"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Higgs and BSM Phenomenology

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Cosener's house, 07/2019

1. Basics of the Higgs

2. BSM Higgs physics (theory)

3. Higgs boson(s) at the LHC

4. Further BSM phenomenology

Higgs and BSM Phenomenology

Higgs boson(s) at the LHC

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Cosener's house, 07/2019

1. The LHC

2. The SM Higgs boson at the LHC

3. MSSM/BSM Higgs boson searches at the LHC

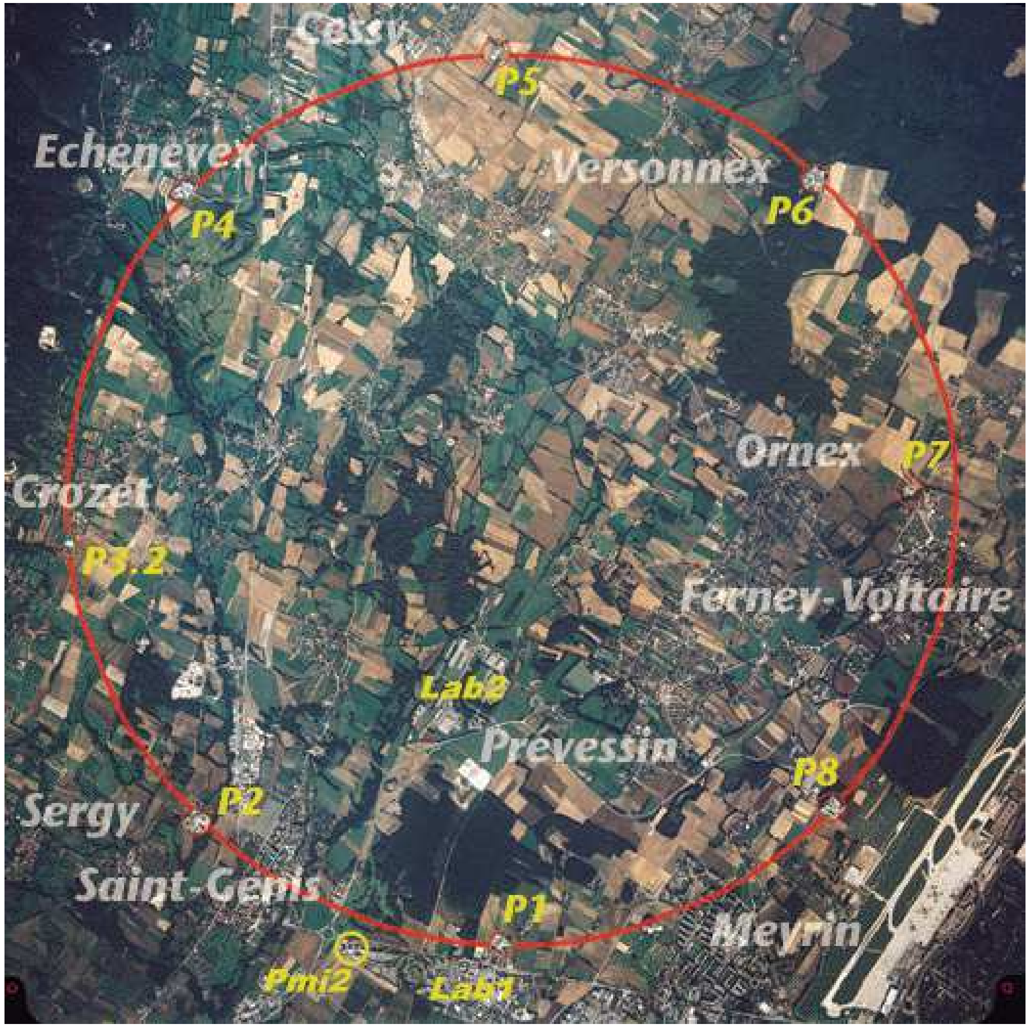
4. My favorite anomaly: a Higgs boson at 96 GeV

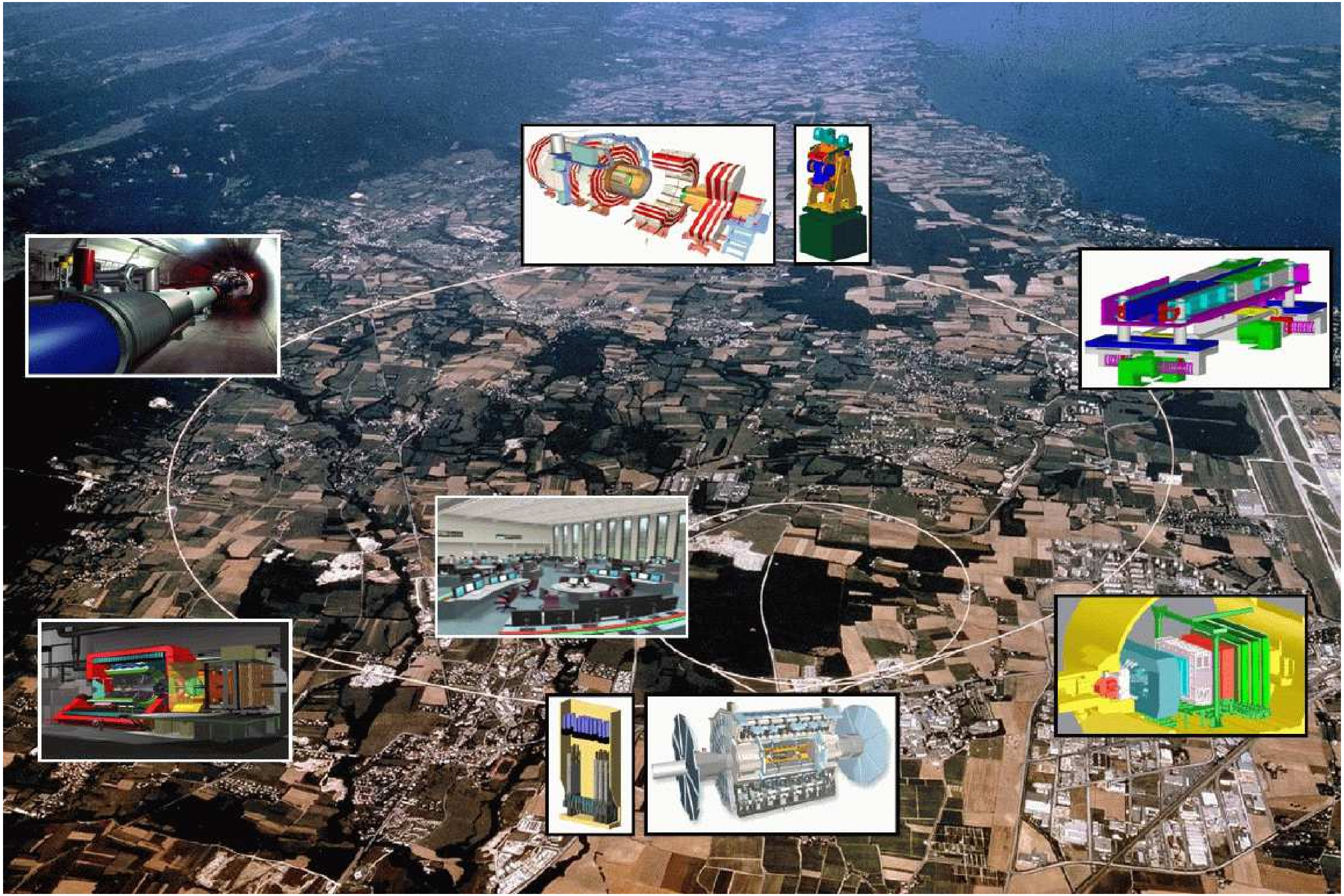
1. The LHC

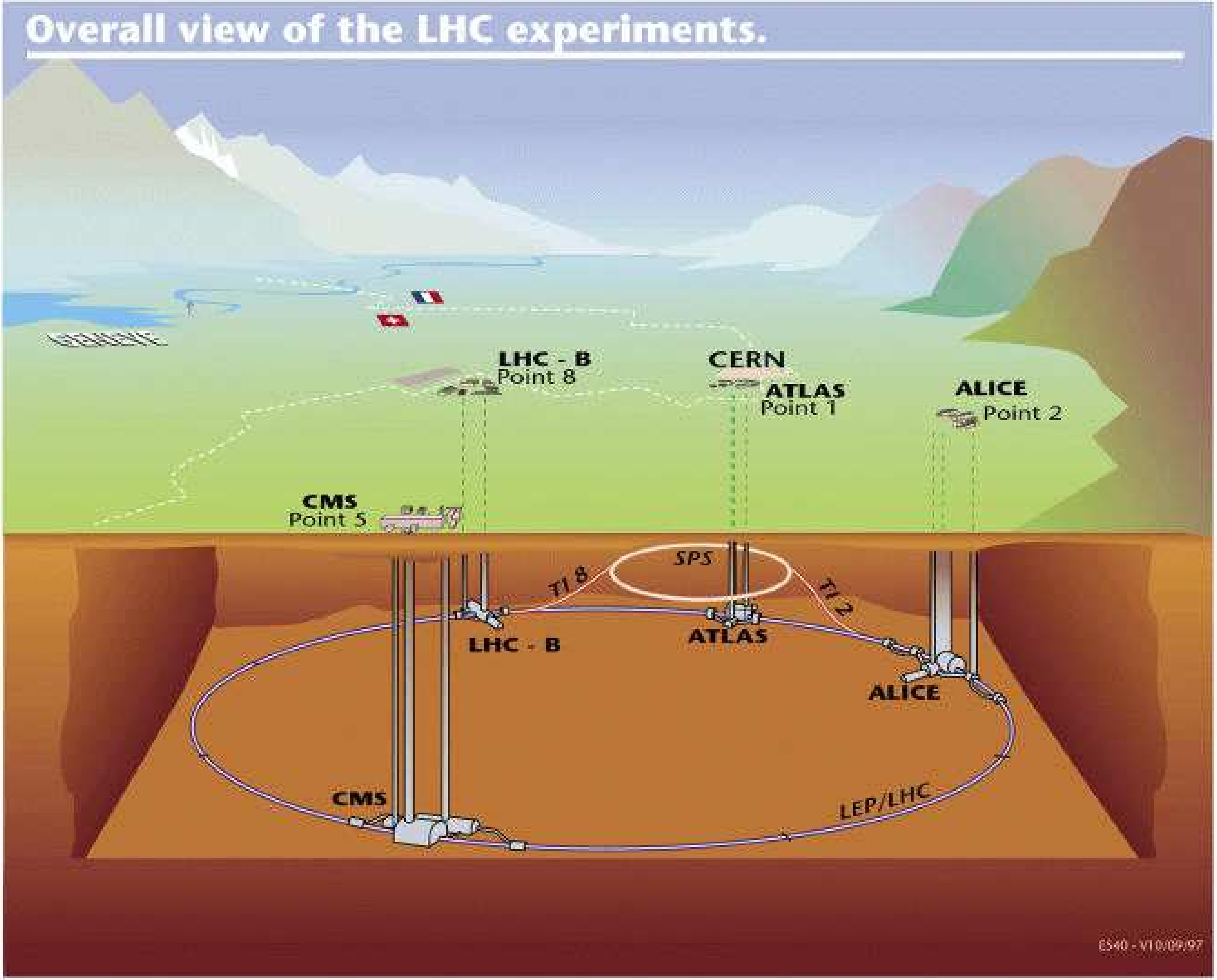
LHC:

$p\,p$ collisions at $\sqrt{s} \lesssim 14$ TeV

– 27 km circumference
– two general purpose detectors: ATLAS and CMS
– one B physics detector: LHCb
– one heavy ion detector: Alice






Overall view of the LHC experiments.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

The (un)official (optimistic?) LHC time line:

03/2010: first collisions at record breaking energy

2010: $\lesssim 0.05\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV)

2011: $\sim 5\,\text{fb}^{-1}$ (at $\sqrt{s} = 7$ TeV) $\Rightarrow$ first physics results!

2012: $\sim 20\,\text{fb}^{-1}$ (at $\sqrt{s} = 8$ TeV) $\Rightarrow$ **Higgs discovery!**

2013 – 2014 shutdown, further splice checks, repairs, . . .

2015 – 2018: $40\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results at $\sqrt{s} \lesssim 14$ TeV

2019 – 2020: shutdown, preparation for "high luminosity"

2021 – 2023: $100\,\text{fb}^{-1}$ per year $\Rightarrow$ physics results with "high" luminosity

2024 – 2026: upgrade to HL-LHC

2026 + X (X > 0): HL-LHC

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YOU live in an exciting time!!!

LHC Results: Executive Summary (of Albert's lecture :-)

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Standard Model has been rediscovered!

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Standard Model has been rediscovered!

No evidence for BSM physics - yet!

But a groundbreaking discovery in the Higgs searches!

Physics at the LHC: basics

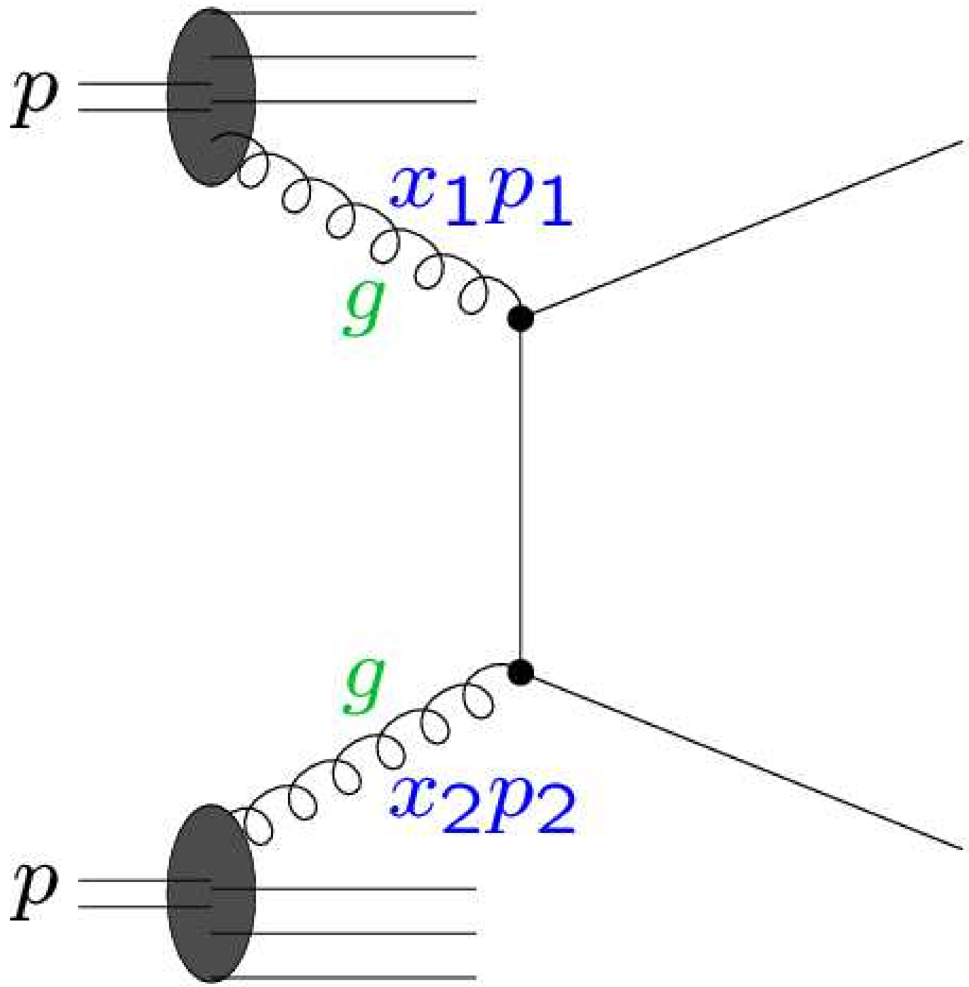
$p\,p$ scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV, strongly interacting

$\Rightarrow$ huge QCD backgrounds,
low signal–to–background ratios

interaction rate of 10^9 events$/s$

$\Rightarrow$ can trigger on only
1 event in 10^7

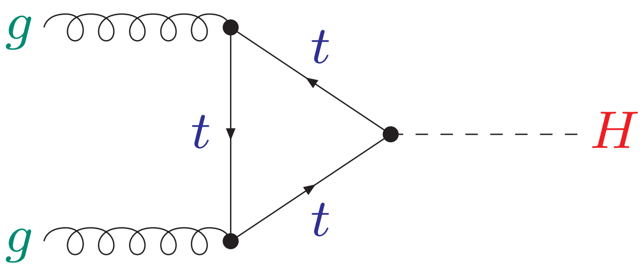


2. The SM Higgs boson at the LHC

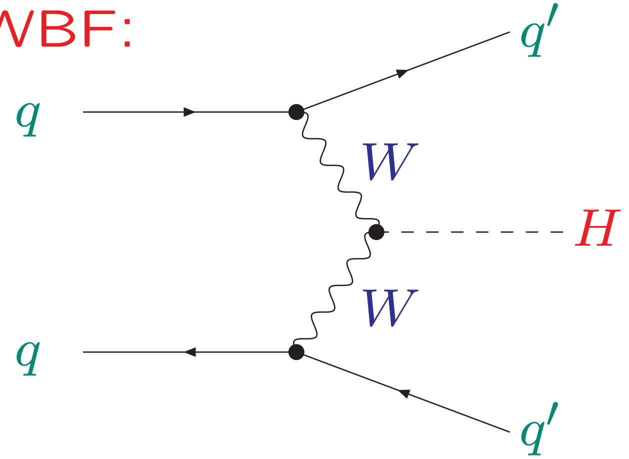
(SM) Higgs search at the LHC: (the minimum to remember)

Important SM production channel at the LHC:

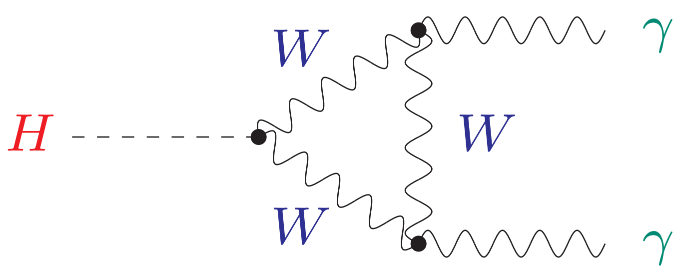
Gluon-Fusion:

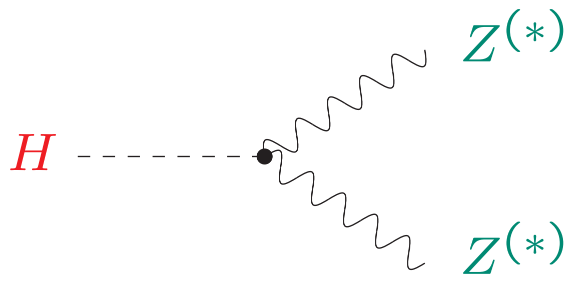


WBF:



Important decays for Higgs discovery/mass measurement:

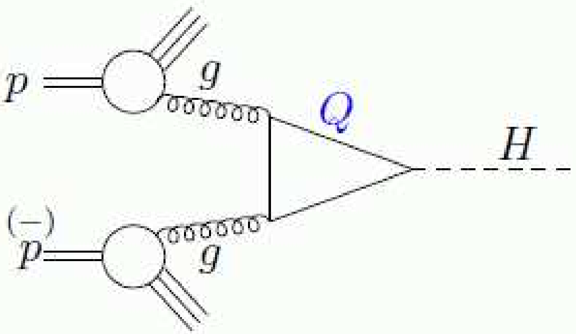




(SM) Higgs search at the LHC: Higgs production:

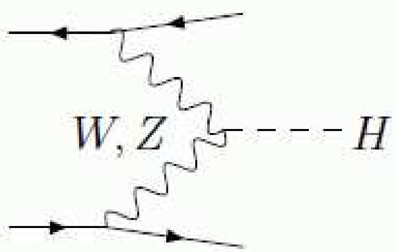
- **Gluon Gluon Fusion**

$pp \to gg \to H$



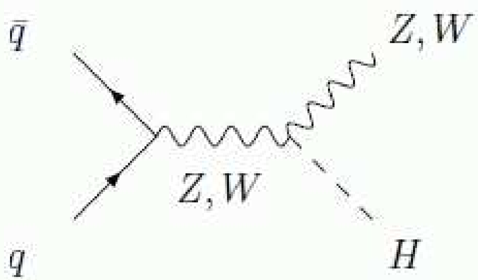
- **W/Z Fusion**

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



- **Higgs-strahlung**

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



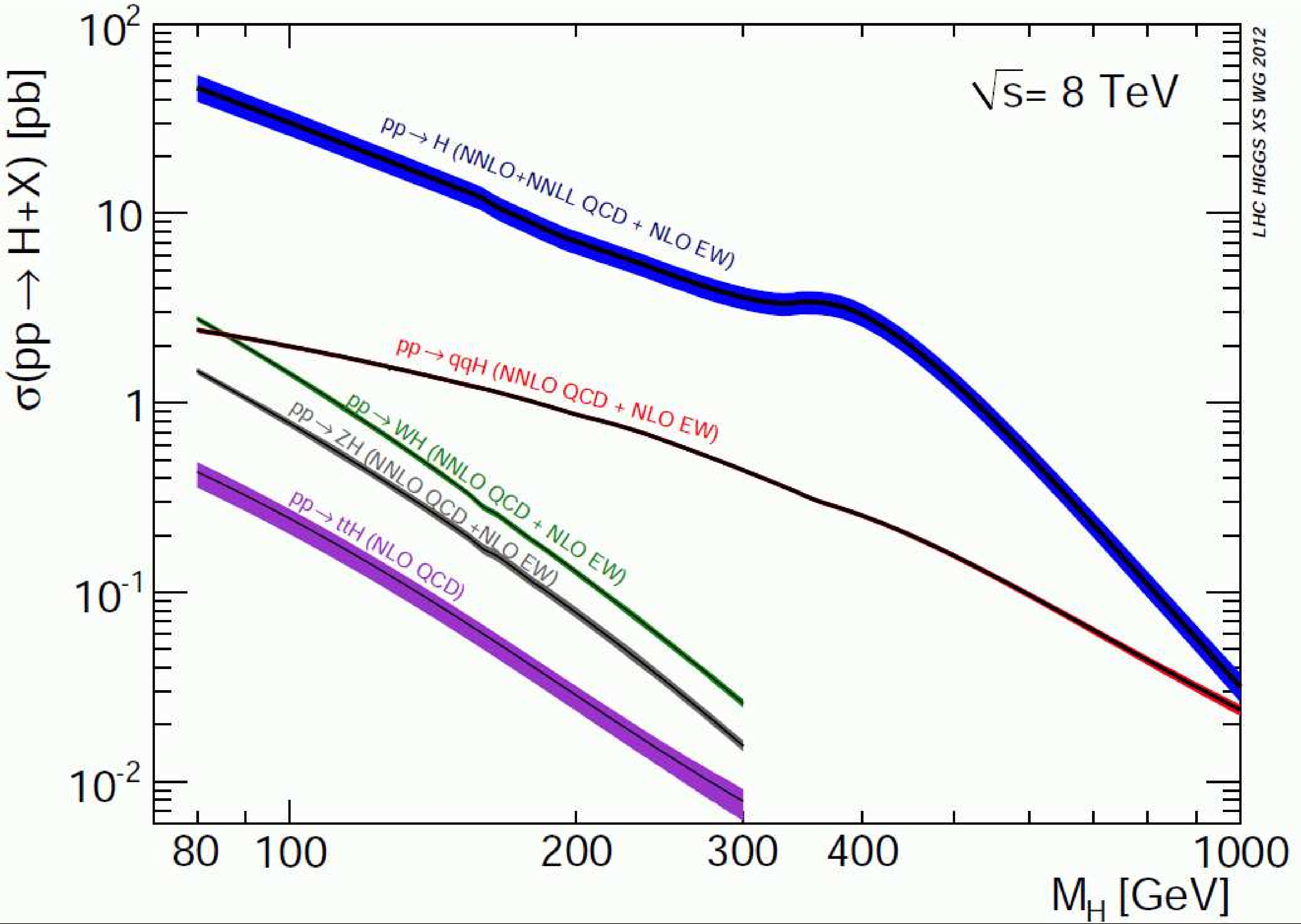
- **Associated production with $t\bar{t}$**

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

[taken from M. Mühlleitner]

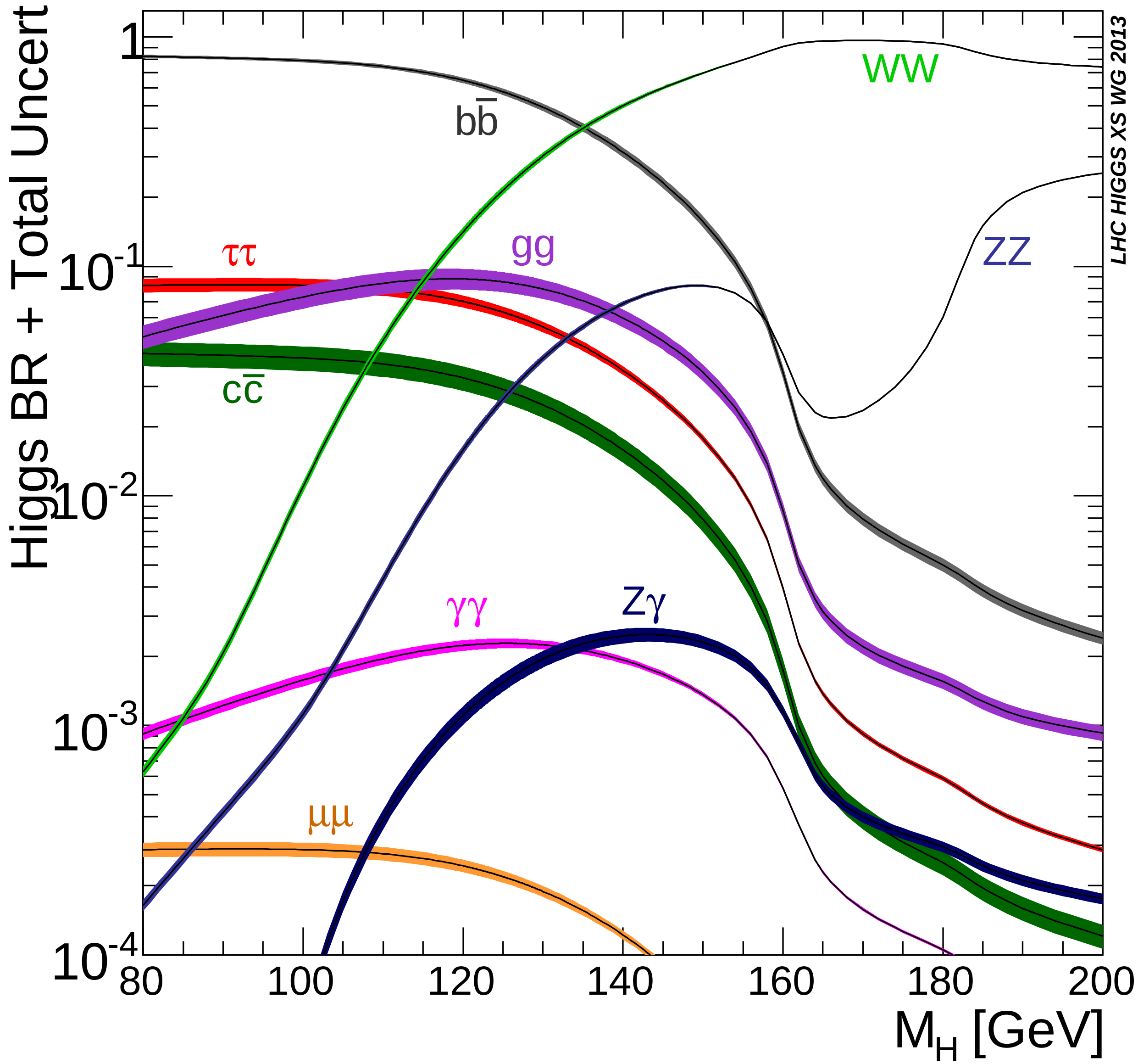
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '12*]



Latest theory predictions for the SM Higgs: branching ratios

[*LHC Higgs XS WG '13*]



Various possible "observables":

$\to$ normally given as a function of M_H

- Local p_0 value:

  probability that the observed signal/number of events is caused by "background only" (i.e. the SM without a Higgs)

- $\sigma_{\text{excl.}}/\sigma_{\text{SM}}$:

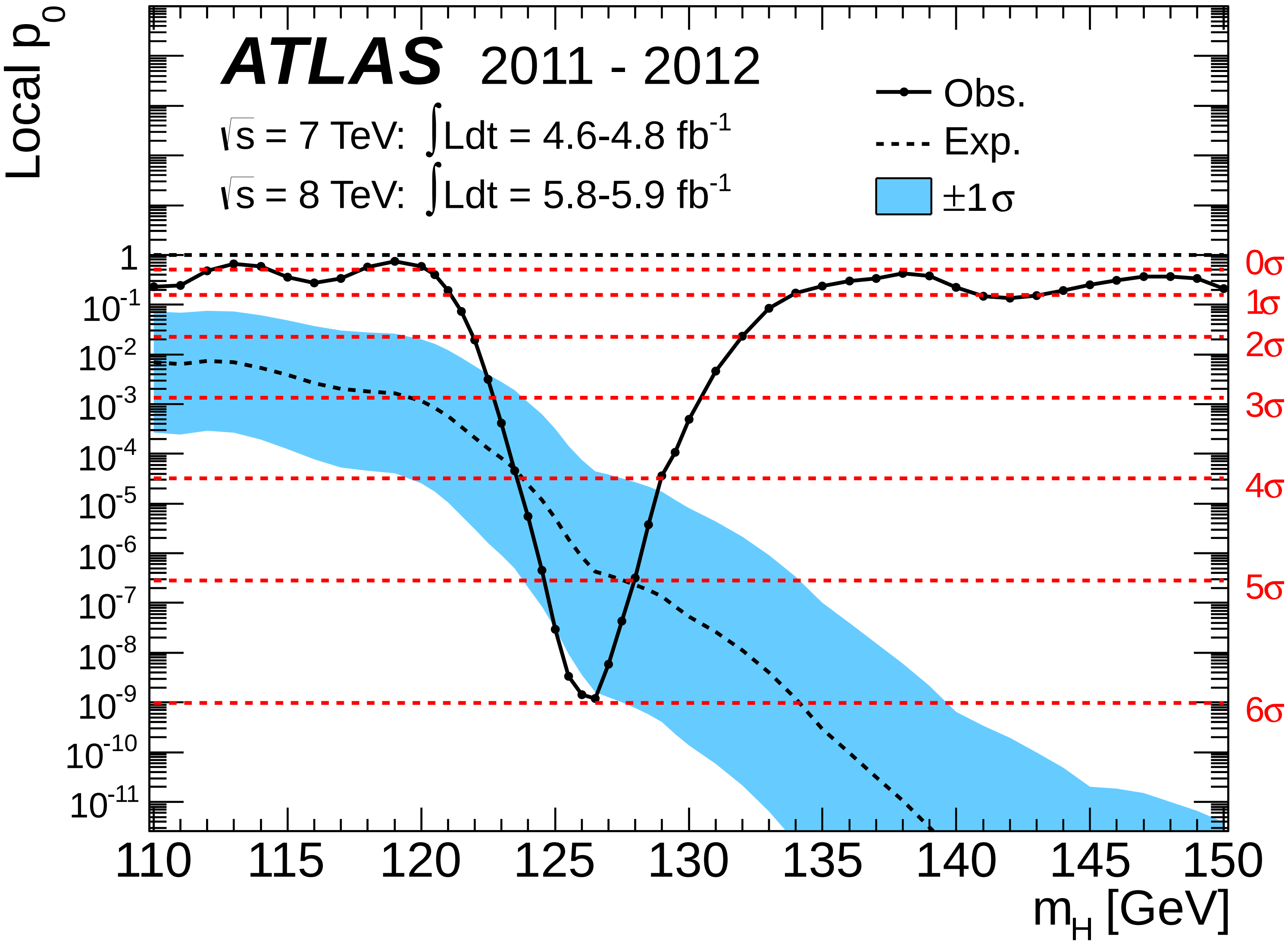
  excluded cross section divided by SM cross section:
  if for a certain M_H a cross section smaller than the SM cross section excluded, this M_H value is excluded, as it would have led to more events than observed.

- signal strength μ:

$$\mu := \frac{\sigma(pp \to H) \times \text{BR}(H \to dd')_{\text{observed}}}{\sigma(pp \to H) \times \text{BR}(H \to dd')_{\text{SM}}}$$

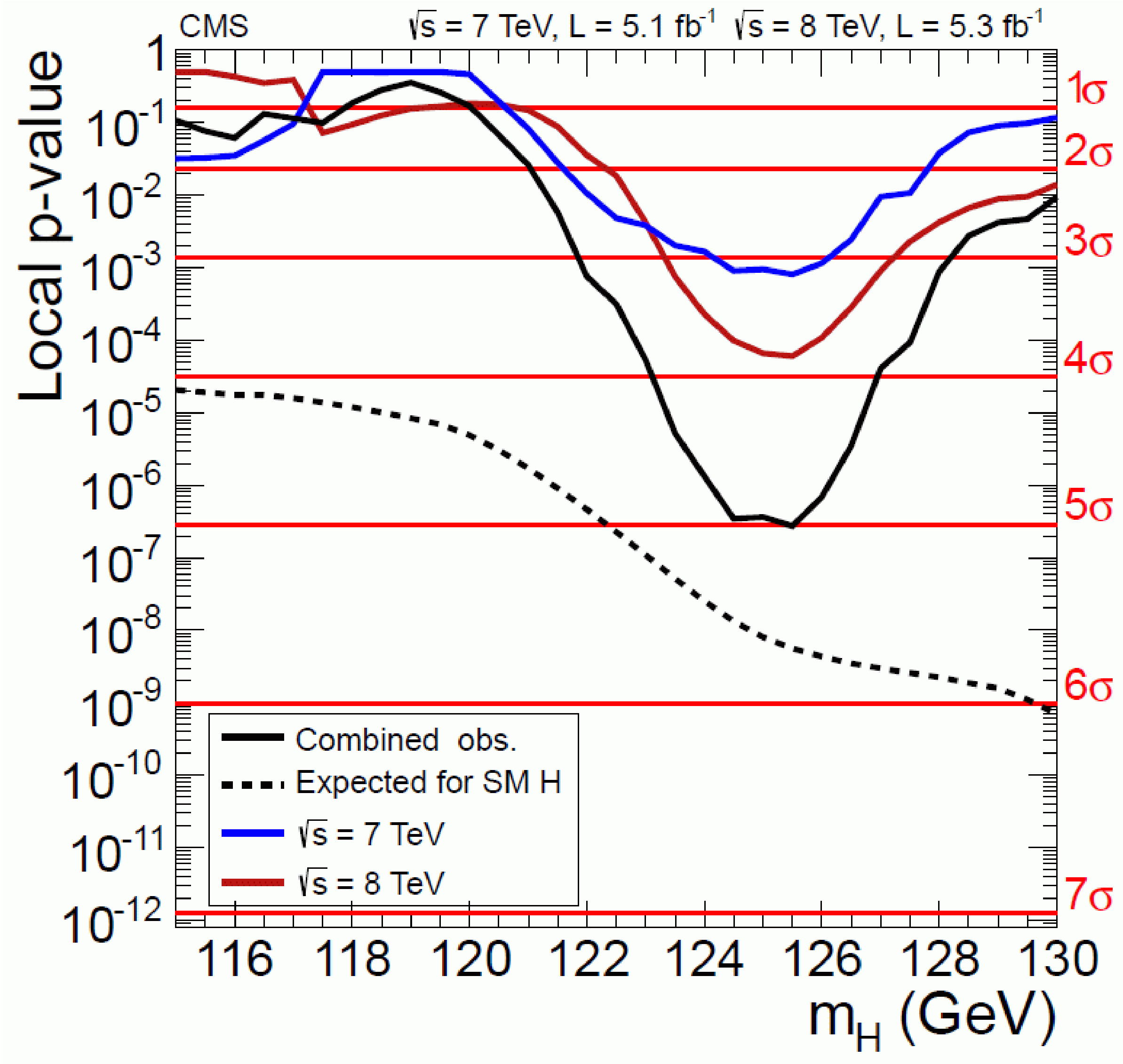
  should be "around 1" to find agreement with SM

04/07 ATLAS results in search for a SM Higgs: p_0 combined: [*ATLAS '12*]



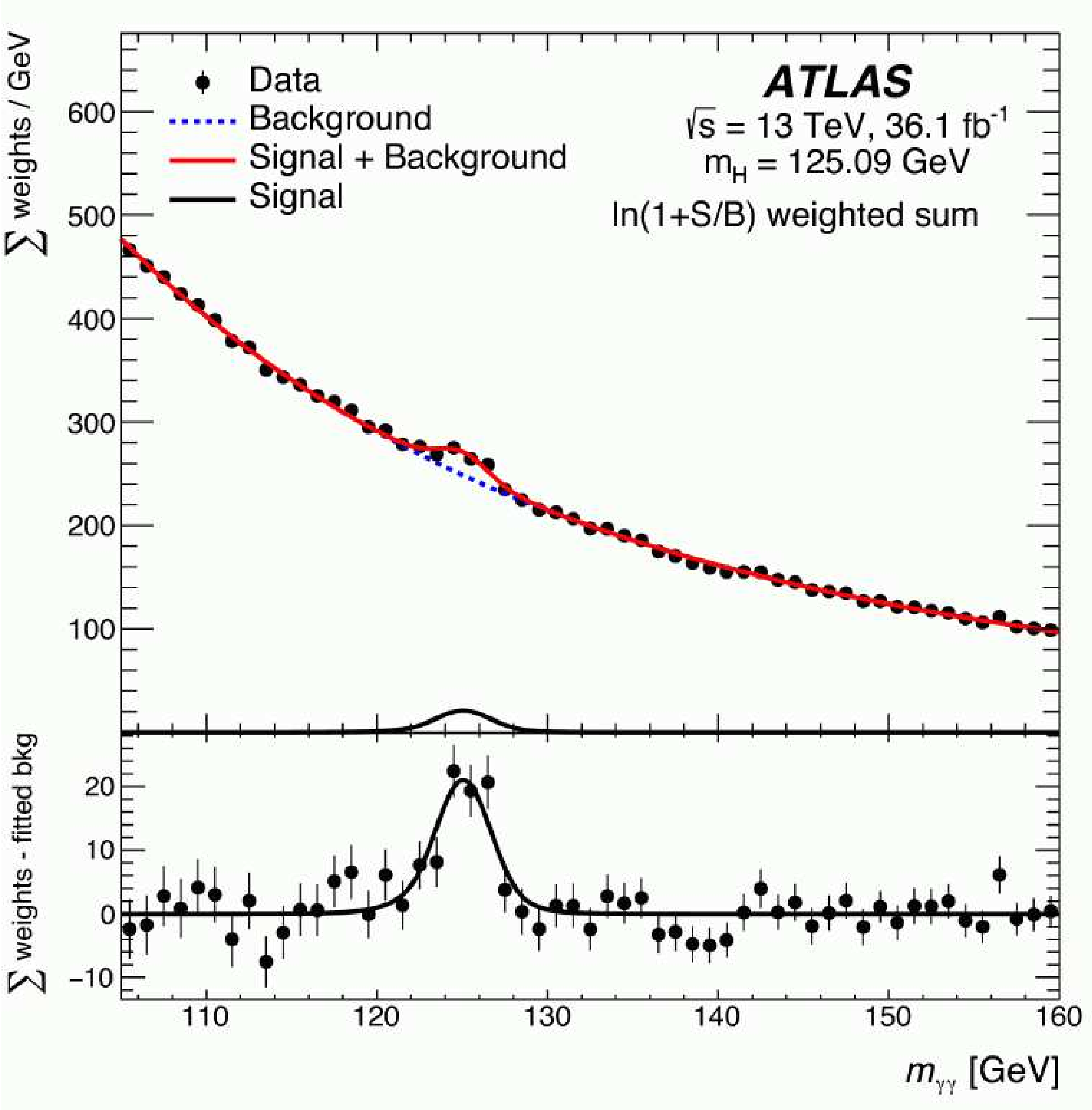
⇒ clear excesses for around $M_H \simeq 126.0$ GeV

04/07 CMS results in search for a SM Higgs: p_0 combined: [*CMS '12*]



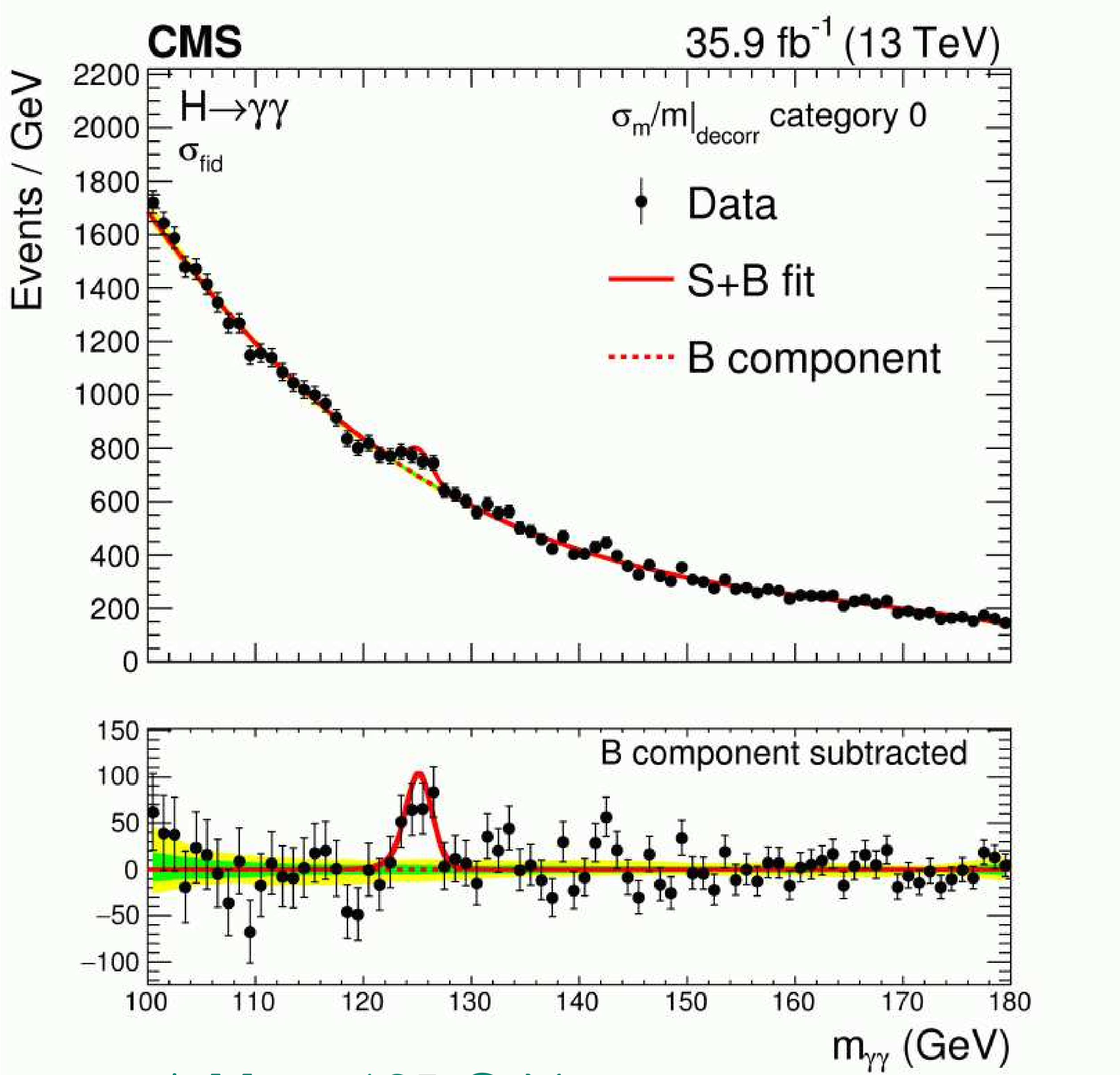
⇒ clear excesses for around $M_H \simeq 125.3$ GeV

ATLAS results in search for a SM Higgs in $\gamma\gamma$: [ATLAS '18]



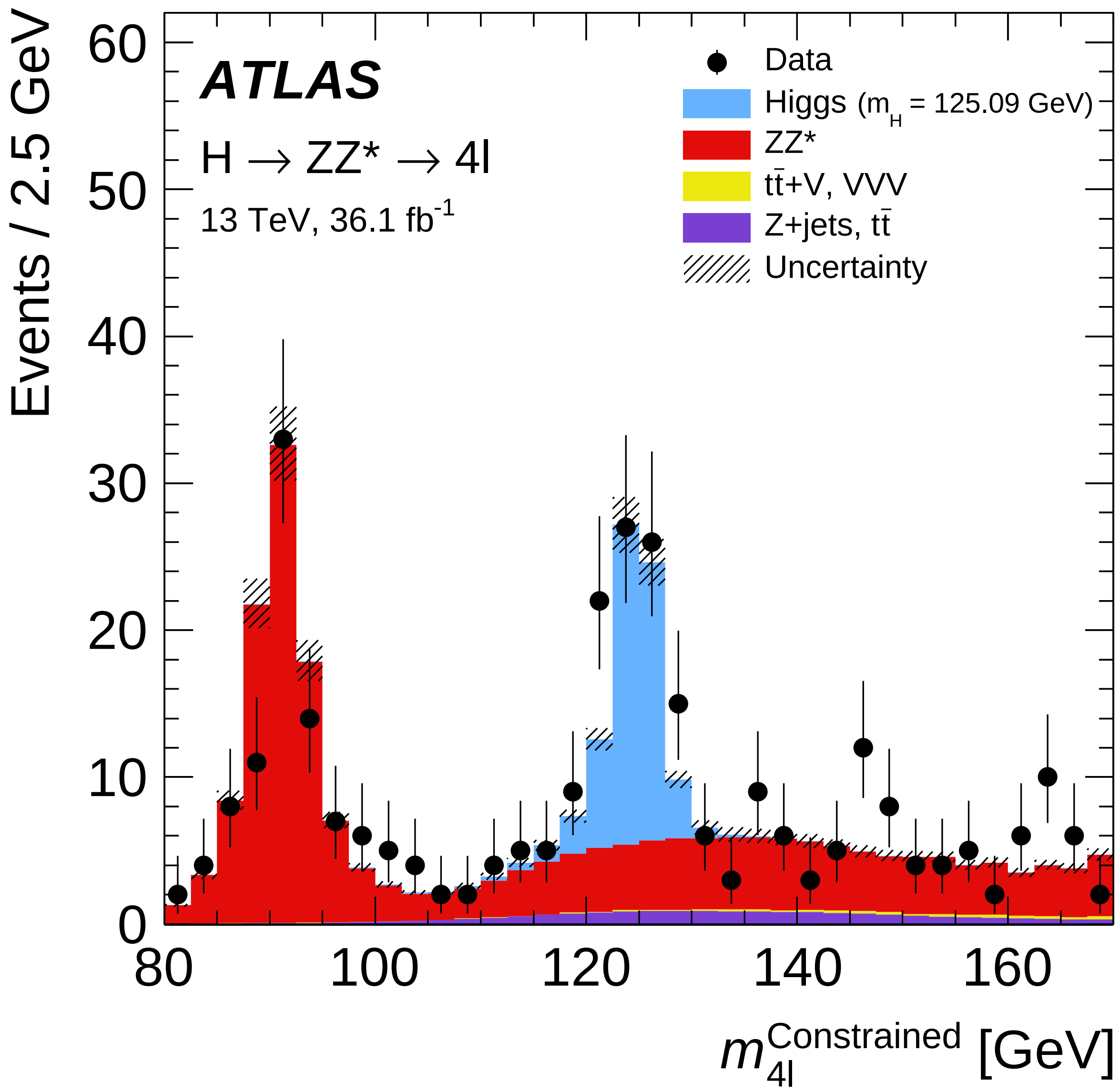
$\Rightarrow$ clear signal around $M_H \simeq 125.1$ GeV

CMS results in search for a SM Higgs in $\gamma\gamma$: [CMS '18]



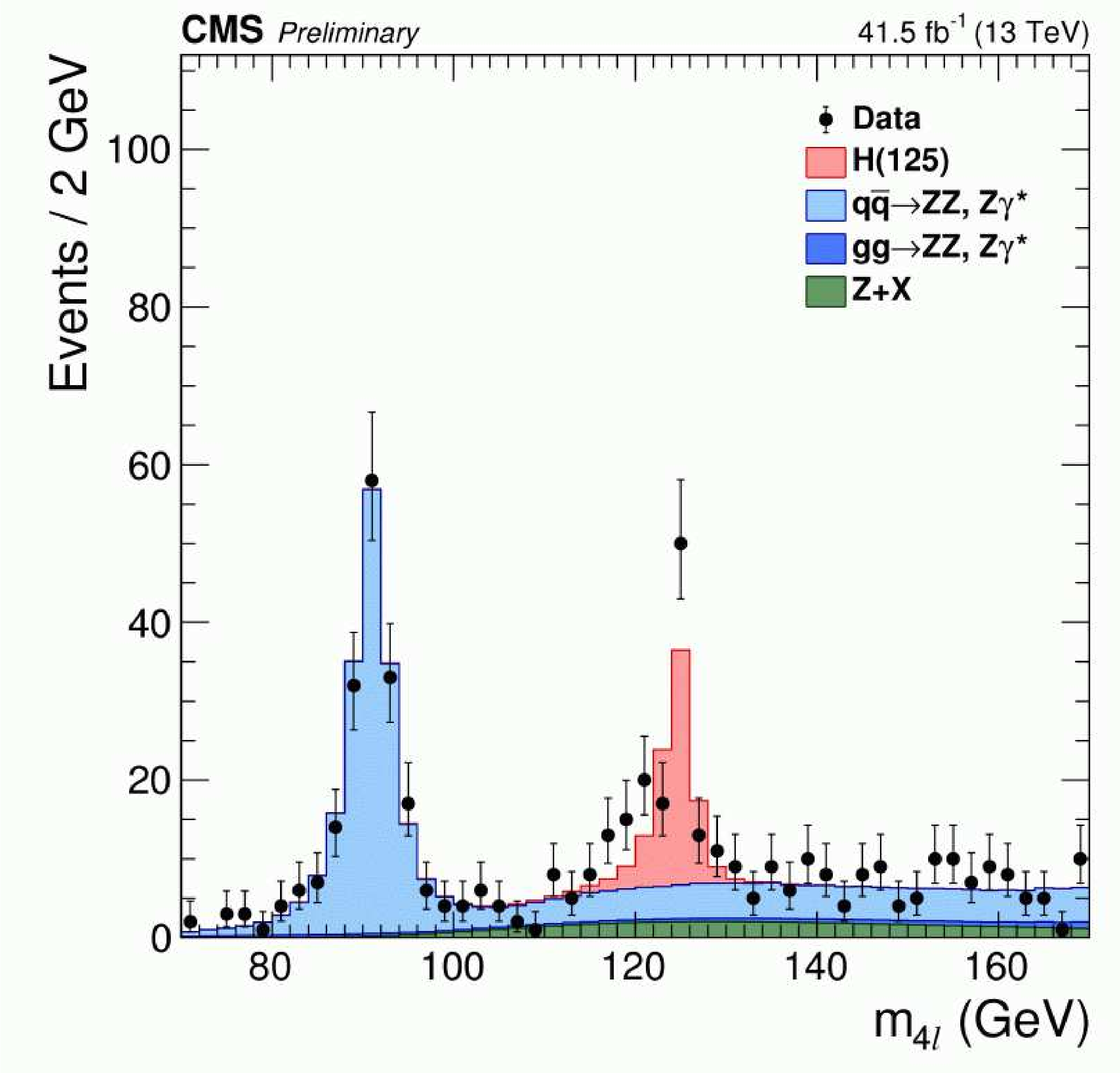
$\Rightarrow$ clear signal around $M_H \simeq 125$ GeV

ATLAS results in search for a SM Higgs in ZZ^*: [ATLAS '18]



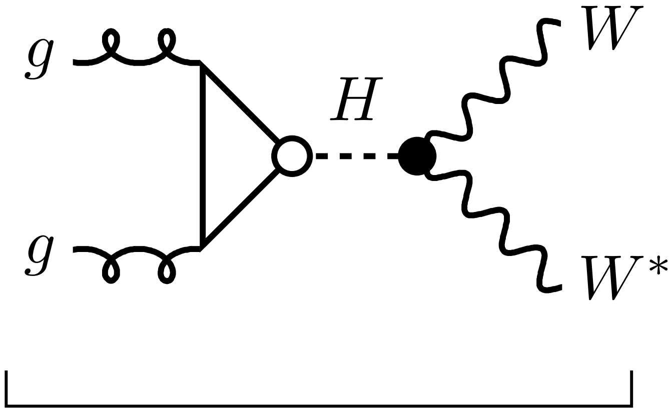
⇒ clear excesses for around $M_H \simeq 125$ GeV

CMS results in search for a SM Higgs in ZZ^*, 08/16: [CMS '18]

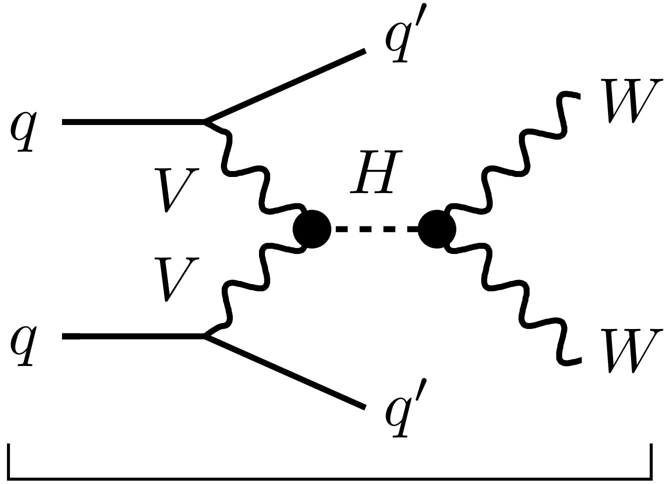


⇒ clear excesses for around $M_H \simeq 125$ GeV

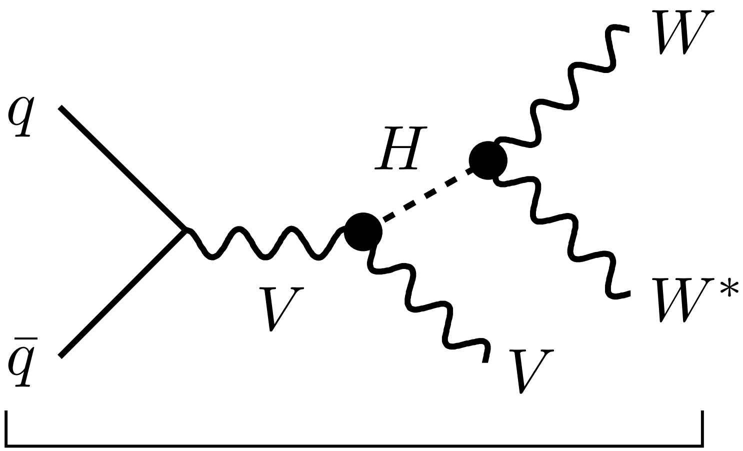
Other channels: $H \to WW^*$



ggF production



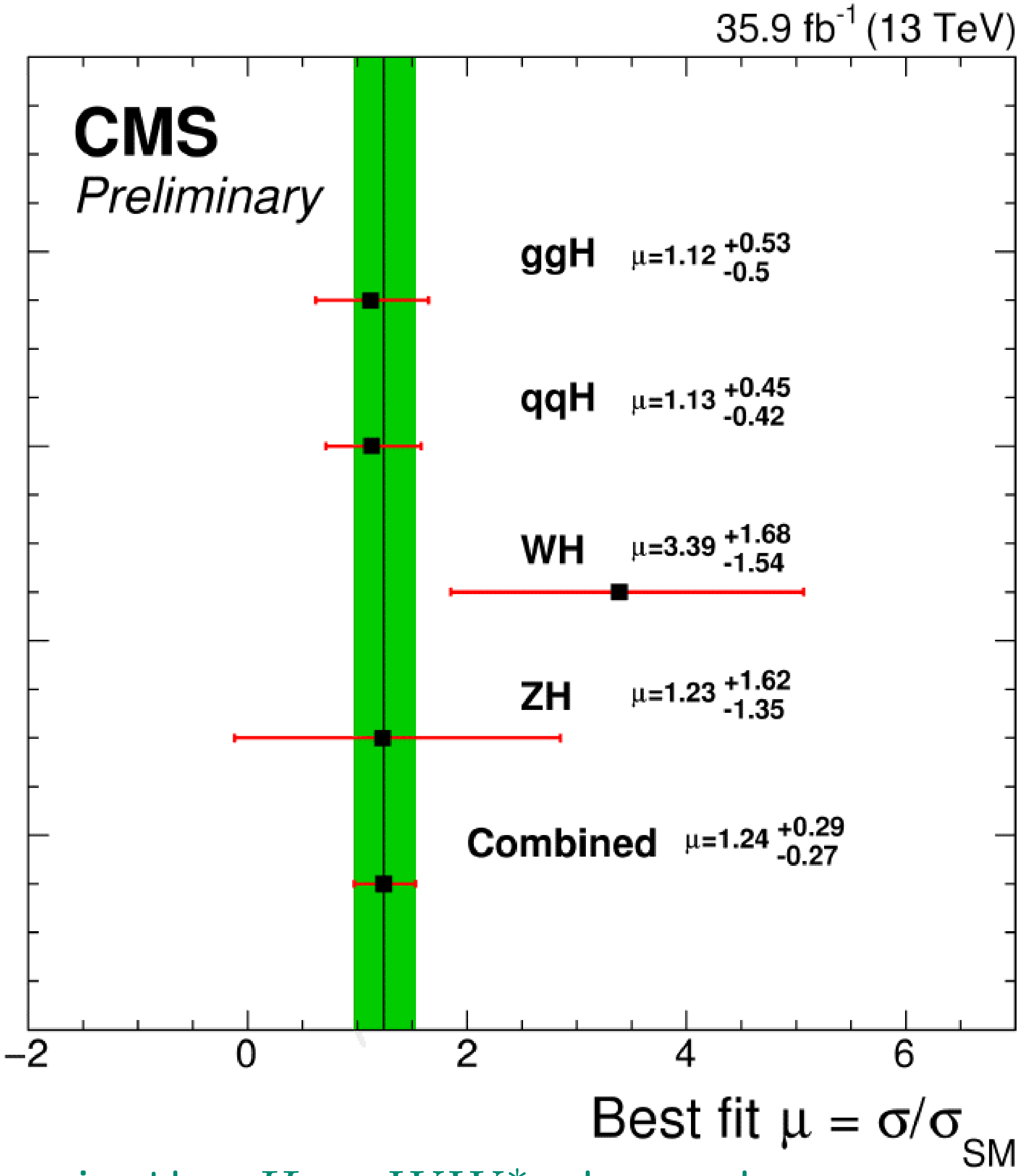
VBF production



VH production

Other channels: $H \to WW^*$

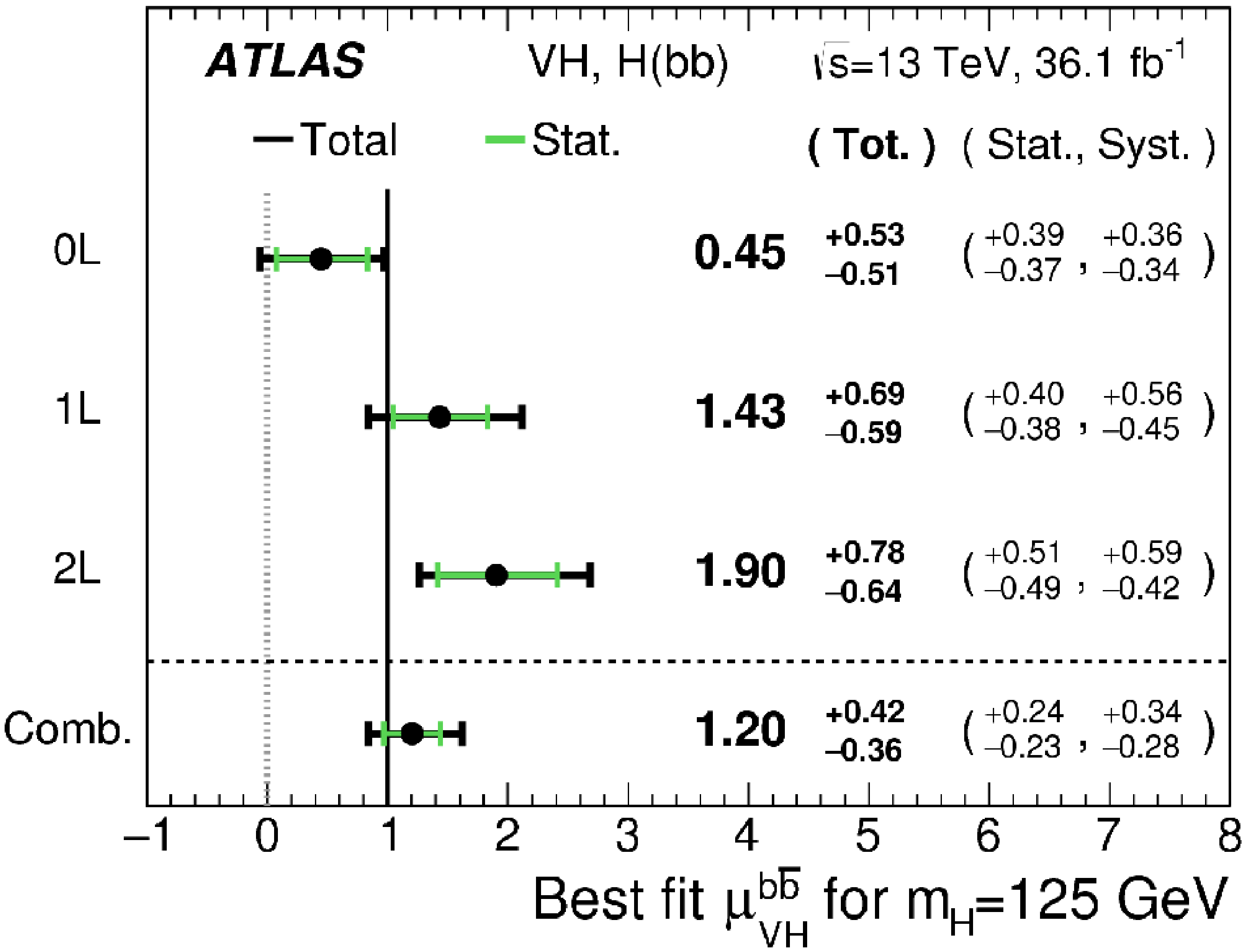
[CMS '18]



$\Rightarrow$ strong confirmation in the $H \to WW^*$ channel

Other channels: $H \to b\bar{b}$

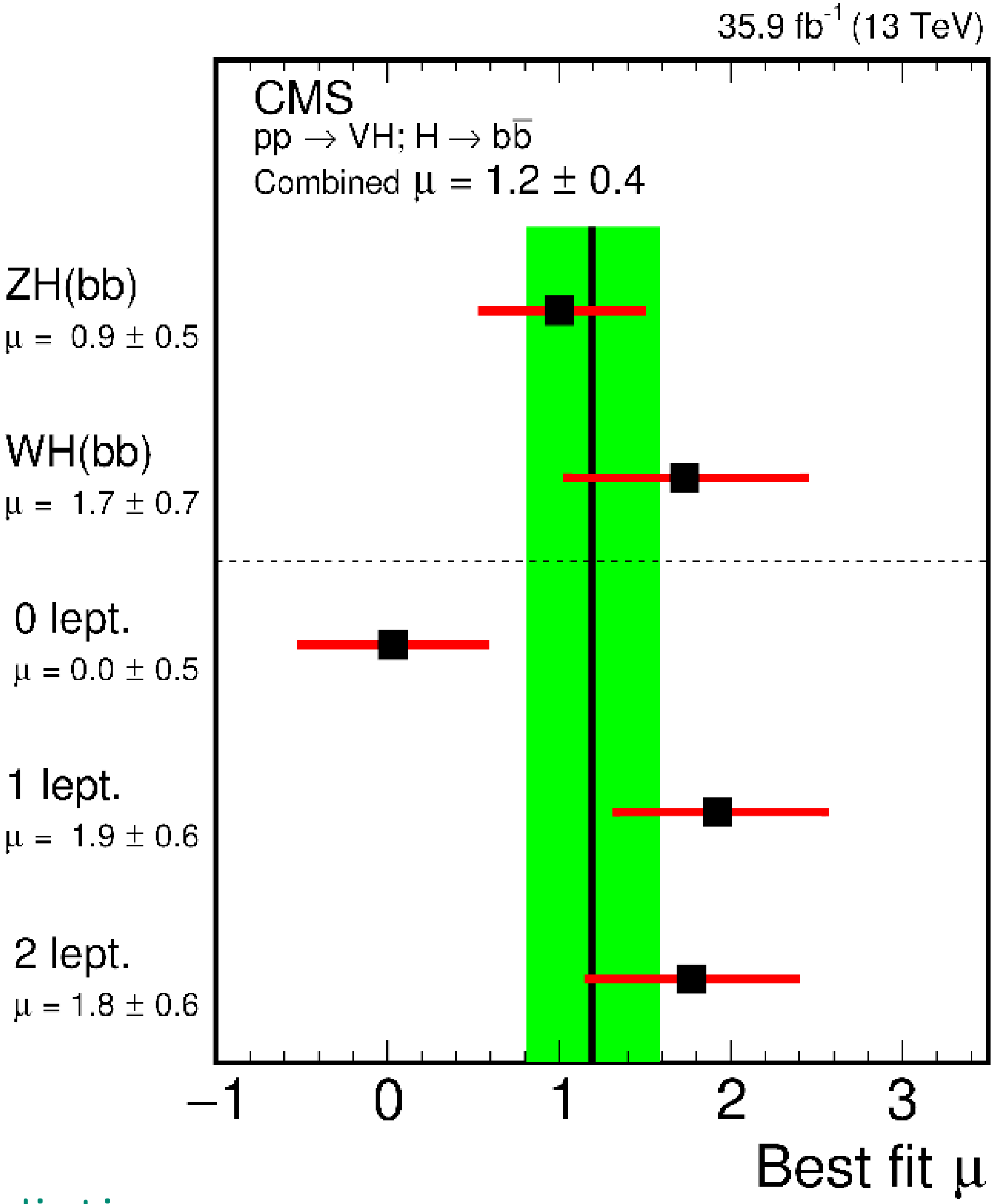
[ATLAS '18]



⇒ close to SM predictions

Other channels: $H \to b\bar{b}$

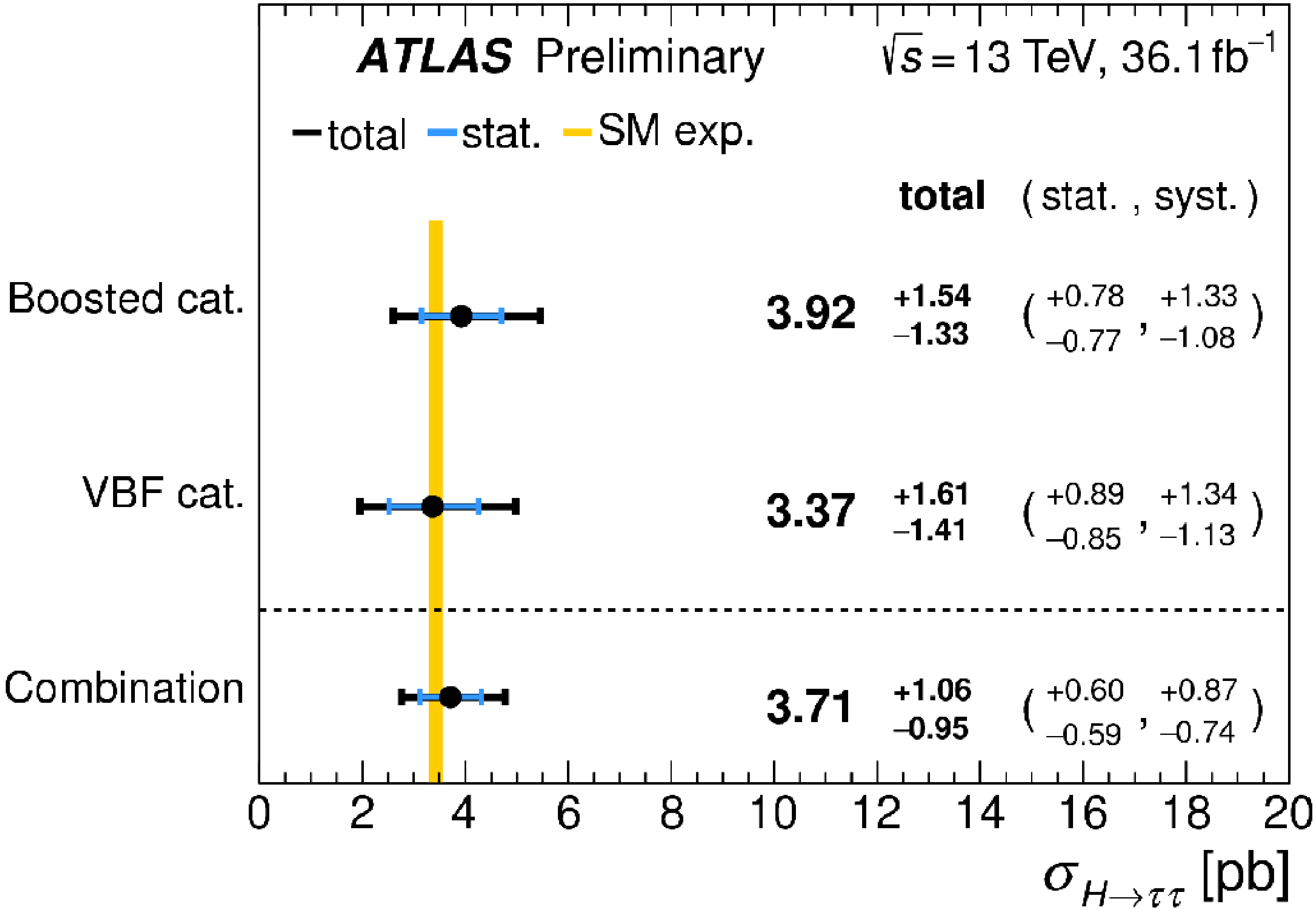
[*CMS '18*]



$\Rightarrow$ close to SM predictions

Other channels: $H \to \tau^+\tau^-$

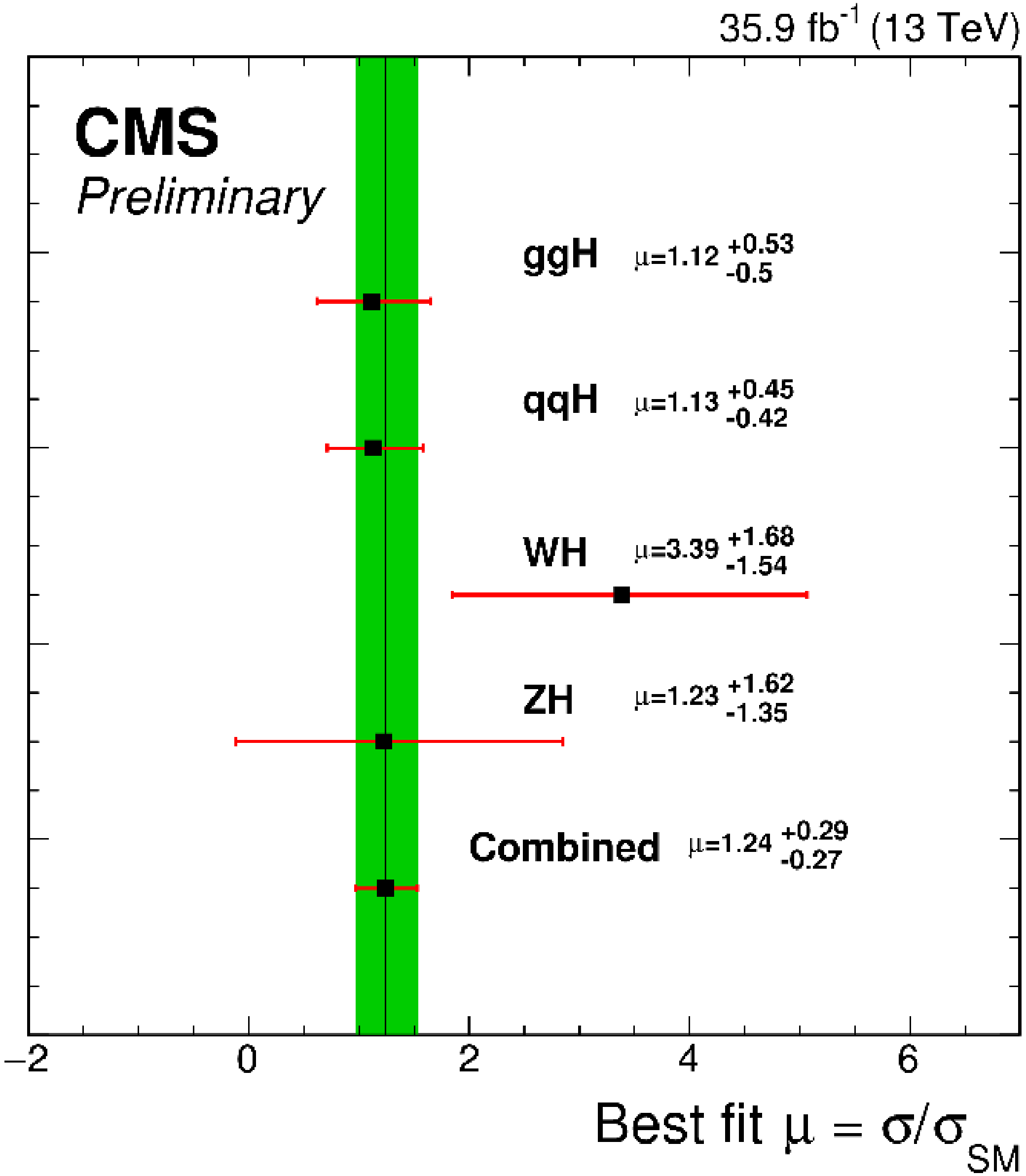
[*ATLAS '18*]



$\Rightarrow$ well compatible with SM prediction

Other channels: $H \to \tau^+\tau^-$

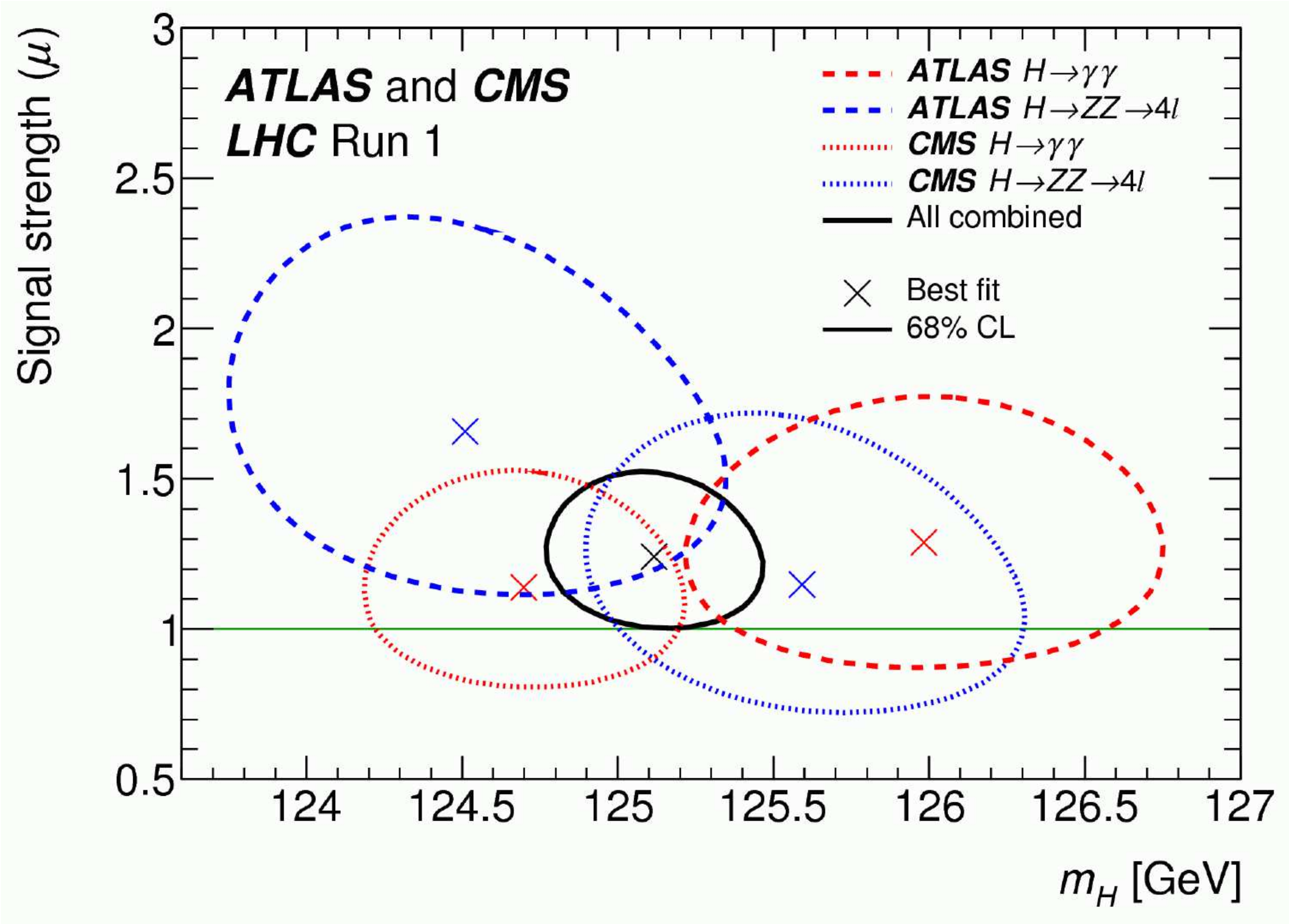
[*CMS '18*]



$\Rightarrow$ well compatible with SM prediction

Mass measurement, combination of $\gamma\gamma$ and ZZ^*:

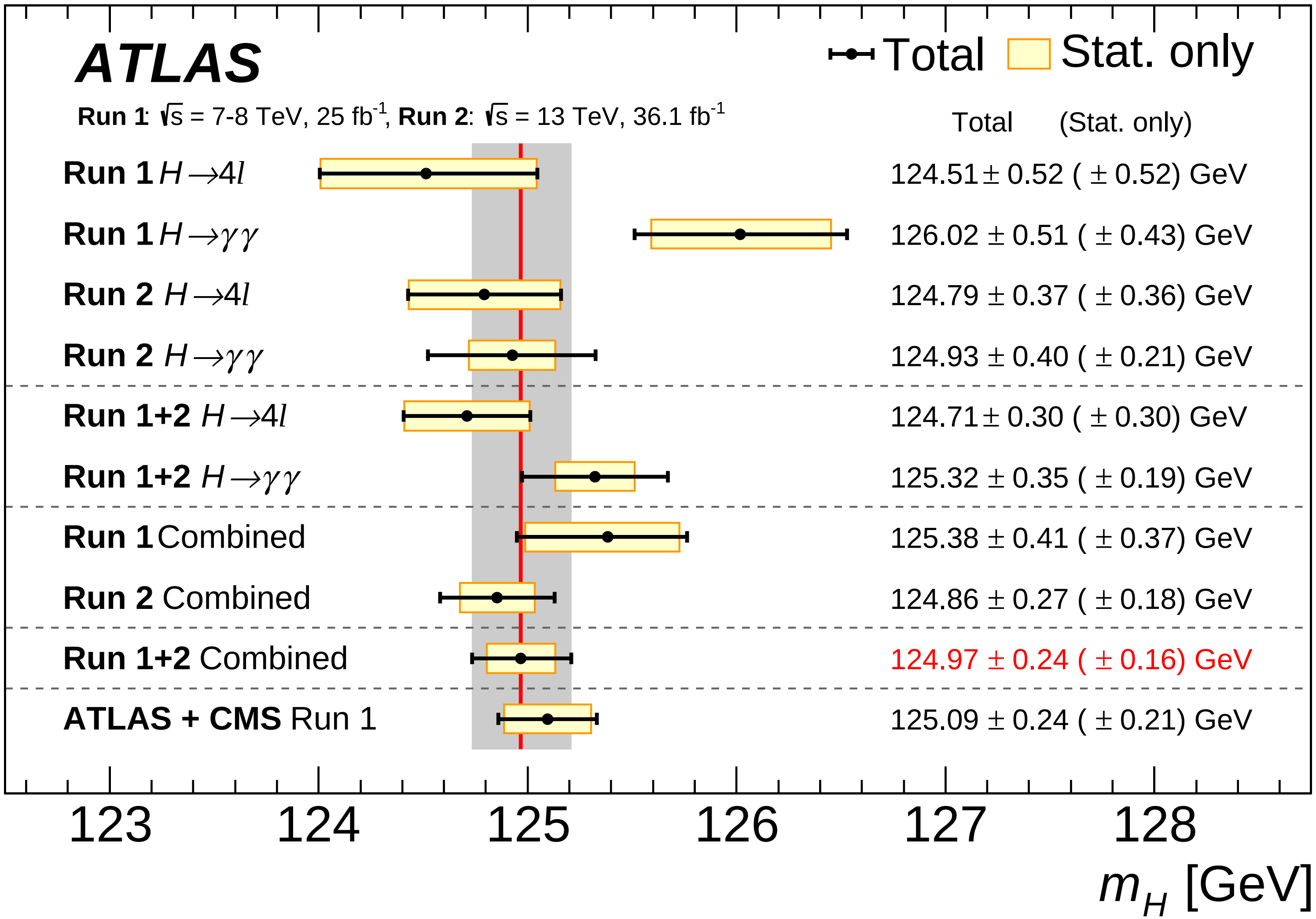
[*ATLAS, CMS '15*]



⇒ permille level "first" combination

Latest mass measurement in $\gamma\gamma$ and ZZ^*:

[ATLAS, CMS '18]



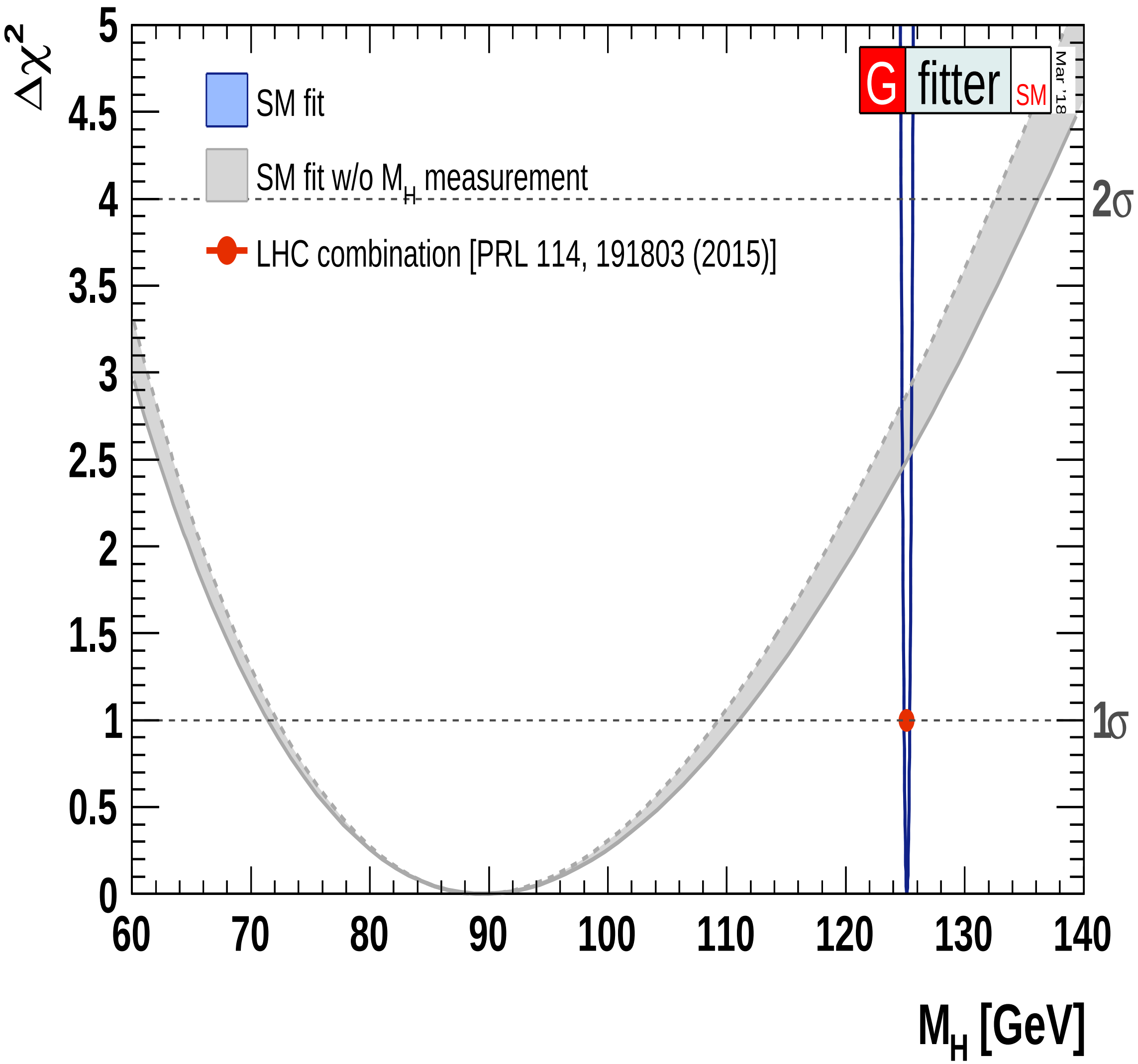
$\Rightarrow$ newer measurements confirm first combination

Comparison to SM prediction:

[*GFitter '18*]

$\Rightarrow M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Observed Higgs well compatible with SM prediction (at $1.8\,\sigma$)

LHC Higgs Cross Section Working Group: Low Mass (LM) subgroup:

Assumptions (for Run I data):

1. Signal corresponds to only one state, no overlapping signal etc.

2. Zero-width approximation

3. Only modification of coupling strength (absolute values of couplings) but not of tensore structure wrt. to SM

Recommendations (for Run I data):

1. Use state-of-the-art predictions in the SM and rescale the predictions with "leading order inspired" scale factors κ_i
($\kappa_i = 1$ corresponds to the SM case)

2. Most general case: κ_W, κ_Z, κ_t, κ_b, κ_τ, ... $\oplus$ extra loop contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$, $\Gamma_{H,\text{tot}}$

3. benchmarks:
   - one parameter: overall signal strength $\kappa^2 \equiv \mu$
   - two parameters: $\kappa_V := \kappa_W = \kappa_Z$, $\kappa_F := \kappa_t = \kappa_b = \kappa_\tau = \ldots$
   - ...

Recommendations continued:

Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions. (This is not a recommendation, but a fact!)

For each benchmark (except overall coupling strength) two versions are proposed:
with and without taking into account the possibility of additional contributions to the total width

1) additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

⇒ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

2) additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

but assume that all additional decays are "invisible" with MET

⇒ Determination of κ_i

3) additional contributions to $\Gamma_{H,\text{tot}}$ are allowed:

but assume that $\kappa_{W,Z} \leq 1$ (fulfilled for Higgs-singlets, -doublets)

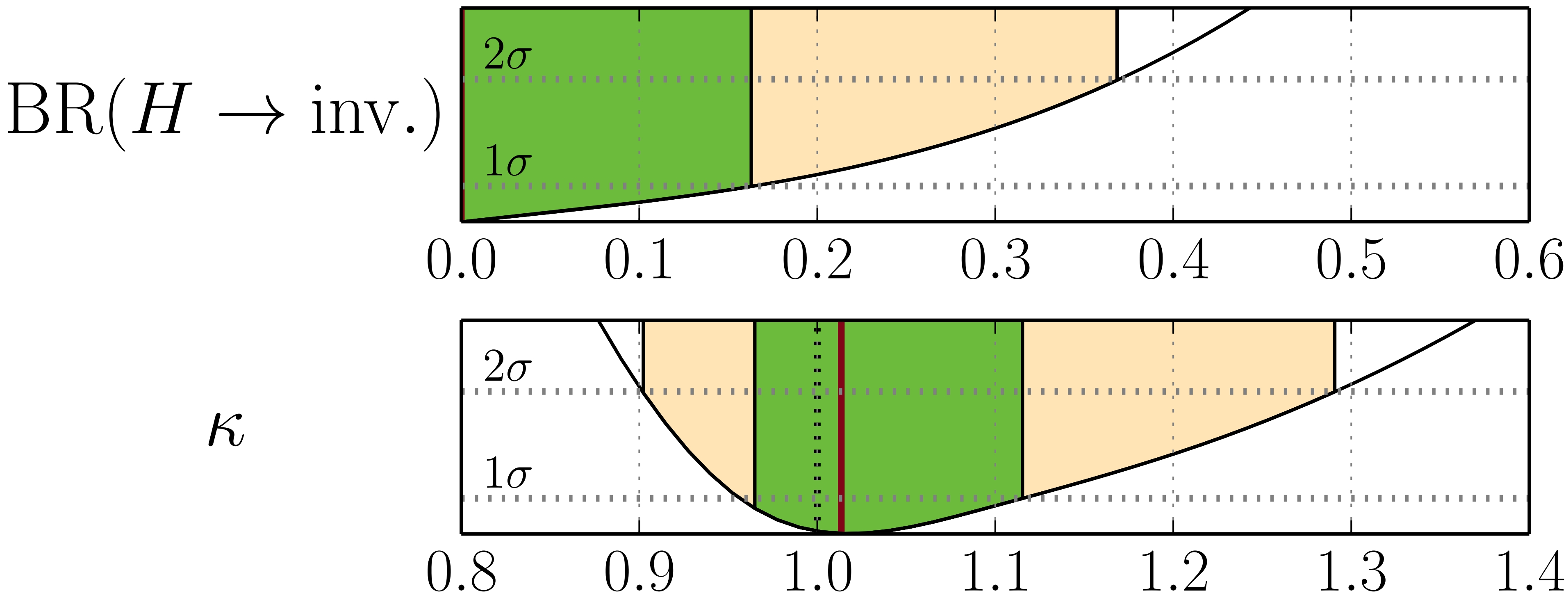
⇒ Determination of κ_i

4) no additional contributions to $\Gamma_{H,\text{tot}}$ are allowed: ⇒ Determination of κ_i

Coupling scale factor results (I):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

Simplest model: $\kappa, \mathrm{BR}(H \to \mathrm{inv.})$



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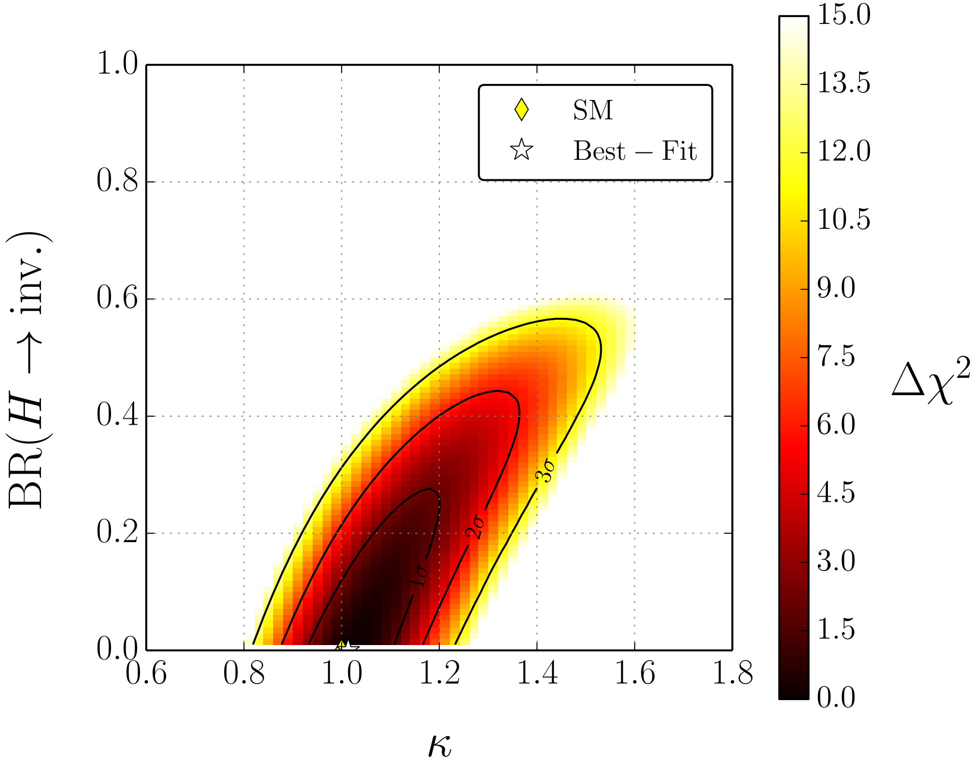
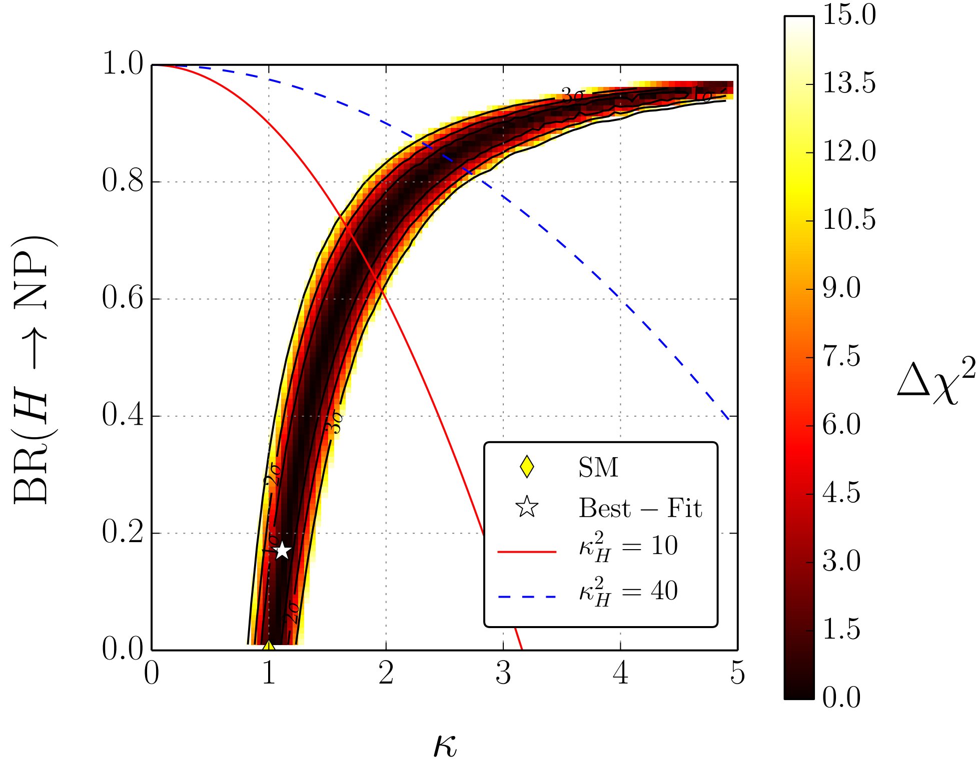
Simplest model: κ, BR$(H \to$ inv.$)$

$\text{BR}(H \to \text{NP}) = \text{BR}(H \to \text{inv.})$



no assumptions

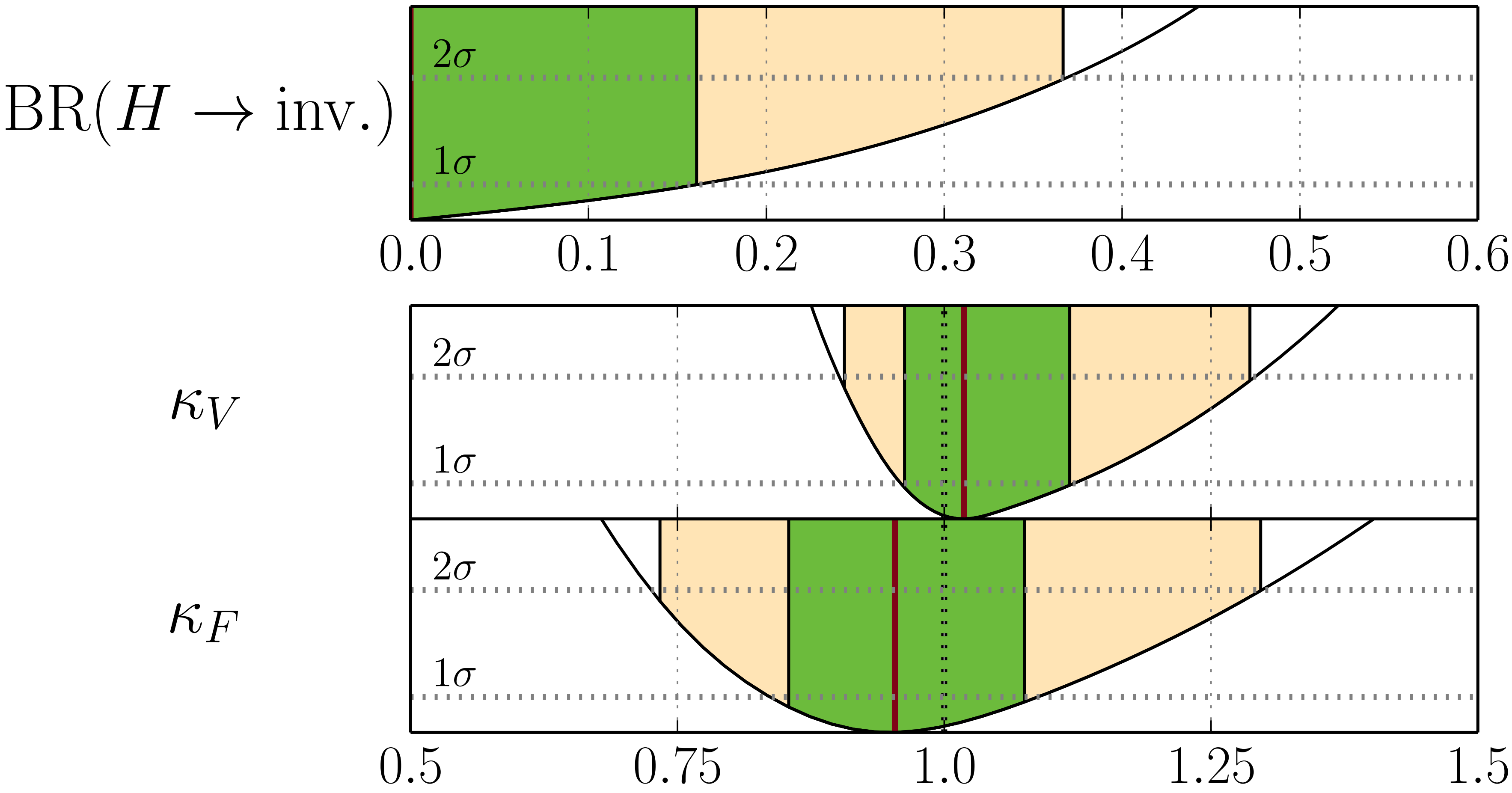


$\Rightarrow$ no theory assumptions on $\Gamma_{H,\text{tot}}$: no limits on κ

Coupling scale factor results (II):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

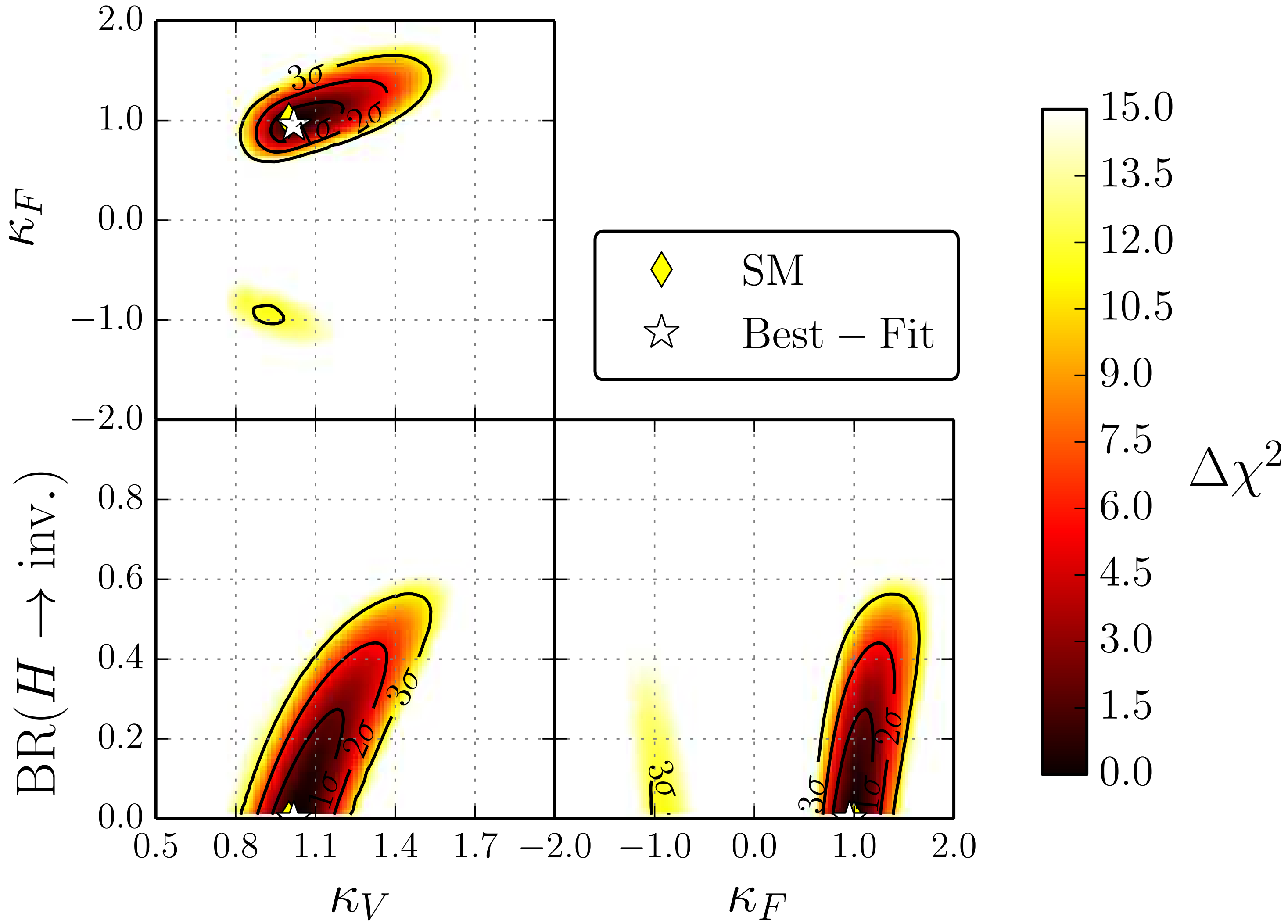
Another simple model: κ_V, κ_F, BR($H \to$ inv.)



Coupling scale factor results (II):

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I]

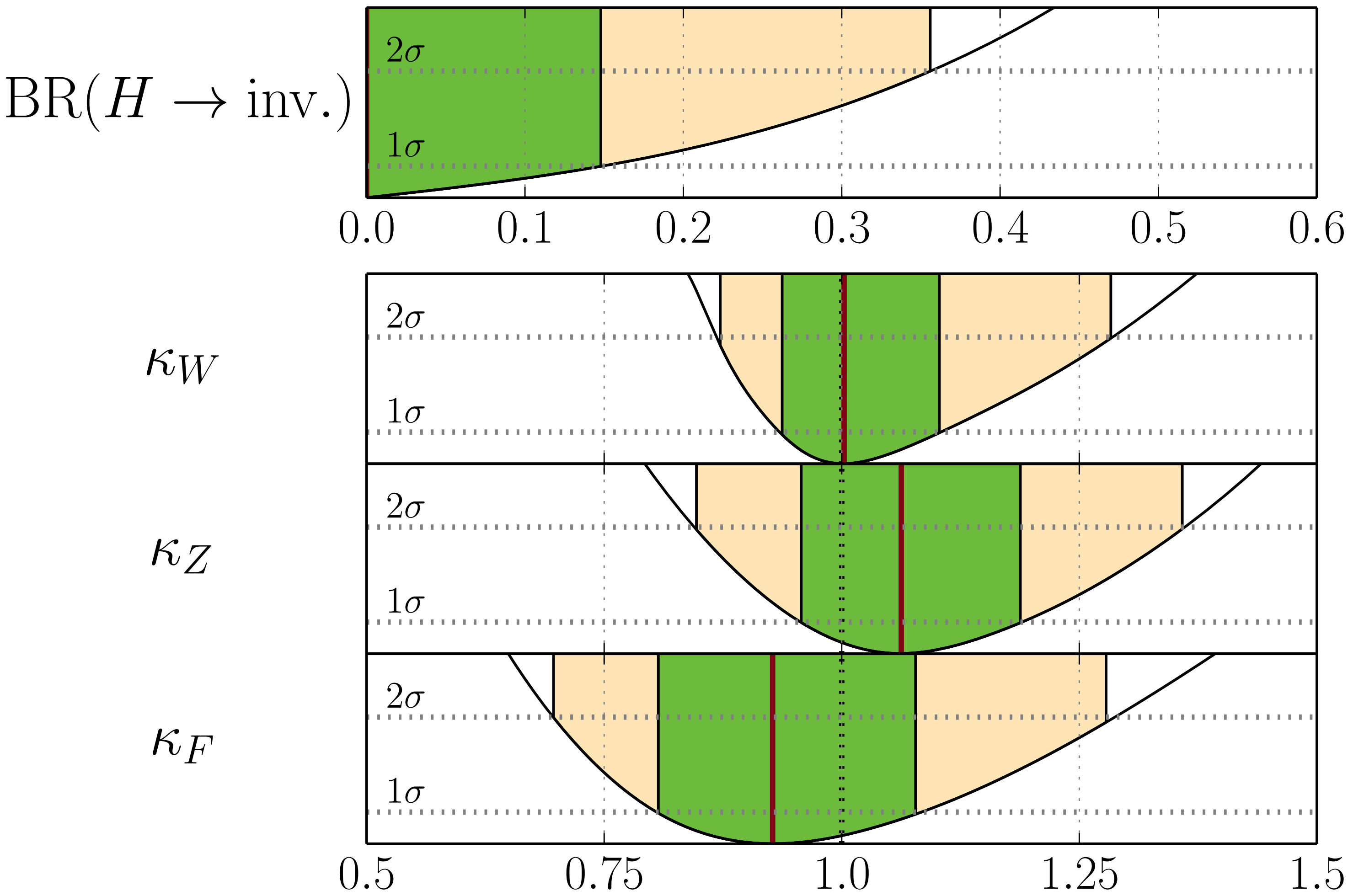
Another simple model: $\kappa_V, \kappa_F, \mathrm{BR}(H \to \mathrm{inv.})$



Coupling scale factor results (III):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

Probing the custodial symmetry: $\kappa_W, \kappa_Z, \kappa_F, \mathrm{BR}(H \to \mathrm{inv.})$



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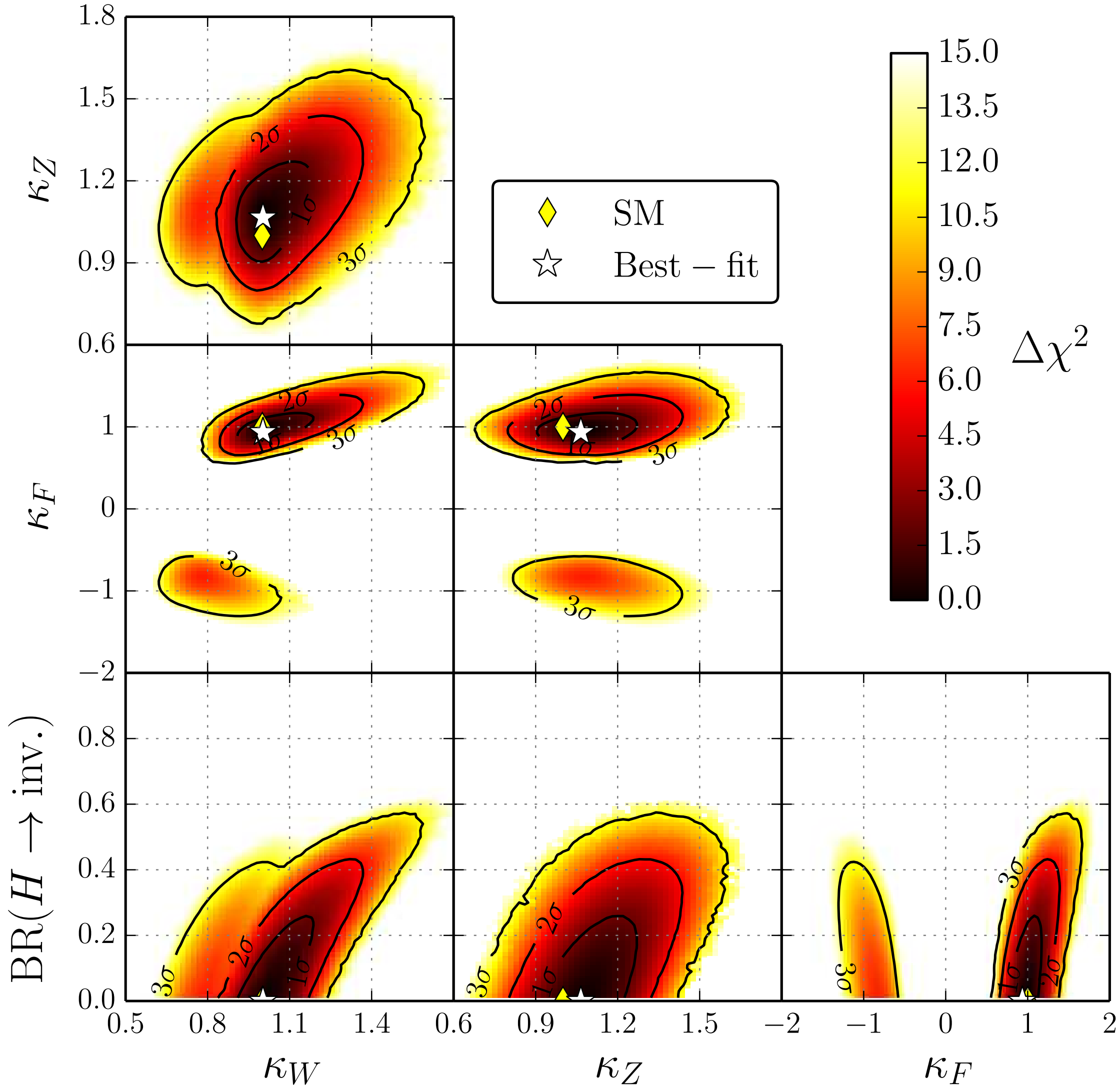
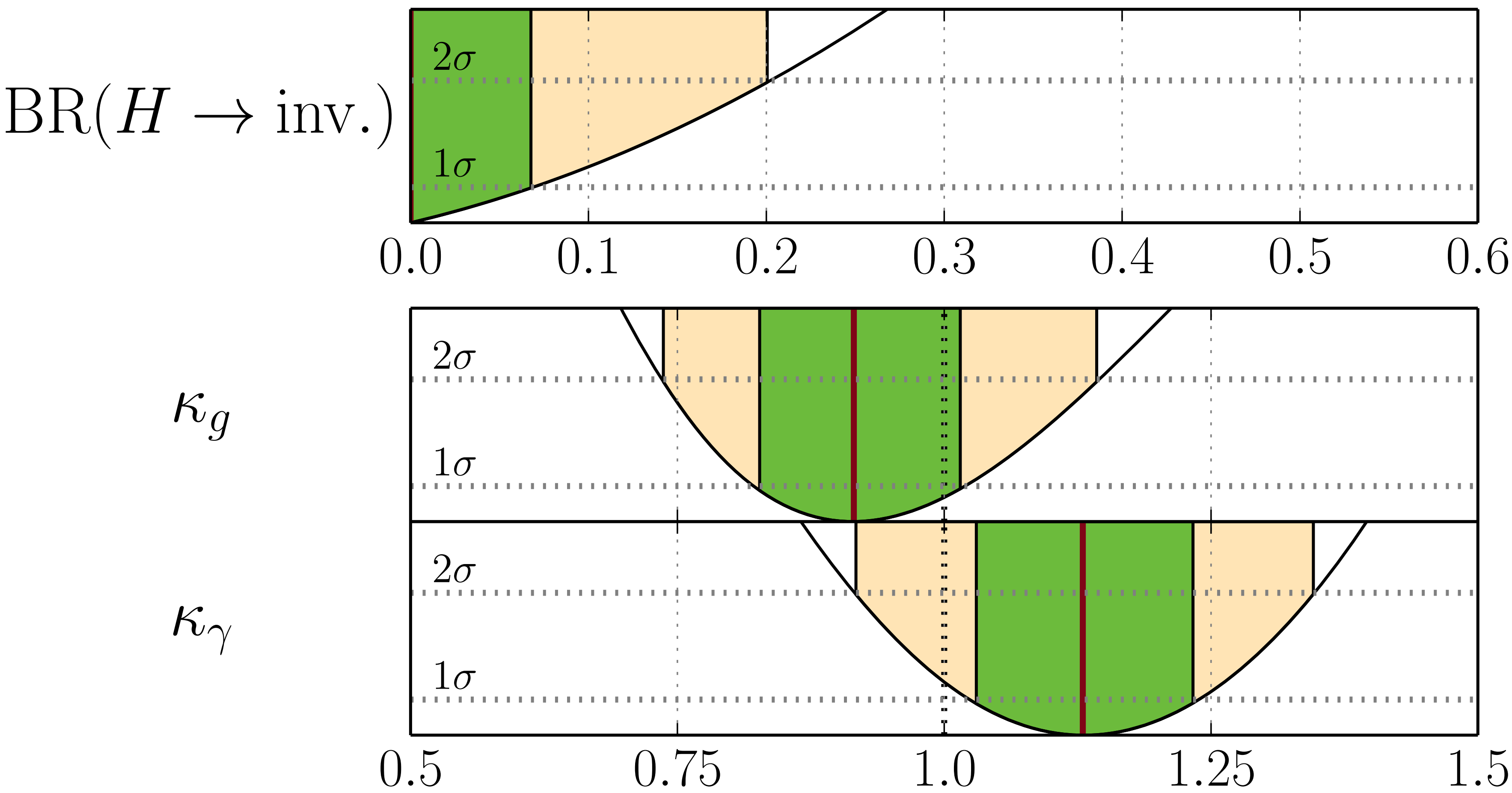


Coupling scale factor results (IV):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

New physics in loop-induced couplings: $\kappa_g, \kappa_\gamma, \text{BR}(H \to \text{inv.})$



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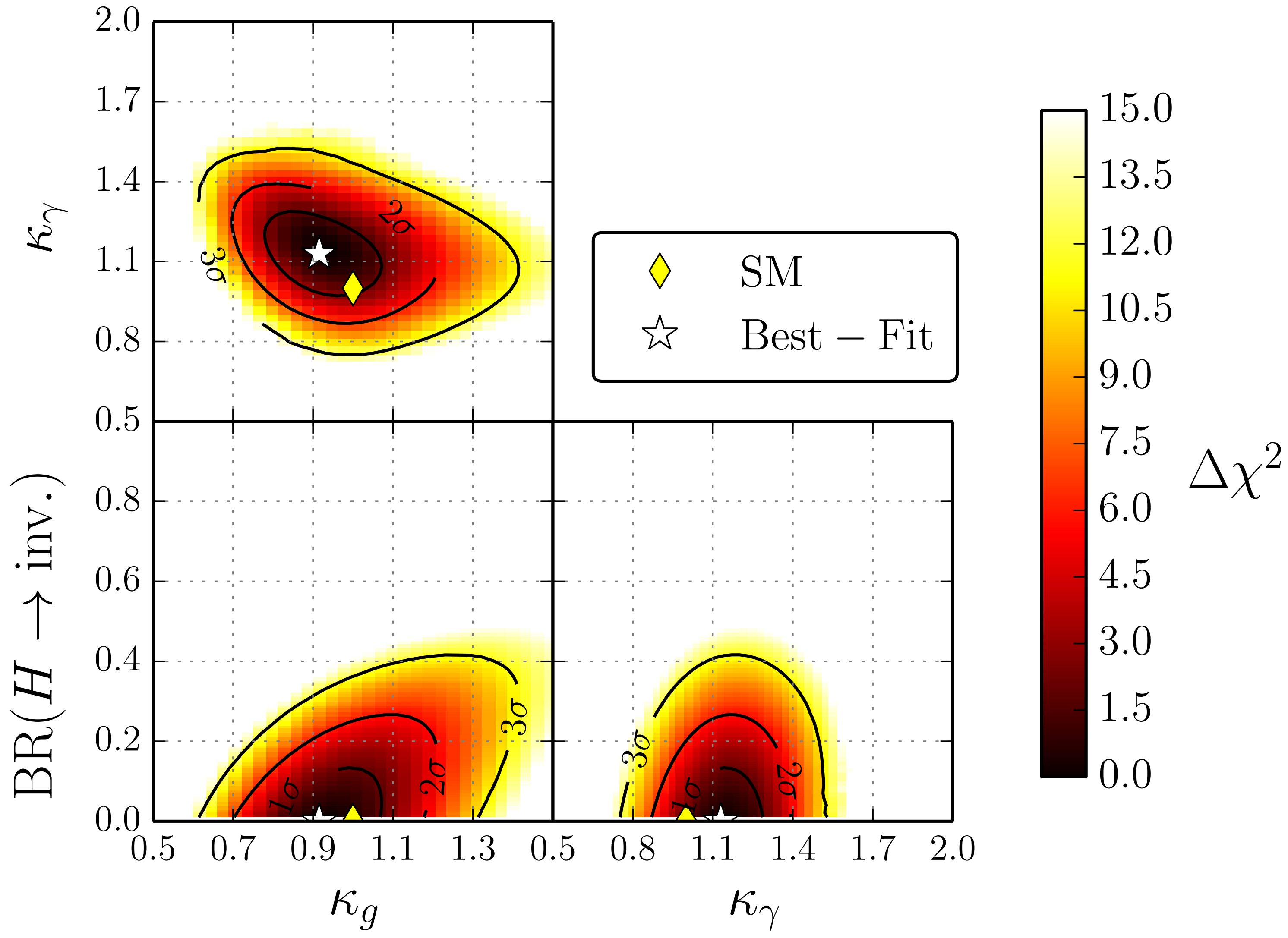
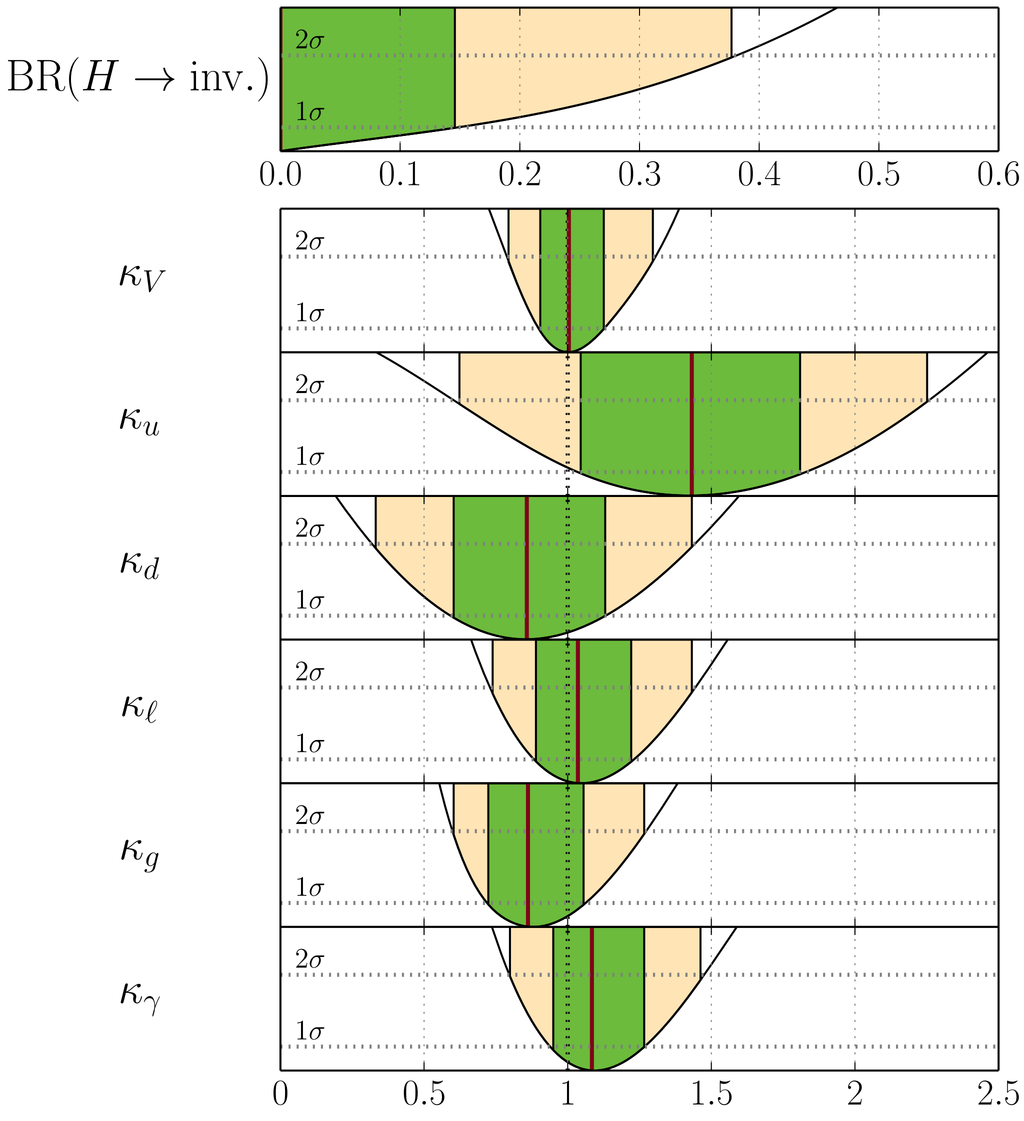


Coupling scale factor results (V):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

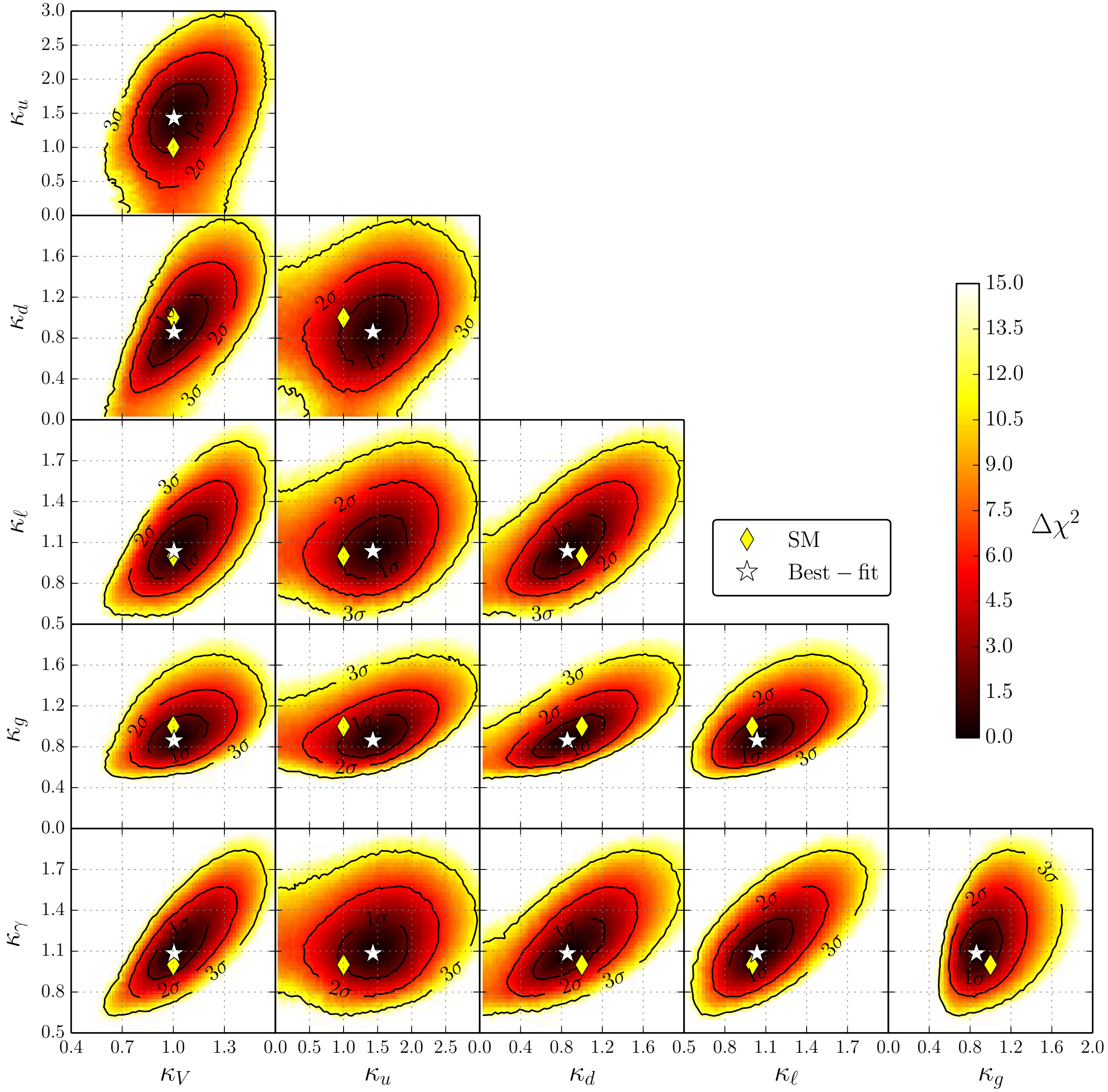
Very general model: $\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)



Coupling scale factor results (V):

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein - full Run I*]

Very general model: $\kappa_V, \kappa_u, \kappa_d, \kappa_l, \kappa_g, \kappa_\gamma$, BR($H \to$ inv.)



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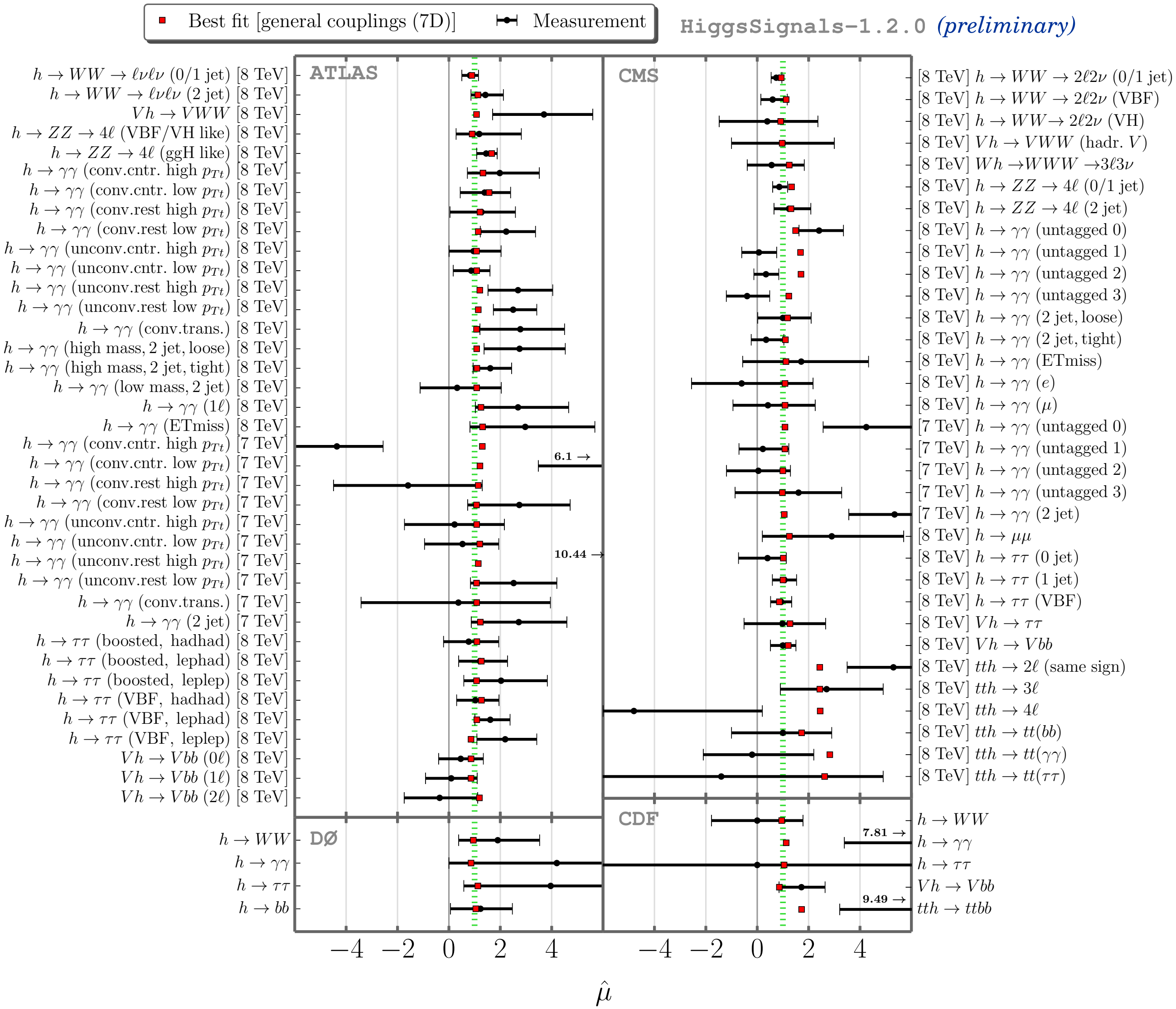


Measurement of the Higgs boson spin

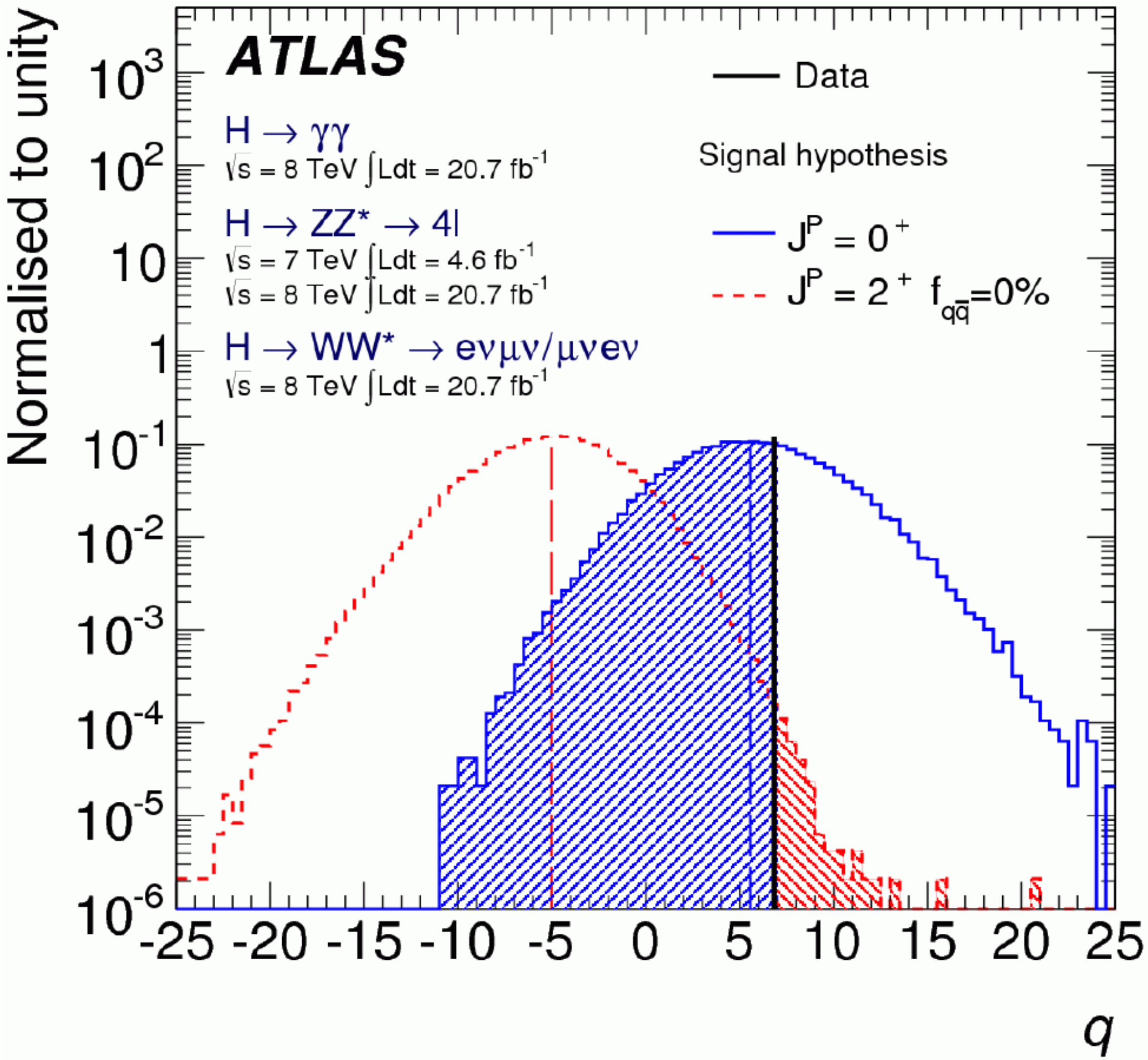
⇒ first results from the LHC:

Investigating the decay
$H \to \gamma\gamma, ZZ^*, WW^*$

comparing predictions . . .

$q = \log\left(\mathcal{L}(O^+)/\mathcal{L}(2^+)\right)$

⇒ Spin 0 clearly preferred



Measurement of the Higgs boson spin

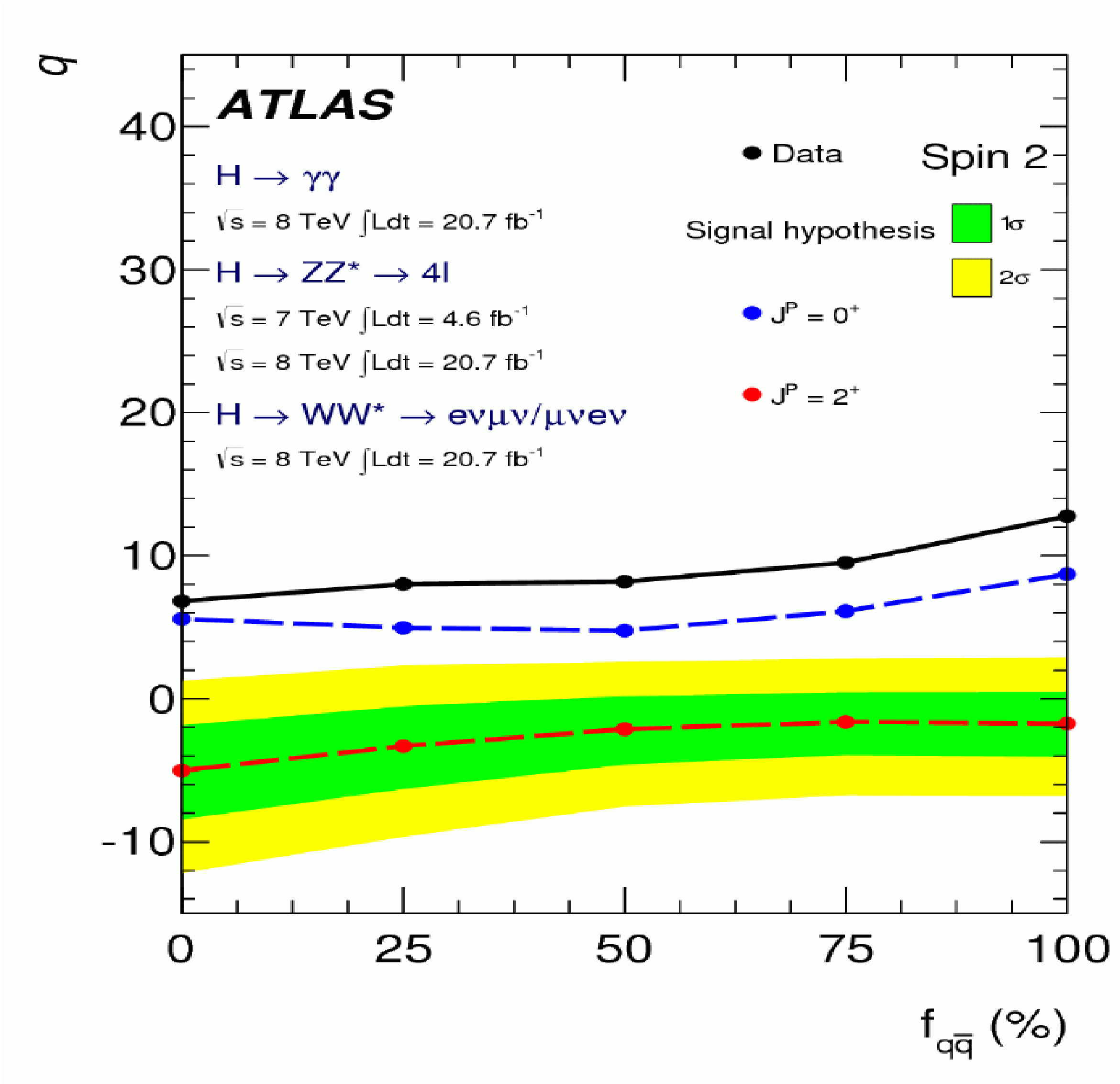
⇒ first results from the LHC:

Investigating the decay
$H \to \gamma\gamma, ZZ^*, WW^*$

comparing predictions . . .

$q = \log\left(\mathcal{L}(O^+)/\mathcal{L}(2^+)\right)$

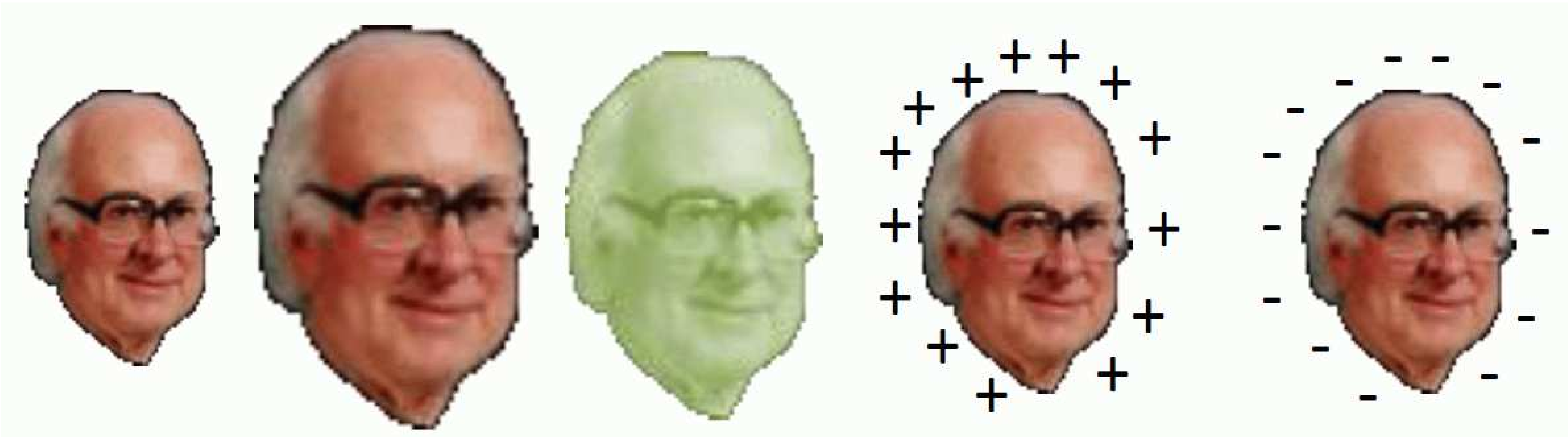
⇒ Spin 0 clearly preferred



Has a Higgs particle been discovered?

Has a Higgs particle been discovered? YES!

3. MSSM/BSM Higgs boson searches at the LHC



We have a ~ 125 GeV SM-like Higgs boson

⇒ What are the options?

1. Decoupling limit:
   $M_A \gg M_Z$ ⇒ the light Higgs becomes SM-like

2. Alignment without decoupling:
   ⇒ a $\mathcal{CP}$-even Higgs becomes SM-like due to an "accidental" cancellation

3. Heavy Higgs SM-like: (in the "alignment w/o decoupling" scen.)
   ⇒ is the case with the heavy $\mathcal{CP}$-even Higgs being SM-like (still) a viable solution?

Obtaining a light Higgs with SM-like couplings

[*J. Gunion, H. Haber, hep-ph/0207010*]

$\to$ $\mathcal{CP}$ conserving 2HDM in the Higgs basis ($\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$)

$\mathcal{V} = \ldots + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[\frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.}\right] + \ldots$

$\Rightarrow$ $\mathcal{CP}$-even mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & M_A^2 + Z_5 v^2 \end{pmatrix}$$

with mixing angle $\cos(\beta - \alpha) \equiv c_{\beta-\alpha}$

Decoupling limit: $M_A^2 \gg Z_i v^2$
$\Rightarrow m_h^2 \sim Z_1 v^2$, $|c_{\beta-\alpha} \ll 1|$, h is SM-like

Alignment limit: $Z_6 = 0$ and $Z_1 < Z_5 + M_A^2/v^2$
$\Rightarrow$ h is identical to the SM Higgs, $c_{\beta-\alpha} = 0$
$Z_6 = 0$ and $Z_1 > Z_5 + M_A^2/v^2$
$\Rightarrow$ H is identical to the SM Higgs, $c_{\beta-\alpha} = 1$

Alignment limit: see e.g.

[M. Carena, I. Low, N. Shah, C. Wagner '13][M. Carena, H. Haber, I. Low, N. Shah, C. Wagner '14]

In the MSSM $Z_6 = 0$ can be obtained through an "accidental" cancellation between tree-level and loop contribution

Example: $m_h^{\rm alt}$ scenario:

$A_t/M_S = 2.45$, $A_t = A_f$,

$M_S = m_{\tilde f} \geq 1$ TeV, $m_{\tilde g} = 1.5$ TeV,

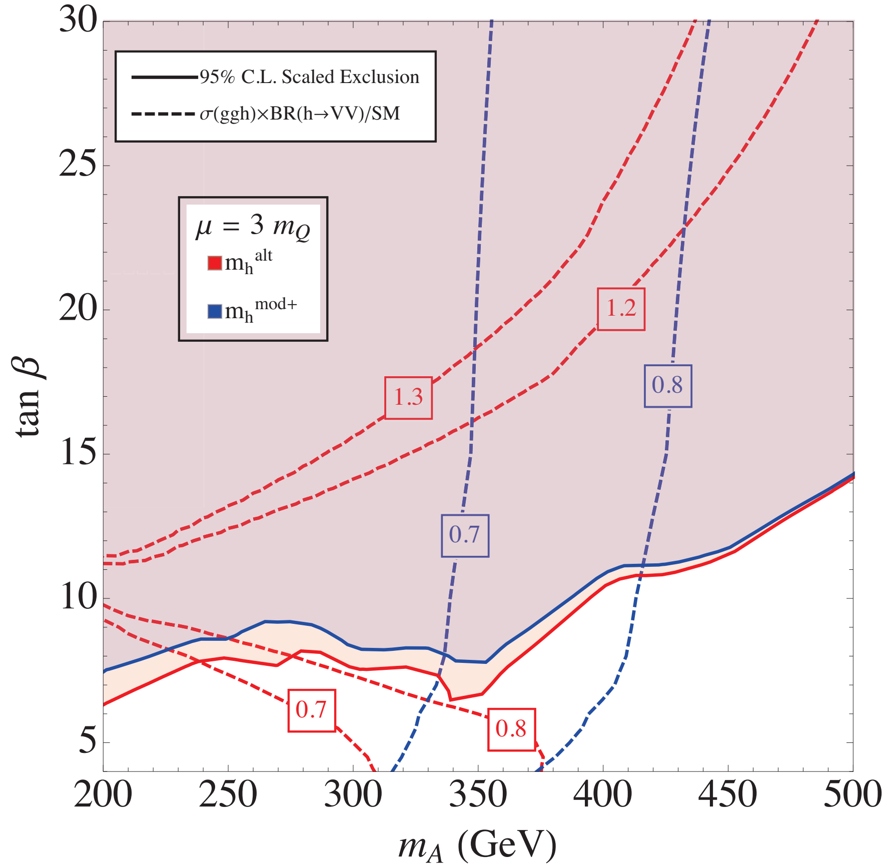
$M_2 = 2\,M_1 = 200$ GeV, μ adjustable

$\Rightarrow$ SM-like Higgs for all M_A

$\tan\beta \sim$

$$\left[M_h^2 + M_Z^2 + \frac{3m_t^2\mu^2}{4\pi^2v^2M_S^2}\left(\frac{A_t^2}{2M_S^2} - 1\right)\right] \Big/ \left[\frac{3m_t^2}{4\pi^2v^2}\frac{\mu A_t}{M_S^2}\left(\frac{A_t^2}{6M_S^2} - 1\right)\right]$$

Compare: $m_h^{\rm mod+}$ and $m_h^{\rm alt}$:



Alignment limit: see e.g.

[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15]

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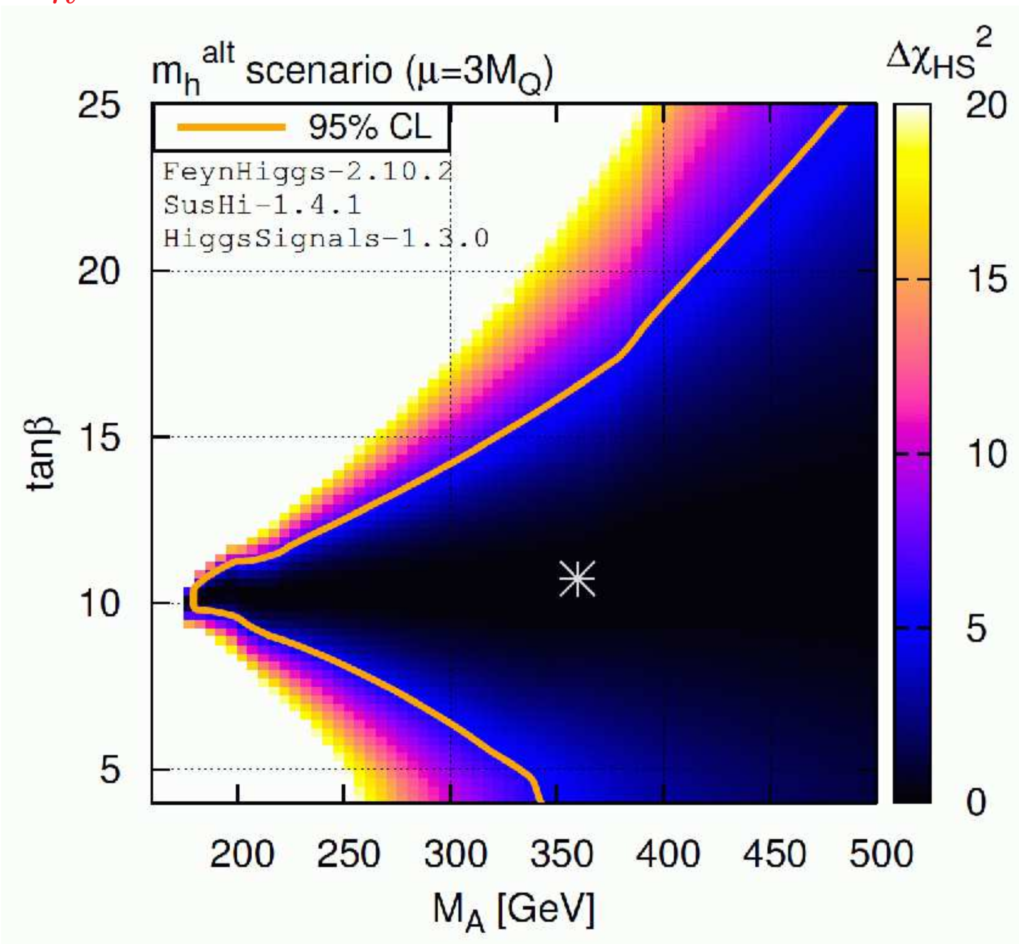
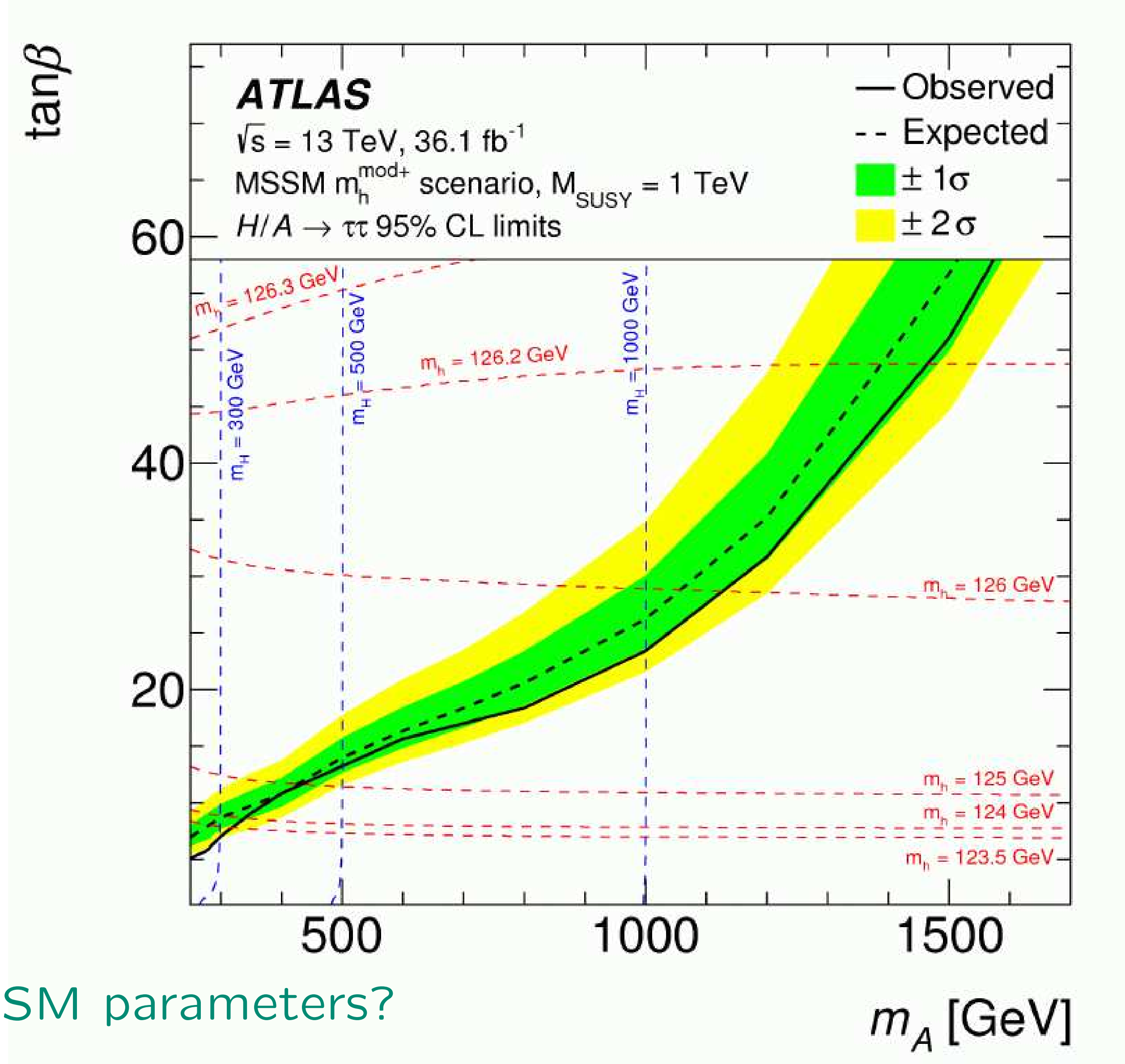
m_h^{alt} scenario with HiggsSignals :



Latest results for neutral heavy Higgs bosons: [ATLAS '18]

MSSM Higgs exclusion contours in M_A–tan β plane: $b\bar{b}, gg \to h, H, A \to \tau^+\tau^-$

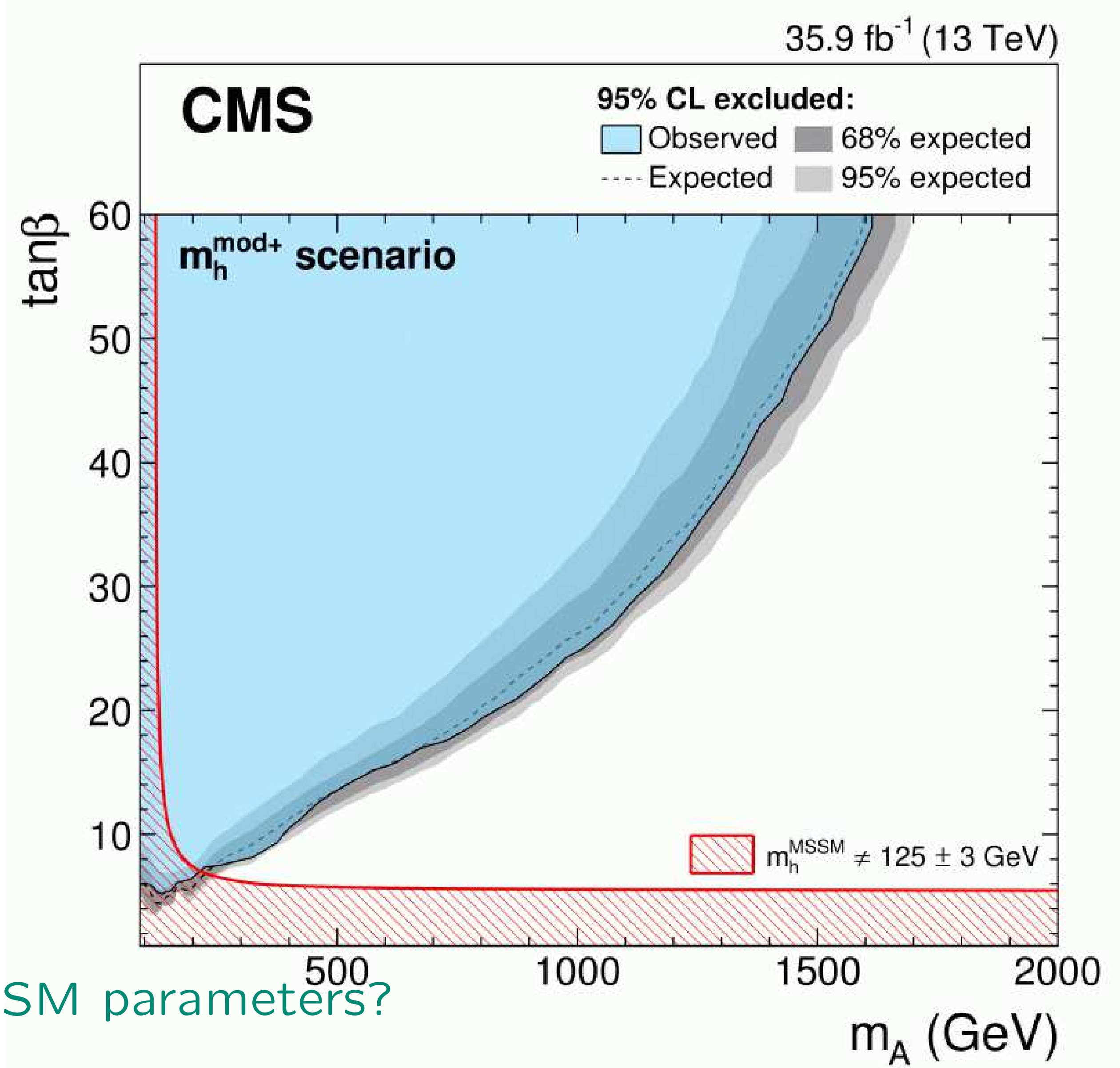


Choice of MSSM parameters?

Latest results for neutral heavy Higgs bosons:

[CMS '18]

MSSM Higgs exclusion contours in M_A–$\tan\beta$ plane: $b\bar{b}, gg \to h, H, A \to \tau^+\tau^-$

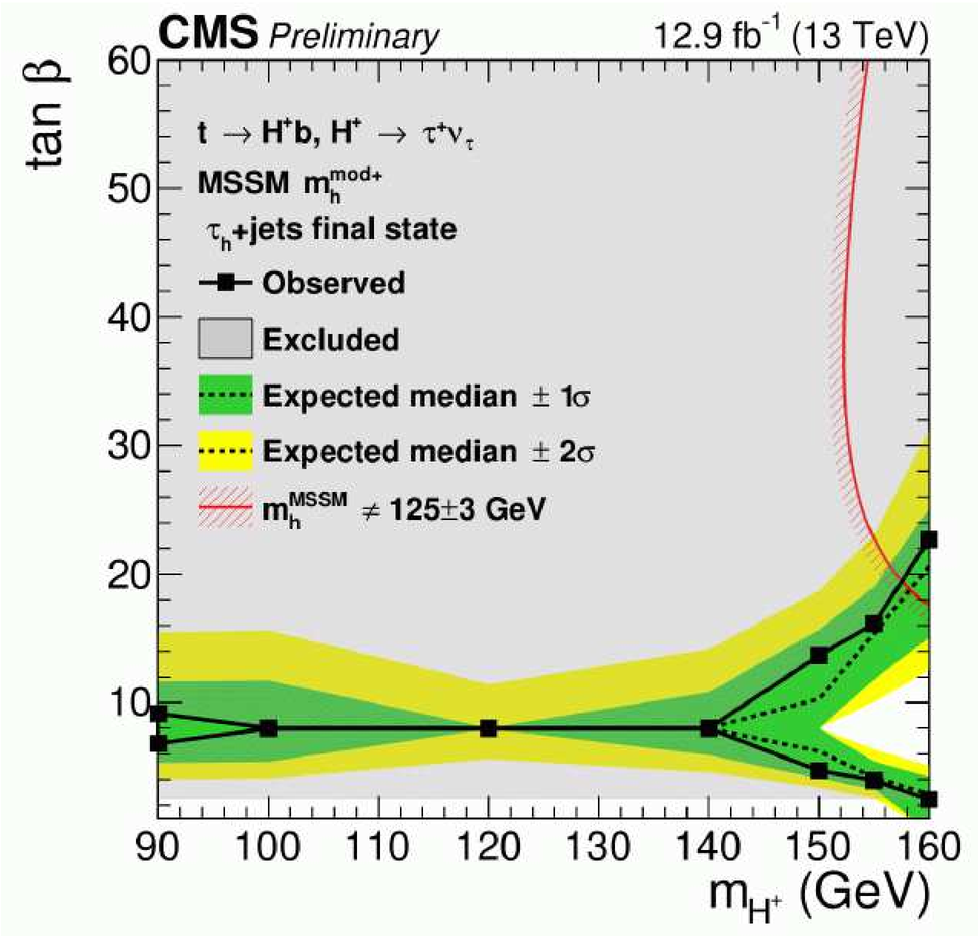


Choice of MSSM parameters?

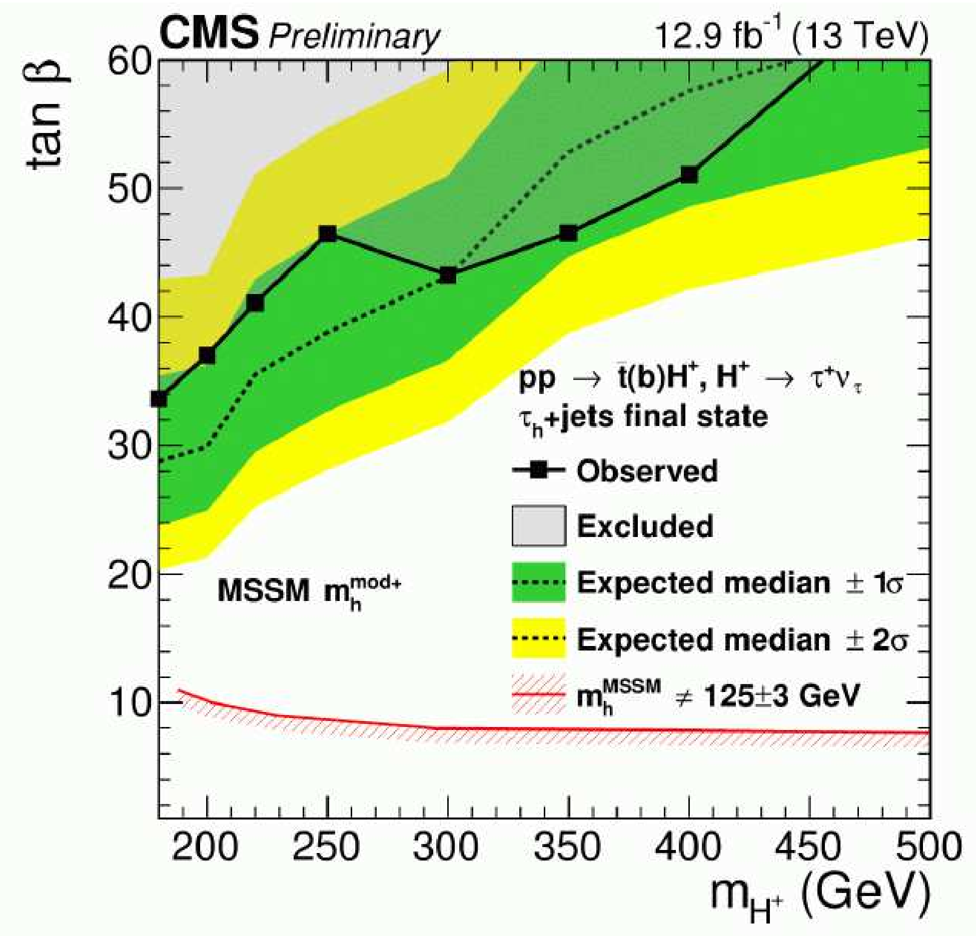
Nearly latest results for charged Higgs bosons: [CMS '17]

MSSM Higgs exclusion contours in M_A–$\tan\beta$ plane: $pp \to H^\pm \to \tau\nu_\tau$

$M_{H^\pm} < m_t$



$M_{H^\pm} > m_t$

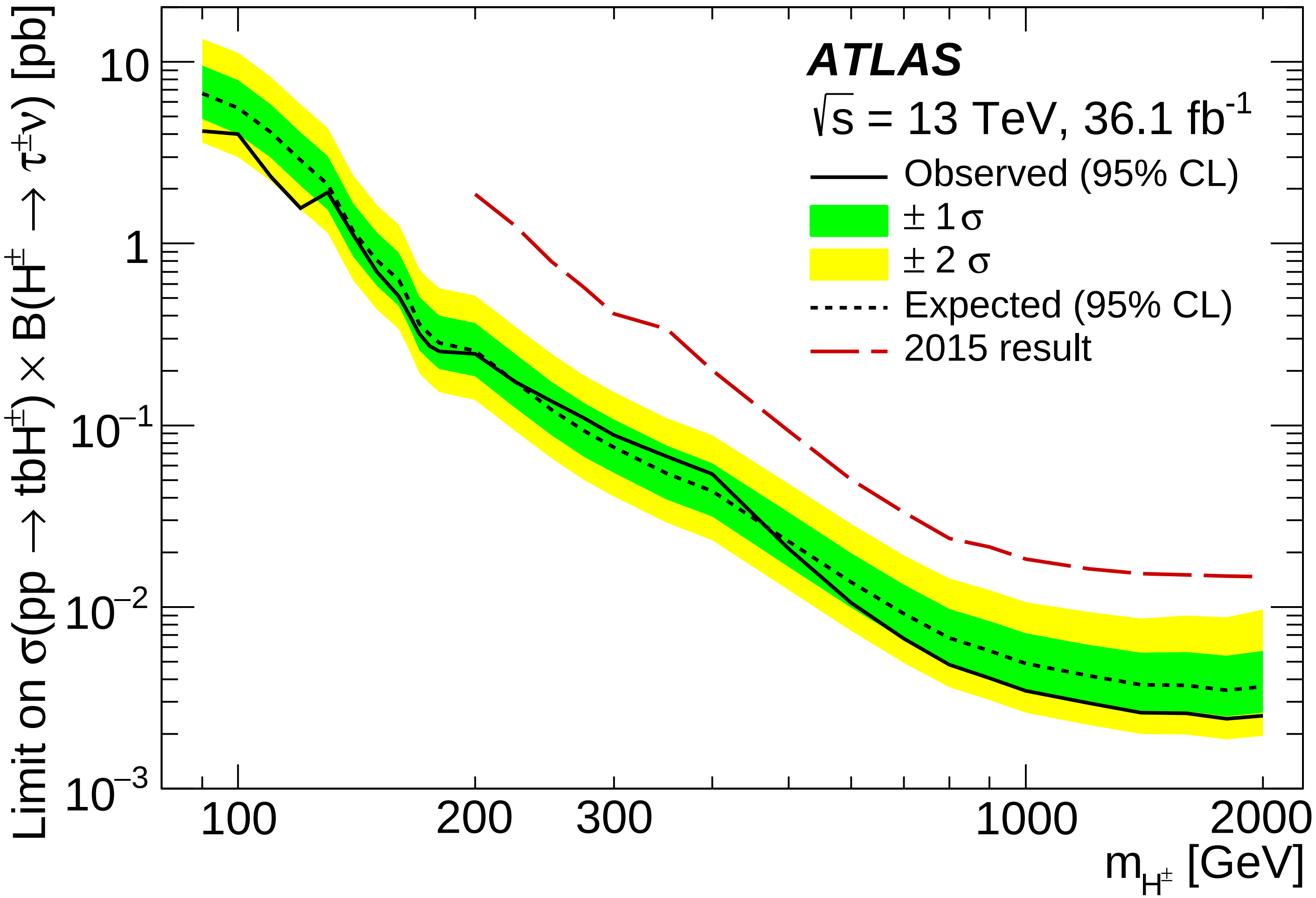


Choice of MSSM parameters?

Latest results for charged Higgs bosons: [ATLAS '18]

2HDM type II results: $pp \to H^{\pm} \to \tau\nu_{\tau}$

$M_{H^{\pm}} < m_t$ $M_{H^{\pm}} > m_t$



⇒ gap finally closed!

Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

$\to$ investigate benchmark scenarios:

$\to$ Vary only M_A and $\tan\beta$
$\to$ Keep all other SUSY parameters fixed

[*E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel, P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18*]

1. M_h^{125} scenario: 2HDM-like model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

Data to be taken into account:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

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– SUSY searches (LHC)

Data to be taken into account:

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– Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds

– SUSY searches (LHC)

Data not necessarily to be taken into account:

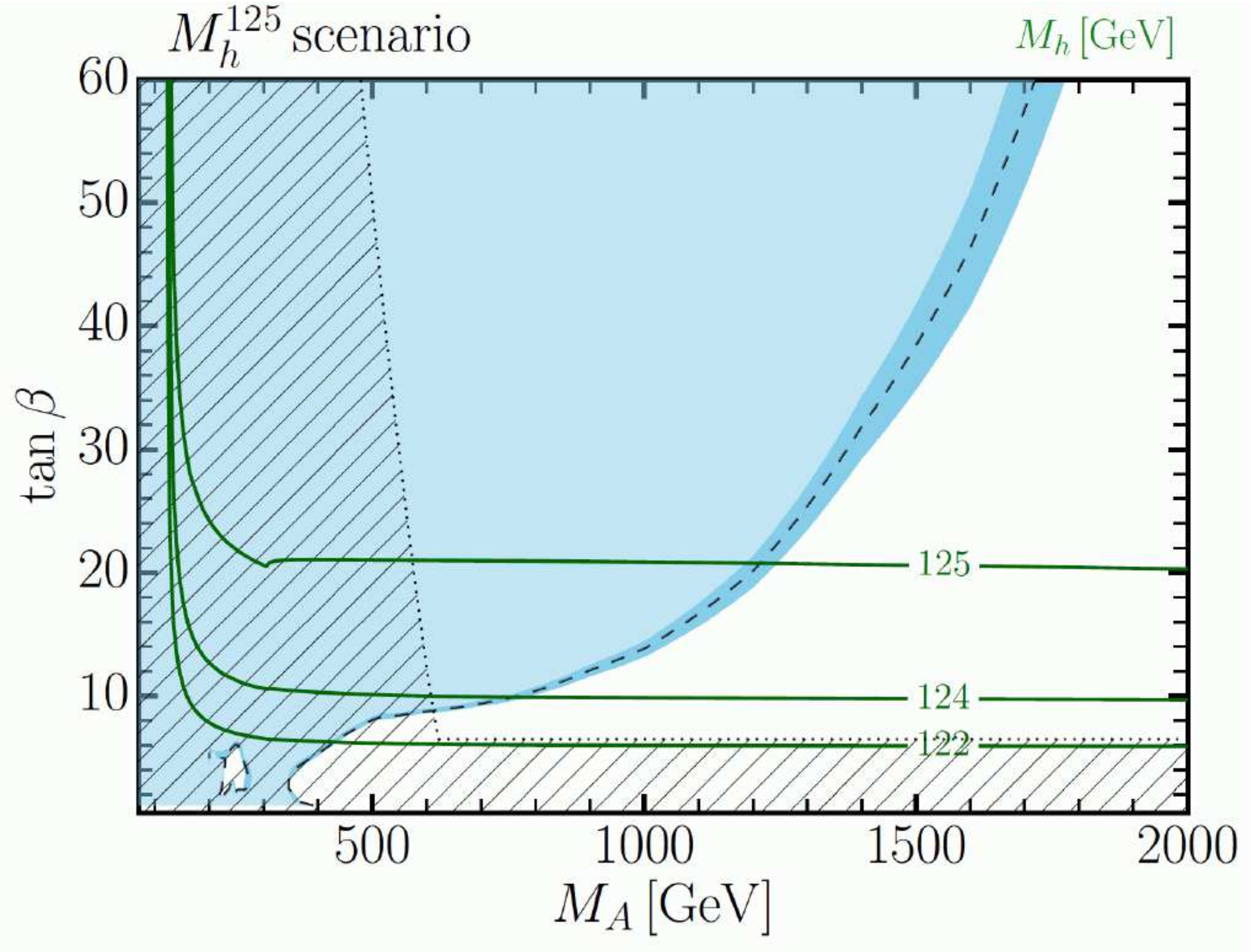
– electroweak precision data

– flavor data

– astrophysical data (DM properties)

New benchmark: M_h^{125}

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 1$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

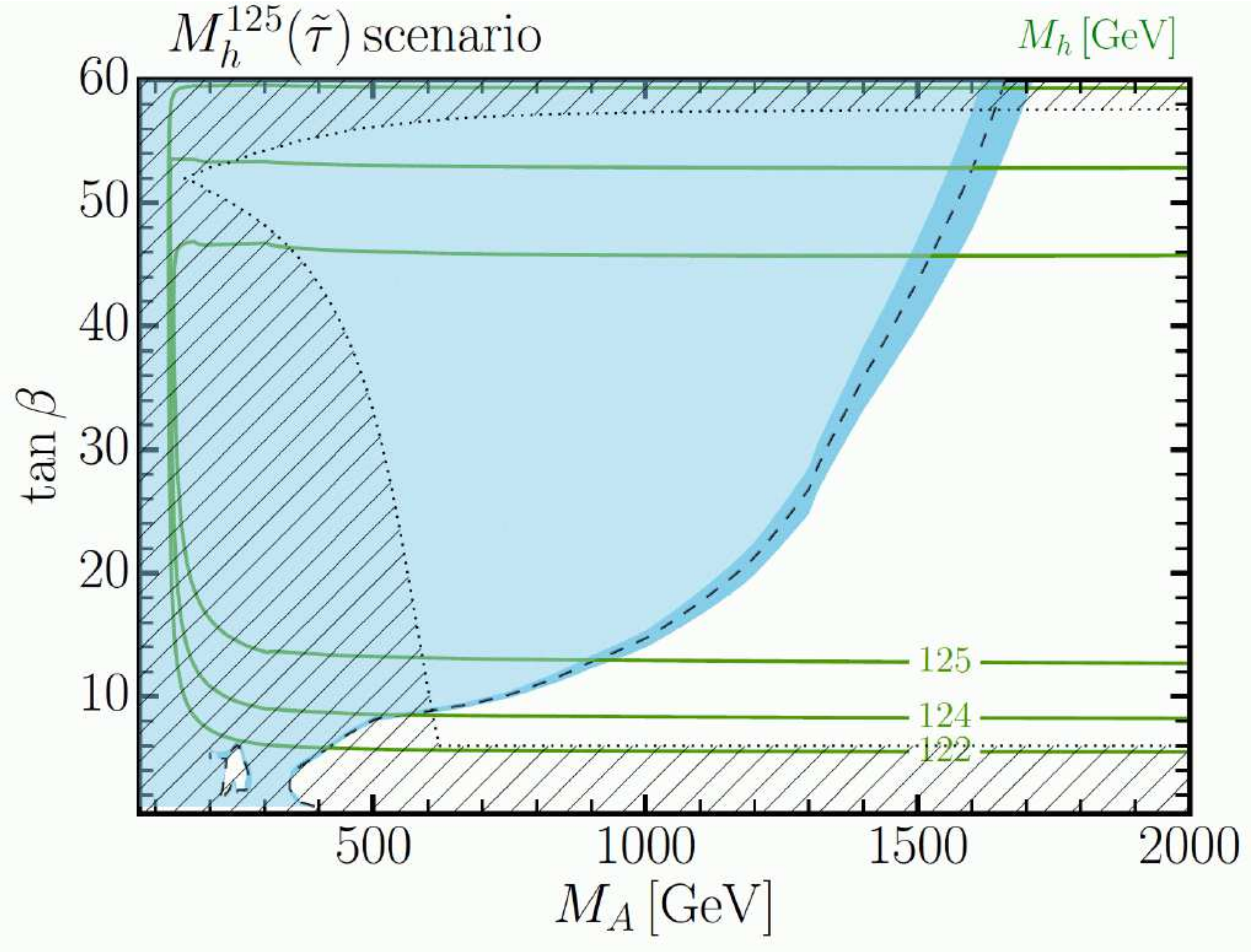
$X_t = 2.8$ TeV

$A_t = A_b = A_\tau$

⇒ new vanilla benchmark model

New benchmark: $M_h^{125}(\tilde{\tau})$

[*E. Bagnaschi et al., '18*]

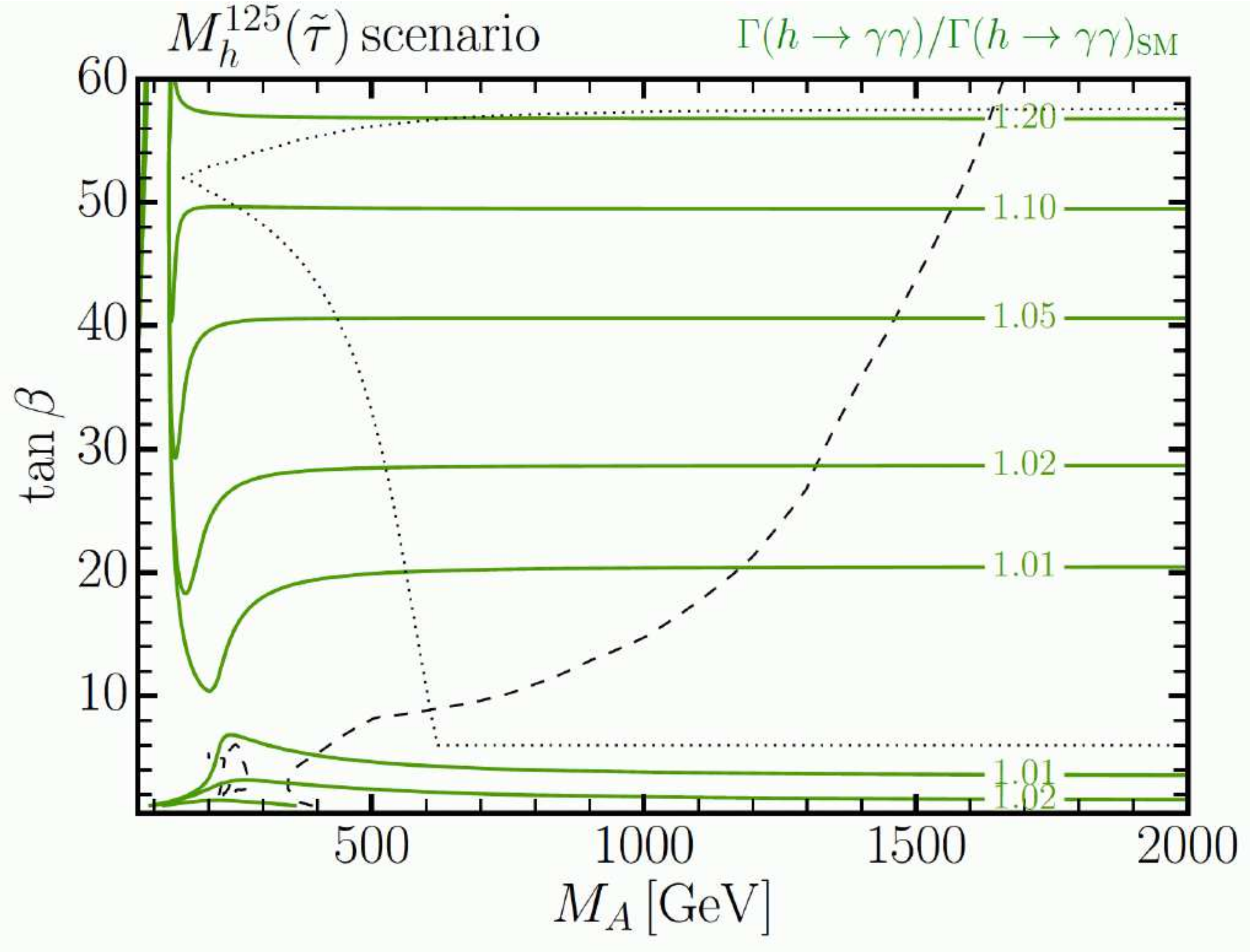


$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$
$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350 \text{ GeV}$$
$$\mu = 1 \text{ TeV}, \; M_1 = 180 \text{ GeV}$$
$$M_2 = 300 \text{ GeV}, \; M_3 = 2.5 \text{ TeV}$$
$$X_t = 2.8 \text{ TeV}$$
$$A_t = A_b, A_\tau = 800 \text{ GeV}$$

⇒ slightly reduced heavy Higgs coverage

New benchmark: $M_h^{125}(\tilde{\tau})$

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 350$ GeV

$\mu = 1$ TeV, $M_1 = 180$ GeV

$M_2 = 300$ GeV, $M_3 = 2.5$ TeV

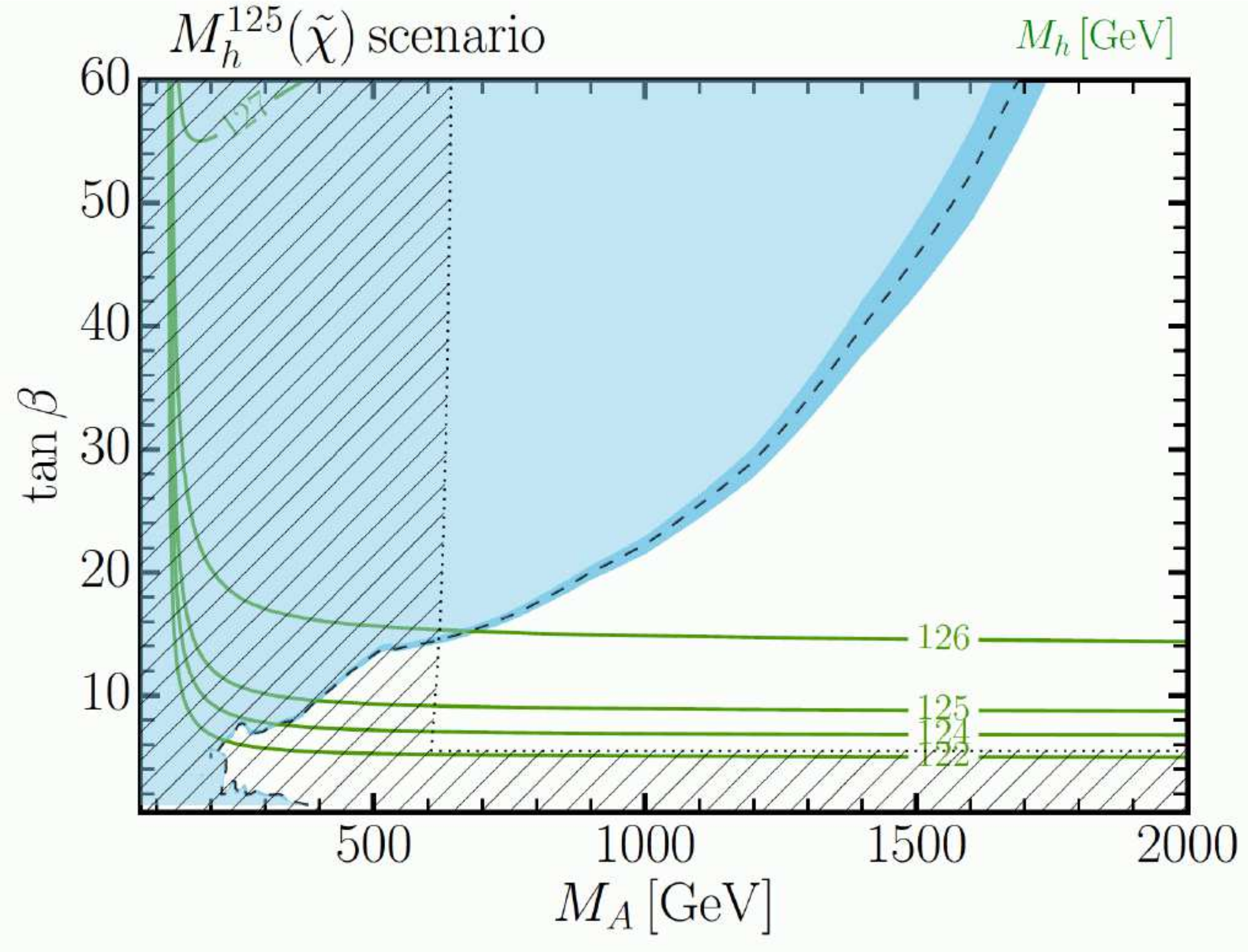
$X_t = 2.8$ TeV

$A_t = A_b, A_\tau = 800$ GeV

$\Rightarrow$ strong impact on $\Gamma(h \to \gamma\gamma)$

New benchmark: $M_h^{125}(\tilde{\chi})$

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 180$ GeV, $M_1 = 160$ GeV

$M_2 = 180$ GeV, $M_3 = 2.5$ TeV

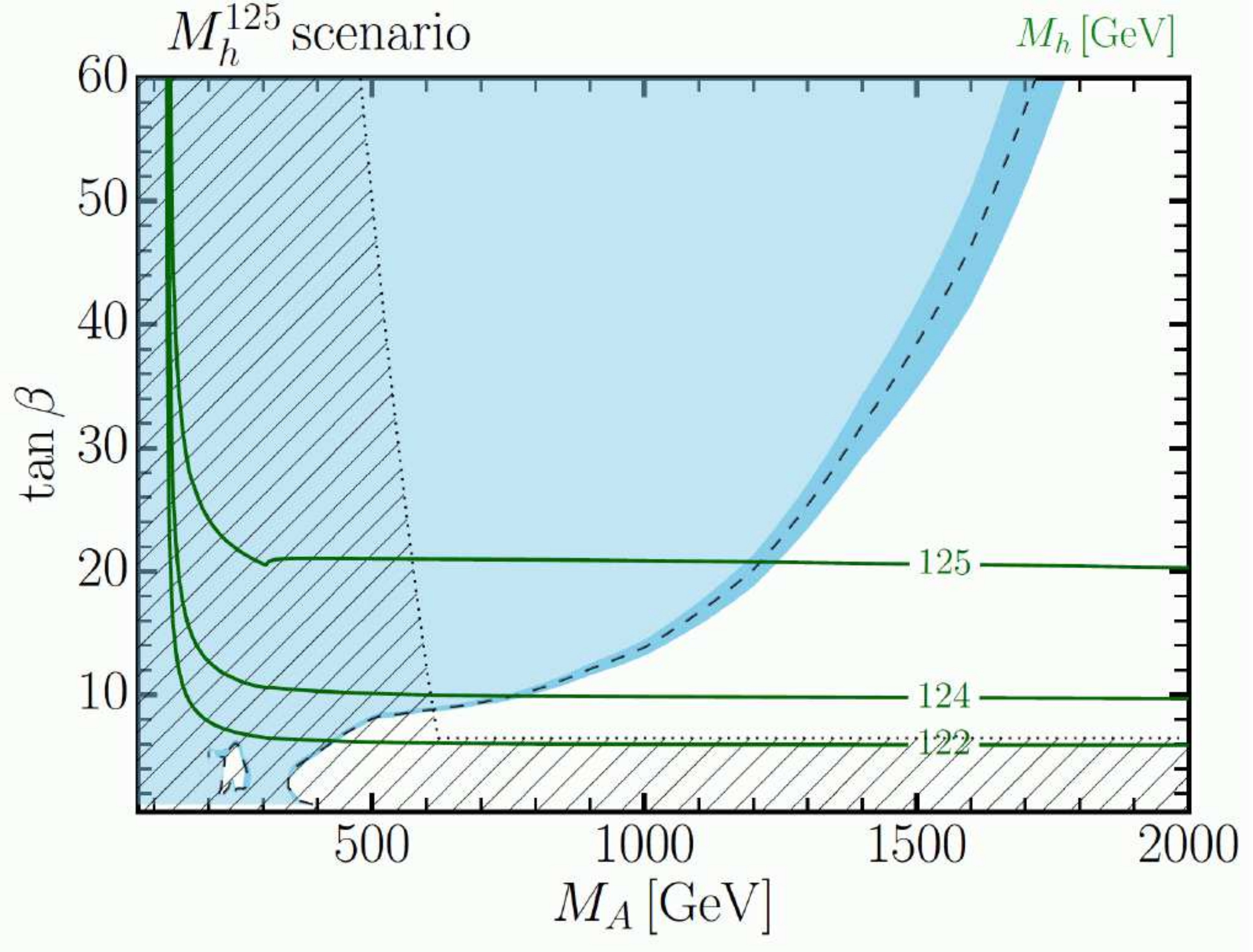
$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

⇒ strongly reduced heavy Higgs coverage

New benchmark: M_h^{125}

[E. Bagnaschi et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 1$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

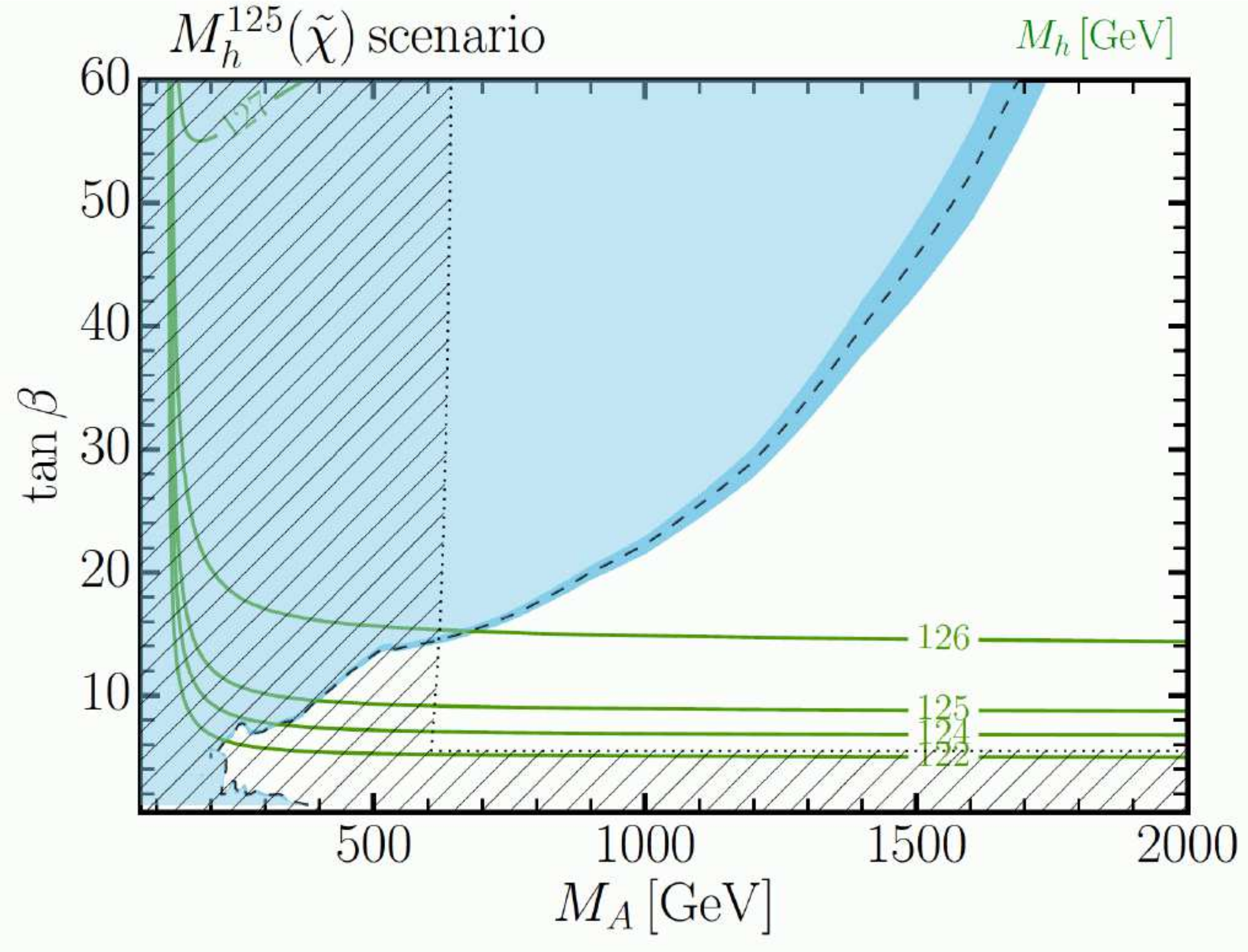
$X_t = 2.8$ TeV

$A_t = A_b = A_\tau$

$\Rightarrow$ new vanilla benchmark model

New benchmark: $M_h^{125}(\tilde{\chi})$

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 180$ GeV, $M_1 = 160$ GeV

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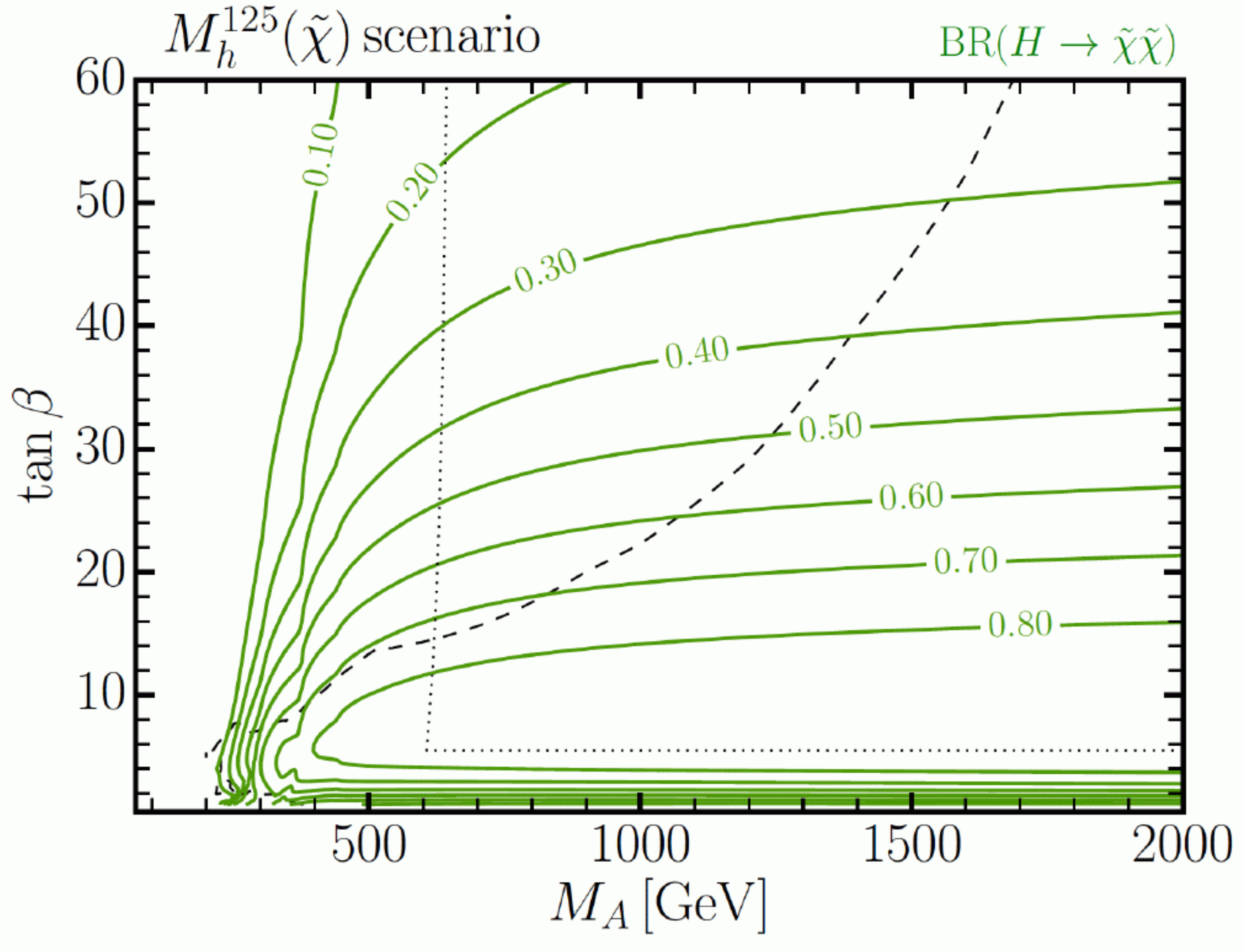
$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

$\Rightarrow$ strongly reduced heavy Higgs coverage

New benchmark: $M_h^{125}(\tilde{\chi})$

[E. Bagnaschi et al., '18]



$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5 \text{ TeV}$$

$$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$$

$$\mu = 180 \text{ GeV}, \; M_1 = 160 \text{ GeV}$$

$$M_2 = 180 \text{ GeV}, \; M_3 = 2.5 \text{ TeV}$$

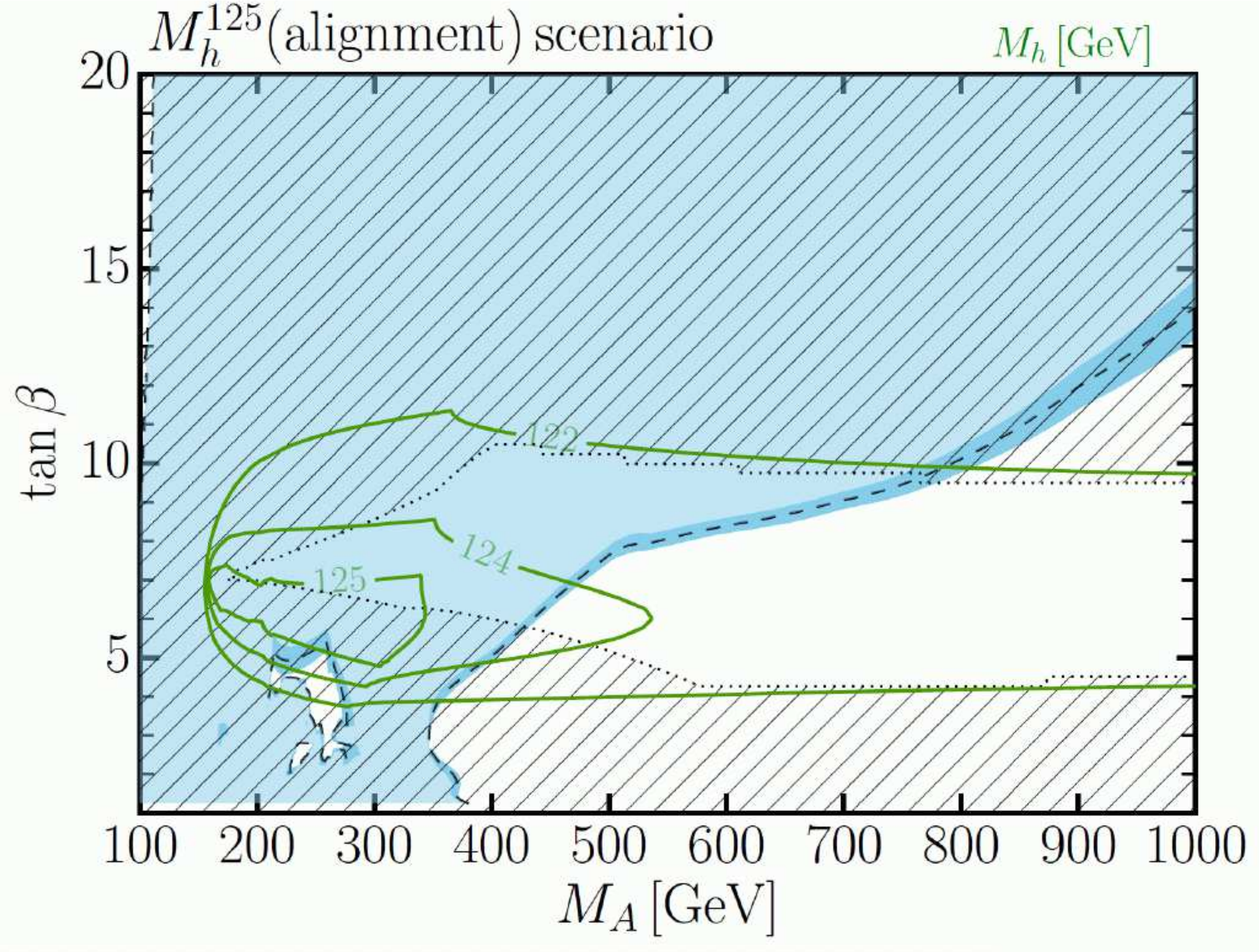
$$X_t = 2.5 \text{ TeV}$$

$$A_t = A_b = A_\tau$$

$\Rightarrow$ Huge BR of heavy Higgses to EW-inos

New benchmark: M_h^{125}(align)

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 7.5$ TeV, $M_1 = 500$ GeV

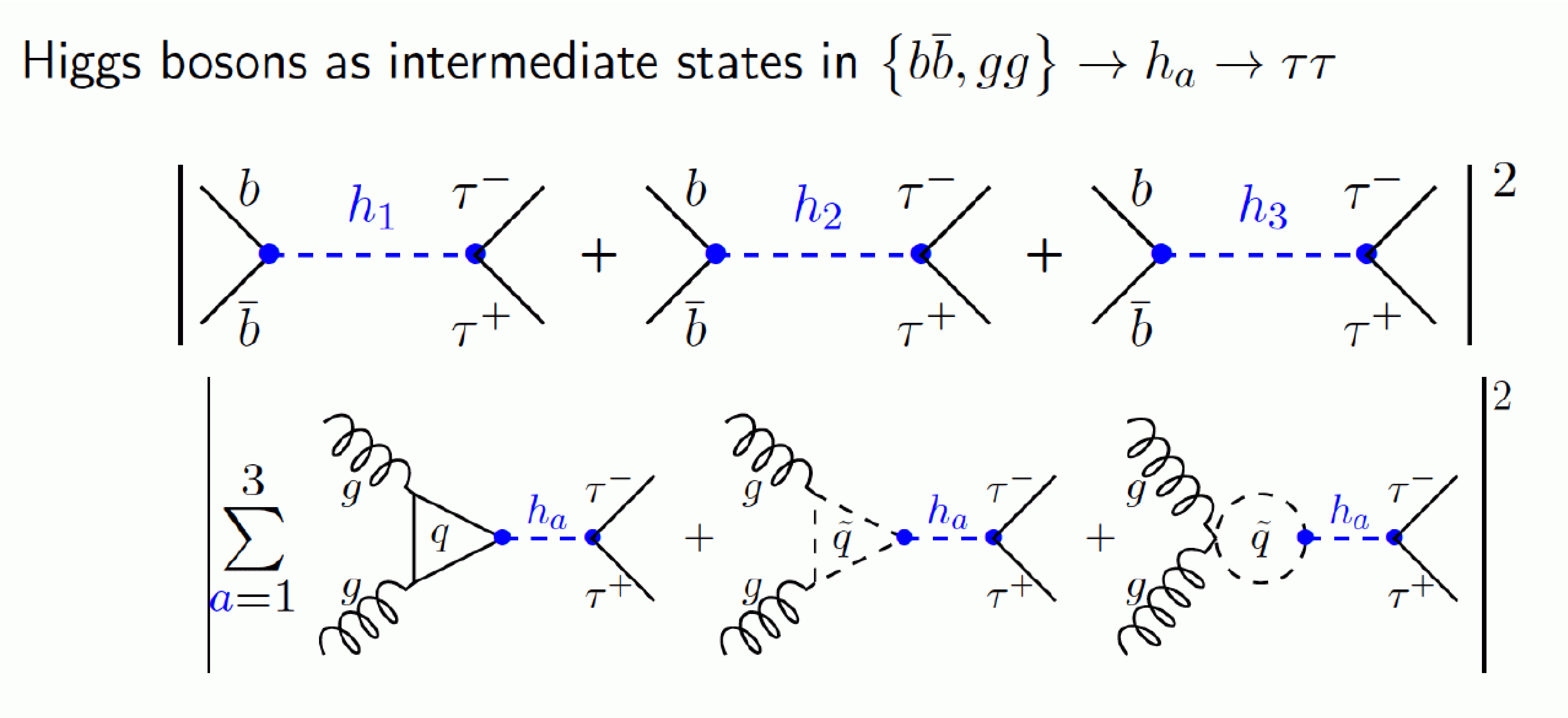
$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$A_t = A_b = A_\tau = 6.25$ TeV

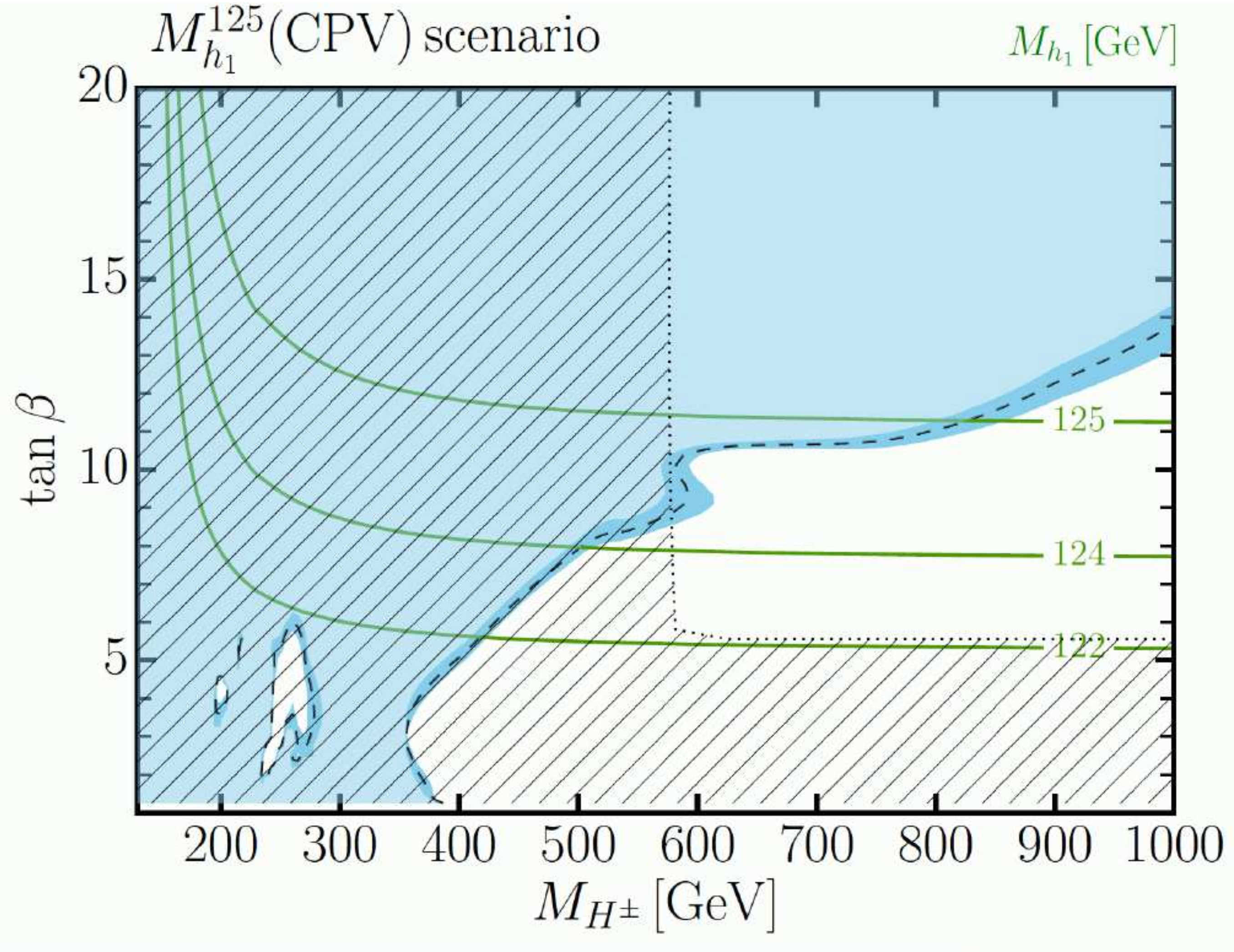
$\Rightarrow h$ SM-like for very low M_A

LHC Higgs searches for complex parameters:

$h_1 \sim H_{125}$, $M_{h_2} \approx M_{h_3}$, CPV: large h_2-h_3 mixing possible:



New benchmark: $M_{h_1}^{125}$(CPV) [E. Bagnaschi et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 1.65$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$|A_t| = \mu/\tan\beta + 2.8$ TeV

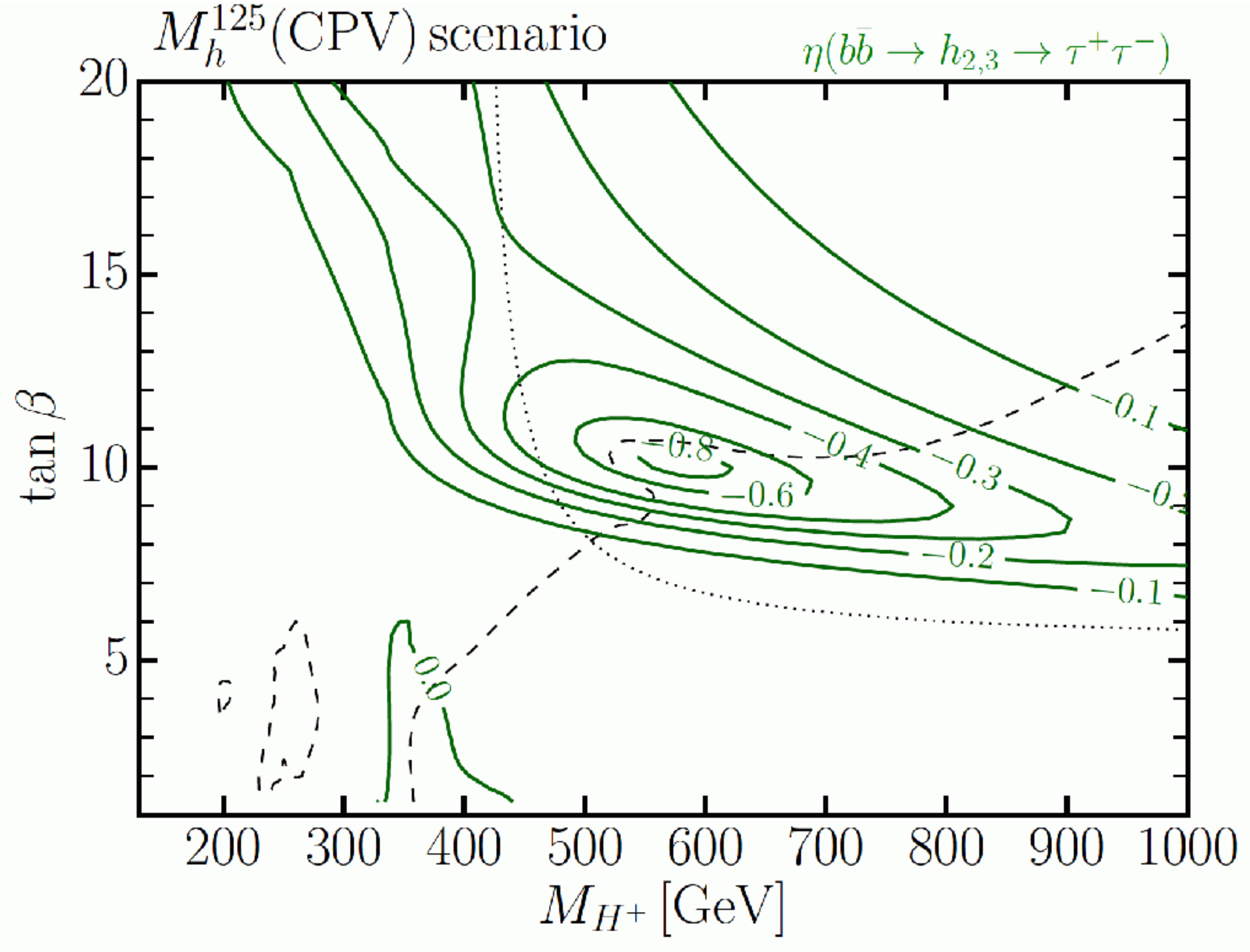
$\phi_{A_t} = 2/15\ \pi$

$|A_t| = A_b = A_\tau$

$\Rightarrow$ reduced coverage due to h_2-h_3 interference

New benchmark: $M_{h_1}^{125}$(CPV)

[*E. Bagnaschi et al., '18*]



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$\mu = 1.65$ TeV, $M_1 = 1$ TeV

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$|A_t| = \mu/\tan\beta + 2.8$ TeV

$\phi_{A_t} = 2/15\ \pi$

$|A_t| = A_b = A_\tau$

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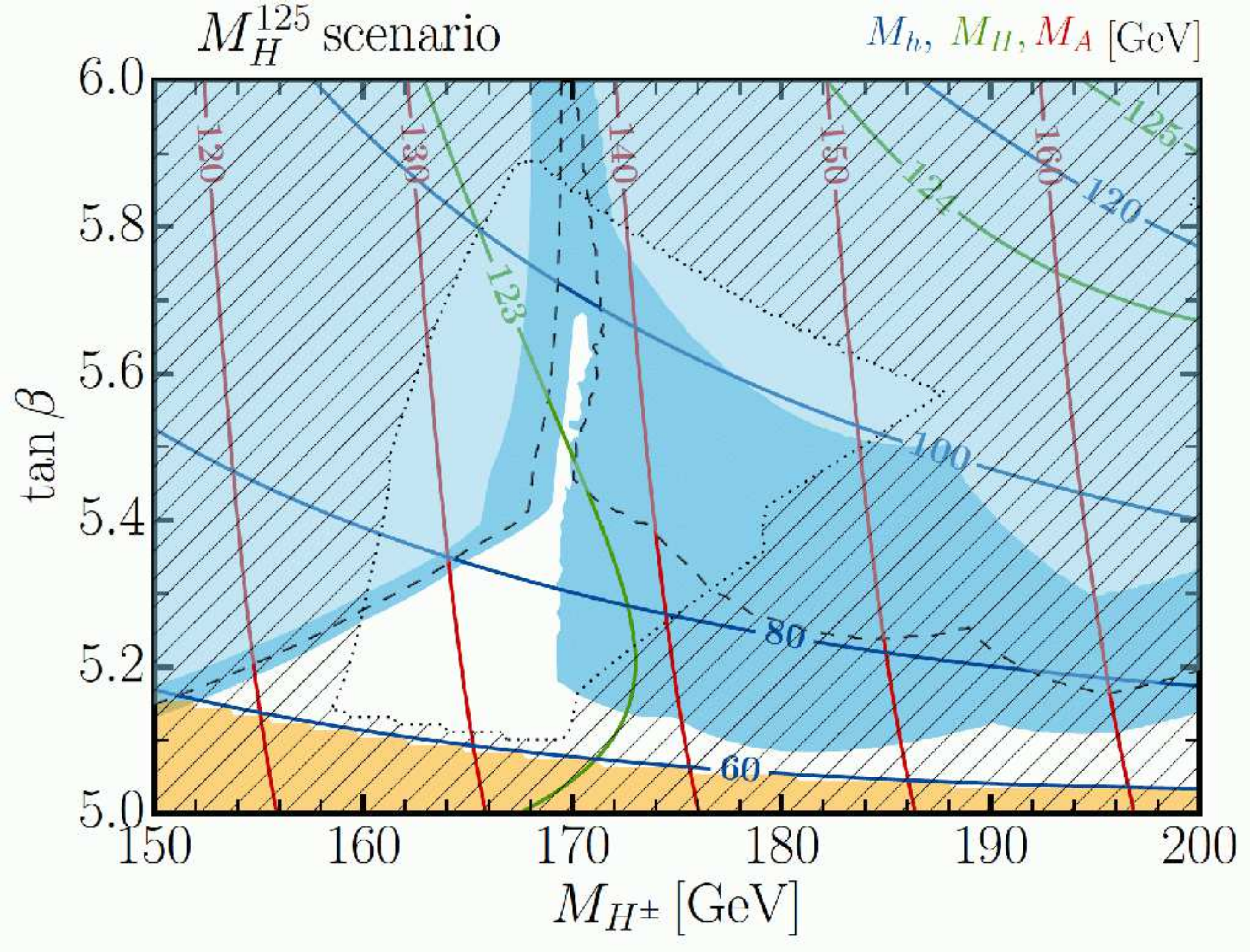
New benchmark: M_H^{125}

[*E. Bagnaschi et al., '18*]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750$ GeV $- 2(M_{H^\pm} - 150$ GeV)

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2$ TeV

$\mu = [5.8$ TeV $+ 20(M_{H^\pm} - 150$ GeV$)] \times M_{\tilde{Q}_3}/750$ GeV

$M_1 = M_{\tilde{Q}_3} - 75$ GeV

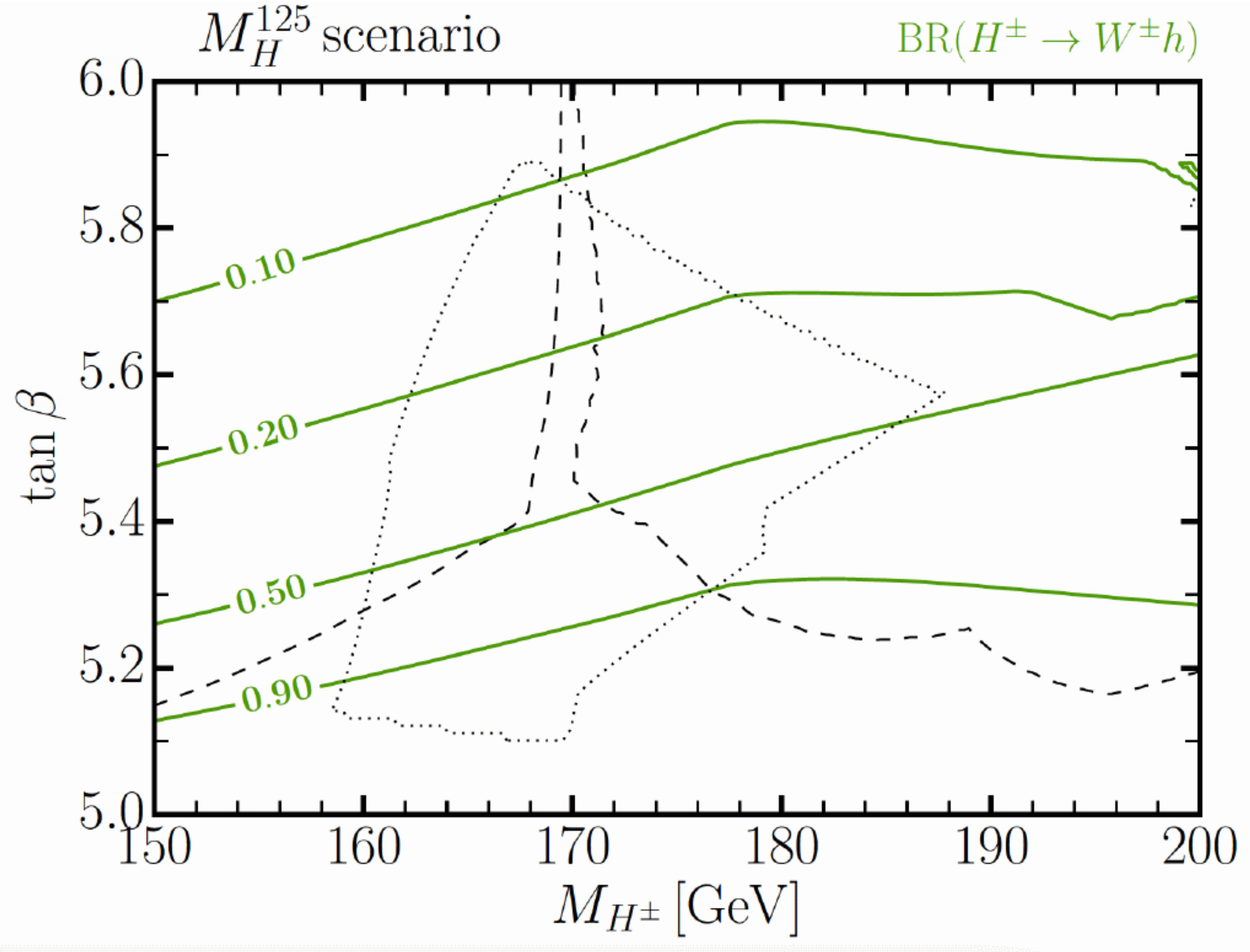
$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$A_t = A_b = A_\tau = 0.65 M_{\tilde{Q}_3}$

⇒ exotic solution still viable!

New benchmark: M_H^{125}

[E. Bagnaschi et al., '18]



$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750$ GeV $- 2(M_{H^\pm} - 150$ GeV$)$

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\tilde{D}_3} = 2$ TeV

$\mu = [5.8$ TeV $+ 20(M_{H^\pm} - 150$ GeV$)] \times M_{\tilde{Q}_3}/750$ GeV

$M_1 = M_{\tilde{Q}_3} - 75$ GeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$A_t = A_b = A_\tau = 0.65 M_{\tilde{Q}_3}$

$\Rightarrow$ large $\mathrm{BR}(H^\pm \to W^\pm h)$

Interesting case: light singlet

Singlet does not couple to SM particles!

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"Non-interacting particles are hard to detect."  [*F. Klinkhamer*]

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Singlet does not couple to SM particles!

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"Easily" possible in the NMSSM:

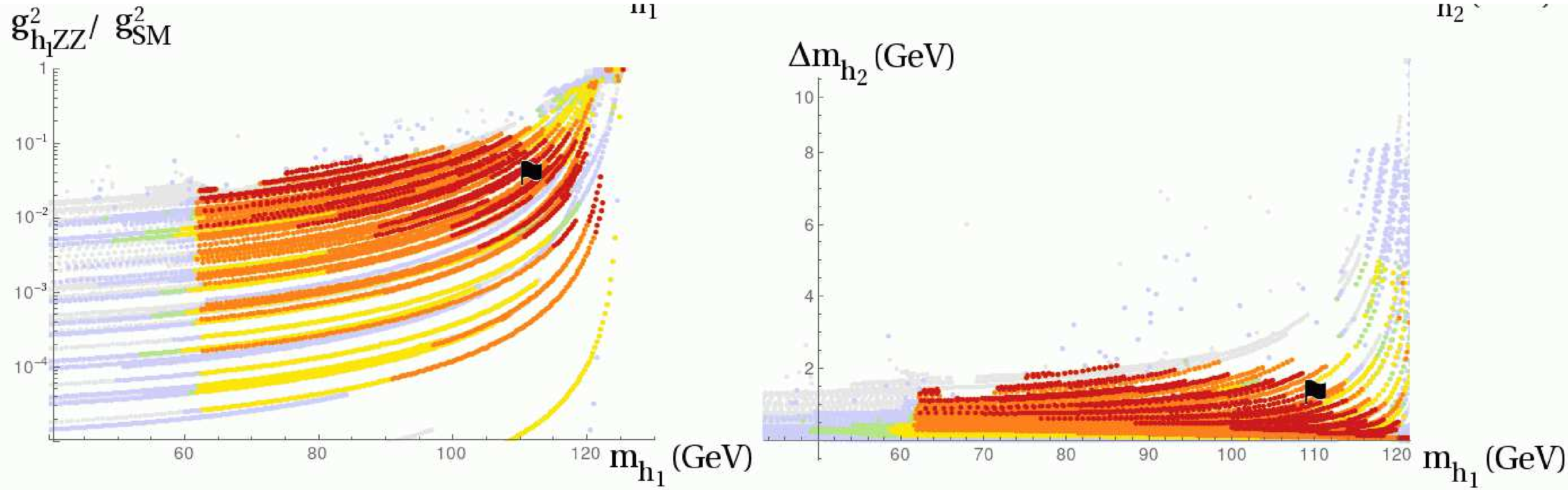
Light, singlet-like Higgs below 125 GeV

Which collider can find them?

NMSSM parameter scan: [*F. Domingo, G. Weiglein '15*]

Parameters:

$\tan\beta = 8$, $M_A = 1$ TeV, $A_\kappa = -2...0$ TeV, $\mu = 120...2000$ GeV,
$2M_1 = M_2 = 500$ GeV, $M_3 = 1.5$ TeV, $m_{\tilde{Q}_3} = 1$ TeV, $m_{\tilde{Q}_{1,2}} = 1.5$ TeV,
$A_t = -2$ TeV, $A_{b,\tau} = -1.5$ TeV



⇒ light Higgs below 125 GeV

⇒ strongly reduced couplings to gauge bosons!

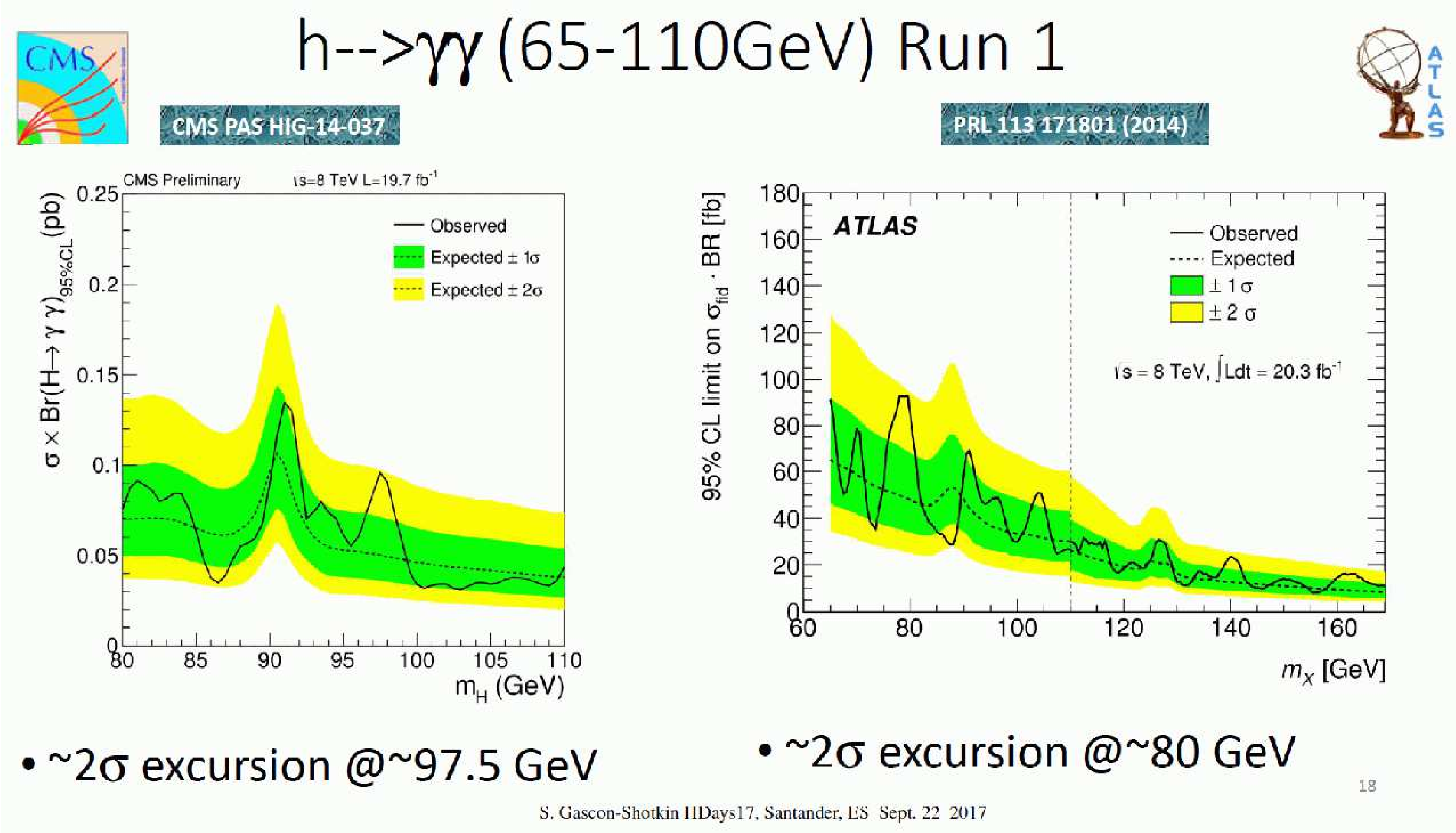
⇒ possibly within ILC reach!

4. My favorite anomaly: a Higgs boson at 96 GeV

- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Should we get excited?
- Which model fits?
- Next project?!

What was seen at Run I?

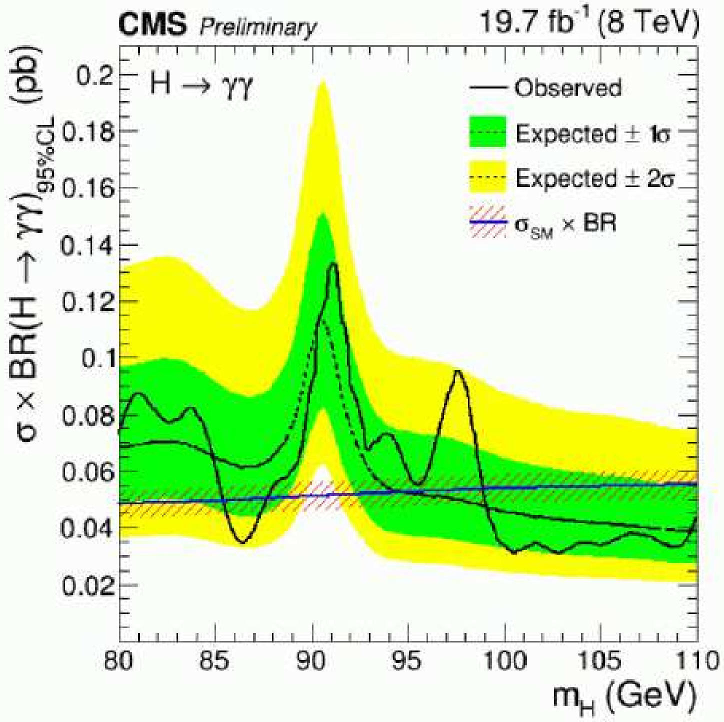
[S. Shotkin, talk at HDays17]

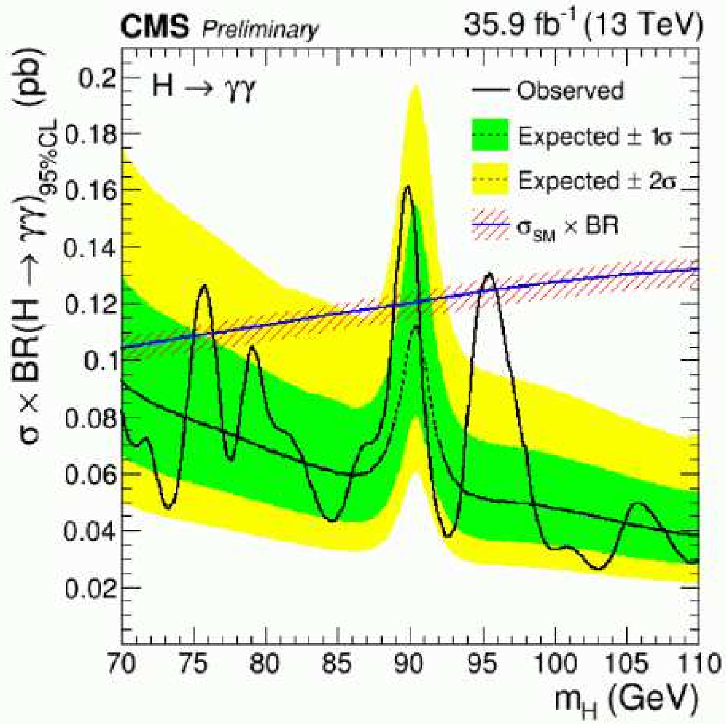


What was seen at Run II? [*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+2

New!





CMS PAS HIG-17-013

8 TeV: minimum(maximum) limit on σ X Br : 31(133) fb at m=102.8(91.1)GeV

13 TeV: minimum(maximum) limit on σ X Br : 26(161) fb at m=103.0(89.9)GeV

- 8 TeV limits on σ X Br redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

26

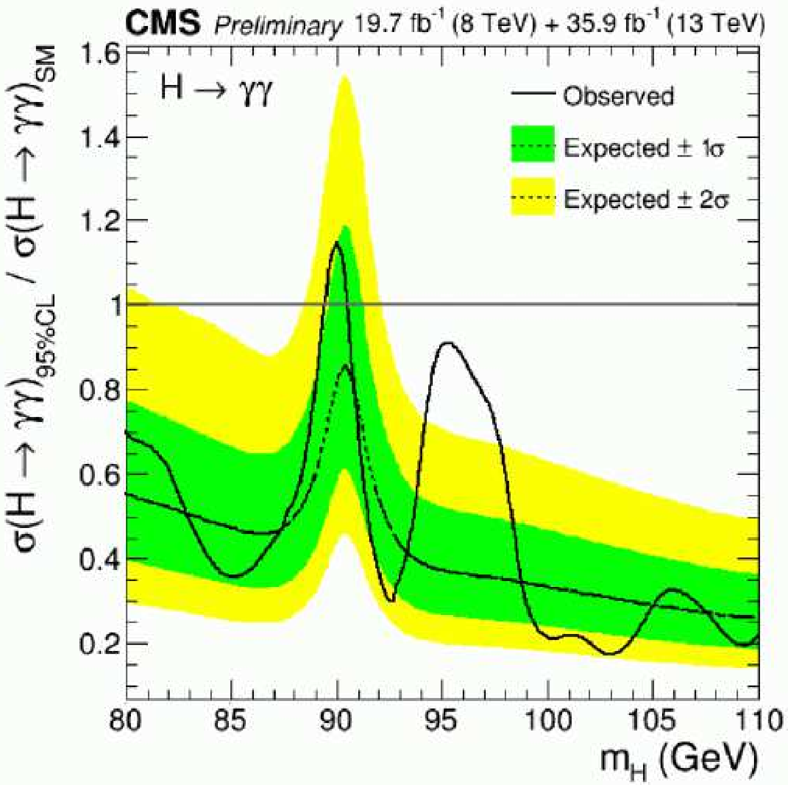
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).



8 TeV+13 TeV: minimum(maximum) limit on (σ X Br)/ $(\sigma \times Br)_{SM}$: 0.17(1.15) at m=103.0(90.0)GeV

- Combined 8 TeV+13 TeV σ X BR limit normalized to SM expectation (production processes assumed in SM proportions). No significant excess with respect to expected limits observed.

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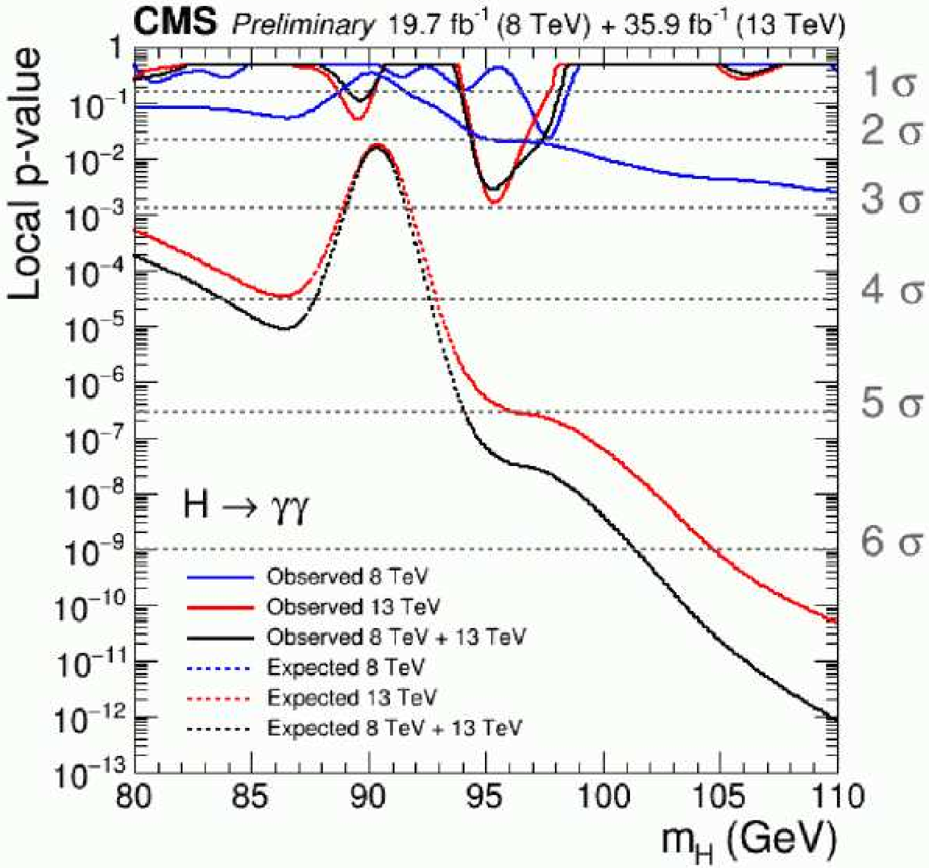
S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

 [*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013



8 TeV: Excess with ~2.0 σ local significance at m=97.6 GeV

13 TeV: Excess with ~2.9 σ local (1.47 σ global) significance at m=95.3 GeV

8TeV+13 TeV: Excess with ~2.8 σ local (1.3 σ global) significance at m=95.3 GeV

More data are required to ascertain the origin of this excess

- Expected and observed local p-values for 8 TeV, 13 TeV and their combination

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017 30

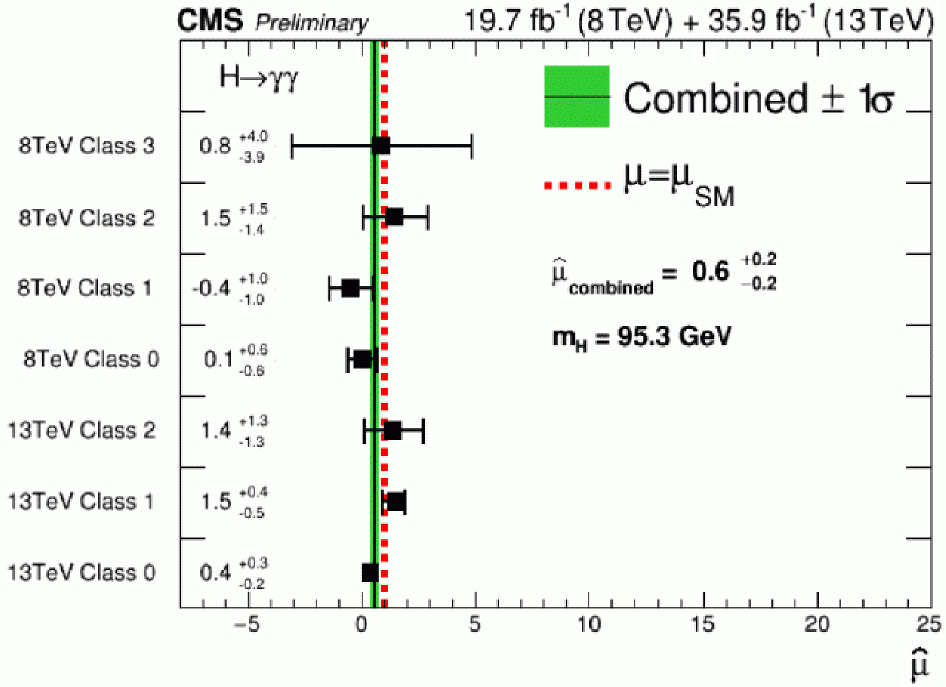
What was seen at Run II?

[*S. Shotkin, talk at HDays17*]

h-->γγ (70-110 GeV) Runs 1+2

New!

CMS PAS HIG-17-013



Excess here mostly driven by class 1 (&2) at 13 TeV

χ^2 probability for the seven individual values to be compatible with a single signal hypothesis: 41%

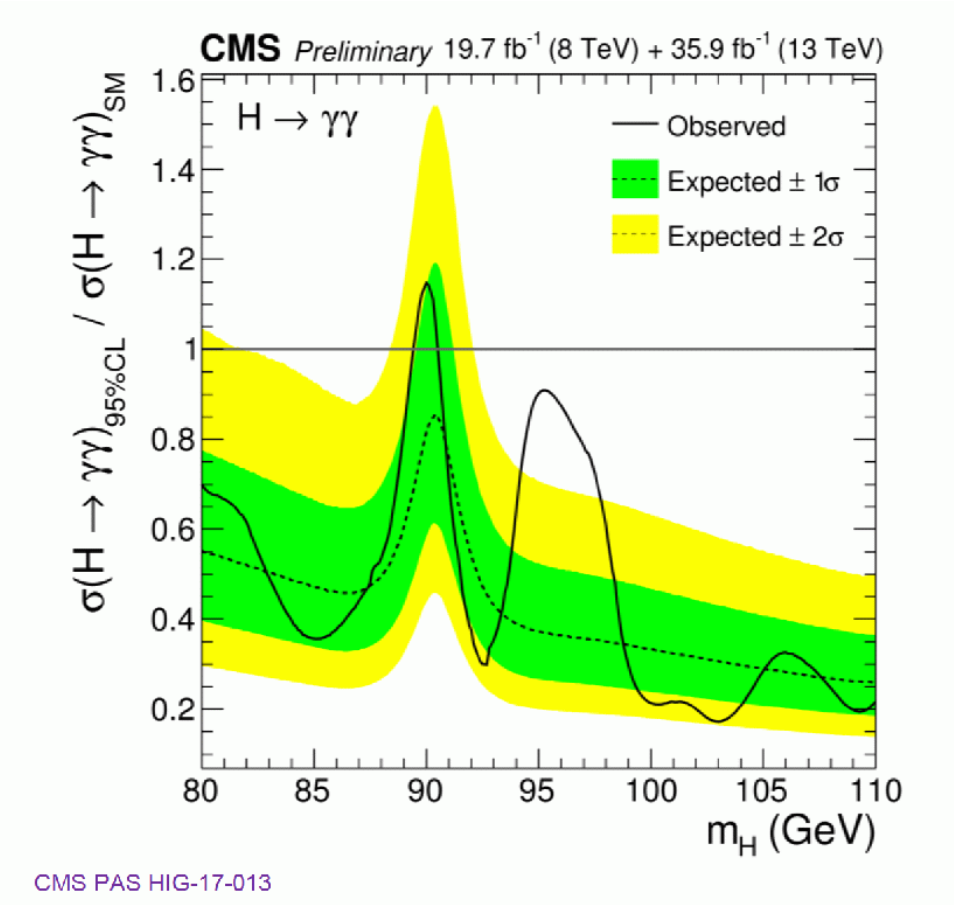
- 'Signal' strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing m_H=95.3 GeV
- More data are required to ascertain the origin of this excess

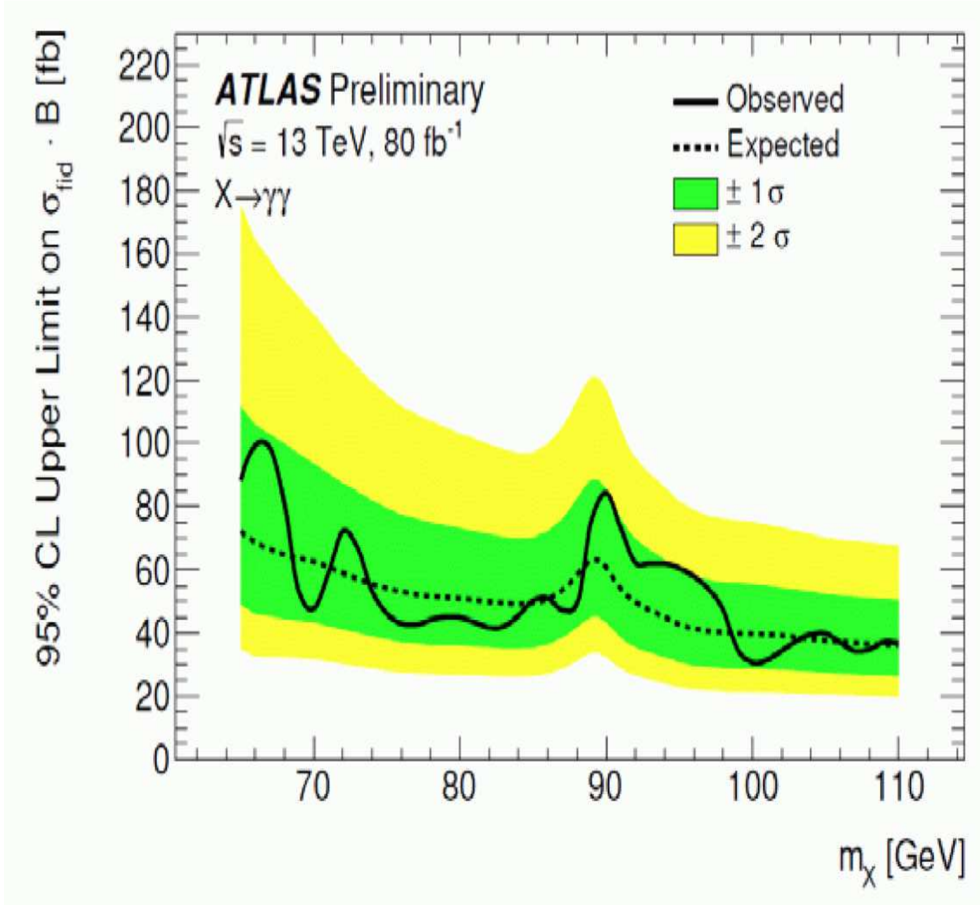
55

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017

$$\mu_{\rm CMS}(96\ {\rm GeV}) = [\sigma(pp \to h_1) \times {\rm BR}(h_1 \to \gamma\gamma)]_{\rm exp/SM} = 0.6 \pm 0.2$$

What about ATLAS?



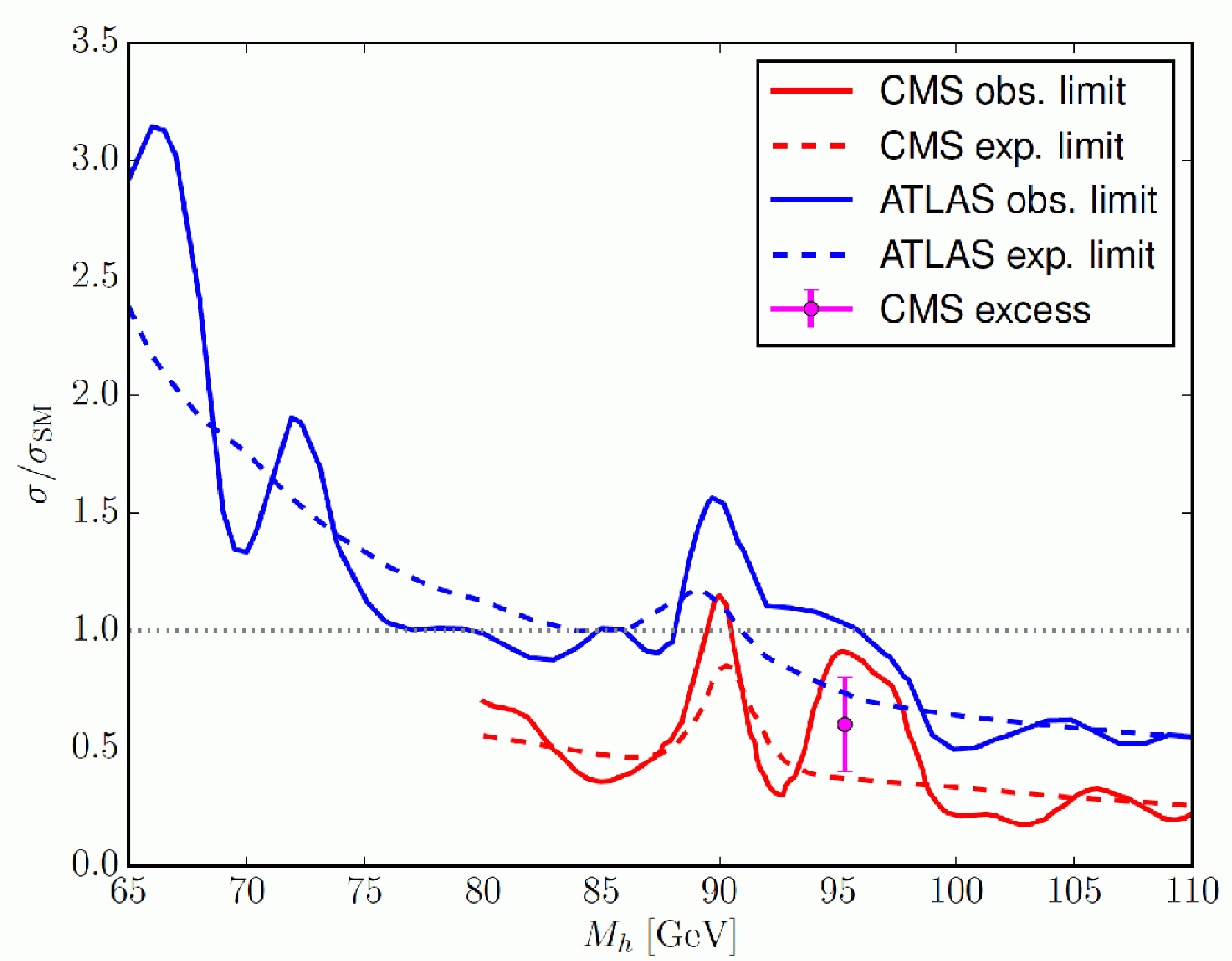


Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

⇒ ATLAS exclusion limit even weaker than CMS!

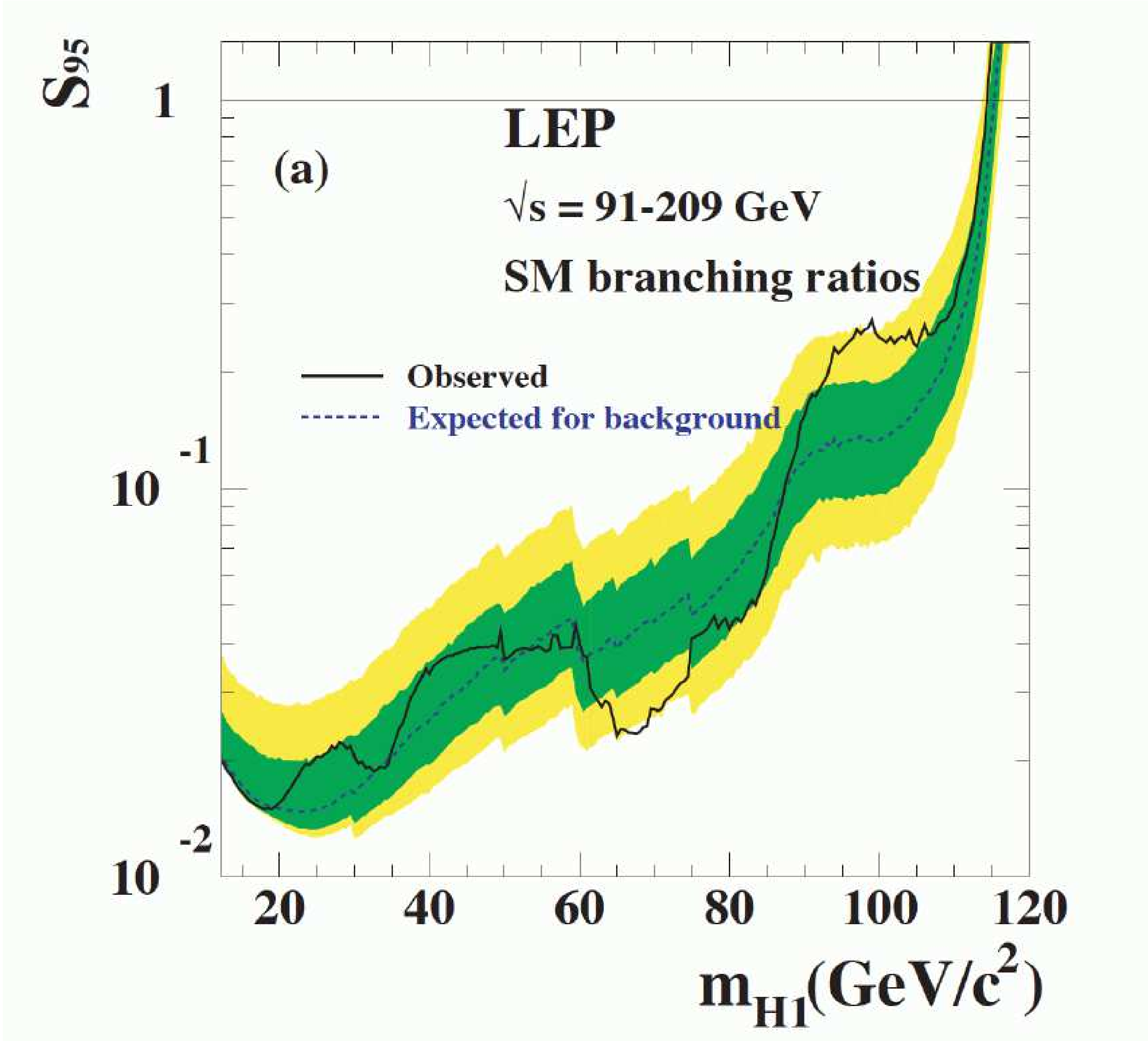
Q: why does ATLAS has same sensitivity with twice amount of data?

CMS and ATLAS in direct comparison: [S.H., T. Stefaniak '18]



⇒ everything well compatible with the excess!

What was seen at LEP?

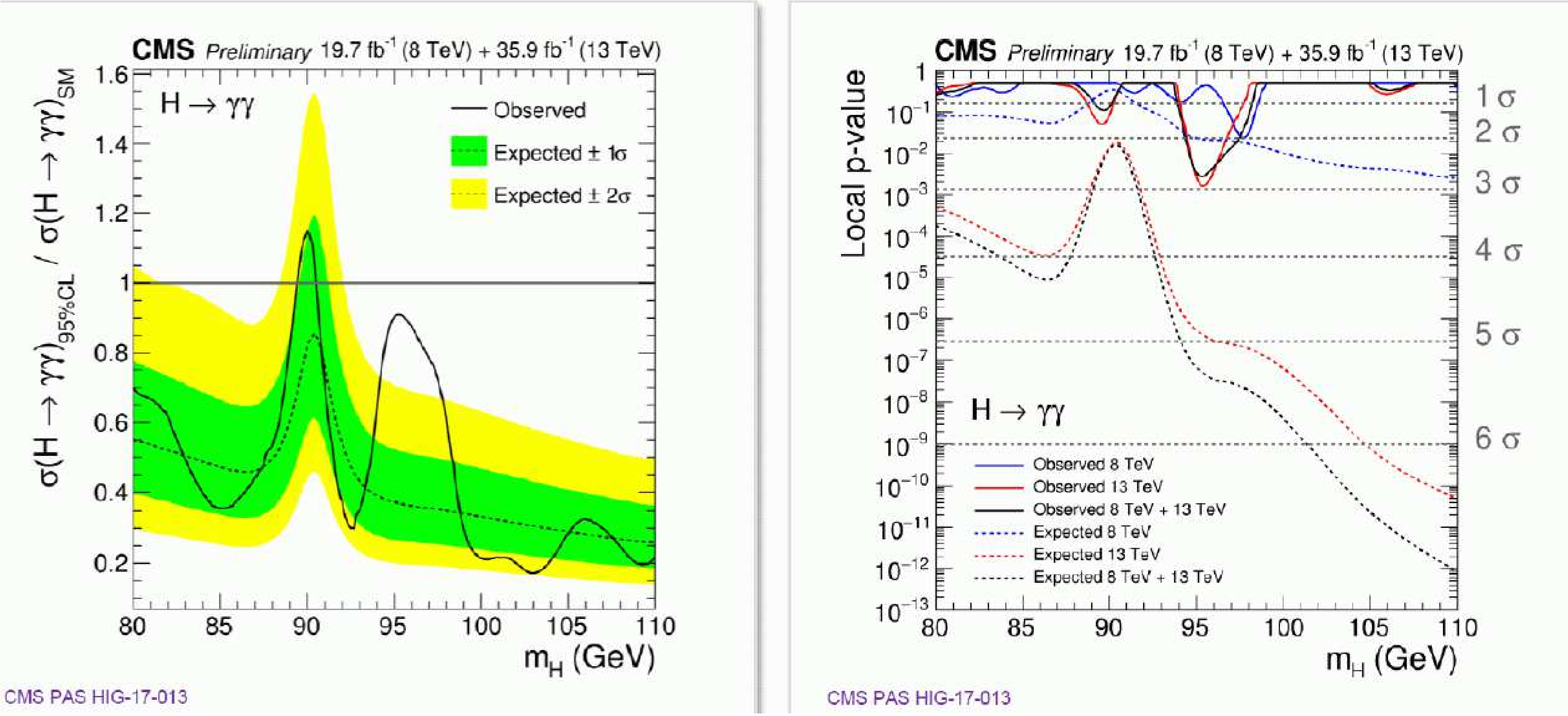


$$\mu_{\text{LEP}}(98\text{ GeV}) = \left[\sigma(e^+e^- \to Zh_1) \times \text{BR}(h_1 \to b\bar{b})\right]_{\text{exp/SM}} = 0.117 \pm 0.057$$

Should we get excited?

[*talk by L. Finco, HiggsHunting 18*]

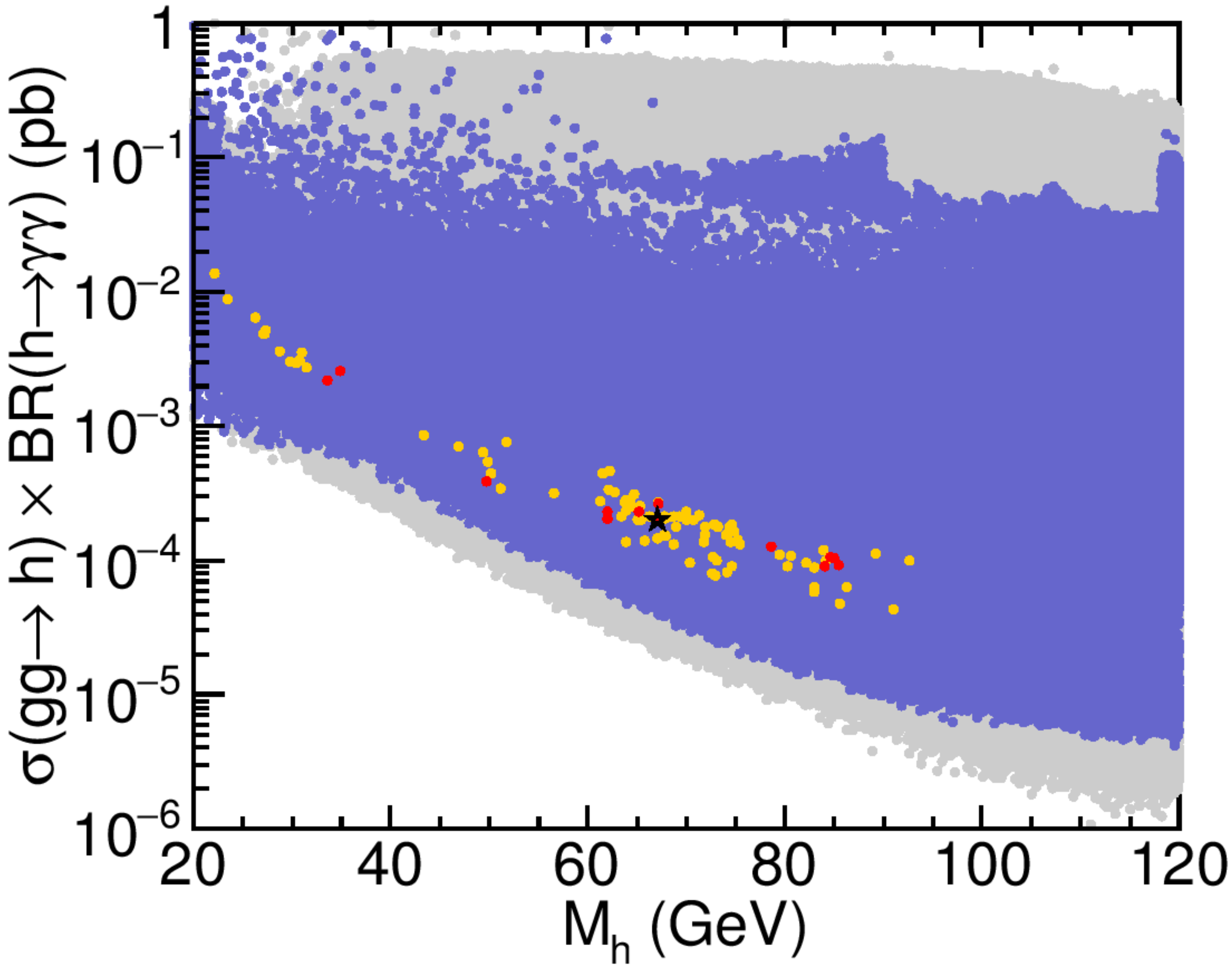
- **Combined 8 TeV + 13 TeV** σ×BR limit normalized to SM expectation:
  - Production processes assumed in SM proportions
  - **No significant excess** with respect to background expectations
- Expected and observed local p-values for **8 TeV**, **13 TeV** and their **combination**



Q: When do you dare to something "significant"?

What about the MSSM?

[*P. Bechtle, H. Haber, S.H., O. Stål, T. Stefaniak, G. Weiglein, L. Zeune '16*]



⇒ too small rates! ⇒ problem: 2HDM structure to "rigid"

More general Ansatz: **N2HDM**

[*T. Biekötter, M. Chakraborti, S.H. '19*]

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S$$

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S$

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton-specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

$\Rightarrow$ exactly as in 2HDM

Three neutral $\mathcal{CP}$-even Higgses:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} , \qquad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Coupling to massive gauge bosons: (identical for all four types)

	$c_{h_i VV} = c_\beta R_{i1} + s_\beta R_{i2}$
h_1	$c_{\alpha_2} c_{\beta-\alpha_1}$
h_2	$-c_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} s_{\beta-\alpha_1}$
h_3	$-c_{\alpha_3} c_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} s_{\beta-\alpha_1}$

Coupling to fermions: (same pattern as in 2HDM)

	u-type ($c_{h_i tt}$)	d-type ($c_{h_i bb}$)	leptons ($c_{h_i \tau\tau}$)
type I	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$
type II	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i1}}{c_\beta}$
type III (lepton-specific)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$
type IV (flipped)	$\frac{R_{i2}}{s_\beta}$	$\frac{R_{i1}}{c_\beta}$	$\frac{R_{i2}}{s_\beta}$

"Physical" input parameters:

$$\alpha_{1,2,3}\,, \quad \tan\beta\,, \quad v\,, \quad v_S\,, \quad m_{h_{1,2,3}}\,, \quad m_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Needed to fit the two excesses: $m_{h_1} \sim 96$ GeV, $m_{h_2} \sim 125$ GeV

- $c^2_{h_1VV}$ strongly reduced for μ_{LEP}
- c_{h_1bb} reduced to enhance $\text{BR}(h_1 \to \gamma\gamma)$
- c_{h_1tt} not reduced for μ_{CMS}
- $c_{h_1\tau\tau}$ possibly reduced to enhance $\text{BR}(h_1 \to \gamma\gamma)$

	Decrease $c_{h_1b\bar{b}}$	No decrease $c_{h_1t\bar{t}}$	No enhancement $c_{h_1\tau\bar{\tau}}$
type I	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{12}}{s_\beta})$:-)
type II	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{11}}{c_\beta})$:-)
type III	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(	$(\frac{R_{11}}{c_\beta})$:-(
type IV	$(\frac{R_{11}}{c_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-)	$(\frac{R_{12}}{s_\beta})$:-(

Type II and IV: c_{h_1bb} and c_{h_1tt} independent

Type II bonus: $c_{h_1\tau\tau}$ can be suppressed (together with c_{h_1bb})

$\Rightarrow$ only type II and IV can fit CMS and LEP excesses

$\Rightarrow$ Parameter scan $\Rightarrow$ ScannerS

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds (N2HDECAY)
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (N2HDECAY, SusHi)
  $\chi^2_{\text{red}} := \chi^2/n_{\text{obs}}$
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

Fitting the excesses:

$$\mu_{\text{LEP}} = 0.117 \pm 0.057, \qquad \mu_{\text{CMS}} = 0.6 \pm 0.2$$

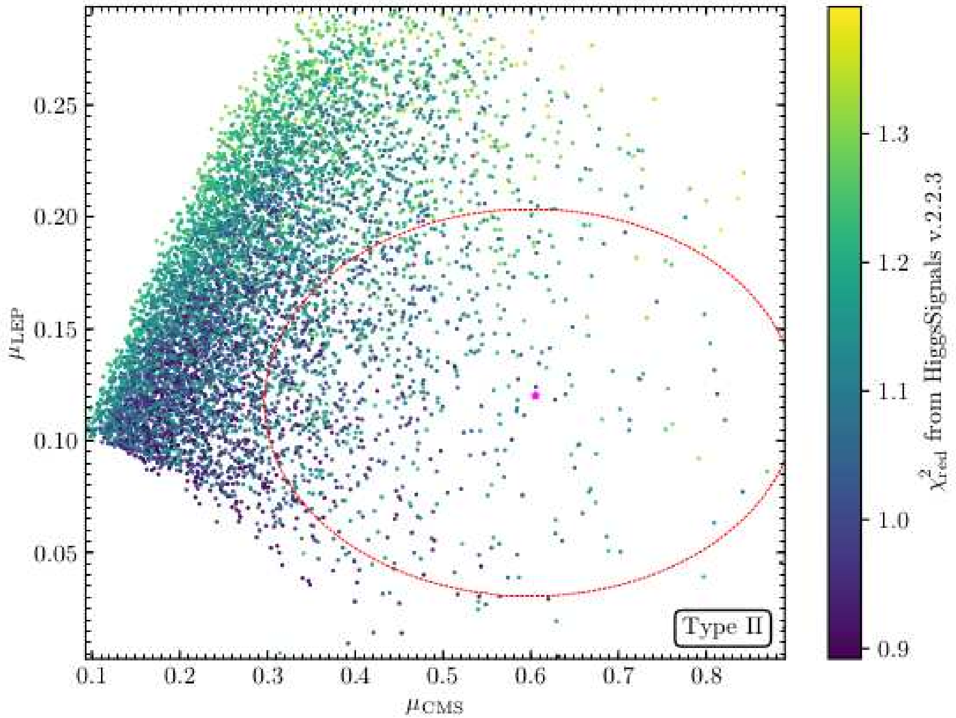
$$\begin{aligned}
\mu_{\text{LEP}} &= \frac{\sigma_{\text{N2HDM}}(e^+e^- \to Zh_1)}{\sigma_{\text{SM}}(e^+e^- \to ZH)} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})} \\
&= \left|c_{h_1VV}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to b\bar{b})}{\text{BR}_{\text{SM}}(H \to b\bar{b})}
\end{aligned}$$

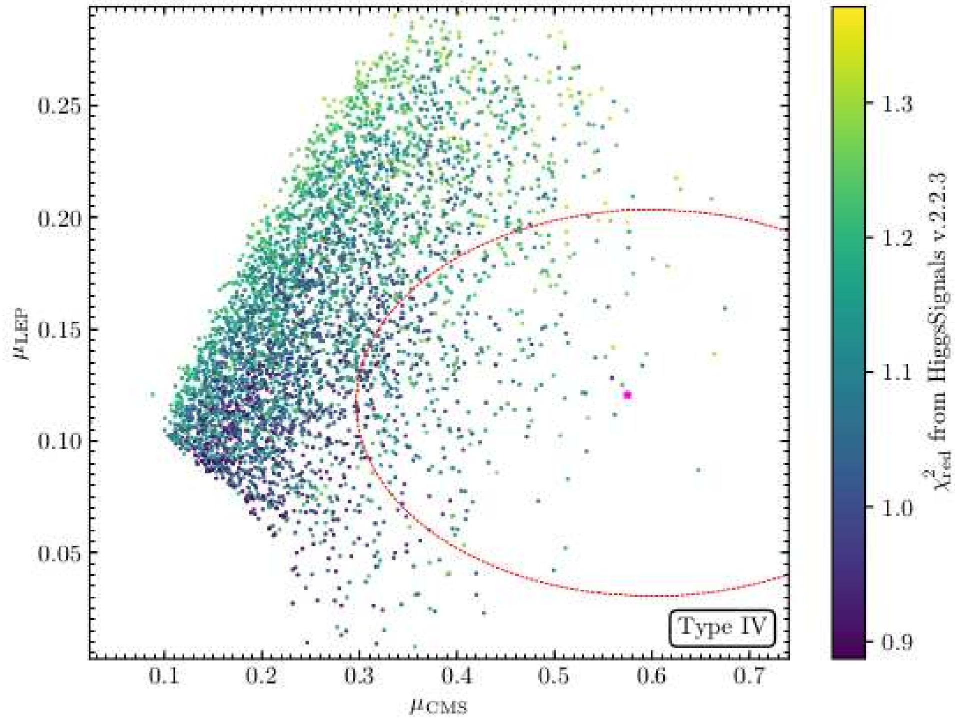
$$\begin{aligned}
\mu_{\text{CMS}} &= \frac{\sigma_{\text{N2HDM}}(gg \to h_1)}{\sigma_{\text{SM}}(gg \to H))} \cdot \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)} \\
&= \left|c_{h_1tt}\right|^2 \frac{\text{BR}_{\text{N2HDM}}(h_1 \to \gamma\gamma)}{\text{BR}_{\text{SM}}(H \to \gamma\gamma)}
\end{aligned}$$

$$\chi^2_{\text{CMS-LEP}} = \frac{(\mu_{\text{LEP}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\text{CMS}} - 0.6)^2}{(0.2)^2}$$

$\Rightarrow$ "best-fit point"

Fitting the excesses: [T. Biekötter, M. Chakraborti, S.H. '19]





$\Rightarrow$ excesses well fitted, with good $\chi^2_{\rm red}$

$\Rightarrow$ preferred $M_{H^\pm}$: 650 GeV – 950 GeV (lower limit: flavor constr.)
$\Rightarrow$ preferred $\tan\beta$: 0.8 – 3.8

Best-fit point in type II:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
96.5263	125.09	535.86	712.578	737.829	
$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.26287	1.26878	-1.08484	-1.24108	80644.3	272.72
$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.5048	0.2682	$5.09 \cdot 10^{-2}$	$2.582 \cdot 10^{-3}$	$1.37 \cdot 10^{-2}$	$1.753 \cdot 10^{-3}$
$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5916	0.0771	$6.36 \cdot 10^{-2}$	$2.153 \cdot 10^{-3}$	0.2087	$2.610 \cdot 10^{-3}$

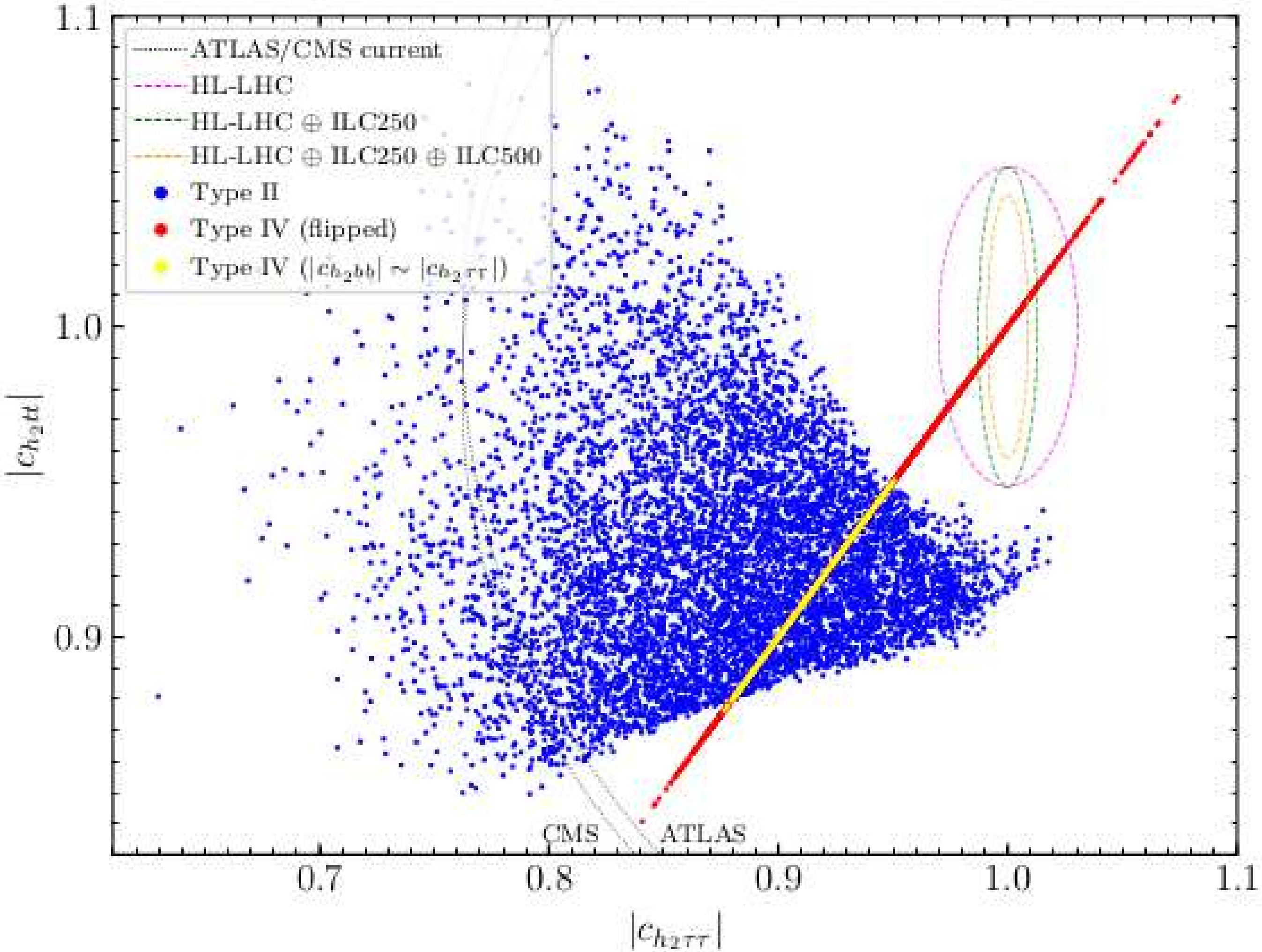
$\Rightarrow$ surprizingly large $\text{BR}_{h_1}^{\gamma\gamma}$

Best-fit point in type IV:

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$M_{H^\pm}$	
97.8128	125.09	485.998	651.502	651.26	
$\tan\beta$	α_1	α_2	α_3	m_{12}^2	v_S
1.3147	1.27039	-1.02829	-1.32496	41034.1	647.886
$\text{BR}_{h_1}^{bb}$	$\text{BR}_{h_1}^{gg}$	$\text{BR}_{h_1}^{\tau\tau}$	$\text{BR}_{h_1}^{\gamma\gamma}$	$\text{BR}_{h_1}^{WW}$	$\text{BR}_{h_1}^{ZZ}$
0.4074	0.20714	0.248324	$2.139 \cdot 10^{-3}$	$1.347 \cdot 10^{-2}$	$1.579 \cdot 10^{-3}$
$\text{BR}_{h_2}^{bb}$	$\text{BR}_{h_2}^{gg}$	$\text{BR}_{h_2}^{\tau\tau}$	$\text{BR}_{h_2}^{\gamma\gamma}$	$\text{BR}_{h_2}^{WW}$	$\text{BR}_{h_2}^{ZZ}$
0.5363	0.09388	$7.58 \cdot 10^{-2}$	$2.247 \cdot 10^{-3}$	0.2267	$2.836 \cdot 10^{-2}$

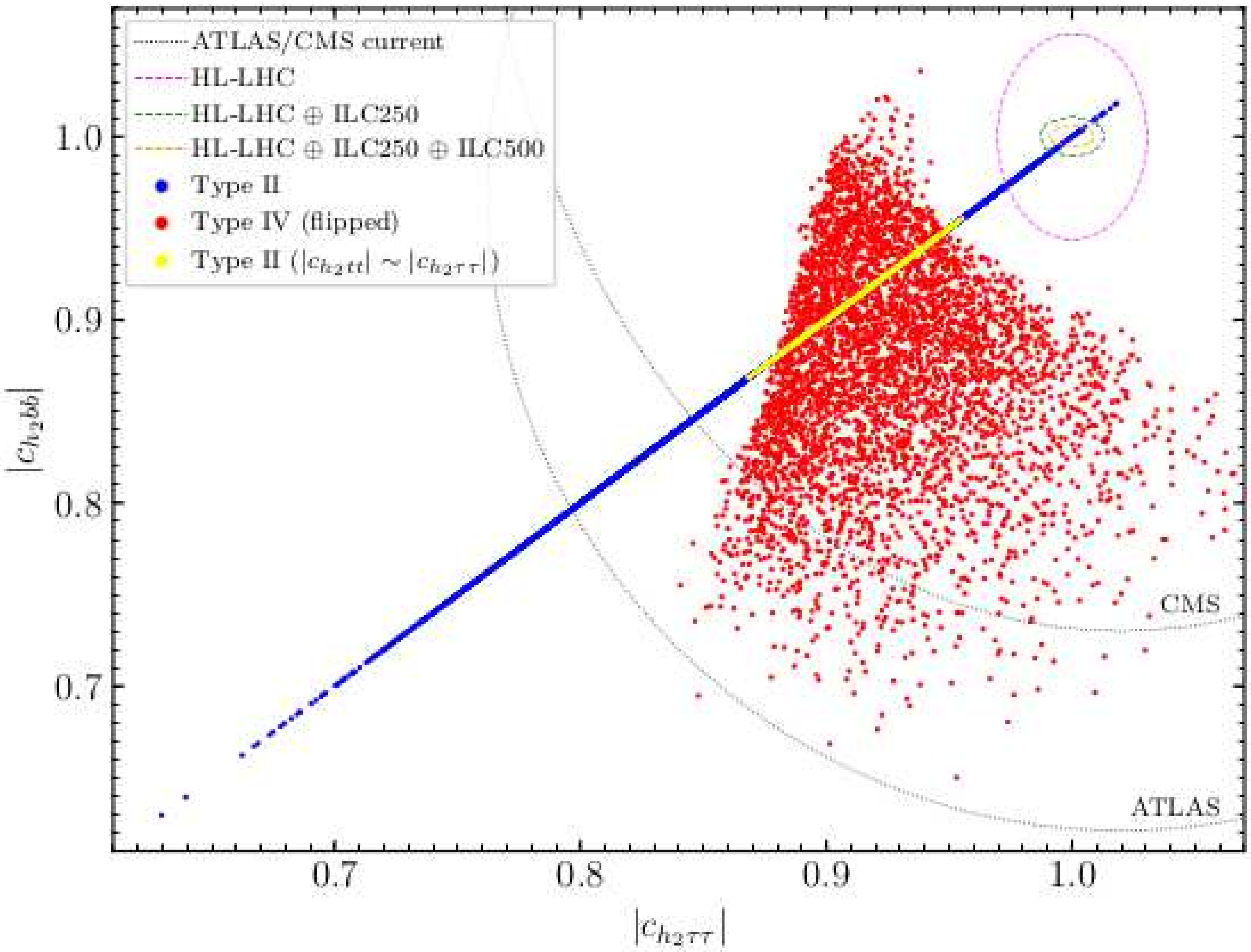
$\Rightarrow$ substantially larger $\text{BR}_{h_1}^{\tau\tau}$ than in type II

Next project? ⇒ ILC Higgs coupling measurements



⇒ type II shows deviation from SM

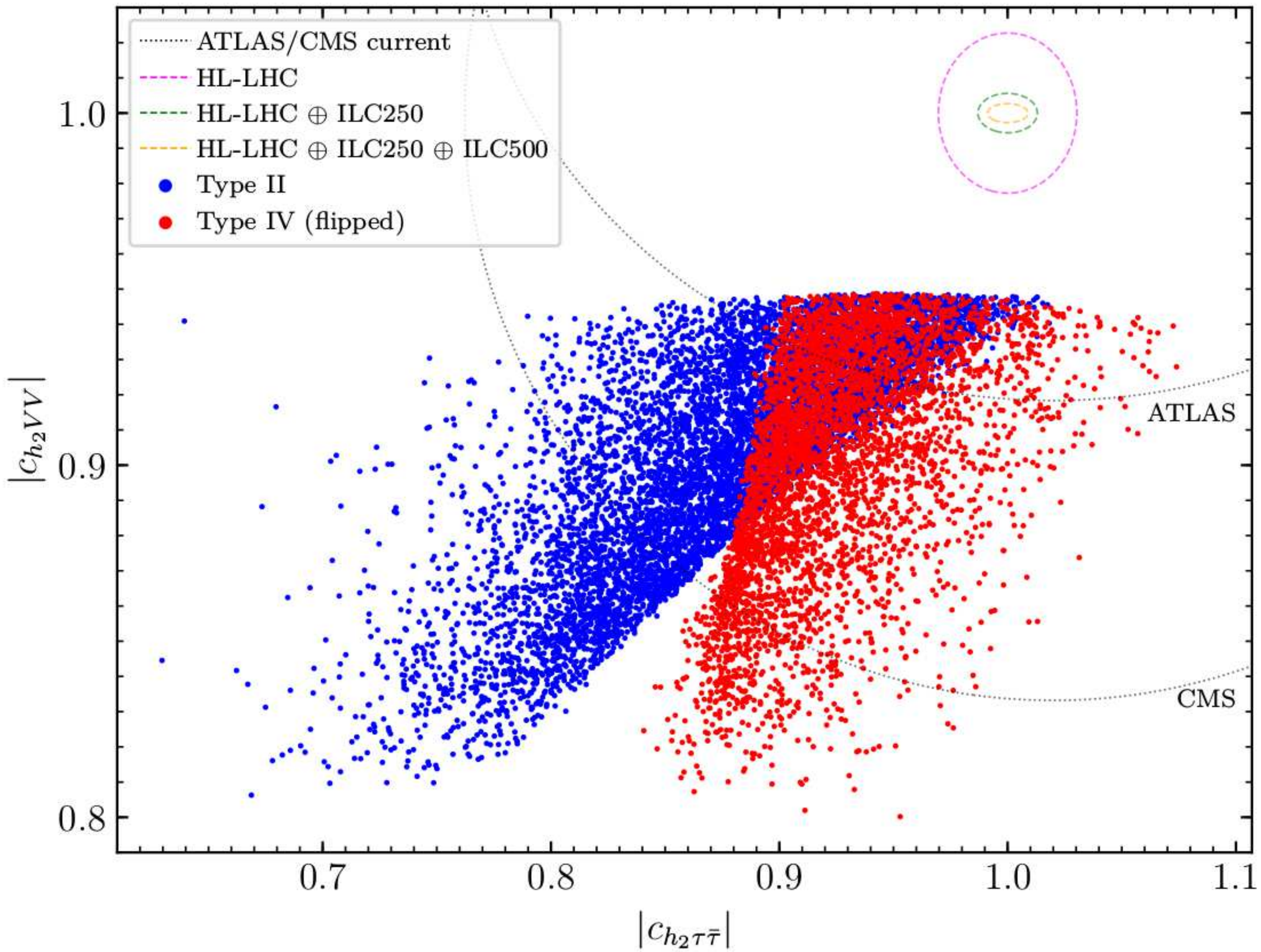
Next project? ⇒ ILC Higgs coupling measurements



⇒ type IV shows deviations from SM

⇒ N2HDM can always be distinguished from SM!

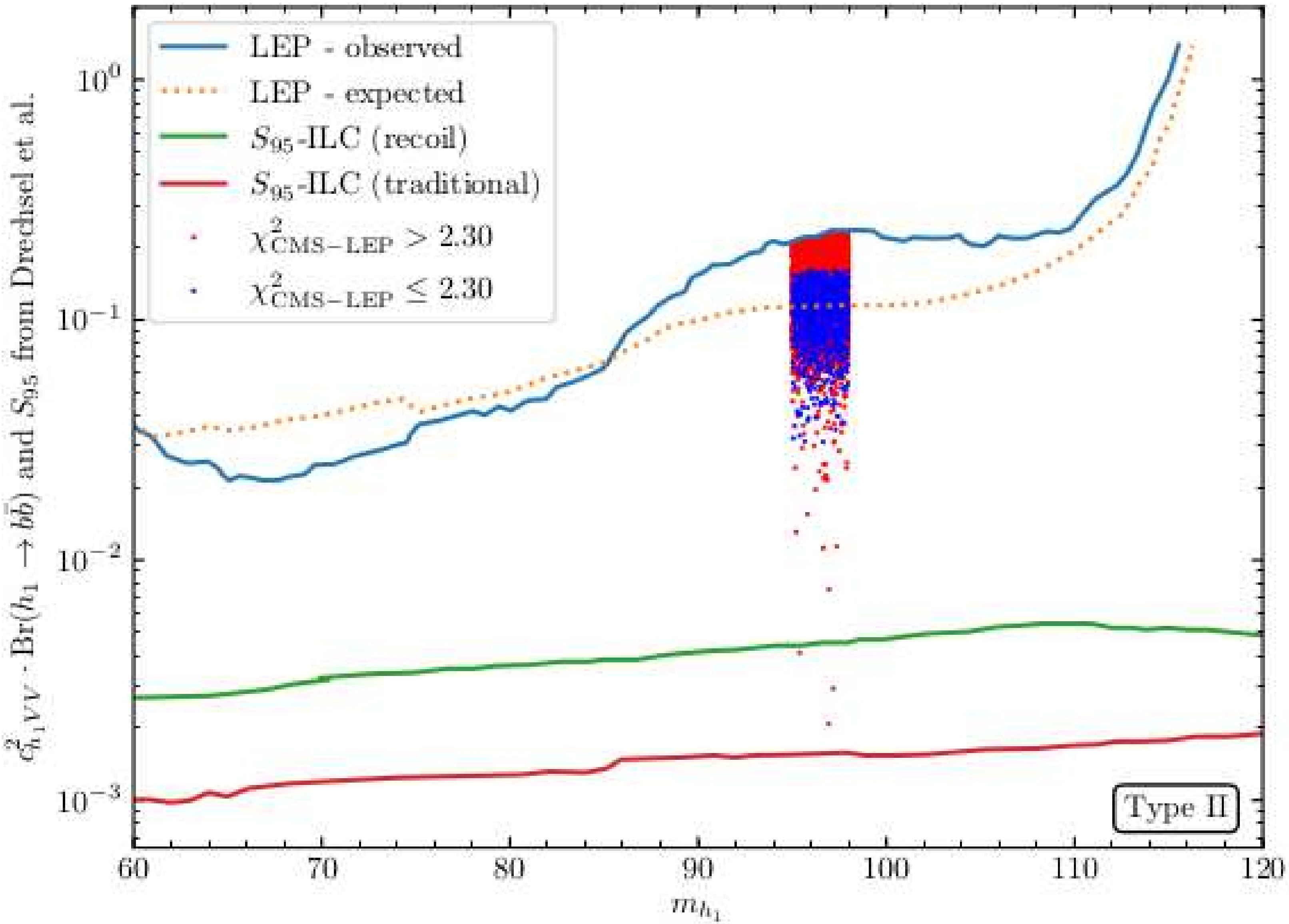
Next project? ⇒ ILC Higgs coupling measurements



⇒ type II and IV show strong deviations from SM

⇒ N2HDM can always be distinguished from SM!

Next project? ⇒ ILC production of the light scalar



⇒ new state easily in the reach of the ILC

What about SUSY??

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⇒ type II fits best, type II is needed for SUSY

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$\Rightarrow$ models with an additional singlet??

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– NMSSM
– $\mu\nu$SSM
– . . .

What about SUSY??

$\Rightarrow$ type II fits best, type II is needed for SUSY

$\Rightarrow$ models with an additional singlet??

- NMSSM
- $\mu\nu$SSM
- ...

Q: Can the models fit the excesses despite the additional SUSY constraints on the Higgs sector **???**

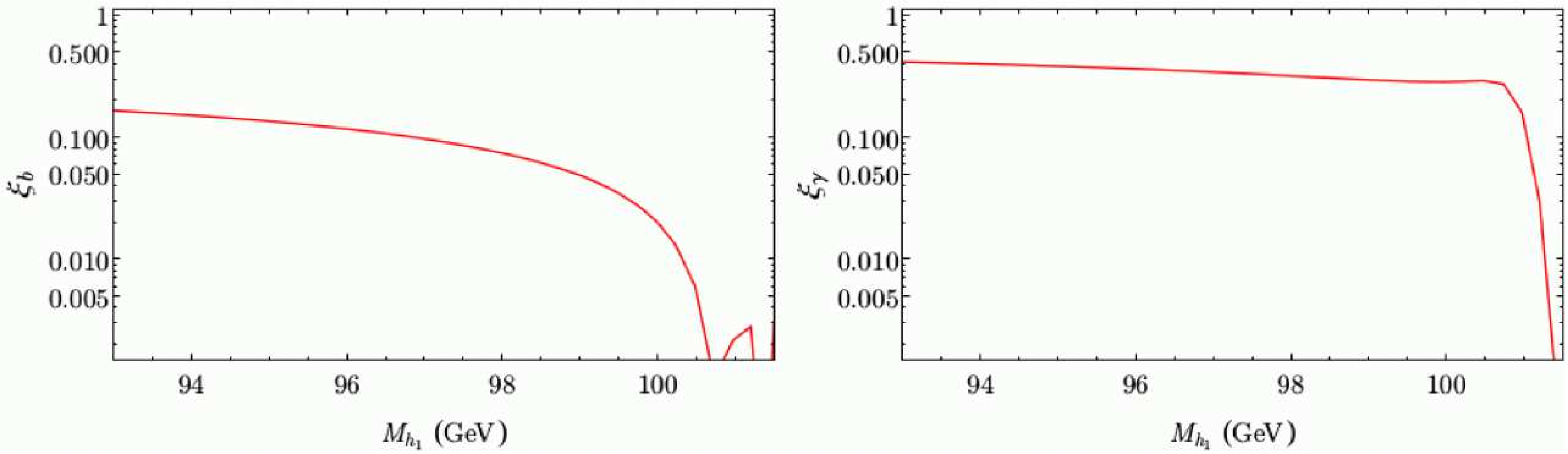
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

$\lambda = 0.6,\ \kappa = 0.035,\ \tan\beta = 2,\ \mu_{\rm eff} = (397 + 15x)$ GeV, $M_{H^\pm} = 1$ TeV, $A_\kappa = -325$ GeV, $M_{\rm SUSY} = 1$ TeV, $A_t = A_b = 0$

$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ]\cdot {\rm BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\rm SM}(M_{h_1}) \to ZZ]\cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\rm SM}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg]\cdot {\rm BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\rm SM}(M_{h_1}) \to gg]\cdot {\rm BR}[H_{\rm SM}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\rm SM}(M_{h_1}) \to \gamma\gamma]}\,.$$



⇒ both excesses can be fitted simultaneously!

What about the $\mu\nu$SSM?

$\mu\nu$SSM: [*D. Lopez-Fogliani, C. Muñoz '06*]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

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$\Rightarrow$ EW scale seesaw to reproduce the neutrino data

Can the $\mu\nu$SSM explain the two excesses?

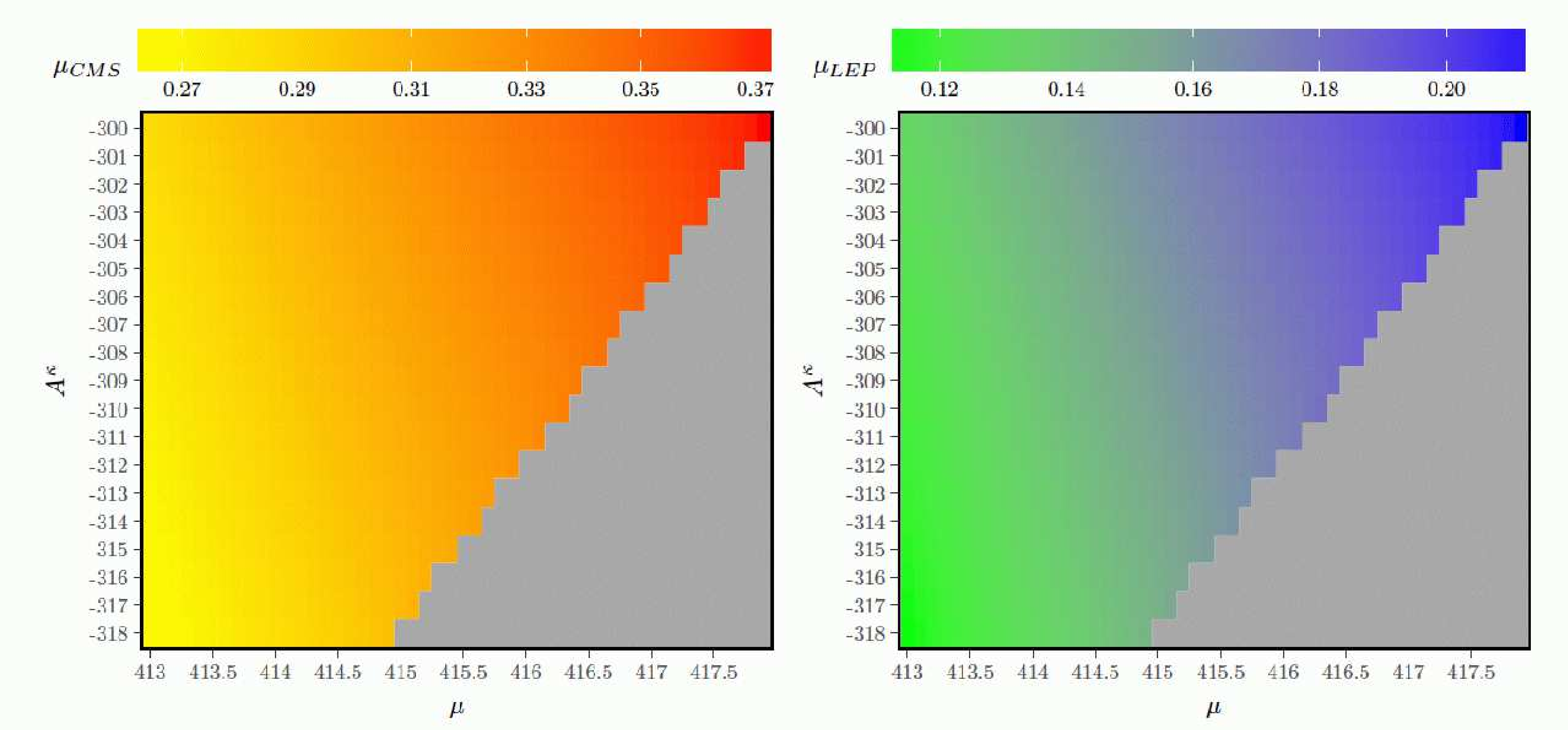
[*T. Biekötter, S.H., C. Muñoz '17*]

v_{iL}	Y_i^ν	A_i^ν	$\tan\beta$	μ	λ	A^λ	κ	A^κ	M_1
$\sqrt{2}\cdot 10^{-5}$	10^{-7}	-1000	2	$[413;418]$	0.6	956.035	0.035	$[-300;-318]$	100

M_2	M_3	$m^2_{\widetilde{Q}_{iL}}$	$m^2_{\widetilde{u}_{iR}}$	$m^2_{\widetilde{d}_{iR}}$	A_1^u	$A_{2,3}^{u,d}$	$(m^2_{\widetilde{e}})_{ii}$	A^e_{33}	$A^e_{11,22}$
200	1500	800^2	800^2	800^2	0	0	800^2	0	0

Can the $\mu\nu$SSM explain the two excesses?

[*T. Biekötter, S.H., C. Muñoz '17*]



$\Rightarrow$ YES, WE CAN! :-)

(at the $1 - 1.5\,\sigma$ level)


Further Questions?