SUSY Higgs and *Composite Higgs*

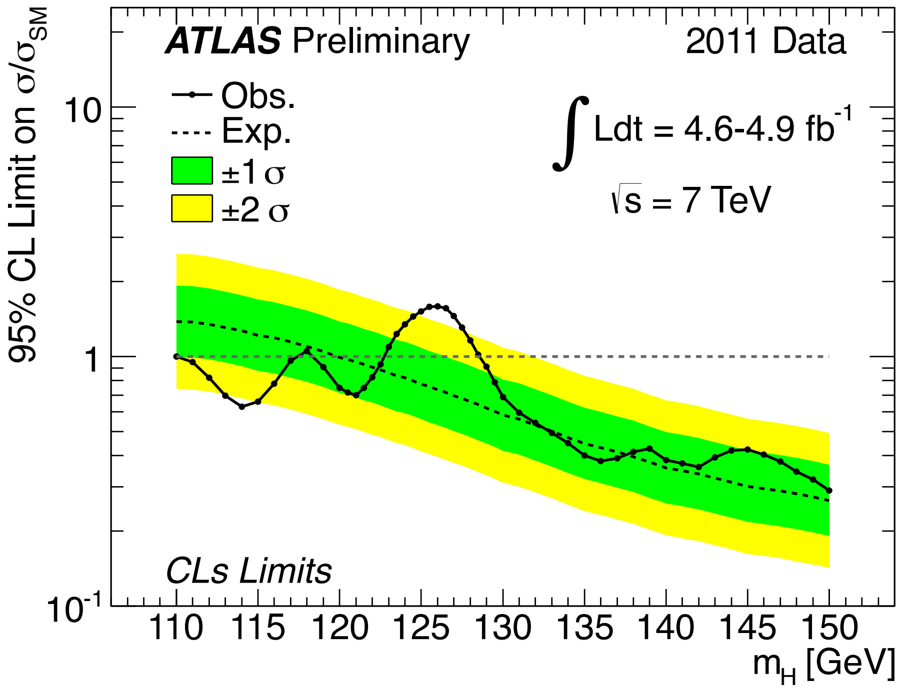
Milada Margarete Mühlleitner
(Karlsruhe Institute of Technology)

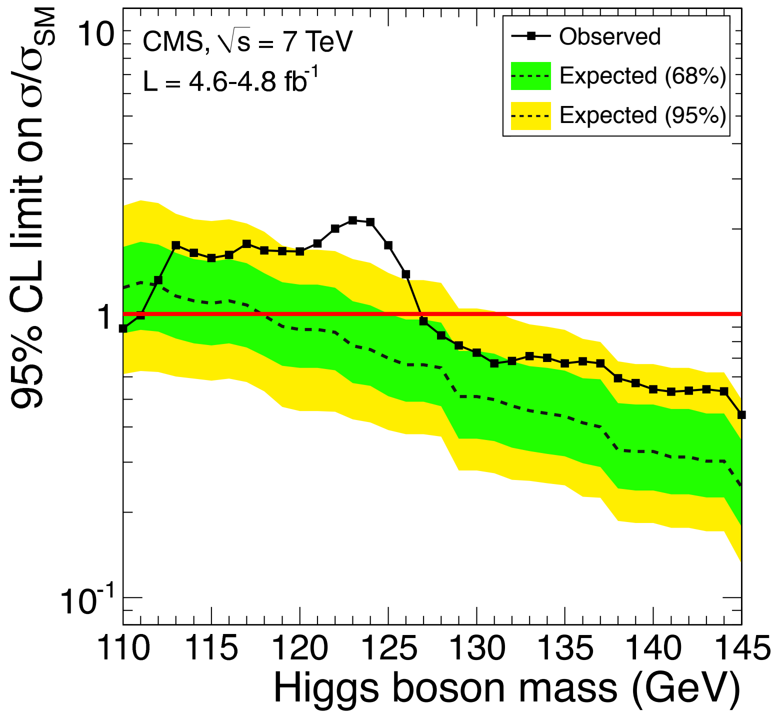
Standard Model at LHC

Copenhagen

10-13 April 2012

$\mathcal{LHC}$ $\mathcal{H}$iggs $\mathcal{S}$earch $\mathcal{R}$esults $\mathcal{M}$oriond 2012





Exclusion: 110-117.5, 118.5-122.5 GeV

129-539 GeV @ 95% CL

Exclusion: 127-600 GeV @ 95% CL

Observed local significance at 126 GeV: 3.6σ

Observed local significance at 124 GeV: 3.1σ

In $H \to \gamma\gamma$ more data than expected in the SM $\to$ hint towards New Physics?

Which Higgs Boson?

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

𝒪utline

(i) MSSM Higgs boson production (very short)

(ii) Interpretation of LHC Higgs search results within

* MSSM
* NMSSM
* Composite Higgs
* Model-independent

The MSSM Higgs Sector

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

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

Higgs masses

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

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

Decoupling limit:

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

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

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

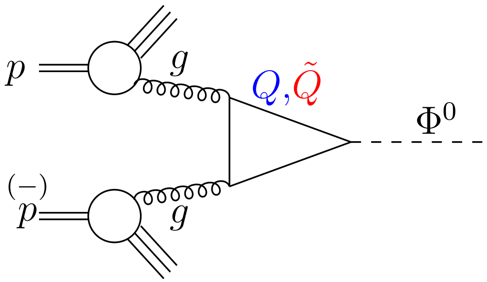
Φ	$g_{\Phi u\bar{u}}$	$g_{\phi d\bar{d}}$	$g_{\Phi VV}$
h	$c_\alpha/s_\beta \longrightarrow 1$	$-s_\alpha/c_\beta \longrightarrow 1$	$s_{\beta-\alpha} \longrightarrow 1$
H	$s_\alpha/s_\beta \longrightarrow 1/\text{tg}\beta$	$c_\alpha/c_\beta \longrightarrow \text{tg}\beta$	$c_{\beta-\alpha} \longrightarrow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

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

Higgs boson production in the MSSM

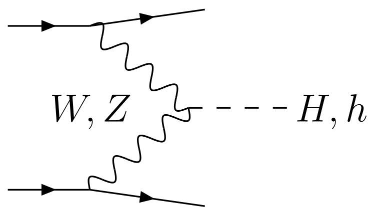
- **Gluon Fusion**

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



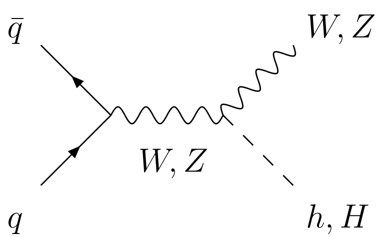
- **W/Z Fusion**

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



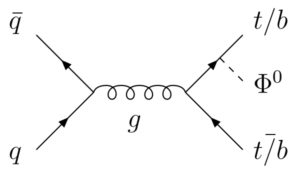
- **Higgs-strahlung**

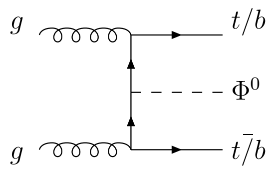
  $pp \to W^*/Z^* \to W/Z + h, H$



- **Associated Production**

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



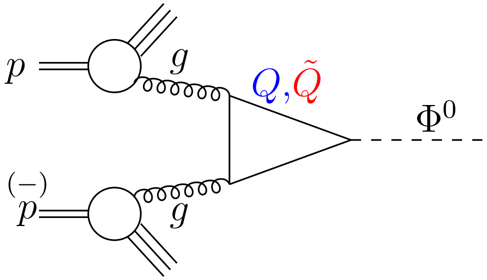


dominant

Higgs boson production in the MSSM

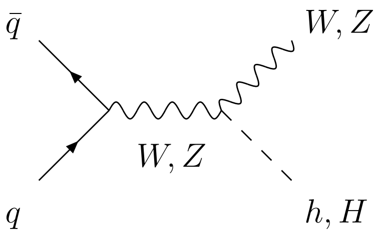
- **Gluon Fusion**

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



- **Higgs-strahlung**

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



- **LHC**

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

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

- **Tevatron**

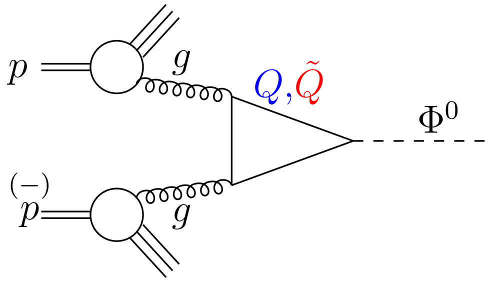
$gg \to \phi$ dominant, for large $\tan\beta : \phi b\bar{b}$

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

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

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

Georgi et al; Gamberini et al



QCD corrections to top & bottom loops

- ▷ NLO (SM, MSSM): increase σ by $\sim$ 10...100%
  [moderate for large $\tan\beta \leftarrow b$-loop]

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

- ▷ SM; tg$\beta \lesssim 5$: limit $M_\Phi \ll m_t$ - approximation $\sim$ 20-30%

  Krämer,Laenen,Spira

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

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

NLO corrections to squark loops

- ▷ in the heavy mass limit — Dawson,Djouadi,Spira
- ▷ full SUSY-QCD corrections in heavy mass limit — Harlander,Steinhauser;Harlander,Hofmann; Degrassi,Slavich '11
- ▷ bottom/sbottom contributions
  asymptotic expansion in large $\tilde{M}$ — Degrassi,Slavich '11; Degrassi,Di Vita,Slavich '11; Harlander,Hofmann,Mantler '11
- ▷ top-stop-gluino contributions
  asymptotic expansion in heavy particle masses — Degrassi,Di Vita,Slavich '12

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

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

NNLO SUSY-QCD corrections from $t/\tilde{t}$ sector — Pak,Steinhauser,Zerf

Impl. of $gg \to \phi$ into POWHEG including mass effects at NLO — Bagnaschi,Degrassi,Slavich,Vicini

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

NLO QCD $\sigma_{\rm tot}$ (SM/MSSM)	$\sim$ 5 bis 10%	Han,Valencia, Willenbrock	SUSY QCD	small	Djouadi,Spira
NLO QCD distributions (SM/MSSM)	$\sim$ 20 %	Figy,Oleari, Zeppenfeld; Berger,Campbell	SUSY QCD&EW	small	Hollik,Plehn, Rauch,Rzehak;Figy Palmer,Weiglein'10
Impl. in POWHEG		Nason,Oleari	NNLO QCD Δ_{th}	$\sim 2\%$	Harlander eal; Bolzoni eal

(iii) Higgs-strahlung: $q\bar{q} \to Z^*/W^* \to Z/W + h, H$

NLO QCD (SM/MSSM)	$\sim +30$ % (Drell-Yan)	Han,Willenbrock	
NNLO QCD (SM/MSSM)	$\sim +5-10$ %	Harlander,Kilgore; Hamberg,Van Neerven,Matsuura; Brein,Djouadi,Harlander	$\Delta_{\rm theor} \sim 5$ %
SUSY QCD	$\lesssim$ few per cent	Djouadi, Spira	

(iv) Associated Production with $t\bar{t}$: $q\bar{q}/gg \to t\bar{t} + h\ (H, A)$

$t\bar{t}\Phi^0$	NLO QCD $\sim +20\%$	Beenakker et al.; Dawson et al.	$\Delta_{\rm theor} \sim 15$ %
SUSY QCD	$\pm(10-30)$ %	Peng et al.; Dittmaier et al	

$\mathcal{A}$ssociated production with a $b\bar{b}$ pair

(v) Higgs $b\bar{b}$ production: dominant MSSM Higgs production mechanism for $\tan\beta \gtrsim 7$

- **Four-flavour scheme 4FS:** LO cxn $gg \to b\bar{b}\Phi^0$ up to NLO — Dittmaier,Krämer,Spira; Dawson,Jackson,Reina,Wackeroth
- **Five-flavour scheme 5FS:** LO cxn $b\bar{b} \to \Phi^0$ up to NNLO — Dicus,Willenbrock; Stelzer et al.;Balazs et al.; Campbell et al.; Harlander,Kilgore; Kidonakis
- **Santander matching:** interpolation between 4FS and 5FS — Harlander,Krämer,Schumacher'11
- **Further corrections:**
  - EW and QCD corrections to $b\bar{b} \to \Phi^0$: few % $(\sim \Delta_b)$ — Dittmaier,Krämer, Mück,Schlüter
  - dominant t contr. to "NNLO" $b\bar{b}h$: few % $M_H \lesssim 120$ GeV, several 10 % above — Boudjema, Ninh
  - SUSY QCD to $gg \to b\bar{b}h$ — Gao et al.; Hollik,Rauch
  - SUSY QCD to $b\bar{b} \to \Phi^0, bg \to b\Phi^0$: few % $(\sim \Delta_b)$ — Dawson, Jackson
  - EW to $bg \to bH^{\text{SM}}$ — Dawson, Jaiswal '10
  - Complete EW to $bg \to b\Phi^0$ — Beccaria, et al. '10

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

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

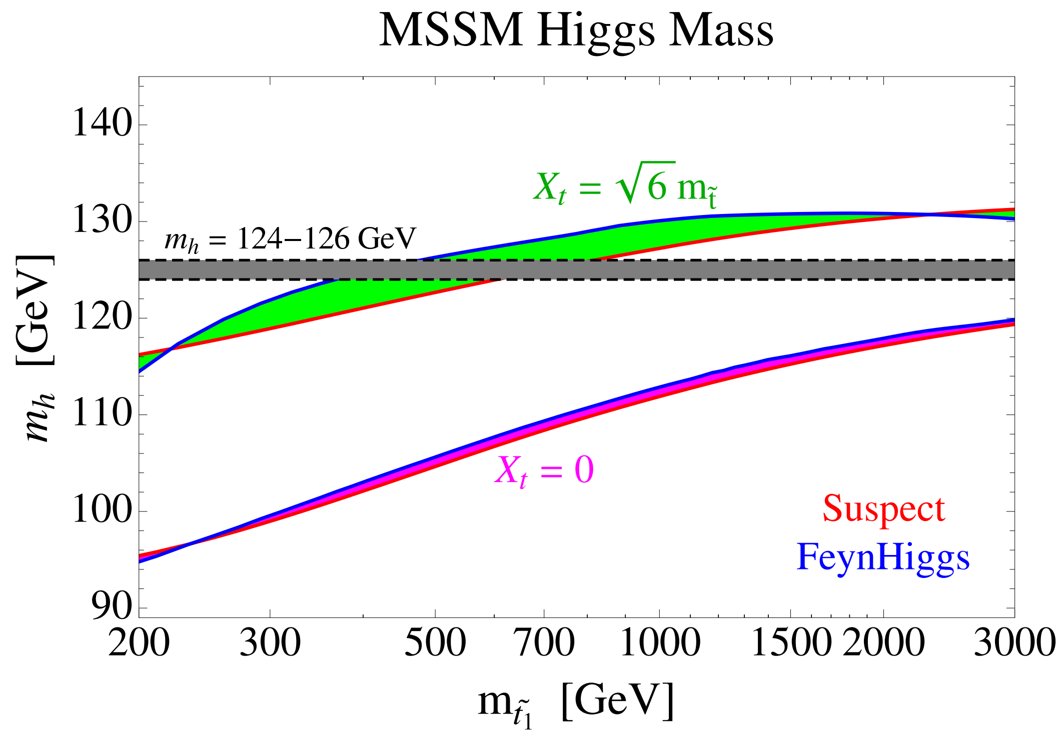
$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$$

$\Rightarrow M_H \approx 125$ GeV requires

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

MSSM Higgs Mass in View of the LHC Results

Hall,Pinner,Ruderman 1112.2703



Maximal stop mixing:

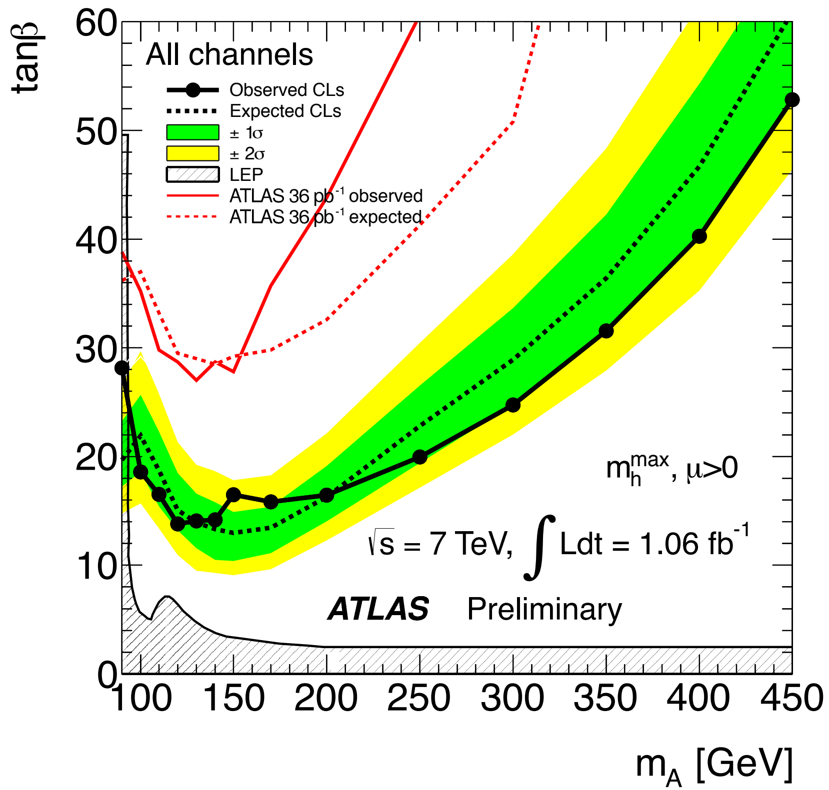
$m_{\tilde{t}_1} \overset{!}{\gtrsim} 500$ GeV

- **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

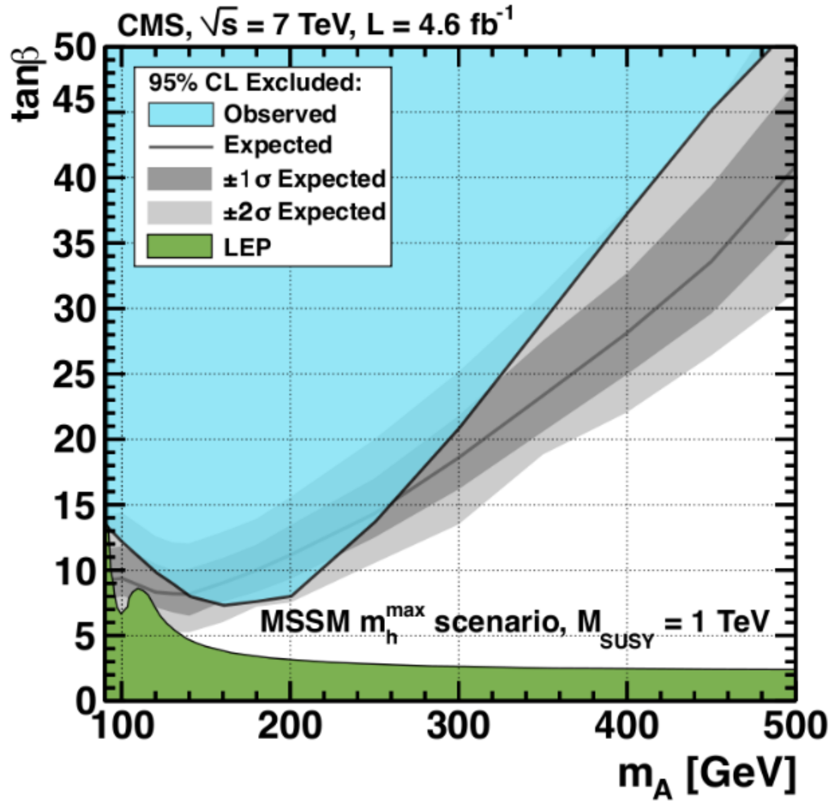
$\mathcal{S}$earch for $\mathcal{MSSM}$ $\mathcal{H}$iggs $\mathcal{B}$osons at the $\mathcal{LHC}$

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

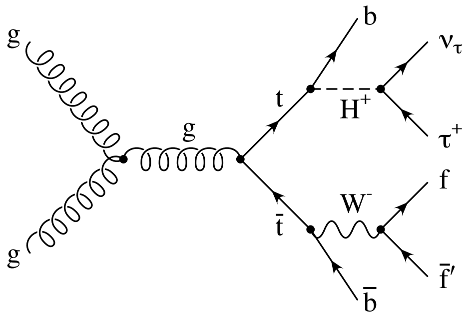
ATLAS-CONF-2011-132



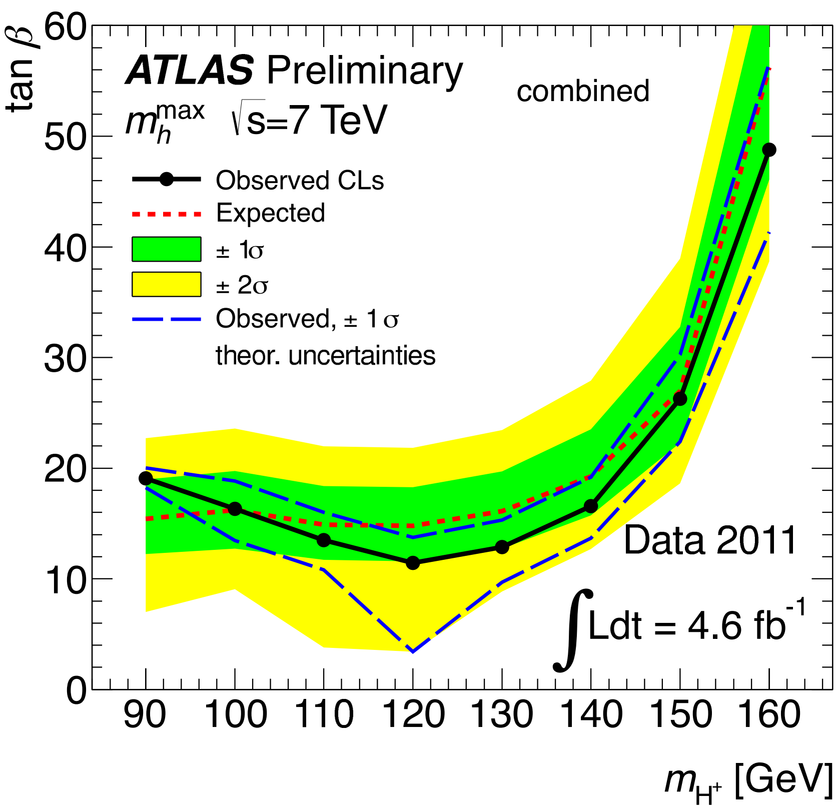
CMS 1202.4083



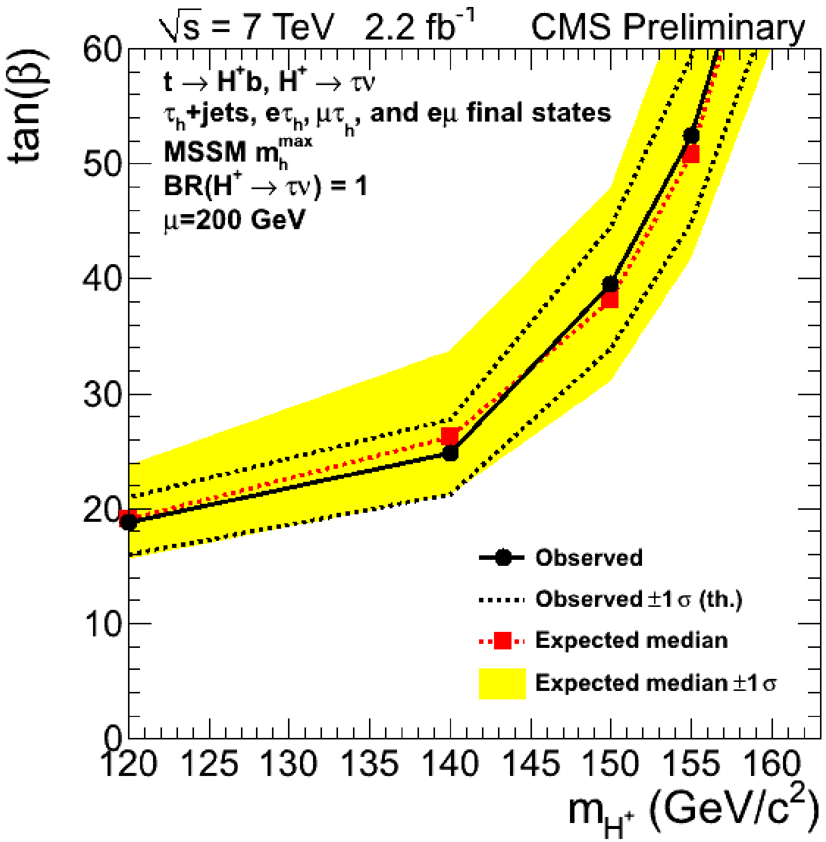
Search for MSSM Higgs Bosons at the LHC



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 $\mathcal{B}$oson $\mathcal{M}$ass

- **Higgs mass prediction** as precise as possible:

  distinguish between MSSM and NMSSM

  properly define scenarios with Higgs-to-Higgs decays

  correctly interpret experimental data

- **Status of Higgs mass calculations:**

  - 1-loop corrections in effective potential approach — Ellwanger eal; Elliott eal; Pandita; Degrassi,Slavich

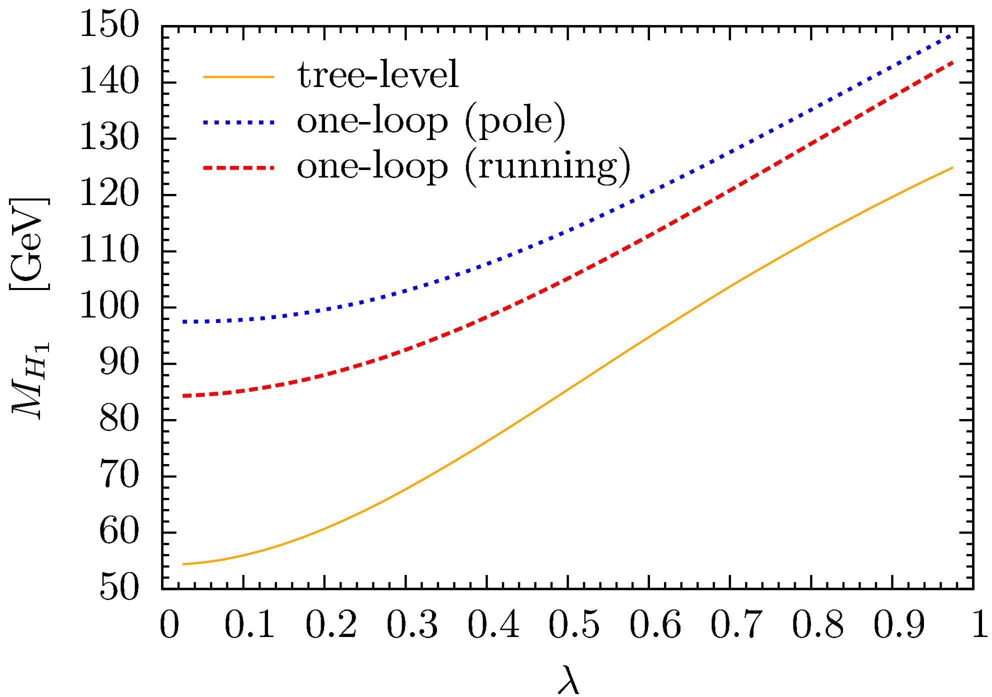
  - 1-loop corrections in Feynman-diagramatic approach — Ender,Graf,MMM,Rzehak '11

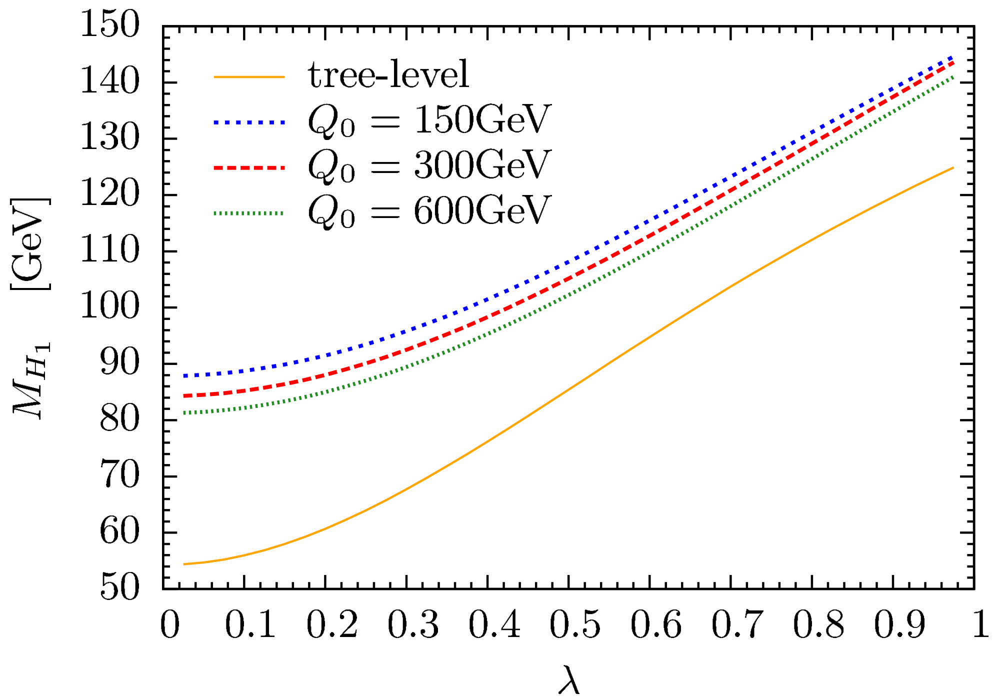
  - 2-loop $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s)$ — Degrassi,Slavich

  - 1-loop w/ CP violation in effective potential approach — Ham eal; Cheung eal

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

Ender,Graf,MMM,Rzehak '11





Top quark mass:

$m_t^{pole} = 173.3$ GeV

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

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

$\mathcal{NMSSM}$ $\mathcal{H}$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

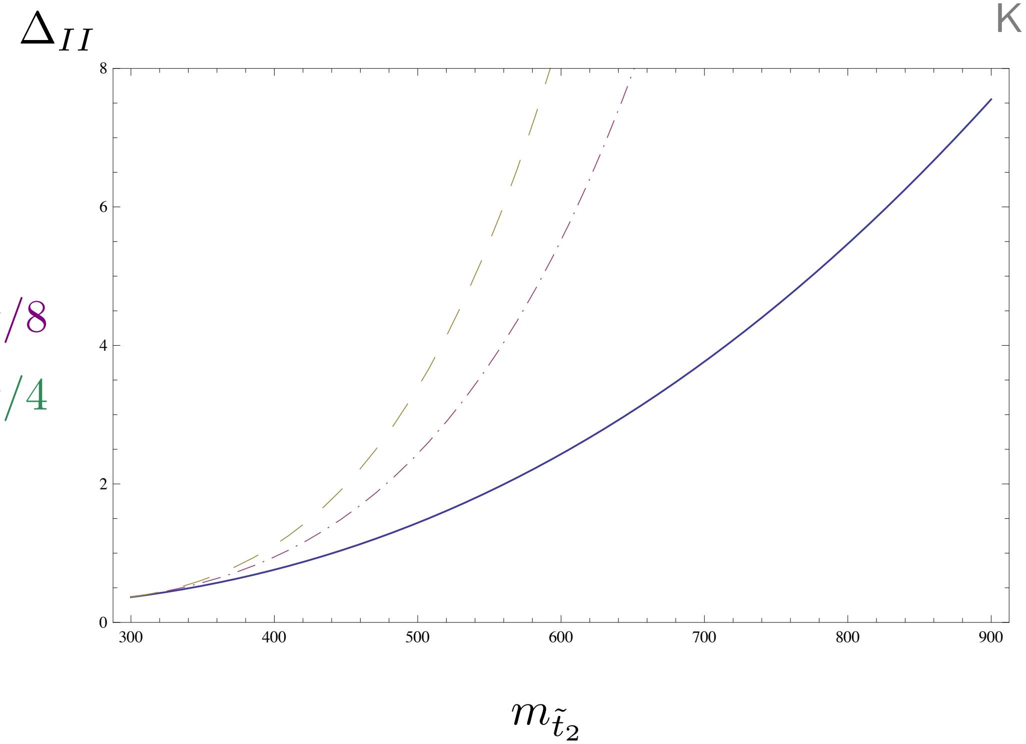
  NMSSM: $\Delta m_h \approx 55\,\text{GeV}$ $(\lambda = 0.7, \tan\beta = 2)$

$\mathcal{F}$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

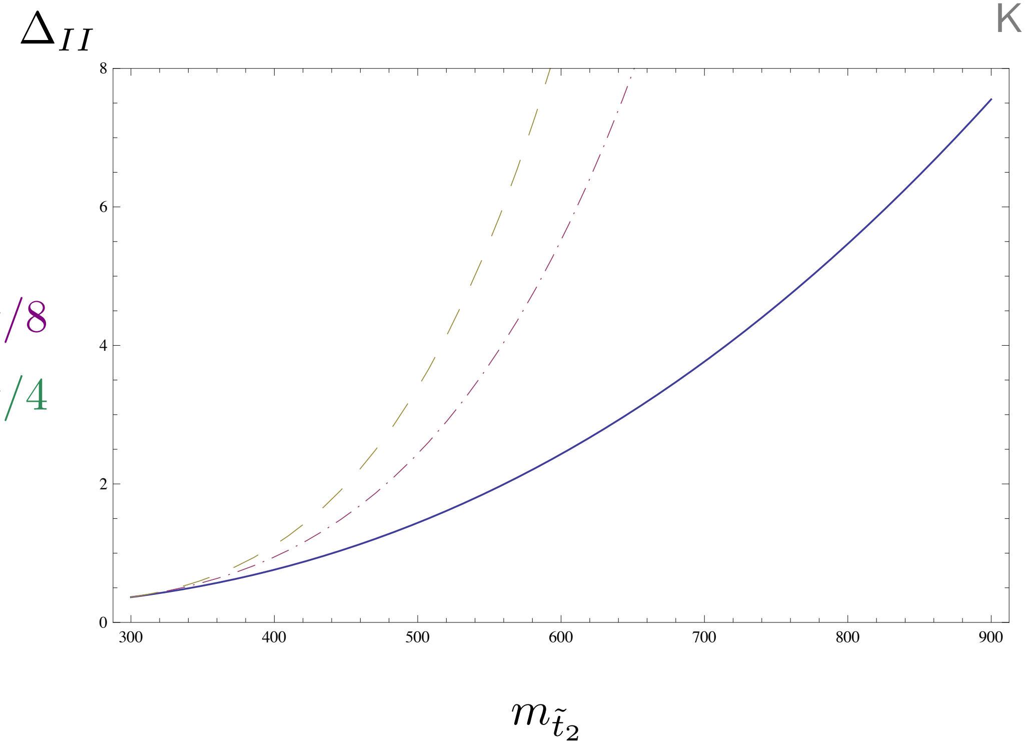
- **The finetuning issue:** study finetuning: calculate 1-loop corrections to the Higgs potential
  - ◇ minimisation conditions of the Higgs potential $\rightsquigarrow$
    to avoid finetuning: correction $\Delta \lesssim \frac{1}{2}M_Z^2$ or $\Delta_{II} = 2\Delta/M_Z^2 \lesssim 1$

King,MMM,Nevzorov '12

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

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

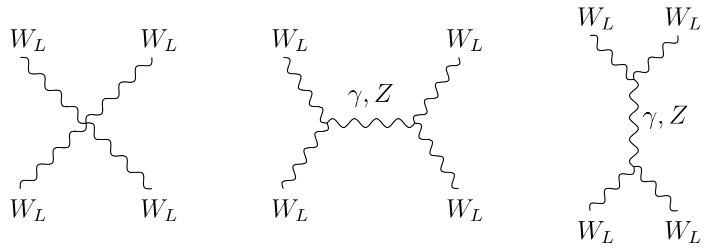
dashed $\theta_{\tilde{t}} = \pi/4$



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

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

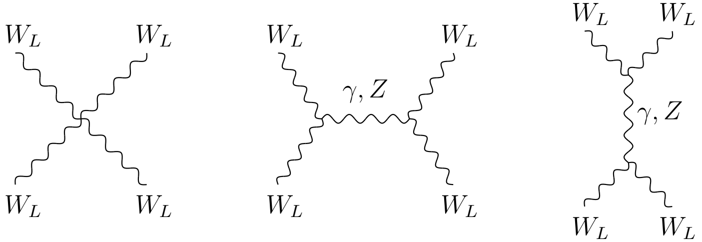
- **Higgs boson: creation of particle masses**



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

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

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



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

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

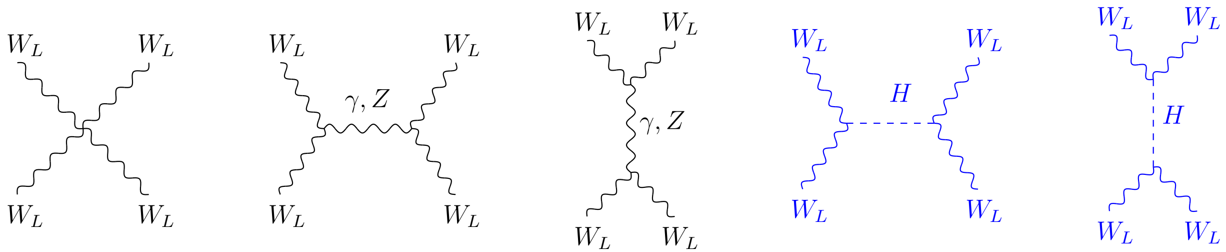
  custodial symmetry and minimal flavour violation (MFV) built-in

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

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

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

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



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

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

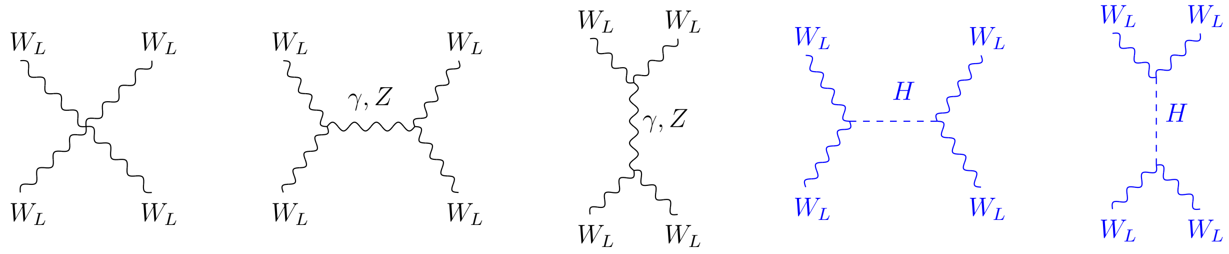
  custodial symmetry and minimal flavour violation (MFV) built-in

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

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

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

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



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

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

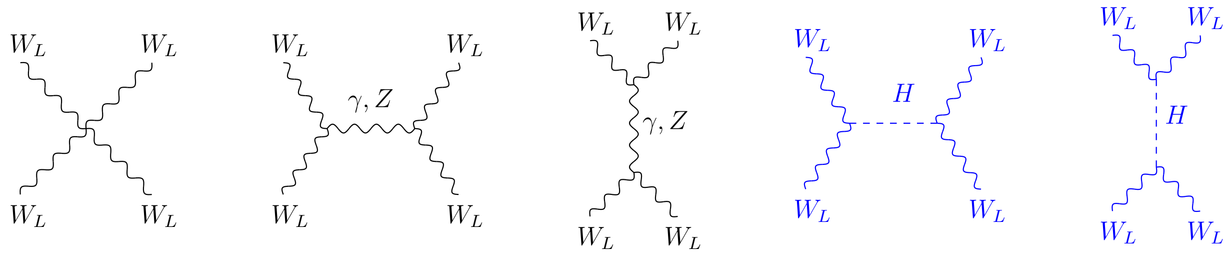
custodial symmetry and minimal flavour violation (MFV) built-in

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

$a = 1$ 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 $\mathcal{H}$iggs $\mathcal{B}$oson?

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



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

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

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

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

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

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

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

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

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

Composite Higgs Boson

- **Composite Higgs boson**
  - ◇ pseudo-Goldstone boson of strongly interacting sector — Kaplan,Georgi;Dimopoulos,Preskill;Dugan eal
    - $SO(5)/SO(4)$: 4 PGBs $= W_L^\pm, Z_L, h \rightarrow$ Minimal Comp. Higgs Model — Agashe,Contino,Pomarol
    - $SO(6)/SO(5)$: 5 PGBs $= W_L^\pm, Z_L, h, a \rightarrow$ Next MCHM — Gripaios,Pomarol,Riva,Serra
  - ◇ Higgs composite object $\rightsquigarrow$ no hierarchy problem
  - ◇ couplings deviate from SM couplings $\rightsquigarrow$ unitary breakdown postponed to higher energies

- **SILH effective Lagrangian** (strongly interacting light Higgs) — Giudice,Grojean,Pomarol,Rattazzi

  Genuine strong operators (sensitive to the scale f $\leftarrow$ compositeness scale)

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

  Form factor operators (sensitive to the scale m_ρ)

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

  SILH: expansion for low $\xi \equiv v^2/f^2$

$\mathcal{M}$inimal $\mathcal{C}$omposite $\mathcal{H}$iggs $\mathcal{E}$xamples

- **Completion for large v/f:** 5D MCHM - $\frac{v}{f}$ $(SO(5)/SO(4))$ Contino eal; Agashe eal

$$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi} \quad \Leftrightarrow \quad a = \sqrt{1-\xi},\ b = 1-2\xi$$

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

spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5
$g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi} \equiv g^{SM}_{Hff}\ c$	$g_{Hff} = g^{SM}_{Hff}\frac{1-2\xi}{\sqrt{1-\xi}} \equiv g^{SM}_{Hff}\ c$
universal shift of couplings no modifications of BRs	BRs depend on $\xi = v^2/f^2$

- **Higgs self-couplings** also model-dependent Contino eal; Gröber,MMM; Bock eal; Barger eal

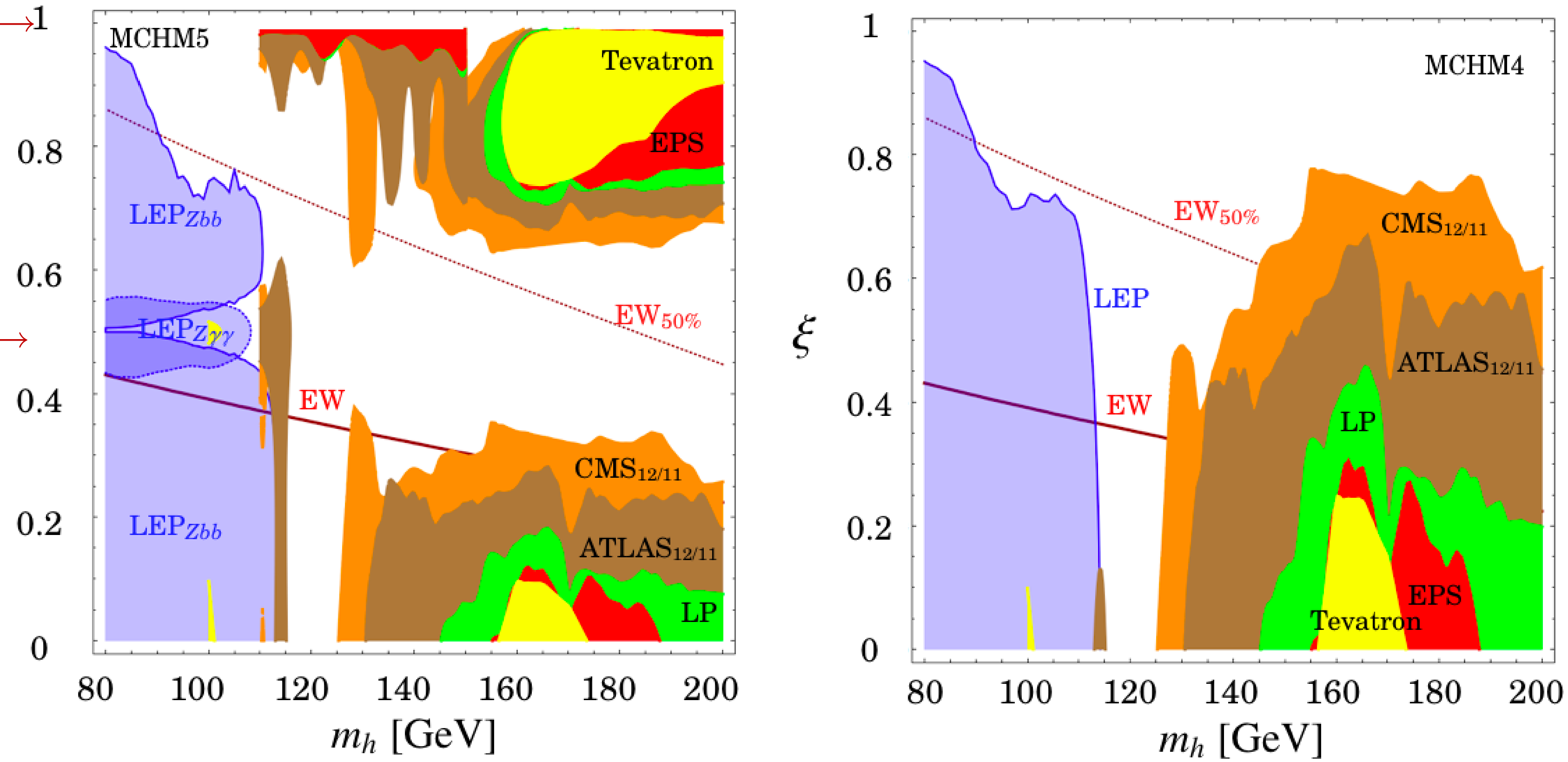
$\mathcal{C}$onstraints from EWPT, LEP, Tevatron, LHC - $\mathcal{P}$re-$\mathcal{M}$oriond '12

Espinosa, Grojean, MMM

gauge-phobic ⟶

fermiophobic ⟶

SM-limit ⟶



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

LEP   EPS-HEP 11   Tevatron

$\mathcal{P}$re-$\mathcal{M}$oriond 2012

Channel [Exp]	m_h[GeV] (Local Significance)	μ (μ_L)	Scaling to SM
$pp \to \gamma\,\gamma$ [ATLAS]	126.5 ± 0.7 $(2.8\,\sigma)$ [22]	$2^{+0.9}_{-0.7}$ [23] (2.6)	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [ATLAS]	$126\pm\sim 2\%$ $(2.1\,\sigma)$ [22]	$1.2^{+1.2}_{-0.8}$ [23] (4.9)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [ATLAS]	$126\pm\sim 20\%$ $(1.4\,\sigma)$ [22]	$1.2^{+0.8}_{-0.8}$ [23] (3.4)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to \gamma\,\gamma\,jj$ [CMS]	$124 \pm 3\%$ [10,11]	$3.7^{+2.5}_{-1.8}$ [11]	$\sim a^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS,b},R_9^{\mathrm{min}} > 0.94]$	$124 \pm 3\%$ [10,11]	$1.5^{+1.1}_{-1.0}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS,b},R_9^{\mathrm{min}} < 0.94]$	$124 \pm 3\%$ [10,11]	$2.1^{+1.5}_{-1.4}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS,e},R_9^{\mathrm{min}} > 0.94]$	$124 \pm 3\%$ [10,11]	$0.0^{+2.9}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to \gamma\,\gamma[\mathrm{CMS,e},R_9^{\mathrm{min}} < 0.94]$	$124 \pm 3\%$ [10,11]	$4.1^{+4.6}_{-4.1}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\,\gamma}[a,c]$
$pp \to Z\,Z^\star \to \ell^+\,\ell^-\,\ell^+\,\ell^-$ [CMS]	$126 \pm 2\%$ $(1.5\,\sigma)$ [11,24]	$0.5^{+1.0}_{-0.7}$ [10] (2.7)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [CMS]	$126 \pm 20\%$ [10,25]	$0.7^{+0.4}_{-0.6}$ [10] (1.8)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to b\,\bar b$ [CMS]	$124 \pm 10\%$ [10]	$1.2^{+1.4}_{-1.7}$ [10] (4.1)	$\sim a^2\,\mathrm{Br}_{b\bar b}[a,c]$
$pp \to \tau\,\bar\tau$ [CMS]	$124 \pm 20\%$ [10]	$0.8^{+1.2}_{-1.7}$ [10] (3.3)	$\sim c^2\,\mathrm{Br}_{\tau\bar\tau}[a,c]$

in the presence of excess, the combined limit is stronger than the quadrature

$$\sum_i \frac{(\mu_L-\hat\mu)^2}{(\mu_L^i-\hat\mu)^2} - \sum_i \frac{\hat\mu}{(\mu_L^i-\hat\mu)^2} = 1$$

Espinos, Grojean, MMM, Trott '12

$\mathcal{M}$odel-$\mathcal{I}$ndependent $\mathcal{F}$it to $\mathcal{LHC}$ $\mathcal{D}$ata

Effective theory assuming: custodial symmetry & MFV

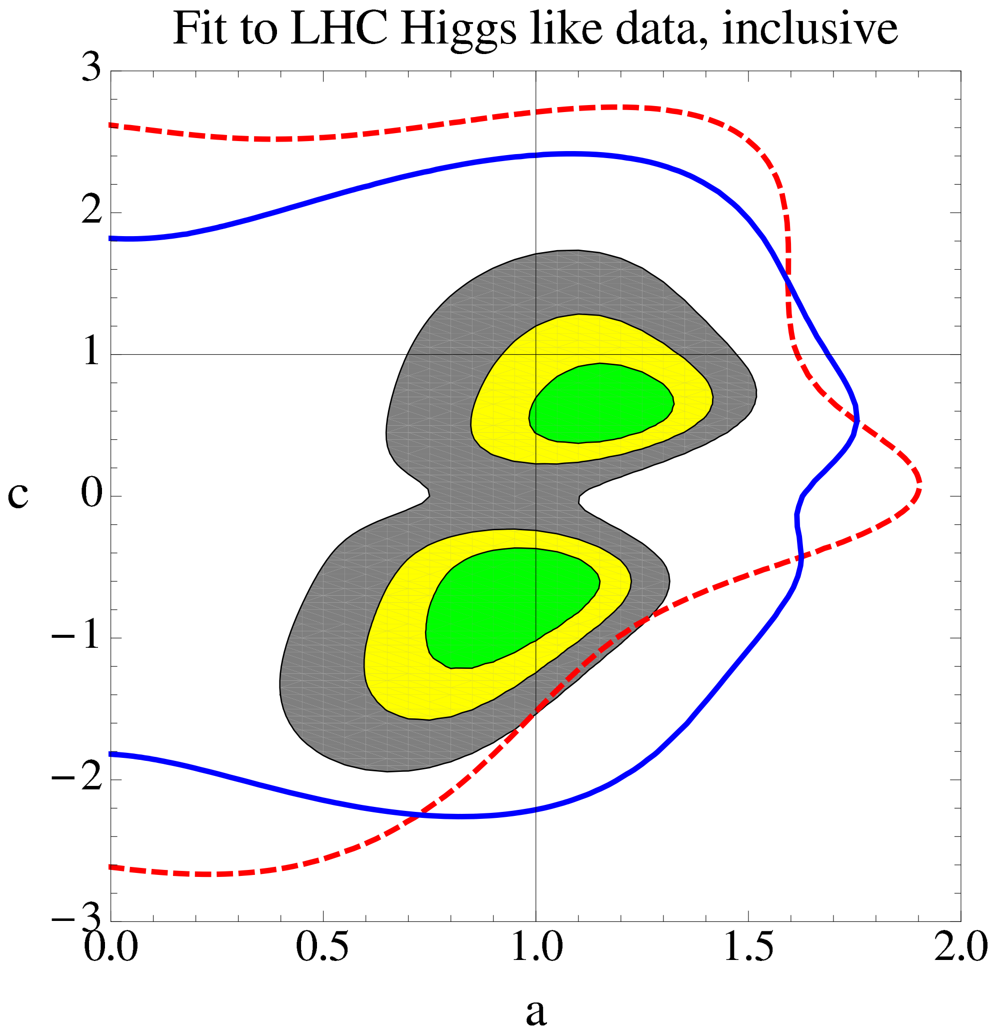
Espinosa,Grojean,MMM,Trott '12

red-dashed:

Atlas 95% CL exclusion

blue-full

CMS 95% CL exclusion



Note: a fermiophobic Higgs is disfavoured by data

Two minima:

$(a, c) = (1.13, 0.58)$
$\chi^2 = 2.86$

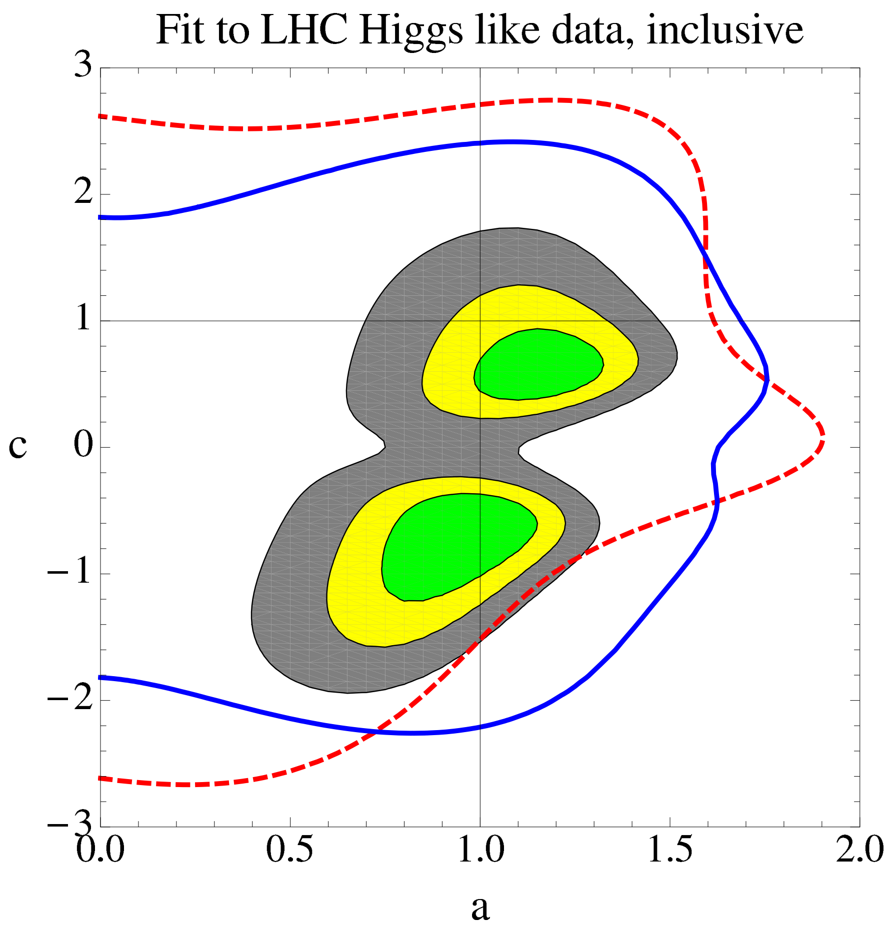
$(a, c) = (0.96, -0.64)$
$\chi^2 = 1.96$

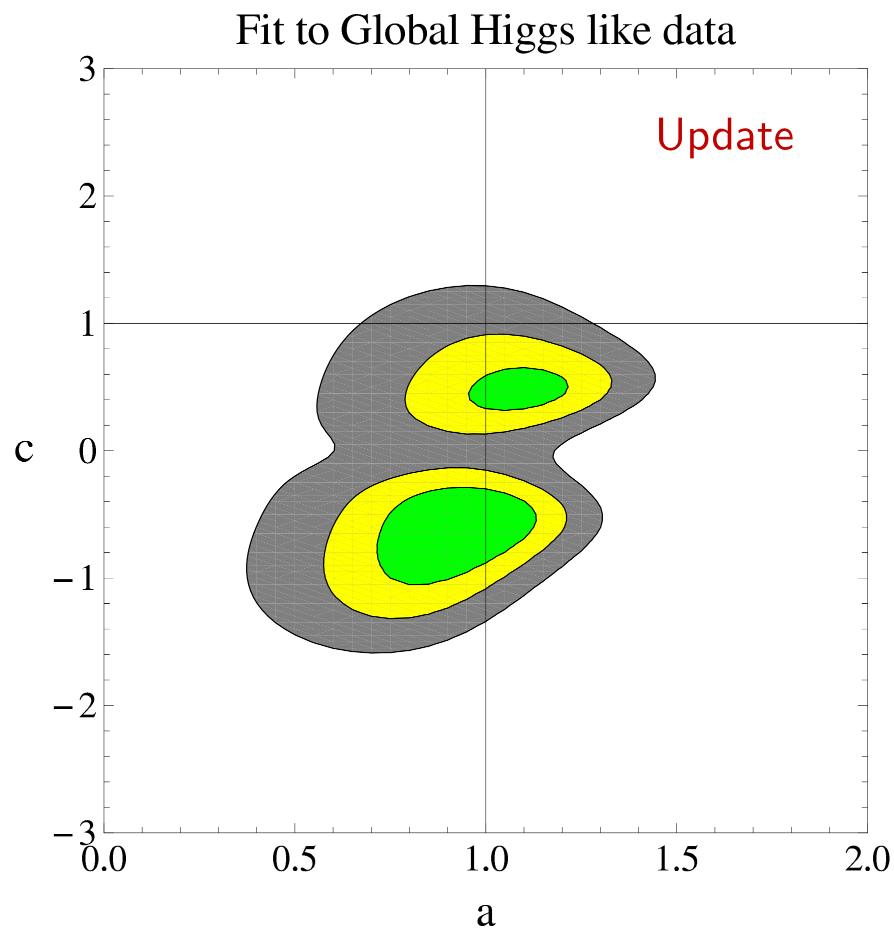
for similar analyses, see also

Azatov,Contino,Galloway '12
Carmi,Falkowski,Kuflik,Volansky '12
Ellis,You '12; Giardino eal '12

Model-Independent Fit to LHC Data - Update with Moriond Data

Espinosa,Grojean,MMM,Trott '12



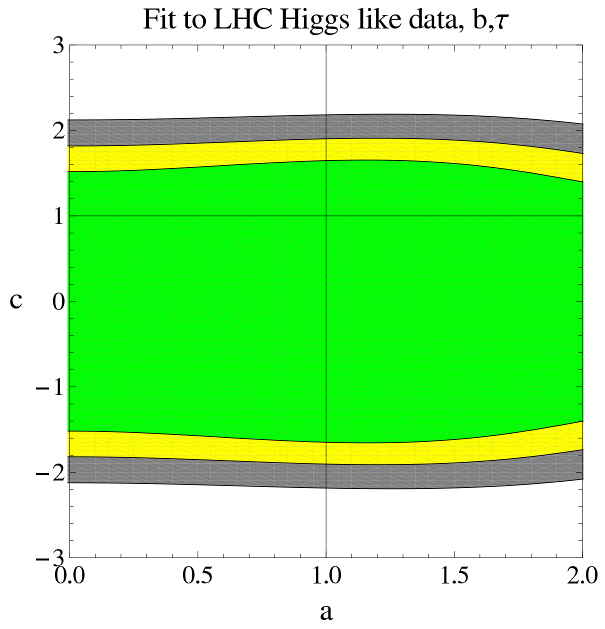


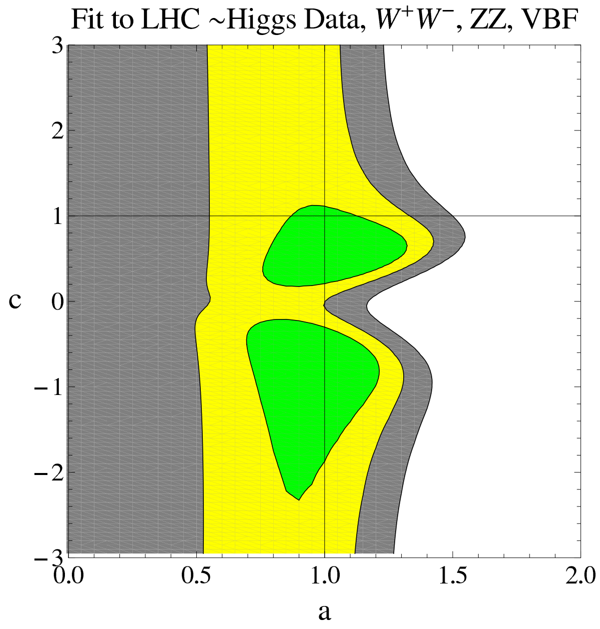
ATLAS update: $pp \to WW^* \to l^+ \nu l^- \bar{\nu}$,
ATLAS $pp \to \tau\tau$, Tevatron $p\bar{p} \to b\bar{b}$

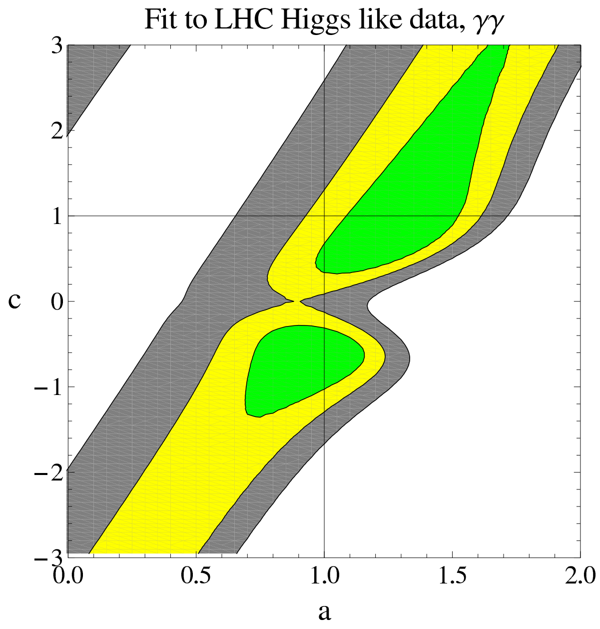
Channels Driving the Fit

Espinosa,Grojean,MMM,Trott '12

fermion couplings	gauge couplings	both couplings







almost no constraints	almost $(a, c) \leftrightarrow (a, -c)$ symmetric	most constraining
at the moment	large a are disfavoured	even if $\Gamma(h \to \gamma\gamma)$ is not really modified (no operator $\|H\|^2 B_{\mu\nu} B^{\mu\nu}$), $BR_{\gamma\gamma}$ has strong dependence on a, c

$\mathcal{C}$onclusions

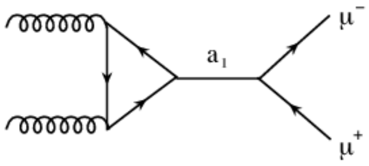
(i) MSSM Higgs boson production including HO corrections available

(ii) Interpretation of LHC Higgs search results within

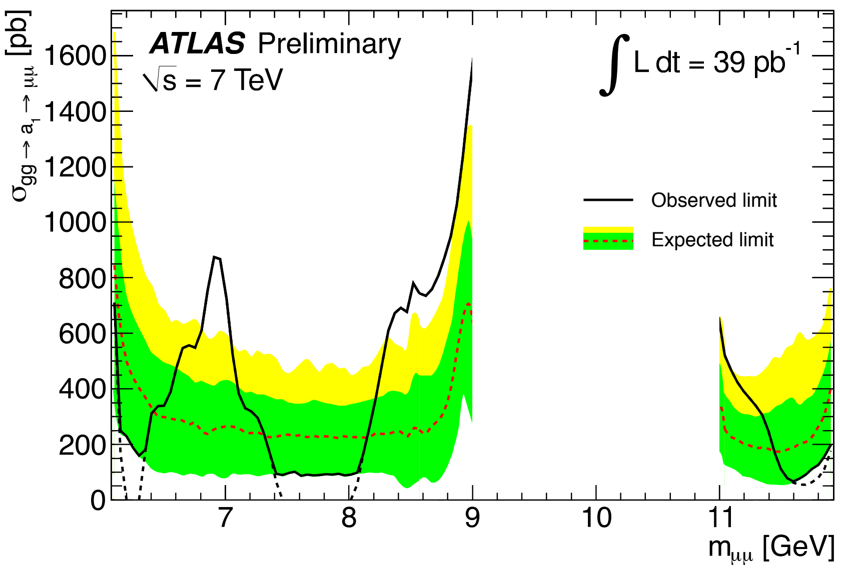
* MSSM: requires 'finetuning'
* NMSSM: less finetuned
* Composite Higgs: compatible with LHC results
* Model-independent
  - effective theory: global fits to best signal strengths and exclusion regions
  - SM Higgs hypothesis consistent w/ data at 94% CL

Thank you for your attention!

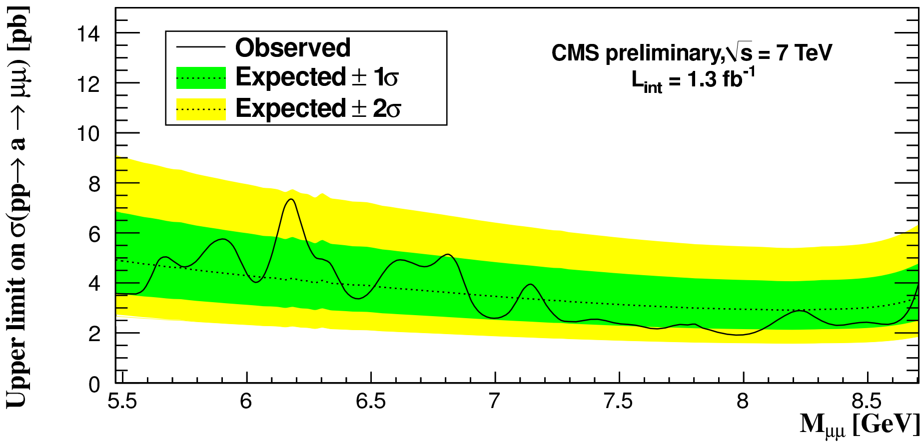
$\mathcal{U}$pper $\mathcal{L}$imit on $\mathcal{NMSSM}$ a_1 $\mathcal{P}$roduction



ATLAS-CONF-2012-020

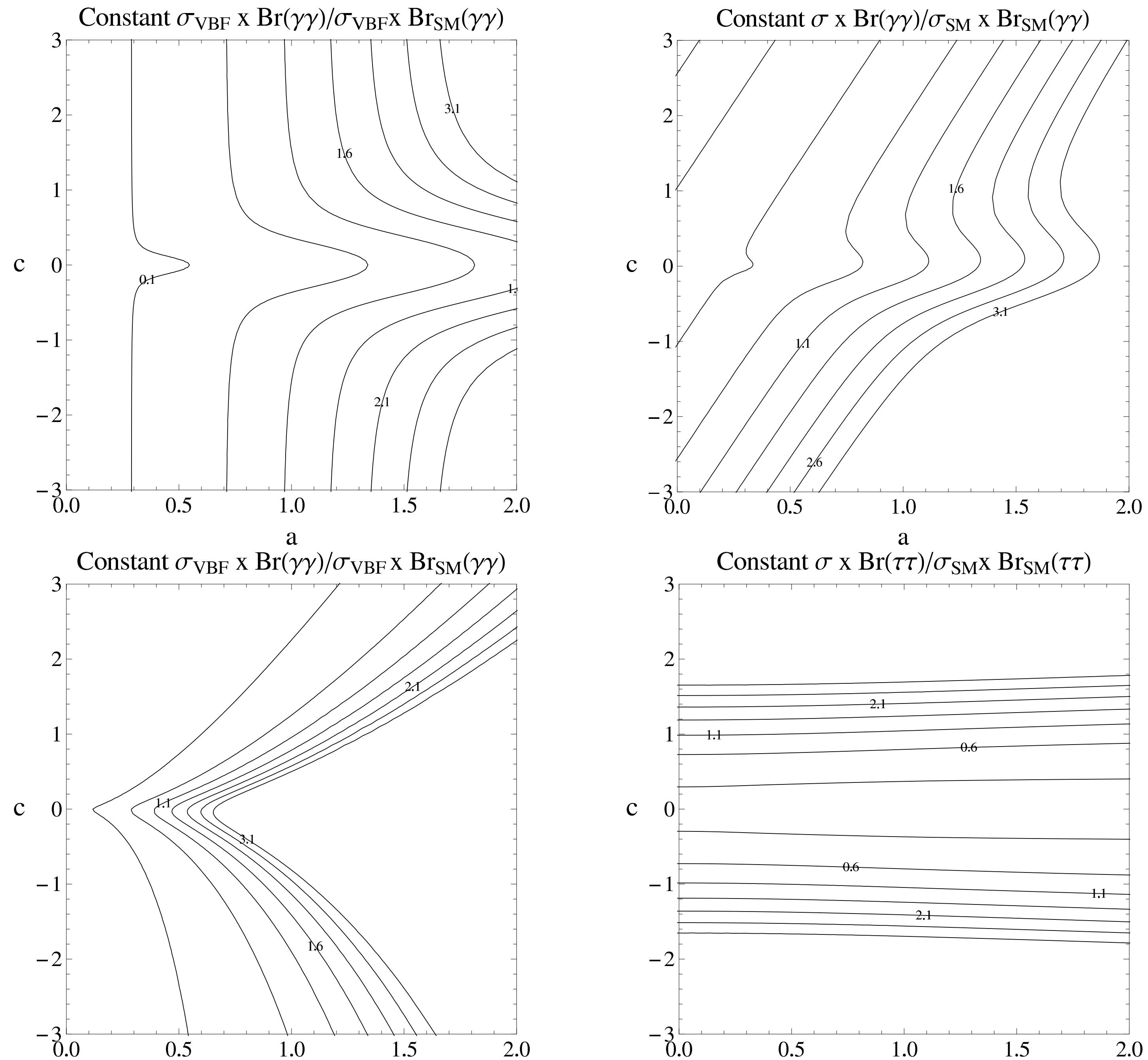


CMS-HIG-12-004



Contours of constant signal production at 8 TeV

Espinosa,Grojean,MMM,Trott '12

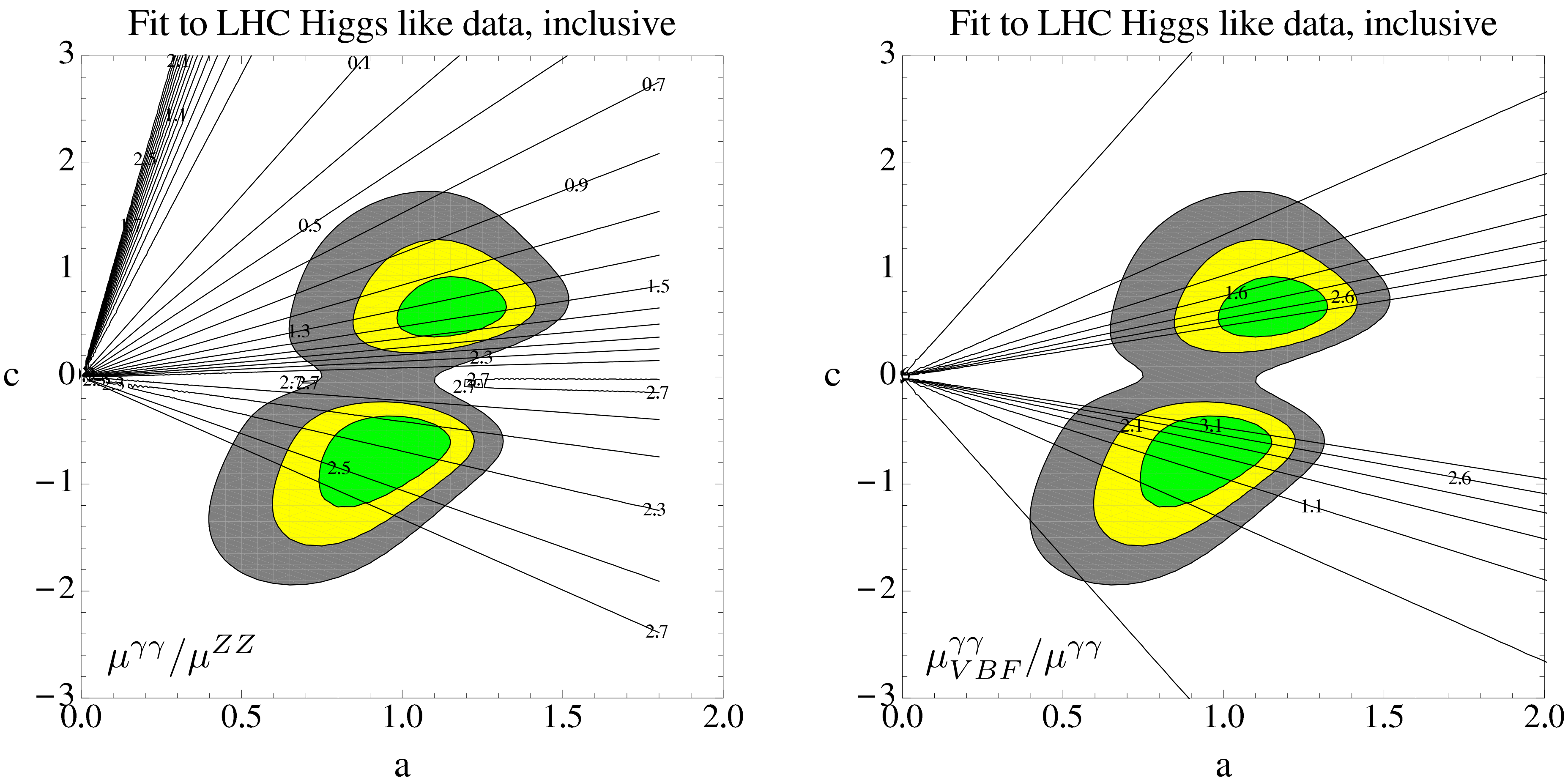


$\mathcal{M}$oriond 2012 $\mathcal{U}$pdate

Channel [Exp]	m_h[GeV]	μ (μ_L)
$pp \to W\,W^\star \to \ell^+\,\nu\,\ell^-\,\bar\nu$ [ATLAS]	126	$0.2^{+0.6}_{-0.7}$ (1.3)
$pp \to b\,\bar b$ [ATLAS]	124	$-0.8^{+1.7}_{-1.7}$ (3.5)
$pp \to \tau\,\bar\tau$ [ATLAS]	124	$-0.1^{+1.7}_{-1.7}$ (3.4)
$pp \to b\,\bar b$ [CDF&D0]	125	$2.0^{+0.8}_{-0.7}$ (3.2)
$pp \to W^+W^-$ [CDF&D0]	125	$0.03^{+1.22}_{-0.03}$ (2.4)

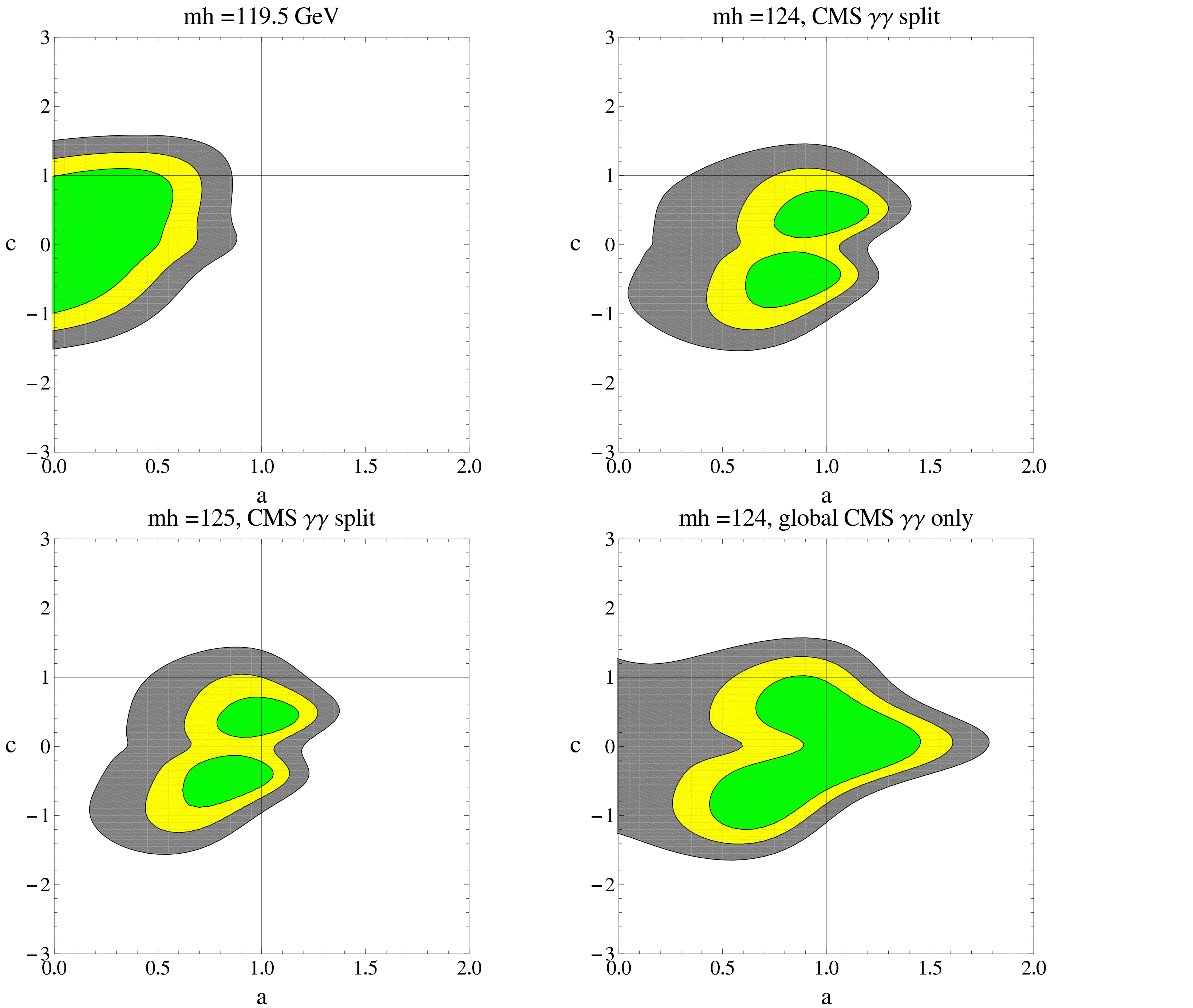
$\mathcal{H}$ow to distinguish the two $\mathcal{M}$inima

Espinosa,Grojean,MMM,Trott '12

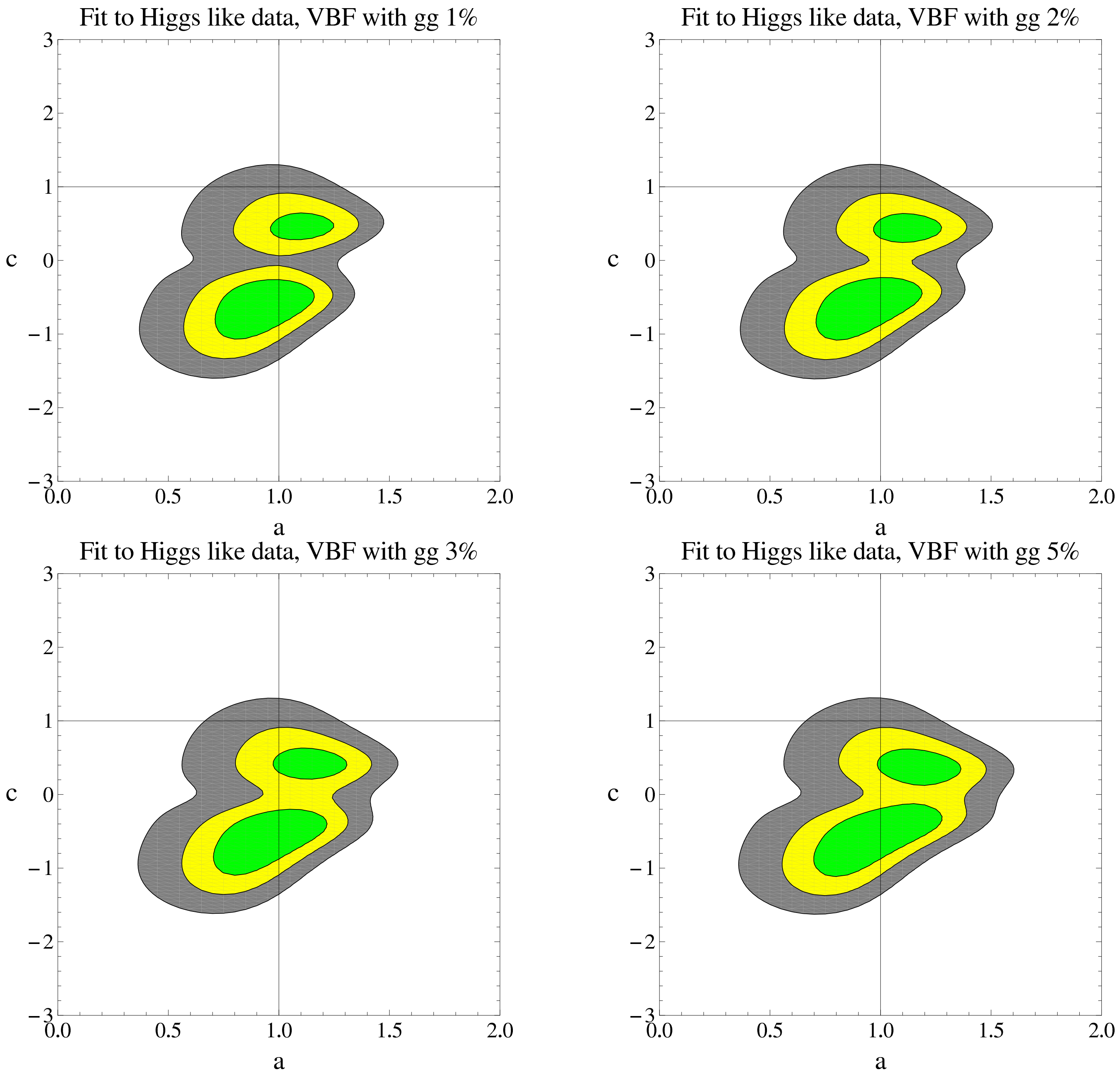


the $(a, c) \leftrightarrow (a, -c)$ symmetry is broken in the $\gamma\gamma$ channel

Espinosa,Grojean,MMM,Trott '12



Espinosa,Grojean,MMM,Trott '12

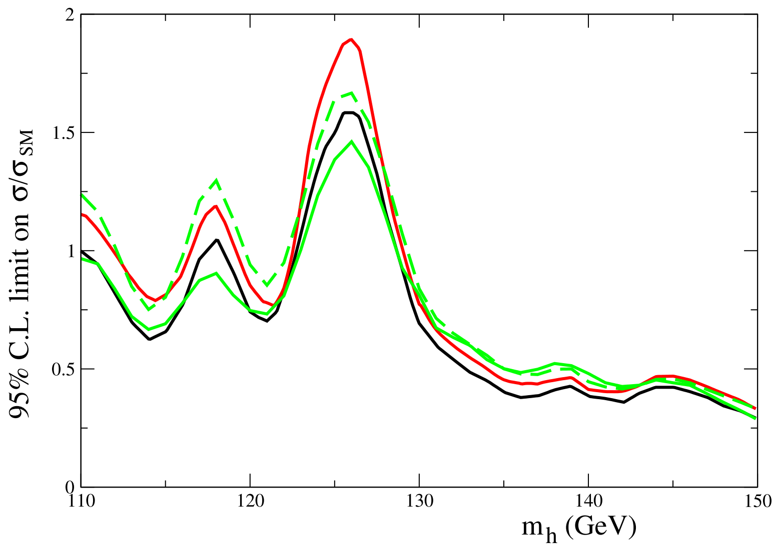


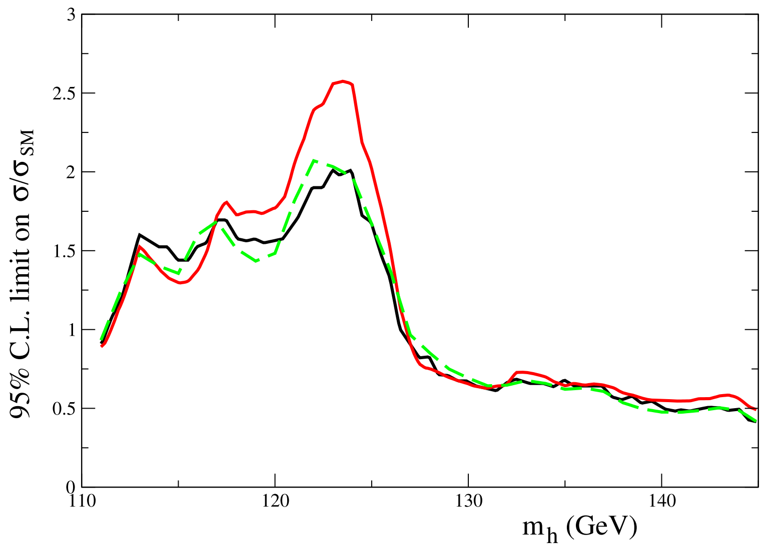
95% CL limits on σ/σ_{SM}

Espinosa,Grojean,MMM,Trott '12

ATLAS

CMS





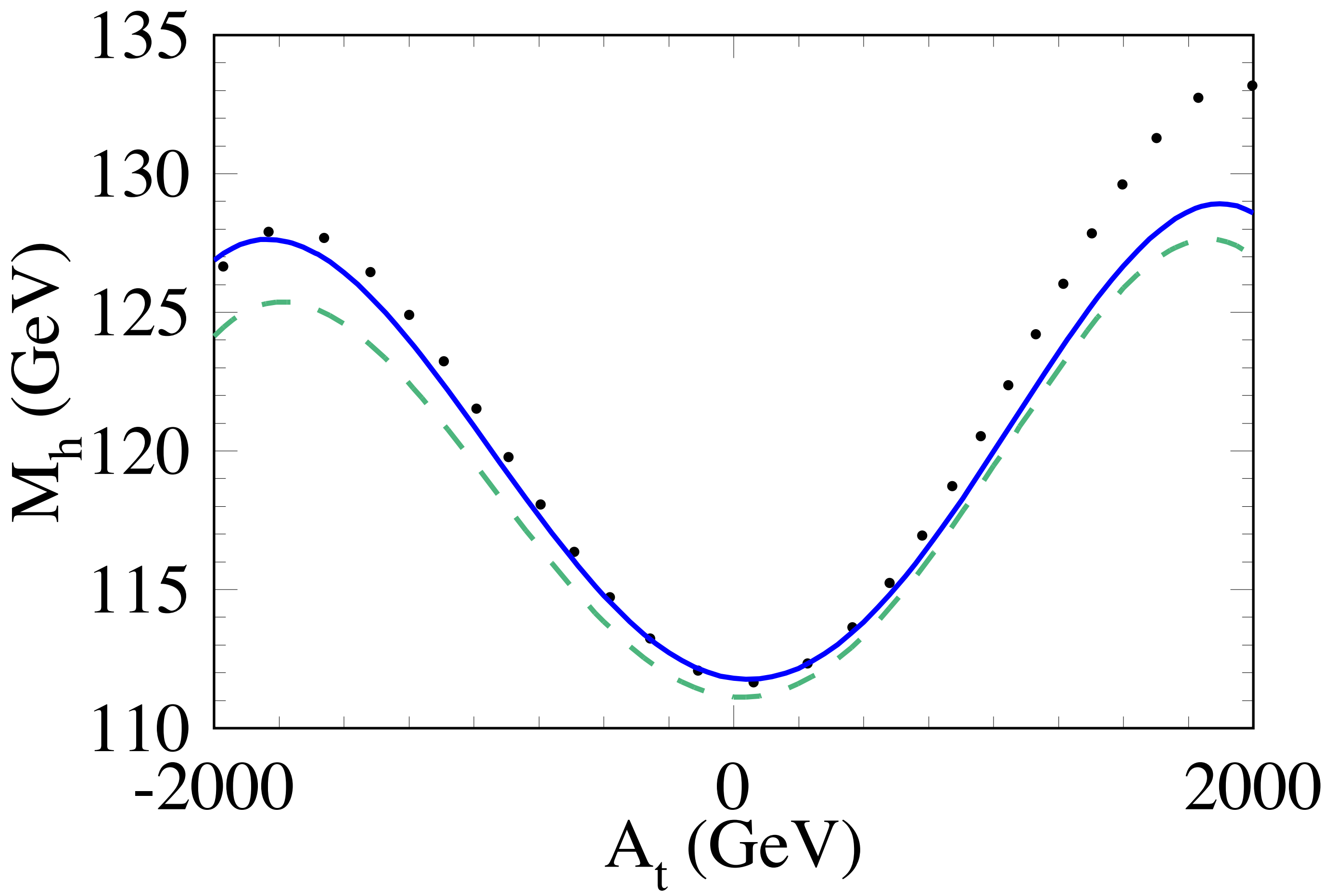
black: official curve

red: simple approximation

green: more precise determination

Light MSSM Higgs mass at three-loop order

Kant,Harlander,Mihaila,Steinhauser '10

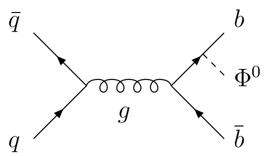


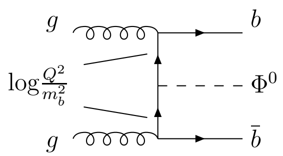
3-loop: $\Delta^{th}(M_h) \approx 200$ MeV (1 GeV) for $m_{1/2} = 100$ GeV (1 TeV)

$\mathcal{A}$ssociated production with a $b\bar{b}$ pair

(v) Higgs $b\bar{b}$ production: dominant MSSM Higgs production mechanism for $\tan\beta \gtrsim 7$
measurement of $\tan\beta$

- Four-flavour scheme 4FS: LO cxn $gg \to b\bar{b}\Phi^0$





dominant

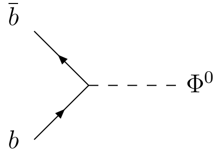
NLO with 0,1,2 high-transverse momentum b jets

Dittmaier,Krämer,Spira;
Dawson,Jackson,Reina,Wackeroth

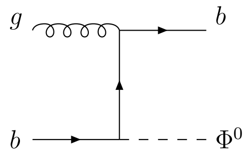
exact $g \to b\bar{b}$ splitting & mass/off-shell effects

large logs from phase space integration $\rightsquigarrow$ absorbed in bottom PDF $\Rightarrow$

- Five-flavour scheme 5FS: LO cxn $b\bar{b} \to \Phi^0$



NNLO



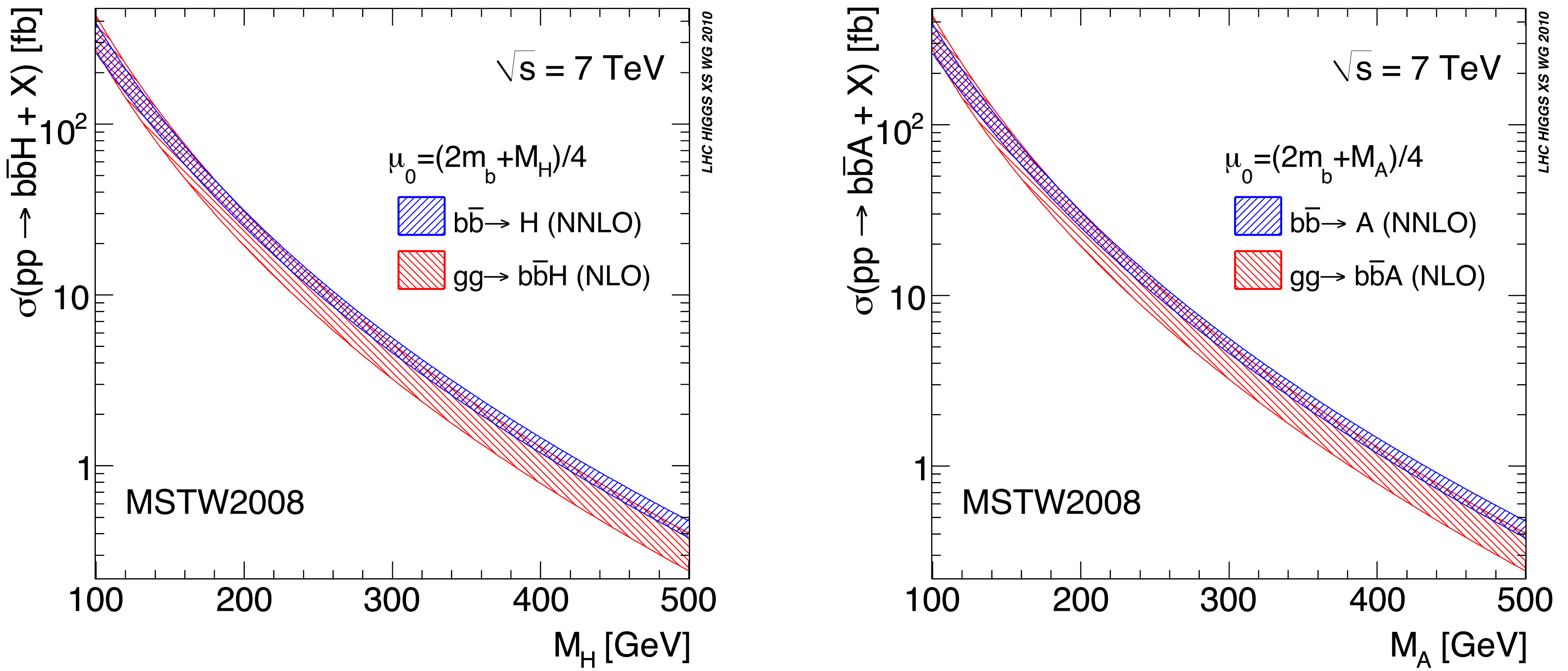
NLO

Dicus,Willenbrock
Stelzer et al.;Balazs et al.
Campbell et al.
Harlander,Kilgore
Kidonakis

massless/on-shell b's, no p_{Tb}, resummation of $\log M_H^2/m_b^2$ terms

$\mathcal{A}$ssociated production with a $b\bar{b}$ pair

LHC Higgs XS WG



blue bands: combined scale and 68% CL PDF+α_s uncertainties of the 5FS

red bands: scale uncertainties of the 4FS

$\mathcal{T}$he $\mathcal{S}$antander $\mathcal{M}$atching

* **Difference 4FS $\leftrightarrow$ 5FS:** logarithmic

Harlander,Krämer,Schumacher

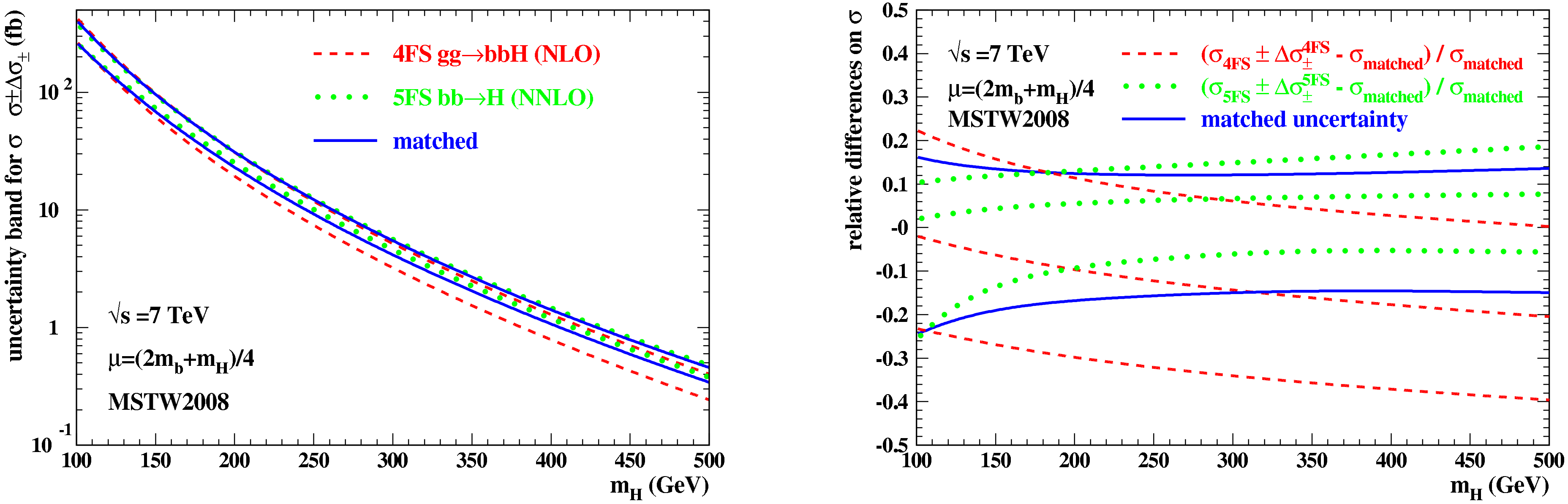
* **Weight:** 5FS 100% weight for $\frac{M_H}{m_b} \to \infty$
  4FS 100% weight for 'small' logarithms: $\ln(M_H/m_b) = 2$ (arbitrariness)

$$\sigma^{\text{matched}} = \frac{\sigma^{\text{4FS}} + w\sigma^{\text{5FS}}}{1+w}$$

$$w = \ln \frac{M_H}{m_b} - 2$$

$\Rightarrow$ 4FS and 5FS have same weight at $M_H = 100$ GeV.

Harlander,Krämer,Schumacher

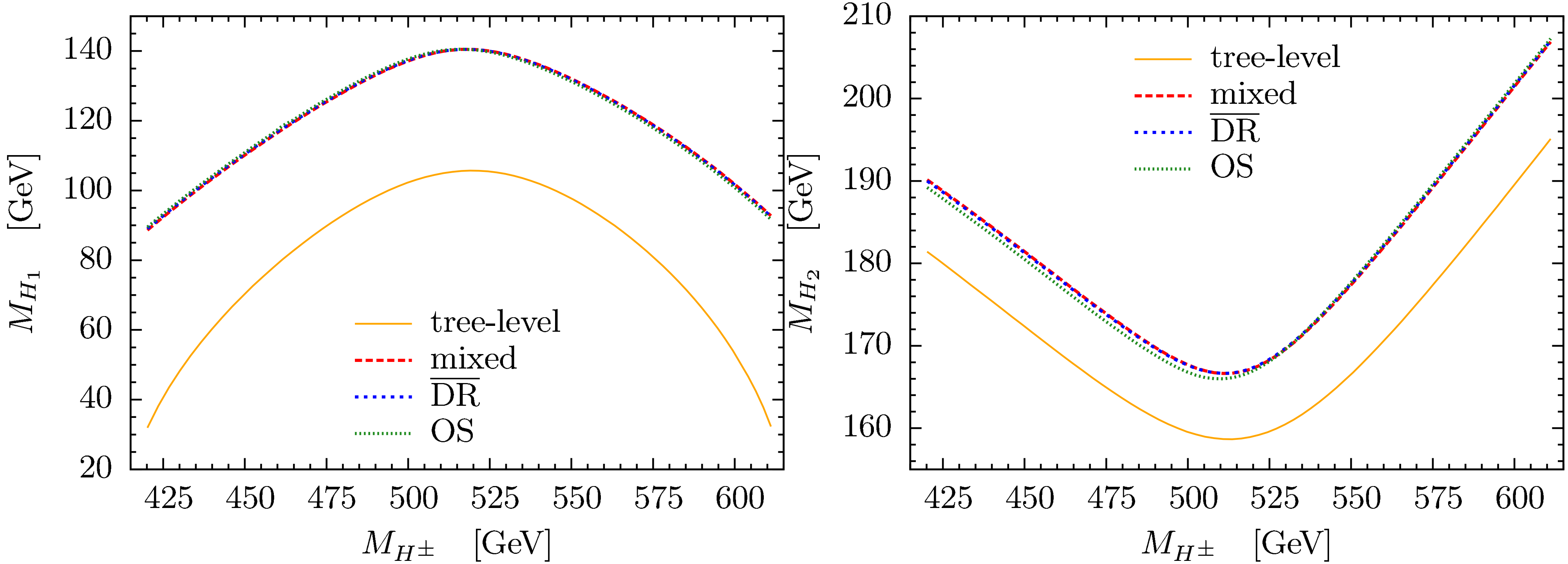


(a) (b)

Figure 2: (a) Theory uncertainty bands for the total inclusive cross section in the 4FS (red, dashed), the 5FS (green, dotted), and for the matched cross section (blue, solid). (b) Uncertainty bands and central values, relative to the central value of the matched result (same line coding as panel (a)).

NMSSM Higgs Boson Mass

Ender,Graf,MMM,Rzehak



Dependence on different renormalisation schemes

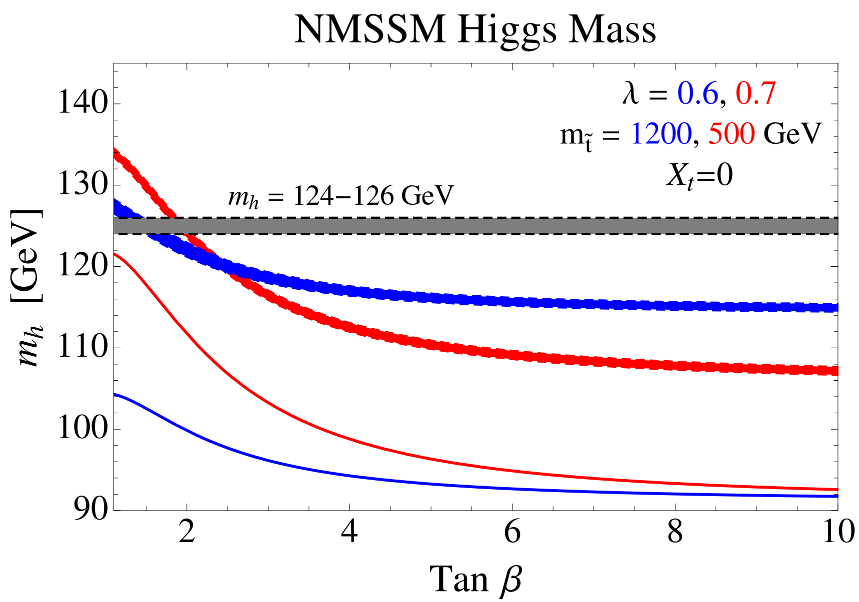
$\mathcal{F}$inetuning - $\mathcal{N}$atural $\mathcal{SUSY}$ $\mathcal{M}$odel

- **Benchmark points** 2 examples $X_t = A_t - \mu \cot\beta$ King,MMM,Nevzorov

SM-like Higgs [GeV]	$\tan\beta$	λ	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	$X_t/m_{\tilde{t}}$	$R_{\gamma\gamma}$	$R_{incl}R_{\gamma\gamma}$
$M_{H_1} = 124.6$	2	0.56	358	686	2.26	1.42	1.11
$M_{H_2} = 125.8$	3	0.68	391	634	1.77	1.78	1.39

- **NMSSM mass versus $\tan\beta$** Hall,Pinner,Ruderman

  approximate
  2-loop M_H mass formula



- **For scans** see Albornoz Vasquez eal; Cao eal

Constraints

- **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
  - ⋆ 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}, add channels in quadrature] $\rightarrow$ T

$\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{P}$enomenology

- **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:**

  ⋆ Existence of light $H_1, A_1, \tilde{\chi}_1^0$: invisible decays into these finals states
  $\rightsquigarrow$ suppressed Higgs decay into $\gamma\gamma$ $\rightsquigarrow$ MSSM/SM search channels could miss it

  ⋆ $H_2 \to H_1 H_1$ or $H_2 \to A_1 A_1$ with H_1, A_1 further decaying into SM particles:
  discovery mode w/ distinctive signature

  ⋆ If $M_{A_1} < 2m_b$ $\rightsquigarrow$ $H_1 \to A_1 A_1$ dominates $\rightsquigarrow$ $BR(H_1 \to b\bar{b})$ suppressed $\rightsquigarrow$ H_1 avoids 114.4 LEP limit $H_1 \to A_1 A_1 \to l^+ l^- b\bar{b}$ could explain observed LEP excess near $m_{\bar{b}b} = 100$ GeV
  Dermisek ,Gunion

  ⋆ Addtitional neutralino: singlino-like lightest $\tilde{\chi}_1^0$, can be very light: possible DM candidate

  ⋆ ...