Physics of the Brout-Englert-Higgs Boson at the LHC in the SM and Beyond

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Outline

(i) SM/MSSM (pseudo-)scalar boson production

∗ Introduction SM/MSSM sector of EWSB

∗ Production channels

∗ Decays

(ii) Interpretation of LHC search results for scalar boson within

∗ MSSM

∗ NMSSM

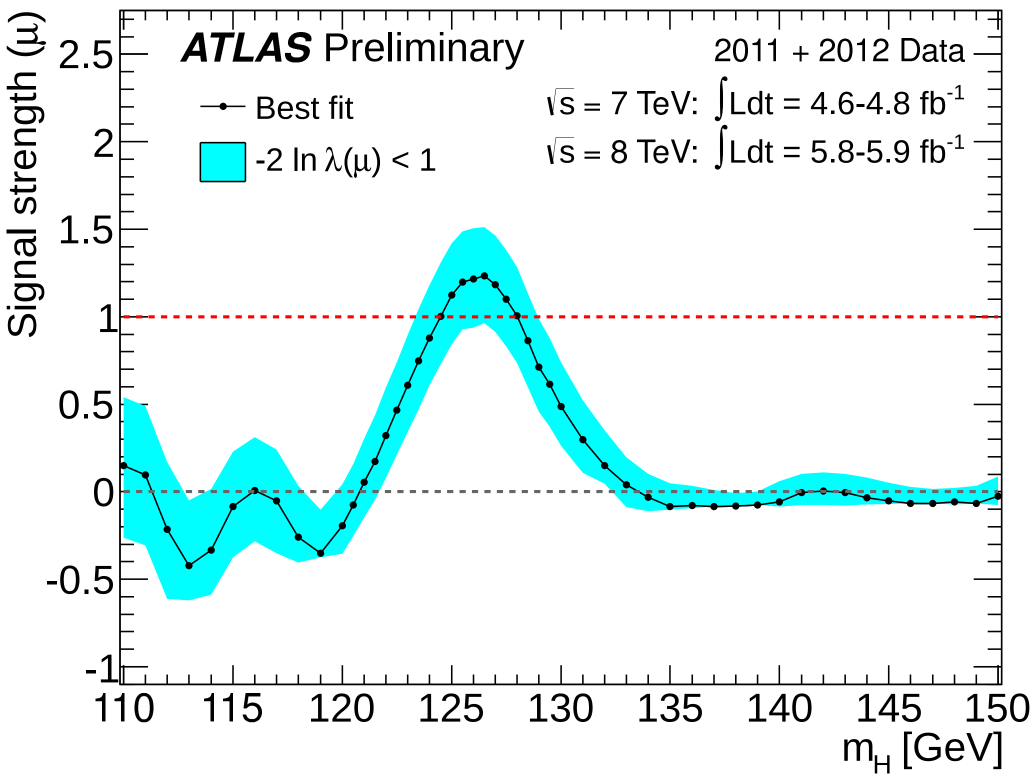
∗ Composite Models

∗ Model-independent

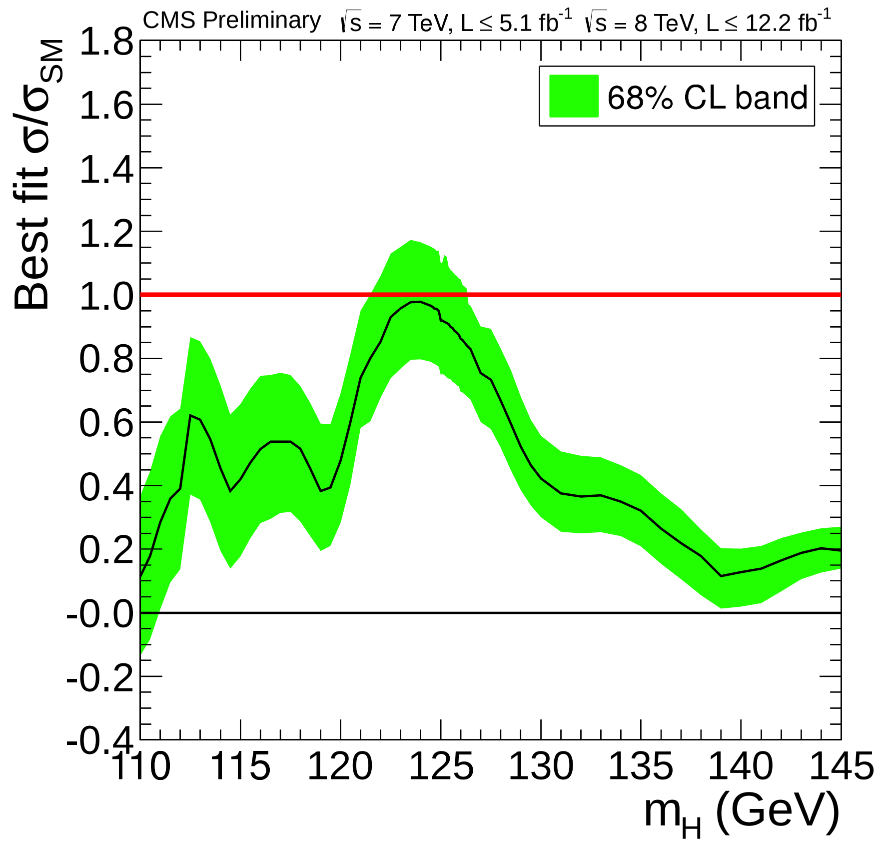
[(iii) Determination of the properties of the new boson]

$\mathcal{LHC}$ $\mathcal{S}$earch $\mathcal{R}$esults for $\mathcal{S}$calar $\mathcal{B}$oson

ATLAS



CMS



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

Why? Explain the existence of massive particles consistently with the basic symmetries of the SM

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

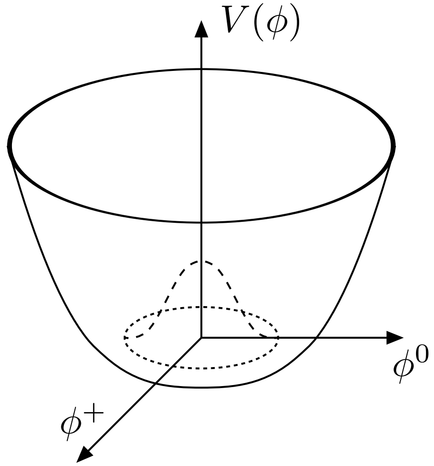
EWSB mechanism

Symmetry of the Lagrangian

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

Doublet field

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



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

Symmetry of the vacuum

$U(1)_{em}$

Vacuum expectation value

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

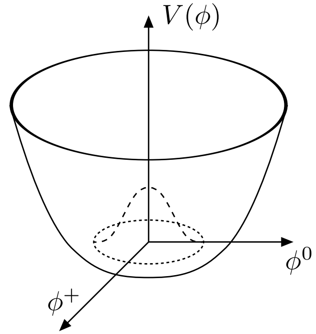
$v = 246$ GeV

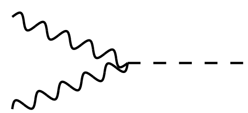
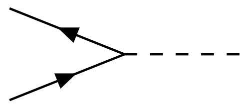
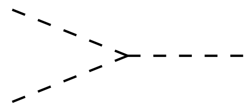
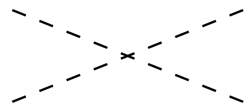
$\mathcal{SM}$ Scalar $\mathcal{B}$oson $\mathcal{S}$ector

Potential w/ non-vanishing VEV: [$v = 246$ GeV]

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

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



$\mathcal{S}$calar 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]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$	

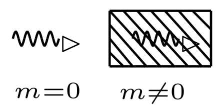
$\mathcal{O}$nly unknown parameter in the SM was the mass of the scalar boson!

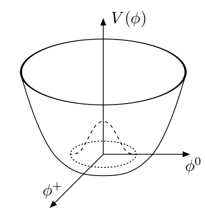
What Have We Seen?

- The production of a new particle with mass $M = 125.8$, 126 GeV
- Is it *the* Standard Model scalar boson *responsible for EWSB*? $\Longrightarrow$

<u>Test of the EWSB mechanism</u>

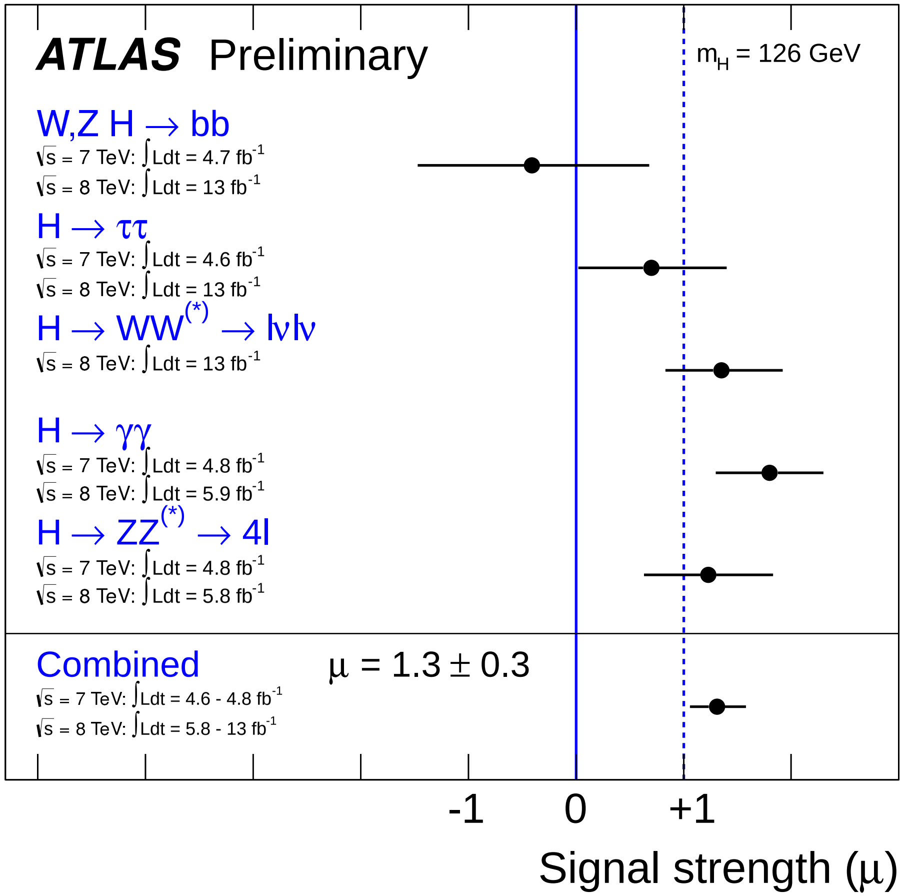
- Discovery – m
- Interaction with the scalar boson with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$
- Spin and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$

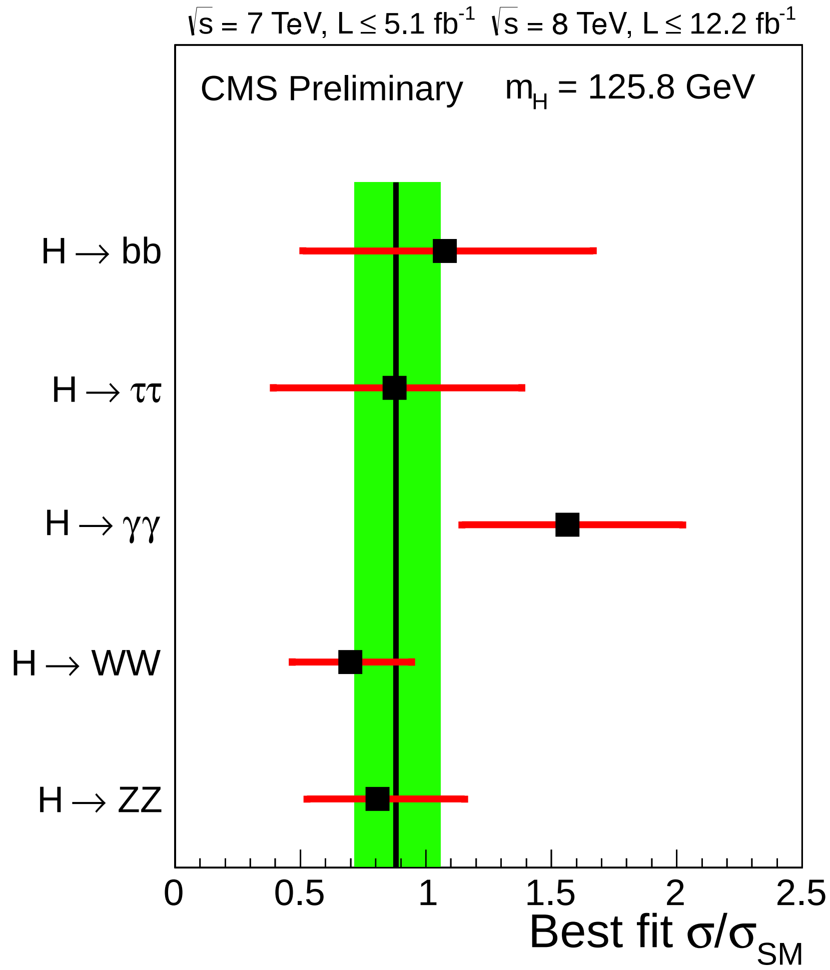




- Is it the scalar boson of the SM, of SUSY, a Composite scalar boson, ...?

What Experiment tells us: Best Fit Values of $\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$





Combination of various search channels grouped by decay mode

Slight excess in $\gamma\gamma$ but not $WW, ZZ, bb, \tau\tau$

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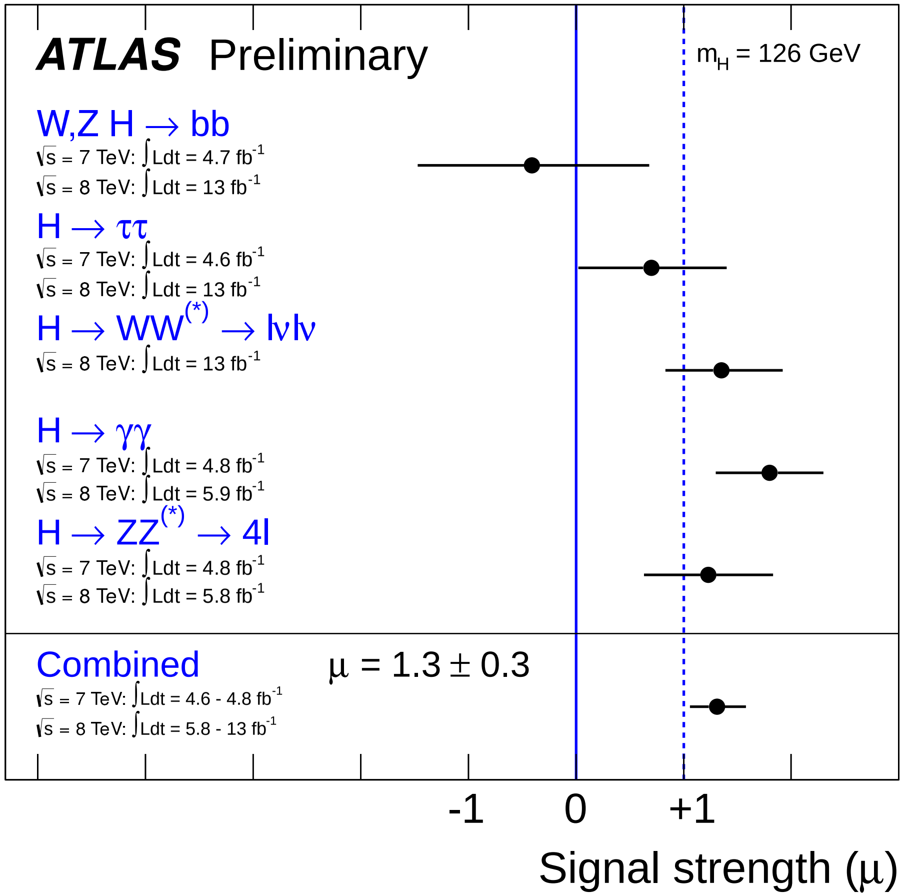

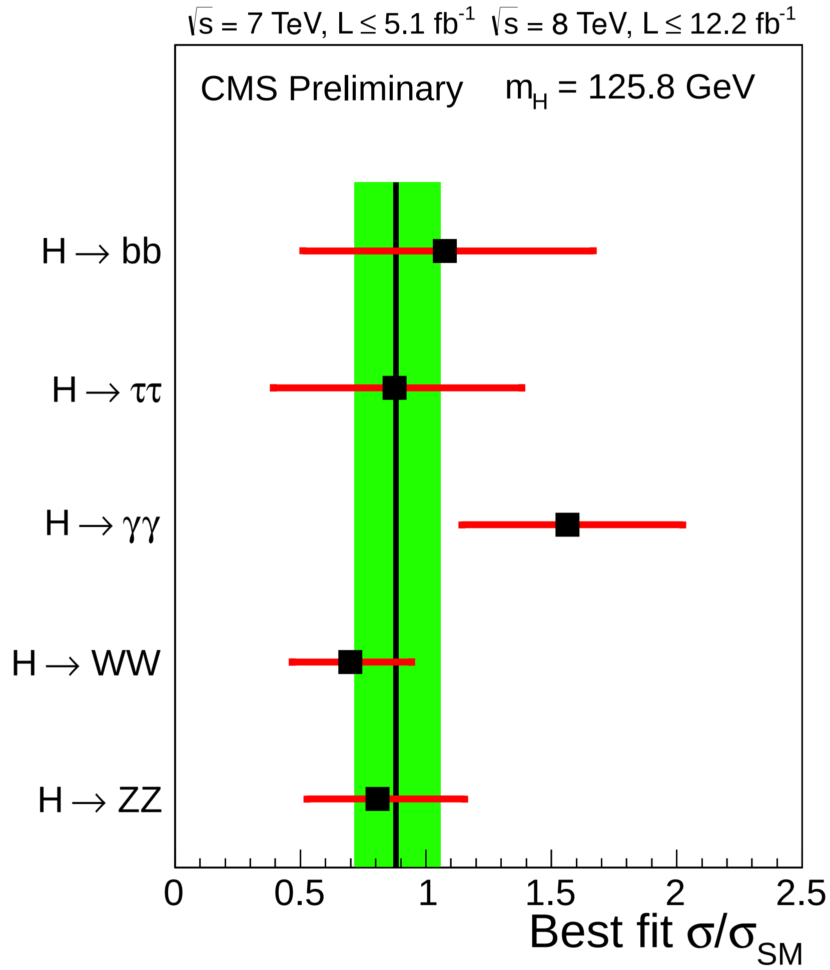

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Slight excess in $\gamma\gamma$ **but not** $WW, ZZ, bb, \tau\tau$ Beyond SM Physics?

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?
- Common origin of all three forces of the SM?
- How to incorporte gravity?
- Candidate for Dark Matter (DM)? ...

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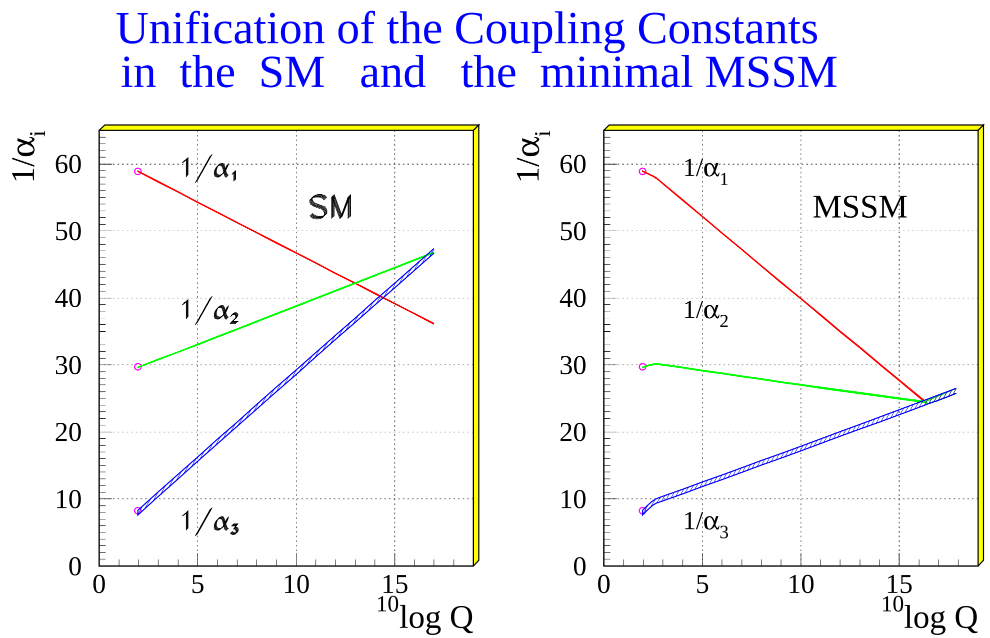

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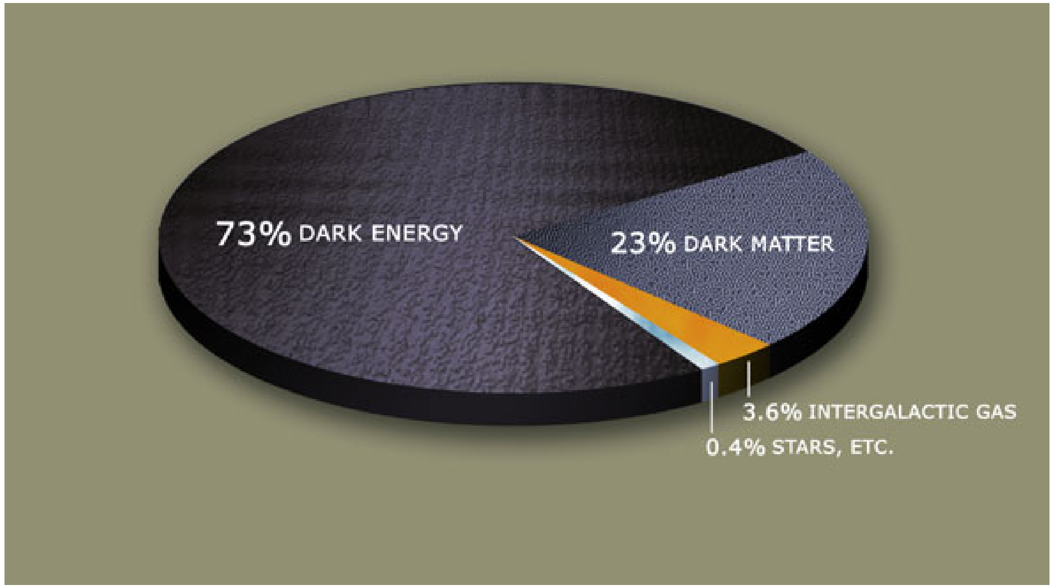

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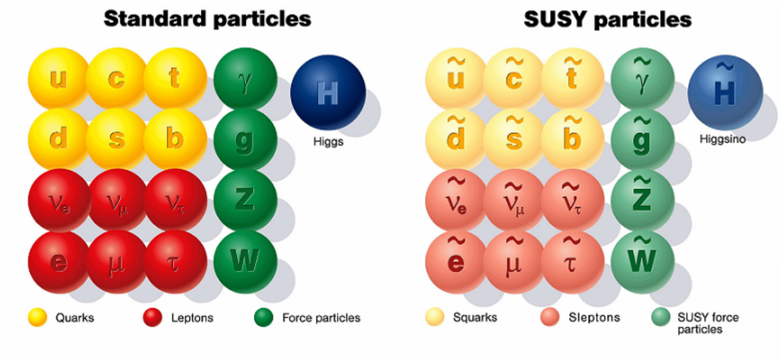
Supersymmetry: relates fermions and bosons

◇ solves hierarchy problem

◇ gauge coupling unification (MSSM)

◇ EWSB mechanism generated radiatively

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



$\mathcal{T}$he $\mathcal{EWSB}$ $\mathcal{S}$ector of the $\mathcal{MSSM}$

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

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

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(Pseudo-)scalar 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;
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$M_A \sim M_H \sim M_{H^\pm} \gtrsim v$

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

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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	$c_\alpha/s_\beta \rightarrow 1$	$-s_\alpha/c_\beta \rightarrow 1$	$s_{\beta-\alpha} \rightarrow 1$
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

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

$g_{\Phi dd} \uparrow$

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

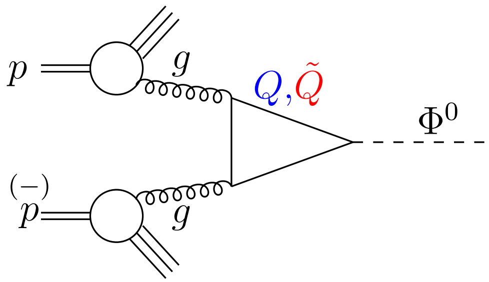
Production

$\mathcal{S}$earch for the ($\mathcal{P}$seudo-)$\mathcal{S}$calar $\mathcal{B}$oson(s) at the $\mathcal{LHC}$

(Pseudo-)Scalar boson production in the SM/MSSM

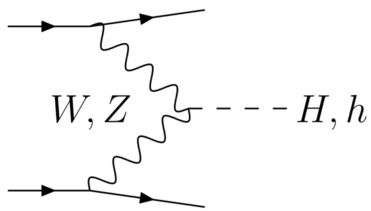
- **Gluon Fusion**

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



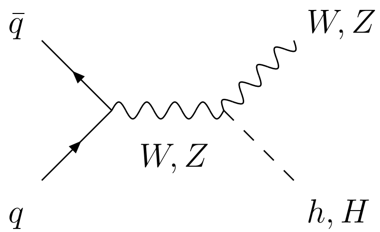
- **W/Z Fusion**

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



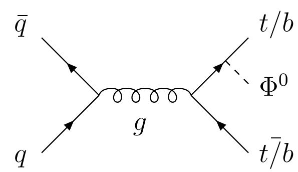
- **Radiation off W, Z**

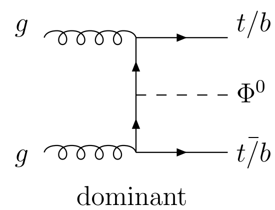
  $pp \to W^*/Z^* \to W/Z + H^{SM}/h, H$



- **Associated Production**

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





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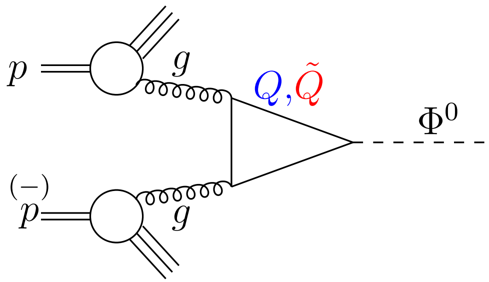


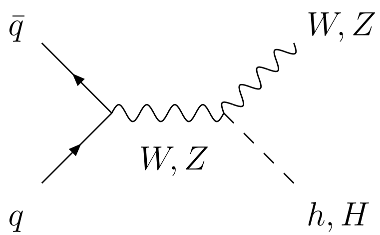
- **LHC - MSSM**

$gg \to \phi$ dominant for $\tan\beta \lesssim 10$

$gg \to \phi b\bar{b}$ dominant for $\tan\beta \gtrsim 10$

- **Radiation off W, Z**

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



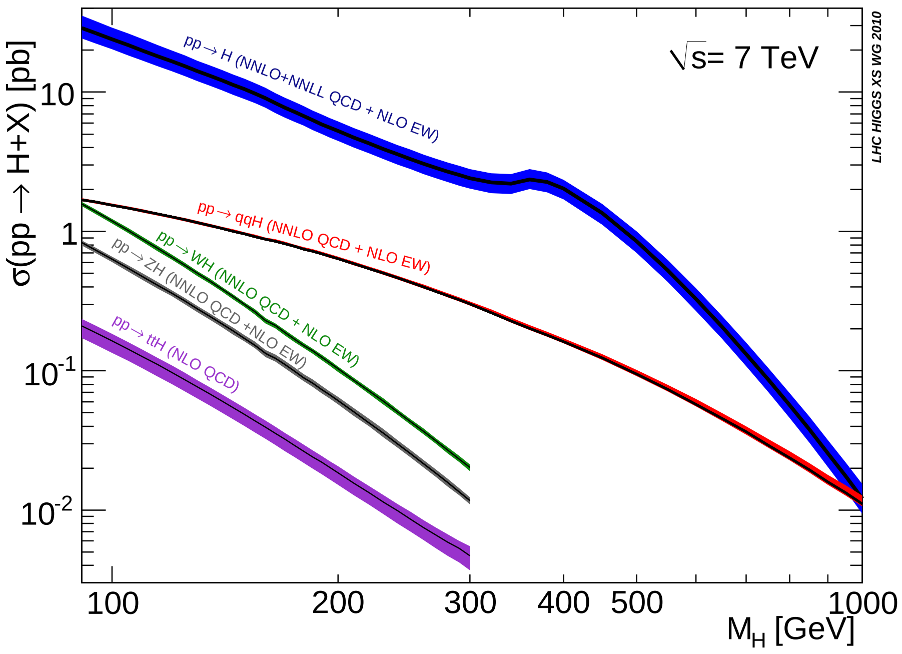
- **Tevatron - MSSM**

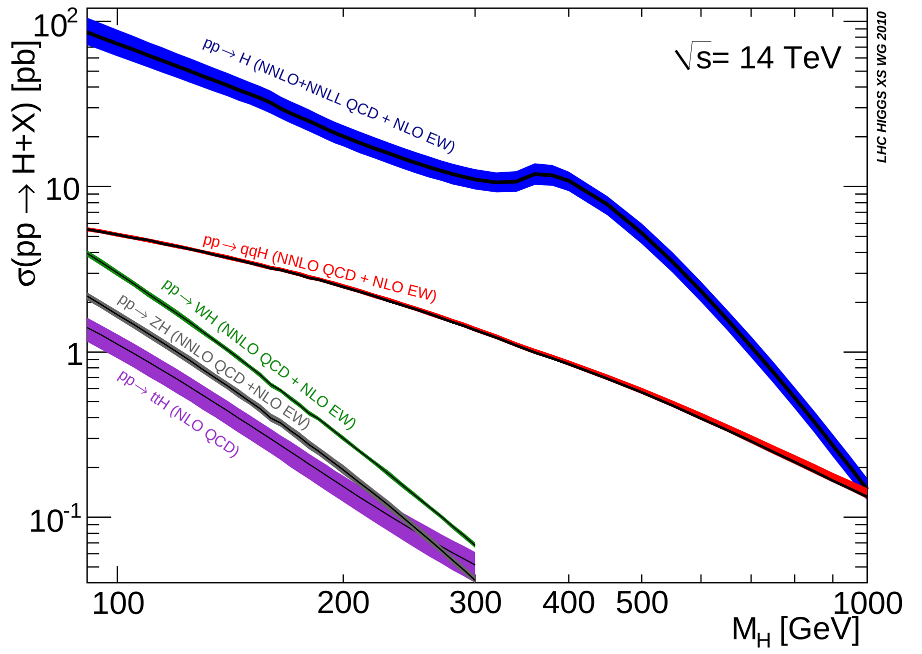
$gg \to \phi$ dominant, forlarge $\tan\beta : \phi b\bar{b}$

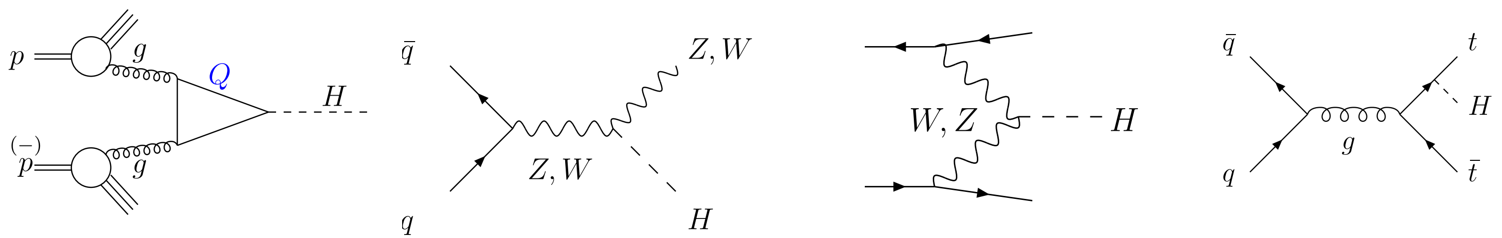
$q\bar{q}' \to \phi W$ most important

SM Scalar Boson Production at the LHC

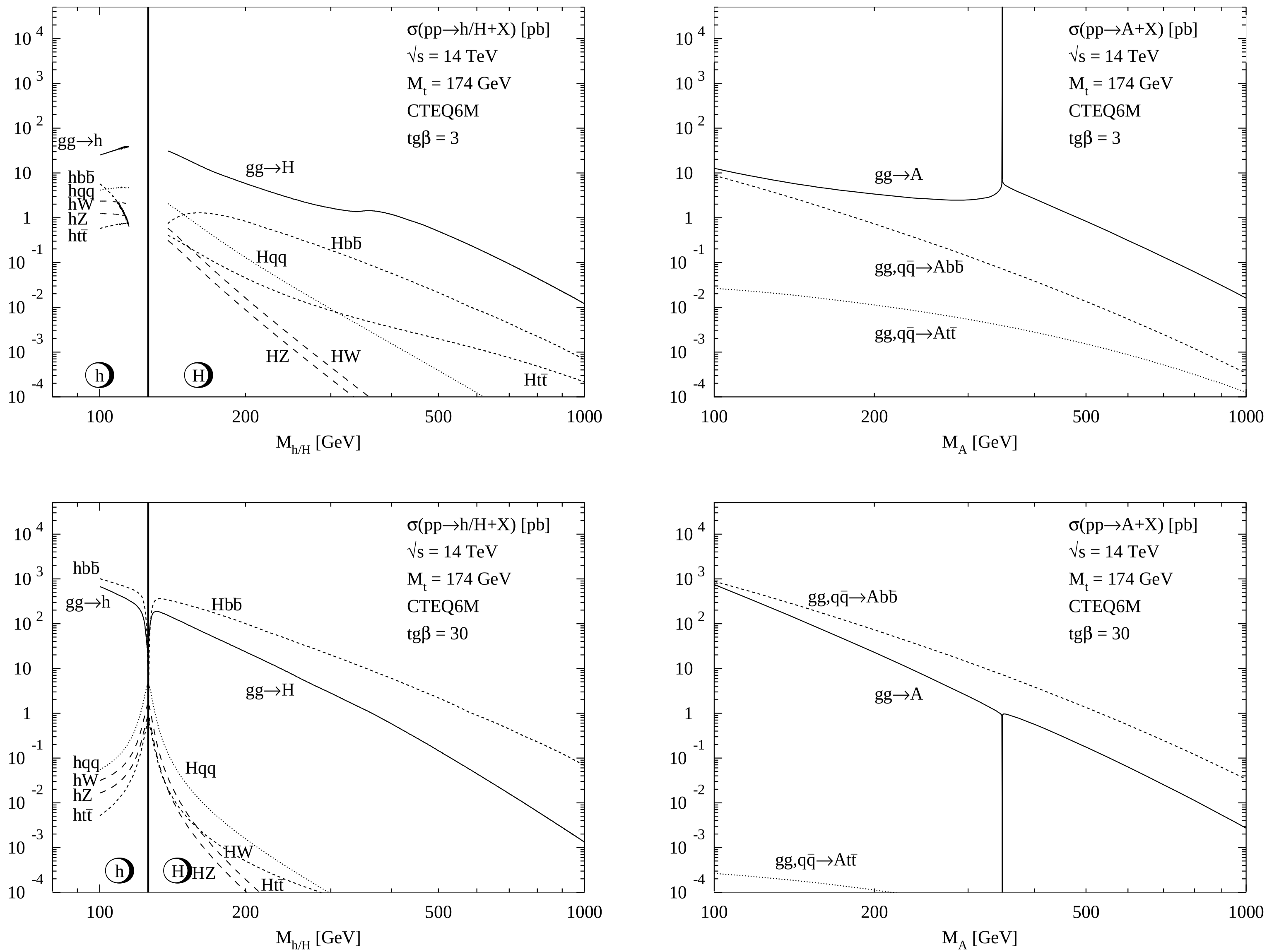
LHC Higgs XS WG, arXiv:1101.0593







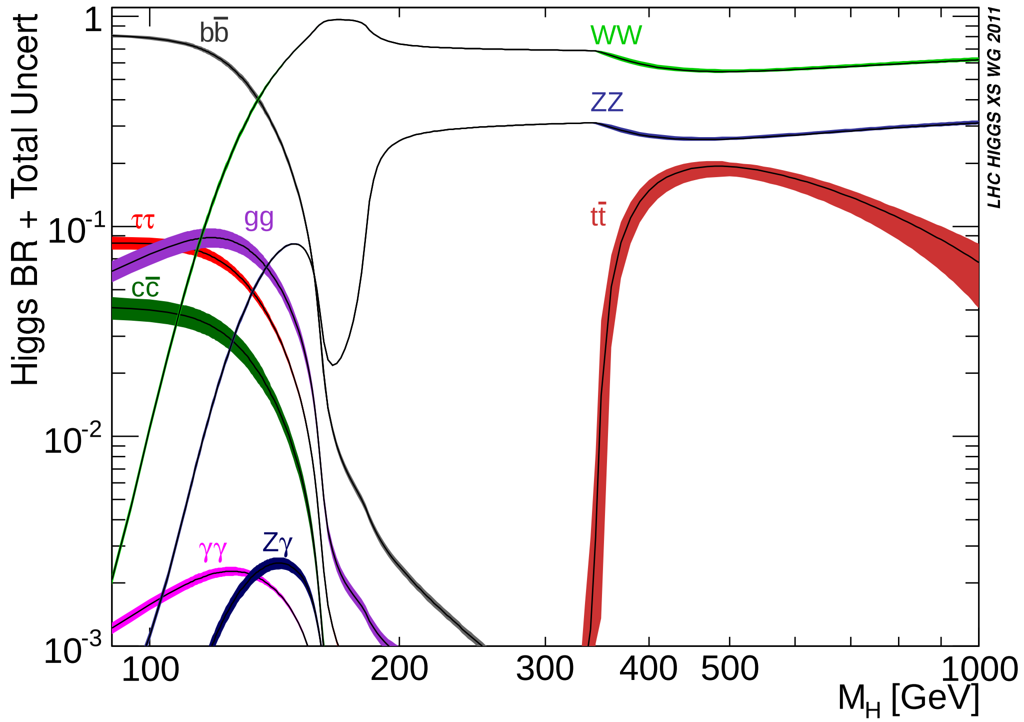
$\mathcal{MSSM}$ ($\mathcal{P}$seudo-)$\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{P}$roduction at the $\mathcal{LHC}$

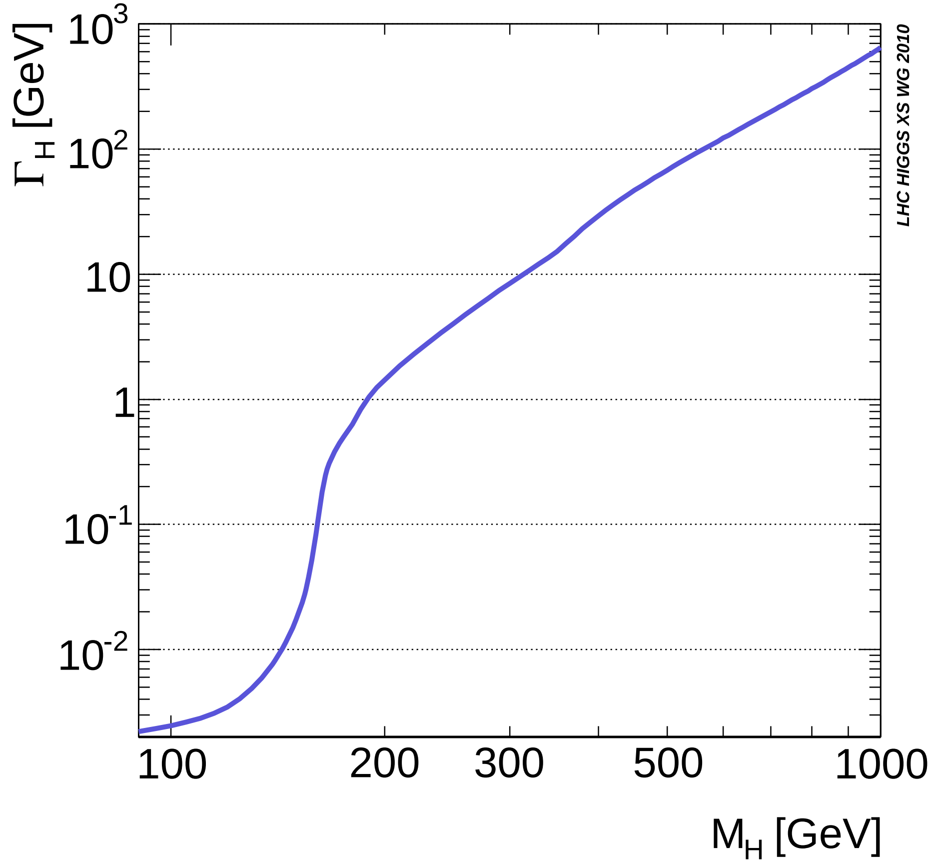


Decays

$\mathcal{B}$ranching $\mathcal{R}$atios

LHC Higgs XS WG





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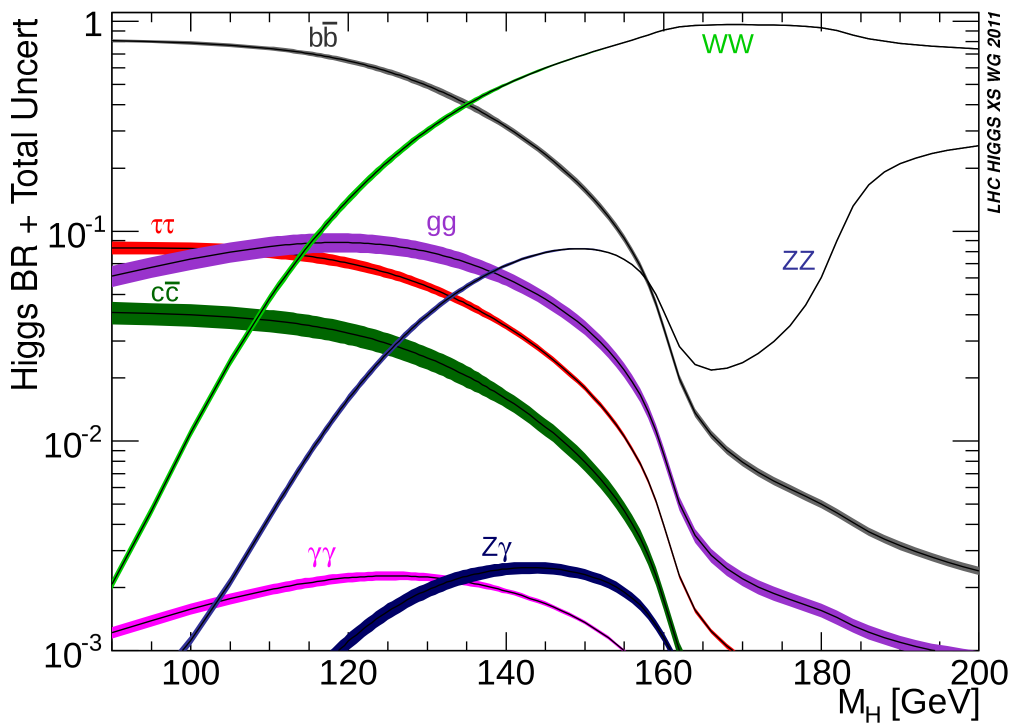

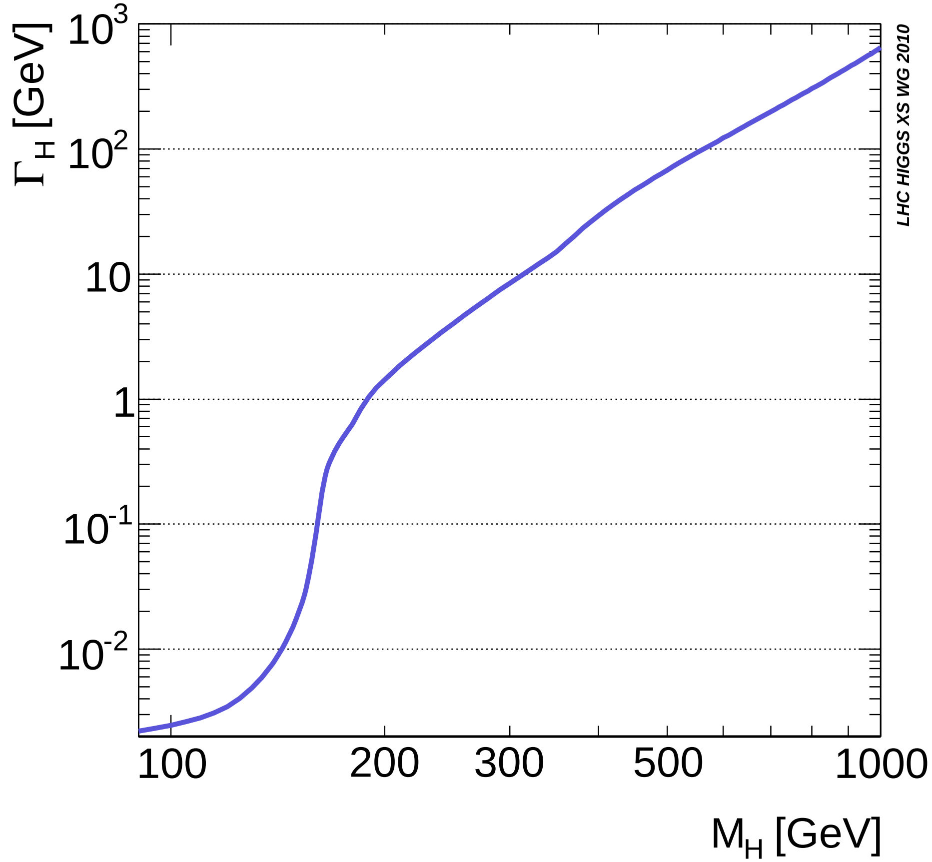

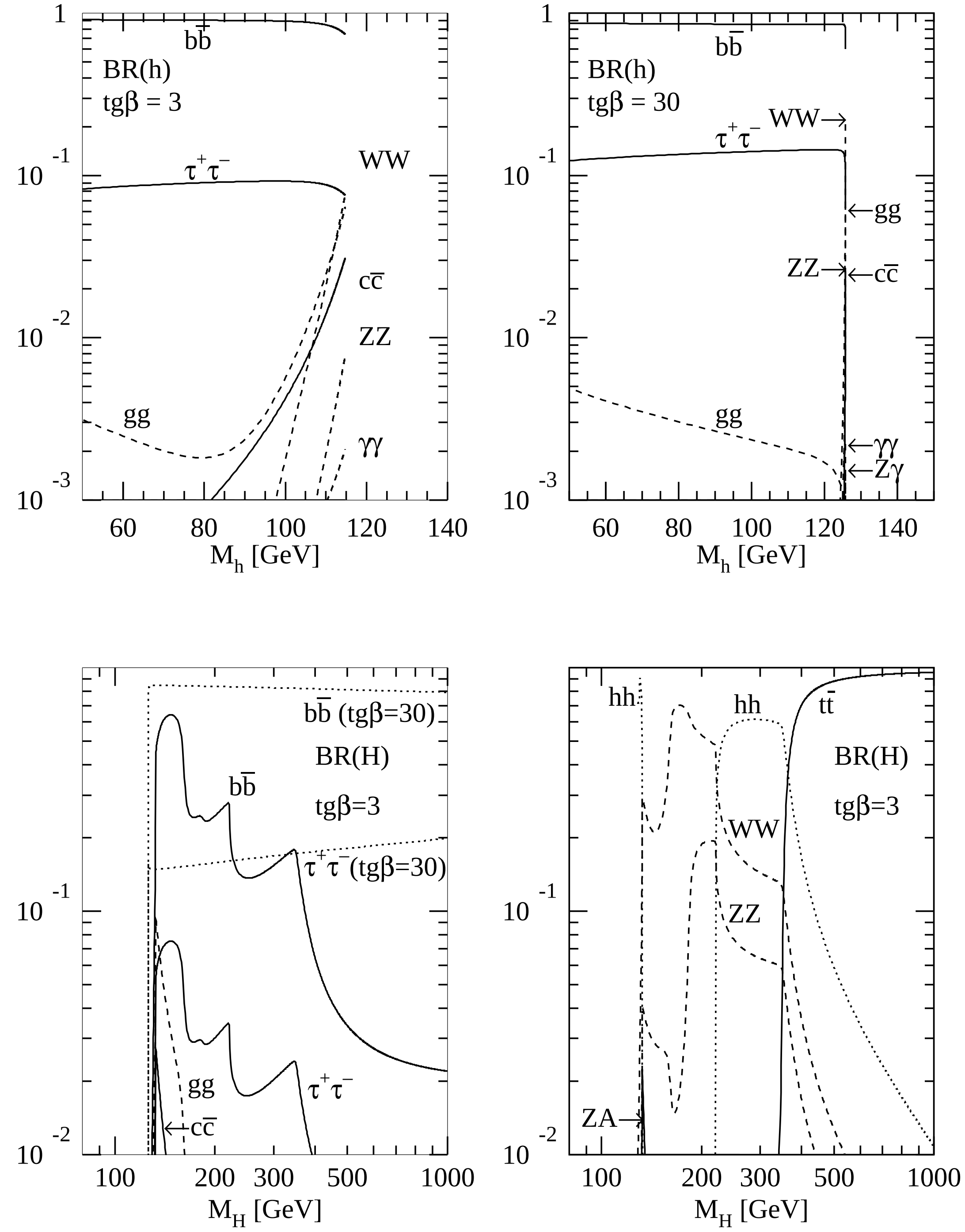
BR(h)
tgβ = 3
bb̄
τ⁺τ⁻
WW
cc̄
ZZ
gg
γγ
M_h [GeV]
BR(h)
tgβ = 30
bb̄
τ⁺τ⁻ WW→
←gg
ZZ→ ←cc̄
←γγ
←Zγ
BR(H)
tgβ=3
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Interpretations

MSSM Scalar Boson Mass in View of the LHC Results

- **Vast literature on MSSM Scalar Boson of ~ 125-126 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 Scalar Boson mass with LHC Search**

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

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

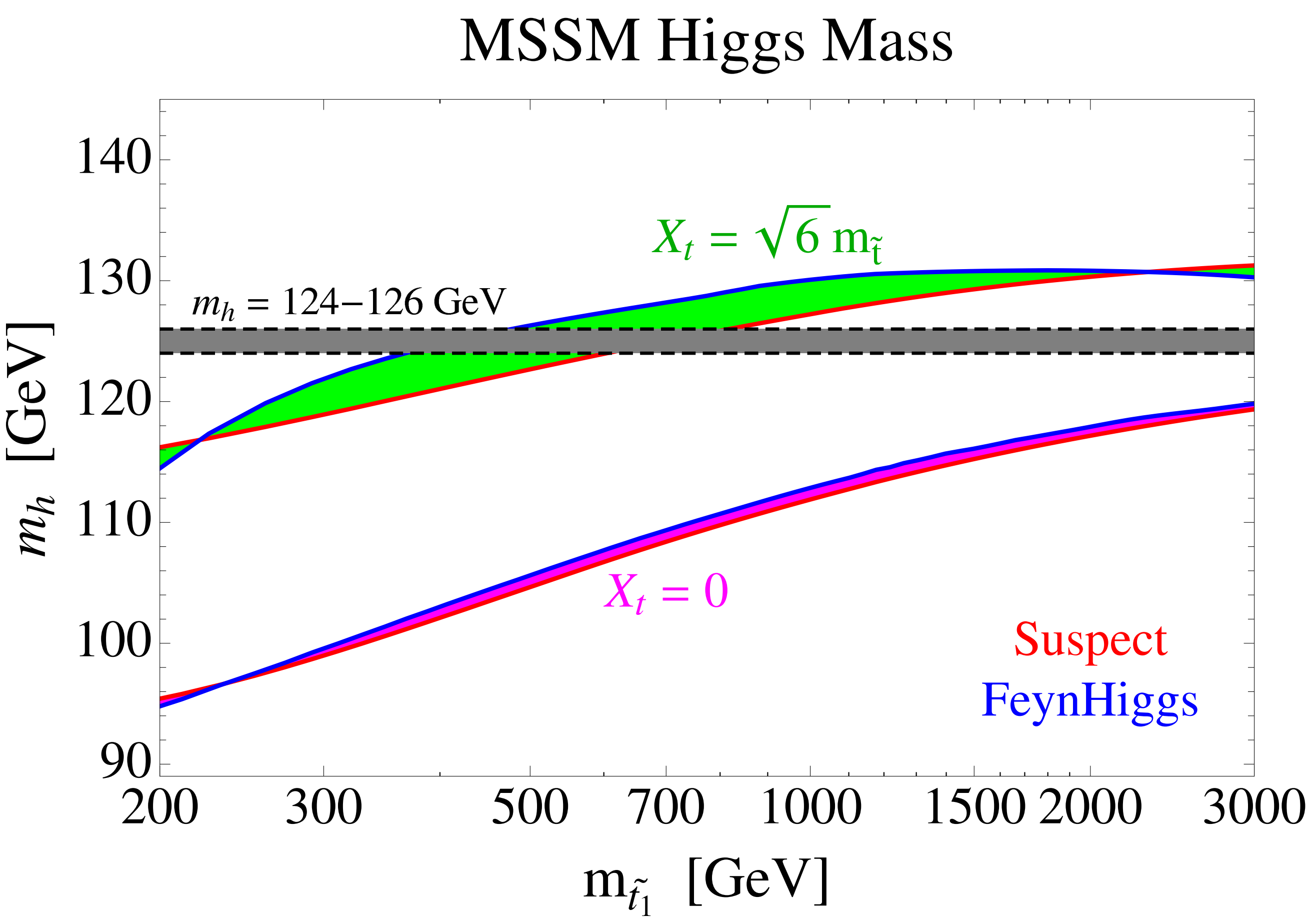
  ⋆ $\Rightarrow M_H \approx 126$ GeV requires

$$\Delta m_h \approx 85 \text{ GeV } (\tan\beta \text{ large}) \Rightarrow \text{large corrections}$$

  ⋆ Corrections require large stop masses $m_{\tilde{t}_1}, m_{\tilde{t}_2}$ and/or large mixing $X_t \rightsquigarrow$ 'fine'-tuning

MSSM Scalar Boson Mass in View of the LHC Results

Hall,Pinner,Ruderman 1112.2703



- **Even for maximal stop mixing:** $m_{\tilde{t}_1} \stackrel{!}{\gtrsim} 500$ GeV

MSSM Scalar Boson and Enhanced Diphoton Rate

- **MSSM Scalar Boson of ~ 126 GeV**

  Next-lightest scalar boson can be the SM-like scalar of ~ 126 GeV (low M_A, moderate $\tan\beta$)
  lightest scalar boson below LEP limit   see e.g. Heinemeyer eal '11

- **Enhanced Diphoton rate**

  Carena eal; Hagiwara eal; Christensen eal; Barger eal; Heinemeyer eal; Arbey eal; ...

$$BR(h^{126\,\text{GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{126\,\text{GeV}}]}$$

∗ Suppression of $\Gamma(h^{126\,\text{GeV}} \to b\bar{b})$ due to

◇ corrections to the boson propagator $\longrightarrow$ mixing angle α

◇ Δ_b corrections to $h^{126\,\text{GeV}} b\bar{b}$ coupling

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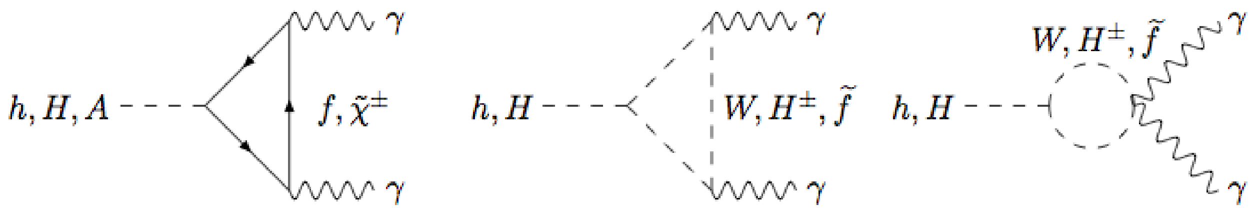

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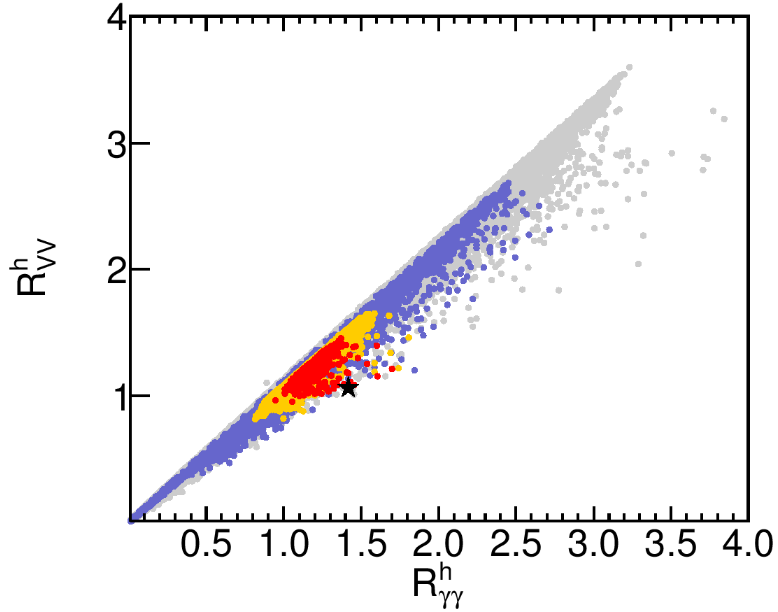
  ⋄ Δ_b corrections to $h^{126\,\text{GeV}} b\bar{b}$ coupling

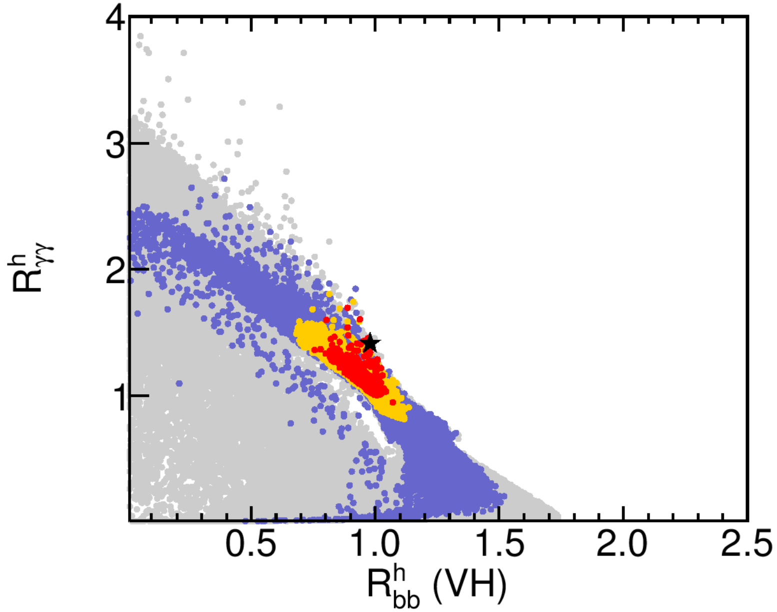
∗ Enhanced $\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)$ due to light stau loops, chargino loop contributions

∗ $h^{126\,\text{GeV}}$ can be h, H

MSSM Scan for Enhanced Diphoton Rate

Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, Zeune





- Pass theoretical constraints and one CP-even scalar with 121...129 GeV mass
- Compatible with direct search limits
- $\Delta\chi^2_h < 2.3$ • $\Delta\chi^2_h < 5.99$
- Best fit point

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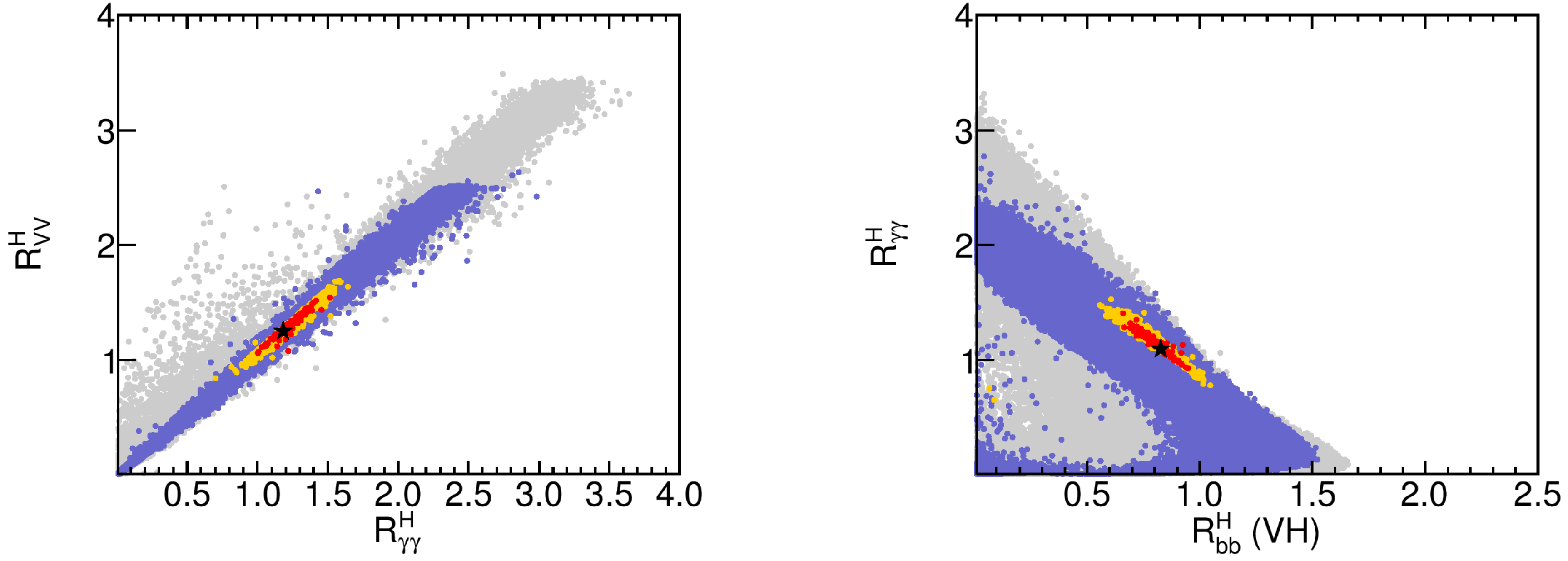

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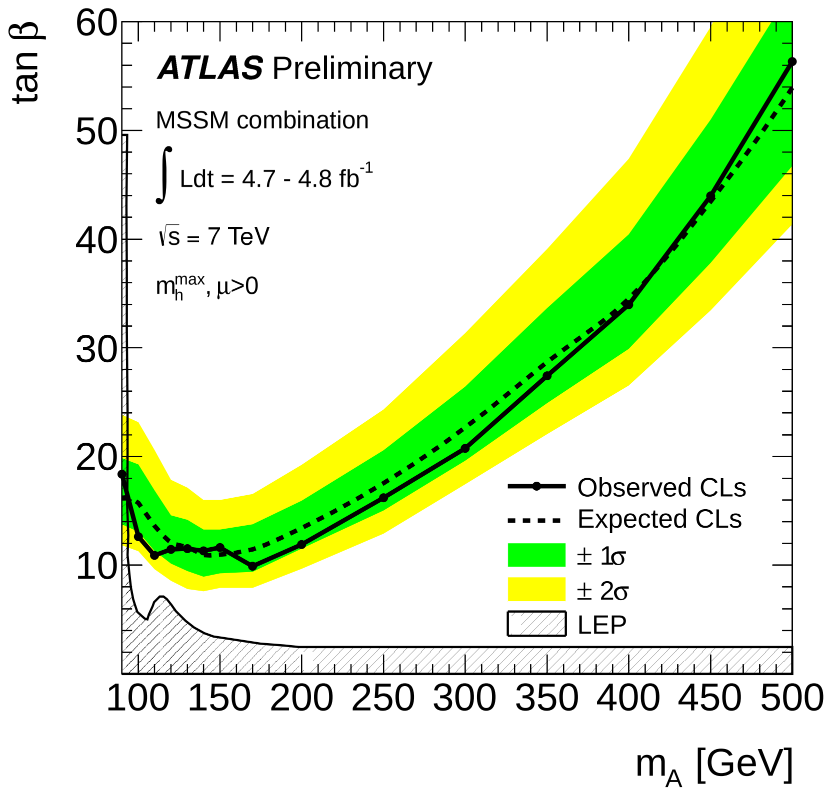
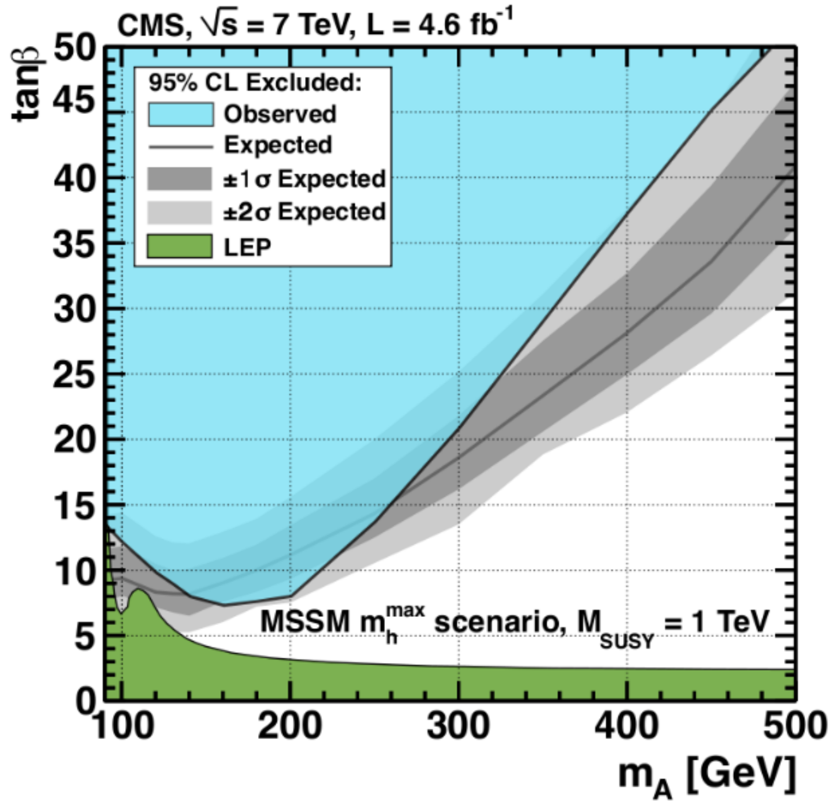
Search for $\mathcal{MSSM}$ Bosons at the $\mathcal{LHC}$

$$gg \to b\bar{b}\phi^0,\ gg \to \phi^0, \qquad \phi^0 \to \tau^+\tau^-$$

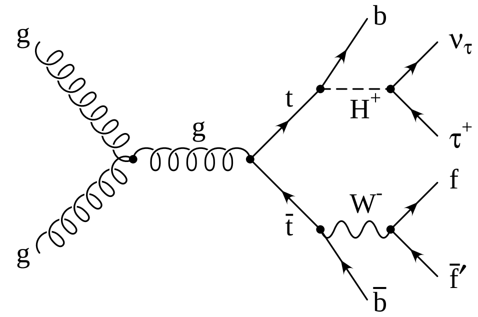
ATLAS-CONF-2012-094



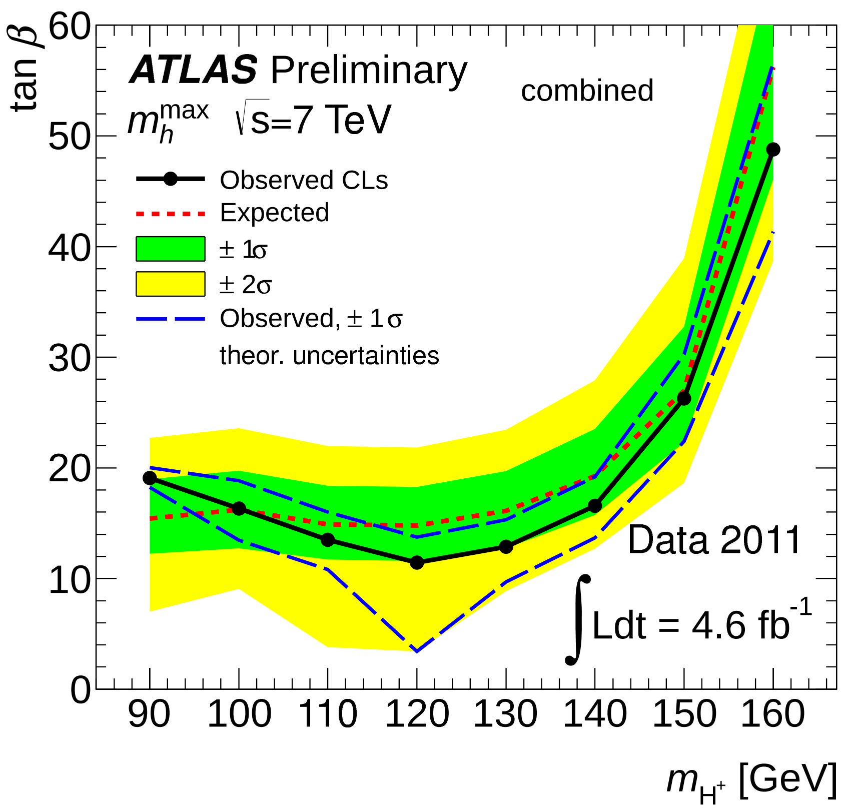
CMS 1202.4083



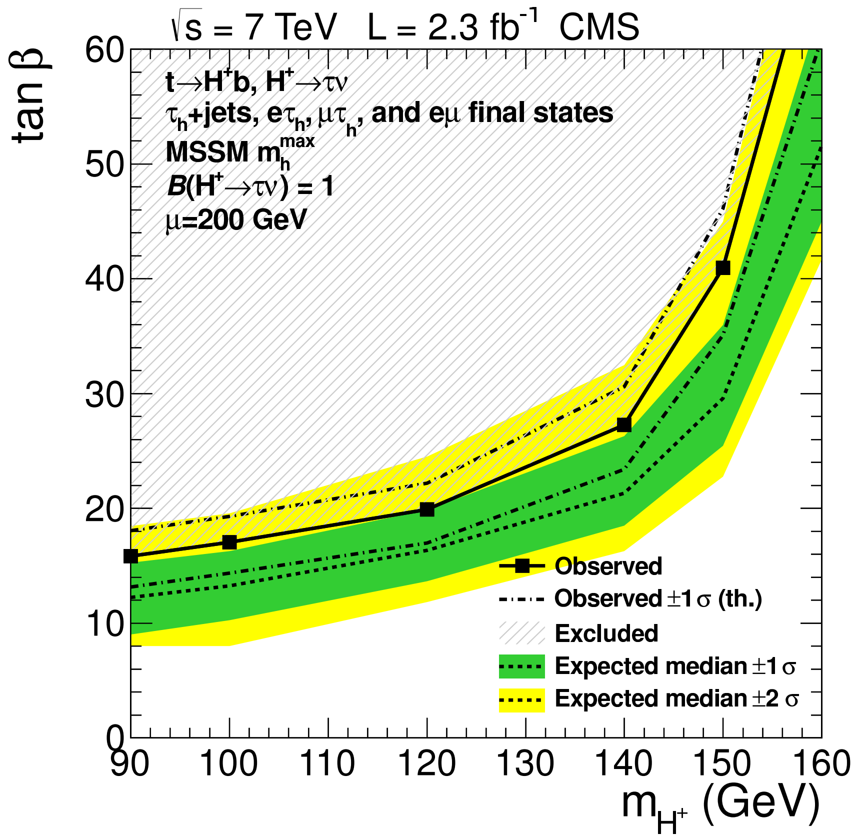
Search for MSSM Bosons at the LHC



ATLAS-CONF-2012-011



CMS-HIG-11-019



The EWSB $\mathcal{S}$ector of the $\mathcal{NMSSM}$

- **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 $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

- **Enlarged (pseudo-)scalar and neutralino sector:** 2 complex doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 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 the phenomenology**

NMSSM Scalar Boson Mass in View of the LHC Results

- **Vast literature on NMSSM scalar boson of ~ 125-126 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 scalar boson mass with LHC Searches:**

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

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

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

  $\Rightarrow M_H \approx 126$ requires:

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

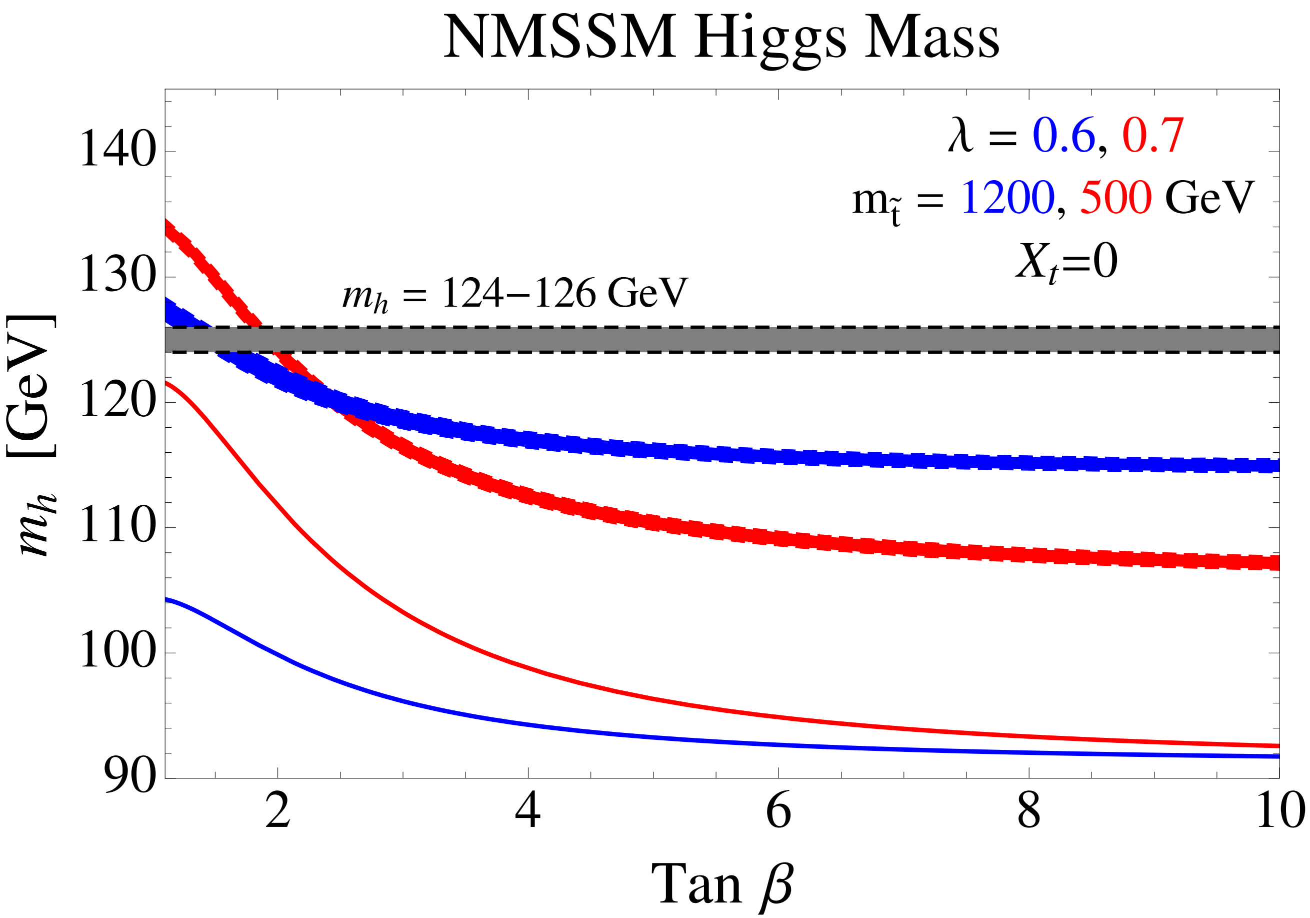
  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan\beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning

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

NMSSM Scalar Boson Mass in View of the LHC Results

Hall,Pinner,Ruderman 1112.2703



- ◇ m_h maximized for small values of $\tan\beta$
- ◇ $m_h \approx 126$ GeV can be achieved also for zero mixing $X_t = 0$ and $m_{\tilde{t}_1} \geq 500$ GeV

NMSSM Scalar Boson Mass

- **Mass prediction** as precise as possible:

  distinguish between MSSM and NMSSM

  properly define scenarios with decays of (pseudo-)scalars in other (pseudo-)scalars

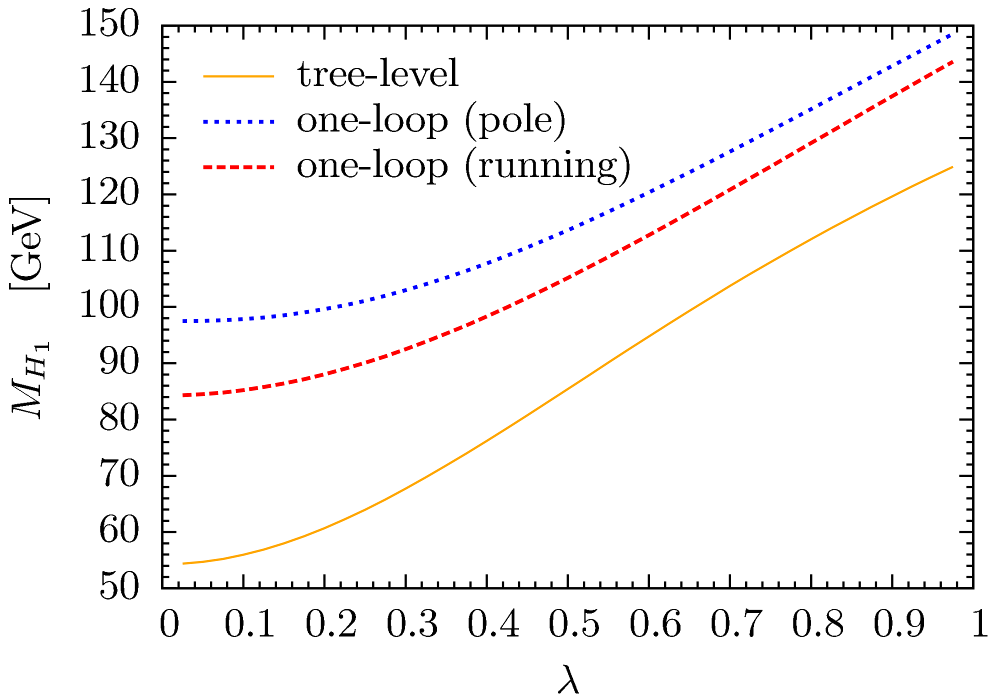
  correctly interpret experimental data

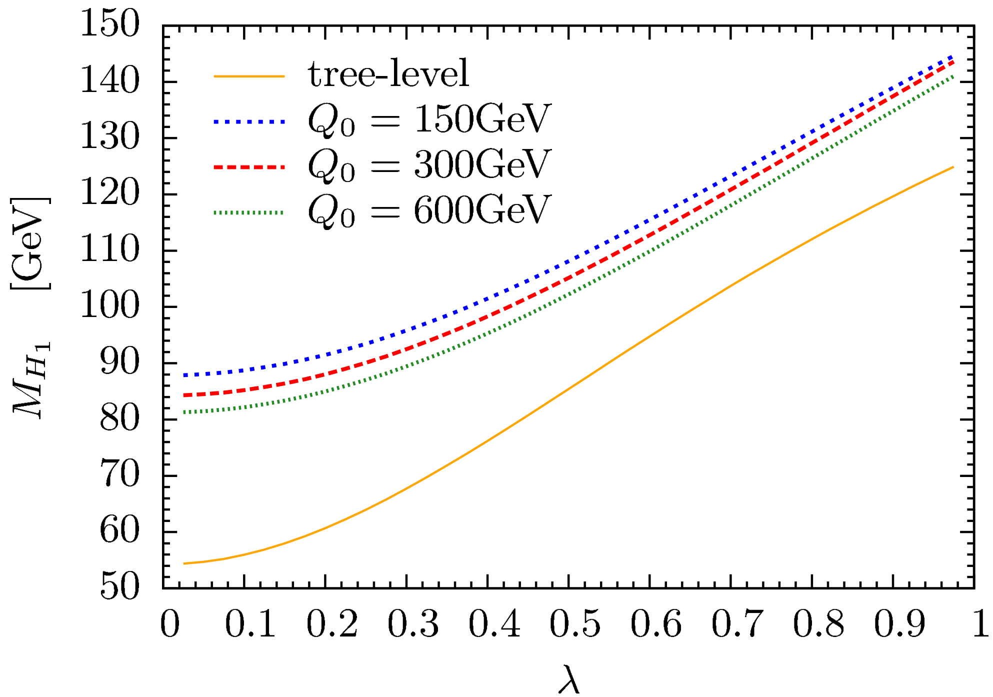
- **Status of the mass calculations:**

  - 1-loop corrections in effective potential approach — Ellwanger eal; Elliott eal; Pandita; Degrassi,Slavich
  - 1-loop corrections in Feynman-diagramatic approach — Ender,Graf,MMM,Rzehak '11
  - 2-loop $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ — Degrassi,Slavich
  - 1-loop w/ CP violation in effective potential approach — Ham eal; Cheung eal

NMSSM Scalar Boson Mass

Ender,Graf,MMM,Rzehak '11





Top quark mass:

$m_t^{pole} = 173.3$ GeV

$m_t^{\overline{DR}} = 150.6$ GeV at $Q = 300$ GeV

⇒ theoretical uncertainty of the one-loop calculation: $\mathcal{O}(10\%)$

For 1-loop mass corrections in the complex NMSSM, see Graf,Grober,MMM,Rzehak,Walz '12

$\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

- **SM-like NMSSM scalar boson of ~ 126 GeV**

  Can be either H_1 or H_2 (H_1 singlet-like, suppr. SM couplings)

- **Enhanced Diphoton rate**

$$BR(h^{126\,\text{GeV}} \to \gamma\gamma) = \frac{\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)}{(\Gamma_{b\bar{b}} + \Gamma_{WW} + \Gamma_{ZZ} + ...)[h^{126\,\text{GeV}}]}$$

$*$ Suppression of $\Gamma(h^{126\,\text{GeV}} \to b\bar{b})$ due to Hall,Pinner,Ruderman; Ellwanger; King,MMM,Nevzorov; Cao,Heng,Yang,Zhang,Zhu; Albornoz-Vasquez,Belanger,Boehm,DaSilva,Richardson,Wymant

◇ strong singlet-doublet mixing $\rightsquigarrow$ reduced coupling to $b\bar{b}$

◇ Δ_b corrections to $h^{126\,\text{GeV}} b\bar{b}$ coupling

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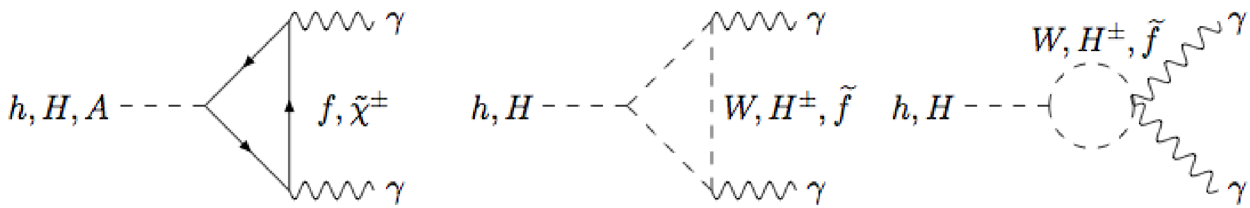

NMSSM Scalar Boson and Enhanced Diphoton Rate

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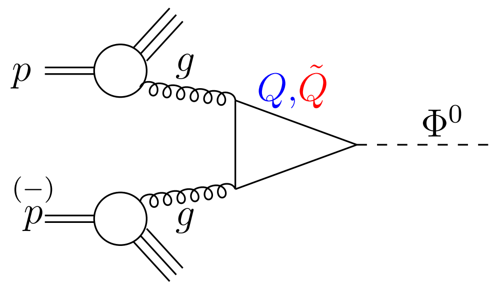
  * $h^{126\,\text{GeV}}$ can be H_1, H_2

$\mathcal{NMSSM}$ $\mathcal{S}$calar $\mathcal{B}$oson and $\mathcal{E}$nhanced $\mathcal{D}$iphoton $\mathcal{R}$ate

- **Enhancement on the production side**

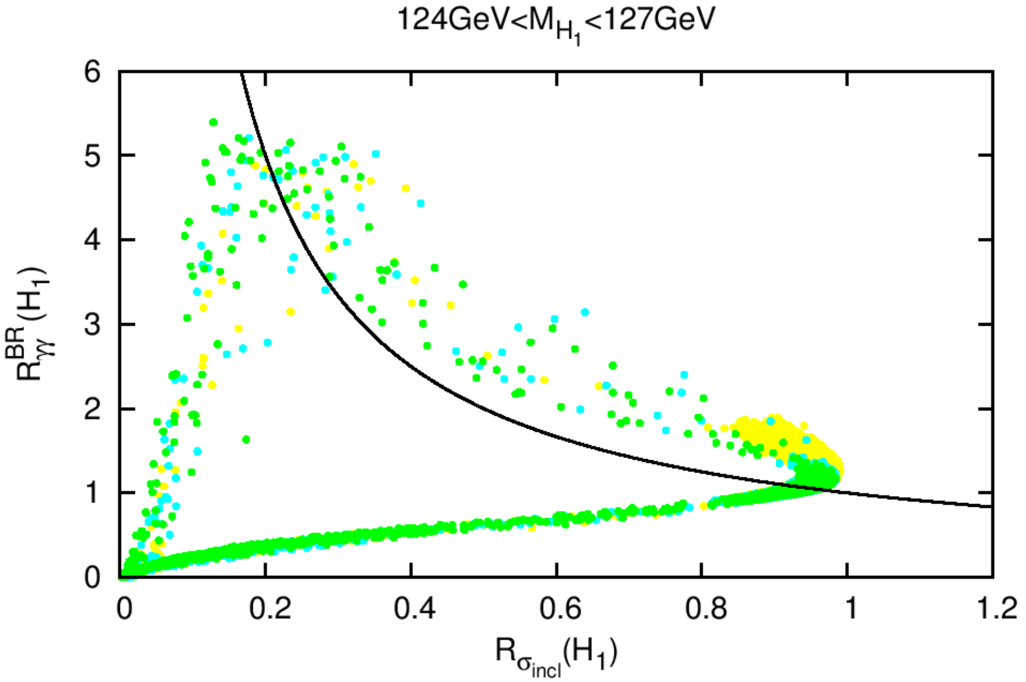


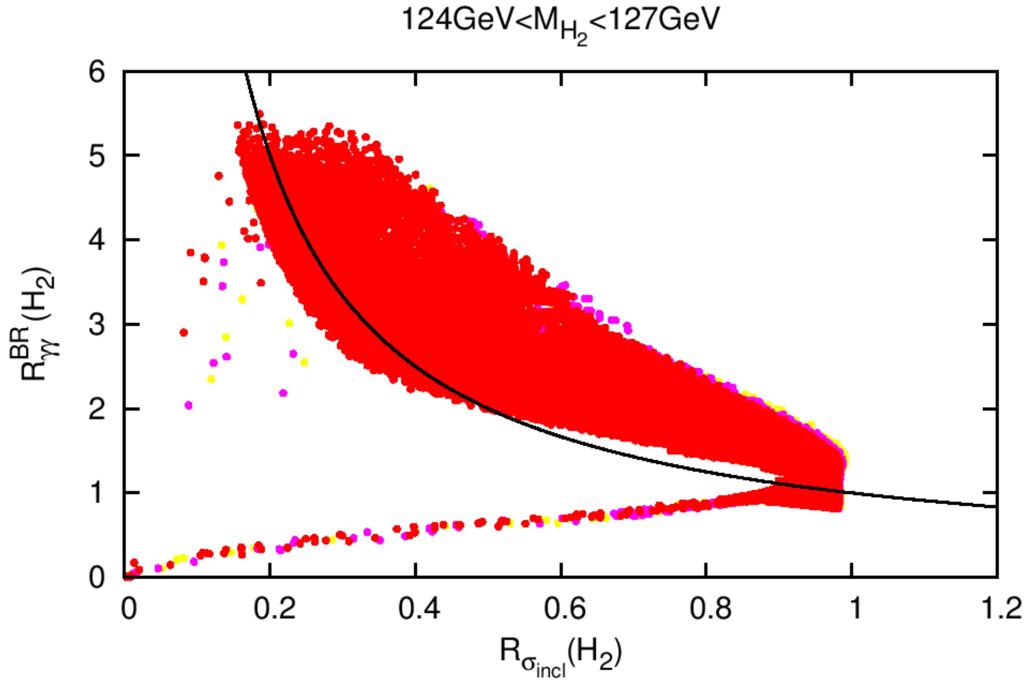
- **Enhanced gluon fusion production** See e.g. King,MMM,Nevzorov,Walz

  * Stop, sbottom loop contributions in $gg \to H_i$ can enhance the production cxn for small mixing
  * Associated *slight* suppression in $BR(h^{126\,\text{GeV}} \to \gamma\gamma)$ compensated by positive chargino, charged boson loop contributions
  * $\Rightarrow$ overall enhanced production in $\gamma\gamma$ final states, $\mu_{\gamma\gamma} > 1$
  * Couplings to WW, ZZ must be suppressed in this case $\rightsquigarrow$ overall production in VV final states $\approx$ SM-like, $\mu_{ZZ,WW} \approx 1$

$\mathcal{NMSSM}$ $\mathcal{S}$can

King, MMM, Nevzorov, Walz





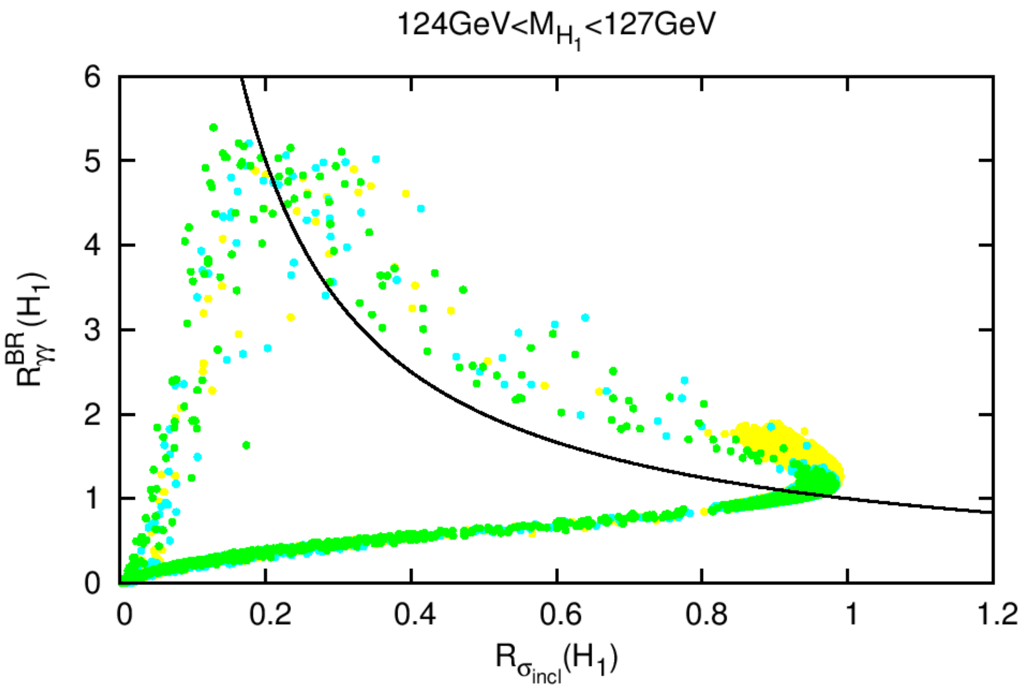
$\star$ $0.55 \leq \lambda \leq 0.8$, $10^{-4} \leq \kappa \leq 0.4$, 100 GeV $\leq \mu_{\text{eff}} \leq$ 200 GeV,

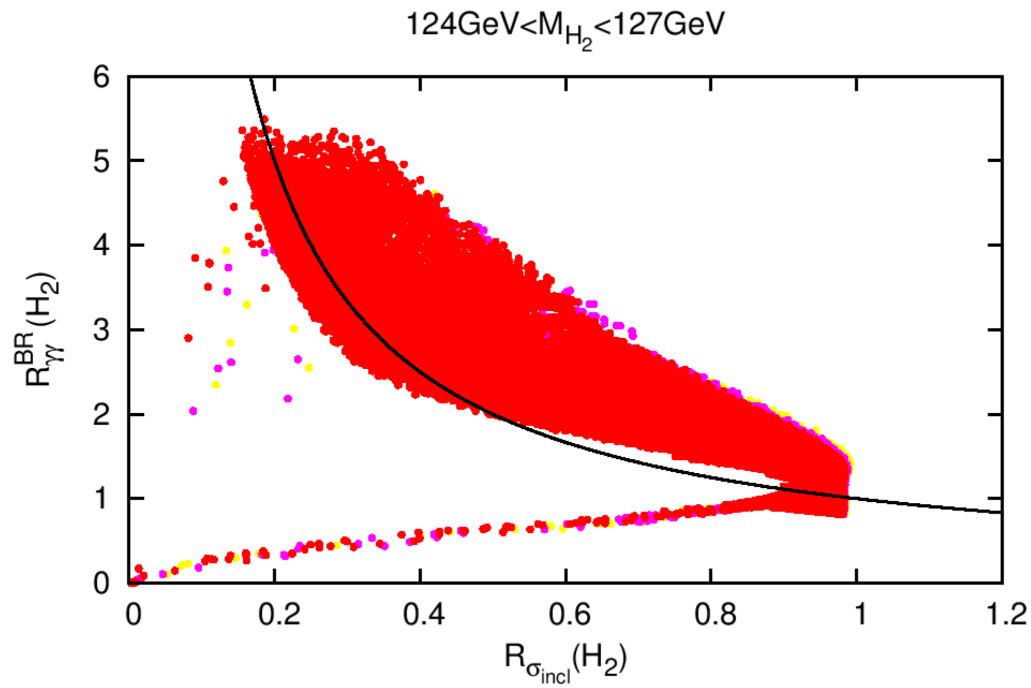
500 GeV $\leq M_{Q_3}, M_{t_R} \leq$ 800 GeV , -500 GeV $\leq A_\kappa \leq 0$ GeV , 200 GeV $\leq A_\lambda \leq$ 800 GeV ,

$\tan\beta = 2, 3$, $A_t = 1$ TeV

$\mathcal{NMSSM}$ $\mathcal{S}$can

King,MMM,Nevzorov,Walz

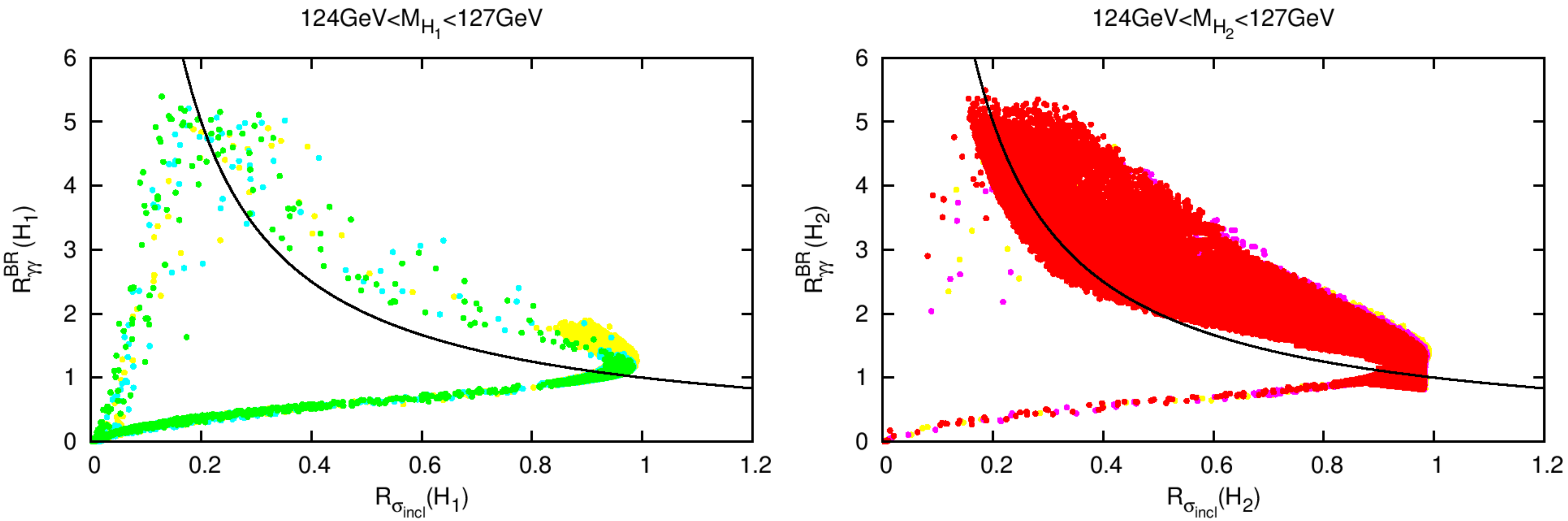




- ⋆ $R^{BR}_{\gamma\gamma} = BR^{NMSSM}_{\gamma\gamma}/BR^{SM}_{\gamma\gamma}$ enhanced: ◦ $BR_{\gamma\gamma}\uparrow$: $H^\pm, \tilde{\chi}^\pm, \tilde{t}$ loops, suppressed $g_{H_i bb}$ coupling
- ⋆ $R_{\sigma_{incl}} = \sigma^{NMSSM}_{incl}/\sigma^{SM}_{incl}$ enhanced: ◦ $\sigma_{prod}\uparrow$: $\tilde{t}$ loops and, or $g_{H_i tt}\uparrow$

$\mathcal{NMSSM}$ Scan

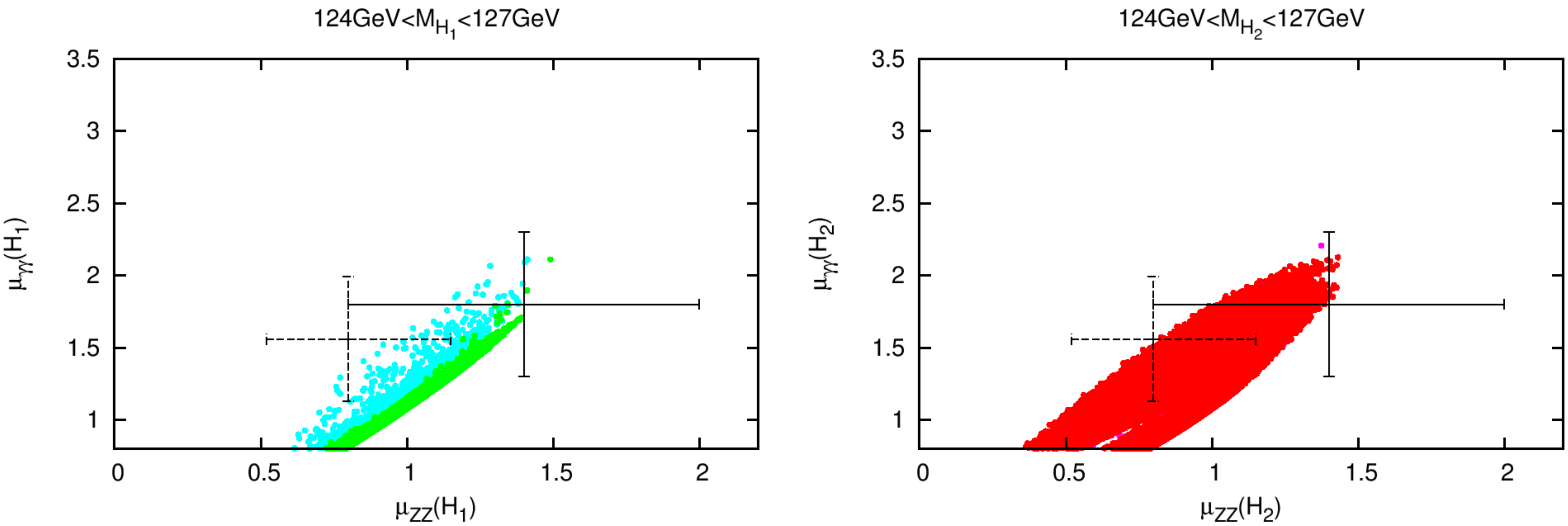
King,MMM,Nevzorov,Walz



* green/red points: perturbation theory valid up to the GUT scale
* cyan/pink points: require extra matter at 1 TeV

$\mathcal{NMSSM}$ $\mathcal{S}$can

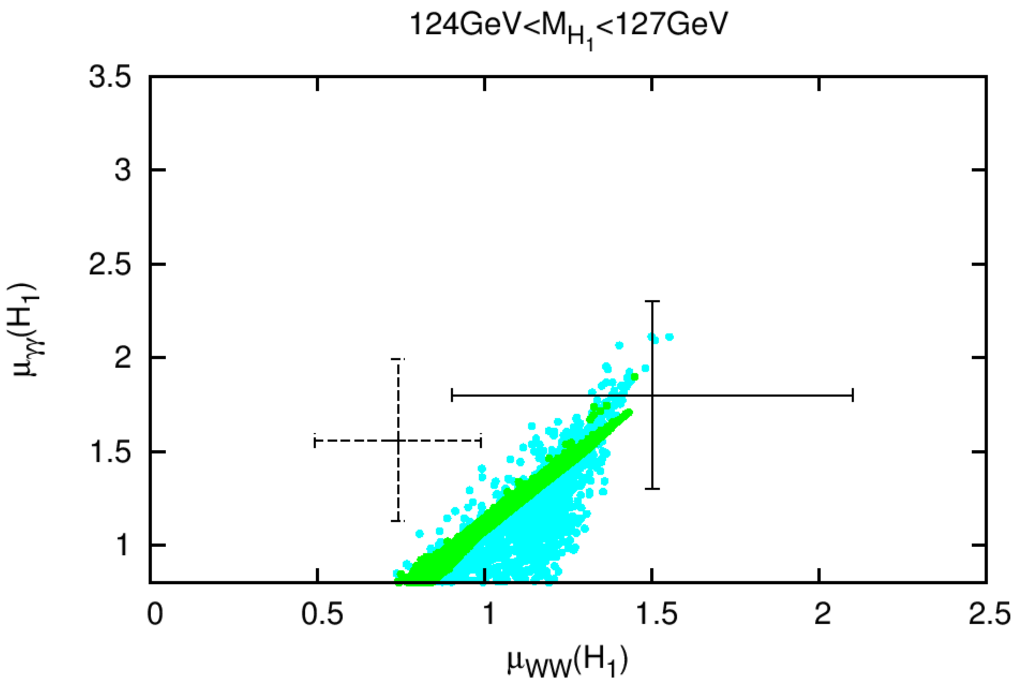
King,MMM,Nevzorov,Walz

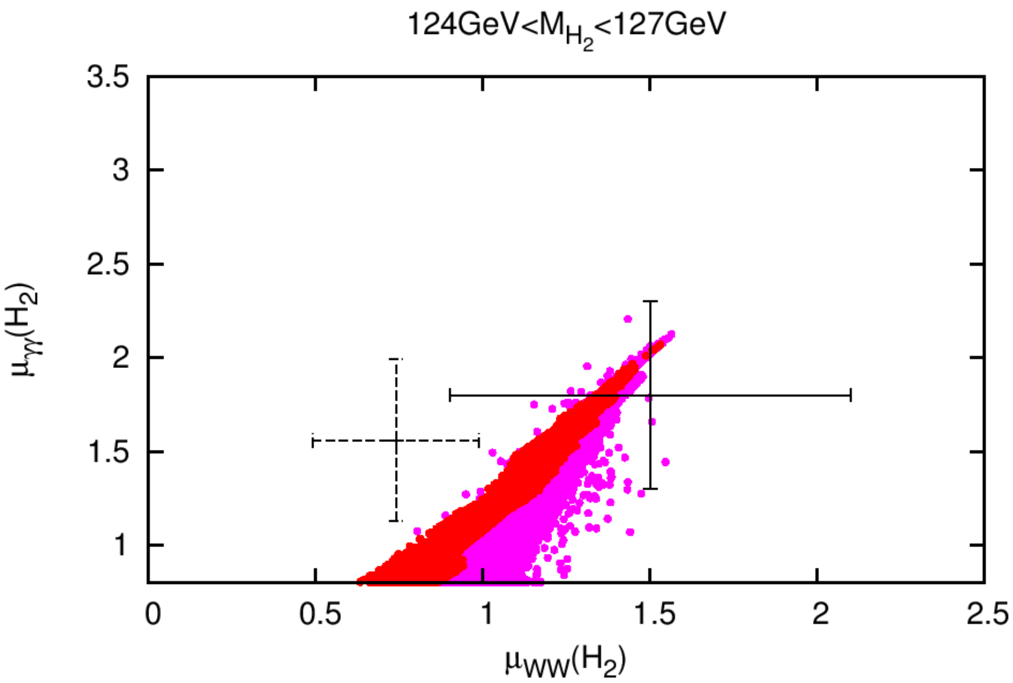


* cyan/pink points: two signals overlap
* crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS

$\mathcal{NMSSM}$ $\mathcal{S}$can

King,MMM,Nevzorov,Walz





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NMSSM Scan

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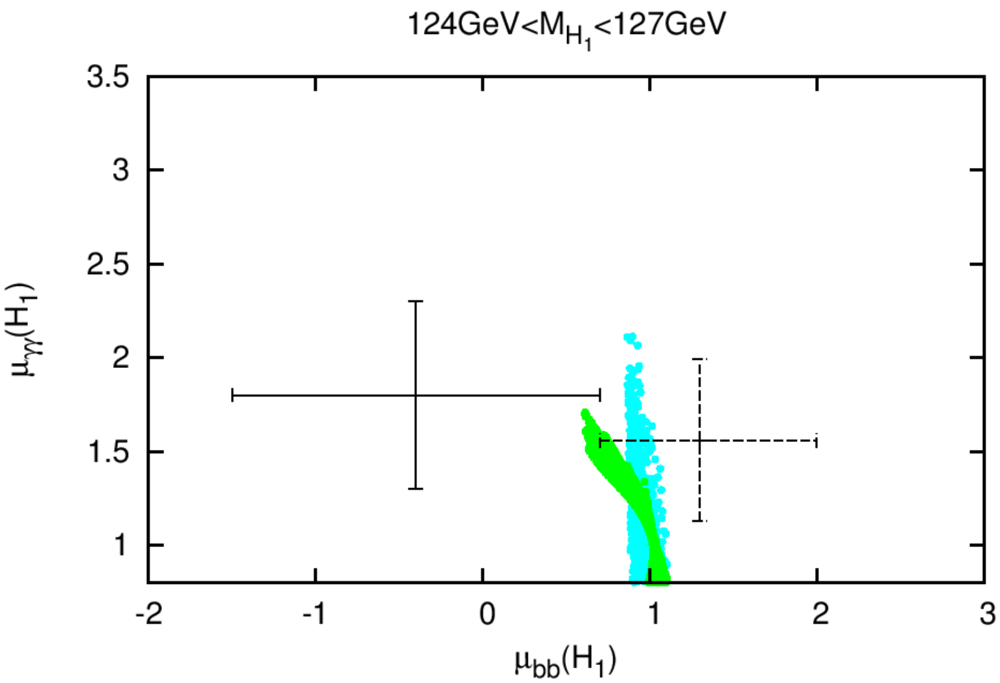

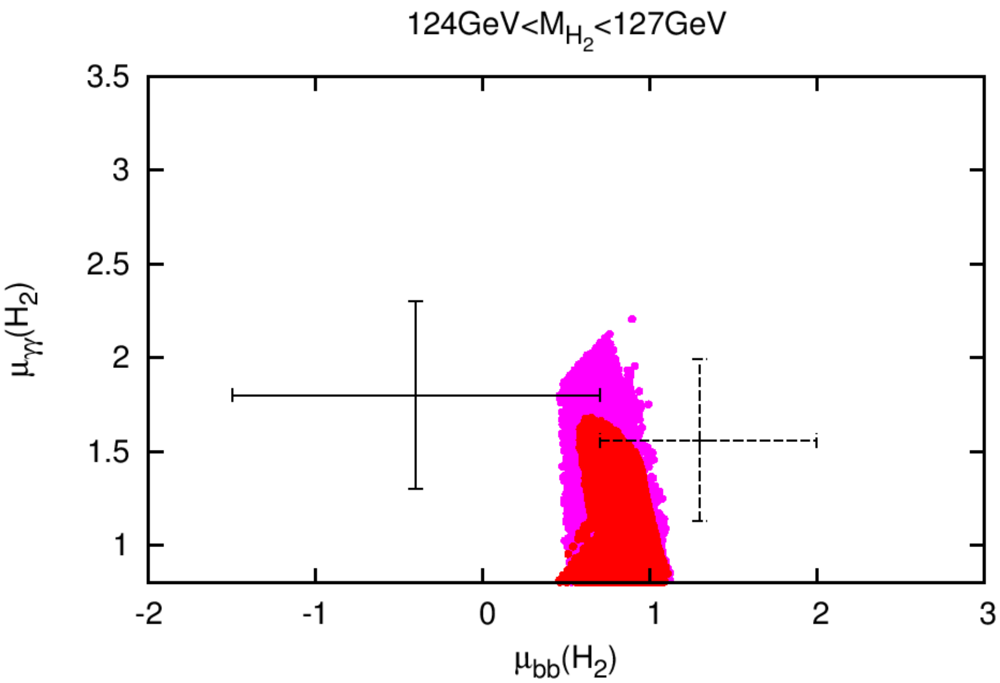

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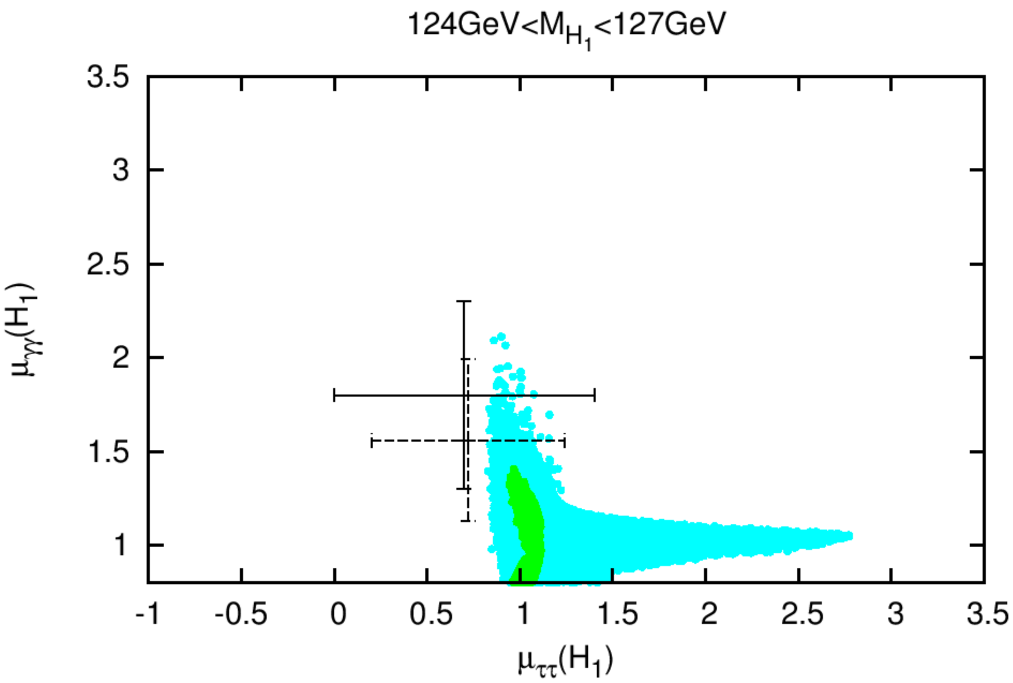

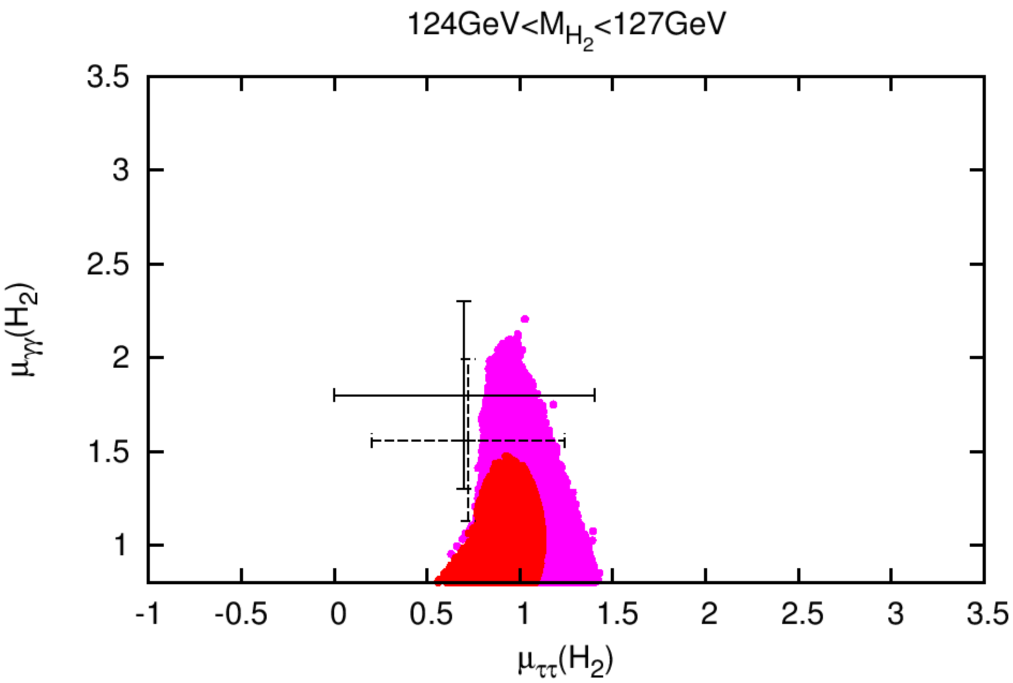

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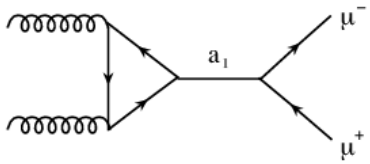
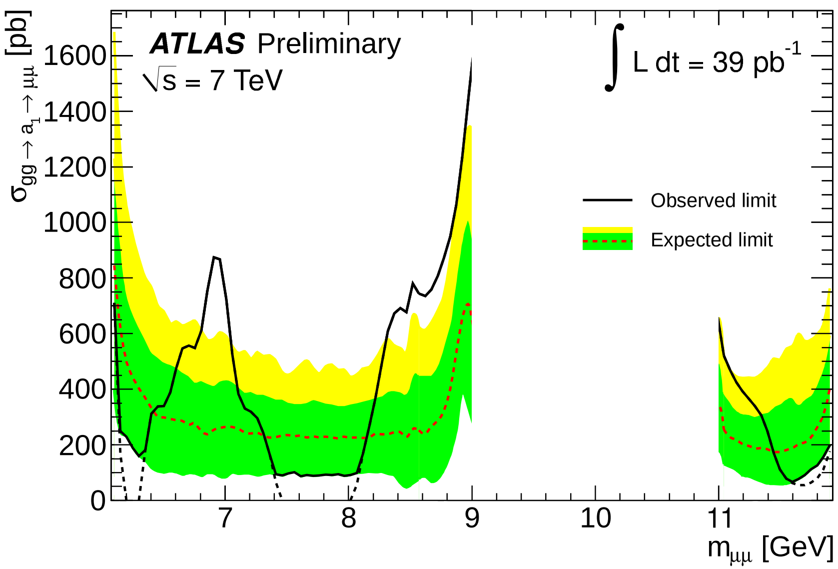
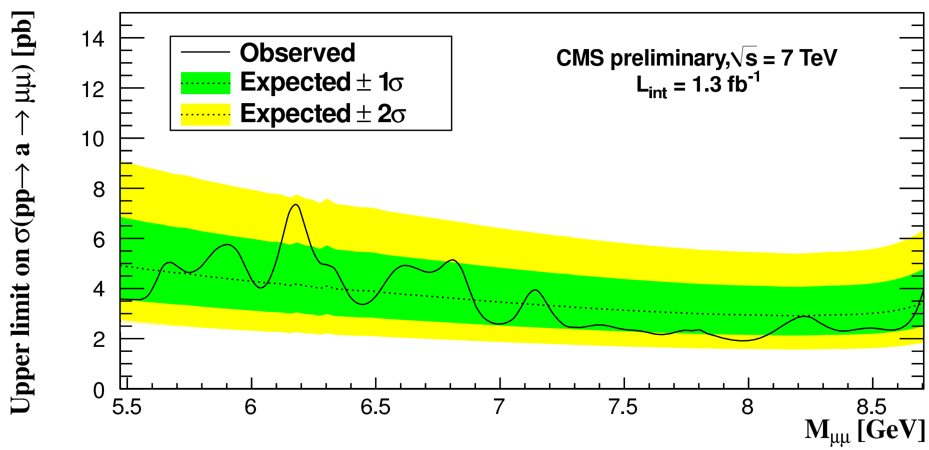
Upper Limit on NMSSM a_1 Production



ATLAS-CONF-2011-020



CMS-HIG-12-004



More Exotic?

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

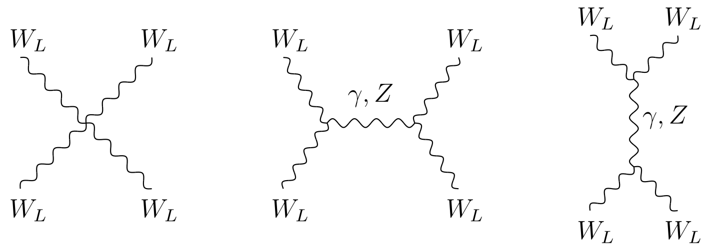
Lone Higgs

Simplest Higgs

Phantom Higgs

$\mathcal{W}$hat is the $\mathcal{SM}$ and what the $\mathcal{C}$omposite $\mathcal{S}$calar $\mathcal{B}$oson?

- **Scalar boson: creation of particle masses**



$$\mathcal{A} = \frac{s}{v^2}$$

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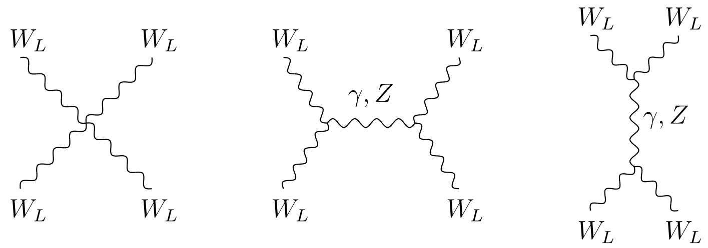
- **Scalar boson: creation of particle masses**



$$\mathcal{A} = \frac{s}{v^2}$$

- **Electroweak symmetry breaking $\mathcal{L}$** Cornwall eal; Contino,Grojean,Moretti,Piccinini,Rattazzi

  custodial symmetry and minimal flavour violation (MFV) built-in

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}(D_\mu\Sigma^\dagger\, D^\mu\Sigma)\left(1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2}\right) - \lambda\bar{\psi}_L\Sigma\,\psi_R\left(1 + c\,\frac{h}{v}\right)$$

$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$

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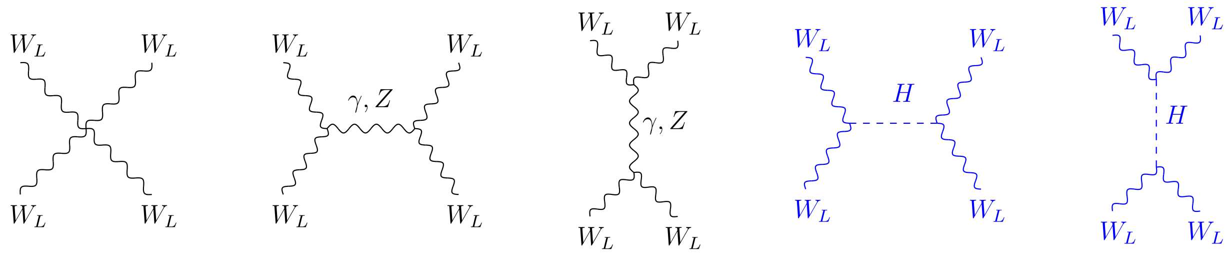

$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

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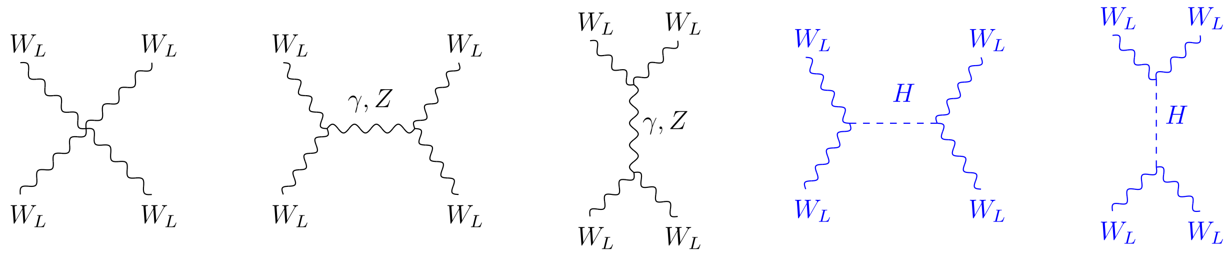

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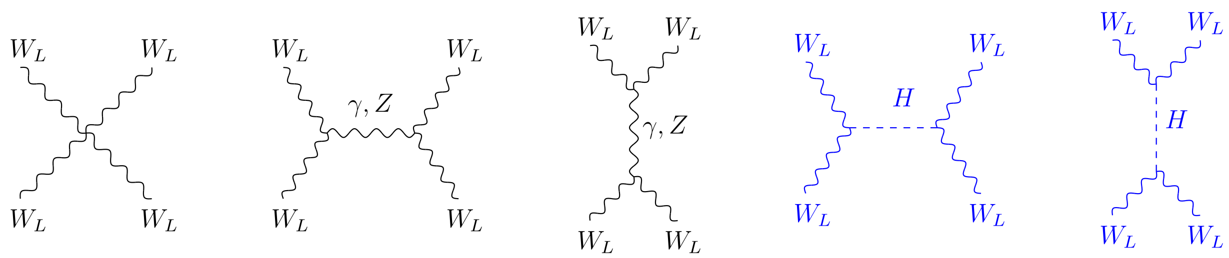
$a = 1$ perturbative unitarity in $WW \to WW$

$b = a^2$ perturbative unitarity in $WW \to hh$

$ac = 1$ perturbative unitarity in $WW \to \psi\psi$

$\mathcal{W}$hat is the $\mathcal{SM}$ and what the $\mathcal{C}$omposite $\mathcal{S}$calar $\mathcal{B}$oson?

- **Scalar boson: creation of particle masses and UV regulator**



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SM Scalar boson: $a = b = c = 1$

Composite boson: $a, b, c \neq 1$

Composite Boson - Introduction

- **Bound state from a strongly interacting sector** Kaplan,Georgi;Dimopoulos eal;Dugan eal

- **How can we obtain a light composite scalar boson?**

  Global symmetry of strong sector G spontaneously broken at scale f to subgroup H

  G/H: 4th Nambu-Goldstone Boson: Scalar 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 doublet field

  Example: - $SO(5)/SO(4) \rightsquigarrow$ PGB: one doublet

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

$\xi = 0$ SM limit	$\longleftarrow$	$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$	$\longrightarrow$	$\xi = 1$ Technicolor limit
strong sector resonances decouple, except boson				boson deccouples, vector resonances like in TC

- **No hierarchy problem** EWSB potential generated at one-loop through gauge and top loops

Anomalous couplings

- **SILH effective Lagrangian** — Giudice,Grojean,Pomarol,Rattazzi
- **Large ξ** 5D MCHM provides completion for large $\frac{v}{f}$ $(SO(5)/SO(4))$ — Contino eal; Agashe eal

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

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

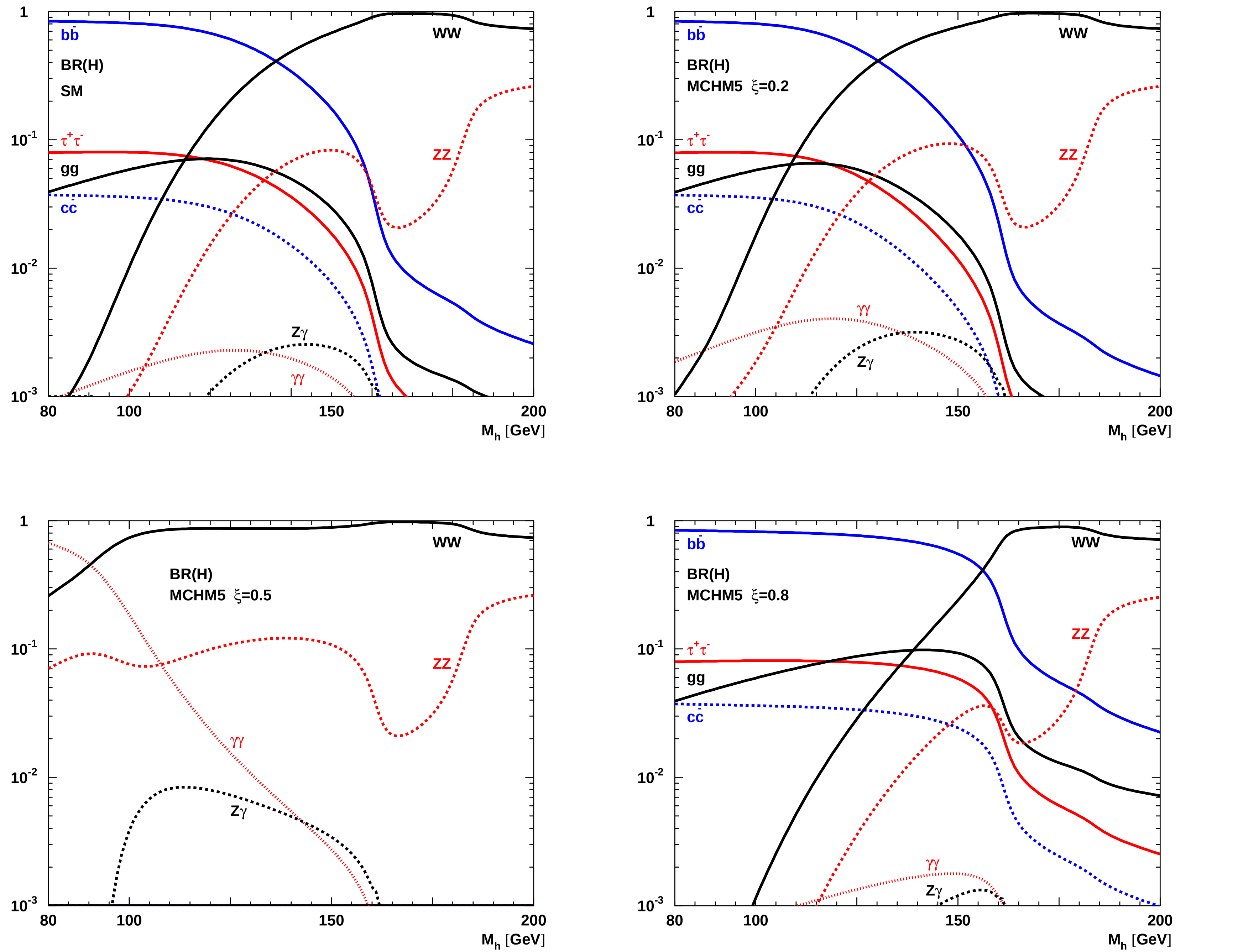
MCHM4	MCHM5
$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$ $g_{Hff} = g_{Hff}^{SM}\sqrt{1-\xi}$	$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi}$ $g_{Hff} = g_{Hff}^{SM}\frac{(1-2\xi)}{\sqrt{1-\xi}}$
universal factor $\rightsquigarrow$ BRs unchanged	g_{Hff} coupling vanishes for $\xi = 0.5$

In the following: $\xi = 0.2, 0.5, 0.8$ (also scalar boson self-coupling depends on representation)

- **Impact on** BR's, Γ_{tot}, production cross sections, search significances

- **Branching ratios MCHM5**

Espinosa, Grojean, Mühlleitner



$\mathcal{C}$onstraints

- **EW precision observables:** constrain only a
  - $*$ $\hat{T} = c_T \frac{v^2}{f^2} \Rightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$ removed by custodial symmetry
  - $*$ $\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2}$ $m_\rho \geq (c_W + c_B)^{1/2} 2.5$ TeV
  - $\star$ 1-loop IR effects Barbieri eal

    $\Delta\epsilon_{1,3} = -c_{1,3}(1-a^2)\log(m_\rho^2/m_h^2)$ constrains a

- **Flavor constraints**
  - $*$ no tree-level FCNC c is flavor universal $\rightarrow$ MFV built in

- **Direct searches LEP, Tevatron, LHC:** constrain a and c

  [rescale σ_{prod} and Γ_{decay}]

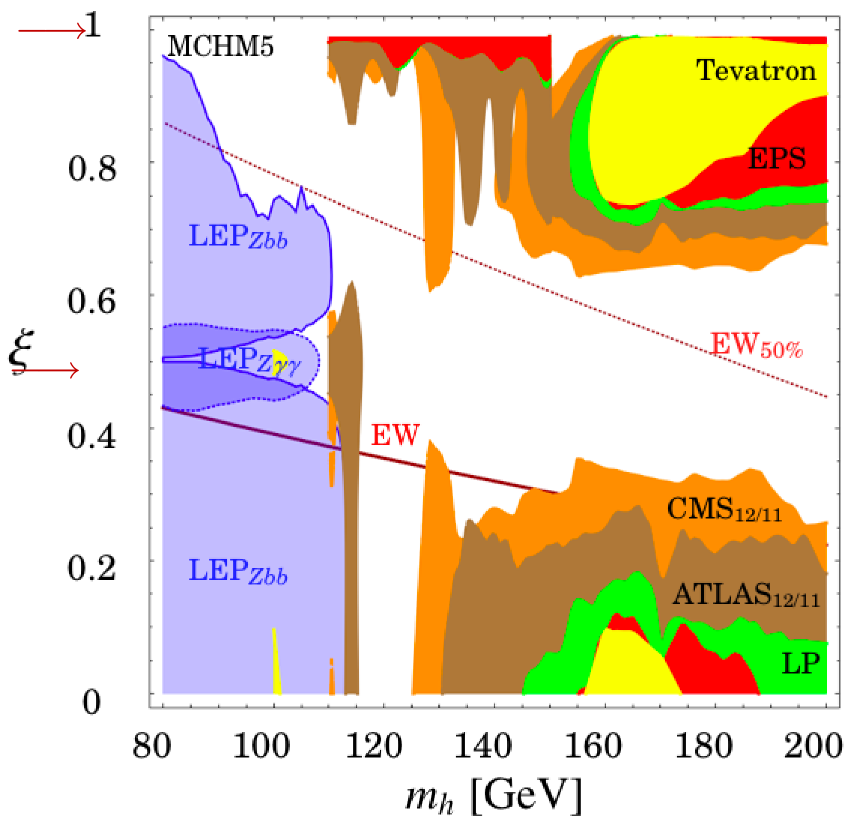
$\mathcal{C}$onstraints from EWPT, LEP, Tevatron, LHC - $\mathcal{P}$re-$\mathcal{M}$oriond '12

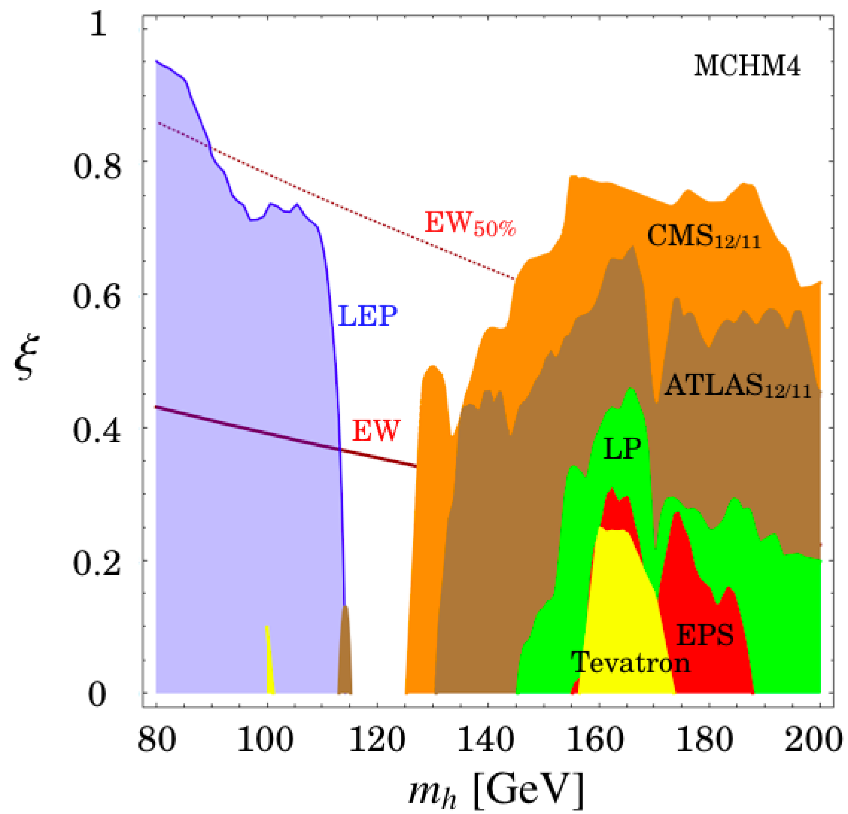
Espinosa,Grojean,MMM

gauge-phobic ⟶

fermiophobic ⟶

SM-limit ⟶





CMS 12/11 ATLAS 12/11 Lepton-Photon 11

LEP EPS-HEP 11 Tevatron

Model-Independent Fit to LHC Data

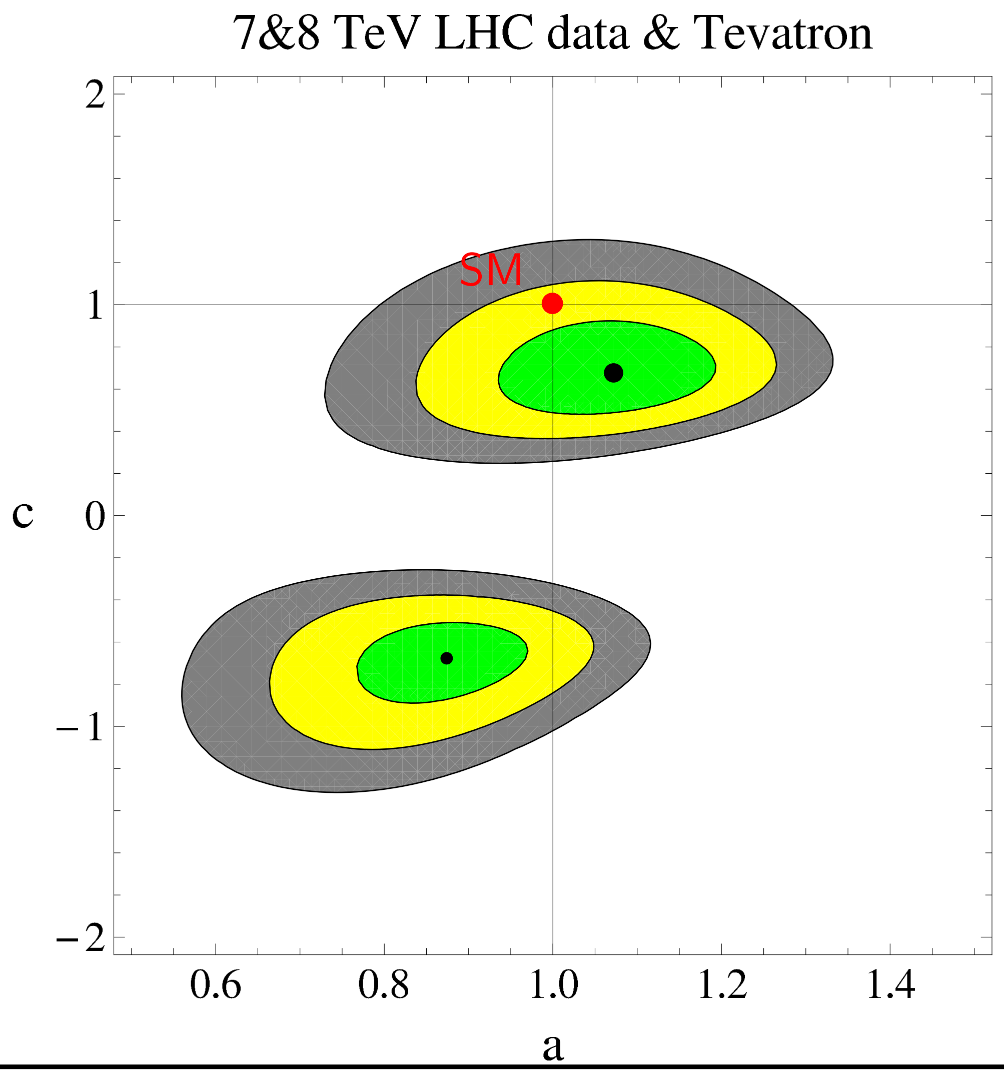
Effective theory assuming: custodial symmetry & MFV

Espinosa,Grojean,MMM,Trott '12

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

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

Two minima



Note: a fermiophobic scalar is disfavoured by data

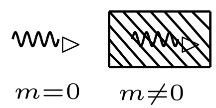
$\mathcal{E}$xperimental $\mathcal{V}$erification of the EWSB $\mathcal{M}$echanism

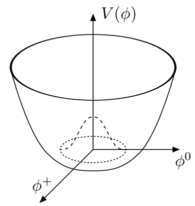
EWSB mechanism:

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 – $\lambda_{HHH}, \lambda_{HHHH}$



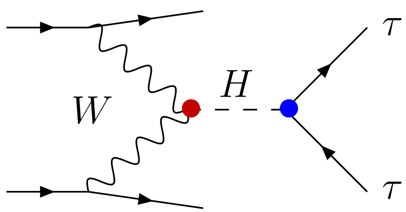


Determination of the Scalar Boson Couplings

Strategy

Combination of the production and decay channels ⇒ decay rates, absolute couplings

E.g.:



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

Coupling measurement at the LHC

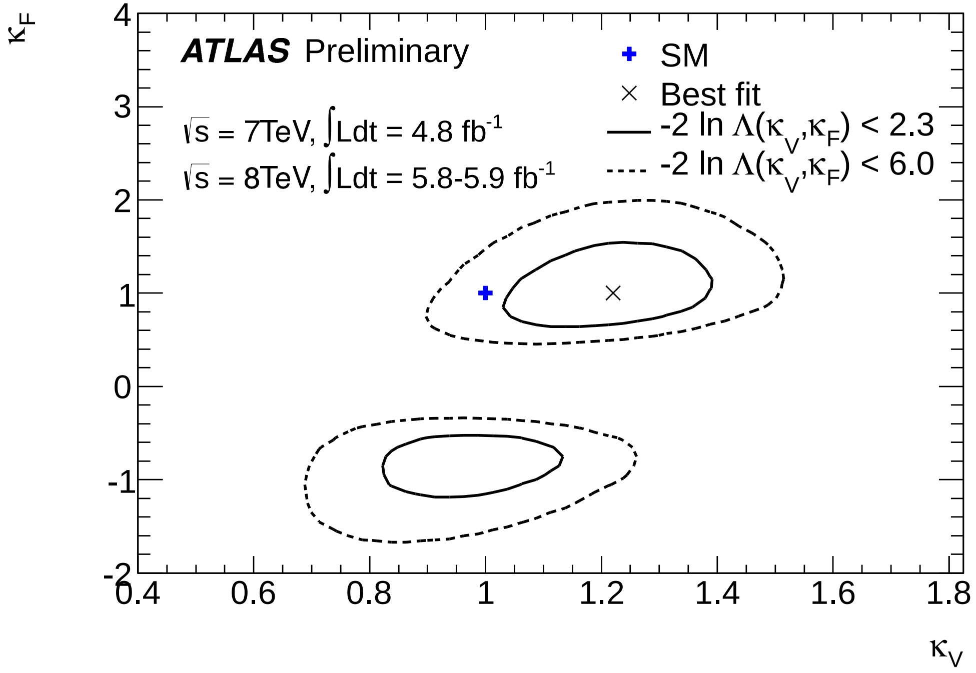
* Only ratios of couplings can be measured w/o model assumptions

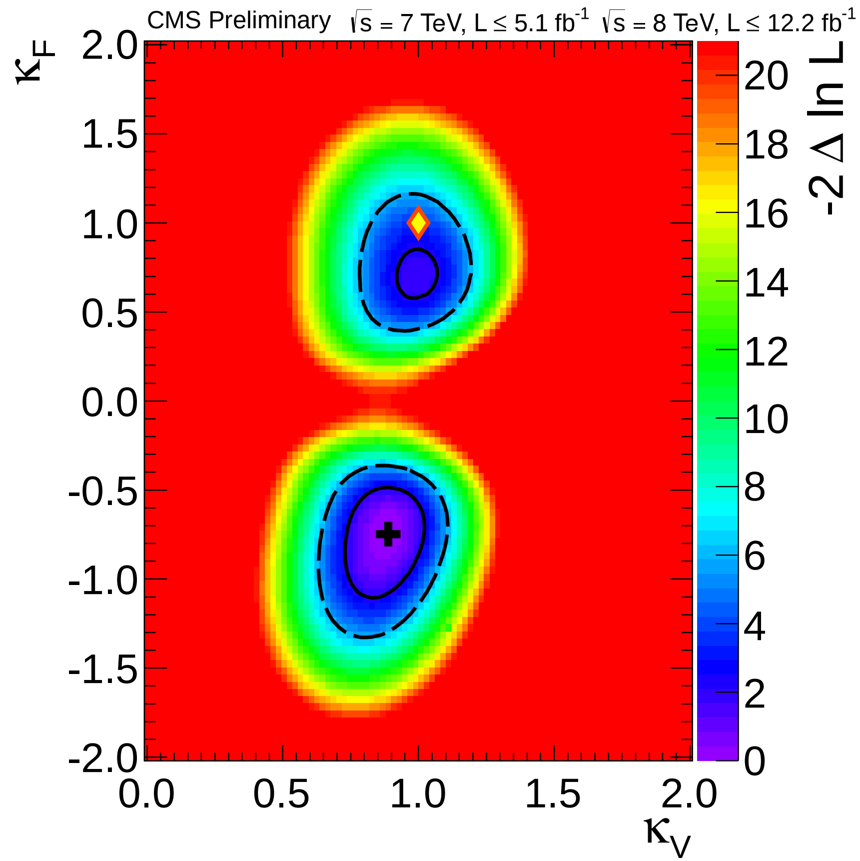
LHC HXSWG Recommendations to explore the coupling structure of a SM scalar boson-like particle

LHCHXSWG-2012-1:David,Denner,Dührssen,Grazzini,Grojean,Passarino,Schumacher,Spira,Weiglein,Zanetti

* Introduction of coupling scale factors
* Assumptions: observed signal from one single resonance; narrow-width approximation; coupling strengths modification but tensor strucure the one of the SM
* Various benchmarks for tests of coupling structure

$\mathcal{E}$xperimental $\mathcal{F}$its to $\mathcal{C}$ouplings





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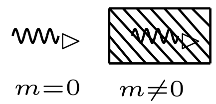
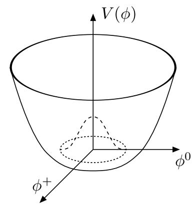


- Spin- and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$



$\mathcal{Q}$uantum $\mathcal{N}$umbers

Quantum numbers of the 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, threshold effects

- angular correlations in production: Hjj in vector boson fusion, gluon gluon fusion
  Plehn,Rainwater,Zeppenfeld; Hankele,Klämke,Zeppenfeld Campanario eal; Del Duca eal

- 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; Englert,Hackstein,Spannowsky: $lljj$

  CP-violation
  Buszello,Marquard,van der Bij Godbole,Miller,MMM

- below ZZ threshold: angular correlations, threshold effects
  Choi,Miller,MMM,Zerwas Buszello,Marquard,van der Bij

Spin and Parity – Recent Works

Hadronic event shapes

separate CP-even from CP-odd boson — Englert, Spannowsky, Takeuchi '12

Distributions

in decays into ZZ:
test spin, parity, CP violation — De Rújula, Lykken, Pierini, Rogan, Spiropulu '10

angular distr. in decays into $\gamma\gamma$, WW^* from spin 2 particle: tell apart spin 0 from spin 2 — Ellis, Hwang '12

M_{ZX} distribution in radiation off Z:
test $J^P = 0^\pm, 2^+$ — Ellis, Hwang, Sanz, You '12

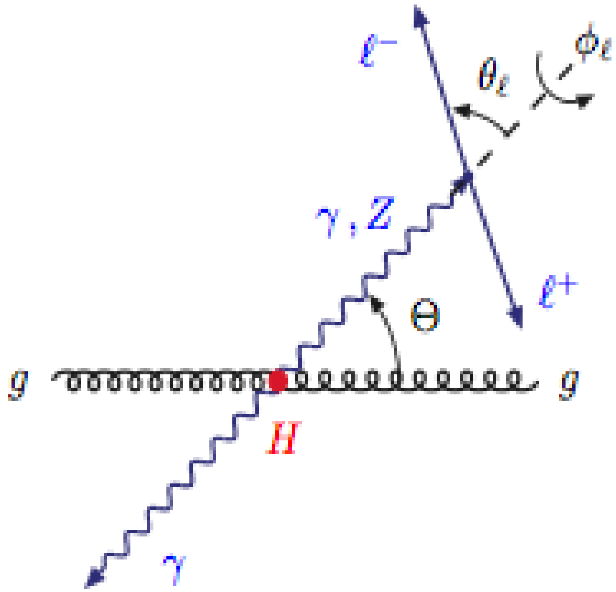
angular and mass distributions in decays into $ZZ, WW, \gamma\gamma$: test $J = 0, 1, 2$ resonance — Bolognesi, Gao, Gritsan, Melnikov Schumacher, Tran, Whitbeck'12(&'10)

angular distribution in decay into $\gamma\gamma$:
discriminate between $J^P = 0^+$ and 2^+ — Alves '12

...

$\mathcal{S}$pin $\mathcal{A}$nalysis in $H \to \gamma\gamma$ and $H \to Z\gamma$ $\mathcal{D}$ecays

Systematic helicity analyses for angular distributions Choi,MMM,Zerwas '12



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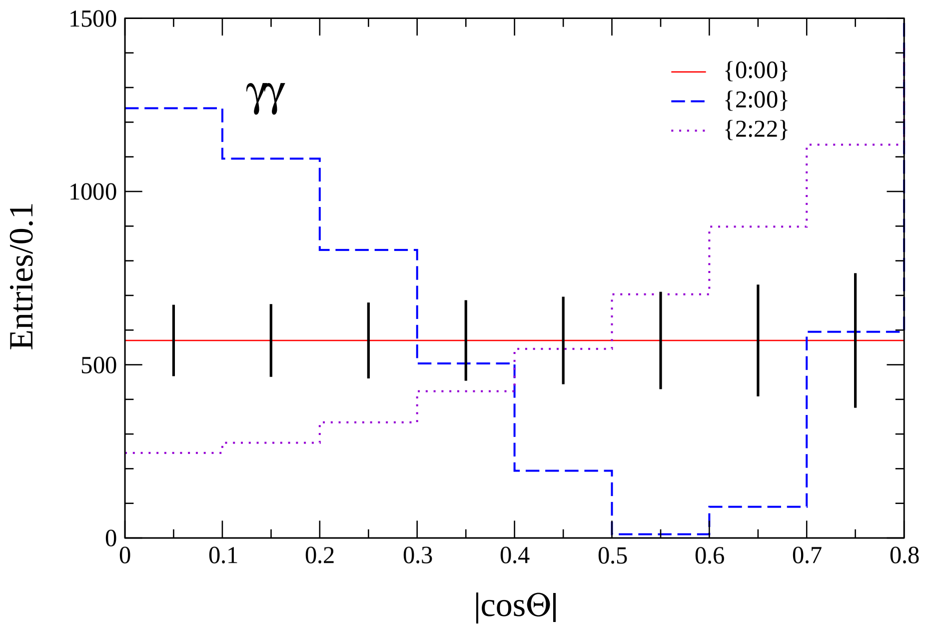

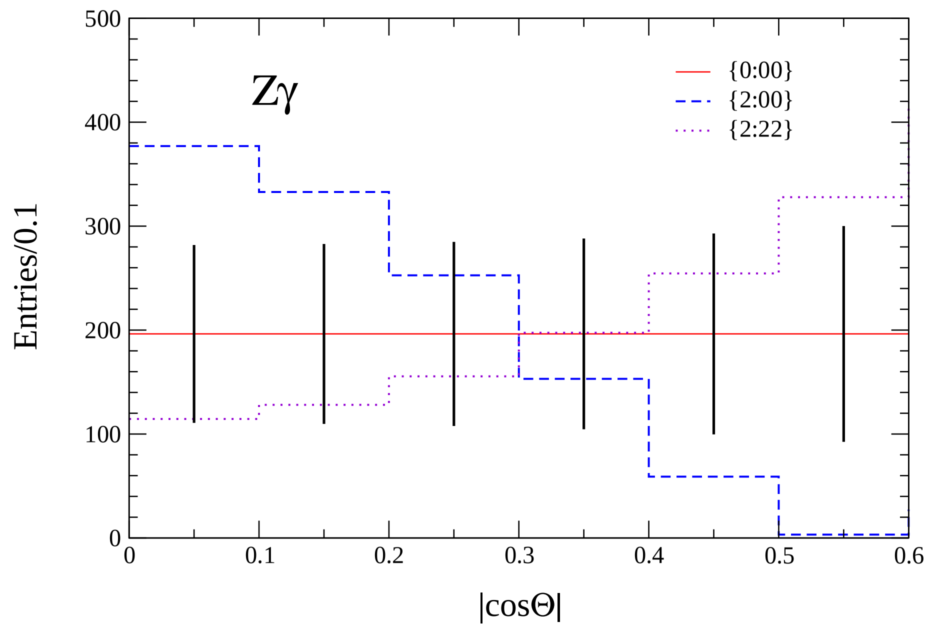

$\gamma\gamma$: $\int \mathcal{L} = 100$ fb^{-1} $\qquad$ $Z\gamma$: $\int \mathcal{L} = 3000$ fb^{-1}

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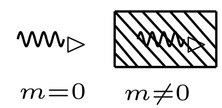
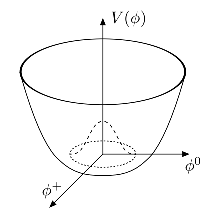


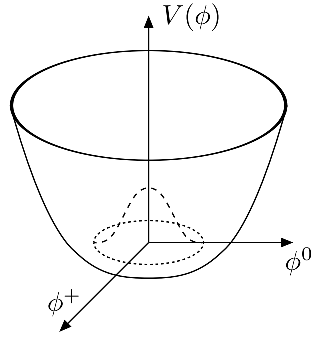
- Spin- and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$

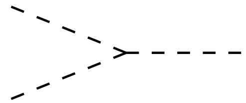
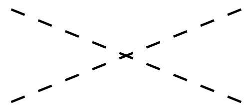


$\mathcal{D}$etermination of the $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{S}$elf-$\mathcal{C}$ouplings

The EWSB potential:

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



$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

$\mathcal{M}$easurement of the scalar boson self-couplings
and
$\mathcal{R}$econstruction of the EWSB potential
} $\mathcal{E}$xperimental verification $\mathcal{O}$f the scalar sector of the $\mathcal{E}$WSB 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

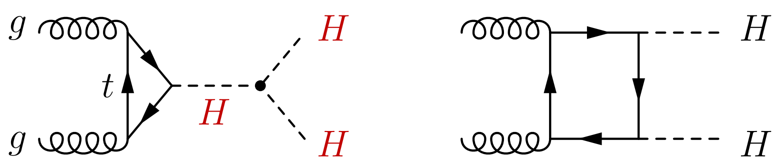
The Trilinear Self-Coupling at the LHC

Determination of λ_{HHH} at the LHC

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

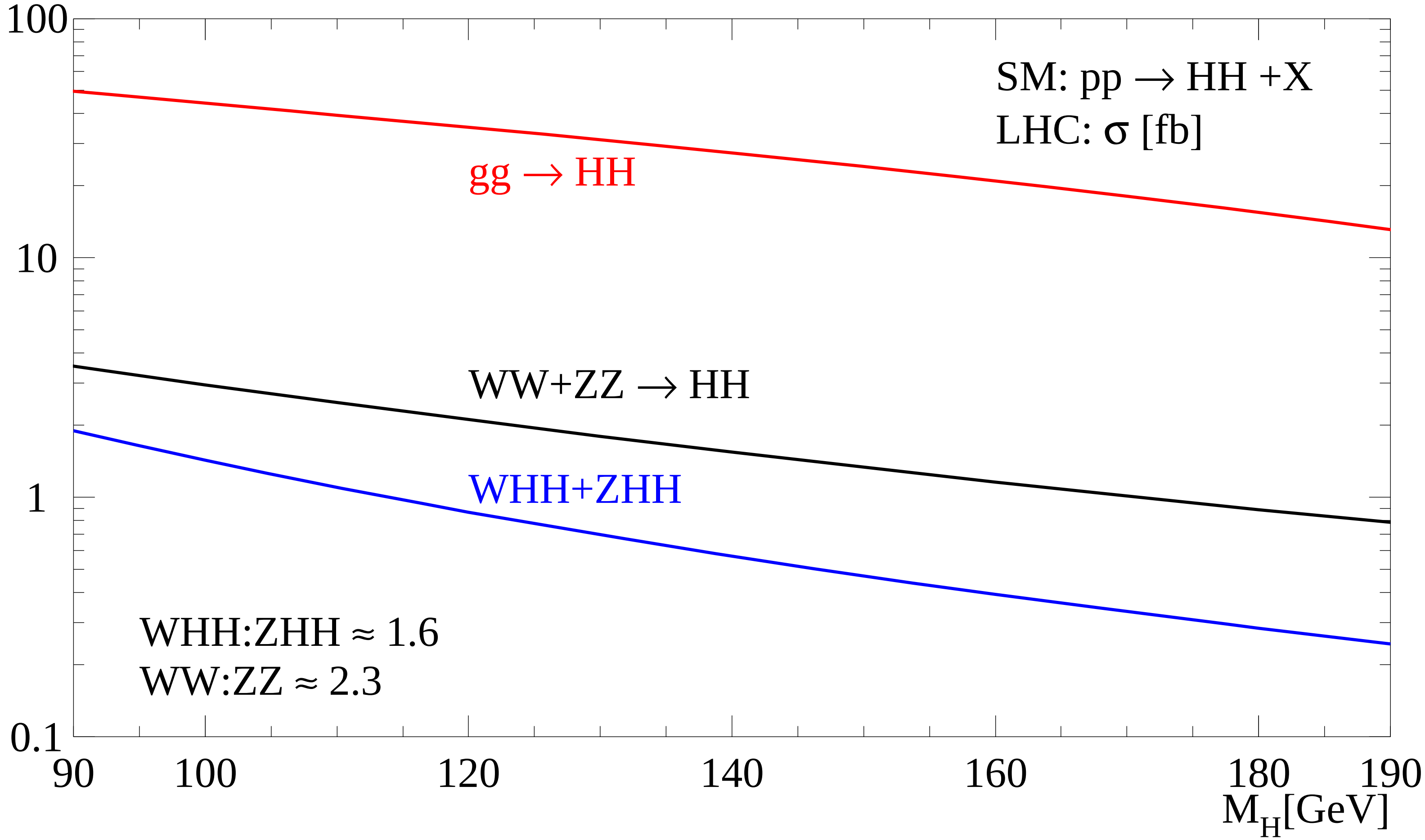
double radiation of W/Z:	$q\bar{q}$	$\longrightarrow$	$W/Z + HH$	Barger,Han,Phillips
WW/ZZ fusion:	qq	$\longrightarrow$	$qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale
gluon gluon fusion:	gg	$\longrightarrow$	HH	Glover,van der Bij Plehn,Spira,Zerwas Dawson,Dittmaier,Spira

gluon gluon fusion - dominant process



Double $\mathcal{SM}$ $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{P}$roduction at the $\mathcal{LHC}$

Djouadi,Kilian,MMM,Zerwas



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

small signal + large QCD background $\leadsto$ 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

Dolan,Englert,Spannowski'12

$M_H = 125$ GeV: diboson system recoiling against a hard jet:

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

Papaefstathiou,Yang,Zurita'12

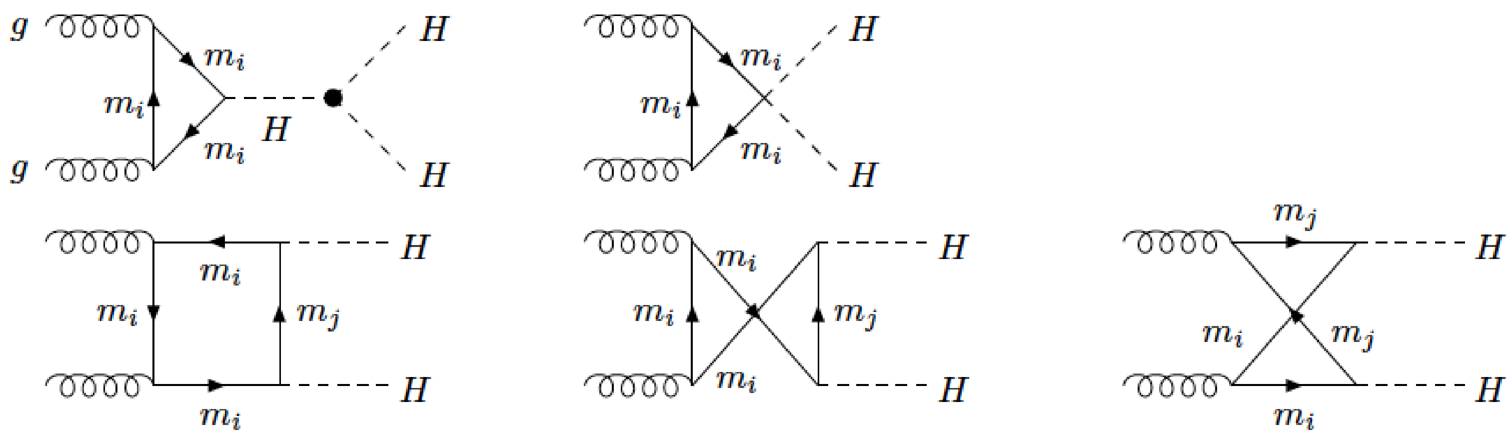
$M_H = 125$ GeV: jet substructure, event reconstruction techniques:

- LHC@14TeV [$\int \mathcal{L} = 600$ fb^{-1}]: $HH \to b\bar{b}W^+W^- \to b\bar{b}l\nu jj$: strong evidence

$\mathcal{D}$ouble $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{P}$roduction in $\mathcal{C}$omposite $\mathcal{M}$odels

- **Double scalar boson production through gluon fusion:**

  $*$ w/o or w/ new heavy fermion partners ($\leftarrow$ composite top)



▷ Can be enhanced compared to the SM process

Gröber,MMM

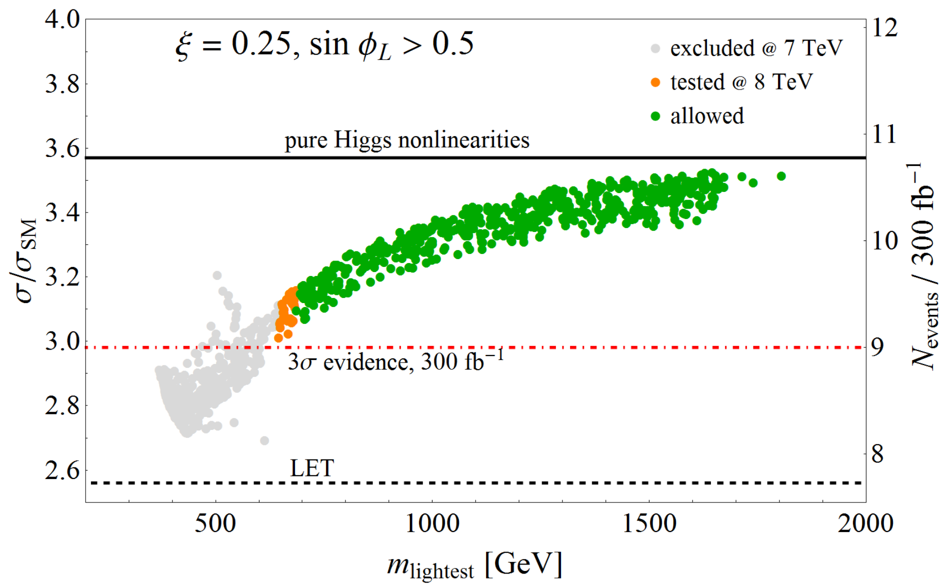
▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

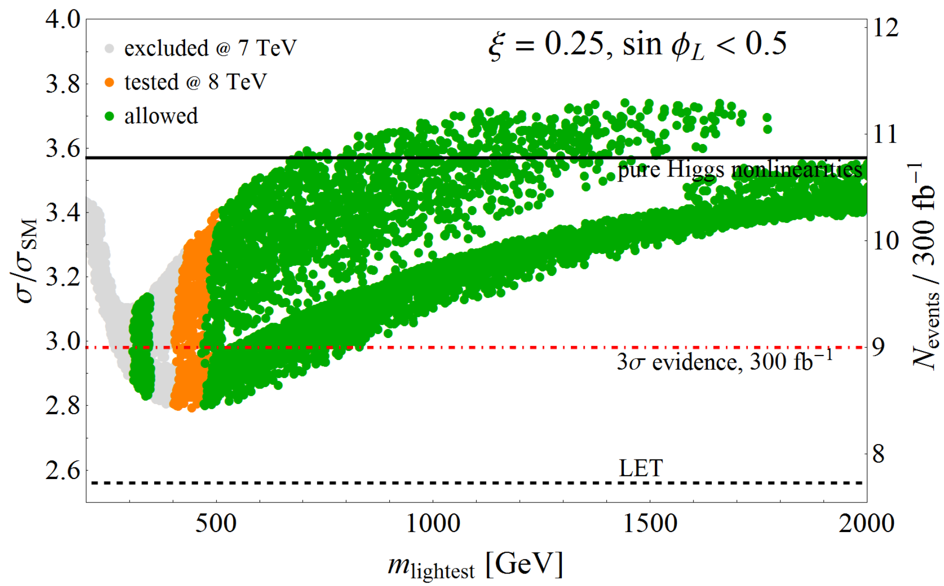
▷ Different fermions can contribute within one loop

▷ Sensitivity to details of heavy composite sector?

Double Scalar Boson Production in MCHM5

Gillioz, Gröber, Grojean, MMM, Salvioni





⋆ Sizeable dependence of cross section on heavy fermion spectrum: $2.7 \lesssim \sigma/\sigma_{SM} \lesssim 3.7$

Conclusions

- **Experimental results compatible with**
  - ⋆ SM scalar boson within 2σ
- **SM-like Supersymmetric boson**
  - ⋆ Possible at ~ 126 GeV
  - ⋆ With more (MSSM) or less (NMSSM) fine-tuning
  - ⋆ Can accommodate enhanced diphoton width
- **Next steps**
  - ⋆ Establish boson as the one *responsible for EWSB*
    - ◇ Coupling determination
    - ◇ Spin and Parity; CP violation
    - ◇ Self-couplings
  - ⋆ Nature of the boson (SM, SUSY, ...)

Thank you for your attention!