$\mathcal{H}$iggs $\mathcal{P}$hysics

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(Karlsruhe Institute of Technology, KIT)

European Summer School

“From the Mystery of Mass to Nobel Prizes”

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Outline

- **Standard Model Higgs Sector**
  - Introduction
  - Verification of the Higgs mechanism
    - Higgs discovery - production and decay
    - Determination of Higgs boson couplings
    - Determination of Spin and CP quantum numbers
    - Determination of the Higgs self-couplings
- **Beyond Standard Model Higgs Sectors (maybe)**
  - Minimal Supersymmetric Extension of the SM (MSSM)
    - LHC results and MSSM Higgs sector
  - Next-Minimal Supersymmetric Extension of the SM (NMSSM)
    - LHC results and NMSSM Higgs sector

$\mathcal{S}$tandard $\mathcal{M}$odel of $\mathcal{P}$article $\mathcal{P}$hysics

- **Local gauge symmetry group** $SU(3) \times SU(2)_L \times U(1)_Y$

I Particle Content

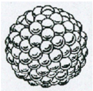
Matter Particles:

u	c	t	Quarks
d	s	b	
ν_e	ν_μ	ν_τ	Leptons
e	μ	τ	
1.	2.	3.	Family

Gauge Particles:

γ	Bosons
g	
Z	
$W^\pm$	

II Fundamental forces

Elektromagnetic	Photon	
Strong	Gluon	
Weak	W, Z	

III Higgs mechanism Masses of the fundamental particles

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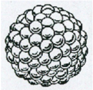
Strong	Gluon	
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III Higgs mechanism Masses of the fundamental particles **?**

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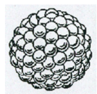
Strong	Gluon	
Weak	W, Z	

III Higgs mechanism Masses of the fundamental particles ✓ (4.7.2012, 14.3.2013)

$\mathcal{S}$tandard $\mathcal{M}$odel of $\mathcal{P}$article $\mathcal{P}$hysics

Construction of the SM Lagrangian

- ◇ Particle content
- ◇ Poincaré invariance
- ◇ Local gauge invariance under $SU(3) \times SU(2) \times U(1)$
- ◇ Renormalizability
- ◇ Mechanism of electroweak symmetry breaking

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\tfrac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{\psi} D \psi && \text{gauge sector} \\
& + \psi_i \lambda_{ij} \psi_j H && \text{flavour sector} \\
& |DH|^2 - V(H) && \text{EWSB sector} \\
& + N_i M_{ij} N_j && \nu\text{- mass sector}
\end{aligned}
$$

$\mathcal{S}$tandard $\mathcal{M}$odel of $\mathcal{P}$article $\mathcal{P}$hysics

Construction of the SM Lagrangian

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$\mathcal{L} =$	$-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\!\!\!/\psi$	gauge sector	
	$+\psi_i\lambda_{ij}\psi_j H$	flavour sector	
	$\lvert DH\rvert^2 - V(H)$	EWSB sector	
	$+N_i M_{ij} N_j$	ν- mass sector	not taken into account here

Gauge symmetry forbids mass terms for gauge bosons and fermions!

$\mathcal{S}$tandard $\mathcal{M}$odel of $\mathcal{P}$article $\mathcal{P}$hysics

Free parameters of the Standard Model: at least 26!

3 gauge couplings

1 CP-violating vacuum angle

6 quark masses

3 charged lepton masses

3 weak mixing angles

1 CP-violating CKM phase

1 W-mass

1 Higgs mass

and the neutrino sector

3 neutrino masses

3 neutrino mixing angles

3 CP-violating phases

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{M}$echanism

Brout-Englert-Higgs-Hagen-Guralnik-Kibble-Mechanism 1964

The Higgs Mechanism

- **Why do we need the Higgs Mechanism?**

∗ Standard Model (SM) based on symmetries: $SU(3)_C \times SU(2)_L \times U(1)_Y$

∗ Symmetries associated with existence of gauge bosons
massive gauge bosons ($W^{\pm}$, Z) and massless gauge bosons (photon, gluons)

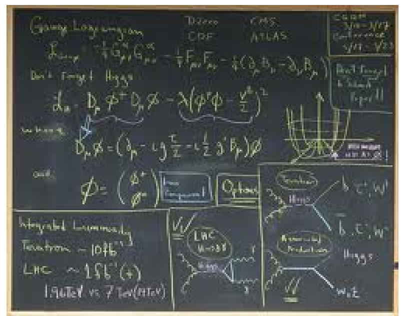
∗ Mass terms of massive gauge bosons violate the SM symmetries

- **Solution:**

∗ Mechanism which introduces particle masses without violating the SM gauge symmetries

- **Realisation:**

∗ Higgs Mechanism



$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking

- **How does it work?** Mass generation via spontaneous symmetry breaking (SSB)

◦ Add Higgs field with Higgs potential to SM Lagrangian

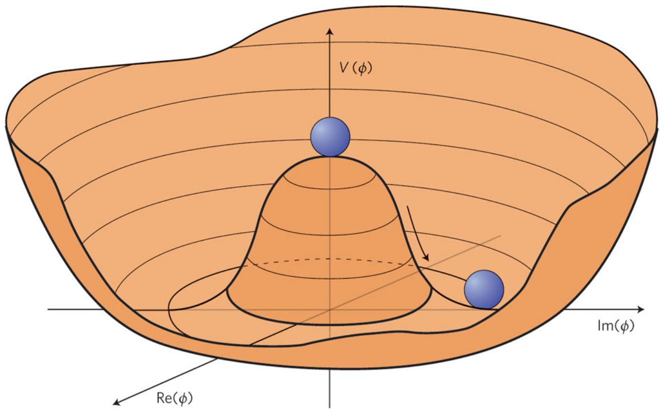
◦ Higgs potential respects SM symmetries
non-vanishing vacuum expectation value (VEV) in the ground state

◦ Choose one of the infinite degenerate ground states as the physical ground state

◦ $SU(2)_L \times U(1)_Y$ hidden, broken down to $U(1)_{em}$

◦ Particles acquire mass through interaction with scalar field in the ground state

◦ Non-vanishing VEV $v = 246$ GeV
$\leftarrow$ typical minimax form of the Higgs potential



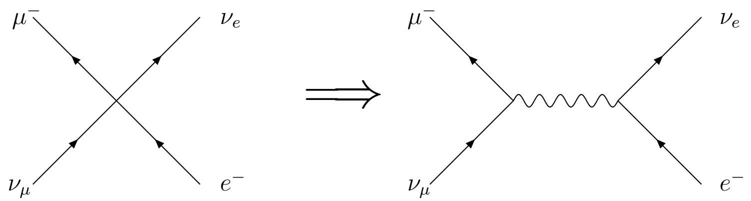
- **Fermi theory:** describes weak interaction with an effective Lagrangian

  E.g. μ decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

  $$\mathcal{L} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma_\lambda (1-\gamma_5)\mu][\bar{e}\gamma^\lambda (1-\gamma_5)\nu_e]$$

  $G_F \approx 1.17 \times 10^{-5}$ GeV^{-2} (Fermi coupling)

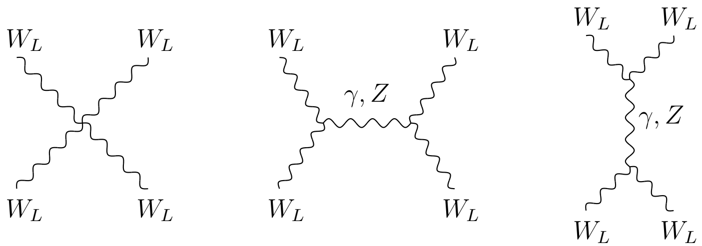
- **Fermi theory at high energies:** $\mathcal{M}[\nu_\mu e^- \to \mu^- \nu_e] \sim \frac{G_F}{2\sqrt{2}\pi} s \Rightarrow$ violates unitarity



$$\mathcal{M}[\nu_\mu e^- \to \mu^- \nu_e] \to \frac{G_F s}{2\sqrt{2}\pi} \frac{M_W^2}{M_W^2 - s} \quad \text{(with } M_W \approx 100 \text{ GeV)}$$

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{P}$article as $\mathcal{UV}$ $\mathcal{R}$egulator

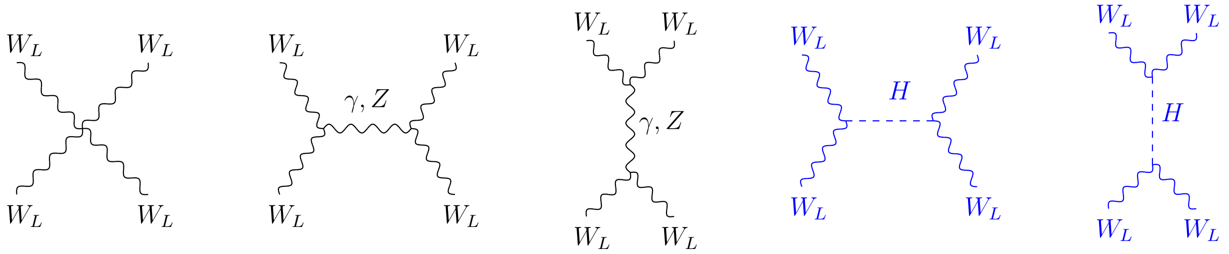
- **Scattering of longitudinally polarized W bosons**



$$\mathcal{A} = \frac{G_F s}{8\pi\sqrt{2}}$$

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{P}$article as $\mathcal{UV}$ $\mathcal{R}$egulator

- **Scattering of longitudinally polarized W bosons**



$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs particle guarantees unitarity of the W scattering
(if its mass $\lesssim 1$ TeV, $g_{XXH} \sim$ particle mass M_X; also unitarity in $WW \to hh$, $WW \to ff$)

A theory with massive gauge bosons and fermions, which is weakly coupled up to very high energies, requires, because of the demand for unitarity, the existence of a Higgs particle.
The Higgs particle is a scalar 0^+ particle, which couples to other particles with a coupling proportional to the mass of the particle.

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

Goal: generate W and Z boson masses without violating gauge invariance. Toy model:

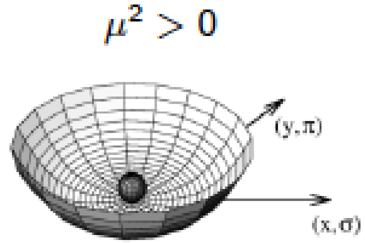
▷ Local $U(1)$ gauge theory with single spin-1 gauge field A_μ

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \quad \text{where} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

→ mass term $\sim m^2 A^\mu A_\mu$ not gauge invariant ⇝ massless gauge boson A

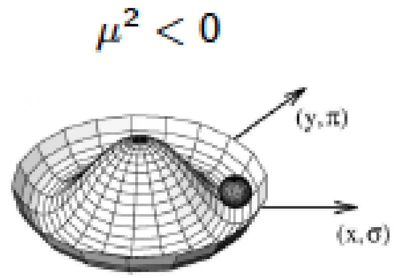
▷ Possible solution: add complex scalar field ϕ $\quad (D_\mu = \partial_\mu + ieA_\mu)$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |D_\mu \phi|^2 - V(\phi) \quad \text{where} \quad V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|$$



if $\mu^2 > 0$: unique minimum at $\phi = 0$ → QED with $M_A = 0$ and $M_\phi = \mu$

▷ Reverse sign of μ^2 so that $V(\phi) = -(-\mu^2)|\phi|^2 + \lambda |\phi|^4$



→ minimum of the potential at $\sqrt{-\frac{\mu^2}{2\lambda}} \equiv v$

▷ Expand ϕ around the vacuum expectation value v: $\phi = v + \frac{1}{\sqrt{2}}(H + i\chi) \Rightarrow$

$\mathcal{C}$alculation

Potential:

$$V(\phi) = -(-\mu^2)|\phi|^2 + \lambda|\phi|^4 \qquad \text{and} \qquad \phi = v + \frac{1}{\sqrt{2}}(H + i\chi) \quad , \quad -\mu^2 = 2\lambda v^2 \quad \Rightarrow \tag{1}$$

$$\begin{aligned}
V &= -(-\mu^2)\left(v^2 + \frac{H^2}{2} + \sqrt{2}Hv + \frac{\chi^2}{2}\right) \\
&+ \lambda\left(v^4 + \frac{H^4}{4} + v^2H^2 + 2H^2v^2 + 2\sqrt{2}Hv^3 + \sqrt{2}H^3v + \frac{\chi^4}{4} + \frac{2v^2\chi^2}{2} + \frac{H^2\chi^2}{2} + \frac{2\sqrt{2}Hv\chi^2}{2}\right) \\
&= \mu^2v^2 + \left(-\frac{(-\mu^2)}{2} + 3\lambda v^2\right)H^2 + \sqrt{2}\lambda vH(H^2+\chi^2) + \frac{\lambda}{4}(H^4 + 2H^2\chi^2 + \chi^4) \\
&+ \sqrt{2}\mu^2Hv + 2\sqrt{2}\lambda Hv^3 + \frac{\mu^2\chi^2}{2} + \frac{2\lambda v^2\chi^2}{2} + \lambda v^4 \\
&= -\mu^2H^2 + \sqrt{2}\lambda vH(H^2+\chi^2) + \frac{\lambda}{4}(H^2+\chi^2)^2 + \text{const.}
\end{aligned} \tag{2}$$

$\mathcal{C}$alculation continued

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\partial_\mu + ieA_\mu)\left(v + \frac{1}{\sqrt{2}}(H + i\chi)\right)(\partial^\mu - ieA^\mu)\left(v + \frac{1}{\sqrt{2}}(H - i\chi)\right) - V(\phi) \\
&= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu(H + i\chi)\partial^\mu(H - i\chi) + \frac{1}{2}(ieA_\mu)(H + i\chi)\partial^\mu(H - i\chi) \\
&+ \frac{1}{2}(H - i\chi)\partial_\mu(H + i\chi)(-ieA^\mu) + v^2e^2A_\mu A^\mu + \frac{ieA_\mu}{\sqrt{2}}(H + i\chi)\frac{(-ieA^\mu)}{\sqrt{2}}(H - i\chi) \\
&+ (-ieA^\mu)(ieA_\mu)v\frac{1}{\sqrt{2}}(H - i\chi) + (ieA^\mu)(-ieA_\mu)v\frac{1}{\sqrt{2}}(H + i\chi) + \sqrt{2}evA_\mu\partial^\mu\chi - V(\phi) \\
&= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu H)(\partial^\mu H) + \frac{1}{2}(\partial_\mu\chi)(\partial^\mu\chi) + \frac{1}{2}(2v^2e^2)A_\mu A^\mu \\
&+ \frac{i^2}{2}eA_\mu\chi(\partial^\mu H) + \frac{(-i)i}{2}eA_\mu H(\partial^\mu\chi) + \frac{(-i)^2}{2}eA^\mu(\partial_\mu H)\chi + \frac{(-i)i}{2}eA^\mu(\partial_\mu\chi)H \\
&+ \frac{e^2}{2}A_\mu A^\mu(H^2 + \chi^2 + 2\sqrt{2}vH) + \sqrt{2}evA_\mu\partial^\mu\chi - V(\phi) \qquad (3)
\end{aligned}
$$

$\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking ($\mathcal{EWSB}$)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{1}{2}\partial_\mu \chi \partial^\mu \chi + \frac{1}{2}(2e^2v^2)A_\mu A^\mu + \sqrt{2}evA^\mu\partial_\mu\chi - eA^\mu(\chi\partial_\mu H + H\partial_\mu\chi)$$
$$+\frac{1}{2}e^2A_\mu A^\mu(H^2+\chi^2-2\sqrt{2}vH) \underbrace{-\frac{1}{2}(-2\mu^2)H^2 - \sqrt{2}\lambda vH(H^2+\chi^2) - \frac{\lambda}{4}(H^2+\chi^2)^2 + const.}_{V(H)}$$

▷ The theory has now

- a photon of mass $M_A^2 = 2e^2v^2$
- a scalar field H with $M_H^2 = -2\mu^2 > 0$
- a massless scalar field χ (Goldstone boson)

▷ Mixed $A - \chi$ propagator: can be removed by a gauge transformation

$A_\mu \to A_\mu + \frac{1}{\sqrt{2}ev}\partial_\mu\chi$ and $\phi \to e^{i\frac{\chi}{\sqrt{2}v}}\phi$ (unitary gauge)

⇝ the χ field has been absorbed by a redefinition of A
(jargon: χ has been "eaten" to give the photon mass)

▷ Degrees of freedom:

before symmetry breaking: massles gauge boson (2 dof) and complex scalar field (2 dof)
after symmetry breaking: massive gauge boson (3 dof) and physical scalar (1 dof)

$\mathcal{S}$pontaneously $\mathcal{B}$roken $\mathcal{G}$auge $\mathcal{S}$ymmetries

▷ In spontaneously broken gauge theories the Goldstone bosons do not appear. They are would-be Goldstone bosons. After spontaneous symmetry breaking they are directly absorbed in the longitudinal degrees of freedom of the massive gauge bosons.

▷ For gauge theories we have:

$$
\begin{aligned}
N &= \text{Dimension of the algebra of the symmetry group of the full Lagrangian.} \\
M &= \text{Dimension of the algebra of the group, under which the vacuum after} \\
  &\quad\ \text{spontaneous symmetry breaking is invariant.} \\
n &= \text{Number of scalar fields.}
\end{aligned}
$$

$$\Longrightarrow$$

There are M massless vector fields. (M is the dimension of the symmetry of the vacuum.)
There are $N - M$ massive vector fields. ($N - M$ is the number of broken generators.)
There are $n - (N - M)$ scalar Higgs fields.

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Add complex Higgs doublet to $\mathcal{L}$**

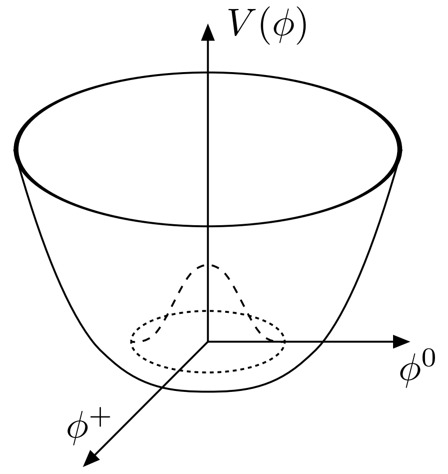
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ with $<\Phi>= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ and $v = 246$ GeV

- **Lagrangian of the Higgs doublet**

$\mathcal{L}_\Phi = |D_\mu \Phi|^2 - V(\Phi)$

- **The Higgs potential:**

$$V(\Phi) = \lambda[\Phi^\dagger \Phi - \frac{v^2}{2}]^2$$



The minimum of the potential is at $v = 246$ GeV
$\rightsquigarrow$ spontaneous symmetry breaking (SSB)

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Higgs field in the unitary gauge**

$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \Rightarrow$

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

- **$\Rightarrow$ Higgs mass and self-couplings:**

$\mathcal{H}$iggs boson mass	$M_H = \sqrt{2\lambda}v$
$\mathcal{T}$rilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$
$\mathcal{Q}$artic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$

Higgs self-couplings in the SM uniquely determined by the Higgs mass!

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Gauge boson masses from**

$\mathcal{L}_\Phi^{\text{kin}} = |D_\mu \Phi|^2$ with the covariant derivative $iD_\mu = i\partial_\mu - \frac{g}{2}\vec{\tau}\vec{W}_\mu - \frac{g'}{2} Y B_\mu$

$\vec{\tau}^T = (\tau_1, \tau_2, \tau_3)$, $\tau^i =$ Pauli matrices

$\vec{W}_\mu^T = (W_\mu^1, W_\mu^2, W_\mu^3)$, B_μ $SU(2)$, $U(1)$ gauge fields g, g' gauge couplings

Expansion of $\Phi = (\phi^+, \phi^0)^T$ about its vacuum expectation value $\Phi \to (0, \frac{1}{\sqrt{2}}[v+H])^T \Rightarrow$ we get for the covariant derivative in the unitary gauge

$$D_\mu \Phi = \frac{1}{\sqrt{2}} \left(\partial_\mu + i\frac{g}{2} \begin{pmatrix} W_\mu^3 & \sqrt{2} W_\mu^- \\ \sqrt{2} W_\mu^+ & -W_\mu^3 \end{pmatrix} + i\frac{g'}{2} B_\mu \right) \begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

with $W_\mu^\pm = W_\mu^1 \pm i W_\mu^2$

leading to

$$|D_\mu \Phi|^2 = \frac{1}{2}(\partial_\mu H)^2 + \frac{g^2 v^2}{4} W^{+\mu} W_\mu^- + \frac{v^2}{8}(g W_\mu^3 - g' B_\mu)^2 + \text{interaction terms}$$

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

$\Rightarrow$ massive gauge boson masses:

$$W_\mu^\pm \qquad \text{and} \quad Z_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gW_\mu^3 - g'B_\mu)$$

with masses $M_W^\pm = \frac{1}{2}gv$ and $M_Z = \frac{1}{2}\sqrt{g^2+g'^2}v$ with v=246 GeV

Orthogonal superposition to Z:

massless photon $A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'W_\mu^3 + gB_\mu)$

introducing the electroweak mixing angle θ_W we have

$$\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}} \qquad \text{and} \qquad \cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

so that $g' = g\tan\theta_W$ and $M_W = M_Z\cos\theta_W$

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Fermion masses:** generated through the Yukawa interactions $(-h_e \bar{L}_L e_R \phi^0 + h.c.)$; $(L_L = (\nu_L, e_L)^T)$;
  e.g. for electrons (after expansion about vacuum expectation value (VEV) v, $\phi^0 = 1/\sqrt{2}(v+H)$)

$$\mathcal{L}^e_{\text{Yuk}} = -\frac{h_e}{\sqrt{2}} \begin{pmatrix} \bar{\nu}_L \\ \bar{e}_L \end{pmatrix}^T \begin{pmatrix} 0 \\ v+H \end{pmatrix} e_R + \text{h.c.}$$

$\rightsquigarrow$ electron mass term

$$\mathcal{L}^e_{\text{Yuk,mass}} = -\frac{h_e v}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L) = -\frac{h_e v}{\sqrt{2}} \bar{e}e \equiv -m_e \bar{e}e \qquad e_{L,R} = \frac{(\mathbb{I} \mp \gamma_5)}{2} e$$

The Yukawa coupling h_e is related to the electron mass by

$$h_e = g\frac{m_e}{\sqrt{2}M_W} \qquad M_W = \frac{gv}{2}$$

We also have an interaction between the electron and the Higgs boson

$$\mathcal{L}_{\text{int}} = -g\frac{m_e}{2M_W} H\bar{e}e$$

$\mathcal{T}$he $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Quark masses** also generated through the Yukawa interactions

$$\mathcal{L}^q_{\text{Yuk}} = -(\bar{u}_R, \bar{c}_R, \bar{t}_R) \begin{pmatrix} h_u & & \\ & h_c & \\ & & h_t \end{pmatrix} \left[\phi^0 \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} - \phi^+ V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right]$$

$$-(\bar{d}_R, \bar{s}_R, \bar{b}_R) \begin{pmatrix} h_d & & \\ & h_s & \\ & & h_b \end{pmatrix} \left[\phi^0 \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} - \phi^- V^\dagger \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} \right] + h.c.$$

V: Cabibbo-Kobayashi-Maskawa (CKM) matrix

Expansion about VEV $\rightsquigarrow$

$$\mathcal{L}^q_{mass} = \underbrace{-\frac{h_d v}{\sqrt{2}} \bar{d}_L d_R + h.c.}_{\text{d-quark mass}} \underbrace{-\frac{h_u v}{\sqrt{2}} \bar{u}_L u_R + h.c.}_{\text{u-quark mass}}$$

$\rightsquigarrow$ Masses: $m_d = \frac{h_d}{\sqrt{2}} v = \sqrt{2} \frac{h_d M_W}{g}$ and $m_u = \frac{h_u}{\sqrt{2}} v = \sqrt{2} \frac{h_u M_W}{g}$

$\rightsquigarrow$ Interactions between the quarks and the Higgs boson: $\mathcal{L}_{\text{int}} = -g \frac{m_u}{2M_W} \bar{u} H u - g \frac{m_d}{2M_W} \bar{d} H d$

$\mathcal{T}$he $\mathcal{S}$tandard $\mathcal{M}$odel with one $\mathcal{F}$amily

- **The Lagrangian of the SM with one family is schematically**

$$\mathcal{L}_{SM,1} = \sum_{\text{gauge bosons}} -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_{\text{fermions}} i\bar{\psi}\gamma^\mu D_\mu\psi + \mathcal{L}_{\text{Yuk}} + |D_\mu\phi|^2 - V(\phi)$$

where

$$F_{\mu\nu} = -\frac{1}{ig}[D_\mu, D_\nu] \qquad D_\mu = \partial_\mu + i\frac{g}{2}\tau^i W^i_\mu + ig'YB_\mu + i\frac{g_S}{2}T^a G^a_\mu$$

The term $F_{\mu\nu}F^{\mu\nu} \rightsquigarrow$ interactions among the gauge bosons, e.g.

$$g\epsilon_{ijk}(\partial_\mu W^i_\nu)W^{\mu j}W^{\nu k} - \frac{1}{4}g^2\epsilon_{ijk}\epsilon_{ilm}W^j_\mu W^k_\nu W^{\mu l}W^{\nu m}$$

The term $i\bar{\psi}\gamma^\mu D_\mu\psi \rightsquigarrow$ interactions among the fermions and gauge bosons, e.g. $(L_L = (\nu_L, e_L)^T)$

$$\begin{aligned} & i\bar{L}^T_L\gamma^\mu D_\mu L_L + i\bar{e}_R\gamma^\mu D_\mu e_R \\ = \quad & -\frac{g}{2\sqrt{2}}\bar{\nu}\gamma^\mu(1-\gamma_5)eW^-_\mu + \text{h.c.} + \overbrace{g\sin\theta_W}^{\equiv e}\bar{e}\gamma^\mu eA_\mu \\ & -\frac{g}{4\cos\theta_W}\bar{\nu}\gamma^\mu(1-\gamma_5)\nu Z_\mu + \frac{g}{4\cos\theta_W}\bar{e}(\gamma^\mu(1-\gamma_5) - 4\sin^2\theta_W\gamma^\mu)eZ_\mu \end{aligned}$$

$\mathcal{T}$he $\mathcal{S}$tandard $\mathcal{M}$odel with one $\mathcal{F}$amily

The free parameters of the $SU(2) \times U(1)$ part with one generation of leptons are

- ▷ the two gauge couplings for the $SU(2)$ and $U(1)$ gauge groups, g and g'
- ▷ the two parameters μ and λ in the scalar potential $V(\phi)$
- ▷ the Yukawa couplings h_f

It is convenient to replace these parameters by parameters which can be measured accurately, e.g.

$$\{g, g', \lambda, v, h_f\} \to \{\alpha, \sin\theta_W, G_F, M_Z, m_f\}$$

where at Born level

$$\begin{aligned} \tan\theta_W &= \frac{g'}{g} & \alpha &= \frac{g^2 \sin^2\theta_W}{4\pi} & M_H^2 &= 2\lambda v^2 \\ M_Z^2 &= \frac{(g^2+g'^2)v^2}{4} & m_f &= \frac{h_f v}{\sqrt{2}} \end{aligned}$$

The values of other observables are predicted

$$M_W = M_Z \cos\theta_W \quad , \quad A_{LR} = \frac{(-\frac{1}{2}+s_{eff}^2)^2 - s_{eff}^4}{(-\frac{1}{2}+s_{eff}^2)^2 + s_{eff}^4} \quad , \quad s_{eff}^2 = s_W^2 = \frac{g'^2}{g^2+g'^2}$$

$$\Gamma(Z \to l^+ l^-) = \frac{\sqrt{2} G_F}{6\pi} m_Z^3 (g_L^2 + g_R^2) \quad , \quad \text{where} \quad g_L = -\frac{1}{2} + s_W^2 \; , \; g_R = s_W^2$$

Additional generations introduce more fermion masses and mixing angles.

$\mathcal{T}$he $\mathcal{S}$tandard $\mathcal{M}$odel with one $\mathcal{F}$amily

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$$M_Z^2 = \frac{(g^2+g'^2)v^2}{4} \qquad m_f = \frac{h_f v}{\sqrt{2}}$$

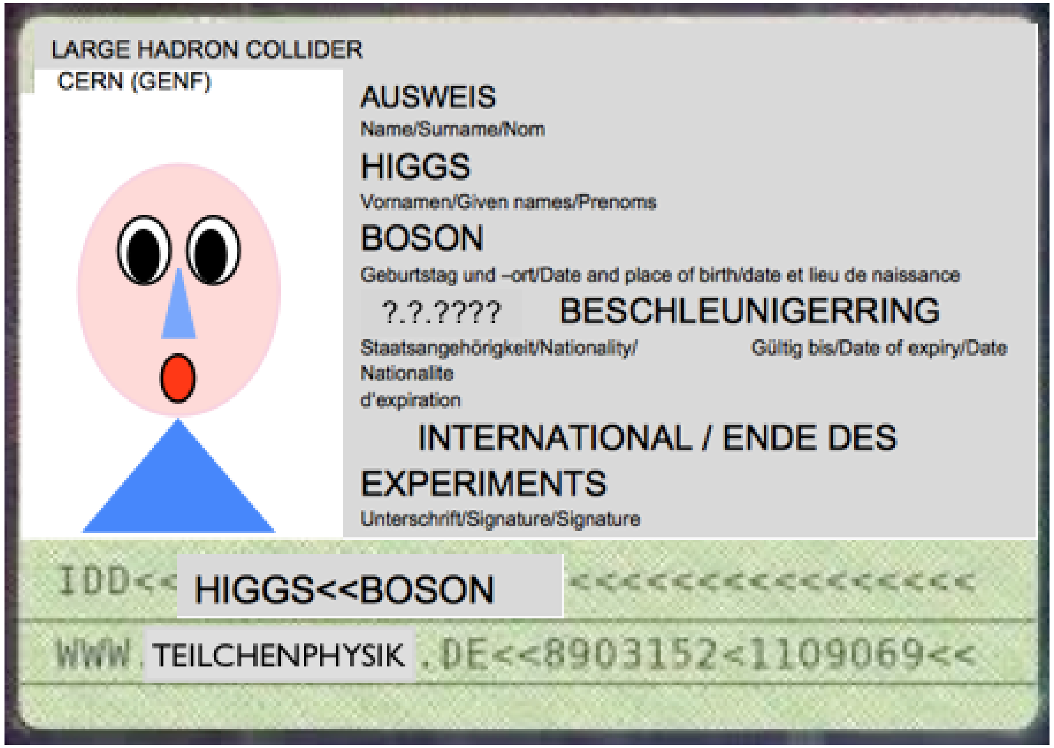
The values of other observables are predicted

$$M_W = \frac{\sqrt{2}\pi\alpha G_F^{-1}}{1-\sqrt{1-4\pi\alpha/(\sqrt{2}G_F M_Z^2)}} \quad , \quad s_{eff}^2 = \frac{1}{2} - \sqrt{1/4 - \pi\alpha/(\sqrt{2}G_F M_Z^2)}$$

$$\Gamma(Z \to l^+ l^-) = \frac{\sqrt{2}G_F M_Z^3}{12\pi} \left(\left(1/2 - \sqrt{1 - 4\pi\alpha/(\sqrt{2}G_F M_Z^2)} \right)^2 + 1/4 \right)$$

𝓗ow to 𝓥erify the 𝓗iggs 𝓜echanism?

- **Higgs Mechanism:** There is a Higgs Particle!
- **Verification:** First step: Production of the Higgs boson



How to Verify the Higgs Mechanism?

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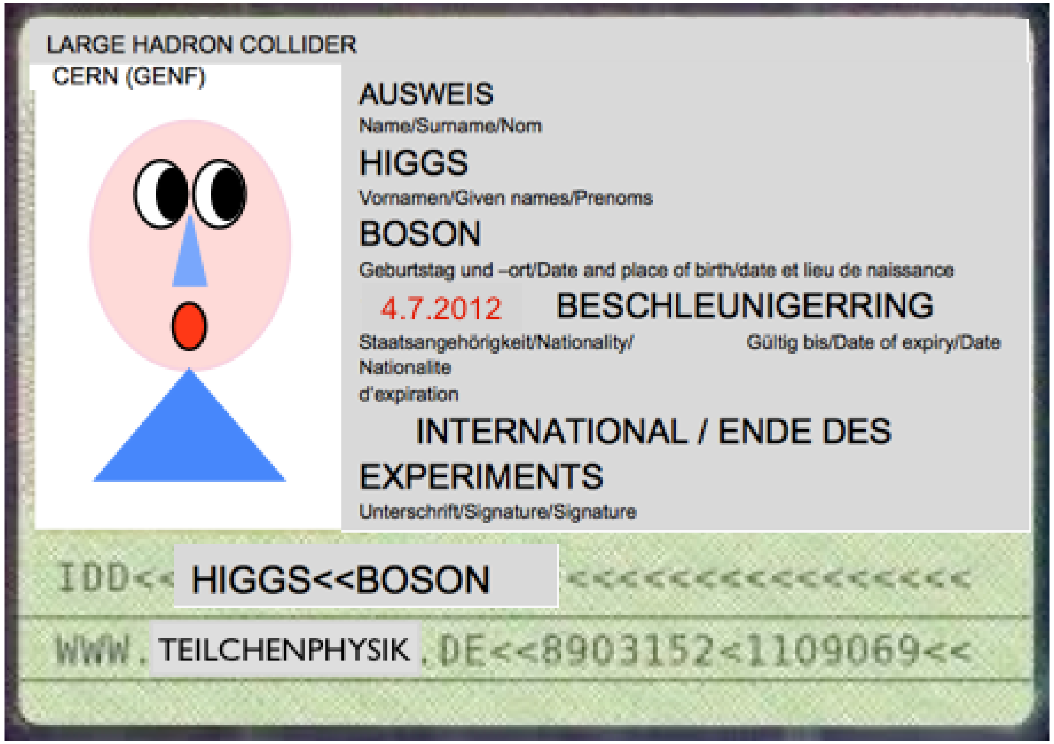

How to *Verify* the *Higgs* *Mechanism*?

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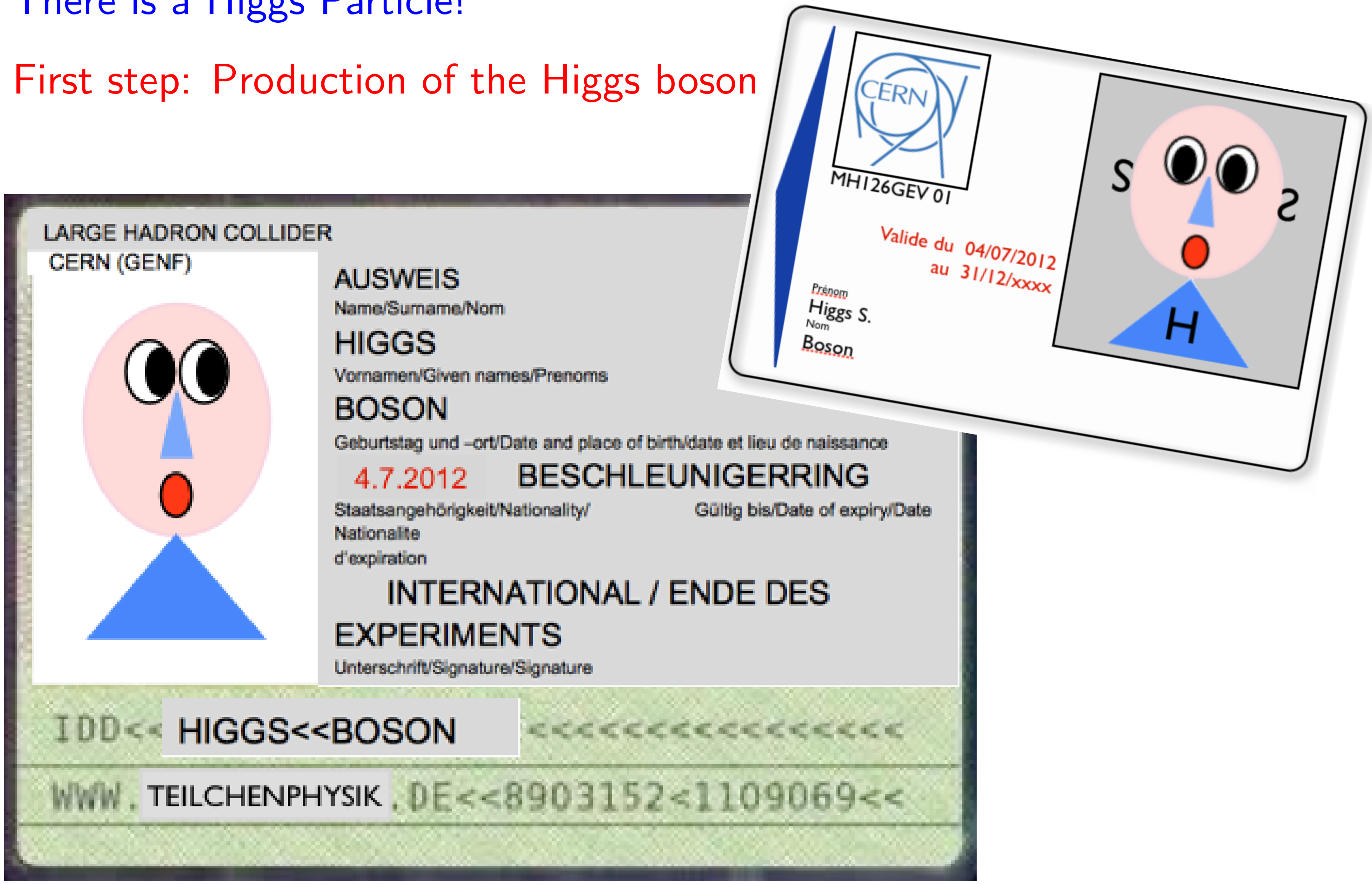
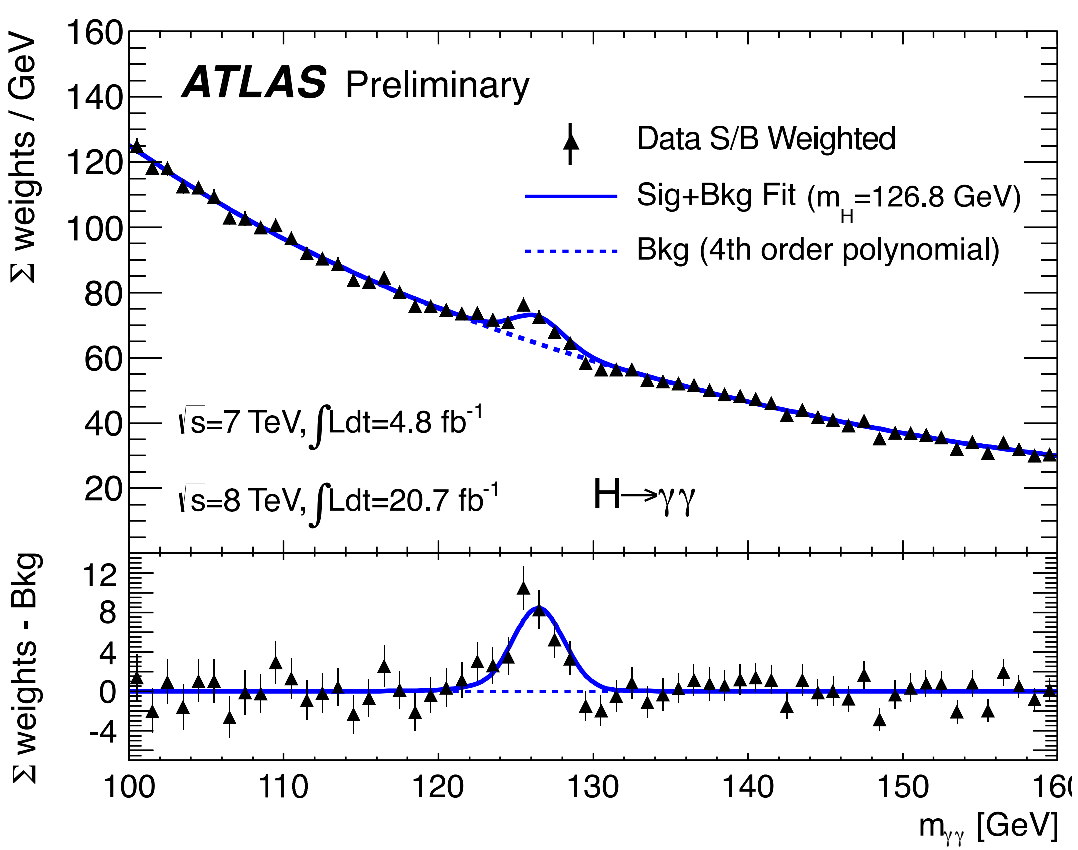


$\mathcal{LHC}$ $\mathcal{D}$iscovery of $\mathcal{N}$ew $\mathcal{S}$calar $\mathcal{P}$article

ATLAS-CONF-2013-12



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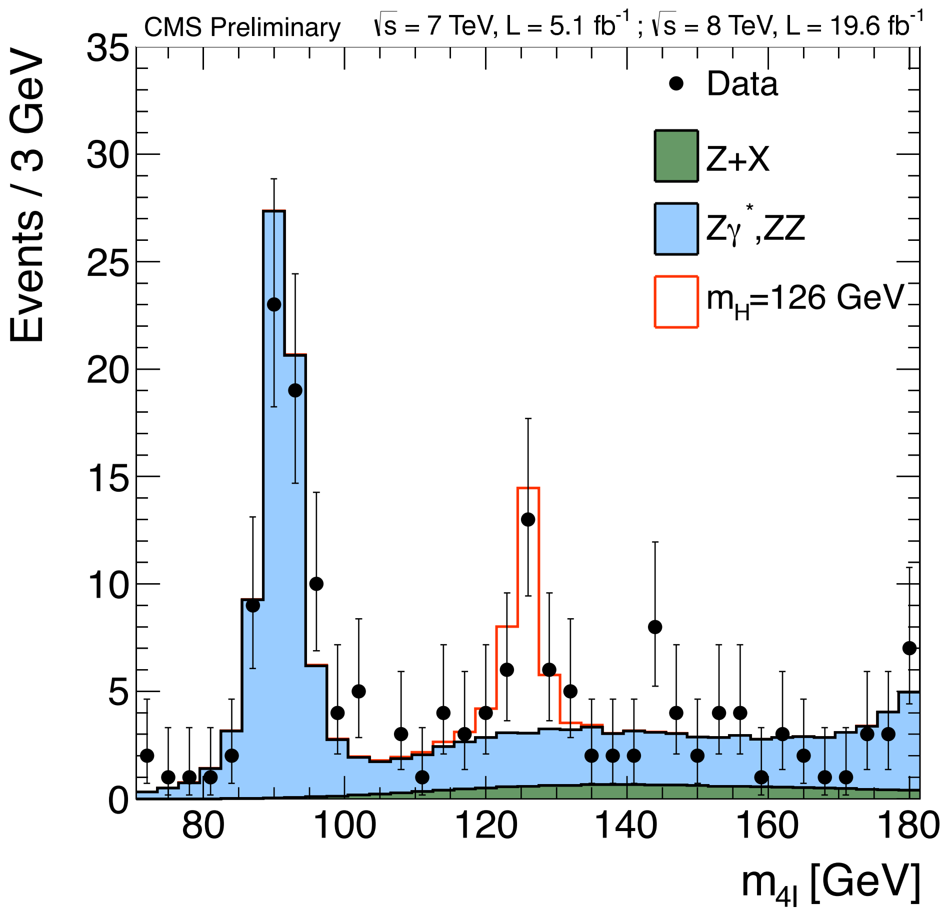


$\mathcal{D}$iscovery of $\mathcal{N}$ew Scalar $\mathcal{P}$article

- **4 July 2012: CERN announces discovery of new scalar Higgs-like particle!**

Higgs-Groupies queueing up in front of CERN audimax

$\mathcal{D}$iscovery of $\mathcal{N}$ew Scalar $\mathcal{P}$article

- **4 July 2012: CERN announces discovery of new scalar Higgs-like particle!**

Two electroweak symmetry breaking heroes

𝒟iscovery of 𝒩ew Scalar 𝒫article

- **4 July 2012: CERN announces discove... e particle!**

Crowd listening announcement at ICHEP 2012 in Melbourne

𝒟iscovery of 𝒩ew Scalar 𝒫article

• **4 July 2012: CERN ann** … **e particle!**

At the university of Tokyo

Discovery of New Scalar Particle

- **4 July 2012: CERN ann … e particle!**

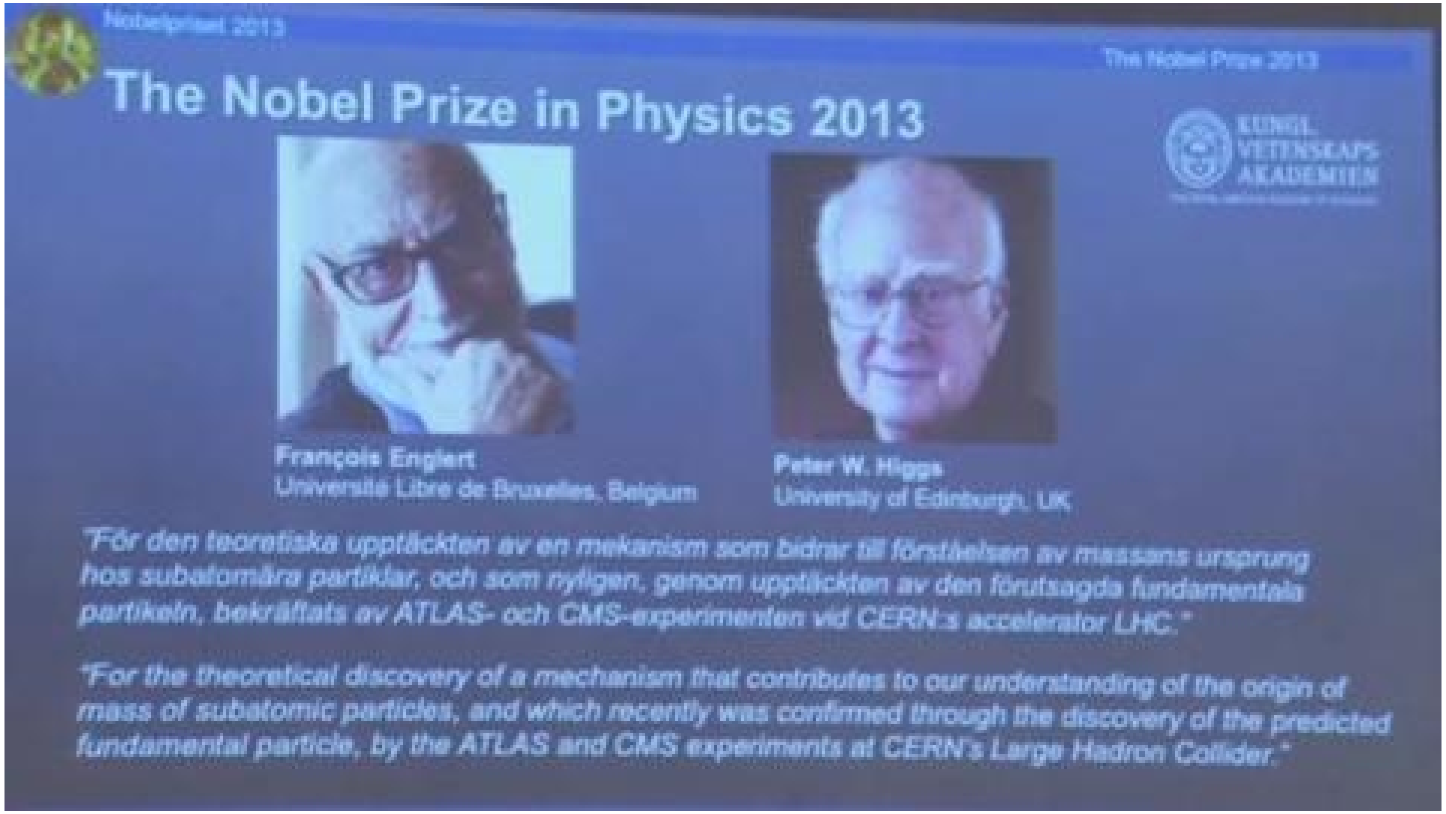
At Fermilab

𝒟iscovery of 𝒩ew Scalar 𝒫article

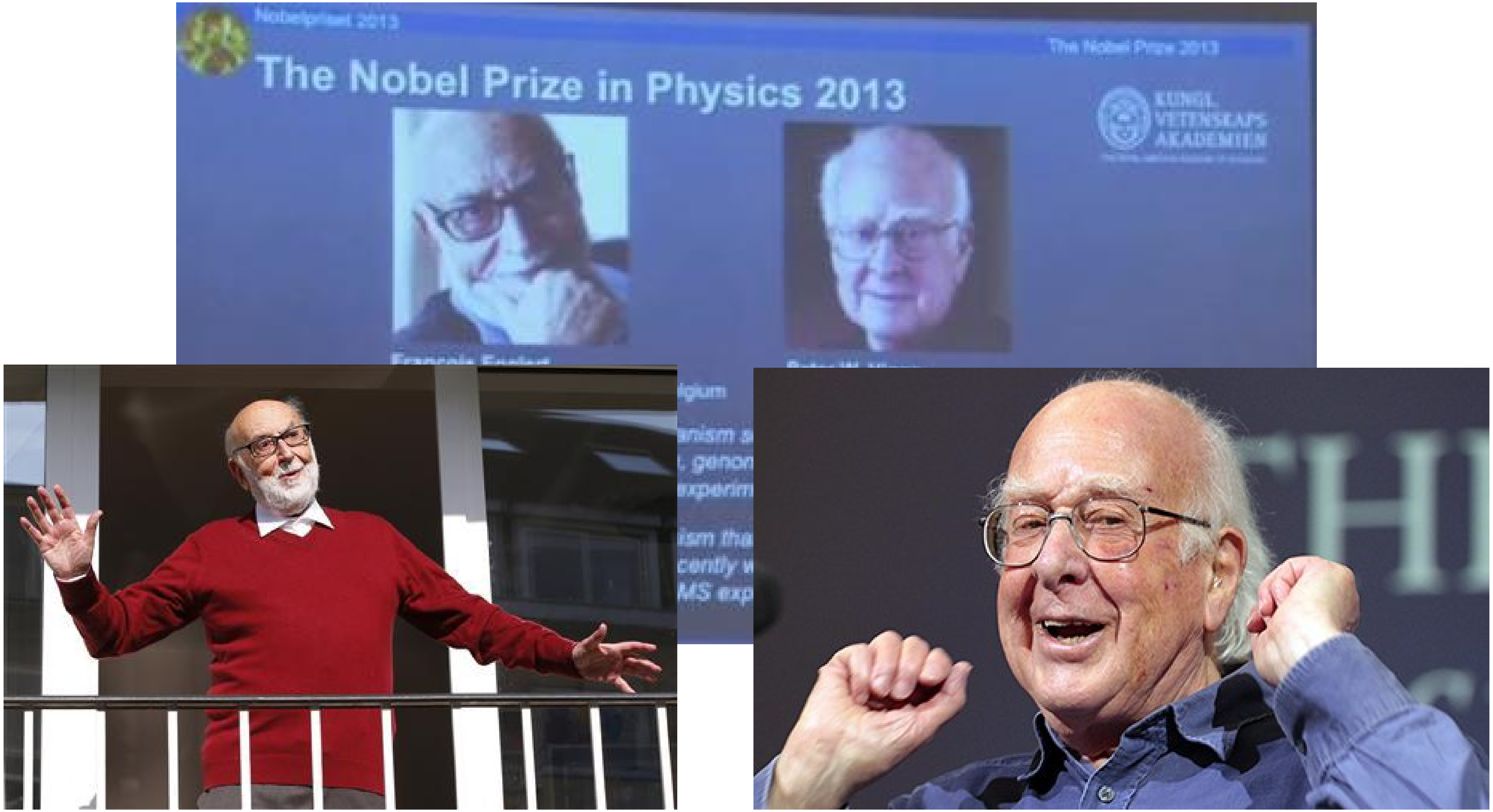
- 4 July 2012: CERN ann… …e particle!

At DESY, Hamburg

$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



$\mathcal{N}$obel $\mathcal{P}$rize in $\mathcal{P}$hysics 2013



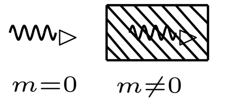
What Have We Seen?

✐ The production of a new particle with mass $M \approx 125$ GeV

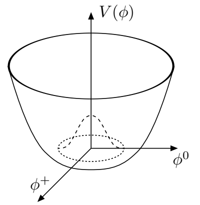
✐ Is it *the* Standard Model *Higgs* boson? $\Longrightarrow$

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



✐ Is it the Standard Model Higgs boson, a SUSY Higgs boson, a Composite Higgs boson, ...?

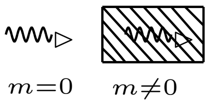
$\mathcal{E}$xperimental $\mathcal{V}$erification of the $\mathcal{H}$iggs $\mathcal{M}$echanism

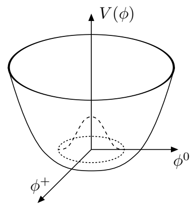
Higgs mechanism:

Creation of particle masses without violating gauge symmetries

Test of the Higgs mechanism

- Discovery – m
- Interaction with a scalar Higgs mit $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$
- Spin and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



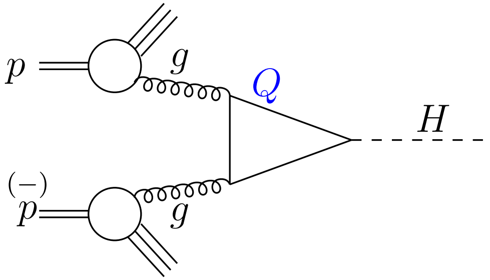


Higgs Boson Production at the LHC

Higgs boson production in the SM

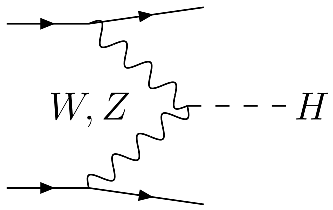
- **Gluon Fusion**

  $pp \to gg \to H$



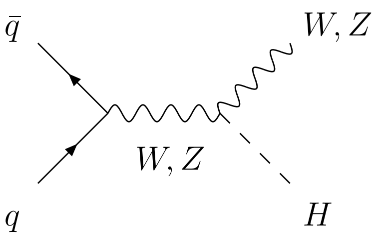
- **W/Z Fusion**

  $pp \to qq \to qq + WW/ZZ \to qq + H$



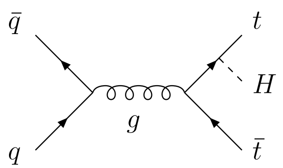
- **Higgs-strahlung**

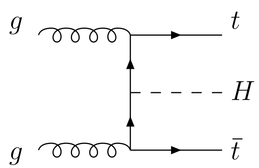
  $pp \to W^*/Z^* \to W/Z + H$



- **Associated Production**

  $pp \to t\bar{t} + H$



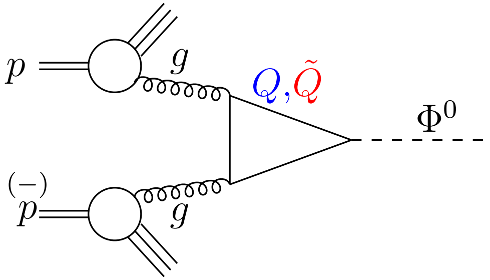


$\mathcal{H}$iggs $\mathcal{P}$roduction at the $\mathcal{LHC}$

Higgs boson production

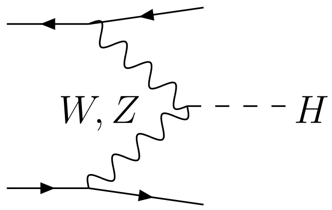
- **Gluon Gluon Fusion** Room for New Physics!

  $pp \to gg \to H$



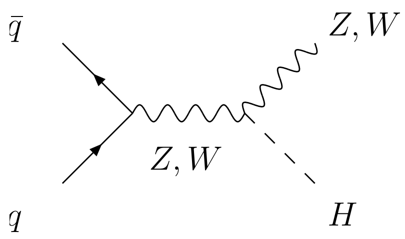
- **W/Z Fusion**

  $pp \to qq \to qq + WW/ZZ \to qq + H$



- **Higgs-strahlung**

  $pp \to W^*/Z^* \to W/Z + H$

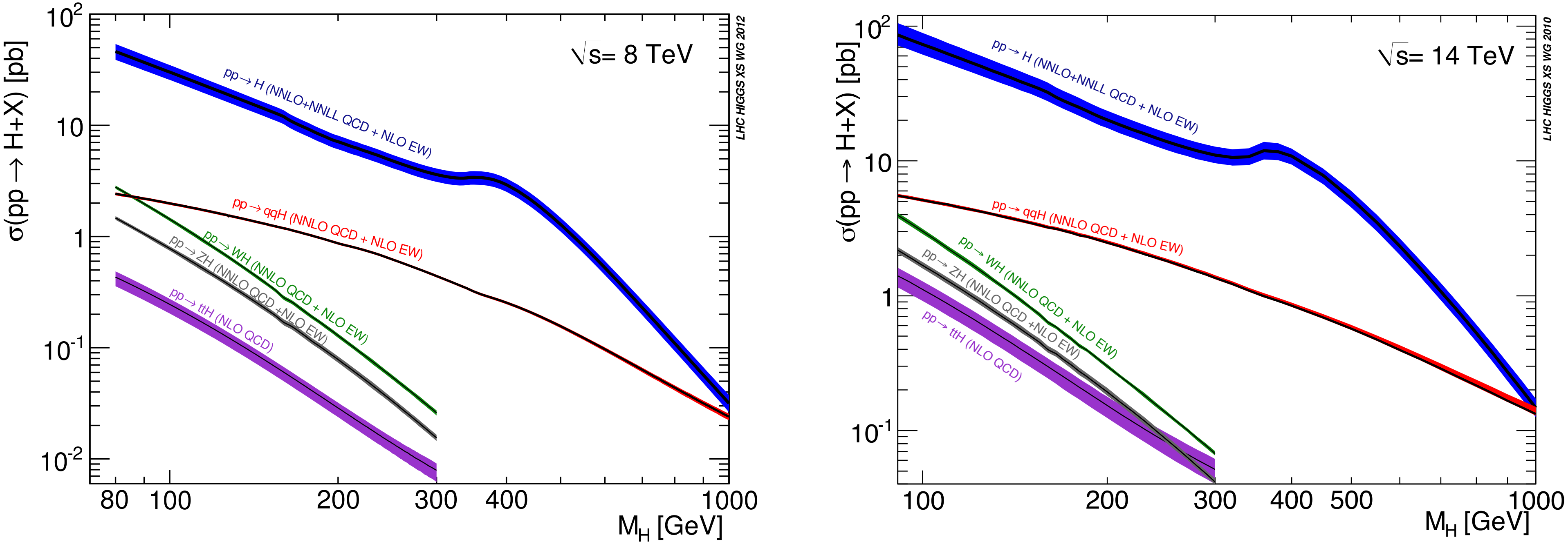


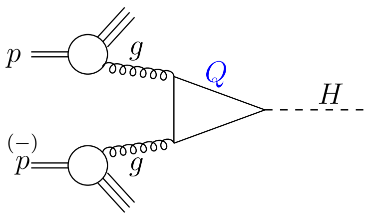
- **Associated production with $t\bar{t}$**

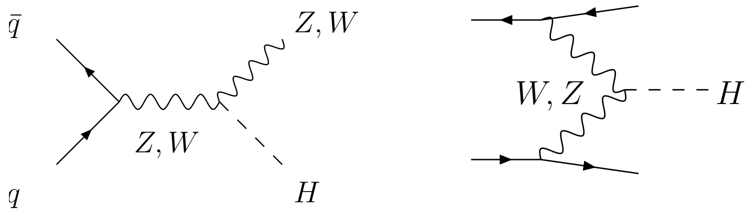
  $pp \to t\bar{t} + H$

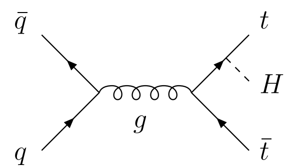
$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction at the $\mathcal{LHC}$

LHC Higgs XS WG, arXiv:1101.0593









LHC Higgs Cross Section Working Group

- ◇ *"Handbook of LHC Higgs cross sections: 1. Inclusive observables."* arXiv:1101.0593
- ◇ provide best theory prediction for Higgs cross sections and branching ratios (SM and MSSM)
- ◇ provide theoretical uncertainties on these quantities
- ◇ give precise common inputs
- ◇ inclusive cross sections (now also distributions (2./1201.3084) and Higgs properties (3./1307.1347))
- ◇ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Cross Sections

$\mathcal{M}$ini-$\mathcal{P}$rimer on $\mathcal{S}$cattering $\mathcal{P}$rocesses at the $\mathcal{LHC}$

Scattering processes at hadron colliders

- Connect incoming quarks, gluons with colliding protons
  outgoing particles with observed hadronic jets

- Scattering processes at high-energy hadron colliders: $\rightarrow$ hard $\longleftarrow$ QCD
  $\rightarrow$ soft

- Hard processes (e.g. Higgs boson or high-p_T jet production): perturbation theory

- Soft processes (e.g. total cross section, underlying event etc.)
  non-perturbative QCD effects

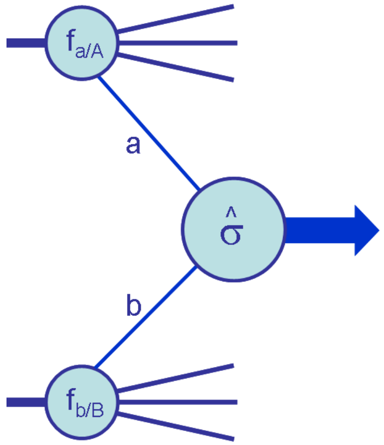
Factorisation theorem of the QCD

Partonic cross sections have collinear divergences in the hadronic initial state, which factorise universally (i.e. independent of the process) from the hard scattering process and can be absorbed in the renormalized parton densities of the initial state. These renormalized parton densities are solutions of the Altarelli-Parisi equations.

Master Formula

- **Master Formula $pp \longrightarrow X$: QCD factorization**

$$\sigma_{AB} = \sum_{ab} \int dx_1 dx_2\, f_{a/A}(x_1, \mu_F^2)\;\; f_{b/B}(x_2, \mu_F^2)\;\; \hat{\sigma}_{ab\to X}$$



$A = B = p$ und $a = b = q/g$

- **Partonic cross section $\hat{\sigma}$:**

  ▷ Partons of the incoming hadrons interact at short distance
  Example Drell-Yan process: $\hat{\sigma}(q\bar{q} \to l^+ l^-)$

- **Parton distribution functions (pdf)** $f_{a/A}(x_1, \mu_F^2),\; f_{b/B}(x_2, \mu_F^2)$

  ▷ $x_1 = 2E_a/\sqrt{S}, x_2 = 2E_b/\sqrt{S}$ momentum fraction carried by the incoming quarks,gluons

  ▷ μ_F^2 factorization scale (separates short- and long-distance physics)

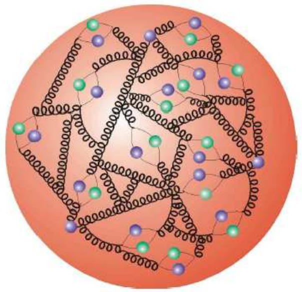
  pdf's extracted from deep-inelastic scattering

Scattering processes at hadron colliders

- **General process $\sigma(pp \to X)$**

$$\sigma_{pp\to X} = \sum_{a,b,k} f_{a/p}(\mu_F^2) \otimes f_{b/p}(\mu_F^2) \otimes \hat{\sigma}_{ab\to k}(\alpha_s(\mu_R^2), \mu_R^2) \otimes D_{k\to X}(\mu_F^2)$$

- **Partonic cross section $\hat{\sigma}_{ab\to k}$**
  calculable with perturbation theory in powers of α_s
  $\hat{\sigma}_{ab\to k} = [\hat{\sigma}_0 + \alpha_s(\mu_R^2)\hat{\sigma}_1 + \alpha_s^2(\mu_R^2)\hat{\sigma}_2 + ...]_{ab\to k}$



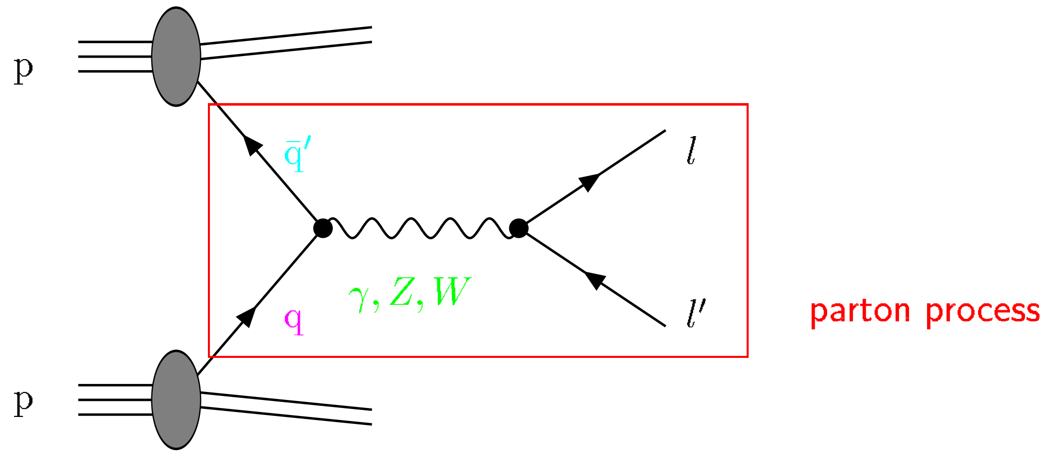
- **Parton luminosity $f_{a/p}(\mu_F^2) \otimes f_{b/p}(\mu_F^2)$**
  proton: very complicated multi-particle bound state

- **Final state X:** hadrons, mesons, jets, ...

  ▷ fragmentation function $D_{k\to X}(\mu_F^2)$ or jet algorithm
  ▷ interface with showering-algorithms (Monte Carlo)

Example Drell-Yan Process

- **Drell-Yan Process**



- **Cross section:** $\sigma(pp \to l^+l^-) = \sum_q \int dx_1 dx_2\; f_q(x_1)\, f_{\bar{q}}(x_2)\; \hat{\sigma}(q\bar{q} \to l^+l^-)$

  ▷ $f_{q/\bar{q}}(x)dx$: probability to find (anti)quark with momenum fraction x

  process independent, measured in DIS

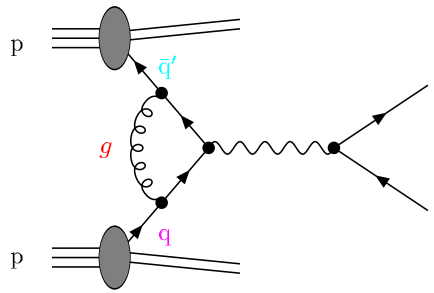
  ▷ $\hat{\sigma}(q\bar{q} \to l^+l^-)$: hard scattering cross section

  calculable in perturbation theory

Example Drell-Yan Process

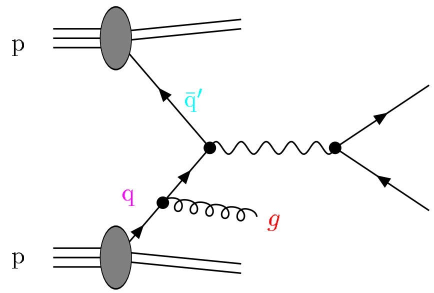
- **Factorisation not trivial beyond leading order**

virtual corrections



▷ UV divergences
▷ IR divergences

real corrections



▷ IR divergences
▷ collinear divergences

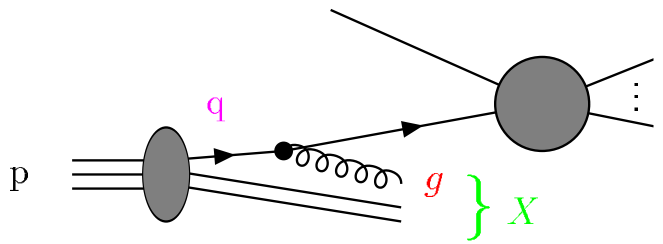
UV divergences → renormalization $\alpha_S(\mu_R)$etc.

IR divergences → cancel between virtual and real correction (Kinoshita-Lee-Nauenberg theorem)

collinear initial state divergences → absorbed in pdf's

Example Drell-Yan Process

- **Example: initial state collinear singularity**



process independent divergence in $\int dk_T^2$ as $k_T^2 \to 0$

$\rightsquigarrow$ absorb singularity in parton densities

$f_q(x, \mu_F) = f_q(x) + (\text{divergent part of } \int_0^{\mu_F^2} dk_T^2)$

- **Hadron collider cross section**

$$\sigma = \int dx_1 \; f_i(x_1, \mu_F) \int dx_2 \; f_j(x_2, \mu_F) \times \sum_n \alpha_S^n(\mu_R) C_n(\mu_R, \mu_F) + \mathcal{O}(\Lambda_{QCD}/Q)$$

Altarelli,Ellis,Martinell;Collins,Soper,Sterman;...

- **Interactions between spectator partons** $\rightsquigarrow$ underlying event and/or multiple hard scattering

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections

LHC is a proton-proton machine processes depend on strong coupling constant $\alpha_s \rightsquigarrow$
higher order corrections can be substantial $\rightsquigarrow$ are important

Precision calculations needed for signal and background processes

- $\diamond$ Higgs discovery in WW decay $\leftarrow$ no reconstruction of the mass peak possible
- $\diamond$ reliable extraction of the discovery/exclusion significances
- $\diamond$ precise measurement of the Higgs couplings
- $\diamond$ ...

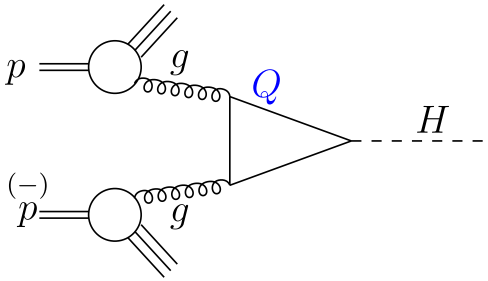
$\Rightarrow$

- $\triangleright$ test of the Higgs mechanism
- $\triangleright$ discrimination between SM and SM extensions (e.g. SUSY)

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in $\mathcal{G}$luon $\mathcal{F}$usion

(i) Dominant: Gluon Fusion $pp \to gg \to H$

Georgi et al; Gamberini et al



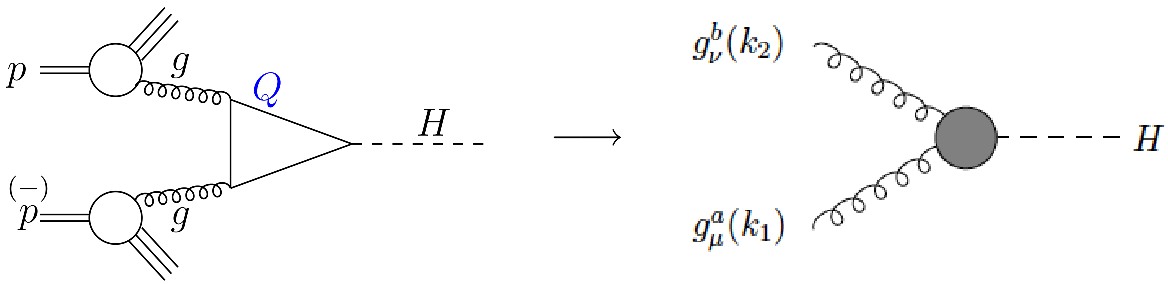
- **Loop-induced process**
  - ∗ dominant contribution: $Q =$ top Quark
  - ∗ subleading contribution: $Q =$ bottom Quark ($< 10\%$)
- **Strong dependence on** factorization and renormalization scales (100%)
  $\rightsquigarrow$ higher order corrections are very important
- **New Physics:** process is sensitive to new heavy particles in the loop
  (no decoupling)

$\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections

- **Effective Theory** for $m_t \to \infty$, $m_b \to 0$ simplifies loop calculations considerably

  physical picture: long-range gluon interaction does not resolve Higgs production

  $\rightsquigarrow$ effective Higgs-gluon-gluon coupling



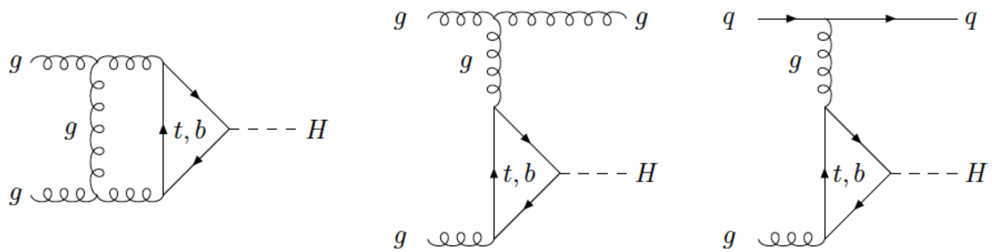
$$= \frac{i\alpha\delta_{ab}}{3\pi v}[-g_{\mu\nu}k_1k_2 + k_{1\mu}k_{2\nu}]$$

- **Local effective interaction:** $\mathcal{L}_{Hgg} = \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{H}{v}(1 + \frac{11\alpha_s}{4\pi} + ...)$

- **NLO correction with full mass dependence:** increase σ by up to $\sim 100\%$

  Spira,Djouadi,Graudenz,Zerwas
  Dawson;Kauffman,Schaffer

- **Typical diagrams contributing to virtual and real corrections including full mass dependence**



$\mathcal{S}$tatus of $\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections

QCD corrections

- ▷ complete NLO: increase σ by $\sim$ 80-100%

  Spira,Djouadi,Graudenz,Zerwas
  Dawson;Kauffman,Schaffer

- ▷ SM: limit $M_\Phi \ll m_t$ - approximation $\sim$ 20-30%

  Krämer,Laenen,Spira

- ▷ NNLO @ $M_\Phi \ll m_t \Rightarrow$ further increase by 20-30%

  Harlander,Kilgore
  Anastasiou,Melnikov
  Ravindran,Smith,van Neerven

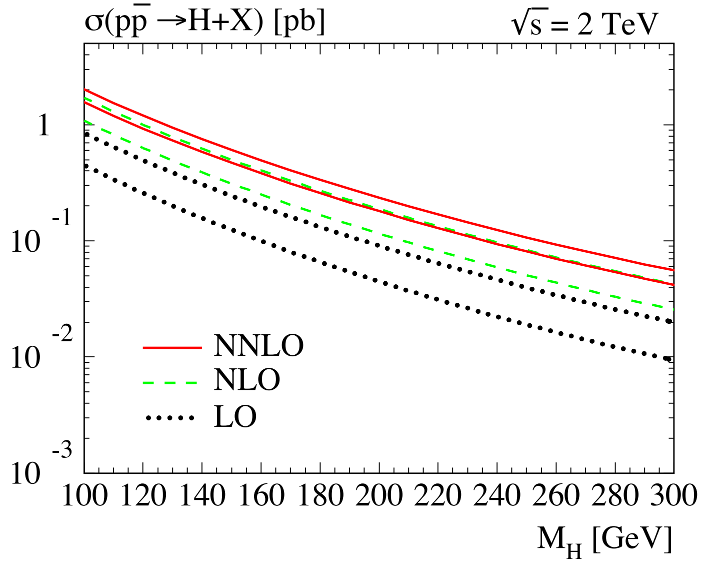
- ▷ Estimate of NNNLO effects @ $M_\Phi \ll m_t \rightsquigarrow$ scale stabilisation

  Moch,Vogt
  Ravindran

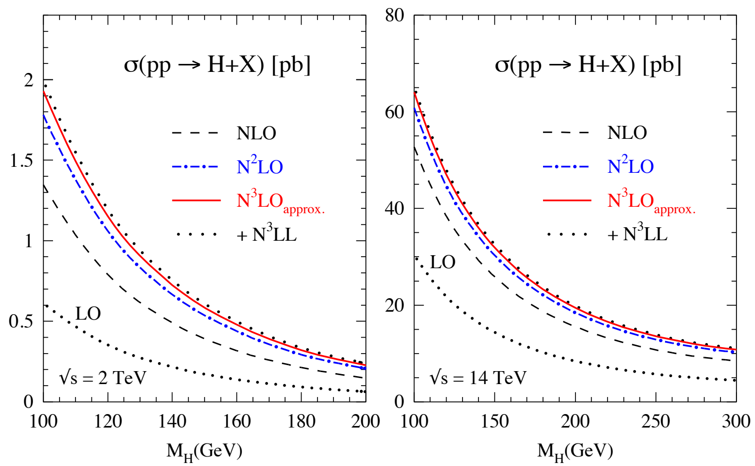
  scale dependence: $\Delta \lesssim 10 - 15\%$

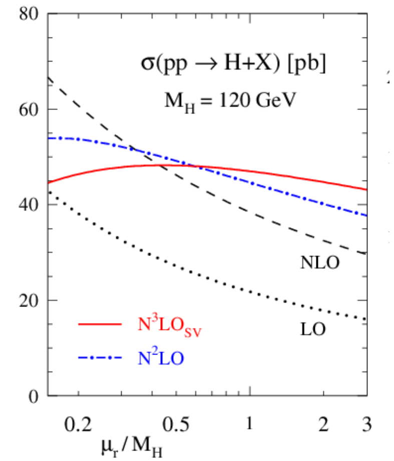
gg → H at $\mathcal{NNLO}$ and beyond

Harlander, Kilgore



Moch, Vogt





Status of Higher Order Corrections

QCD corrections

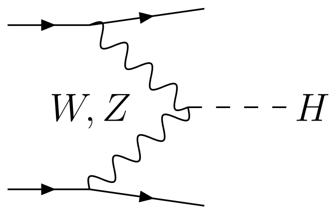
- ▷ complete NLO: increase σ by $\sim$ 80-100% — Spira,Djouadi,Graudenz,Zerwas; Dawson;Kauffman,Schaffer
- ▷ SM: limit $M_\Phi \ll m_t$ - approximation $\sim$ 20-30% — Krämer,Laenen,Spira
- ▷ NNLO @ $M_\Phi \ll m_t \Rightarrow$ further increase by 20-30% — Harlander,Kilgore; Anastasiou,Melnikov; Ravindran,Smith,van Neerven
- ▷ NNNLO effects estimate @ $M_\Phi \ll m_t \rightsquigarrow$ scale stabl. — Moch,Vogt; Ravindran

  scale dependence: $\Delta \lesssim 10-15\%$
- ▷ NNLL resummation: $\sim 6-9\%$ — Catani,de Florian,Grazzini,Nason; Moch,Vogt; Laenen,Magnea; Idilbi eal
- ▷ leading soft contribution at N^{3}LO in limit $m_t \to \infty$ — Ravindran,Smith,van Nerven; Ahrens eal
- ▷ NNLO mass effects (t loops) — Harlander,Ozeren;Pak,Rogal,Steinhauser; Marzani et al.

  for $M_H \lesssim 300$ GeV $\Rightarrow \mathcal{O}(0.5\%)$
- ▷ NLO electroweak corrections $\sim \mathcal{O}(5\%)$ (SM) — Aglietti et al.;Degrassi,Maltoni; Actis et al
- ▷ mixed QCD and EW corrections — Anastasiou,Boughezal,Petriello
- ▷ NLO for H+jet $\lesssim 1\%$ — Keung,Petriello; Brein
- ▷ Steps towards N^{3}LO in gluon fusion — Chetyrkin eal;Schröder,Steinhauser;Baikov eal; Gehrmann eal;Lee eal;Anastasiou eal; Höschele eal; Bühler,Lazopoulos;Boughezal eal;Ball eal;Moch,Vogt

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{P}$roduction in W/Z $\mathcal{B}$oson $\mathcal{F}$usion

(ii) W/Z Boson Fusion: $pp \to qq \to qq + WW/ZZ \to qq + H$



Cahn,Dawson
Hikasa
Altarelli,Mele,Pitolli

Contribution to $H \to \gamma\gamma$ discovery contour

Important role in Higgs coupling determination at the LHC Dührssen et al.; Hankele et al. Rauch et al.; Englert et al.

Typical signature: 2 hard jets with large rapidity interval, no hadronic activity in between

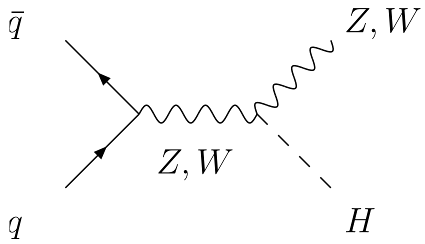
- **VBF cuts and background suppression:**
  - ∗ 2 hard tagging jets demanded: $p_{T_j} > 20$ GeV, $|y_j| < 4.5$
  - ∗ tagging jets forward-backward directed: $\Delta y_{jj} > 4$, $y_{j1} \cdot y_{j2} < 0$

$\mathcal{S}$tatus of $\mathcal{H}$igher $\mathcal{O}$rder $\mathcal{C}$orrections to $\mathcal{H}$iggs+2jets $\mathcal{P}$roduction

▷	**NLO QCD corrections to**		
	total rate	$\sim$ 5 to 10%	Han,Valencia,Willenbrock Spira; Djouadi,Spira
	Distributions	~ 20 %	Figy,Oleari,Zeppenfeld Berger,Campbell
	dominant NLO QCD to H+3j		Figy,Hankele,Zeppenfeld
▷	**NLO QCD corrections to**		
	gluon-initiated channels		Campbell,Ellis,Zanderighi
	contribution to VBF $\sim 5\%$	scale uncert $\sim 35\%$	Nikitenko,Vázquez,Acosta
▷	**Matching with parton shower (POWHEG)**		Nason,Oleari
▷	**Full EW & QCD corrections**	$\sim$ 5%	Ciccolini,Denner,Dittmaier Figy,Palmer,Weiglein
▷	**One-loop interference effects in H+jj**		Andersen,Binoth,Heinrich,Smillie Bredenstein,Hagiwara,Jäger
	between gg-initiated and VBF	below percent level	
	implemented in `VBFNLO`		Bredenstein,Hagiwara,Jäger
▷	**NNLO QCD effects in DIS-like approx**	$\sim 1-2\%$ $\mathcal{O}(M_W)$	Bolzoni,Maltoni,Moch,Zaro
▷	**Loop-induced VBF in gg scattering**	impact $\sim 0.1\%$	Harlander,Vollinga,Weber

$\mathcal{H}$iggs-$\mathcal{S}$trahlung

(iii) $pp \to q\bar{q} \to Z^*/W^* \to Z/W + H$



Glashow et al.
Kunszt et al.

- Important production process at Tevatron
- LHC: contribution to $\Phi \to \gamma\gamma$ discovery contours

- **NLO QCD Korrekturen** $\sim +30\%$ (Drell-Yan) Han,Willenbrock

  NNLO QCD Korrekturen $\sim +5\text{-}10\%$ Harlander,Kilgore; Hamberg,Van Neerven, Matsuura; Brein,Djouadi,Harlander $\quad \mathbf{\Delta_{theor} \sim 5\ \%}$

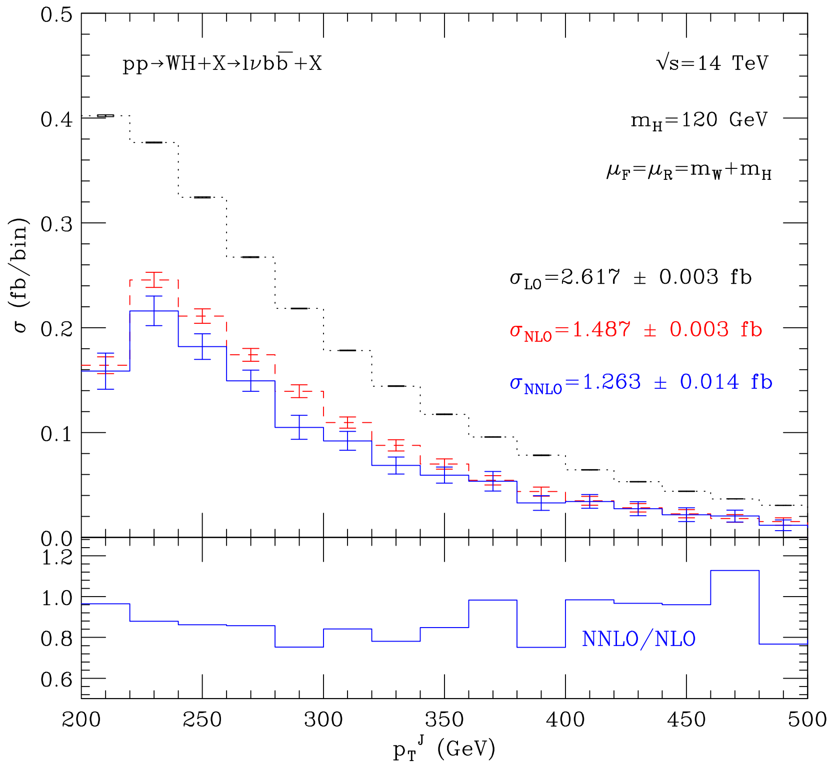
- **Complete EW corrections** $\sim -5\text{-}10\%$ Ciccolini,Dittmaier,Krämer

WH: $\mathcal{F}$ully $\mathcal{E}$xclusive at $\mathcal{NNLO}$ QCD

WH: fully exclusive at NNLO QCD Ferrera,Grazzini,Tramontano '11

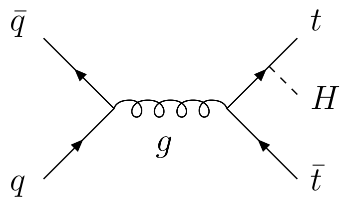
- finite width effects
- W boson leptonic decay w/ spin correlations
- Higgs decay into $b\bar{b}$

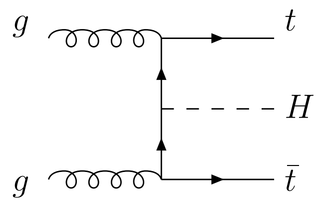
scale dep $\pm 13\%$ (NLO) $\rightarrow$ $\pm 6\%$ (NNLO)



$\mathcal{A}$ssociated $\mathcal{P}$roduction with a $t\bar{t}$ $\mathcal{P}$air

(iv) Higgs $t\bar{t}$ Production: $pp \to q\bar{q}/gg \to t\bar{t} + H$





Kunszt;Gunion;
Marciano,Paige

Significant role for: $M_H^{SM} \lesssim 150$ GeV

- **$t\bar{t}H \to t\bar{t}\gamma\gamma$ important contribution to $H \to \gamma\gamma$ discovery contour**
- **$t\bar{t}H \to t\bar{t}b\bar{b}$ important at LHC $\leadsto$ top Yukawa coupling**

Gunion et al.;
Drollinger et al.

- **NLO bkg $t\bar{t}b\bar{b}$, $t\bar{t}jj$ important**

Bredenstein,Denner,
Dittmaier,Pozzorini;
Bevilacqua,Czakon,Papadopoulos,
Pittau,Worek

$\mathcal{NLO}$ QCD $\mathcal{C}$orrections to $t\bar{t}b\bar{b} + X$ at the $\mathcal{LHC}$

- **$t\bar{t}b\bar{b}$ final states very important background to $t\bar{t}H$**

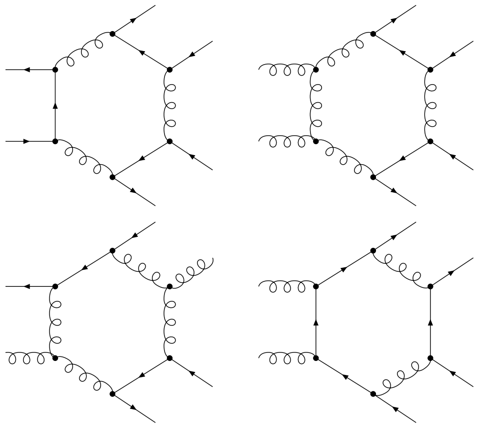
- **$t\bar{t}H$ discovery contour** $\leftarrow$ very good control of $t\bar{t}b\bar{b}$, $t\bar{t}$+jets background necessary

- **NLO QCD corrections** to
  - ▷ $t\bar{t}H$ Beenakker eal;Dawson eal $\sim +20\%$ $\Delta_{\text{theor}} \sim 15\%$
  - ▷ $t\bar{t}$+jet Dittmaier,Uwer,Weinzierl
  - ▷ $t\bar{t} + jj$ Bevilacqua,Czakon,Papadopoulos,Worek

- **NLO QCD corrections** to $t\bar{t}b\bar{b}$ Bredenstein,Denner,Dittmaier,Pozzorini; Bevilacqua,Czakon,Papadopoulos,Pittau,Worek

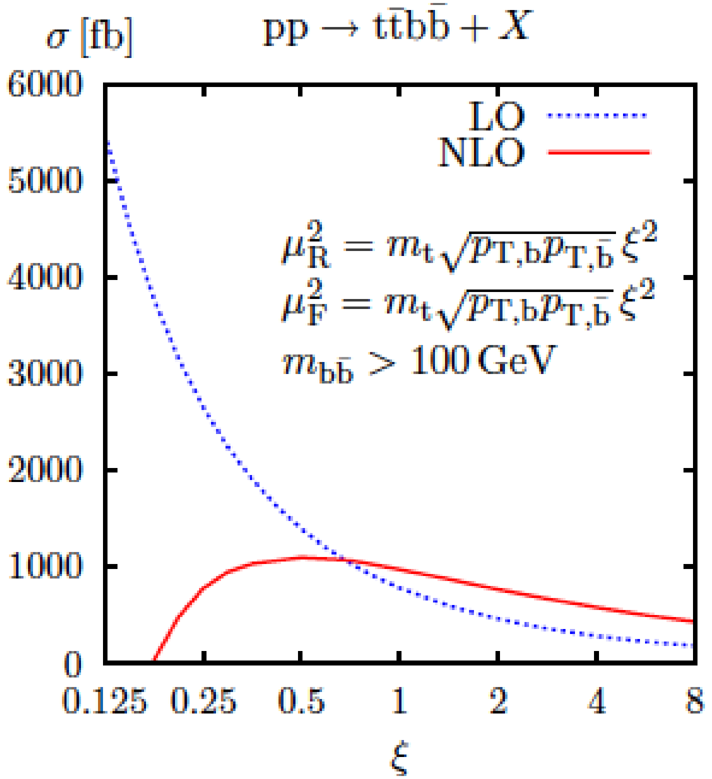
  First full NLO calculation for $2 \rightarrow 4$ process at a hadron collider

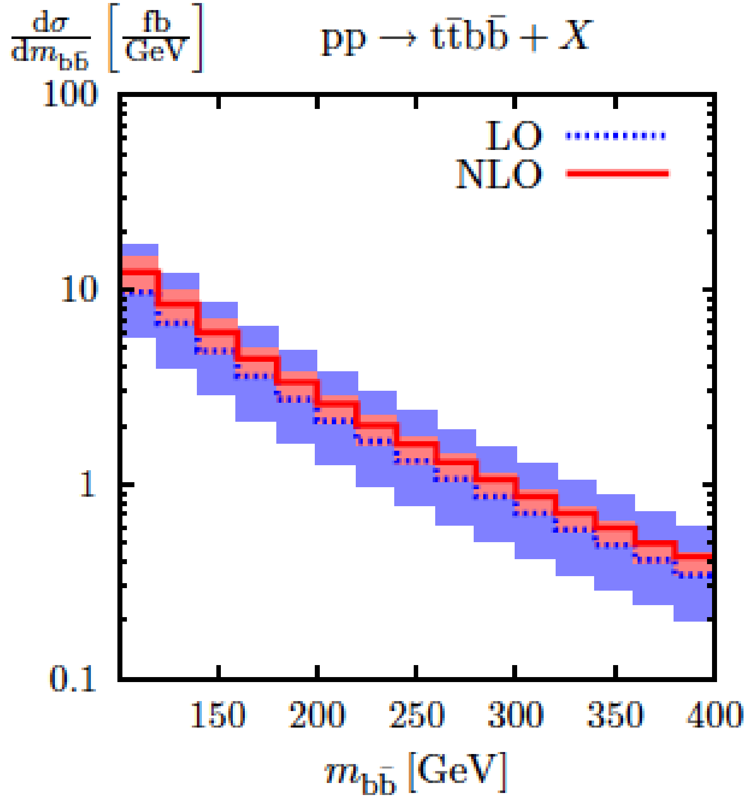
- **Some generic hexagon diagrams** to the virtual corrections



$\mathcal{NLO}$ QCD $\mathcal{C}$orrections to $t\bar{t}b\bar{b} + X$ at the $\mathcal{LHC}$

Bredenstein,Denner,Dittmaier,Pozzorini





- reduction of scale dependence: LO 100 % → NLO 20-30 %
- increased cross section: K factor ≈ 1.24

Higgs Boson Decays

Higgs Boson Decays

- **Higgs boson coupling $\sim$ particle mass** $\rightsquigarrow$ most important decays: into heavy particles

Fermions

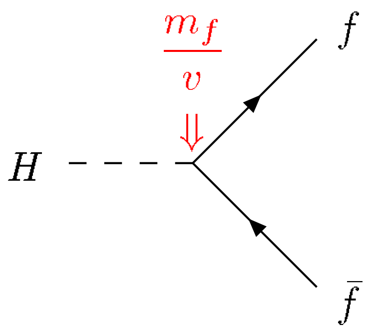
$BR(H \to b\bar{b}) \quad \lesssim \quad 85\%$

$BR(H \to \tau^+\tau^-) \quad \lesssim \quad 8\%$

$BR(H \to c\bar{c}) \quad \lesssim \quad 4\%$

$BR(H \to t\bar{t}) \quad \lesssim \quad 20\%$

large QCD corrections, up to $\mathcal{O}(50\%)$



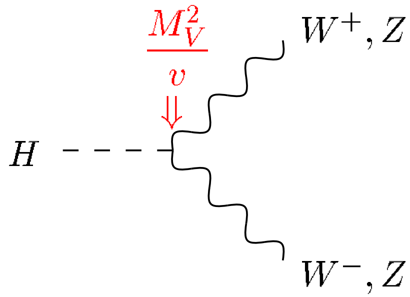
Braaten,Leveille; Sakai; Inami,Kubota; Drees,Hikasa; Gorishnii,Kataev,Larin,Surguladze; Kataev,Kim; Larin,van Ritbergen, Vermaseren; Chetyrkin,Kwiatkowski; Baikov,Chetyrkin,Kühn

Gauge bosons

$BR(H \to W^+W^-) \quad \lesssim \quad 60-95\%$

$BR(H \to ZZ) \quad \lesssim \quad 30\%$

EW corrections $\mathcal{O}(5-20\%)$



Off-shell decays $H \to V^*V^* \to 4l$ important for $M_H = 125$ GeV

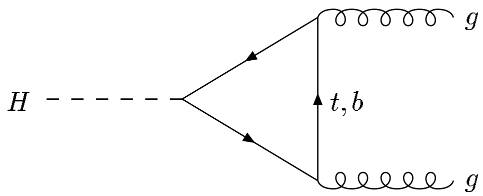
Bredenstein,Denner, Dittmaier,Mück,Weber

PROPHECY4F for $H \to WW/ZZ \to 4f$ (complete QCD and EW NLO corrections)

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

<u>Gluons</u>

$$BR(H \to gg) \quad \lesssim \quad 6\%$$



Loop-mediated decays, dominant contribution from top loops

large QCD corrections, up to +70% at NLO; known up to N^{3}LO

Baikov,Chetyrkin;
Chetyrkin,Kniehl,Steinhauser;Krämer,Laenen,Spira;
Schröder,Steinhauser;Chetyrkin,Kühn,Sturm;
Inami eal;Djouadi,Graudenz,Spira,Zerwas;
Dawson eal;Harlander,Steinhauser;Harlander,Hofmann

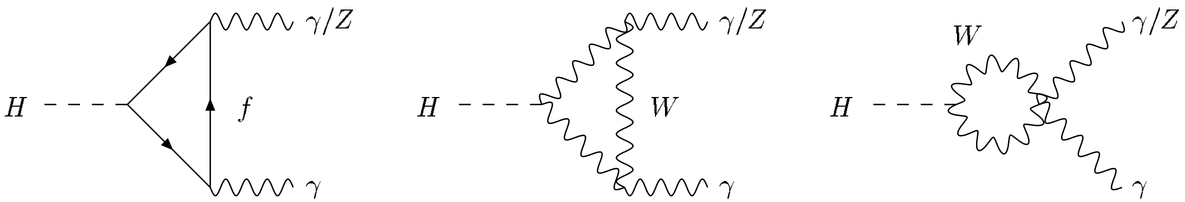
<u>$\gamma\gamma$ and $Z\gamma$</u>

$$BR(H \to \gamma\gamma, Z\gamma) \quad \lesssim \quad 2 \times 10^{-3}$$

Loop-mediated decay via charged fermions and W bosons

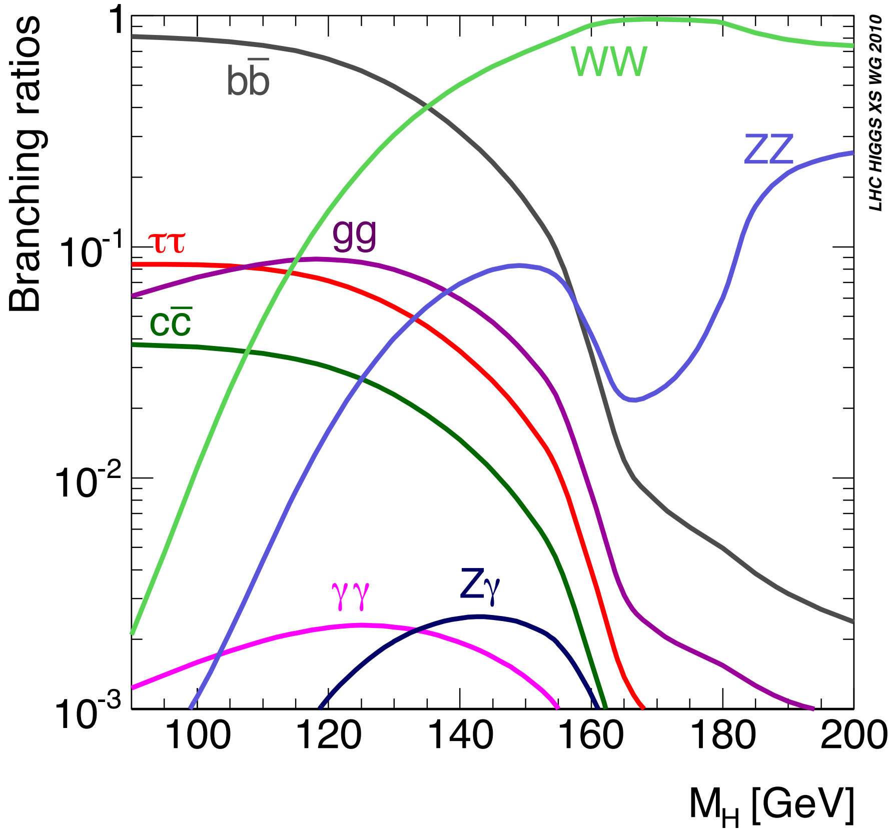
QCD corrections small

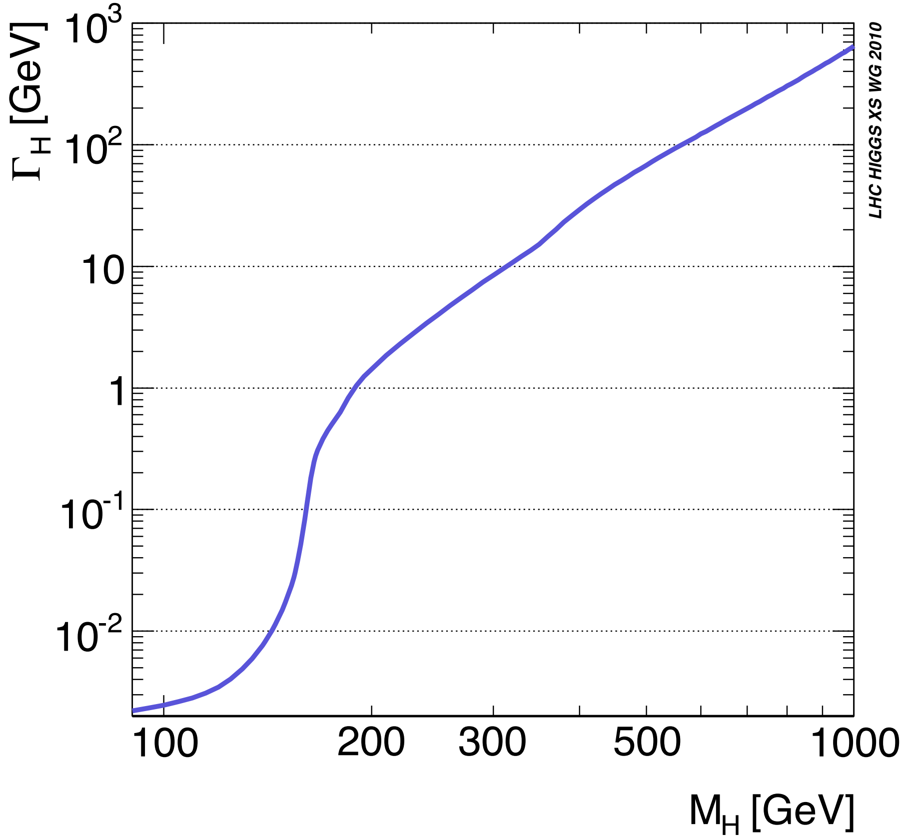
Djouadi,Graudenz,Spira,Zerwas;
Melnikov,Spira,Yakovlev; Zheng,Wu
Dawson,Kauffmann;Melnikov,Yakovlev;
Inoue,Najima,Okada,Saito



$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

Higgs cxn working group





$\mathcal{T}$otal $\mathcal{W}$idth

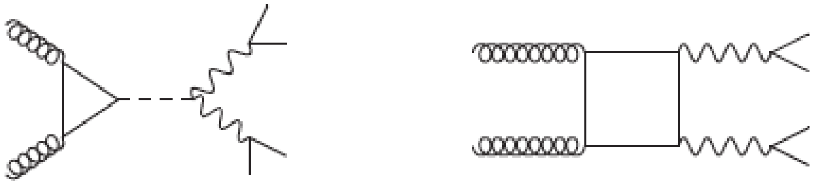
Higgs Total Width $\Gamma_H \approx 4.4$ MeV

- interference between Higgs signal $gg \to H \to \gamma\gamma$ and continuum $gg \to \gamma\gamma \rightsquigarrow$ Higgs mass shift

S.P.Martin '12,'13; Dixon,Li '13

- Off-shell $H \to Z^* Z^*$ production

Caola,Melnikov '13; Campbell,Ellis,Williams '13; Kauer,Passarino '12



Present Value - combined $4l$ and $2l2\nu$ final states

CMS Moriond '13 New!

$\Gamma <$ 17 MeV (35 MeV expected) 95% CL

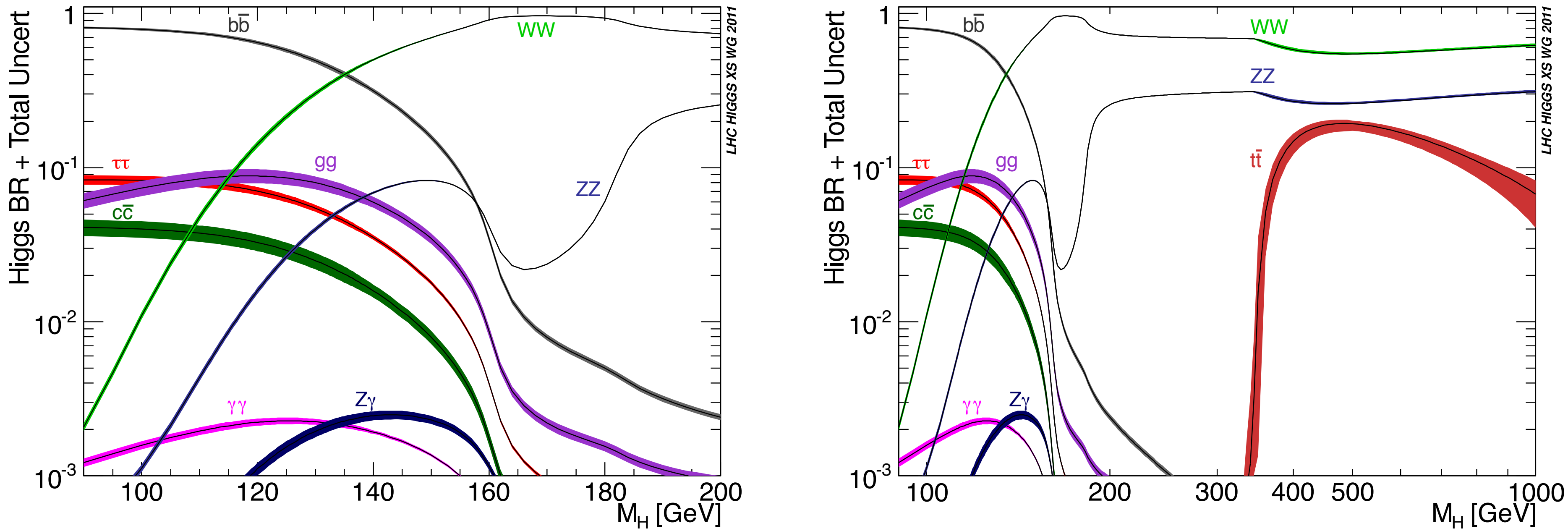
Projection to HL-LHC

dominated by systematics

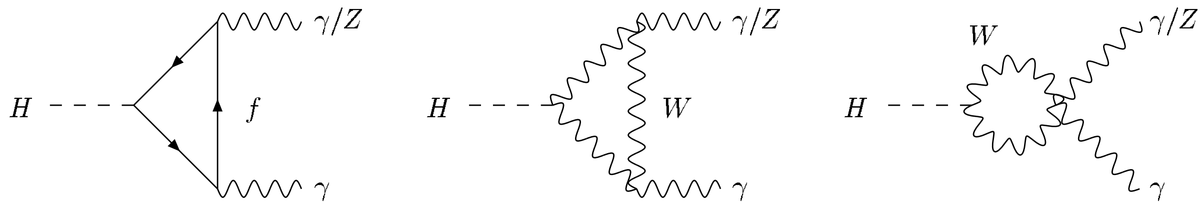
e.g. $pp \to ZZ$ at NNLO QCD required, realistic target, see e.g. Gehrmann,Tancredi,Weihs '13

What Theory tells us: SM Higgs Boson Decays

LHC Higgs XS WG



Note: Decay into $\gamma\gamma$ is loop-mediated (also into $Z\gamma$ and gg): Room for New Physics!



$\mathcal{H}$iggs $\mathcal{S}$earch at the $\mathcal{LHC}$

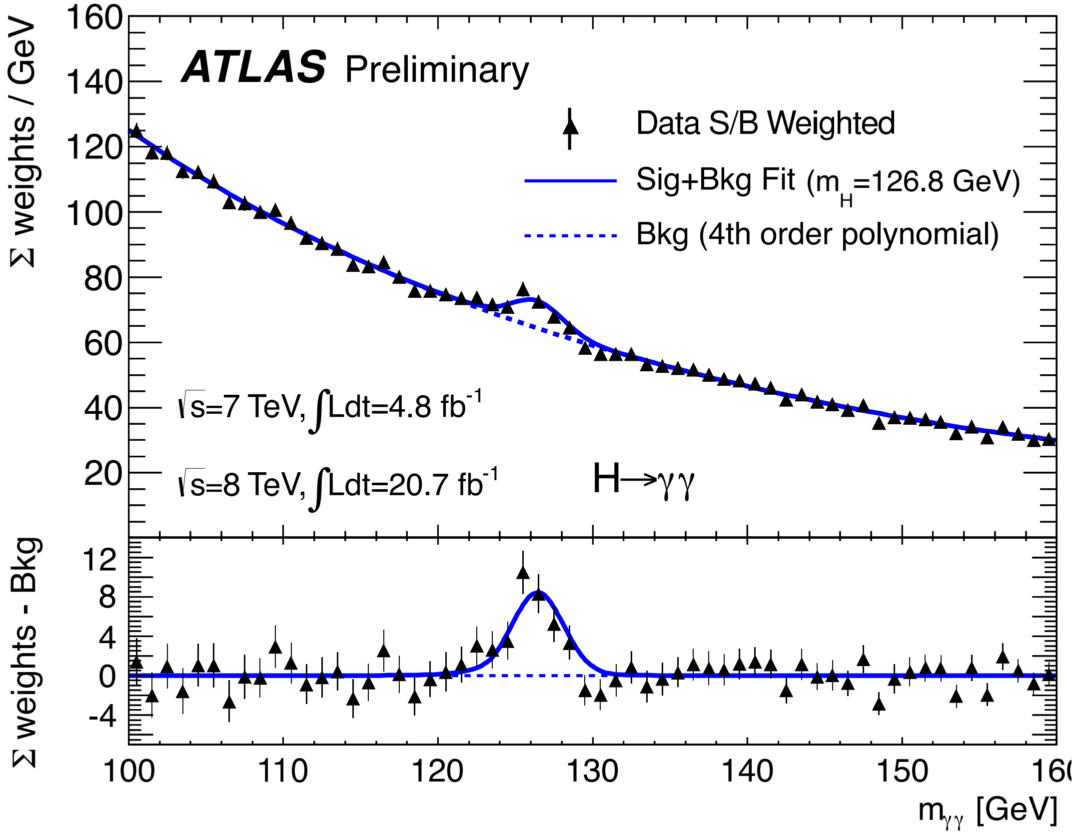
- **Combination of all production and decay channels:** exploit data maximally
- **Production:** dominant process gluon fusion, followed by VBF
- **Decay:**
  * Gold plated: ZZ (off-shell for $M_H = 125$ GeV) $\rightsquigarrow$ clean 4l final state
  * $\gamma\gamma$: small branching ratio, but clean final state
  * WW: (off-shell for $M_H = 125$ GeV) missing energy in final state, exploit transverse mass
  * $b\bar{b}$: large uncertainties due to large QCD background
  * $\tau\tau$: large uncertainties, difficult to measure
- **What experiment tells us:** best fit values to signal rates

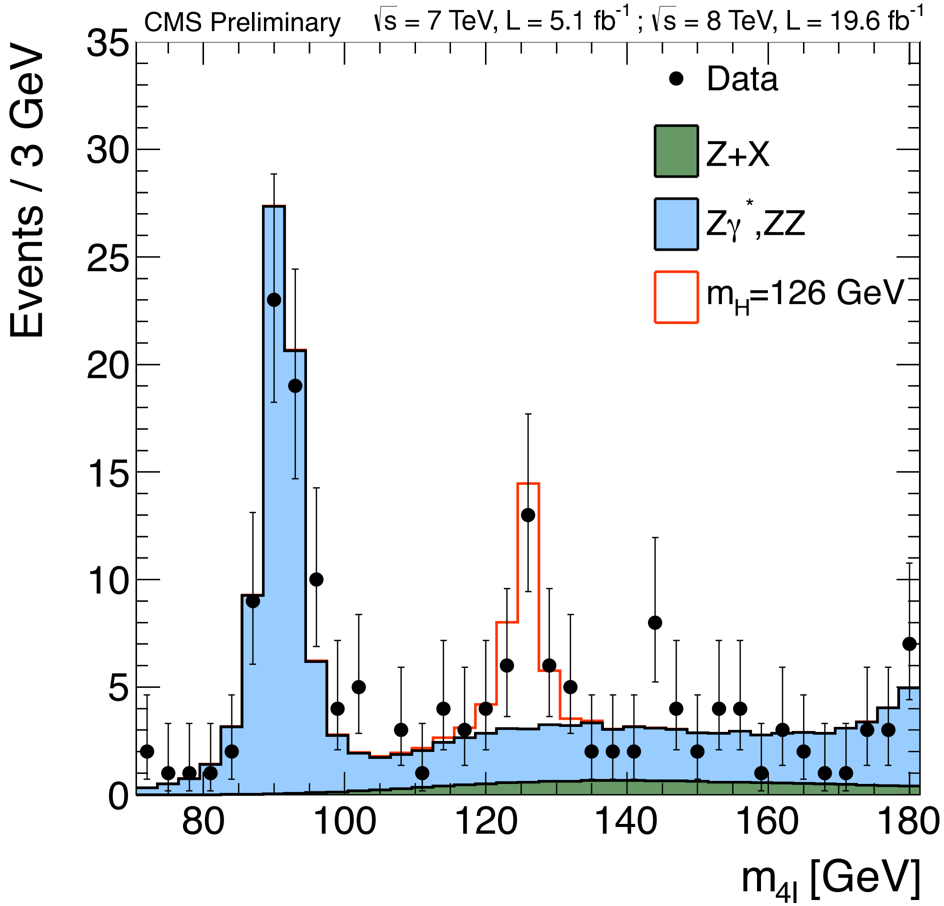
$$\mu = \frac{\sigma_{prod} \times BR(H \to XX)}{(\sigma_{prod} \times BR(H \to XX))_{SM}}$$

$\mathcal{LHC}$ $\mathcal{D}$iscovery of $\mathcal{N}$ew $\mathcal{S}$calar $\mathcal{P}$article

ATLAS-CONF-2013-12

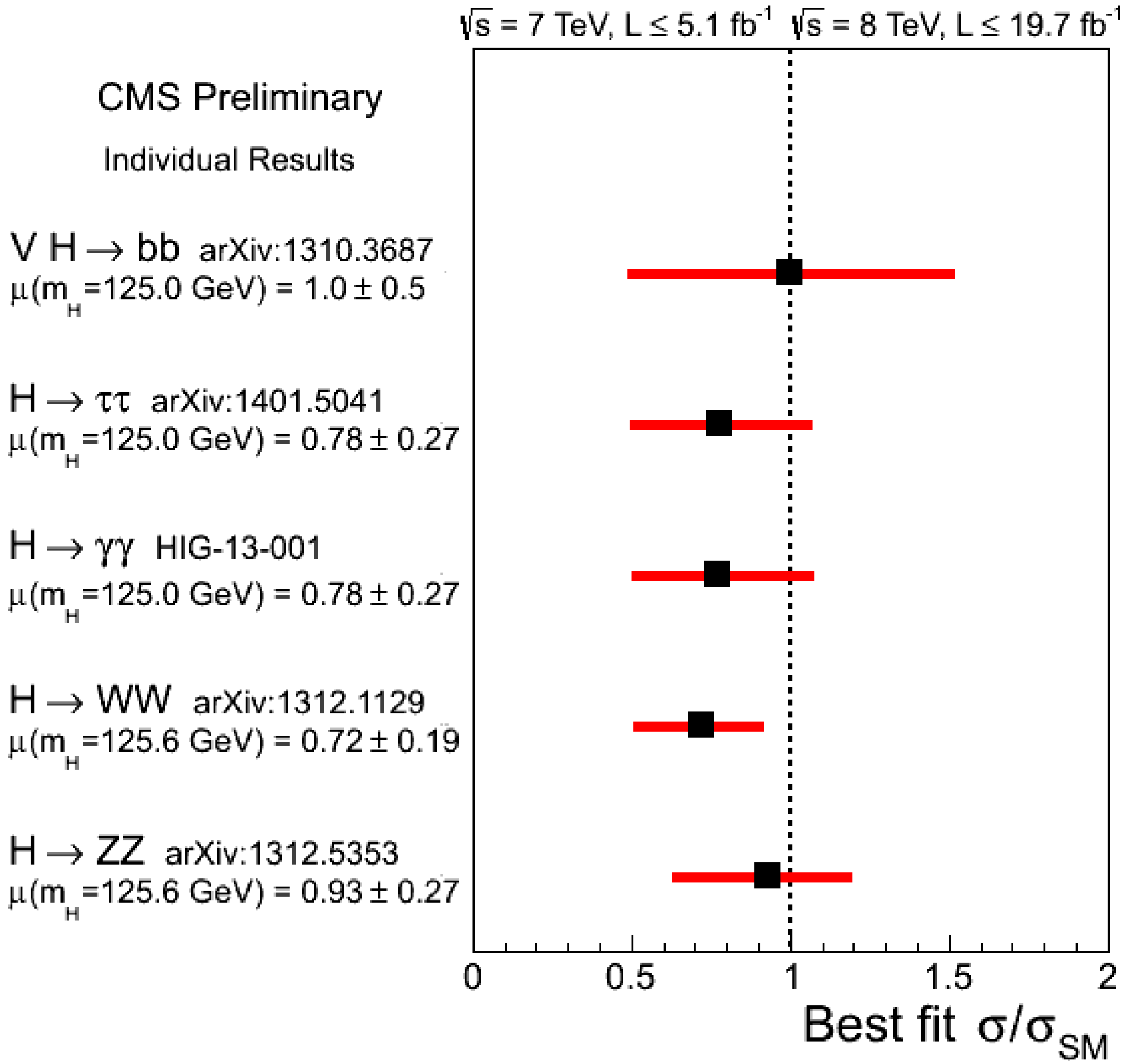
CMS-PAS-HIG-13-002





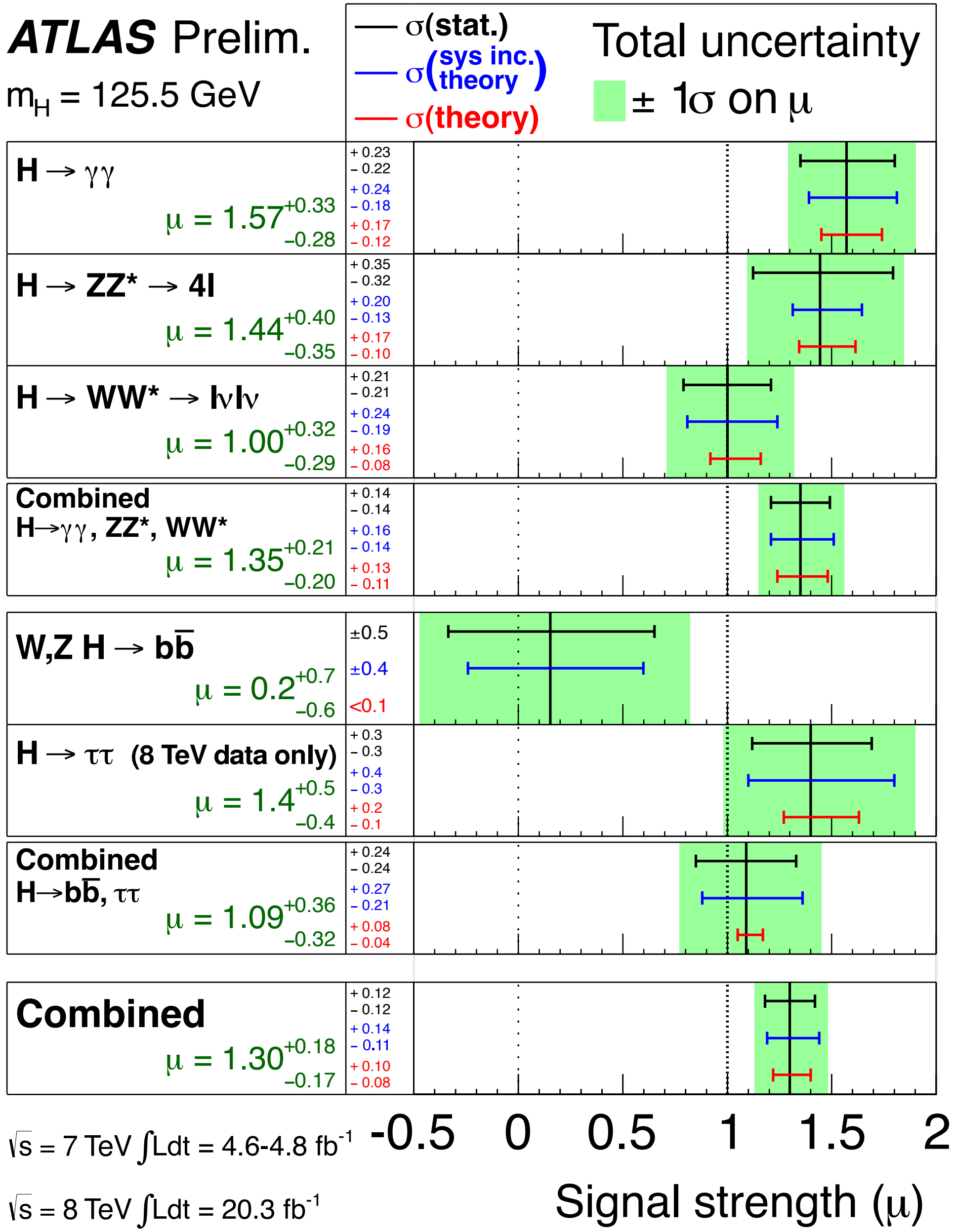
$\mathcal{W}$hat $\mathcal{E}$xperiment tells us: $\mathcal{B}$est $\mathcal{F}$it $\mathcal{V}$alues of $\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$

CMS April 2014



$\mathcal{W}$hat $\mathcal{E}$xperiment tells us: $\mathcal{B}$est $\mathcal{F}$it $\mathcal{V}$alues of $\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$

ATLAS-CONF-2014-009



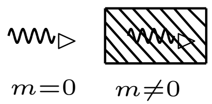
$\mathcal{E}$xperimental $\mathcal{V}$erification of the EWSB $\mathcal{M}$echanism

EWSB mechanism:

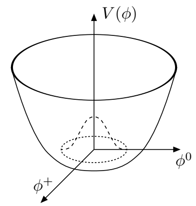
Creation of particle masses without violating gauge principles

Test of the EWSB mechanism

- Discovery – m
- Interaction with the scalar boson with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin- and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$

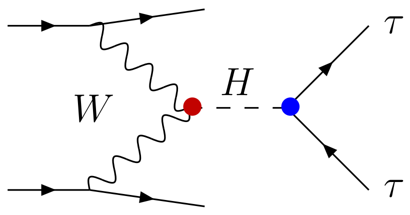


$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

E.g.:



$\sim \Gamma_{WW} \frac{\Gamma(H\to\tau\tau)}{\Gamma_{\text{tot}}}$ (narrow width approximation)

$\mathcal{D}$etermination of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{C}$ouplings

Strategy

Combination of the production and decay channels $\Rightarrow$ decay rates, absolute couplings

$$\sigma_{\text{prod}}(H) \times \text{BR}(H \to XX) \sim \Gamma_{\text{prod}} \times \frac{\Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

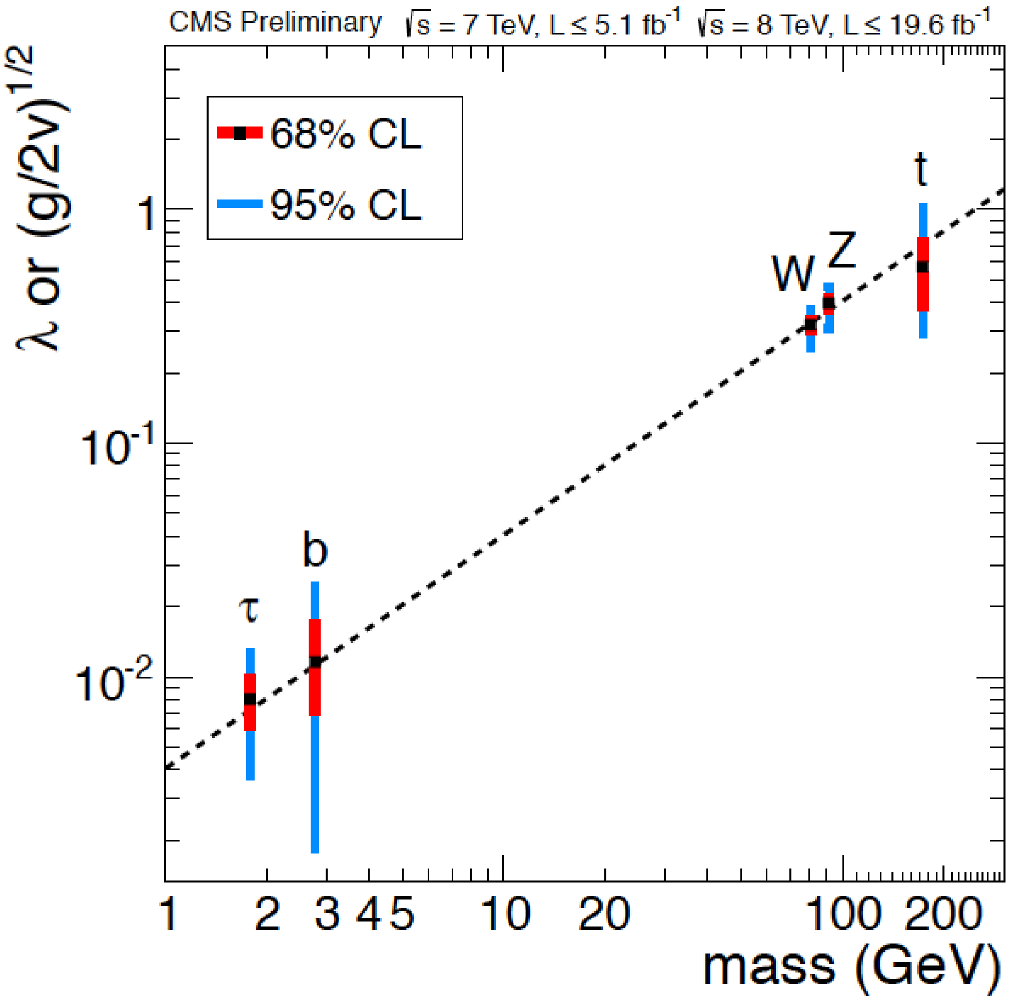
Coupling measurement at the LHC

* Determination of total width impossible w/o further assumptions
* Not all final states are accessible
* $\Rightarrow$ Only ratios of couplings can be measured
* $\Rightarrow$ Perform fits to reduced signal strengths μ

$$\mu = \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}}$$

$\mathcal{E}$xperimental $\mathcal{S}$tatus: $\mathcal{C}$ouplings

CMS-PAS-HIG-13-005



$\mathcal{T}$heoretical $\mathcal{A}$pproach to $\mathcal{C}$oupling $\mathcal{E}$xtraction

- **Couplings extracted** from $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$ values provided by experiments

- **Theoretical approach**
  - ∗ Effective Lagrangian which defines the meaning of the couplings
  - ∗ Effective Lagrangian w/ modified Higgs couplings → signal rates → fit to experimental μ values

◇ **For further work, see:**

D.Carmi, A.Falkowski, E.Kuflik, T.Volansky; D.Carmi, A.Falkowski, E.Kuflik, T.Volansky, J.Zupan;
A.Azatov, R.Contino, J.Galloway; P.Giardino, K.Kannike, M.Raidal, A.Strumia;
J.Ellis, T.You; M.Klute, R.Lafaye, T.Plehn, M.Rauch, D.Zerwas; M.Montull, F.Riva;
I.Low, J.Lykken, G.Shaugnessy; T.Corbett, O.Eboli, J.González-Fraile, M.C. González-Garcia;
S. Banerjee, S. Mukhopadhyay, B. Mukhopadhyaya; Cao eal; T.Plehn, M. Rauch;
Baglio, Djouadi, Godbole; Bélanger, Dumon, Ellwanger, Gunion, Kraml; Buchalla, Cata, Krause; ...

$\mathcal{N}$on-$\mathcal{L}$inear $\mathcal{E}$ffective $\mathcal{L}$agrangian

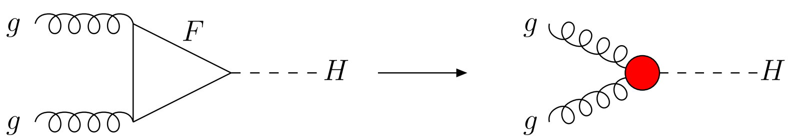
◇ **Field content:** SM with scalar field h; SM: $\kappa_i = 1, \overline{\kappa}_i = 0$

Contino eal '10,'12; Azatov eal; Alonso eal; Brivio eal; Elias-Miró eal; Isidori eal; Buchalla eal

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_3 \left(\frac{m_h^2}{2v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + \kappa_\psi \frac{h}{v} + \ldots\right)$$
$$- M_W^2\, W_\mu^+ W^{-\,\mu}\left(1 + 2\kappa_W \frac{h}{v} + \ldots\right) - \frac{1}{2}M_Z^2\, Z_\mu Z^\mu \left(1 + 2\kappa_Z \frac{h}{v} + \ldots\right) + \ldots$$
$$+ \left(\frac{\bar{\kappa}_{WW}\,\alpha}{\pi} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\bar{\kappa}_{ZZ}\,\alpha}{2\pi} Z_{\mu\nu}Z^{\mu\nu} + \frac{\bar{\kappa}_{Z\gamma}\,\alpha}{\pi} Z_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_\gamma\,\alpha}{2\pi}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{\bar{\kappa}_g\,\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(\left(\bar{\kappa}_{W\partial W}\, W_\nu^- D_\mu W^{+\mu\nu} + h.c.\right) + \bar{\kappa}_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \bar{\kappa}_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

◇ **Remarks:** $*$ Valid for h being singlet or doublet

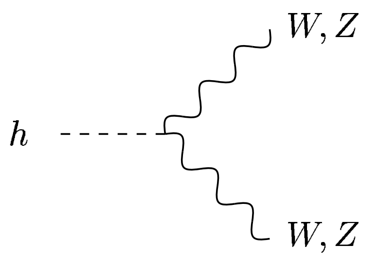
$*$ $\overline{\kappa}_{g,\gamma,Z\gamma}$ parametrize new physics in the hgg, $h\gamma\gamma$ and $hZ\gamma$ loop couplings



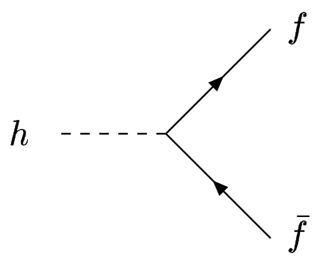
Is it the SM Higgs Boson? - Effective Lagrangian Approach

$$
\begin{aligned}
\mathcal{L} \;&=\; \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)] \\
&\quad -m_{\psi_i}\bar{\psi}_i\psi_i[1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + \ldots
\end{aligned}
$$

- **Extension of the SM Lagrangian by two parameters** κ_V, κ_F; SM: $(\kappa_V, \kappa_F) = (1, 1)$
- **Modified decays rates:** `HDECAY`: Djouadi, Spira, Kalinowski, MMM



$\kappa_V\; g_{hVV}$



$\kappa_F\; g_{hff}$

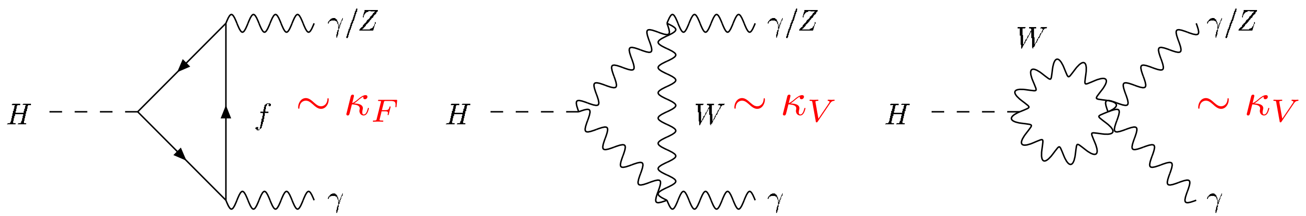
$\mathcal{I}$s it the $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson? - $\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)] \\ &\quad - m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + \ldots\end{aligned}$$

- **Extension of the SM Lagrangian by two parameters** κ_V, κ_F; SM: $(\kappa_V, \kappa_F) = (1,1)$

- **Modified decays rates:** `HDECAY`: Djouadi, Spira, Kalinowski, MMM

$h \to \gamma\gamma$:

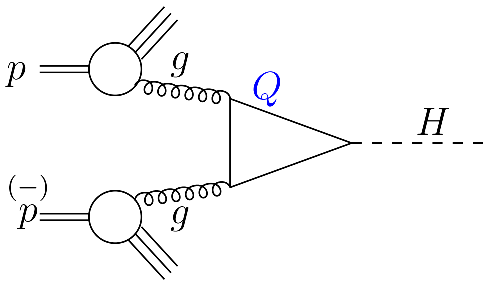


$\mathcal{I}$s it the $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson? - $\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)] \\ & \quad -m_{\psi_i}\bar{\psi}_i\psi_i[1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + ...\end{aligned}$$

- **Extension of the SM Lagrangian by two parameters** κ_V, κ_F; SM: $(\kappa_V, \kappa_F) = (1, 1)$
- **Modified decays rates:** `HDECAY`: Djouadi, Spira, Kalinowski, MMM

Modified Higgs-gluon-gluon coupling:



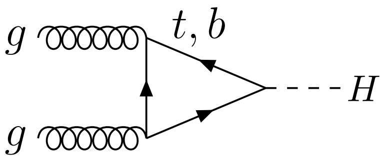
$\sim \kappa_F^2$

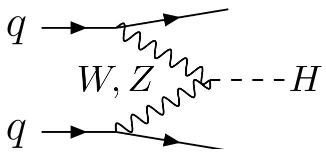
$\mathcal{S}$ignal $\mathcal{R}$ates

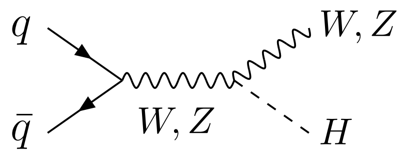
▷ **Coupling modifications affect** Higgs signal but not background
signal rates changed, but kinematics unaffected ⇒ Rescale SM searches

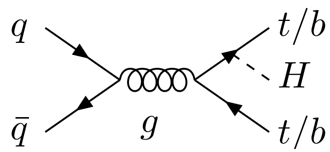
▷ **NNLO QCD corrections:** not affected by modified Higgs couplings (not true for NLO EW)

▷ **Rescaling - Production (NNLO QCD)**









$\frac{\sigma_{QCD}}{\sigma_{QCD}^{SM}}$ κ_F^2 κ_V^2 κ_V^2 κ_F^2

▷ **Rescaling - Decay**

$$\frac{\Gamma(H\to f\bar{f})}{\Gamma(H\to f\bar{f})^{SM}} = \frac{\Gamma(H\to gg)}{\Gamma(H\to gg)^{SM}} = \kappa_F^2 \quad \frac{\Gamma(H\to VV)}{\Gamma(H\to VV)^{SM}} = \kappa_V^2 \quad \frac{\Gamma(H\to \gamma\gamma)}{\Gamma(H\to \gamma\gamma)^{SM}} = \frac{(\kappa_V J_\gamma - \kappa_F I_\gamma)^2}{(J_\gamma - I_\gamma)^2}$$

$\mathcal{F}$it to $\mathcal{LHC}$ $\mathcal{D}$ata within SM($a \equiv \kappa_V, c \equiv \kappa_F$) - $\mathcal{S}$ummer 2012

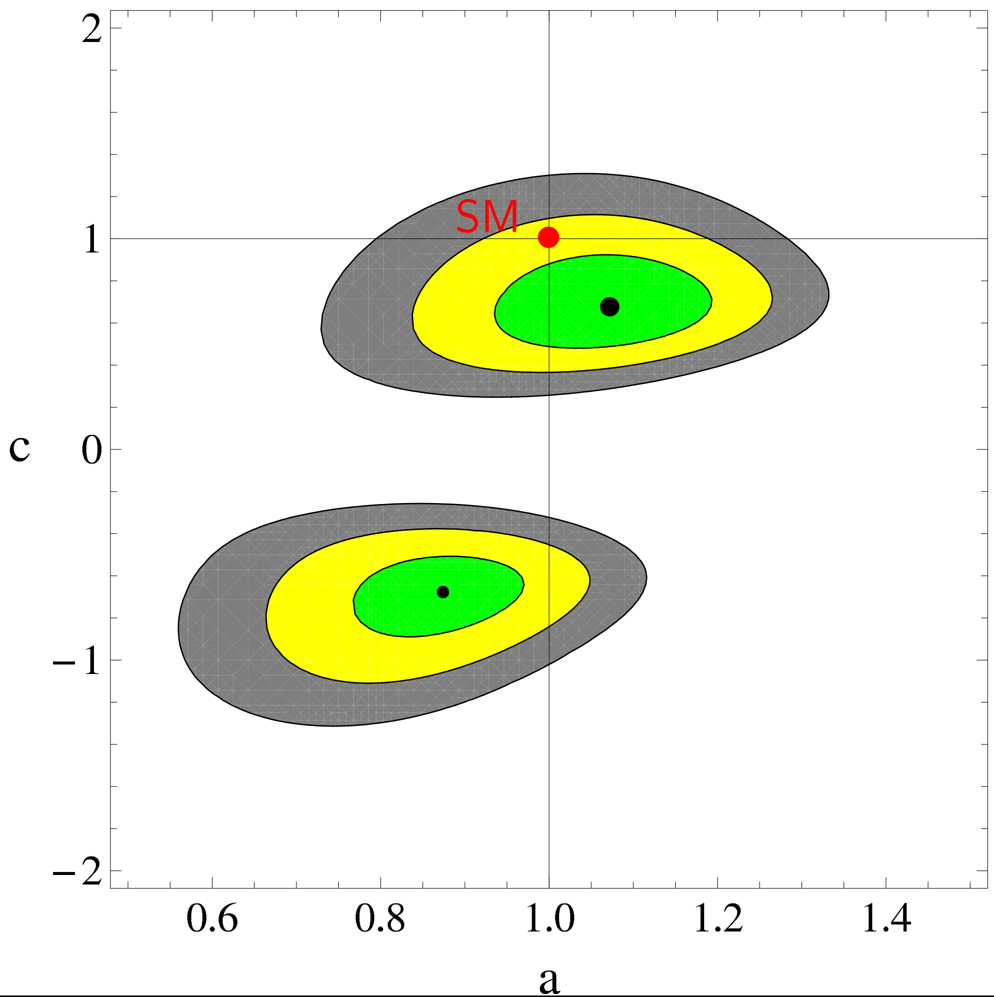
χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron) Espinosa,Grojean,MMM,Trott '12

(green/yellow/grey)
(65/90/99% CL)

SM within $\sim 2\sigma$
from best fit point

Two minima:
approx. symmetry
$a \leftrightarrow -a \quad c \leftrightarrow -c$
broken by $H\gamma\gamma$ couplg
$\sim |1.26a - 0.26c|^2$

7&8 TeV LHC data & Tevatron



Note: a fermiophobic Higgs is disfavoured by data

$\mathcal{F}$it to $\mathcal{LHC}$ $\mathcal{D}$ata within SM(κ_V, κ_F)

- **Best fit points**

  ◇ Solution for $\kappa_F < 0$

$$\Gamma(H \to \gamma\gamma) = \frac{(\kappa_V J_\gamma - \kappa_F I_\gamma)^2}{(J_\gamma - I_\gamma)^2} \Gamma^{SM}(H \to \gamma\gamma)$$

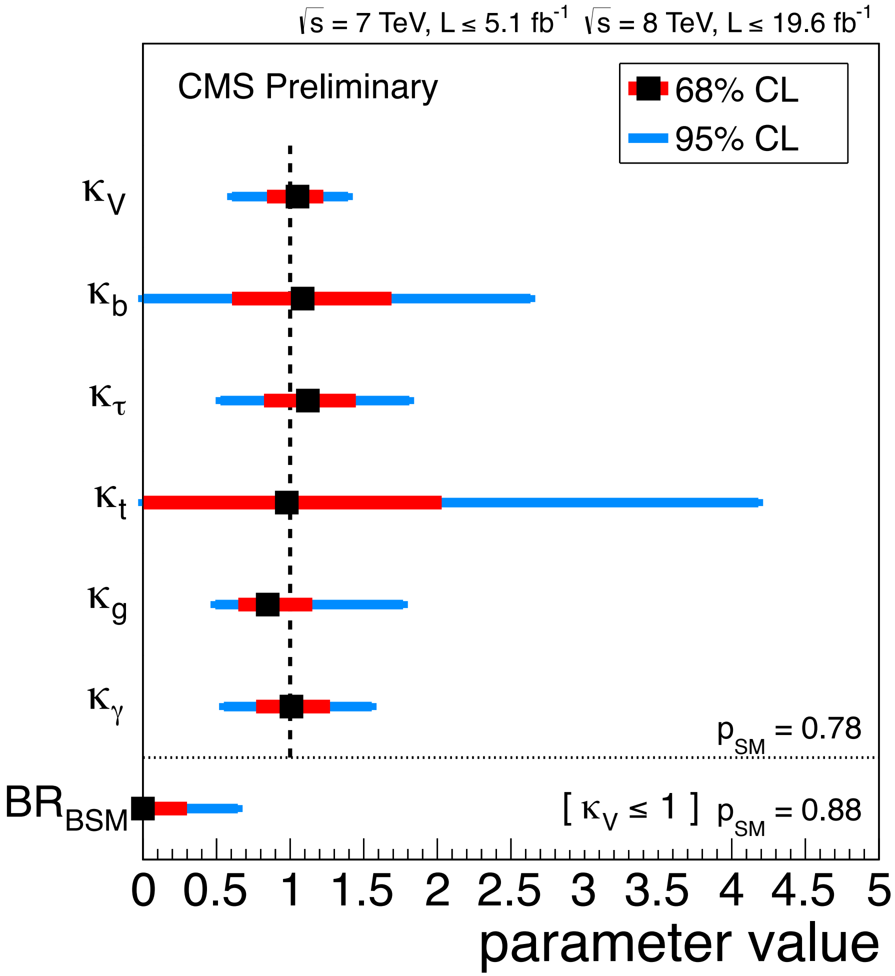
  Constructive interference for $\kappa_F < 0$.

- **For further work, see:**

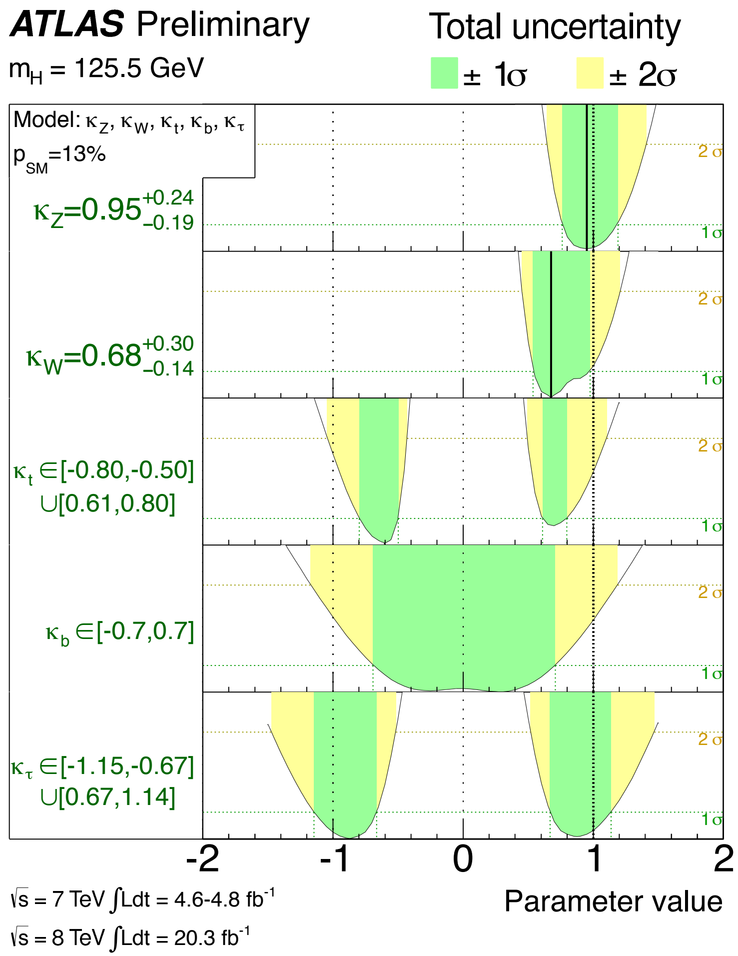
  D.Carmi, A.Falkowski, E.Kuflik, T.Volansky; D.Carmi, A.Falkowski, E.Kuflik, T.Volansky, J.Zupan;
  A.Azatov, R.Contino, J.Galloway; P.Giardino, K.Kannike, M.Raidal, A.Strumia;
  J.Ellis, T.You; M.Klute, R.Lafaye, T.Plehn, M.Rauch, D.Zerwas; M.Montull, F.Riva;
  I.Low, J.Lykken, G.Shaugnessy; T.Corbett, O.Eboli, J.González-Fraile, M.C. González-Garcia;
  S. Banerjee, S. Mukhopadhyay, B. Mukhopadhyaya; Cao eal; T.Plehn, M. Rauch;
  Baglio, Djouadi, Godbole; Bélanger, Dumon, Ellwanger, Gunion, Kraml ...

Status: Coupling Scale Factor Measurements

CMS Collaboration



ATLAS-CONF-2014-009



$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Quantum numbers of the Higgs boson:** J^{PC}
  - J spin
  - P parity
  - C charge conjugation

- **Vast literature:**

Miller eal; Plehn eal; Choi eal; Odagiri; Buszello eal; Ellis eal; Godbole eal; Kramer eal; Berge al; Hagiwara eal; Hankele eal; Gao eal; De Rujula eal; Christensen eal; Englert eal; De Sanctis eal; Bolognesi eal; Boughezal eal; Coleppa eal; Stolarski eal; Alves; Chen eal; Banerjee eal; Freitas, Schwaller; Modak eal; Frank eal; Djouadi eal; Artoisenet eal; Desai eal; Schlegel eal; de Aquino, Mawatari; ...

- **Observation in $\gamma\gamma$:** No spin 1 [Landau-Yang]; C=+1 [assuming charge invariance]

- **Theoretical Tools:**
  - ∗ helicity analyses
  - ∗ operator expansions

- **Systematic analysis of production and decay processes**

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Systematic analysis of production and decay processes**

  $*$ V^*V decays — Buszello,Fleck,Marquard,van der Bij;Choi eal; Gao eal; De Rujula eal; Bolognesi eal; Englert eal; Boughezal eal

  $*$ $\gamma\gamma$ decays — Ellis, Hwang; Alves; Choi eal

  $*$ $Z\gamma$ decays — Stolarski, Vega-Morales; Choi eal

  $*$ CP-violating decays — Soni, Xu; Chang eal; Godbole eal; Nelson; De Rujula eal: Buszello eal; Freitas, Schwaller

  $*$ Fermionic decays ($\rightarrow$ CP violation) — Kramer eal; Berge eal; Banerjee eal

  $*$ Production in gluon fusion, in vector boson fusion — Plehn eal; Hagiwara eal; Buszello, Marquard; Hankele eal; Campanario eal; Del Duca eal; Frank eal

  $*$ Production in Higgs-strahlung — Miller eal; Ellis eal; Englert eal; Frank eal; Djouadi eal; Christensen eal

  $*$ Hadronic event shapes — Englert eal

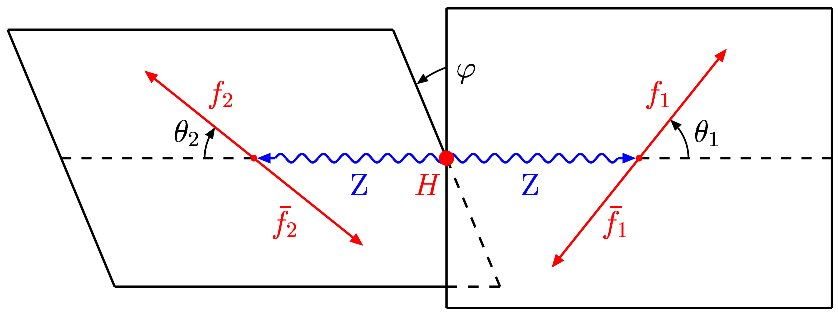
  $*$ Correlations among branching ratios — Coleppa eal; Ellis eal

(I) $\mathcal{A}$ngular $\mathcal{D}$istributions/$\mathcal{T}$hresholds in $H \to VV^* \to 4\ell$

◇ Determination of spin and parity in

$$H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$$

in H c.m. frame



◇ Helicity methods to generalize to arbitrary spin and parity

$$\langle Z(\lambda_1)Z(\lambda_2)|H_{\mathcal{J}}(m)\rangle = \mathcal{T}_{\lambda_1\lambda_2} d^{\mathcal{J}}_{m,\lambda_1-\lambda_2}(\Theta) e^{-i(m-\lambda_1+\lambda_2)\varphi}$$

◇ General tensor for HZZ vertex for each $\mathcal{J}^{\mathcal{P}}$

$$\mathcal{J} = T_{\mu\nu\beta_1\ldots\beta_{\mathcal{J}}} \epsilon^*(Z_1)^{\mu} \epsilon^*(Z_2)^{\nu} \epsilon(H)^{\beta_1\ldots\beta_{\mathcal{J}}}$$

$\mathcal{D}$ifferential $\mathcal{D}$istributions $\mathcal{P}$ure-$\mathcal{S}$pin/$\mathcal{P}$arity $\mathcal{U}$npolarized $\mathcal{B}$oson H^J

◇ **Double polar angular distribution (CP-invariant theory)**

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\cos\theta_1 d\cos\theta_2} = \Big[\sin^2\theta_1\sin^2\theta_2\,|\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right] + (1+\cos^2\theta_1)\,\sin^2\theta_2\,|\mathcal{T}_{10}|^2 + \sin^2\theta_1\,(1+\cos^2\theta_2)\,|\mathcal{T}_{01}|^2\Big]/\mathcal{N}$$

$\mathcal{N} = (16/9)\sum|\mathcal{T}_{\lambda\lambda'}|^2$ – normalization

◇ **Azimuthal angular distribution (CP-invariant theory)**

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\phi} = \frac{1}{2\pi}\left[1 + |\zeta_1|\cos 2\phi\right]$$

$|\zeta_1| = |\mathcal{T}_{11}|^2/\left[2\sum|\mathcal{T}_{\lambda\lambda'}|^2\right]$

suppressing terms quadratic in $\eta_i = 2v_i a_i/(v_i^2 + a_i^2) \sim 0.02$, v_i, a_i electroweak fermion f_i charges

$\mathcal{D}$etermination of $\mathcal{S}$pin and $\mathcal{P}$arity - $\mathcal{G}$eneral $\mathcal{C}$ase

- $M_H < 2M_Z$: $d\Gamma/dM_*^2 \sim \beta$ for $\mathcal{J}^{\mathcal{P}} = 0^+$
  - $\diamond$ $d\Gamma/dM_*^2$ rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm$
  - $\diamond$ $d\Gamma/dM_*^2$ and no $[1 + \cos^2\theta_1]\sin^2\theta_2$
    $[1 + \cos^2\theta_2]\sin^2\theta_1$ rules out $\mathcal{J}^{\mathcal{P}} = 1^+, 2^+$

- $M_H > 2M_Z$:
  - $\diamond$ odd normality: $\mathcal{J}^{\mathcal{P}} = 0^-, 1^+, 2^-, 3^+, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - $\diamond$ even normality: $\mathcal{J}^{\mathcal{P}} = 1^-, 3^-, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - $\diamond$ rule out $\mathcal{J}^{\mathcal{P}} = 2^+, 4^+$ with:
    $\frac{d\sigma}{d\cos\theta}[gg/\gamma\gamma \to H \to ZZ]$ only isotropic for spin 0

- Caveat: HO corrections to $H \to WW/ZZ \to 4f$ distort the shapes of the distributions

Bredenstein,Denner,Dittmaier,Walser

$\mathcal{D}$etermination of $\mathcal{S}$pin and $\mathcal{P}$arity of $\mathcal{SM}$ $\mathcal{H}$iggs, $\mathcal{N}$ecessary $\mathcal{C}$onditions

- **Standard Model:**

$$\mathcal{T}_{00} = (M_H^2 - M_*^2 - M_Z^2)/(2M_* M_Z), \qquad \mathcal{T}_{11} = +\mathcal{T}_{-1,-1} = -1, \qquad \mathcal{T}_{10} = \mathcal{T}_{01} = \mathcal{T}_{1,-1} = 0$$

Necessary conditions:

◇ Double polar angular distribution

$$\frac{1}{\Gamma'} \frac{d\Gamma'}{d\cos\theta_1 d\cos\theta_2} = \frac{9}{16} \frac{1}{\gamma^4 + 2} \Big[\gamma^4 \sin^2\theta_1 \sin^2\theta_2 + \frac{1}{2} (1 + \cos^2\theta_1)(1 + \cos^2\theta_2) \Big]$$

◇ Azimuthal angular distribution

$$\frac{1}{\Gamma'} \frac{d\Gamma'}{d\phi} = \frac{1}{2\pi} \left[1 + \frac{1}{2} \frac{1}{\gamma^4 + 2} \cos 2\phi \right]$$

$$\gamma^2 = (M_H^2 - M_*^2 - M_Z^2)/(2M_* M_Z)$$

$\mathcal{D}$etermination of $\mathcal{S}$pin and $\mathcal{P}$arity of $\mathcal{SM}$ $\mathcal{H}$iggs, $\mathcal{S}$ufficient $\mathcal{C}$onditions

- $\boldsymbol{M_H < 2M_Z}$: $\quad d\Gamma/dM_*^2 \sim \beta$ for $\mathcal{J}^{\mathcal{P}} = 0^+$

  - ◇ $d\Gamma/dM_*^2$ rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm$ [threshold rise]
  - ◇ $d\Gamma/dM_*^2$ and no $[1+\cos^2\theta_1]\sin^2\theta_2$
    $[1+\cos^2\theta_2]\sin^2\theta_1$ rules out $\mathcal{J}^{\mathcal{P}} = 1^+, 2^+$

  $\Rightarrow$ only 0^+ left (sufficient conditions)

- Caveat: HO corrections to $H \to WW/ZZ \to 4f$ distort the shapes of the distributions

  Bredenstein,Denner,Dittmaier,Walser

$\mathcal{P}$seudoscalar A with $J^P = 0^-$

- **Differential Distributions:** Parity invariance $\rightsquigarrow$

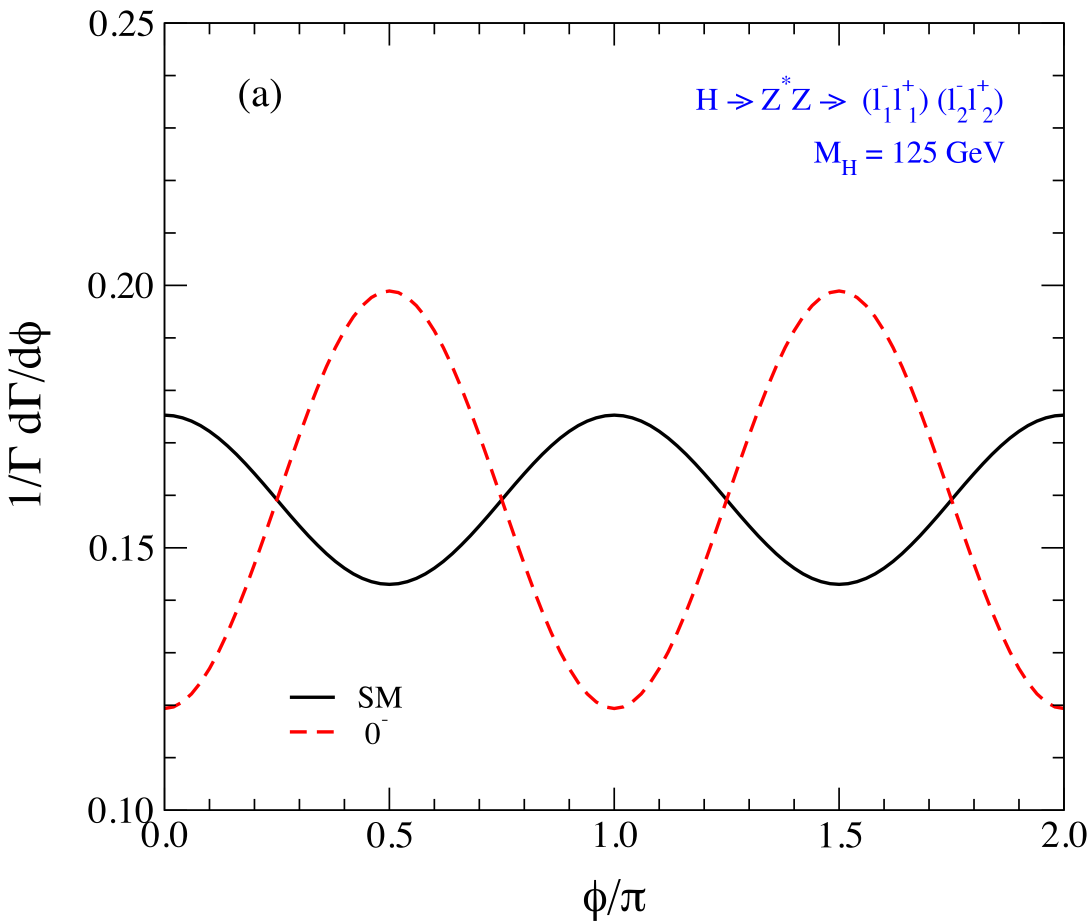
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\cos\theta_1\cos\theta_2} = \frac{9}{64}(1+\cos^2\theta_1)(1+\cos^2\theta_2)$$
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\phi} = \frac{1}{2\pi}\left[1-\frac{1}{4}\cos 2\phi\right]$$

- **Threshold Behaviour:** $d\Gamma_A/dM_*^2 \sim \beta^3$

- **If too small branching ratio $A \to Z^*Z$:** sufficient and necessary conditions of spin/parity
  - Spin 0: isotropic angular distribution in $gg \to A \to \gamma\gamma$
  - Jets in $gg \to A + gg$ anti-correlated for pseudoscalar (correlated for scalar) Hagiwara eal
  - Exploit fermionic decay channels

Azimuthal Angular Distributions: Parity

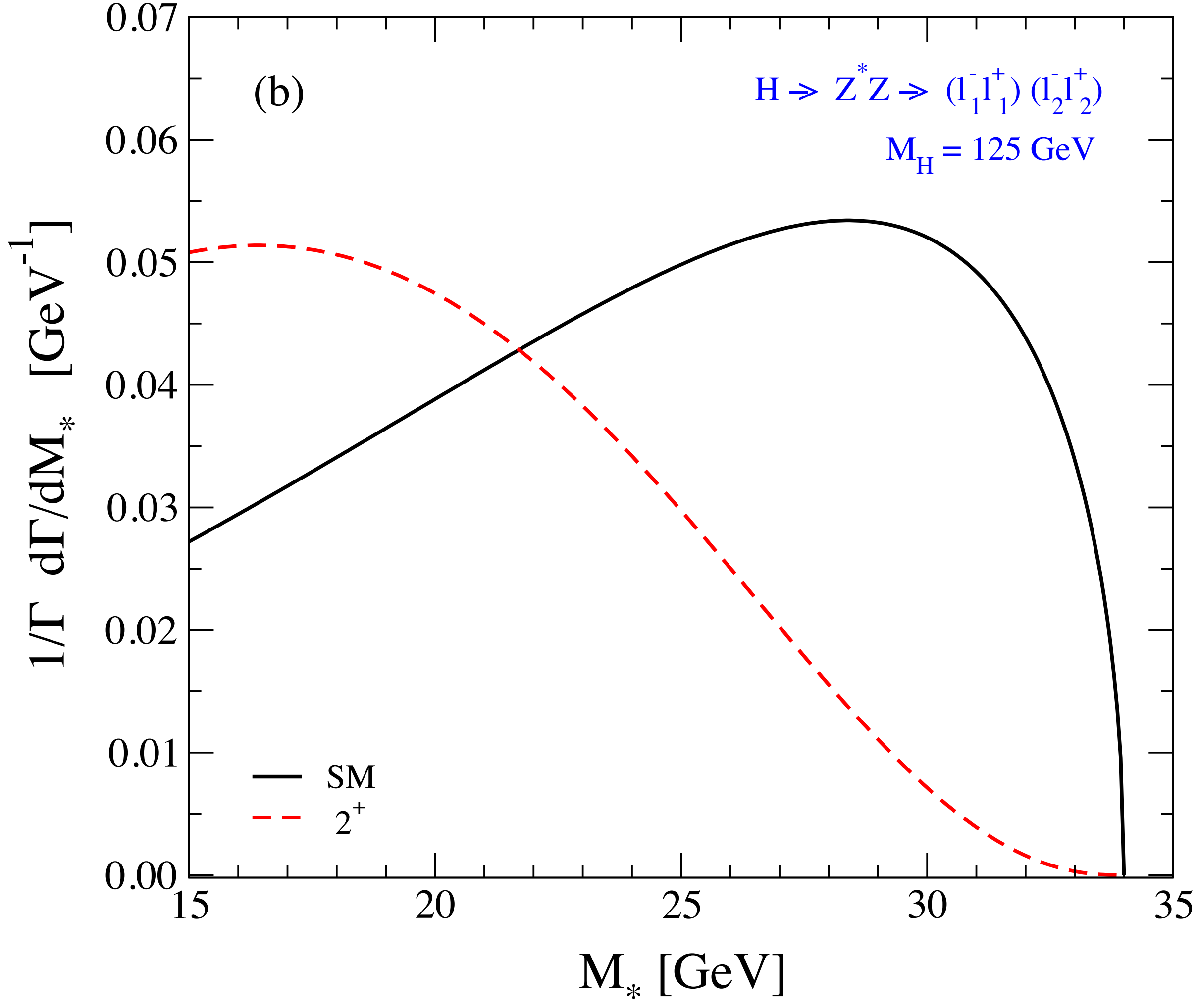
Choi,Miller,MMM,Zerwas



$0^+ : d\Gamma/d\varphi \sim 1 + f_{\mathsf{kin}} \cos 2\phi,$ $\qquad 0^- : d\Gamma/d\varphi \sim 1 - 1/4 \cos 2\phi$

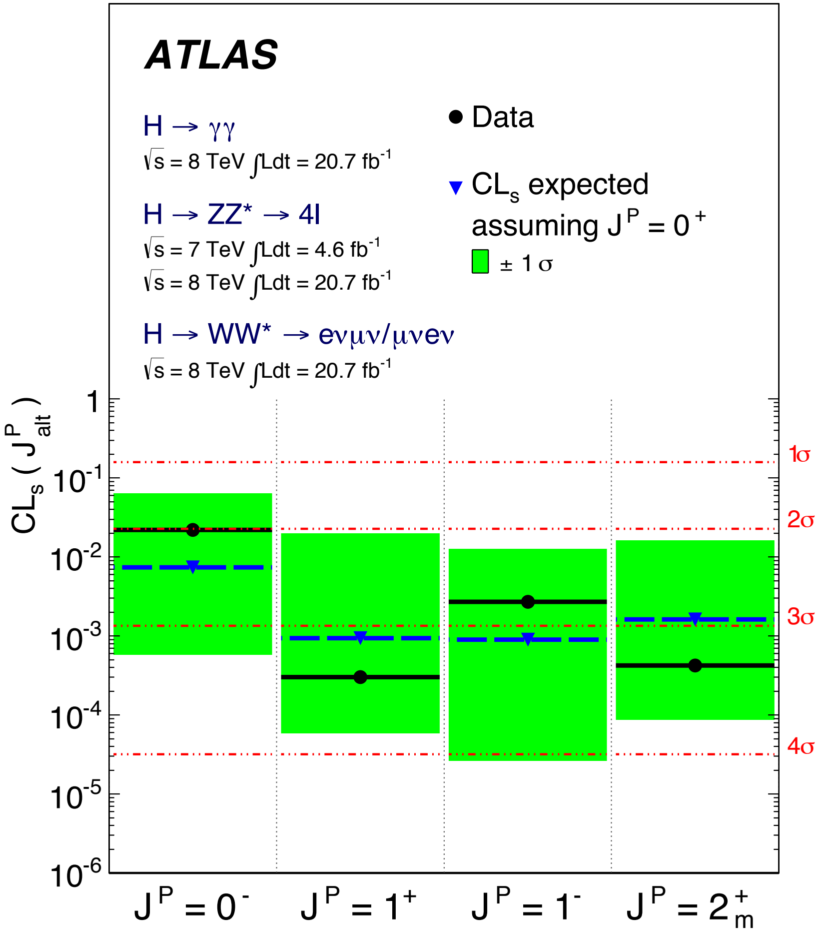
$\mathcal{T}$hreshold $\mathcal{B}$ehaviour: $\mathcal{S}$pin

Choi,Miller,MMM,Zerwas



ATLAS $\mathcal{R}$esults

ATLAS Phys.Lett.**B726**(2013)120



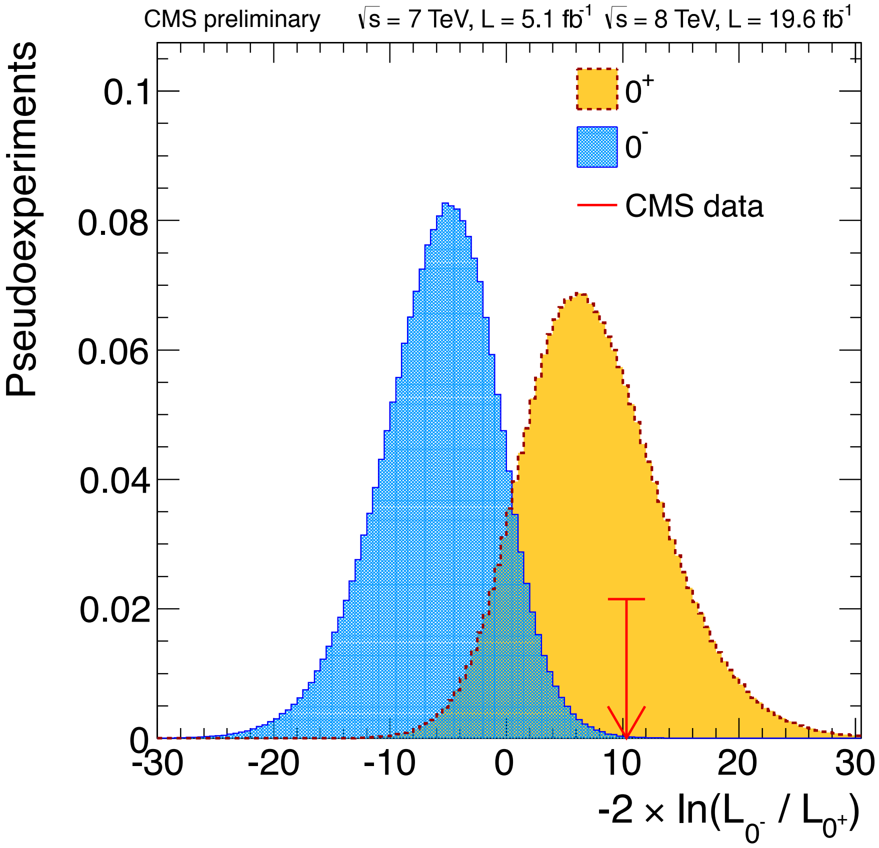
0^- rejected at 97.8% CL ($H \to ZZ^* \to 4l$); $1^\pm$ at $\gtrsim 99.7\%$ CL ($ZZ^* \to 4l$, $WW^* \to l\nu l\nu$)

2^+ rejected at $\gtrsim 99.9\%$ CL ($H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, $H \to WW^* \to l\nu l\nu$), indep gg, $q\bar{q}$

CMS $\mathcal{R}$esults

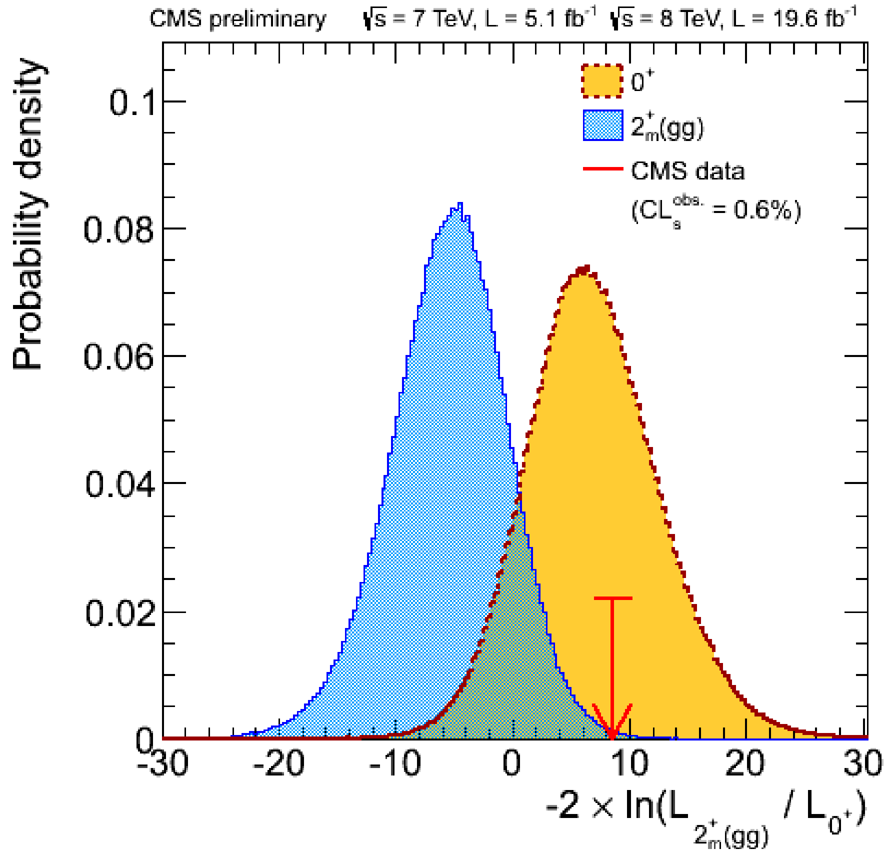
- $\mathbf{0^+, 0^-, 1^+, 1^-, 2^+, 2^-}$ **hypotheses in** $H \to ZZ^* \to 4l$ PRL 110 (2013)

CMS-PAS-HIG-13-002



0^- excluded at 95% CL

CMS-PAS-HIG-13-005



$2^+_m(gg)$ excluded at 60% CL

- **Spin studies in** $H \to WW^* \to l\nu l\nu$ CMS-PAS-HIG-13-003

(II) $\mathcal{H}$iggs-$\mathcal{S}$pin $\mathcal{A}$nalysis through $gg \to H^J \to \gamma\gamma$ $\mathcal{D}$ecays

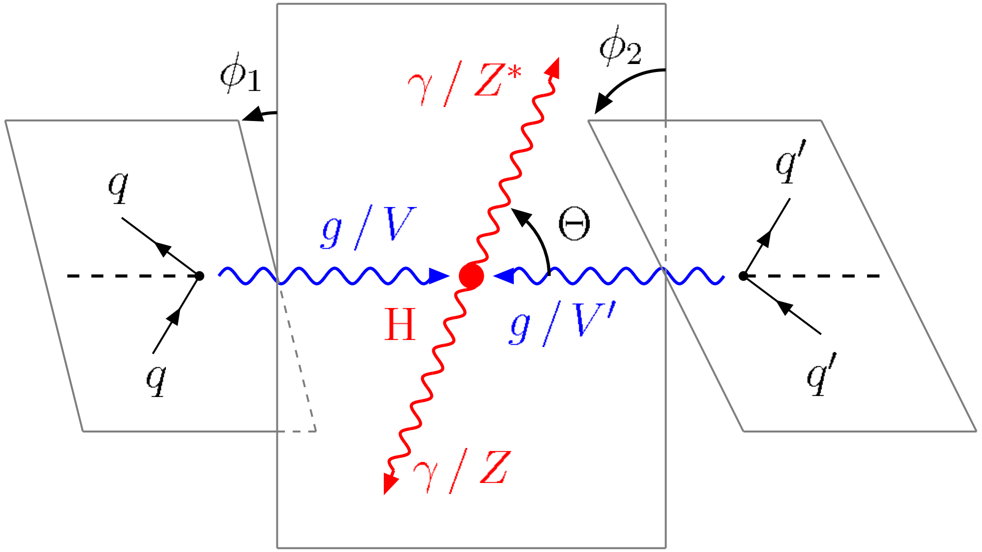
- **Systematic helicity analyses for angular distributions** $\rightsquigarrow$

- **Selection rules**

  from polar angular distribution

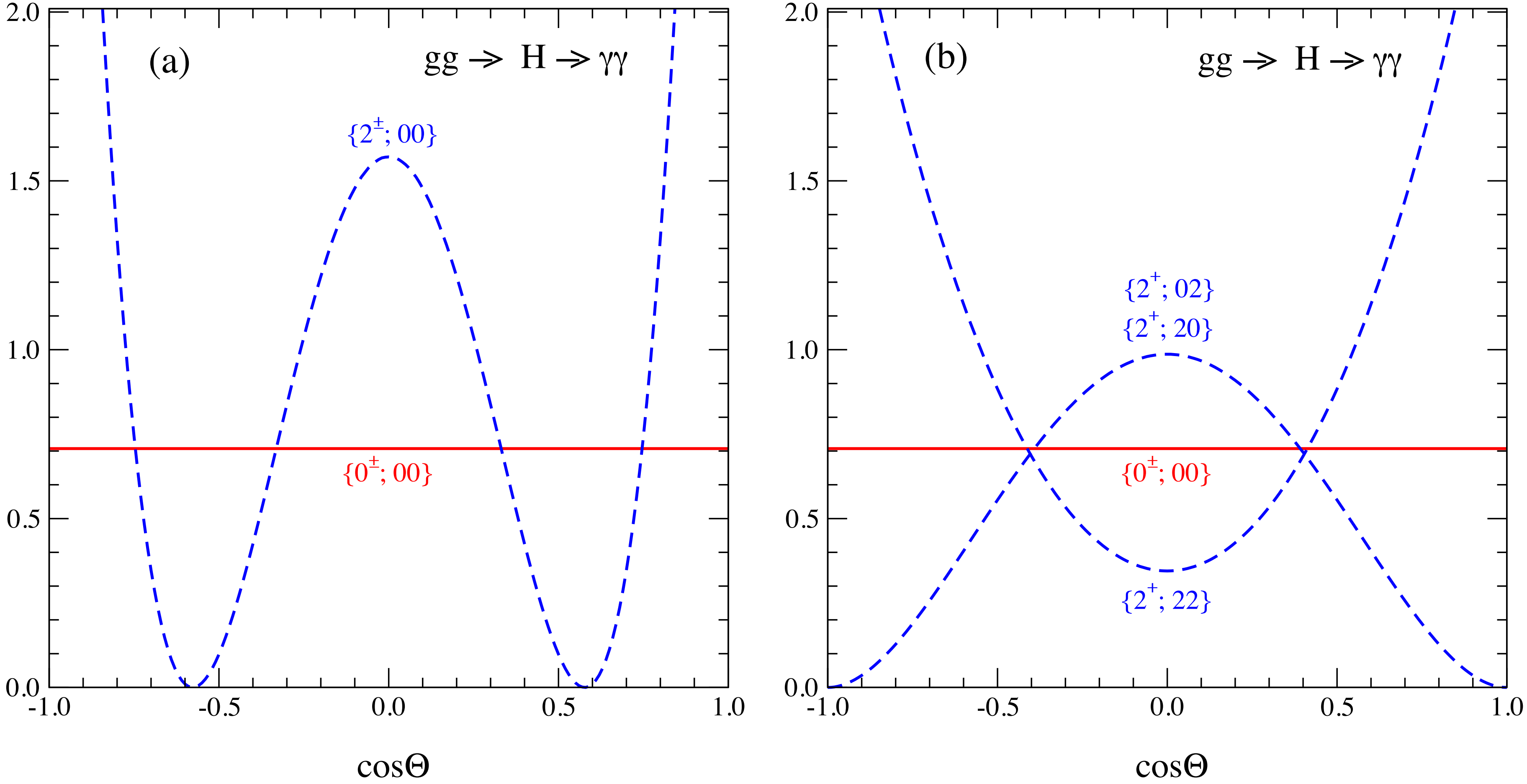
  spin-0: isotropic

(b)



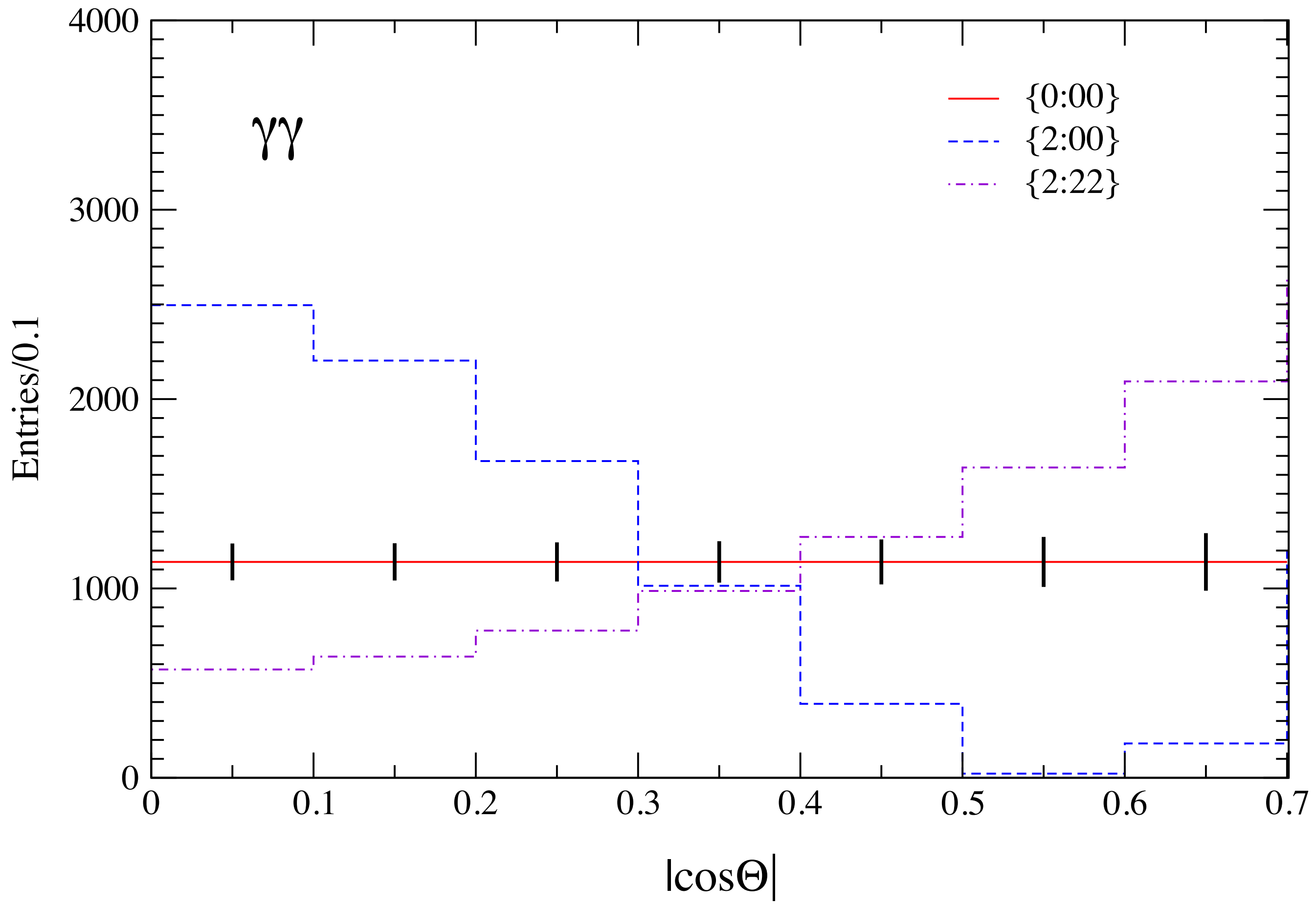
$\mathcal{S}$calar-type, $\mathcal{T}$ensor-type

Choi,Miller,MMM,Zerwas



$\mathcal{D}$istinction $\mathcal{S}$calar-type, $\mathcal{T}$ensor-type

Choi,MMM,Zerwas



Discovered Particle is the Higgs Boson

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New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

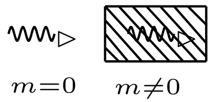
$\mathcal{E}$xperimental $\mathcal{V}$erification of the EWSB $\mathcal{M}$echanism

EWSB mechanism:

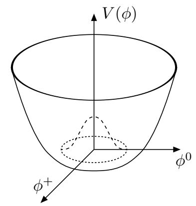
Creation of particle masses without violating gauge principles

Test of the EWSB mechanism

- Discovery – m
- Interaction with the scalar boson with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



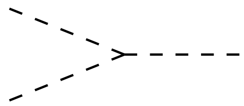
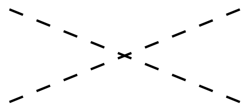
- Spin- and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$

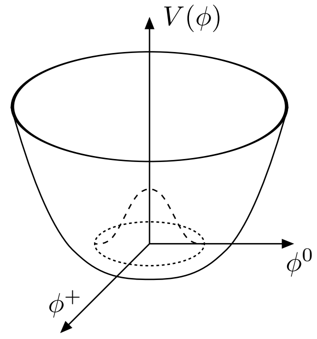


Determination of the Scalar Boson Self-Couplings

The EWSB potential:

$$V(H) = \frac{1}{2!}\lambda_{HH} H^2 + \frac{1}{3!}\lambda_{HHH} H^3 + \frac{1}{4!}\lambda_{HHHH} H^4$$

Trilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
Quartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	



Measurement of the scalar boson self-couplings and Reconstruction of the EWSB potential } Experimental verification Of the scalar sector of the EWSB mechanism

Determination of the scalar boson self-couplings at colliders:

$\boldsymbol{\lambda_{HHH}}$ via pair production

$\boldsymbol{\lambda_{HHHH}}$ via triple production

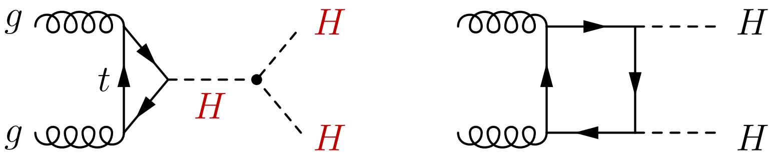
radiation off W/Z, WW/ZZ fusion, gg fusion

Determination of λ_{HHH} at the LHC

Djouadi,Kilian,MMM,Zerwas

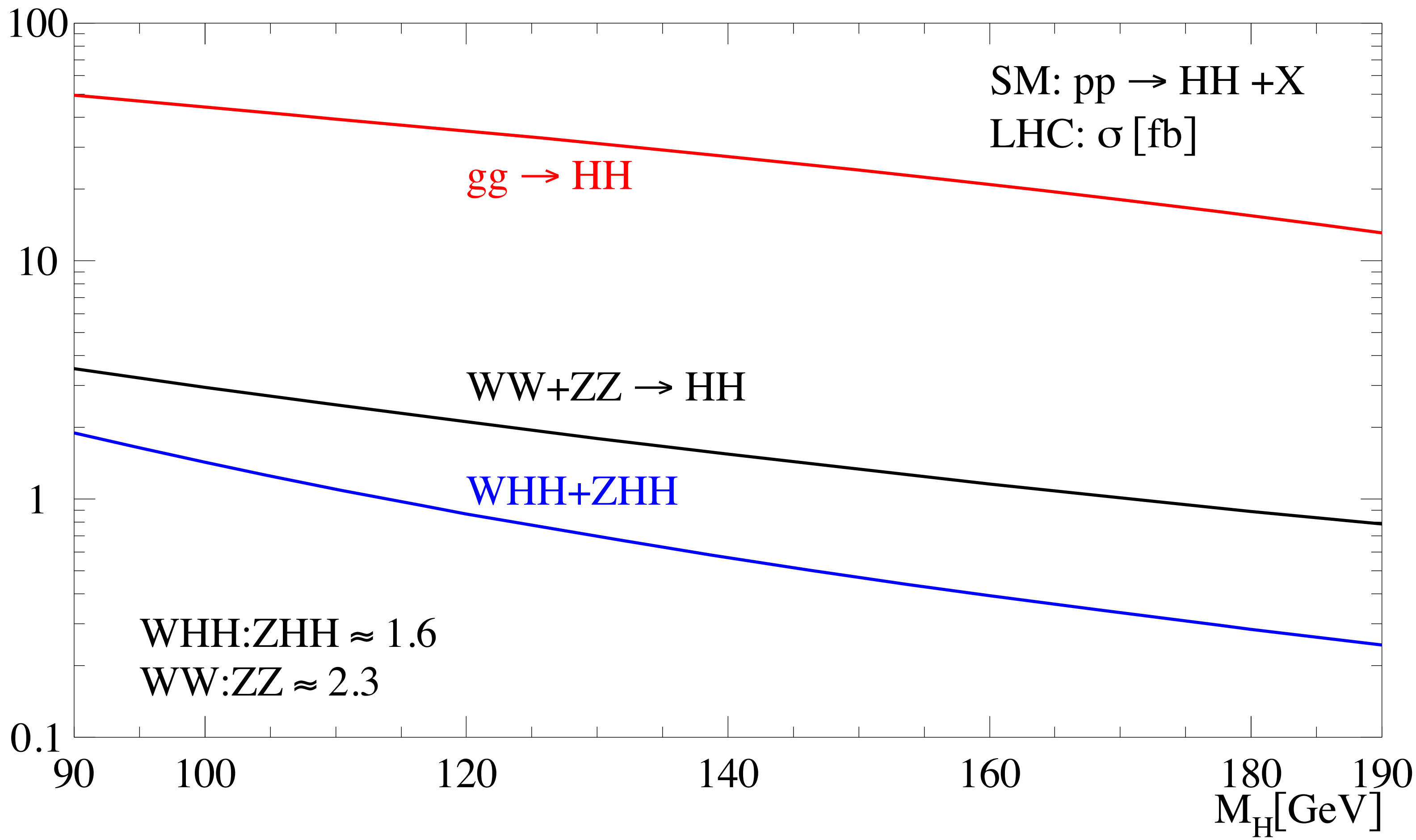
double radiation of W/Z:	$q\bar{q}$	$\rightarrow$	$W/Z + HH$	Barger,Han,Phillips;Baglio eal
WW/ZZ fusion:	qq	$\rightarrow$	$qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale Liu-Sheng eal;Baglio eal
gluon gluon fusion:	gg	$\rightarrow$	HH	Glover,van der Bij Plehn,Spira,Zerwas Dawson,Dittmaier,Spira de Florian,Mazzitelli Grigo,Hoff,Melnikov,Steinhauser

gluon gluon fusion - dominant process



Double SM Scalar Boson Production at the LHC

Djouadi,Kilian,MMM,Zerwas

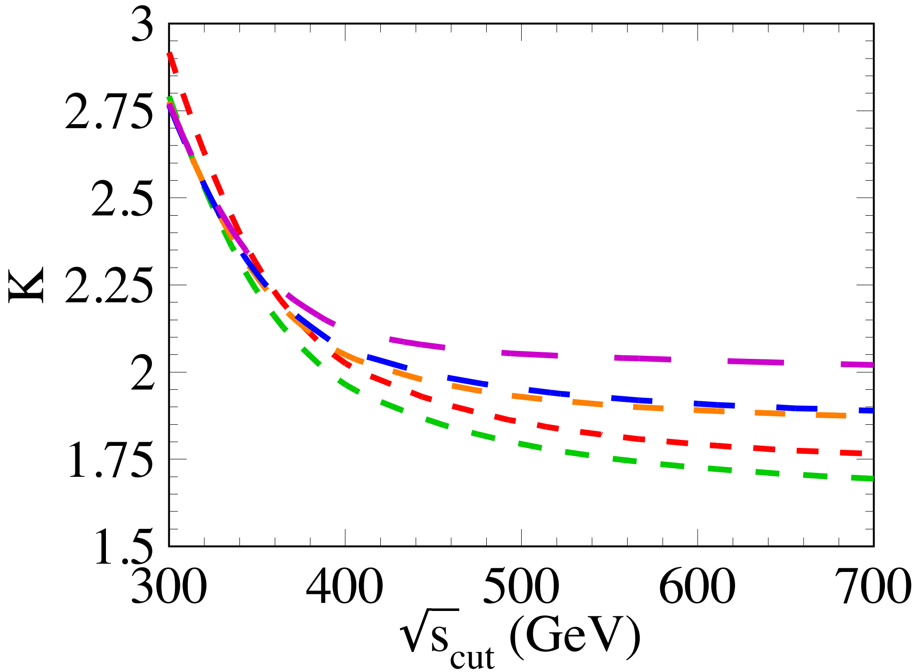


Higher Order Corrections to Double Higgs Production

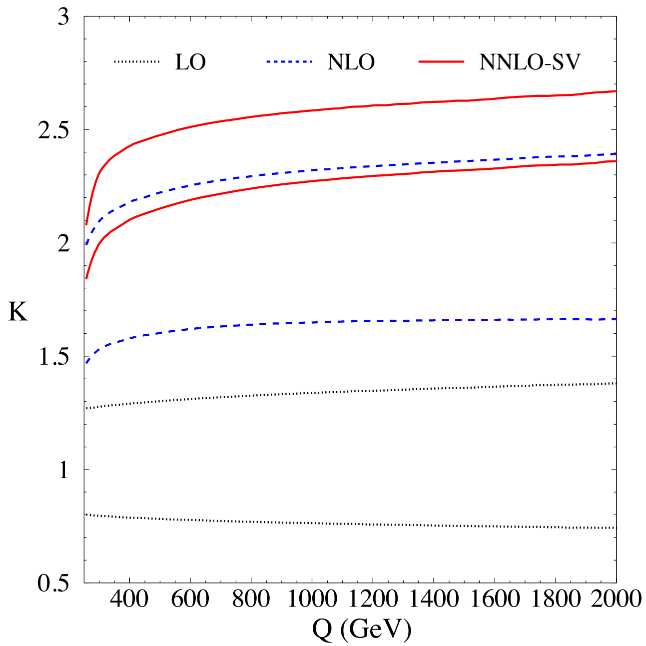
Higher order corrections:

- ▷ 2-loop QCD corrections $(M_H^2 \ll 4m_t^2) \sim 90 - 100\%$ Dawson,Dittmaier,Spira
- ▷ 2-loop QCD corrections $\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + ... + \frac{\sigma_4}{m_t^8}$ Grigo,Hoff,Melnikov,Steinhauser
- ▷ NNLO soft+virtual QCD corrections: $\sim 20\%$ $(M_H^2 \ll 4m_t^2)$ de Florian,Mazzitelli
- ▷ soft gluon resummation (SCET): $\sim 30\%$ $(M_H^2 \ll 4m_t^2)$ Shao,Li,Li,Wang

Grigo,Hoff,Melnikov,Steinhauser

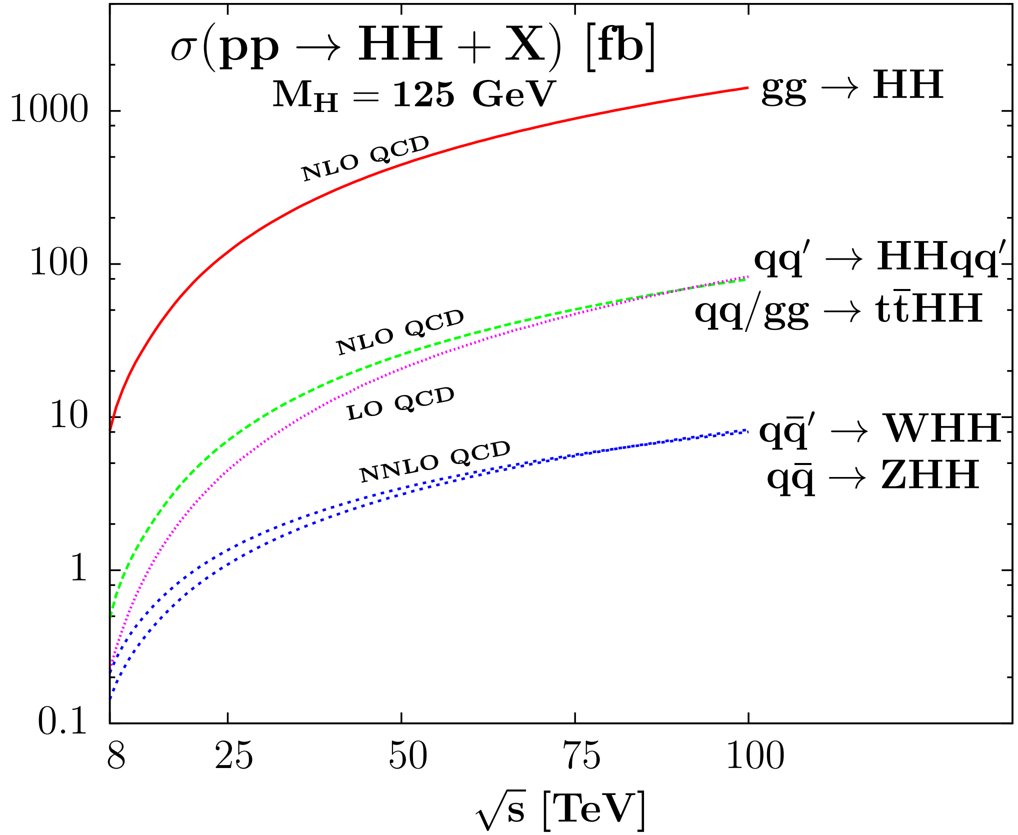


de Florian,Mazzitelli



$\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{P}$rocesses

Baglio,Djouadi,Gröber,MMM,Quevillon,Spira

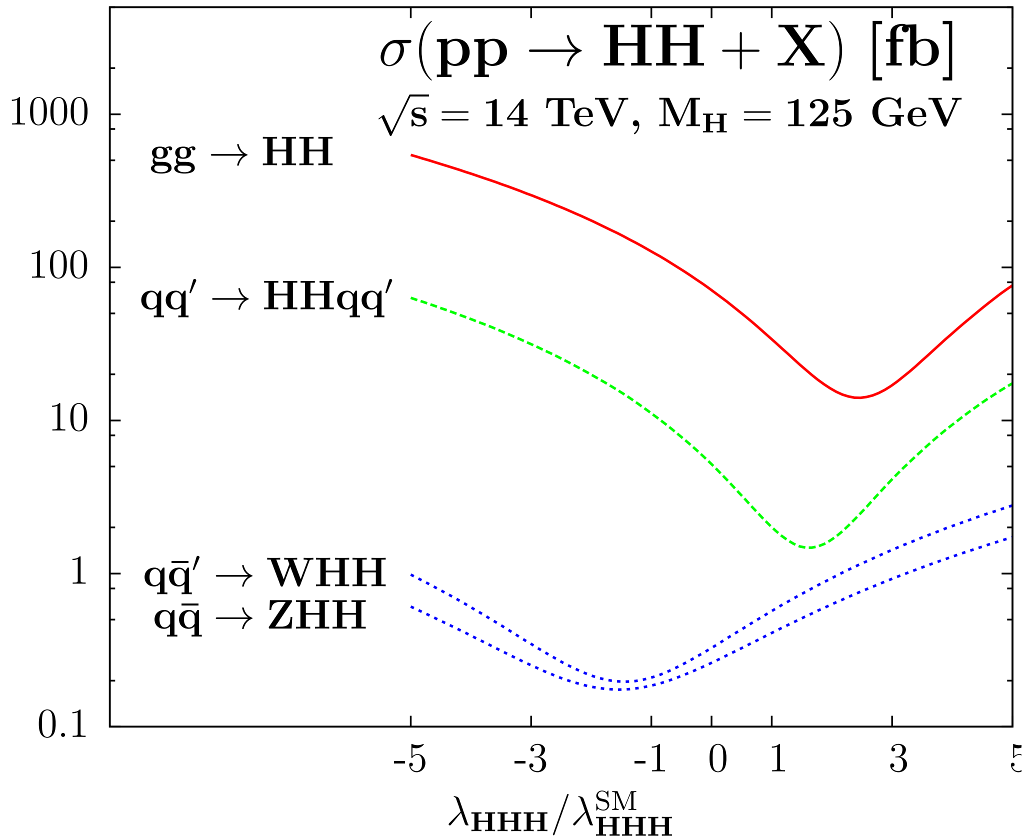


Uncertainty (scale, pdf+α_s, EFT) ggF at 14 TeV: $\sim -30\%... + 37\%$; VBF: $\sim -7.5\%... + 5\%$

[For NLO cxns w/ parton shower, see also Frederix eal]

$\mathcal{S}$ensitivity to λ_{HHH}

Baglio,Djouadi,Gröber,MMM,Quevillon,Spira



$gg \to HH : \Delta\sigma/\sigma \sim -\Delta\lambda/\lambda$ (decreasing with $\sqrt{s}$)

Measurement of cross section with 50% accuracy yields 50% accuracy in λ_{HHH}

$\mathcal{E}$xpected $\mathcal{A}$ccuracies in λ_{HHH} at the $\mathcal{LHC}$

- **Vast literature:**

Baur,Plehn,Rainwater; Lafaye,Miller,Moretti,MMM; Osland,Pandita; M.Moretti eal; Arhrib eal; Asakawa eal; Dolan,Englert,Spannowski; Papaefstathiou,Yang,Zurita; Goertz,Papaefstathiou,Yang,Zurita; W. Yao; Contino eal; Gupta eal; No,Ramsey-Musolf; Barger,Everett,Jackson,Shaughnessy; deLima,Papaefstathiou,Spannowsky; ...

$\mathcal{E}$xpected $\mathcal{A}$ccuracies in λ_{HHH} at the $\mathcal{LHC}$

Small signal + large QCD background $\rightsquigarrow$ challenge! Sample studies:

$M_H < 140$ GeV: $gg \to HH \to b\bar{b}\gamma\gamma$: Baur,Plehn,Rainwater

- SLHC [$\int \mathcal{L} = 6$ ab^{-1}]: $M_H = 120$ GeV $\lambda_{HHH} = 0$ exclusion at 90% CL

$M_H = 125$ GeV: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$: Baglio,Djouadi,Gröber,MMM,Quevillon,Spira '12

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ look promising: $S/\sqrt{B} \approx 6$ for $\int \mathcal{L} = 3$ ab^{-1}

$M_H = 125$ GeV: exploit subjet techniques: Dolan,Englert,Spannowski'12 Papaefstathiou,Yang,Zurita'12

- LHC@14TeV [$\int \mathcal{L} = 1000$ fb^{-1}]: $HHj \to b\bar{b}\tau^+\tau^- j$: most promising to constrain λ_{HHH}
- LHC@14TeV [$\int \mathcal{L} = 600$ fb^{-1}]: $HH \to b\bar{b}W^+W^- \to b\bar{b}l\nu jj$: strong evidence

$M_H = 125$ GeV: exploit ratios of cross sections Goertz,Papaefstathiou,Yang,Zurita '13

$M_H = 125$ GeV: $gg \to HH \to b\bar{b}\gamma\gamma$: (to be analysed experimentally) Barger,Everett Jackson,Shaughnessy '13

- LHC@14 TeV [$\int \mathcal{L} = 3$ ab^{-1}]: $\delta\lambda_{HHH}/\lambda_{HHH} = 40\%$ (?) $\leftarrow$ multivariate analysis

$\mathcal{E}$xpected $\mathcal{A}$ccuracies in λ_{HHH} at the $\mathcal{LHC}$

Small signal + large QCD background $\rightsquigarrow$ challenge! **Sample studies:**

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$M_H = 125$ **GeV:** $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$: ...,Quevillon,Spira '12

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$M_H = 125$ **GeV: expl**... **of cross sections** Goertz,Papaefstathiou,Yang,Zurita '13

$M_H = 125$ **GeV:** $gg \to HH \to b\bar{b}\gamma\gamma$: (to be analysed experimentally) Barger,Everett Jackson,Shaughnessy '13

- LHC@14 TeV [$\int \mathcal{L} = 3$ ab^{-1}]: $\delta\lambda_{HHH}/\lambda_{HHH} = 40\%$ (?) $\leftarrow$ multivariate analysis

High Luminosities Indispensable !

Beyond The Standard Model

$\mathcal{W}$hat $\mathcal{A}$bout $\mathcal{B}$eyond $\mathcal{S}$tandard $\mathcal{M}$odel ($\mathcal{BSM}$) $\mathcal{P}$hysics?

Standard Model: incomplete picture of the universe

- SM has 19 free parameters: What are the values of these parameters?
- Common origin of all three forces of the SM?
- How to incorporte gravity?
- Candidate for Dark Matter (DM)? ...

Why Beyond Standard Model (BSM) Physics?

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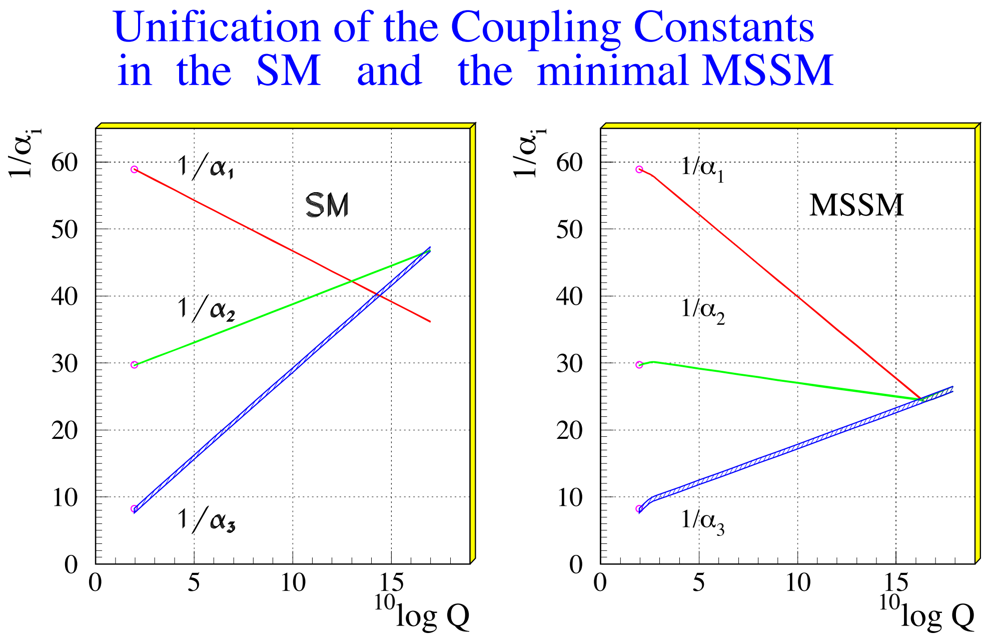

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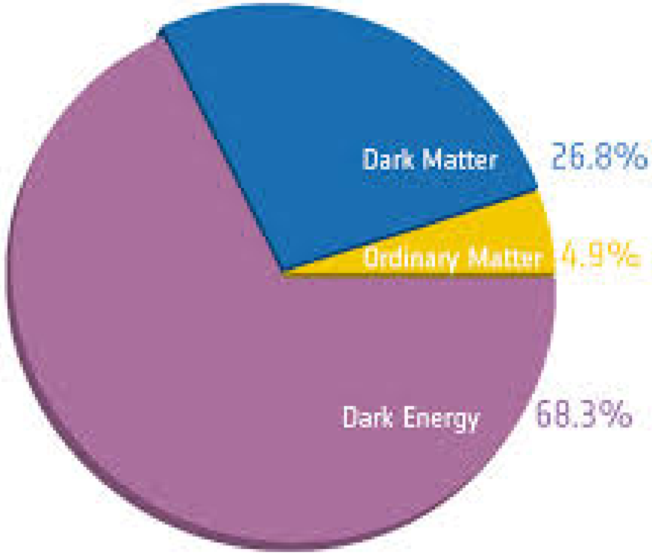

Why Beyond Standard Model (BSM) Physics?

Standard Model: incomplete picture of the universe

- SM has 19 free parameters: What are the values of these parameters?
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- Candidate for Dark Matter (DM)? ...

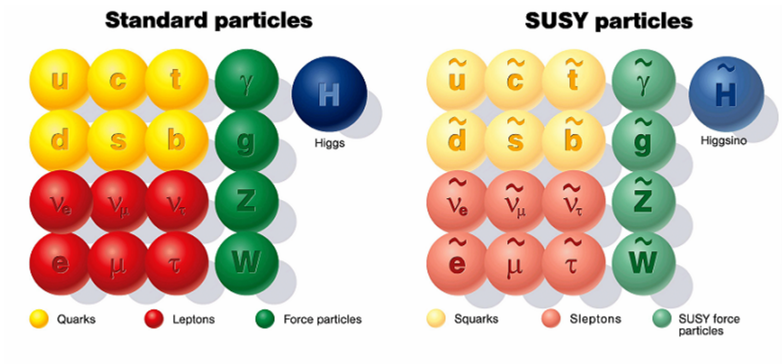
Supersymmetry: relates fermions and bosons

◇ solves hierarchy problem

◇ gauge coupling unification (MSSM)

◇ Higgs mechanism generated radiatively

◇ Cold Dark Matter candidate (← R-parity) ...



Consequences: new particles (*e.g.* running in the loops), extended Higgs sectors (scalar, pseudoscalar Higgs bosons, Higgs bosons with no definite CP quantum number)

Going Beyond the SM

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

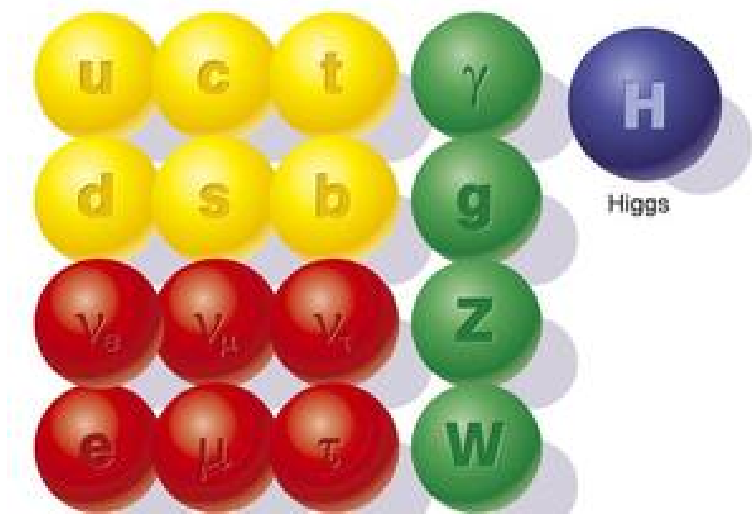
Gauge Higgs

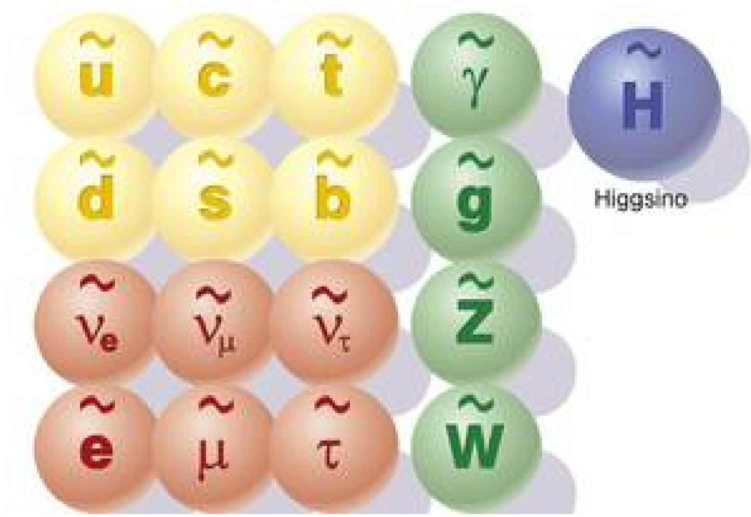
Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs





$\mathcal{M}$any good reasons for $\mathcal{S}$upersymmetry

- Solution of the hierarchy problem
- Gauge coupling unification
- Dark Matter candidate
- Dynamical generation of Higgs potential
- Maximal possible symmetry of the S-matrix
- Way to incorporate gravity?
- ...

The MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\overset{\text{EWSB}}{\longrightarrow}$ neutral, CP-even h, H neutral, CP-odd A charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling; Hoang et al;Carena et al;Heinemeyer et al; Zhang et al;Brignole et al;Harlander et al Degrassi et al;Kant et al;...

Decoupling limit:

$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

$M_h \to$ max. value, $\tan\beta$ fixed; h becomes SM-like

Modified couplings with respect to the SM: (decoupling limit Gunion,Haber)

Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \to 1$	$-s_\alpha/c_\beta \to 1$	$s_{\beta-\alpha} \to 1$
H	$s_\alpha/s_\beta \to 1/\text{tg}\beta$	$c_\alpha/c_\beta \to \text{tg}\beta$	$c_{\beta-\alpha} \to 0$
A	$1/\text{tg}\beta$	$\text{tg}\beta$	0

$\tan\beta \uparrow \;\Rightarrow g_{\Phi uu} \downarrow$

$g_{\Phi dd} \uparrow$

$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

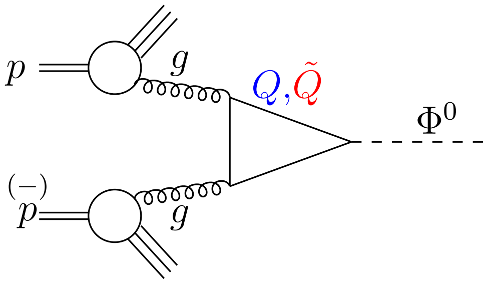
$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{P}$roduction at the $\mathcal{LHC}$

Higgs boson production in the MSSM

- **Gluon Fusion**

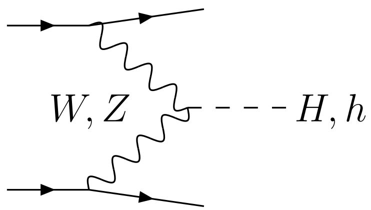
  $pp \to gg \to h, H, A$

  Additional squark loops



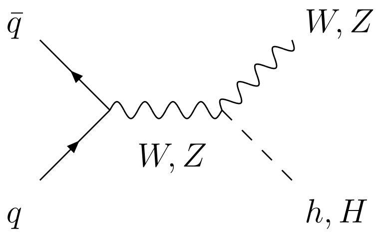
- **W/Z Fusion**

  $pp \to qq \to qq + WW/ZZ \to qq + h, H$



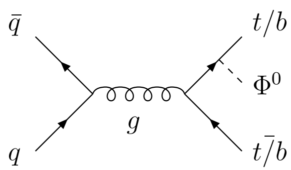
- **Higgs-strahlung**

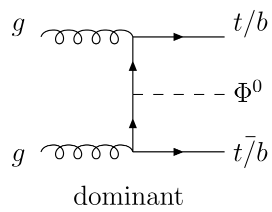
  $pp \to W^*/Z^* \to W/Z + h, H$



- **Associated Production**

  $pp \to t\bar{t}/b\bar{b} + h, H, A$





$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on MSSM Higgs of ~ 125 GeV**

  Arbey eal; Li eal; Feng eal; Baer eal; Akula eal; Hall eal; Albornoz Vasquez eal; Heinemeyer eal; Desai et al.; Draper eal; Carena eal; Cao eal; Christensen eal; Kadastik eal; Buchmuller eal; Arvanitaki eal; Ellis eal; Curtin eal; Brummer eal; Barger eal; Hagiwara eal; Arbey eal; Blum eal; Beskidt eal; Baer eal; Giudice eal; Carena eal; Benbrik eal; Akula eal; Cahill-Rowley eal; Hirsch eal; ...

- **Compatibility of MSSM Higgs mass with LHC Search**

  ⋆ Upper mass bound on SM-like Higgs with higher-order correction Δm_h

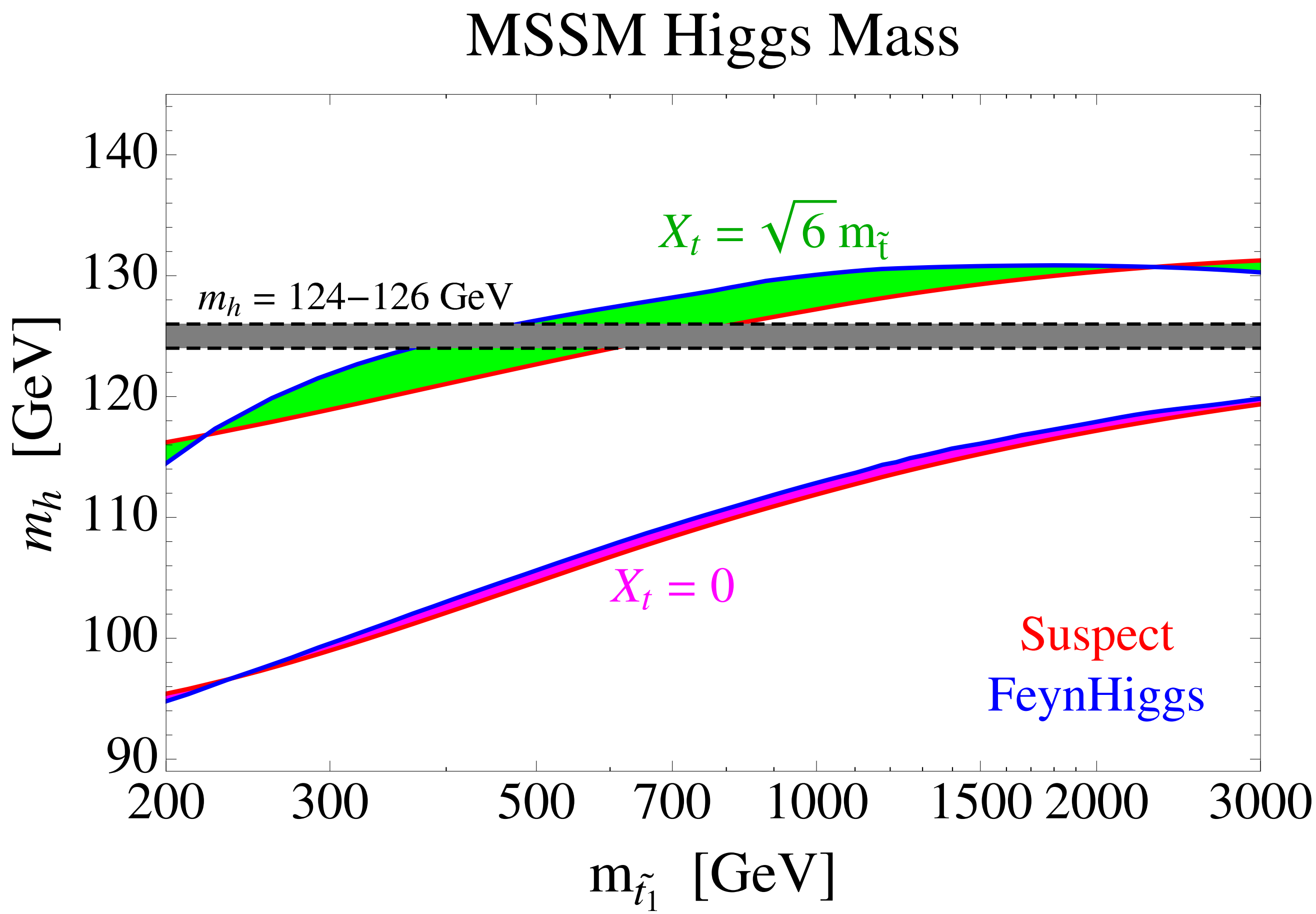
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

  ⋆ $\Rightarrow M_H \approx 125$ GeV requires

$$\Delta m_h \approx 85 \text{ GeV } (\tan\beta \text{ large}) \Rightarrow \text{large corrections} \rightsquigarrow \text{'fine'-tuning}$$

MSSM Higgs Mass in View of the LHC Results

Hall,Pinner,Ruderman 1112.2703



- **Maximal stop mixing:** $m_{\tilde{t}_1} \overset{!}{\gtrsim}$ 500 GeV

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

- **The μ-problem of the MSSM:**

  Higgsino mass parameter μ must be of order of EWSB scale Kim,Nilles

- **Solution in the NMSSM:**

  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$

- **Enlarged Higgs and neutralino sector:**

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Significant changes of Higgs boson phenomenology**

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

- **Vast literature on NMSSM Higgs of ~ 125 GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; ...

- **Compatibility of NMSSM Higgs mass with LHC Searches:**

  ⋆ Upper mass bounds + corrections to the MSSM, NMSSM Higgs boson mass:

  MSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$

  NMSSM: $m_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 125$ requires:

  MSSM: $\Delta m_h \approx 85$ GeV ($\tan\beta$ large) $\Rightarrow$ large corrections are needed $\rightsquigarrow$ conflict with fine-tuning

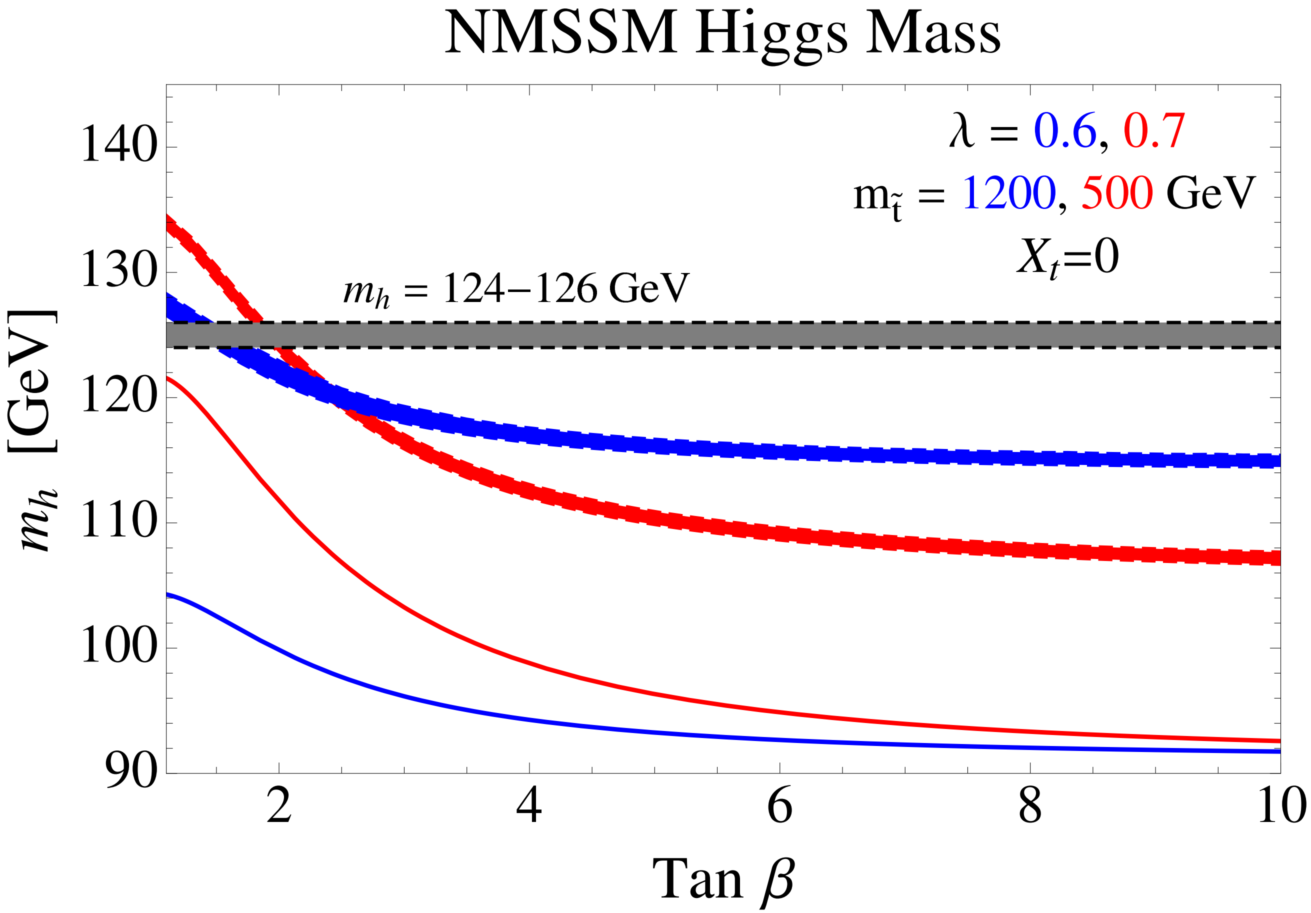
  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning

  Hall,Pinner,Ruderman; Ellwanger; Arvanitaki,Villadoro; King,MMM,Nevzorov; Kang,Li,Li; Cao,Heng,Yang,Zhang,Zhu

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass in $\mathcal{V}$iew of the $\mathcal{LHC}$ $\mathcal{R}$esults

Hall,Pinner,Ruderman 1112.2703



- ◇ m_h maximized for small values of $\tan\beta$
- ◇ $m_h \approx 125$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

Thank you for your attention!

Higgs Boson Mass

Higgs Boson Mass SM - fundamental parameter, not given by theory

- self-consistency test of SM at quantum level (Higgs loop corrections to W boson mass)
- Higgs mass uncertainty feeds back in uncertainty on SM Higgs couplings
- $M_H \leftrightarrow$ stability of the electroweak vacuum $\rightarrow$ T
- Test parameter relations in BSM theories (Higgs mass calculable; requires precise m_t)

Present Value from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$

$$M_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst}) \text{ GeV}$$ CMS-PAS-HIG-13-005

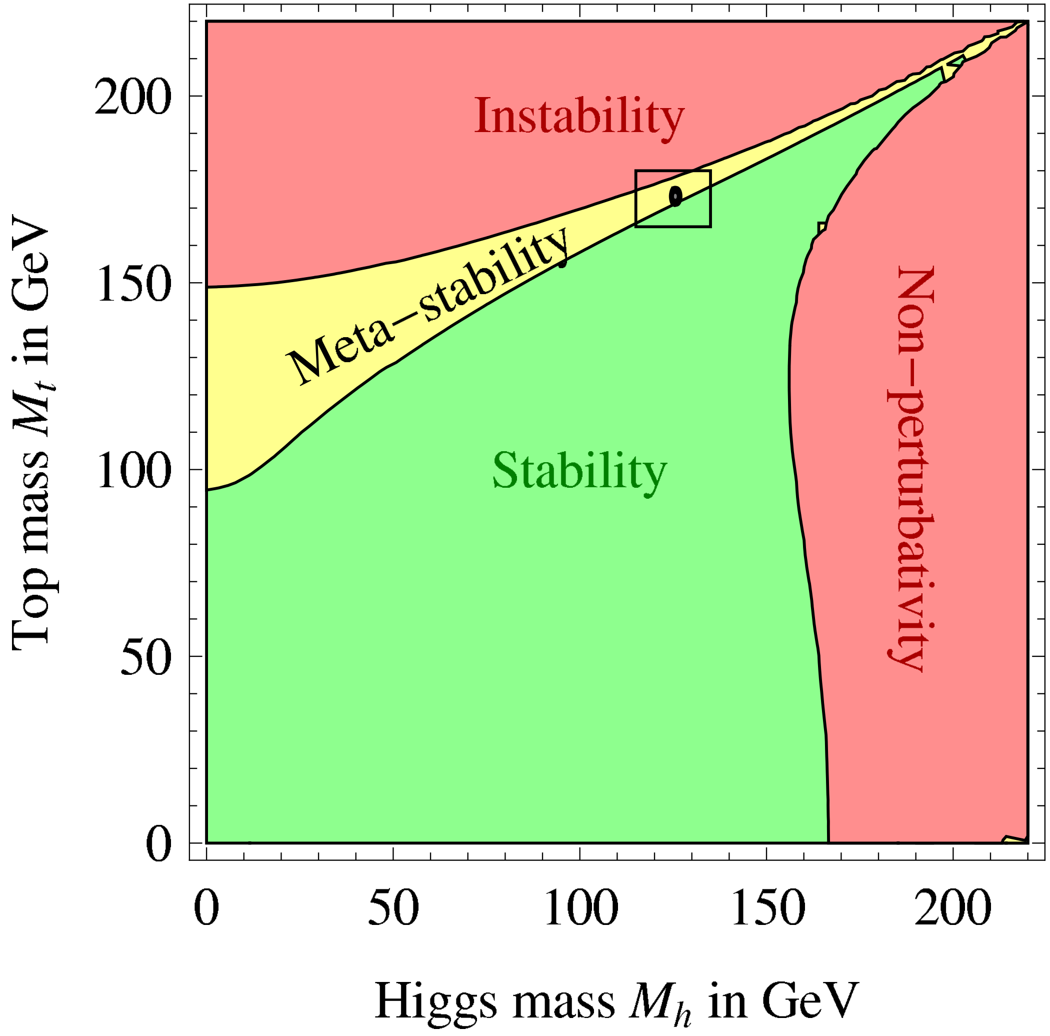
Expected Precision

- future measurements dominated by systematics
- interference effects signal and background, ...

Projected: $\delta M_H \sim 100/50$ MeV at LHC/HL-LHC

$\mathcal{S}$tability of the $\mathcal{V}$acuum

Degrassi et al. '12



Vacuum stability:

$$M_H > 129.4 \text{ GeV} + 1.4 \text{ GeV} \left(\frac{m_t - 173.2 \text{ GeV}}{0.7 \text{ GeV}} \right) - 0.35 \text{ GeV} \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}} \text{ GeV}$$

$\mathcal{T}$otal $\mathcal{W}$idth

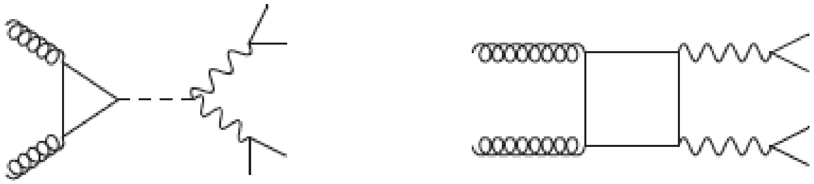
Higgs Total Width $\Gamma_H \approx 4.4$ MeV

- interference between Higgs signal $gg \to H \to \gamma\gamma$ and continuum $gg \to \gamma\gamma \rightsquigarrow$ Higgs mass shift

S.P.Martin '12,'13; Dixon,Li '13

- Off-shell $H \to Z^* Z^*$ production

Caola,Melnikov '13; Campbell,Ellis,Williams '13; Kauer,Passarino '12



Present Value - combined $4l$ and $2l2\nu$ final states CMS Moriond '13 New!

$\Gamma <$ 17 MeV (35 MeV expected) 95% CL

Projection to HL-LHC

dominated by systematics

e.g. $pp \to ZZ$ at NNLO QCD required, realistic target, see e.g. Gehrmann,Tancredi,Weihs '13

$H \to \gamma\gamma$

Dixon,Li '13