$\mathcal{H}$iggs and $\mathcal{E}$lectroweak $\mathcal{S}$ymmetry $\mathcal{B}$reaking

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Electroweak Symmetry Breaking (EWSB)

LHC Understand the mechanism of electroweak symmetry breaking

Why? Creation of particle masses without violating the basic symmetries of the SM

How? Higgs mechanism [SM, SUSY, ...]
Strong EW symmetry breaking [Composite, LH, "Higgsless", Extra Dims., ...]

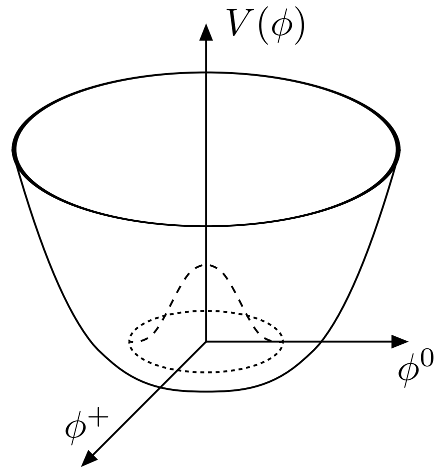
Higgs mechanism

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs doublet

$$\Phi = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$



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

Symmetry of the vacuum

$$U(1)_{em}$$

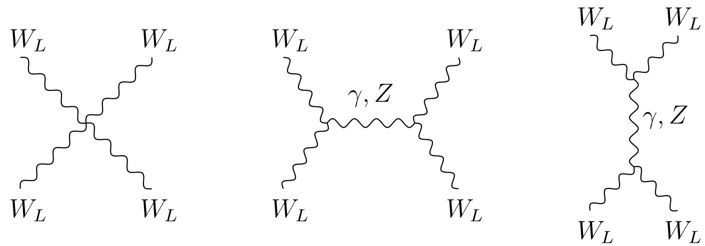
vacuum expectation value

$$< \Phi > = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$v = 246$ GeV

The Higgs particle as UV regulator

Scattering of longitudinally polarized W bosons



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

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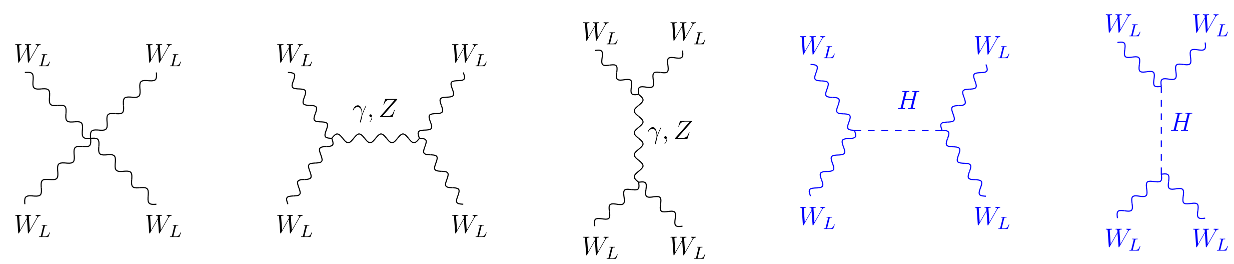


$$\mathcal{A} = \frac{G_F M_H^2}{4\sqrt{2}\pi}$$

Higgs boson guarantees unitarity of the W scattering (if its mass is $\lesssim 1$ TeV.)

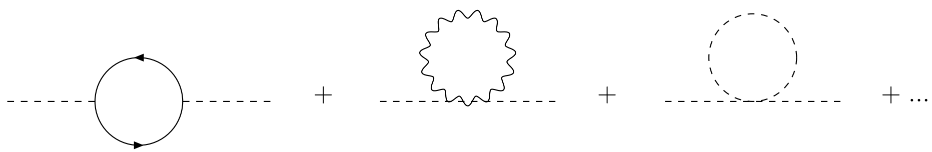
Higgs mechanism - model without dynamics: description but no explanation of the EWSB

Shortcomings of the SM:

fails at the Planck scale; hierarchy problem; mass and mixing patterns?; no DM candidate; baryon asymmetry; gauge coupling unification ...

Hierarchy problem

- **Quantum corrections to the Higgs boson mass:**



$$\delta m_H^2 = -\frac{\lambda_F^2}{8\pi^2}\left[\Lambda^2 - m_F^2 \ln \frac{\Lambda^2}{m_F^2}\right] + \ldots$$

- **Renormalization:**

$$\begin{aligned} m_H^2 &= m_{H0}^2 - \delta m_H^2 \\ \mathcal{O}(10^4\ \text{GeV}^2) &= \mathcal{O}(10^{30}\ \text{GeV}^2) - \delta m_H^2 \qquad (\Lambda = \Lambda_{GUT} = 10^{16}\ \text{GeV}) \end{aligned}$$

$\Rightarrow$ extreme finetuning necessary

Hierarchy problem

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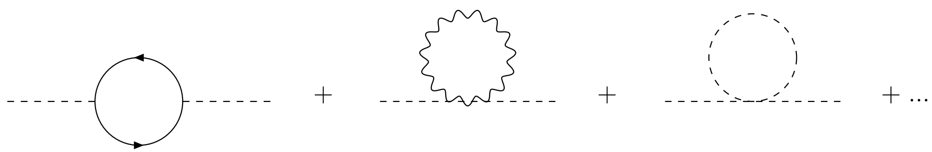

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◇ additional symmetry: forbids Higgs mass until symmetry is broken
  - supersymmetry
  - gauge-Higgs unification
  - Higgs as a pseudo Nambu-Goldstone boson $\longrightarrow$ this talk: Composite Higgs

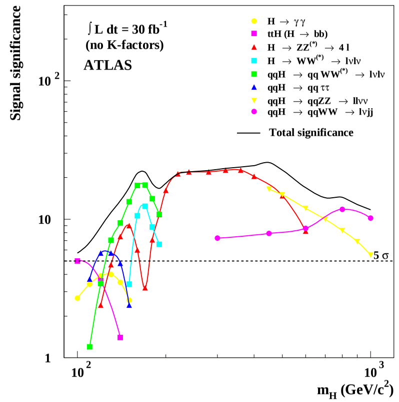
◇ lower the UV scale
  - large extra dimension

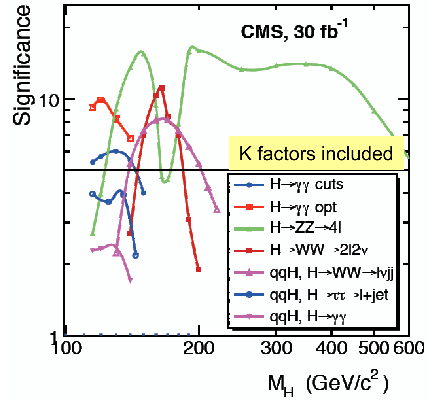
◇ remove the Higgs
  - technicolor

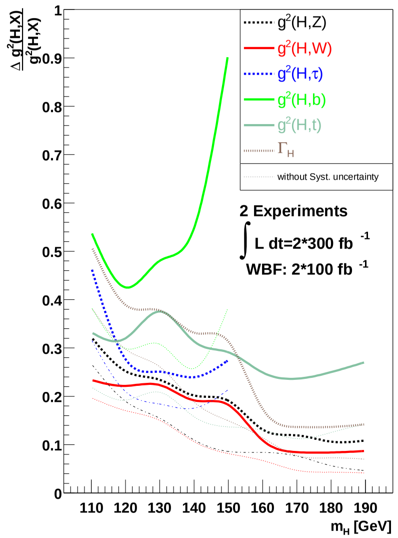
SM Higgs phenomenology mini-summary

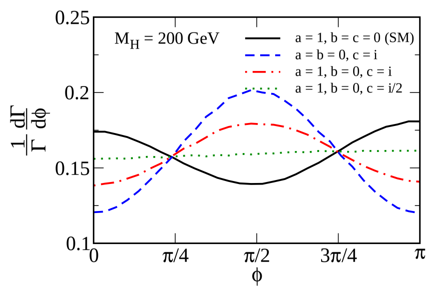
LHC

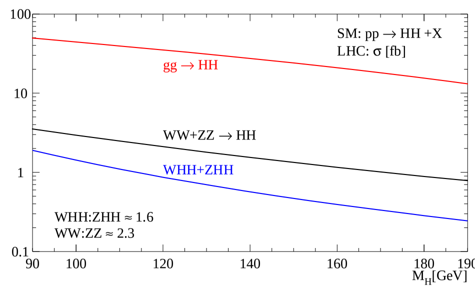
- ◇ Higgs discovery over canonical mass range, $\delta M_H/M_H \leq 10^{-2}$
- ◇ BR's, coupling ratios absolute & $\Gamma_H \rightsquigarrow$ model-dependent $\mathcal{O}$ (several 10%)
- ◇ spin/CP $\leftarrow$ angular distributions CP-even $\leftrightarrow$ CP-odd @ 5σ
- ◇ Higgs potential: $\lambda_{HHH} = 0$ exclusion @ 90% CL











Composite Higgs boson - Introduction

- **Revisit longitudinal W scattering: SM Higgs is peculiar!**

  Couplings: $HWW: \quad a\frac{2M_W^2}{v} \qquad HHWW: \quad b\frac{2M_W^2}{v^2}$

$\Rightarrow W_L W_L \to W_L W_L$: $\quad \mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s-m_H^2}\right) \qquad \boxed{\text{SM: } a = b = 1}$ ($\leftarrow$ unitarize $W_L W_L \to HH$)

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- **Continuous interpolation between the SM and Technicolor:**

$\boxed{\xi = 0 \text{ SM limit}} \quad \longleftarrow \quad \boxed{\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}} \quad \longrightarrow \quad \boxed{\xi = 1 \text{ Technicolor limit}}$

strong sector resonances decouple, except Higgs

Higgs deccouples, vector resonances like in TC

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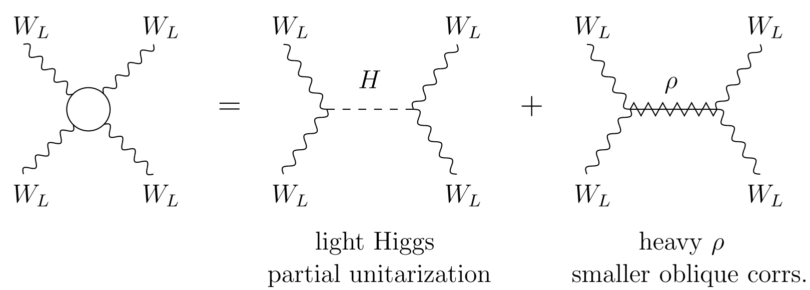
- **Composite Higgs models:** Higgs = composite object: couplings deviate from $a = b = 1$



unitarity breakdown postponed to higher enery
$\rightsquigarrow$ smaller oblique corrections

Composite Higgs boson - Introduction

- **Idea: Higgs as composite bound state from a strongly interacting sector**

- **How can we obtain a light composite Higgs?**

Higgs: Pseudo-Goldstone boson of strongly interacting sector

$$\text{Global symmetry of strong sector } G \xrightarrow[\text{broken at } f]{\text{spontaneously}} \text{subgroup } H$$

G/H: 4th Nambu-Goldstone Boson: Higgs boson

$(g_{SM} = 0 \rightsquigarrow m_H = 0)$

- **3 scales**

———*——————————*————————*————————->

$v = 246$ GeV Higgs = light resonance of strong sector	$m_\rho = g_\rho f$ usual resonances of strong sector	$4\pi f = 10$ TeV	UV completion

Composite Higgs boson - Introduction

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  Higgs: Pseudo-Goldstone boson of strongly interacting sector

  Global symmetry of strong sector G $\xrightarrow{\text{spontaneously broken at } f}$ subgroup H

  G/H: 4th Nambu-Goldstone Boson: Higgs boson

- **Possible symmetry patterns**

  $*$ H must contain SM gauge group

  $*$ G must contain an $SU(2) \times SU(2) \sim SO(4)$ symmetry $\rightsquigarrow$ PGB is a Higgs doublet

  Examples:

  - $SO(5)/SO(4) \rightsquigarrow$ PGB: one doublet
  - $SO(6)/SO(5) \rightsquigarrow$ PGB: one doublet $+$ singlet
  - ...

Composite Higgs boson - Physics

- **SILH effective Lagrangian** Giudice,Grojean,Pomarol,Rattazzi

  (SILH=strongly interacting light Higgs)

- **Genuine strong operators** (sensitive to the scale f)

$$\frac{c_H}{2f^2}(\partial_\mu(|H|^2))^2 + \frac{c_T}{2f^2}(H^\dagger \overleftrightarrow{D^\mu})^2 + \left(\frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + h.c.\right) + \frac{c_6\lambda}{f^2}|H|^6$$

- **Form factor operators** (sensitive to the scale m_ρ)

$$\frac{ic_w g}{2m_\rho^2}(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}(H^\dagger \overleftrightarrow{D^\mu} H)(\partial^\nu B_{\mu\nu}) + \ldots$$

$c_H, c_T, \ldots$: $\mathcal{O}(1)$, MFV built in (no FCNC)

- **Contribution to Higgs kinetic term:** $\frac{c_H}{2f^2}(\partial_\mu(|H|^2))^2$

Rescale Higgs field $\rightsquigarrow$ $g_{Hf\bar{f}} = g^{SM}_{Hf\bar{f}}\left(1-(c_y+c_H/2)\frac{v^2}{f^2}\right)$ $g_{HWW} = g^{SM}_{HWW}\left(1-c_H\frac{v^2}{f^2}\right)$

Higgs anomalous couplings

- **Large v/f?**

  SILH: expansion for small $\frac{v}{f}$
  The 5D MCHM provides completion for large $\frac{v}{f}$ $(SO(5)/SO(4))$ Contino eal; Agashe eal

  $$\boxed{g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}} \qquad \boxed{\xi = \frac{v^2}{f^2}}$$

- **Fermion couplings** depend on embedding into representations of the bulk symmetry

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5
$\boxed{g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi}}$	$\boxed{g_{Hff} = g_{Hff}^{SM}\frac{1-2\xi}{\sqrt{1-\xi}}}$
universal shift of couplings no modifications of BRs	BRs depend on ξ

How to test composite nature of the Higgs boson?

- **Resonances**

  Production of heavy resonances m_ρ

- **Coupling modifications:**

◇ modification of production and decay rates*

LHC/300 fb^{-1}: $\delta g \approx 20-40\%$ Dührssen eal. $\leadsto$ probe $4\pi f = 5-7$ TeV

ILC/500 GeV $\leadsto$ probe $4\pi f \sim 30$ TeV, $\delta\lambda_{HHH} \sim 10-20\%$ Barger eal

CLIC/3 TeV $\leadsto$ improve sensitivity by factor 2

◇ strong WW scattering: $W_L W_L \to W_L W_L$

difficult: disentangle L from T polarization Giudice eal

◇ strong HH production: $W_L W_L \to HH$

SLHC/5 ab^{-1}: $3l$ final state: rather clean signal $\xi > 0.5$ Contino eal

* no direct probe of strong sector at origin of EWSB

- **This talk:** Impact on Higgs boson searches at the LHC Espinosa,Grojean,Mühlleitner

Impact on LHC searches

- **Outline**
  - ▷ Branching ratios and total widths
  - ▷ Constraints from LEP, Tevatron searches and EWPT
  - ▷ Production cross sections
  - ▷ Higgs boson search: significances

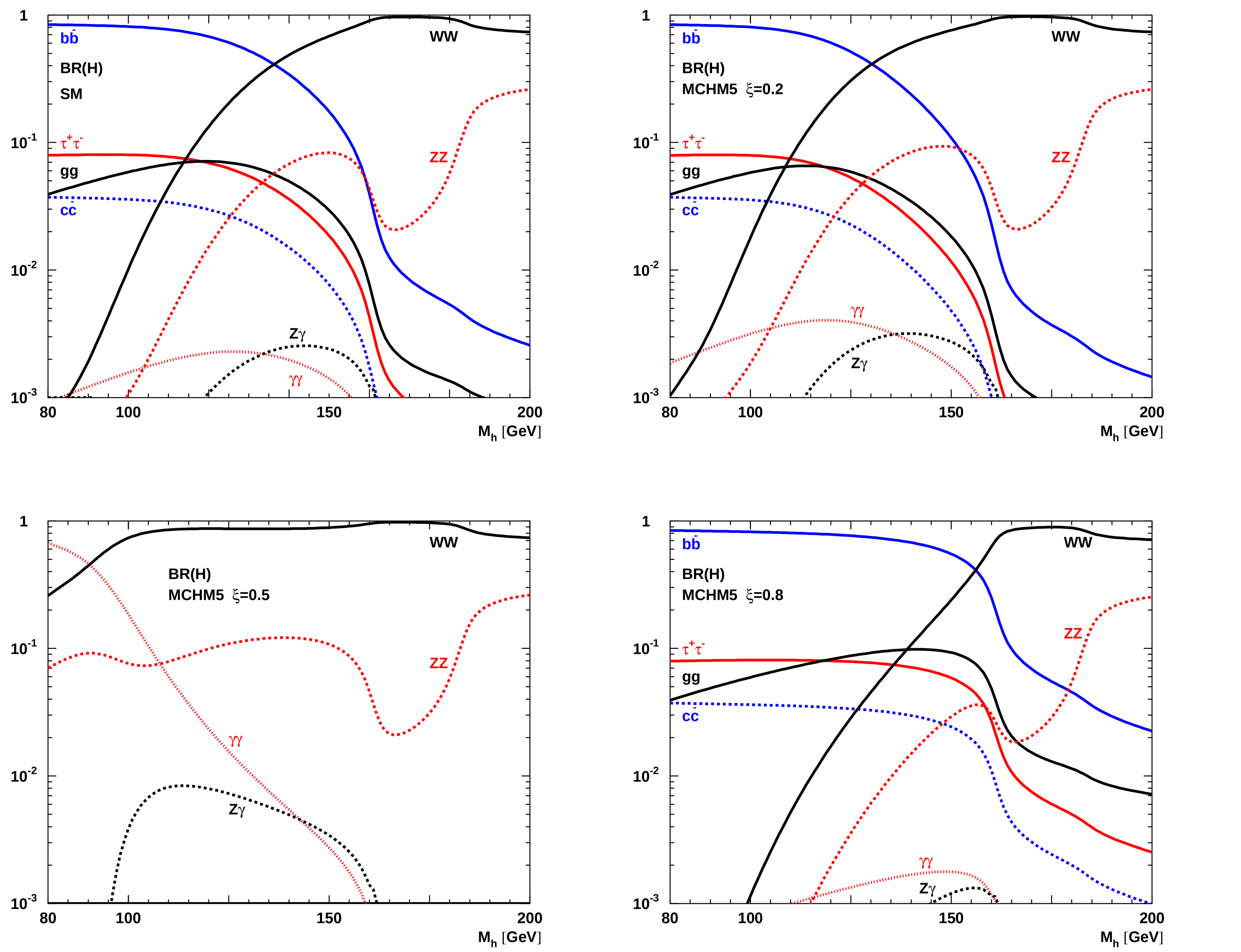
- **Reminder**

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

In the following: $\xi = 0.2, 0.5, 0.8$

- **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

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◇ 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)

Constraints from EWPT, LEP, Tevatron

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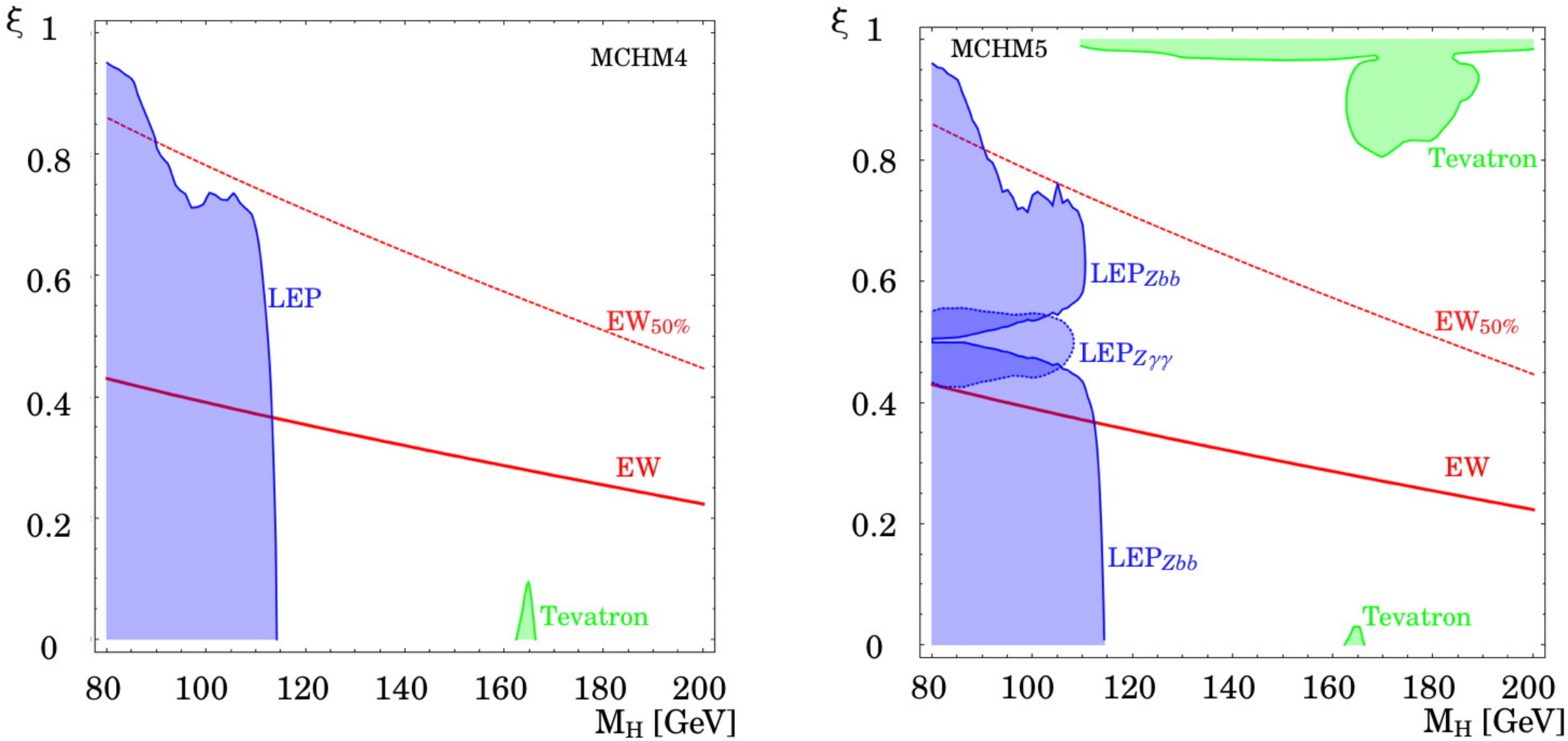
- **Searches at LEP** $e^+e^- \to ZH \to Zb\bar{b}$

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

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

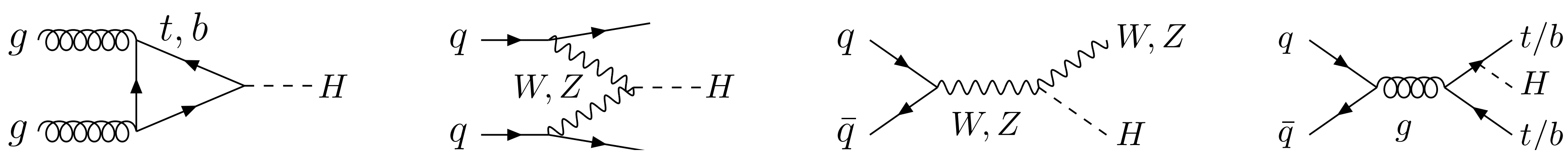
Constraints from EWPT, LEP, Tevatron

Espinosa,Grojean,Mühlleitner



Production Processes

- **Production cross sections**



- **Higgs gauge boson couplings**

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

- **Higgs fermion couplings**

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

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

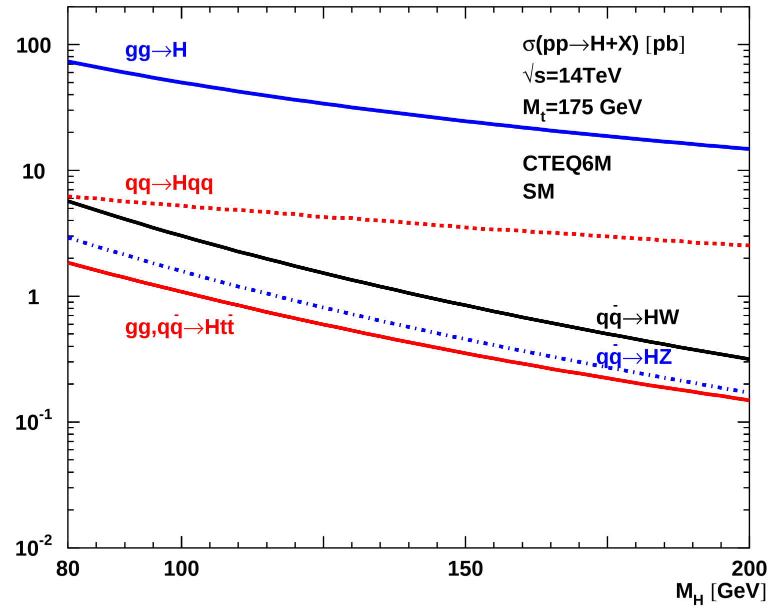
NLO QCD corrections: not affected by modified Higgs couplings

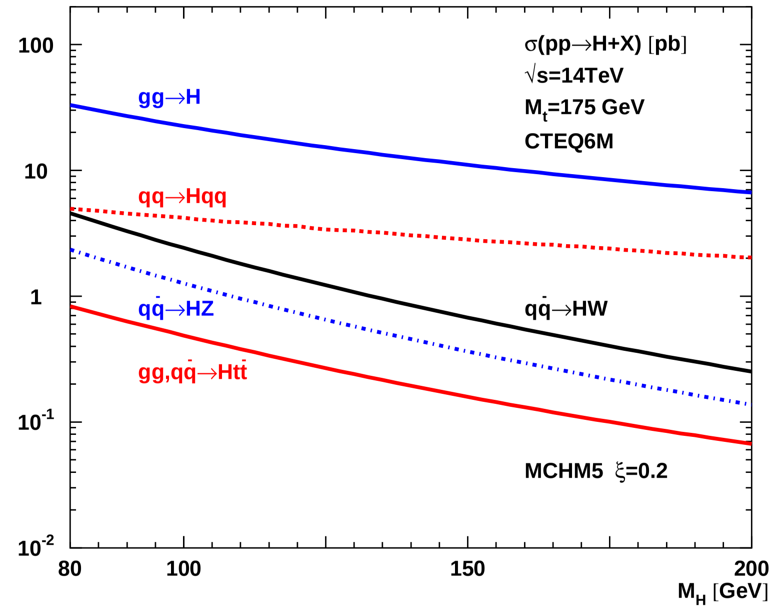
$$\sigma_{NLO}(gg \to H) = \left\{ \begin{array}{c} (1-\xi) \\ \frac{(1-2\xi)^2}{(1-\xi)} \end{array} \right\} \sigma^{SM}_{NLO}(gg \to H)$$ $\sigma_{NLO}(Ht\bar{t})$ analogous

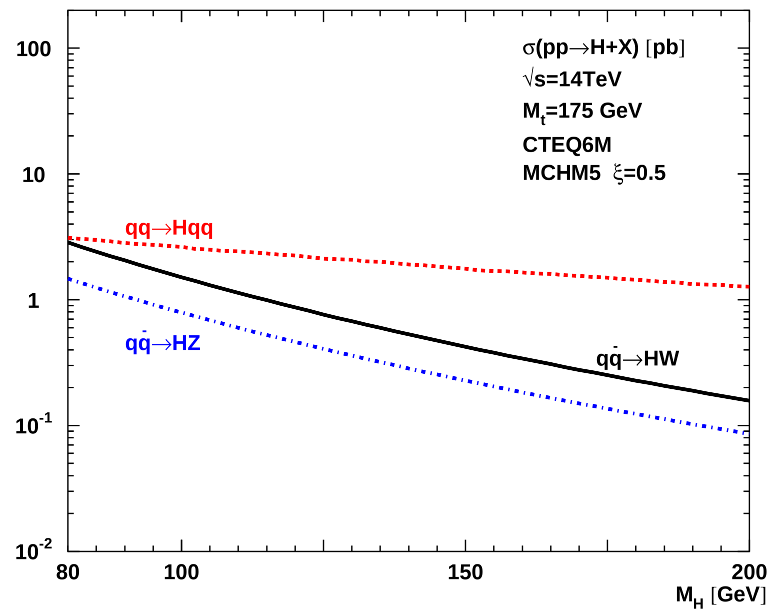
$$\sigma_{NLO}(qqH) = (1-\xi) \quad \sigma^{SM}_{NLO}(qqH)$$ $\sigma_{NLO}(VH)$ analogous

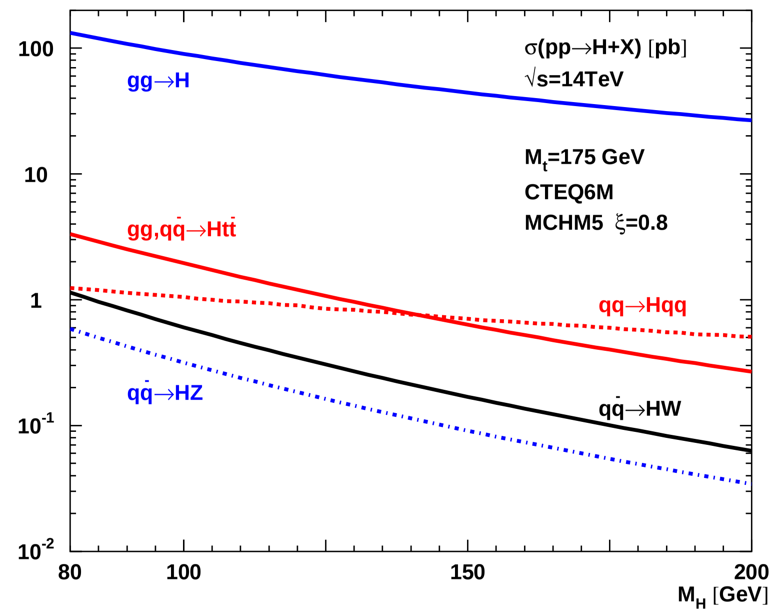
- **Production cross sections MCHM5**

Espinosa, Grojean, Mühlleitner

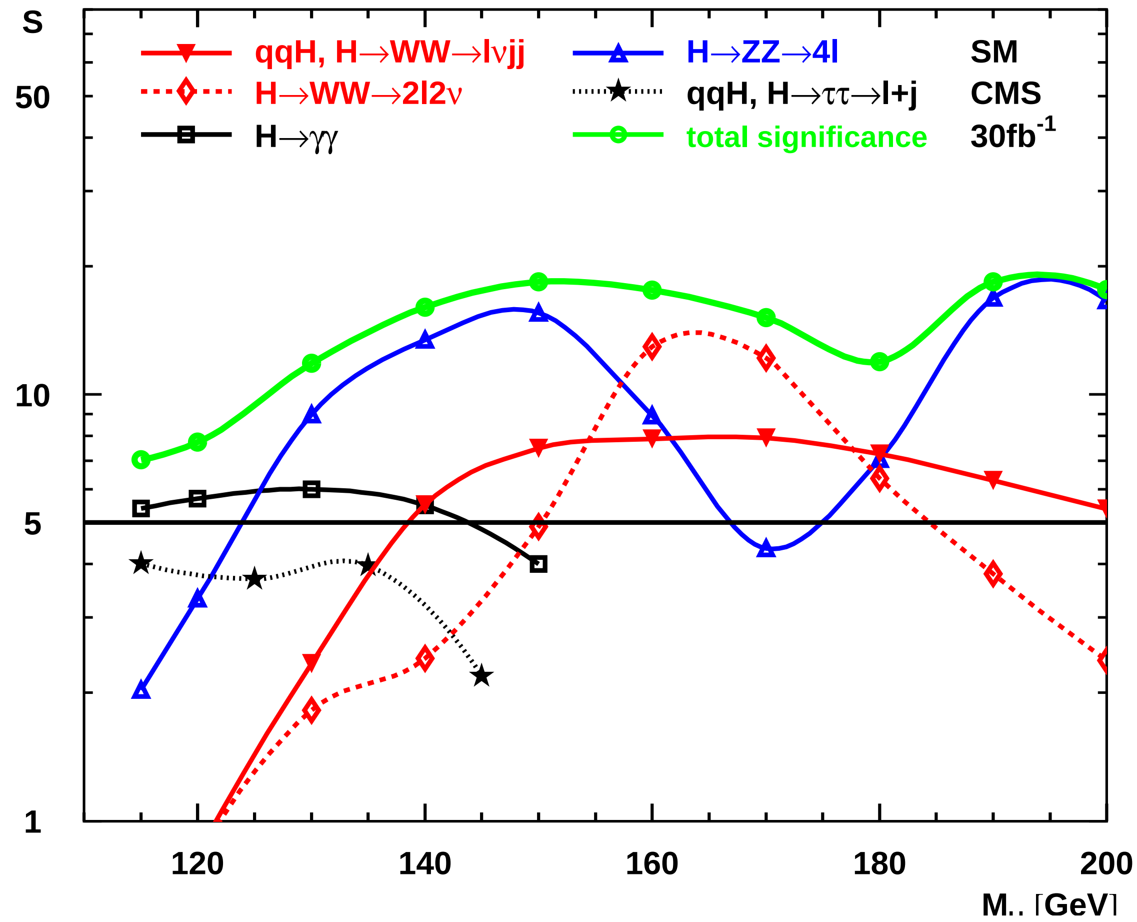








SM Higgs discovery potential



Significances: Composite Higgs

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

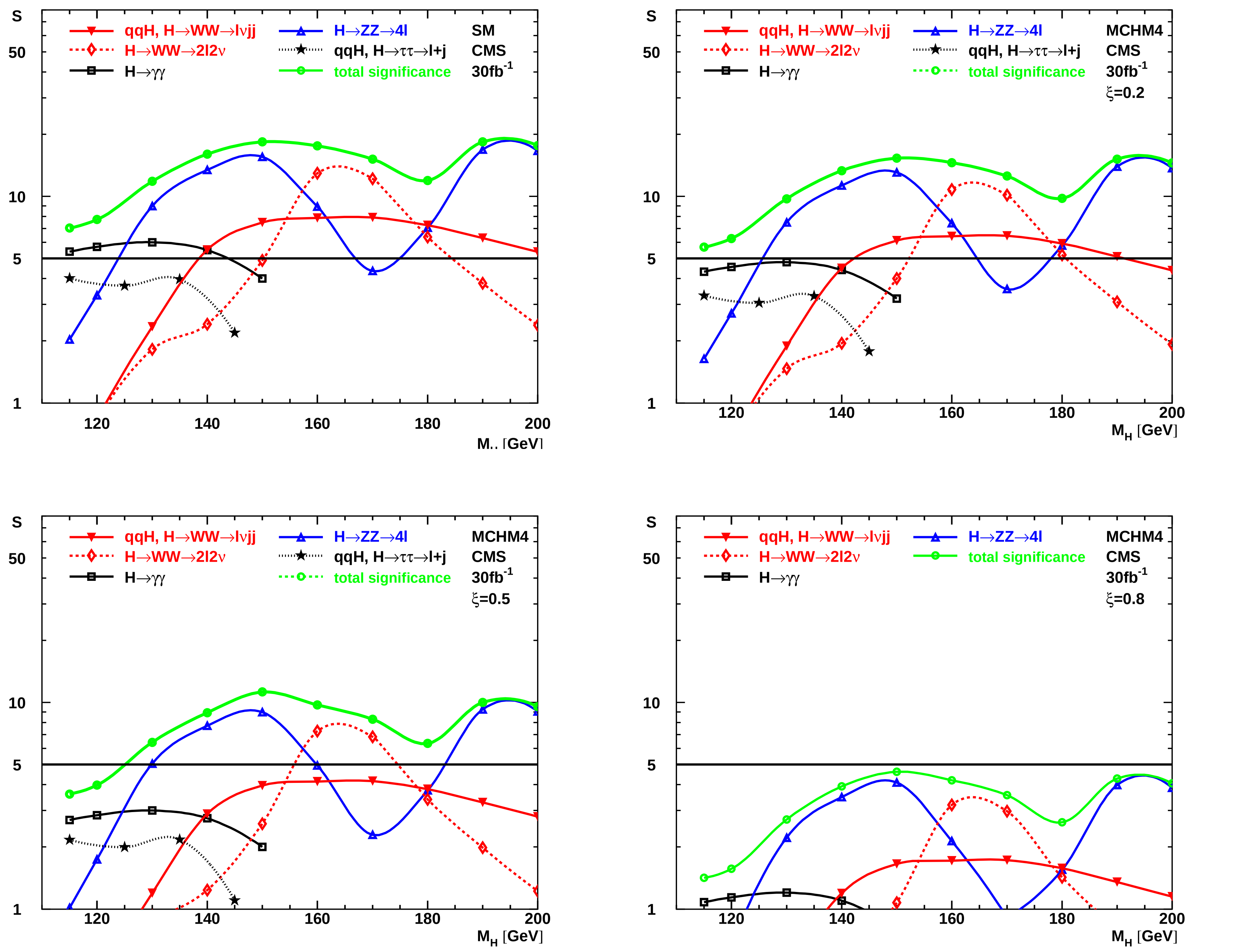
$$\kappa = \frac{\sigma^{\xi}_{prod} BR^{\xi}(H \to X)}{\sigma^{SM}_{prod} BR^{SM}(H \to X)}$$

  - ◇ 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)

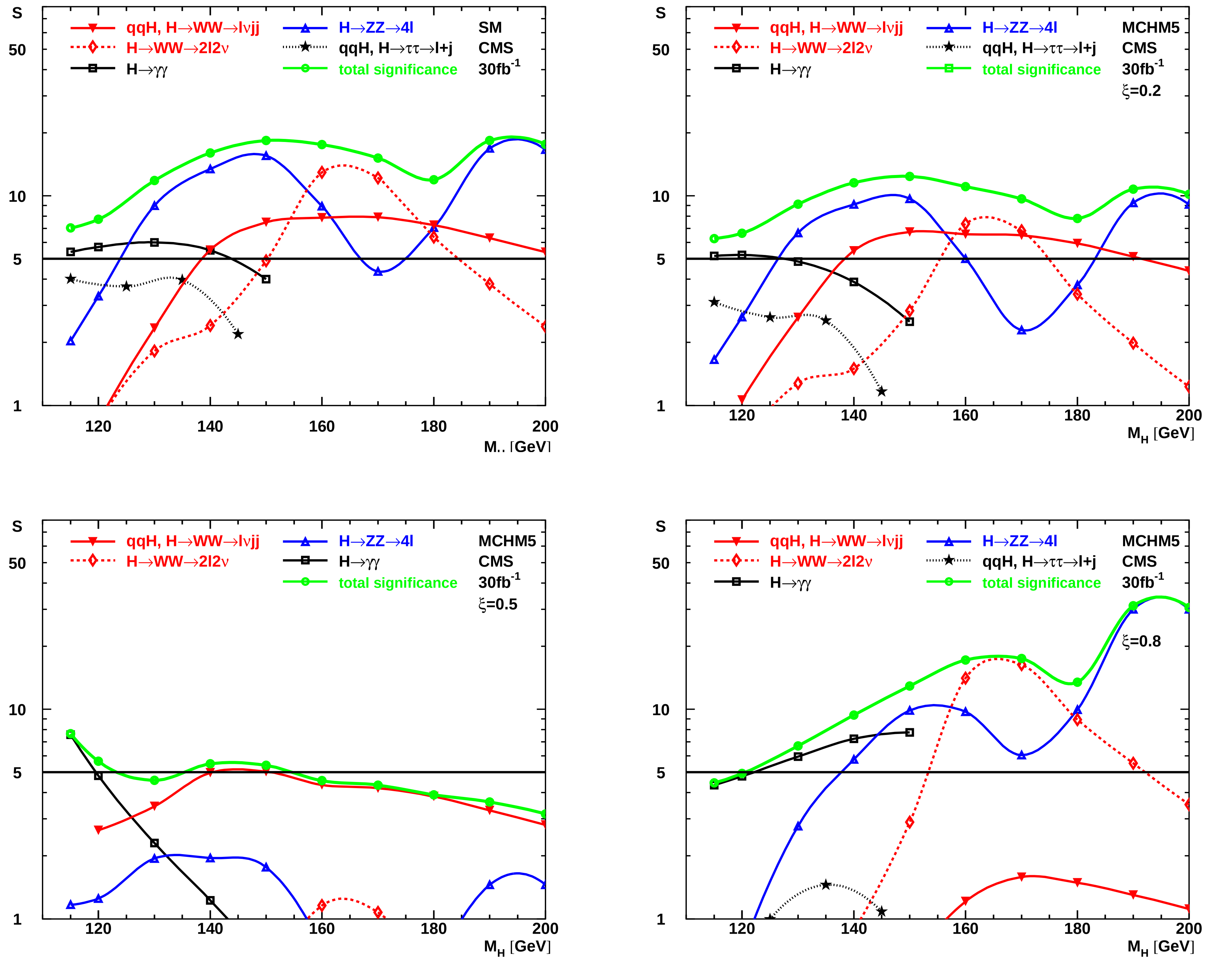
$$\begin{aligned} \text{Inclusive production with subsequent decay :} \quad & H \to \gamma\gamma \\ & H \to ZZ \to 2e2\mu, 4e, 4\mu \\ & H \to WW \to 2l2\nu \\ \text{Vector boson fusion with subsequent decay :} \quad & H \to WW \to l\nu jj \\ & H \to \tau\tau \to l + j + E_T^{miss} \,. \end{aligned}$$

• Significances MCHM4



• Significances MCHM5

Espinosa, Grojean, Mühlleitner



Conclusions

- **Composite Higgs Model** Higgs as pseudo-Goldstone boson of the strong sector
- **Higgs matter couplings** modified (Higgs is a bound state)
- **Discovery prospects at LHC** may be significantly changed
- **After Higgs disovery:** Which Higgs have we discovered?

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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

Processes involved and significance definitions

- $H \to \gamma\gamma$

  Processes: gluon fusion, VBF, VH, $Ht\bar{t}$

  Significance: cut-based analysis, $S^{\xi} = \kappa \sum_i \frac{s_i}{\sqrt{b_i}}$

- $H \to ZZ \to 4l$

  Processes: gluon fusion, VBF

  Significance: Poisson significance S_P, neglecting the (small) systematic uncertainty.
  S_P is the solution of the equation

$$\sum_{i=0}^{s+b-1} \frac{e^{-b} b^i}{i!} = \int_{-\infty}^{S_P} dx \frac{e^{-x^2/2}}{\sqrt{2\pi}}$$

- $H \to WW \to 2l2\nu$

  Processes: gluon fusion, VBF

  Significance: $ScP2$ w/ systematic uncertainty 10% at 30 fb^{-1}

$$ScP2[s,b,\Delta b] \equiv 2\left(\sqrt{s+b} - \sqrt{b}\right)\sqrt{\frac{b}{b+\Delta b^2}}$$

Processes involved and significance definitions

- $H \to WW \to l\nu jj$

  Processes: VBF

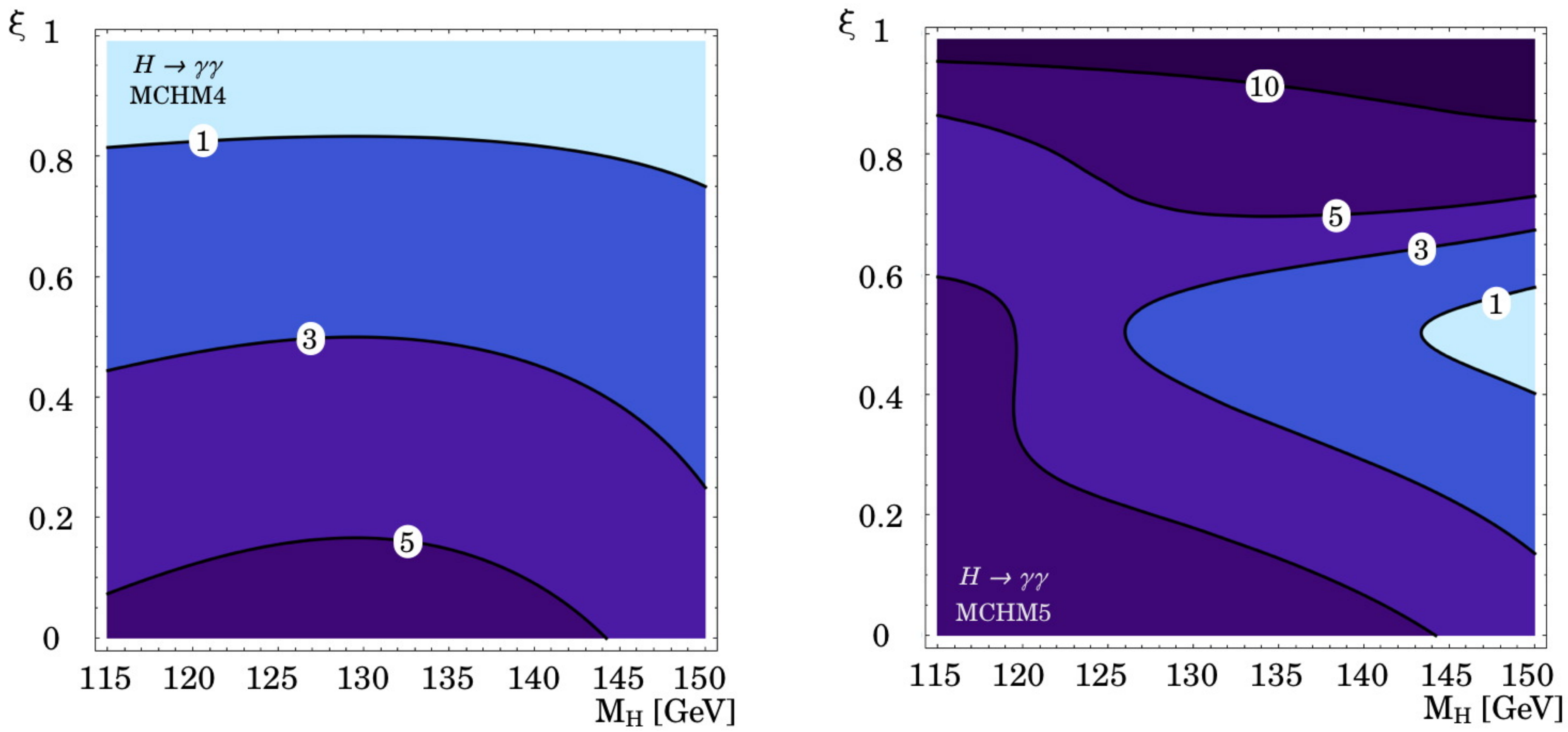
  Significance: ScL' w/ 16% bkg uncertainty

$$\begin{aligned} ScL[s,b] &\equiv \sqrt{2[(s+b)\log(1+s/b)-s]}\ , \\ ScL'[s,b,\Delta b] &\equiv ScL[s,b+\Delta b^2] \end{aligned}$$

- $H \to \tau\tau \to l + j + E_T^{miss}$

  Processes: VBF

  Significance: Poisson significance w/ systematic uncertainty 7.8%.


ξ
1
0.8
0.6
0.4
0.2
0
H → γγ
MCHM4
1
3
5
115 120 125 130 135 140 145 150
M_H [GeV]
ξ
1
0.8
0.6
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10
5
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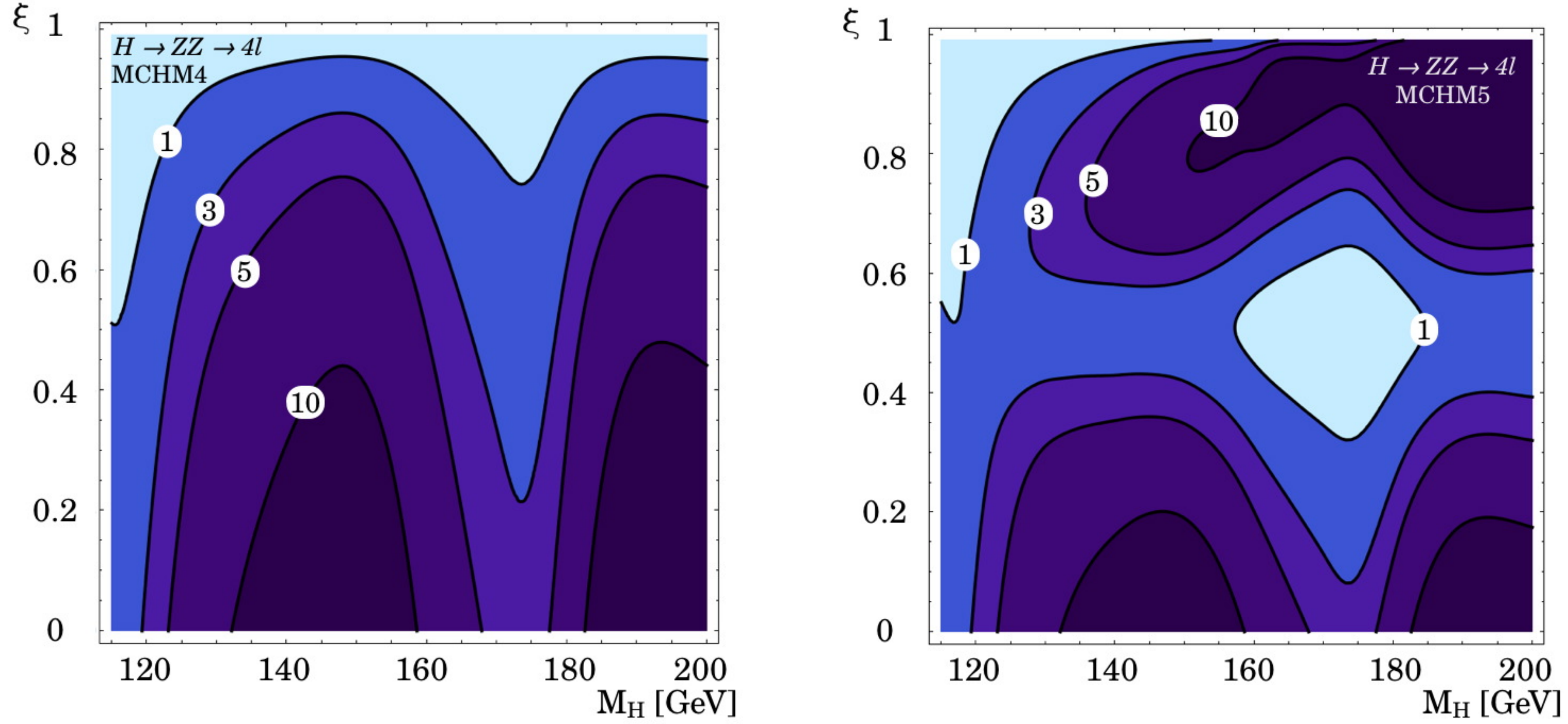
1
H → γγ
MCHM5
115 120 125 130 135 140 145 150
M_H [GeV]


ξ
1
0.8
0.6
0.4
0.2
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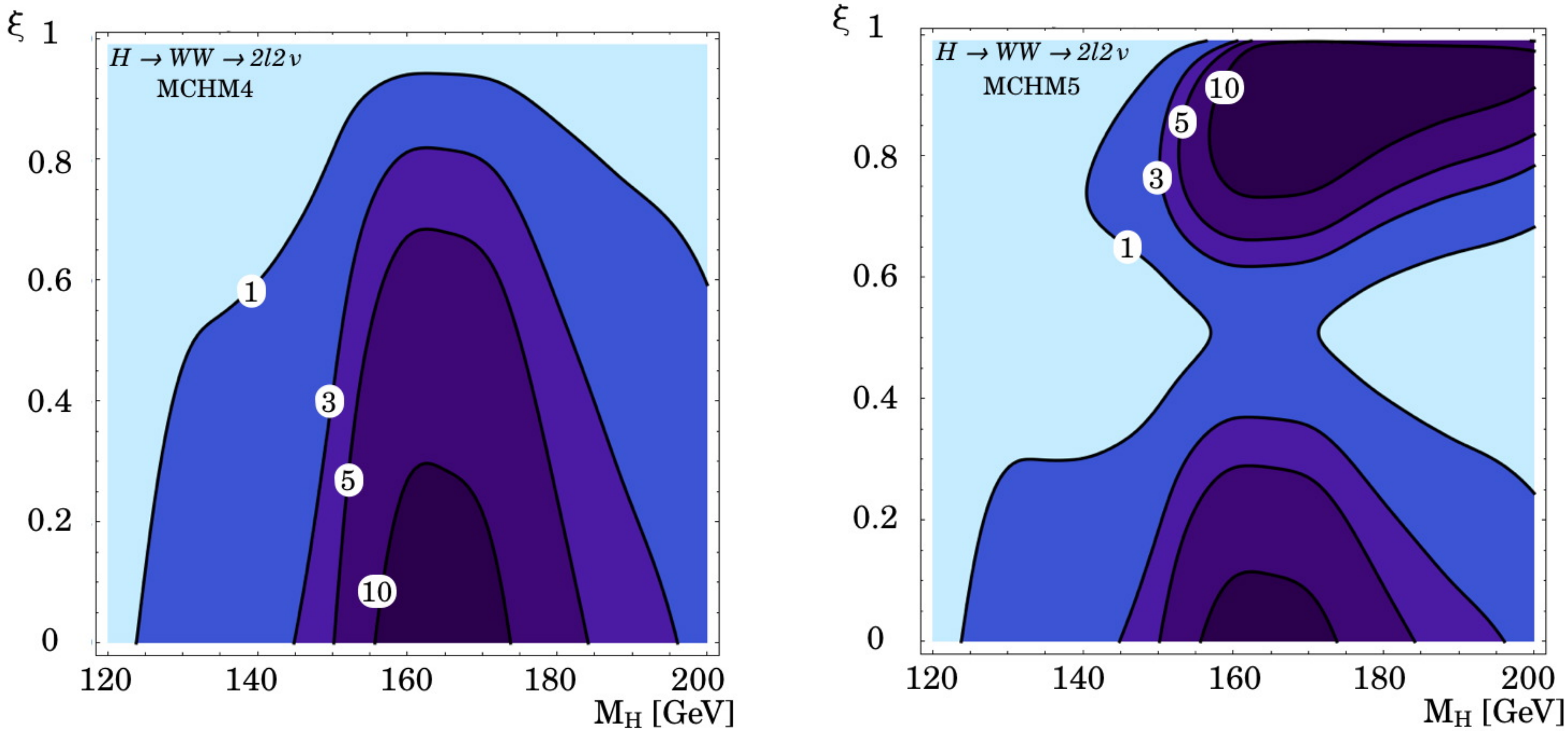
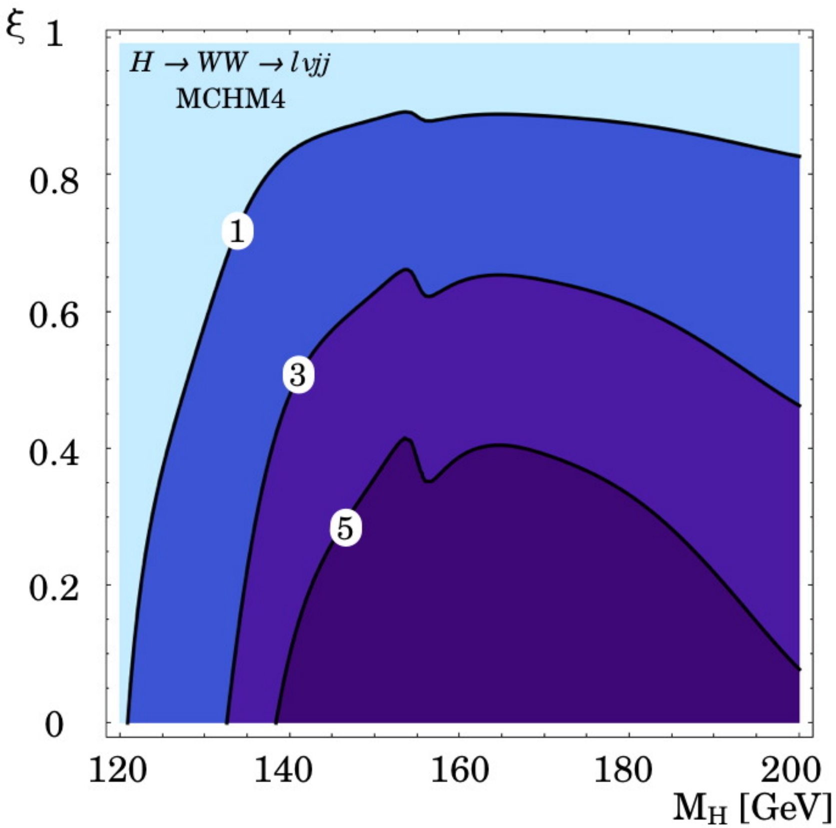
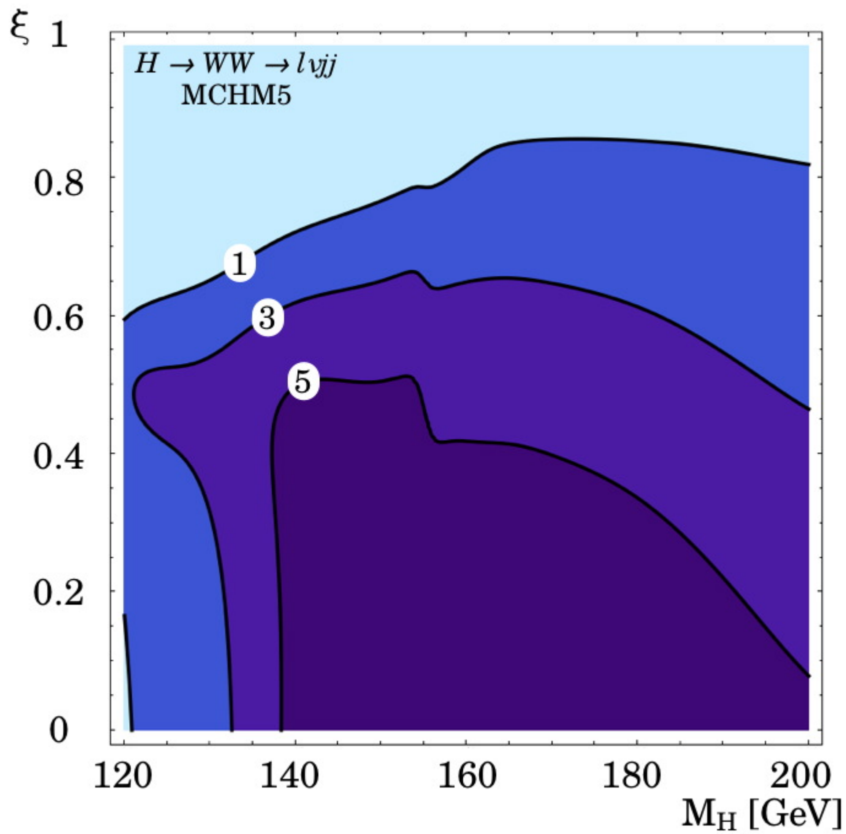
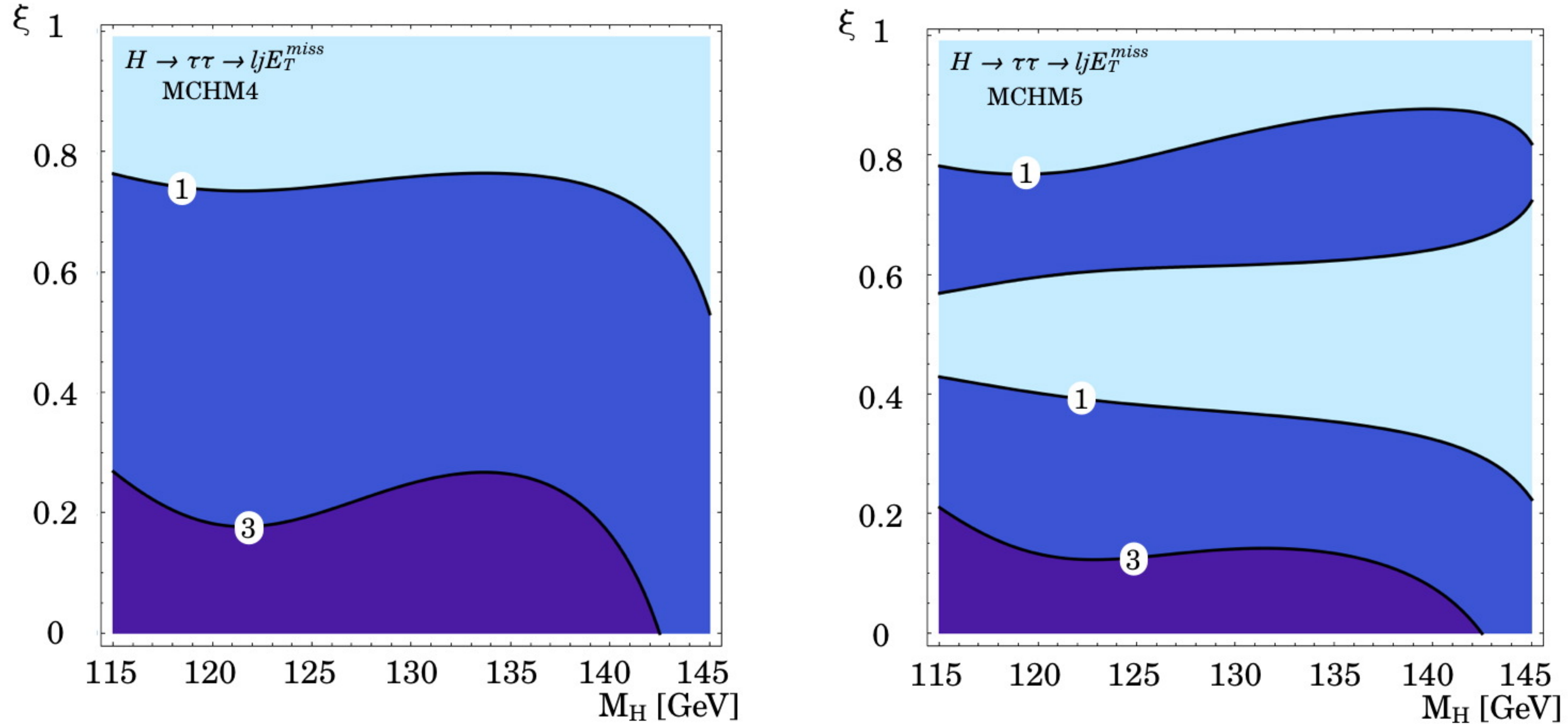
120
140
160
180
200
M_H [GeV]
H → ZZ → 4l
MCHM4
1
3
5
10
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → ZZ → 4l
MCHM5
10
5
3
1
1


ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → WW → 2l2ν
MCHM4
1
3
5
10
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
H → WW → 2l2ν
MCHM5
1
3
5
10


$H \to WW \to l\nu jj$
MCHM4
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
1
3
5

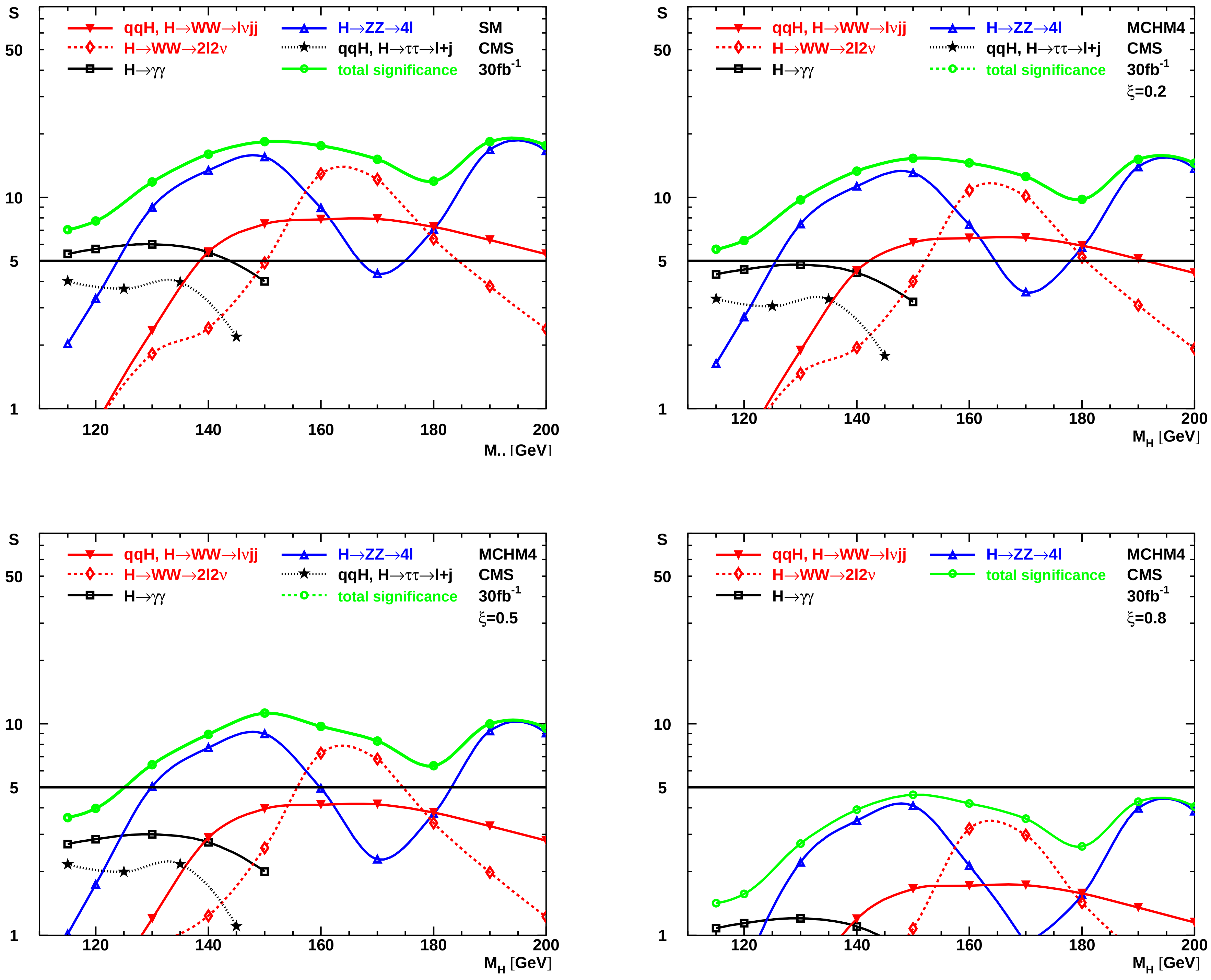

$H \to WW \to l\nu jj$
MCHM5
ξ
1
0.8
0.6
0.4
0.2
0
120
140
160
180
200
M_H [GeV]
1
3
5

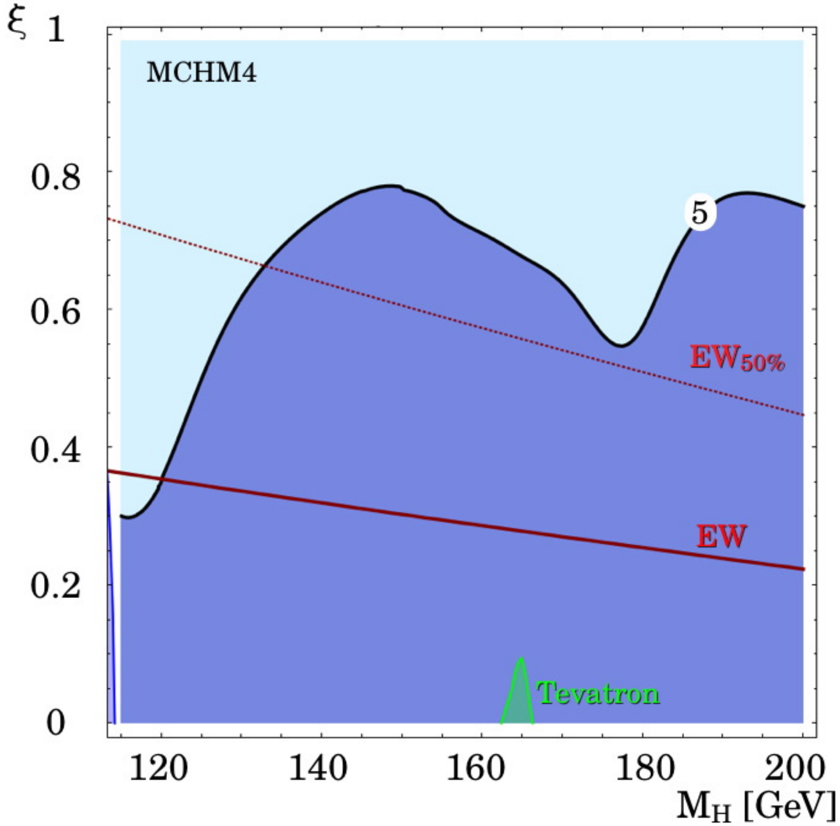


$H \to \tau\tau \to ljE_T^{miss}$
MCHM4
ξ
1
0.8
0.6
0.4
0.2
0
115
120
125
130
135
140
145
M_H [GeV]
1
3
$H \to \tau\tau \to ljE_T^{miss}$
MCHM5
ξ
1
0.8
0.6
0.4
0.2
0
115
120
125
130
135
140
145
M_H [GeV]
1
1
3

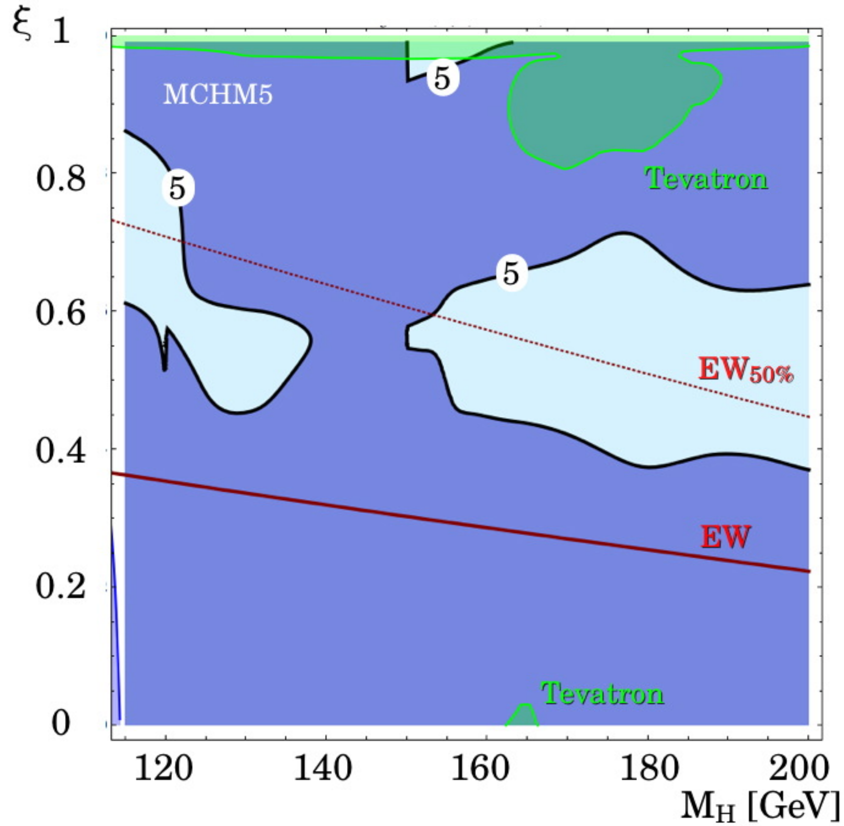
- **Significances MCHM4**

Espinosa, Grojean, Mühlleitner





ξ
1
0.8
0.6
0.4
0.2
0
MCHM4
5
EW50%
EW
Tevatron
120
140
160
180
200
M_H [GeV]



ξ
1
0.8
0.6
0.4
0.2
0
MCHM5
5
5
5
Tevatron
EW50%
EW
Tevatron
120
140
160
180
200
M_H [GeV]