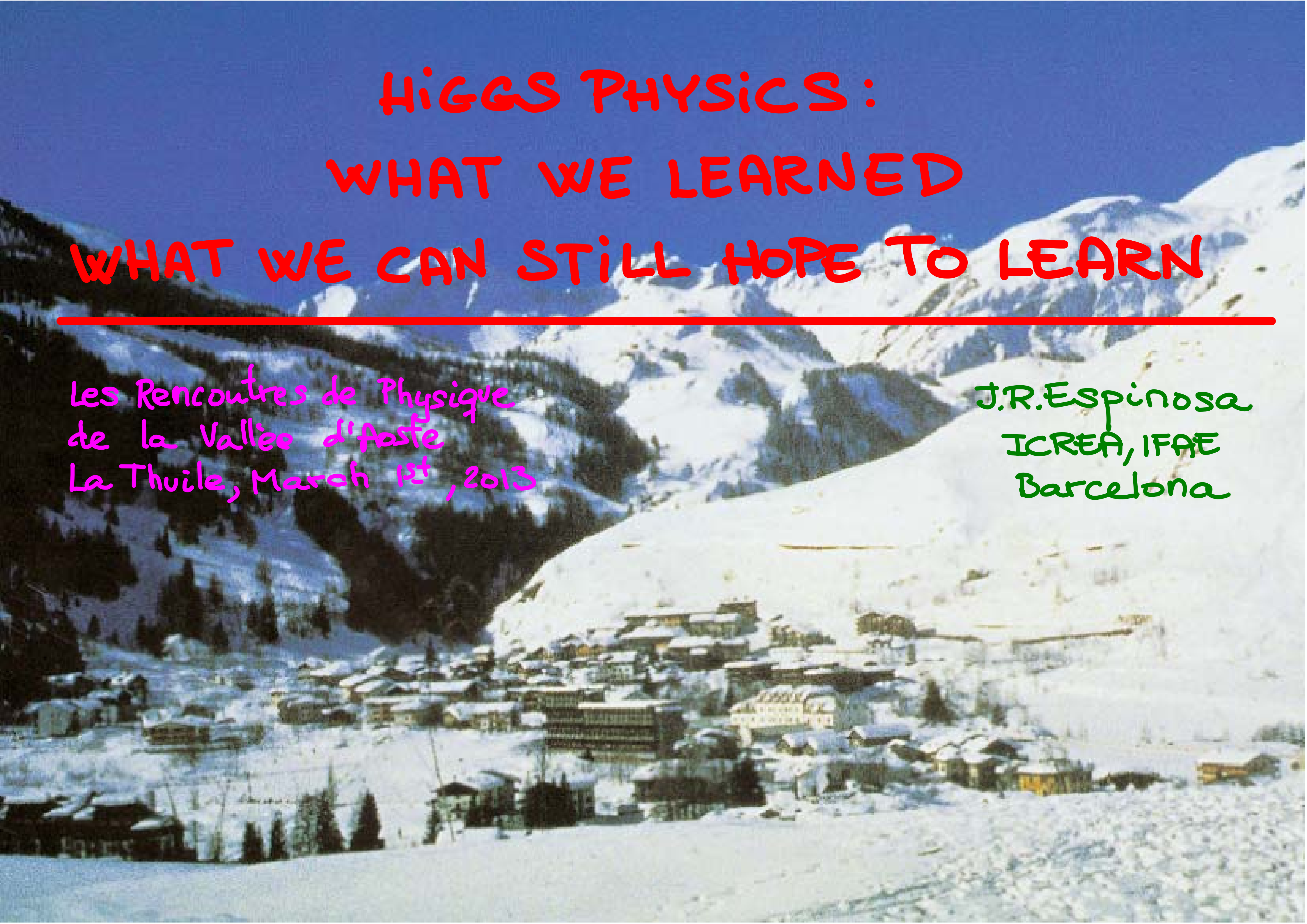


HIGGS PHYSICS: WHAT WE LEARNED WHAT WE CAN STILL HOPE TO LEARN

Les Rencontres de Physique
de la Vallée d'Aoste
La Thuile, March 1st, 2013

J.R.Espinosa
ICREA, IFAE
Barcelona

FIRST GLIMPSES OF HIGGS' FACE

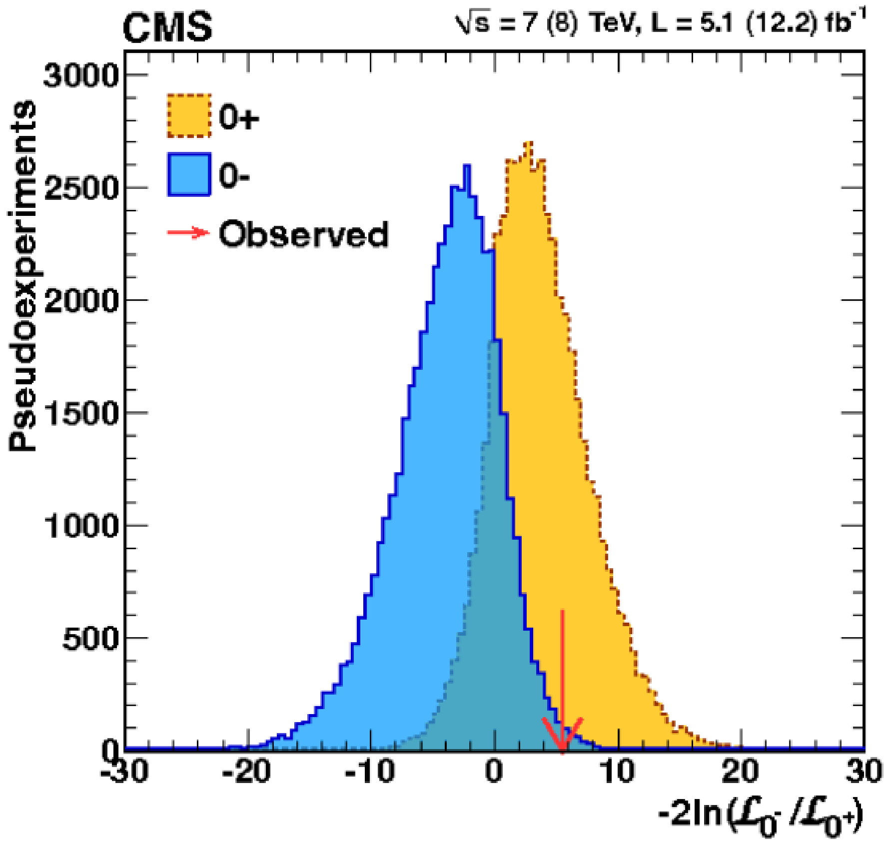
HIGGS BOSON

h^0

HIGGS BOSON

h^0

$J^P = 0^+$



0^- excluded@ 97%CL

HIGGS BOSON

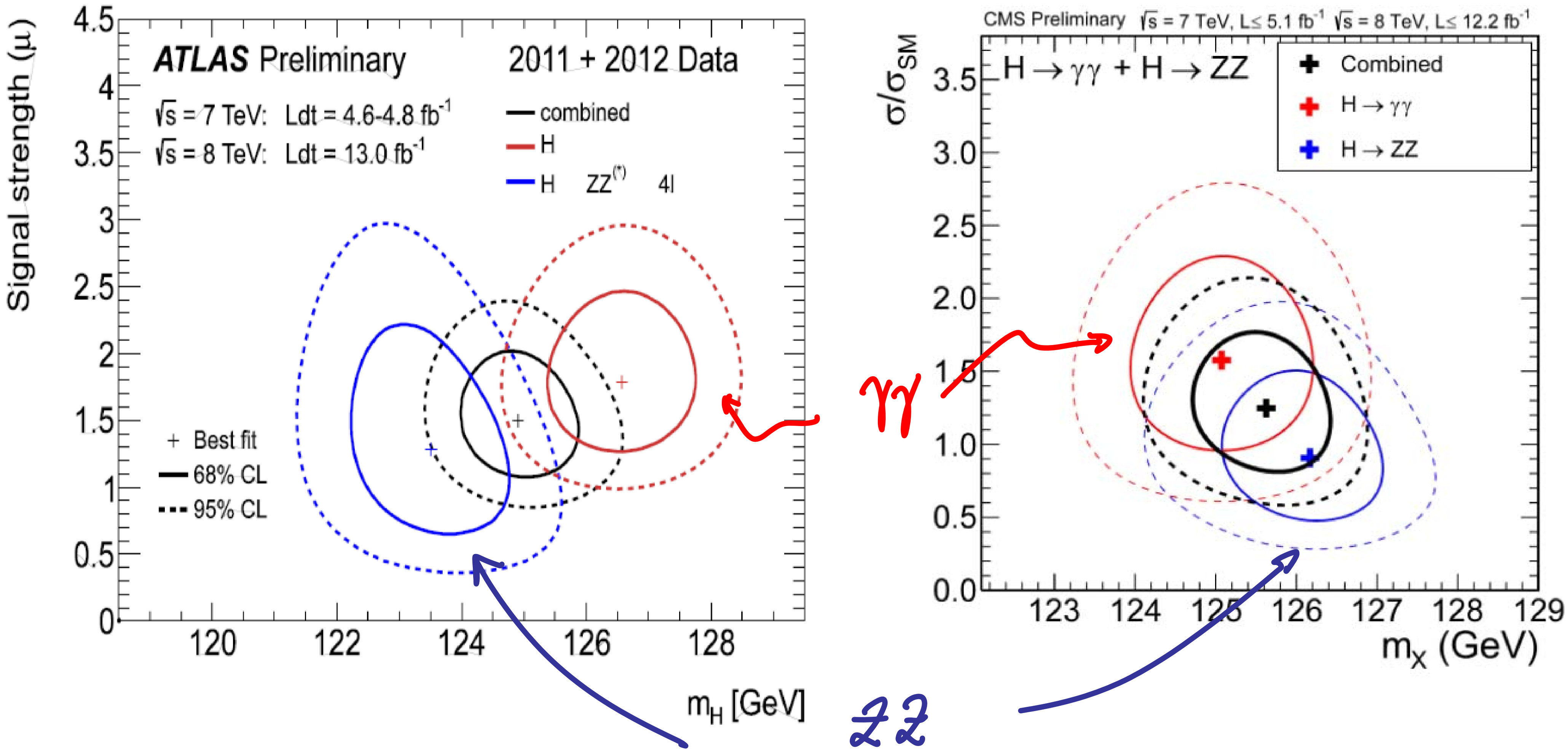
h^0

$J^P = 0^+$

h^0 MASS

VALUE (GeV)	*DOCUMENT ID*
125.2 + 0.3(stat) + 0.6 (syst)	ATLAS-CONF-2012-170
125.3 + 0.4(stat) + 0.5 (syst)	CMS-HIG-12-028

MASS DETERMINATION



MASS DETERMINATION

HIGGS BOSON

h^0

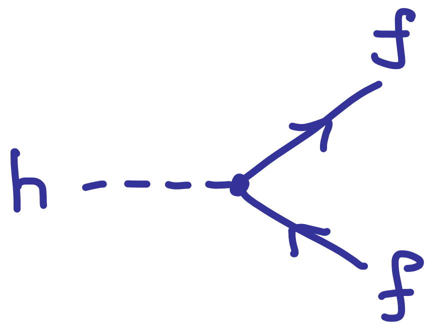
$J^P = 0^+$

h^0 MASS

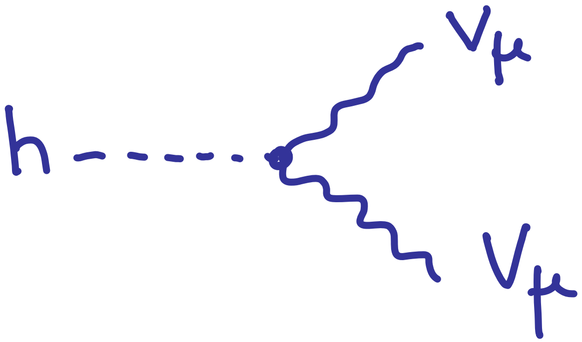
VALUE (GeV)	*DOCUMENT ID*
125.2 + 0.3(stat) + 0.6 (syst)	ATLAS-CONF-2012-170
125.3 + 0.4(stat) + 0.5 (syst)	CMS-HIG-12-028

h^0 couplings

HIGGS COUPLINGS SEEN SO FAR

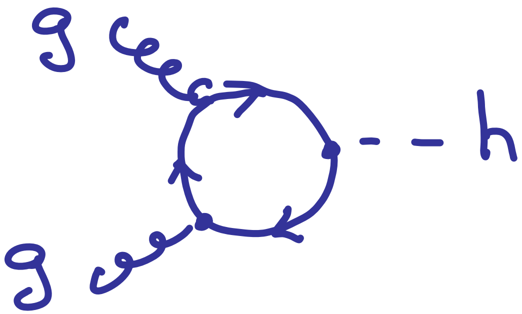


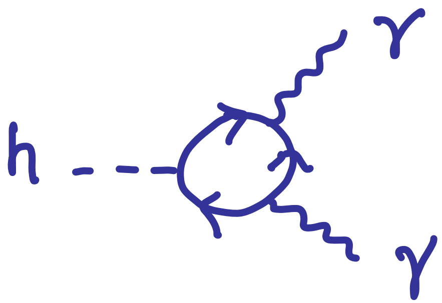
$$f = \begin{cases} \text{top (indirectly)} \\ \text{bottom} \\ \text{tau} \end{cases}$$

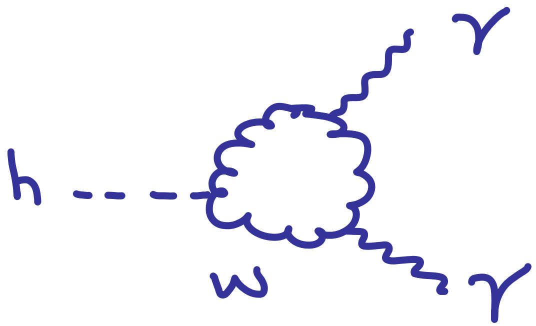


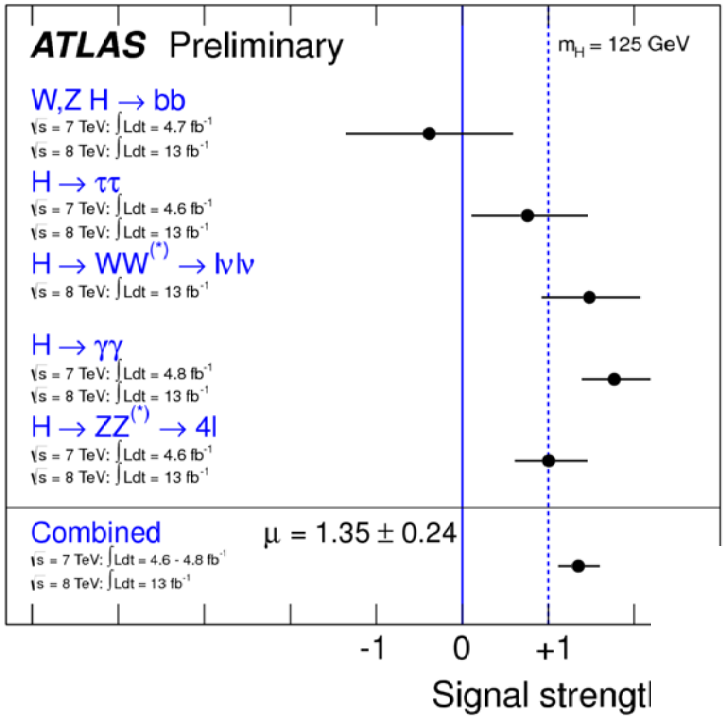
$$V_\mu = \begin{cases} W \\ Z \end{cases}$$

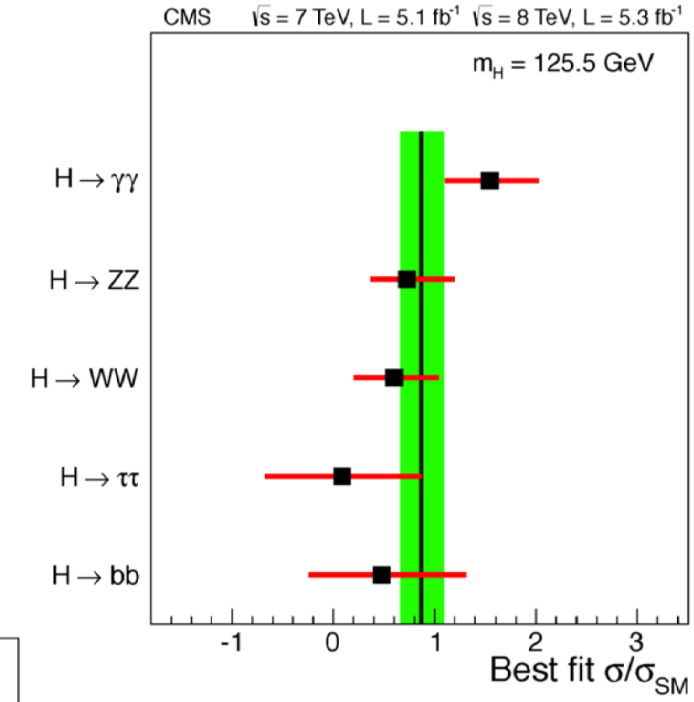
LOOP INDUCED

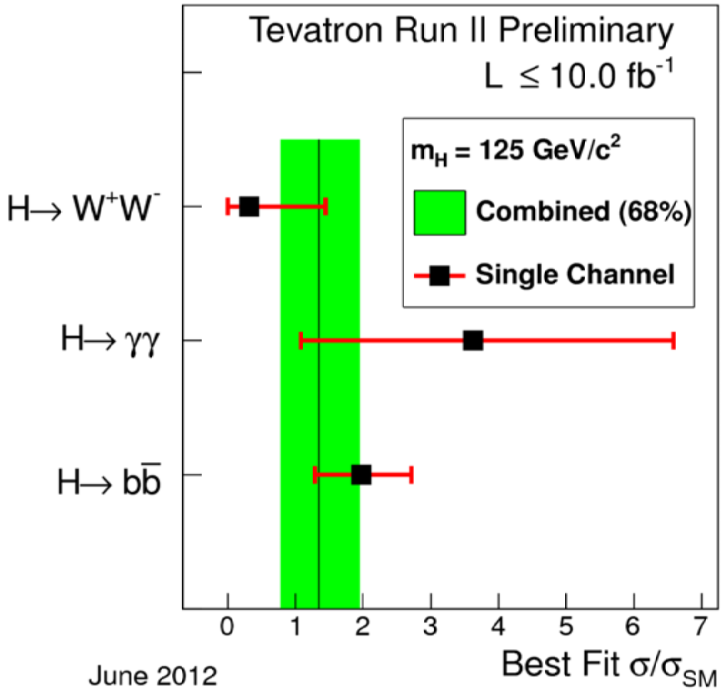












See next talks by Rescigno & Azzurri.

Values close to SM-like.

But wait, The Higgs is no ordinary particle!

* We're seeing the first non-gauge interactions
* We might be seeing the first spin 0 fundamental particle!
* We want to learn about the mechanism behind electroweak symmetry breaking!
* From that perspective, some quantities are more important than others:

Mass value — Important

Determining J^P/Discarding $J=2$ — Less so

Precise measurement of couplings — Crucial

WHY COUPLINGS MATTER

SM Higgs sector is the less tested and more problematic

Affected by hierarchy problem

Calls for new physics at the TeV scale

It's very likely that the Higgs will depart from its SM properties

The importance of measuring Higgs couplings: window to natural new physics

LEARNING ABOUT THE ~~HIGGS BOSON~~ EWSB

1. Implications from $M_h \sim 125$ GeV
   - ➡ Potential Instability in SM
2. Global Fits to Higgs Data
   BSM Hopes
   - ➡ Deviations from SM couplings

For recent work see:

- Stability

M. Holthausen, K.S. Lim, M. Lindner [hep-ph/1112.2415]

F. Bezrukov, M.Y. Kalmykov, B.A. Kniehl, M. Shaposhnikov [hep-ph/1205.2893]

J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Riotto, A. Strumia + H.M. Lee + G. Degrassi, S. Di Vita

[hep-ph/1112.3022], [hep-ph/1203.0237], [hep-ph/1205.6497]

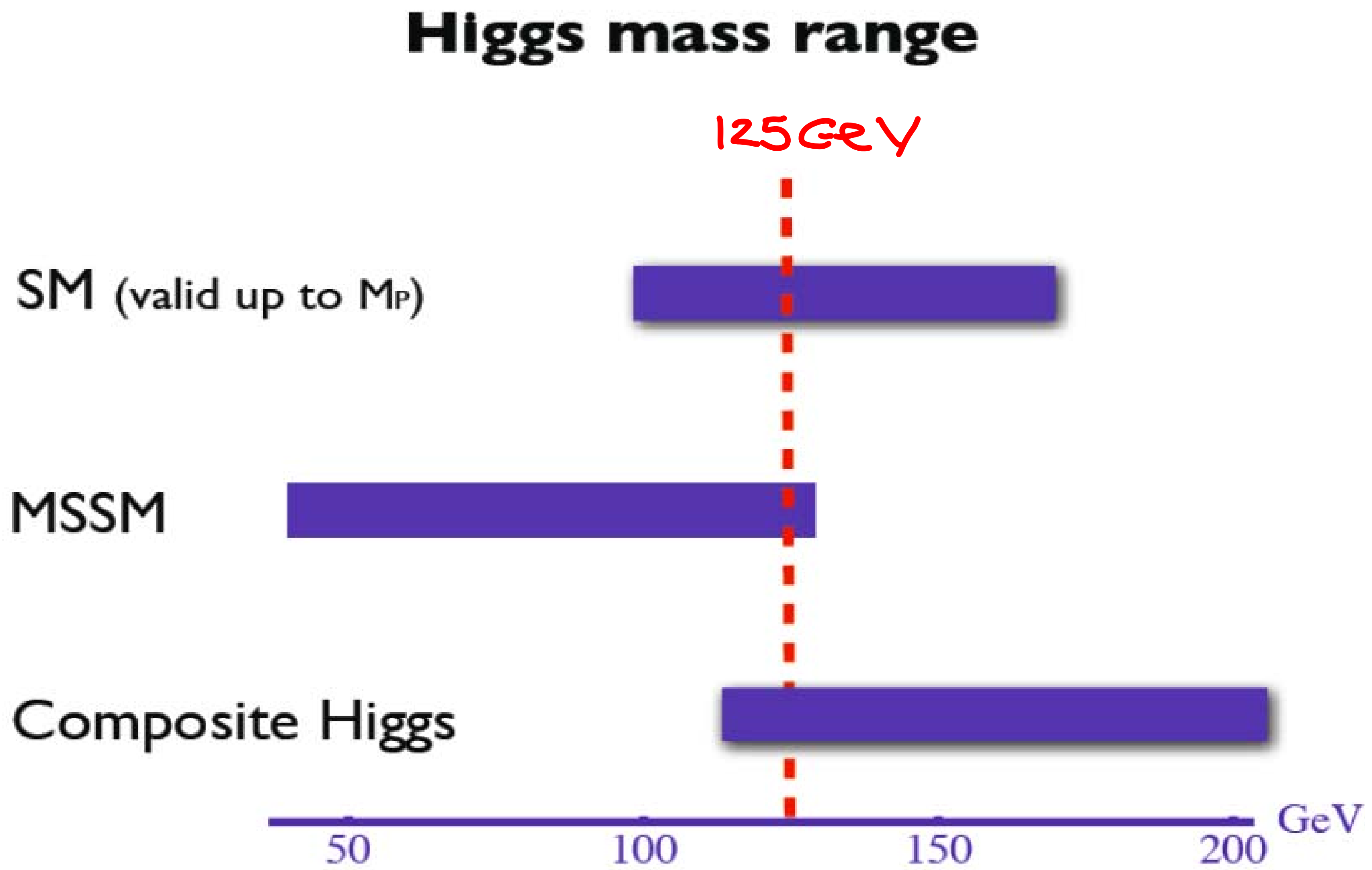
For recent work see:

- **Global Fits to Higgs Data**

Carmi, Falkowski, Kuflik, Volansky [1202.3144][1206.4201]
+ Zupan [1207.1718] Azatov, Contino, Galloway [1202.3415][1206.3171]
Giardino, Kannike, Raidal, Strumia [1203.4254][1207.1347]
Ellis, You [1204.0464][1207.1693]
Klute, Lafaye, Plehn, Rauch, Zerwas [1205.2699]
Plehn, Rauch [1207.6108] Low, Lykken, Shaughnessy [1207.1093]
Corbett, Eboli, González-Fraile, González-García [1207.1344][1211.4580]
Montull, Riva [1207.1716], Belanger et al. [1212.5244][1302.5694]
Cacciapaglia et al. [1211.4580] +...

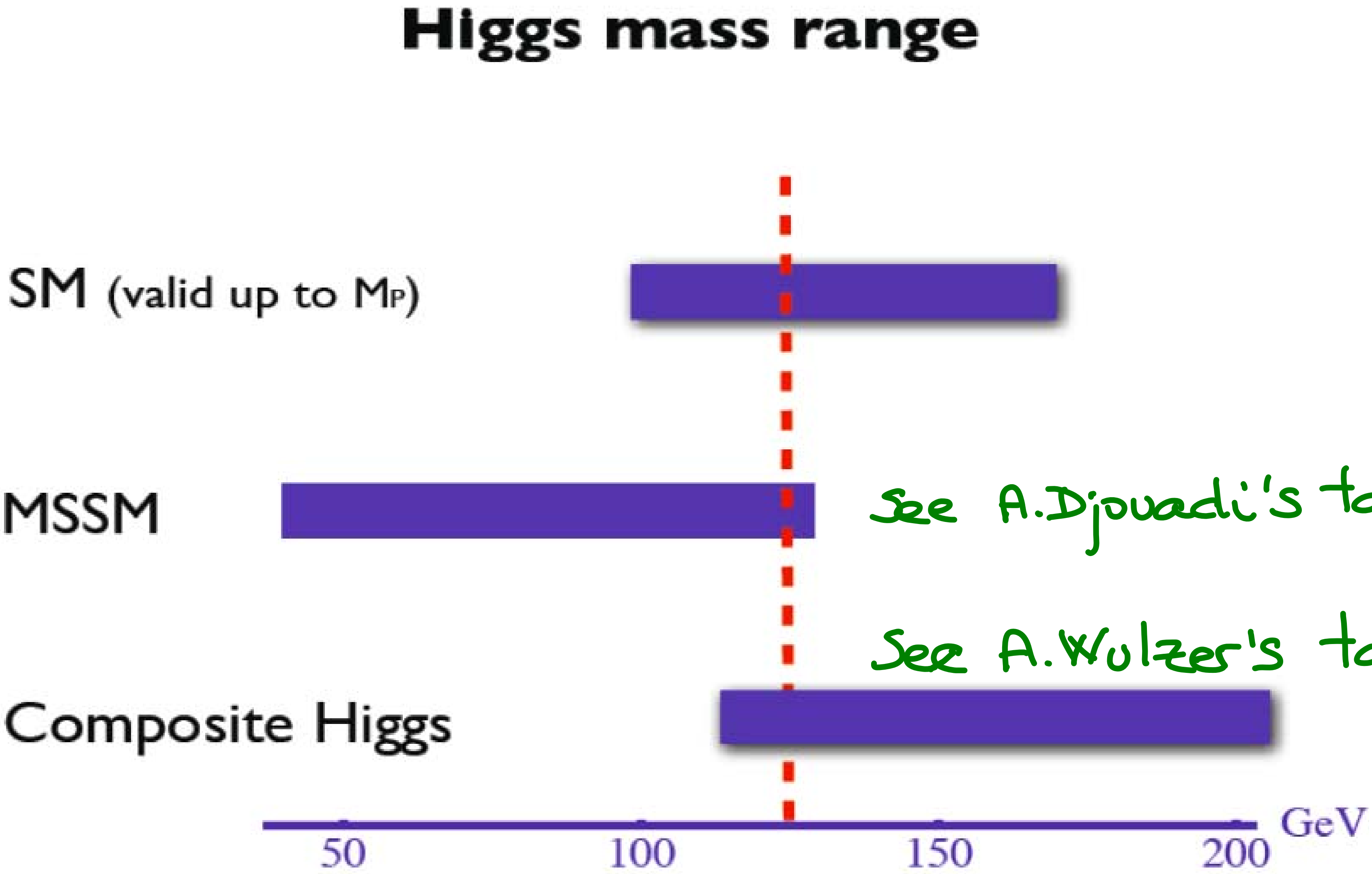
J.R.E, C. Grojean, M. Muhlleitner, M. Trott
[hep-ph/1202.3697], [hep-ph/1205.6790], [hep-ph/1207,1717]

M_h AS MODEL DISCRIMINATOR



A. Pomarol, ICHEP'12

M_h AS MODEL DISCRIMINATOR



See A. Djouadi's talk

See A. Wulzer's talk

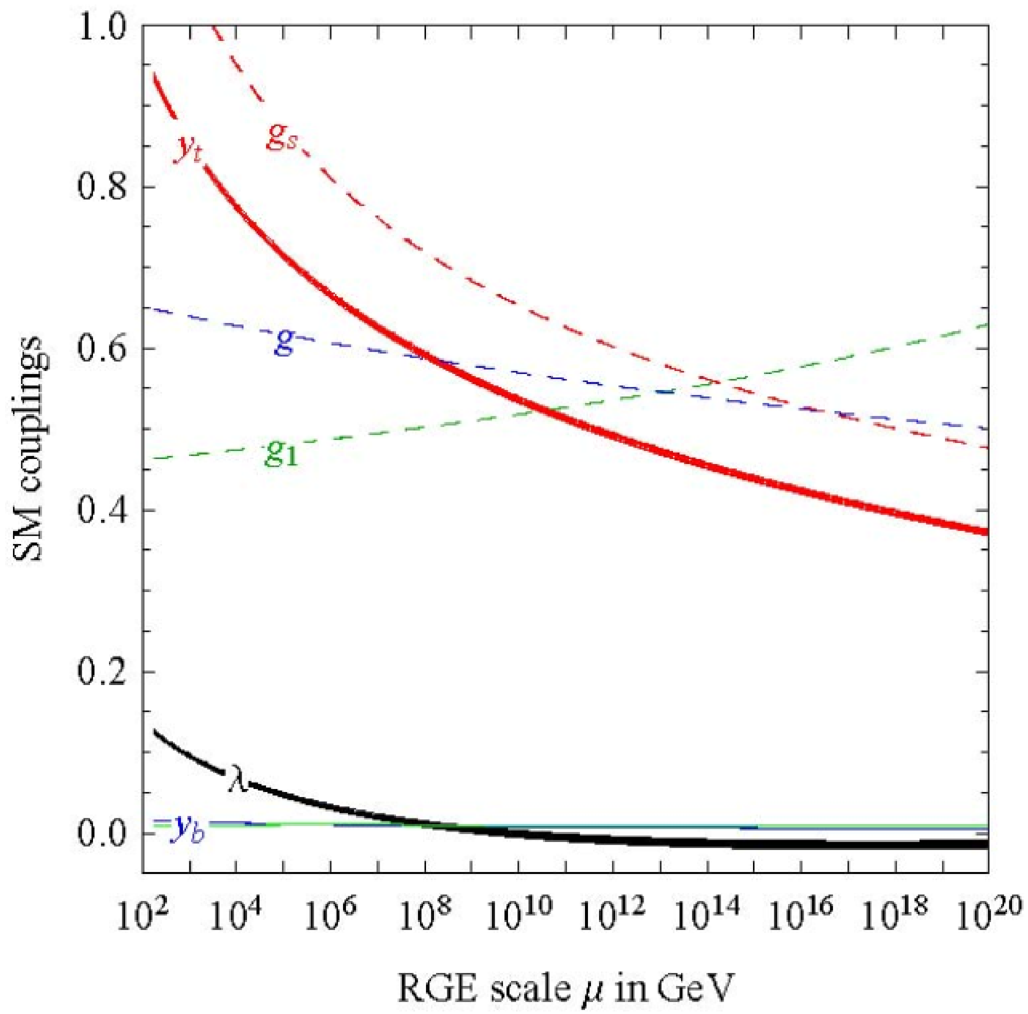
A. Pomarol, ICHEP'12

(1) $M_H \sim 125$ GeV. Implications for Stability

Assume scalar has SM props. and no BSM Physics

All SM parameters known

$M_h \Rightarrow \lambda(EW)$

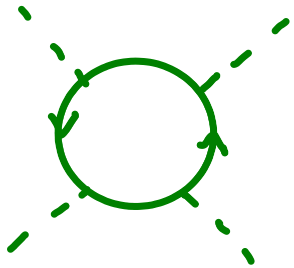


Forgetting naturalness, can the pure SM be valid up to M_{Pl}?

Weakly coupled up to M_{Pl}

VACUUM INSTABILITY

$$\frac{d\lambda}{d\ln Q} \sim -\frac{h_t^4}{16\pi^2}$$

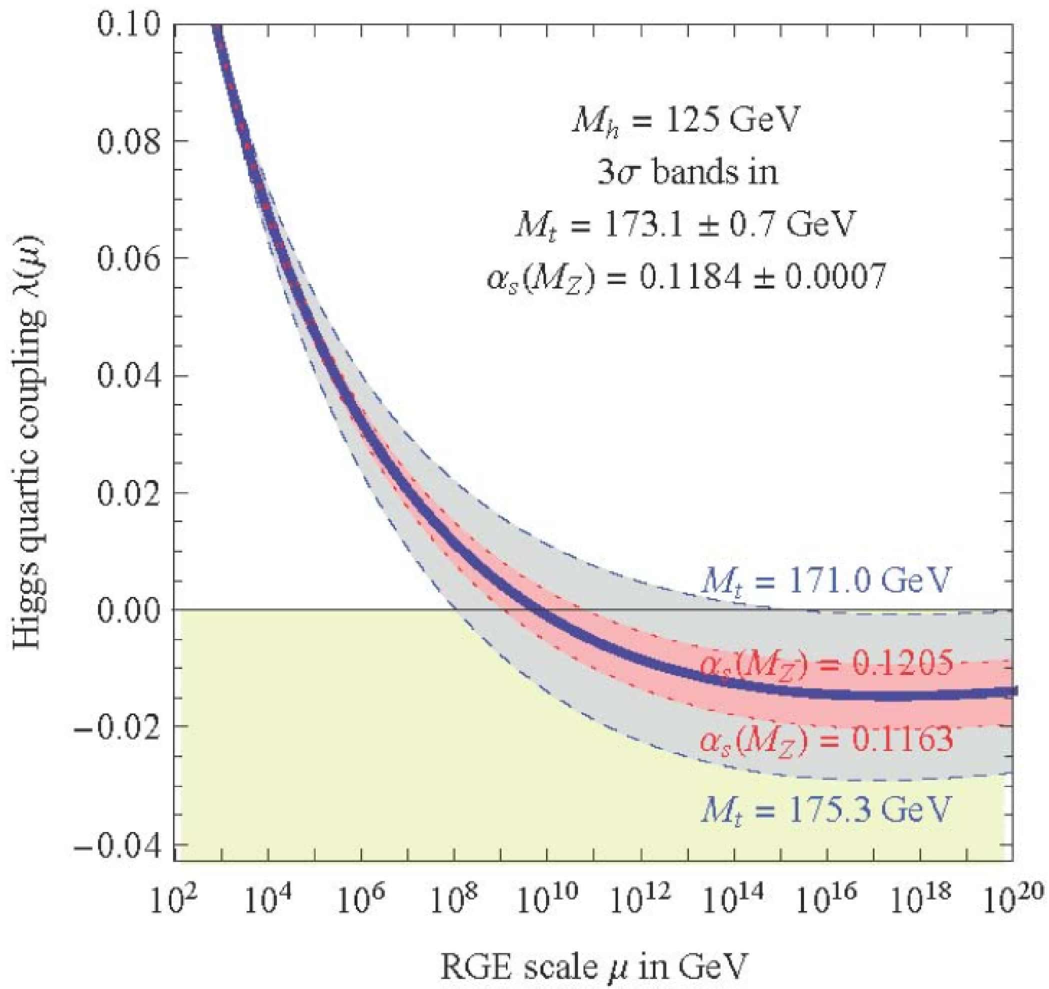


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

⇓

Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4}\lambda(Q \simeq h)\, h^4$$



Cabibbo et al '79, Hung '79, Lindner '86

VACUUM INSTABILITY

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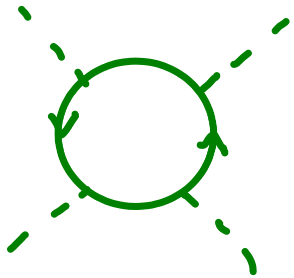

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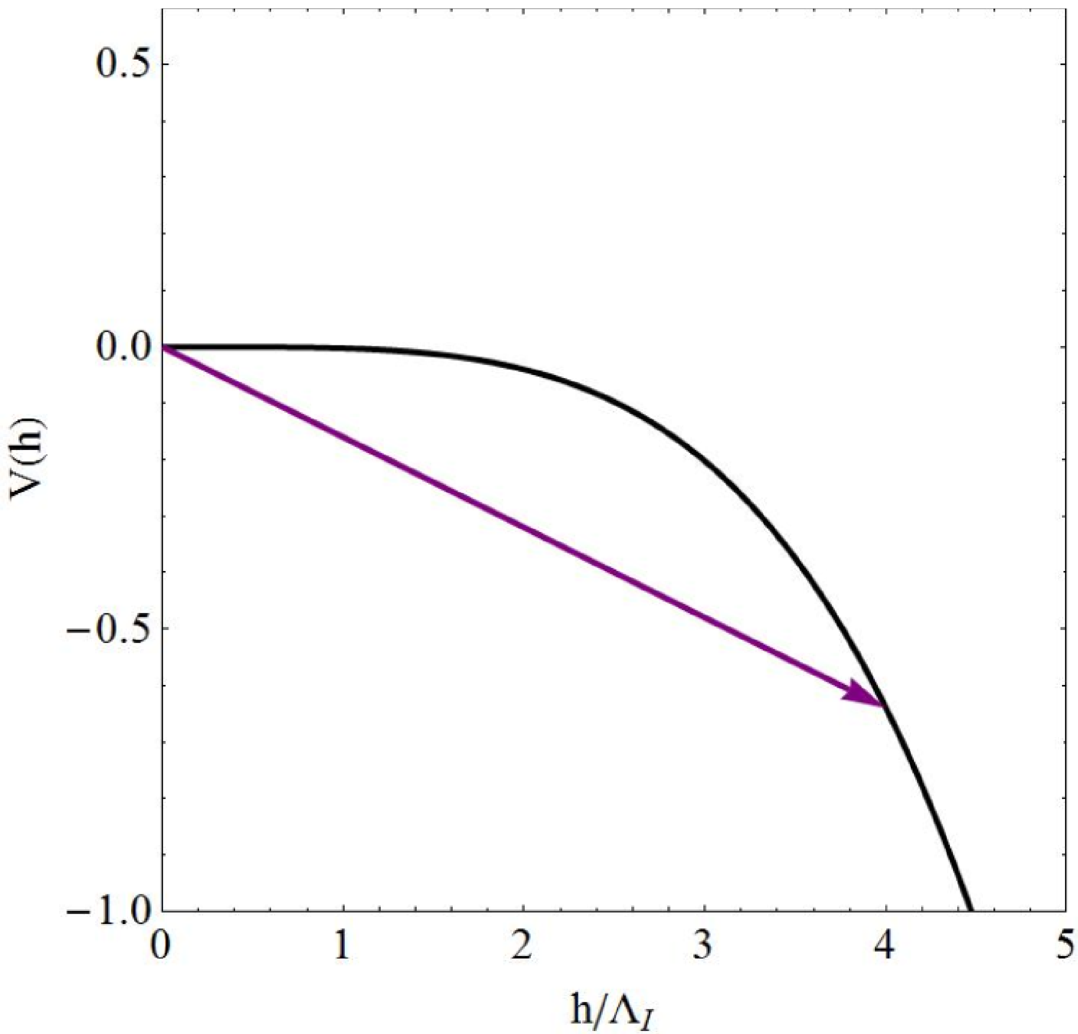
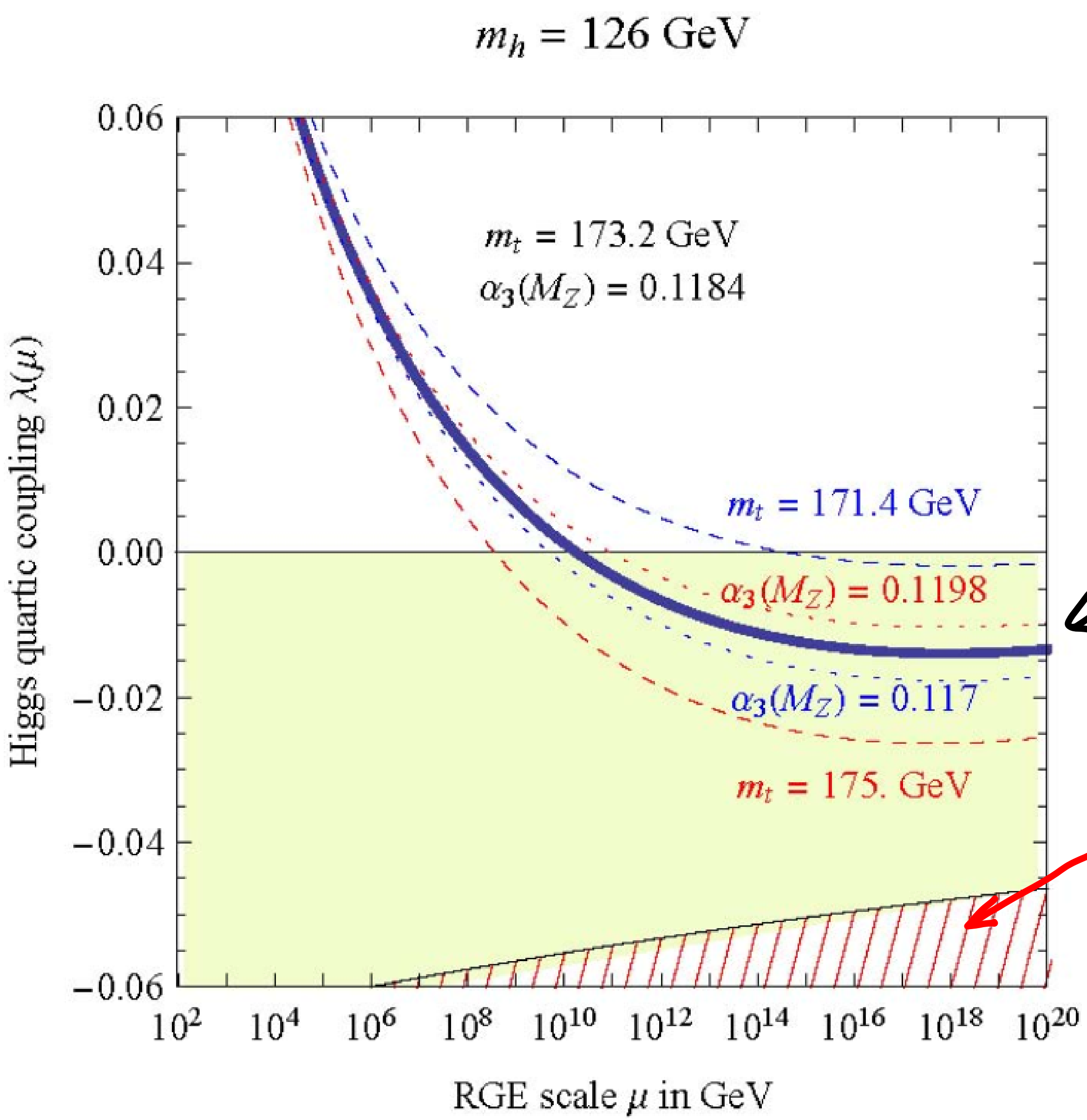


LIFE IN A METASTABLE VACUUM



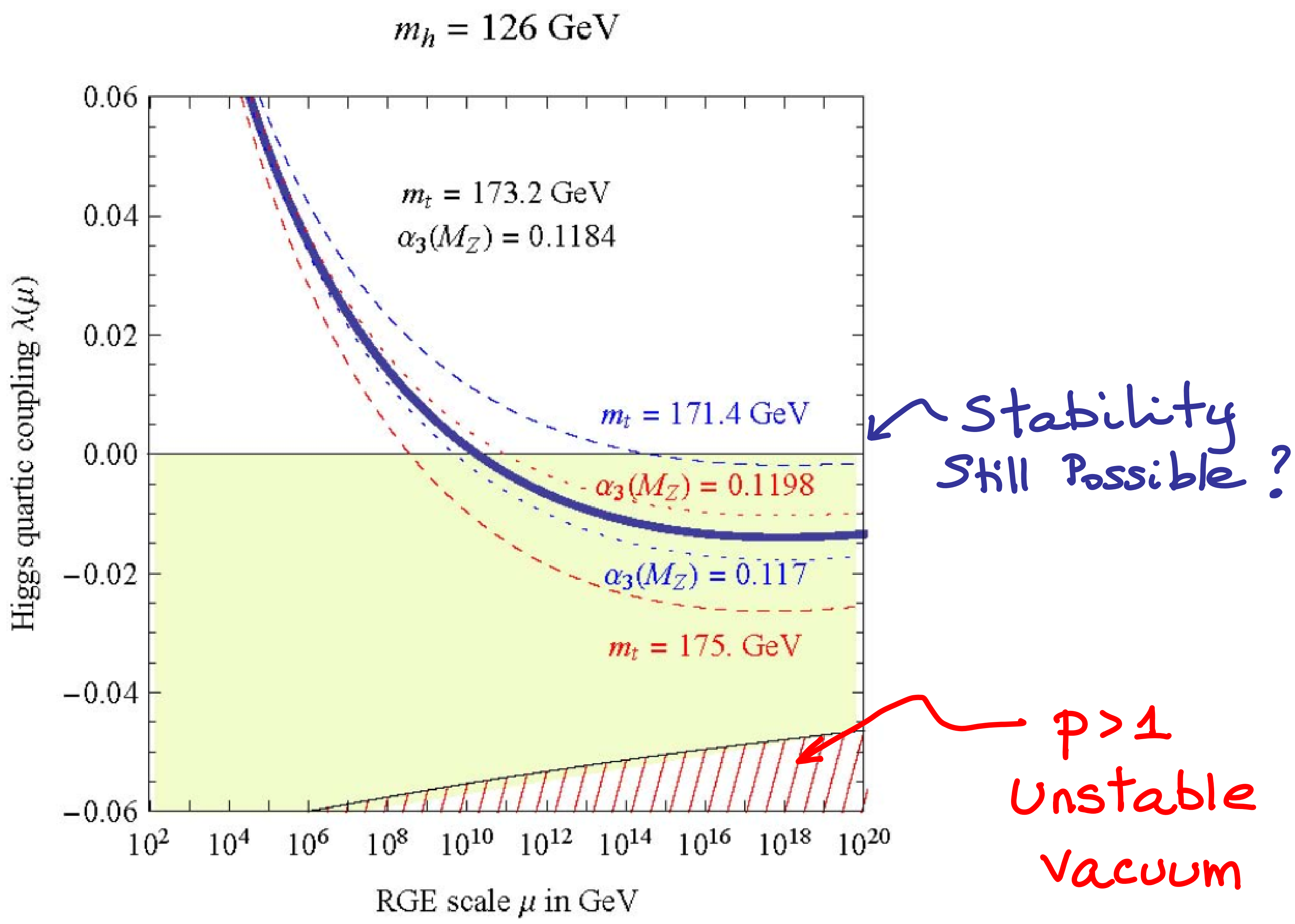
Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

$p > 1$

Unstable vacuum

LIFE IN A METASTABLE VACUUM



NNLO STABILITY BOUND

For stability up to M_{Pl} :

$$M_h\,[\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t(\mathrm{GeV}) - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$

State-of-the-art NNLO calculation:

- 2-loop V_{eff} (Ford, Jack, Jones [hep-ph/0111190])
- 3-loop RGES (..., Chetyrkin, Zoller [hep-ph/1205.2892])
- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$
  (..., Shaposhnikov et al [hep-ph/1205,2893],
  , Degrassi et al [hep-ph/1205.6497])

TOP MASS CAVEATS

Have assumed

$$M_t = 173.1 \pm 0.7\ \text{GeV}$$

from Tevatron+LHC is the top pole mass.

Mitov's & Uwer's talks

Theoretically cleaner determination from $\sigma(t\bar{t})$
but larger error

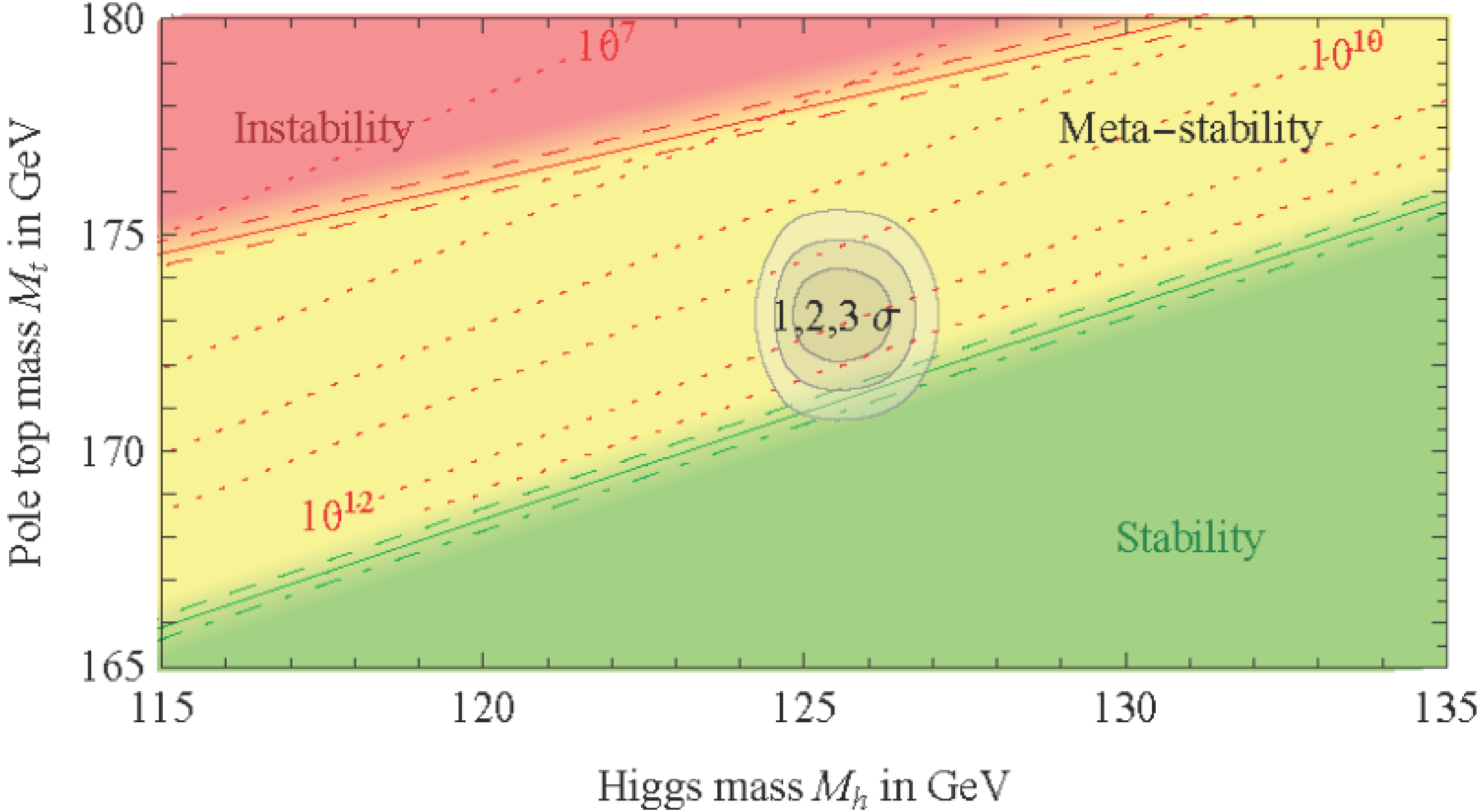
$$M_t = 173.3 \pm 2.8\ \text{GeV}$$

would still allow for stability

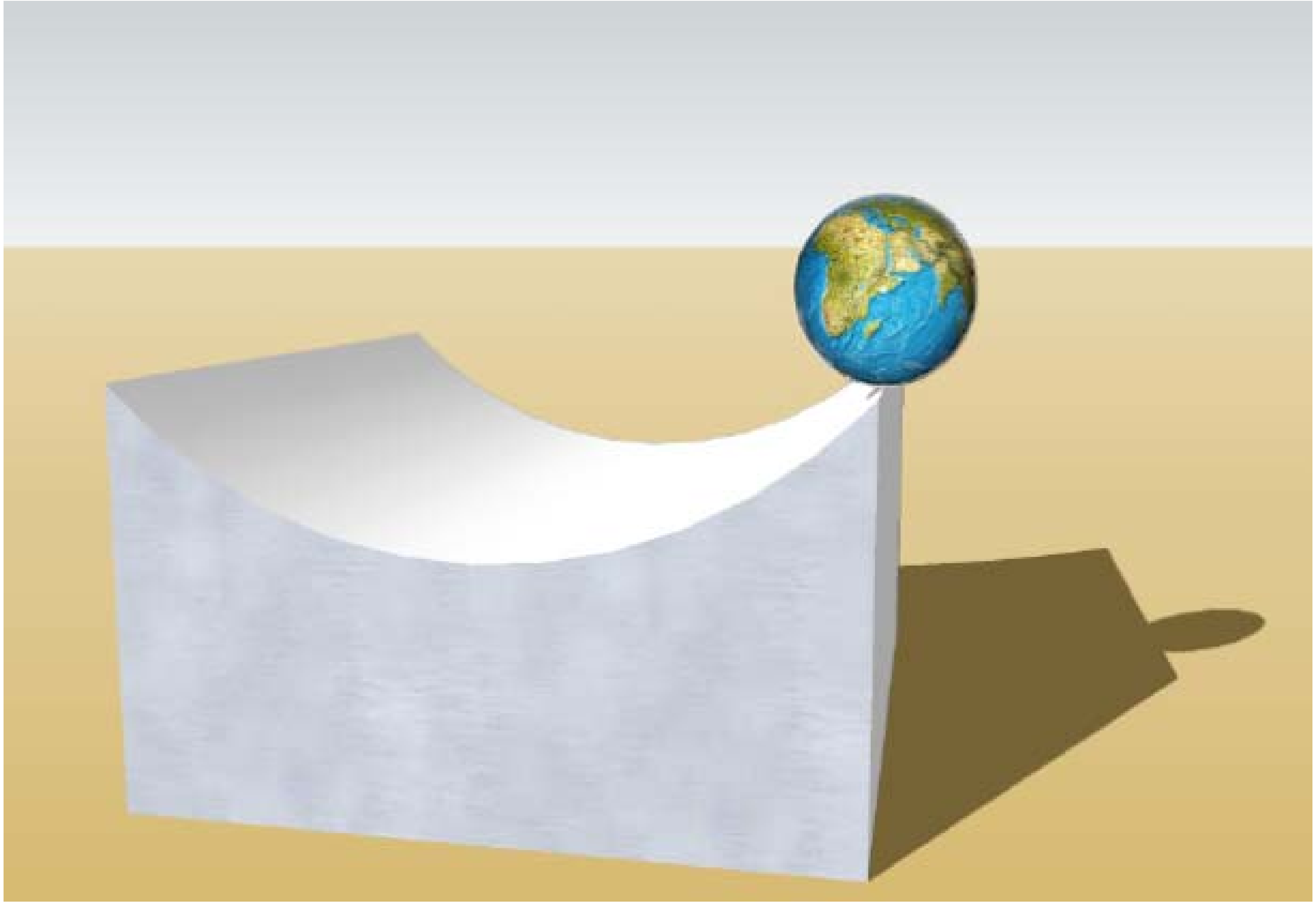
Alekhin, Djouadi, Moch [hep-ph/1207.0980]

Too conservative given the good agreement...

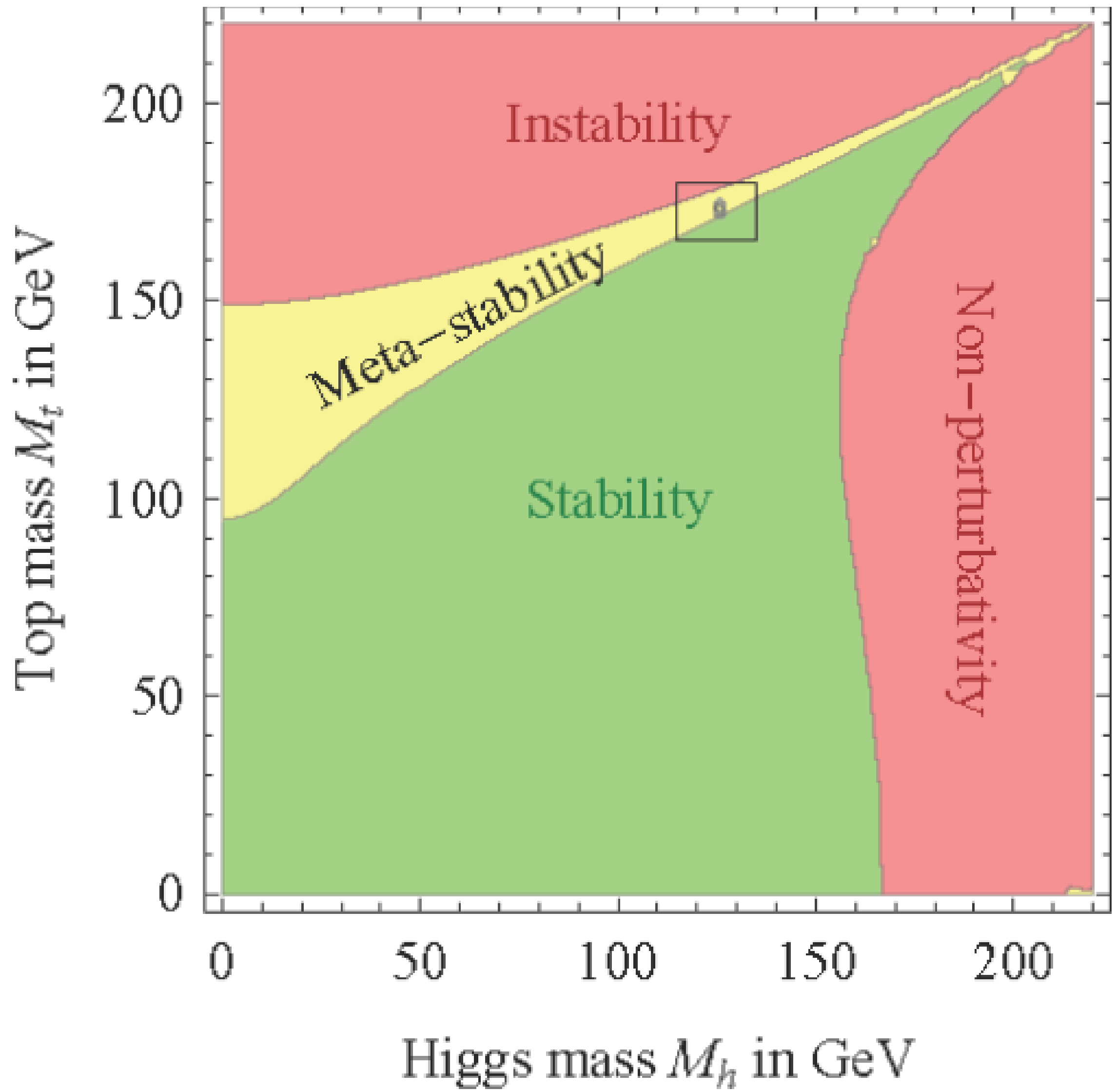
LIVING AT THE EDGE



LIVING AT THE EDGE



LIVING AT THE EDGE

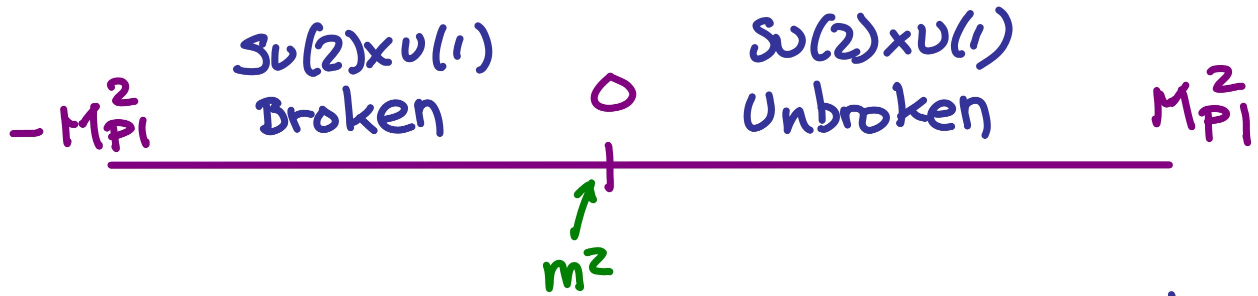


NEW KNOWLEDGE BRINGS NEW QUESTIONS

- ★ Why do we live near the critical boundary for stability?

$$\lambda(M_{Pl}) \simeq 0$$

- ★ Is this related to our living near the phase boundary $m^2/M_{Pl}^2 \simeq 0$?

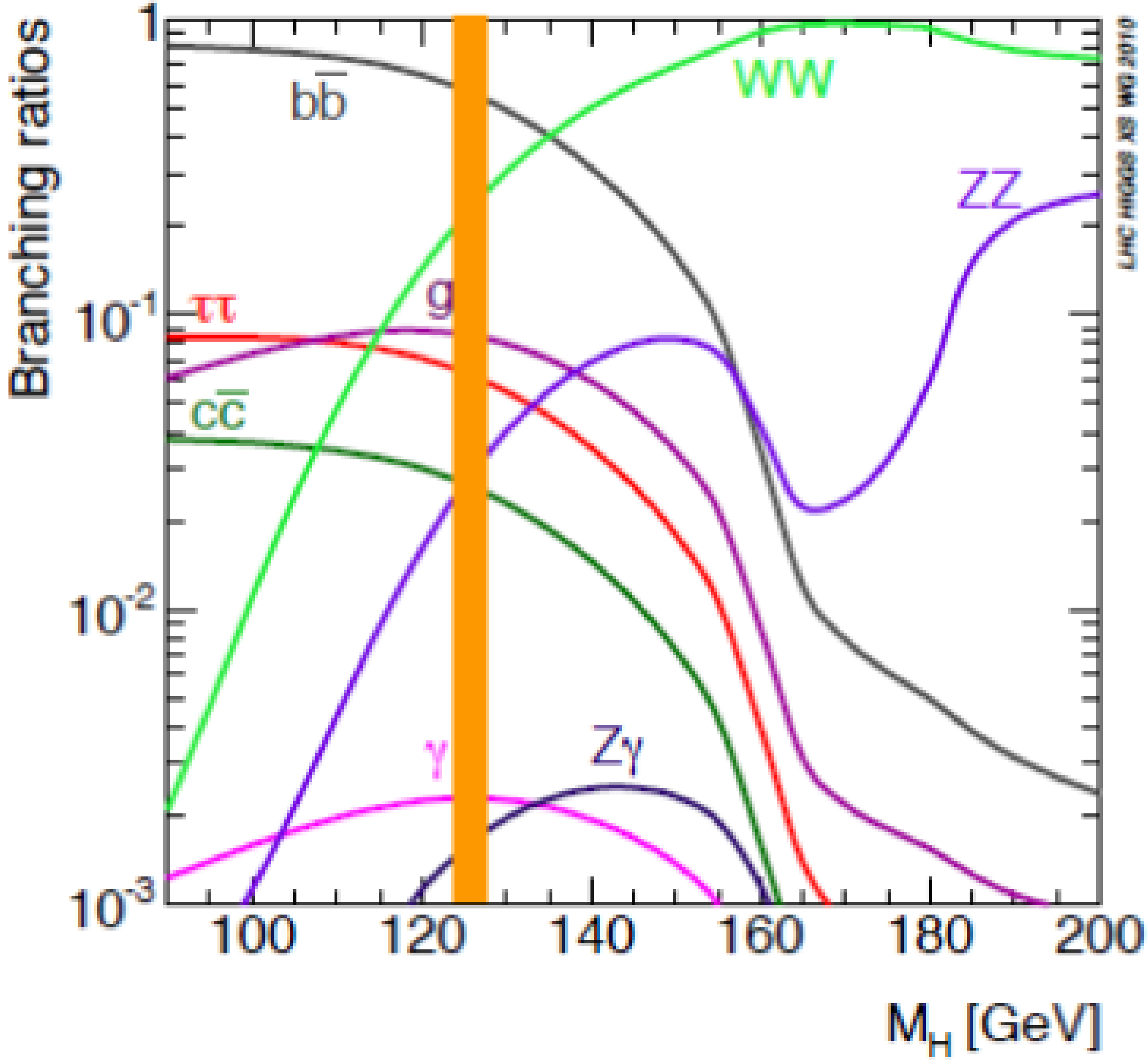


- ★ Is the EW scale determined by Planck scale physics?
- ★ Or is this just a coincidence? BSM...

2

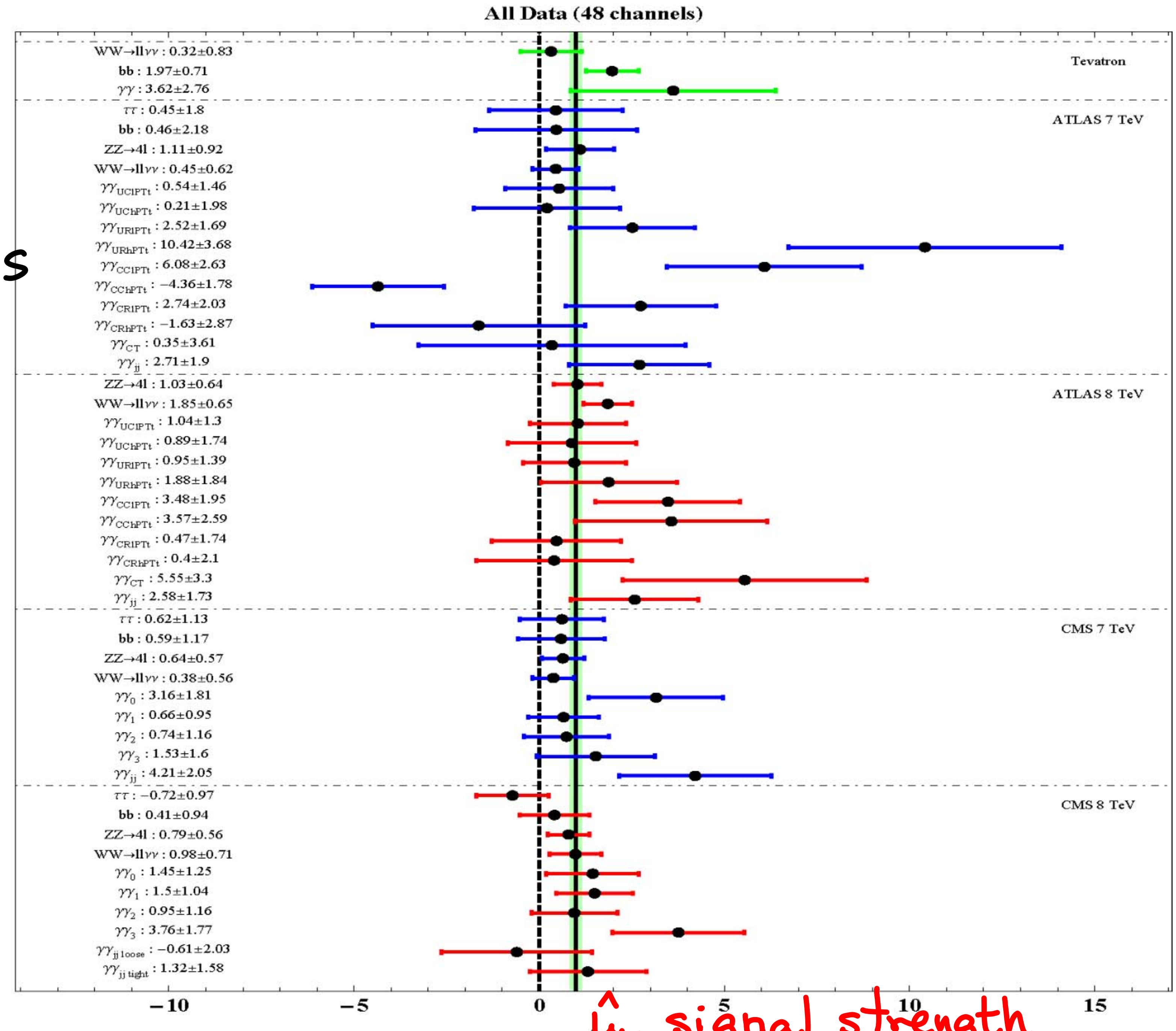
HIGGS COUPLINGS

$m_h \sim 125$ GeV : many channels!



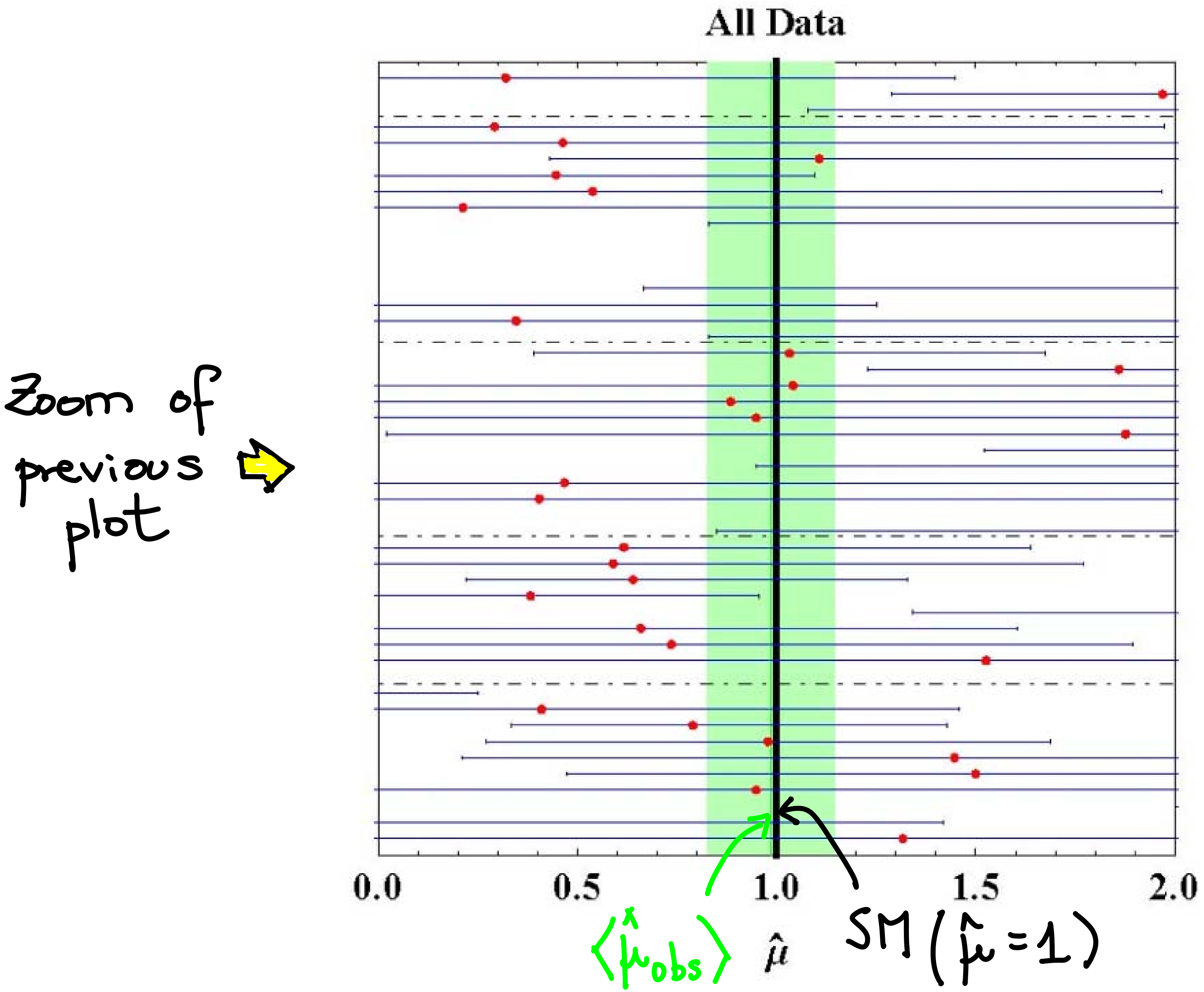
DATA USED IN OUR FITS

48 channels



$\hat{\mu}$, signal strength

DATA USED IN OUR FITS



EFFECTIVE LAGRANGIAN APPROACH

$\mathcal{L}$ valid at $E \sim M_t$.

Field content : SM + scalar h (no extra light states)

$$\mathcal{L} = \mathcal{L}[h] - \left(M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu\right)\left[1 + 2a\frac{h}{v} + O(h^2)\right]$$
$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\frac{h}{v} + O(h^2)\right] + \dots$$

Contino et al '10 '12

Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

EFFECTIVE LAGRANGIAN APPROACH

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$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\frac{h}{v} + O(h^2)\right] + \dots$$

Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

+ custodial symmetry

EFFECTIVE LAGRANGIAN APPROACH

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Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

+ custodial symmetry

+ no tree-level FCNC from h exchange

EFFECTIVE LAGRANGIAN APPROACH

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Incorporates $SU(2)_L \times U(1)_Y \to U(1)_{em}$ breaking

+ custodial symmetry

+ no tree-level FCNC from h exchange

First terms in a "chiral lagrangian" with cutoff

$$\Lambda \gtrsim 4\pi v$$

EFFECTIVE LAGRANGIAN APPROACH

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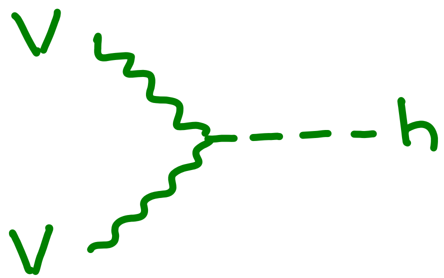
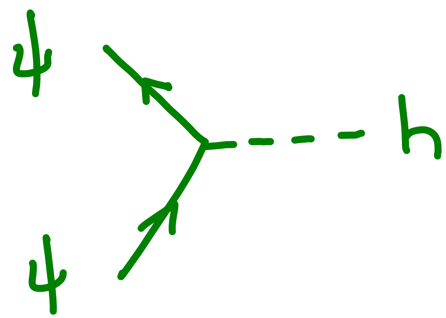
$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\,\frac{h}{v} + O(h^2)\right] + \dots$$

2-parameter extension of the SM with



$a\, g^{SM}_{hVV}$



$c\, h^{SM}_{\psi\psi h}$

$$SM \equiv (a, c) = (1, 1)$$

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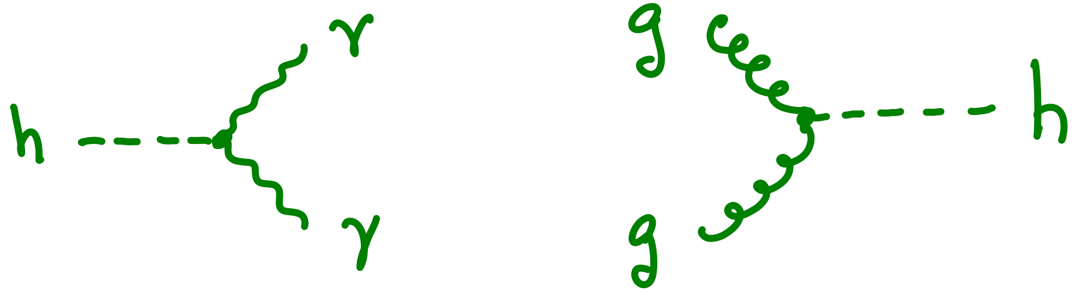
$$- m_{\psi_i} \bar{\psi}_i \psi_i \left[1 + c\frac{h}{v} + O(h^2)\right] + \dots$$

Other operators very relevant for Higgs searches:

$$\frac{g^2}{16\pi^2}\left[c_\gamma A_{\mu\nu}A^{\mu\nu} + c_g G^A_{\mu\nu} G^{A\mu\nu}\right]\frac{h}{v}$$



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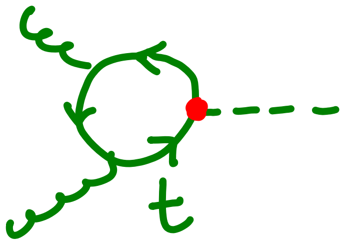
are assumed to come from SM loops only :

$gg \to h$



$\sim c$

EFFECTIVE LAGRANGIAN APPROACH

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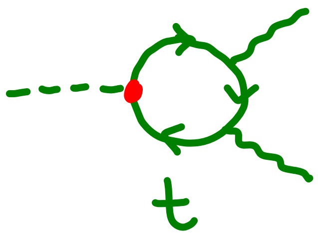
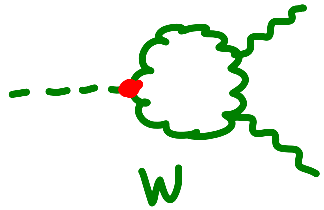
are assumed to come from SM loops only:

$h \to \gamma\gamma$: 

$\sim c$ + 

$\sim a$

EFFECTIVE LAGRANGIAN APPROACH

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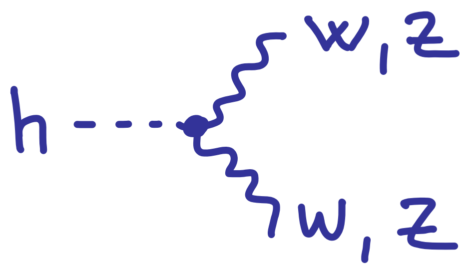
are assumed to come from SM loops only.

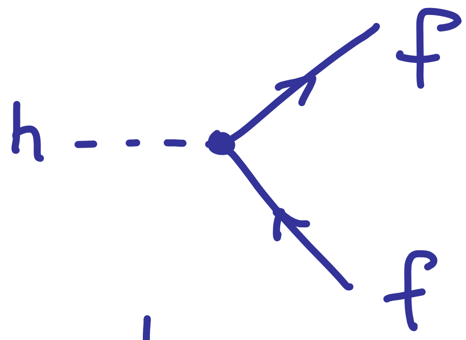
Motivated by composite PNGB Higgs scenarios

Will relax this assumption later on.

PHYSICAL RANGE OF (a,c)



$a g_{SM}$



$c\, h_{f,SM}$

$a g_{SM} h V_\mu V^\mu$ set $a>0$ by chosing sign of h

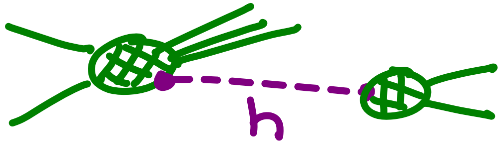
indep. $\left\{ \begin{array}{l} m_f \bar{f} f \\ c\, h_{f,SM} h \bar{f} f \end{array} \right.$

$m_f \bar{f} f$ — set $m_f>0$ by chosing phase of $\bar{f} f$

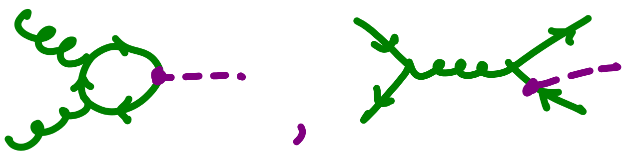
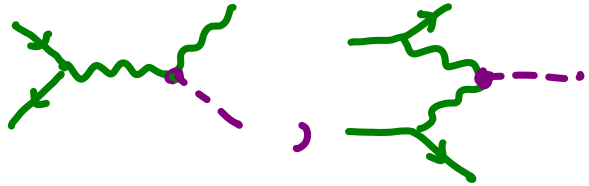
$c\, h_{f,SM} h \bar{f} f$ — c can be of either sign.

RATES IN SM(a,c)

- Only h couplings are modified:
  Signal rate modified
  kinematics unchanged



- Different production mechanisms change differently.

$\sigma\big[$  $\big] \sim c^2$ $\qquad \sigma\big[$  $\big] \sim a^2$

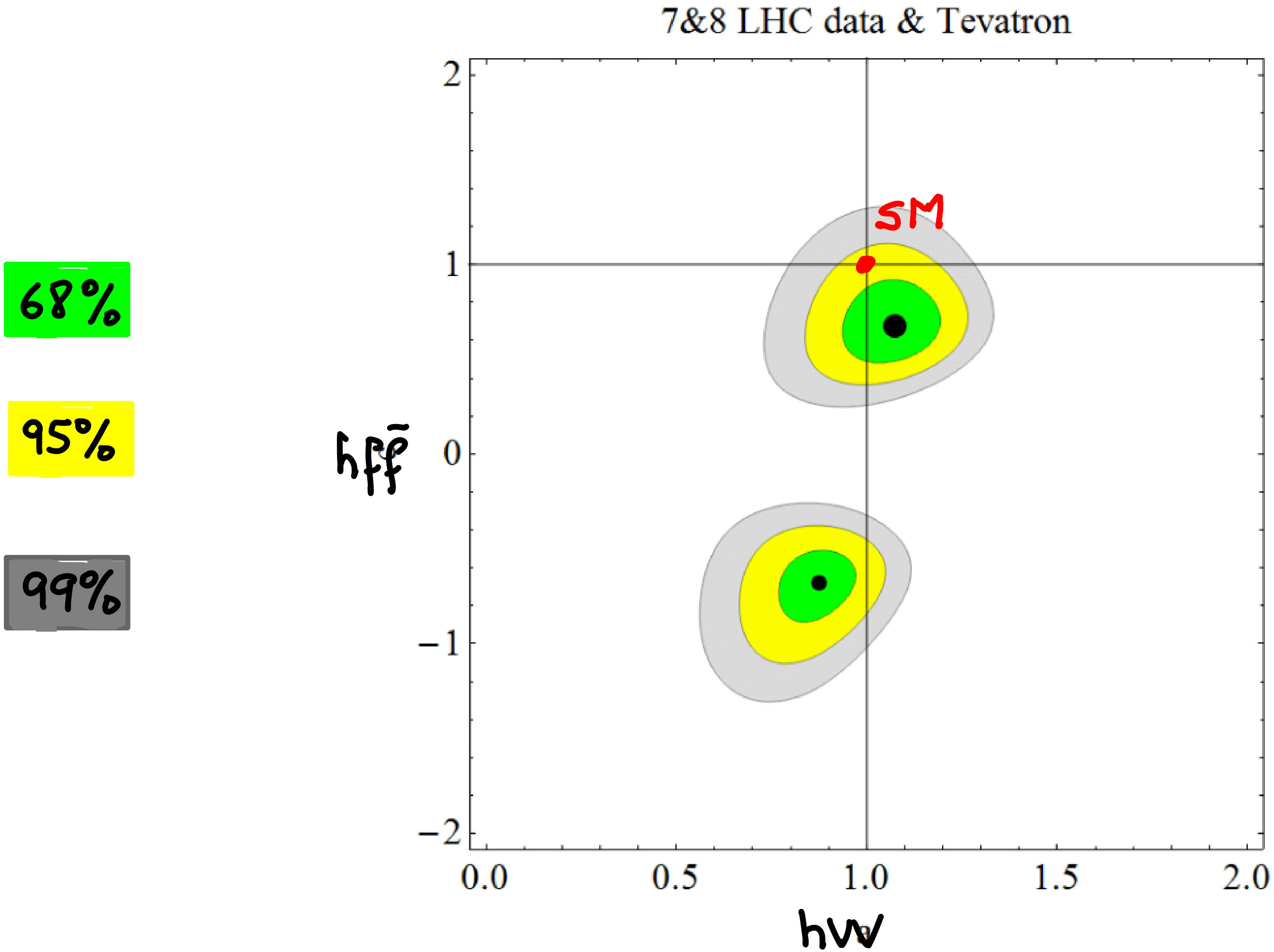
- Expected signal strengths:

$$\mu_i = \left[\frac{\sigma^{SM(a,c)}_{pp\to h\to X}}{\sigma^{SM}_{pp\to h\to X}}\right]_i = \frac{\sum_{p_i} \epsilon_{p_i}\sigma_{p_i}(a,c)\times BR^{SM(a,c)}_{h\to X}}{\sum_{p_i} \epsilon_{p_i}\sigma_{p_i}\times BR^{SM}_{h\to X}}$$

Calculate $\mu_i(a,c)$ and confront with the measured μ_i's using a χ^2 fit.

FITS IN SM(a,c)

χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron)



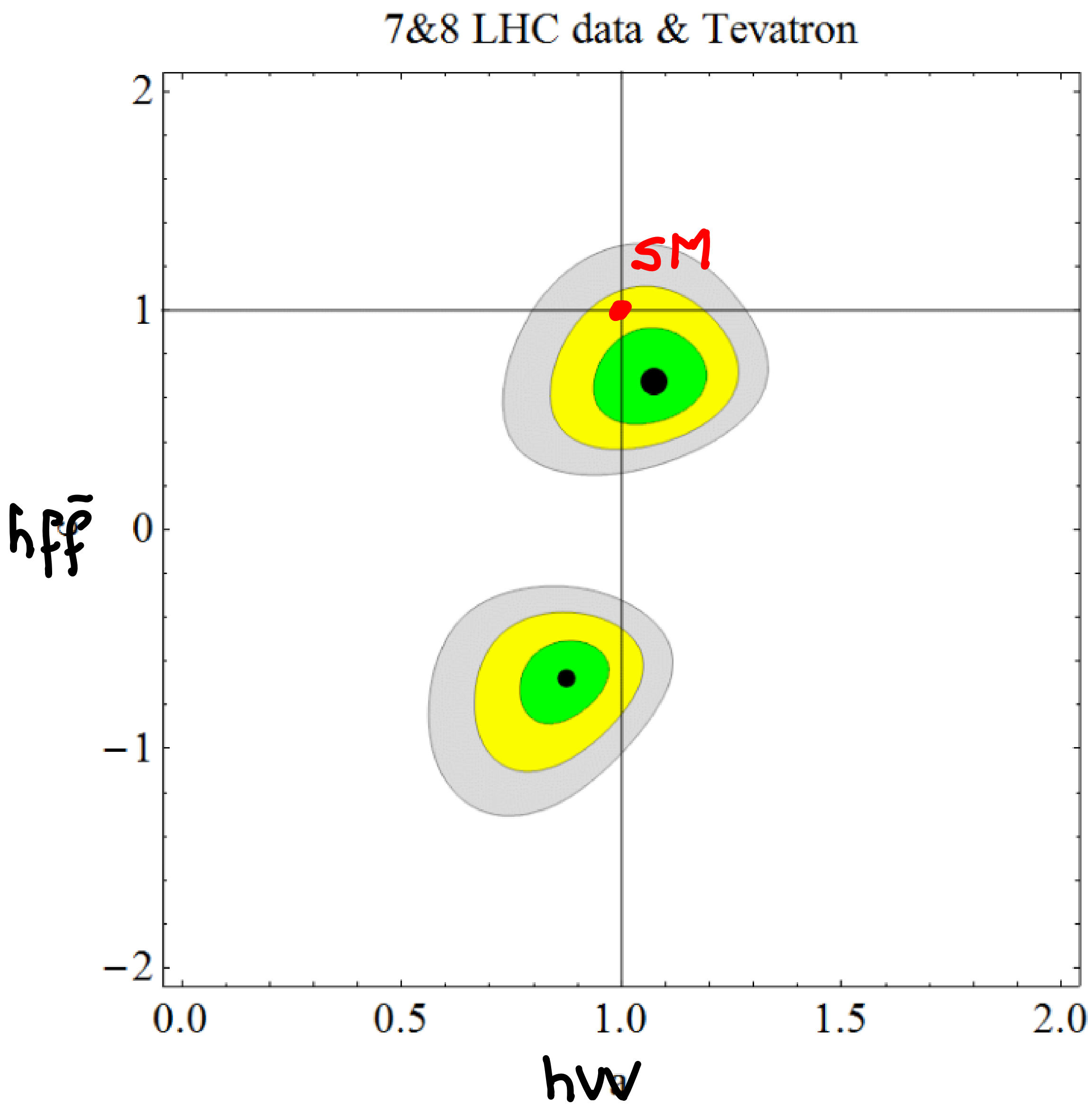
FiTS iN SM(a,c)

χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron)

68%

95%

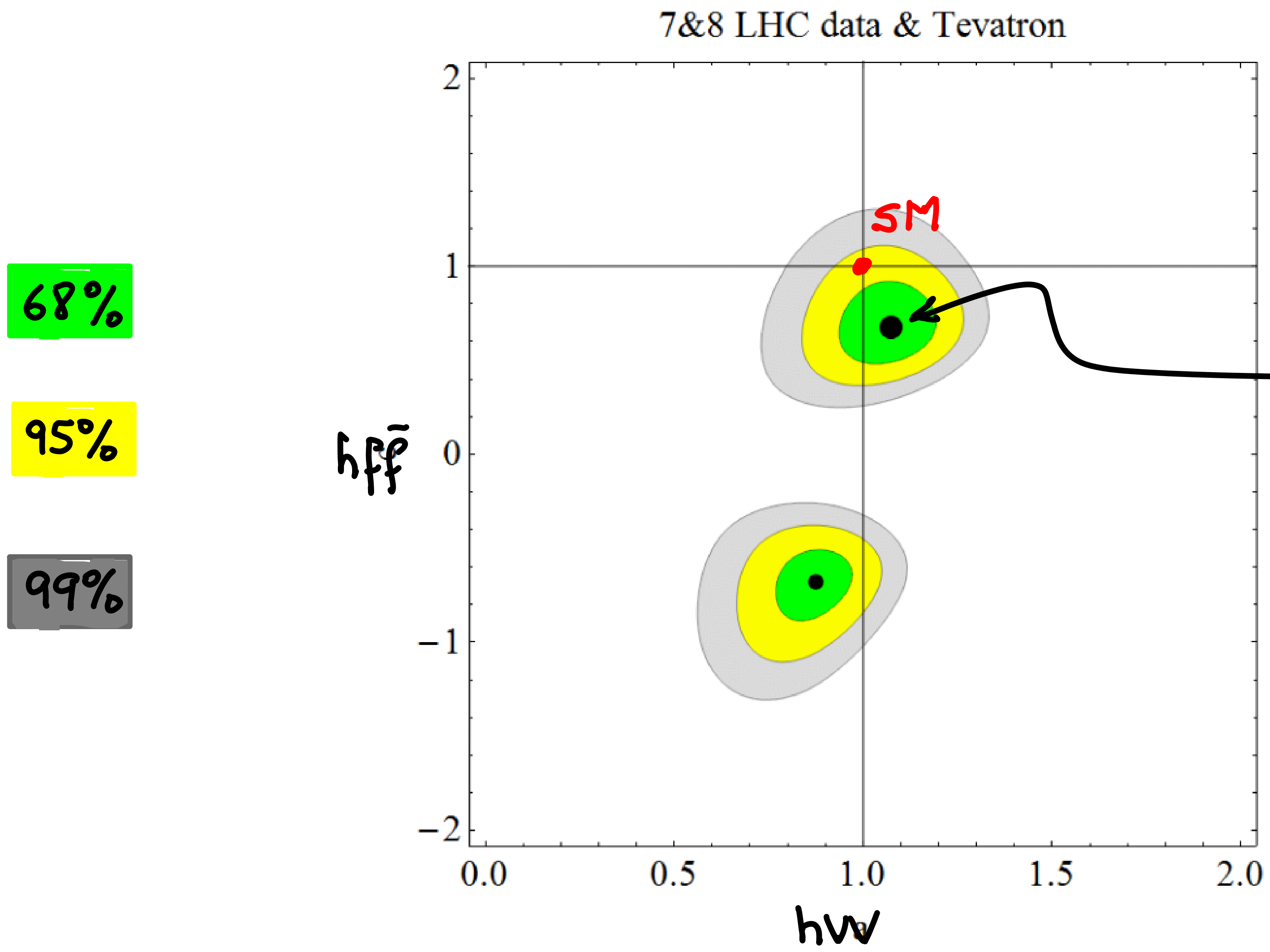
99%



SM gives a reasonable fit

FITS IN SM(a,c)

χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron)

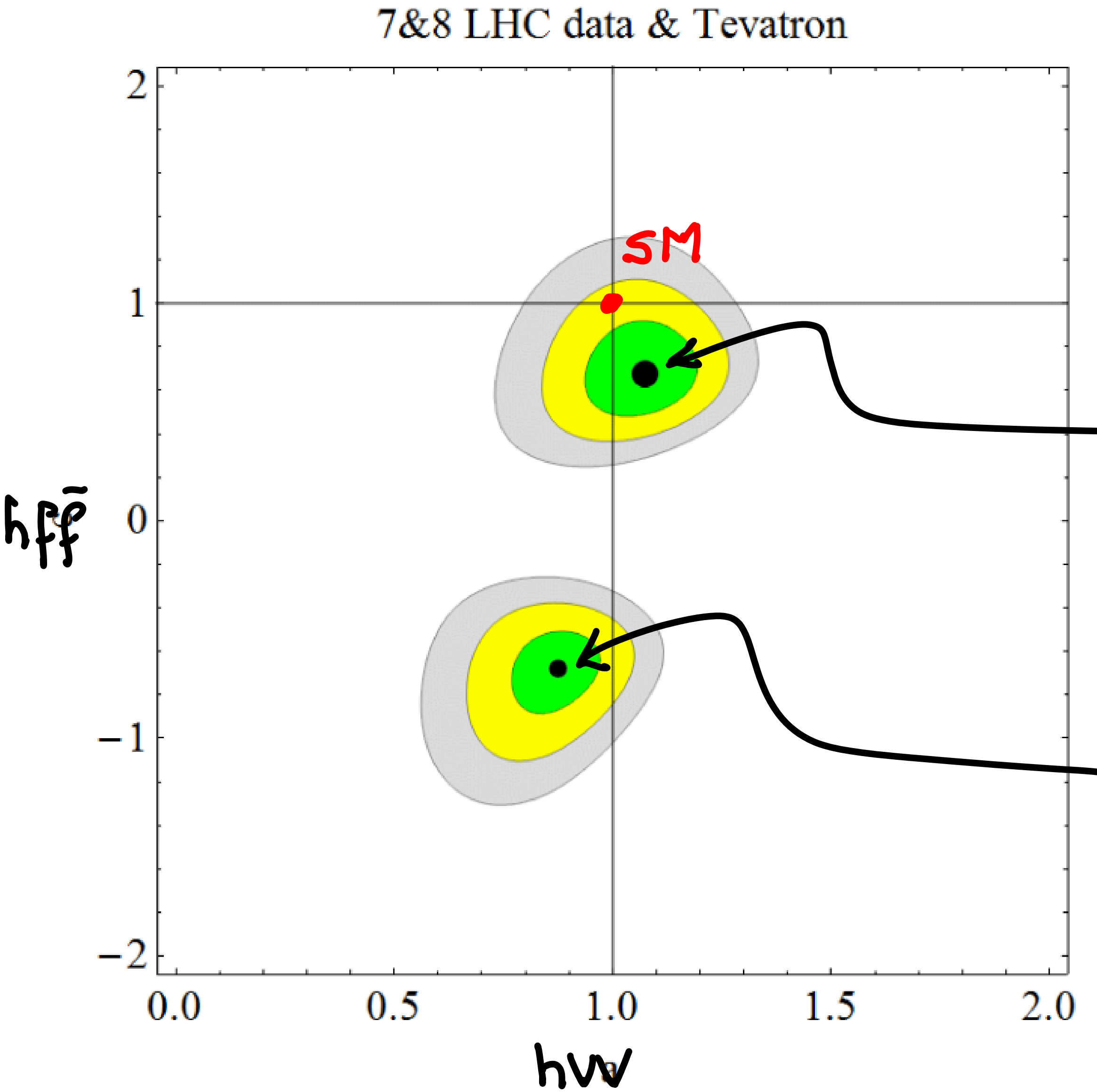


SM gives a reasonable fit

Best fit point
(a>1 , c<1)

FITS IN SM(a,c)

χ^2 fit to $\hat{\mu}_i \pm \sigma_i$ from 48 channels (ATLAS+CMS+Tevatron)



68%

95%

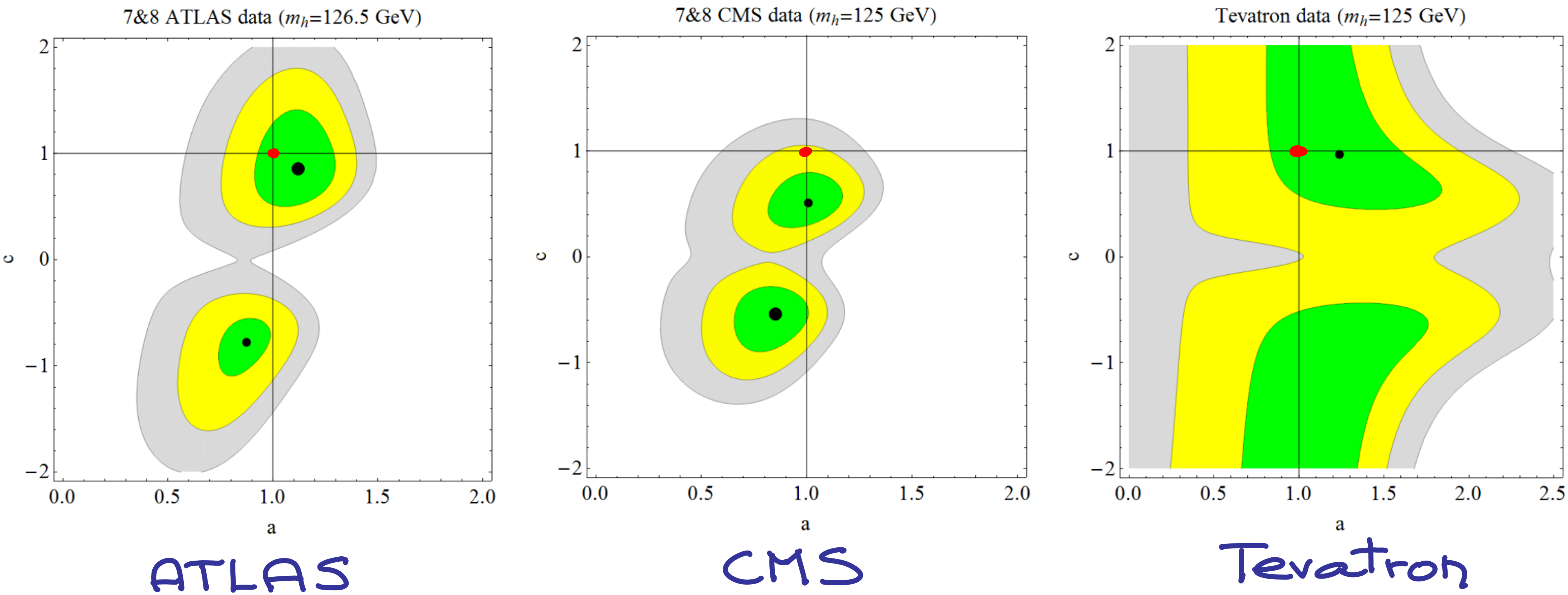
99%

SM gives a reasonable fit

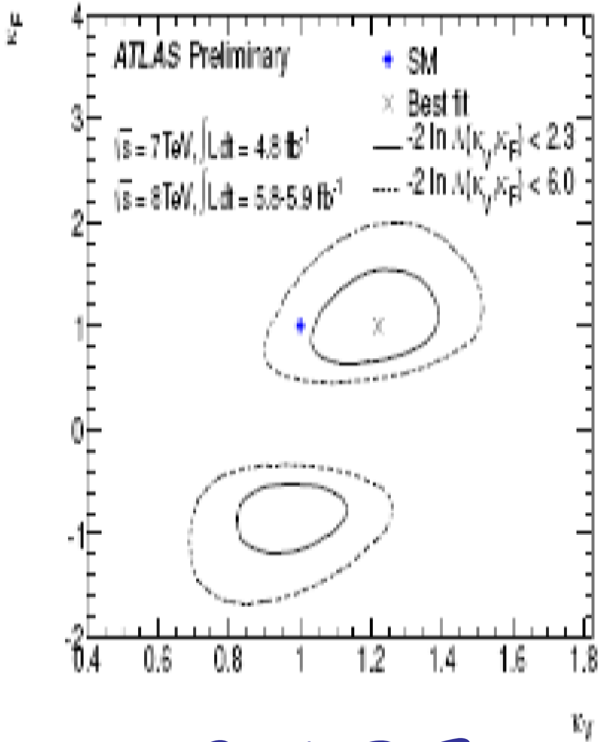
Best fit point ($a>1$, $c<1$)

Nearly deg. Second χ^2_{min} ($a<1$, $c<0$, $|c|<1$)

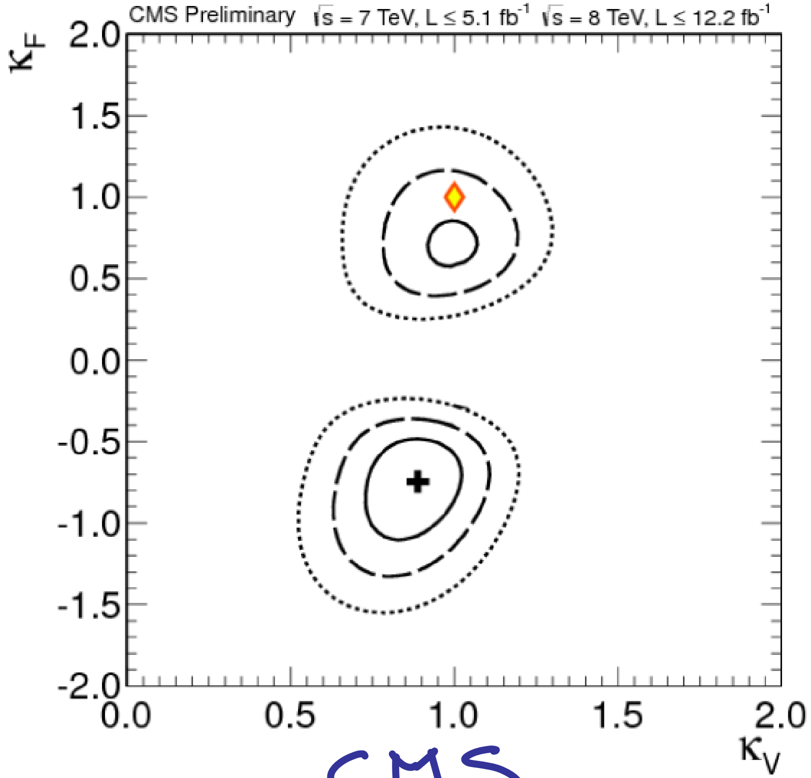
FITS TO SEPARATE EXP.



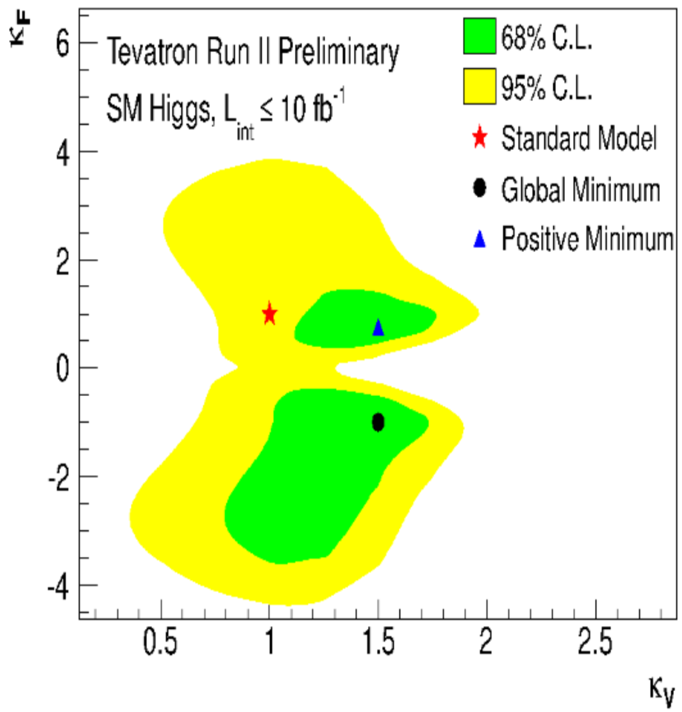
FITS TO SEPARATE EXP.



ATLAS



CMS



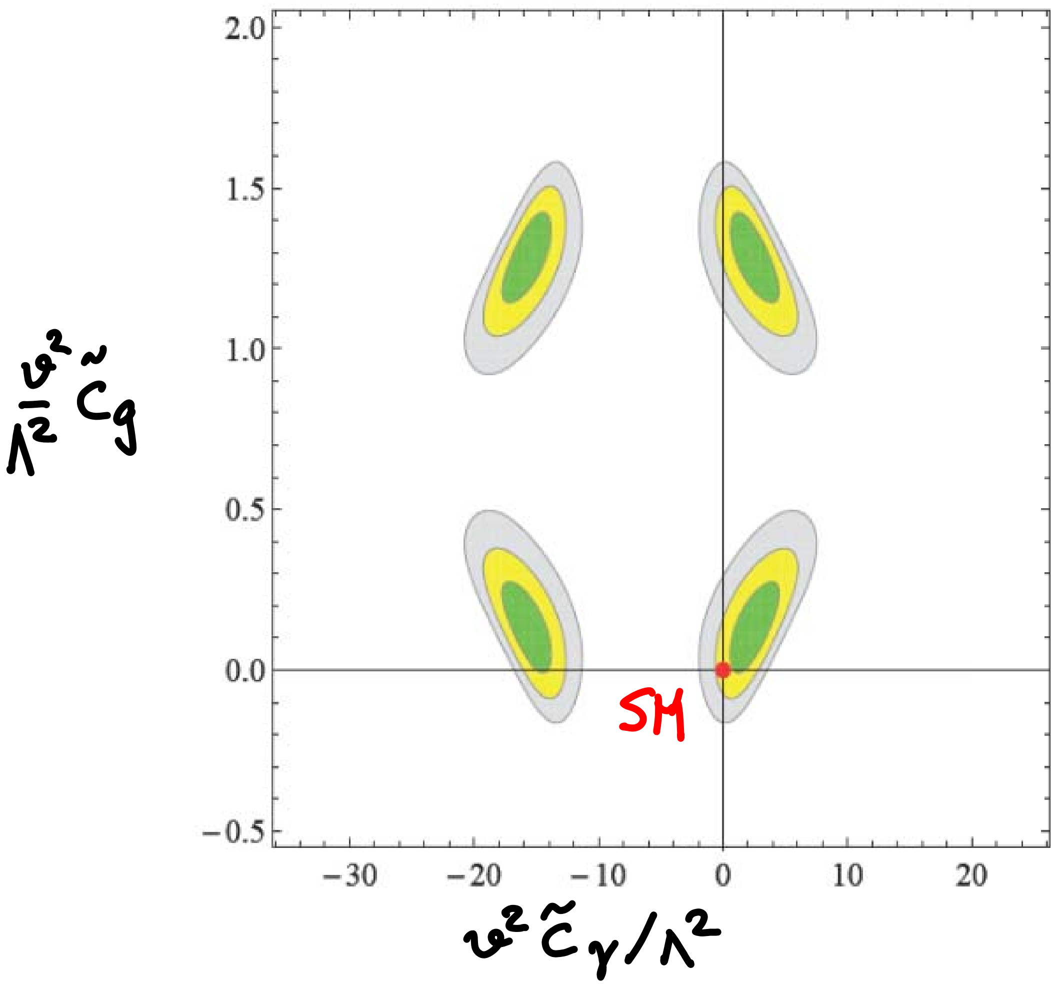
Tevatron

OFFICIAL VERSION

BSM EFFECTS IN $h\gamma\gamma$, hgg

Take $a=c=1$, add $\frac{-1}{32\pi^2}\left[e^2\tilde{c}_\gamma F_{\mu\nu}F^{\mu\nu} + g_s^2\tilde{c}_g G^A_{\mu\nu}G^{A\mu\nu}\right]\frac{H^\dagger H}{\Lambda^2}$

e.g. from loops of heavy charged particles $\Rightarrow$ SM $(\tilde{c}_\gamma, \tilde{c}_g)$

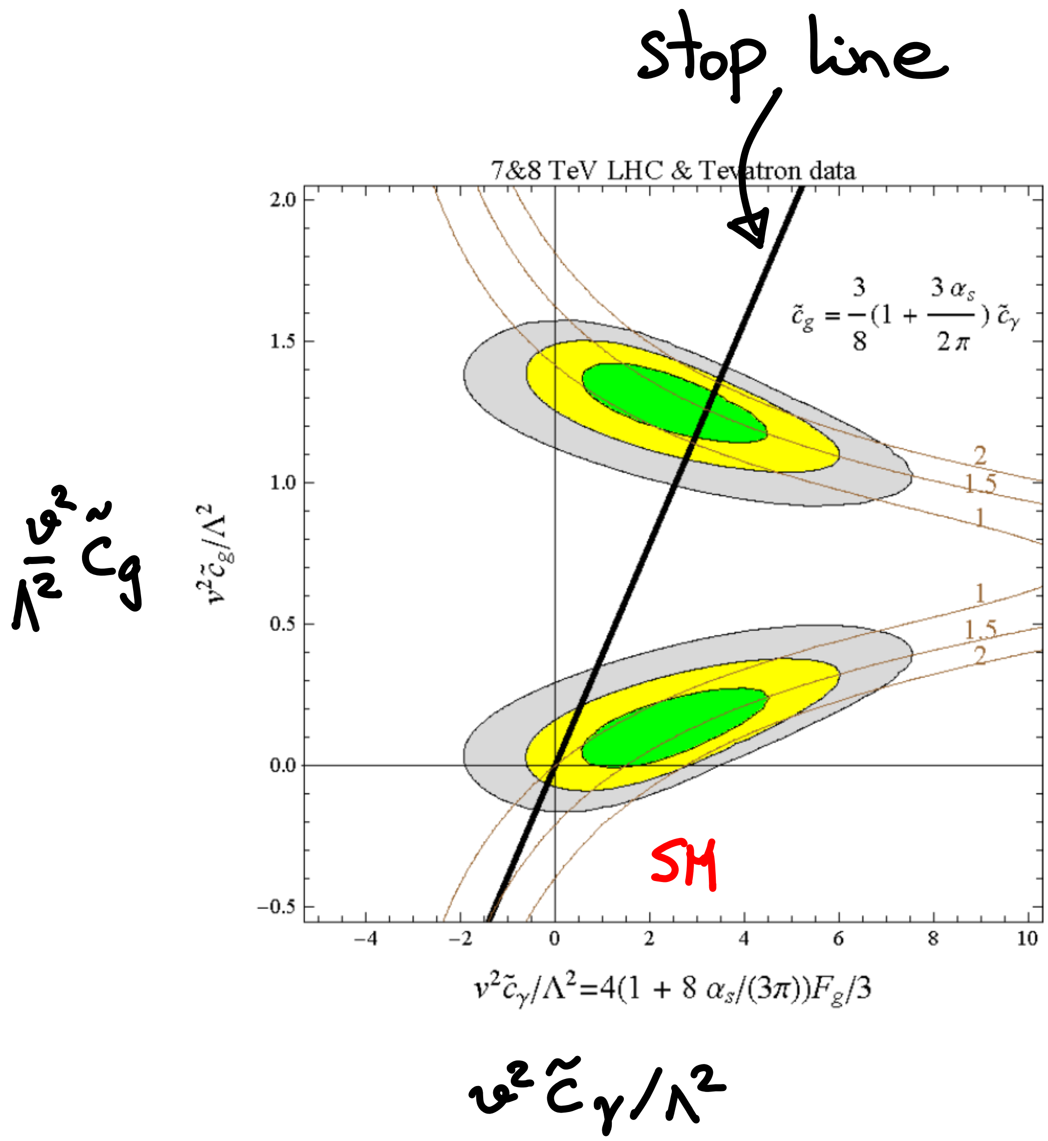


Model-independent result:

Map particular models to this plane

BSM EFFECTS IN $h\gamma\gamma$, hgg

Example: Stop, which gives $\tilde{c}_\gamma = 2N_c Q_{\tilde{t}}^2 \tilde{c}_g$



See JRE, Grojean, Sanz, Trott '12

SOME REMARKS

- ★ With more data, fits to more parameters will be possible.
- ★ Higher order (p-dep) operators in $\mathcal{L}_{eff}$ will be required for highly boosted Higgs.
- ★ Current Higgs data can be used to constrain BSM models either for giving two large signal rates or too small (eg. limits on Higgs invisible BR)
- ★ Higgs data can be used to probe indirectly regions of parameter space hard for direct searches (eg. light stops)

CONCLUSIONS

We finally have data to explore the physics of electroweak symmetry breaking!

★ $M_h \simeq 125\,GeV$ ⇨ Unstable EW vacuum w/o BSM

Long-lived and intriguinly close to stability boundary

Deviations of Higgs properties from the SM are a must of natural BSM: extremely important measurements.

★ Couplings compatible with SM

Some interesting deviations ($\gamma\gamma$), not statistically signif (yet?)

Future deviations can be crucial to steer the search for physics beyond the SM.

Looking forward to Moriond'13!

LIFE IN A METASTABLE VACUUM

$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_U^4 \quad \text{with} \quad \tau_U^4 \sim \left(e^{140}/M_{Pl}\right)^4$$

$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

easily wins over τ_U^4

$p \lll 1$: Lifetime of EW vacuum much longer than τ_U

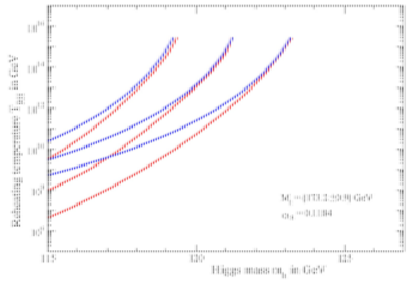
Error Budget of Stab. Bound

Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	Total combined in quadrature	± 1.5 GeV
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{QCD})$ correction to M_t	± 0.6 GeV
y_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	± 0.2 GeV
Theory	Total combined in quadrature	± 1.0 GeV

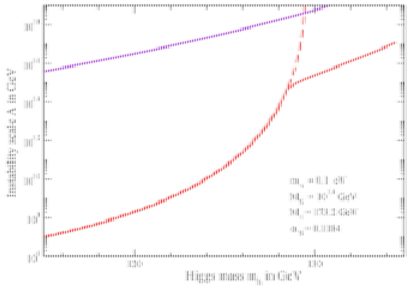
Table 1: *Dominant sources of experimental and theoretical errors in the computation of the SM stability bound on the Higgs mass, eq. (2).*

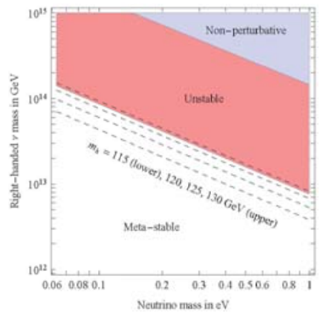
OTHER IMPLICATIONS NOT DISCUSSED

- Cosmology:
  Bound on T_{RH}; inflation, ...

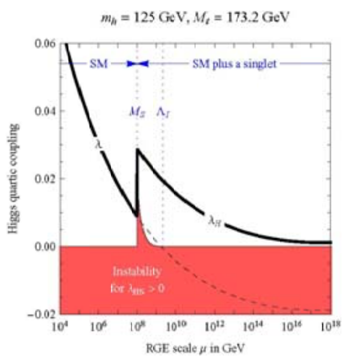


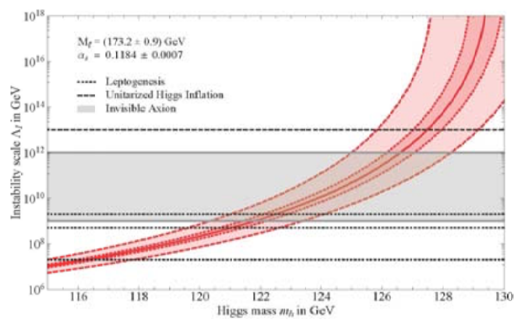
- See-saw neutrinos:
  Bound on $M_{\nu R}$



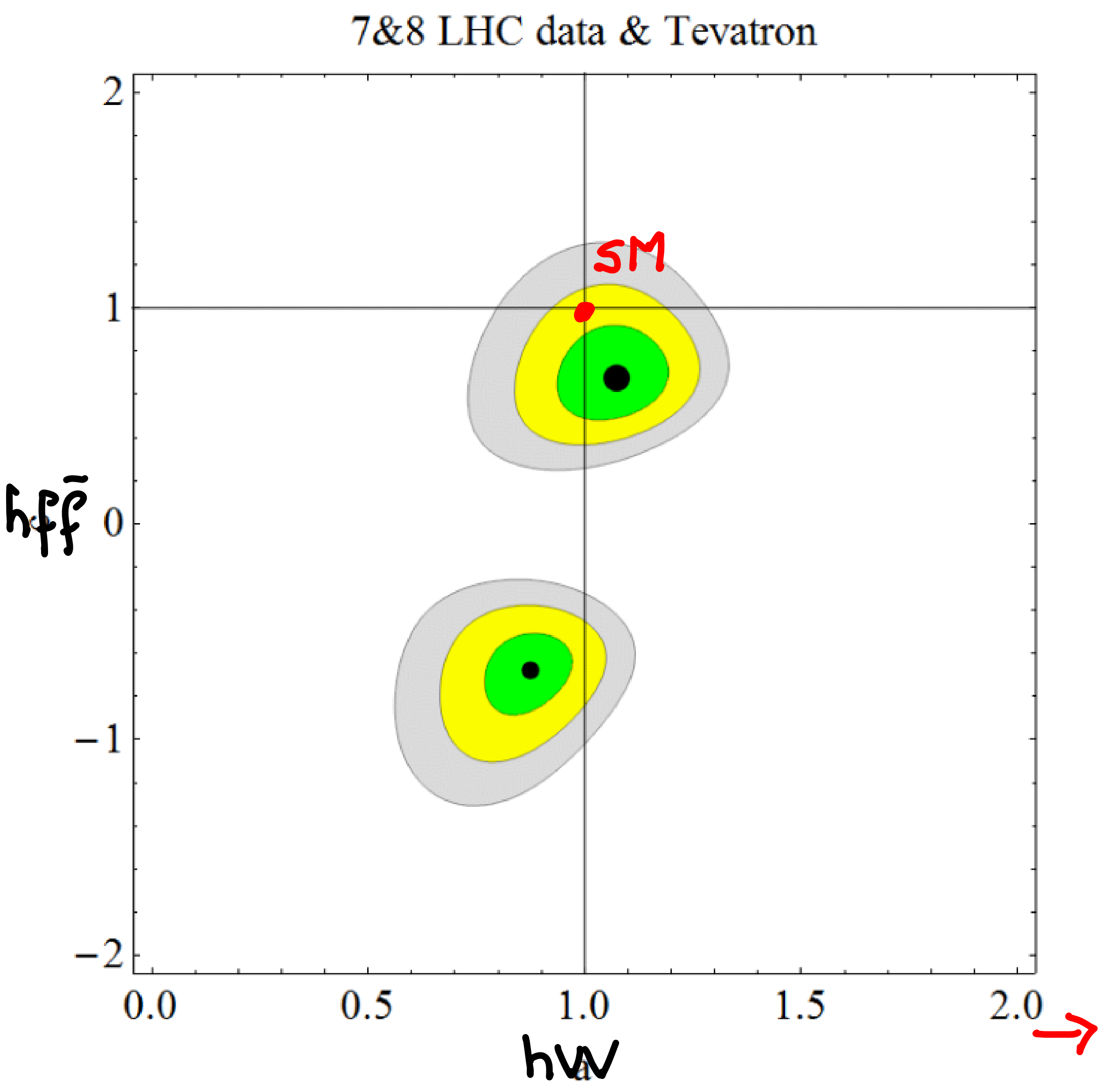


- Singlet fix of instability
  (from see-saw; axion;
  Higgs inflation, ...)





FiTS iN SM(a,c)



How to improve SM's fit:

$|c|<1 \Rightarrow BR_{b\bar{b}} \downarrow$ ~20%

$\Downarrow$

$BR_{\gamma\gamma} \uparrow\uparrow$ x2-3

$BR_{WW} \uparrow$

compensating $\sigma_{gg} \downarrow$ ~50%

Two solutions due to approx.

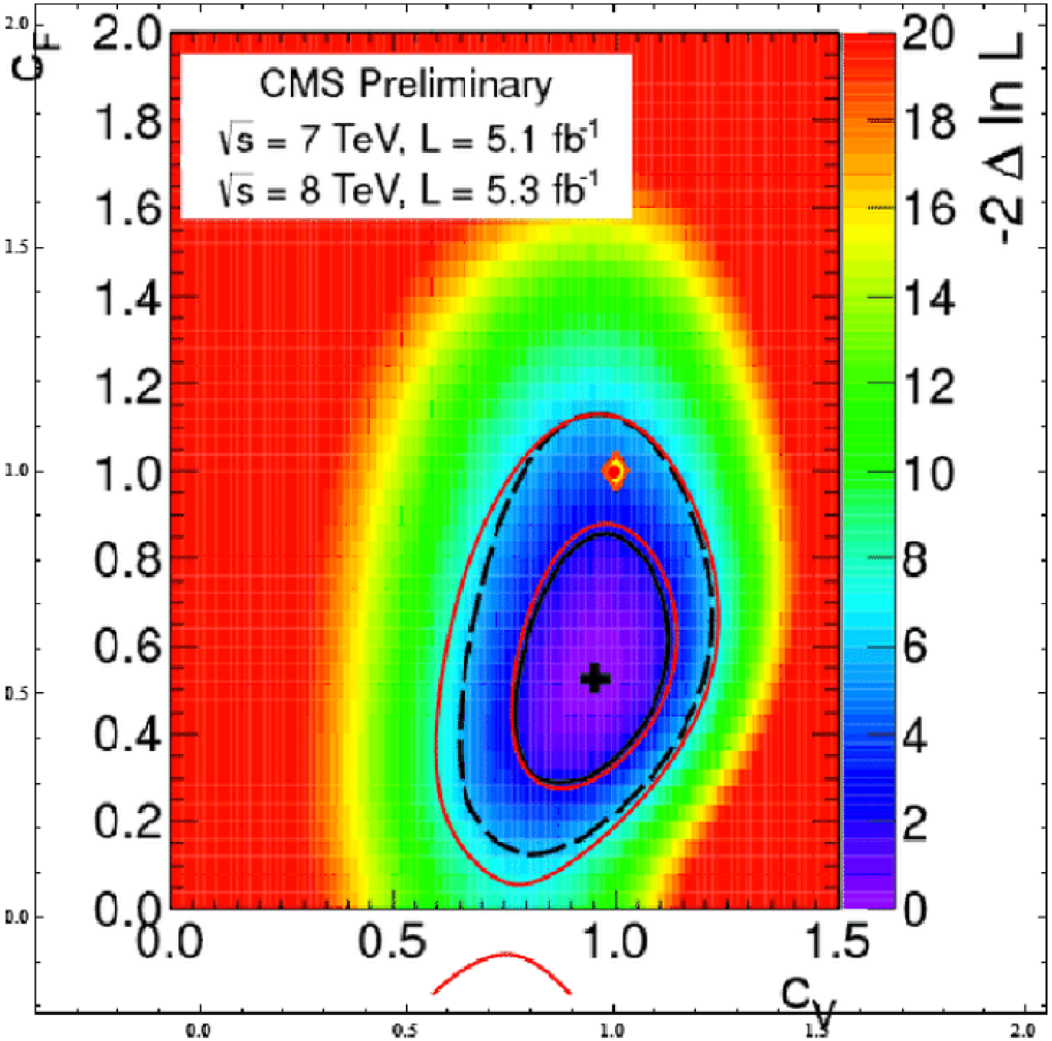
$a \leftrightarrow -a \quad c \leftrightarrow -c$ sym.

Broken by $h\gamma\gamma$ amplitude

$\sim |1.26\,a - 0.26\,c|^2$

→ Constr. interference for $c<0$

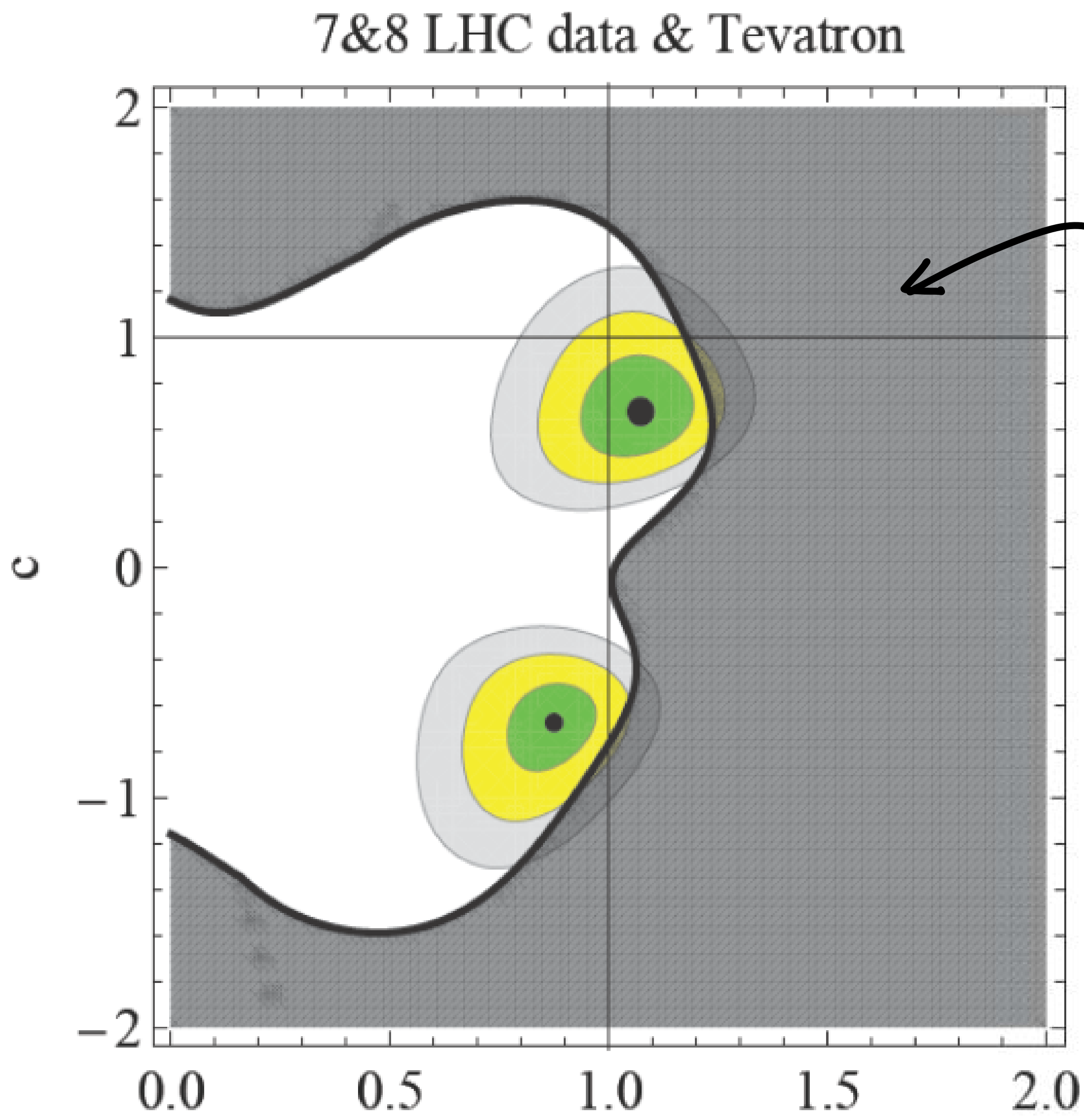
COMPARISON WITH CMS



Good agreement

Had to impose prior $c > 0$. (Best fit point for $c < 0$).

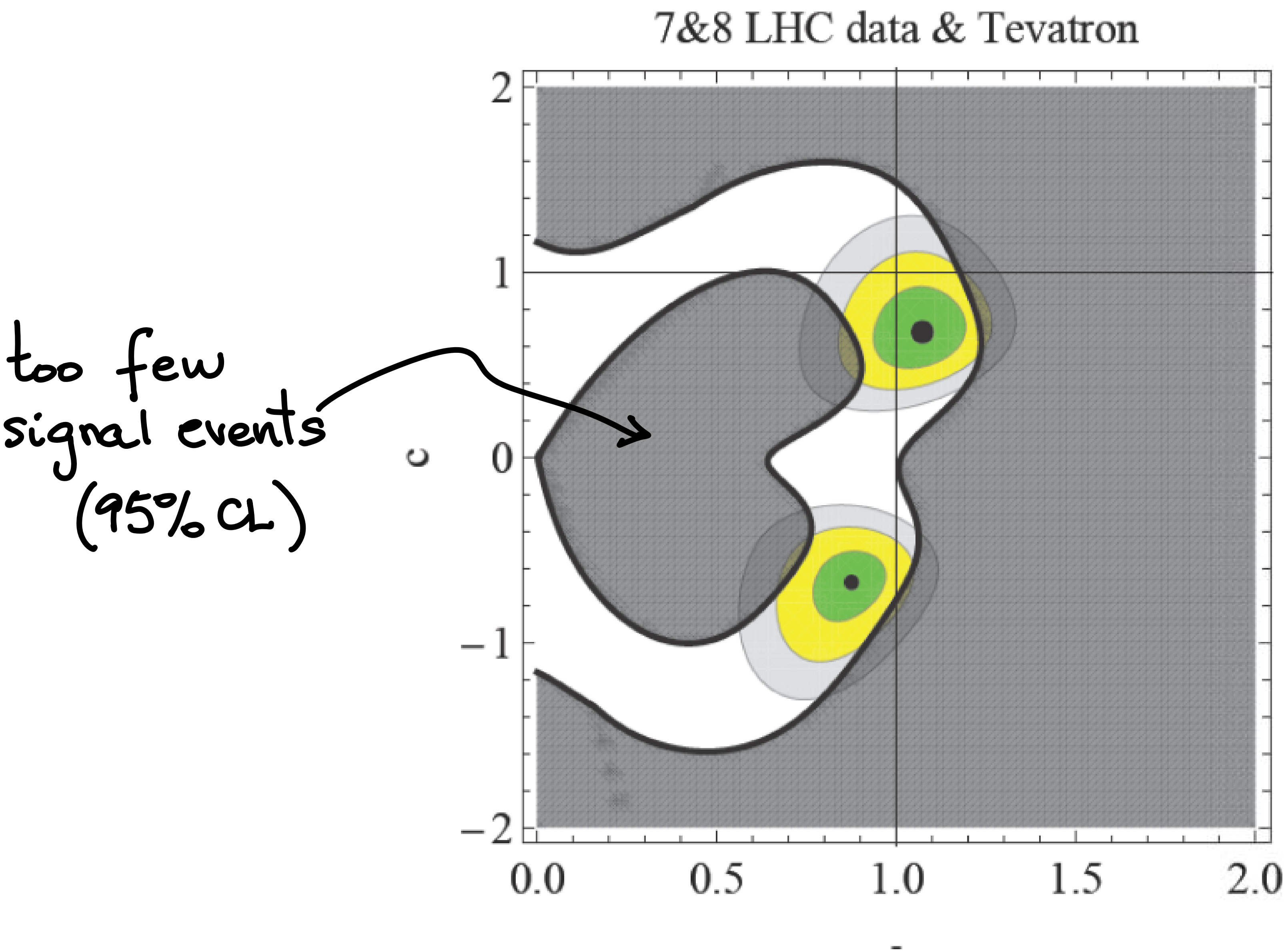
EXCLUDING SM (a,c)



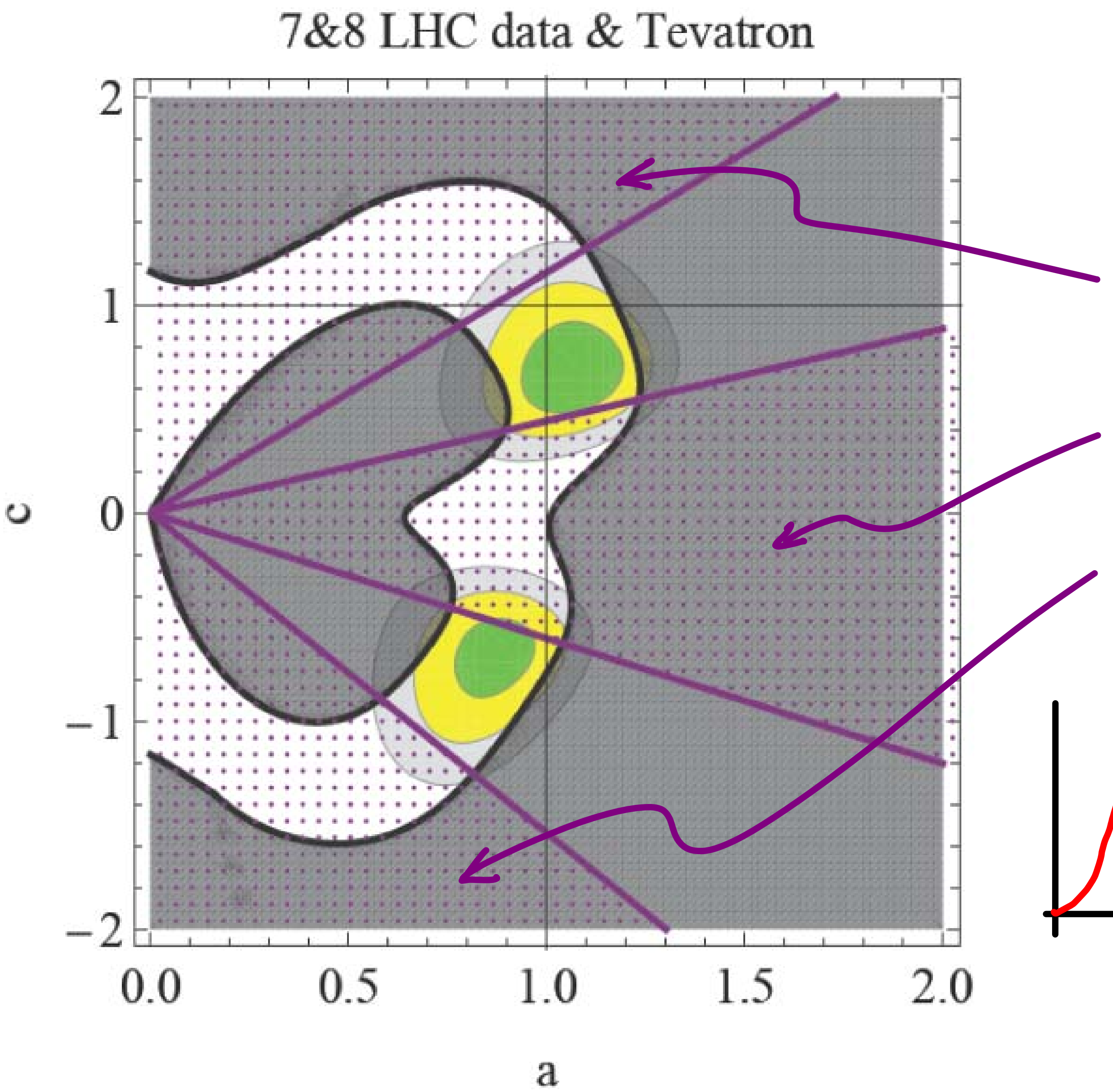
too large signal

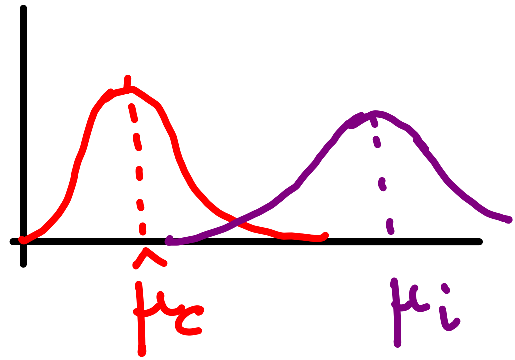
$\hat{\mu}_{exp} > \mu_L^{95\%}$

EXCLUDING SM (a,c)



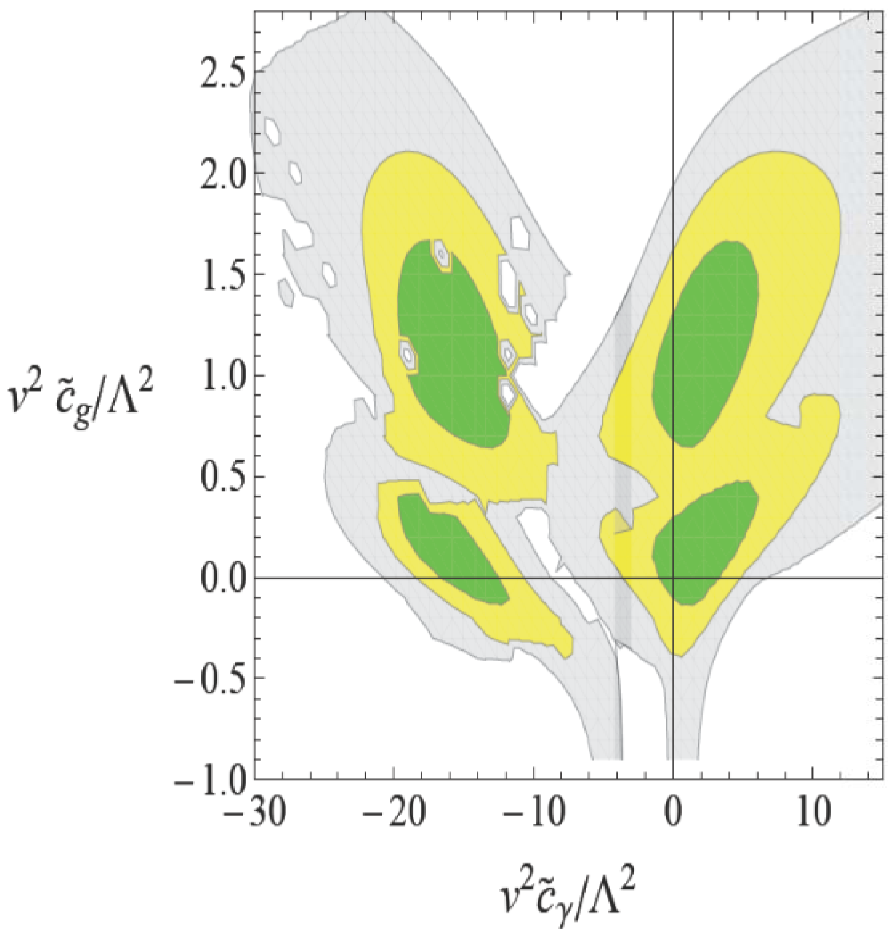
EXCLUDING SM (a,c)



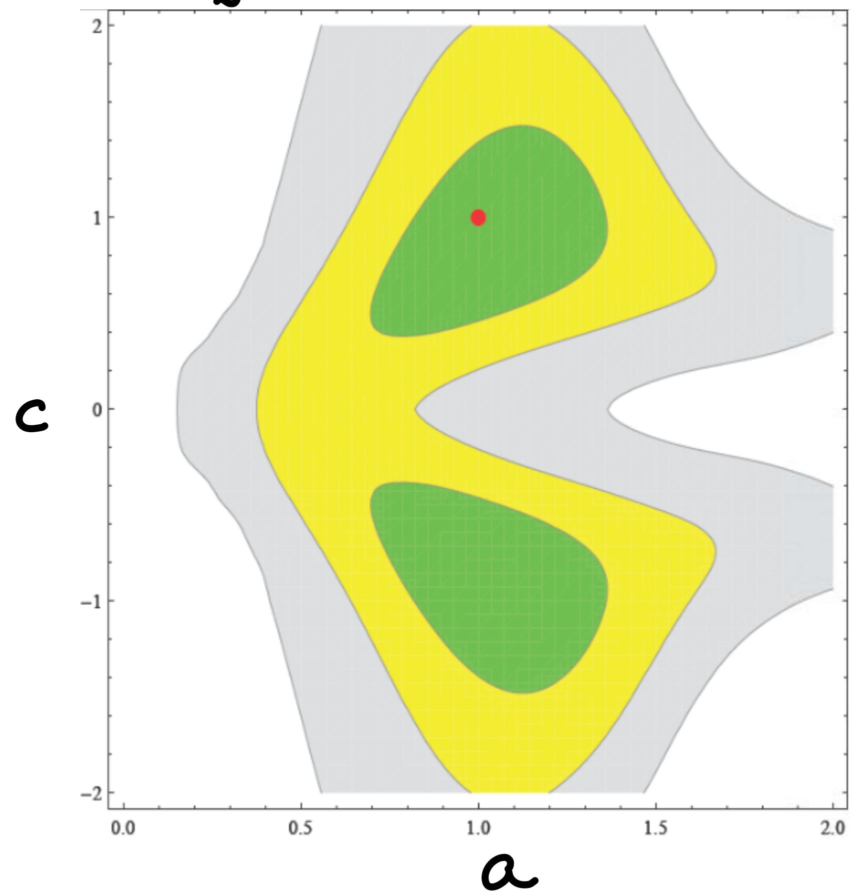


ANOMALOUS h COUPLINGS $(a,c) \neq (1,1)$ OR LOOP INDUCED EFFECTS $(\tilde{c}_g, \tilde{c}_\gamma) \neq (0,0)$?

(a,c) marginalized



$(\tilde{c}_g, \tilde{c}_\gamma)$ marginalized



Need more data !

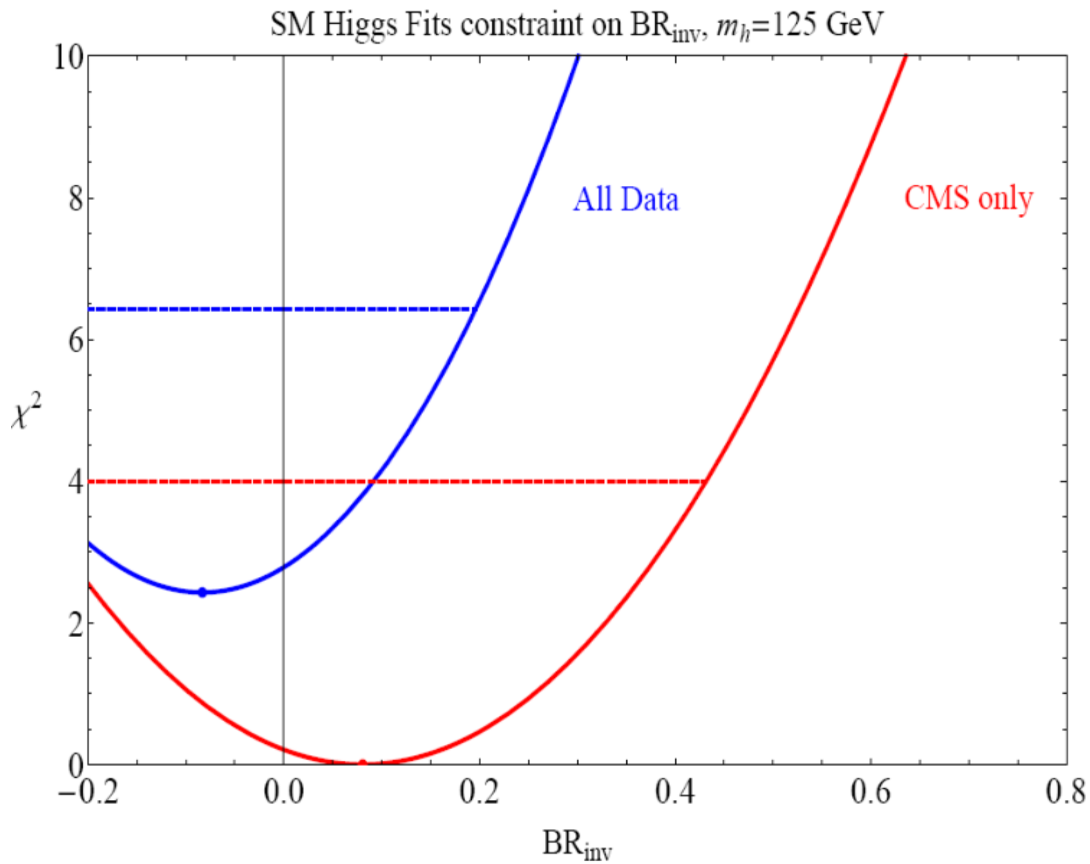
4b

HIGGS INVISIBLE WIDTH ?

$h \to XX$ for light (SM singlet) X (Higgs portal, DM, ...)

Universal reduction of $Br_j = \frac{\Gamma(h \to j)}{\Gamma_{SM} + \Gamma_{inv}} = (1 - BR_{inv}) Br_j^{SM}$

χ^2 fit to combined $\hat{\mu}_c \pm \sigma_c$



χ^2_{min} at $BR_{inv} \sim (-0.1, 0.1)$

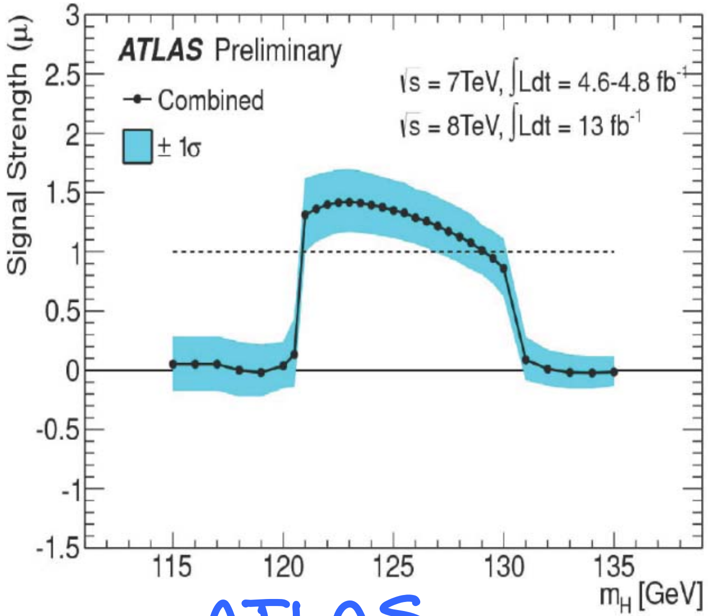
SM with $BR_{inv} = 0$ OK

Still there is room for

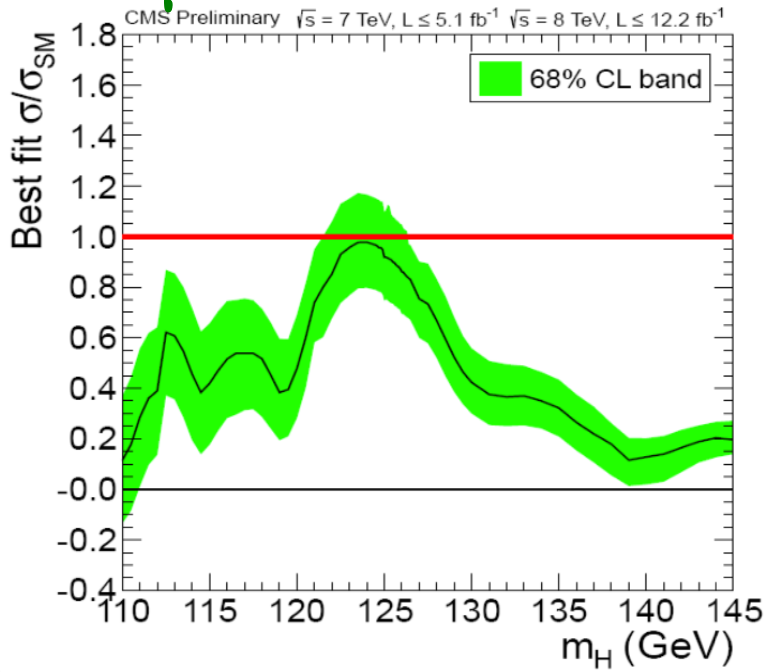
large BR_{inv} ($\lesssim {0.2 \atop 0.45}$ @ 95% CL)

HIGGS INVISIBLE WIDTH ?

Indirect evidence. Interpret $\hat{\mu} < 1$ as $\hat{\mu} = 1 - BR_{inv}$

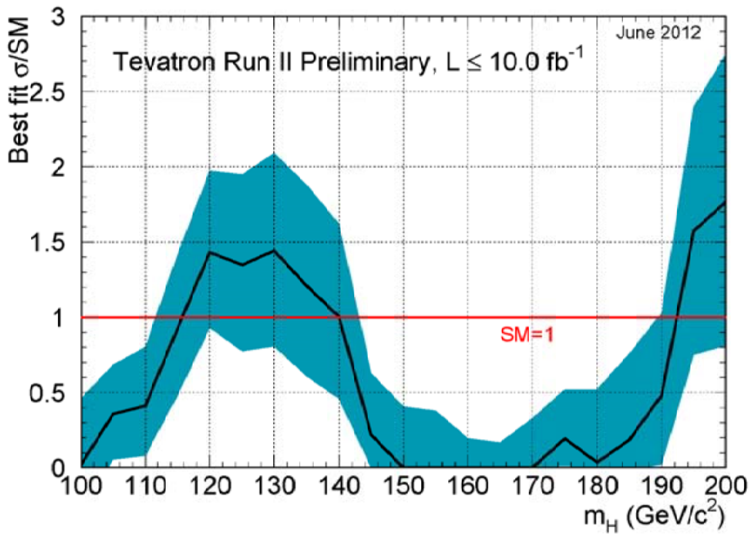


ATLAS



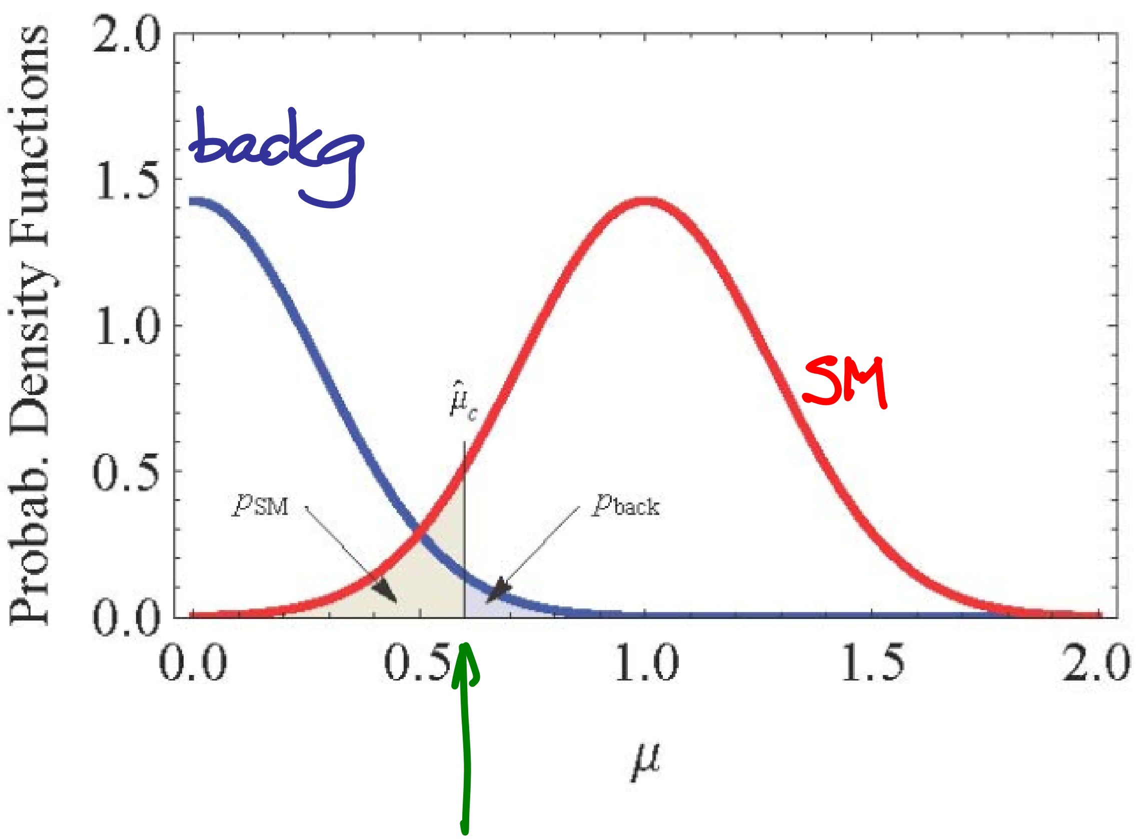
CMS

Tevatron



HIGGS INVISIBLE WIDTH ?

To trust this indirect evidence need $p_{SM}, p_{backg} \ll 1$



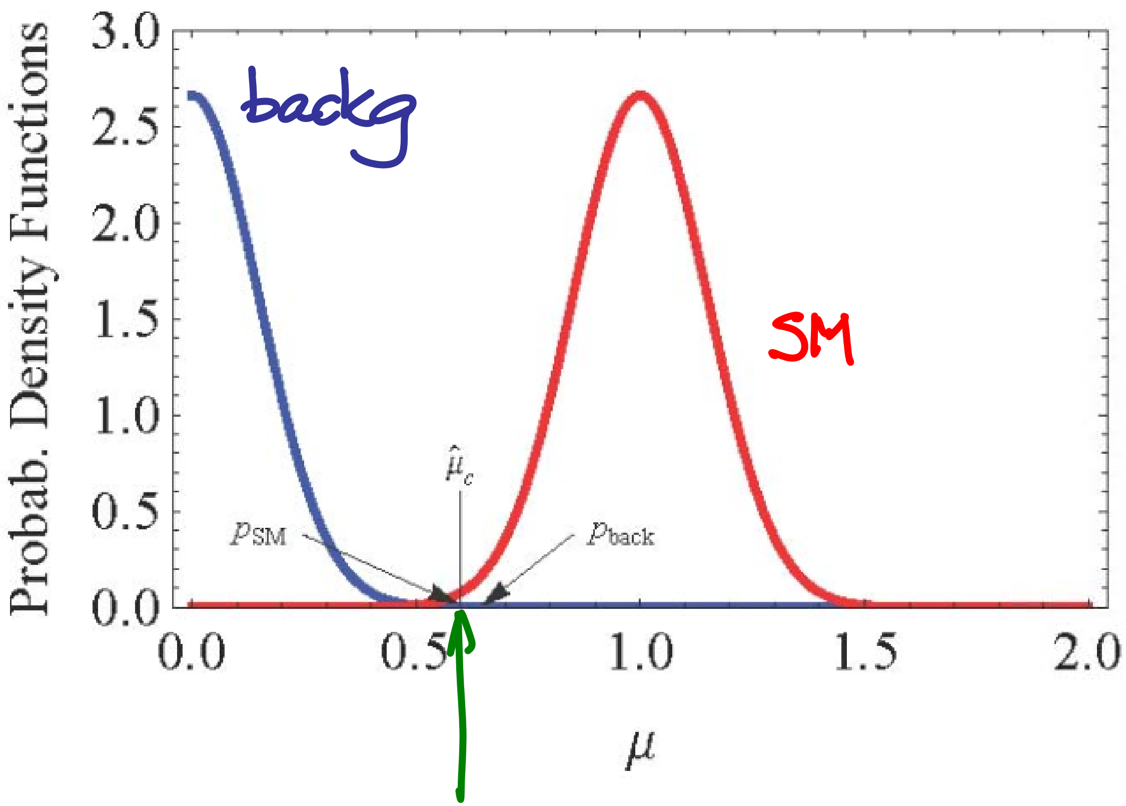
$\hat{\mu} = 1 - BR_{inv}$

It's crucial to reduce σ

HIGGS INVISIBLE WIDTH ?

To trust this indirect evidence need $p_{SM}, p_{backg} \ll 1$

Must also give small χ^2_{min}



$\hat{\mu} = 1 - BR_{inv}$

It's crucial to reduce σ

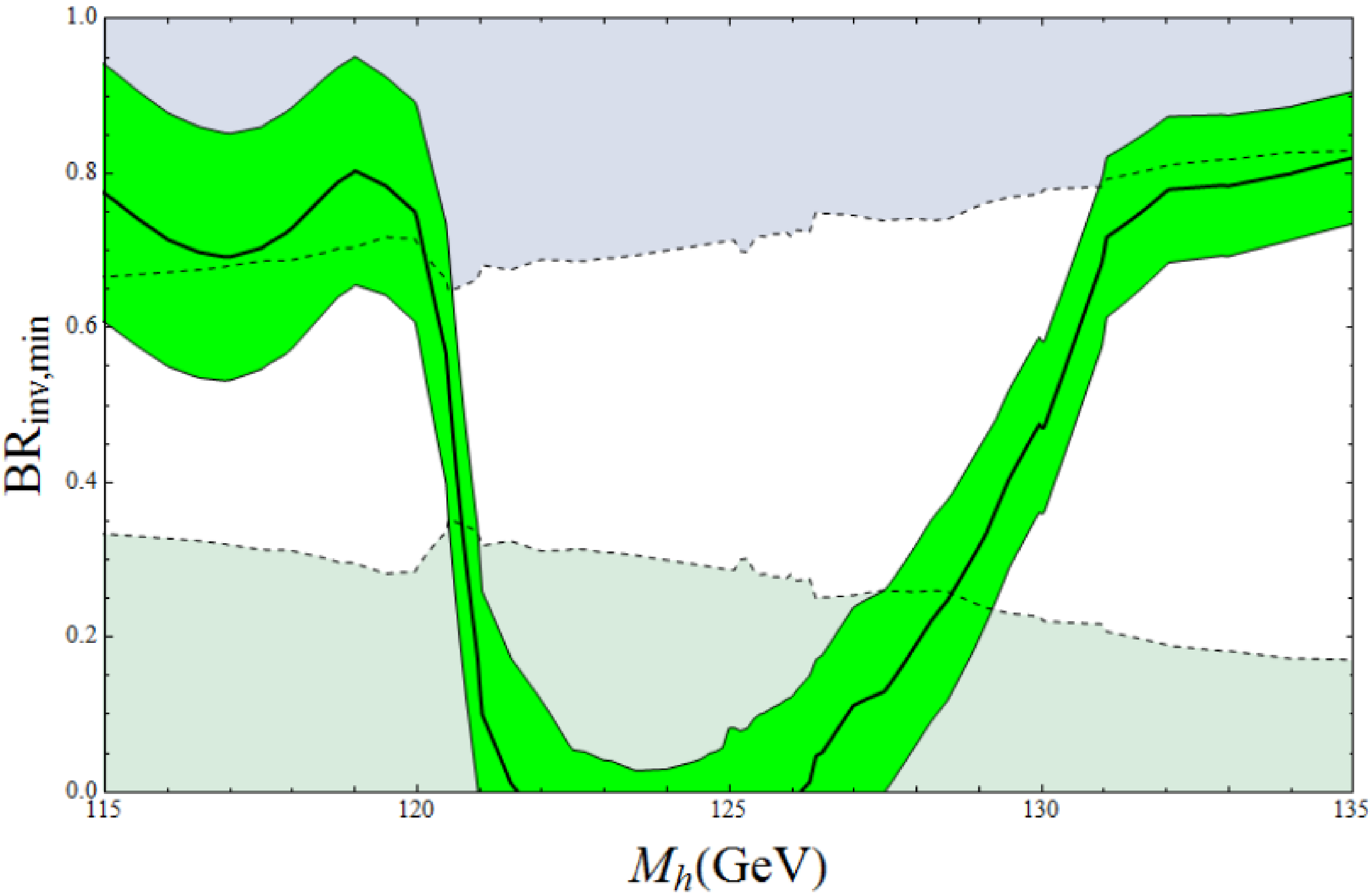
$$\frac{1}{\sigma^2} = \sum_i^{N_{ch}} \frac{1}{\sigma_i^2} \Rightarrow \sigma \sim \frac{\sigma_i}{\sqrt{N_{ch}}}$$

$$\sigma_i \sim \frac{\sqrt{n_{b,i}}}{n_{s,i}^{SM}} \sim \frac{1}{\sqrt{\mathcal{L}}}$$

HIGGS INVISIBLE WIDTH ?

Current situation as a function of m_h

$BR_{inv} = 1 - \hat{\mu}_c$

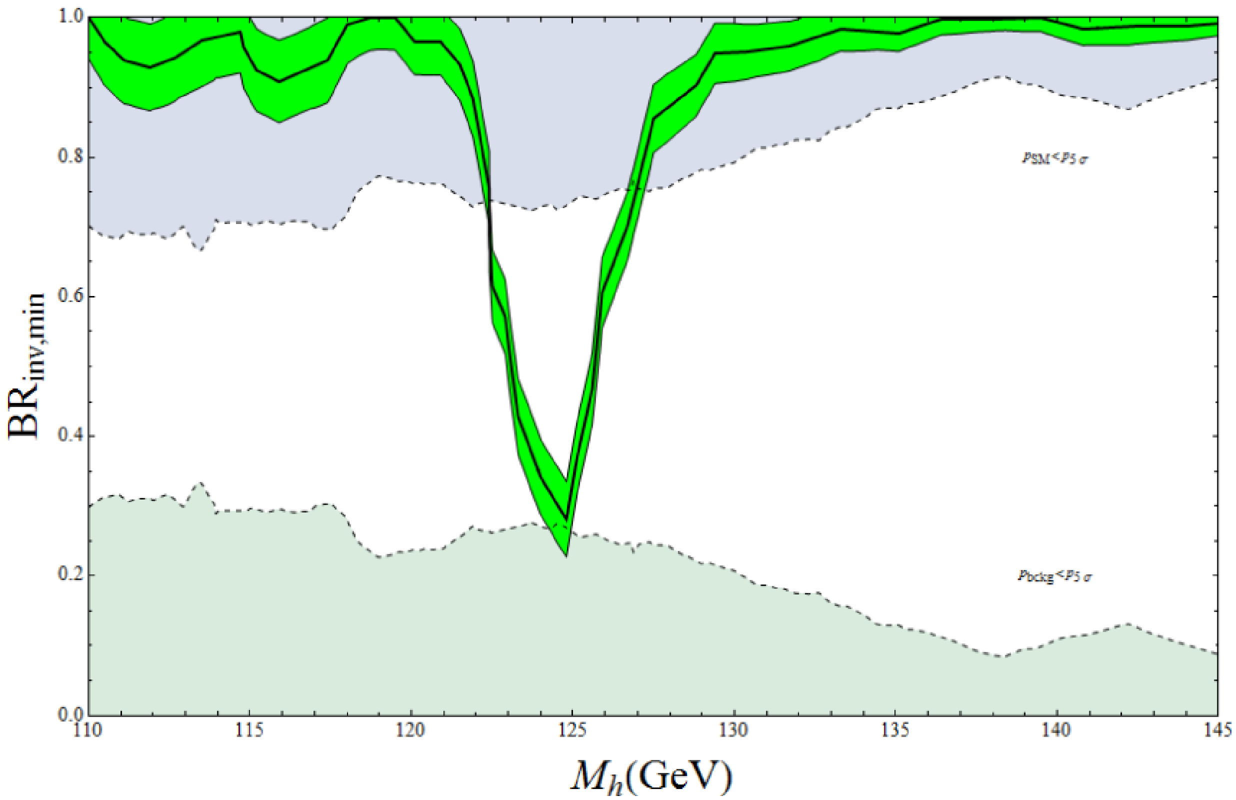


No strong conclusion possible

HIGGS INVISIBLE WIDTH ?

Future situation ($\sigma_c \sim \frac{0.3}{5}$ for $m_h = 125$ GeV)

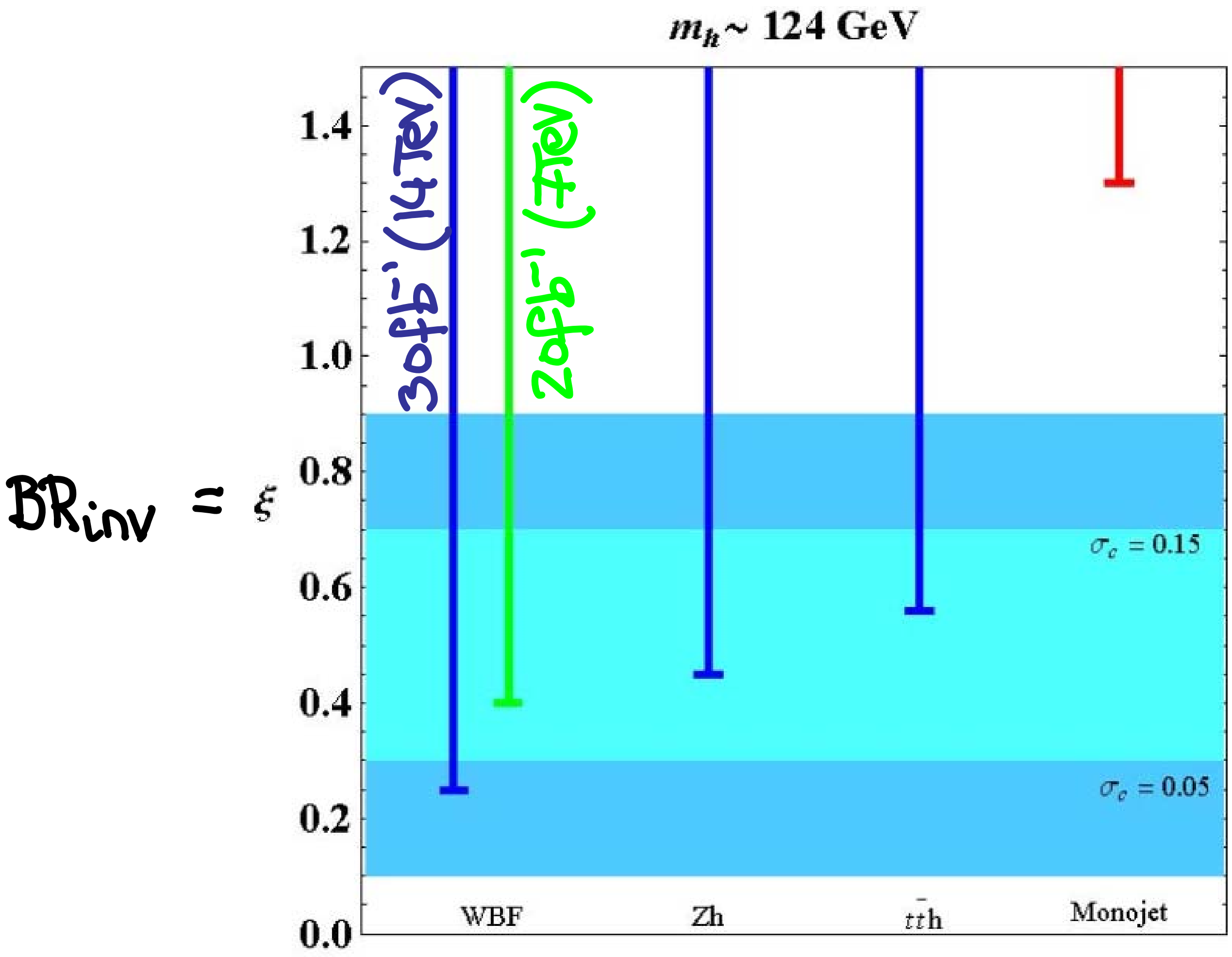
Hypothetical observed $\hat{\mu}$, of course...



HIGGS INVISIBLE WIDTH ?

How to tell apart $BR_{inv} > 0$ from e.g. $a = c < 1$?

Must validate with direct searches for inv. Higgs decays



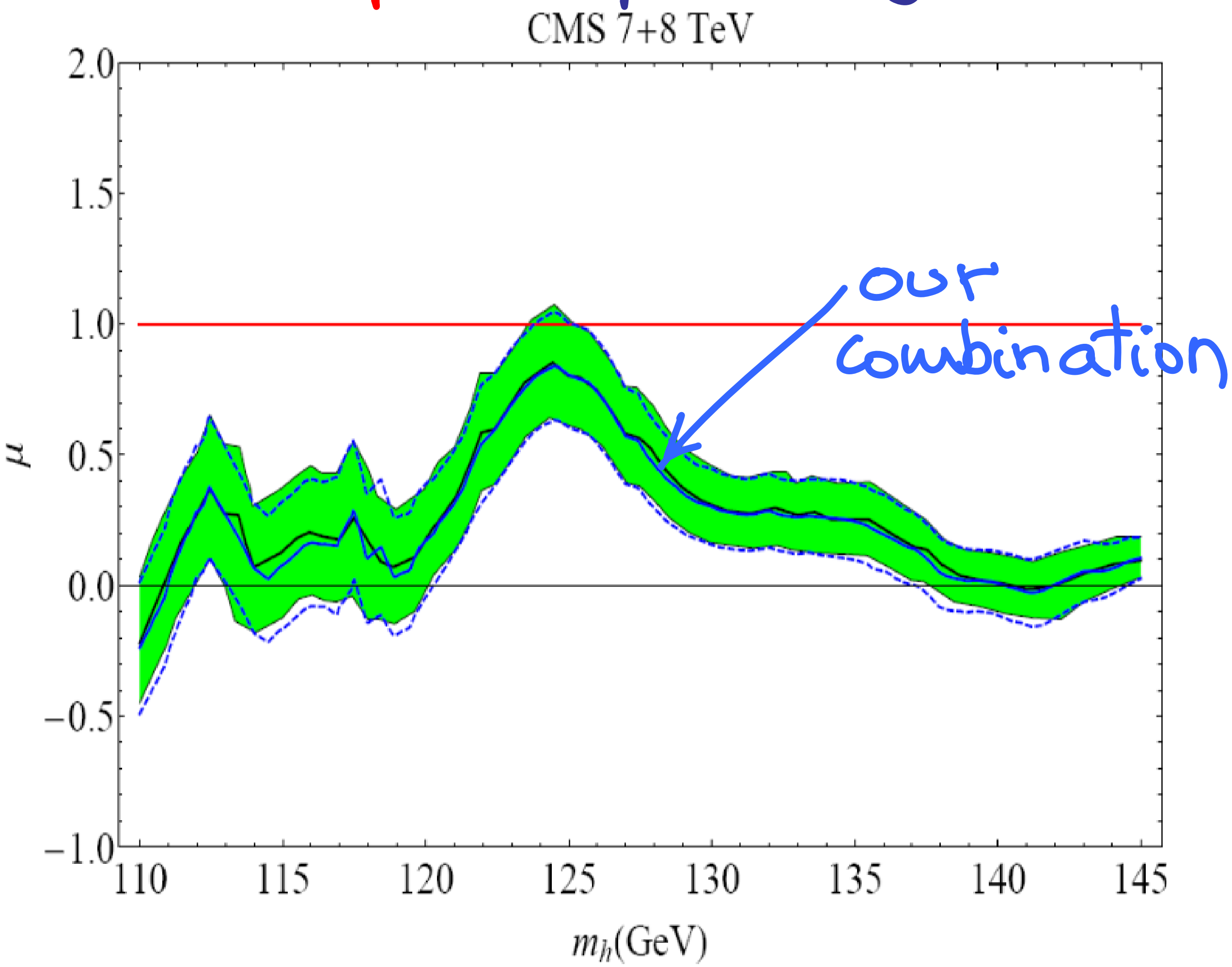
95% CL reach compared

RATES IN SM(a,c)

- ★ Need to know efficiencies ϵ_{p_i} to properly rescale σ_i
- ★ Need to know measured $\hat{\mu}$'s separately at 7,8 TeV

We ckecked this works well :

Official CMS combination at 7+8 TeV



ASKING THE HIGGS ABOUT STOPS