Prospects of Higgs Physics at the LHC

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Karlsruhe
15. Dezember 2011

Outline

I Introduction

– Higgs mechanism

– Supersymmetry

II Test of the Higgs mechanism at the LHC

– Higgs search at the LHC

– Higgs couplings to fermions, bosons

– Higgs boson quantum numbers

– Higgs self-couplings

III The Composite Higgs Boson

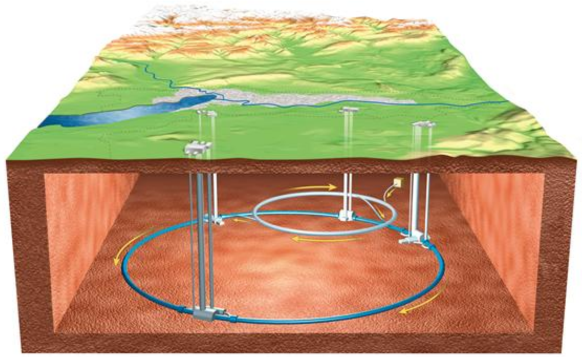
IV Conclusion

Research at the Large Hadron Collider LHC

Research at the LHC

Discoveries $\Rightarrow$

Understanding of matter and its interactions:

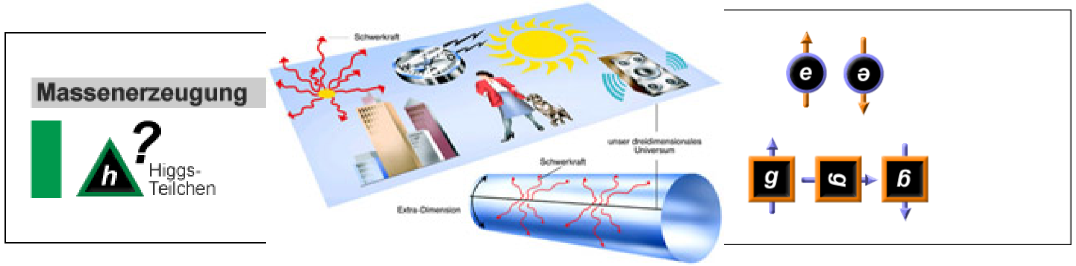


$\longrightarrow$ Verification of the Higgs mechanism

$\longrightarrow$ Search for supersymmetric particles

$\longrightarrow$ Search for extra dimensions

$\vdots$



The Standard Model of Particle Physics

Symmetry group $SU(3) \times SU(2)_L \times U(1)_Y$

I Particle content

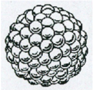
Matter particles:

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

Interaction particles:

γ	Bosons
g	
Z	
$W^\pm$	

II Fundamental Forces

Electromagnetic	Photon	
Strong	Gluon	
Weak	W, Z	

III Higgs mechanism

Masses of the fundamental particles

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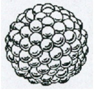
Strong	Gluon	
Weak	W, Z	

III Higgs mechanism

Masses of the fundamental particles **?**

The Higgs mechanism

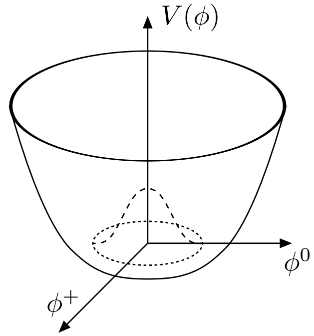
Why? Explain the existence of massive particles consistently with the underlying symmetries of the Standard Model

Solution Mechanism, which "breaks" the gauge symmetry in a specific way

Realisation Higgs mechanism $\rightsquigarrow$ Higgs particle

How it works Mass generation through spontaneous symmetry breaking (SSB)

- Self-interaction of the scalar field $\rightsquigarrow$ ∞ number of degenerate ground states with non-vanishing field strength
- Choice of one ground state as the physical ground state $\rightsquigarrow$ $SU(2)_L \times U(1)_Y$ symmetry hidden, $U(1)_{em}$ symmetry left: SSB
- Particles acquire mass through the interaction with the scalar field in the ground state



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

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Test of the Higgs mechanism? Accelerator experiments!

Why Supersymmetry?

Standard Model: incomplete picture of the universe

- Common origin of all three forces of the Standard Model?
- How can we incorporate gravity?
- Candidate for Dark Matter? ...

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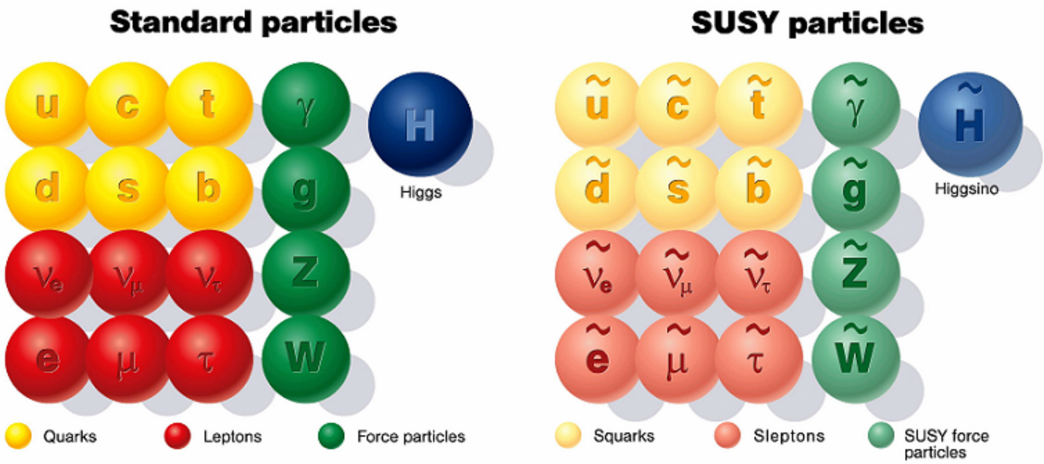
Supersymmetry: provides answers

Fermions $\leftrightarrow$ Bosons

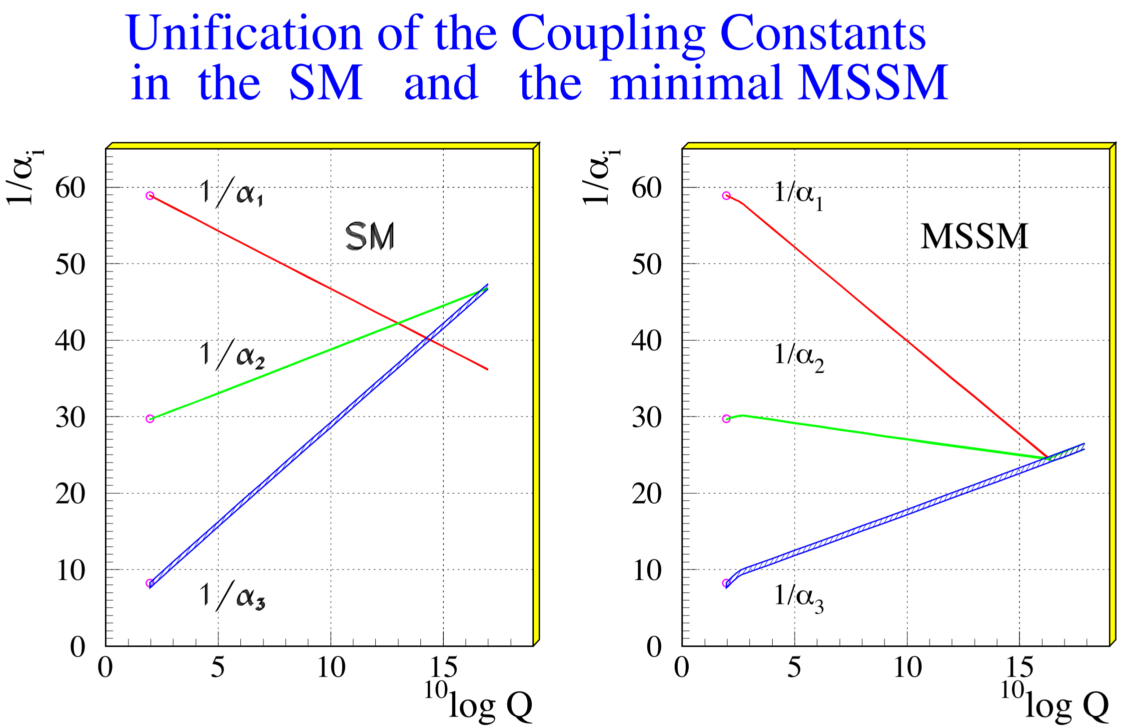
Price: doubling of the particle spectrum



SUSY's answers

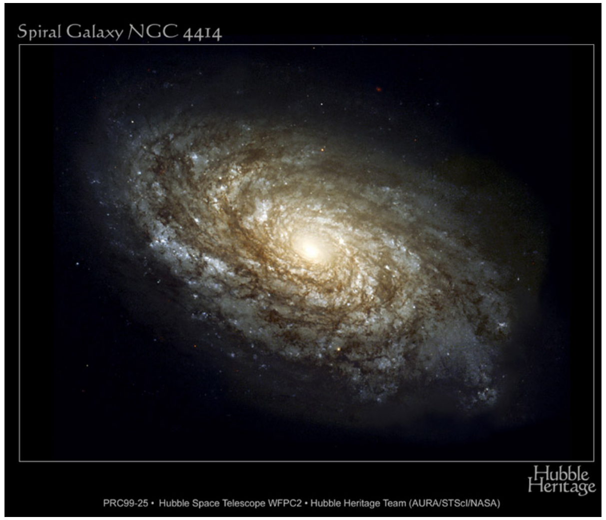
◇ **Unification of the coupling constants** electromagnetic - weak - strong

Amaldi,de Boer,Fürstenau



SUSY's Antworten

- ◇ **Unification of the couplings constants** — elektromagnetic - weak - strong
- ◇ **Solution of the hierarchy problem** — bosonic masses ($\rightarrow$ Higgs mass) kept small in a natural way $\leftarrow$ fermions $\leftrightarrow$ bosons
- ◇ **Candidate for Cold Dark Matter** — SUSY with R parity (DM $\sim 25\%$ of the universe)



SUSY's answers

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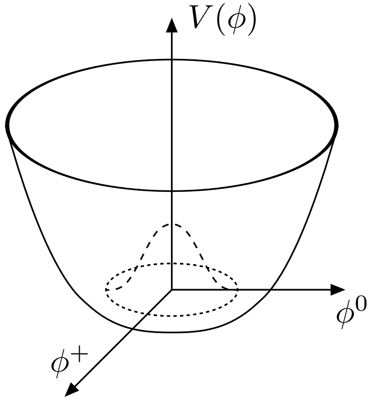
◇ **Candidate for cold Dark Matter**	SUSY with R-Parity (DM $\sim 25\%$ of the universe)
◇ **Local supersymmetry**	enforces gravity
◇ **Higgs mechanism**	generated through radiative corrections



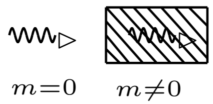
Experimental verification of the Higgs mechanism

Higgs mechanism:

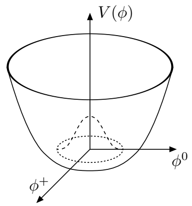
Creation of particle masses without violating gauge principles

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 – $\lambda_{HHH}, \lambda_{HHHH}$



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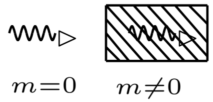

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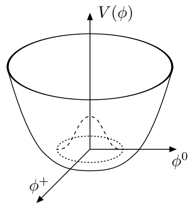
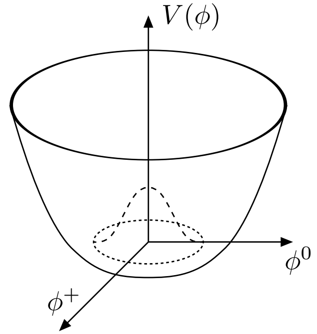


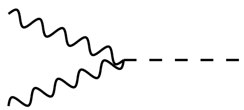
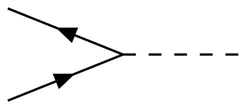
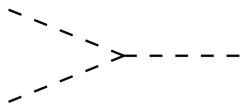
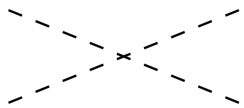
The SM Higgs Sector

The Higgs potential: $[v = 246 \text{ GeV}]$

$$V(\Phi) = \lambda[\Phi^\dagger\Phi - \frac{v^2}{2}]^2 \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightarrow$$



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

$\mathcal{H}$iggs boson mass	$M_H = \sqrt{2\lambda}v$	
$\mathcal{G}$auge couplings	$g_{VVH} = \frac{2M_V^2}{v}$	
$\mathcal{Y}$ukawa couplings	$g_{ffH} = \frac{m_f}{v}$	
$\mathcal{T}$rilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$	
$\mathcal{Q}$uartic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$	

$\mathcal{T}$he only unknown parameter in the SM is the Higgs boson mass!

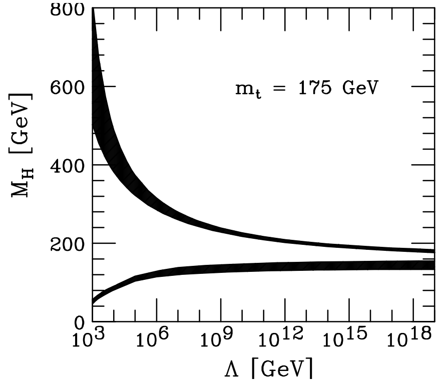
SM Higgs Mass Limits

- Triviality → upper bound
  Vacuum stability → lower bound

Cabibbo,...;Sher; Lindner;Hasenfratz,...; Lüscher, Weisz; Hambye,...;...

$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV
$\Lambda_{GUT} = 10^{16}$ GeV: 130 GeV $\lesssim M_H \lesssim$ 190 GeV

Hambye,Riesselmann



$\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{L}$imits

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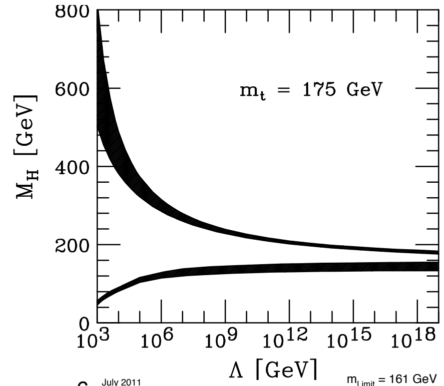
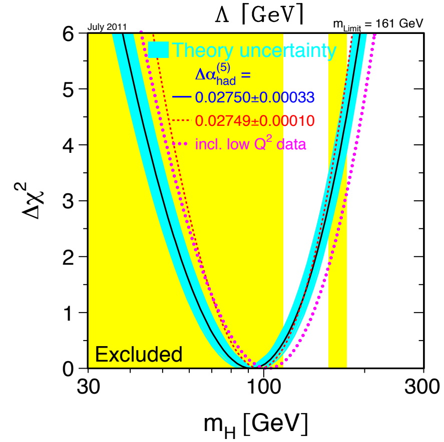


- Fits to electroweak precision data

EWWG

$$M_H = 92^{+34}_{-26} \text{ GeV}, \; M_H \lesssim 185 \text{ GeV @ } 95\% \text{ CL}$$



LEP Coll.

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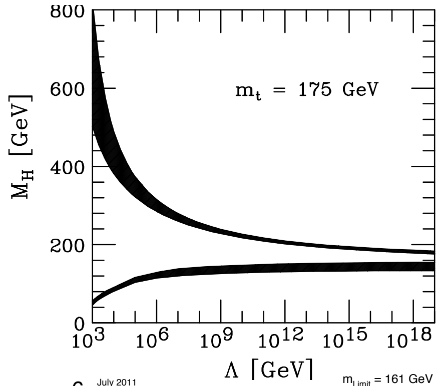

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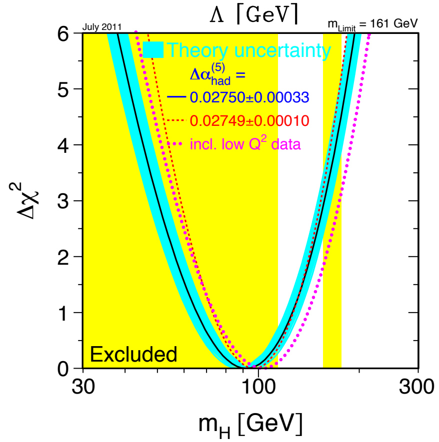
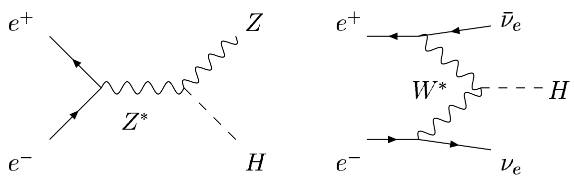


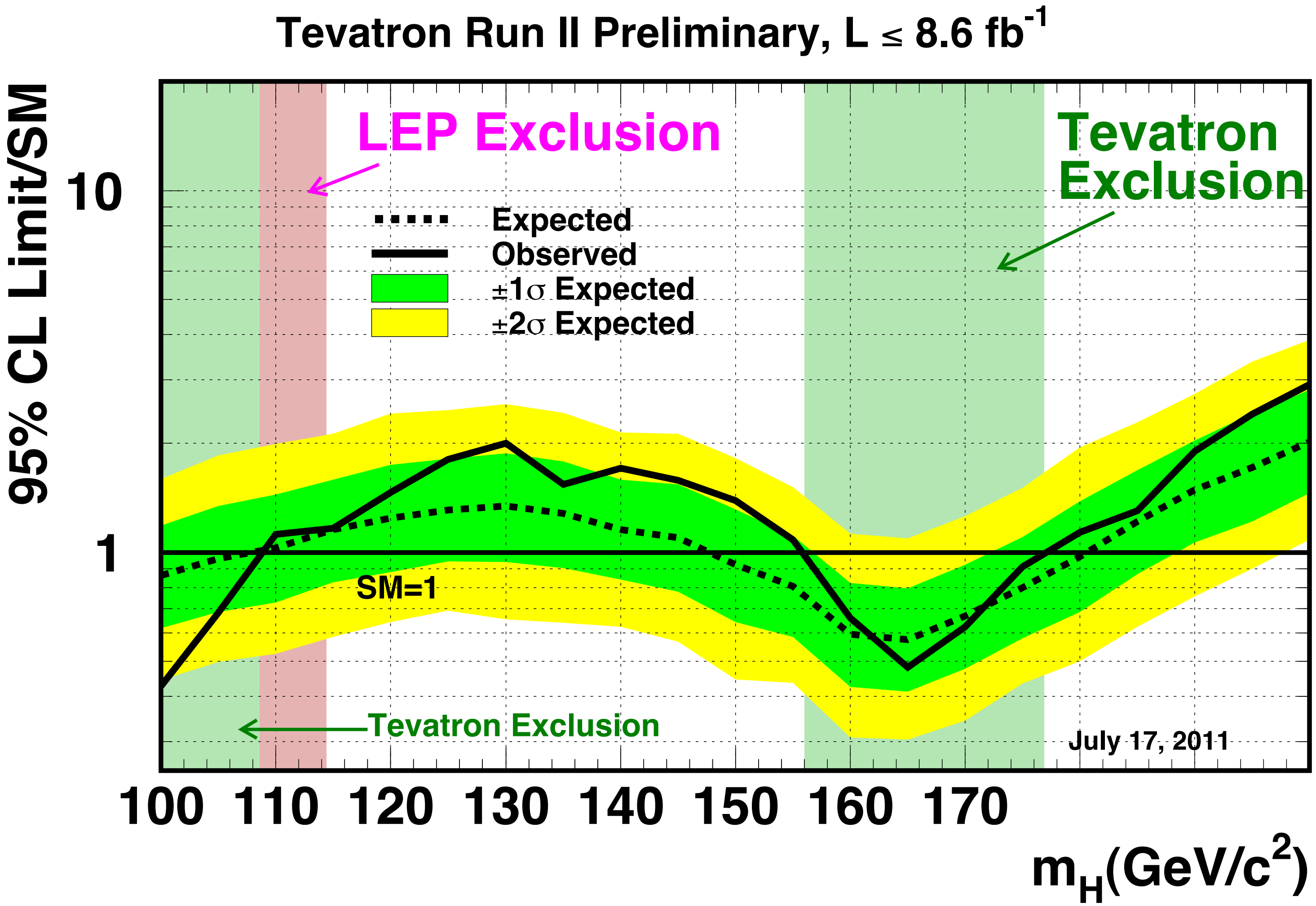
LEP Coll.

- Direct search @ LEP: $[M_H = 115.3 \text{ GeV}]$

$$M_H > 114.4 \text{ GeV @ 95\% CL}$$

LEP Coll.



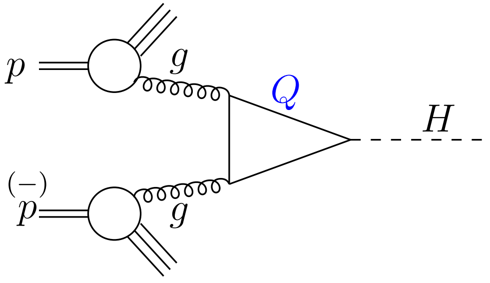

Tevatron Run II Preliminary, L ≤ 8.6 fb^{-1}
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
100
110
120
130
140
150
160
170
m_H(GeV/c^2)

$\mathcal{H}$iggs $\mathcal{S}$uche am $\mathcal{LHC}$

Higgsboson Produktion im SM

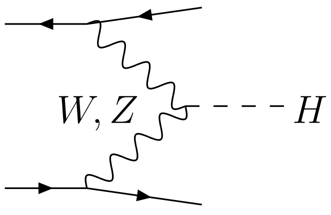
- **Gluon Gluon Fusion**

  $pp \to gg \to H$



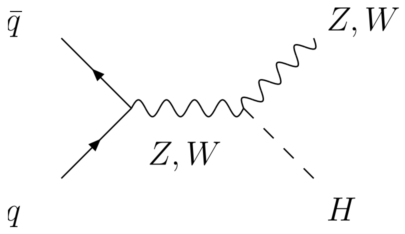
- **W/Z Fusion**

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



- **Higgs-strahlung**

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

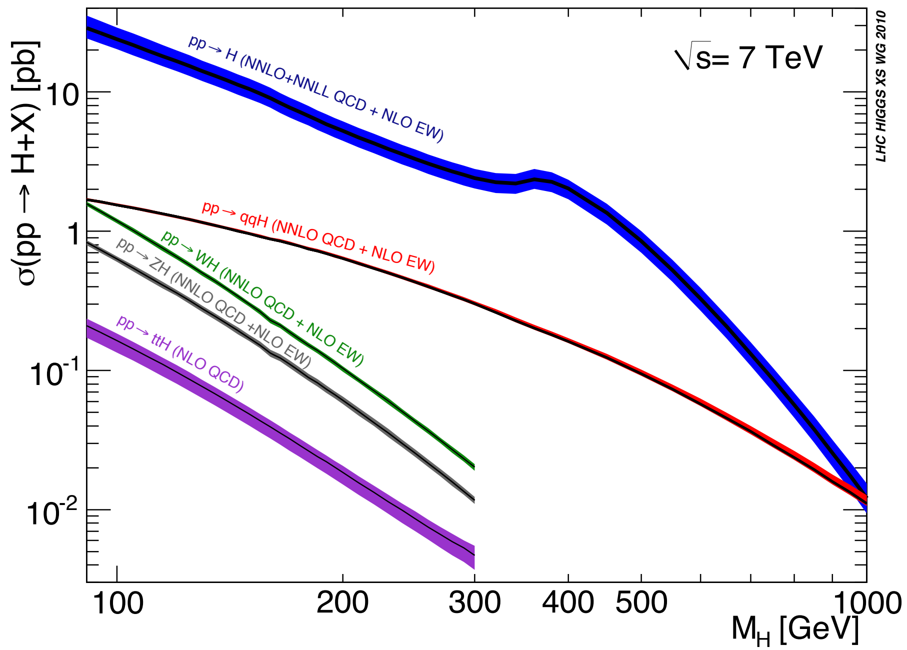


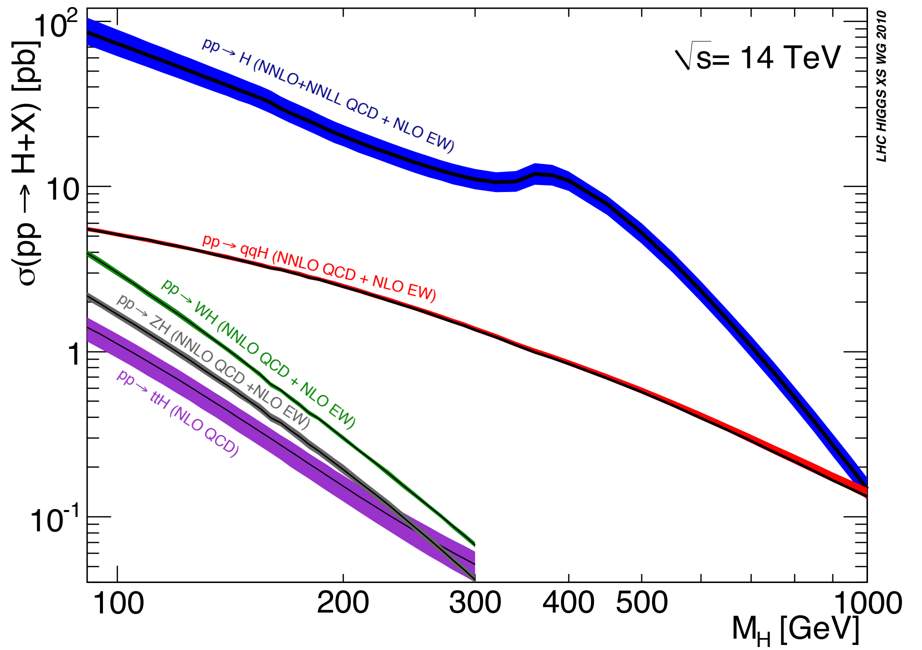
- **Bremsstrahlung**

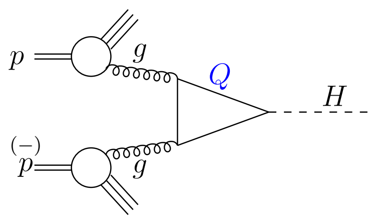
  $pp \to t\bar{t} + H$

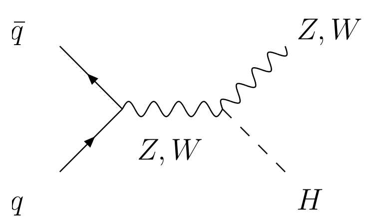
SM Higgs Boson Production at the LHC

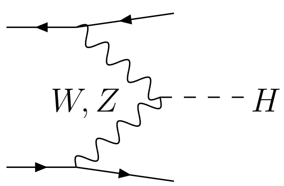
LHC Higgs XS WG, arXiv:1101.0593

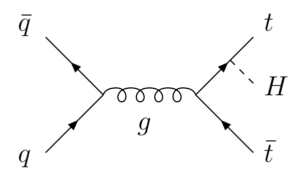




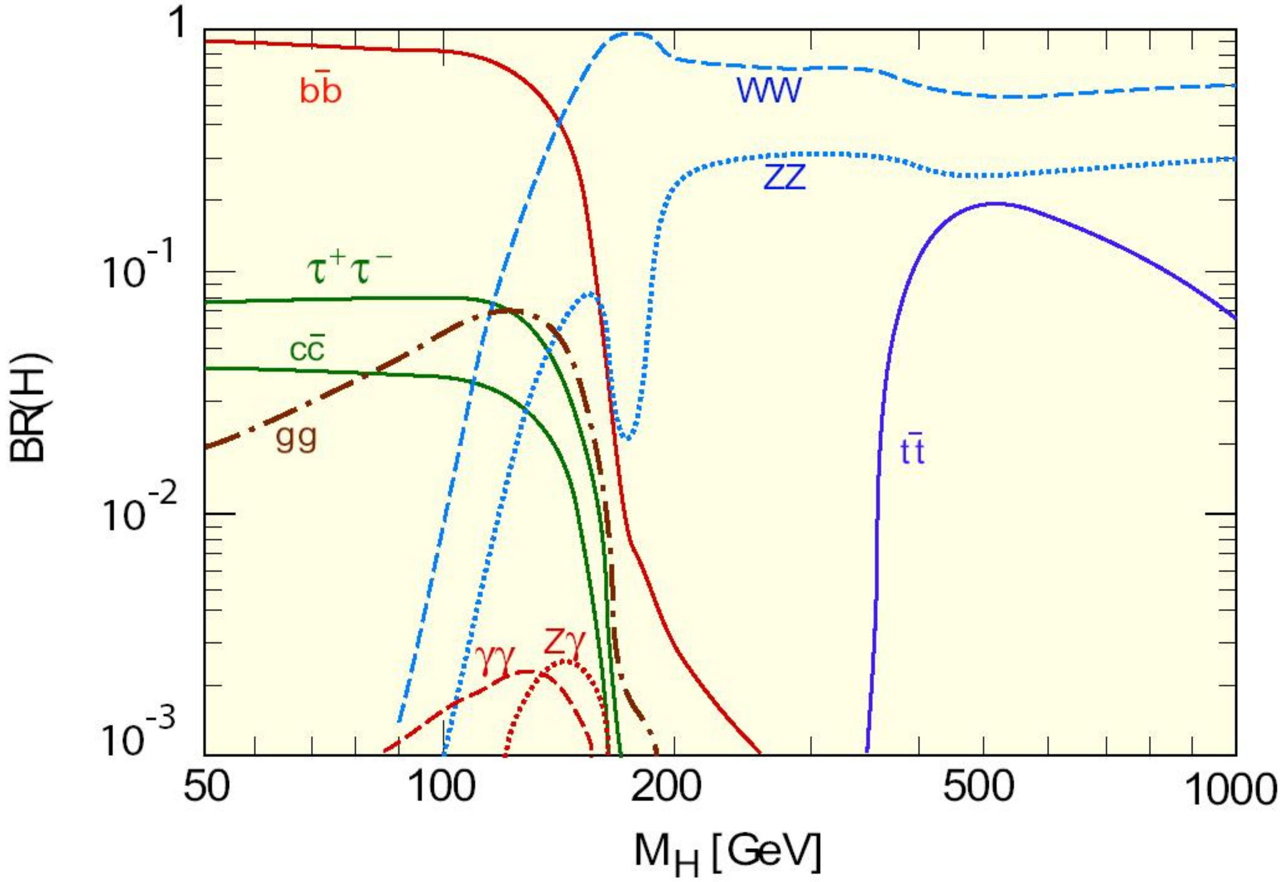








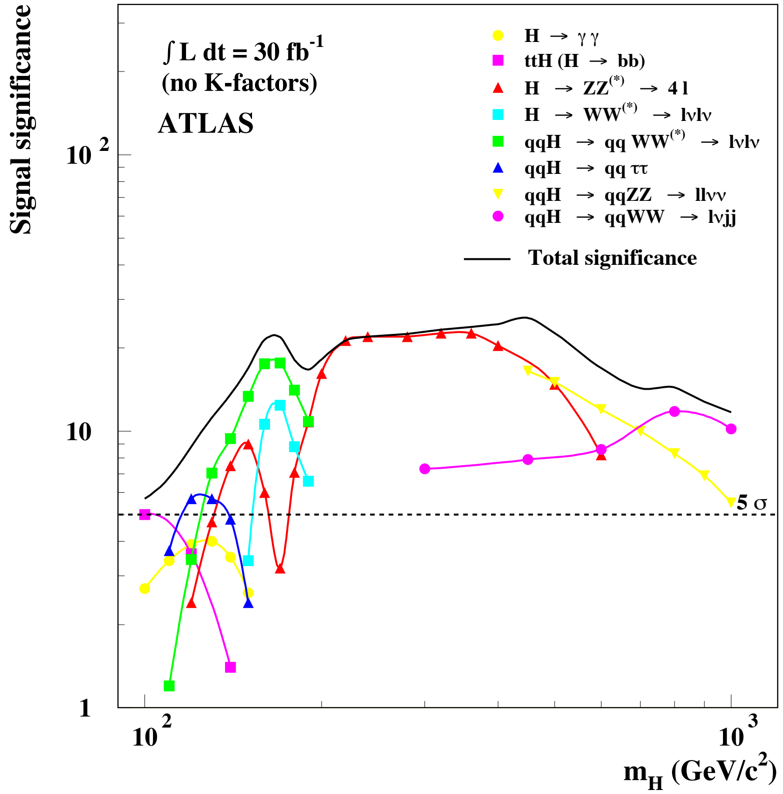
Higgsboson-Verzweigungsverhältnisse

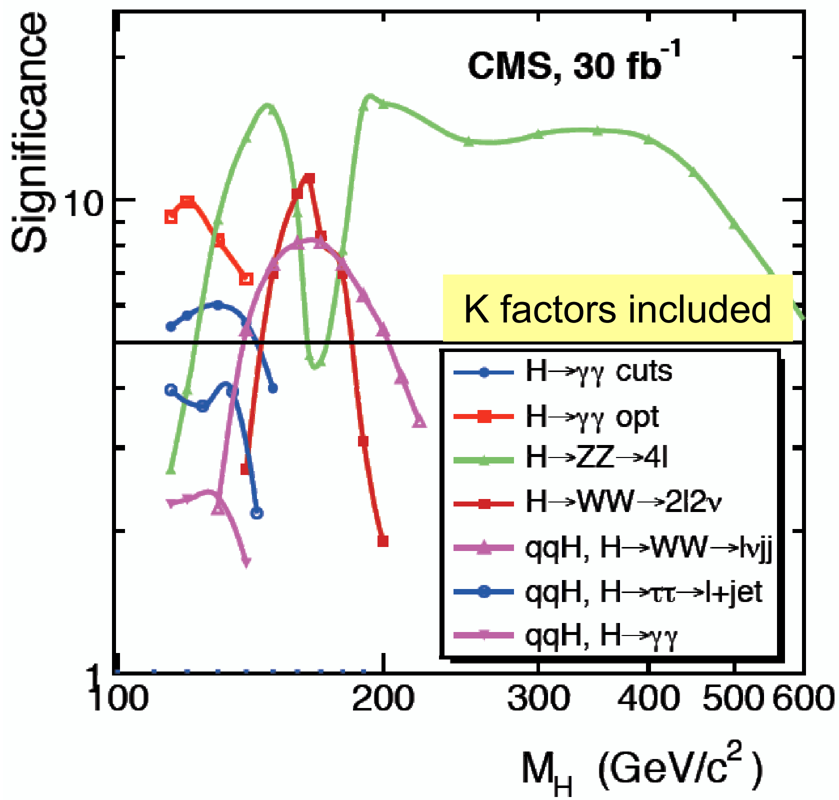


Higgs koppelt proportional zur Masse des Teilchen $\rightsquigarrow$ Zerfälle in schwere Teilchen dominant (falls kinematisch erlaubt)

ATLAS

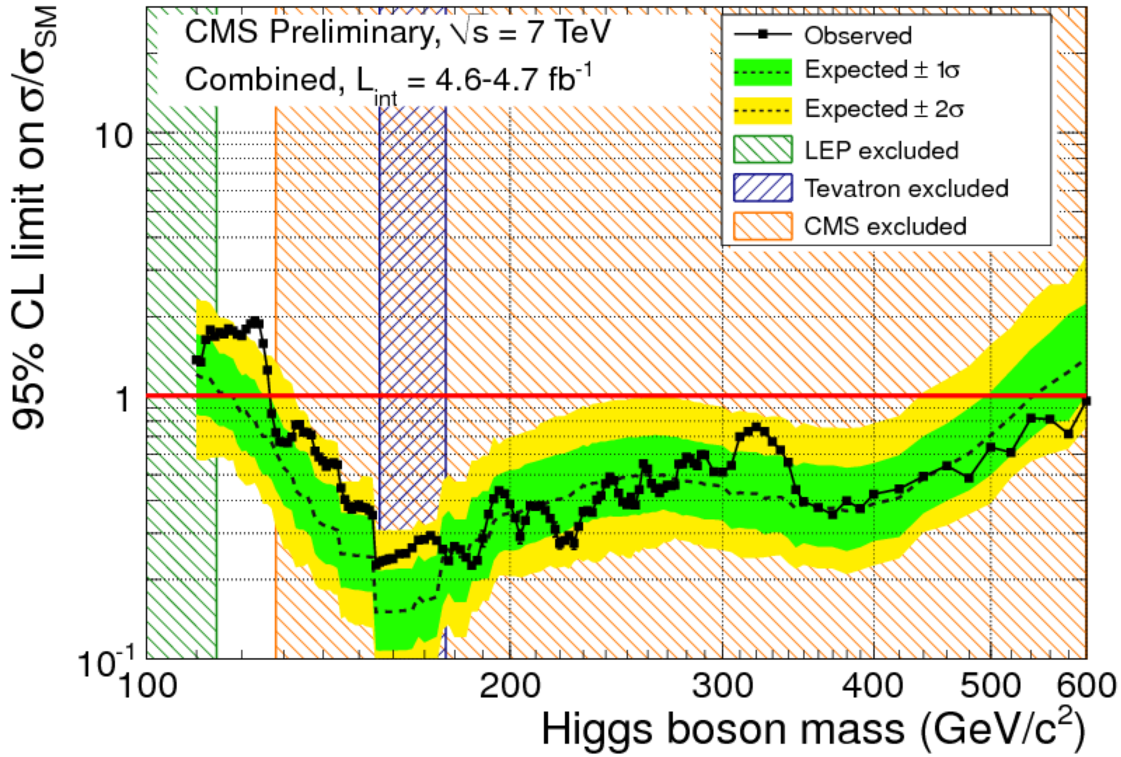
CMS





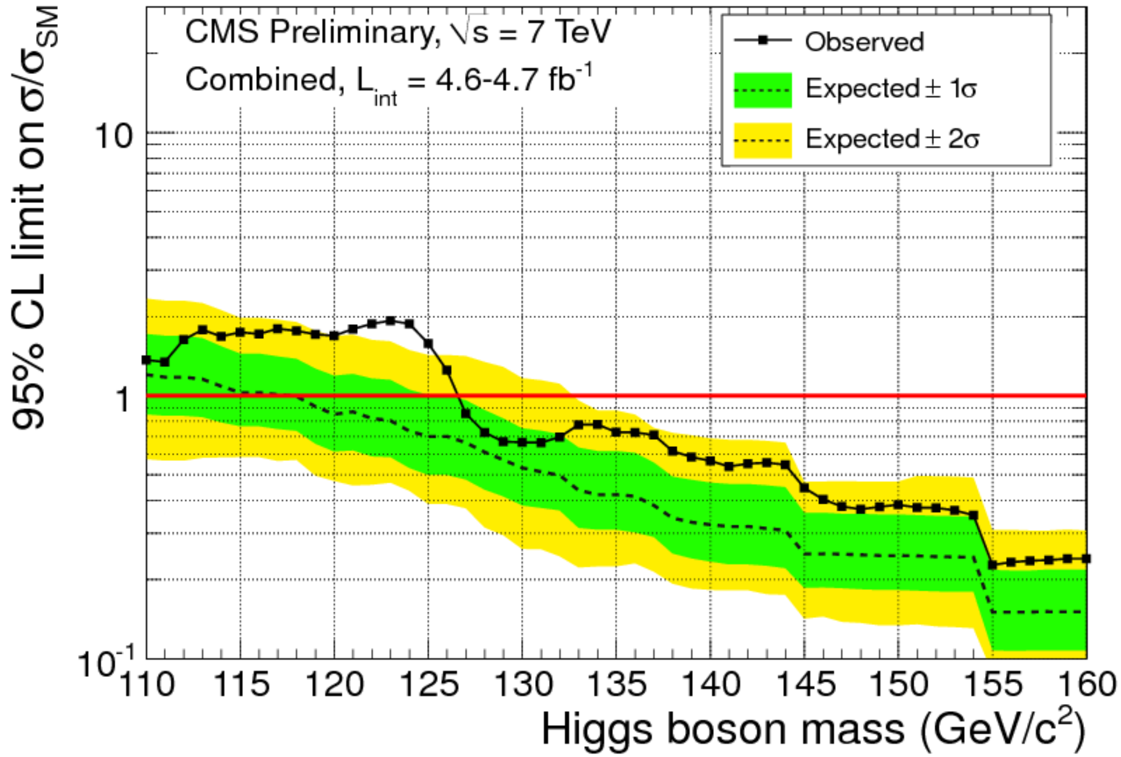
Genauigkeit: $\delta M_H / M_H \sim 10^{-3}$

$\mathcal{CMS}$ $\mathcal{E}$rgebnisse



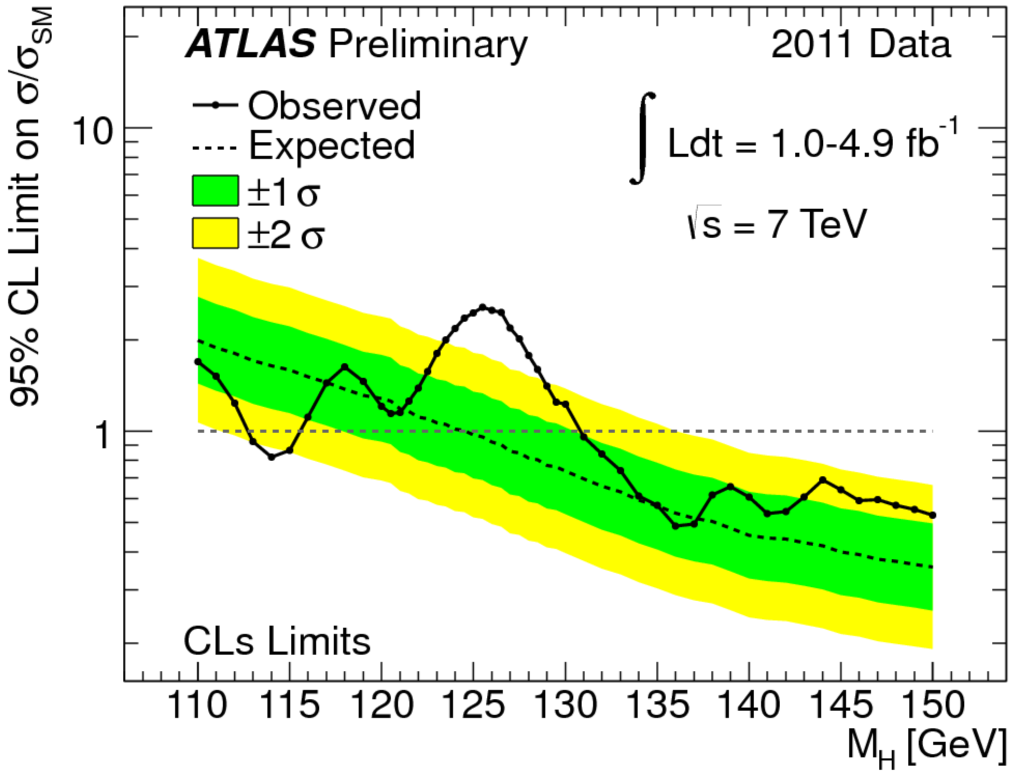
- Daten entsprechend 4.7 fb^{-1} integrierter Luminosität ausgewertet
- CMS kann den gesamten Massenbereich 114 GeV - 600 GeV untersuchen
- Kombination der Higgssuchen in den Higgszerfallskanälen in $WW^{(*)}, ZZ^{(*)}, bb, \tau\tau, \gamma\gamma$
- Ausschluß: 127-600 GeV auf 95% CL und 128-525 GeV auf 99% CL

$\mathcal{CMS}$ $\mathcal{E}$rgebnisse



- Im Vergleich zum SM ein Überschuß an Daten in der Region 115-127 GeV konsistent in 5 unabh. Kanälen
- Mit den bisherigen Daten schwierig, zu unterscheiden zwischen den beiden Hypothesen Existenz bzw. Nicht-Existenz in der niedrigen Massenregion
- Überschuß ist kompatibel mit SM Higgs Hypothese bei etwa 124 GeV mit weniger als 2σ bei Einschluß von LEE; ohne LEE 2.6σ.

𝒜𝒯ℒ𝒜𝒮 ℰrgebnisse



- Higgsboson am wahrscheinlichsten in der Region 115-130 GeV
- Kombination der Higgssuchen in den Higgszerfallskanälen in $WW^{(*)} \to l\nu l\nu, ZZ^{(*)} \to 4l, \gamma\gamma$
- Ausschluß: 112.7-115.5 GeV, 131-453 GeV, außer 237-251 GeV auf 95% CL (hohe Massenregion noch nicht untersucht)
- Überschuß ist kompatibel mit SM Higgs Hypothese bei etwa 126 GeV mit 2.6σ bei Einschluß von LEE; ohne LEE 3.6σ.

$\mathcal{M}$inimal $\mathcal{S}$upersymmetric $\mathcal{E}$xtension of the $\mathcal{SM}$ ($\mathcal{MSSM}$)

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

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

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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;...

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Decoupling limit:

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

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

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

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;...

Decoupling limit:

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

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

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

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

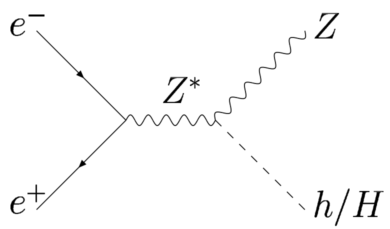
$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$

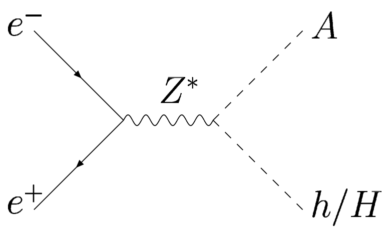
$g_{\Phi dd} \uparrow$

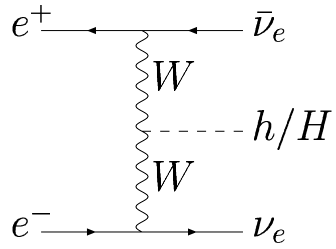
$g_{\Phi VV}^{MSSM} \lesssim g_{\Phi VV}^{SM}$

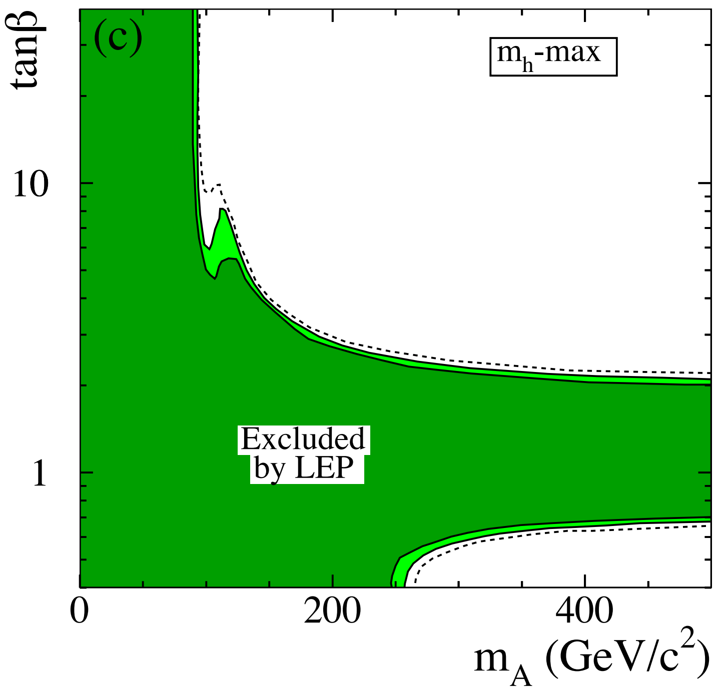
$\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{L}$imits

▷ Direct Search at LEP $e^+e^- \to Z + h/H,\ A + h/H,\ \nu_e\bar{\nu}_e + h/H$









$M_{h/H} \gtrsim 92.6$ GeV

$M_A \gtrsim 93.4$ GeV

$M_{H^\pm} > 78.6$ GeV

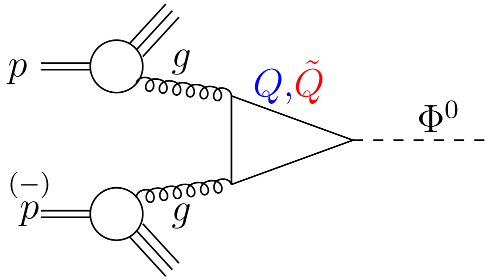
$0.6 < \tan\beta < 2.5$ excluded

(only in this scenario, $m_t = 174.3$ GeV!)

Higgs boson production in SM/MSSM

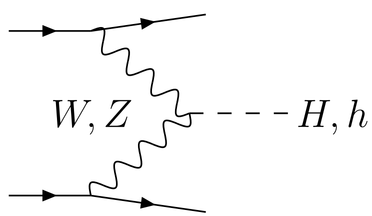
- **Gluon Gluon Fusion**

$pp \to gg \to H^{SM} \,/\, h, H, A$



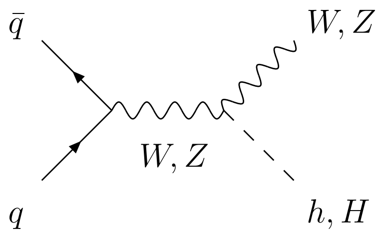
- **W/Z Fusion**

$pp \to qq \to qq + WW/ZZ \to qq + H^{SM} \,/\, h, H$



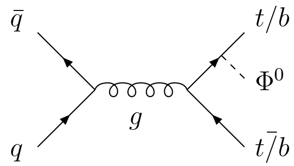
- **Higgs-strahlung**

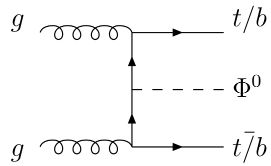
$pp \to W^*/Z^* \to W/Z + H^{SM} \,/\, h, H$



- **Associated Production**

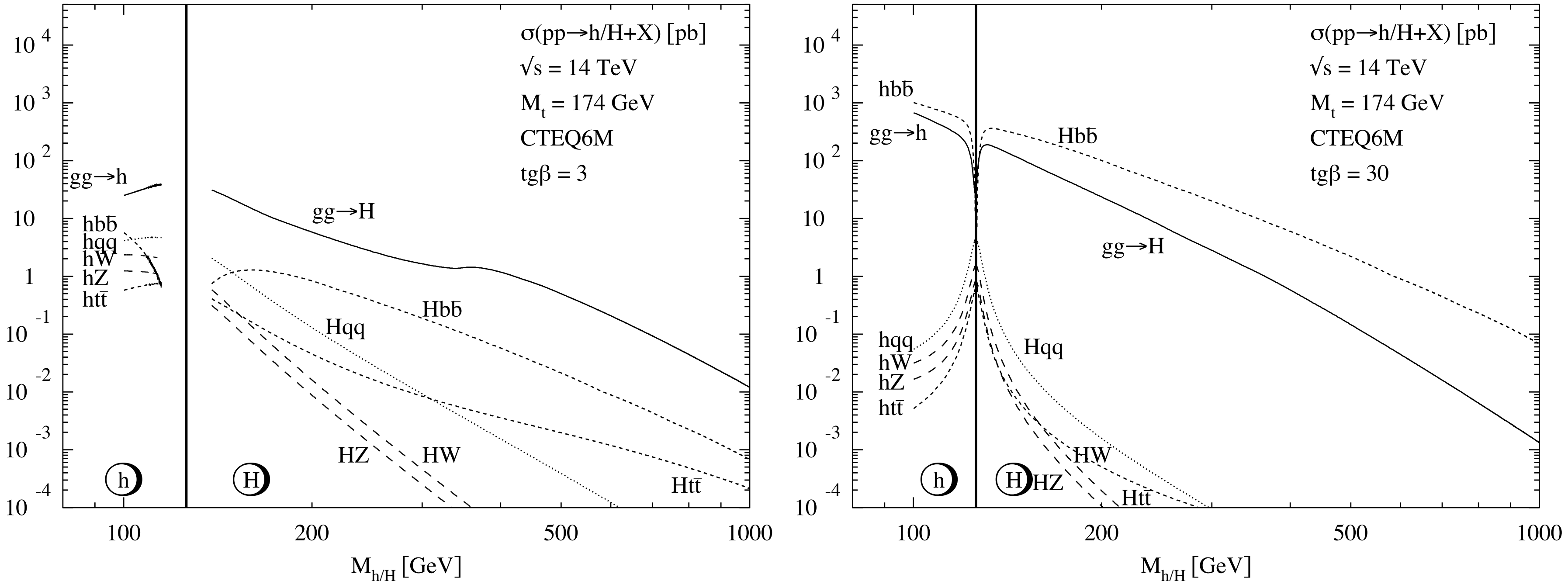
$pp \to t\bar{t}/b\bar{b} + (H^{SM}) \,/\, h, H, A$



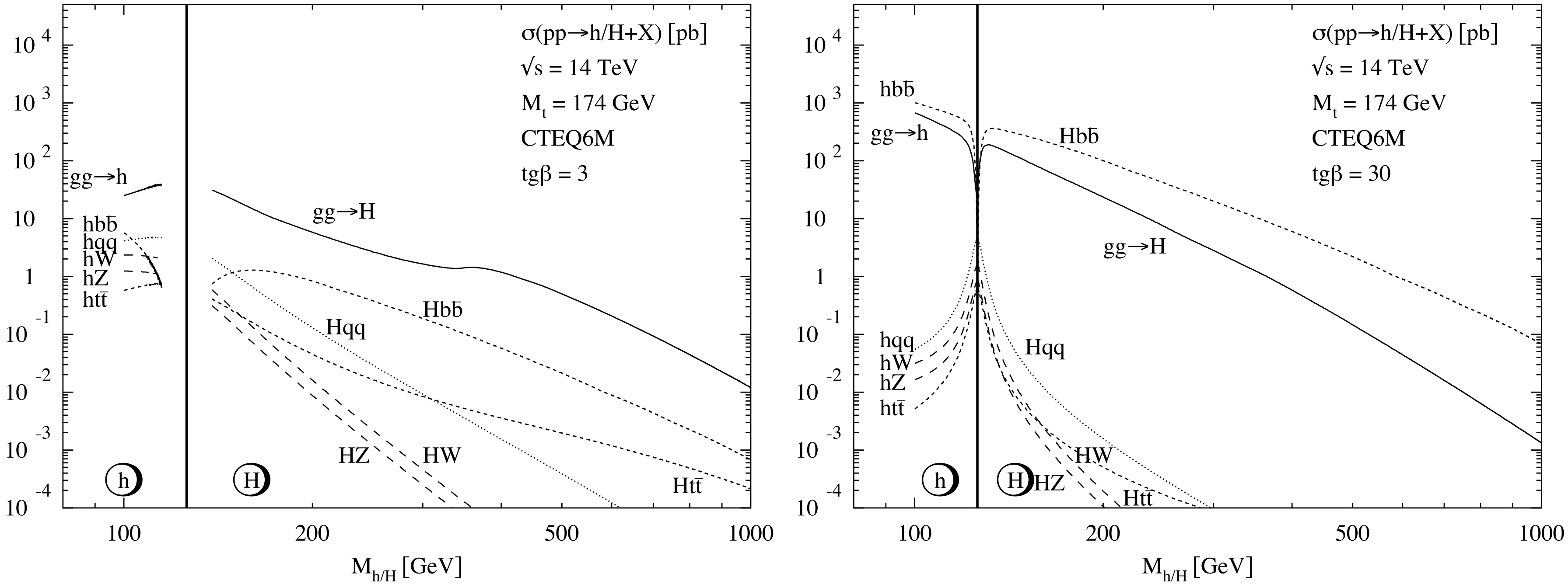


dominant

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



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



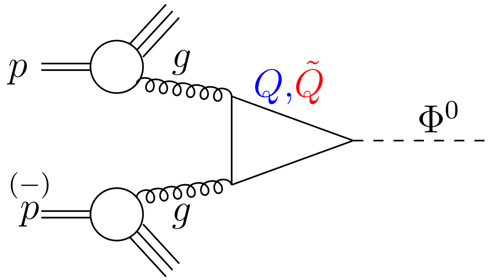
Reminder

$$\tan\beta \uparrow \quad \Rightarrow g_{\Phi uu} \downarrow$$
$$g_{\Phi dd} \uparrow$$
$$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$$

$\mathcal{H}$iggs Boson Production in gluon fusion

(i) Dominant: Gluon Fusion $pp \to gg \to H^{SM} / \, h, H, A$ (small & moderate $\tan\beta$)

Georgi et al; Gamberini et al



QCD corrections to top & bottom loops

- ▷ NLO (SM, MSSM): increase σ by $\sim$ 10...100%
  [moderate for large $\tan\beta \leftarrow b$-loop]
  Spira,Djouadi,Graudenz,Zerwas
  Dawson;Kauffman,Schaffer
- ▷ SM; tg$\beta \lesssim 5$: 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
  Moch,Vogt
  Ravindran
- ▷ Estimate of NNNLO effects @ $M_\Phi \ll m_t \rightsquigarrow$ scale stabilisation
  scale dependence: $\Delta \lesssim 10 - 15\%$
- ▷ NNLL resummation: $+ \sim 10\%$
  Catani,de Florian,Grazzini,Nason
- ▷ resummation of soft gluons @ N^{3}LL and of π^2 enhanced terms
  Ahrens,Neubert,Becher,Yang

$\mathcal{H}$iggs Boson Production in gluon fusion

Corrections to top & bottom loops

- ▷ 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 $\sim -4\% - 6\%$ (SM) — Aglietti et al.;Degrassi,Maltoni; Actis et al
- ▷ mixed QCD and EW corrections — Anastasiou,Boughezal,Petriello

NLO corrections to squark loops

- ▷ in the heavy mass limit — Dawson,Djouadi,Spira
- ▷ full SUSY-QCD corrections in heavy mass limit — Harlander,Steinhauser;Harlander,Hofmann; Degrassi,Slavich '11
- ▷ bottom/sbottom contributions — Degrassi,Slavich '11 Harlander,Hofmann,Mantler '11
  asymptotic expansion in $\tilde{M} \gg m_b, M_\phi$

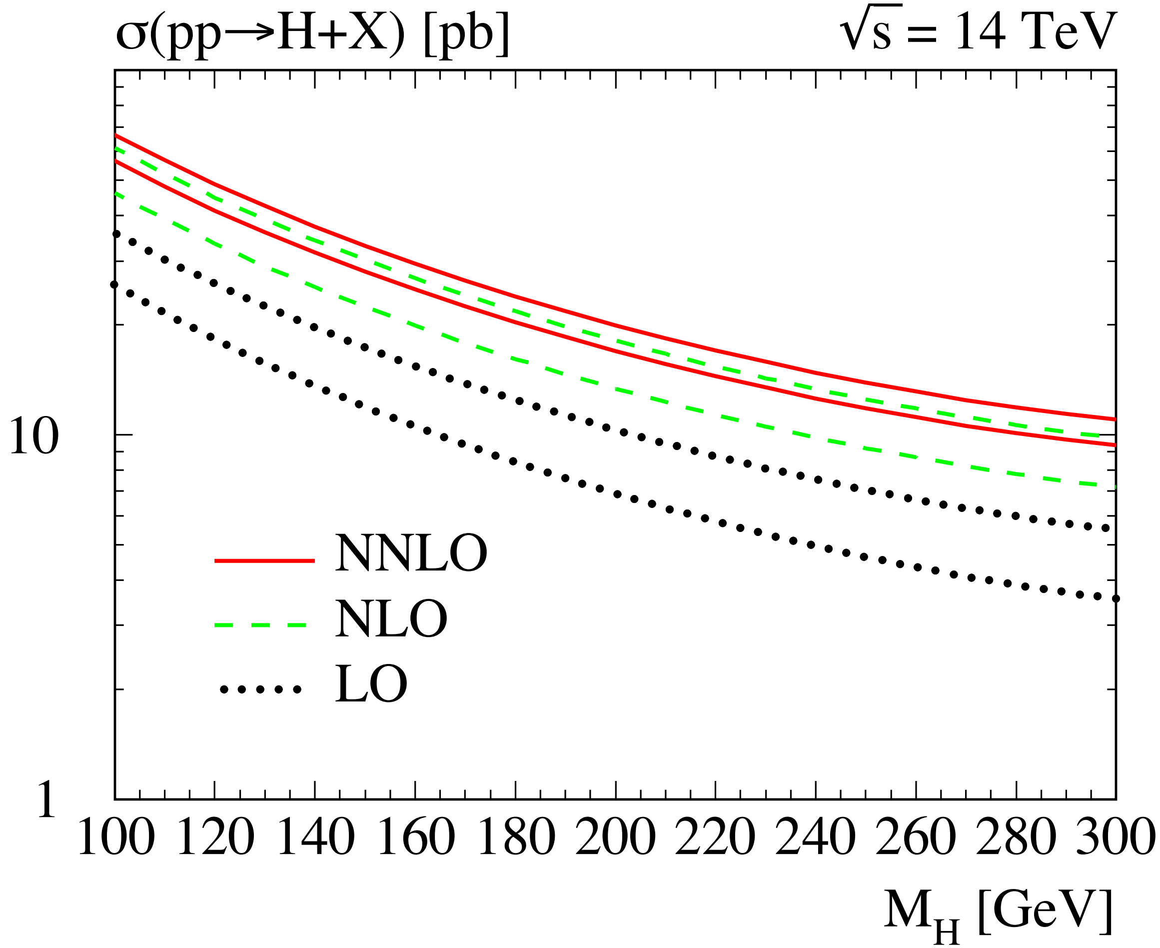
$m_{\tilde{Q}} \lesssim 400$ GeV:

- ▷ NLO squark mass effects $\sim 15\%$ — MMM,Spira;Anastasiou,Beerli,Bucherer, Daleo,Kunszt;Aglietti,Bonciani,Degrassi,Vicini
- ▷ full NLO SUSY QCD calculation — Anastasiou,Beerli,Daleo; MMM,Rzehak,Spira

NNLO SUSY-QCD corrections from $t/\tilde{t}$ sector — Pak,Steinhauser,Zerf '10

gg → H $\mathcal{NNLO}$

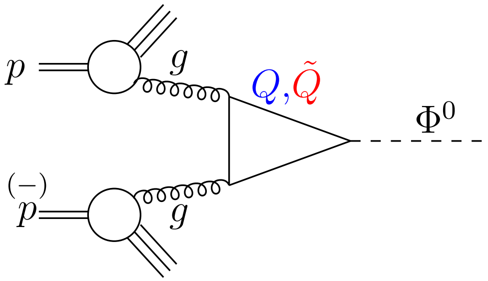
Harlander,Kilgore



$gg \to H, h$ at leading order

Lowest order - 1 loop

Georgi,...;Gamberini,...



$$\boxed{\sigma(pp \to \Phi + X) \quad = \quad \sigma_0^\Phi \tau_\Phi \frac{d\mathcal{L}^{gg}}{d\tau_\Phi}}$$

$$\sigma_0^{h/H} = \frac{G_F \alpha_S^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} F_Q^{h/H}(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} F_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2 \qquad \sigma_0^A = \frac{G_F \alpha_s^2}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A F_Q^A(\tau_Q) \right|^2$$

$$F_Q^{h/H}(\tau_Q) \quad = \quad \frac{3}{2}\tau_Q \Big[1 + (1-\tau_Q) f(\tau_Q)\Big] \qquad F_Q^A(\tau_Q) = \tau_Q f(\tau_Q)$$

$$F_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \quad = \quad -\frac{3}{4}\tau_{\tilde{Q}} \Big[1 - \tau_{\tilde{Q}} f(\tau_{\tilde{Q}})\Big]$$

$$f(\tau) \quad = \quad \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \end{cases} \qquad \tau_\Phi = \frac{M_\Phi^2}{s}, \quad \tau_{Q,\tilde{Q}} = \frac{4m_{Q,\tilde{Q}}^2}{M_\Phi^2}$$

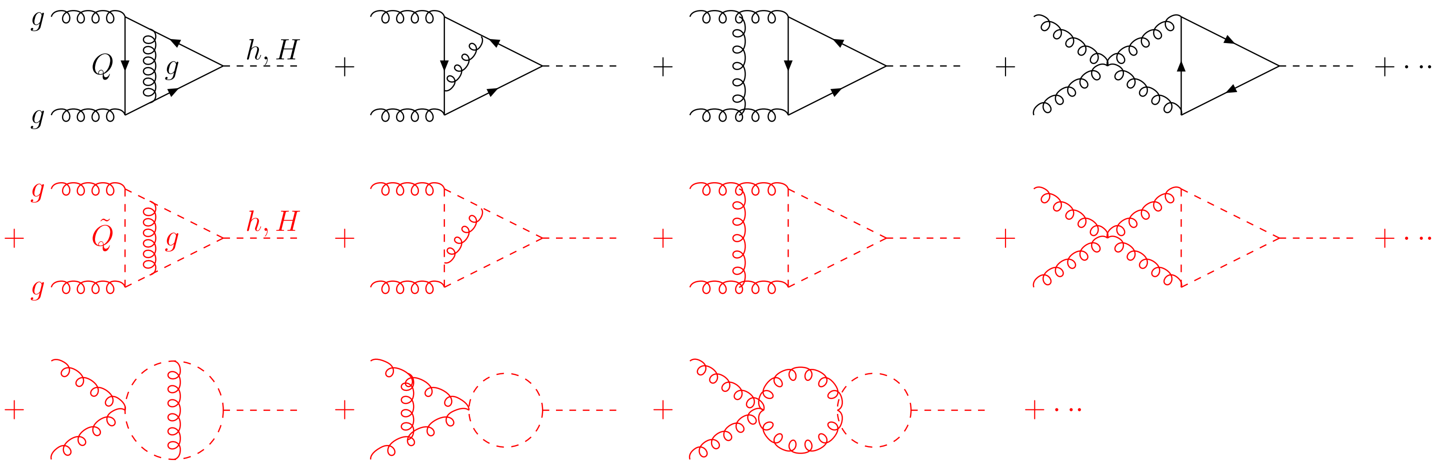
$\mathcal{F}$irst $\mathcal{S}$tep: QCD corrections

$$\Delta\hat{\sigma}_{ij} = \sigma_0 \Big\{ C_{ij}\delta(1-\hat{\tau}) + D_{ij}\Theta(1-\hat{\tau}) \Big\} \frac{\alpha_s}{\pi} \qquad \hat{\tau} = \frac{M_\Phi^2}{\hat{s}}$$

$\nearrow$ virtual+soft corrections

$\uparrow$ real corrections

Virtual corrections [2 loops, first step: no gluino contributions]



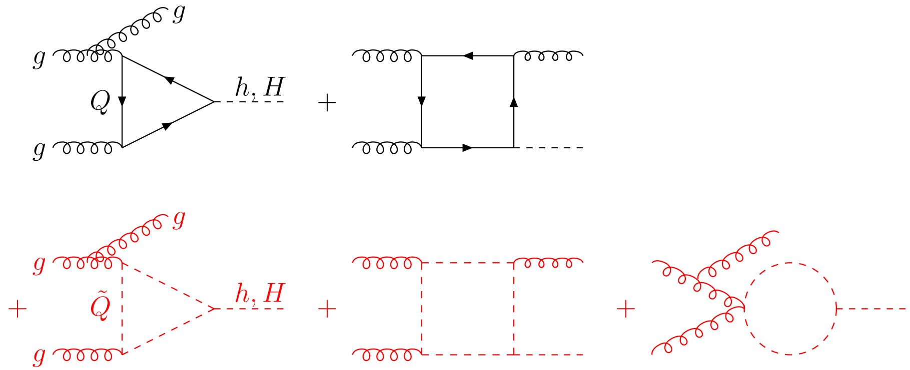
UV-,IR-,Coll-singularities in $n = 4 - 2\epsilon$ dimensions.

Real Corrections

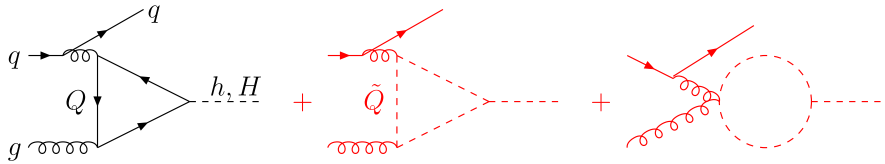
After renormalization: IR & coll. singularities $\rightsquigarrow$ real corrections have to be added.

3 incoherent processes:

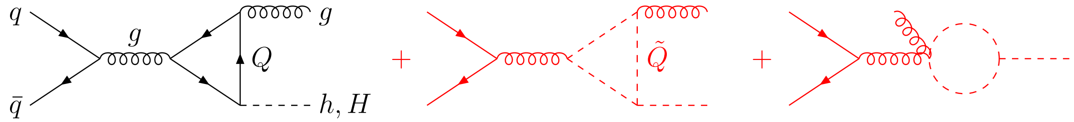
gg → Hg:



gq → Hq:



q$\bar{q}$ → Hg:



Phase space integration in $n = 4 - 2\epsilon$ dimensions $\rightsquigarrow$ IR, Coll. singularities: poles in ϵ

Result

- α_S: $\overline{\text{MS}}$ scheme, 5 active flavours

- μ=Ren. scale, Q=Fact. scale, $\mu^2 = Q^2 = M_\phi^2$

$$
\begin{aligned}
\sigma(pp \to \phi + X) &= \sigma_0^\phi [1 + C^\phi \frac{\alpha_S}{\pi}] \tau_\phi \frac{d\mathcal{L}_{gg}}{d\tau_\phi} + \Delta\sigma_{gg}^\phi + \Delta\sigma_{gq}^\phi + \Delta\sigma_{q\bar{q}}^\phi \\
C^\phi(\tau_Q, \tau_{\tilde{Q}}) &= \pi^2 + C_1^\phi(\tau_Q, \tau_{\tilde{Q}}) + \frac{33-2N_F}{6} \log \frac{\mu^2}{M_\phi^2} \\
\Delta\sigma_{gg}^\phi &= \int_{\tau_\phi}^1 d\tau \frac{d\mathcal{L}_{gg}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0^\phi \Big\{ -\hat{\tau} P_{gg}(\hat{\tau}) \log \frac{Q^2}{\hat{s}} + d_{gg}^\phi(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \\
&\quad + 12 \Big[\Big(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}} \Big)_+ - \hat{\tau}[2 - \hat{\tau}(1-\hat{\tau})] \log(1-\hat{\tau}) \Big] \Big\} \\
\Delta\sigma_{gq}^\phi &= \int_{\tau_\phi}^1 d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}_{gq}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0^\phi \Big\{ -\frac{\hat{\tau}}{2} P_{gq}(\hat{\tau}) \Big[\log \frac{Q^2}{\hat{s}(1-\hat{\tau})^2} \Big] d_{gq}^\phi(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}}) \Big\} \\
\Delta\sigma_{q\bar{q}}^\phi &= \int_{\tau_\phi}^1 d\tau \sum_q \frac{d\mathcal{L}_{q\bar{q}}}{d\tau} \frac{\alpha_S}{\pi} \sigma_0^\phi \; d_{q\bar{q}}^\phi(\hat{\tau}, \tau_Q, \tau_{\tilde{Q}})
\end{aligned}
$$

- $\tau_{Q,\tilde{Q}} = \frac{4m_{Q,\tilde{Q}}^2}{M_\Phi^2}$, $\quad \hat{\tau} = \frac{m_\phi^2}{\hat{s}}$

The Scenario

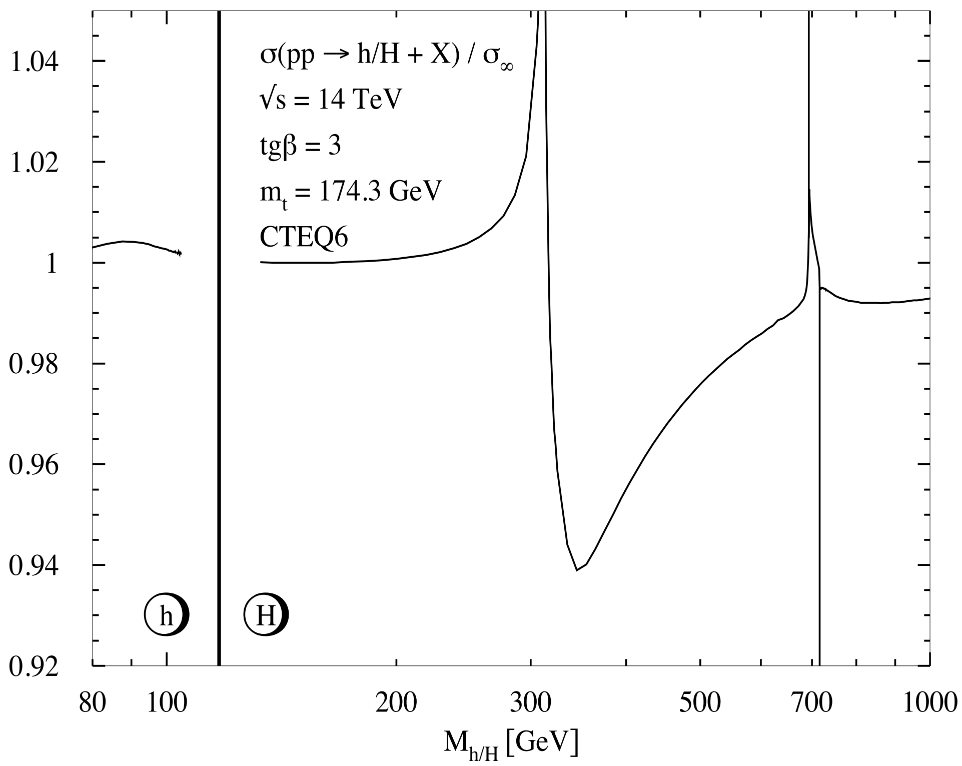
The gluophobic Higgs scenario $[m_t = 174.3$ GeV$]$ Carena,Heinemeyer,Wagner,Weiglein

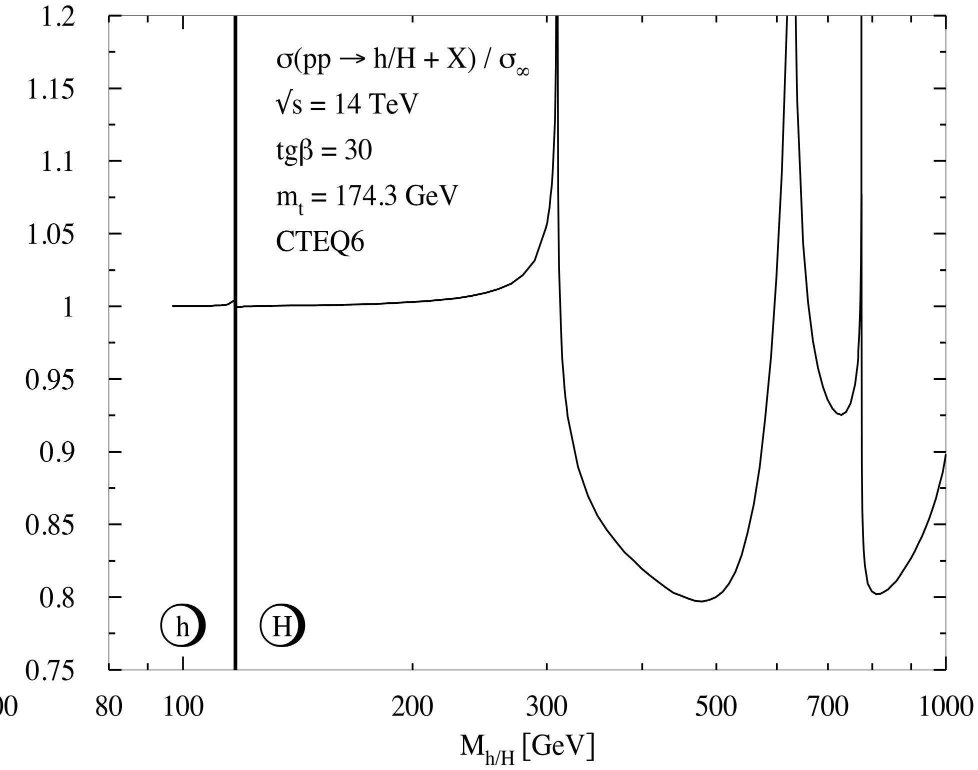
$$M_{SUSY} = 350 \text{ GeV},\ \mu = M_2 = 300 \text{ GeV},\ X_t = -770 \text{ GeV},\ A_b = A_t,\ m_{\tilde{g}} = 500 \text{ GeV}$$

$\tan\beta = 3$		$\tan\beta = 30$	
$m_{\tilde{t}_1} = 156$ GeV	$m_{\tilde{t}_2} = 517$ GeV	$m_{\tilde{t}_1} = 155$ GeV	$m_{\tilde{t}_2} = 516$ GeV
$m_{\tilde{b}_1} = 346$ GeV	$m_{\tilde{b}_2} = 358$ GeV	$m_{\tilde{b}_1} = 314$ GeV	$m_{\tilde{b}_2} = 388$ GeV

NLO cross section $\rightarrow$

σ_{NLO} w/ full squark mass dependence / σ_{NLO} in the heavy squark limit





$\sigma(pp \to h/H + X)/\sigma_\infty$ up to 20%

Kinks, bumps, spikes: $\tilde{t}_1\bar{\tilde{t}}_1, \tilde{b}_1\bar{\tilde{b}}_1, \tilde{b}_2\bar{\tilde{b}}_2$ thresholds in consecutive order with rising Higgs mass.

Coulomb singularities

$\tilde{Q}\bar{\tilde{Q}}$ thresholds: Formation of 0^{++} states $\rightsquigarrow$ Coulomb singularities

Singular behaviour can be derived from the Sommerfeld rescattering corrections $\rightsquigarrow$

At each specific $\tilde{Q}_0\bar{\tilde{Q}}_0$ threshold:

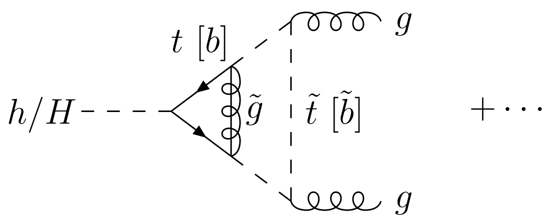
$$C_1(\tau_Q, \tau_{\tilde{Q}}) \to \text{Re}\left\{ \frac{g^{\Phi}_{\tilde{Q}_0} \tilde{F}(\tilde{Q}_0) \frac{16\pi^2}{3(\pi^2-4)} \left[-\ln\left(\tau^{-1}_{\tilde{Q}_0} - 1\right) + i\pi + const \right]}{\sum_Q g^{\Phi}_Q F(\tau_Q) + \sum_{\tilde{Q}} g^{\Phi}_{\tilde{Q}} \tilde{F}(\tau_{\tilde{Q}})} \right\}$$

Agrees quantitatively with numerical results.

Genuine SUSY-QCD corrections

- **Limit heavy SUSY masses** $\rightarrow \mathcal{O}(10\ \%)$

Harlander,Steinhauser,Hofmann



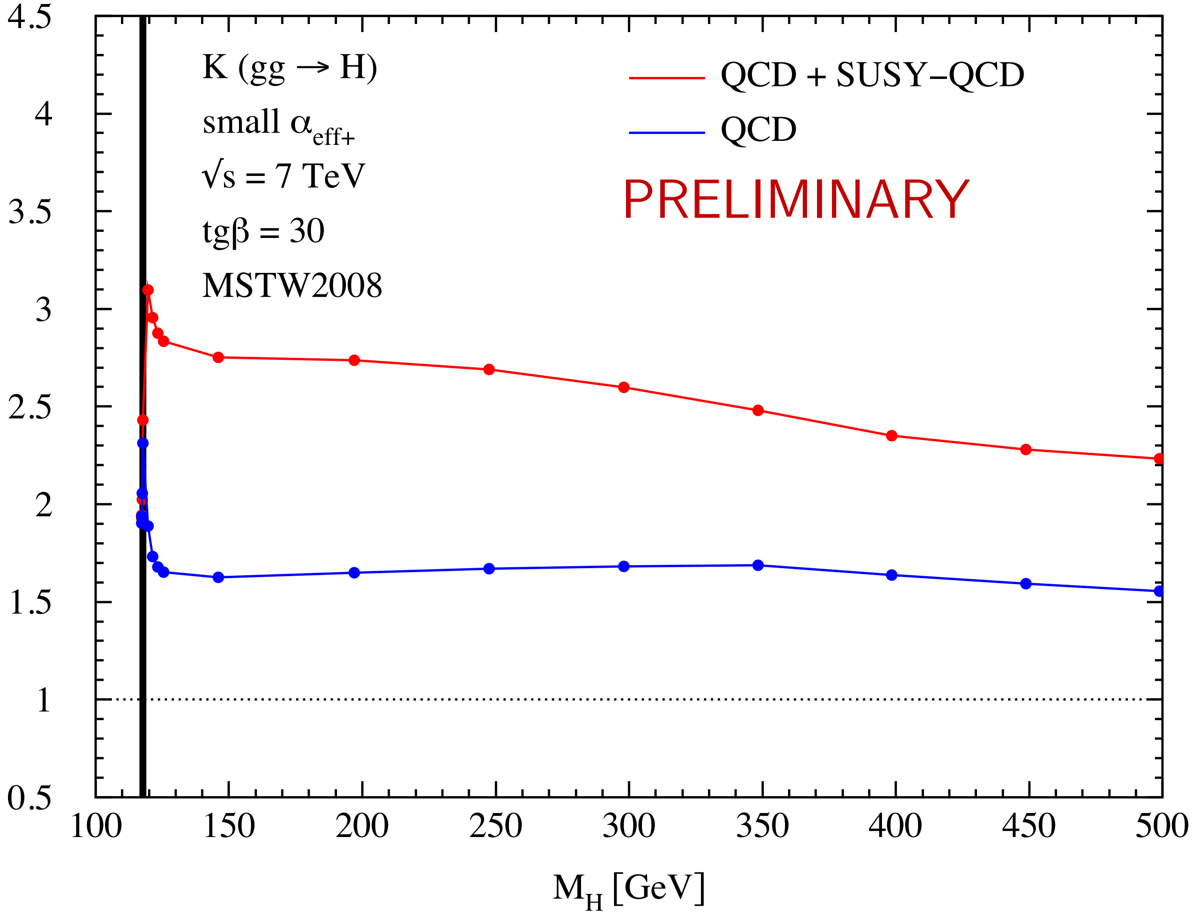
Anastasiou,Beerli,Daleo
MMM,Rzehak,Spira

- **Small α_{eff} scenario [modified]**

$$\tan\beta = 30$$
$$M_{\tilde{Q}} = 800 \text{ GeV}$$
$$M_{\tilde{g}} = 1000 \text{ GeV} \qquad \longleftarrow$$
$$M_2 = 500 \text{ GeV}$$
$$A_b = A_t = -1.133 \text{ TeV}$$
$$\mu = 2 \text{ TeV}$$

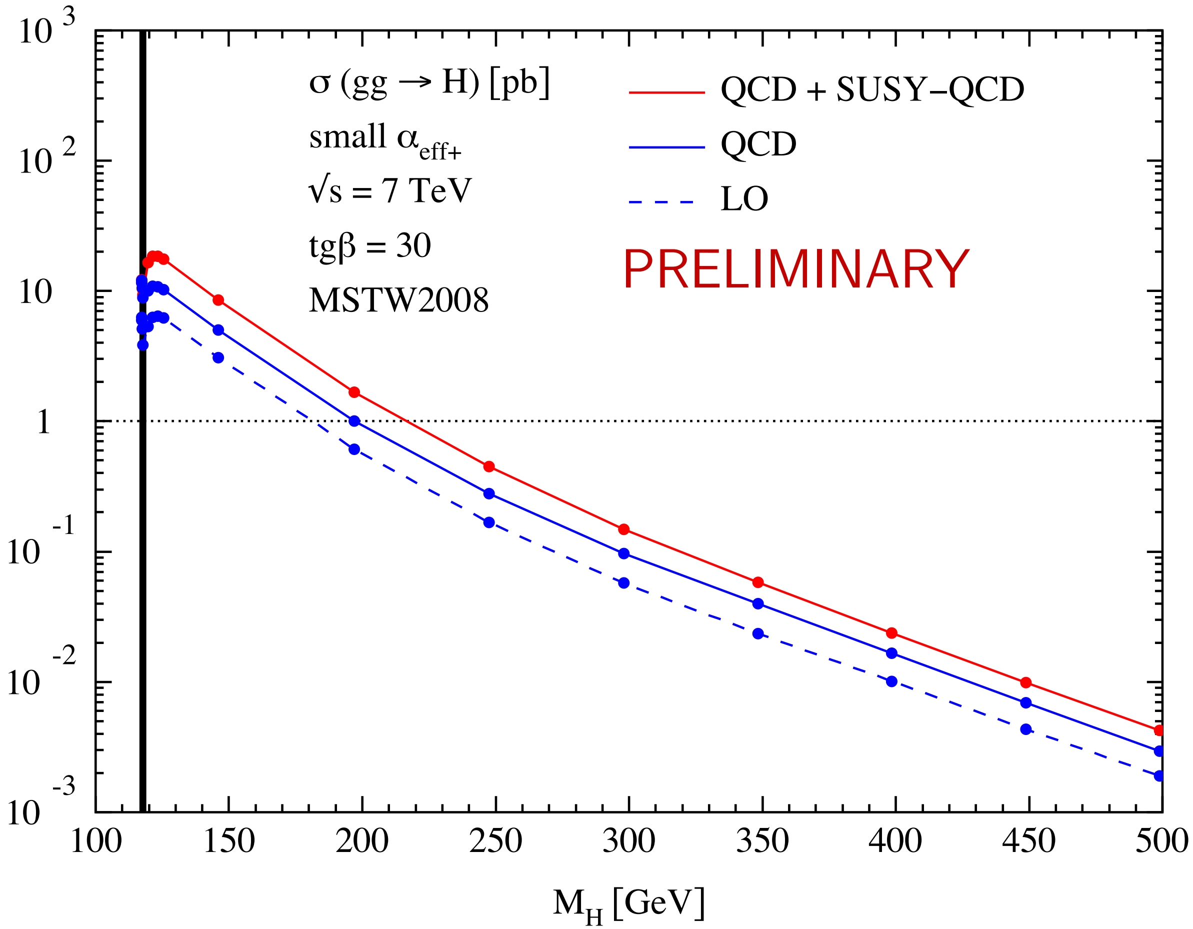
$$m_{\tilde{t}_1} = 679 \text{ GeV} \qquad m_{\tilde{t}_2} = 935 \text{ GeV}$$
$$m_{\tilde{b}_1} = 601 \text{ GeV} \qquad m_{\tilde{b}_2} = 961 \text{ GeV}$$

Genuine SUSY-QCD Corrections - K-factor



MMM, Rzehak, Spira

Genuine SUSY-QCD Corrections - Total Cross Section



MMM, Rzehak, Spira

$\mathcal{H}$igher order corrections to $\mathcal{H}$iggs boson production at the $\mathcal{LHC}$

- W/Z **Fusion**

NLO QCD σ (SM/MSSM)	$\sim$ 5 bis 10%	Han,Valencia, Willenbrock	EW & QCD	~ 5 %	Ciccolini,Denner Dittmaier
distributions	$\sim$ 10 %	Figy,Oleari, Zeppenfeld; Berger,Campbell	SUSY QCD	klein	Djouadi,Spira
NLO QCD H+3j		Figy,Hankele, Zeppenfeld	SUSY QCD&EW	klein	Hollik et al. Figy et al.

- **Higgs-strahlung**

NLO QCD (SM/MSSM)	$\sim +30$ % (Drell-Yan)	Han,Willenbrock	
NNLO QCD (SM/MSSM)	$\sim +5-10$ %	Harlander,Kilgore;Hamberg et al. Brein,Djouadi,Harlander	$\Delta_{\text{theor}} \sim 5$ %

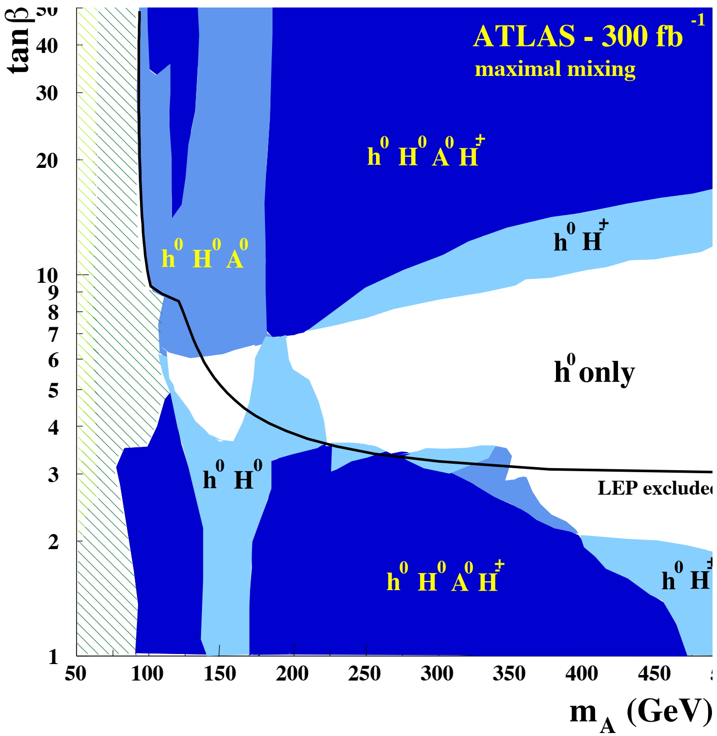
SUSY QCD: klein — Djouadi, Spira — Volle EW(SM):-5-10% — Ciccolini,Dittmaier,Krämer

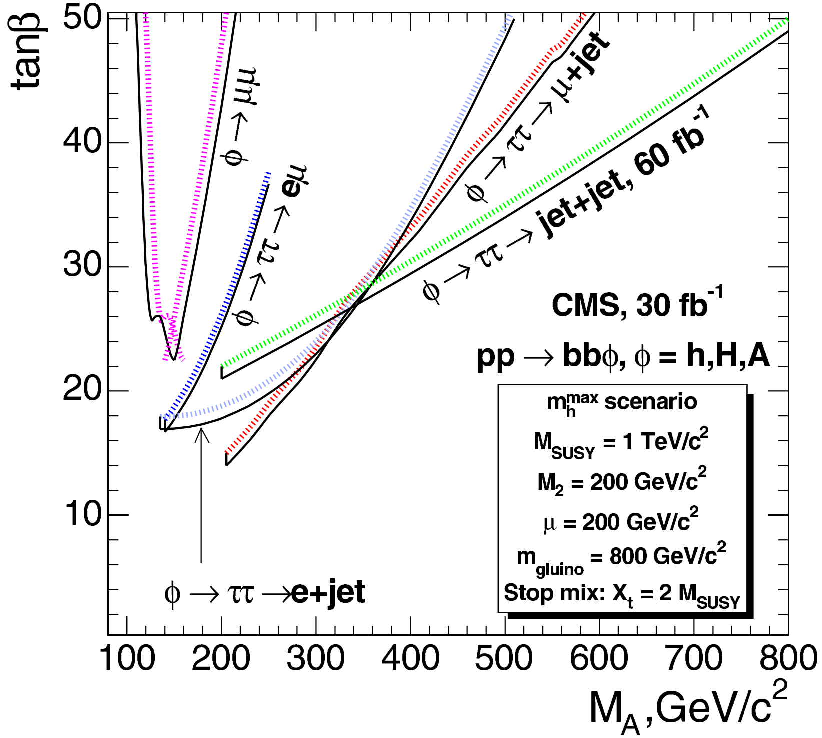
- **Associated production**

$b\bar{b}\Phi^0$	NLO	Dittmaier,Krämer,Spira, Walser;Dawson,Jackson, Reina,Wackeroth	$b\bar{b} \to \Phi^0$	NLO,NNLO	Dicus,Willenbrock;Stelzer et al.; Balazs et al.;Campbell et al.; Harlander,Kilgore;Kidonakis
t Beitr.	NNLO	Boudjema,Ninh		EW	Dittmaier,Krämer, Mück,Schlüter
	SUSY QCD	Gao et al.; Hollik,Rauch	$b\bar{b} \to \Phi^0$ $bg \to b\Phi^0$	SUSY QCD SUSY EW	Dawson,Jackson (also $bg \to b\Phi^0$) Dawson,Jaiswal; Beccaria et al. et al.
$t\bar{t}\Phi^0$	NLO QCD+20%	Beenakker et al.; Dawson et al.	SUSY QCD 20-30%		Peng et al.; Dittmaier et al.

ATLAS

CMS





accuracy: $\delta M_H / M_H(\mathrm{SM/MSSM}) \sim 10^{-3}$

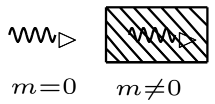
Experimental verification of the Higgs mechanism

Higgs mechanism:

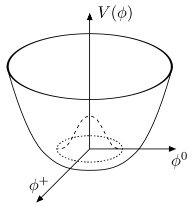
Creation of particle masses without violating gauge principles

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 – $\lambda_{HHH}, \lambda_{HHHH}$

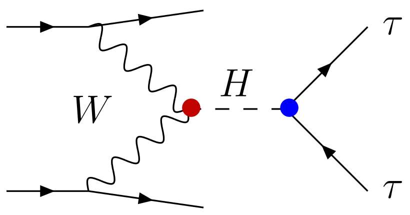


Determination of the Higgs Couplings

Strategy

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

E.g.:



$\sim \Gamma_{WW}\, \mathrm{BR}(H \to \tau\tau)$

Problem

- total Higgs production cross section not measurable
- some Higgs decay channels not observable

$\Rightarrow$ only ratios of couplings are measurable

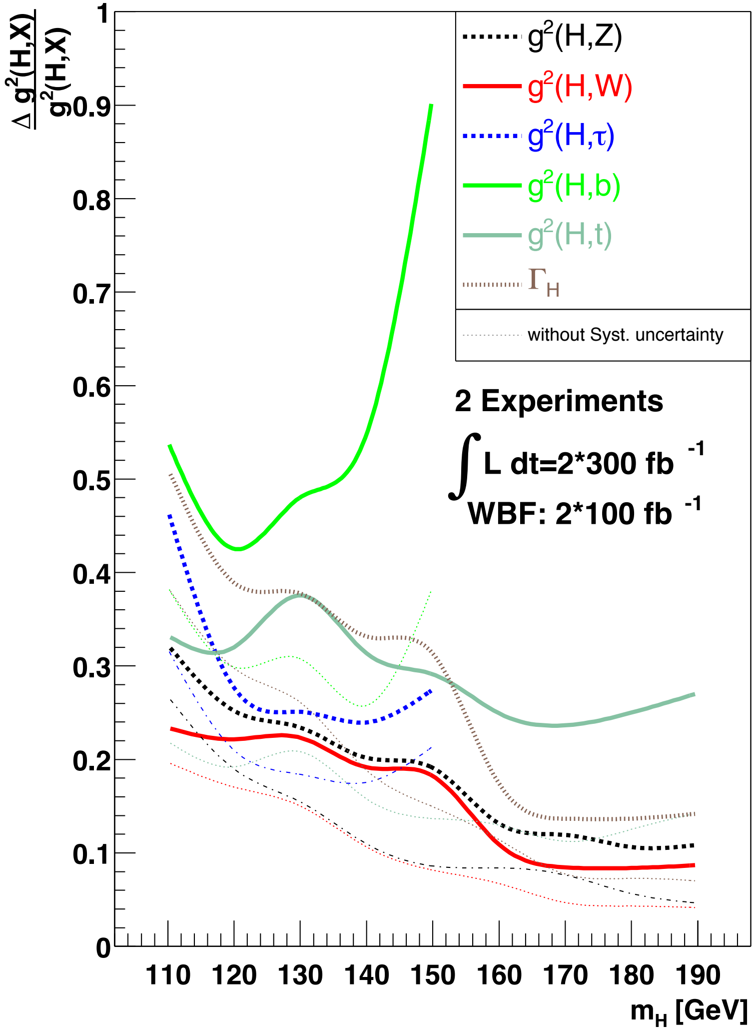
Ansatz

Mild theoretical assumptions $\Rightarrow$ total Higgs width and absolute couplings

- Light Higgs with SM-like couplings — Kinnunen,Nikitenko,Richter-Was,Zeppenfeld
- General two-Higgs doublet model — Dührssen,Heinemeyer,Logan,Rainwater,Weiglein, Zeppenfeld

Determination of the Higgs Couplings

Dührssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld



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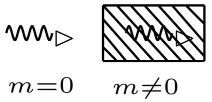
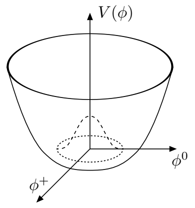


- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



Higgs boson quantum numbers

Quantum numbers of the Higgs boson: J^{PC}

J	spin
P	parity
C	charge conjugation

$\diamond$ $\gamma\gamma \to H$ or $H \to \gamma\gamma \rightsquigarrow J \neq 1$.

Spin and CP quantum numbers: angular correlations

- angular correlations in production: Hjj in vector boson fusion, gluon gluon fusion

  Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld

- angular correlations in Higgs decays, e.g. $H \to ZZ \to l^+l^-l^+l^-$

  Dell'Aquila,Nelson; Kramer,Kühn,Stong,Zerwas; Choi,Miller,MMM,Zerwas;Bluj; Buszello,Fleck,Marquard,van der Bij

  observables sensitive to CP-violation

  Godbole,Miller,MMM

- below ZZ threshold: angular correlations, threshold effects

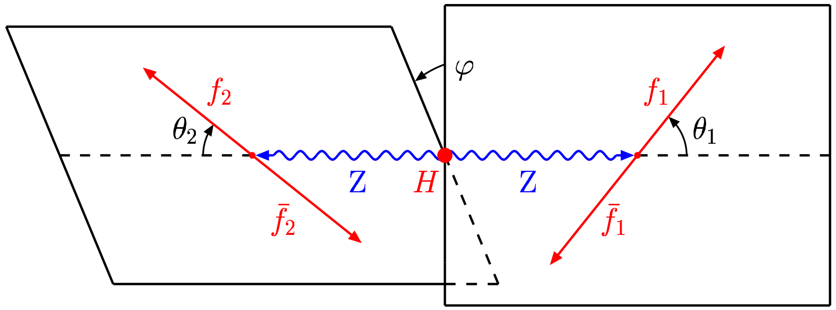
  Choi,Miller,MMM,Zerwas Buszello,Marquard

Higgs boson quantum numbers

Miller,Choi,Eberle,MMM,Zerwas;Choi,Miller,MMM,Zerwas

◇ Determination of spin and parity in

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



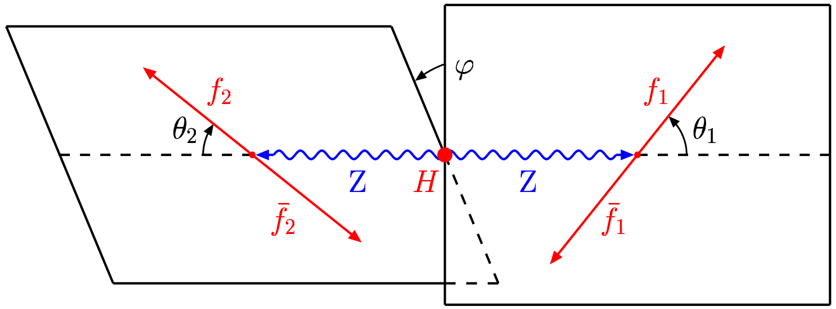
◇ Helicity methods: general HZZ coupling for arbitrary spin and parity

$$\langle Z(\lambda_1)Z(\lambda_2)|H_{\mathcal{J}}(m)\rangle = \frac{g_W M_Z}{\cos\theta_W}\mathcal{T}_{\lambda_1\lambda_2} d^{\mathcal{J}}_{m,\lambda_1-\lambda_2}(\Theta)e^{-i(m-\lambda_1+\lambda_2)\Phi}$$

Higgs boson quantum numbers

◇ Determination of spin and parity in

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



◇ Helicity methods: general HZZ coupling for arbitrary spin and parity

◇ Threshold behaviour and angular correlations $\rightsquigarrow$ determination of $\mathcal{J}^{\mathcal{P}}$

• $M_H < 2M_Z$: $d\Gamma/dM_*^2 \sim \beta$ for $\mathcal{J}^{\mathcal{P}} = 0^+$ Choi,Miller,MM,Zerwas

◇ $d\Gamma/dM_*^2$ rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm$

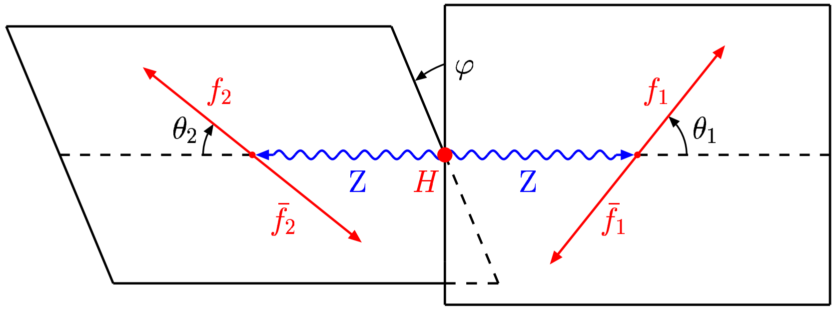
◇ $d\Gamma/dM_*^2$ and no $[1 + \cos^2\theta_1]\sin^2\theta_2$

$[1 + \cos^2\theta_2]\sin^2\theta_1$ rules out $\mathcal{J}^{\mathcal{P}} = 1^+, 2^+$

Higgs boson quantum numbers

◇ Determination of spin and parity in

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



◇ Helicity methods: general HZZ coupling for arbitrary spin and parity

◇ Threshold behaviour and angular correlations $\rightsquigarrow$ determination of $\mathcal{J}^{\mathcal{P}}$

• $M_H > 2M_Z$: Choi,Miller,MM,Zerwas

◇ odd normality: $\mathcal{J}^{\mathcal{P}} = 0^-, 1^+, 2^-, 3^+, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$

◇ even normality: $\mathcal{J}^{\mathcal{P}} = 1^-, 3^-, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$

◇ 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

$\mathcal{CP}$ Violation

- **$\mathcal{CP}$ Violation:** Examine behaviour with

  most general vertex =
  sum of even and odd normality tensors

- **Case spin 0:** $p = p_{Z_1} + p_{Z_2}$, $k = p_{Z_1} - p_{Z_2}$

$$\text{Vertex } HZZ: \quad \frac{igM_Z}{\cos\theta_W}\left[\, a\, g_{\mu\nu} + \frac{b}{M_Z^2}\, p_\mu p_\nu + i\, \frac{c}{M_Z^2}\, \epsilon_{\mu\nu\alpha\beta}\, p^\alpha k^\beta\right]$$

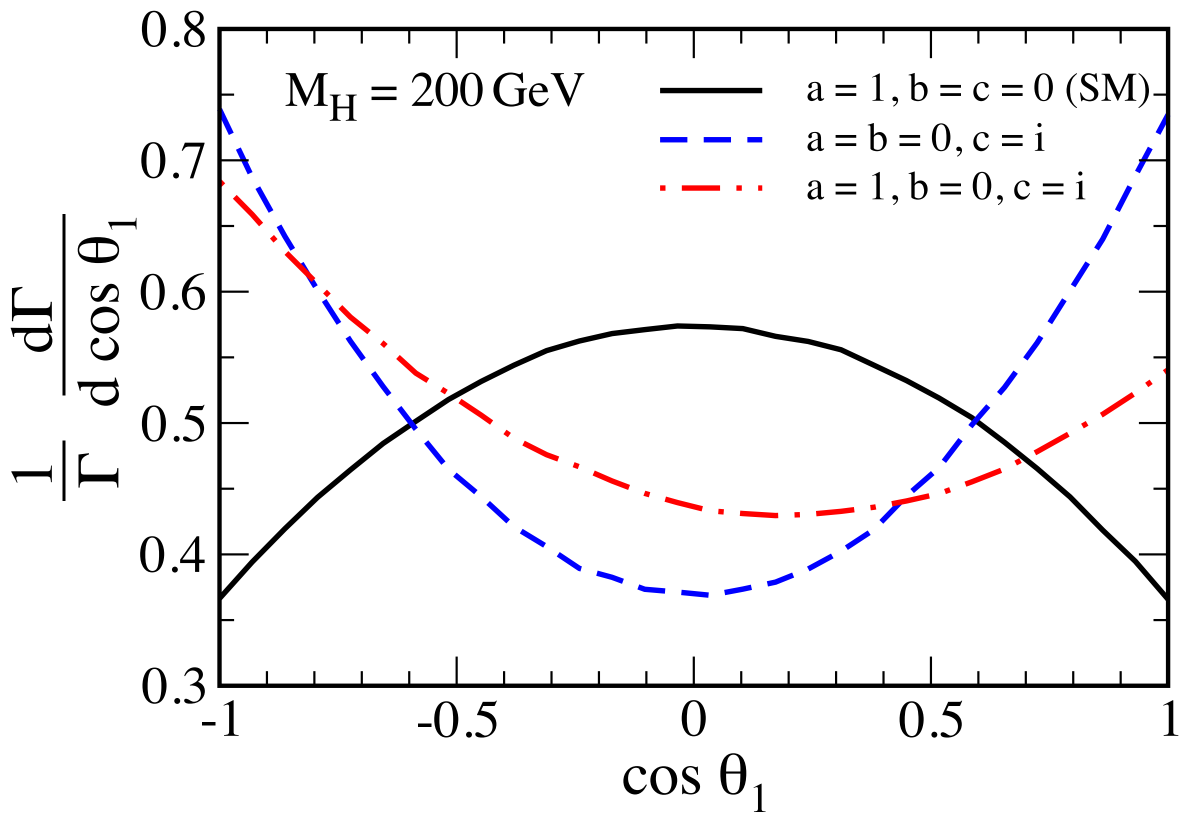
  ◇ $a = 1$, $b = c = 0$: SM

  ◇ $(a \neq 0 \wedge c \neq 0) \quad \vee \quad (b \neq 0 \wedge c \neq 0)$: $\mathcal{CP}$-violation

- **Observables sensitive to $\mathcal{CP}$**
  - ◇ angle ϕ between oriented Z decay planes in the Higgs rest frame
  - ◇ cos of the fermion polar angle θ in the Z rest frame

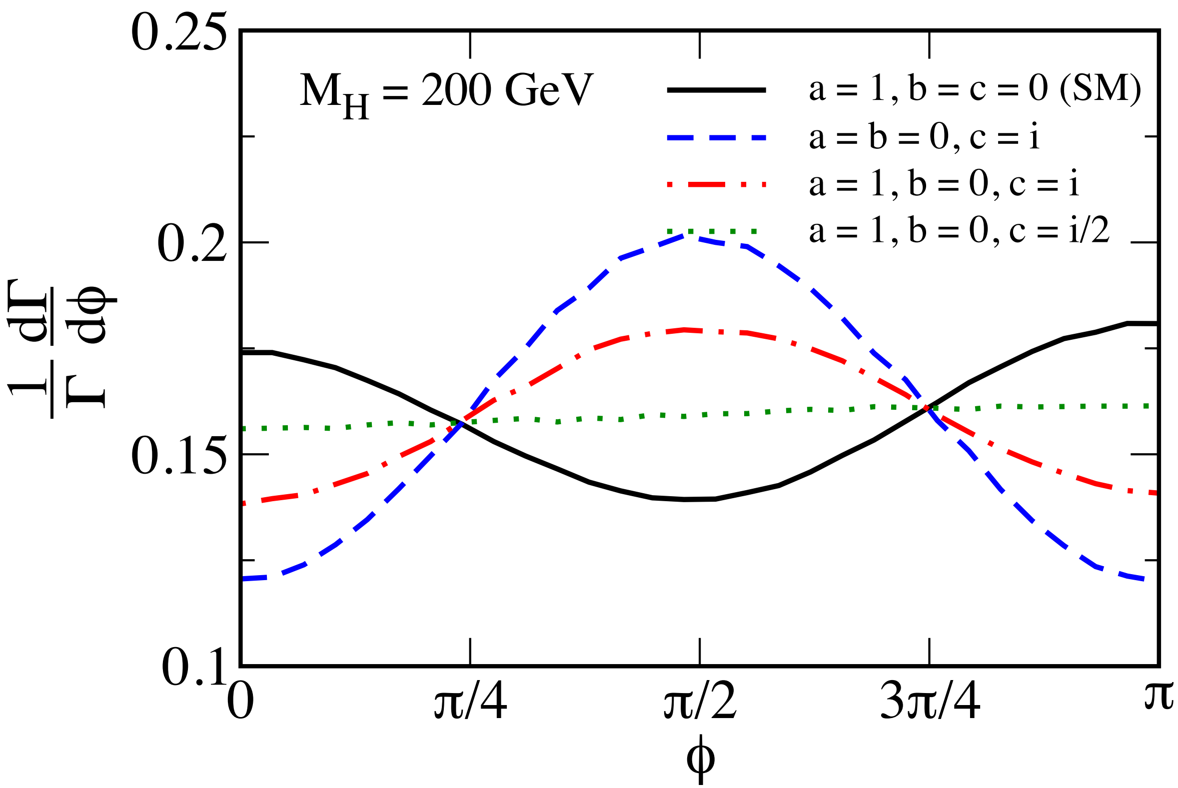
angular distribution in $\cos\theta$

Godbole,Miller,MMM



angular distribution in ϕ

Godbole,Miller,MMM



Higgs boson quantum numbers

Asymmetries sensitive to $\mathcal{CP}$

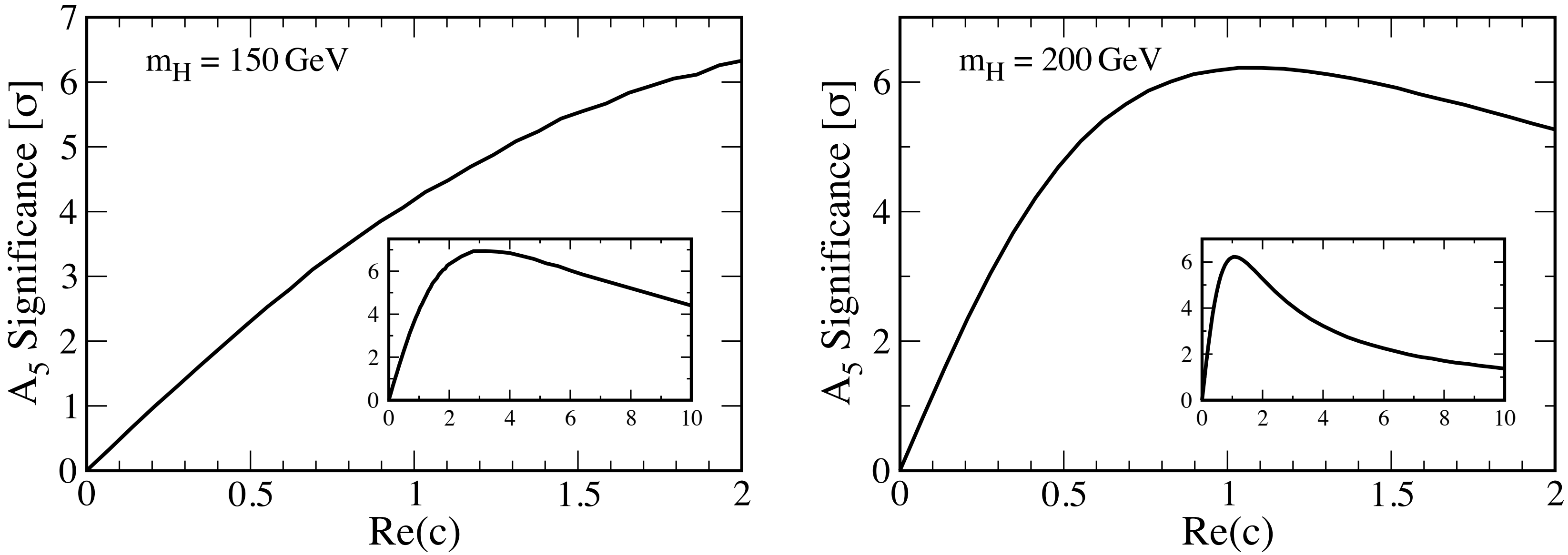
Godbole,Miller,MMM

◇ Example:

$$O_5 = \sin\theta_1 \sin\theta_2 \sin\phi[\sin\theta_1 \sin\theta_2 \cos\phi - \cos\theta_1 \cos\theta_2]$$

$$O_5 = \frac{[(\vec{p}_{4H} \times \vec{p}_{3H}) \cdot \vec{p}_{1H}][(\vec{p}_{1Z} - \vec{p}_{2Z}) \cdot \vec{p}_{3Z}]}{|\vec{p}_{3H} + \vec{p}_{4H}||\vec{p}_{3Z} - \vec{p}_{4Z}|^2|\vec{p}_{1Z} - \vec{p}_{2Z}|^2/8}$$

$$\mathcal{A}_5 = \frac{\Gamma(O_5 > 0) - \Gamma(O_5 > 0)}{\Gamma(O_5 > 0) + \Gamma(O_5 > 0)}$$



Higgs boson quantum numbers

gluon gluon fusion	CP-even Htt can be distinguished from CP-odd at $> 5\sigma$ ($M_H = 160$ GeV)	Klämke,Zeppenfeld
$H \to ZZ \to 4l$	consistency with SM; $0^-, 1^\pm$ excluded ($\int \mathcal{L} = 100$fb^{-1}, $M_H = 200$ GeV)	Buszello,Fleck, Marquard,van der Bij
CMS: $H \to ZZ \to 4l$	scalar, pseudoscalar can be distinguished at 3σ ($\int \mathcal{L} = 60$fb^{-1}, $M_H = 300$ GeV)	CMS
ALTAS: $H \to ZZ \to 4l$	strong limits to anomalous couplings	Buszello,Fleck,Marquard, van der Bij
	▷ CP-odd excluded at 8.7σ (2.9σ) for $M_H = 200$ GeV (130 GeV), $\int \mathcal{L} = 100$fb^{-1}	Strässner
	▷ b/c w/ precision 1 (0.35/0.2) for $M_H = 130$ GeV (higher M_H)	
	▷ include info from measured signal cxn	
	⇝ further increase in precision	

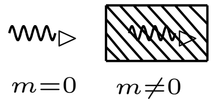
Experimental verification of the Higgs mechanism

Higgs mechanism:

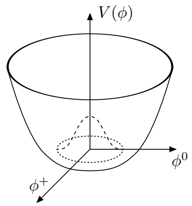
Creation of particle masses without violating gauge principles

Test of the Higgs mechanism

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



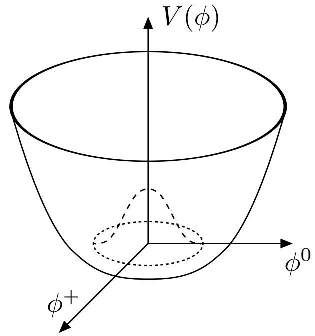
- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$

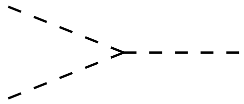
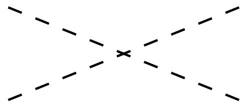


Determination of the Higgs Self-Couplings

The Higgs 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 Higgs self-couplings
and
Reconstruction of the Higgs potential

} Experimental verification
Of the scalar sector of the
Higgs mechanism

Determination of the Higgs self-couplings at colliders:

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

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

Higgs-strahlung, WW/ZZ fusion, gg fusion

Determination of λ_{HHH} at the LHC

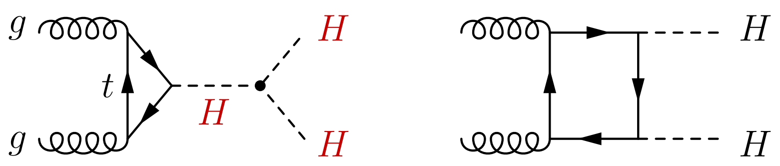
Djouadi,Kilian,MMM,Zerwas;
Lafaye,Miller,Moretti,MMM

double Higgs-strahlung: $q\bar{q} \longrightarrow W/Z + HH$ — Barger,Han,Phillips

WW/ZZ fusion: $qq \longrightarrow qq + HH$ — Dicus,Kallianpur,Willenbrock; Abbasabadi,Repko,Dicus,Vega; Dobrovolskaya,Novikov; Eboli,Marques,Novaes,Natale

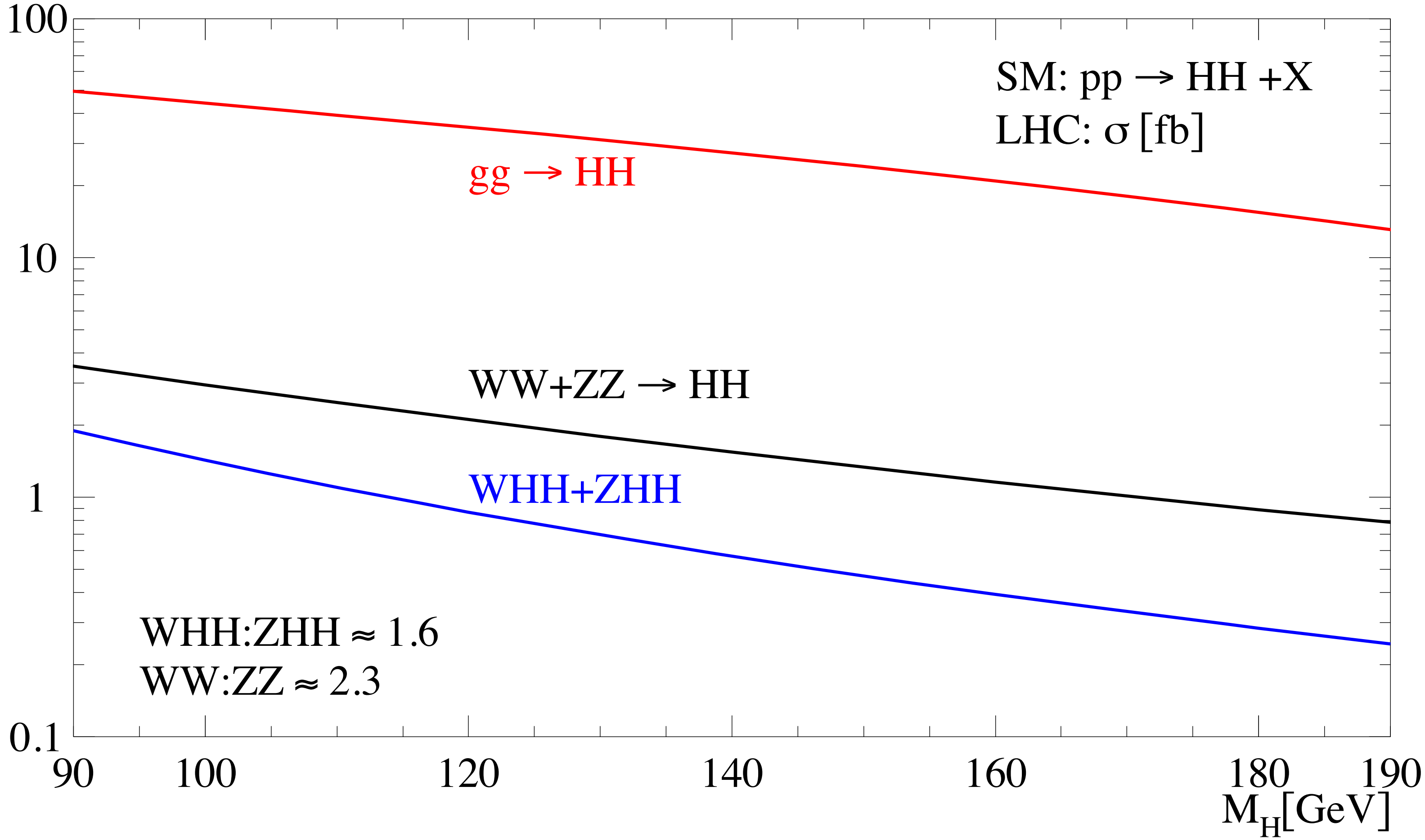
gluon gluon fusion: $gg \longrightarrow HH$ — Glover,van der Bij; Plehn,Spira,Zerwas; Dawson,Dittmaier,Spira

gluon gluon fusion - dominant process



Double SM Higgs Production at the LHC

Djouadi,Kilian,MMM,Zerwas



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

small signal + large QCD background $\rightsquigarrow$ challenge!

Baur,Plehn,Rainwater

$M_H < 140$ GeV: $gg \to HH \to b\bar{b}\gamma\gamma$:

- SLHC [$\int \mathcal{L} = 6$ ab^{-1}]:

  $M_H = 120$ GeV $\lambda_{HHH} = 0$ exclusion at 90% CL

- VLHC [$\sqrt{s} = 200$ TeV]:

  $M_H = 120$ GeV: $\delta\lambda_{HHH}/\lambda_{HHH} = 20 - 40\%$ at 1 σ

Gianotti et al.;Blondel,Clark,Mazzucato
Baur,Plehn,Rainwater
Dahlhoff

$M_H > 140$ GeV: $gg \to HH \to W^+W^-W^+W^-$:

- LHC [$\int \mathcal{L} = 300$ fb^{-1}]:

  $150 \lesssim M_H \lesssim 200$ GeV: $\lambda_{HHH} = 0$ exclusion at 95% CL

- SLHC [$\int \mathcal{L} = 3$ ab^{-1}]:

  $150 < M_H < 200$ GeV $\delta\lambda_{HHH}/\lambda_{HHH} = 20 - 30\%$ at 1 σ

Higgs Physics - Beyond

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

Composite Higgs Boson - Introduction

- **Higgs: bound state from a strongly interacting sector** — Kaplan,Georgi;Dimopoulos eal;Dugan eal
- **SILH** effective low energy description, Higgs couplings modified by $\xi = \frac{v^2}{f^2}$ — Giudice,Grojean Pomarol,Rattazzi
- **Fermion couplings** depend on embedding into representations of the bulk symmetry — Contino eal; Agashe eal

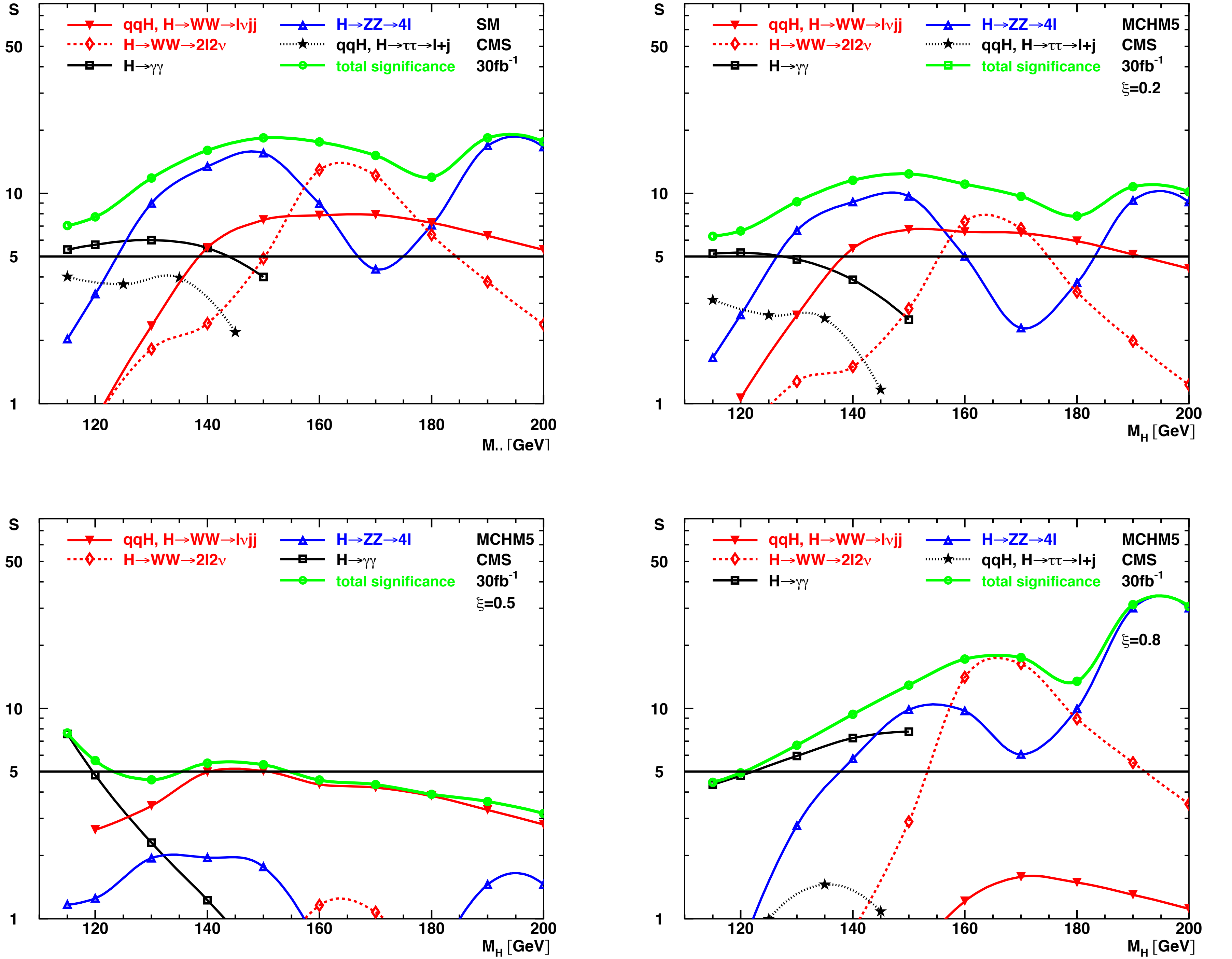
spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5

MCHM4	MCHM5
$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi}$	$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\frac{(1-2\xi)}{\sqrt{1-\xi}}$
universal factor $\rightsquigarrow$ BRs unchanged	g_{Hff} coupling vanishes for $\xi = 0.5$

- **Impact on** BR's, Γ_{tot}, production cross sections, Higgs searches at the LHC — Espinosa,Grojean,MMM
  (gg fusion at NNLO Furlan '11)

• Significances MCHM5

Espinosa, Grojean, Mühlleitner



Sensitivity to the triple Higgs self-coupling

- **Can we extract the Higgs self-coupling?** Gröber,Mühlleitner

- **First step: plot sensitivity areas**

- **Sensitivity criteria:** $\int \mathcal{L} = 300$ fb^{-1}

$$\lambda_{HHH} \neq 0 \quad \rightsquigarrow \quad \sigma^{HH}(\lambda_{HHH}) \quad \rightsquigarrow \quad N^{\lambda\neq 0}_{\text{events}}$$

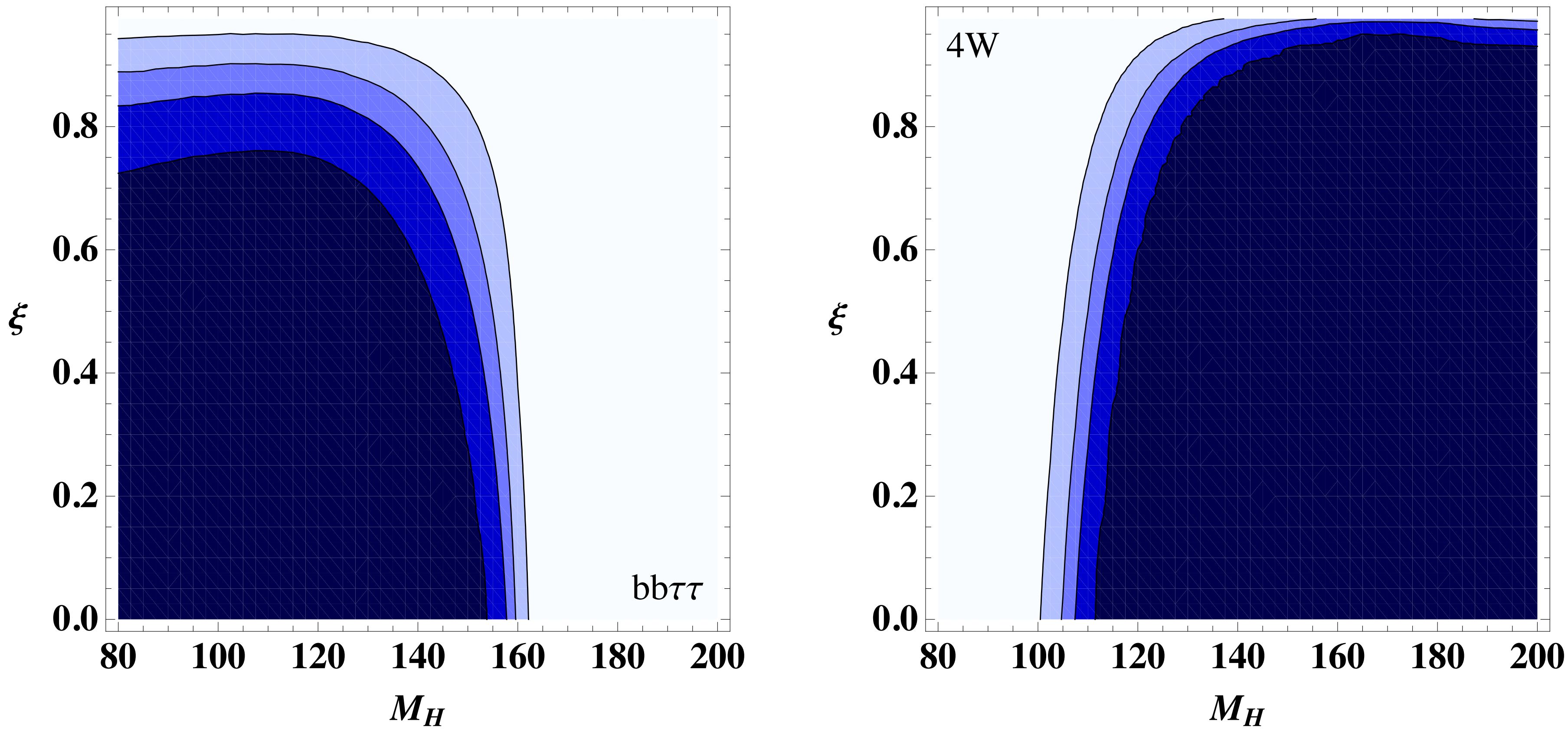
$$\lambda_{HHH} = 0 \quad \rightsquigarrow \quad \sigma^{HH}(\lambda_{HHH}=0) \quad \rightsquigarrow \quad N^{\lambda=0}_{\text{events}}$$

Demand: $N^{\lambda=0} + \beta\sqrt{N^{\lambda=0}} < N^{\lambda\neq 0}$ or $N^{\lambda=0} - \beta\sqrt{N^{\lambda=0}} > N^{\lambda\neq 0}$ $(\beta = 1,2,3,5)$

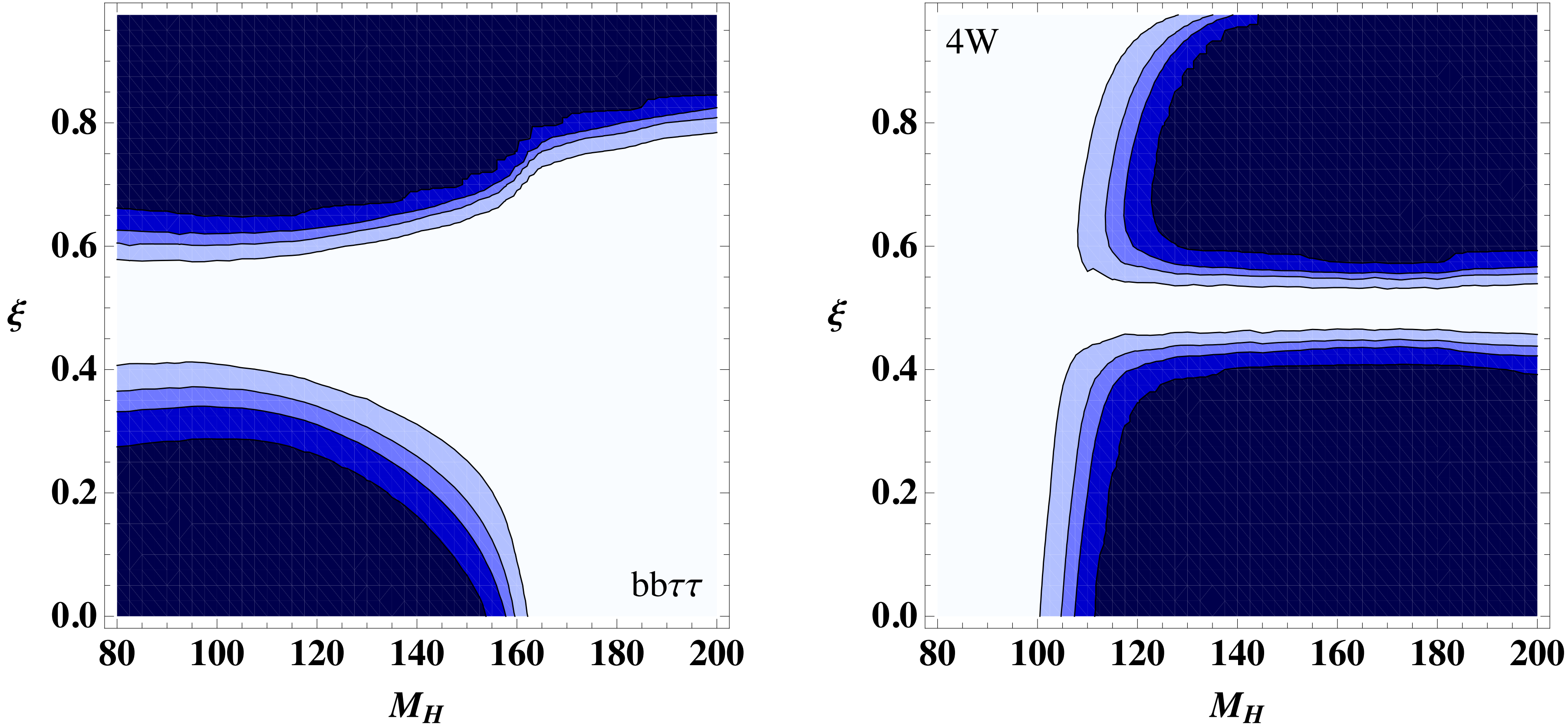
- **Plots:** $gg \to HH$ for MCHM4, MCHM5

- **Final states:** $HH \to bb\gamma\gamma$, $HH \to W^+W^-W^+W^-$, $HH \to bb\tau\tau$, $HH \to bb\mu\mu$

• **Significances to non-vanishing λ_{HHH} in MCHM4**



- **Significances to non-vanishing λ_{HHH} in MCHM5**



$\mathcal{C}$onclusions

The LHC is a discovery machine

- **Higgs particle(s) can be discovered**

- **First tests of the Higgs mechanism are possible**
  - ◇ Determination of the Higgs couplings to fermions and bosons
  - ◇ Determination of the Higgs quantum numbers (spin and CP)
  - ◇ Determination of the trilinear Higgs self-coupling(s)

$\Rightarrow$ Important steps towards the understanding of the creation of masses

Conclusions

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⇒ Important steps towards the understanding of the creation of masses

- **Composite Higgs Model** Higgs as pseudo-Goldstone boson of strong sector
- **After discovery:** Which Higgs boson have we discovered?

Conclusions

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

Backup Slides

Differential distributions

◇ Double polar angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\cos\theta_1 d\cos\theta_2} \sim \sin^2\theta_1 \sin^2\theta_2 |\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right]$$

$$+(1+\cos^2\theta_1)\sin^2\theta_2 |\mathcal{T}_{10}|^2 + \sin^2\theta_1 (1+\cos^2\theta_2)|\mathcal{T}_{01}|^2$$

$$+2\,\eta_1\eta_2 \cos\theta_1 \cos\theta_2 \left[|\mathcal{T}_{11}|^2 - |\mathcal{T}_{1,-1}|^2\right]$$

SM: $\mathcal{T}_{00} = M_H^2/(2M_Z^2) - 1,\ \mathcal{T}_{11} = -1,\ \mathcal{T}_{10} = \mathcal{T}_{01} = \mathcal{T}_{1,-1} = 0$

◇ Azimuthal angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\varphi} \sim |\mathcal{T}_{11}|^2 + |\mathcal{T}_{10}|^2 + |\mathcal{T}_{1,-1}|^2 + |\mathcal{T}_{01}|^2 + |\mathcal{T}_{00}|^2/2$$

$$+\eta_1\eta_2\left(\frac{3\pi}{8}\right)^2 \Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{00}^* + \mathcal{T}_{10}\mathcal{T}_{0,-1}^*)\cos\varphi + \frac{1}{4}\Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{-1,-1}^*)\cos 2\varphi$$

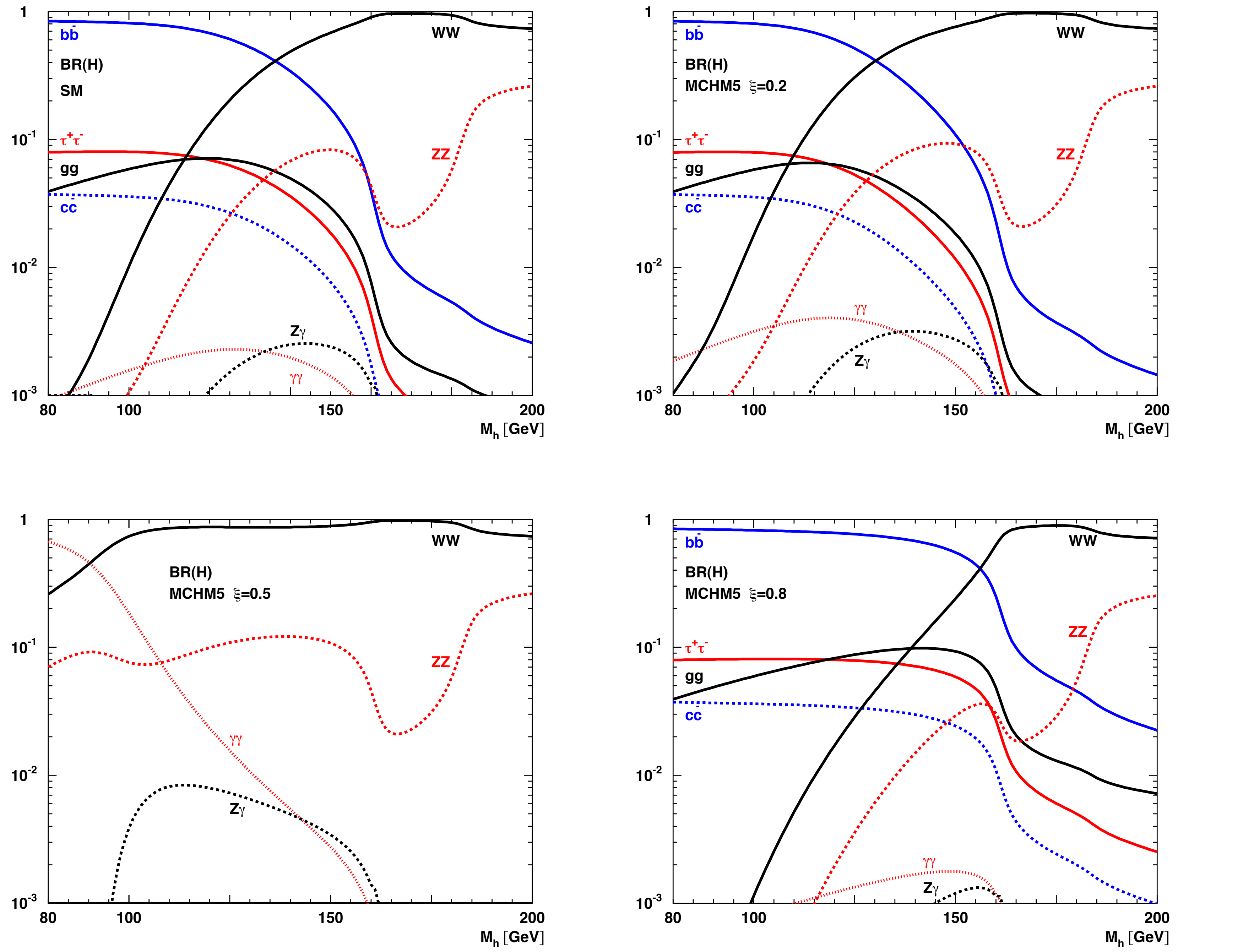
Determination of spin and parity

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

- $M_H > 2M_Z$:
  - ◇ odd normality: $\mathcal{J}^\mathcal{P} = 0^-, 1^+, 2^-, 3^+, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - ◇ even normality: $\mathcal{J}^\mathcal{P} = 1^-, 3^-, ...$ excluded by non-zero $\sin^2\theta_1 \sin^2\theta_2$
  - ◇ 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

• Branching ratios MCHM5

Espinosa,Grojean,Mühlleitner



Constraints from EWPT, LEP, Tevatron

- **EWPT constraints**

  ◇ $\hat{T} = c_T \frac{v^2}{f^2} \;\Rightarrow\; |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$ — removed by custodial symmetry

  ◇ $\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \;\Rightarrow$ — $m_\rho \geq (c_B + c_W)^{1/2}\, 2.5$ TeV

  ◇ 1-loop IR effects Barbieri eal

  $\hat{S}, \hat{T} = a \ln m_H + b$ — modified Higgs coupling to matter $\Rightarrow$

  $\hat{S}, \hat{T} = a((1 - c_H \xi) \ln m_H + c_H \xi \ln \Lambda) + b$

  effective Higgs mass: $m_H^{eff} = m_H \left(\frac{\Lambda}{m_H}\right)^{c_H v^2/f^2} > m_H$

  LEPII, $m_H \approx 115$ GeV: $c_H \frac{v^2}{f^2} < \frac{1}{3} \sim \frac{1}{2}$

  IR effects can be cancelled by heavy fermions (model-dependent)

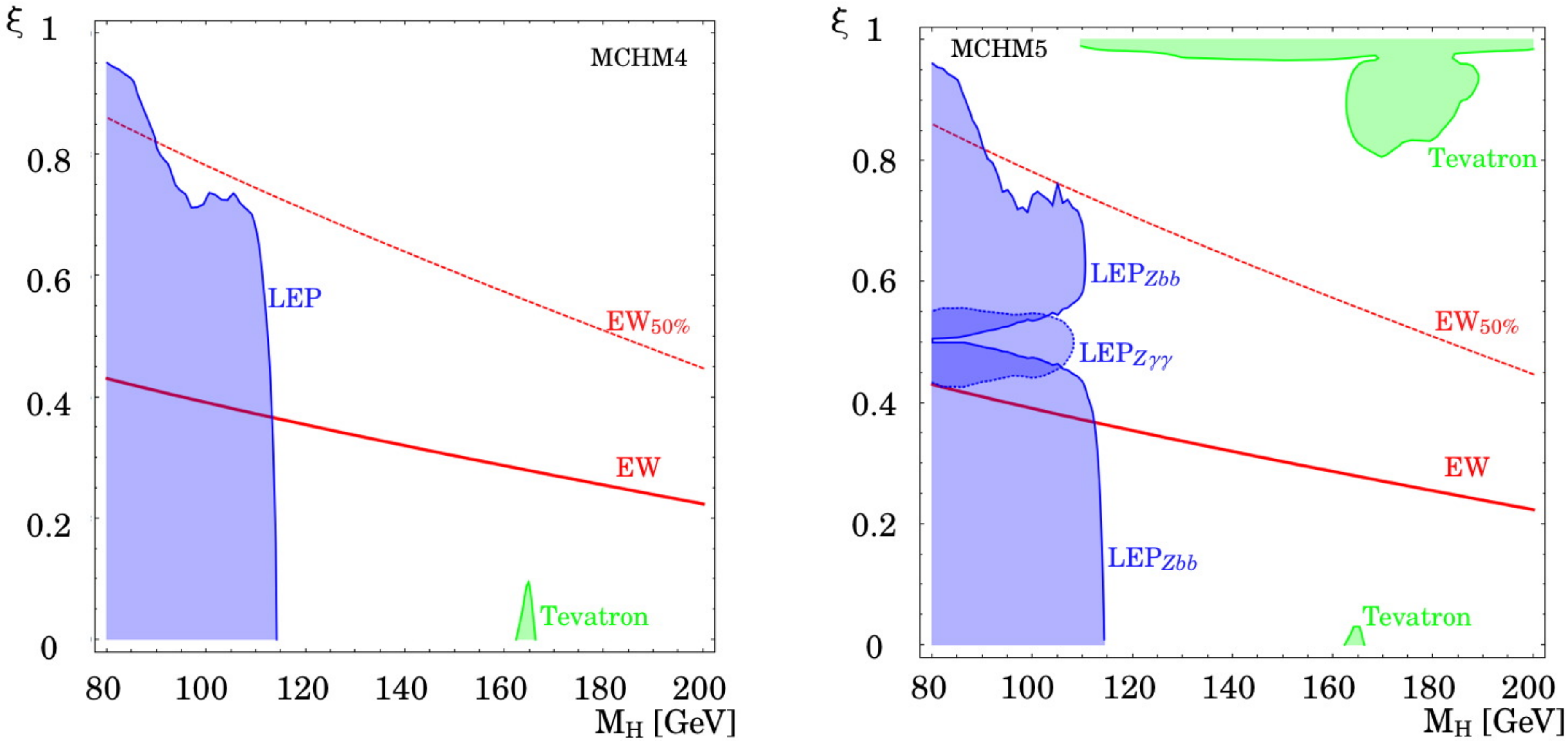
- **Searches at LEP** $e^+e^- \to ZH \to Zb\bar{b}$

- **Tevatron search** most relevant $H \to WW$

  LEP/Tevatron exclusion limits generated with `Higgsbounds` Bechtle eal

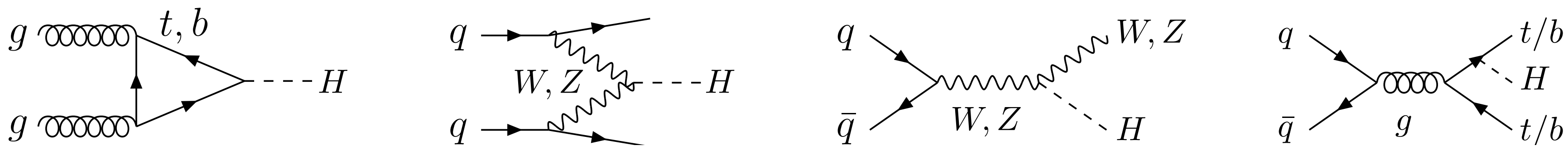
Constraints from EWPT, LEP, Tevatron

Espinosa,Grojean,Mühlleitner



Production Processes

- **Production cross sections**



- **Higgs gauge boson couplings**

MCHM4/5: $g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$

- **Higgs fermion couplings**

MCHM4: $g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi}$

MCHM5: $g_{Hff} = g_{Hff}^{SM}\frac{1-2\xi}{\sqrt{1-\xi}}$ vanishes for $\xi = 0.5$!!!

NLO QCD corrections: not affected by modified Higgs couplings

$$\sigma_{NLO}(gg \to H) = \left\{ \begin{array}{c} (1-\xi) \\ \frac{(1-2\xi)^2}{(1-\xi)} \end{array} \right\} \sigma_{NLO}^{SM}(gg \to H)$$ $\sigma_{NLO}(Ht\bar{t})$ analogous

$$\sigma_{NLO}(qqH) = (1-\xi) \quad \sigma_{NLO}^{SM}(qqH)$$ $\sigma_{NLO}(VH)$ analogous

Significances: Composite Higgs

- **Composite Higgs search:**
  - ◇ Composite couplings affect signal events, not background events
  - ◇ Rescaling factor

$$\kappa = \frac{\sigma^{\xi}_{prod} BR^{\xi}(H \to X)}{\sigma^{SM}_{prod} BR^{SM}(H \to X)}$$

  - ◇ Exp analyses provide signal & bkg events after cuts, s^{SM}, b^{SM} $\rightsquigarrow$ significances composite model from $s^{\xi} = \kappa\, s^{SM}$ and $b^{\xi} = b^{SM}$

- **Investigated Channels:** CMS analyses (similar results expected for ATLAS)

$$\begin{aligned}
\text{Inclusive production with subsequent decay :}\quad & H \to \gamma\gamma \\
& H \to ZZ \to 2e2\mu, 4e, 4\mu \\
& H \to WW \to 2l2\nu \\
\text{Vector boson fusion with subsequent decay :}\quad & H \to WW \to l\nu jj \\
& H \to \tau\tau \to l + j + E_T^{miss}\,.
\end{aligned}$$