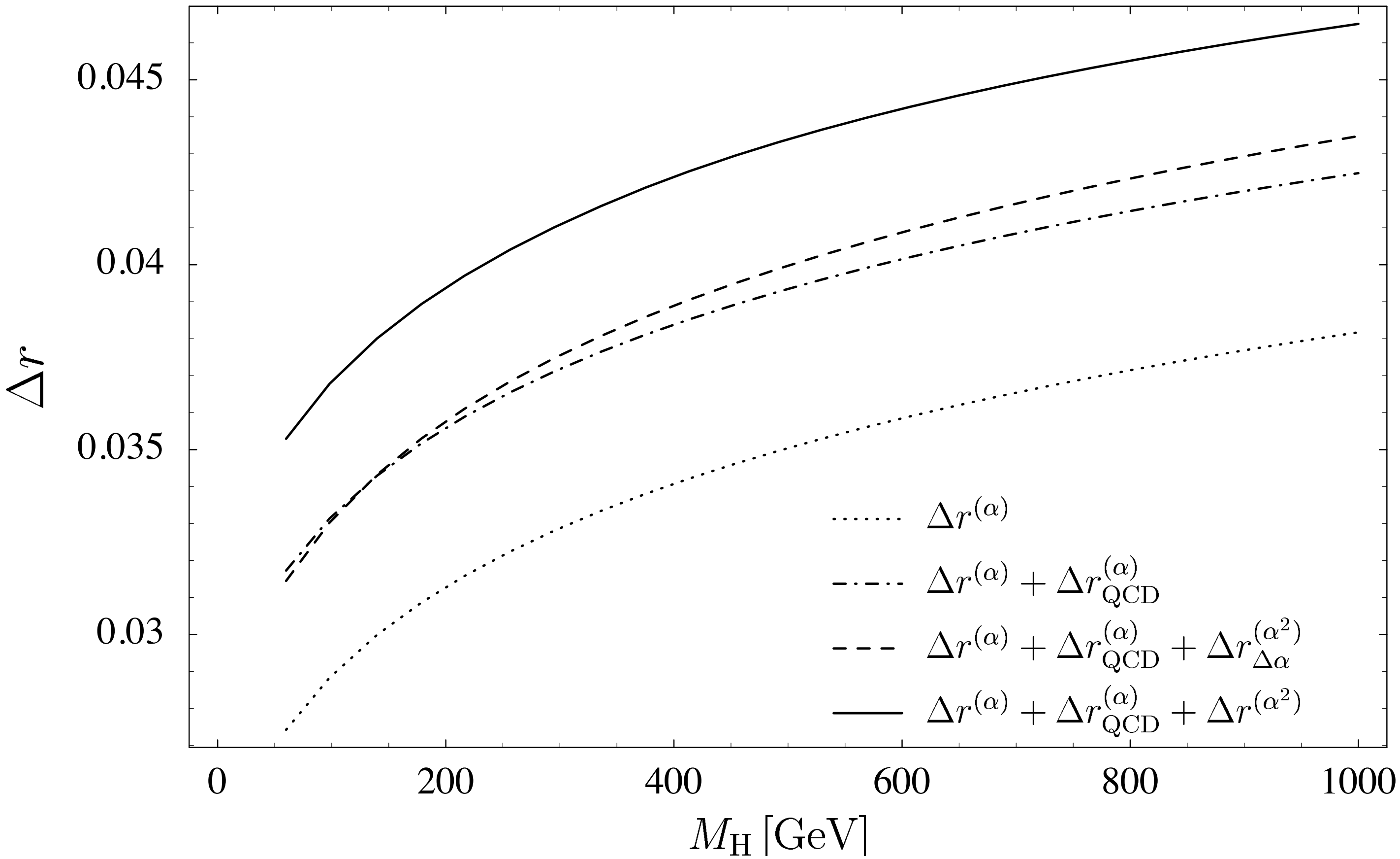



*full structure of SM*



*2-loop examples*

# effects of higher-order terms on $\Delta r$

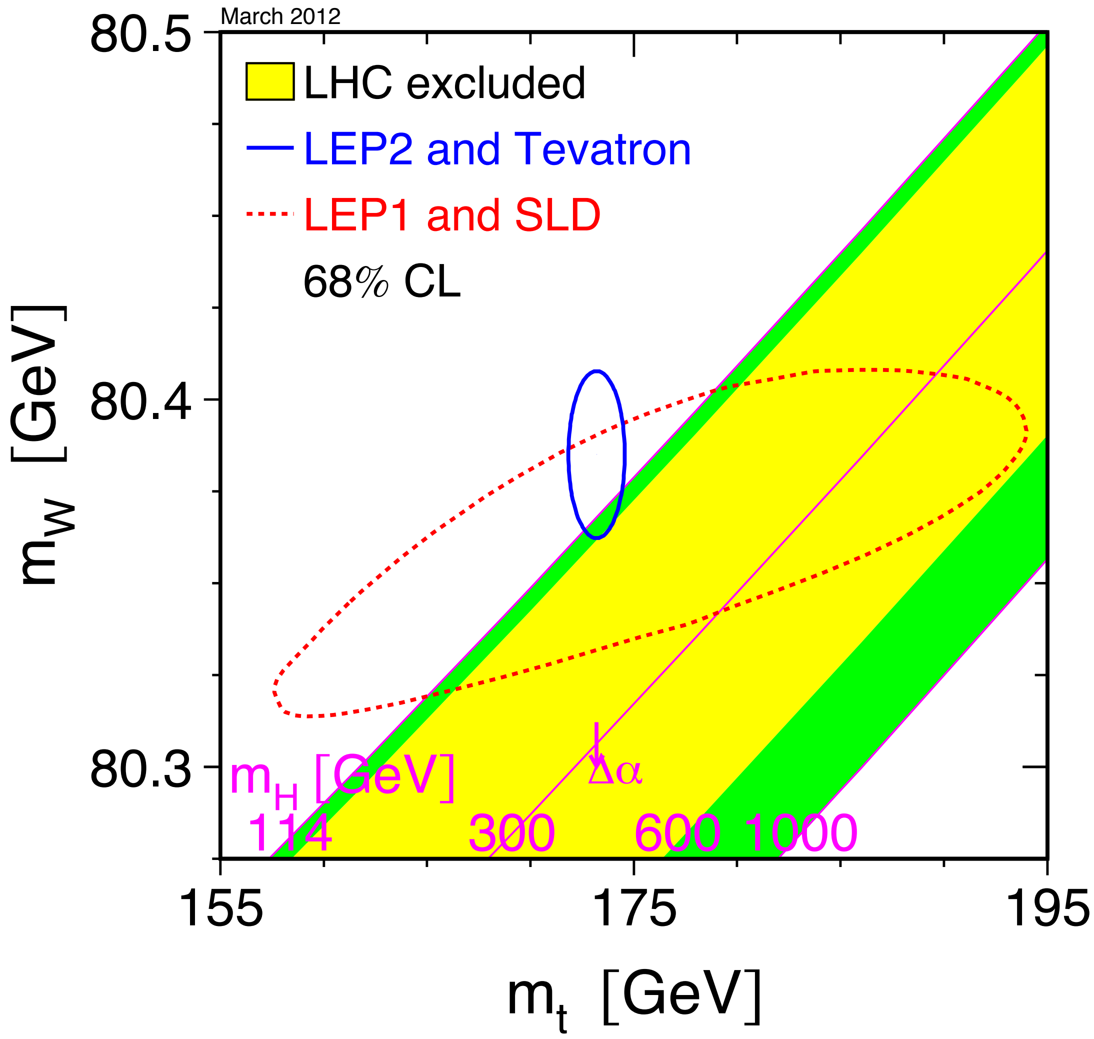



variation of $\Delta r$ by 0.001 $\Rightarrow$ $\delta M_W = 18\,\mathrm{MeV}$

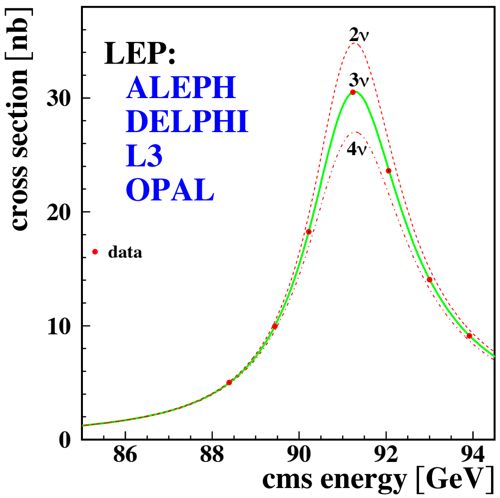
3-loop ($\Delta\rho$) $\Rightarrow$ $\delta M_W = 12\,\mathrm{MeV}$

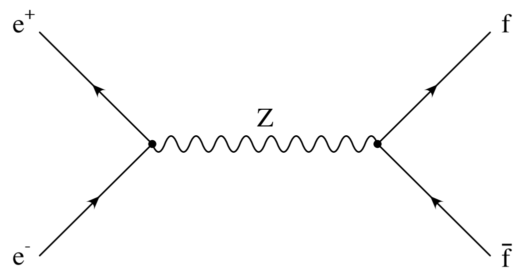
present exp. error: $\Delta M_W = 15\,\mathrm{MeV}$ / theo: $4\,\mathrm{MeV}$

# LEP Electroweak Working Group



# Z resonance



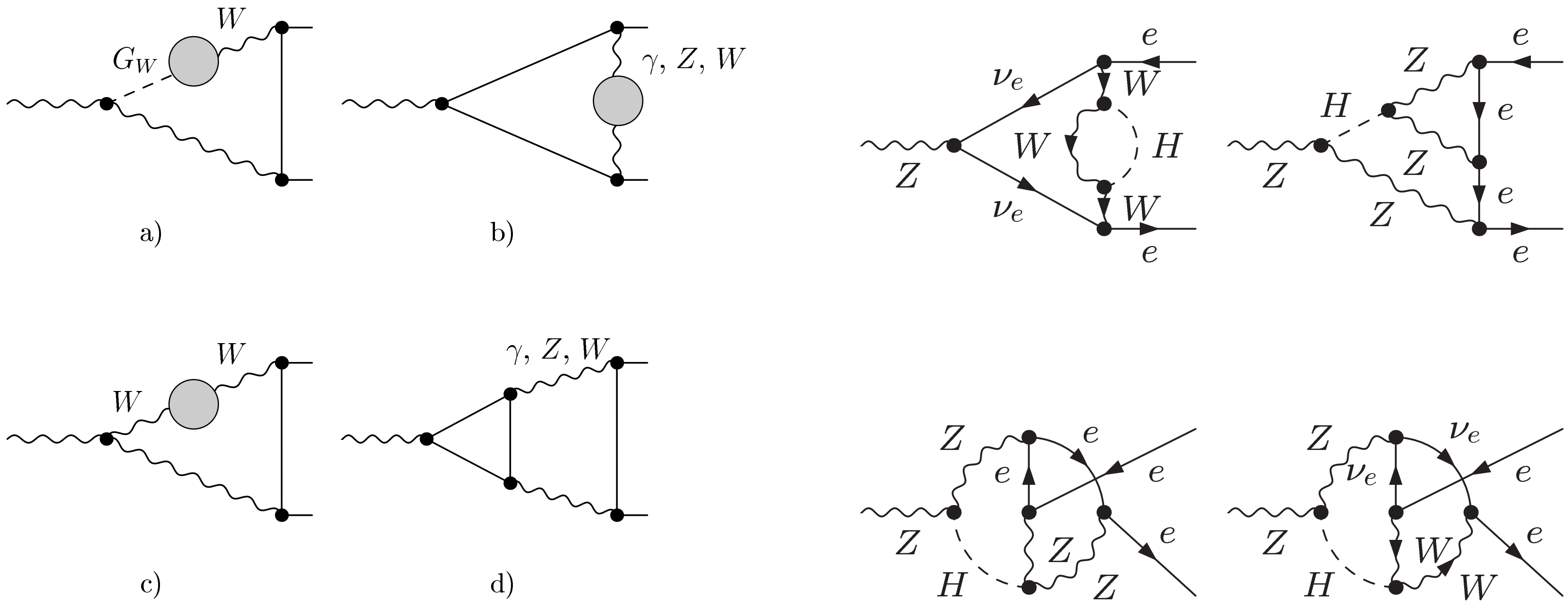




- effective $Z$ boson couplings with higher-order $\Delta g_{V,A}$

$$v_f \to g_V^f = v_f + \Delta g_V^f, \qquad a_f \to g_A^f = a_f + \Delta g_A^f$$

- effective ew mixing angle (for $f = e$):

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4}\left(1 - \text{Re}\,\frac{g_V^e}{g_A^e}\right) = \kappa \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$




*2-loop examples for Z couplings*

complete 2-loop calculation available for $\sin^2\theta_{\rm eff}$

## EW 2-loop calculations for $\Delta r$

*Freitas, Hollik, Walter, Weiglein*

*Awramik, Czakon*

*Onishchenko, Veretin*

## EW 2-loop calculations for $\sin^2\theta_{\mathrm{eff}}$

*Awramik, Czakon, Freitas, Weiglein*

*Awramik, Czakon, Freitas*

*Hollik, Meier, Uccirati*

## universal terms at 3- and 4-loops (EW and QCD)

*van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker*

*Faisst, Kühn Seidensticker, Veretin*

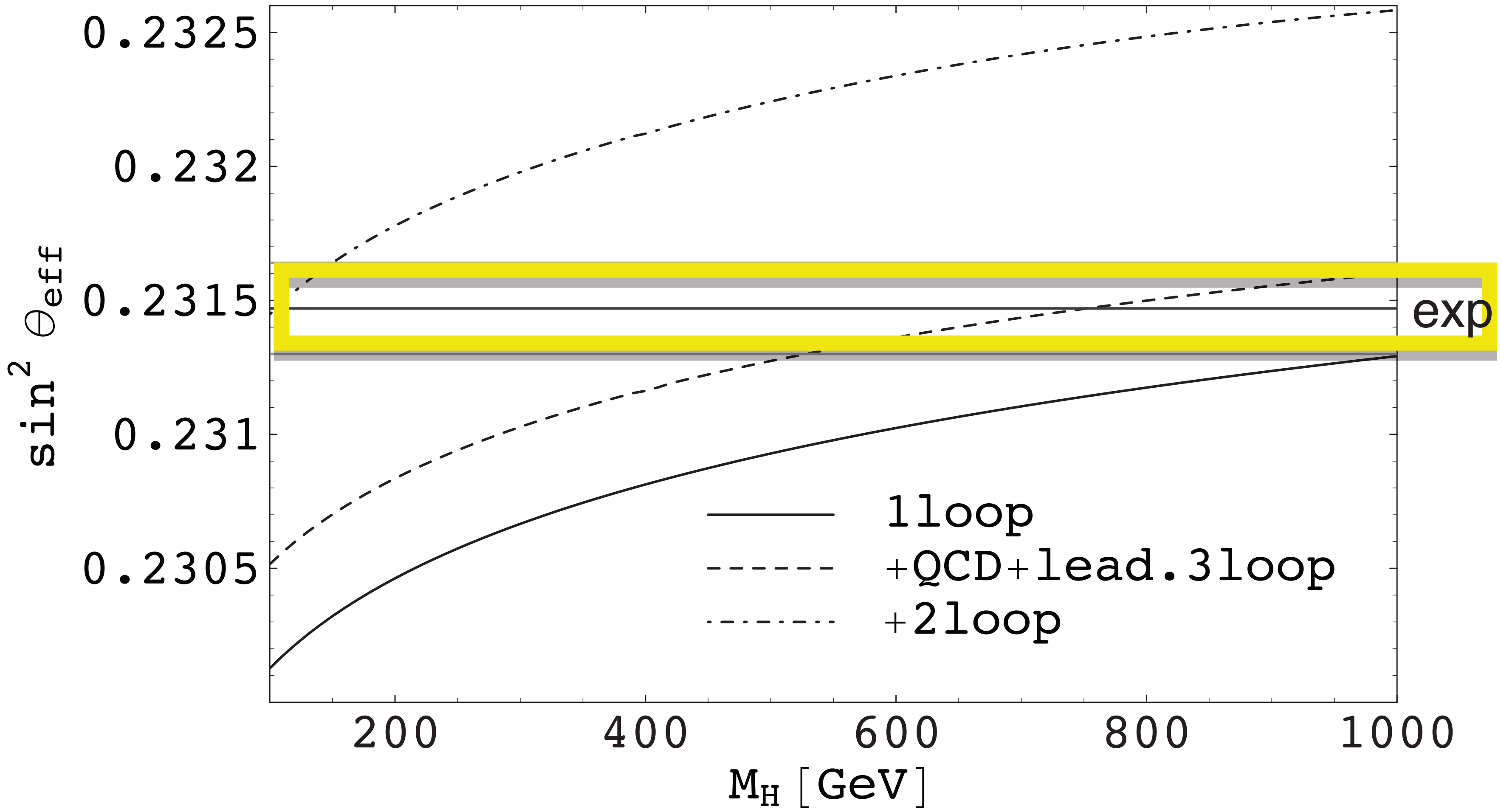
*Boughezal, Tausk, van der Bij*

*Schröder, Steinhauser*

*Chetyrkin, Faisst, Kühn* *Chetyrkin, Faisst, Kühn, Maierhofer, Sturm*

*Boughezal, Czakon*

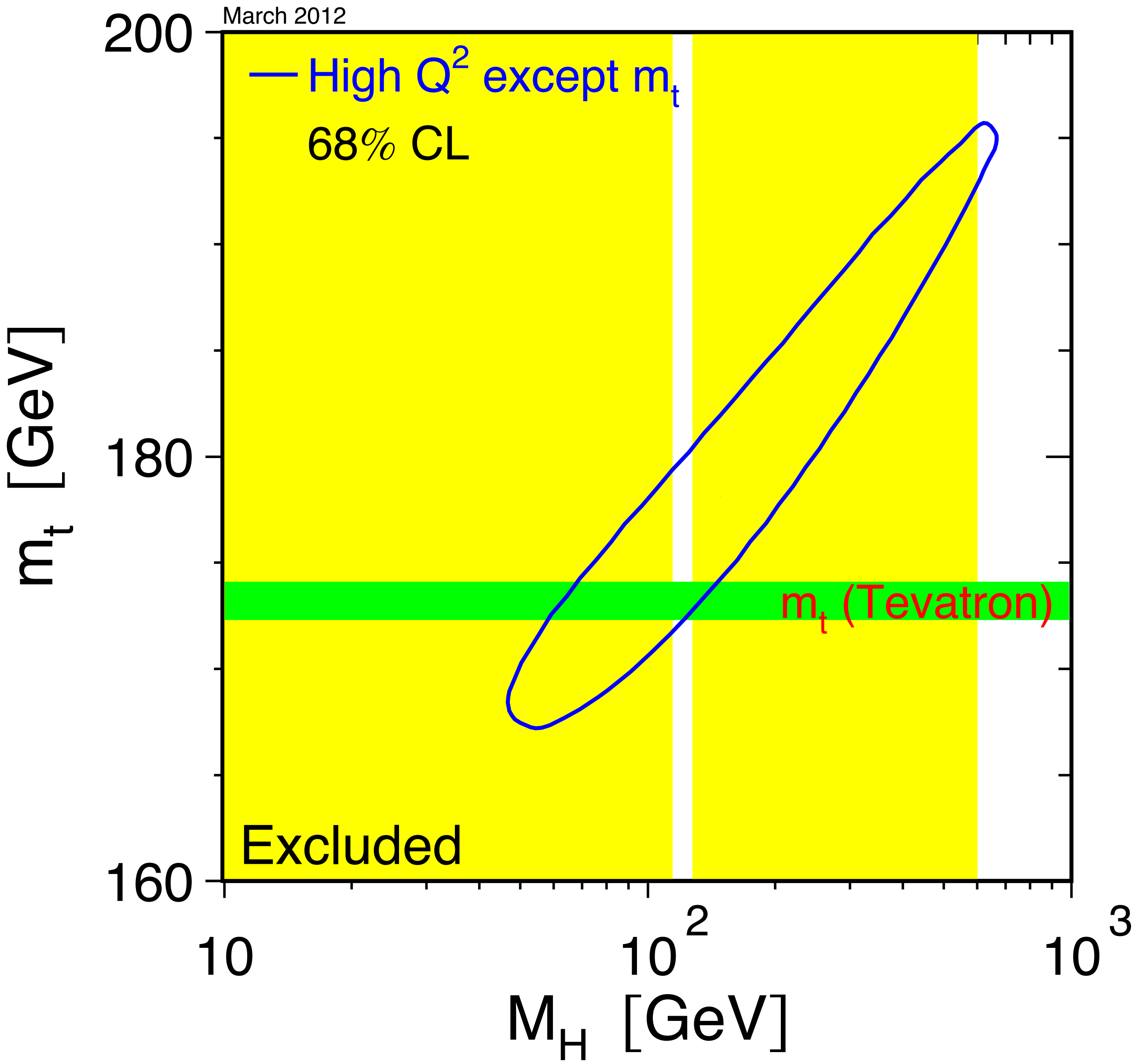
# importance of two-loop calculations




lowest order: $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.22290 \pm 0.00029$

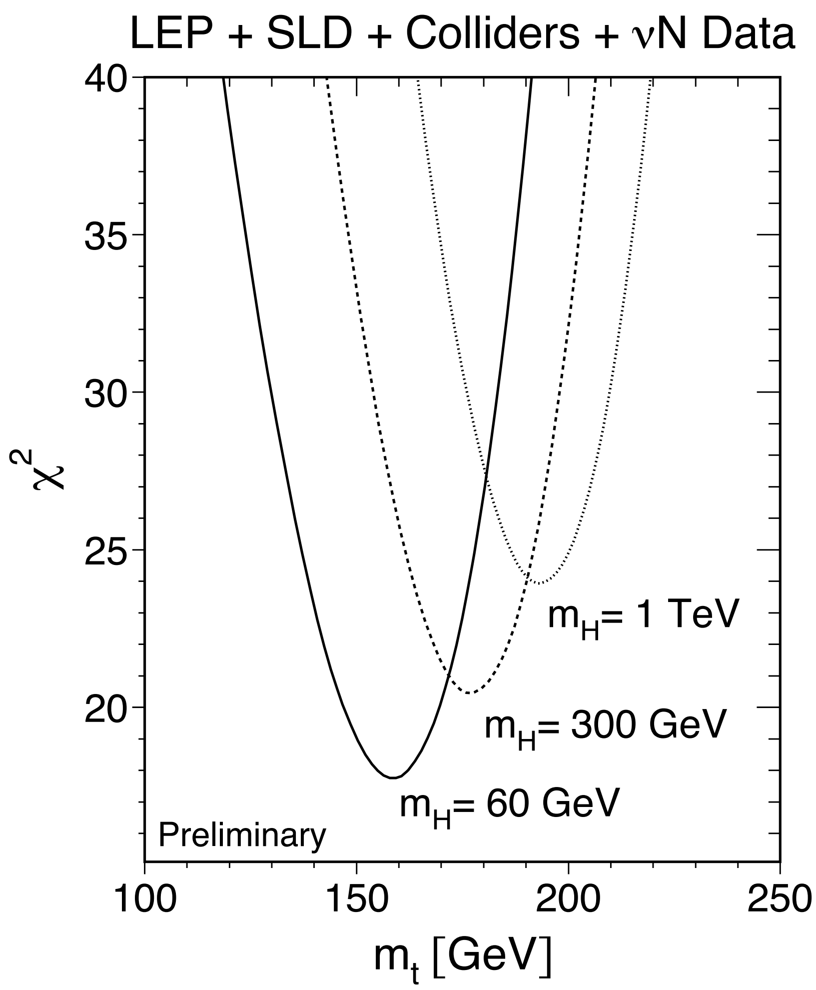
exp. value: $\sin^2 \theta_{\text{eff}} = \quad 0.23153 \pm 0.00016$

Global analysis within the SM



before the top quark was discovered (< 1995):

indirect mass determination $\Rightarrow$ $\mathrm{m_t} = 178 \pm 8 \,^{+17}_{-20}\,\mathrm{GeV}$



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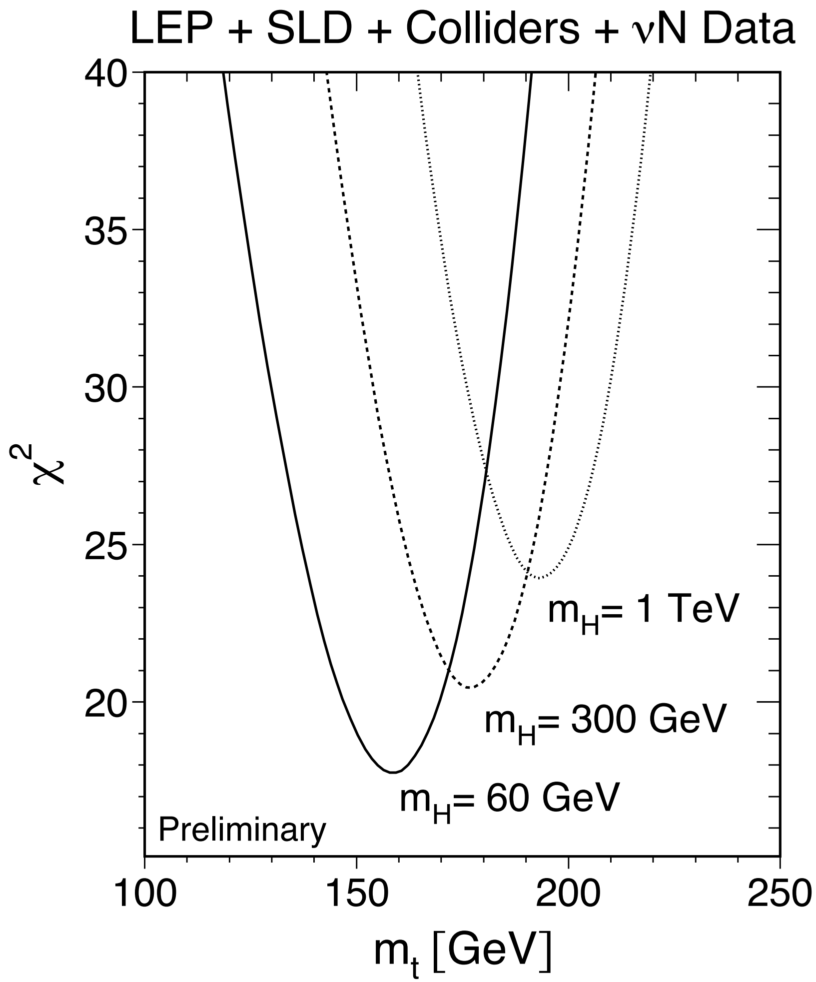


top discovery: *Tevatron 1995* $m_t = 180 \pm 12\,\mathrm{GeV}$

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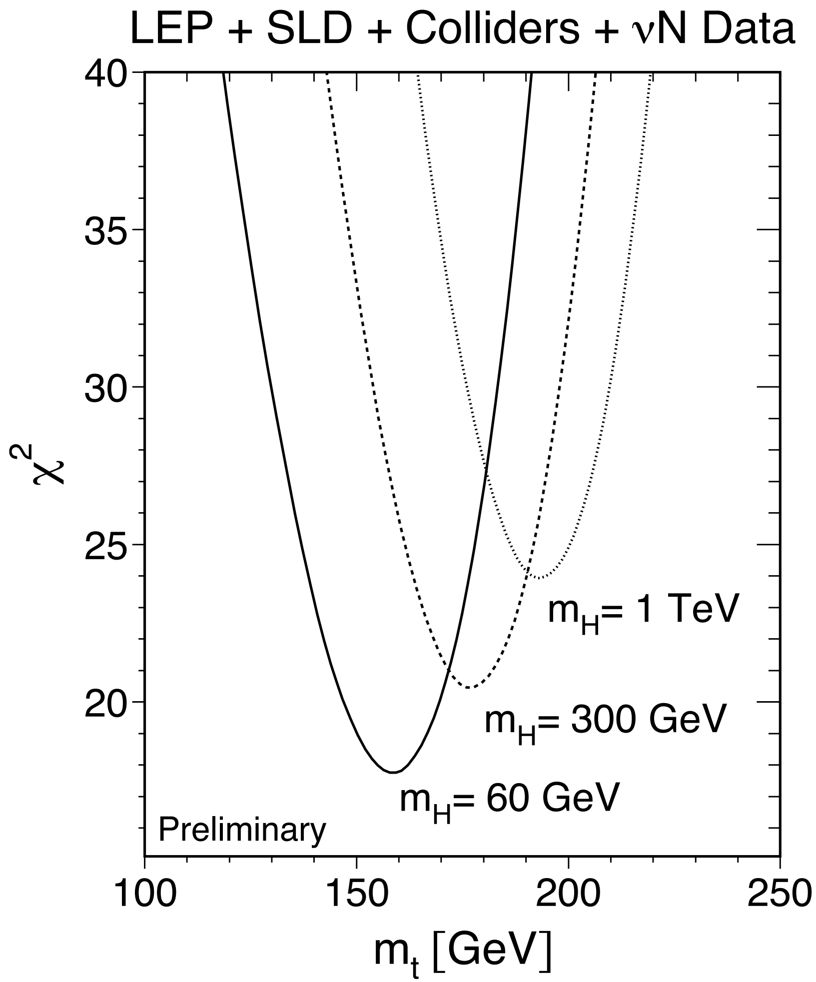
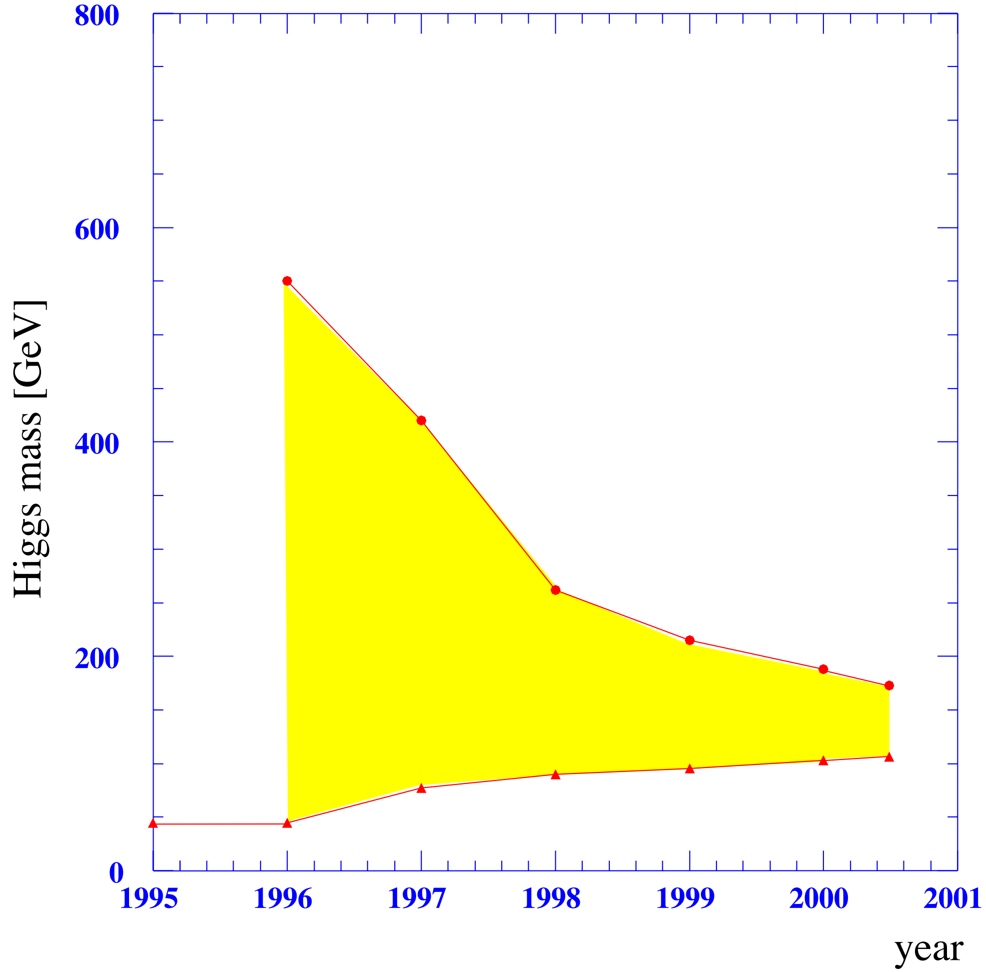



top discovery: *Tevatron 1995* $m_t = 180 \pm 12\,\text{GeV}$

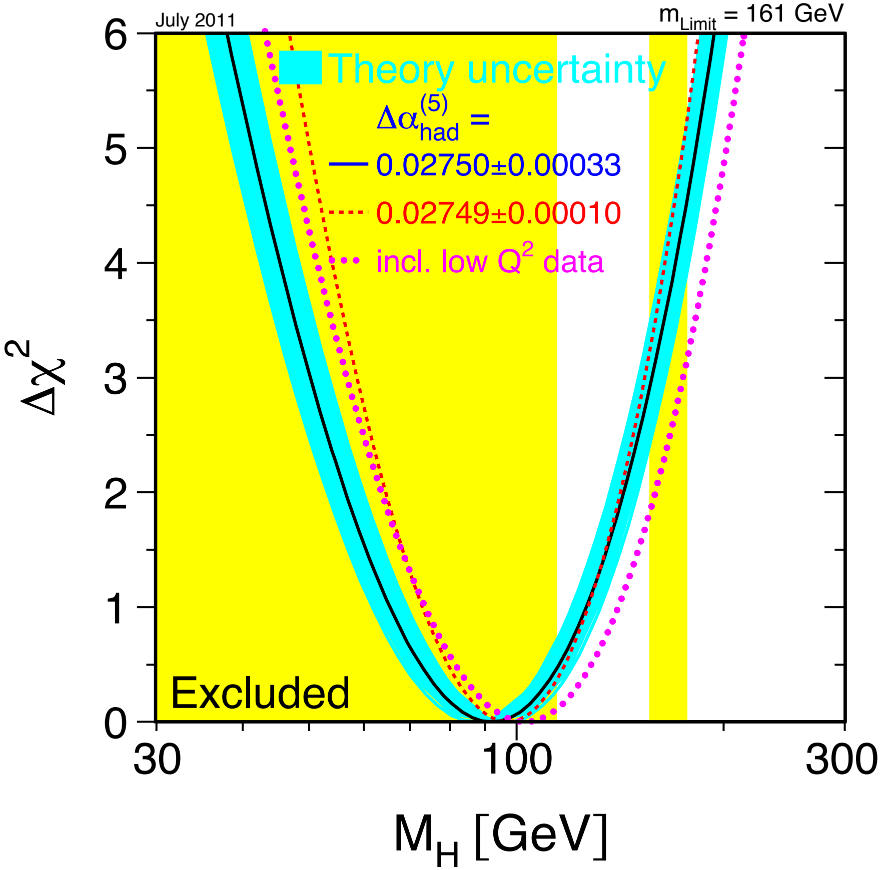
today: $m_t = 173.2 \pm 0.9\,\text{GeV}$

# The way to the Higgs boson

development of bounds from direct and indirect searches



# Global fit to the Higgs boson mass

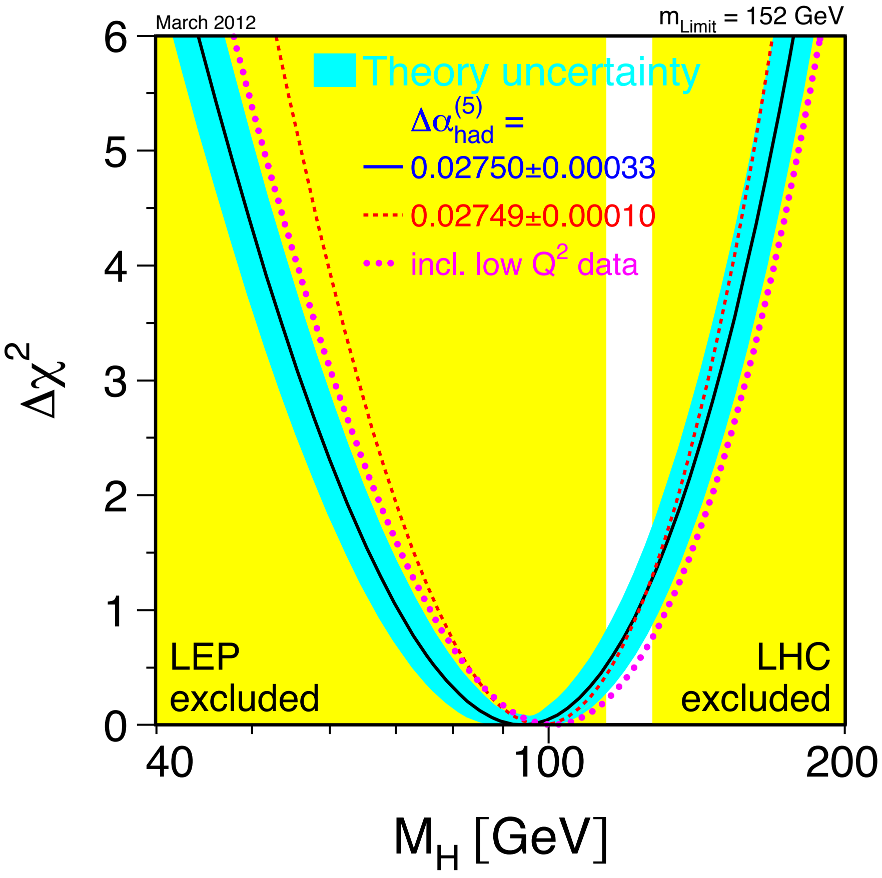



blueband: Theory uncertainty

“Precision Calculations
at the $Z$ Resonance”
CERN 95-03

*[Bardin, WH, Passarino (eds.)]*

$$M_{\rm H} < 161\ {\rm GeV} \quad ({\rm at}\ 95\%\ {\rm C.L.})$$




after the 2011 results

from the LHC

on the Higgs boson mass

$$M_{\mathrm{H}} < 152\ \mathrm{GeV} \quad (95\%\mathrm{C.L.})$$

$$M_{\mathrm{H}} = 94^{+29}_{-24}\,\mathrm{GeV}$$

# 5. Higgs bosons

Higgs potential: $$\boxed{V = -\mu^2 \left(\Phi^\dagger \Phi\right)^2 + \frac{\lambda}{4} \left(\Phi^\dagger \Phi\right)^4}$$

Higgs field in unitary gauge: $$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

$H(x)$ : *real scalar field, describes neutral spin-0 bosons*

minimum of $V$: $$v = \frac{2\mu}{\sqrt{\lambda}}, \quad M_H = \mu\sqrt{2}$$

$$\Rightarrow \quad \lambda = \frac{4\mu^2}{v^2} = \frac{2M_H^2}{v^2}$$

$$\boxed{V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4}$$

$M_H$ *is the only free parameter*

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$M_H$ *is the only free parameter*

general gauge: $$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \frac{1}{\sqrt{2}} \left[ v + H(x) + i\chi(x) \right] \end{pmatrix}$$

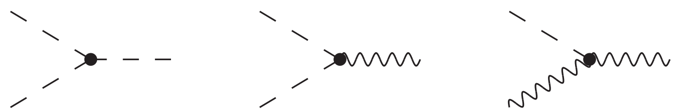
# gauge invariant Lagrangian of the Higgs sector

$$\mathcal{L}_\mathrm{H} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \qquad \text{with } D_\mu = \partial_\mu - \mathrm{i} g_2 \frac{\sigma^a}{2} W^a_\mu + \mathrm{i} \frac{g_1}{2} B_\mu$$

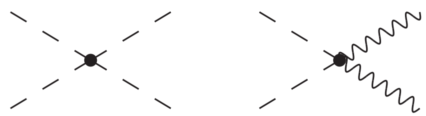
$$= (\partial_\mu \phi^+)(\partial^\mu \phi^-) - \frac{\mathrm{i}ev}{2s_\mathrm{W}} (W^+_\mu \partial^\mu \phi^- - W^-_\mu \partial^\mu \phi^+) + \frac{e^2 v^2}{4 s^2_\mathrm{W}} W^+_\mu W^{-,\mu}$$

$$+ \frac{1}{2} (\partial \chi)^2 + \frac{ev}{2 c_\mathrm{W} s_\mathrm{W}} Z_\mu \partial^\mu \chi + \frac{e^2 v^2}{4 c^2_\mathrm{W} s^2_\mathrm{W}} Z^2 + \frac{1}{2} (\partial H)^2 - \mu^2 H^2$$

$+$ (trilinear $SSS$, $SSV$, $SVV$ interactions)



$+$ (quadrilinear $SSSS$, $SSVV$ interactions)



$\Rightarrow$ **H-V-V gauge interactions, V=W and Z**

## gauge invariant Lagrangian of the Higgs sector

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$$+ \frac{1}{2}(\partial\chi)^2 + \frac{ev}{2c_{\mathrm{W}} s_{\mathrm{W}}} Z_\mu \partial^\mu \chi + \frac{e^2 v^2}{4 c_{\mathrm{W}}^2 s_{\mathrm{W}}^2} Z^2 + \frac{1}{2}(\partial H)^2 - \mu^2 H^2$$

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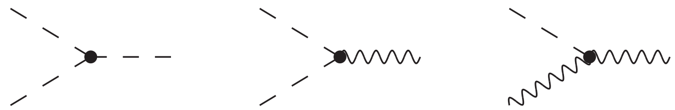
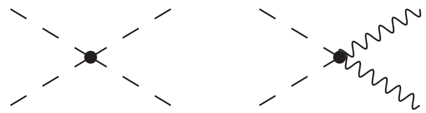


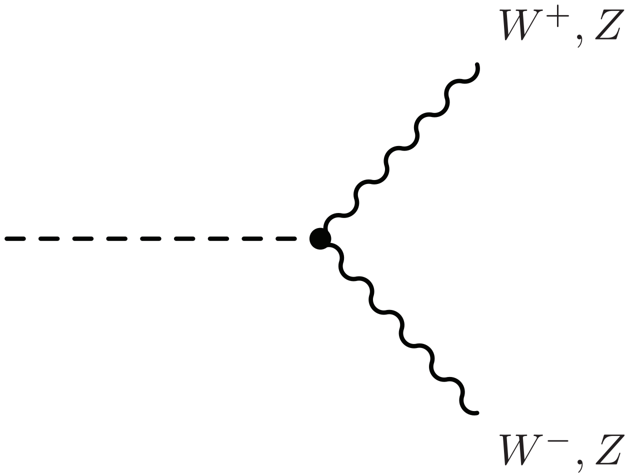
$+$ (quadrilinear $SSSS$, $SSVV$ interactions)

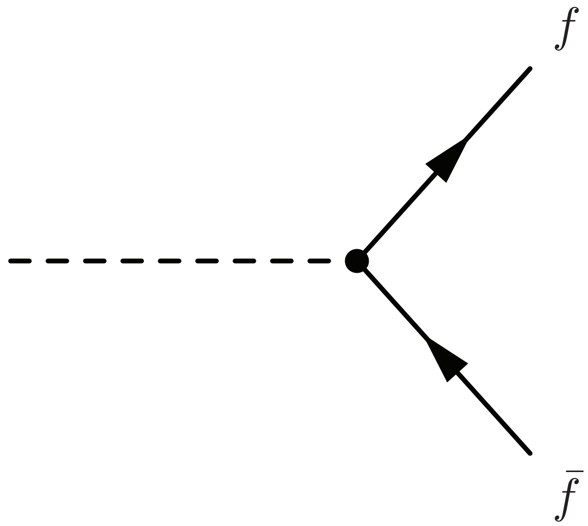


**$\Rightarrow$ H-V-V gauge interactions, V=W and Z**

$$\mathcal{L}_{\mathrm{Yuk}} = -\sum_f \left(m_f + \frac{m_f}{v} H\right) \overline{\psi}_f \psi_f + \cdots (f f \chi, \phi^\pm)$$

**$\Rightarrow$ H-f-f Yukawa interactions**



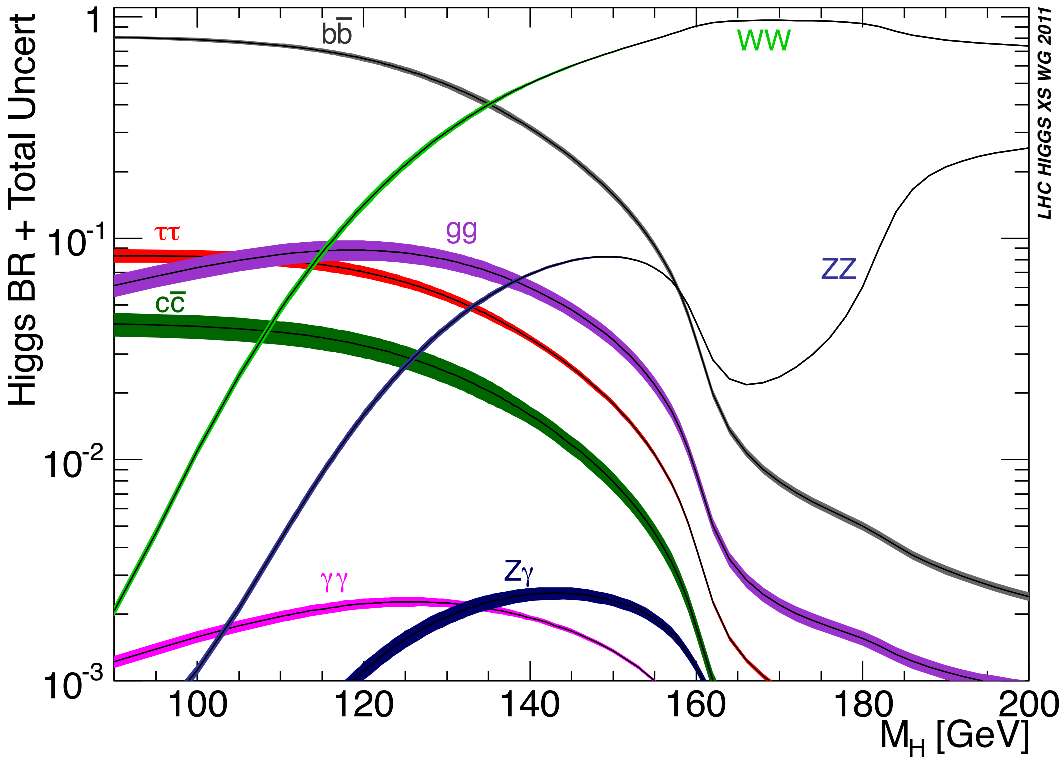

$$g_2 M_W \,, \quad g_2 \frac{M_Z}{c_W} \qquad\qquad \frac{m_f}{v} \;=\; \frac{g_2\, m_f}{2M_W}$$

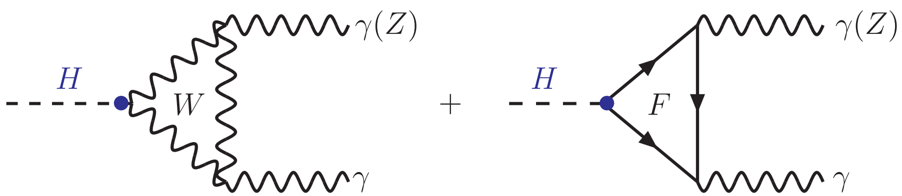
$$\Gamma(H \to f\bar{f}) \;=\; N_c \frac{G_F M_H}{4\pi\sqrt{2}}\, m_f^2\, \beta_f^3, \quad N_C = 3\,(1) \text{ for quarks}\,(\text{leptons})$$

$$\Gamma(H \to VV) \;=\; \frac{G_F M_H^3}{8\pi\sqrt{2}}\, F(r)\, \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

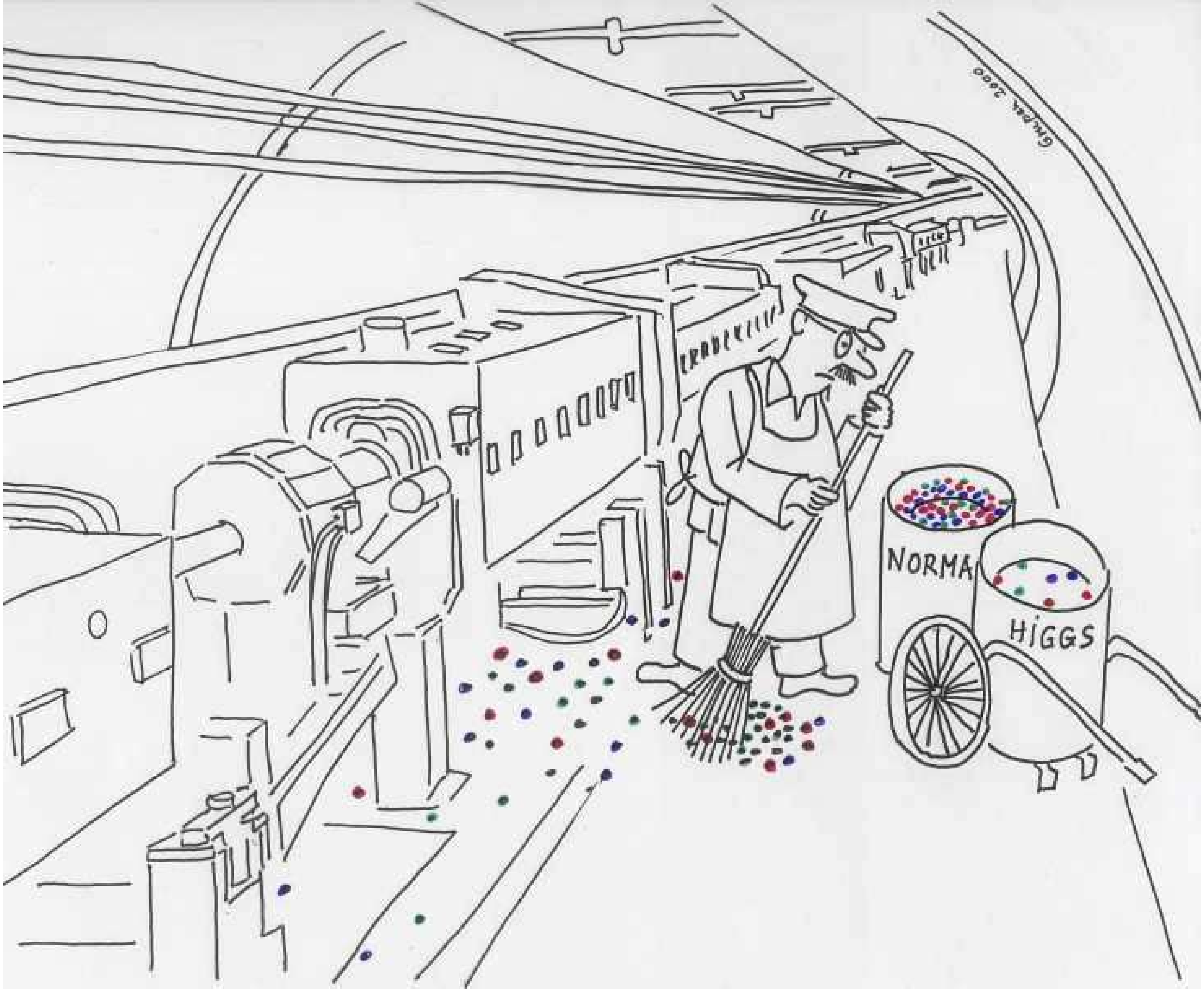
# Higgs boson decay channels

*branching ratios* $BR(H \to X) = \frac{\Gamma(H \to X)}{\Gamma(H \to \text{all})}$

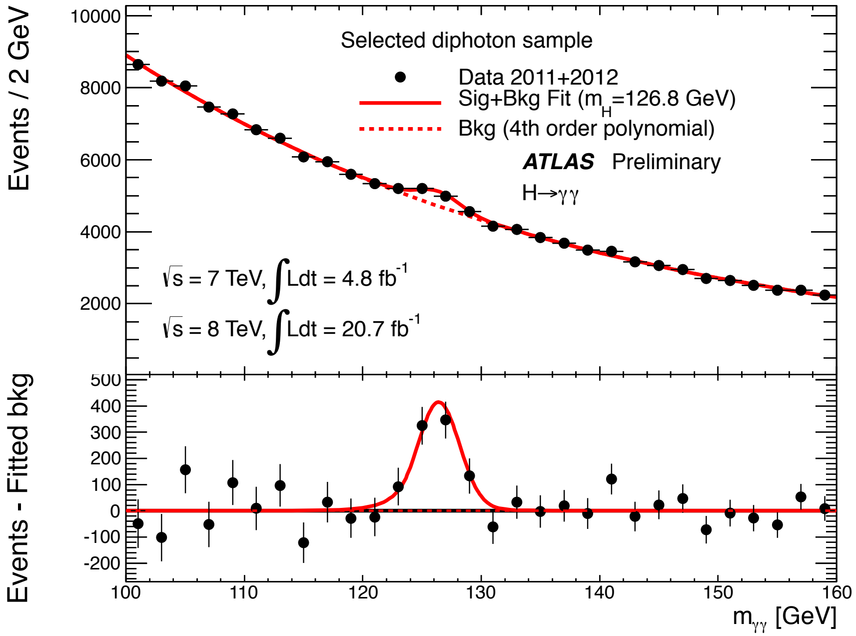


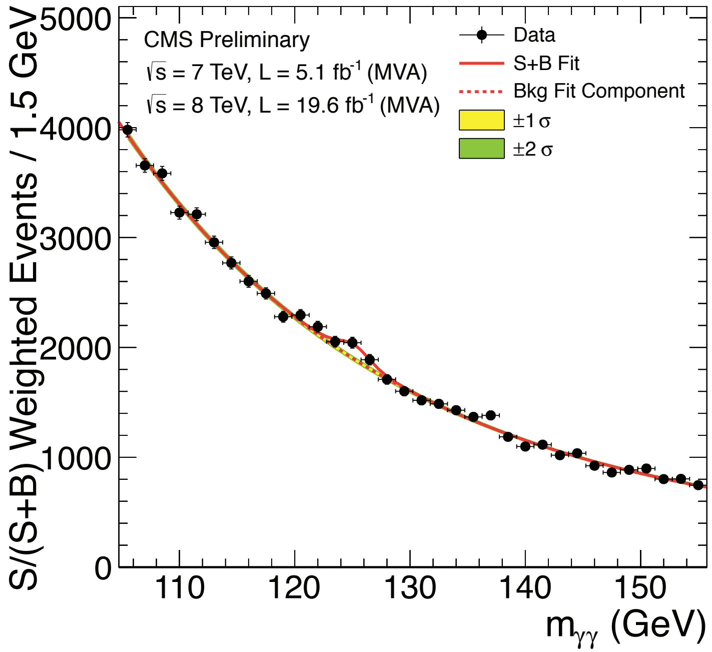



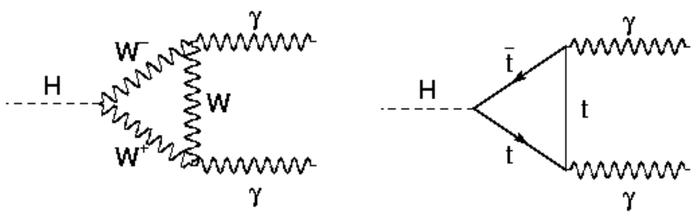

*loop-induced (rare) decays*


NORMA
HIGGS

# $H \to \gamma\gamma$

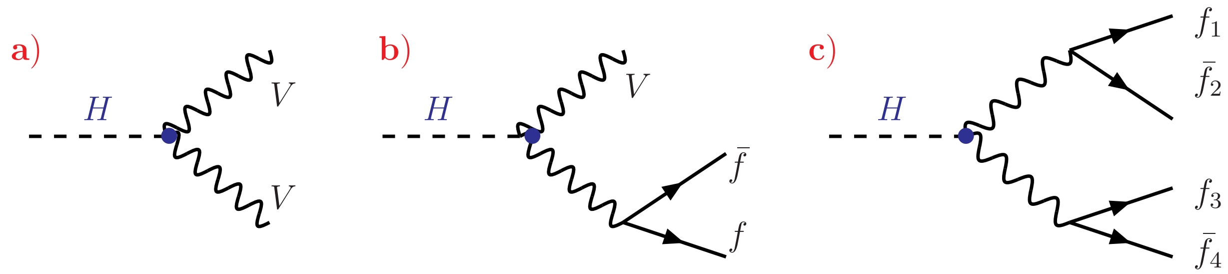


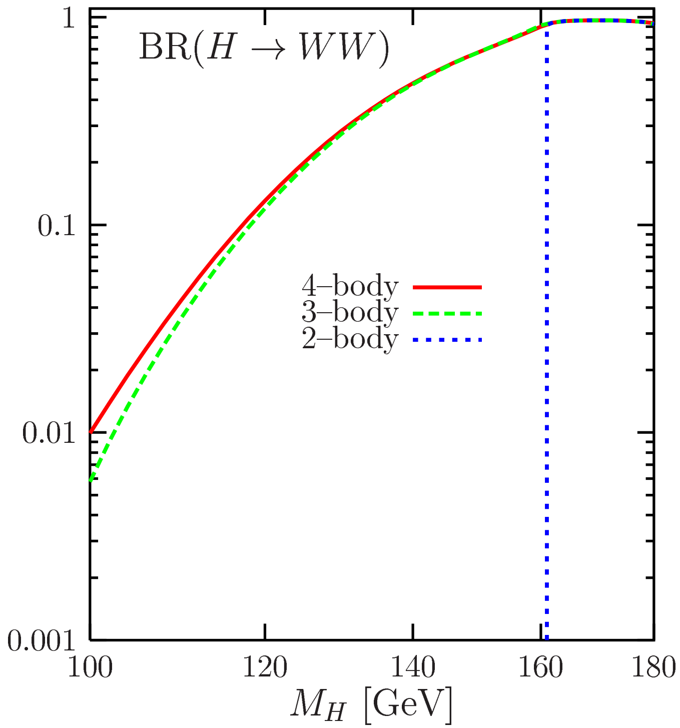



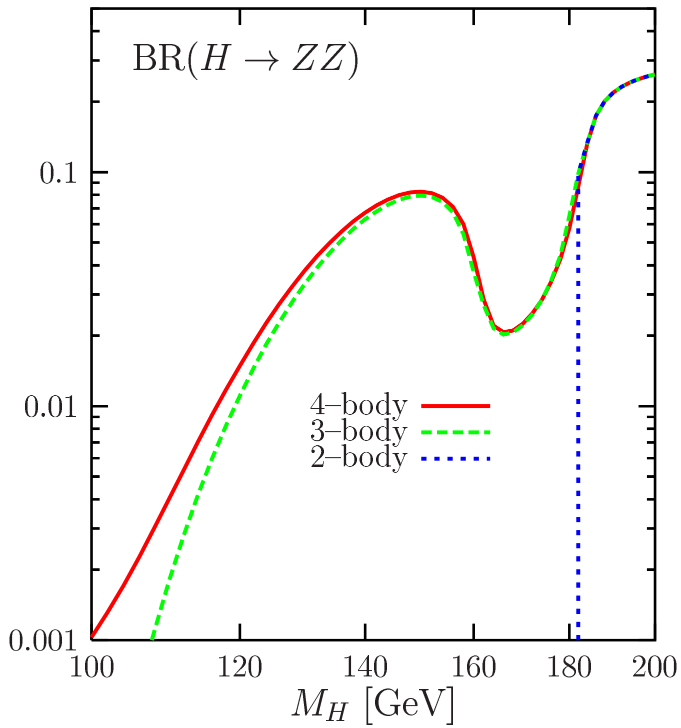



# Higgs decays into 4 fermions

also below $VV$ threshold with one or two V off-shell



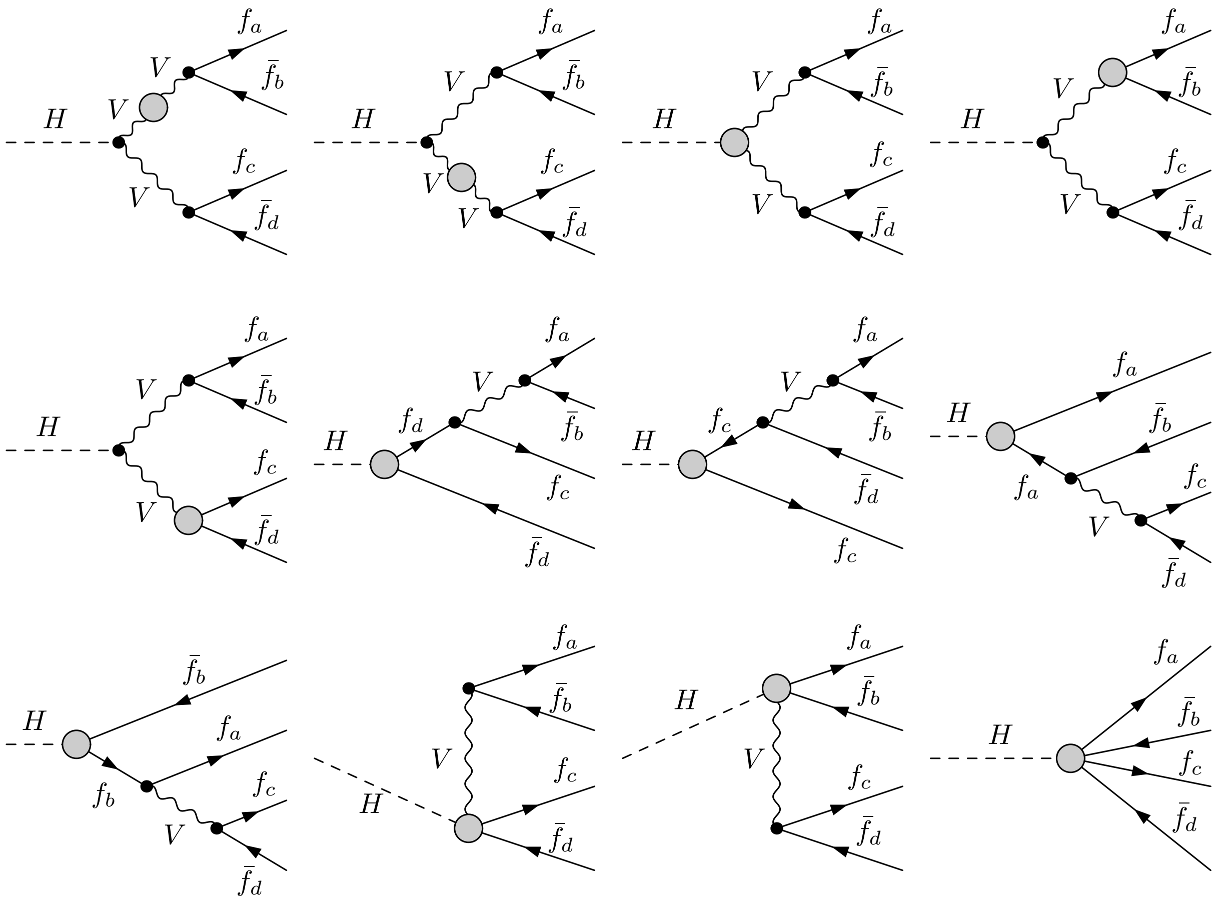




*[Djouadi]*

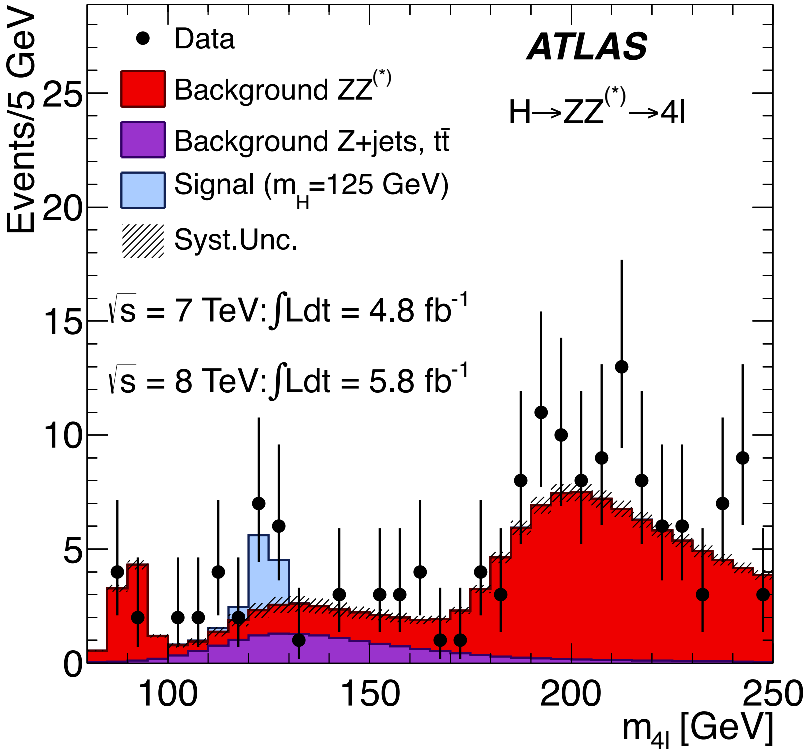
# $H \to VV \to 4f$

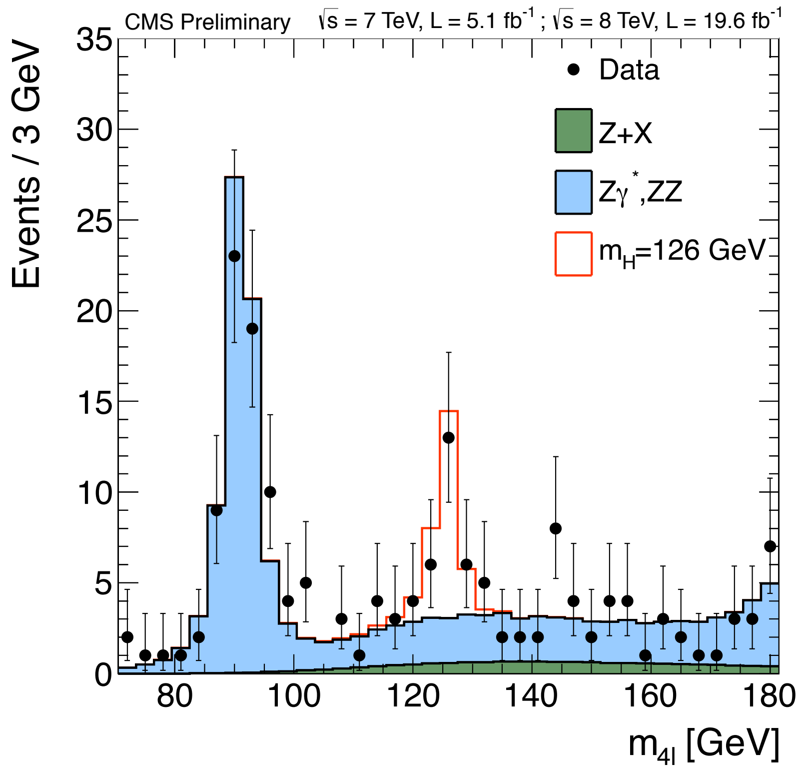
needs also background pocesses + h.o.

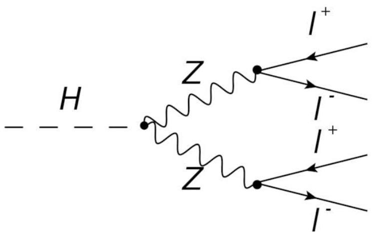



*Bredenstein et al.* $\rightarrow$ `PROPHECY`

$$H \to ZZ \to l^+l^- \; l^+l^-$$



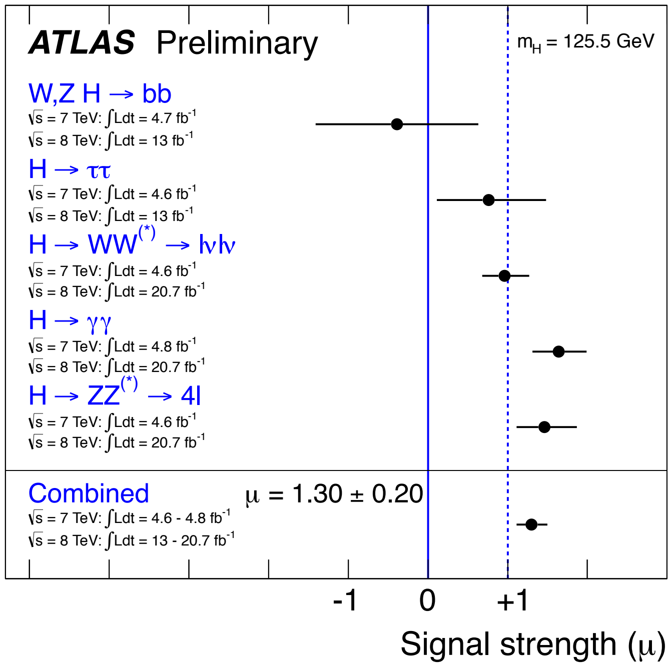

signal + background

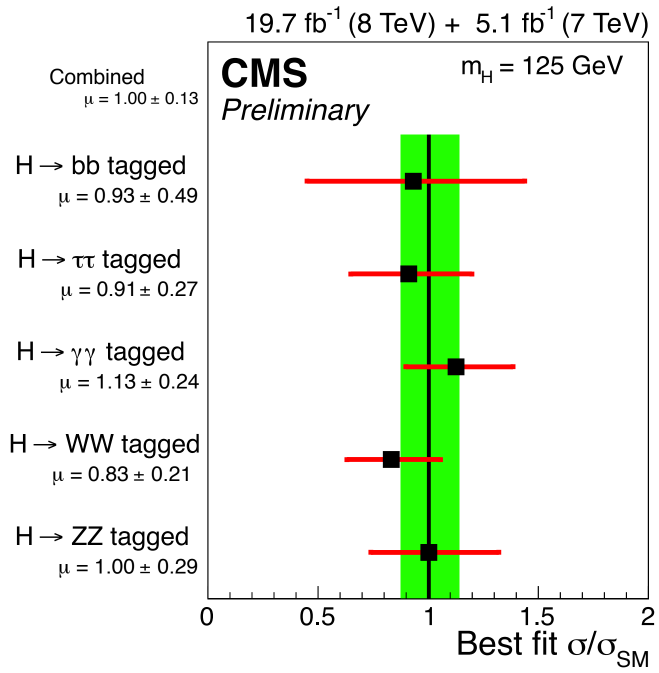
# the Higgs – or not the Higgs?

*CERN, July 2012*


*Oviedo, October 2013*

# A Standard Model Higgs boson at the LHC?



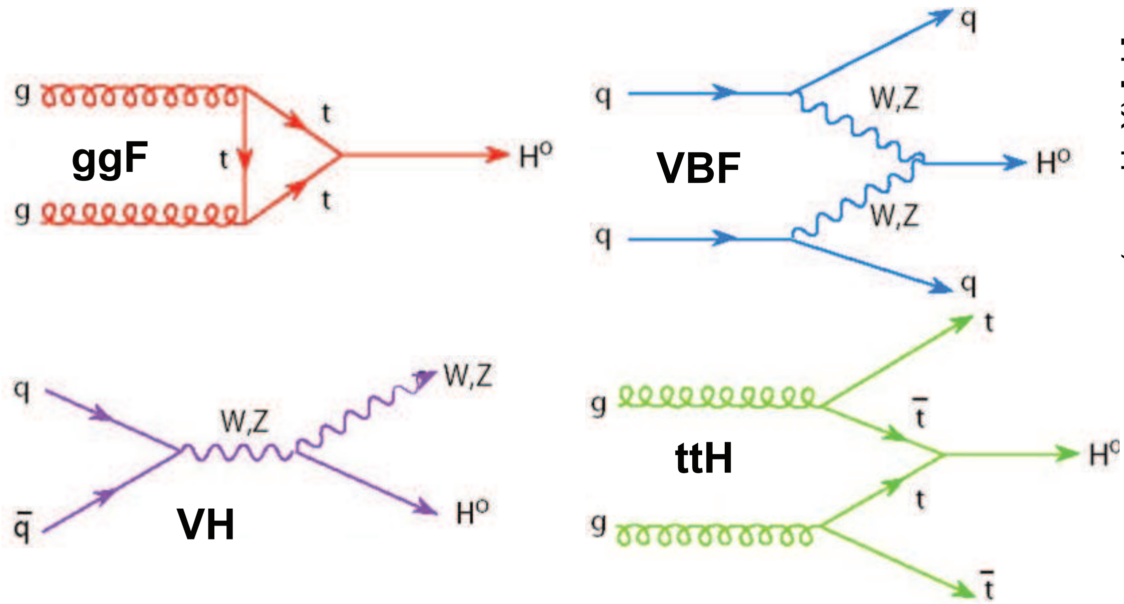



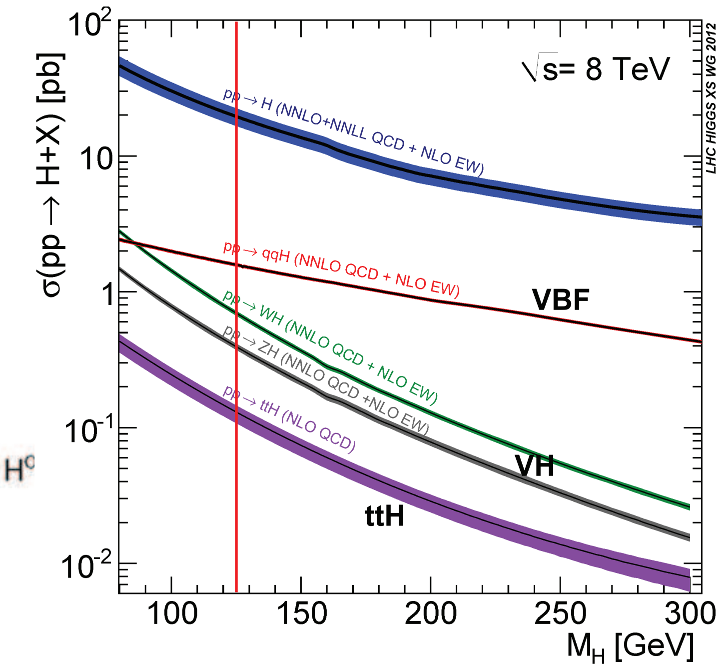

*new:* $\mu_{\gamma\gamma} = 1.17 \pm 0.27$

| **H mass ATLAS (GeV)** | **H mass CMS (GeV)** |
| --- | --- |
| $\mathbf{125.4 \pm 0.4 \pm 0.2}$ | $\mathbf{125.0 \pm 0.3 \pm 0.2}$ |

Theory: $\boldsymbol{\sigma(pp \to H) \cdot BR(H \to X)}$

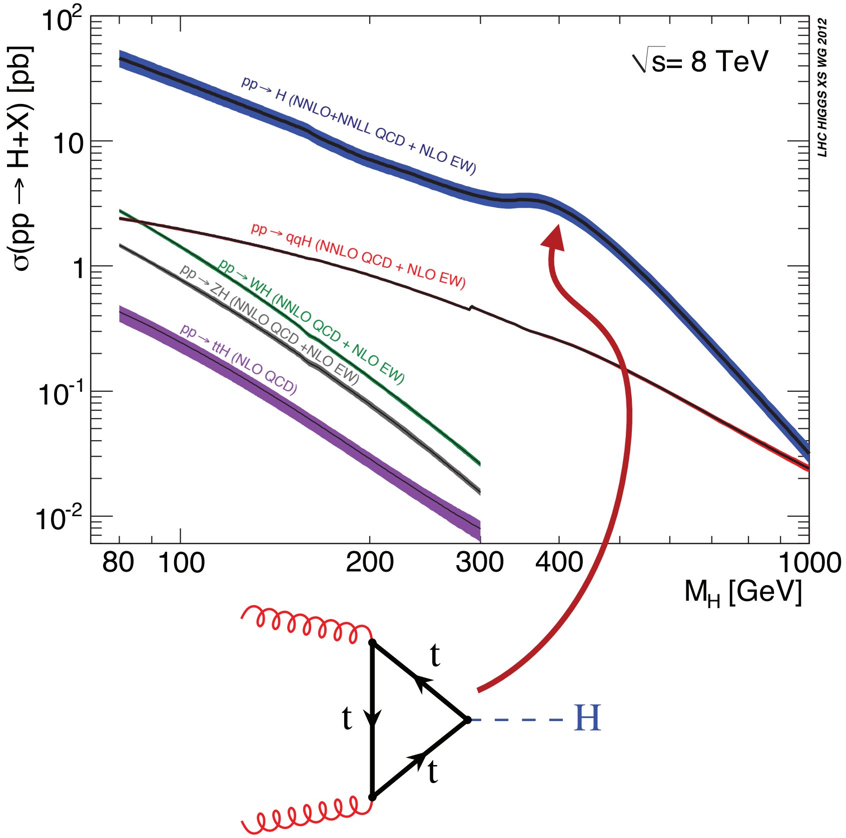
# Higgs production at the LHC




*Handbook of Higgs Cross sections,*
*arXiv:1101.0593, arXiv:1201.3084*

# cross section for Higgs-boson production – theory




NLO: Spira, Djouadi, Graudenz, Zerwas '91, '93
Dawson '91

~80%

NNLO: RH, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, v. Neerven '03

~30%

Resummation:

Catani, de Florian, Grazzini, Nason '02
Ahrens, Becher, Neubert, Zhang '08

~10%

Electroweak:

Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94

~5%

Mixed EW/QCD:

Anastasiou, Boughezal, Petriello '09

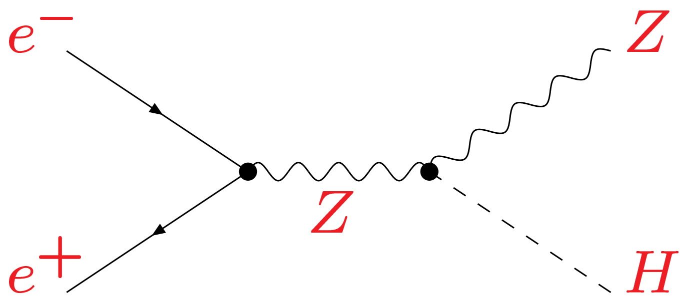
Fully differential NNLO:

Anastasiou, Melnikov, Petriello '04
Catani, Grazzini '07

*[courtesy R. Harlander]*

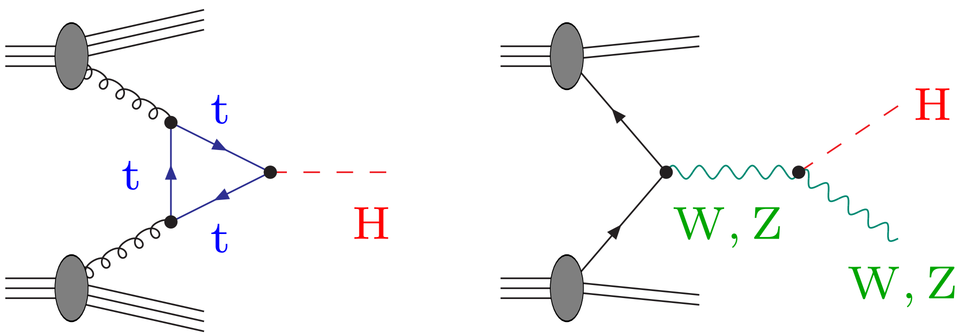
**other colliders:**

## Higgs production at LEP:




*excluded* $M_H < 114\,\mathrm{GeV}$

## Higgs production at the Tevatron:



## Theoretical bounds on Higgs boson mass

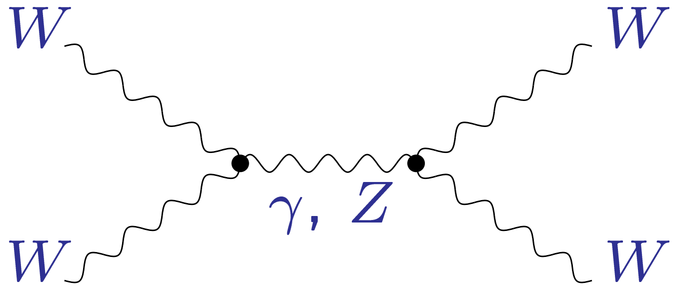
- unitarity $\rightarrow$ upper bound
- Landau pole $\rightarrow$ upper bound
- vacuum stability $\rightarrow$ lower bound

# unitarity

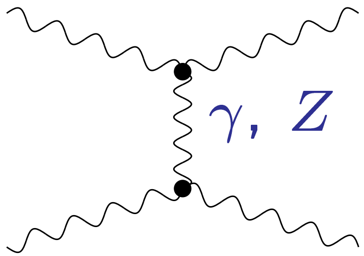
scattering of longitudinally polarized $W$ bosons:

$$W_L W_L \to W_L W_L$$

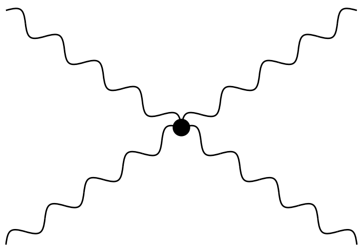
$\mathcal{M}_V =$




$+$

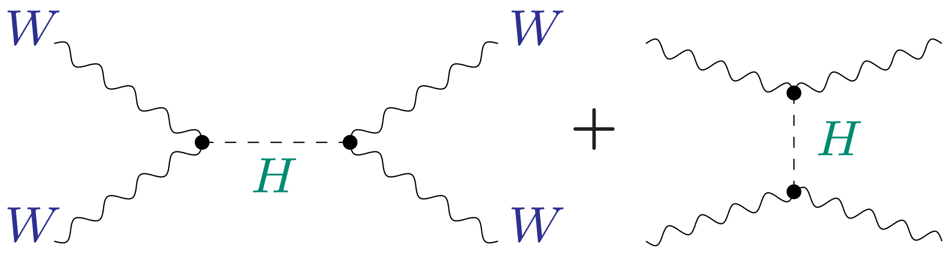



$+$



$$= -g^2 \frac{E^2}{M_{\mathrm{W}}^2} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

Extra contribution from scalar particle:

$\mathcal{M}_S =$ 



$$= g^2_{WWH} \frac{E^2}{M_W^4} + \mathcal{O}(1) \qquad \text{for } E \to \infty$$

$$\mathcal{M} \quad = \mathcal{M}_V + \mathcal{M}_S$$

$\Rightarrow$ terms with bad high-energy behavior cancel for

$$g_{WWH} = g\, M_W$$

for $s >> M_W^2$, with $t = -\frac{s}{2}\,(1 - \cos\theta)$,

$$\mathcal{M} \approx \frac{M_H^2}{v^2} \left( 2 + \frac{M_H^2}{s - M_H^2} + \frac{M_H^2}{t - M_H^2} \right)$$

partial wave expansion:

$$\mathcal{M}(s,t) \;=\; 8\pi \sum_{l=0}^{\infty} (2l+1)\, P_l(\cos\theta)\, a_l$$

unitarity condition: $|a_l| < 1$

project on $l = 0$ partial wave:

$$a_0 \;=\; \frac{1}{16\pi} \int_{-1}^{1} d\cos\theta\; \mathcal{M}(s,t)$$

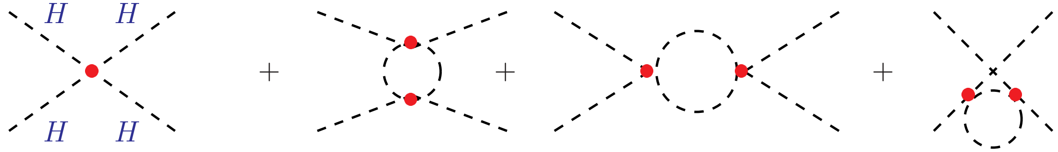
$$\;=\; \frac{M_H^2}{8\pi v^2} \left[ 2 + \frac{M_H^2}{s - M_H^2} - \frac{M_H^2}{s} \log\left(1 + \frac{s}{M_H^2}\right) \right]$$

$$\;\approx\; \frac{M_H^2}{8\pi v^2} \quad \text{for} \quad s >> M_H^2$$

$$\boxed{a_0 < 1 \quad \Rightarrow \quad M_H < 872\,\mathrm{GeV}}$$

# Landau pole

Higgs self coupling is scale dependent, $\lambda(Q)$




variation with scale $Q$ described by RGE

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

solution:

$$\lambda(Q) = \frac{\lambda(v)}{1 - \frac{3}{4\pi^2}\lambda(v)\log\frac{Q^2}{v^2}} \quad \text{with} \quad \lambda(v) = \frac{M_H^2}{2v^2}$$

diverges at scale $Q = \Lambda_C$ (Landau pole)

$$\Lambda_C = v\,\exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

self-coupling diverges at

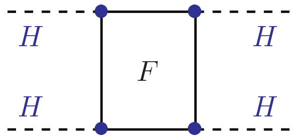
$$\Lambda_C = v \, \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

maximum Higgs mass by condition $\Lambda_C > M_H$

$$\Rightarrow \quad M_H < 800\,\mathrm{GeV}$$

# vacuum stability

top-quark Yukawa coupling $g_t \sim m_t$ contributes to the running Higgs self coupling $\lambda(Q)$ through top loop $\sim g_t^4$




variation with scale $Q$ described by RGE

$$Q^2 \frac{d\lambda}{dQ^2} = \frac{3}{4\pi^2} \left( \lambda^2 - \frac{m_t^4}{v^4} \right)$$

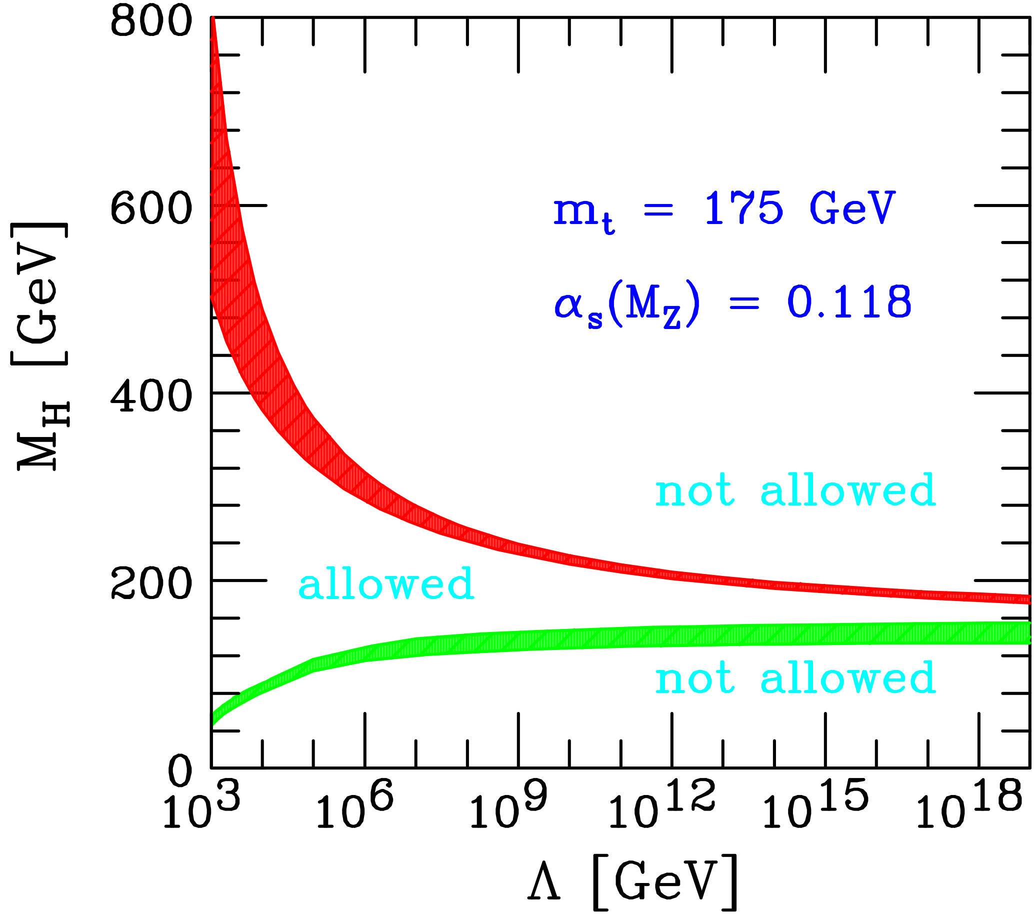
approximate solution:

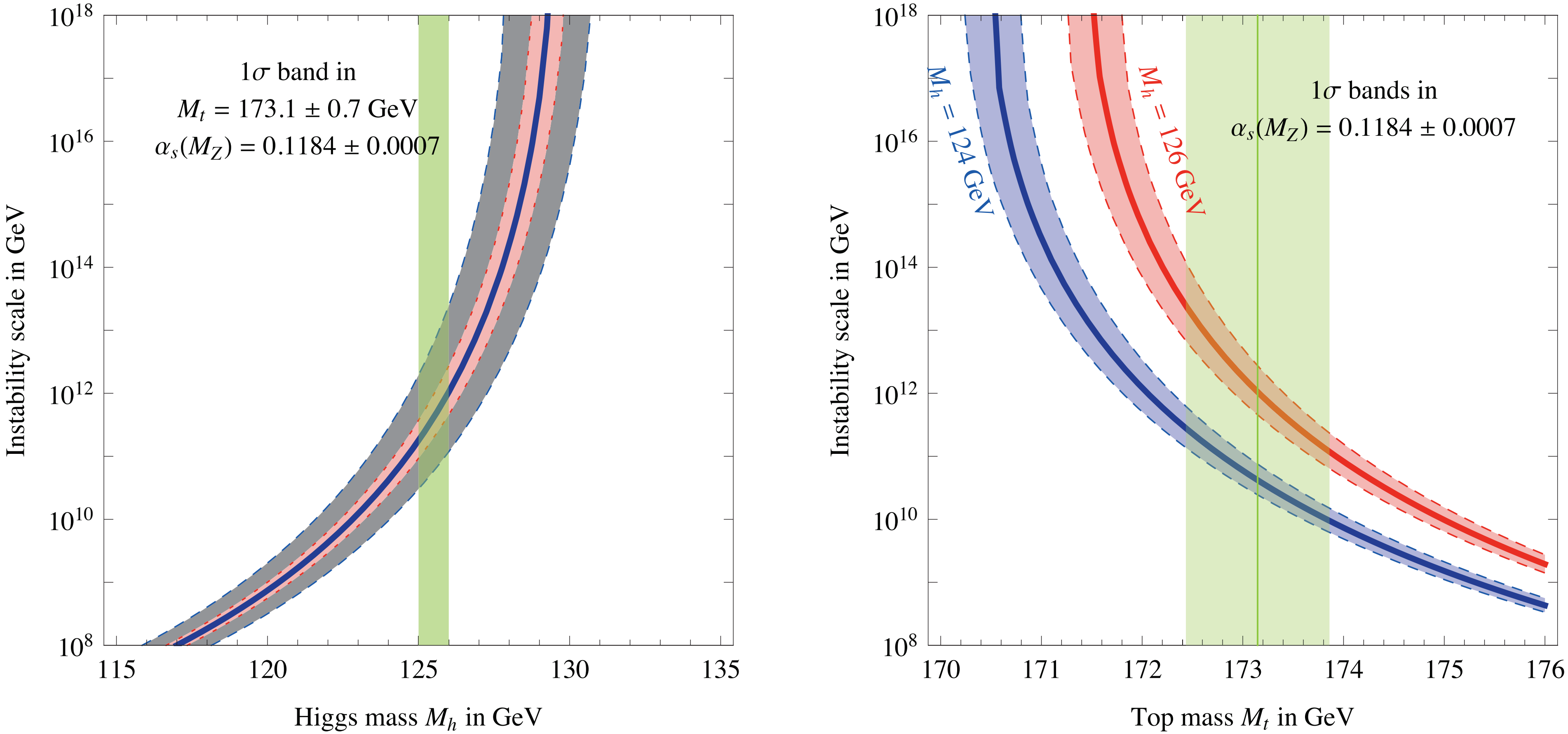
$$\lambda(Q) = \lambda(v) - \frac{3 m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

$\lambda(Q) < 0$ for $Q > \Lambda_C$ $\rightarrow$ vacuum not stable

high value of $\Lambda_C$ needs $M_H$ large enough combined effects:

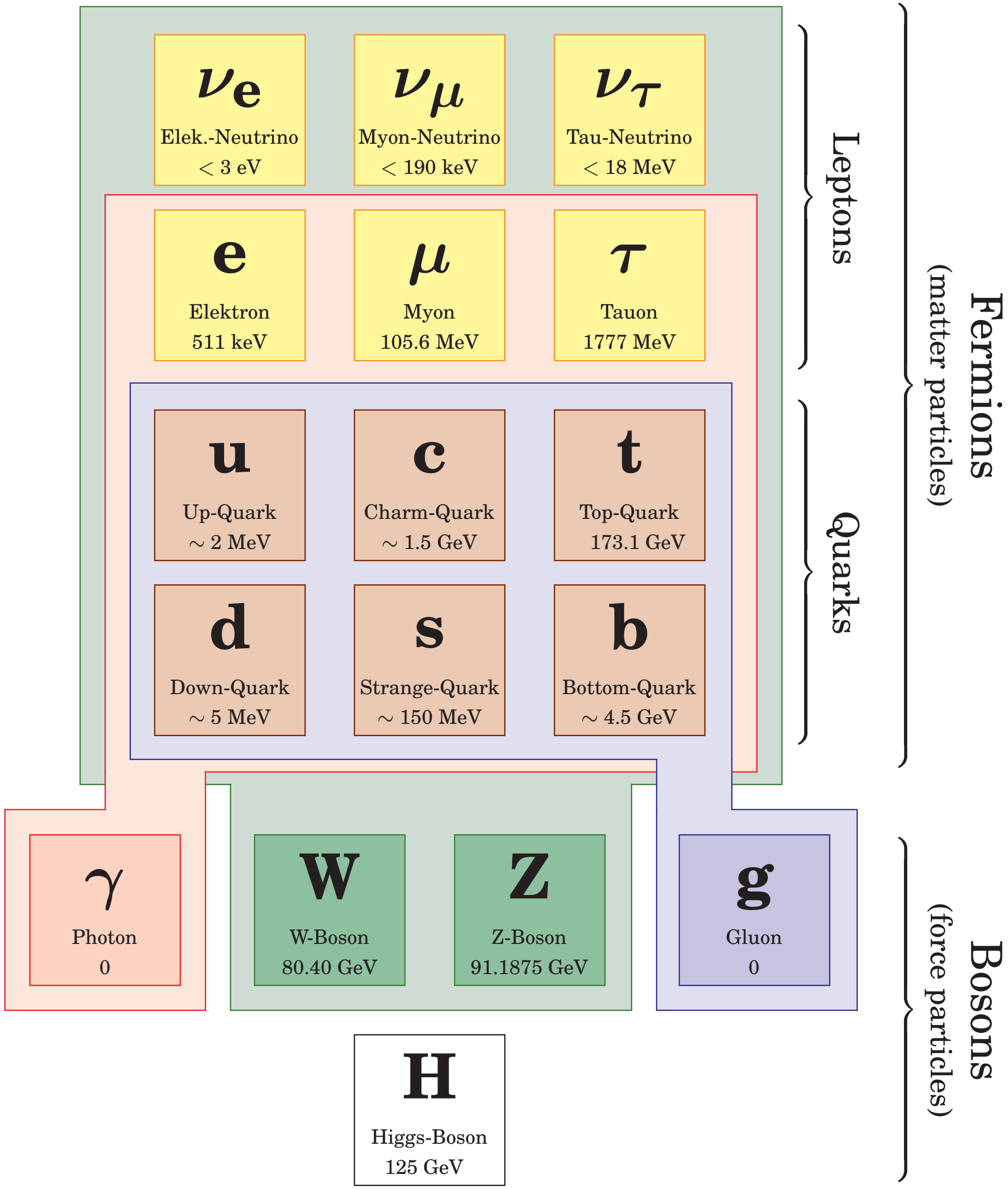
$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2} \left(12\lambda^2 - 3\, g_t^4 + 6\, \lambda\, g_t^2 \, + \cdots \right)$$





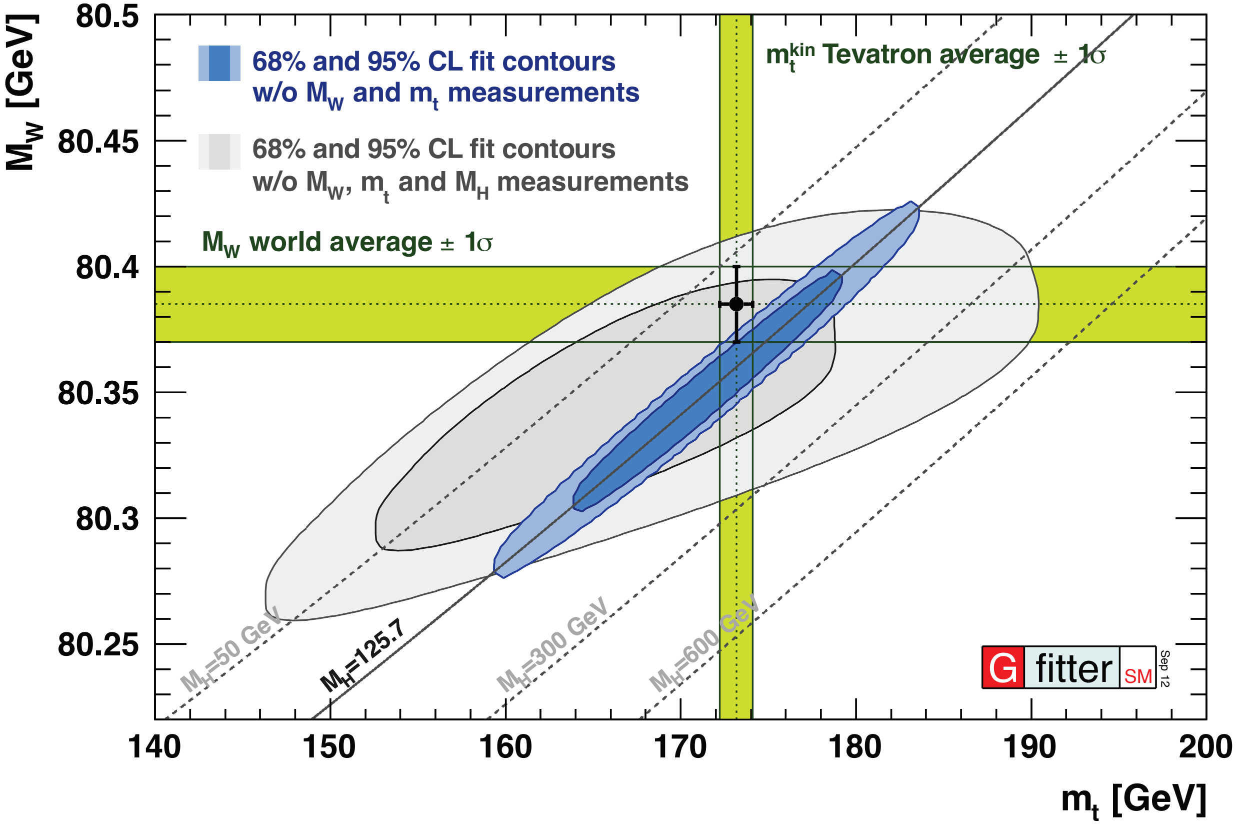

*[Degrassi et al. 2012]*

# Status of the Standard Model



SM input now completey determined $\Rightarrow$ PO uniquely predicted

| | theo | exp |
|---|---|---|
| $\sin^2\theta_{\mathrm{eff}}$ | $0.23152 \pm 0.00005 \pm 0.00005$ | $0.23153 \pm 0.00016$ |
| $M_W$ (GeV) | $80.361 \pm 0.006 \pm 0.004$ | $80.385 \pm 0.015$ |



# The success of the Standard Model

- impressive confirmation by a huge data sample from low to high energies, no significant deviations
- quantum effects have been established at many $\sigma$
- perfect indirect and direct determination of the top quark
- now being repeated for the Higgs boson
- new particle around 126 GeV strong candidate for the Higgs boson
- if confirmed: Standard Model closed

Happy End of a successful story ?

# Shortcomings of SM

- no mass terms for neutrinos [introduce $\nu_R$ $\ldots$ ]

- hierarchy problem $v \ll M_{\mathrm{Pl}}, \quad M_H \ll M_{\mathrm{Pl}}$
- large number of free parameters $g_1,\ g_2,\ v,\ m_f,\ V_{\mathrm{CKM}}$
- no further unification of forces
- missing link to gravity

- nature of dark matter?
- baryon asymmetry of the universe?

- next steps with upgraded LHC
  – confirm the Higgs boson properties
  – check versus electroweak precision measurements
  – or find deviations, new structures:
    - more Higgs bosons (doublets, singlet, .. )
    - supersymmetry (minimal or non-minimal)
    - new strong sector, substructure
    - . . .


RESEARCH INSTITUTE
UNANSWERED QUESTIONS
UNQUESTIONED ANSWERS
S. Harris

# extra slides

## few observables with not-so-good agreement

- in general, SM is in overall agreement with data
- yet a few quantities prefer to stand a bit apart ($\sim 3\sigma$)
  - the forward-backward asymmetry for b quarks, $A_{\rm FB}^{b\bar{b}}$ at the Z peak
  - the anomalous magnetic moment of the muon
  - the forward-backward asymmetry for top quarks at the Tevatron, $p\bar{p} \to t\bar{t}$

no conclusive situation

SM Higgs:

- $\lambda\, H^4$ term ad hoc
- Higgs boson mass: free parameter $\sim \sqrt{\lambda}$
- no a-priori reason for a light Higgs boson

SM Higgs:

- $\lambda\, H^4$ term ad hoc
- Higgs boson mass: free parameter $\sim \sqrt{\lambda}$
- no a-priori reason for a light Higgs boson

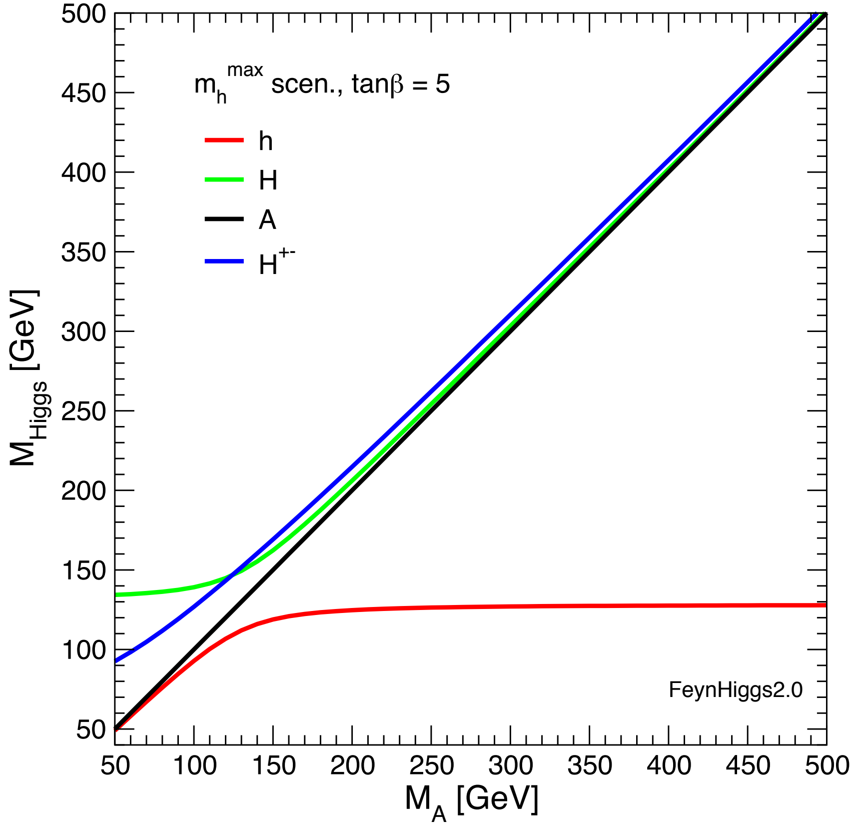
SUSY Standard Model avoids these questions

$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

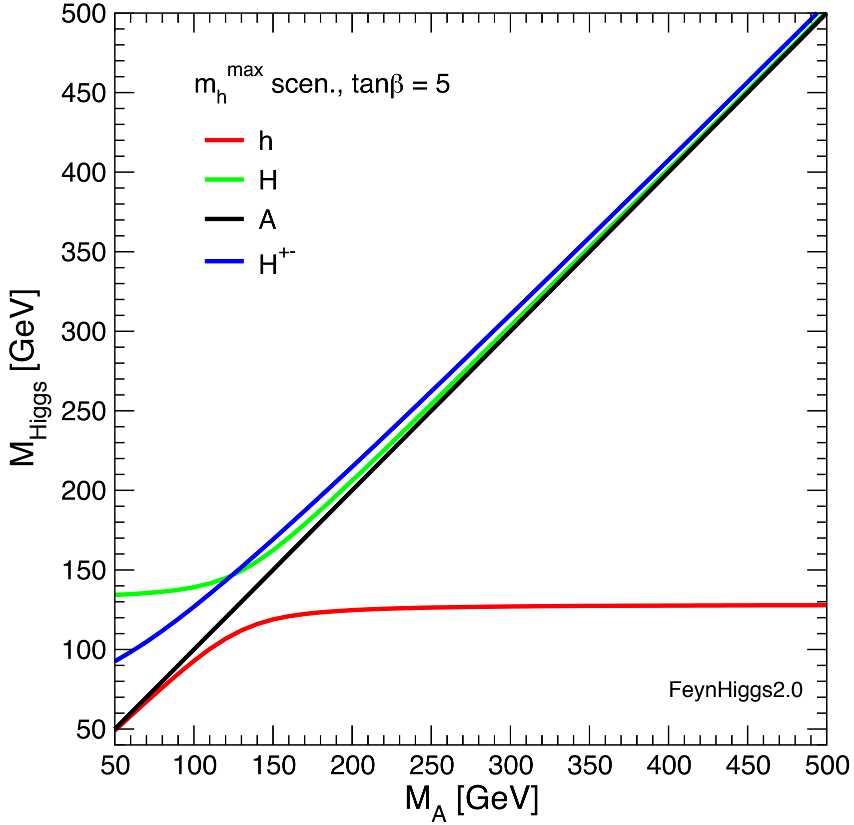
$$\text{couples to } u \qquad\qquad \text{couples to } d$$

- SUSY gauge interaction $\rightarrow$ $H^4$ terms
- self coupling remains weak

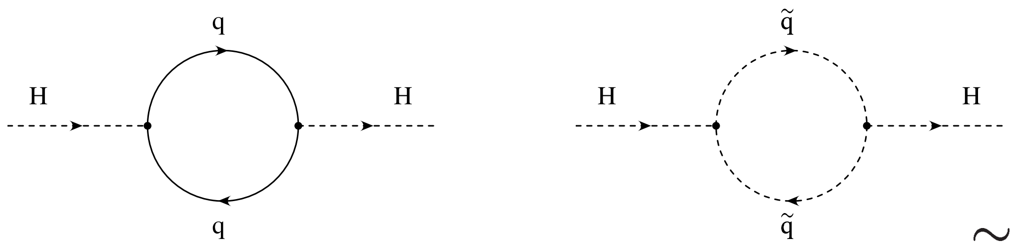
# spectrum of Higgs bosons in the MSSM: $h^0,\ H^0,\ A^0,\ H^\pm$



# spectrum of Higgs bosons in the MSSM: $h^0$, $H^0$, $A^0$, $H^\pm$



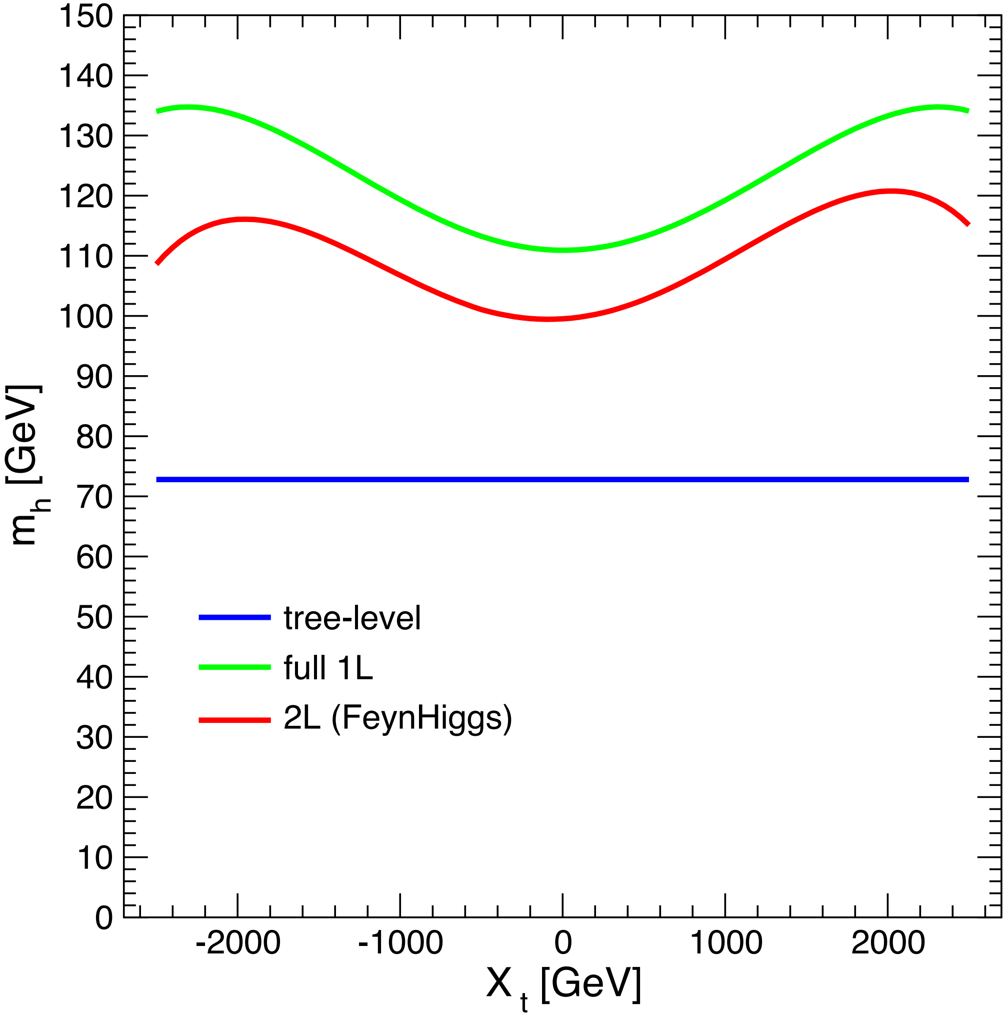

$m_h^0$ strongly influenced by quantum effects, e.g. $t$, $\tilde{t}$




$\sim \alpha_t$

# sensitivity to mass/mixing parameters

$m_{h^0}$ prediction at different levels of accuracy:



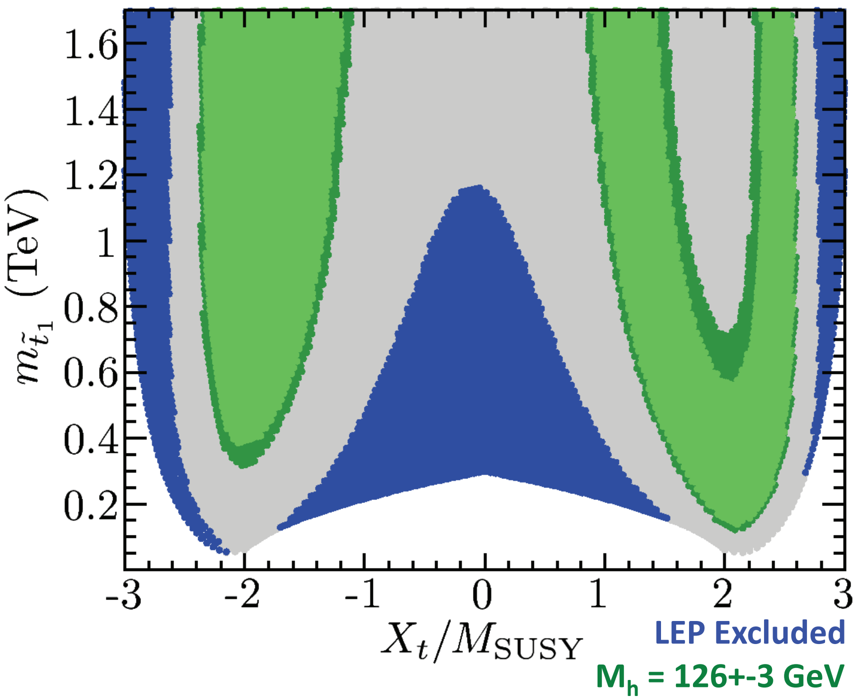

$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1$ TeV, $\quad m_{\tilde{g}} = 800$ GeV

$X_t$ : top-squark mixing parameter

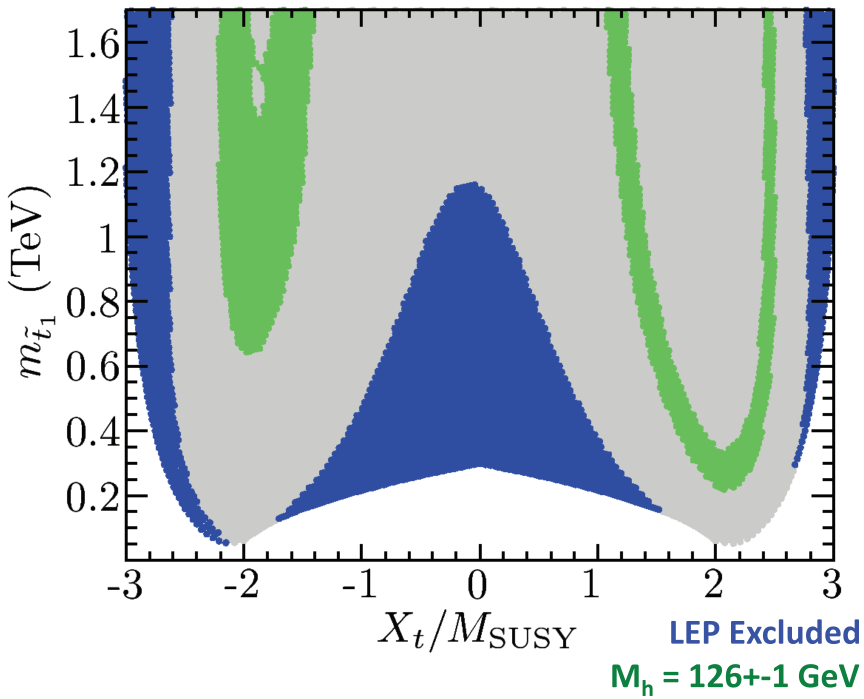
$$\mathrm{X_t = A_t - \mu \cot\beta}$$

# allowed region for top-squark mass and mixing

Theory uncertainties included




No theory uncertainties




*[Heinemeyer,Staal, Weiglein '12]*

compatible with light top-squarks

ongoing experimental search