Facing a new era of discoveries in particle physics

higher energies, higher precision, higher expectations

Laura Reina (FSU)

University af Florida, Department of Physics, September 2010

Very special time for particle physics

Two hadron colliders teaming in the discovery of new physics:

- the Tevatron is collecting higher and higher statistics at $\sqrt{s} = 1.96$ TeV;
- the Large Hadron Collider (LHC) is successfully operating at $\sqrt{s} = 7$ TeV, and will reach the designed $\sqrt{s} = 14$ TeV in about two years, eventually collecting more than 100 times the data of the Tevatron.

Because ..... $E = mc^2$ (!) we do expect to see new particles and to be able to identify them with reasonable accuracy.

BUT .... WHY DO WE NEED MORE PARTICLES?

Because the most important unanswered questions . . .

- is there a Higgs boson particle responsible for the different nature of weak vs strong and electromagnetic interactions?
- what are neutrino masses telling us?
- do all forces become one? at what energy scale?
- what is the nature of dark matter?
- what is dark energy?
- what happened to antimatter?
- . . .

all require to go beyond the Standard Model of particle physics and we think that new physics lives at energies accessible to existing colliders.

Particle Physics in a nutshell

Testing the Standard Model for evidence of new physics

Particles and forces are a realization of fundamental symmetries of nature

Very old story: Noether's theorem in *classical mechanics*

$$L(q_i, \dot{q}_i) \text{ such that } \frac{\partial L}{\partial q_i} = 0 \longrightarrow p_i = \frac{\partial L}{\partial \dot{q}_i} \text{ conserved}$$

to any symmetry of the Lagrangian is associated a conserved physical quantity:

- ▷ $q_i = x_i \quad \longrightarrow \quad p_i$ linear momentum;
- ▷ $q_i = \theta_i \quad \longrightarrow \quad p_i$ angular momentum.

Generalized to the case of a *relativistic quantum theory* at multiple levels:

- ▷ $q_i \rightarrow \phi_j(x)$ coordinates become "fields"$\leftrightarrow$ "particles"!
- ▷ $L(\phi_j(x), \partial_\mu \phi_j(x))$ can be symmetric under many transformations.

The symmetries that make the world as we know it …

- *translations*:
  conservation of energy and momentum;
- *Lorentz transformations* (rotations and boosts):
  conservation of angular momentum (orbital and spin);
- *discrete transformations* (P,T,C,CP,…):
  conservation of corresponding quantum numbers;
- *global transformations of internal degrees of freedom* (ϕ_j "rotations")
  conservation of "isospin"-like quantum numbers;
- *local transformations of internal degrees of freedom* ($\phi_j(x)$ "rotations"):
  define the interaction of fermion (s=1/2) and scalar (s=0) particles in terms of exchanged vector (s=1) massless particles $\longrightarrow$ "forces"!

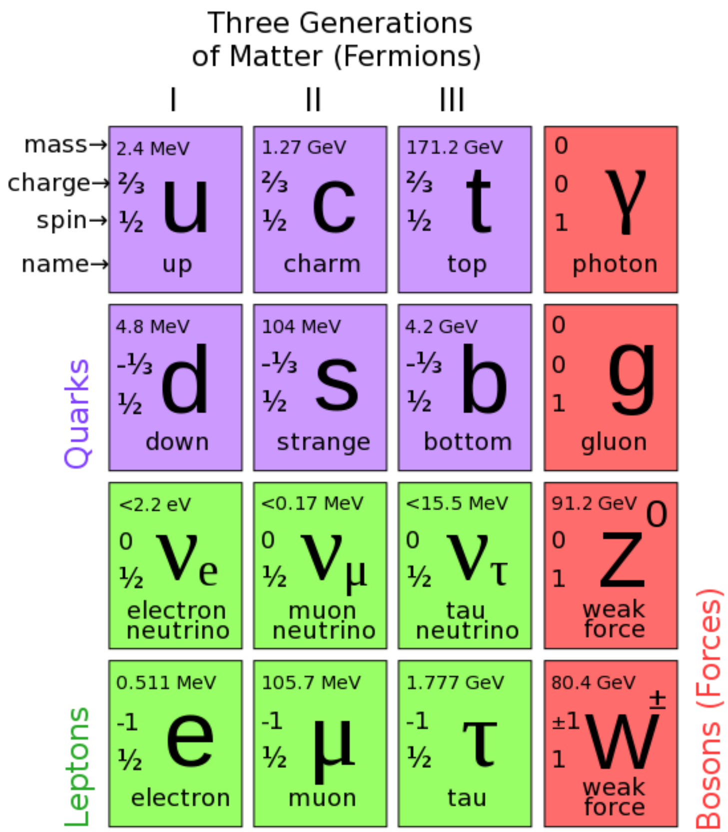
Requiring different global and local symmetries defines a theory!

AND

Keep in mind that they can be broken!

The Standard Model of particle physics

"*The Standard Model is a quantum field theory based on the local symmetry group* $SU(3) \times SU(2) \times U(1)$."



$SU(3)_c \longrightarrow$ strong force (g)

$SU(2)_L \times U(1)_Y$ electroweak force (W, Z, γ)

particle multiplets:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} u \\ d \end{pmatrix}_L \leftrightarrow \underbrace{\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}_L}_{SU(3)} \Big\} SU(2)$$

$$e_R \ , \ u_R = (u \ u \ u)_R \ , \ d_R = (d \ d \ d)_R$$

Masses of Z and W bosons: indication of EW symmetry breaking.

Fermion masses: very strong hierarchy, unexplained.

Spectrum of ideas to explain EWSB

based on weakly or strongly coupled dynamics embedded into some more fundamental theory at a scale Λ (probably $\simeq$ TeV)

- ▷ Elementary Higgs: SM, 2HDM, SUSY (MSSM, NMSSM,. . .), . . .
- ▷ Composite Higgs: technicolor, little Higgs models, . . .
- ▷ Extra Dimensions: flat,warped, . . .
- ▷ Higgsless models
- ▷ . . .

$$\Downarrow$$

All introduce new particles at scales now accessible to the LHC.

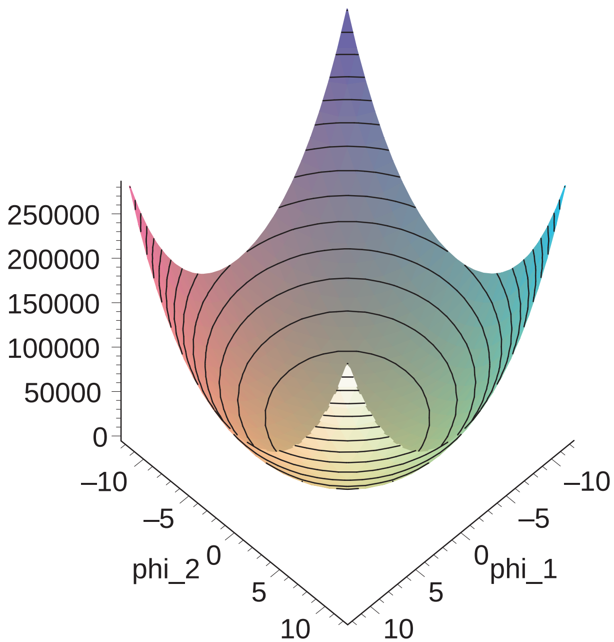
Focus on "elementary Higgs" for the rest of this talk.

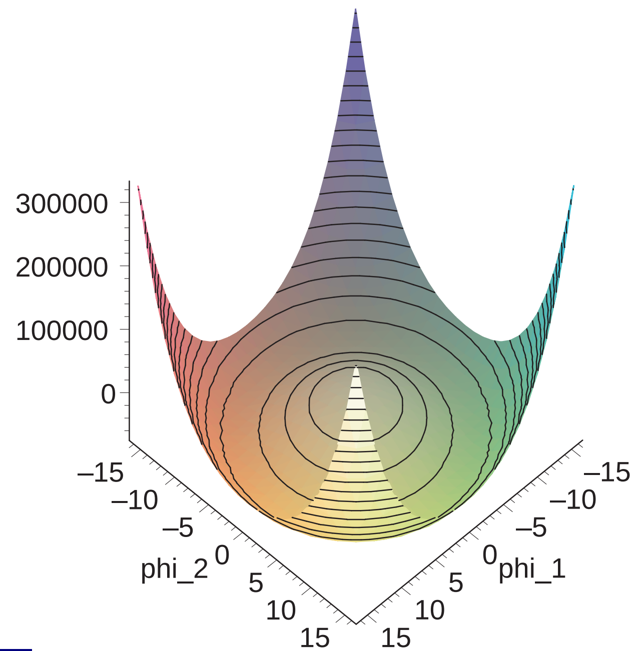
The Higgs sector of the Standard Model in a nutshell

Introduce one complex scalar doublet of $SU(2)_L$ (4 degrees of freedom):

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \longleftrightarrow \quad \begin{array}{l} \mathcal{L} = D^\mu \phi^\dagger D_\mu \phi - V(\phi, \phi^\dagger) \\ V(\phi, \phi^\dagger) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \end{array}$$

coupled to gauge fields in a gauge invariant way (via D_μ).





$\boxed{\mu^2 > 0}$ $\longrightarrow$ unique minimum:

$$\phi^\dagger \phi = 0$$

$\boxed{\mu^2 < 0}$ $\longrightarrow$ degeneracy of minima:

$$\phi^\dagger \phi = \frac{-\mu^2}{2\lambda}$$

The EW symmetry is spontaneously broken, such that $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$, when $\langle\phi\rangle$ (vacuum expectation value or v.e.v.) is chosen to be (e.g.):

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v \end{array}\right) \quad \text{with} \quad v = \left(\frac{-\mu^2}{\lambda}\right)^{1/2} \quad (\mu^2 < 0,\ \lambda > 0)$$

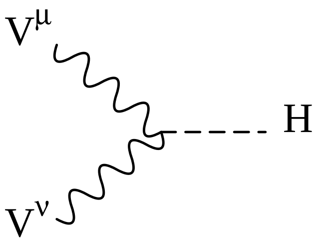
As a consequence:

- Z and $W^{\pm}$ acquire mass: $\boxed{M_W = g\frac{v}{2}}$ and $\boxed{M_Z = \sqrt{g^2 + g'^2}\,\frac{v}{2}}$
- 3 degrees of freedom are absorbed to give longitudinal components to the (now massive) Z and $W^{\pm}$ gauge bosons
- one degree of freedom remains: the physical Higgs boson with mass $\boxed{M_H = -2\mu^2 = 2\lambda v^2}$

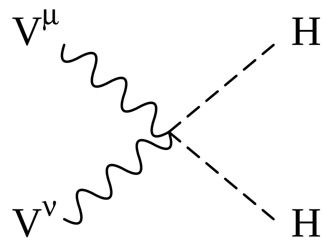
The Higgs-gauge boson sector depends on only two parameters, e.g M_H and v
(and v measured in μ-decay: $v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV)

very constrained → very testable

In the broken theory, the Higgs boson interacts with Z and W

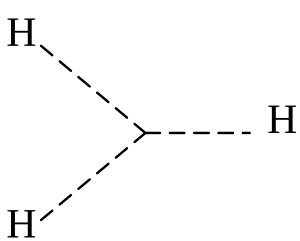


$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$

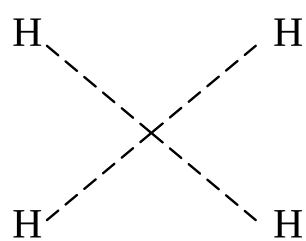


$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

and with itself



$$= -3i\frac{M_H^2}{v}$$



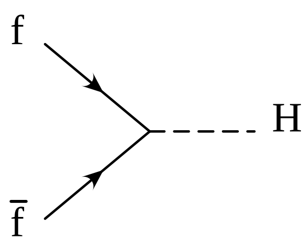
$$= -3i\frac{M_H^2}{v^2}$$

always preferring massive objects!

Meanwhile, but independently!

- masses are given to elementary fermions via Yukawa interactions ($\sim y_f \bar{f} f \phi$) such that upon EWSB $\boxed{m_f = y_f v}$

and the Higgs boson interacts with fermions according to



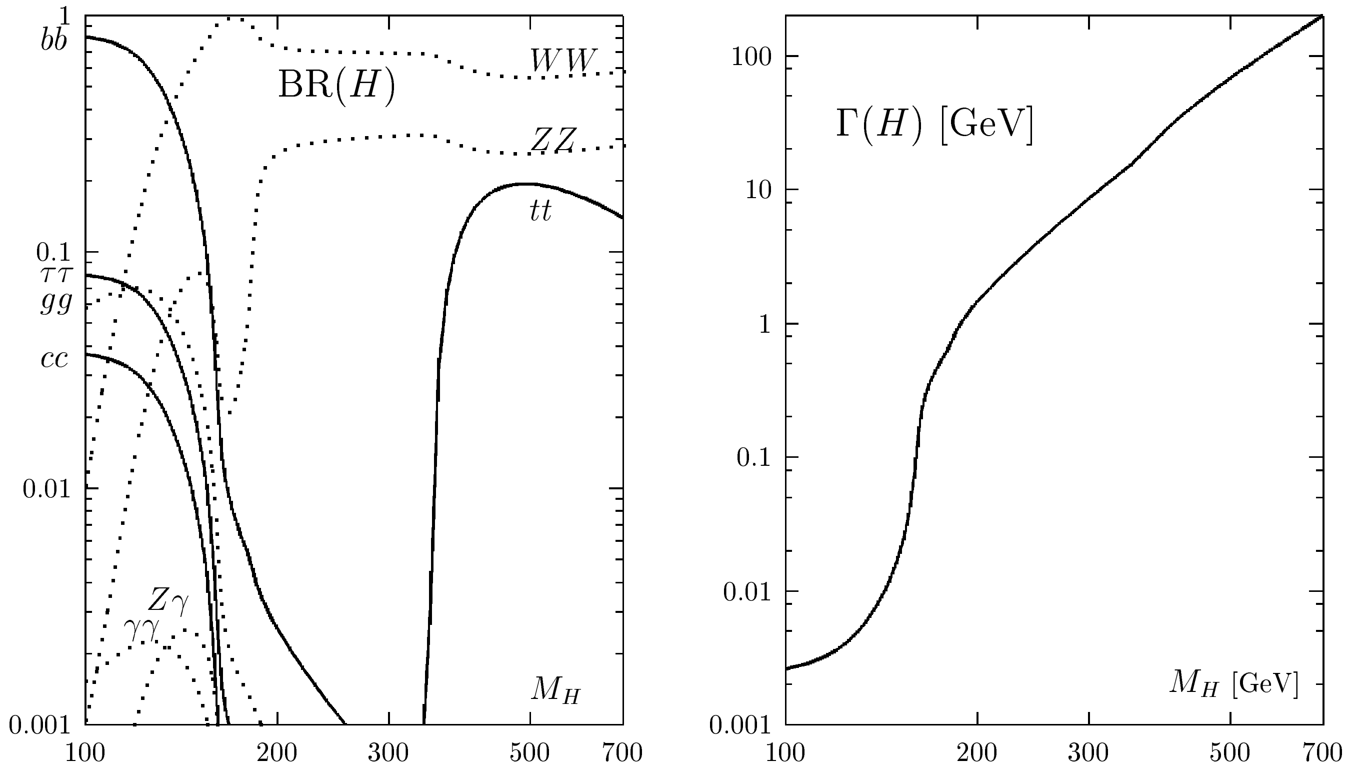
$$= -i\frac{m_f}{v} = -i y_f$$

$$\Downarrow$$

Less robust: dependence on several arbitrary parameters (y_f)

SM Higgs boson decay branching ratios at a glance

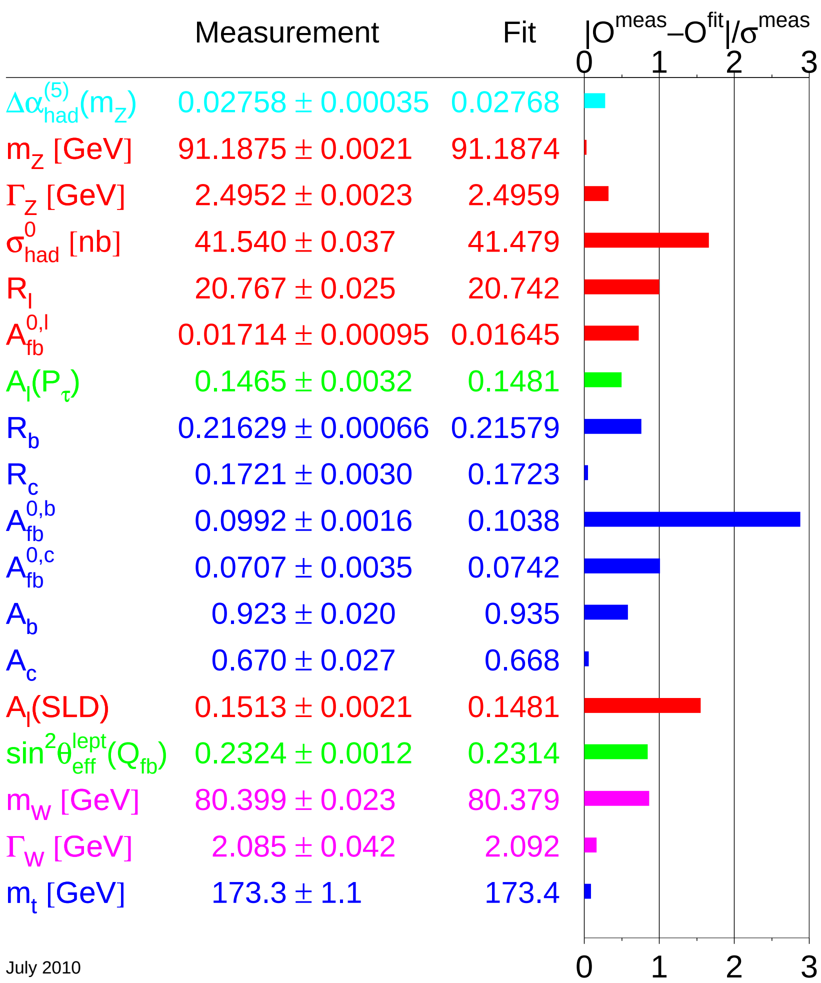
Light vs heavy Higgs boson: very different behavior.



Curves include the full quantum structure of strong and electroweak corrections.

Precision EW Physics confirms the SM

LEP, SLD, and Run I+II of the Tevatron have and are thoroughly testing the Standard Model (SM) of EW interactions (see LEP EWWG web page)



$\longrightarrow$ only high Q^2 data included

plus

direct measurements (Tevatron):

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

and

$$M_W = 80.399 \pm 0.023 \text{ GeV}$$

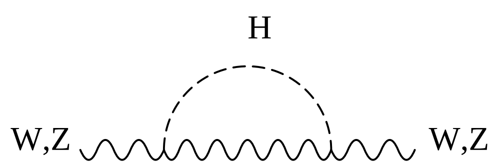
$$\Gamma_W = 2.098 \pm 0.048 \text{ GeV}$$

EW precision fits: perturbatively calculate observables in terms of few parameters:

$$M_Z, G_F, \alpha(M_Z), M_W, m_f, (\alpha_s(M_Z))$$

extracted from experiments with high accuracy.

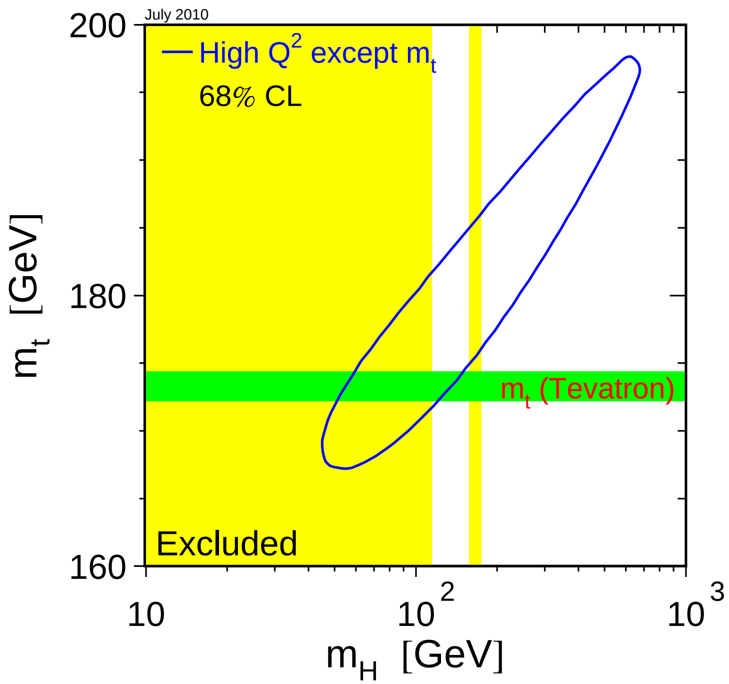
▷ Higgs boson quantum corrections modify theoretical predictions for SM parameters (masses, couplings), e.g.

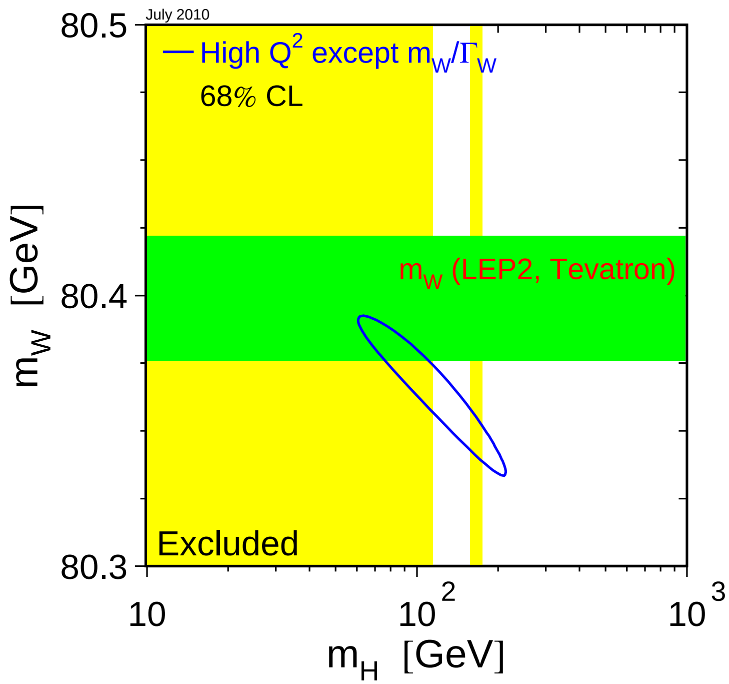
$M_W, M_Z \longrightarrow$ 

▷ Finite logarithmic contributions survive in radiative corrections: strong correlations between M_H and other SM parameters.

▷ New physics at a given scale Λ will appear as higher dimension effective operators that has to *mimic* the effect of the SM Higgs boson or *improve the fit*.

Ex.: correlation between M_W and M_H





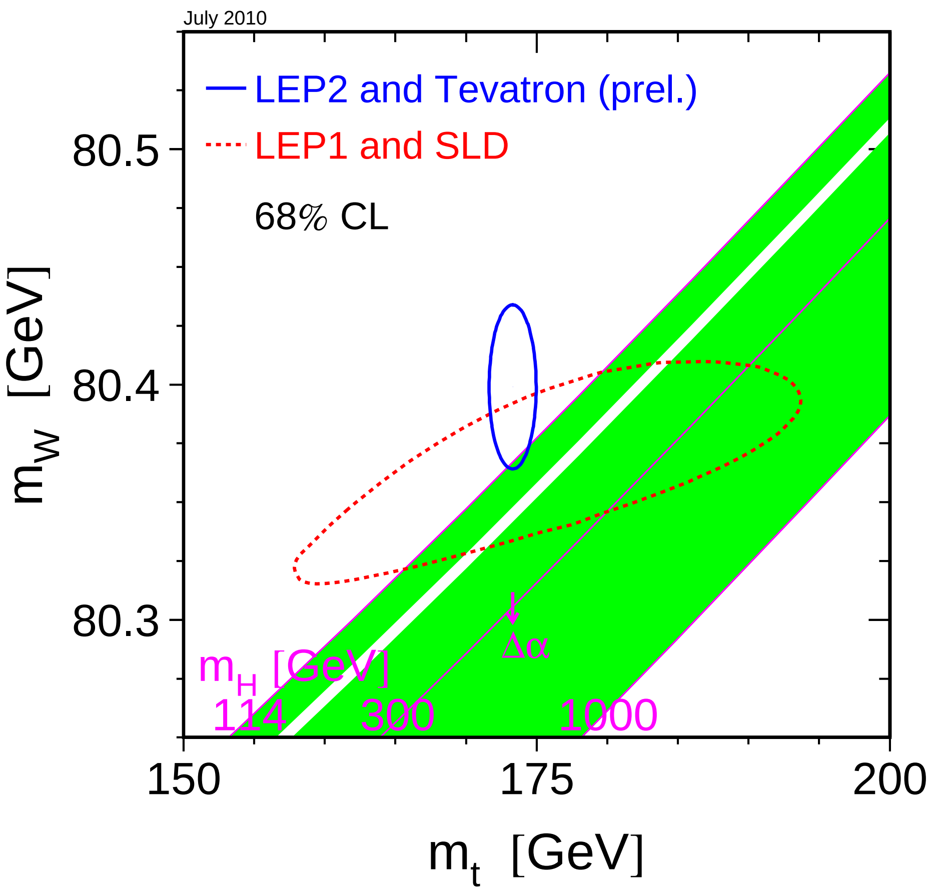
$$
\begin{aligned}
M_W/(\mathrm{GeV}) &= 80.409 - 0.507\left(\frac{\Delta\alpha_h^{(5)}}{0.02767} - 1\right) + 0.542\left[\left(\frac{m_t}{178\,\mathrm{GeV}}\right)^2 - 1\right] \\
&- 0.05719\ln\left(\frac{M_H}{100\,\mathrm{GeV}}\right) - 0.00898\ln^2\left(\frac{M_H}{100\,\mathrm{GeV}}\right)
\end{aligned}
$$

A. Ferroglia, G. Ossola, M. Passera, A. Sirlin, PRD 65 (2002) 113002

W. Marciano, hep-ph/0411179

Light SM Higgs boson strongly favored

Increasing precision will provide an invaluable tool to test the consistency of the SM and its extensions.



$$m_W = 80.399 \pm 0.023 \text{ GeV}$$

$$m_t = 173.3 \pm 1.1 \text{ GeV}$$

$$\Downarrow$$

$$M_H = 89^{+35}_{-26} \text{ GeV}$$

$$M_H < 158\,(185) \text{ GeV}$$

plus exclusion limits (95% c.l.):

$$M_H > 114.4 \text{ GeV (LEP)}$$

$$M_H \neq 158 - 175 \text{ GeV (Tevatron)}$$

Experimental uncertainties, estimate

	Present	Tevatron	LHC	LC	GigaZ
$\delta(M_W)$(MeV)	23	27	10-15	7-10	7
$\delta(m_t)$ (GeV)	1.1	2.7	1.0	0.2	0.13
$\delta(M_H)/M_H$ (indirect)	30%	35%	20%	15%	8%

(U. Baur, LoopFest IV, August 2005)

Intrinsic theoretical uncertainties

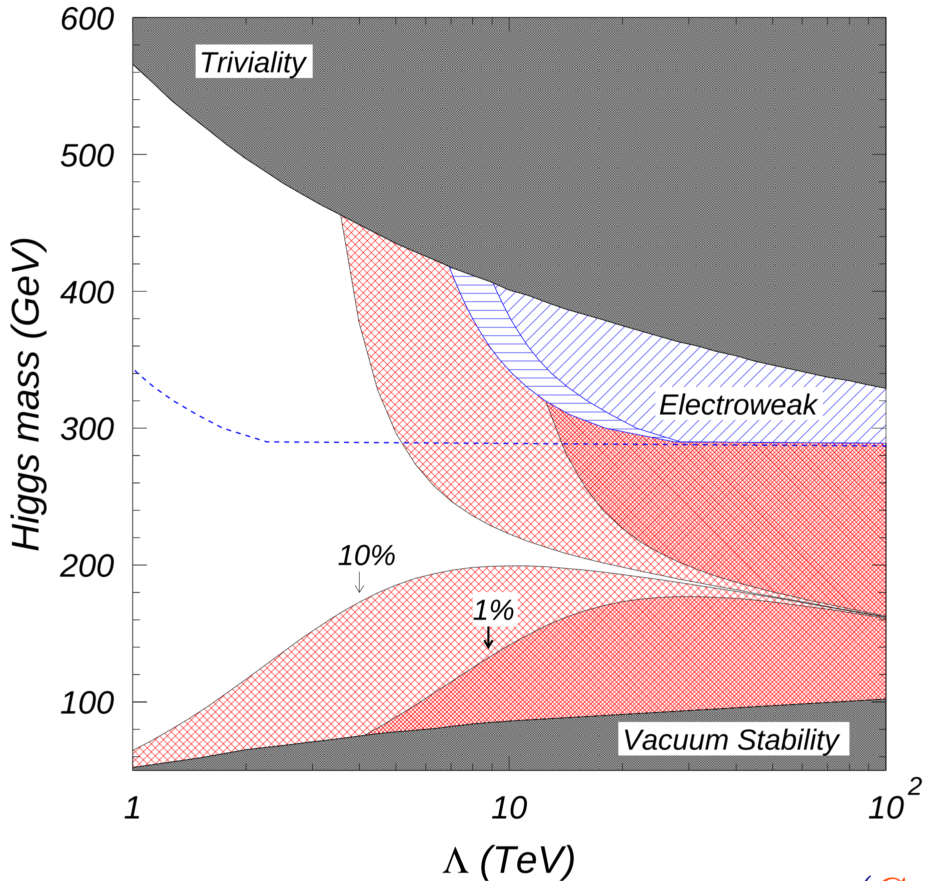
$\longrightarrow$ $\delta M_W \approx 4$ MeV: full $O(\alpha^2)$ corrections computed.

(M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, PRD 69:053006,2004)

$\longrightarrow$ estimated: $\Delta m_t/m_t \sim 0.2\Delta\sigma/\sigma + 0.03$ (LHC)

(R. Frederix and F. Maltoni, JHEP 0901:047,2009)

Does a light SM Higgs constrain new physics?



$\Lambda \to$ scale of new physics

amount of fine tuning $=$

$$\frac{2\Lambda^2}{M_H^2}\left|\sum_{n=0}^{n_{max}} c_n(\lambda_i)\log^n(\Lambda/M_H)\right|$$

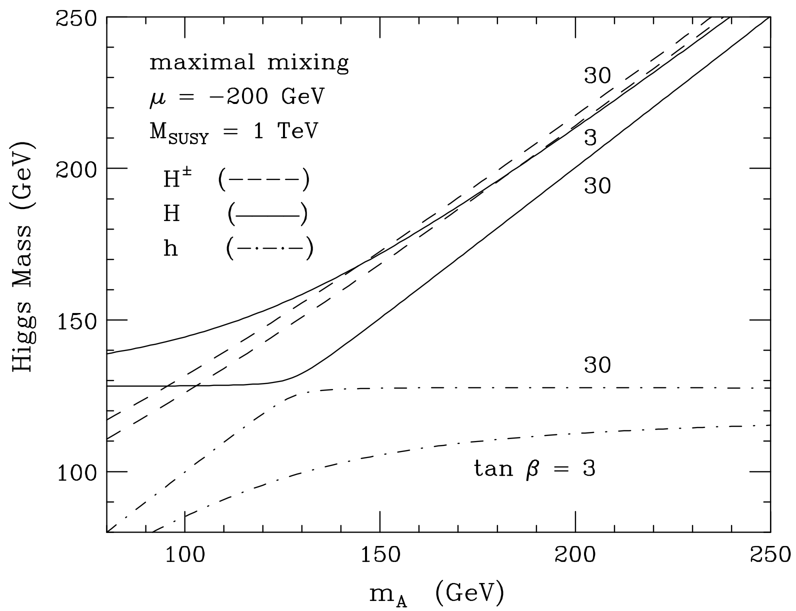
$\longleftarrow n_{max} = 1$

(C. Kolda and H. Murayama, JHEP 0007:035,2000)

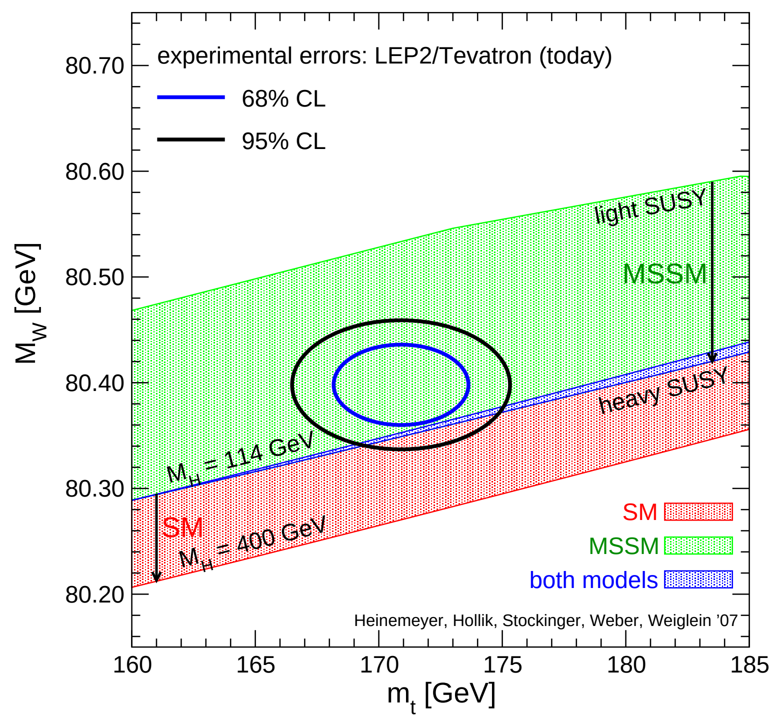
Light Higgs consistent with low Λ: new physics at the TeV scale.

Beyond SM: new physics at the TeV scale can be a better fit

Ex. 1: MSSM



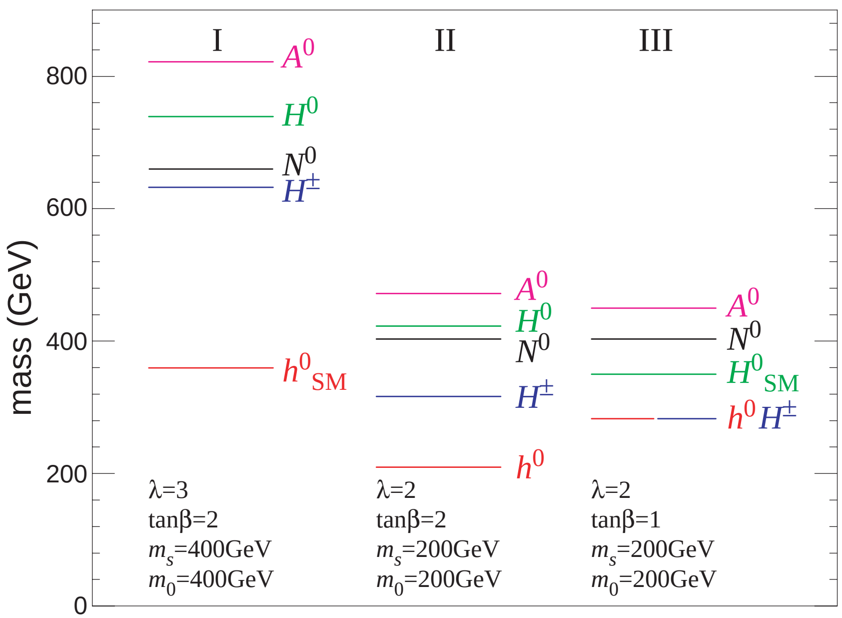
(M. Carena et al.)

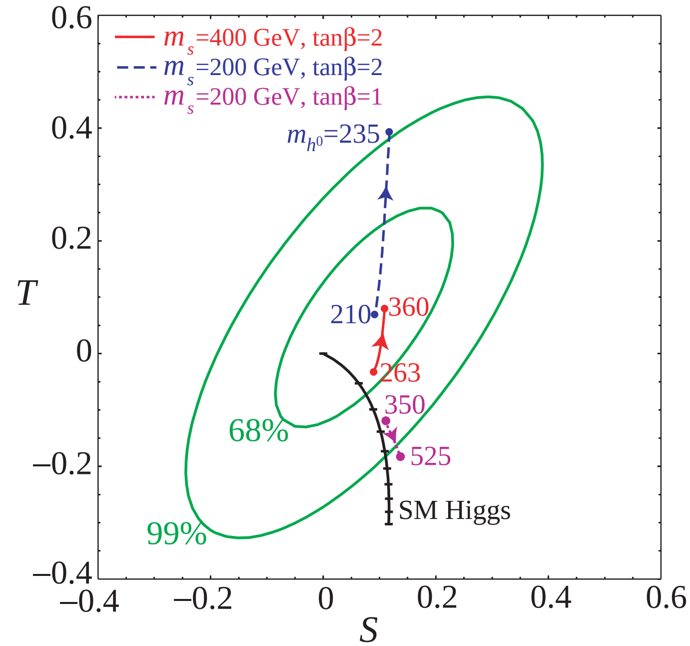


- ▷ a light scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ similar although less constrained pattern in any 2HDM;
- ▷ MSSM main uncertainty: unknown masses of SUSY particles.

Beyond SM: new physics at the TeV scale can be a better fit

Ex. 2: "Fat Higgs" models





(Harnik, Kribs, Larson, and Murayama, PRD 70 (2004) 015002)

- ▷ supersymmetric theory of a composite Higgs boson;
- ▷ moderately heavy lighter scalar Higgs boson, along with a heavier scalar, a pseudoscalar and a charged scalar;
- ▷ consistent with EW precision measurements without fine tuning.

This is why we believe that new physics can appear at both the Tevatron and the LHC

Will we see it?

- $\triangleright$ Spectrum of ideas to explain EWSB:
  elementary/composite Higgs,extra dimensions, higgsless models, ...
  after many decades we are truly "facing the unknown"!

- $\triangleright$ Searching for the SM Higgs boson will be our learning ground

Upon discovery:

  $\longrightarrow$ measure mass (first crucial discriminator!);

  $\longrightarrow$ measure couplings to gauge bosons and fermions;

  $\longrightarrow$ test the potential: measure self couplings;

  $\longrightarrow$ hope to see more physics.

- $\triangleright$ Beyond SM we could have:

  $\longrightarrow$ more scalars and/or pseudoscalars particles over broad mass spectrum;

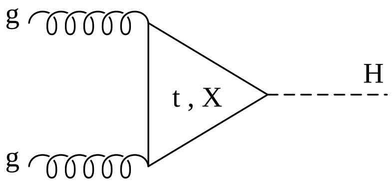
  $\longrightarrow$ no scalar (!);

  $\longrightarrow$ several other particles (fermions and vector gauge bosons).

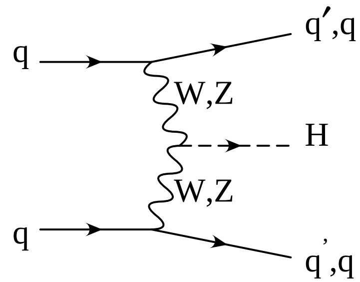
  $\longrightarrow$ lots of room for unknown parameters to be adjusted: little predictivity until discoveries won't populate more the physical spectrum.

$p\bar{p}, pp$ colliders: SM Higgs production modes

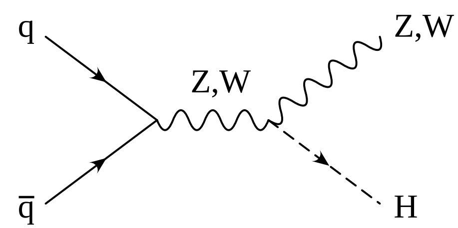
$gg \to H$



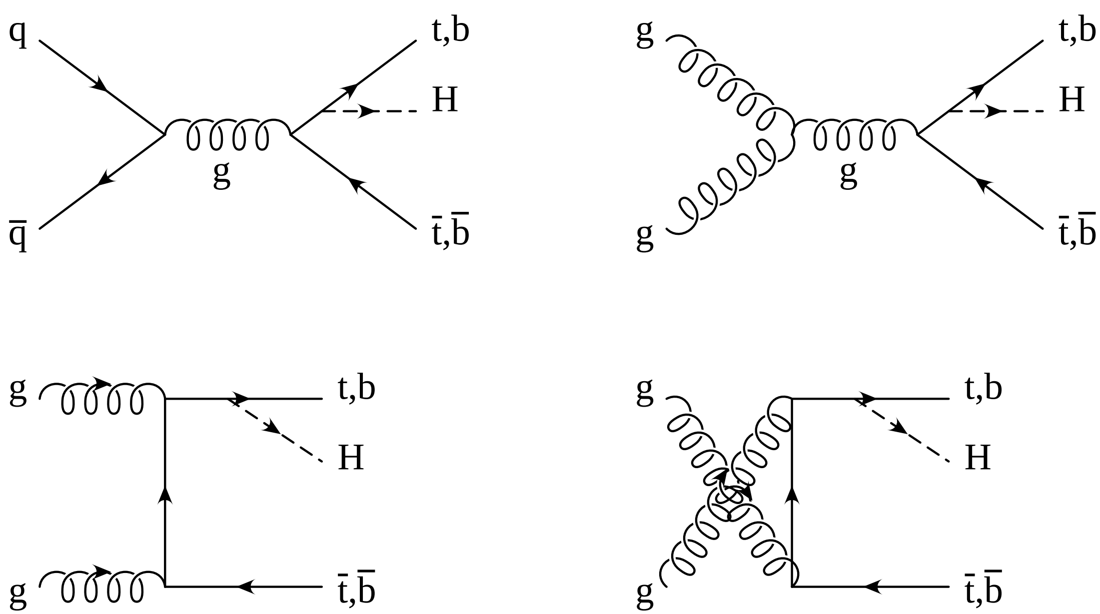
$qq \to qqH$



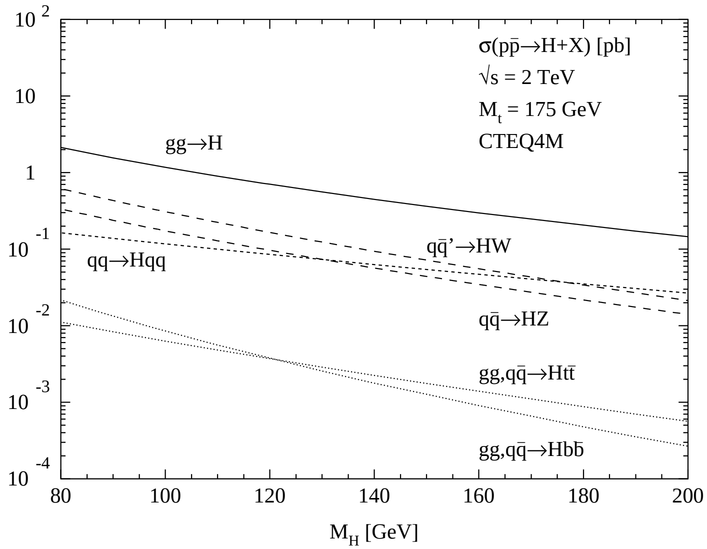
$qq \to WH, ZH$

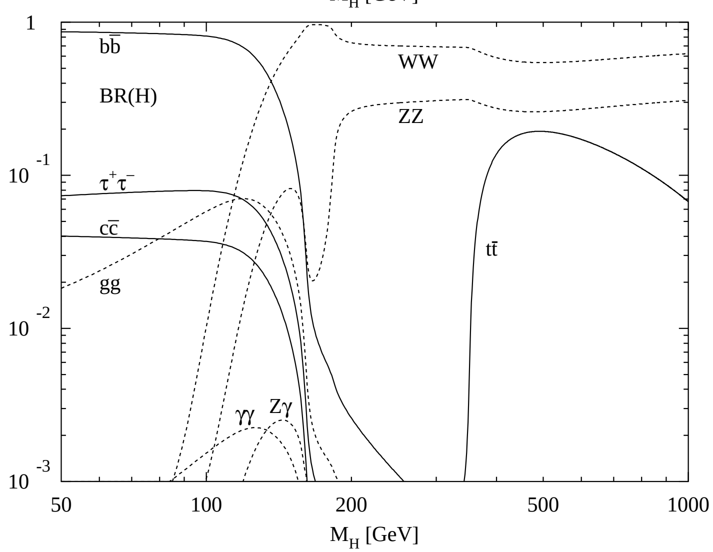


$q\bar{q}, gg \to t\bar{t}H, b\bar{b}H$



Tevatron: great potential for a light SM-like Higgs boson





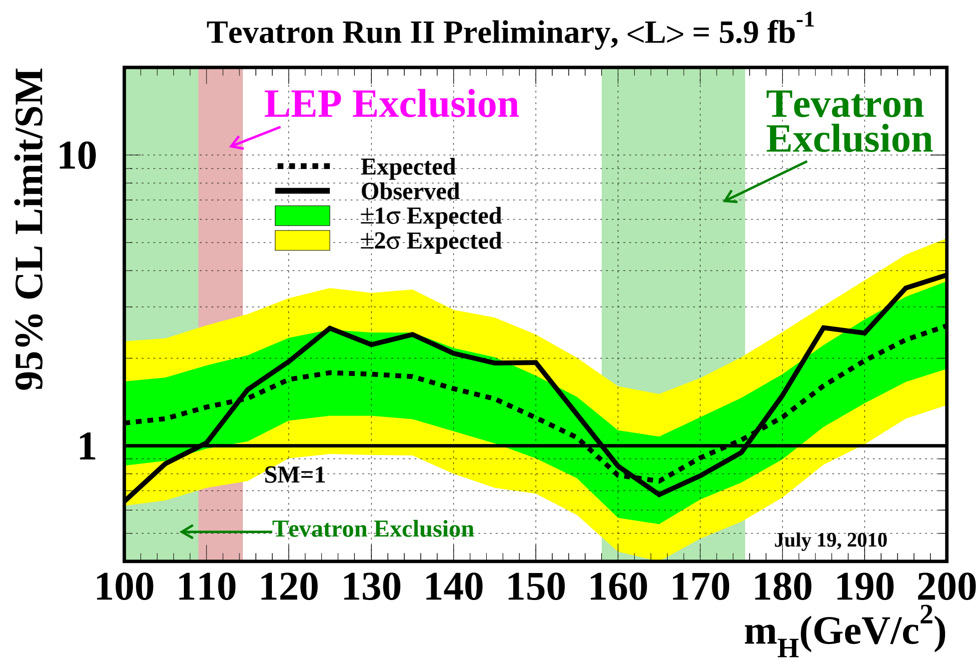
(M. Spira, Fortsch.Phys. 46 (1998) 203)

Several channels used:

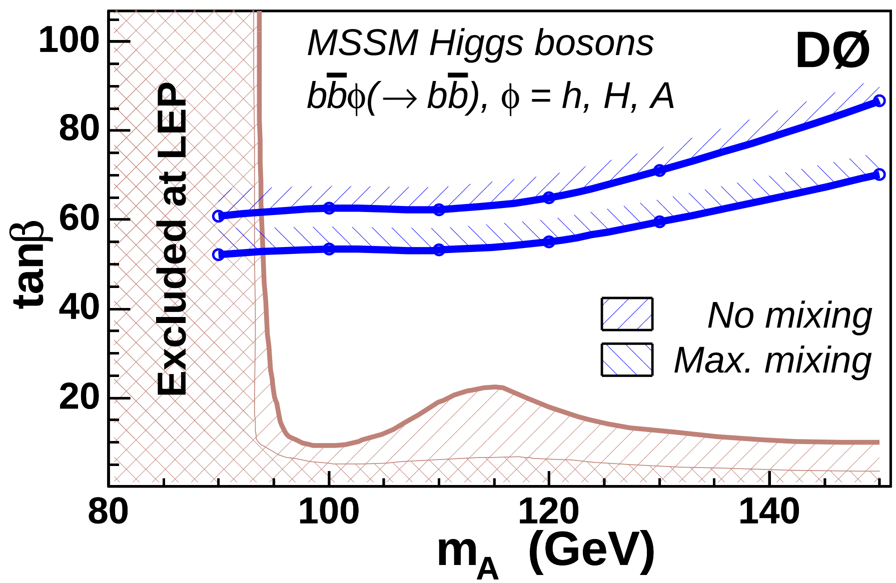
$$gg \to H,\ q\bar{q} \to q'\bar{q}'H,$$
$$q\bar{q}' \to WH,\ q\bar{q}, gg \to t\bar{t}H$$

with

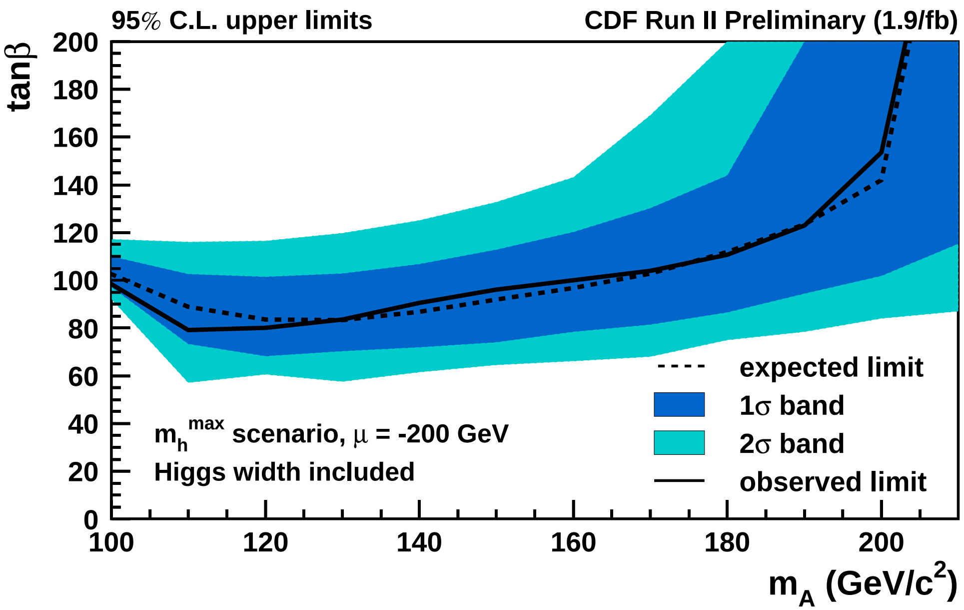
$$H \to b\bar{b}, \tau^+\tau^-, W^+W^-, \gamma\gamma$$



. . . and first constraints on MSSM parameters from Higgs physics



(DØ, PRL 95 (2005) 151801)

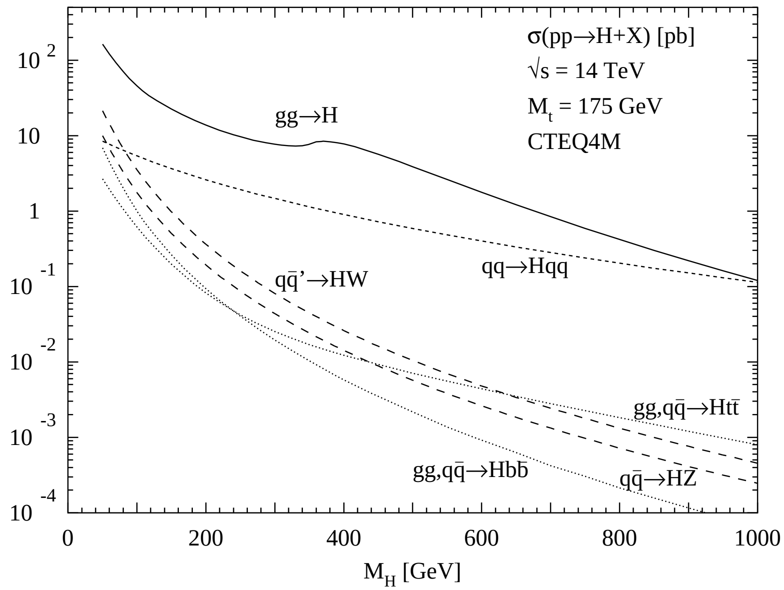


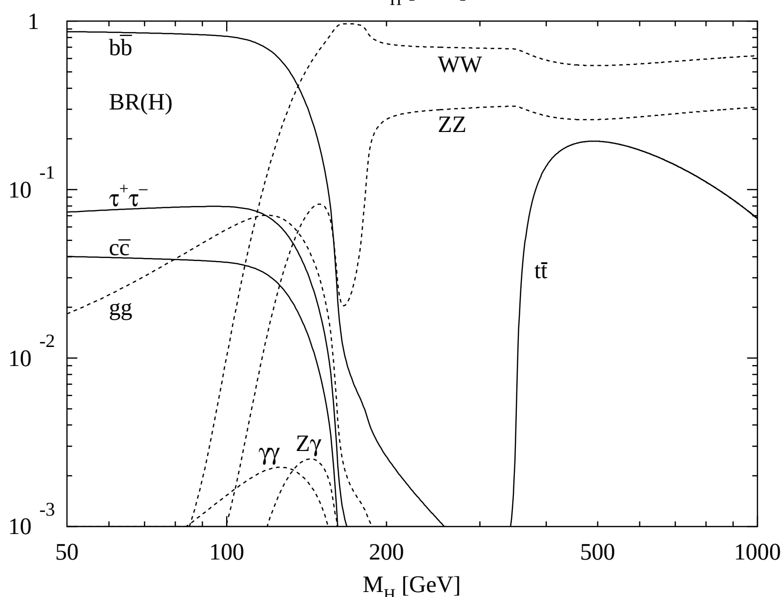
(CDF, Note 9284, 2008)

$$g^{MSSM}_{b\bar{b}h^0,H^0} = \frac{(-\sin\alpha, \cos\alpha)}{\cos\beta} g_{b\bar{b}H} \quad \text{and} \quad g^{MSSM}_{b\bar{b}A^0} = \tan\beta \; g_{b\bar{b}H}$$

where $g_{b\bar{b}H} = m_b/v \simeq 0.02$ (Standard Model) and $\tan\beta = v_1/v_2$ (MSSM).

LHC: entire SM Higgs mass range accessible





(M. Spira, Fortsch.Phys. 46 (1998) 203)

Many channels have been studied:

Below 130-140 GeV:

$gg \to H \, , \, H \to \gamma\gamma, WW, ZZ$

$qq \to qqH \, , \, H \to \gamma\gamma, WW, ZZ, \tau\tau$

$q\bar{q}, gg \to t\bar{t}H \, , \, H \to \gamma\gamma, b\bar{b}, \tau\tau$

$q\bar{q}' \to WH \, , \, H \to \gamma\gamma, b\bar{b}$

Above 130-140 GeV:

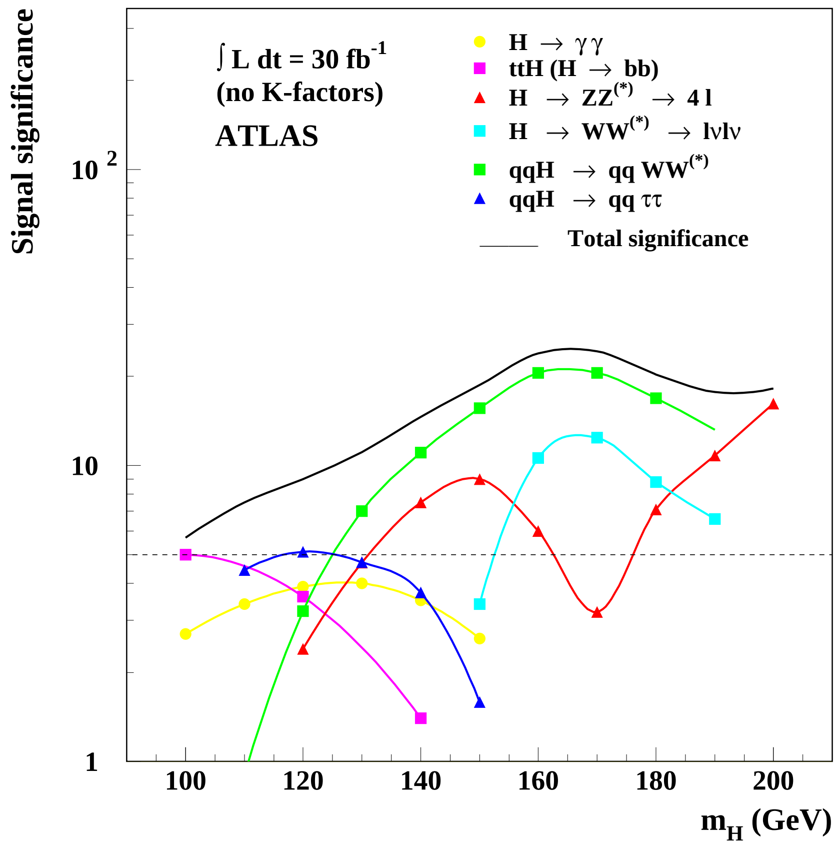
$gg \to H \, , \, H \to WW, ZZ$

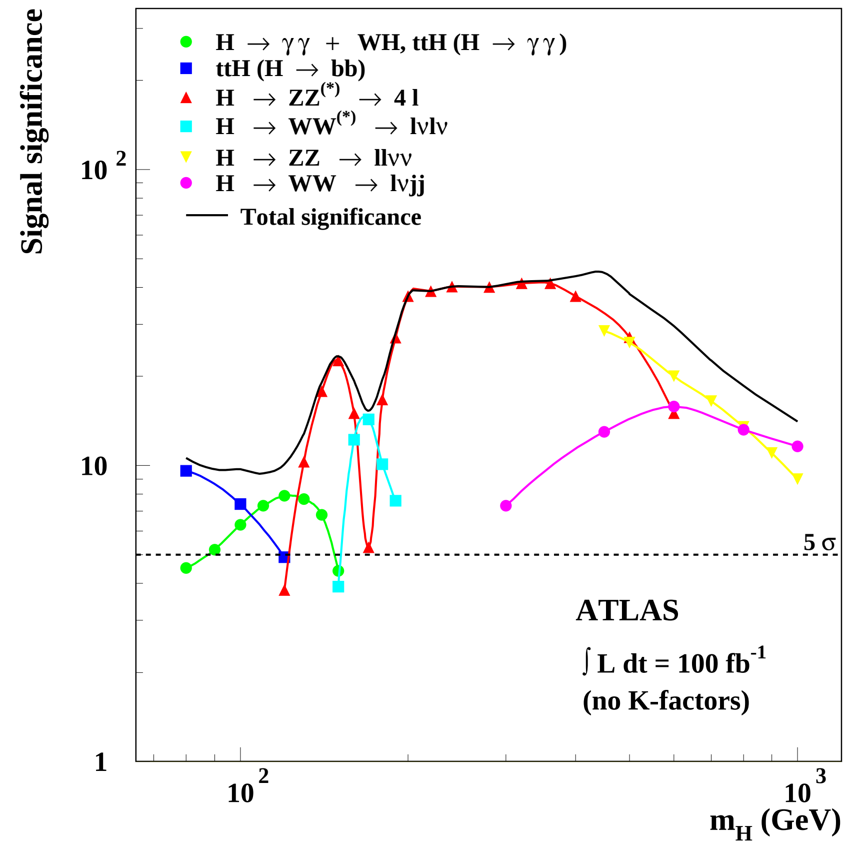
$qq \to qqH \, , \, H \to \gamma\gamma, WW, ZZ$

$q\bar{q}, gg \to t\bar{t}H \, , \, H \to \gamma\gamma, WW$

$q\bar{q}' \to WH \, , \, H \to WW$

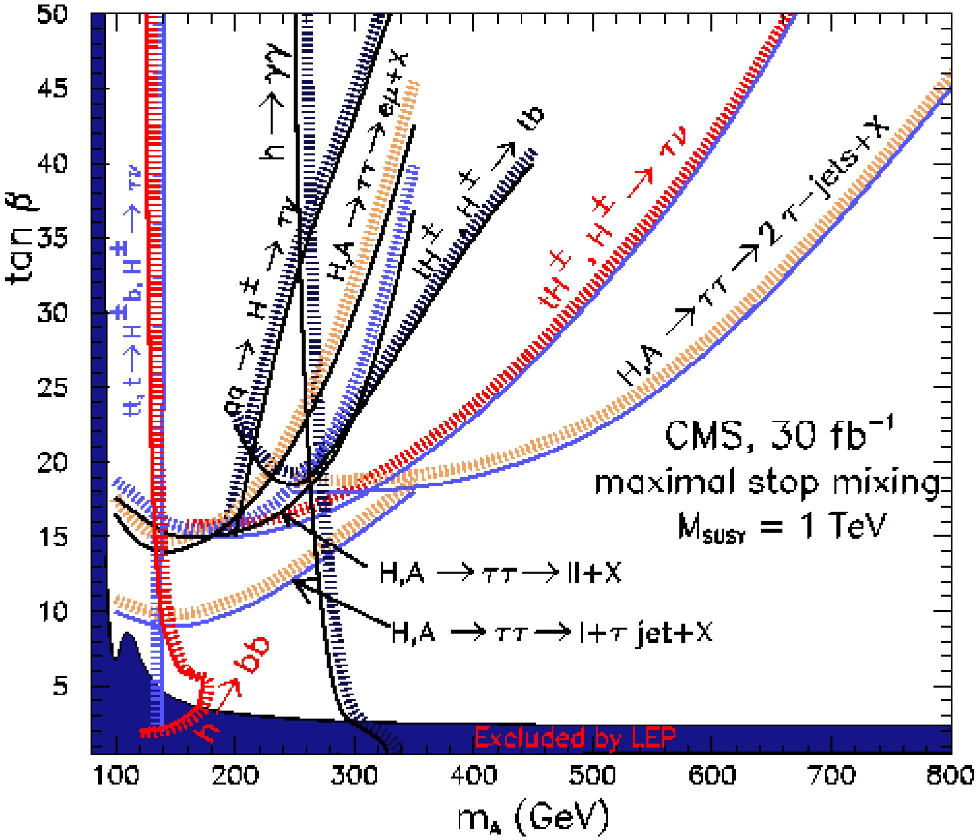
LHC: discovery reach for a SM Higgs boson

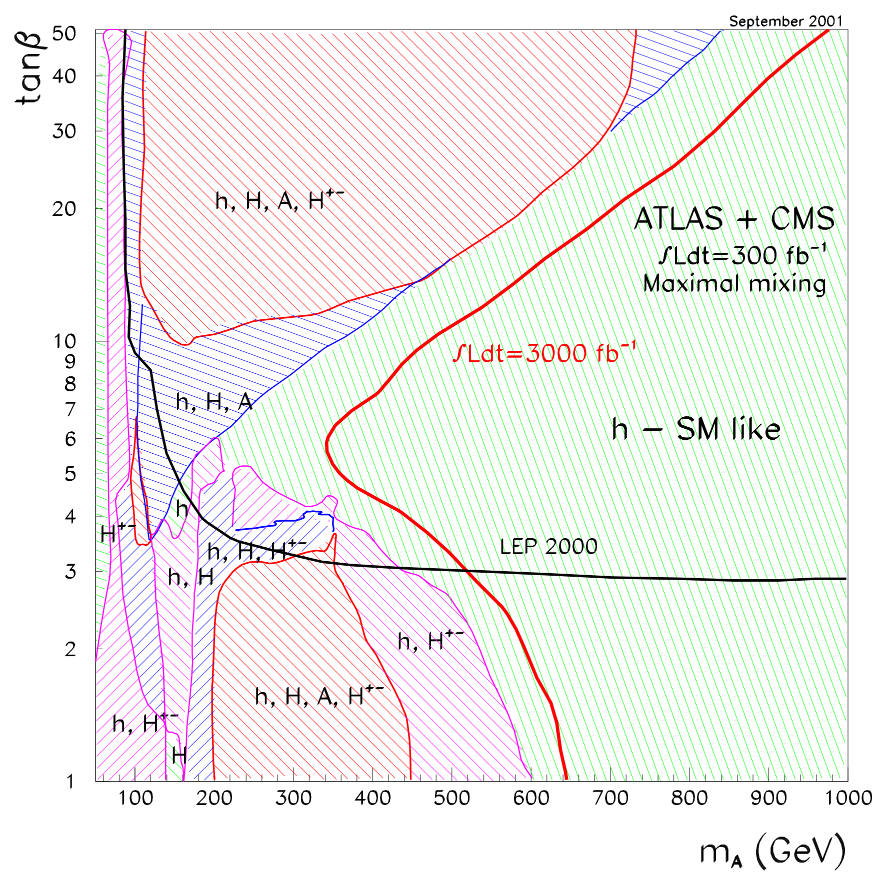




- ▷ Low mass region difficult at low luminosity: need to explore as many channels as possible. Indications from the Tevatron most valuable!
- ▷ high luminosity reach needs to be updated;
- ▷ identifying the SM Higgs boson requires high luminosity, above 100 fb^{-1}: very few studies exist above 300 fb^{-1} (per detector).

LHC: discovery reach in the MSSM parameter space

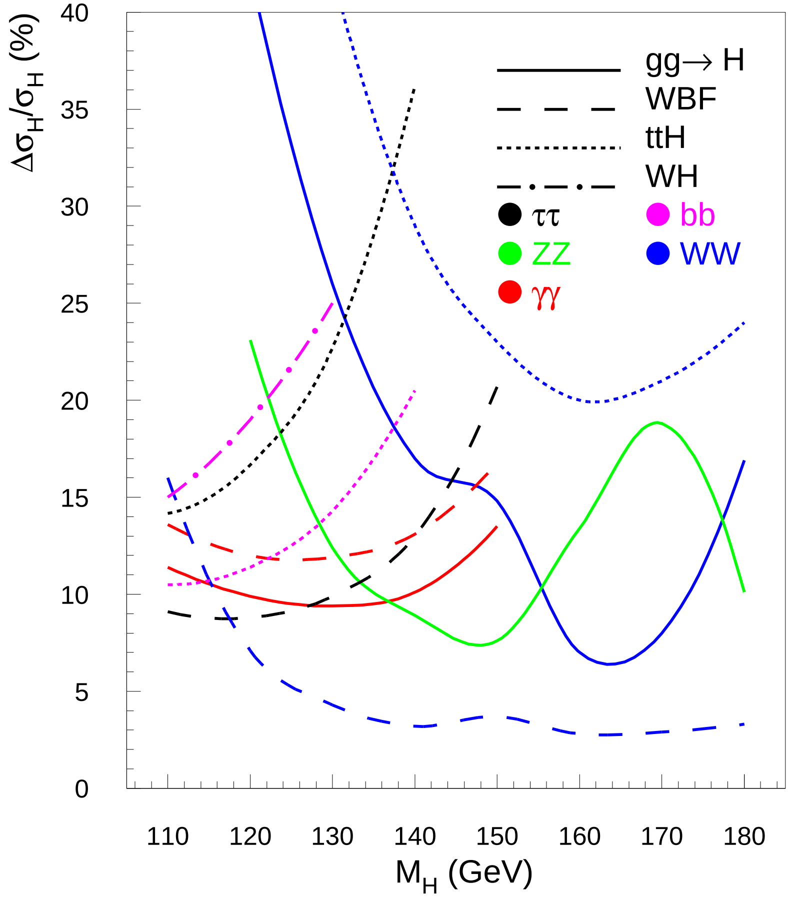




Low luminosity, CMS only

High luminosity, ATLAS+CMS

LHC: can measure most SM Higgs couplings at 10-30%



Consider all "accessible" channels:

- Below 130-140 GeV

  $gg \to H\ ,\ H \to \gamma\gamma, WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ, \tau\tau$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to \gamma\gamma, b\bar{b}, \tau\tau$

  $q\bar{q}' \to WH\ ,\ H \to \gamma\gamma, b\bar{b}$

- Above 130-140 GeV

  $gg \to H\ ,\ H \to WW, ZZ$

  $qq \to qqH\ ,\ H \to \gamma\gamma, WW, ZZ$

  $q\bar{q}, gg \to t\bar{t}H\ ,\ H \to \gamma\gamma, WW$

  $q\bar{q}' \to WH\ ,\ H \to WW$

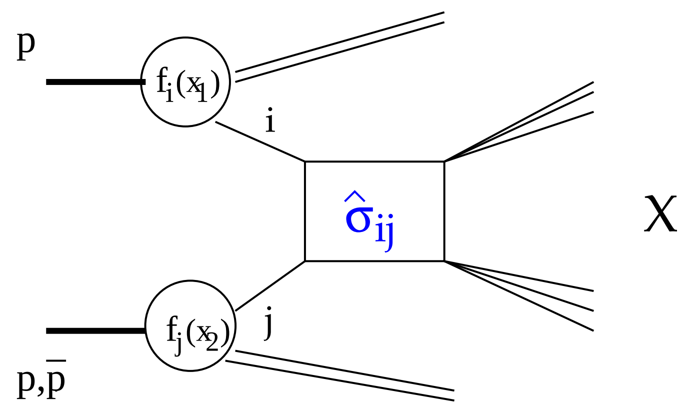
Observing a given production+decay (p+d) channel gives a relation:

$$(\sigma_p(H)\mathrm{Br}(H \to dd))^{exp} = \frac{\sigma_p^{th}(H)}{\Gamma_p^{th}} \frac{\Gamma_d \Gamma_p}{\Gamma_H}$$

(D. Zeppenfeld, PRD 62 (2000) 013009; A. Belyaev et al., JHEP 0208 (2002) 041)

How good are our theoretical predictions?

The basic picture of a $p\bar{p}, pp \to X$ high energy process ...



where the short and long distance part of the QCD interactions can be factorized and the cross section for $pp, p\bar{p} \to X$ can be calculated as:

$$\sigma(pp, p\bar{p} \to X) = \sum_{ij} \int dx_1 dx_2 f_i{}^p(x_1) f_j{}^{p,\bar{p}}(x_2) \hat{\sigma}(ij \to X)$$

$\longrightarrow$ $ij \to$ quarks or gluons (partons)

$\longrightarrow$ $f_i^p(x)$, $f_i^{p,\bar{p}}(x)$: Parton Distributions Functions: probability densities (probability of finding parton i in p or $\bar{p}$ with a fraction x of the original hadron momentum)

$\longrightarrow$ $\hat{\sigma}(ij \to X)$: partonic cross section

. . . is complicated by the presence of interactions

$\longrightarrow$ Focus on strong interactions, dominant at hadron colliders

$\longrightarrow$ In the $ij \to X$ process, initial and final state partons radiate and absorb gluons/quarks:

How to calculate the physical cross section?

$\longrightarrow$ Due to the very same interactions: the strong coupling constant ($\alpha_s = g_s^2/4\pi$) becomes a function of the energy scale (Q^2), such that

$\alpha_s(Q^2) \to 0$ for large scales Q^2 : running coupling

$$\Downarrow$$

we can calculate $\hat{\sigma}(ij \to X)$ perturbatively

$$\hat{\sigma}(ij \to X) = \alpha_s^k \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)} \alpha_s^m$$

n=0 : Leading Order (LO), or tree level or Born level

n=1 : Next to Leading Order (NLO), include $O(\alpha_s)$ corrections

. . . . . .

Perturbative approach and scale dependence

$\longrightarrow$ At each order in α_s the expression of $\hat{\sigma}(ij \to X)$ contains infinities that are canceled by a subtraction procedure: renormalization.

$\longrightarrow$ A remnant of the subtraction point is left at each perturbative order as a renormalization scale dependence (μ_R)

$$\hat{\sigma}(ij \to X) = \alpha_s^k(\mu_R) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu_R, Q^2)\alpha_s^m(\mu_R)$$

$\longrightarrow$ A similar approach introduces a subtraction point dependence in the initial state parton densities: factorization scale dependence (μ_F)

Setting $\boxed{\mu_R = \mu_F = \mu}$:

$$\sigma(pp, p\bar{p} \to X) = \sum_{ij} \int dx_1 dx_2 f_i^p(x_1, \mu) f_j^{p,\bar{p}}(x_2, \mu) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu, Q^2)\alpha_s^{m+k}(\mu)$$

Theoretical error is systematically organized as an expansion in α_s

Ex.: General structure of a NLO calculation

NLO total cross section:

$$\sigma^{NLO}_{p\bar{p},pp} = \sum_{i,j} \int dx_1 dx_2 f_i^p(x_1,\mu_F) f_j^{\bar{p},p}(x_2,\mu_F) \hat{\sigma}^{NLO}_{ij}(x_1,x_2,\mu_R,\mu_F)$$

where

$$\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{LO}_{ij} + \frac{\alpha_s}{4\pi} \delta\hat{\sigma}^{NLO}_{ij}$$

NLO corrections made of:

$$\delta\hat{\sigma}^{NLO}_{ij} = \hat{\sigma}^{ij}_{virt} + \hat{\sigma}^{ij}_{real}$$

- $\hat{\sigma}^{ij}_{virt}$: one loop virtual corrections.
- $\hat{\sigma}^{ij}_{real}$: one gluon/quark real emission.
- use $\alpha_s^{NLO}(\mu)$ and match with NLO PDF's.

$\longrightarrow$ renormalize UV divergences ($d\!=\!4-2\epsilon_{UV}$)

$\longrightarrow$ cancel IR divergences in $\hat{\sigma}_{virt} + \hat{\sigma}_{real}$ ($d\!=\!4-2\epsilon_{IR}$)

$\longrightarrow$ check μ-dependence of $\sigma^{NLO}_{p\bar{p},pp}$ (μ_R,μ_F)

Why pushing the Loop Order ...

- Stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales. First reliable normalization of total cross-sections and distributions. Crucial for:
  $\longrightarrow$ precision measurements (M_W, m_t, M_H, $y_{b,t}$, ...);
  $\longrightarrow$ searches of new physics (precise modelling of signal and background);
  $\longrightarrow$ reducing systematic errors in selection/analysis of data.

- Physics richness: more channels and more partons in final state, i.e. more structure to better model (in perturbative region):
  $\longrightarrow$ differential cross-sections, exclusive observables;
  $\longrightarrow$ jet formation/merging and hadronization;
  $\longrightarrow$ initial state radiation.

- First step towards matching with parton shower Monte Carlo programs.

Main challenges . . .

- Multiplicity and Massiveness of final state: complex events leads to complex calculations. For a $2 \to N$ process one needs:
  - $\longrightarrow$ calculation of the $2 \to N+1$ (NLO) or $2 \to N+2$ real corrections;
  - $\longrightarrow$ calculation of the 1-loop (NLO) or 2-loop (NNLO) $2 \to N$ virtual corrections;
  - $\longrightarrow$ explicit cancellation of IR divergences (UV-cancellation is standard).
- Flexibility of NLO/NNLO calculations via Automation:
  - $\longrightarrow$ algorithms suitable for automation are more efficient and force the adoption of standards;
  - $\longrightarrow$ faster response to experimental needs .
- Matching to Parton Shower Monte Carlos.
  - $\longrightarrow$ resum effects of leading kinematics configurations;
  - $\longrightarrow$ avoid double counting.

- NLO: challenges have largely been faced and enormous progress has been made:

  → traditional approach (FD's) becomes impracticable at high multiplicity;

  → new techniques based on unitarity methods and recursion relations offers a powerful and promising alternative, particularly suited for automation;

  → interface to parton shower well advanced.

- When is NLO not enough?

  → When NLO corrections are large, to tests the convergence of the perturbative expansion. This may happen when:

    ▷ processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
    ▷ new parton level subprocesses first appear at NLO;
    ▷ new dynamics first appear at NLO;
    ▷ ...

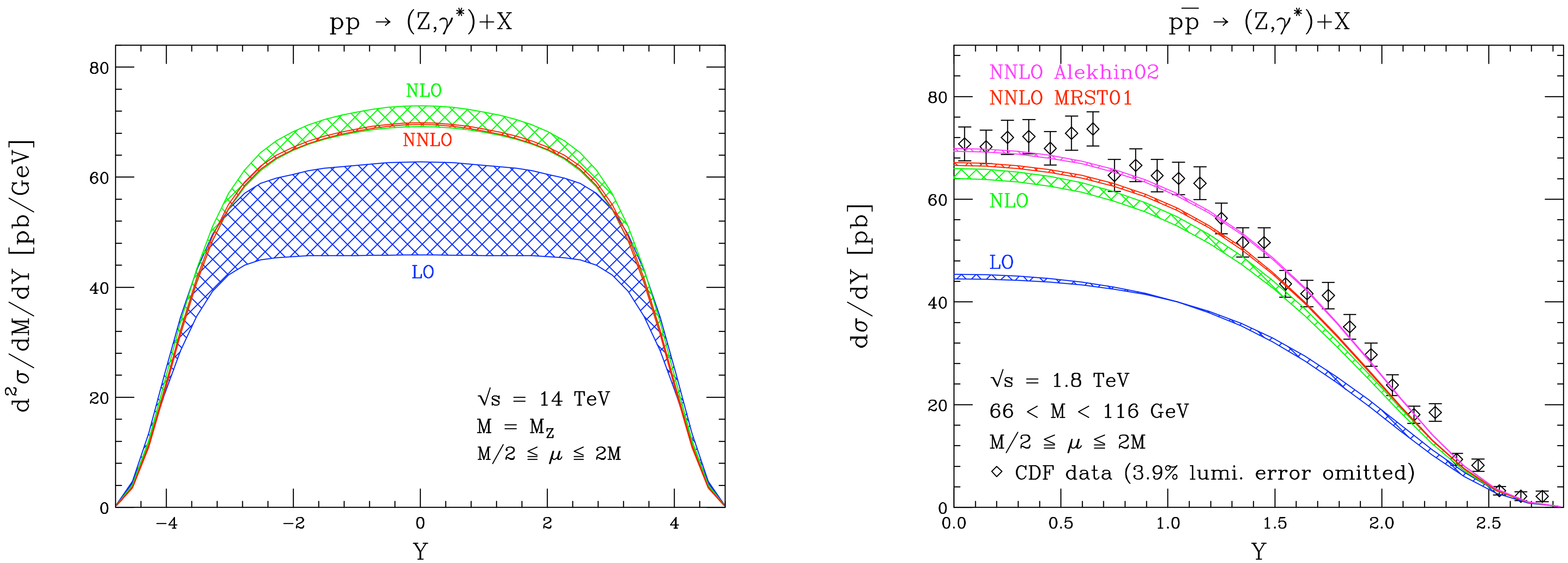
  → When truly high precision is needed (very often the case!).

  → When a really reliable error estimate is needed.

Ex. 1: W/Z production at the Tevatron and LHC.

Anastasiou, Dixon, Melnikov, Petriello (03)

Rapidity distributions of W and Z boson calculated at NNLO:

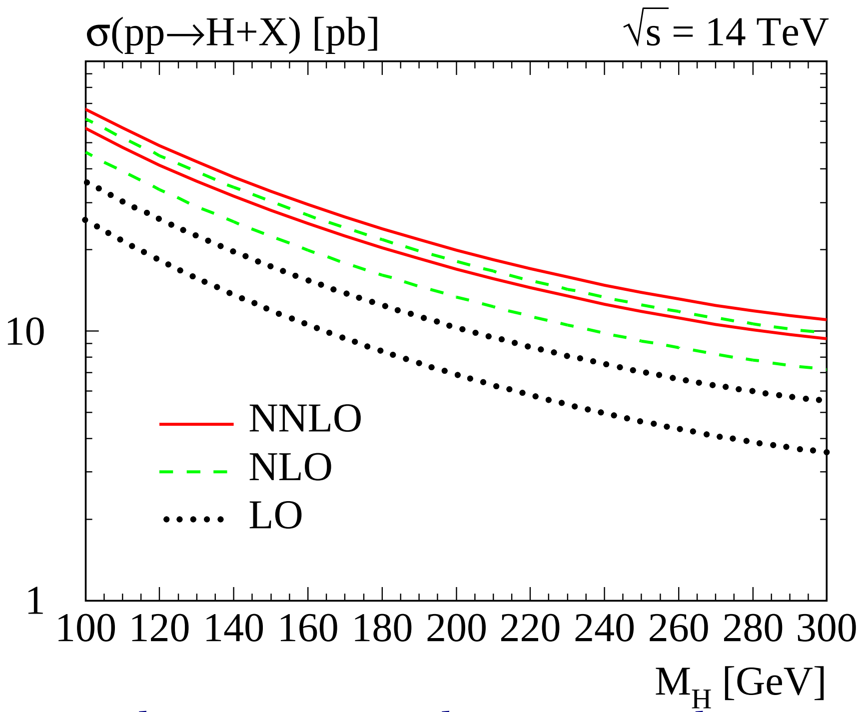


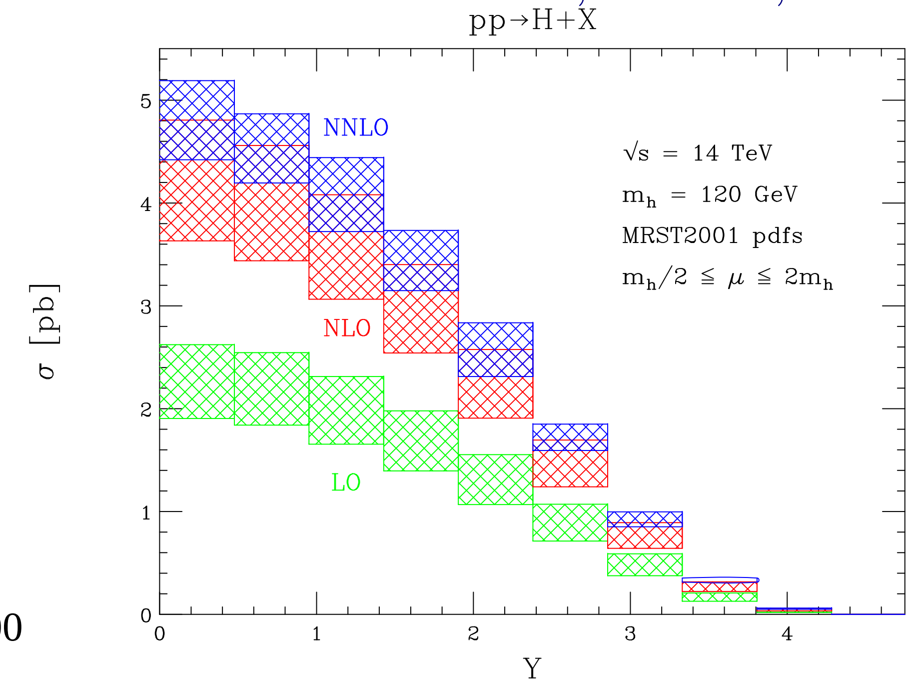
- W/Z production processes are standard candles at hadron colliders.
- Testing NNLO PDF's: parton-parton luminosity monitor, detector calibration (NNLO: 1% residual theoretical uncertainty).

Ex. 2: $gg \to H$ production at the Tevatron and LHC

Harlander,Kilgore (03)

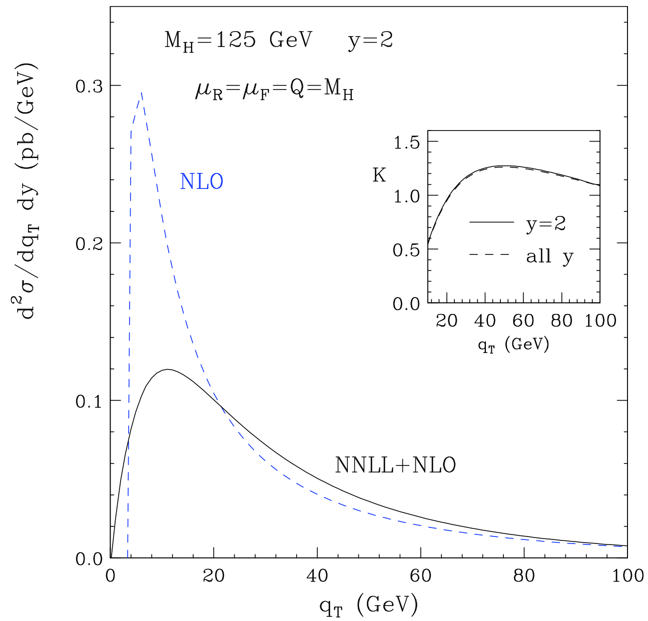
Anastasiou,Melnikov,Petriello (03)





- dominant production mode in association with $H \to \gamma\gamma$ or $H \to WW$ or $H \to ZZ$;
- perturbative convergence LO $\to$ NLO (70%) $\to$ NNLO (30%): residual 10% theoretical uncertainty.

Inclusive cross section, resum effects of soft radiation:



large $q_T \xrightarrow{q_T > M_H}$

perturbative expansion in $\alpha_s(\mu)$

small $q_T \xrightarrow{q_T \ll M_H}$

need to resum large $\ln(M_H^2/q_T^2)$

Bozzi,Catani,de Florian,Grazzini (04-08)

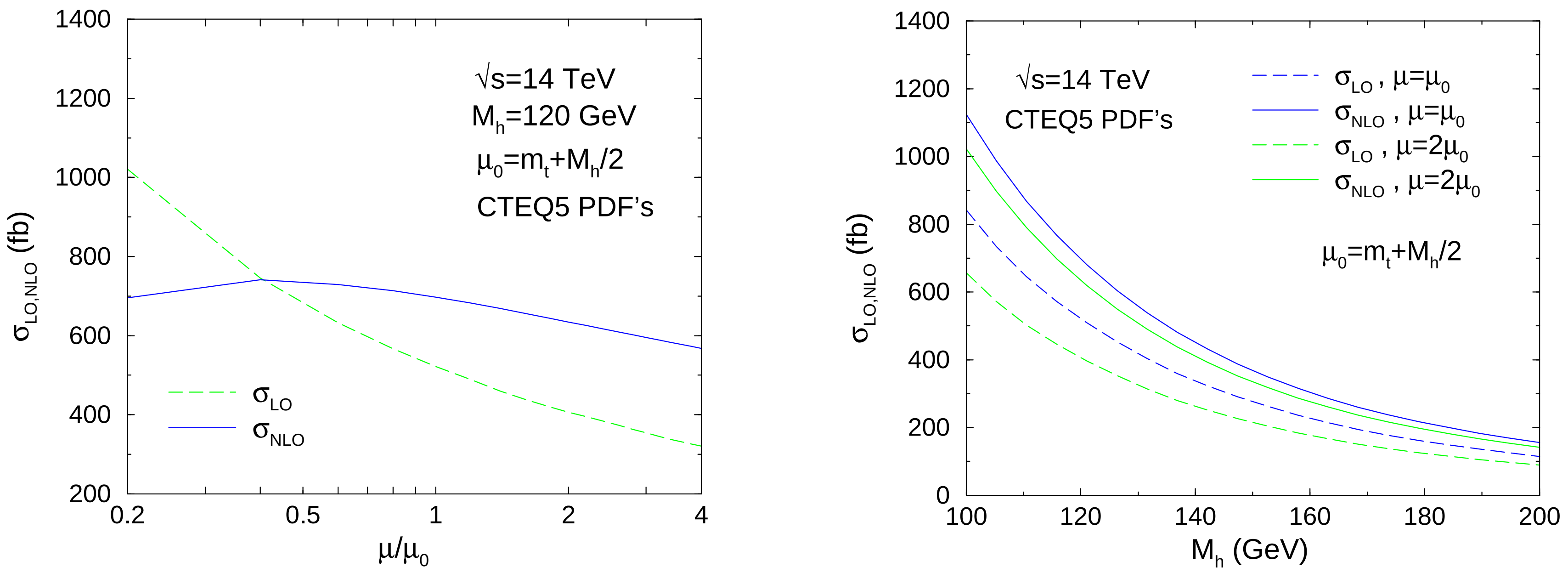
Exclusive NNLO results: e.g. $gg \to H \to \gamma\gamma, WW, ZZ$

Extension of (IR safe) subtraction method to NNLO:

$\longrightarrow$ HNNLO (Catani,Grazzini)

$\longrightarrow$ FEHiP (Anastasiou,Melnikov,Petriello)

Ex. 3: $pp \to t\bar{t}H$ production at the LHC



Dawson, Jackson, Orr, L.R., Wackeroth

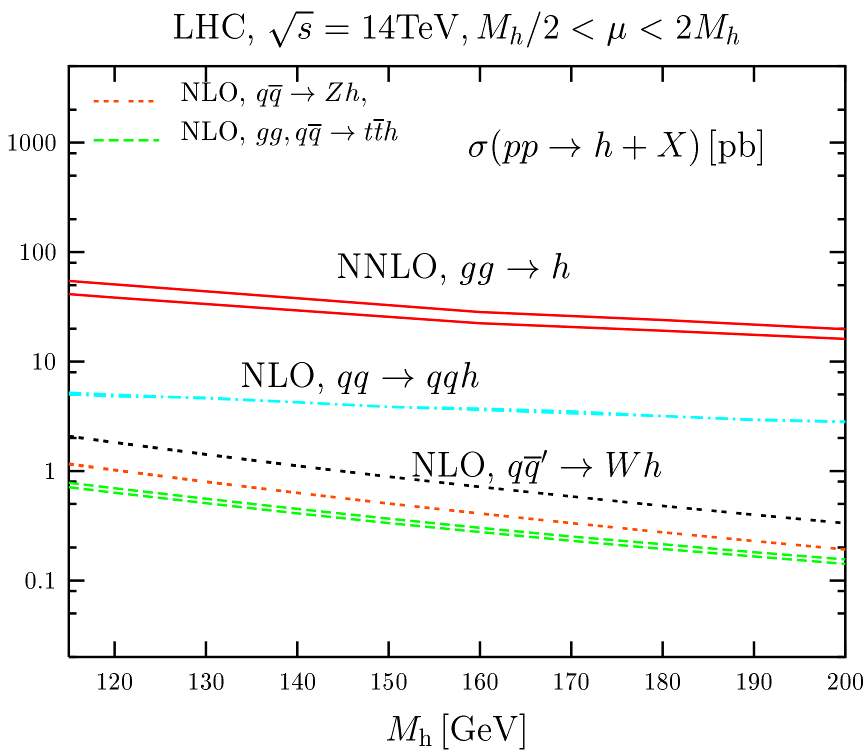
$\longrightarrow$ Fully massive $2 \to 3$ calculation: testing the limit of FD's approach (pentagon diagrams with massive particles).

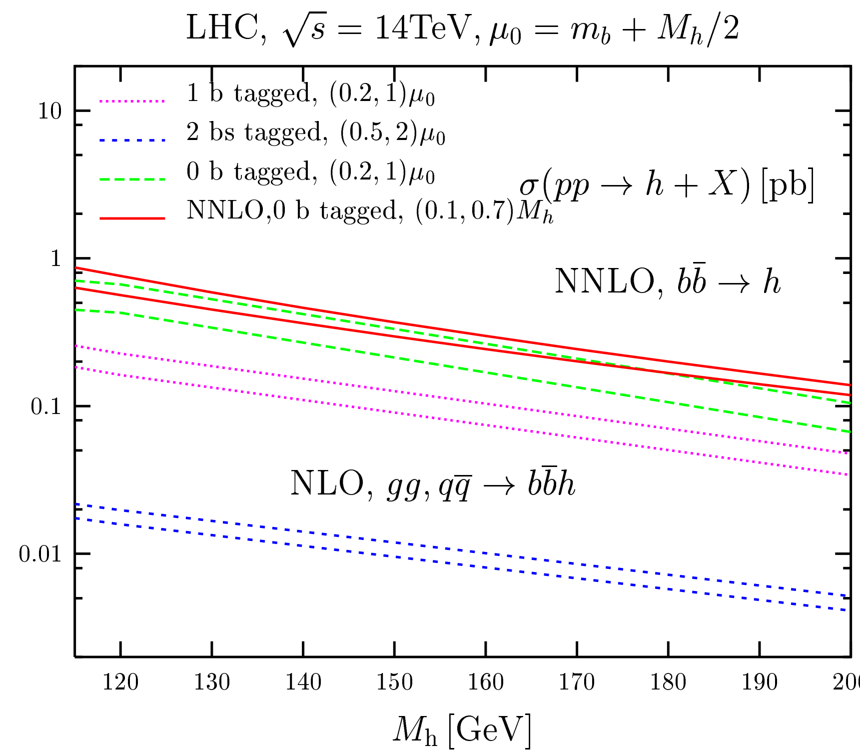
$\longrightarrow$ Theoretical uncertainty reduced to about 15%

$\longrightarrow$ Several crucial backgrounds also known at NLO: $t\bar{t}+j$ (Dittmaier et al.), $t\bar{t}b\bar{b}$ (Denner et al., Papadopoulos et al.).

SM Higgs-boson production: theoretical precision at a glance.

QCD predictions for total hadronic cross sections of Higgs-boson production processes are under good theoretical control:





Same accuracy should be now reached in background processes and consistent interface with event generators.

LHC-Higgs cross section Working Group (started in 2010)
(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections)

In summary . . .

We are at the verge of a new revolution in Particle Physics.

Years of relentless experimental and theoretical efforts have given us a mature field that can face the exceptionally high energies now coming on-line with unprecedented precision.

Collider physics along with ground and space based astrophysical observations will start answering some of the oustanding open questions that have been with us for decades and will lead us through the exploration and understanding of the quantum universe.