Standard Model Theory

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on Fundamental Physics

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Outline

- The Standard Model in the pre-Higgs era
- The Standard Model in the Higgs era
- The status of Standard Model
- Future prospects

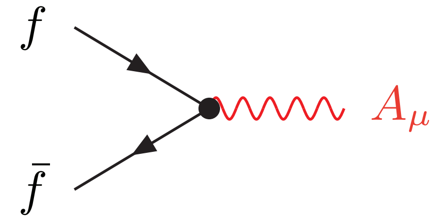
the rise of the EW Standard Model

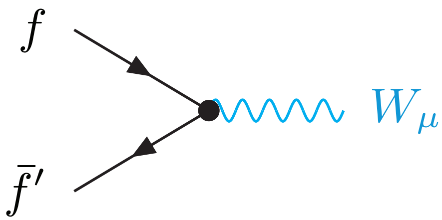
- the symmetry group SU(2) $\times$ U(1)
  – discovery of neutral currents 1973
- the W and Z bosons
  – discovery 1983 at SPS (CERN)
- the coupling structure from local gauge invariance
  – precise measurements at LEP/SLC 1989 - 2000
- the Higgs mechanism and Yukawa interactions
  – top discovery at Tevatron 1995
  – Higgs discovery at LHC 2012

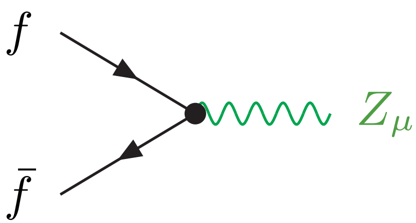
precision physics: major role in establishing the SM
restricting BSM physics

interactions from gauge-symmetric Lagrangian

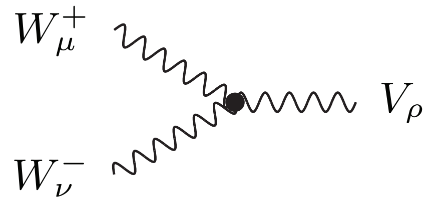
fermion–vectorbosons

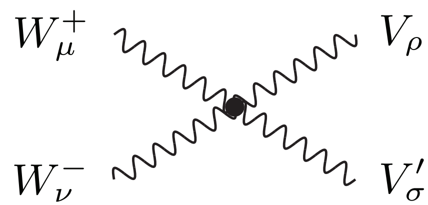






vectorboson self interactions



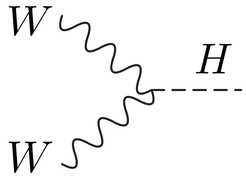


coupling constants: $g_{\text{em}} = e, \quad g_{\text{weak}} = e/\sin\theta_{\text{w}}$

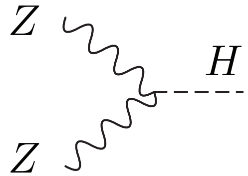
group entries: isospin I_3^f, charge Q_f

interactions from symmetry-breaking Lagrangian

WWH and ZZH couplings

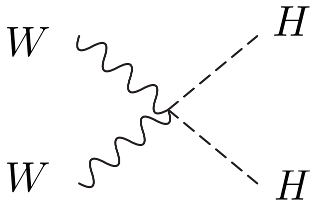


$$2i\frac{m_W^2}{v}g^{\mu\nu}$$

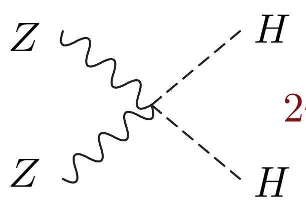


$$2i\frac{m_Z^2}{v}g^{\mu\nu}$$

WWHH and ZZHH couplings

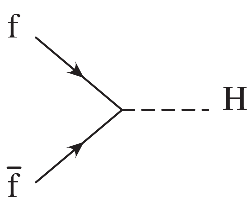


$$2i\frac{m_W^2}{v^2}g^{\mu\nu}$$



$$2i\frac{m_Z^2}{v^2}g^{\mu\nu}$$

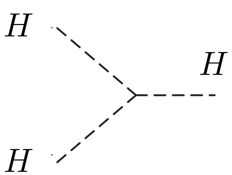
Fermion-Higgs coupling



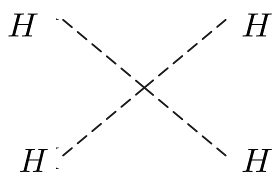
$$-i\frac{m_f}{v}$$

couplings proportional to masses

Cubic and Quartic self-couplings



$$-3i\frac{m_H^2}{v}$$

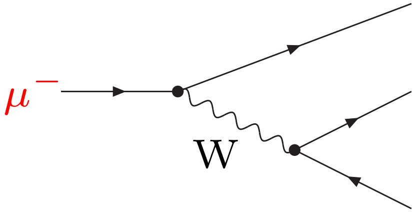


$$-3i\frac{m_H^2}{v^2}$$

- Higgs boson probably found, all other particles confirmed
- consistent quantum field theory
  - in accordance with unitarity
  - renormalizable $\Rightarrow$ predictions at higher orders
- formal parameters: $g_2,\ g_1,\ v,\ \lambda,\ g_f,\ V_{\mathrm{CKM}}$
  physical parameters: $\alpha,\ M_W,\ M_Z,\ M_H,\ m_f,\ V_{\mathrm{CKM}}$

observables and experiments

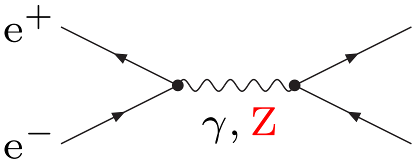
- Muon decay: $\mu^- \to \nu_\mu e^- \bar{\nu}_e$



determination of the Fermi constant

$$G_\mu = \frac{\pi \alpha M_Z^2}{\sqrt{2} M_W^2 (M_Z^2 - M_W^2)} + \dots$$

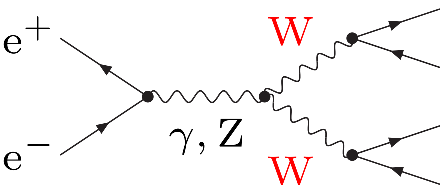
- Z production (LEP1/SLC): $e^+e^- \to Z \to f\bar{f}$

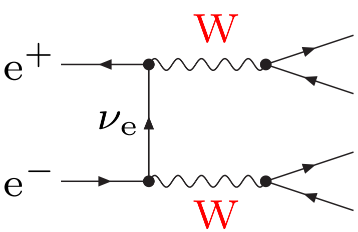


various precision measurements at the Z resonance: $M_Z, \Gamma_Z, \sigma_{had}, A_{FB}, A_{LR}$, etc.

$\Rightarrow$ good knowledge of the $Zf\bar{f}$ sector

- W-pair production (LEP2/ILC): $e^+e^- \to WW \to 4f(+\gamma)$





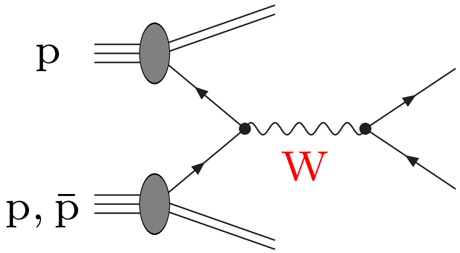
– measurement of M_W

– γWW/ZWW couplings

– quartic couplings: $\gamma\gamma WW$, γZWW

experiments at hadron colliders

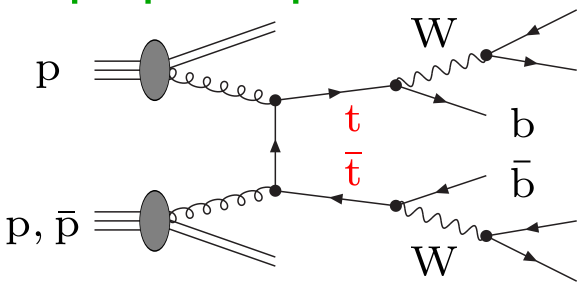
- W production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{W} \to l\nu_l(+\gamma)$



  – measurement of M_W

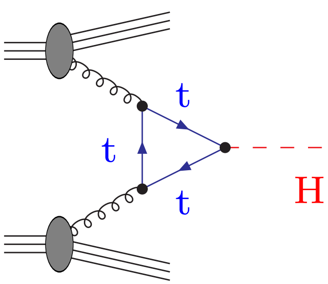
  – bounds on $\gamma\mathrm{WW}$ coupling

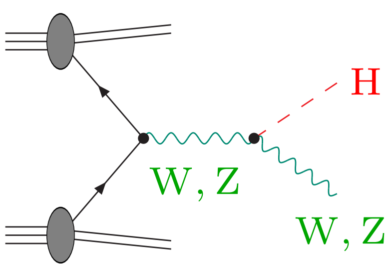
- top-quark production (Tevatron/LHC): $\mathrm{pp}, \mathrm{p\bar{p}} \to \mathrm{t\bar{t}} \to 6f$



  – measurement of m_t

- Higgs production (LHC): $\mathrm{pp} \to \mathrm{H} \to \gamma\gamma, \mathrm{ZZ}, \ldots$



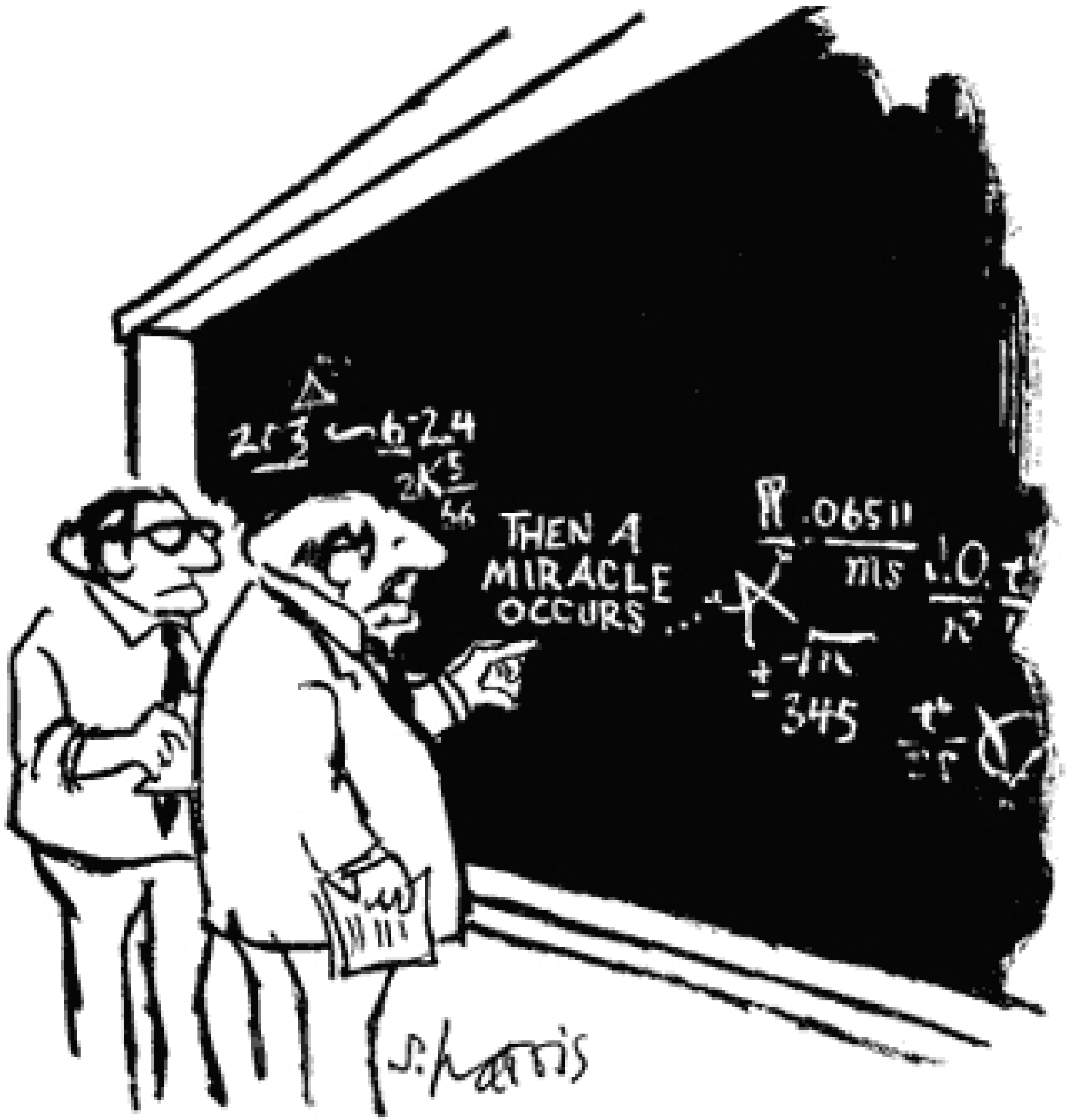


input quantities

G_F	=	$1.1663787(6) \cdot 10^{-5}\,\mathrm{GeV}^{-2}$
M_Z	=	$91.1875 \pm 0.0021\,\mathrm{GeV}$
M_W	=	$80.385 \pm 0.015\,\mathrm{GeV}$
m_t	=	$173.2 \pm 0.9\,\mathrm{GeV}$
M_H	=	$125.09 \pm 0.24\,\mathrm{GeV}$
$\alpha_s(M_Z)$	=	0.1185 ± 0.0006

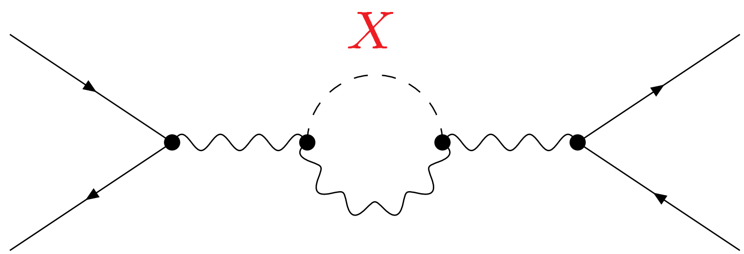
precise experiments . . .

. . . need precise calculations



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

role of theory: exploiting the quantum structure



sensitivity to heavy internal particles (X)

Standard Model: X = Higgs, top

electroweak precision observables

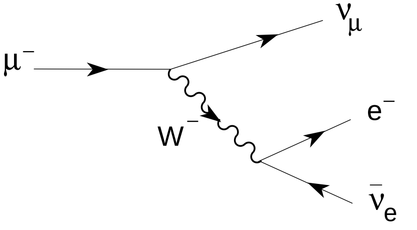
- μ lifetime: G_F
- Z observables: $M_Z, \Gamma_Z, \sin^2\theta_\mathrm{eff}, \ldots$
- LEP 2, Tevatron, LHC: $M_W, m_t \quad + \; M_H$
- low energy: $(g-2)_\mu$

$M_W - M_Z$ correlation

Definition of Fermi constant G_F via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1+\Delta q)$$

Δq: QED corrections in Fermi Model,



$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)} + \text{[higher orders]}$$

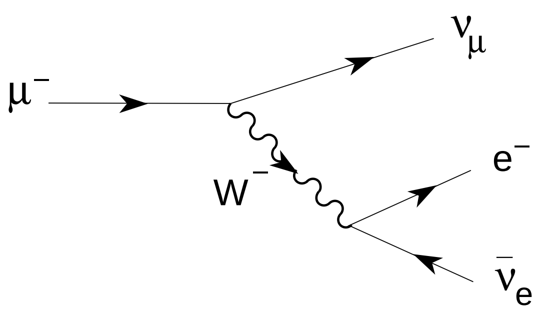
- ⋆ $\Rightarrow$ prediction of M_W from other parameters
- ⋆ $\Rightarrow$ each amplitude $\sim G_F$ requires these higher-order terms

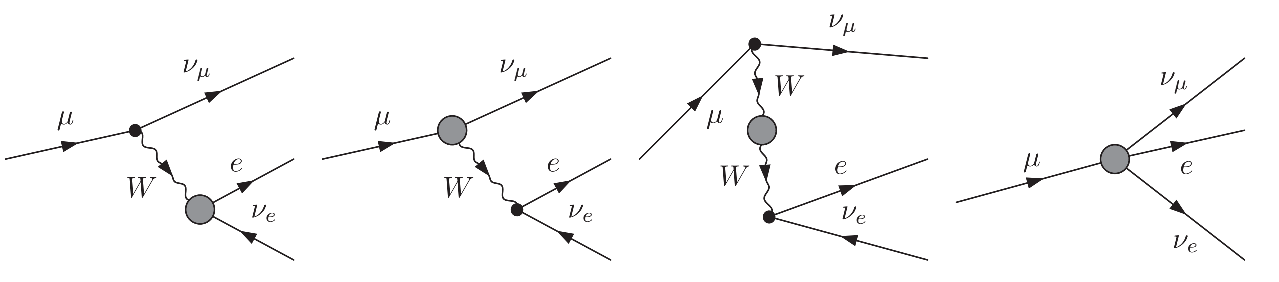
$M_W - M_Z$ correlation

Definition of Fermi constant G_F via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1 + \Delta q)$$

Δq: QED corrections in Fermi Model,





vector-boson mass correlation

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

Δr : quantum correction

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

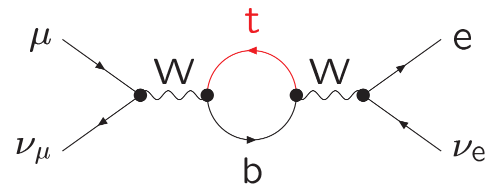
determines W mass

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

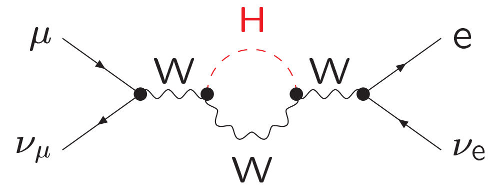
complete at 2-loop order α^2 and $\alpha\alpha_s$

1-loop entries

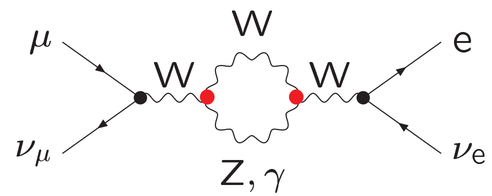
- top quark



- Higgs boson



- gauge-boson self-couplings



dominant contributions to Δr

$$\Delta r = \Delta\alpha - \frac{c_{\rm w}^2}{s_{\rm w}^2}\Delta\rho + \cdots$$

Large universal terms:

$$\Delta\alpha = \Pi^{\gamma}_{\rm ferm}(M_Z^2) - \Pi^{\gamma}_{\rm ferm}(0) = 0.05907 \pm 0.0001$$

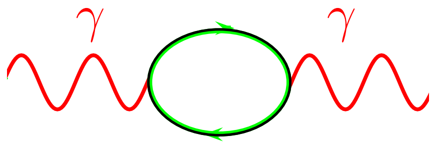
$$\Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2} = 3\frac{G_F m_t^2}{8\pi^2\sqrt{2}} = 0.0094 \quad \textit{[one-loop]} \quad \sim \frac{m_t^2}{v^2} \sim \alpha_t$$

beyond 2-loop order: $\Delta\rho^{(3)} + \Delta\rho^{(4)} \quad \sim \quad \alpha_s^2\alpha_t,\ \alpha_s\alpha_t^2,\ \alpha_t^3,\ \alpha_s^3\alpha_t$

reducible higher order terms from $\Delta\alpha$ and $\Delta\rho$ via

$$1 + \Delta r \quad \to \quad \frac{1}{\left(1-\Delta\alpha\right)\,\left(1+\frac{c_{\rm w}^2}{s_{\rm w}^2}\Delta\rho\right)+\cdots}$$

photon vacuum polarization



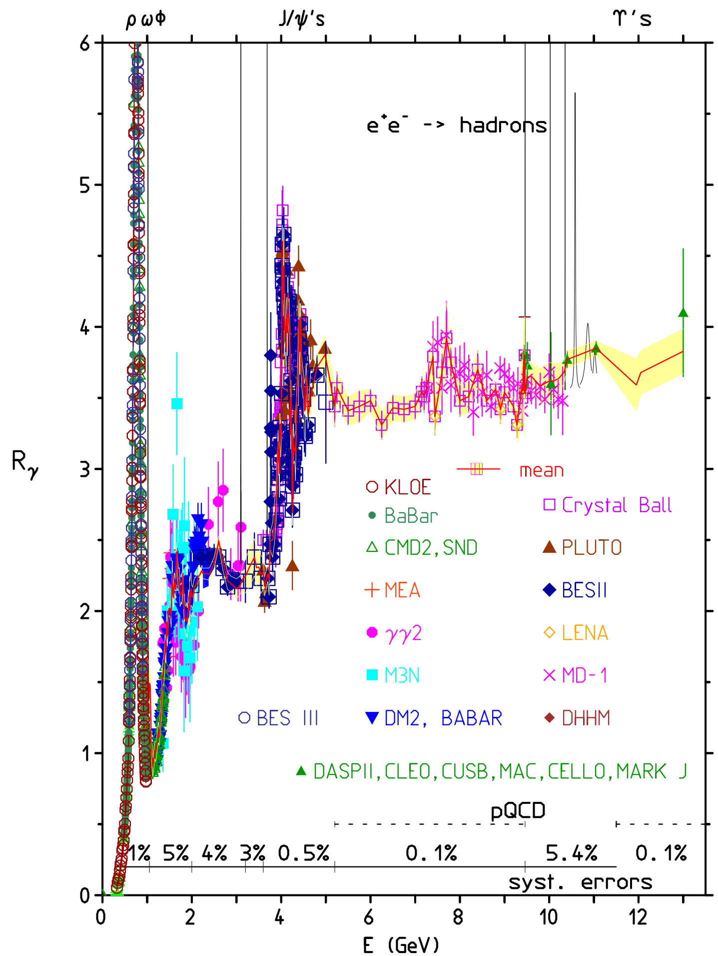
$$\Pi^{\gamma}_{\rm ferm}(M_Z^2) - \Pi^{\gamma}_{\rm ferm}(0) \equiv \Delta\alpha \quad \rightarrow \quad \alpha(M_Z) = \frac{\alpha}{1-\Delta\alpha} \simeq \frac{1}{129}$$

$$\begin{aligned}
\Delta\alpha &= \Delta\alpha_{\rm lept} + \Delta\alpha_{\rm had}, \\
\Delta\alpha_{\rm lept} &= 0.031498\ (4-\text{loop}) \quad \text{Steinhauser 1998; Sturm 2013} \\
\Delta\alpha_{\rm had} &= 0.02757 \quad \pm 0.00010 \quad \text{Davier et al. 2010} \\
&= 0.027626 \pm 0.000103 \quad \text{Hagiwara et al. 2011} \\
&= 0.027504 \pm 0.000118 \quad \text{Jegerlehner 2015}
\end{aligned}$$

significant parametric uncertainty

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

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



Jegerlehner 2015

EW 2-loop calculations for Δr

Freitas, Hollik, Walter, Weiglein

Awramik, Czakon

Onishchenko, Veretin

Degrassi, Gambino, Giardino

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

van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker

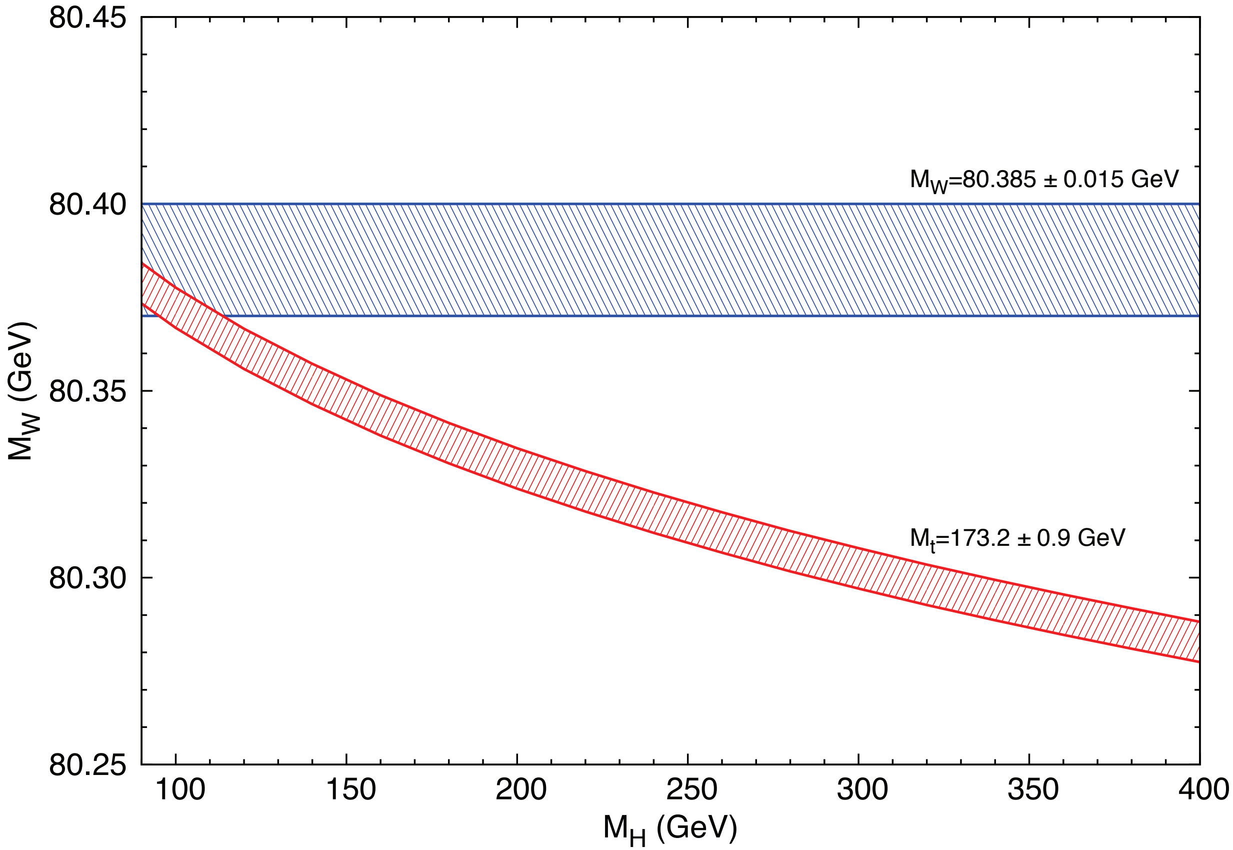
Faisst, Kühn Seidensticker, Veretin

Boughezal, Tausk, van der Bij

Schröder, Steinhauser

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

Boughezal, Czakon

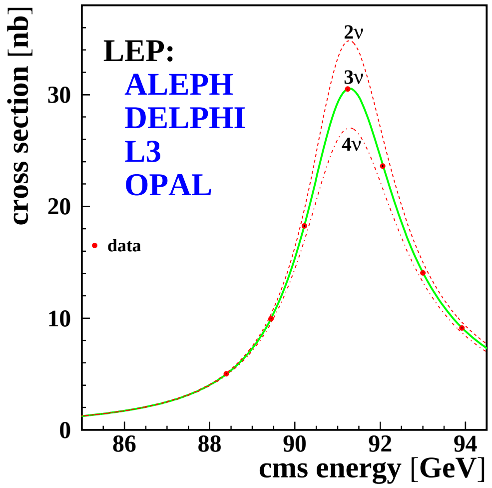


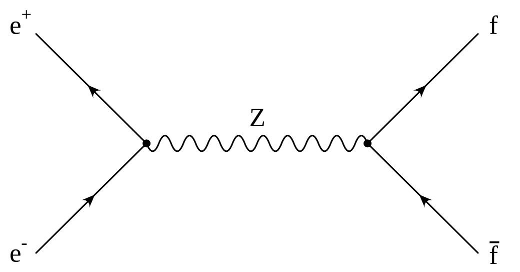
variation of Δr by 0.001 $\quad \Rightarrow \quad \delta M_W = 18\,\mathrm{MeV}$

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

$\delta\big(\Delta\alpha\big) = 10^{-4}$: $\Delta M_W = 1.8\,\mathrm{MeV}$

Z resonance





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

$$g_V^f \to g_V^f + \Delta g_V^f, \qquad g_A^f \to g_A^f + \Delta g_A^f$$

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

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

two classes of observables;

- line-shape observables: M_Z, Γ_Z, *partial widths*, $\sigma_{\rm peak}$, ...

$$R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_{\rm lept}}\,, \qquad R_{\rm b} = \frac{\Gamma_{\rm b}}{\Gamma_{\rm had}}$$

EW 2-loop fermionic corrections *[Freitas; Freitas, Y.-C. Huang]*

hadronic width:

$$\Gamma_{\rm had} = \Gamma_{\rm had}^{\rm EW} \cdot R_{\rm QCD}$$

$$R_{\rm QCD} = 1 + \frac{\alpha_s}{\pi} + A_2 \left(\frac{\alpha_s}{\pi}\right)^2 + A_3 \left(\frac{\alpha_s}{\pi}\right)^3 + A_4 \left(\frac{\alpha_s}{\pi}\right)^4$$

[Baikov, Chetyrkin, Kühn, Rittinger]

two classes of observables;

- asymmetries: $A_{FB},\, A_{LR}, \ldots$

$\Rightarrow$ *forward-backward asymmetry* $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\, A_e\, A_f$

$$A_f = \frac{2\, g_V^f / g_A^f}{1 + (g_V^f / g_A^f)^2} \quad \Rightarrow \quad \sin^2 \theta_{\text{eff}}^f$$

polarized cross section for $e^-_{L,R}$*:*

$\Rightarrow$ *left-right asymmetry* $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = A_e \quad \Rightarrow \quad \sin^2 \theta_{\text{eff}}$

asymmetries determine $\sin^2 \theta_{\text{eff}}$

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

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

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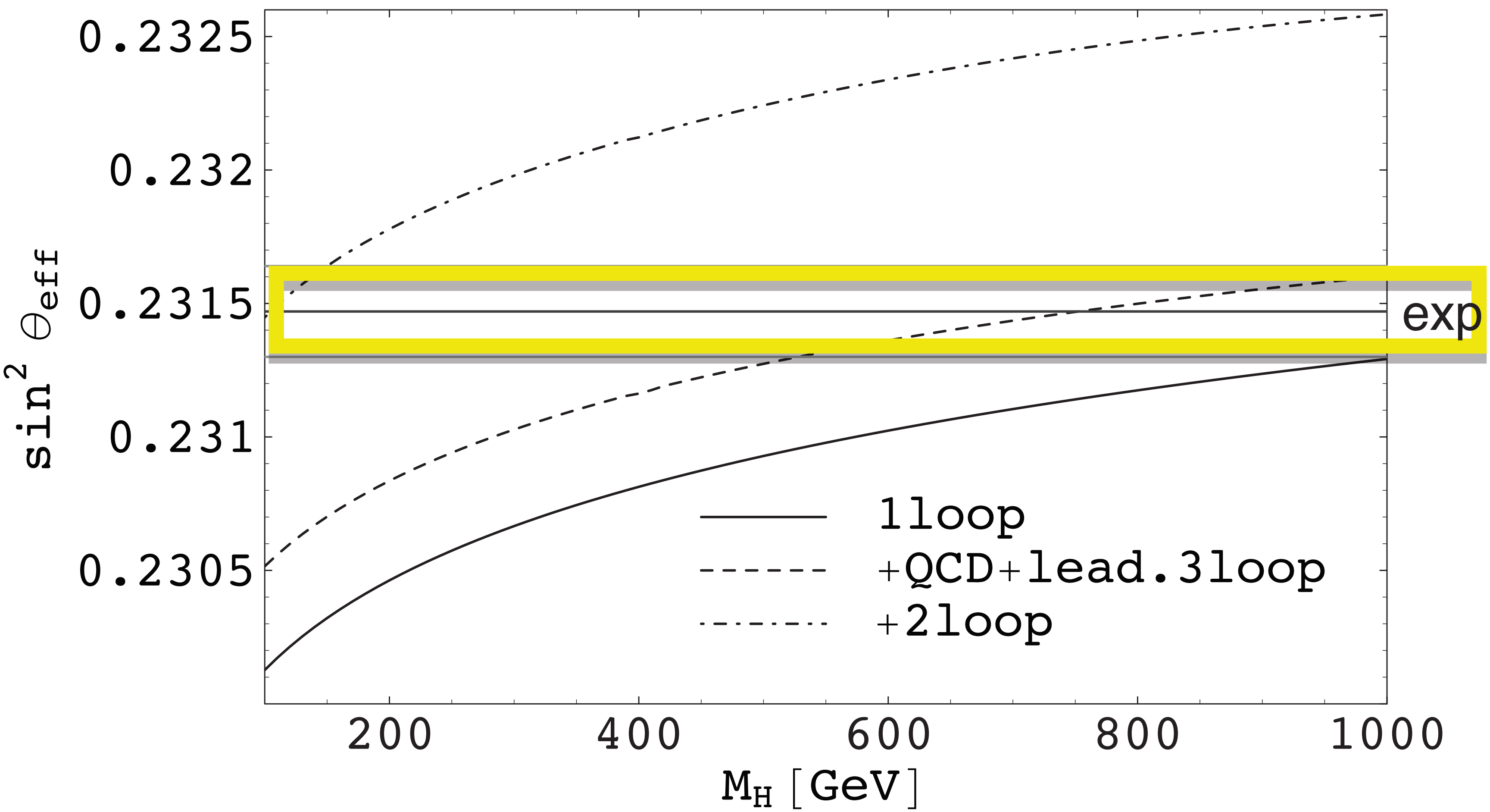


theory uncertainty: $\delta \sin^2 \theta_{\text{eff}} = 5 \cdot 10^{-5}$

$\delta\left(\Delta\alpha\right) = 10^{-4}$: $\delta \sin^2 \theta_{\text{eff}} = 3.5 \cdot 10^{-5}$

some observables with not-so-good agreement

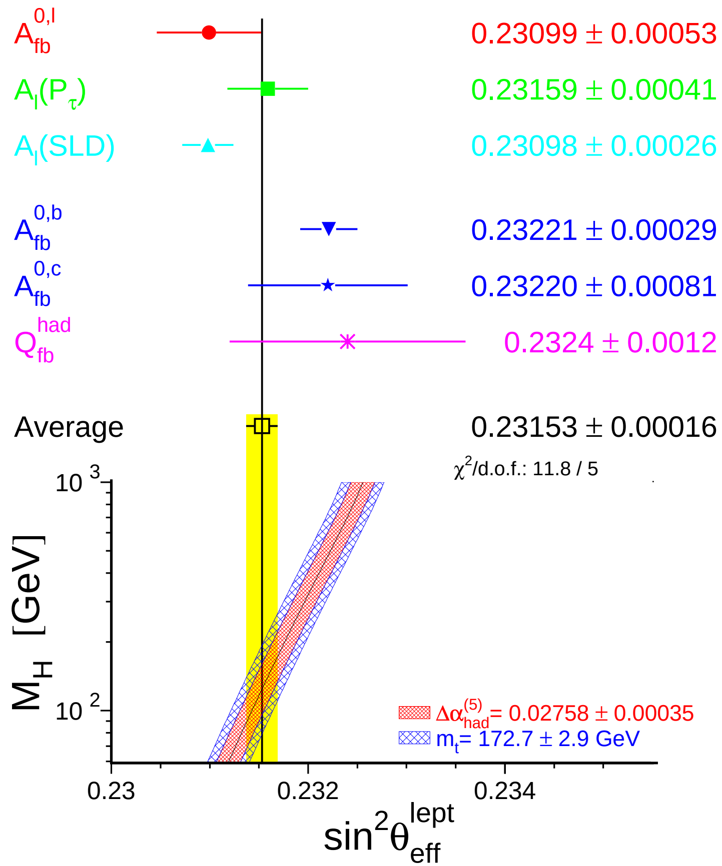
- in general, SM is in overall agreement with data
- yet a few quantities stand a bit apart ($\sim 3\sigma$)
  - the forward-backward asymmetry for b quarks, $A_{\mathrm{FB}}^{b\bar{b}}$ at the Z peak
  - the anomalous magnetic moment of the muon
  - the forward-backward asymmetry for top quarks at the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

    new NNLO QCD calculation: *Czakon, Fiedler, Mitov 2015*

    data now compatible with SM prediction (QCD + EW)

forward-backward asymmetry for b quarks

- is around since the days of LEP/SLC
- indicates presence of some extra right-handed contributions to the Zbb coupling
- no convincing explanation in current new physics models



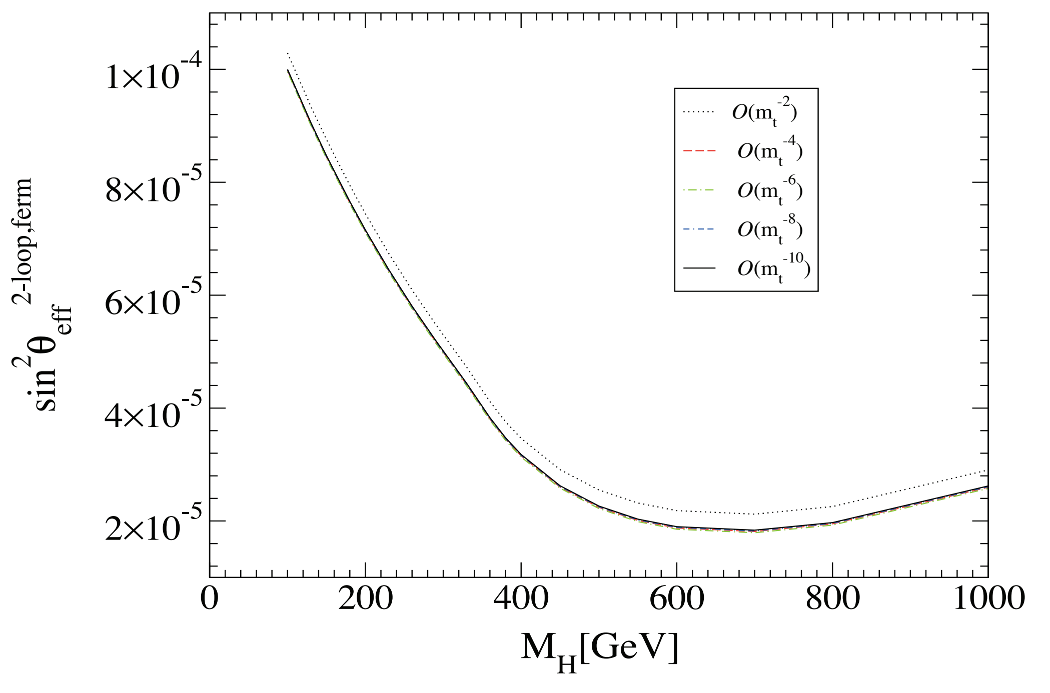
$A^b_{\rm FB}$ determined by $\sin^2\theta_e$ and $\sin^2\theta_b$:

$$A^b_{\rm FB} = \frac{3}{4}\, A_e\, A_b$$

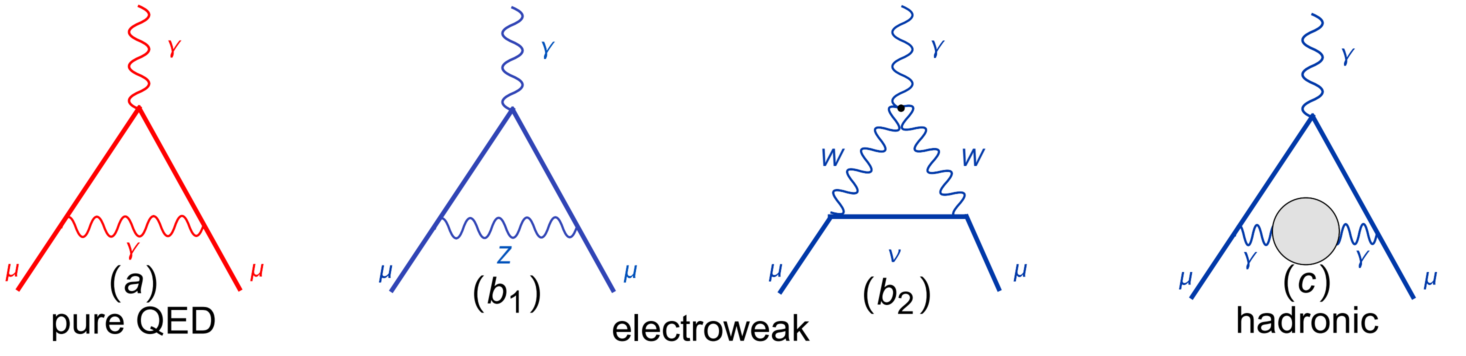
$$A_e = \frac{1-4\sin^2\theta_e}{1+(1-4\sin^2\theta_e)^2}, \qquad A_b = \frac{1-4/3\,\sin^2\theta_b}{1+(1-4/3\,\sin^2\theta_b)^2}$$

recent electroweak 2-loop calculation – too small

Awramik, Czakon, Freitas, Kniehl 08



anomalous magnetic moment of the muon

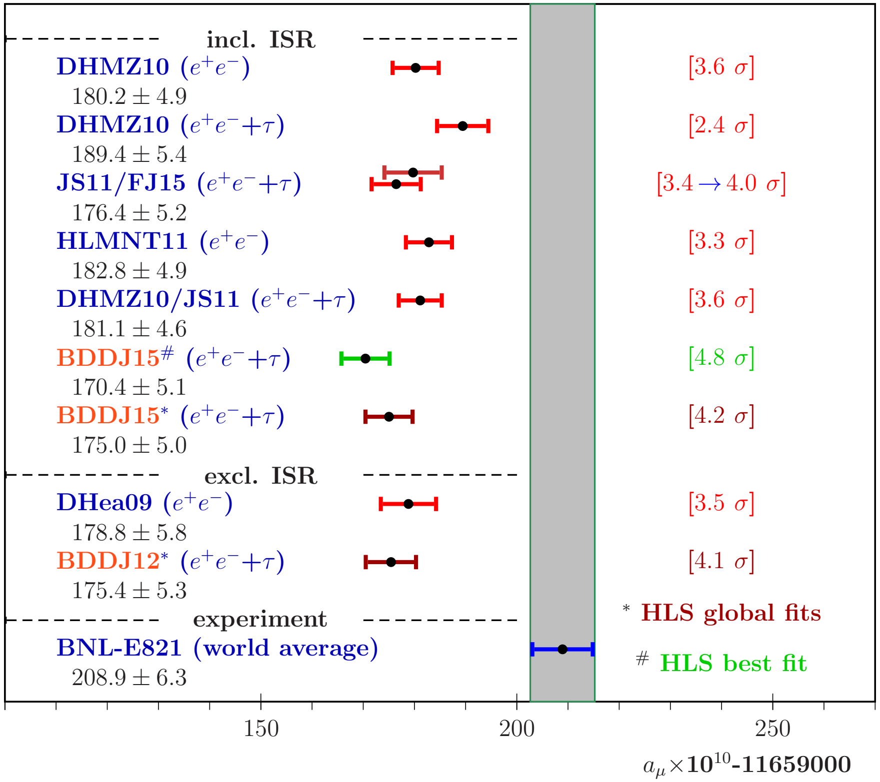


- The QED part is known to 5 loops
  Kinoshita et al.

- The EW part is known to 2 loops
  Czarnecki, Krause, Marciano;
  Gnendiger, Stöckinger, Stöckinger-Kim

- The hadronic part is known with limited accuracy, hadronic vacuum polarization from data at low energies
  many authors, most recent: Jegerlehner 2015

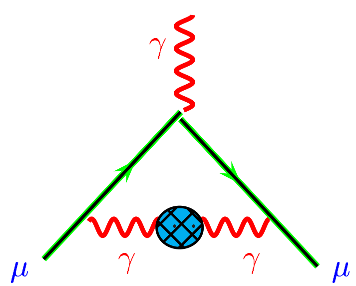
Anomalous g-factor of the muon



Jegerlehner 2015

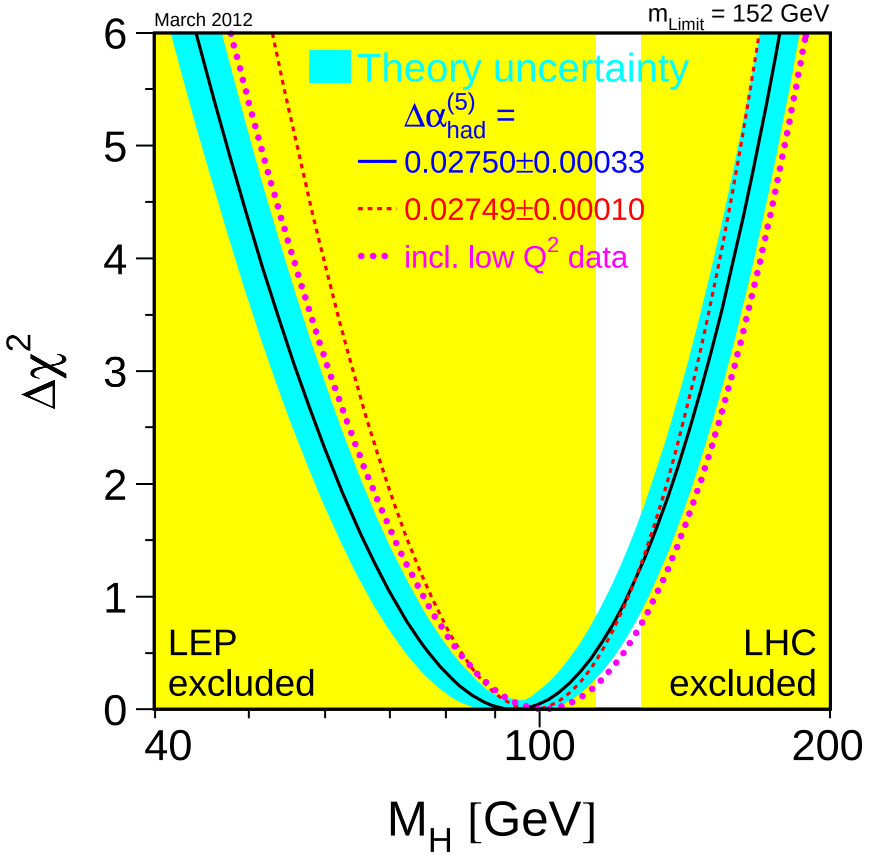
SM prediction: 4σ below exp. value

theory uncertainty from hadronic vacuum polarization



Global fit to the Higgs boson mass

before the discovery in 2012



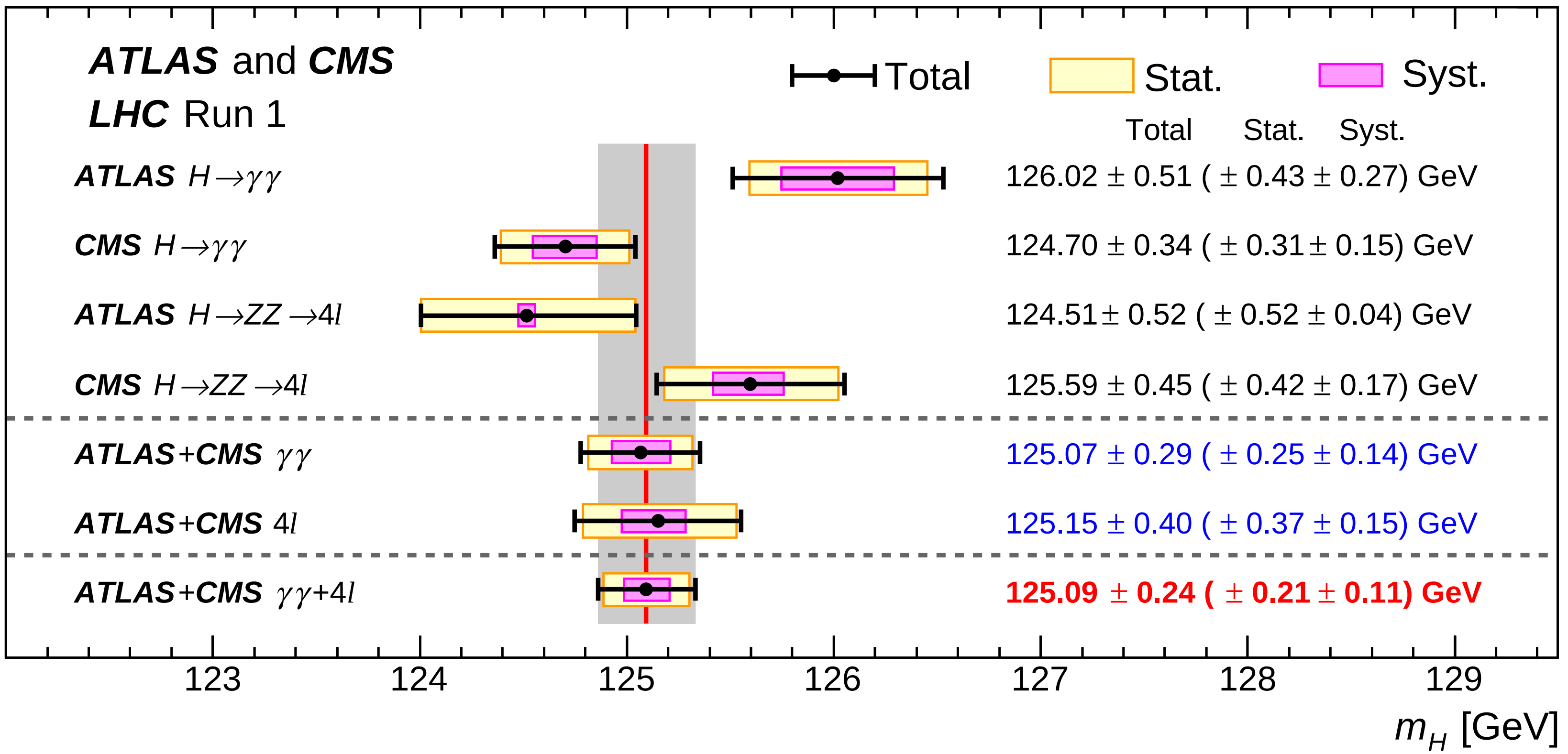
blueband: Theory uncertainty

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

$$M_{\rm H} = 94^{+29}_{-24} \text{ GeV}$$

The Higgs era

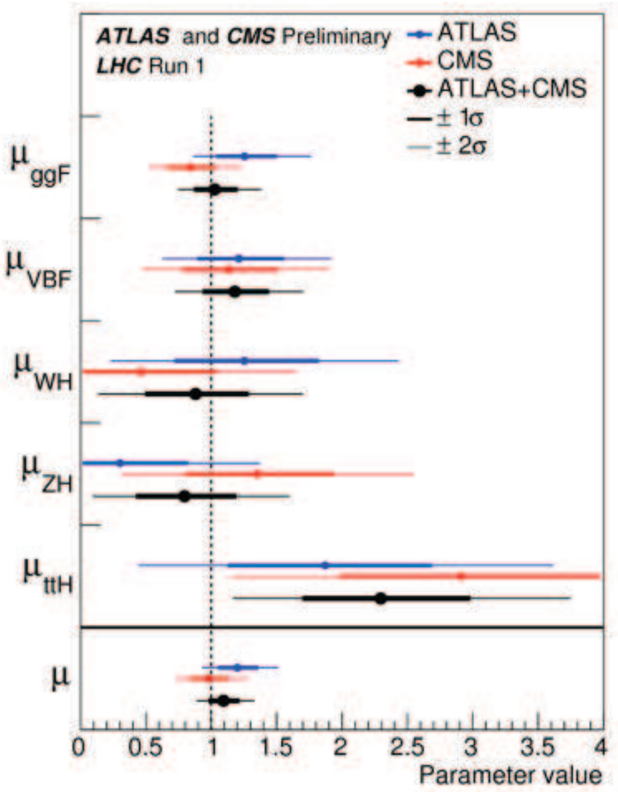
2015: first combined ATLAS/CMS Higgs-boson mass determination

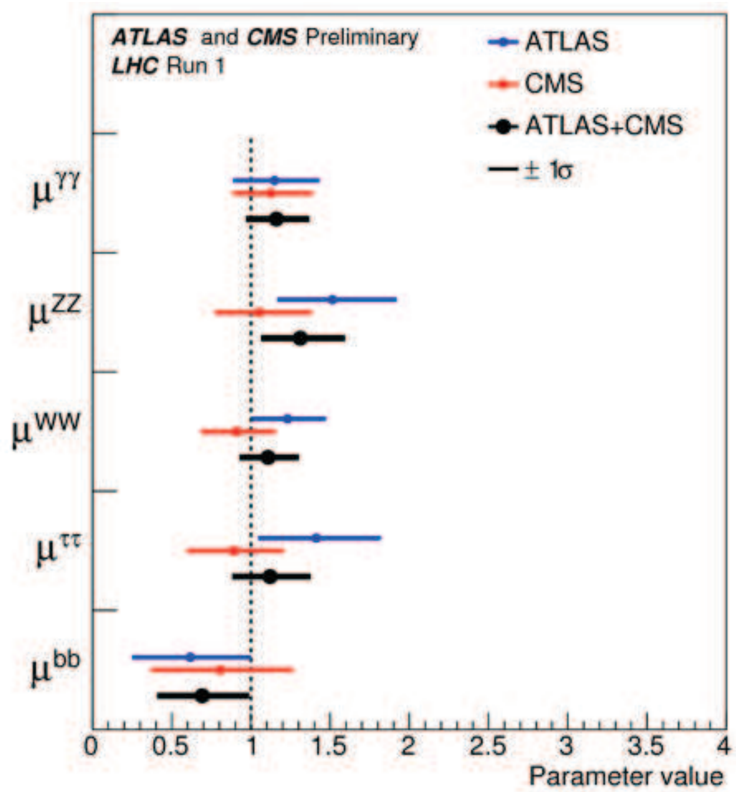



THANKS for
the
BOSON

A Standard Model Higgs boson at the LHC?

Moriond 2016

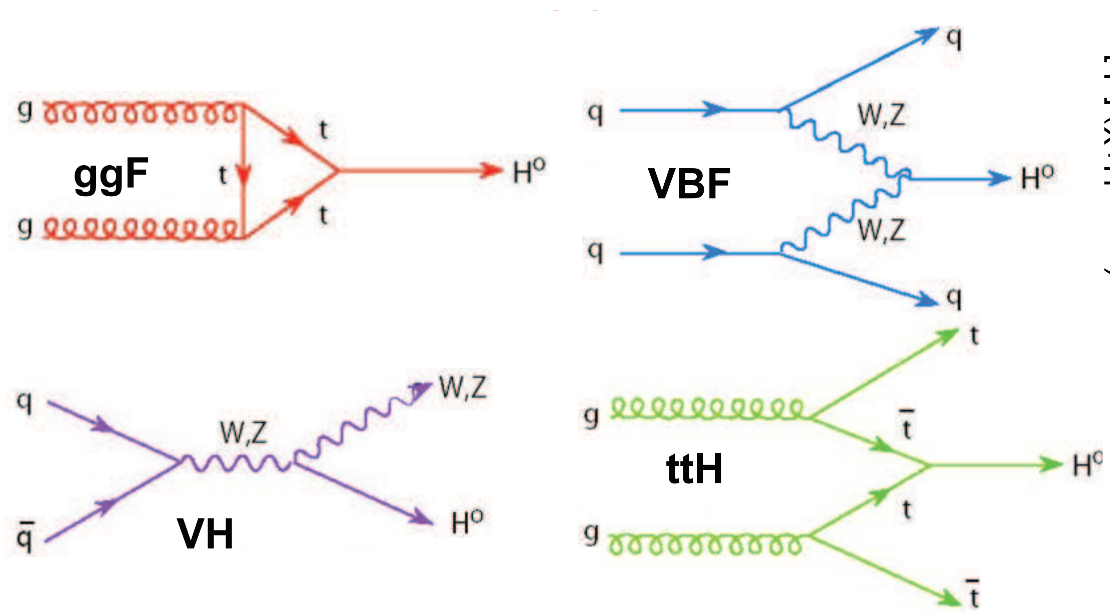


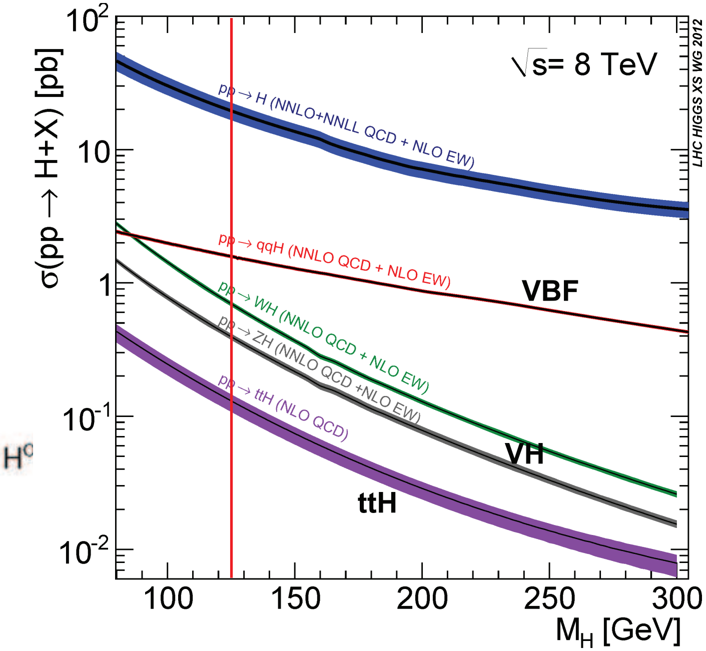


$$\mu = 1.09^{+0.11}_{-0.10}$$

$$\mu = \sigma(pp \to H) \cdot BR(H \to X)/[\mathrm{SM_{theory}}]$$

Higgs production at the LHC



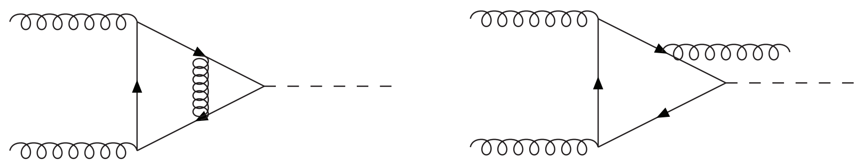


Handbook of Higgs Cross Sections, Vol. 1, 2, 3

CERN-2011-002, CERN-2012-002, CERN-2013-004

NLO exact

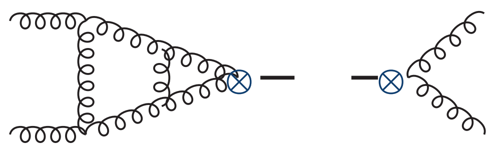
Dawson (1991); Djouadi, Spira, Zerwas (1991) Graudenz, Spira, Zerwas (1993)



NNLO computed using effective vertex

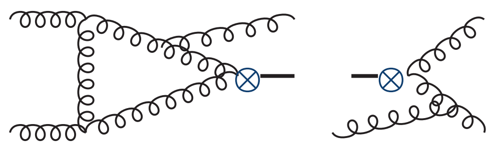
Harlander, Kilgore (2002)
Anastasiou, Melnikov (2002)
Ravindran, Smith, van Neerven (2003)

Double Virtual:



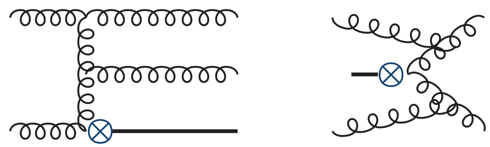
+ 148 terms;

Real Virtual:



+ 635 terms;

Double Real:



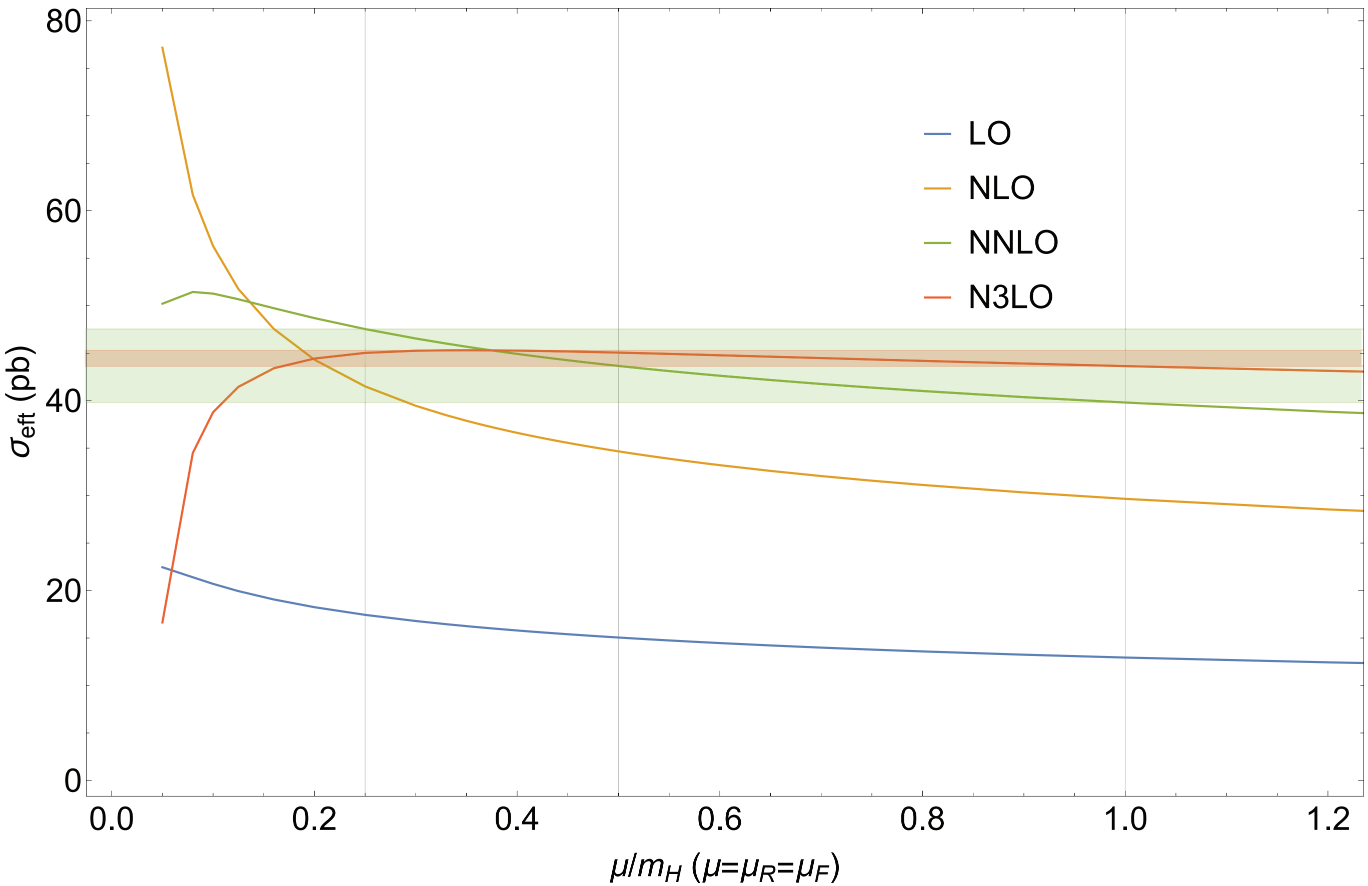
+ 594 terms.

In addition:

$q + g \to h + X(q, \overline{q}, g)$ $q_i + q_j(\overline{q}_j) \to h + X(q, \overline{q}, g)$

NNNLO for $gg \to H$

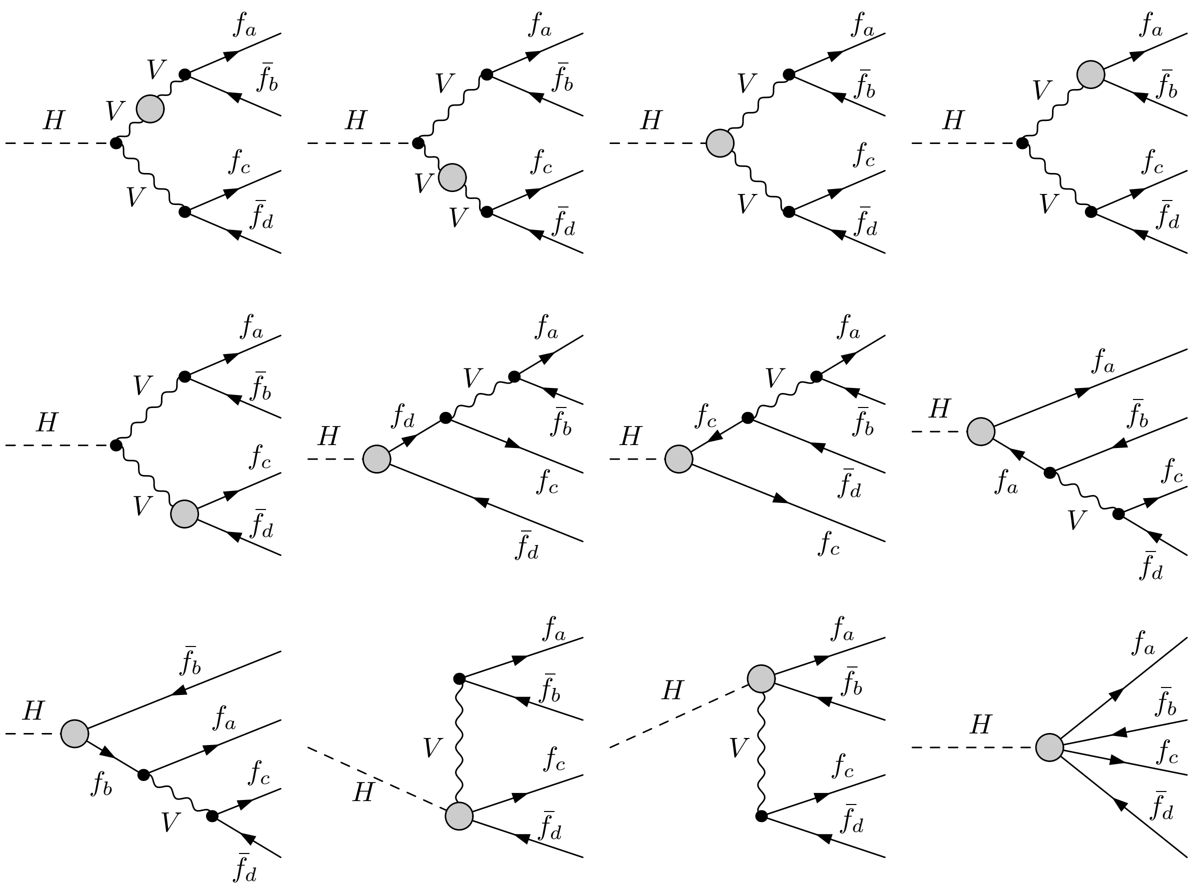
Anastasiou et al. 2015



scale variation at N3LO ~2%

decays: $H \to VV \to 4f$

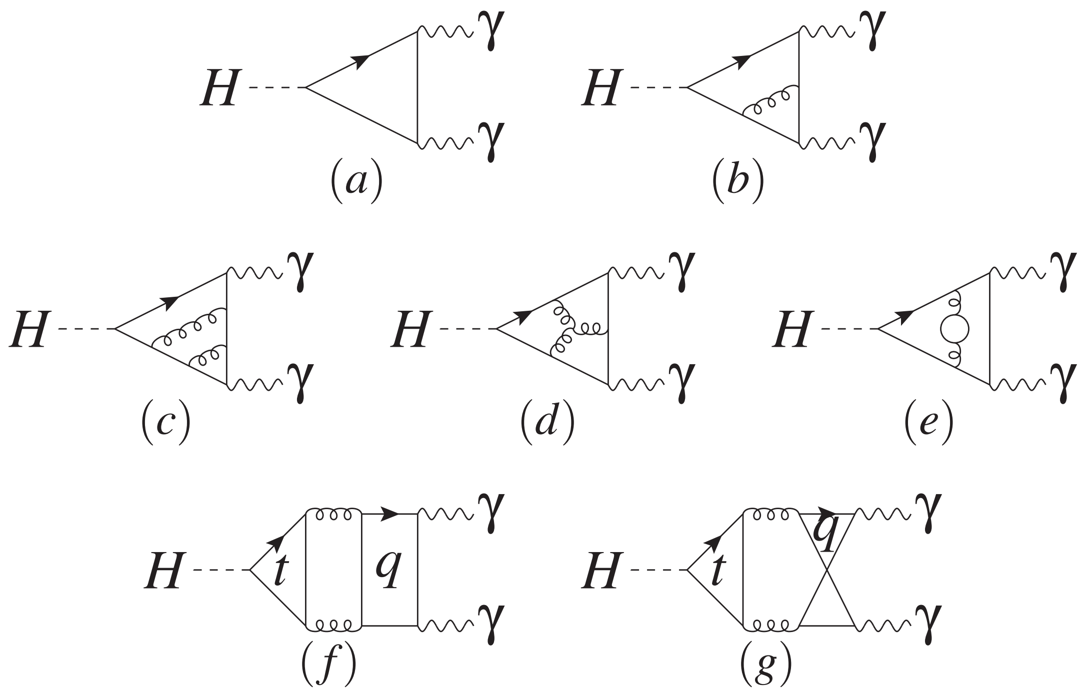
needs also background pocesses + h.o.



Bredenstein, Denner, Dittmaier, Weber 2007

`PROPHECY4f`

decays: $H \to \gamma\gamma$



non-singlet and singlet terms; electroweak corrections (Passarino,. . .)

$$\Gamma_{H\to\gamma\gamma} = (9.398 - \underset{\text{LO}\times\text{NLO-EW}}{0.148} + \underset{\text{LO}\times\text{NLO-QCD}}{0.168} + \underset{\alpha_s^2}{0.00793})\ \text{keV}$$

α_s^2 term dominated by singlet part of prediction,

prediction good to 1 permille!

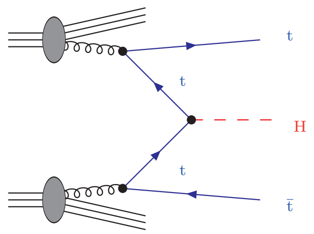
Maierhöfer, Marquard 2012

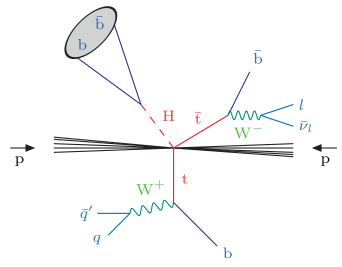
precision physics in the Higgs era

- Higgs boson mass M_H is now an additional precise input parameter
- partial decay widths influenced by quantum effects
  - accordingly, affected also by non-standard physics
  - new set of sensitive precision observables
- M_H itself is a prediction/ precision observable in specific classes of models
- further empirical information available on top of the “classical” set of precision observables

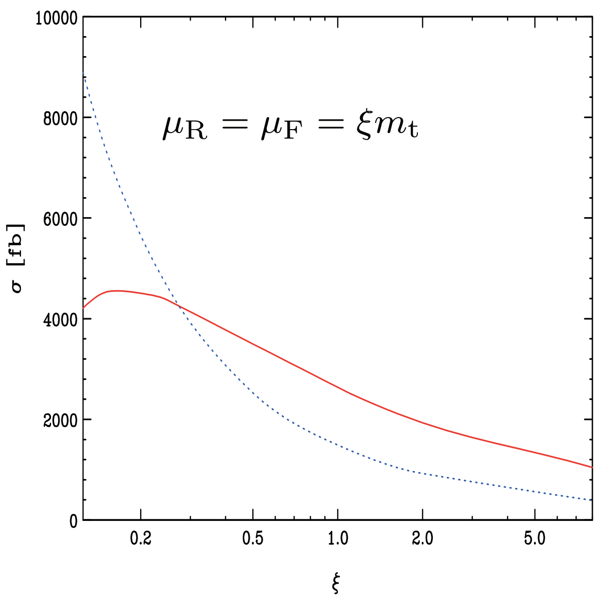
production of $t\bar{t}H$

- measurement of the Higgs–top Yukawa coupling





- requires accurate background calculations, e.g. for $pp \to t\bar{t}\,b\bar{b}$



.... *LO*

— *NLO*

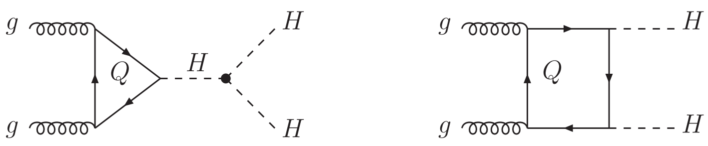
Bredenstein et al.

Bevilacqua et al.

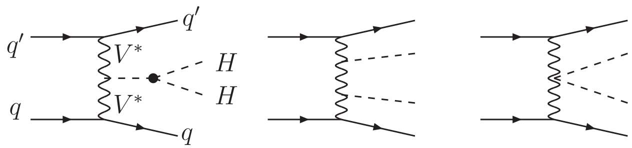
measurement of Higgs self-coupling

HH production channels

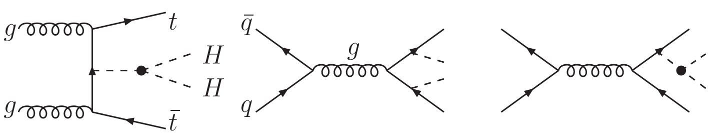
gg fusion



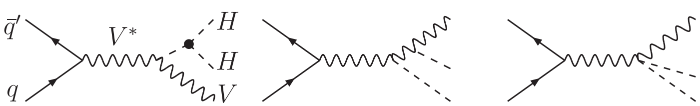
VV fusion

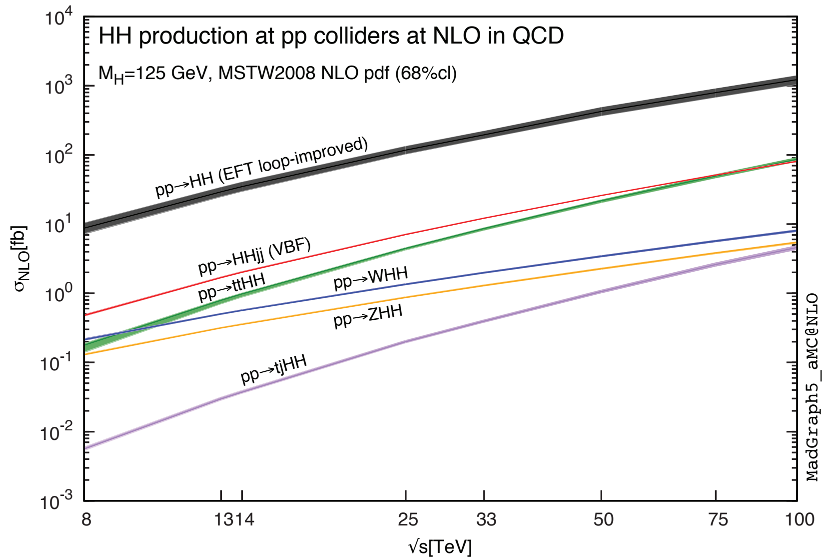


Associated production with top



Higgs-strahlung



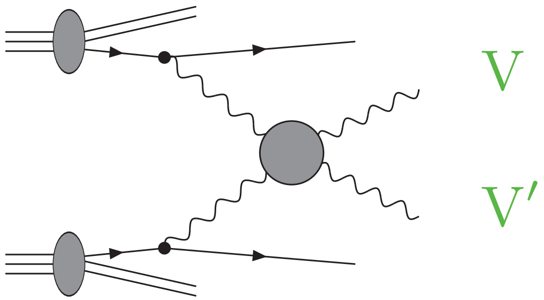


$\sqrt{s}$ [TeV]	$\sigma^{\text{NLO}}_{gg\to HH}$ [fb]	$\sigma^{\text{NLO}}_{qq'\to HHqq'}$ [fb]	$\sigma^{\text{NNLO}}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\text{NNLO}}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\text{LO}}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.21
14	33.89	2.01	0.57	0.42	1.02
33	207.29	12.05	1.99	1.68	7.91
100	1417.83	79.55	8.00	8.27	77.82

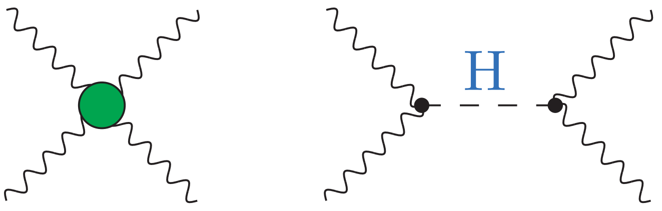
Gluon-gluon fusion dominates
Only some contribute with HHH

production of VV + 2 jets

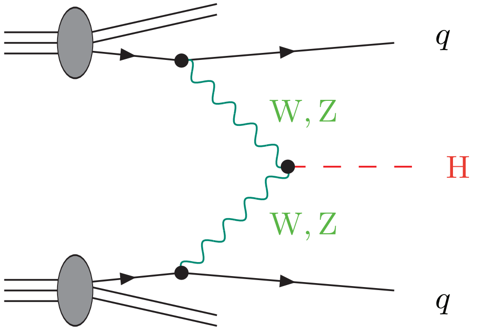
- measure $VV \to VV$ scattering
  sensitive to electroweak symmetry breaking – BSM?



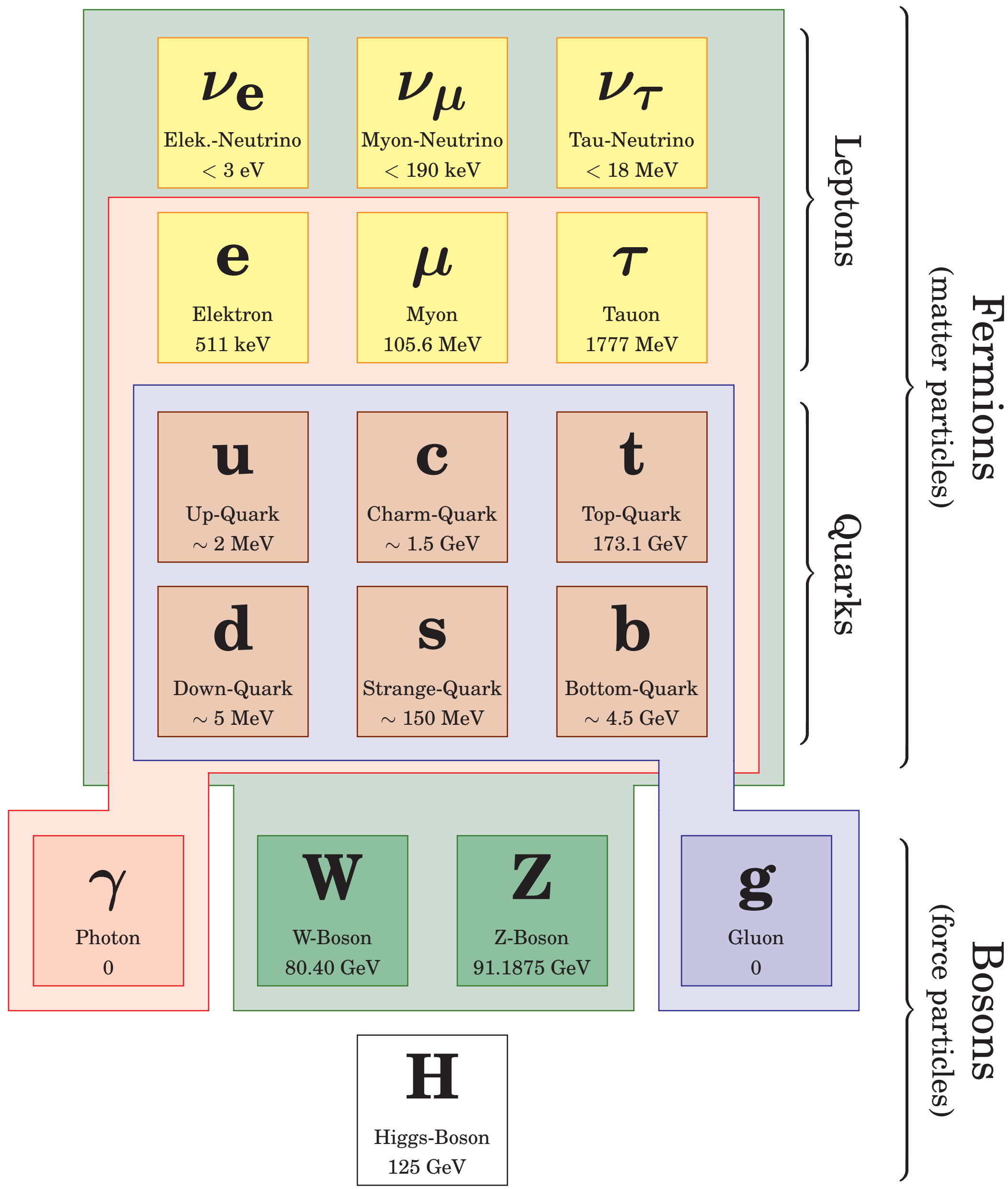
e.g.



- background for Higgs production via vectorboson fusion with $H \to VV$

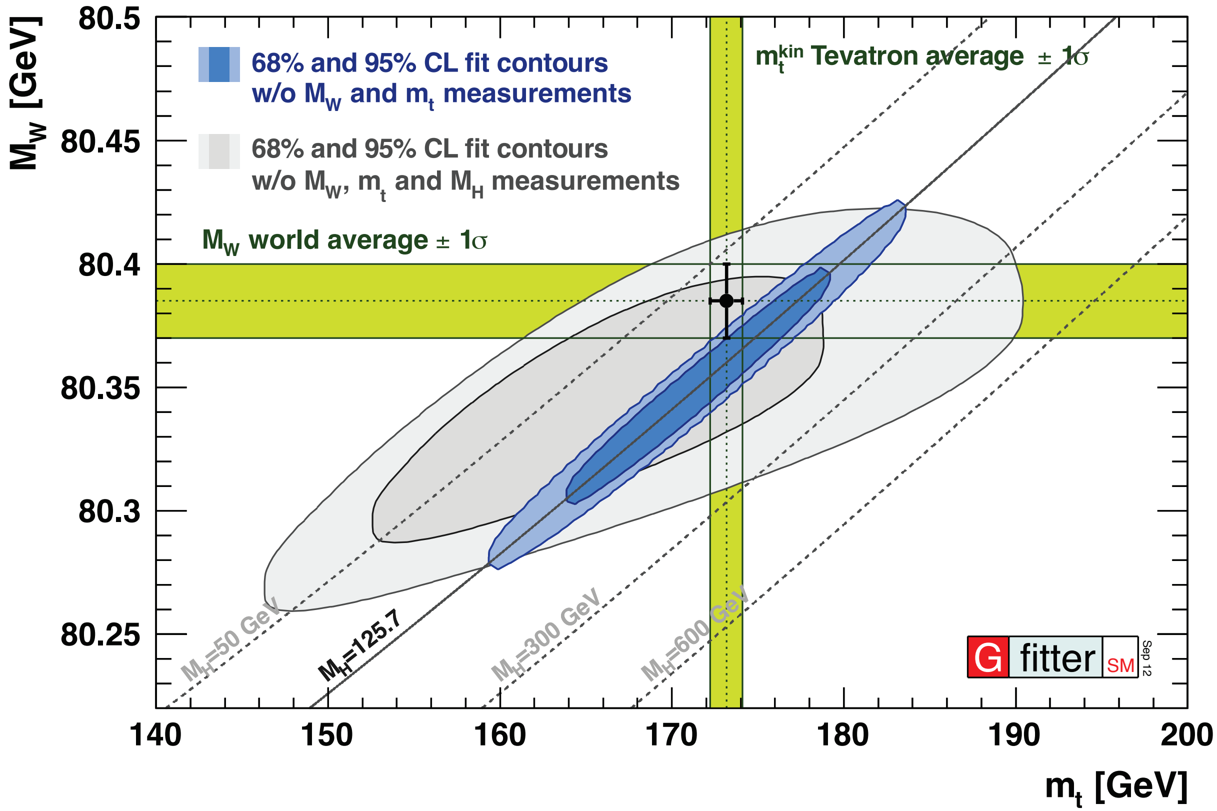


Status of the Standard Model



SM input completey determined $\Rightarrow$ precision observables

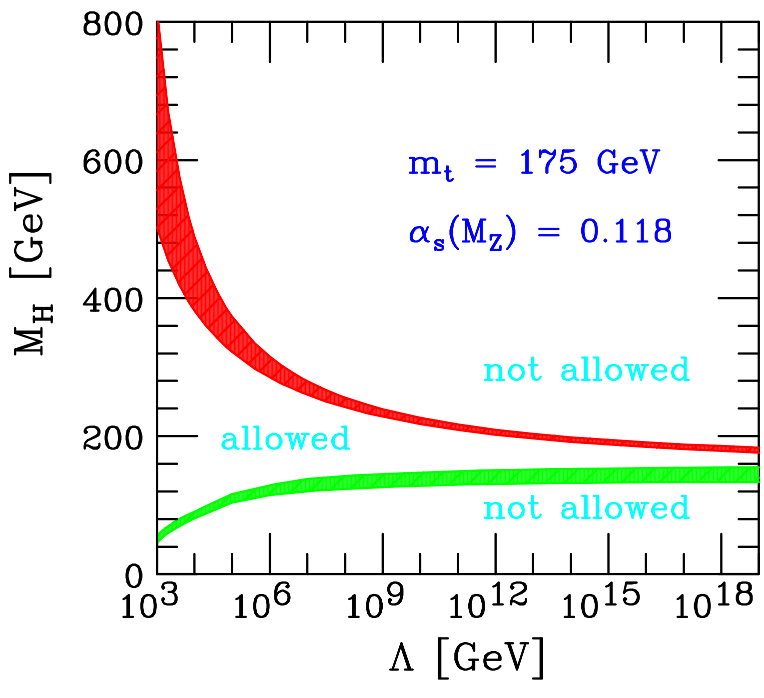
	theo	exp
$\sin^2\theta_{\rm eff}$	$0.23152 \pm 0.00005 \pm 0.00005$	0.23153 ± 0.00016
M_W (GeV)	$80.361 \pm 0.006 \pm 0.004$	80.385 ± 0.015



evolution of self-coupling λ with scale Q

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

vacuum stability: $\lambda(Q) > 0$ up to scale Λ



Hambye, Riesselmann 1997

evolution of self-coupling λ with scale Q

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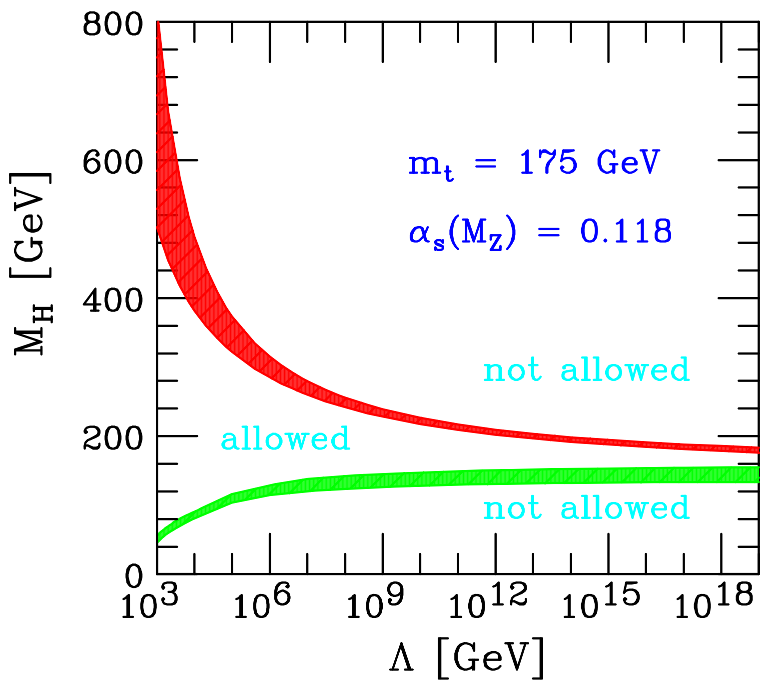
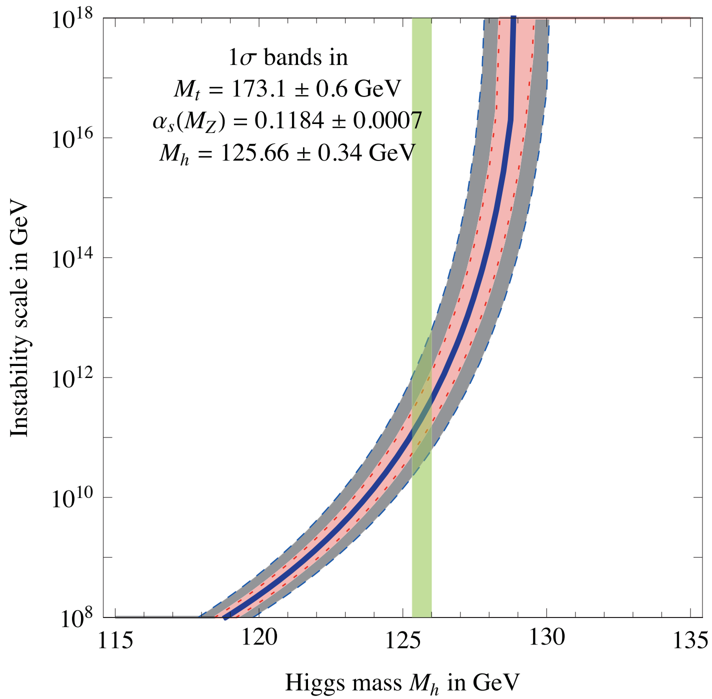
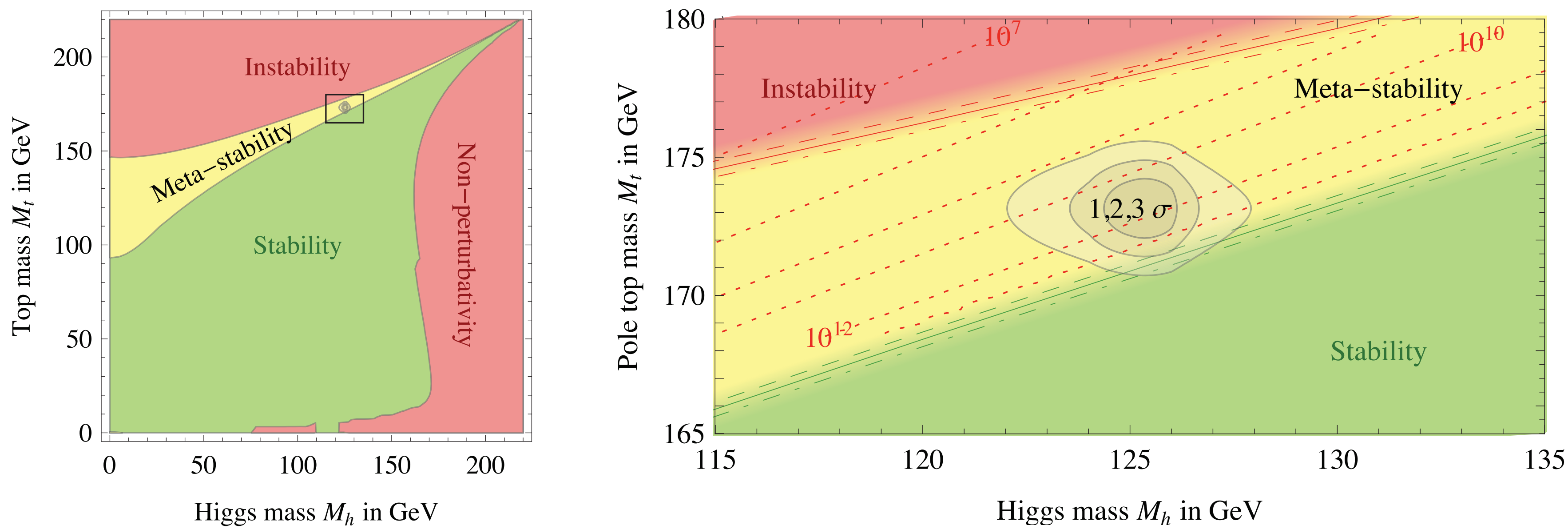




Hambye, Riesselmann 1997

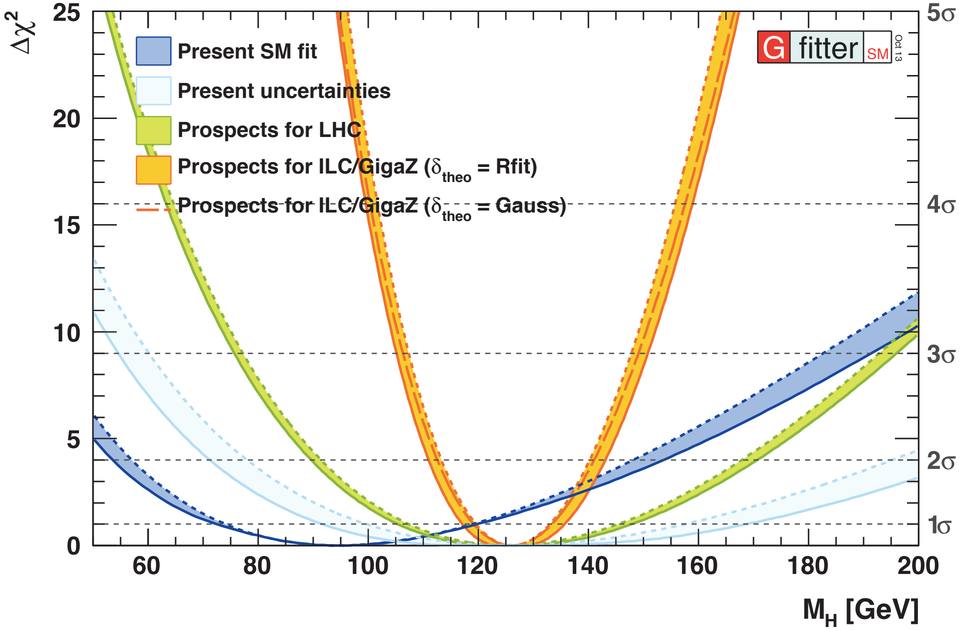
Degrassi et al. 2012

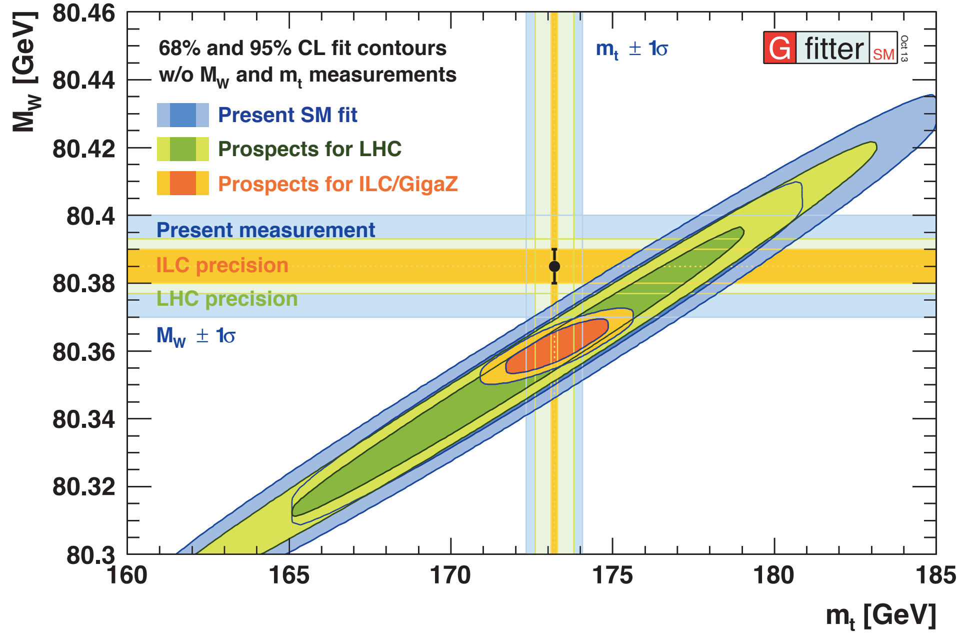


[Degrassi et al. 2012]

precise measurement of m_t crucial input

the future of SM tests

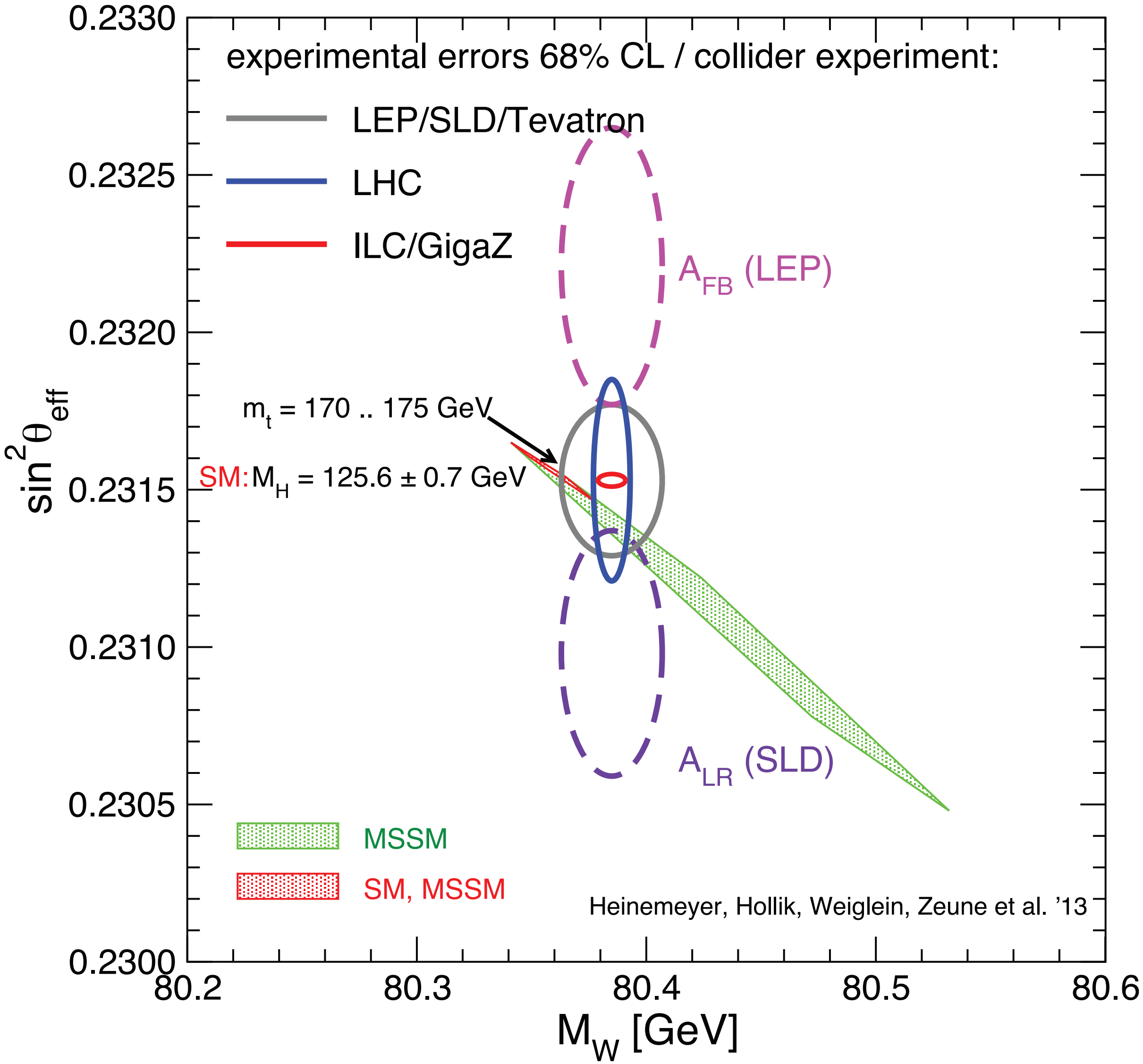




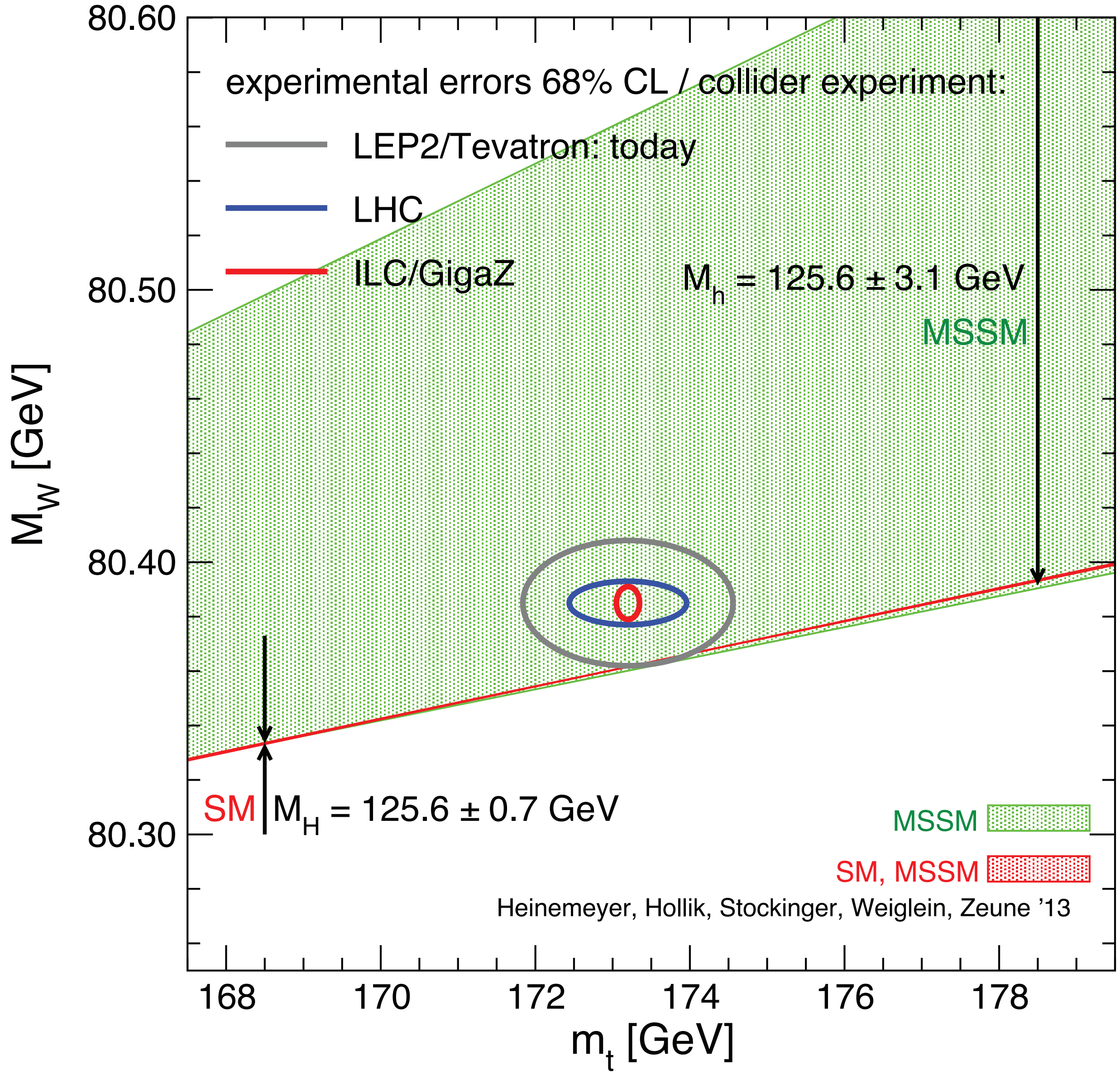
from: Working Group Report of the 2013 Community Summer Study (Snowmass) on the Energy Frontier Precision Study of Electroweak Interactions

present and aimed experimental precision

exp. error	LEP/Tev/LHC	LC/GigaZ	FCee
$M_Z\,[\mathrm{MeV}]$	2.1	2.1	0.1
$M_W\,[\mathrm{MeV}]$	10	3-5	1
$\sin^2\theta_{\mathrm{eff}}\,[10^{-5}]$	17	1.3	0.6
$R_b[10^{-5}]$	66	15	5
$m_{\mathrm{top}}\,[\mathrm{GeV}]$	0.7	0.1	0.05
$\Delta\alpha$	$1 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	$< 5 \cdot 10^{-5}$
α_s	$6 \cdot 10^{-4}$	$< 6 \cdot 10^{-4}$	$1 \cdot 10^{-4}$



experimental errors 68% CL / collider experiment:
LEP/SLD/Tevatron
LHC
ILC/GigaZ
A_FB (LEP)
A_LR (SLD)
m_t = 170 .. 175 GeV
SM: M_H = 125.6 ± 0.7 GeV
MSSM
SM, MSSM
Heinemeyer, Hollik, Weiglein, Zeune et al. '13
sin²θ_eff
M_W [GeV]
0.2330
0.2325
0.2320
0.2315
0.2310
0.2305
0.2300
80.2
80.3
80.4
80.5
80.6



experimental errors 68% CL / collider experiment:
LEP2/Tevatron: today
LHC
ILC/GigaZ
$M_h = 125.6 \pm 3.1$ GeV
MSSM
SM
$M_H = 125.6 \pm 0.7$ GeV
MSSM
SM, MSSM
Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '13
M_W [GeV]
m_t [GeV]
80.60
80.50
80.40
80.30
168
170
172
174
176
178

Conclusions and perspectives

- impressive confirmation by a huge data sample from low to high energies, no significant deviations
- quantum effects have been established at many σ
- perfect indirect and direct determination of the top quark
- now repeated for the Higgs boson
- scalar particle at 125 GeV: SM Higgs boson or first signal of BSM?
- next steps with upgraded LHC / improved precison
  – confirm the Higgs boson properties
  – check versus electroweak precision measurements
  – or find deviations, new structures


RESEARCH INSTITUTE
UNANSWERED QUESTIONS
UNQUESTIONED ANSWERS
S. Harris