Higgs Physics at the LHC

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Seminar

LAL Orsay
14 May 2013

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

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

Higgs-Groupies queueing up in front of CERN audimax

Discovery of New Scalar Particle

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

Two electroweak symmetry breaking heroes

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

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

Croud listening announcement at ICHEP 2012 in Melbourne

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

- 4 July 2012: CERN announces di... particle!

At the university of Tokyo

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

• 4 July 2012: CERN ann

e particle!

At Fermilab

Discovery of New Scalar Particle

• 4 July 2012: CE

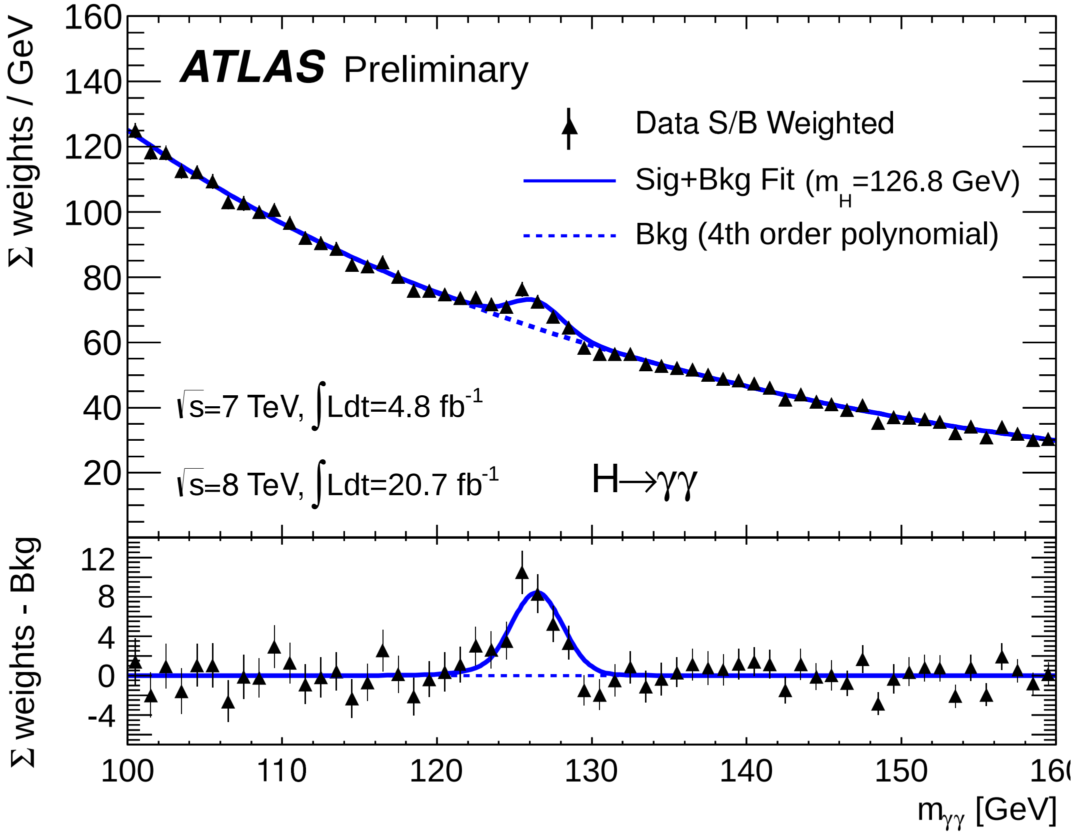
e particle!

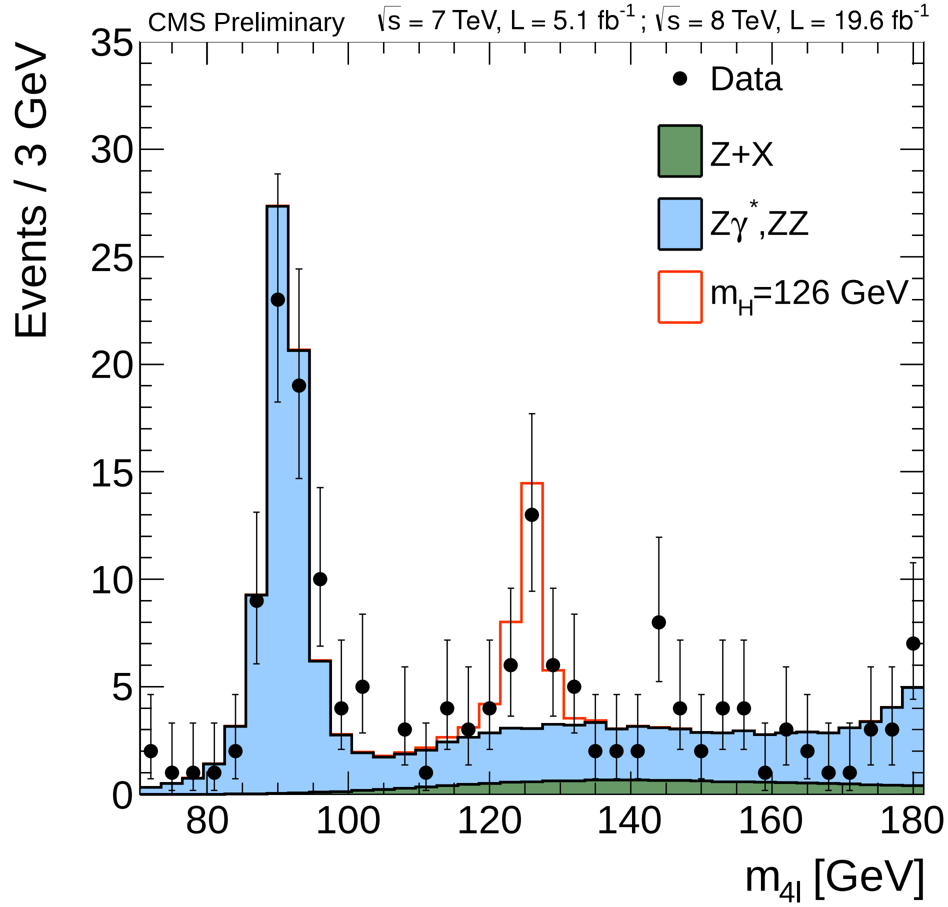
At DESY, Hamburg

LHC Higgs Search Results

ATLAS-CONF-2013-12

CMS-PAS-HIG-13-002





Reminder: Electroweak Symmetry Breaking (EWSB)

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

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

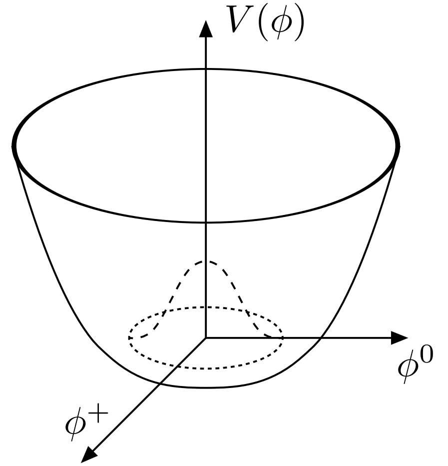
Higgs mechanism

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

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

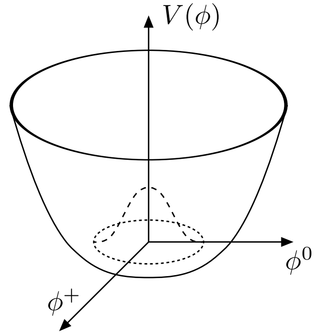
$v = 246$ GeV

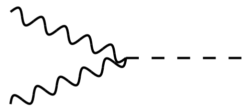
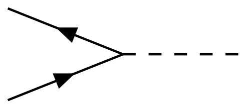
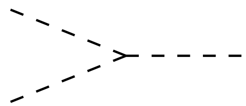
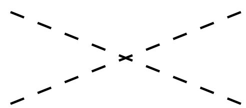
SM Higgs Sector

Higgs potential: [$v = 246$ GeV]

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

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



Higgs boson mass	$M_H = \sqrt{2\lambda}v$	
Gauge couplings	$g_{VVH} = \frac{2M_V^2}{v}$	
Yukawa couplings	$g_{ffH} = \frac{m_f}{v}$	
Trilinear coupling [units $\lambda_0 = 33.8$ GeV]	$\lambda_{HHH} = 3\frac{M_H^2}{M_Z^2}$	
Quartic coupling [units λ_0^2]	$\lambda_{HHHH} = 3\frac{M_H^2}{M_Z^4}$	

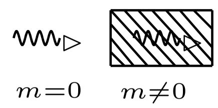
Only unknown parameter in the SM was the mass of the Higgs boson!

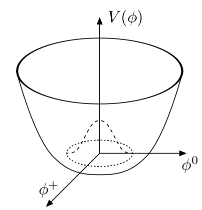
What Have We Seen?

- The production of a new particle with mass $M \approx 125$ GeV
- Is it *the* Standard Model *Higgs* boson? $\Longrightarrow$

Test of the Higgs mechanism

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





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

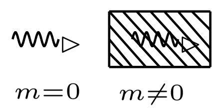
$\mathcal{E}$xperimental $\mathcal{V}$erification of the EWSB $\mathcal{M}$echanism

EWSB mechanism:

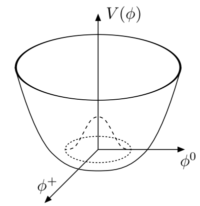
Creation of particle masses without violating gauge principles

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 – $\lambda_{HHH}, \lambda_{HHHH}$

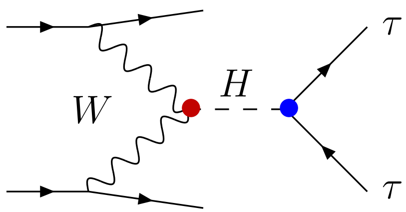


Determination of the Scalar Boson Couplings

Strategy

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

E.g.:



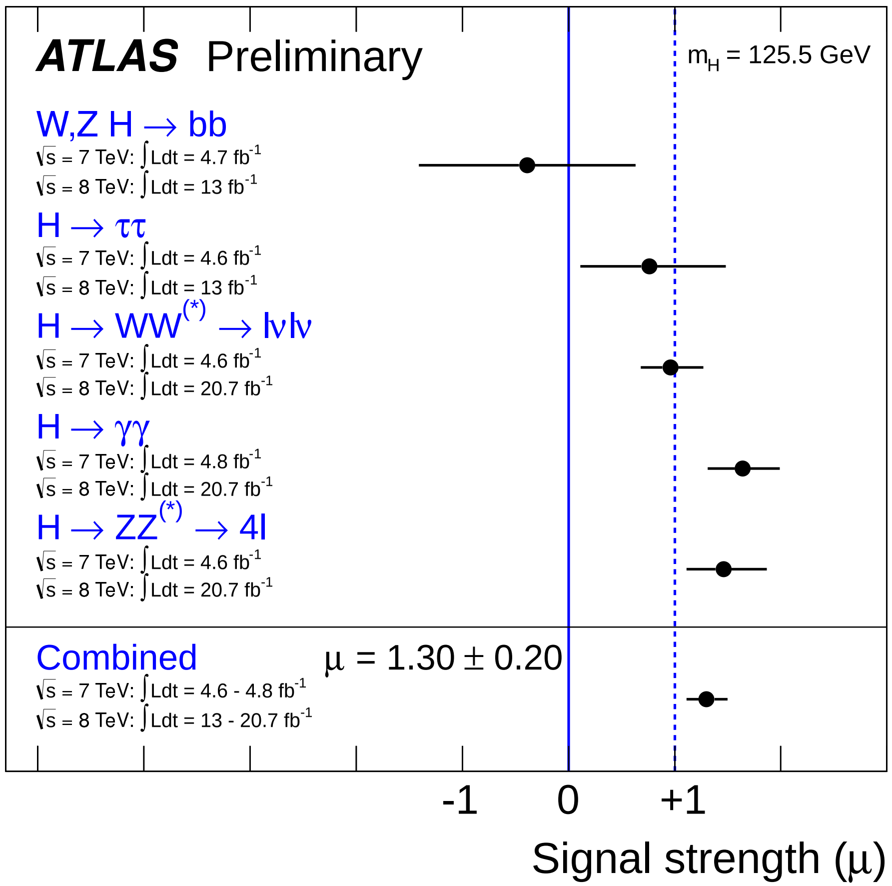
$\sim \Gamma_{WW}$ BR$(H \to \tau\tau)$

Coupling measurement at the LHC

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

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

ATLAS-CONF-2013-034

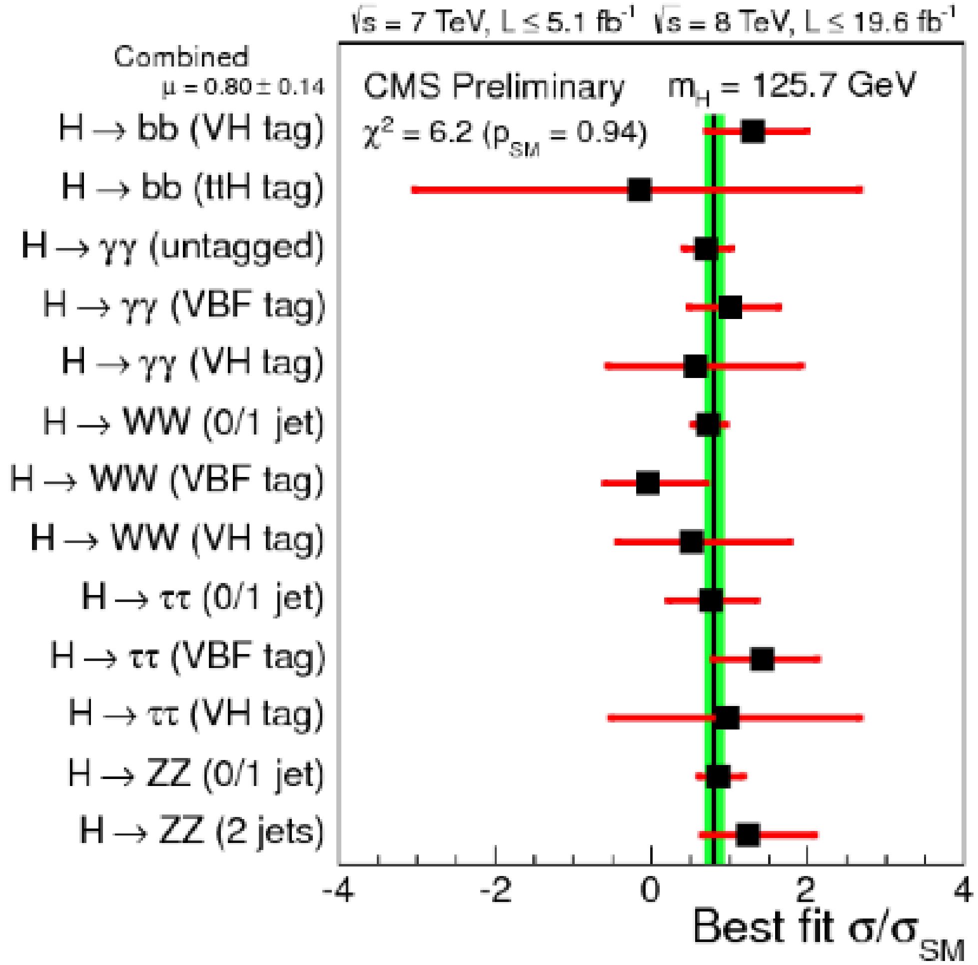


Best fit values of $\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$

$\gamma\gamma$ and $4l$: $M_H = 125.5 \pm 0.2$(stat)$^{+0.5}_{-0.6}$(sys); **slight excess in $\gamma\gamma$ but not $WW, bb, \tau\tau$**

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

CMS-PAS-HIG-13-005



$\mathcal{N}$ew: $\mu_{\gamma\gamma} = \mathbf{0.78^{+0.28}_{-0.26}}$ (MVA); $\mu_{\gamma\gamma} = \mathbf{1.11^{+0.32}_{-0.30}}$ (cut-based)

$$\mu = 0.80 \pm 0.14$$

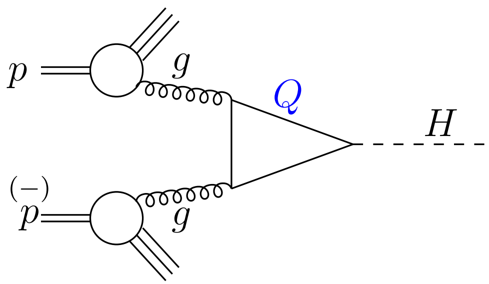
$\gamma\gamma$ and 4l: $M_H = (125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst}))$ GeV

$\mathcal{W}$hat $\mathcal{T}$heory tells us: $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{P}$roduction at the $\mathcal{LHC}$

Higgs boson production

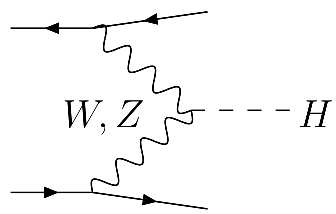
- **Gluon Gluon Fusion**

  $pp \to gg \to H$



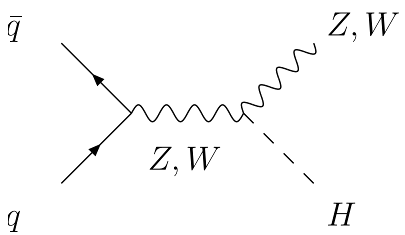
- **W/Z Fusion**

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



- **Higgs-strahlung**

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



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

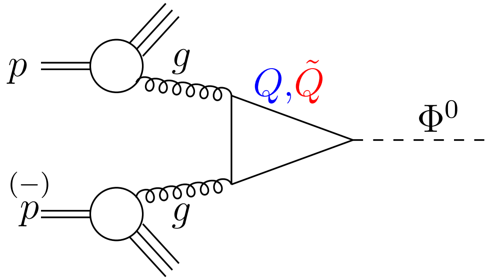
  $pp \to t\bar{t} + H$

What Theory tells us: SM Higgs Production at the LHC

Higgs boson production

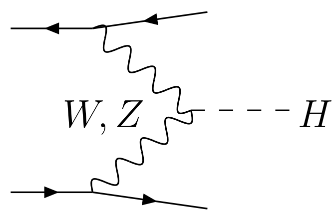
- **Gluon Gluon Fusion** Room for New Physics!

  $pp \to gg \to H$



- **W/Z Fusion**

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



- **Higgs-strahlung**

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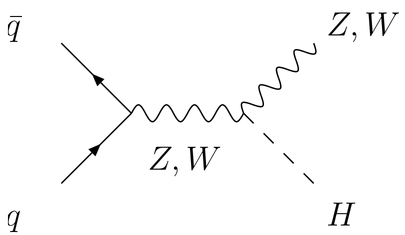
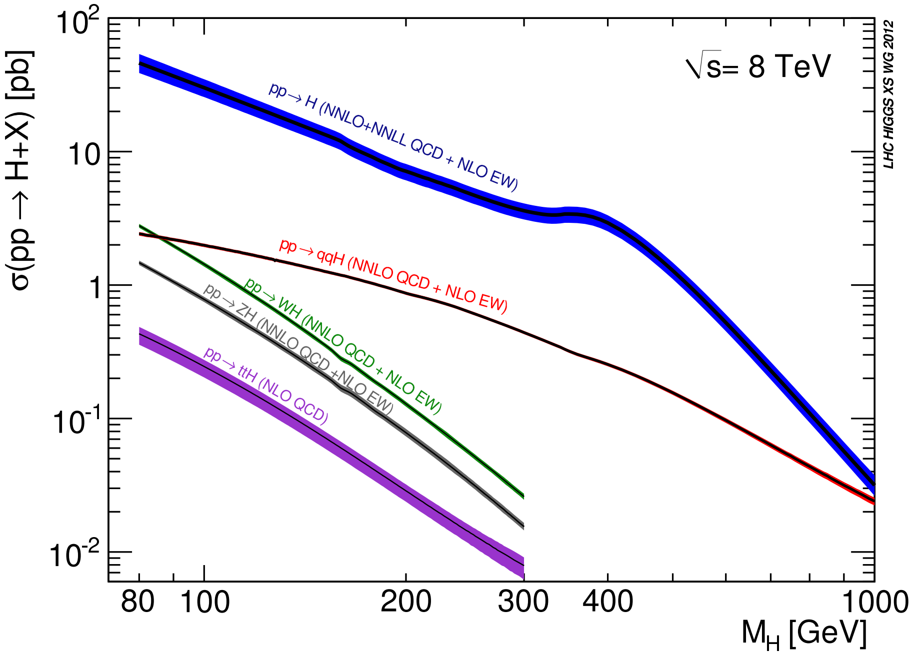


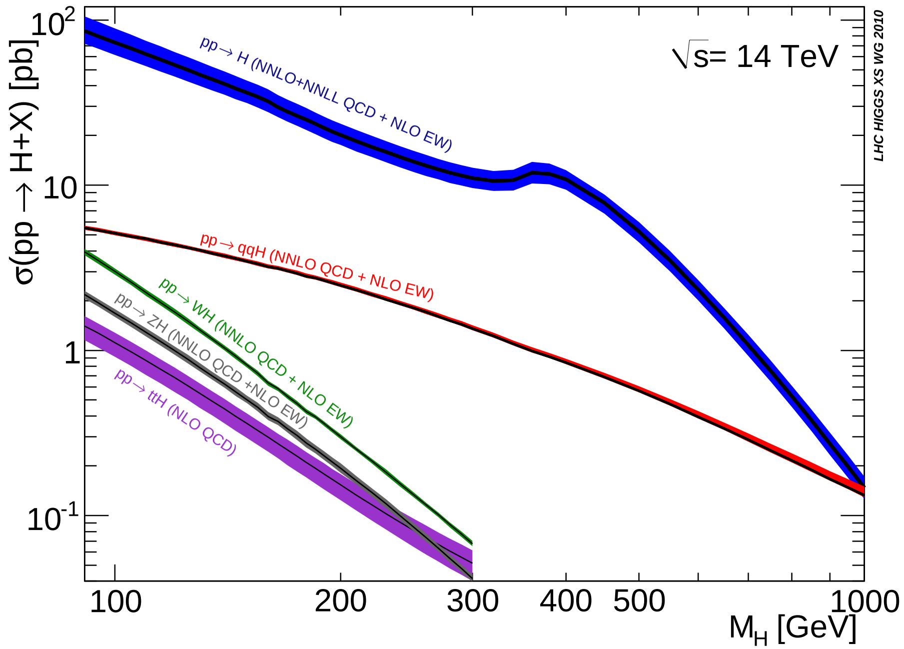
- **Associated production with $t\bar{t}$**

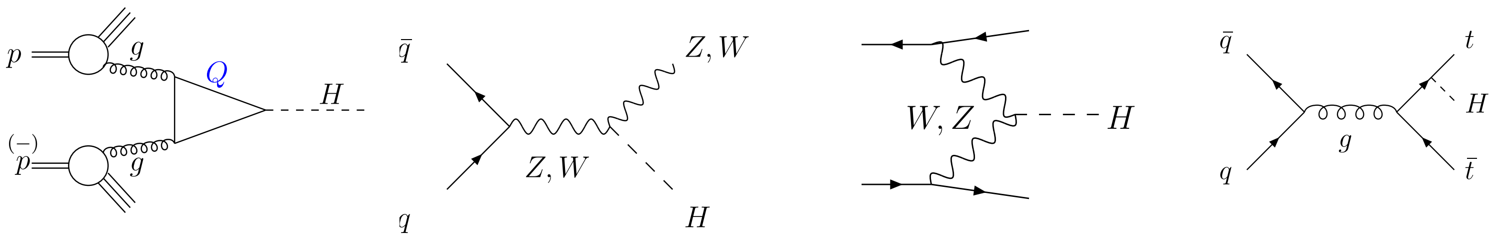
  $pp \to t\bar{t} + H$

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

LHC Higgs XS WG, arXiv:1101.0593

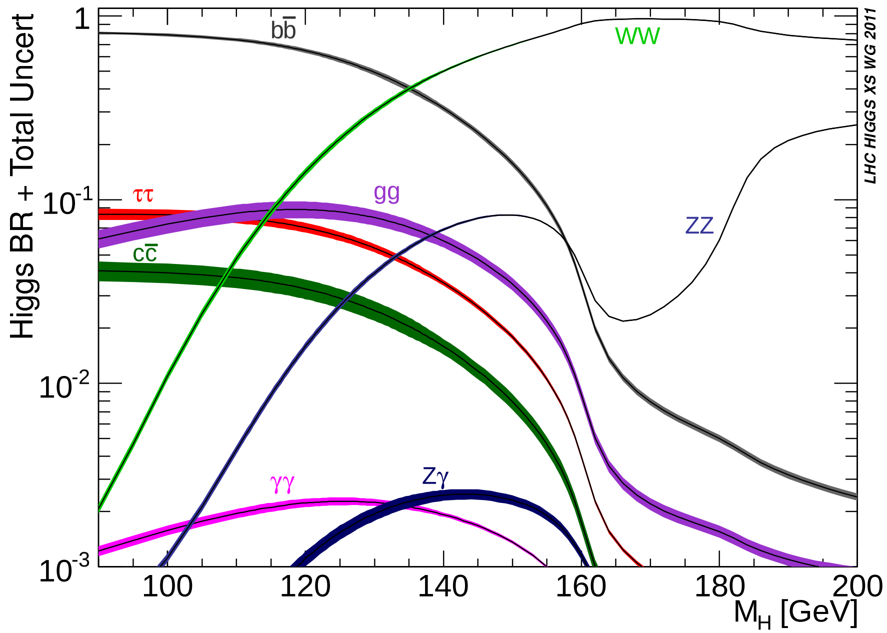


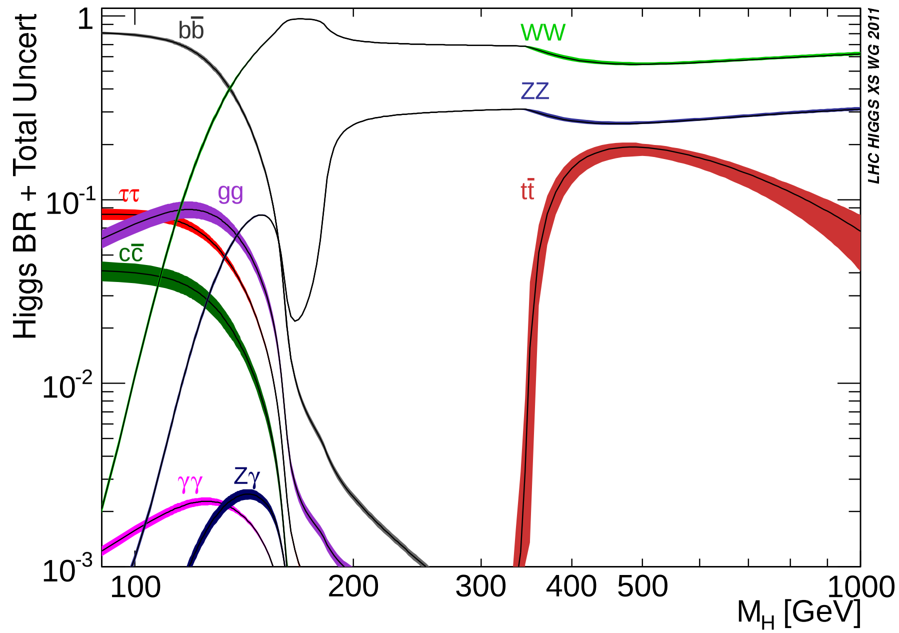




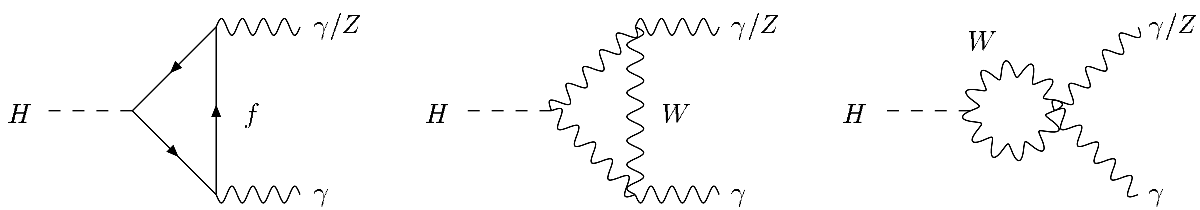
$\mathcal{W}$hat $\mathcal{T}$heory tells us: $\mathcal{SM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{D}$ecays

LHC Higgs XS WG





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

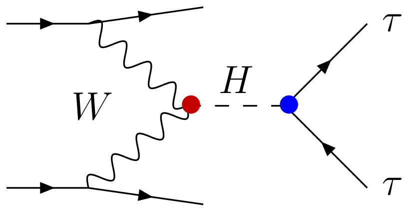


Determination of the Scalar Boson Couplings

Strategy

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

E.g.:



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

Coupling measurement at the LHC

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

Theoretical approach to explore the coupling structure of a SM scalar boson-like particle

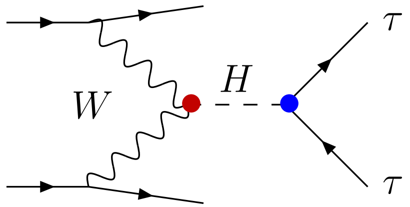
* Effective Lagrangian with modified Higgs couplings - first approach: scaling factors κ_V, κ_F
* Calculate signal rates as function of scaling factors $\rightsquigarrow \mu(\kappa_V, \kappa_F)$
* Fit to experimental μ values

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
* Perform fit to couplings

See also: LHC HXSWG Recommendations

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

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

◇ **Effective Lagrangian** valid at $E \sim v$

◇ **Field content:** SM with scalar field h Contino eal '10,'12

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

◇ **Remarks:**

* Chiral Lagrangian with a cutoff at $\Lambda \gtrsim 4\pi v$
* $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking implemented
* Custodial symmetry incorporated: $(M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)]$
* No tree-level FCNC due to h exchange: $-m_{\psi_i}\bar{\psi}_i\psi_i[1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)]$

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

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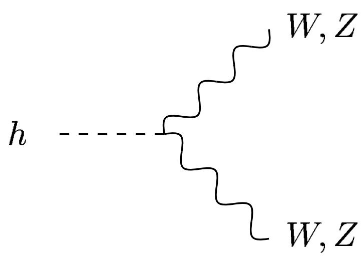
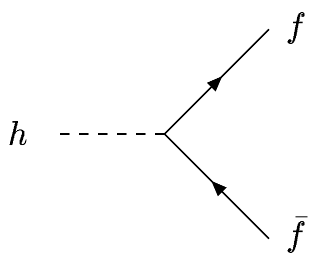
- **Extension of the SM Lagrangian by two parameters** κ_V, κ_F; SM: $(\kappa_V, \kappa_F) = (1, 1)$
- **Modified decays rates:** HDECAY: Djouadi, Spira, Kalinowski, MMM



$\kappa_V\, g_{hVV}$



$\kappa_F\, g_{hff}$

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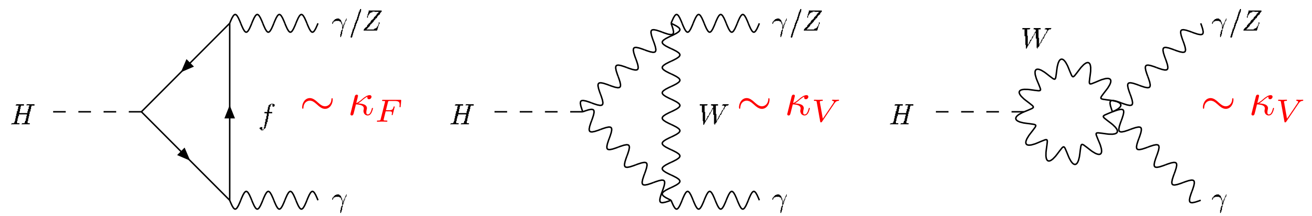
$h \to \gamma\gamma$:



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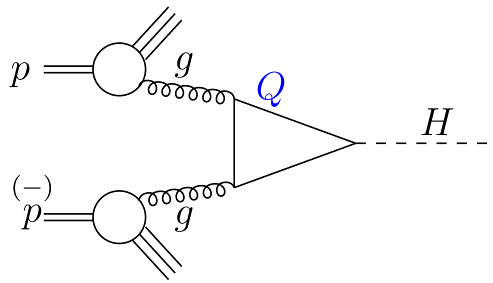
$$\mathcal{L} = \mathcal{L}_h - (M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu)[1 + 2\,\kappa_V\,\frac{h}{v} + \mathcal{O}(h^2)] - m_{\psi_i} \bar{\psi}_i \psi_i [1 + \kappa_F\,\frac{h}{v} + \mathcal{O}(h^2)] + \ldots$$

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

Modified Higgs-gluon-gluon coupling:



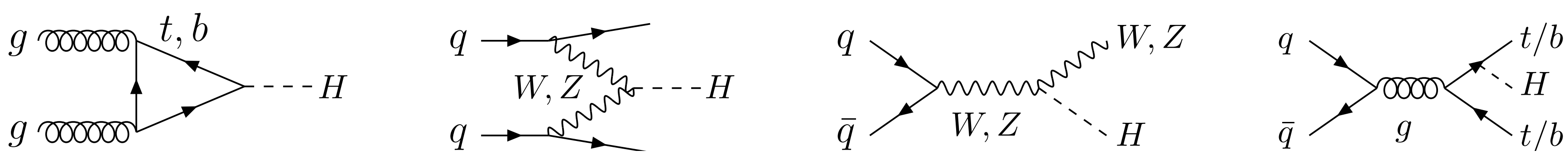
$\sim \kappa_F^2$

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

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

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

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



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

▷ **Rescaling - Decay**

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

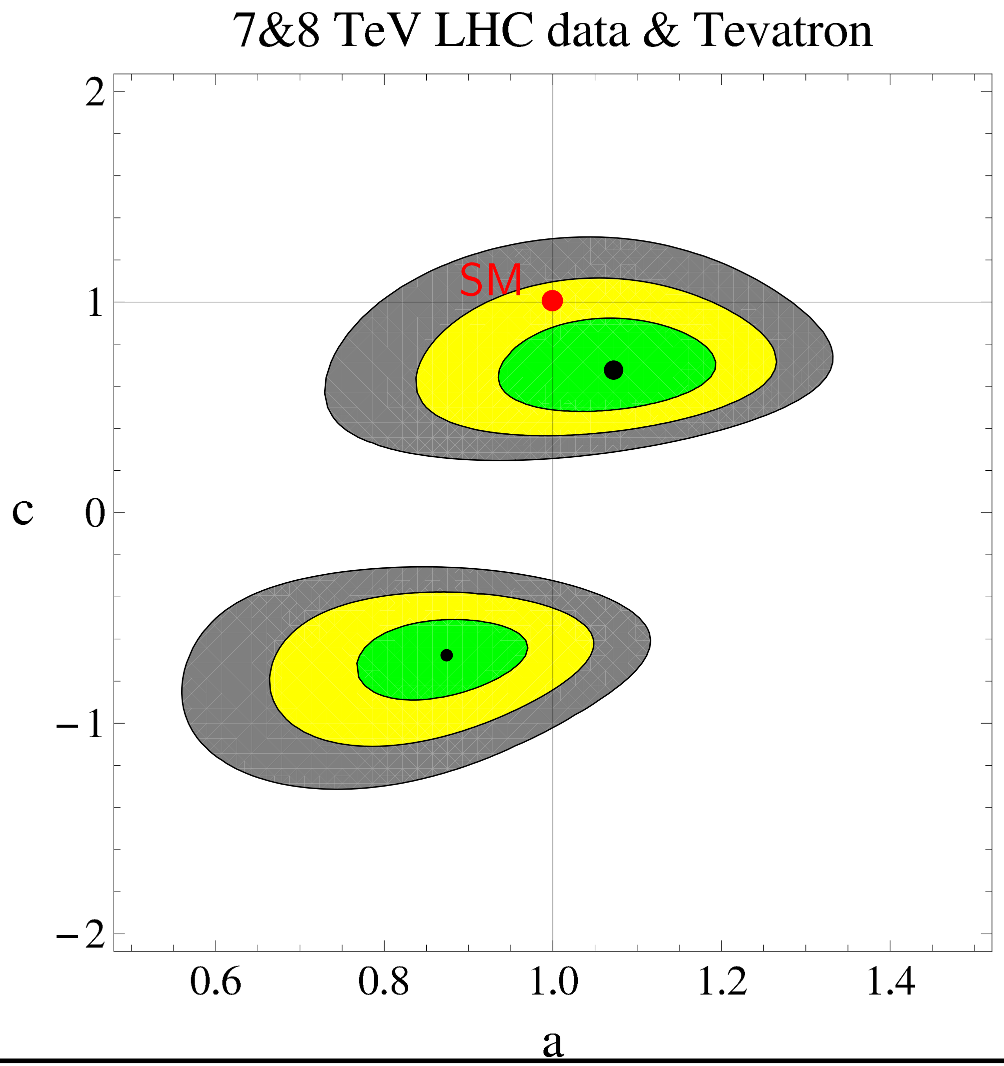
$\mathcal{F}$it to $\mathcal{LHC}$ $\mathcal{D}$ata within SM($a \equiv \kappa_V, c \equiv \kappa_F$) - $\mathcal{S}$ummer 2012

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

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

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

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



Note: a fermiophobic
Higgs is disfavoured
by data

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

- **Best fit points**
  - ◇ Solution for $\kappa_F < 0$

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

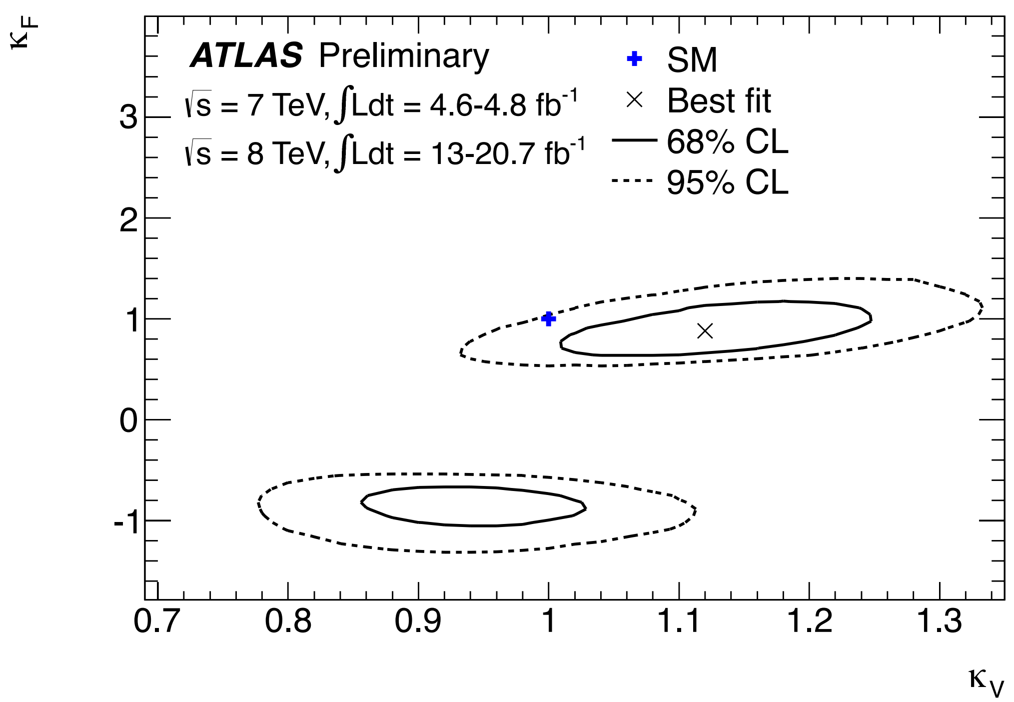
Constructive interference for $\kappa_F < 0$.

- **For further work, see:**

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

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

ATLAS-CONF-2013-034



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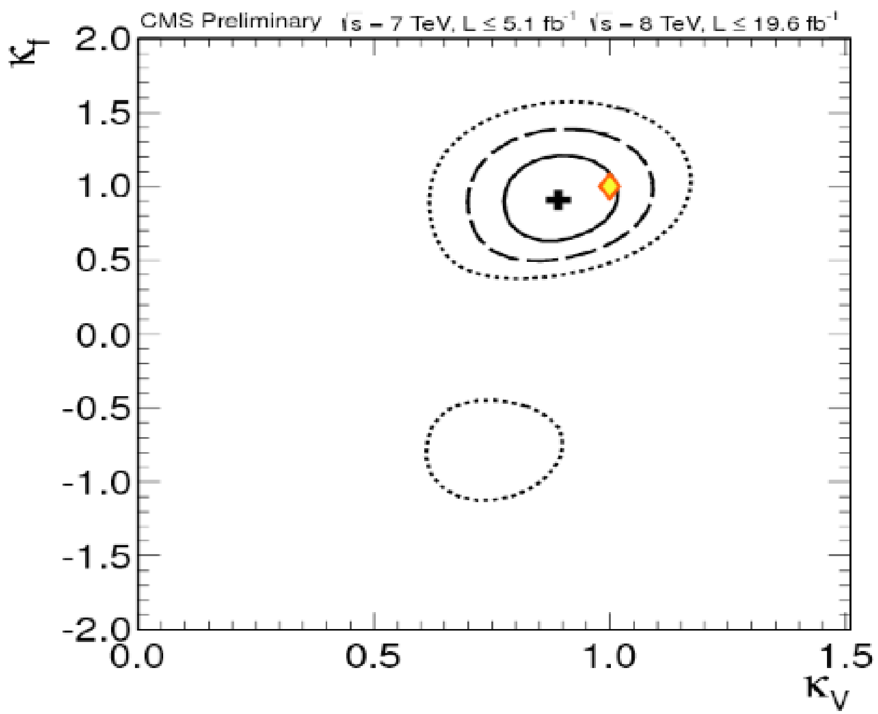


Why Beyond Standard Model (BSM) Physics?

Standard Model: incomplete picture of the universe

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

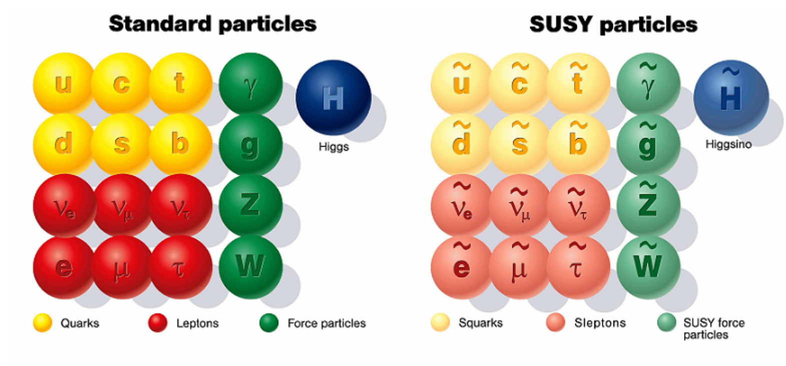
Supersymmetry: relates fermions and bosons

◇ solves hierarchy problem

◇ gauge coupling unification (MSSM)

◇ Higgs mechanism generated radiatively

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



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

Going 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

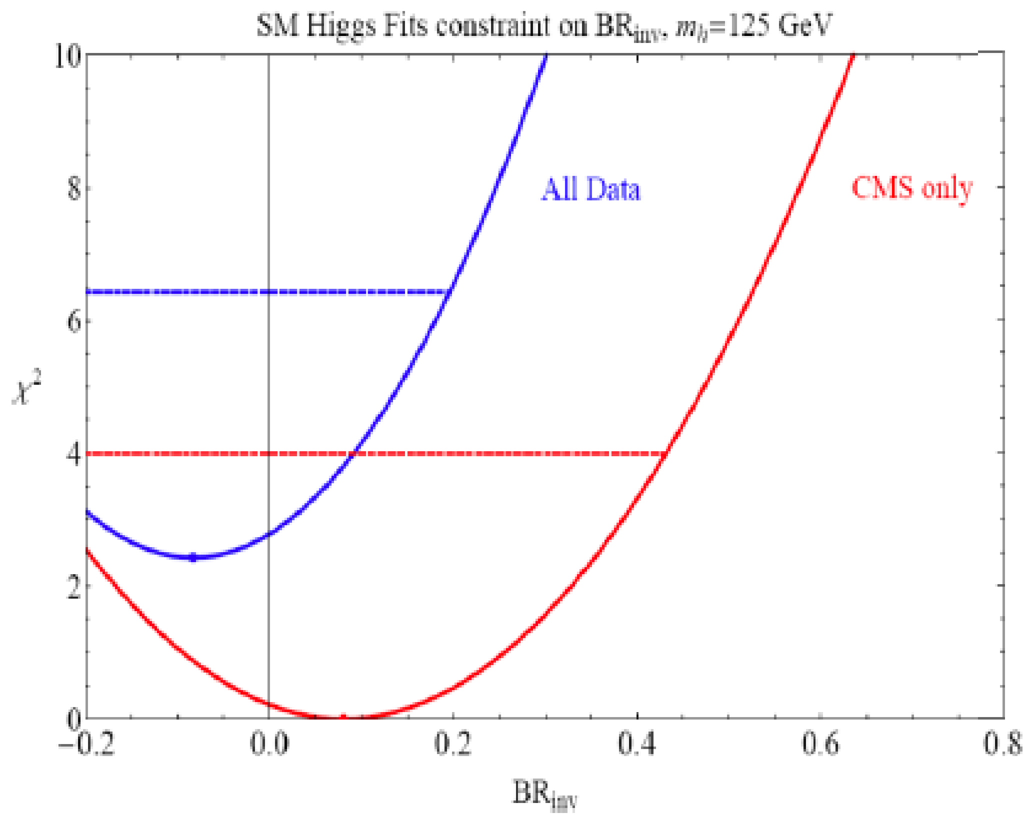
Phantom Higgs

$\mathcal{T}$est $\mathcal{H}$iggs $\mathcal{I}$nvisible $\mathcal{W}$idth

- **New Physics particles X SM singlets:** $h \to XX \rightsquigarrow$ universal reduction of SM branching ratios

$$BR(h \to f) = (1 - BR_{inv})BR(h \to f)^{SM}$$

Espinosa,Grojean,MMM,Trott '12



◇ χ^2 fit to combined $\hat{\mu}_c \pm \sigma_c$ ◇ χ^2_{min} at $BR_{inv} \approx (-0.1, 0.1)$

◇ SM with $BR_{inv} = 0$ ok ◇ Still room for sizeable $BR_{inv} \lesssim (0.2, 0.45)$ at 95%CL

$\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach with $\mathcal{BSM}$ $\mathcal{E}$ffects

- **Based on** R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira, arXiv:1303.3876
- **Strongly Interacting Light Higgs (SILH) Lagrangian** Giudice eal

Composite Boson

- **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

$\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach with $\mathcal{BSM}$ $\mathcal{E}$ffects

- **Based on** R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira, arXiv:1303.3876
- **Strongly Interacting Light Higgs (SILH) Lagrangian** — Giudice eal
  - ∗ Expansion in H/f $\rightsquigarrow$ coupling deviations from SM are small

$\mathcal{E}$ffective $\mathcal{L}$agrangian $\mathcal{A}$pproach with $\mathcal{BSM}$ $\mathcal{E}$ffects

- **Based on** R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira, arXiv:1303.3876

- **Strongly Interac**

Giudice eal

$$\begin{aligned}\Delta\mathcal{L}_{SILH} =& \frac{\bar{c}_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\,(H^\dagger H)^3 \\ &+ \left(\frac{\bar{c}_u}{v^2}\, y_u\, H^\dagger H\, \bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\, y_d\, H^\dagger H\, \bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\, y_l\, H^\dagger H\, \bar{L}_L H l_R + h.c.\right) \\ &+ \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}^\mu H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)(\partial^\nu B_{\mu\nu}) \\ &+ \frac{i\bar{c}_{HW}\, g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ &+ \frac{\bar{c}_\gamma\, g'^2}{m_W^2}\, H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,\end{aligned} \tag{2.2}$$

$$\begin{aligned}\Delta\mathcal{L}_{F_1} =& \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\,(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu\sigma^i q_L)\,(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H) \\ &+ \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\,(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}_{Hd}}{v^2}\,(\bar{d}_R\gamma^\mu d_R)\,(H^\dagger \overleftrightarrow{D}_\mu H) \\ &+ \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\,(H^{c\,\dagger} \overleftrightarrow{D}_\mu H) + h.c.\right) \\ &+ \frac{i\bar{c}_{HL}}{v^2}\,(\bar{L}_L\gamma^\mu L_L)\,(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{HL}}{v^2}\,(\bar{L}_L\gamma^\mu\sigma^i L_L)\,(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H) \\ &+ \frac{i\bar{c}_{Hl}}{v^2}\,(\bar{l}_R\gamma^\mu l_R)\,(H^\dagger \overleftrightarrow{D}_\mu H)\,,\end{aligned} \tag{2.3}$$

$$\begin{aligned}\Delta\mathcal{L}_{F_2} =& \frac{\bar{c}_{uB}\, g'}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{uW}\, g}{m_W^2}\, y_u\, \bar{q}_L \sigma^i H^c \sigma^{\mu\nu} u_R\, W^i_{\mu\nu} + \frac{\bar{c}_{uG}\, g_S}{m_W^2}\, y_u\, \bar{q}_L H^c \sigma^{\mu\nu} \lambda^a u_R\, G^a_{\mu\nu} \\ &+ \frac{\bar{c}_{dB}\, g'}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} d_R\, B_{\mu\nu} + \frac{\bar{c}_{dW}\, g}{m_W^2}\, y_d\, \bar{q}_L \sigma^i H \sigma^{\mu\nu} d_R\, W^i_{\mu\nu} + \frac{\bar{c}_{dG}\, g_S}{m_W^2}\, y_d\, \bar{q}_L H \sigma^{\mu\nu} \lambda^a d_R\, G^a_{\mu\nu} \\ &+ \frac{\bar{c}_{lB}\, g'}{m_W^2}\, y_l\, \bar{L}_L H \sigma^{\mu\nu} l_R\, B_{\mu\nu} + \frac{\bar{c}_{lW}\, g}{m_W^2}\, y_l\, \bar{L}_L \sigma^i H \sigma^{\mu\nu} l_R\, W^i_{\mu\nu} + h.c.\end{aligned} \tag{2.4}$$

$\mathcal{E}$ffective $\mathcal{L}$agrangian for a $\mathcal{L}$ight $\mathcal{H}$iggs-$\mathcal{L}$ike $\mathcal{S}$calar

- **Based on** R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira, arXiv:1303.3876
- **SILH Lagrangian**
- **Non-linear Lagrangian** Contino eal

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \ldots\right)$$
$$+ \left(m_W^2\, W_\mu W^\mu + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\right)\left(1 + 2c_V\,\frac{h}{v} + \ldots\right) + \ldots$$
$$+ \left(c_{WW}\, W^+_{\mu\nu}W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v} \quad (3.46)$$
$$+ \left(c_{W\partial W}\,\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu\partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

∗ Expansion in E/M - $E =$ typical scale of external 4-momenta, $M =$ New Physics scale

∗ Coupling deviations from SM need not be small

- **Implementation for Higgs decay rates:** eHDECAY
  URL: http://www.itp.kit.edu/∼maggie/eHDECAY/

Program eHDECAY

eHDECAY

The program eDHECAY is a modified version of the latest release of HDECAY 5.10. It allows for the calculation of the partial decay widths and branching ratios of a Higgs-like boson within different parametrisations of the Lagrangian: the non-linear Lagrangian, the SILH Lagrangian and the composite Higgs parametrization according to MCHM4 or MCHM5.

Released by: Roberto Contino, Margherita Ghezzi, Christophe Grojean, Margarete Mühlleitner and Michael Spira
Program: eHDECAY obtained from extending HDECAY 5.10

When you use this program, please cite the following references:

eHDECAY:	R. Contino, M. Ghezzi, C. Grojean, M. Mühlleitner, M. Spira, in arXiv 1303.3876
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margherita.ghezzi@roma1.infn.it or margarete.muehlleitner@kit.edu.

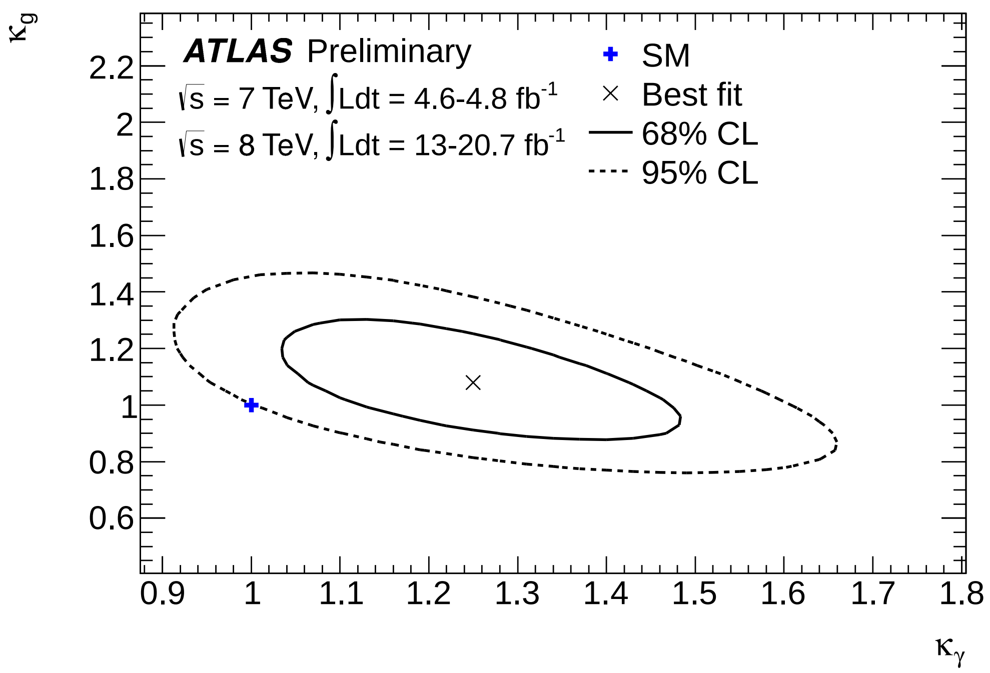
Downloading the files needed for eHDECAY:

$\mathcal{P}$rogram eHDECAY - $\mathcal{I}$nput $\mathcal{F}$ile

```
************** LAGRANGIAN 0 - chiral  1 - SILH  2 - MCHM4/5 **************
LAGPARAM = 0
**** Turn off (0) or on (1) the elw corrections for LAGPARAM = 1 or 2 ****
IELW     = 1
******************* VARIATION OF HIGGS COUPLINGS *************************
CW       = 1.D0
CZ       = 1.D0
Ctau     = 0.95D0
Cmu      = 0.95D0
Ct       = 0.95D0
Cb       = 0.95D0
Cc       = 0.95D0
Cs       = 0.95D0
Cgaga    = 0.005D0
Cgg      = 0.001D0
CZga     = 0.D0
CWW      = 0.D0
CZZ      = 0.D0
CWdW     = 0.D0
CZdZ     = 0.D0
**************************** SILH Lagrangian *****************************
CHbar    = 0.D0
Ctaubar  = 0.D0
Cmubar   = 0.D0
Ctbar    = 0.D0
Cbbar    = 0.D0
Ccbar    = 0.D0
Csbar    = 0.D0
CWbar    = 0.D0
CBbar    = 0.D0
CHWbar   = 0.D0
CHBbar   = 0.D0
Cgambar  = 0.D0
Cgbar    = 0.D0
******** MCHM4 (fermrepr=1), MCHM5 (fermrepr=2) parametrisation ********
fermrepr = 1
xi       = 0.D0
```

Probing $\mathcal{N}$on-$\mathcal{SM}$ $\mathcal{P}$articles in the $H \to \gamma\gamma$, $gg \to H$ $\mathcal{L}$oops

ATLAS-CONF-2013-034



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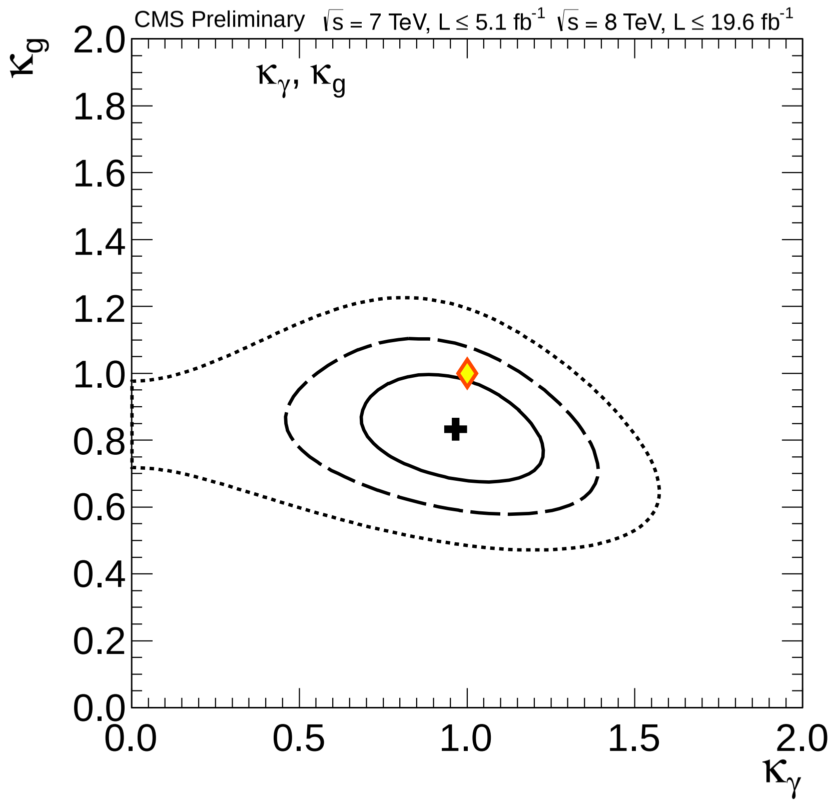
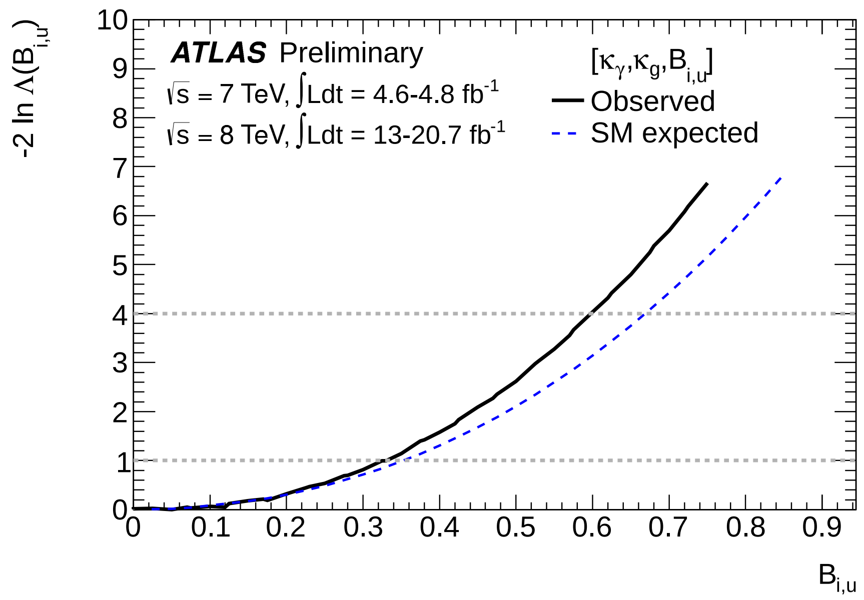


- All other scaling factors SM-like: $\kappa_i = 1$
- Only SM contributions to total width (no undetected modes)

$\mathcal{F}$it to $\mathcal{I}$nvisible or $\mathcal{U}$ndetectable $\mathcal{F}$inal $\mathcal{S}$tates

ATLAS-CONF-2013-034



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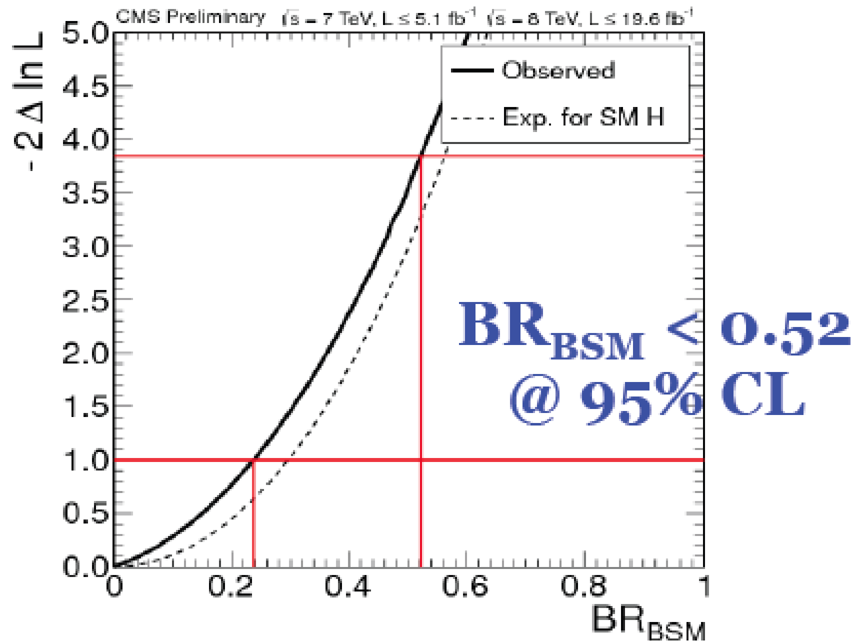


$\text{BR}_{\text{inv,undet}} < 0.6$ at 95% CL (ATLAS) $\text{BR}_{\text{inv,undet}} < 0.52$ at 95% CL (CMS)

(profile κ_g, κ_γ)

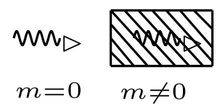
$\mathcal{E}$xperimental $\mathcal{V}$erification of the $\mathcal{H}$iggs $\mathcal{M}$echanism

Higgs mechanism:

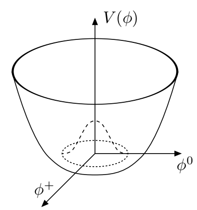
Creation of particle masses without violating gauge principles

Test of the Higgs mechanism

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



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



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

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

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

Necessary and sufficient conditions for $J^P = 0^+$ [vis-a-vis SM]

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

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

Higgs Boson Quantum Numbers

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

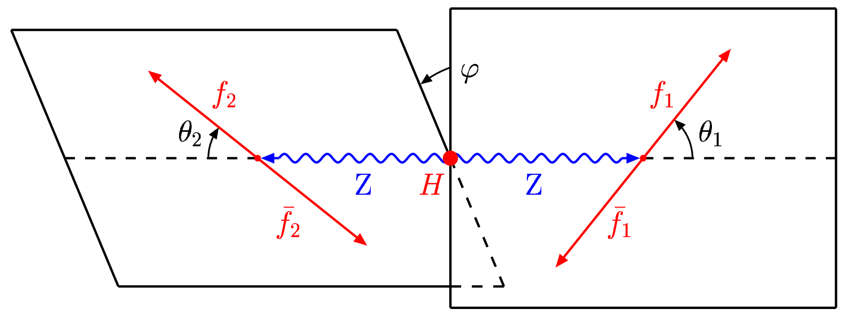
  * Z^*Z decays — Choi eal; Gao eal; De Rujula eal; Bolognesi eal; Buszello eal; Englert eal
  * $\gamma\gamma$ decays — Ellis, Hwang; Alves; Choi eal
  * CP-violating decays — Soni, Xu; Chang eal; Godbole eal; Nelson; De Rujula eal: Buszello eal
  * Production in gluon fusion, in vector boson fusion — Plehn eal; Hagiwara eal; Hankele eal; Campanario eal; Del Duca eal
  * Production in Higgs-strahlung — Miller eal; Ellis eal Englert eal; Frank eal; Djouadi eal
  * Hadronic event shapes — Englert eal
  * Fermionic decays — Kramer eal; Berge eal

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

◇ Determination of spin and parity in

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

in H c.m. frame



◇ Helicity methods to generalize to arbitrary spin and parity

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

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

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

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

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

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

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

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

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

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

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

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

- **Standard Model:**

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

Necessary conditions:

◇ Double polar angular distribution

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

◇ Azimuthal angular distribution

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

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

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

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

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

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

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

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

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

  Bredenstein, Denner, Dittmaier, Walser

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

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

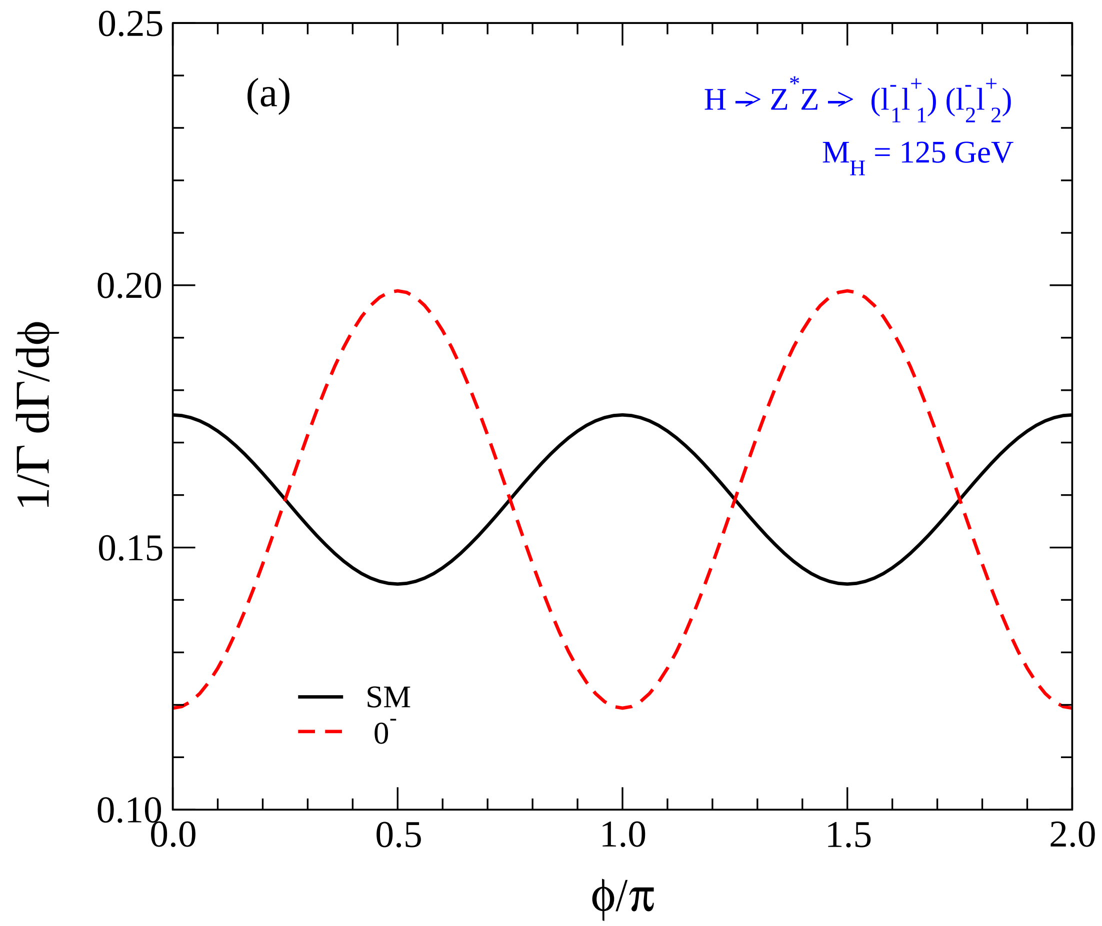
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\cos\theta_1\cos\theta_2} = \frac{9}{64}(1+\cos^2\theta_1)(1+\cos^2\theta_2)$$
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\phi} = \frac{1}{2\pi}\left[1-\frac{1}{4}\cos 2\phi\right]$$

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

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

Azimuthal Angular Distributions: Parity

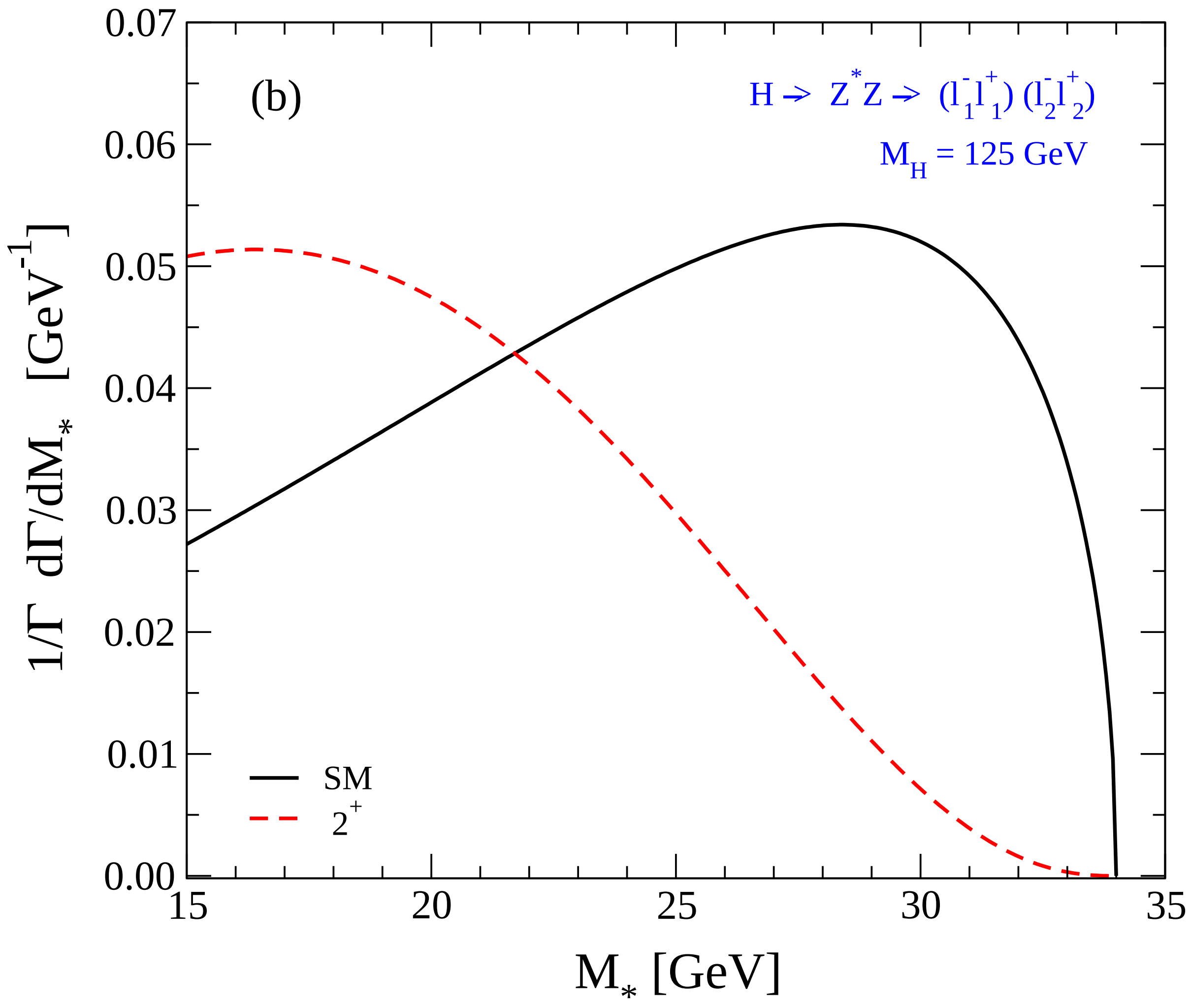
Choi,Miller,MMM,Zerwas



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

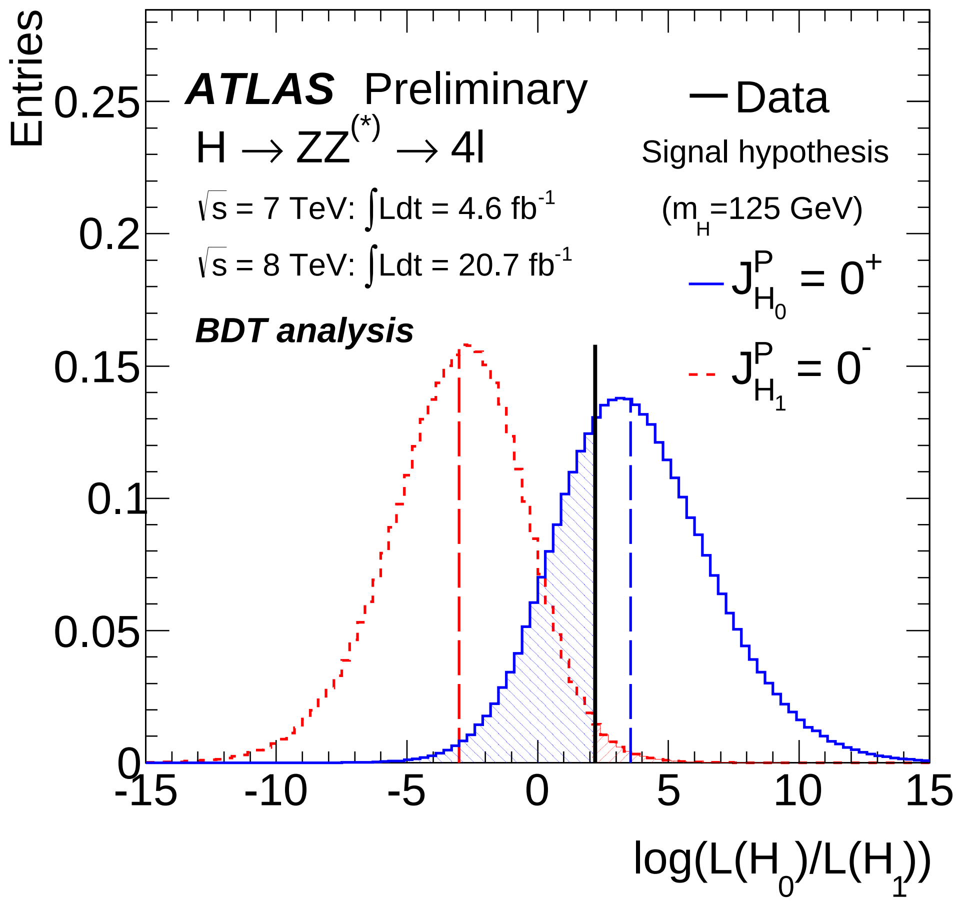
Threshold Behaviour: Spin

Choi, Miller, MMM, Zerwas



ATLAS $\mathcal{R}$esults

- $0^+, 0^-, 1^+, 1^-, 2^+, 2^-$ **hypotheses in** $H \to ZZ^* \to 4l$ ATLAS-CONF-2013-013



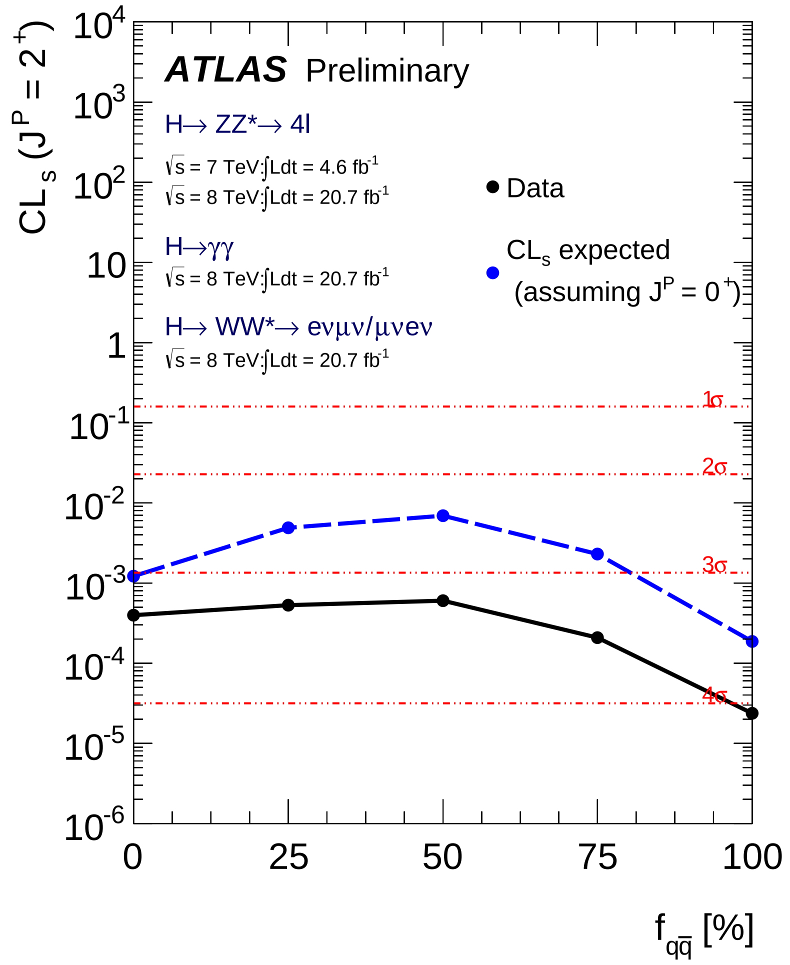
$0^-, 1^+(1^-)$ hypotheses excluded at $> 95\%$ (94%) CL in favour of 0^+
WW, ZZ, $\gamma\gamma$ channels exclude 2^+_m model at 99.9% CL

- **Spin studies in** $H \to \gamma\gamma$ ATLAS-CONF-2012-168, $H \to WW^* \to e\nu\mu\nu$ ATLAS-CONF-2013-031

ATLAS $\mathcal{R}$esults

- **Comparison $J^P = 0^+$ (SM) to graviton-inspired $J^P = 2^+$ model w/ minimal couplings**

ATLAS-CONF-2013-040



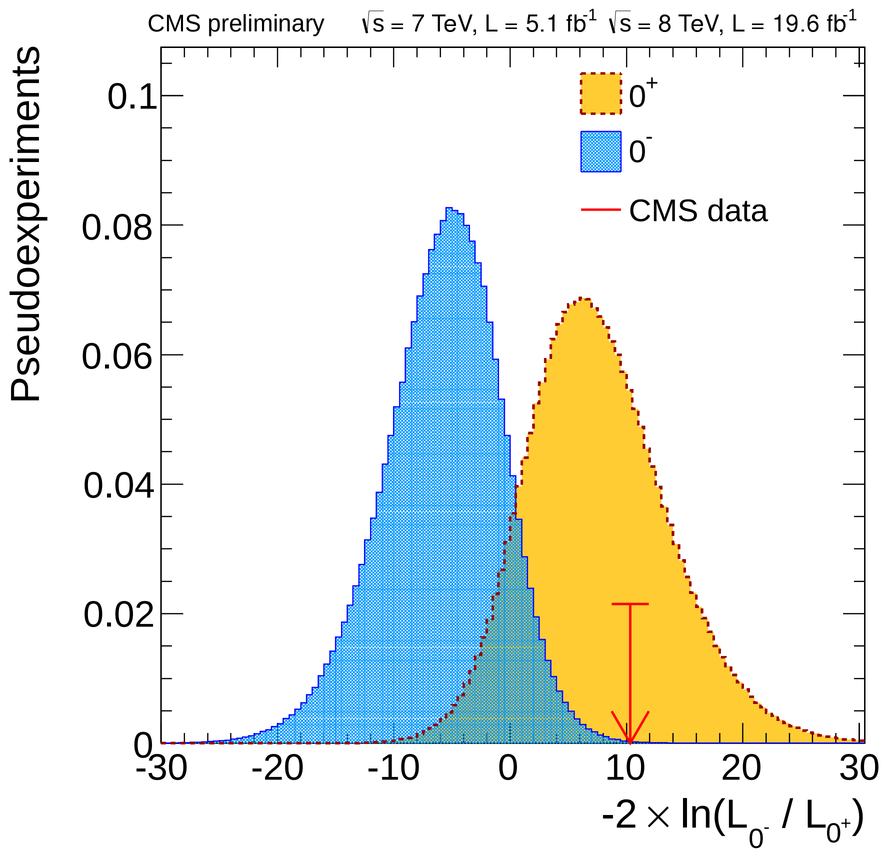
Exclusion at more than 99.9% CL

for all admixtures of gg fusion and $q\bar{q}$ production processes

CMS $\mathcal{R}$esults

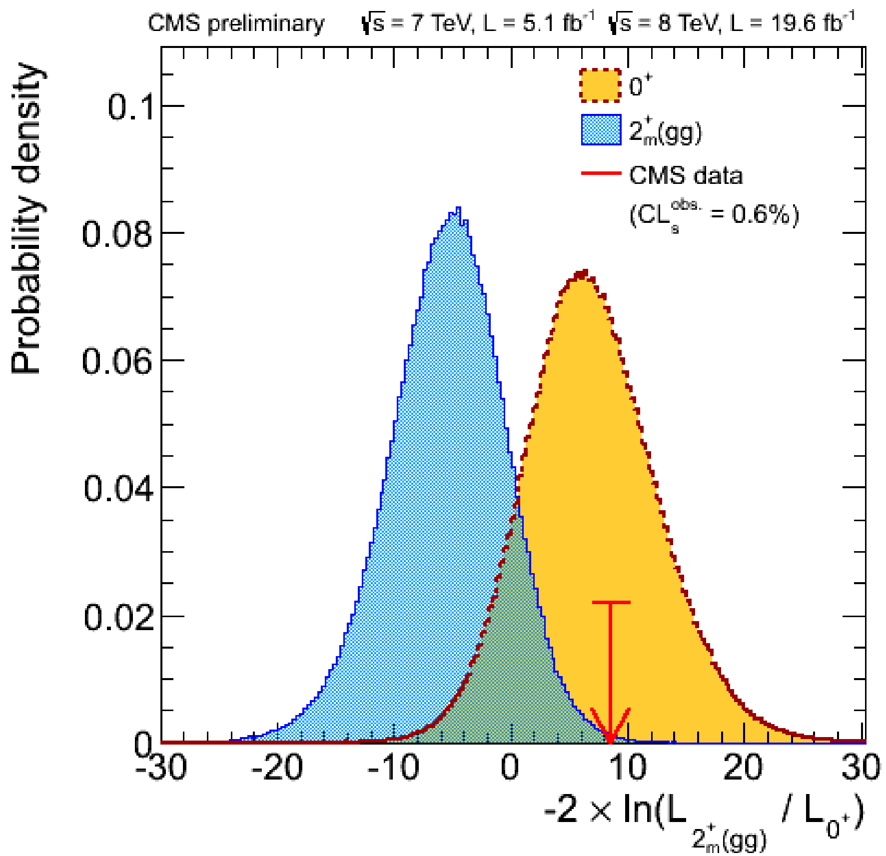
- $0^+, 0^-, 1^+, 1^-, 2^+, 2^-$ **hypotheses in** $H \to ZZ^* \to 4l$ PRL 110 (2013)

CMS-PAS-HIG-13-002



0^- excluded at 95% CL

CMS-PAS-HIG-13-005



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

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

Some Comments

Correlation: between spin/parity and coupling measurements; example

- observed strong interaction of new particle with EW gauge bosons $\rightsquigarrow$ not pseudoscalar ?
- pseudoscalar interacts w/ gauge bosons through higher-dim operators
- if significant contributions $\rightsquigarrow$ beyond SM physics at low scale
- would have been observed experimentally

Nevertheless: Experimental test of these arguments is important

Momentum dependence

- coupling coefficients can be in general momentum-dependent
- momentum dependence involves ratios of typical momenta in the process to scale of New Physics Λ
- first approximation: neglect scale dependence

Some Comments

More refined analyses (more sophisticated parametrisations, kinematic dependences of coupling constants, multi-parameter fits, ...)

- ◇ if introduced non-minimal couplings cannot describe properties of new particle
- ◇ when more data available

With present data

- ◇ first step: test of different hypotheses
- ◇ extreme spin/parity hypotheses can be excluded
- ◇ small anomalous coupling contributions to Higgs-gauge coupling cannot be excluded

Strategy

1. Prove that decay distributions are compatible with 0^+ (SM) , but not 0^- ✓
2. Rule out in a model-independent way higher spins with both parities (so far only KKG(2^+))
3. $0^+/0^-$ CP-violating mixture?
   - ◇ Large enough ZZH^- couplings $\leadsto$ simple analysis
   - ◇ Otherwise work out other channels, including fermions

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

- **Systematic helicity analyses for angular distributions**

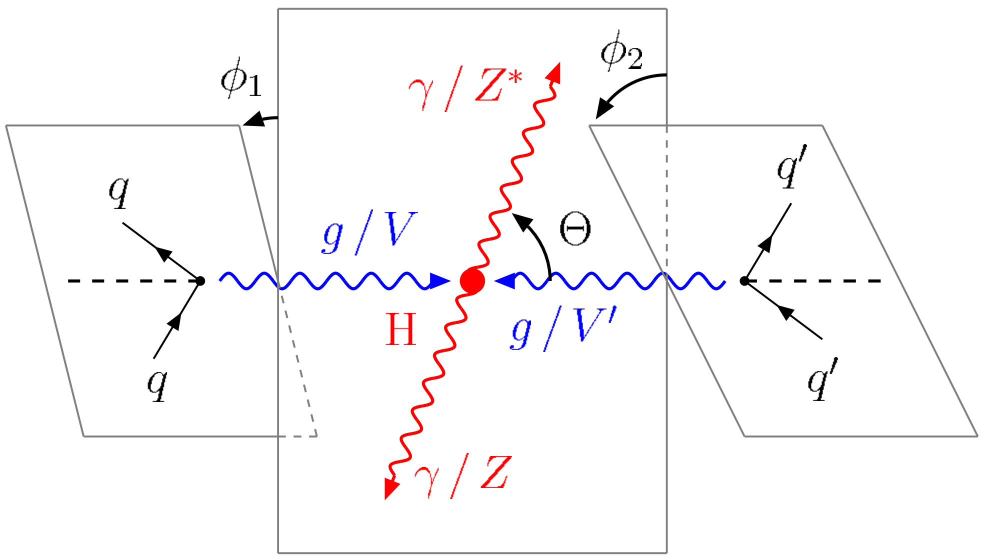
$$\frac{1}{\sigma}\frac{d\sigma(\gamma\gamma)}{d\cos\Theta} = (2J+1)[\mathcal{X}_0^J\mathcal{Y}_0^J\mathcal{D}_{00}^J + \mathcal{X}_0^J\mathcal{Y}_2^J\mathcal{D}_{02}^J + \mathcal{X}_2^J\mathcal{Y}_0^J\mathcal{D}_{20}^J + \mathcal{X}_2^J\mathcal{Y}_2^J\mathcal{D}_{22}^J]$$

∗ $\mathcal{D}_{m\lambda}^J$ squared Wigner functions, $m = S_z$ spin component, $\lambda \equiv \lambda_\gamma - \lambda'_\gamma$

∗ $\mathcal{X}$ production helicity probability

∗ $\mathcal{Y}$ decay helicity probability

(b)



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$*$ $\mathcal{X}$ production helicity probability

$*$ $\mathcal{Y}$ decay helicity probability

- **Types**

'scalar-type assignment' (Higgs): $\mathcal{X}_0^J = \mathcal{Y}_0^J = 1$ and $\mathcal{X}_2^J = \mathcal{Y}_2^J = 0$ $[J \geq 0]$

'tensor-type assignment' (graviton-like): $\mathcal{X}_0^J = \mathcal{Y}_0^J = 0$ and $\mathcal{X}_2^J = \mathcal{Y}_2^J = 1$ $[J \geq 2]$

General Spin/Parity Assignments

- **Selection rules for Higgs spin/parity** from observing the polar angular distributions of a spin-J Higgs state in $gg \to H \to \gamma\gamma$

$\mathcal{P} \setminus J$	0	1	$2, 4, \cdots$	$3, 5, \cdots$
even	1	forbidden	$\mathcal{D}^J_{00}$ $\mathcal{D}^J_{02}$ $\mathcal{D}^J_{20}$ $\mathcal{D}^J_{22}$	$\mathcal{D}^J_{22}$
odd	1	forbidden	$\mathcal{D}^J_{00}$	forbidden

- **Squared Wigner functions** $\mathcal{D}^J_{m\lambda}$ up to $\sim |\cos^{2J}\Theta|$

$$\mathcal{D}^0_{00} = 1$$

$$\mathcal{D}^2_{00} = (3\cos^2\Theta - 1)^2/4 \qquad \mathcal{D}^2_{22} = (\cos^4\Theta + 6\cos^2\Theta + 1)/16$$

$\mathcal{G}$eneral $\mathcal{S}$pin/$\mathcal{P}$arity $\mathcal{A}$ssignments

- **Selection rules for Higgs spin/parity** from observing the polar angular distributions of a spin-J Higgs state in $gg \to H \to \gamma\gamma$

$\mathcal{P} \setminus J$	0	1	$2, 4, \cdots$	$3, 5, \cdots$
even	1	forbidden	$\mathcal{D}^J_{00}$ $\mathcal{D}^J_{02}$ $\mathcal{D}^J_{20}$ $\mathcal{D}^J_{22}$	$\mathcal{D}^J_{22}$
odd	1	forbidden	$\mathcal{D}^J_{00}$	forbidden

$0^\pm$: D^0_{00} observed, none else $\rightsquigarrow \pm$ undisc

2^+ : D^2_{00} and $D^2_{22} \neq 0$, both

2^- : $D^2_{00} \neq 0$, none else

...

$1^\pm$: forbidden by Landau/Yang

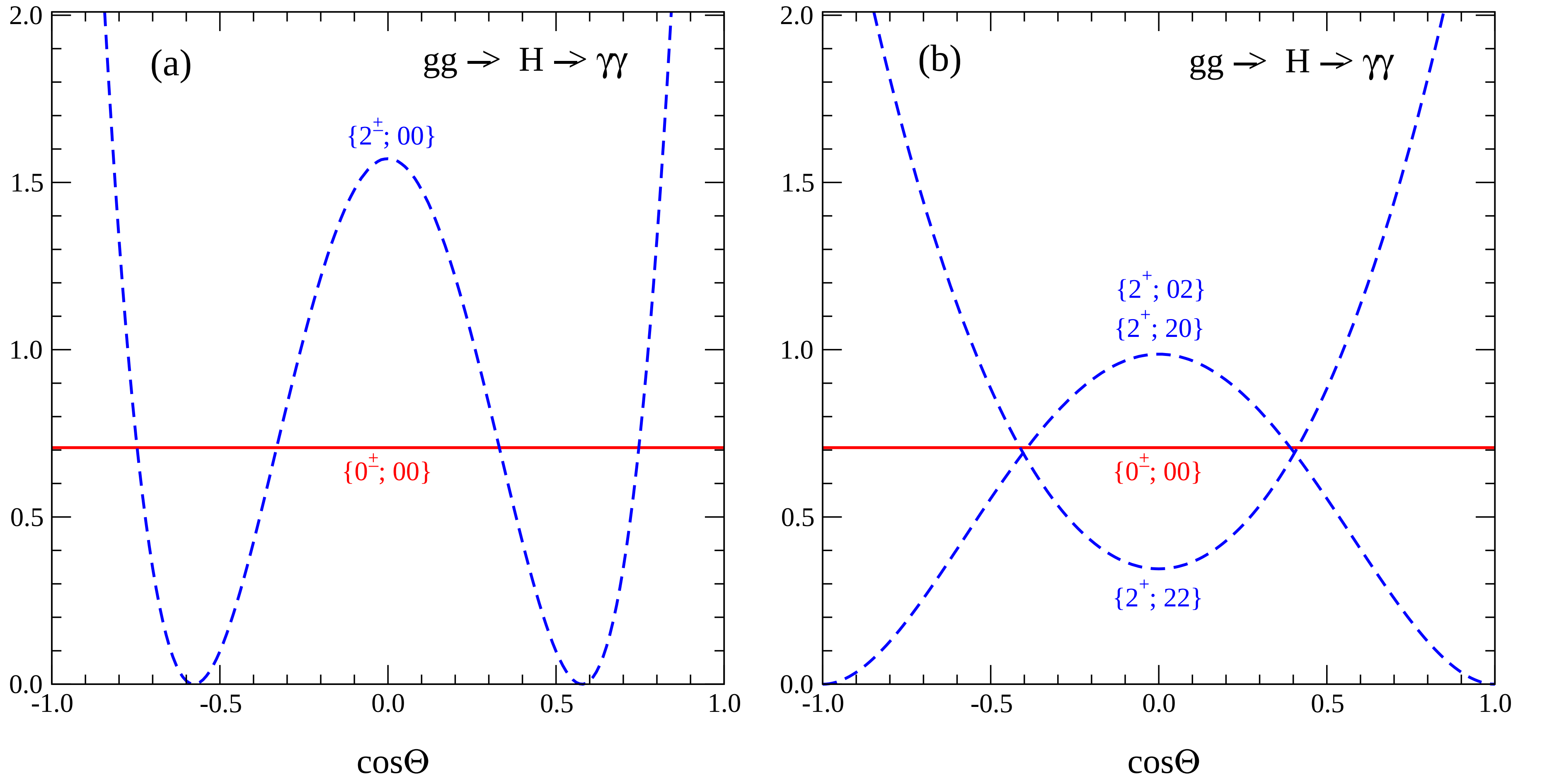
3^+ : $D^3_{22} \neq 0$, none else

3^- : forbidden

...

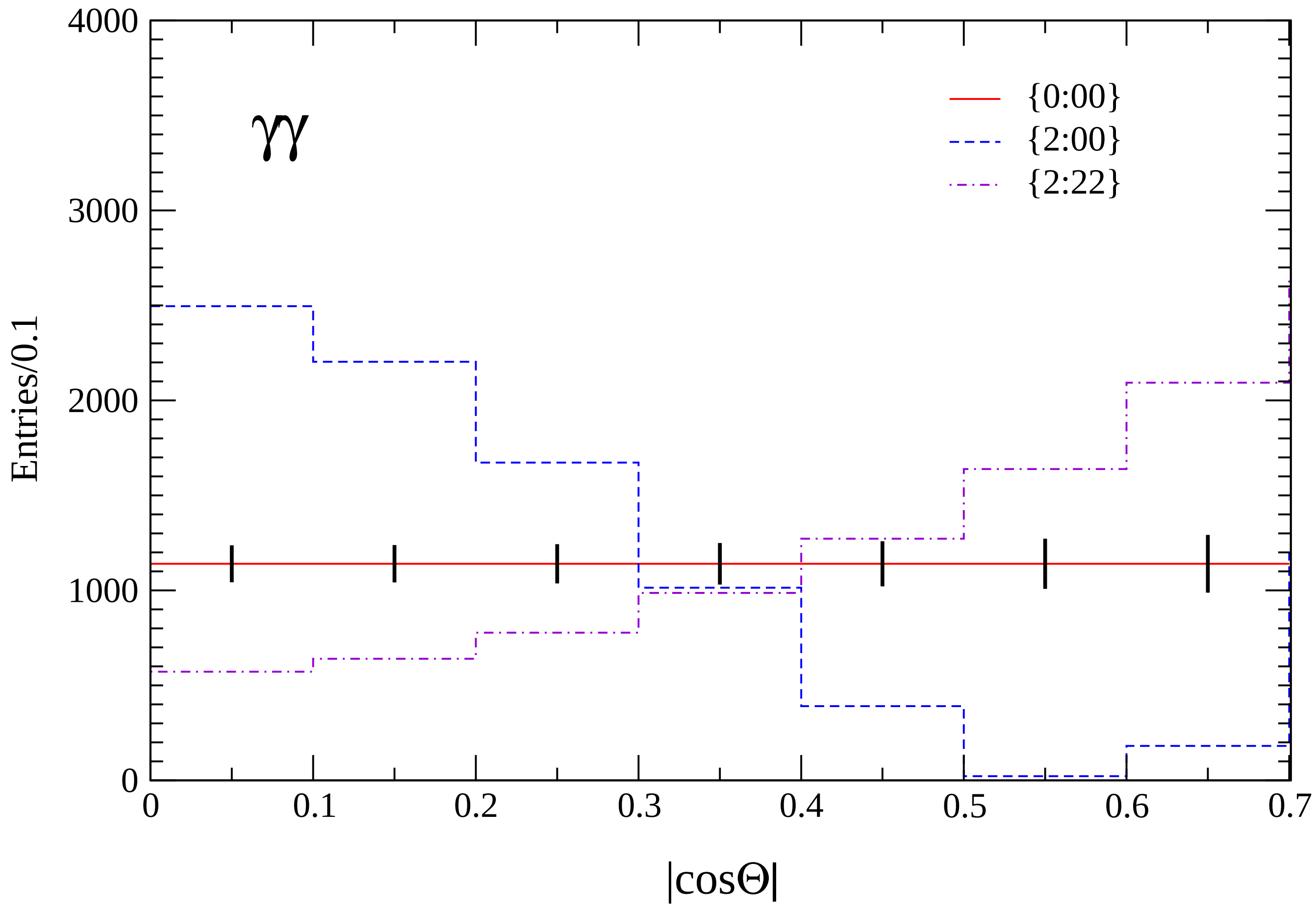
$\mathcal{S}$calar-type, $\mathcal{T}$ensor-type

Choi,Miller,MMM,Zerwas



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

Choi,MMM,Zerwas



(III) $\mathcal{F}$urther $\mathcal{A}$nalyses

- **Analoguous analysis:** Angular distribution of Z^*Z axis in Z^*Z final states

- **Parity check in:**
  - $*$ Azimuthal corr. between radiation planes in $qq \to VV' + qq \to H, A + qq$ — Plehn eal; Hagiwara eal
  - $*$ Correlations of planes in $gg \to H, A+$ 2 jets — Hagiwara eal

- **Spin/Parity in Higgs-strahlung:** $q\bar{q} \to Z/W + H^J$ — Choi eal; Ellis eal; Englert eal; Frank eal; Djouadi eal

- **Fermionic decays:** Angular correlations among fermion decay products in $H^J \to f\bar{f} \to a\bar{a} \ldots$ — Kramer eal; Berge eal

- **CP-violating H':**
  - $*$ In $H' \to Z^*Z$, hopefully — Godbole,Miller,MMM
  - $*$ Alternatively in Higgs + 2 jets, in fermionic decays — Berge,Bernreuther,Ziethe; Berge,Bernreuther; Berge,Bernreuther,Niepelt,Spiesberger

$\mathcal{CP}$ $\mathcal{V}$iolation in $H' \to Z^*Z \to 4l$

- **CP-violating $H'ZZ$ vertex:** Godbole, Miller, MMM

$$V^{\mu\nu}_{H'ZZ} = \frac{igM_Z}{\cos\theta_W}\left[a\, g^{\mu\nu} + b\,\frac{p^\mu p^\nu}{M^2_{H'}} + c\,\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho k_\sigma}{M^2_{H'}}\right]$$

$p = k_1 + k_2, k = k_1 - k_2, \quad k_1, k_2$ 4-momenta of Z^*, Z

- **CP-violation:** simultaneously a, c non-zero, or b, c non-zero (SM: $a = 1, b = c = 0$)

- **Angular correlations and CP-properties**

Angular correlation	Observed quantity	CP
$\mathcal{O}_1 = s^2_{\theta_1} s^2_{\theta_2}$	$\gamma^4 \lvert\tilde{a}\rvert^2$	even
$\mathcal{O}_2 = (1 + c^2_{\theta_1})(1 + c^2_{\theta_2})/4 + \eta_1\eta_2 c_{\theta_1} c_{\theta_2}$	$2\,(\lvert a\rvert^2 + \beta^2 \lvert c\rvert^2)$	even
$\mathcal{O}_3 = s^2_{\theta_1} s^2_{\theta_2} c_{2\phi}/2$	$\lvert a\rvert^2 - \beta^2 \lvert c\rvert^2$	even
$\mathcal{O}_4 = s^2_{\theta_1} s^2_{\theta_2} s_{2\phi}/2$	$2\beta\,\mathrm{Re}(ac^*)$	odd
$\mathcal{O}_5 = \eta_1 s_{\theta_1} c_{\theta_2} s_{\theta_2} s_\phi + \eta_2 c_{\theta_1} s_{\theta_1} s_{\theta_2} s_\phi$	$-2\kappa\gamma^2\,\mathrm{Im}(ab^*)$	even

Table 1: $c_{\theta_1} \equiv \cos\theta_1$ *etc., and* $\tilde{a} \equiv a + \kappa\, b$ *where* $\kappa = M^2_{H'}\beta^2/[2(M^2_{H'} - M^2_Z - M^2_*)]$.

$\mathcal{CP}$ $\mathcal{V}$iolation in $H' \to Z^*Z \to 4l$

- **CP-violating $H'ZZ$ vertex:** Godbole,Miller,MMM

$$V^{\mu\nu}_{H'ZZ} = \frac{igM_Z}{\cos\theta_W}\left[a\,g^{\mu\nu} + b\,\frac{p^\mu p^\nu}{M^2_{H'}} + c\,\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho k_\sigma}{M^2_{H'}}\right]$$

$p = k_1 + k_2, k = k_1 - k_2,\quad k_1, k_2$: 4-momenta of Z^*, Z

- **CP-violation:** simultaneously a, c non-zero, or b, c non-zero (SM: $a = 1, b = c = 0$)

- **Angular correlations and CP-properties**

$$O_4 = \frac{[(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot \vec{p}_{1H}][(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot (\vec{p}_{1H} \times \vec{p}_{2H})]}{|\vec{p}_{3H} + \vec{p}_{4H}|^2|\vec{p}_{1H} + \vec{p}_{2H}||\vec{p}_{3Z} - \vec{p}_{4Z}|^2|\vec{p}_{1Z} - \vec{p}_{2Z}|^2/16}$$

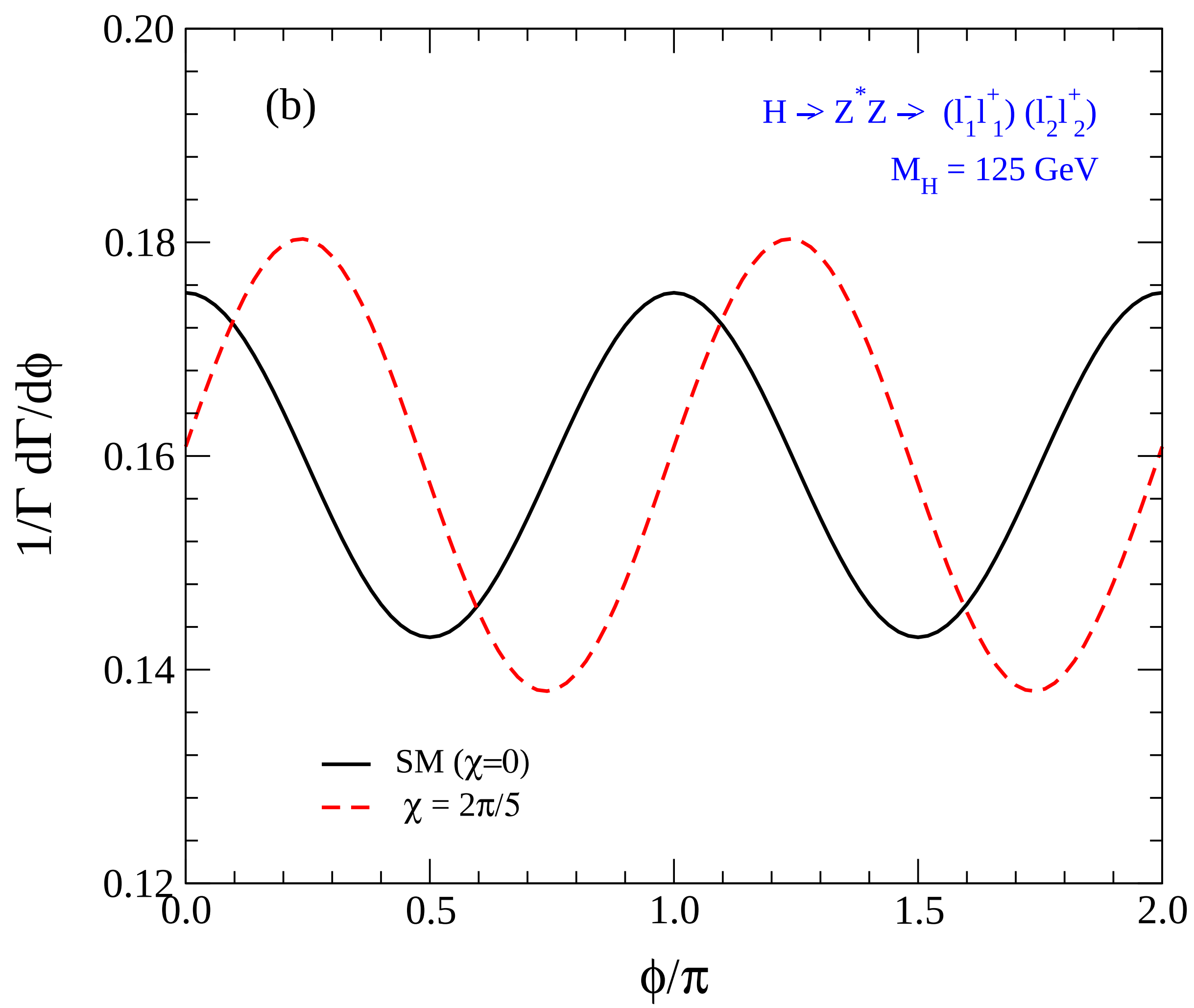
$$\mathcal{A}_4 = \frac{\Gamma(O_4 > 0) - \Gamma(O_4 < 0)}{\Gamma(O_4 > 0) + \Gamma(O_4 < 0)}$$

Achieved significance for Re(c)/a $= 2.7$ (max asymm):

$7+8$ TeV :	$S_{\mathcal{A}_4} = 0.45 - 0.5$	ATLAS-CMS
14 TeV :	$S_{\mathcal{A}_4} = 0.74$	at $\int\mathcal{L} = 100$ fb^{-1}
	$S_{\mathcal{A}_4} = 1.28$	at $\int\mathcal{L} = 300$ fb^{-1}

$\mathcal{CP}$ Violating $\mathcal{W}$ave $\mathcal{F}$unction in $H' \to Z^*Z \to 4l$

Choi,Miller,MMM,Zerwas

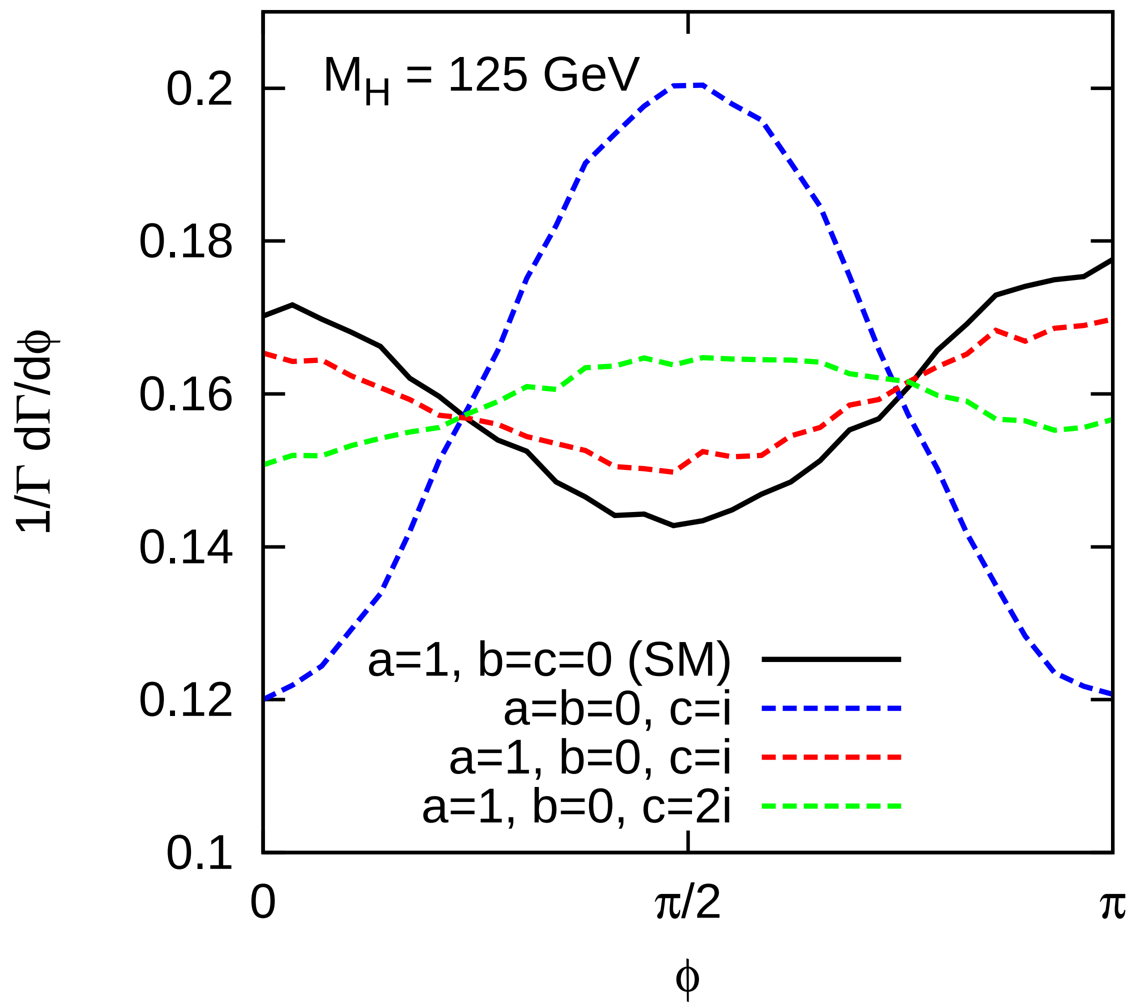


$H' = \cos\chi H + \sin\chi e^{i\xi} A$

Ellis eal; Choi eal

$\mathcal{CP}$ $\mathcal{V}$iolating in $\mathcal{K}$inematical $\mathcal{D}$istributions

Godbole,Miller,MMM



$\mathcal{CP}$ $\mathcal{V}$iolation in $gg \to H' + gg$ with $H' \to \gamma\gamma$

- **CP-violating $H'gg$ vertex:**

$$V_{H'gg} = \cos\chi V_{Hgg} + \sin\chi e^{i\xi} V_{Agg}$$

- **Modulation of azimuthal angular modulation of the two jets:**

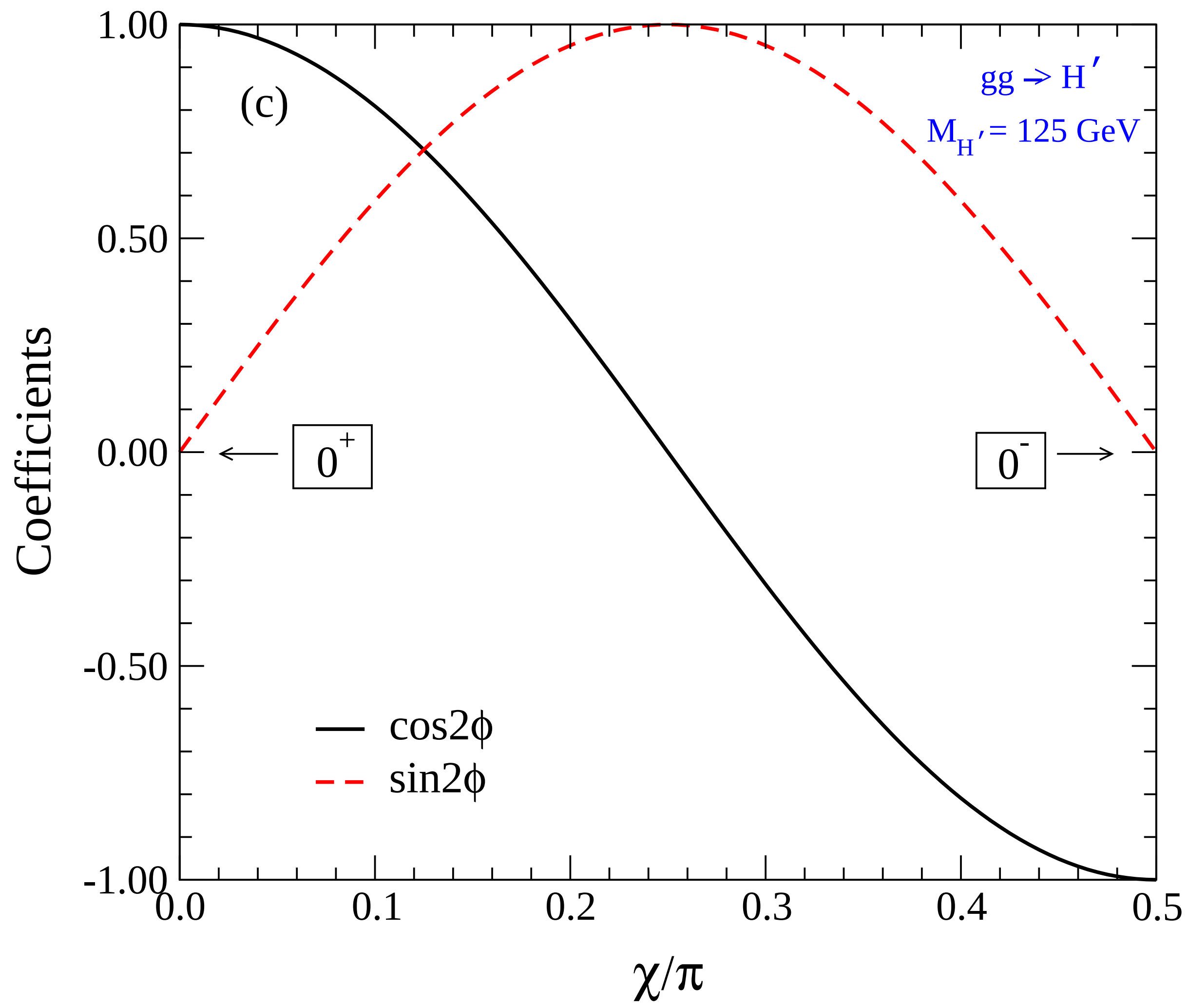
$$\frac{1}{\sigma}\frac{d\sigma}{d\phi} = \frac{1}{2\pi}\left[1 + |\zeta|\left\{\left(c_\chi^2 - \rho_g^2 s_\chi^2\right)\cos 2\phi + \rho_g\, s_{2\chi} c_\xi\, \sin 2\phi\right\}/\mathcal{N}'\right]$$

$|\zeta|$: polarisation parameter, $\mathcal{N}' = c_\chi^2 + \rho_g^2 s_\chi^2$: normalisation, $\rho_g = Agg/Hgg$

Azimuthal-Angle Distribution

CP- and CP-odd coefficients in the azimuthal-angle distribution of the two initial two-jet emission planes in $gg \to H' + gg$ ($\rho_g = 1$, $\xi = 0$, $|\zeta| = 1$)

Choi,Miller,MMM,Zerwas



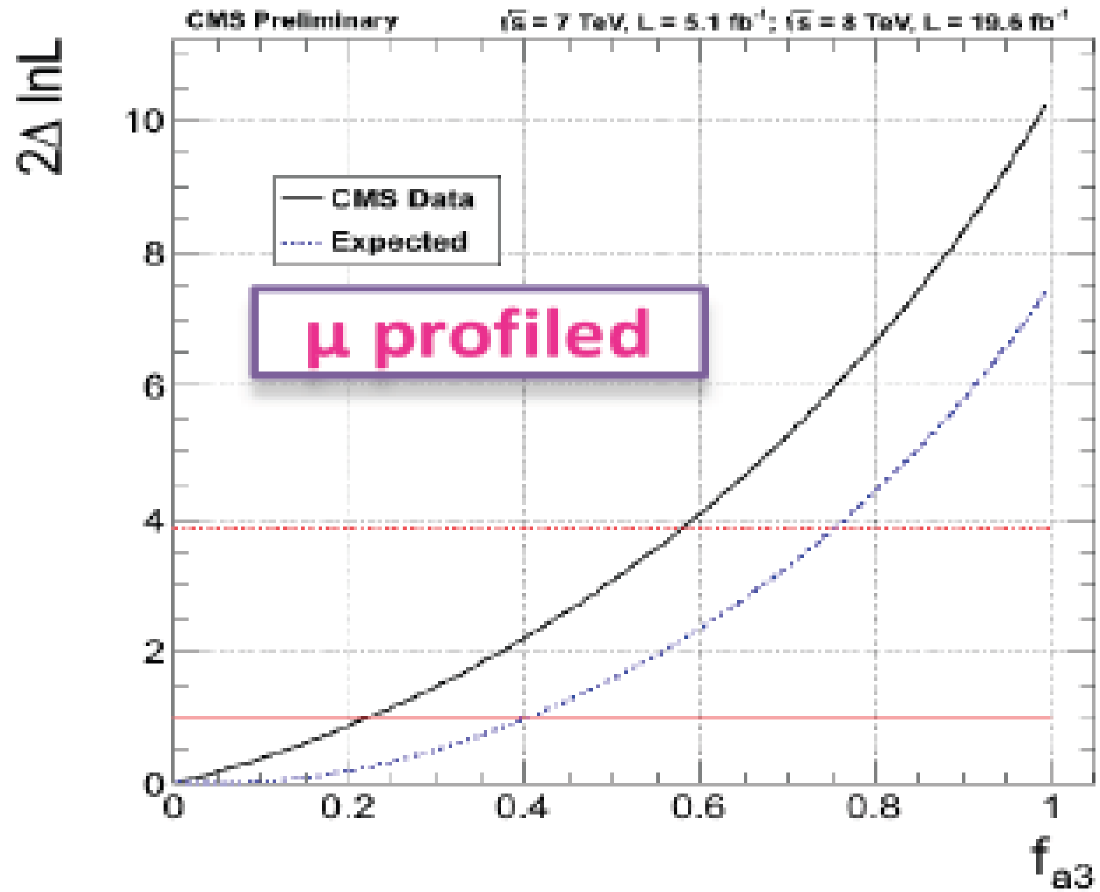
$\mathcal{R}$esults on $\mathcal{M}$ixed $\mathcal{P}$arity

Mixed parity in $H \to ZZ \to 4l$

$$A(X \to V_1 V_2) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}(a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma)$$

CP-odd admixture: $f_{a_3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$

CMS



$f_{a_3} = 0.00^{+0.23}_{-0.00}$

$f_{a_3} < 0.58$ @ 95% CL

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

14 Mar 2013

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

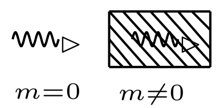
$\mathcal{E}$xperimental $\mathcal{V}$erification of the EWSB $\mathcal{M}$echanism

EWSB mechanism:

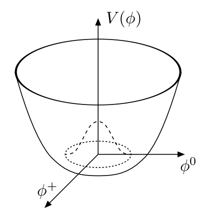
Creation of particle masses without violating gauge principles

Test of the EWSB mechanism

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



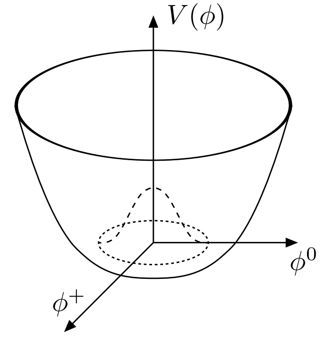
- Spin- and parity quantum numbers – J^{PC}
- EWSB: potential w/ non-vanishing VEV – $\lambda_{HHH}, \lambda_{HHHH}$

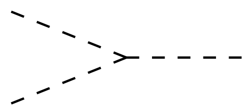
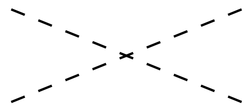


$\mathcal{D}$etermination of the $\mathcal{S}$calar $\mathcal{B}$oson $\mathcal{S}$elf-$\mathcal{C}$ouplings

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

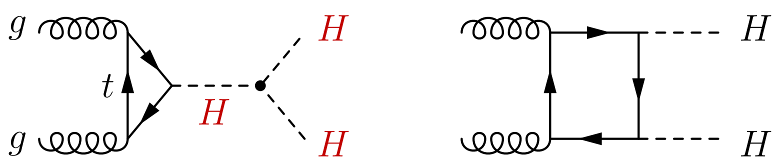
The Trilinear Self-Coupling at the LHC

Determination of λ_{HHH} at the LHC

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

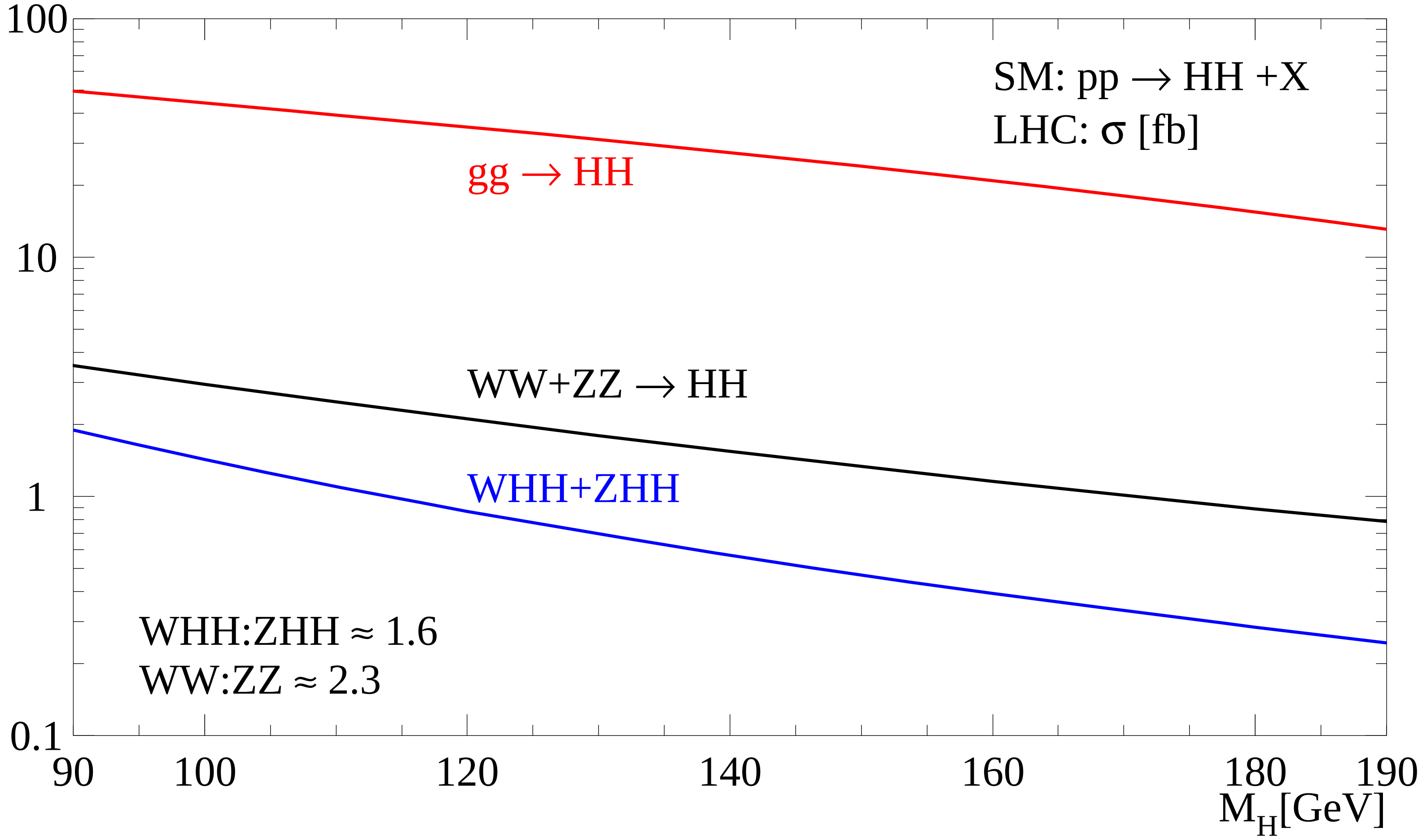
double radiation of W/Z:	$q\bar{q}$	$\rightarrow$	$W/Z + HH$	Barger,Han,Phillips
WW/ZZ fusion:	qq	$\rightarrow$	$qq + HH$	Dicus,Kallianpur,Willenbrock Abbasabadi,Repko,Dicus,Vega Dobrovolskaya,Novikov Eboli,Marques,Novaes,Natale
gluon gluon fusion:	gg	$\rightarrow$	HH	Glover,van der Bij Plehn,Spira,Zerwas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

gluon gluon fusion - dominant process



Double SM Scalar Boson 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!

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

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

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

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

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

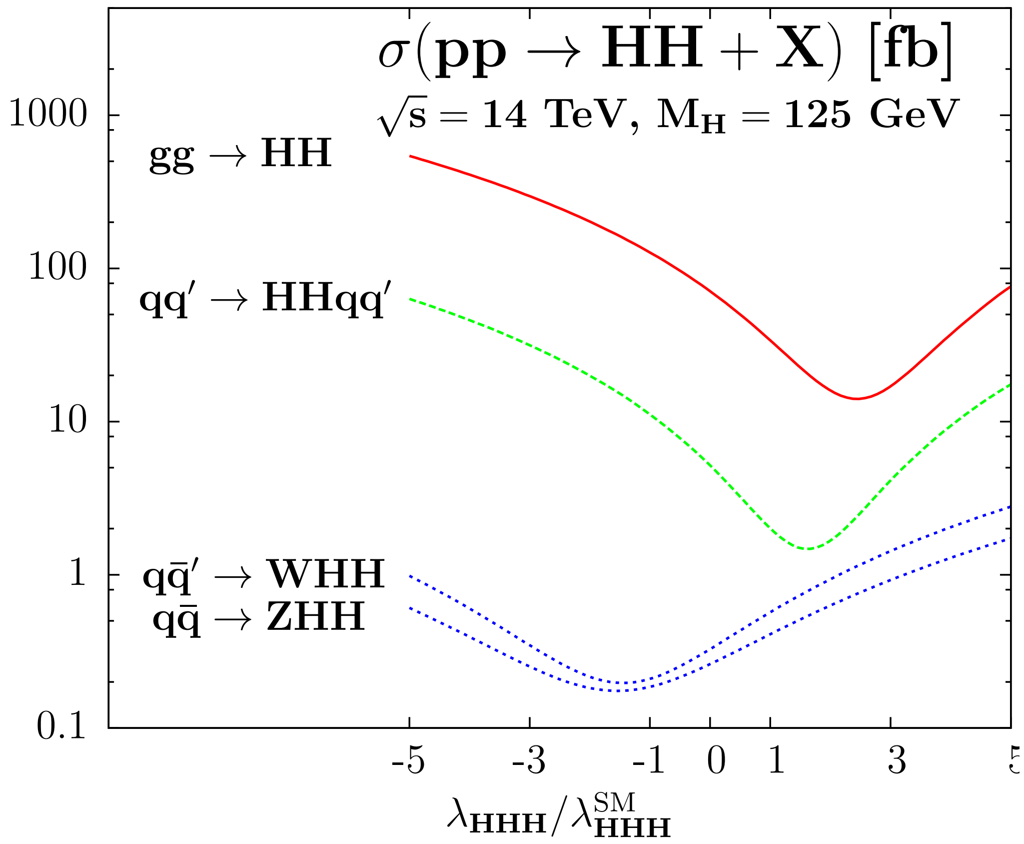
∘ LHC@14TeV [$\int \mathcal{L} = 1000$ fb^{-1}]: $HHj \to b\bar{b}\tau^+\tau^- j$: most promising to constrain λ_{HHH}

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

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

Sensitivity to λ_{HHH}

Baglio, Djouadi, Gröber, MMM, Quevillon, Spira

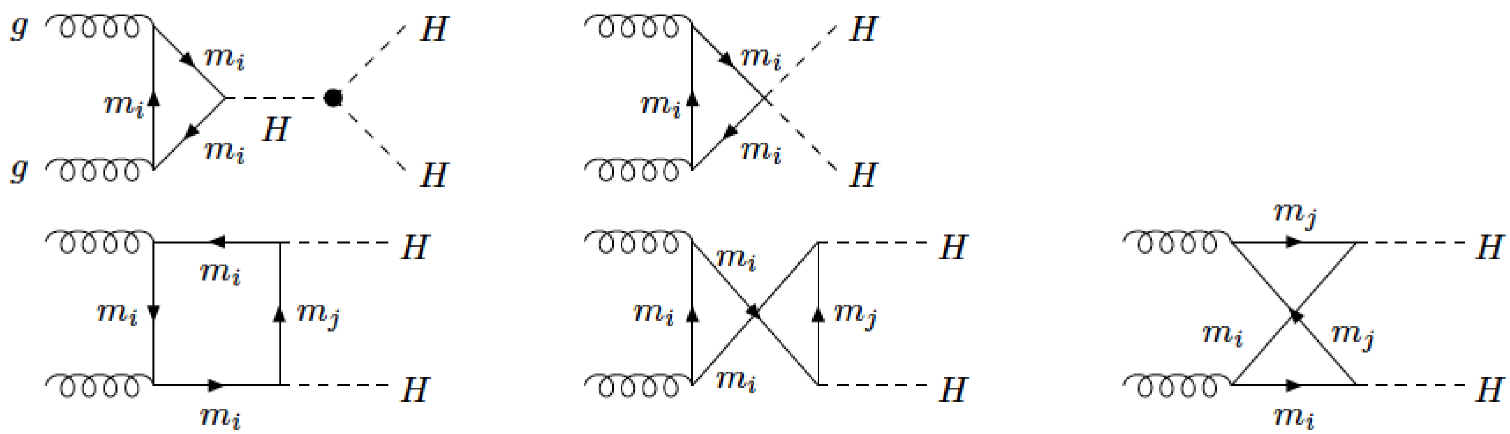


Measurement of cross section with 50% accuracy yields 50% accuracy in λ_{HHH}

$\mathcal{D}$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 (← composite top)



▷ Can be enhanced compared to the SM process

Gröber,MMM

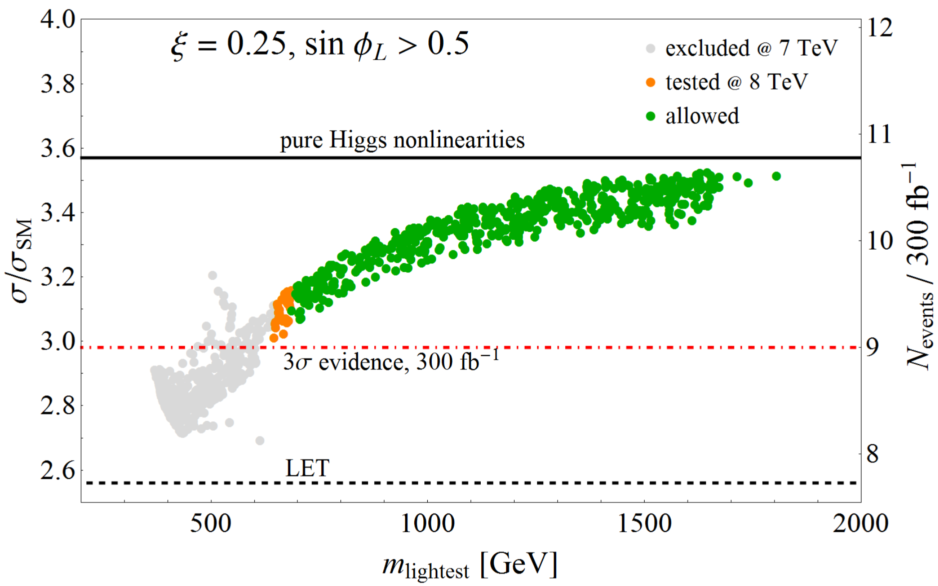
▷ Mediated by top and bottom loops and heavy quark loops; here heavy top partners

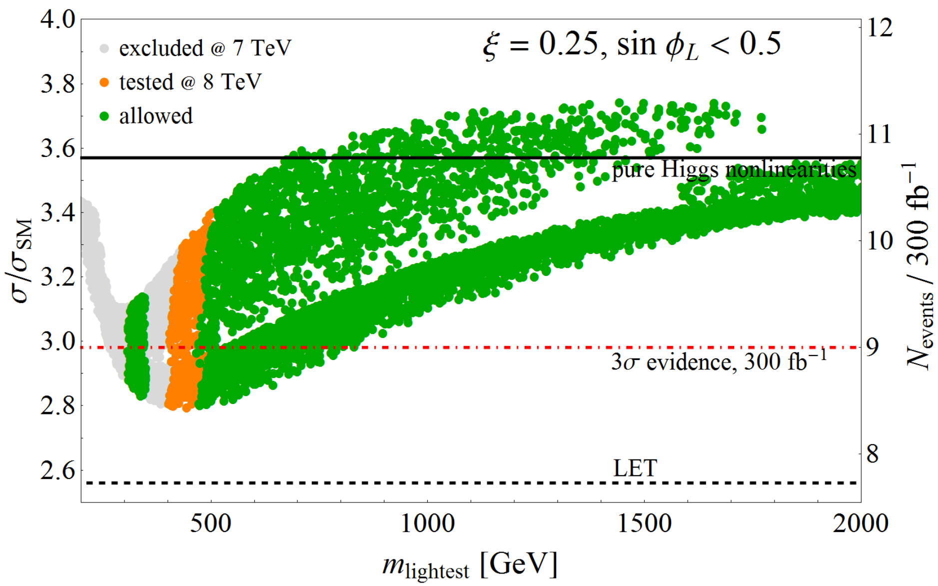
▷ Different fermions can contribute within one loop

▷ 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: $2.7 \lesssim \sigma/\sigma_{SM} \lesssim 3.7$

Going 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

Cone Higgs

Simplest Higgs

Phantom Higgs

MSSM Higgs Mass in View of the LHC Results

- **Vast literature on MSSM Higgs of $\sim 122...128$ GeV**

  Arbey eal; Li eal; Feng eal; Baer 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; ...

- **MSSM Higgs mass corrections**

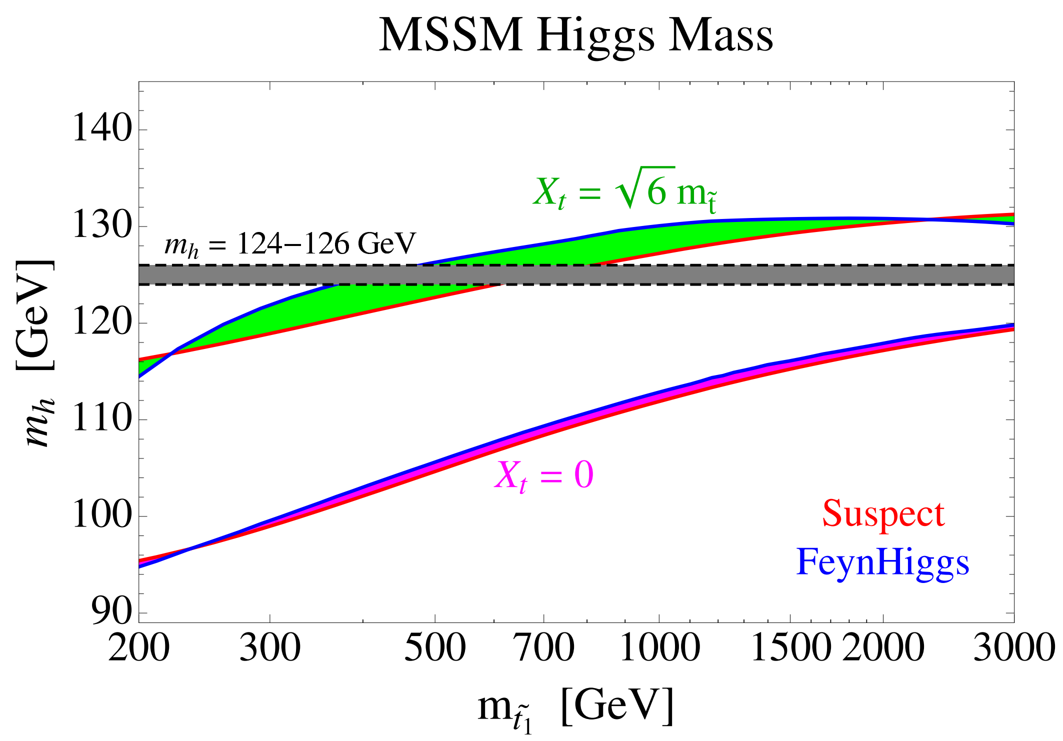
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$\Rightarrow M_H \approx 125$ GeV requires

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

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

Hall,Pinner,Ruderman 1112.2703



Maximal stop mixing:

$m_{\tilde{t}_1} \overset{!}{\gtrsim} 500$ GeV

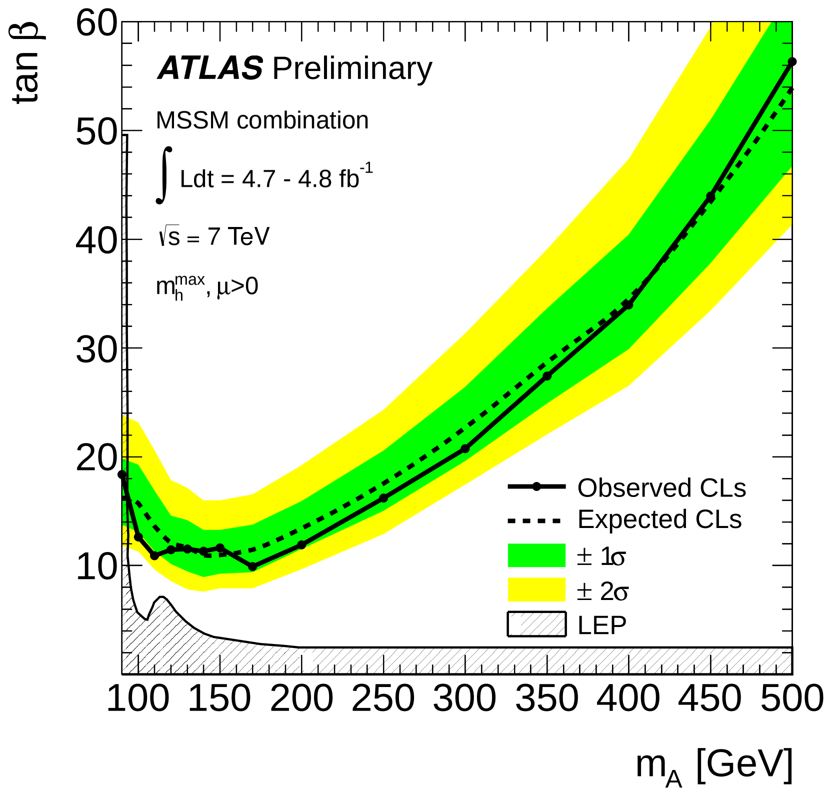
- **Further remarks:**
  - next-lightest Higgs can be SM-like 122-128 GeV Higgs (low M_A, moderate $\tan\beta$) lightest Higgs below LEP limit see e.g. Heinemeyer eal '11
  - enhanced diphoton rate can be achieved within MSSM w/ light staus Carena eal '11
  - $\gamma\gamma$ excess, but no WW excess requires New Physics beyond MSSM Christensen eal '12

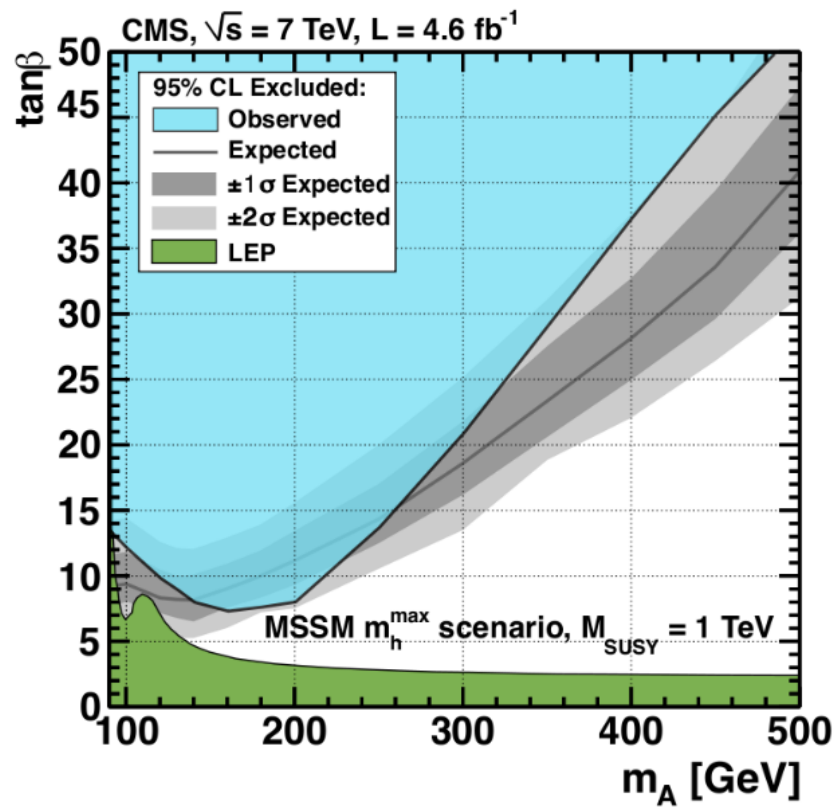
Search for MSSM Higgs Bosons at the LHC

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

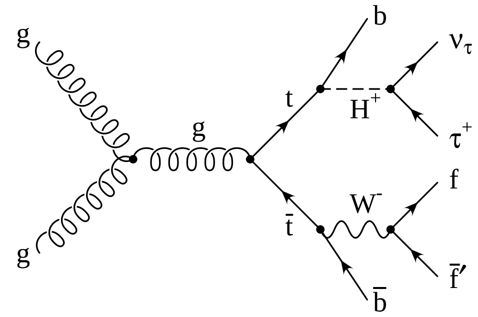
ATLAS-CONF-2012-094

CMS 1202.4083

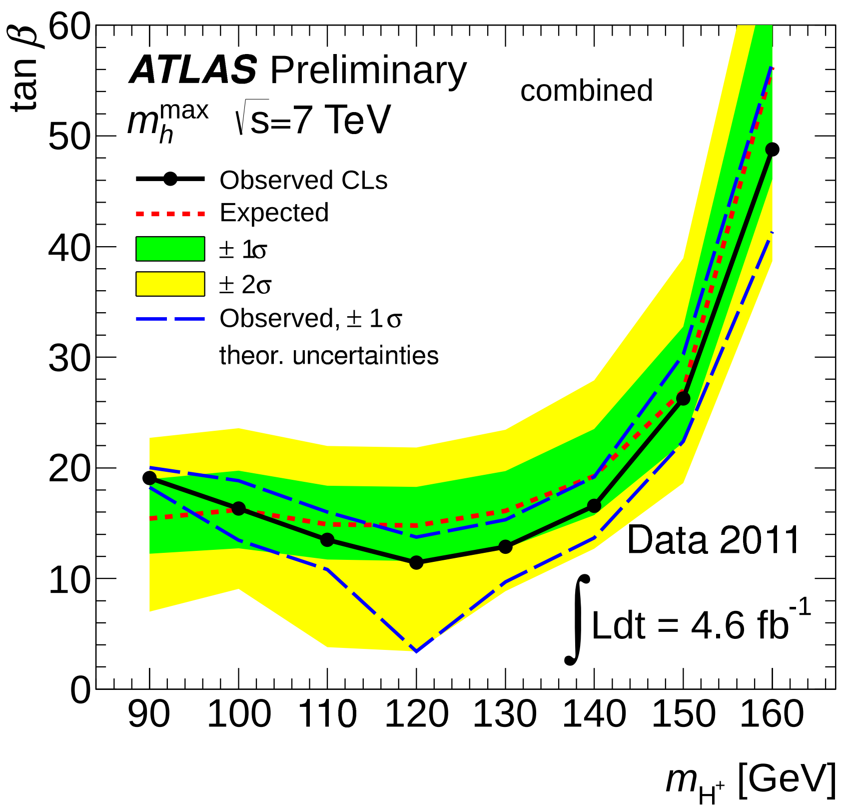




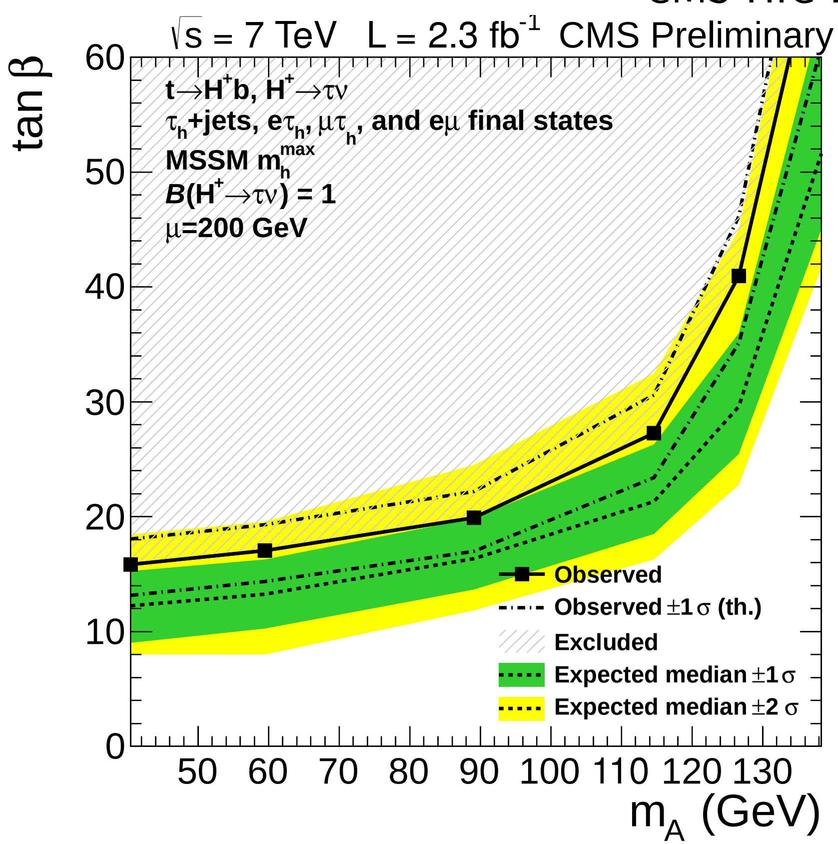
Search for MSSM Higgs Bosons at the LHC



ATLAS-CONF-2012-011



CMS-HIG-11-019



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

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

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

- **The μ-problem of the MSSM:**

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

- **Solution in the NMSSM:**

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

- **Enlarged Higgs and neutralino sector:**

  7 Higgs bosons: $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

  5 neutralinos: $\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Significant changes of Higgs boson phenomenology**

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

- **Vast literature on NMSSM Higgs of $\sim$ 122...128 GeV**

  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Vasquez eal; Cao eal; Gabrielli eal; ...

- **Remarks**

  ◇ SM-like Higgs with ~ 125 GeV can be either H_1 or H_2 (H_1 singlet-like, suppr. SM couplings)

  ◇ strong singlet-doublet mixing $\rightsquigarrow$ reduced coupling to $b\bar{b}$ $\rightsquigarrow$ $BR(H \to \gamma\gamma)$ enhanced

  ◇ mass value of ~ 125 GeV more easily obtained $\rightsquigarrow$ less finetuning

- **Corrections to the MSSM, NMSSM Higgs boson mass:**

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

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

  $\Rightarrow M_H \approx 125$ requires:

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

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

$\mathcal{F}$inetuning - $\mathcal{N}$atural $\mathcal{SUSY}$ $\mathcal{M}$odel

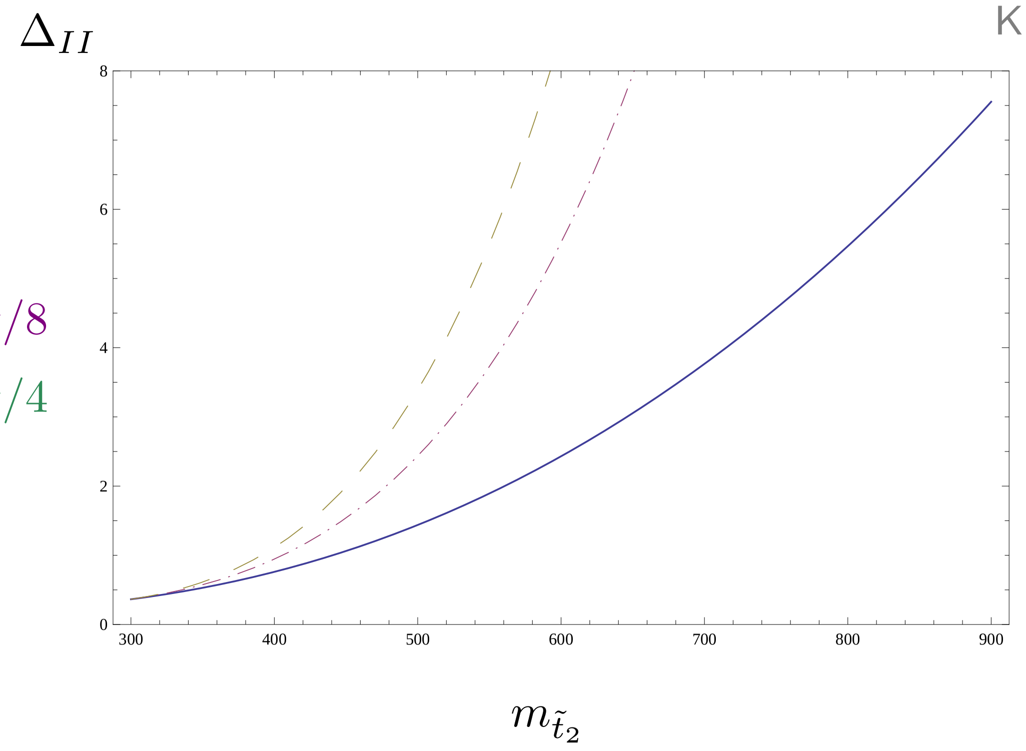
- **The finetuning issue:** study finetuning: calculate 1-loop corrections to the Higgs potential
  - ◇ minimisation conditions of the Higgs potential $\rightsquigarrow$
    to avoid finetuning: correction $\Delta \lesssim \frac{1}{2}M_Z^2$ or $\Delta_{II} = 2\Delta/M_Z^2 \lesssim 1$

King,MMM,Nevzorov '12

solid $\theta_{\tilde{t}} = 0$

dashed-dotted $\theta_{\tilde{t}} = \pi/8$

dashed $\theta_{\tilde{t}} = \pi/4$



To avoid finetuning:
- ∗ both stop masses should be below 500 GeV
- ∗ mixing should be small

$\mathcal{F}$inetuning - $\mathcal{N}$atural $\mathcal{SUSY}$ $\mathcal{M}$odel

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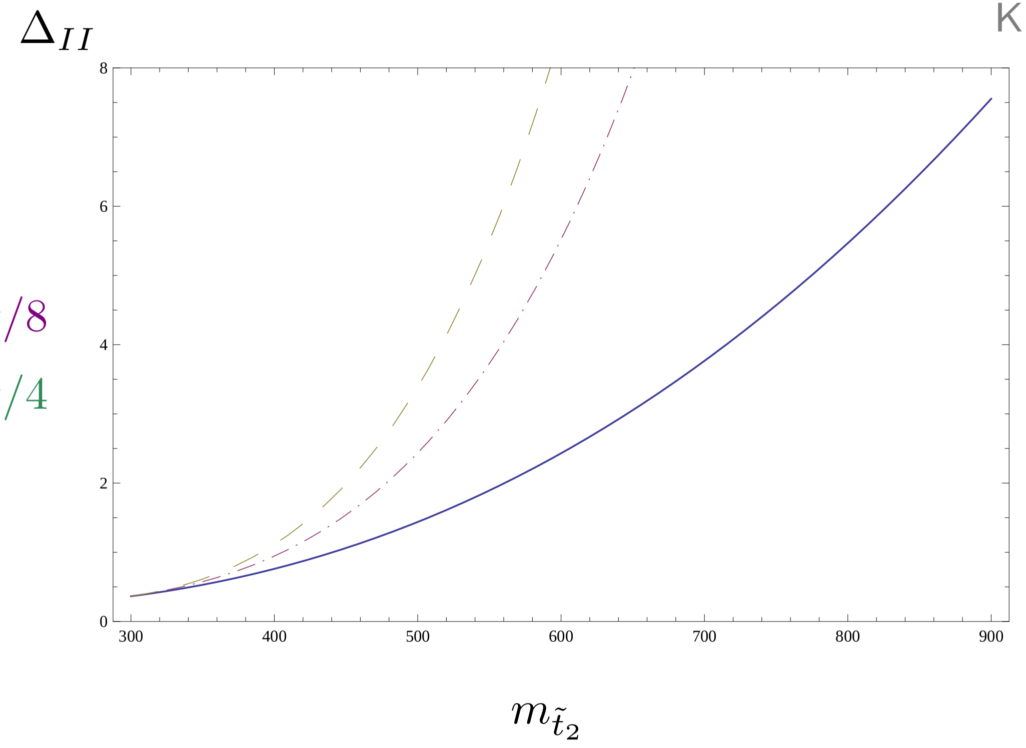
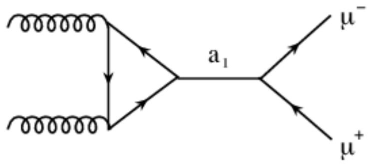
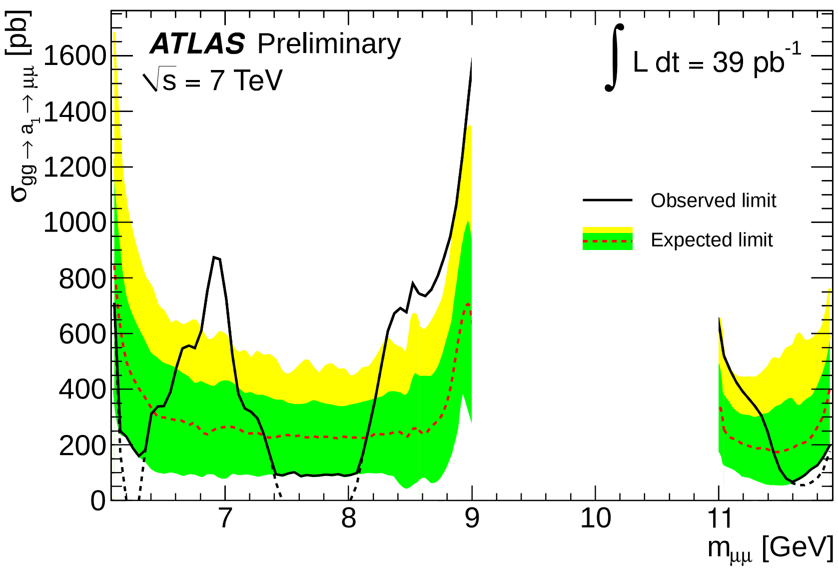


- **Benchmark points:** compatible w/ LHC, finetuning, enhanced $BR(h \to \gamma\gamma)$ King,MMM,Nevzorov
- **NMSSM scans** Albornoz Vasquez eal '12; Cao eal '12

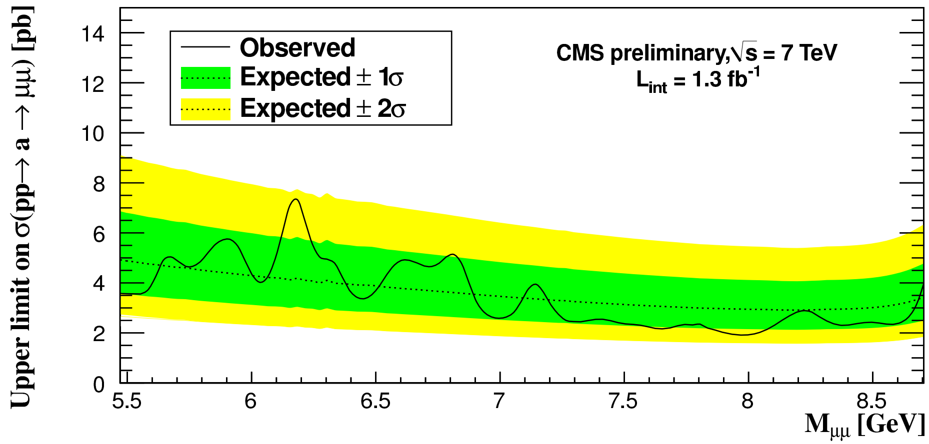
$\mathcal{U}$pper $\mathcal{L}$imit on $\mathcal{NMSSM}$ a_1 $\mathcal{P}$roduction



ATLAS-CONF-2011-020



CMS-HIG-12-004



Conclusions

- **Experimental results compatible with**
  - ⋆ SM scalar boson within 2σ
  - ⋆ Vanishing invisible width

- **Next steps**
  - ⋆ Establish boson as the one *responsible for EWSB*
    - ◇ Coupling determination
    - ◇ Spin and Parity; CP violation
    - ◇ Higgs Boson Self-couplings
  - ⋆ Nature of the boson (SM, SUSY, ...)

Thank you for your attention!

Signal Rates

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

▷ **Expected signal strength**

$$\mu_X = \left[\frac{\sigma^{SM(\kappa_V,\kappa_F)}_{pp\to h\to X}}{\sigma^{SM}_{pp\to h\to X}}\right] = \frac{\sum_{p_i}\epsilon_{p_i}\sigma_{p_i}(\kappa_V,\kappa_F)\times BR^{SM(\kappa_V,\kappa_F)}_{h\to X}}{\sum_{p_i}\epsilon_{p_i}\sigma_{p_i}\times BR^{SM}_{h\to X}}$$

Efficiencies ϵ_{p_i} are the same as in the SM (if interferences w/ bkg are negligible)

▷ **Fit ingredients**

* Efficiencies ϵ_{p_i}
* Measured $\hat{\mu}$'s separately at 7 and 8 TeV
* If only $\hat{\mu}_{7+8}$ is available, then $\hat{\mu}_8 \pm \sigma_8$ from $\hat{\mu}_7 \pm \sigma_7$, $\hat{\mu}_{7+8} \pm \sigma_{7+8}$ with the Gaussian combination formula

$$\frac{\hat{\mu}_{7+8}}{\sigma^2_{7+8}} = \frac{\hat{\mu}_7}{\sigma^2_7} + \frac{\hat{\mu}_8}{\sigma^2_8} \quad , \quad \frac{1}{\sigma^2_{7+8}} = \frac{1}{\sigma^2_7} + \frac{1}{\sigma^2_8}$$

* Assumed Gaussian distributed $\hat{\mu}$'s; neglect correlations (not given by exp) in combinations of different channels and/or experiments

$\mathcal{E}$ffective $\mathcal{L}$agrangian for a $\mathcal{L}$ight $\mathcal{H}$iggs-$\mathcal{L}$ike $\mathcal{S}$calar

- **Based on** R. Contino, M. Ghezzi, C. Grojean, MMM, M. Spira, arXiv:1303.3876
- **SILH Lagrangian**
- **Non-linear Lagrangian**
- **Discussion of bounds** from EWPD, Z-pole measurements, $b \to s\gamma$, electric dipole moments, anomalous magnetic moments, $t\bar{t}$ cross sections
- **Discussion of operators** sensitive to strongly-interacting Higgs boson, sensitive to the scale of New Physics
- **Implementation of the Higgs effective Lagrangian** beyond the tree-level
- **Implementation for Higgs decay rates:** `eHDECAY`
  URL: http://www.itp.kit.edu/∼maggie/eHDECAY/

NMSSM Scalar Boson and Enhanced Diphoton Rate

- **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 (now only ATLAS)**

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

∗ 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 — Carena eal

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

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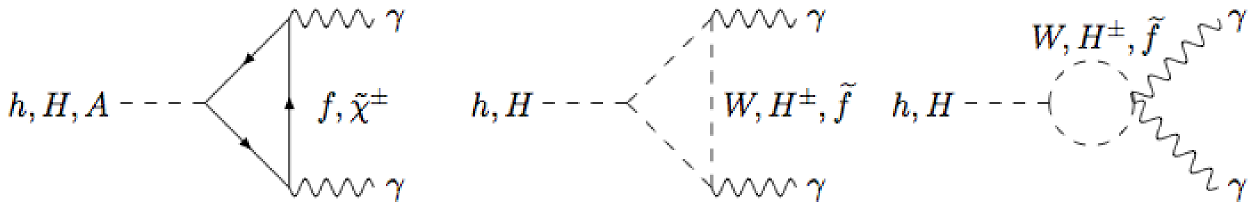
$*$ Enhanced $\Gamma(h^{126\,\text{GeV}} \to \gamma\gamma)$ due to charged boson, chargino, stop loop contributions



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

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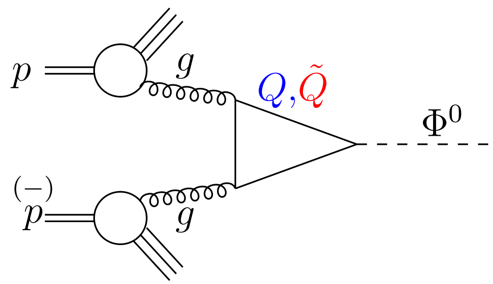
  - ◇ strong singlet-doublet mixing $\rightsquigarrow$ reduced coupling to $b\bar{b}$
  - ◇ Δ_b corrections to $h^{126\,\mathrm{GeV}} b\bar{b}$ coupling   Carena eal
* Enhanced $\Gamma(h^{126\,\mathrm{GeV}} \to \gamma\gamma)$ due to charged boson, chargino, stop loop contributions
* $h^{126\,\mathrm{GeV}}$ 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 charged boson, chargino 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 - $\mathcal{L}$ight $\mathcal{S}$top $\mathcal{M}$asses

$\star$ $\tan\beta = 2,\ 4$	maximize tree-level mass of lightest Higgs boson
$\star$ $0.55 \le \lambda \le 0.8\ ,\ 10^{-4} \le \kappa \le 0.4$	validity of perturbativity
$\star$ $100\ \text{GeV} \le \mu_{\text{eff}} \le 200\ \text{GeV}$	avoid finetuning
$\star$ $500\ \text{GeV} \le M_{Q_3} = M_{t_R} \le 800\ \text{GeV}$ $A_t = 0\ \text{GeV}, 1\ \text{TeV}$	avoid finetuning
$*$ $-500\ \text{GeV} \le A_\kappa \le 0\ \text{GeV}$ $200\ \text{GeV} \le A_\lambda \le 800\ \text{GeV}$	
$*$ $M_{\tilde{u}_R} = M_{\tilde{c}_R} = M_{\tilde{D}_R} = M_{\tilde{Q}_{1,2}} =$ $M_{\tilde{e}_R} = M_{\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 2.5\ \text{TeV}$ $M_{\tilde{\tau}_R} = M_{\tilde{L}_3} = 300\ \text{GeV}\ , \quad A_D = A_E = 1\ \text{TeV}$	comply with LHC results
$*$ $M_1 = 150\ \text{GeV},\ M_2 = 300\ \text{GeV},\ M_3 = 1\ \text{TeV}$	

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

- **Typical mass values:**

$$\begin{aligned} m_{\tilde{t}_1} &= 400 - 820 \text{ GeV}\,, \quad m_{\tilde{t}_2} = 530 - 890 \text{ GeV} \\ M_{H^\pm} &= 200 - 500 \text{ GeV}\,, \quad M_{\tilde{\chi}_1^\pm} = 105 - 165 \text{ GeV}\,, \quad M_{\tilde{\chi}_2^\pm} = 345 - 360 \text{ GeV} \end{aligned}$$

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

- **Conditions on the parameter scan:**

  ∗ At least one CP-even Higgs boson h with: 124 GeV $\lesssim M_h \lesssim 127$ GeV

  ∗ The reduced cross section for $\gamma\gamma$ must fulfill: $\mu_{\gamma\gamma}(h) \gtrsim 0.8$ with 124 GeV $\lesssim M_h = M_{H^{\rm SM}} \lesssim 127$ GeV

  ∗ No restriction on rates into WW, ZZ, $b\bar{b}$, $\tau^+\tau^-$

  ∗ Higgs bosons outside $124...127$ GeV: exclusion limits of LEP, Tevatron and LHC searches

- **Signal can be superposition of two Higgs boson rates close in mass: h and $\Phi = H_i, A_j$**

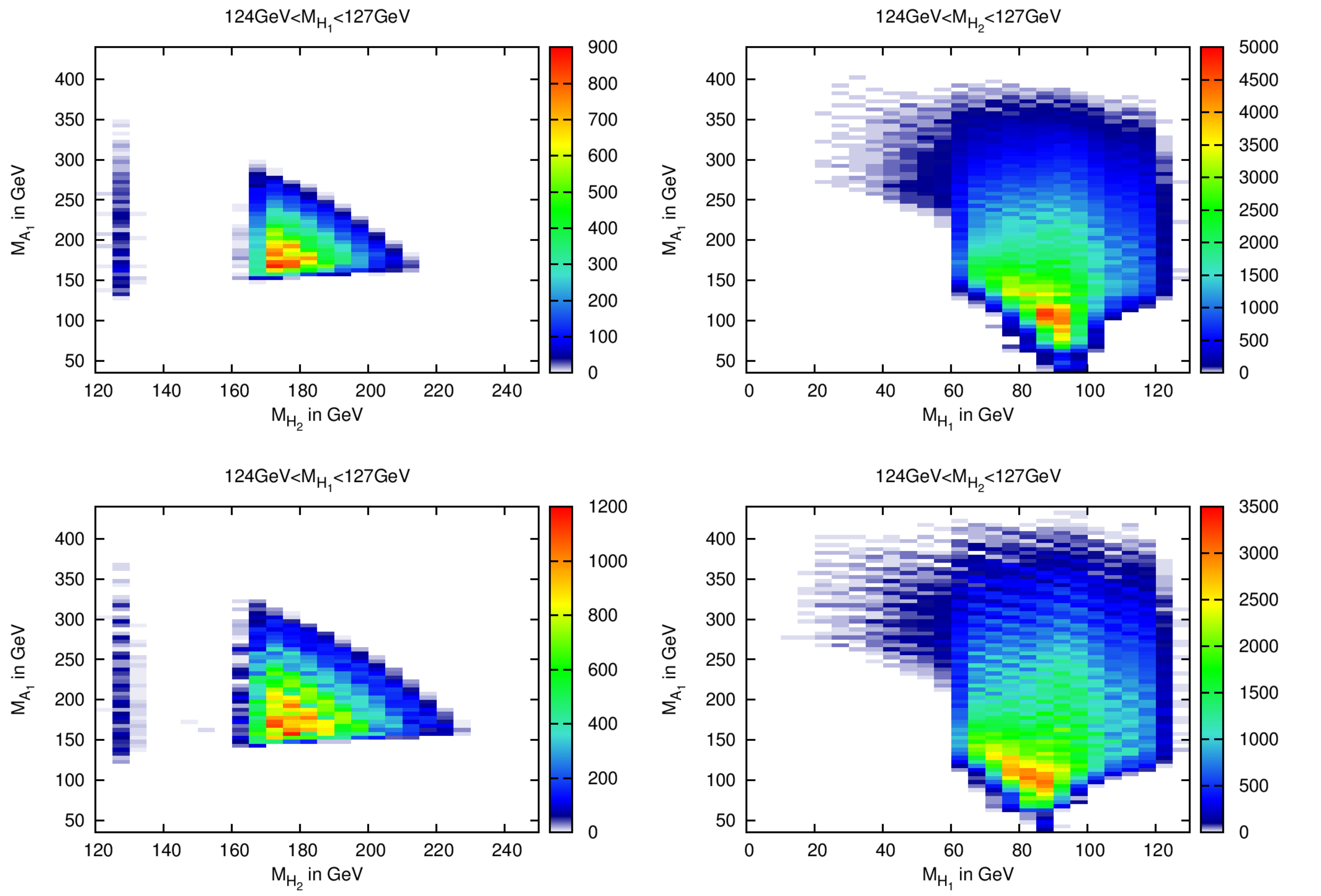
$$\mu_{XX}(h) \equiv R_\sigma(h)\, R^{BR}_{XX}(h) \; + \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R^{BR}_{XX}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

δ : mass resolution in the respective XX final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

d_{XX}: experimental resolution of final state XX

NMSSMTools

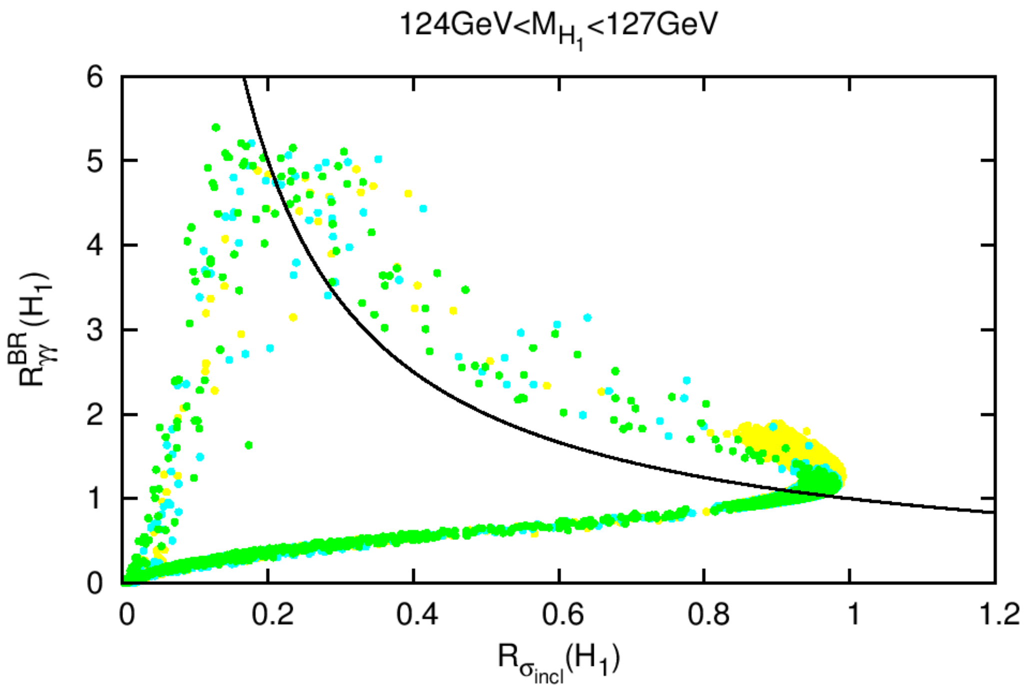


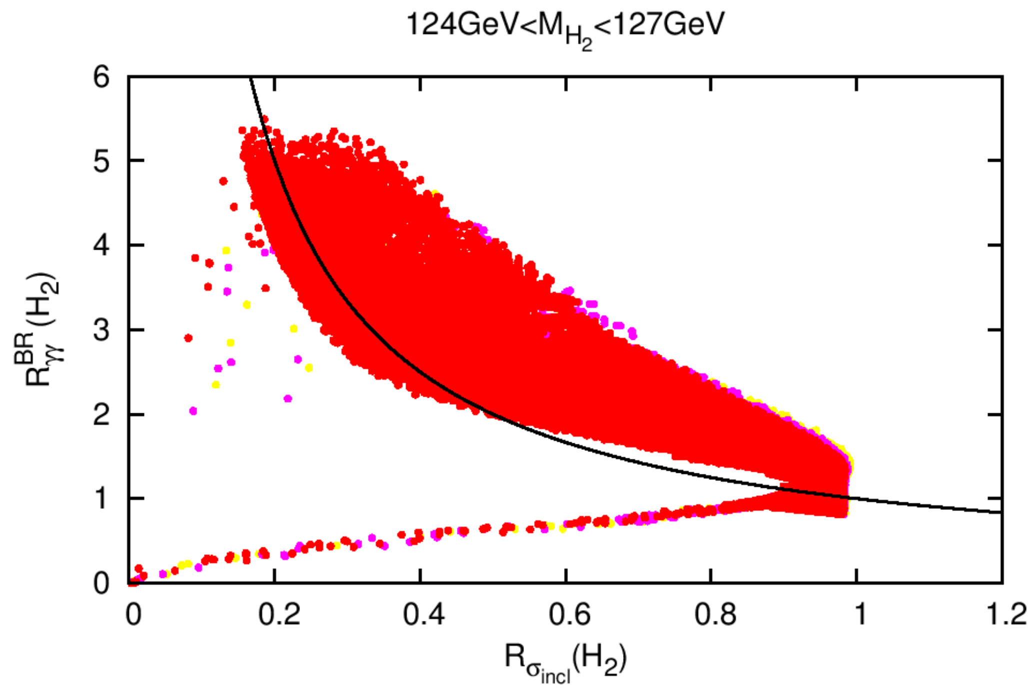
⋆ Upper/Lower: $A_t = 0$, 1 TeV ⋆ M_{H_3}, M_{A_2} between 300 and 500 GeV

⋆ Possible degeneracy of $h - H_{1,2}$ ($H_{1,2} \neq h$), $h - A_1$, possible decays $H_2 \to H_1H_1, A_1A_1, \chi_1^0\chi_1^0$

$\mathcal{NMSSM}$ $\mathcal{S}$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,

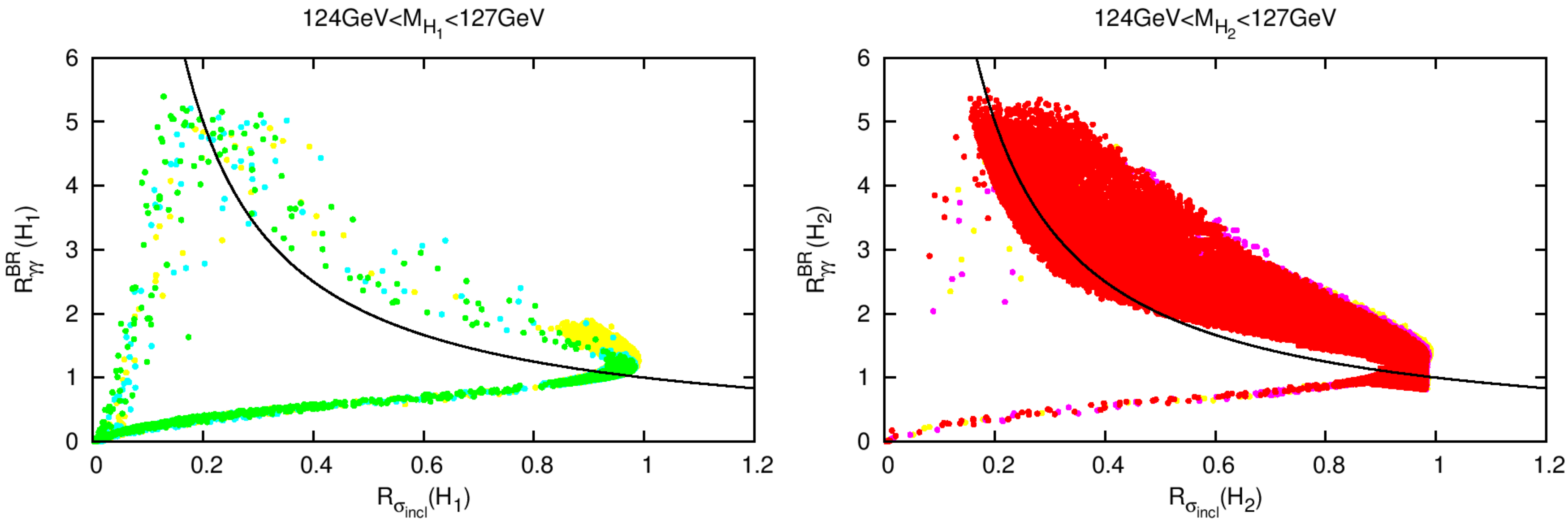
500 GeV $\leq M_{Q_3}, M_{t_R} \leq$ 800 GeV , -500 GeV $\leq A_\kappa \leq 0$ GeV , 200 GeV $\leq A_\lambda \leq$ 800 GeV ,

$\tan\beta = 2, 4$, $A_t = 1$ TeV

Above black line: $R_{\gamma\gamma} = R^{\text{BR}}_{\gamma\gamma}(h)\, R_{\sigma_{\text{incl}}}(h) > 1$

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

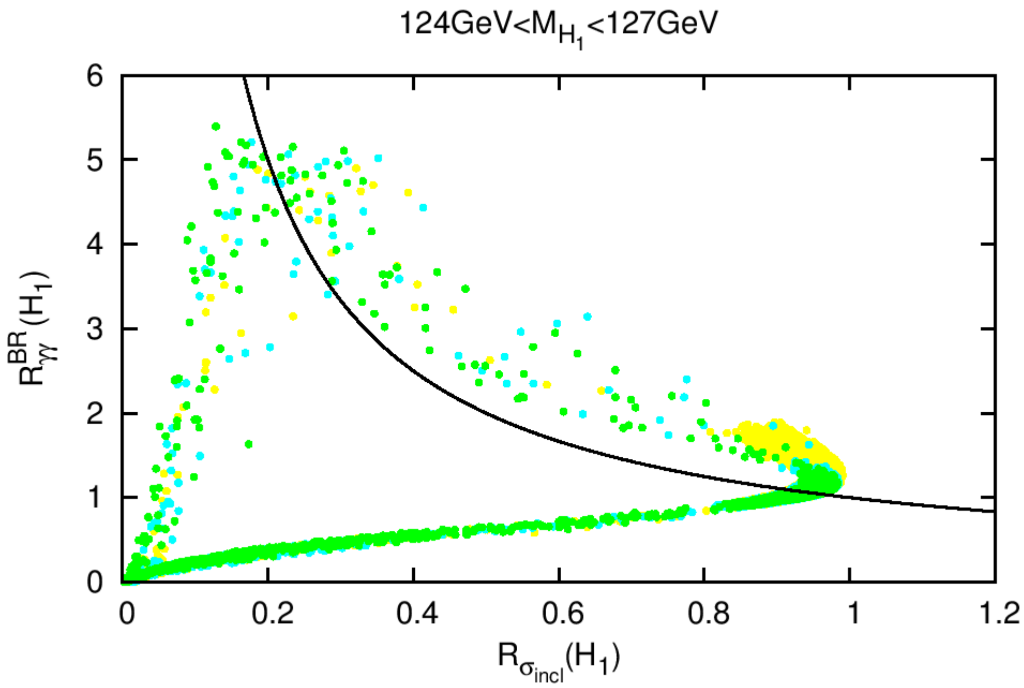
King,MMM,Nevzorov,Walz

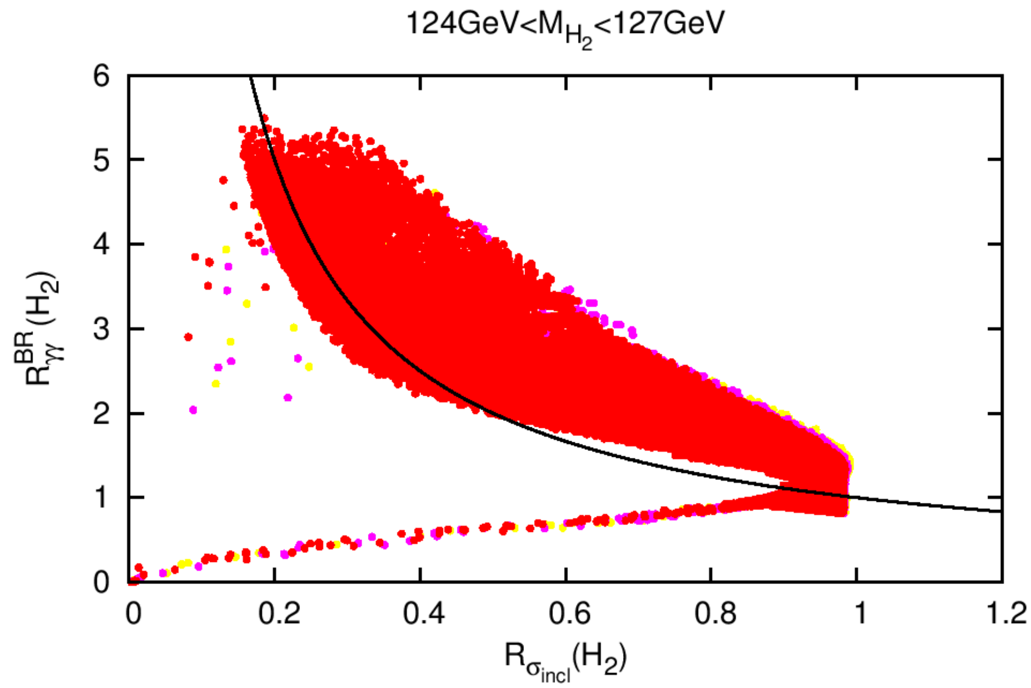


- $\star$ $R^{\text{BR}}_{\gamma\gamma} = BR^{NMSSM}_{\gamma\gamma}/BR^{SM}_{\gamma\gamma}$ enhanced: $\circ$ $BR_{\gamma\gamma}\uparrow$: $H^\pm, \tilde{\chi}^\pm, \tilde{t}$ loops, suppressed g_{H_ibb} coupling
- $\star$ $R_{\sigma_{incl}} = \sigma^{NMSSM}_{incl}/\sigma^{SM}_{incl}$ enhanced: $\circ$ $\sigma_{prod}\uparrow$: $\tilde{t}$ loops and, or $g_{H_itt}\uparrow$

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

King, MMM, Nevzorov, Walz

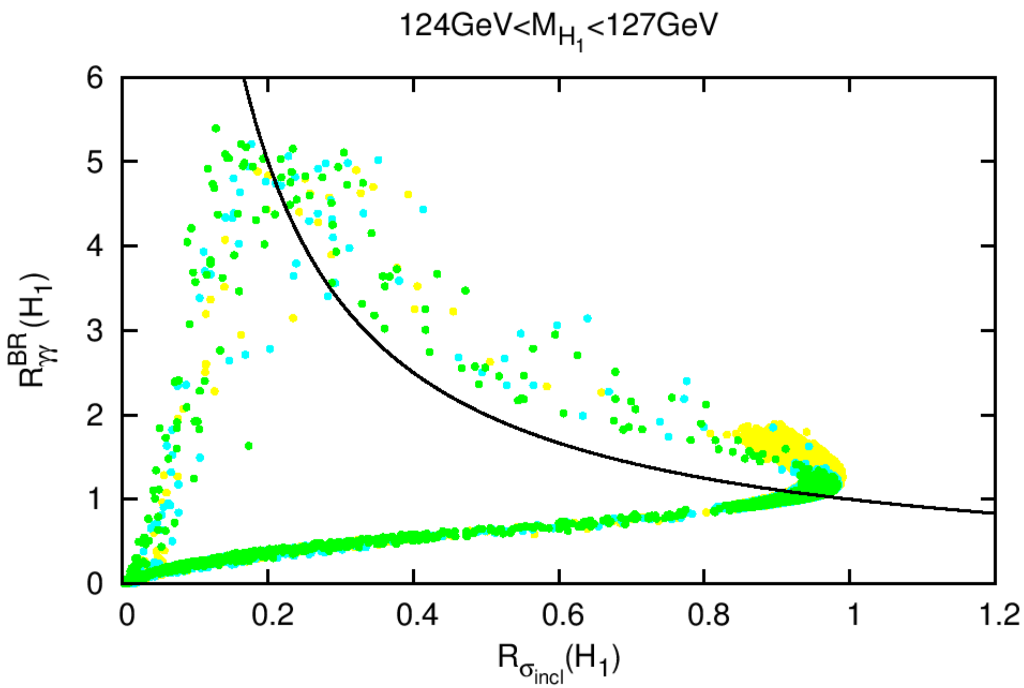


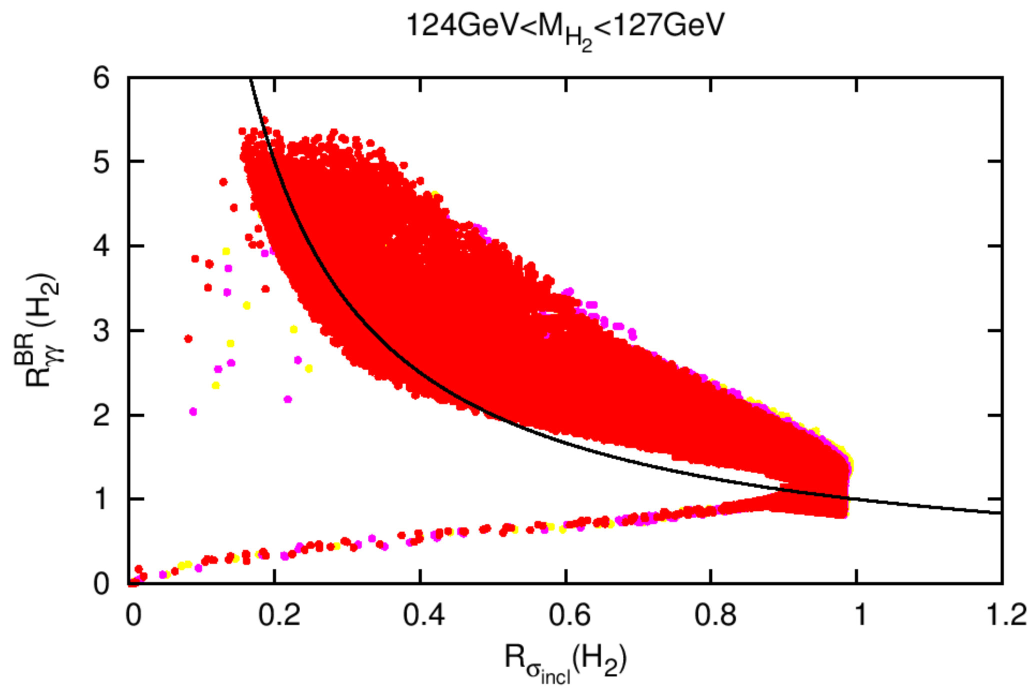


* green/red points: perturbation theory valid up to the GUT scale
* cyan/pink points: require extra matter at 1 TeV
* yellow points: violate two-loop upper bounds on λ, κ

NMSSM Scan

King,MMM,Nevzorov,Walz





* points with $R^{\text{BR}}_{\gamma\gamma}$ and $R_{\sigma_{\text{incl}}}$ small not recjected as

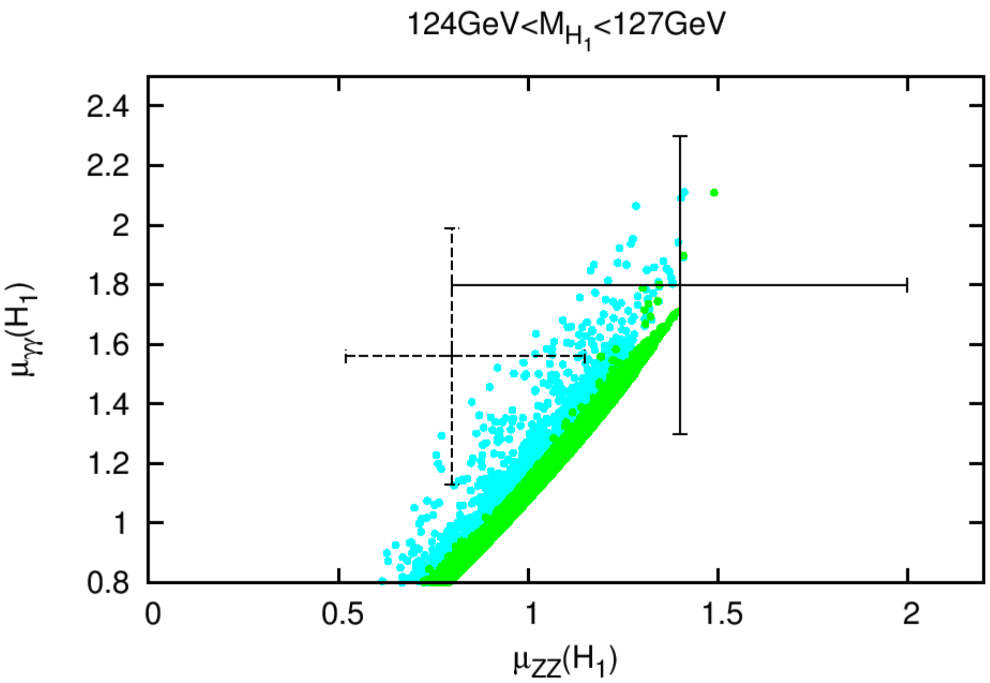
$\mu_{\gamma\gamma}(h) > 0.8$ possible due to superpositions of rates of two Higgs bosons close in mass

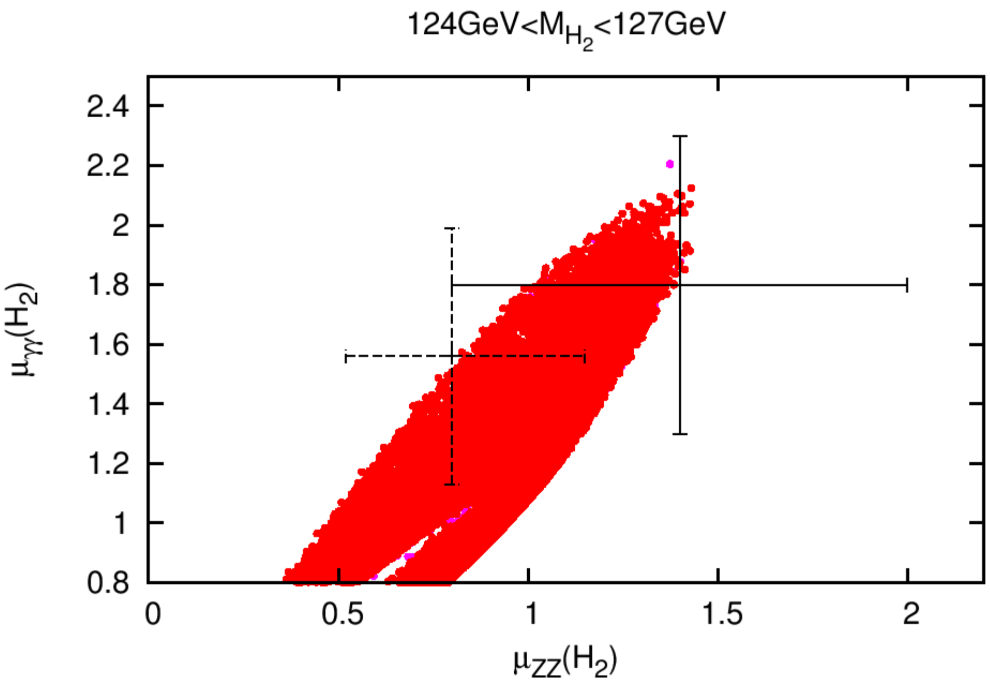
For $h = H_2$: degeneracy $H_2 - H_1$ and $H_2 - A_1$ possible

For $h = H_1$: degeneracy $H_1 - H_2$ and $H_1 - A_1$ possible

NMSSM Scan - Pre-Moriond

King,MMM,Nevzorov,Walz



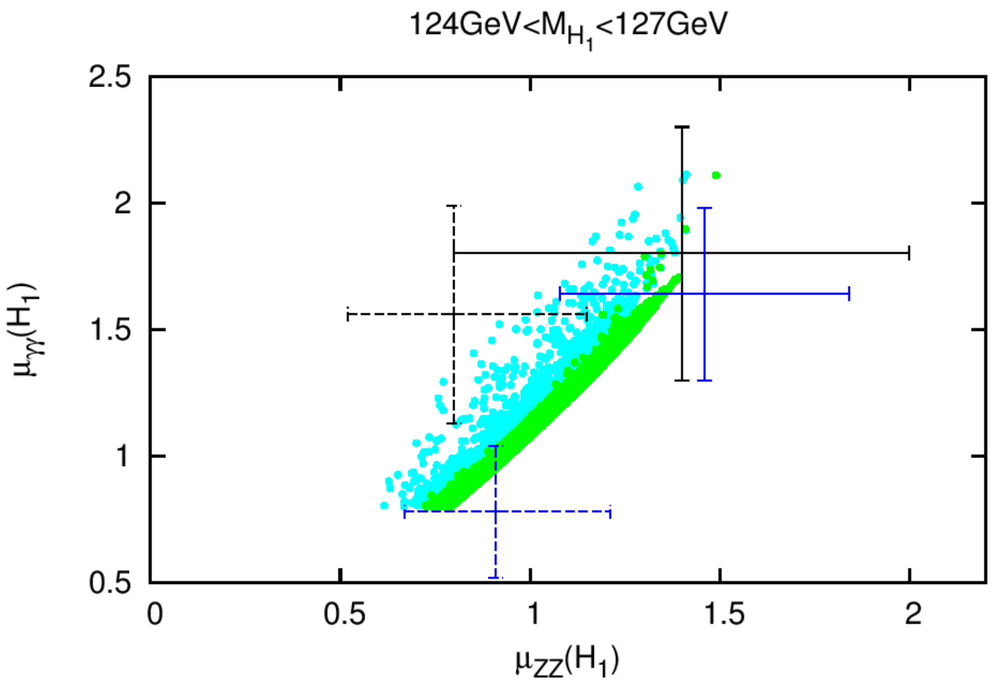


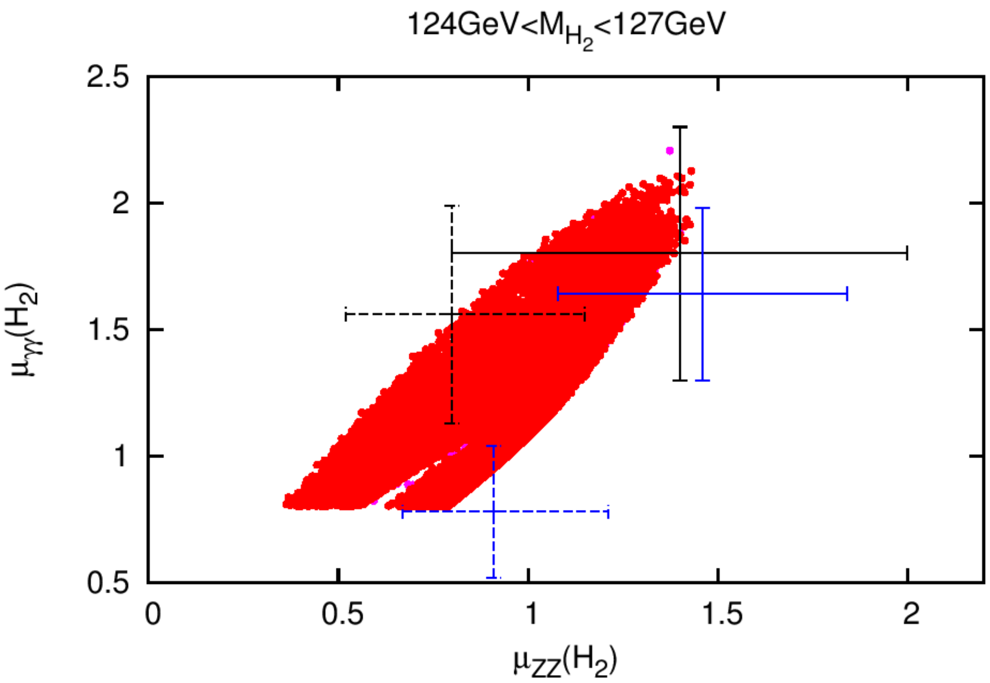
∗ cyan/pink points: two signals overlap

∗ crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS

$\mathcal{NMSSM}$ $\mathcal{S}$can - $\mathcal{A}$fter-$\mathcal{M}$oriond

King,MMM,Nevzorov,Walz





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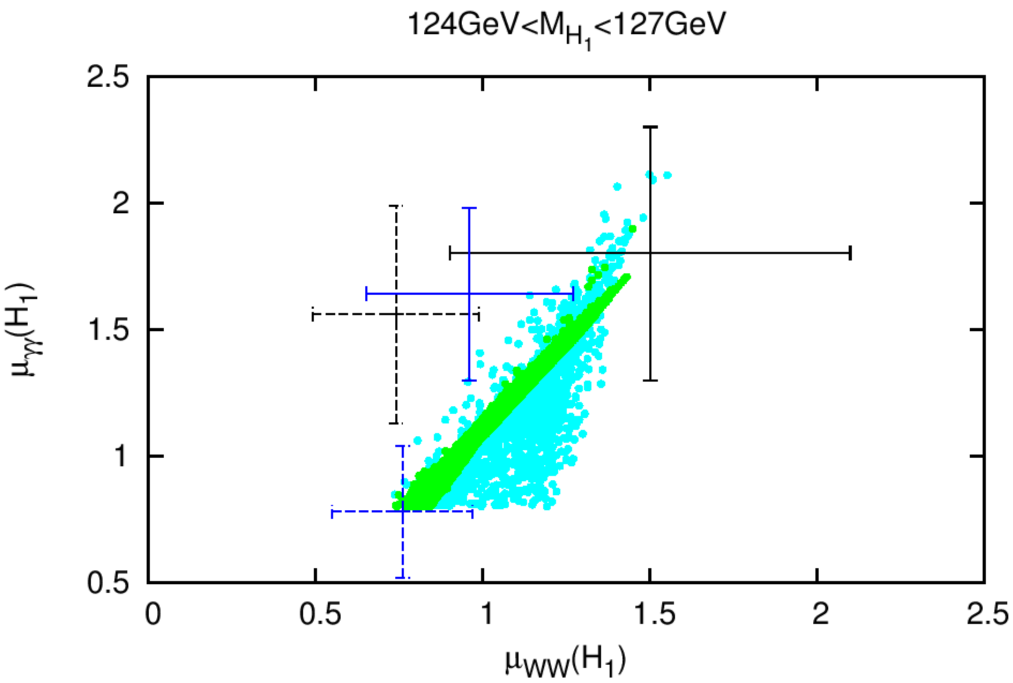
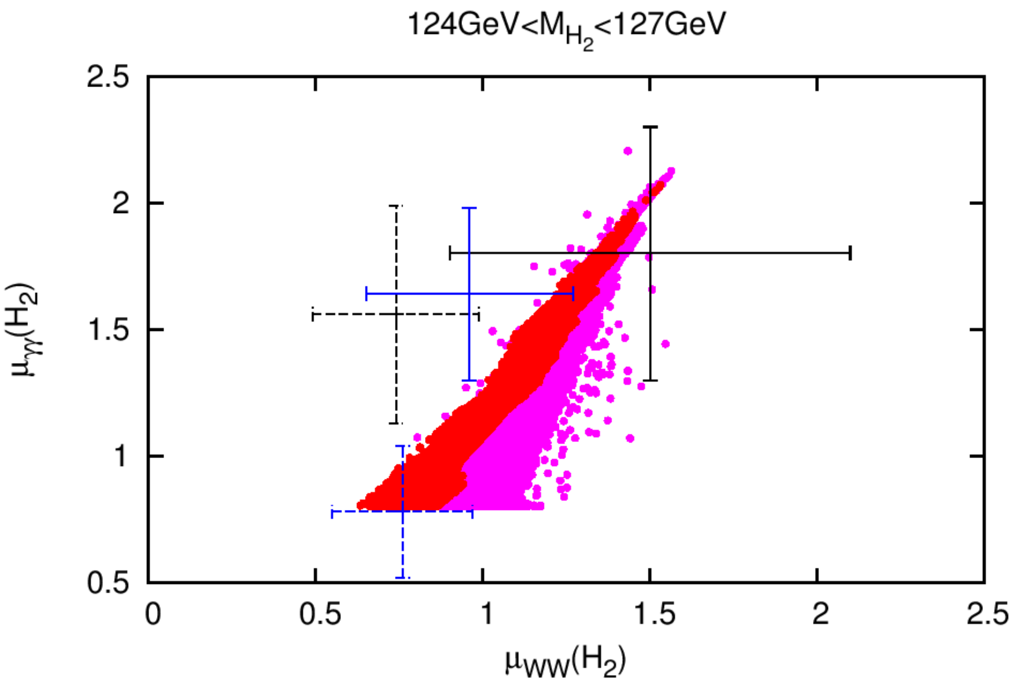
NMSSM Scan - After Moriond

King,MMM,Nevzorov,Walz





* cyan/pink points: two signals overlap
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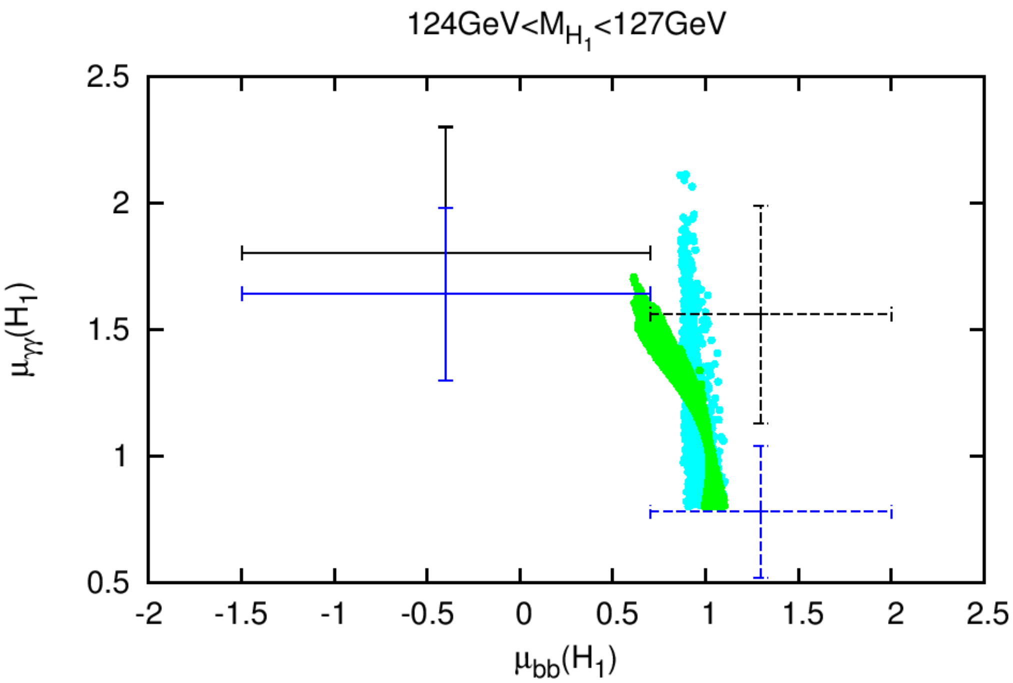

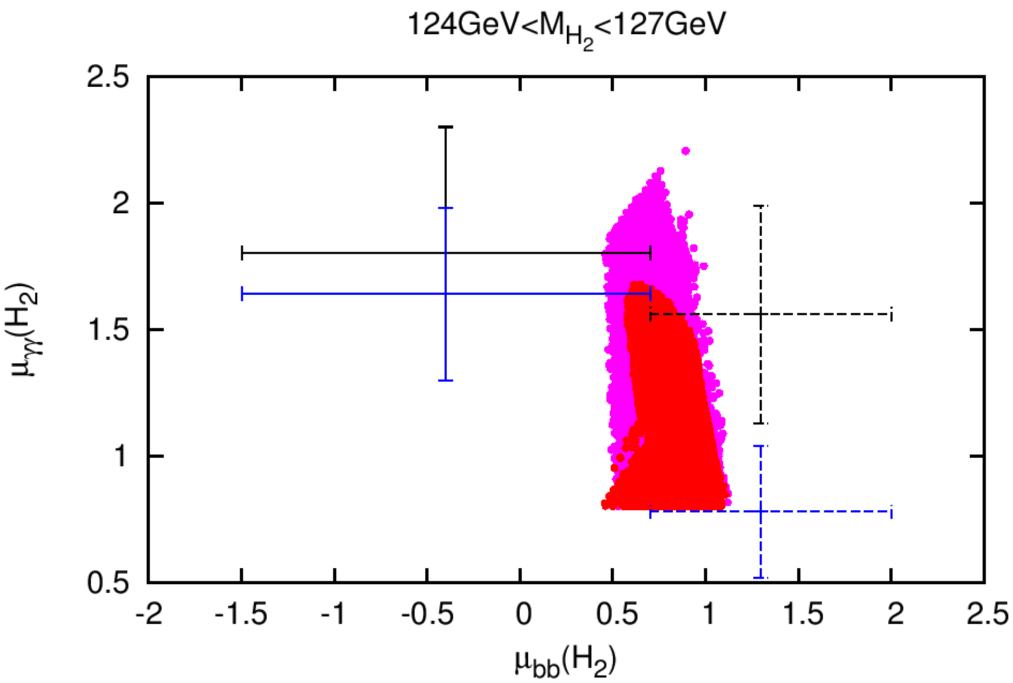

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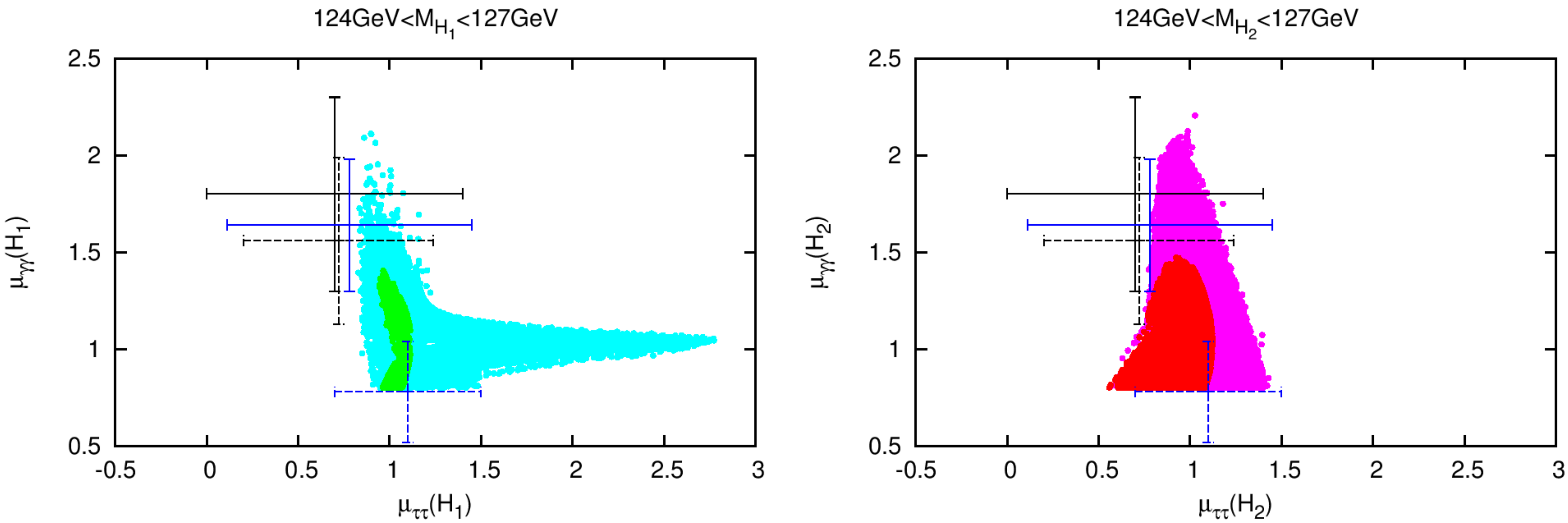
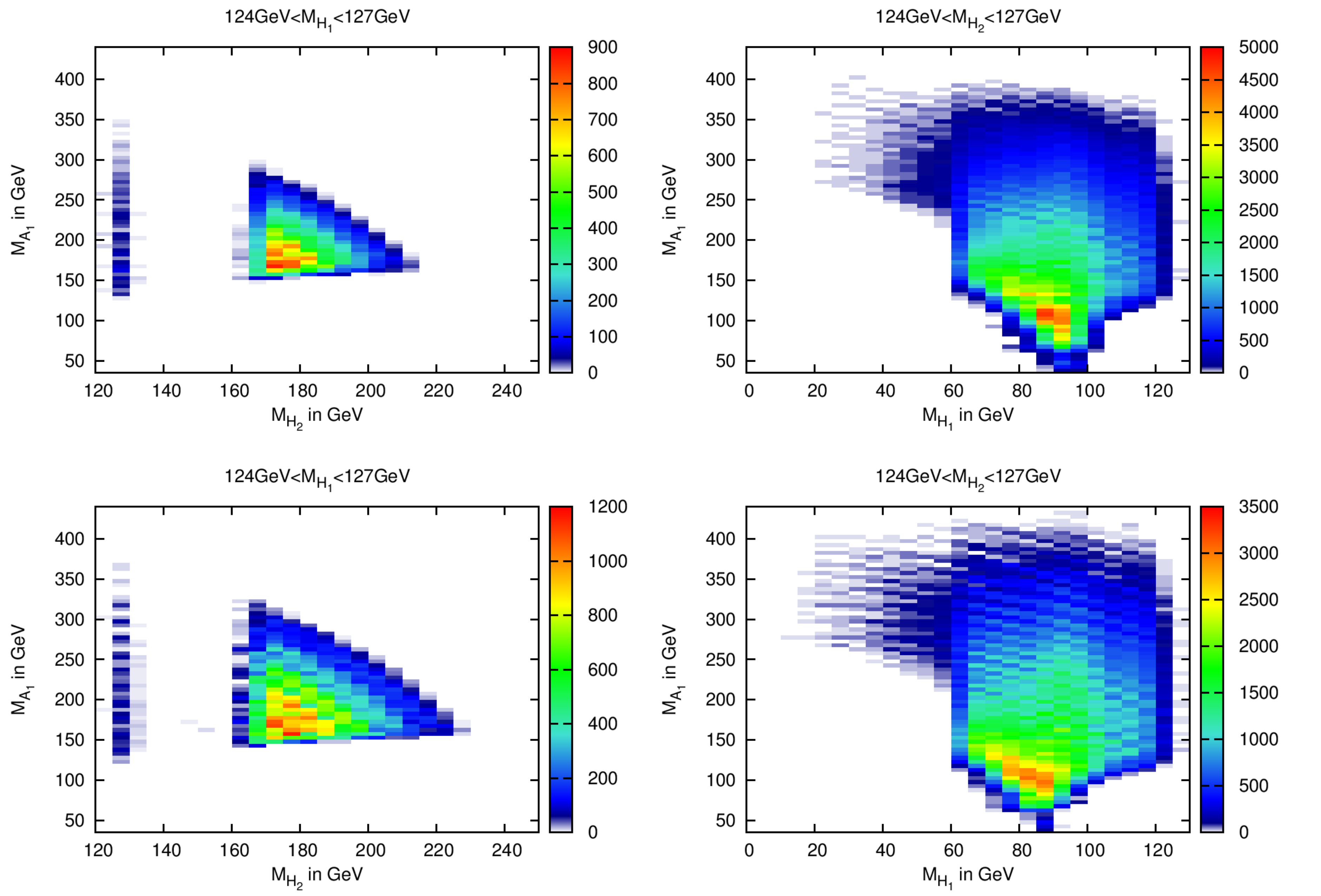
NMSSM Scan - After Moriond

King,MMM,Nevzorov,Walz



∗ cyan/pink points: two signals overlap

∗ crosses: Exp. best fit of $\mu = \sigma/\sigma_{SM}$, full/ATLAS, dashed/CMS



⋆ Upper/Lower: $A_t = 0$, 1 TeV ⋆ M_{H_3}, M_{A_2} between 300 and 500 GeV

⋆ Possible degeneracy of $h - H_{1,2}$ ($H_{1,2} \neq h$), $h - A_1$, possible decays $H_2 \to H_1 H_1, A_1 A_1, \chi_1^0 \chi_1^0$

$\mathcal{E}$xotic $\mathcal{D}$ecays

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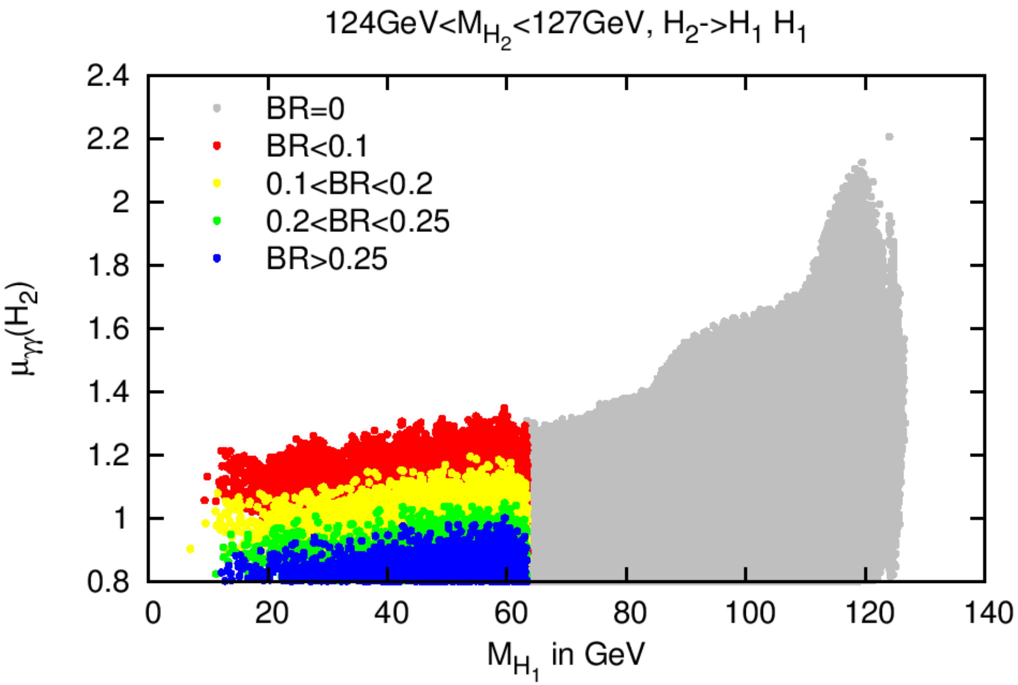
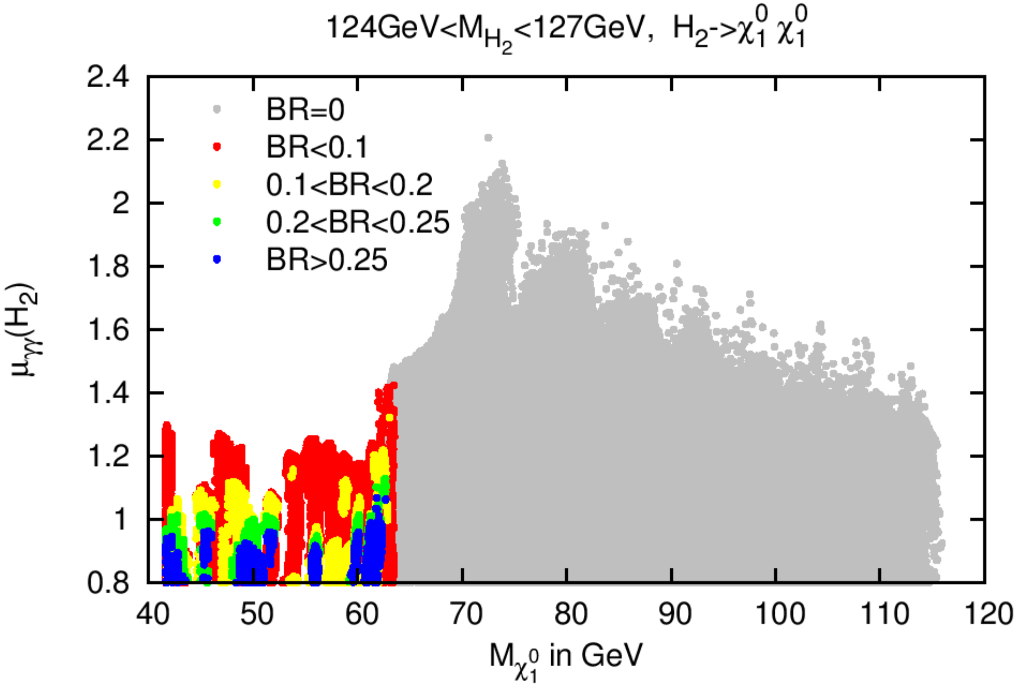
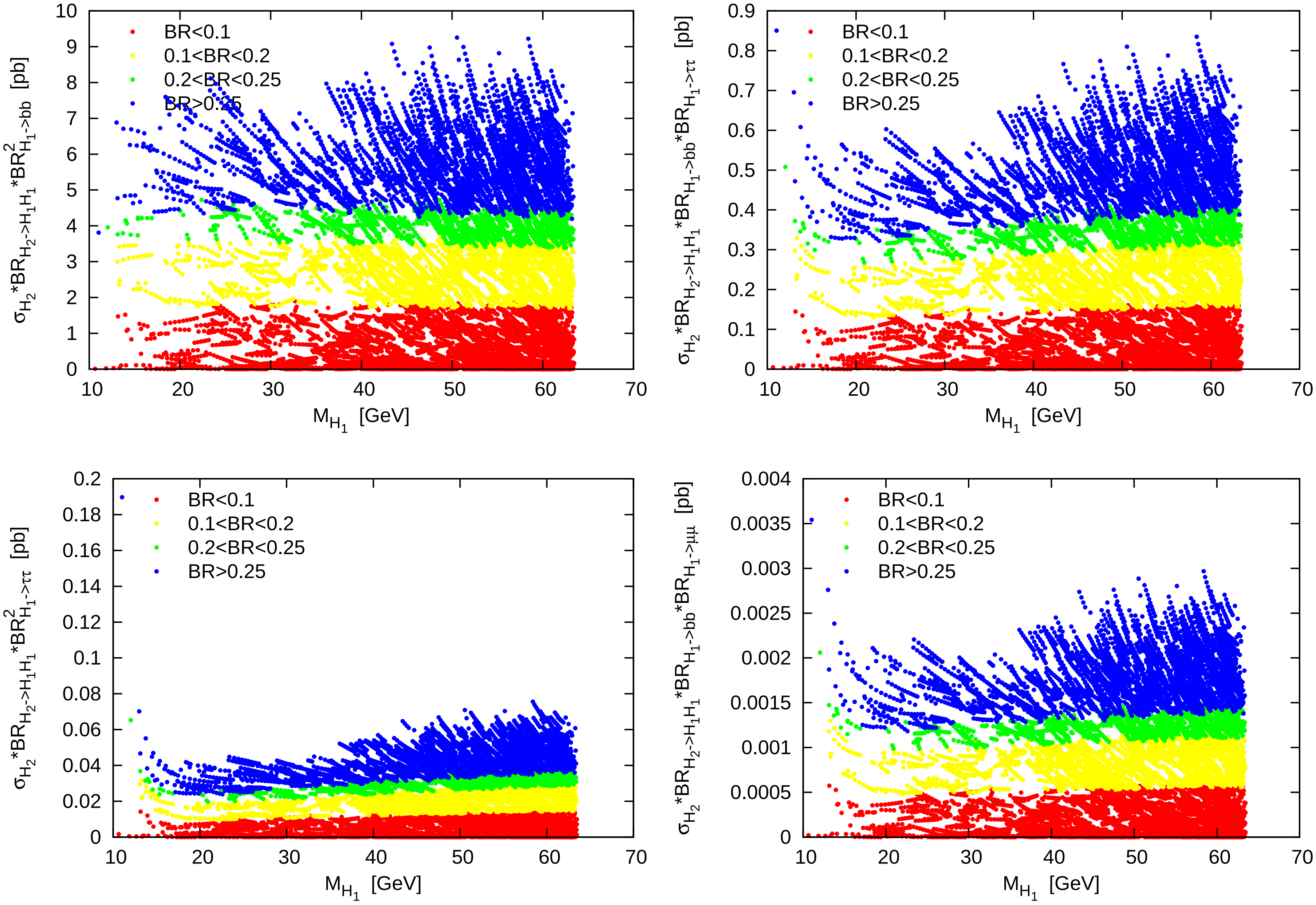




* $\tan\beta = 2,\ A_t = 1$ TeV
* $BR_{H_2}^{\max}(H_1H_1) \approx 0.36,\ BR_{H_2}^{\max}(A_1A_1) \approx 0.35$ and $BR_{H_2}^{\max}(\tilde{\chi}_1^0\tilde{\chi}_1^0) \approx 0.43$
* $\sigma_{\text{prod}}(H_2) \times BR(H_2 \to \chi_1^0\chi_1^0) \approx 4 - 8.5$ pb



$*$ Decays $H_2 \to H_1 H_1$ $A_t = 0$ TeV

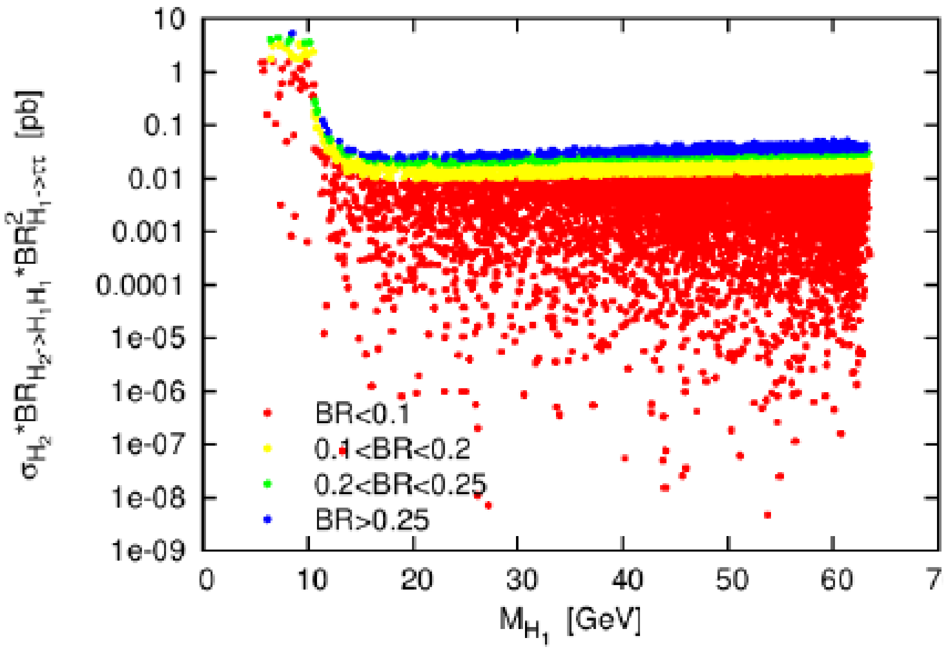
$* \; BR(H_1 \to b\bar{b}) \approx 0.9$ $BR(H_1 \to \tau^+\tau^-) \approx 0.07 - 0.085$ $BR(H_1 \to \mu^+\mu^-) \lesssim 0.0006$

$\mathcal{E}$xpected $\mathcal{S}$ignal - $\mathcal{R}$esults by $\mathcal{S}$asha $\mathcal{N}$ikitenko

Consider two mass regions for m_{H1}

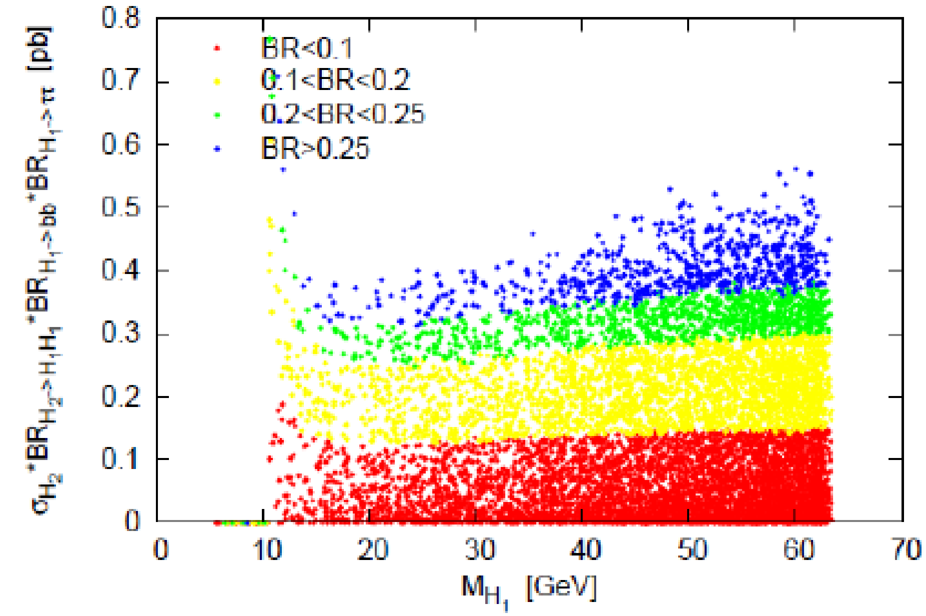
<u>**6 GeV < m_{H1} < $2m_b$**</u>

ττττ dominates



<u>**2mb < m_{H1} < $2m_{H2}$**</u>

ττbb and bbbb dominates



Expected signal event yield for 20 fb^{-1} at 8 TeV

σ x Br (ττττ) from theory : 3 pb	60 000
Two τ->μ, two τ->hadr: $0.17^2 \times 0.65^2 \times 6 = 0.0732$	4392
$p_T^{\mu 1}>17$ GeV, $\lvert\eta^{\mu 1}\rvert<2.1$, $p_T^{\mu 2}>10$ GeV, $\lvert\eta^{\mu 2}\rvert<2.4$: 0.0713	313
$p_T^{\tau h}>10$ GeV, $\lvert\eta^{\tau h}\rvert<2.4$: 0.277	87
ΔR(μ–μ) > 1.0 : 0.579	50
Probably ask SS muons against DY, tt~, WW: 0.5	25
Probably ask only 1 track around muon against QCD: 0.75^2= 0.56	14

- $\tau\tau\tau\tau \to \tau_\mu \tau_h \tau_\mu \tau_h$ from inclusive H_2 production and $2m_\tau < M_{H_1} < 2m_b$ promising, but estimate of expected bkg needed