Superymmetric scenarios after the Brout - Englert - Higgs boson discovery

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LAL - Orsay, February 7th, 2014

Low Energy Supersymmetry (as seen by many)

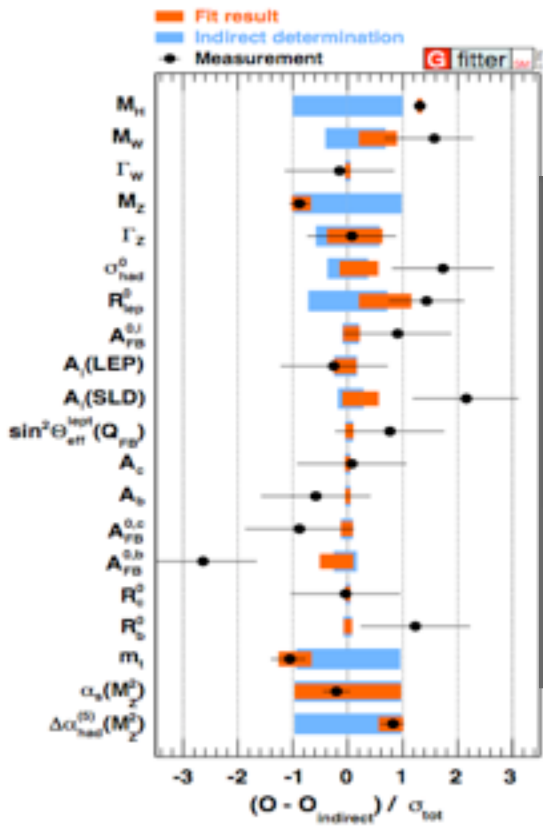
- In the Standard Model, no increased symmetry is gained by letting the mass of the elementary scalar to vanish
- as a consequence, extraordinary fine-tuning of quantum corrections is needed to keep the Higgs boson mass to values so much smaller than the natural cutoff given by gravity (or grand unification)
- *low energy* supersymmetry relates scalars and fermions, whose mass is protected by chiral symmetry, and reduces the cutoff scale to M_{SUSY}.
- Alternative: there are no elementary scalars, the Higgs boson is composite by fermion fields, possibly a would-be-Goldstone boson of some symmetry.
- New physics of the strong-interaction type is not favoured by electroweak precision data (which are really becoming high-precision data).
- In addition, the value found for the Higgs boson mass speaks in favour of SUSY.

- Veltman used to say: *I go on until I go wrong*
- until now, nothing wrong did show up...

ELECTROWEAK FIT

Electroweak Fit – SM Fit Results

- Results drawn as *pull values:* → deviations to the *indirect* determinations, divided by *total error*.
- Total error: *error of direct measurement plus error from indirect determination.*
- Black: direct measurement (data)
- Orange: full fit
- Light-blue: fit excluding input from the row
- The prediction (light blue) is often more precise than the measurement!



Max Baak (CERN) The ElectroWeak fit of Standard Model 24

Max Baak (CERN), on behalf of the Gfitter group (*)

CERN seminar, Geneva, 23rd September, 2013

G fitter

http://cern.ch/Gfitter

EPJC 72, 2205 (2012), arXiv:1209.2716

After the Higgs: Status and Prospects of The ElectroWeak fit of the SM and Beyond

- Fit result:

$S = 0.03 \pm 0.10$

$T = 0.05 \pm 0.12$

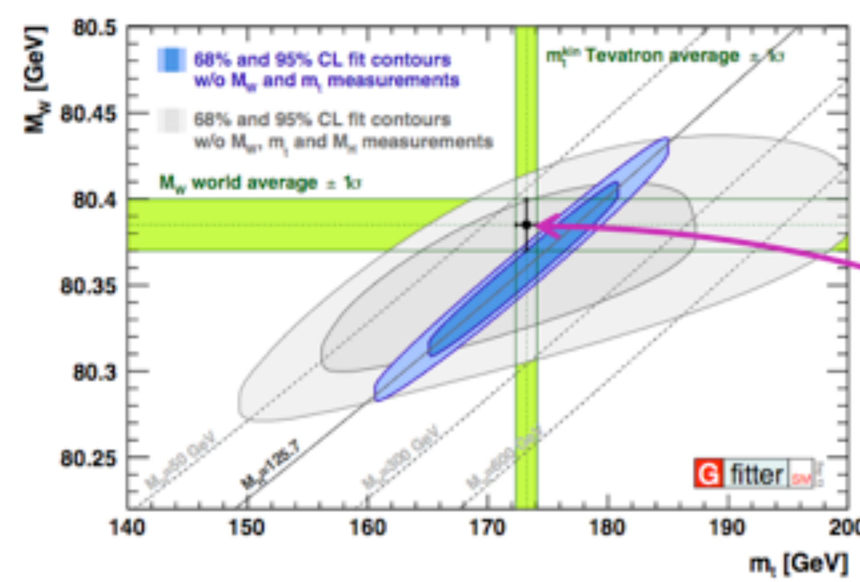
$U = 0.03 \pm 0.10$

	S	*T*	*U*
S	1	+0.89	-0.54
T		1	-0.80
U			1

- Stronger constraints from fit with U=0.
- Also available for Z→bb correction.

State of the SM: W versus top mass

- Scan of M_W vs m_t, with the direct measurements excluded from the fit.
- Results from Higgs measurement significantly reduces allowed indirect parameter space → corners the SM!



- Observed agreement demonstrates impressive consistency of the SM!

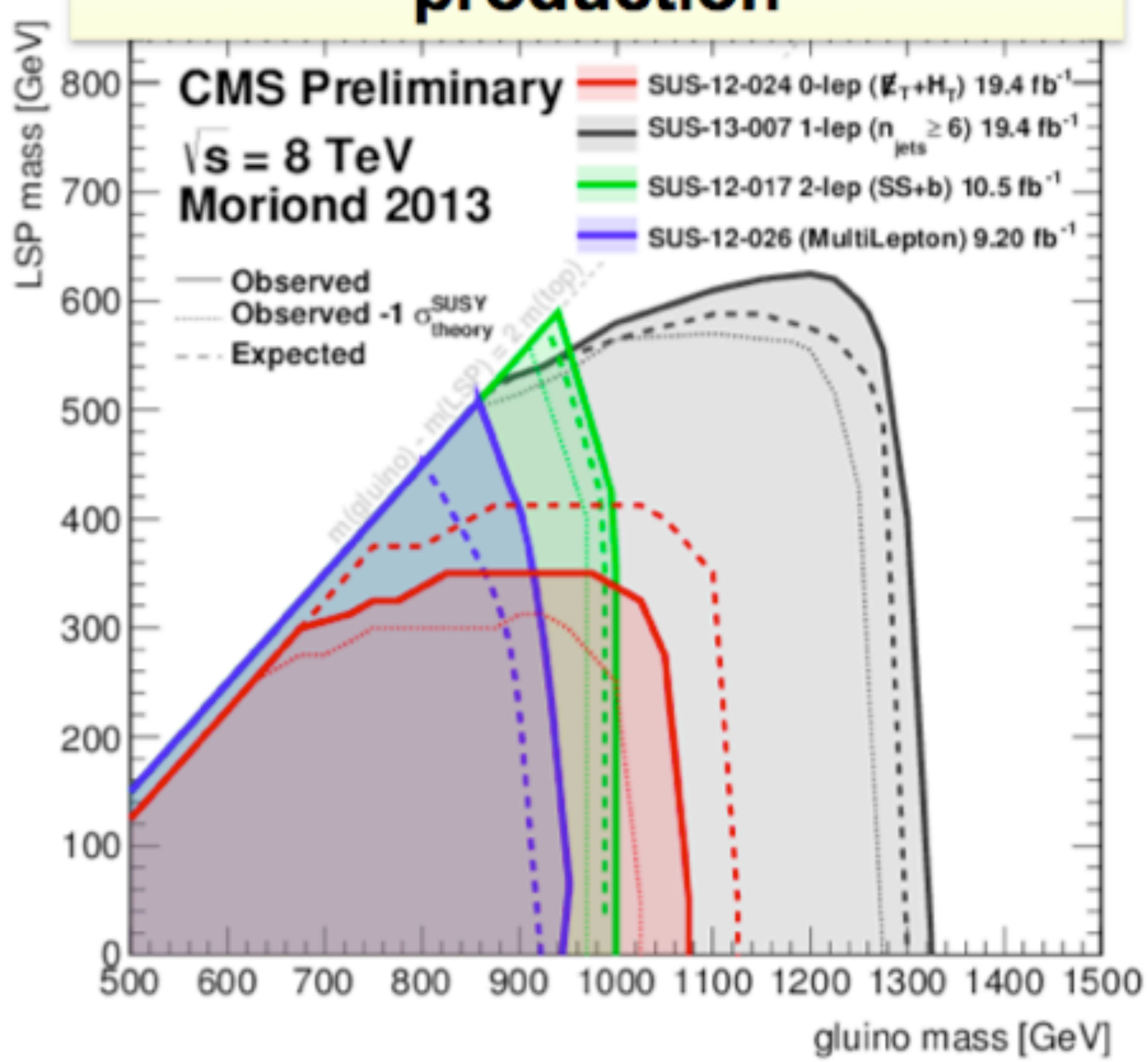
Max Baak (CERN) The ElectroWeak fit of Standard Model 32

- No detectable oblique corrections: S, T, U
- Perturbative corrections from BSM physics?
- Too early to say, ...but

YET, NO SUSY PARTNERS IN SIGHT…

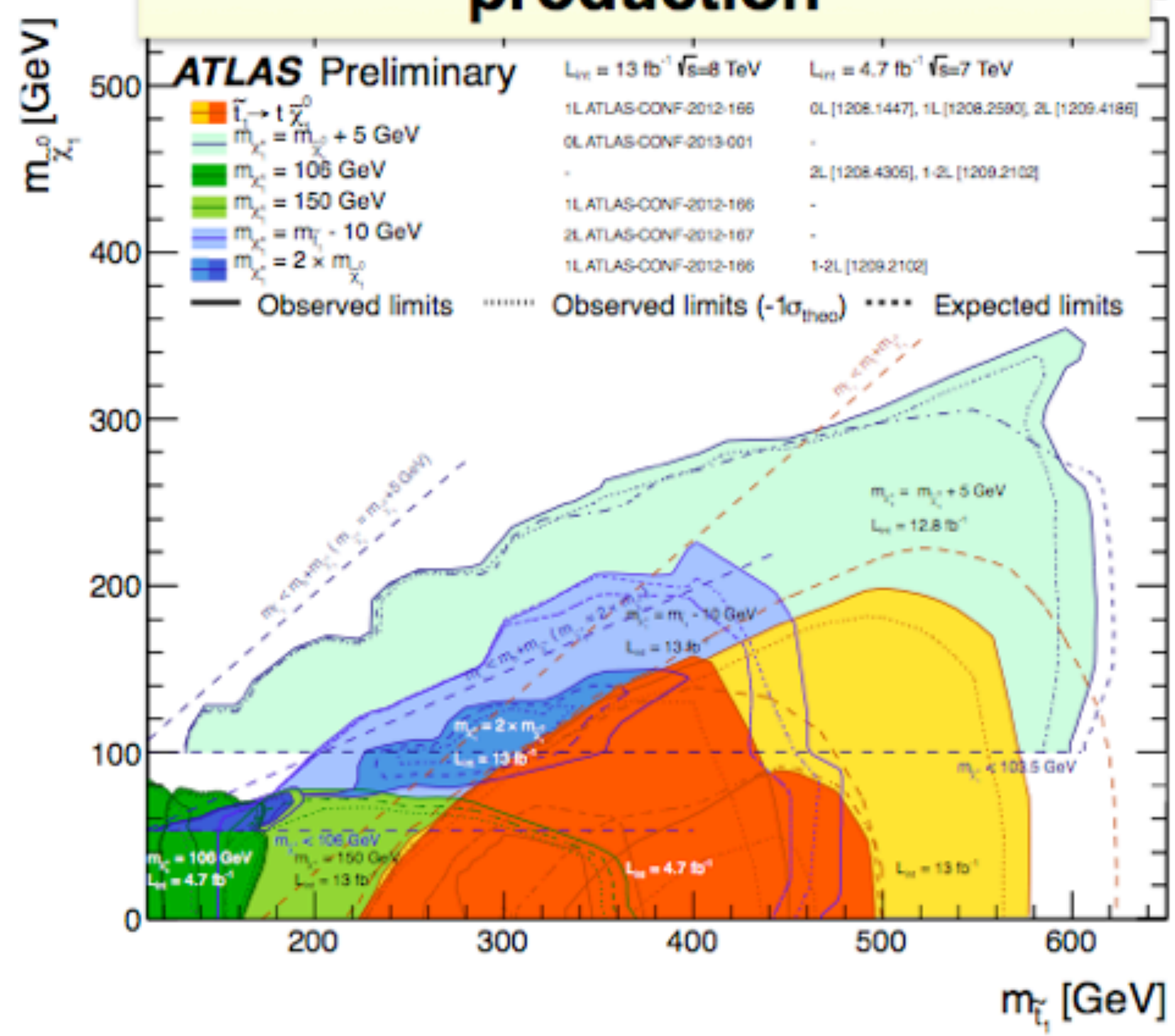
If gluino light enough:
→ gluino induced production

CMS gluino-induced stop production



If third-generation squarks light enough:
→ direct production

ATLAS direct stop production



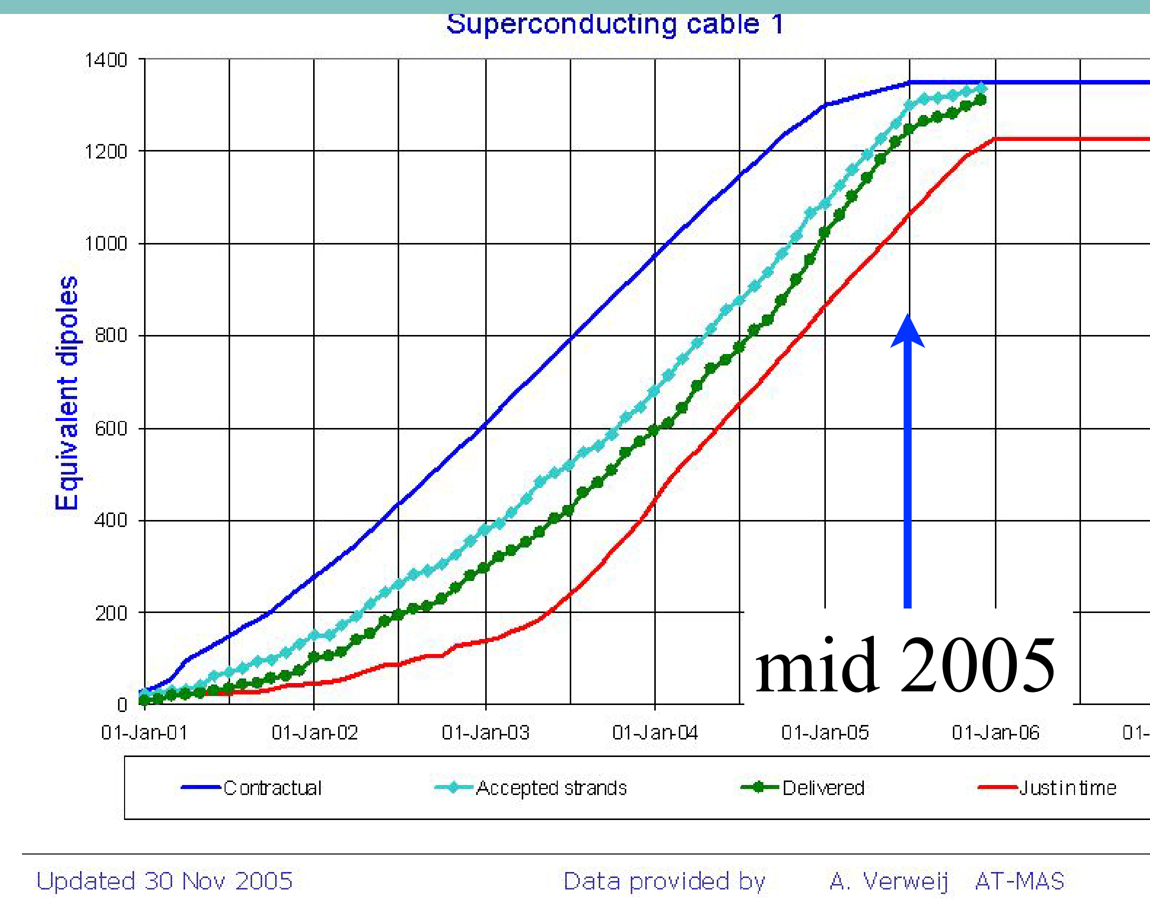
1. EARLY ESTIMATES OF THE LHC DISCOVERY POTENTIAL

BUILDING LHC WAS A GREAT ENTERPRISE WHICH CERN LED WITH GREAT SKILL

1.1. LHC Schedule

- Contracts for dipole cold mass… CERN has a double role: supplier of SC cables, end-customer of the dipoles. We must be prudent in defining the dipole delivery schedule, hence the LHC schedule.
- SC cable production to end mid 2005;
- last dipole delivered July 1st, 2006;
- Machine closed and cold: Oct. 2006;
- First beam: April 2007;
- First physics: mid 2007;
- Very solid foundation of the LHC confirmed by SC cable panel and Machine Advisory Committee.

L. Maiani. March 21, 2002 Committee of Council 8



- 1.5 year delay due to problems with QRL
- another 1.5 year for the accident
- later resolved by Steve Myers

Sept. 10th 08: first beams

- useful beams: 2010
- Higgs physics: 2011

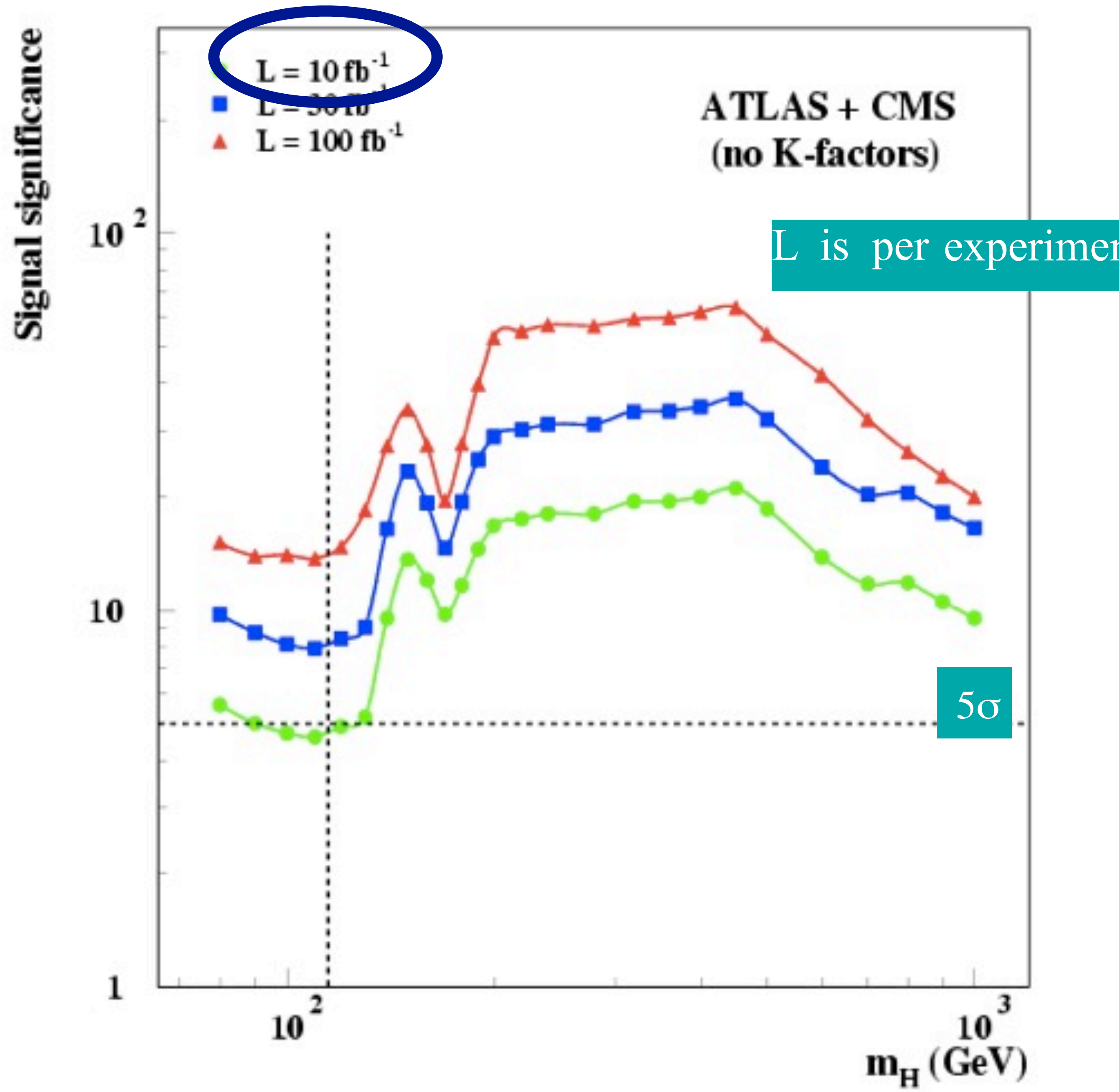
Lyn Evans and Lucio Rossi receive at CERN the last dipole

Higgs Boson at the LHC

- SM Higgs boson can be discovered at ≈ 5 σ after ≈1 year of operation (10 fb^{-1}/ experiment) for $m_H \approx 150$ GeV
- Discovery faster for larger masses
- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

Discovered by each expt

Discovered in the difficult region with $20 fb^{-1}$ for each expt.



<u>results are conservative:</u>

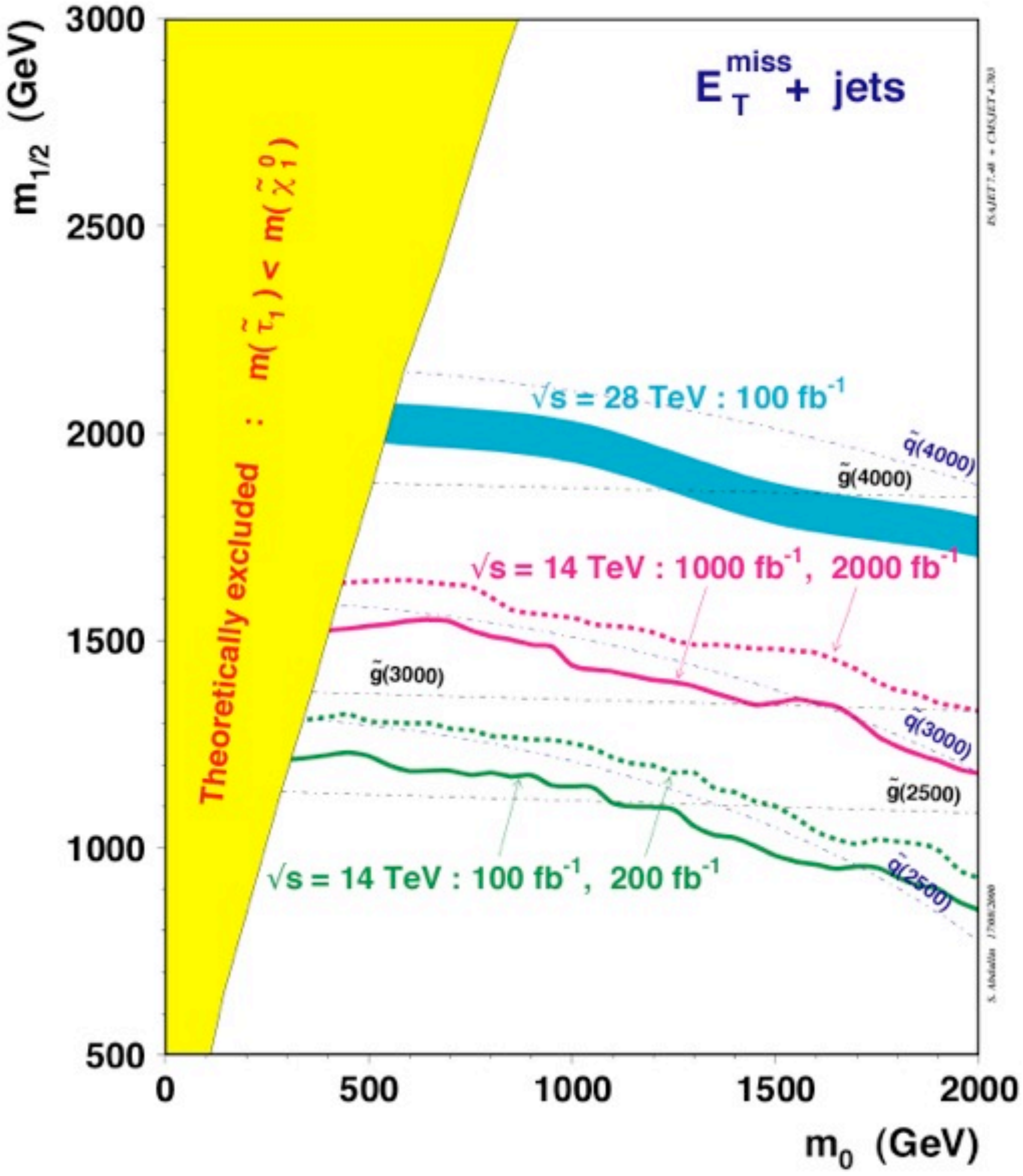
-- no k-factors

-- simple cut-based analyses

-- conservative assumptions on detector performance

-- channels where background control is difficult not included, e.g $WH \rightarrow l\nu bb$

F. Gianotti



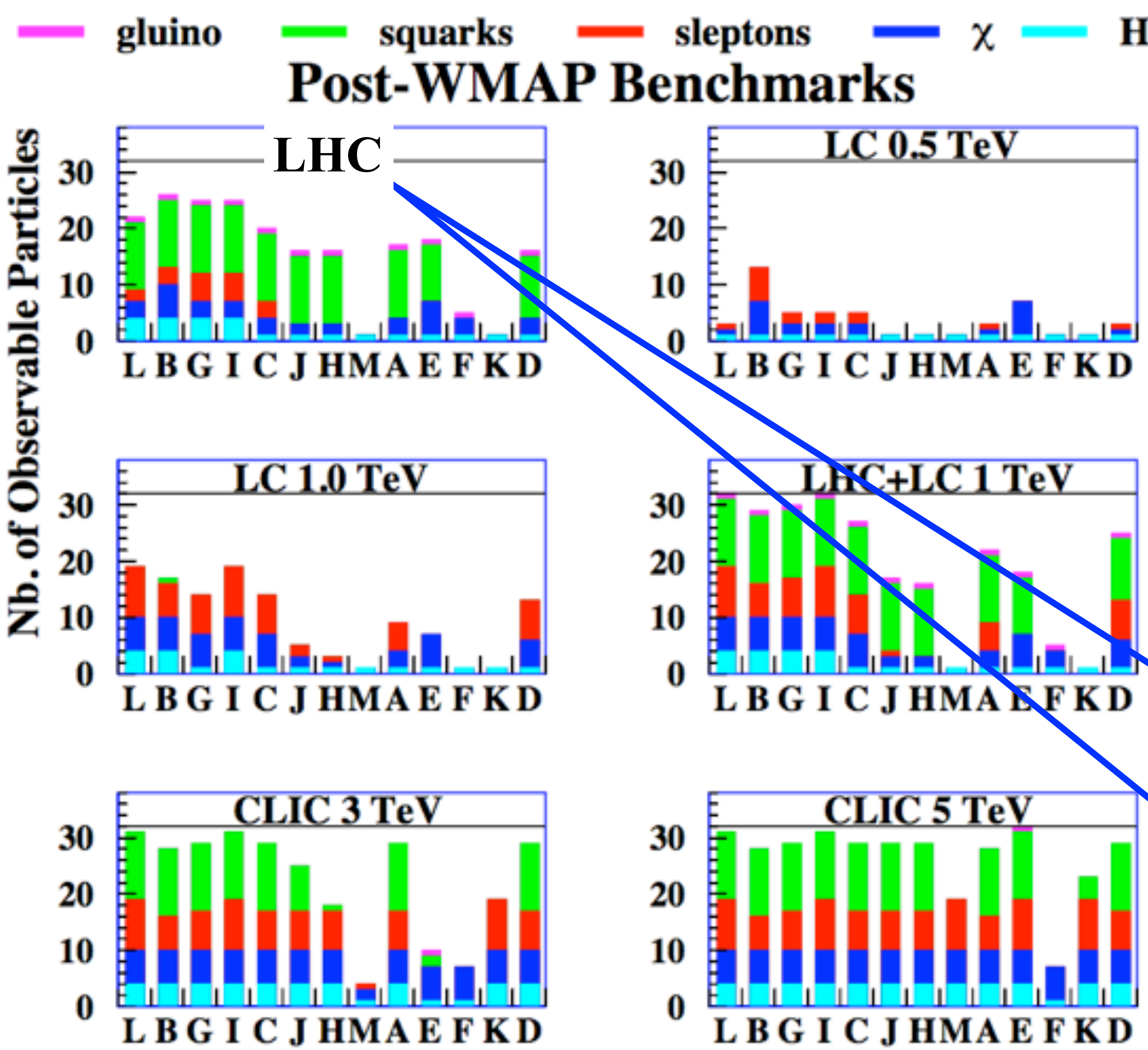
Energy reach for SUSY particle searches of a PP collider vs E&Lum.

HOW MANY MSSM PARTICLES AT LHC ? AND FUTURE LC ?

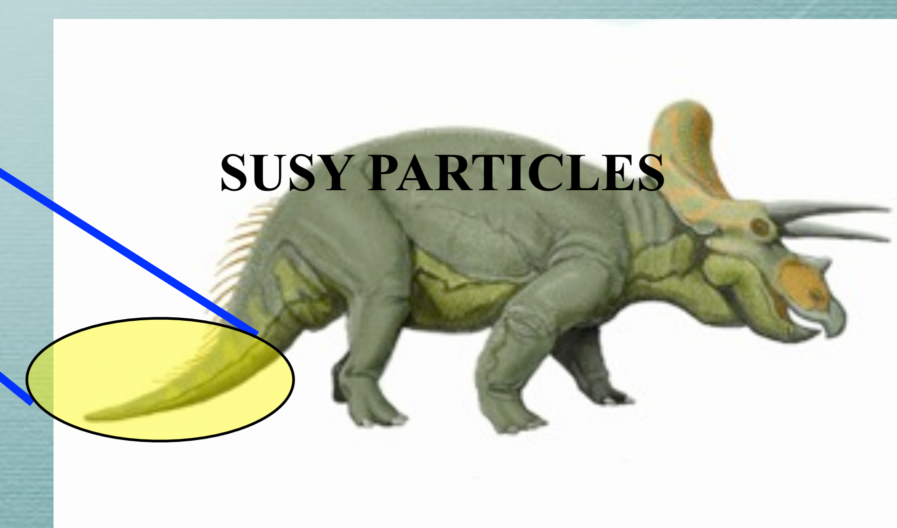
Updated Post-WMAP Benchmarks for Supersymmetry

2004

M. Battaglia[1], A. De Roeck[1], J. Ellis[1], F. Gianotti[1], K. A. Olive[2] and L. Pape[1]



- Numbers and types of MSSM particles discovered, for representative regions of SUSY parameters
- LHC: E_{cm}=14 TeV ; integrated luminosity =100 fb^{-1}
- with a little luck we could be able to see the tail...



2. THE MESSAGE IN THE MASS

A famous inequality of SUSY:

$$M_h^2 \leq M_Z^2 \rightarrow_{(\text{rad. corr.})} M_h^2 \approx \cos^2(2\beta) M_Z^2 + \delta$$

- Can we make δ so as to reproduce 125 GeV?
- A nice formula for δ (M. Carena, S. Gori, N. R. Shah, C. E. M. Wagner, JHEP 1203, (2012), 014, arXiv:1112.3336 [hep-ph]):

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right],$$

where

$$t = \log \frac{M_{\rm SUSY}^2}{m_t^2}.$$

The parameter $\tilde{X}_t$ is given by

$$\tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{\tilde{A}_t^2}{12 M_{\rm SUSY}^2}\right),$$

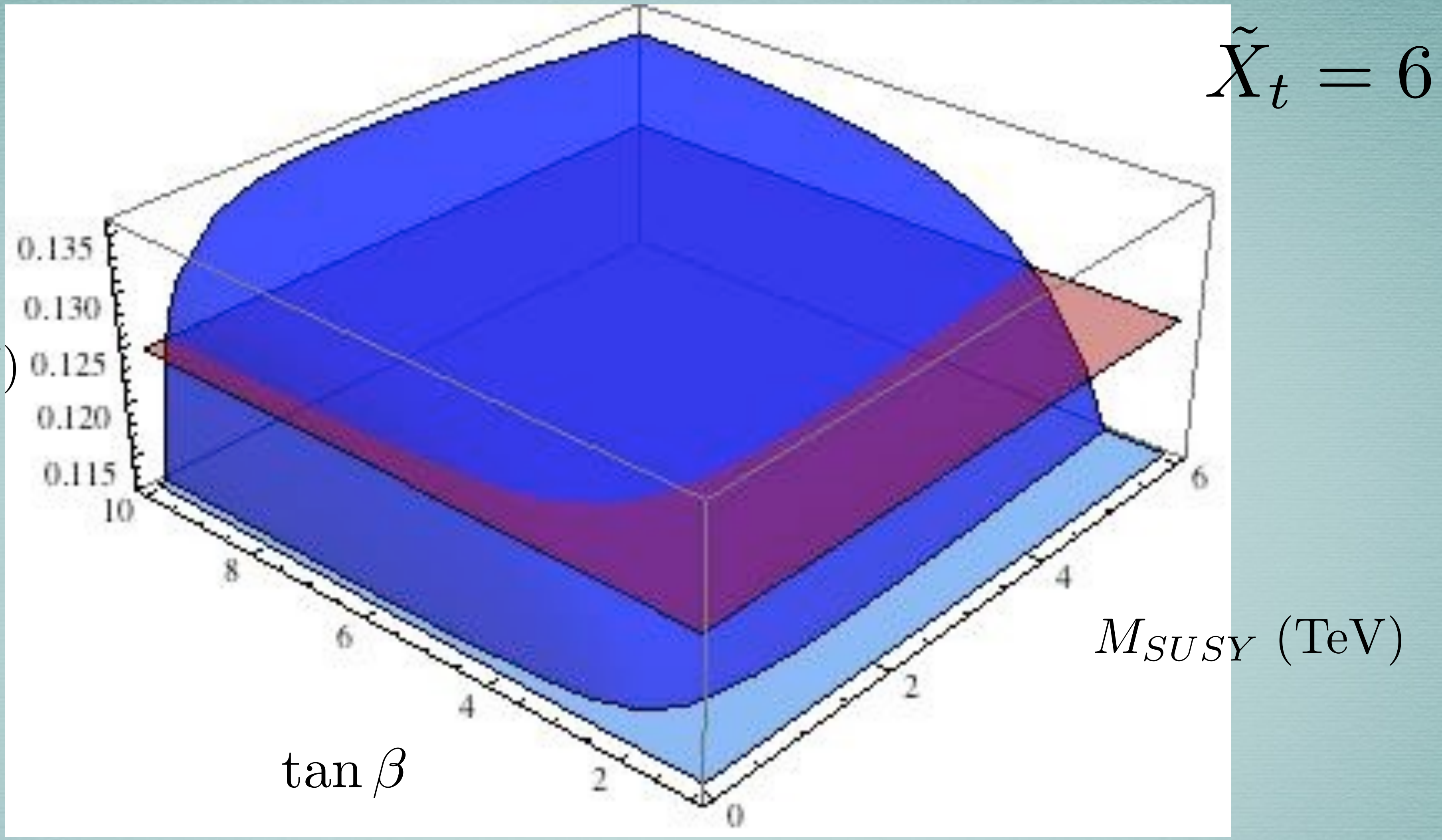
$$\tilde{A}_t = A_t - \mu \cot\beta ,$$

$$M_{SUSY}^2 = M_{stopL} \times M_{stopR}$$

$$\tilde{X}_t \leq 6$$

- leading top/s-top contributions, of $O(y_t^4)$
  - neglected terms $O(g^2 y_t^2) \approx 20\%$ of the leading ones
  - neglected even smaller s/s-b contr'btns.

REPRODUCING 125 IN MSSM

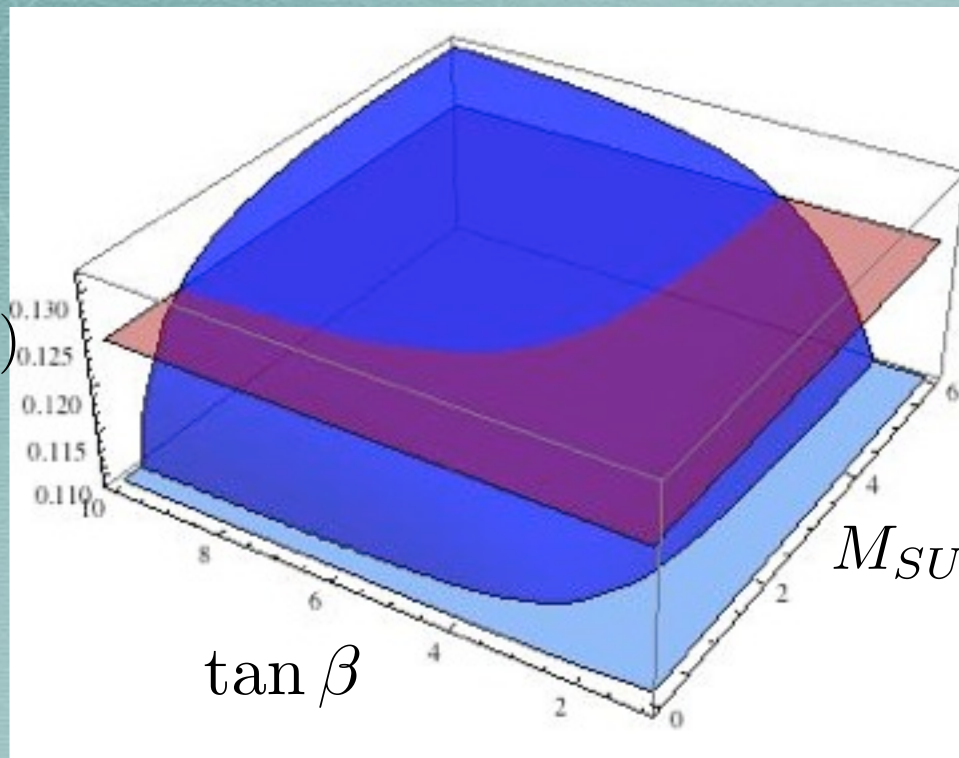


- maximal mixing assumed, X_t=6;
- requires tan β ⩾ 4;
- the branch with high stop mass goes rapidly into the few TeV region
-a relatively light stop, with tan β ≈ 10 considered in:

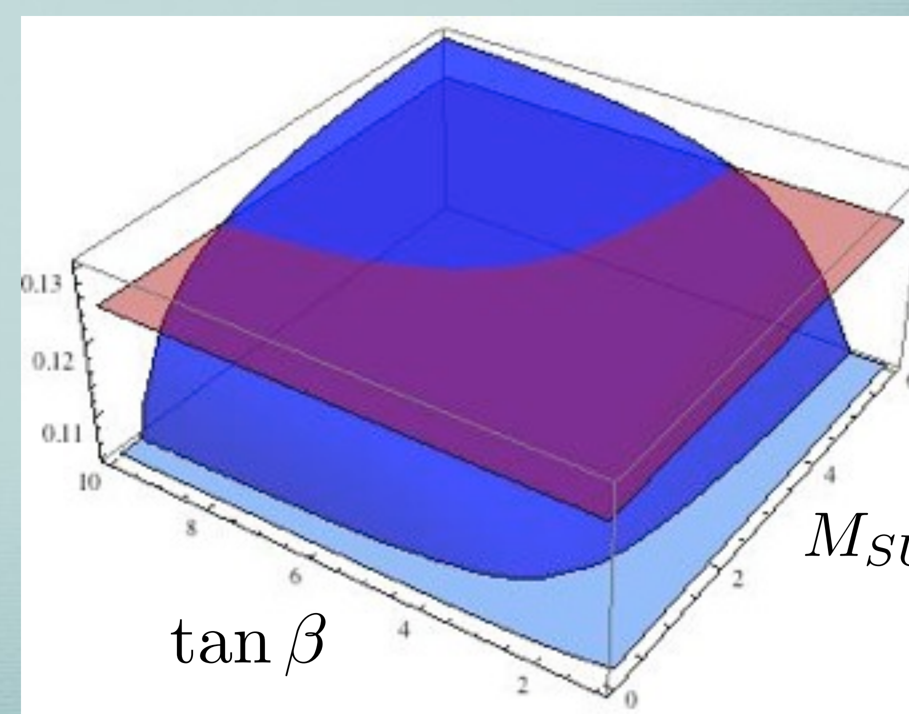
A. Delgado, G. F. Giudice, G. Isidori, M. Pierini, A. Strumia, arXiv:1212.6847 [hep-ph]

THE ROLE OF MIXING

$\tilde{X}_t = 2$



$\tilde{X}_t = 0$



$$M_h^2 \approx \cos^2(2\beta) M_Z^2 + \delta \leq 135\text{GeV}$$

The mass of h speaks for SUSY

3. Implications of $M_h \approx 126$ GeV for the MSSM

Main results:

- **Large M_S values needed:**

– $M_S \approx 1$ TeV: only maximal mixing

– $M_S \approx 3$ TeV: only typical mixing.

- **Large tanβ values favored**

but tan$\beta \approx 3$ possible if $M_S \approx 3$TeV

How light sparticles can be with the constraint $M_h = 126$ GeV?

- 1s/2s gen. $\tilde{q}$ should be heavy...

But not main player here: the stops:

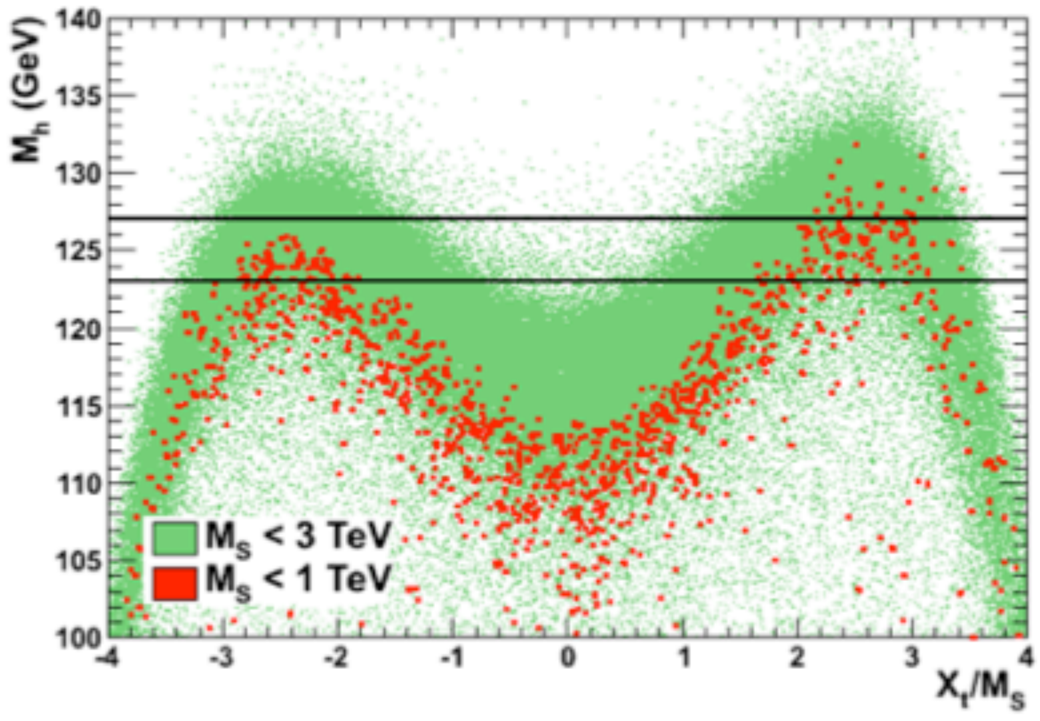
$\Rightarrow m_{\tilde{t}_1} \lesssim 500$ GeV still possible!

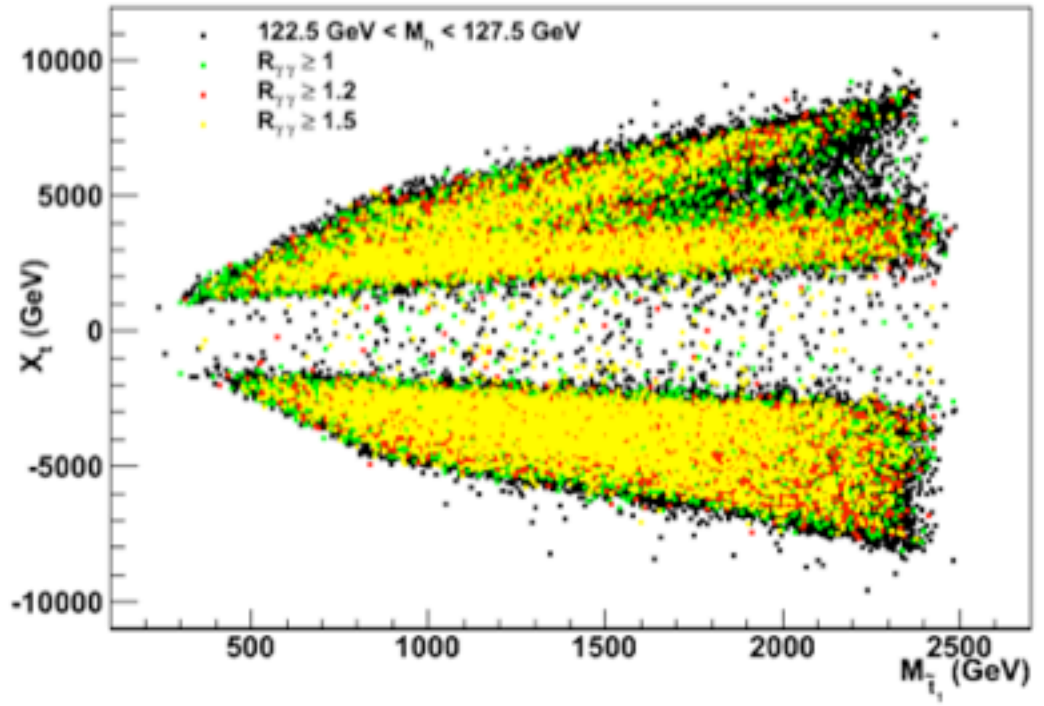
(see also G. Isidori et al. e.g.)

- M_1, M_2 and μ unconstrained,
- non-univ. $m_{\tilde{f}}$: decouple $\tilde{\ell}$ from $\tilde{q}$

EW sparticles can be still very light

but watch out the new LHC limits..





Roma, 13/01/2014 Implications of the Higgs discovery – A. Djouadi – p.13/27

CMSSM, BOUNDS FROM $B_s \to \mu^+\mu^-$

Supersymmetric constraints from $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ observables

F. Mahmoudi[1,2*] S. Neshatpour[2†] and J. Orloff[2‡]

arXiv:1205.1845v1 [hep-ph]

- The Constrained MSSM (CMSSM) is a SUSY model which satisfies the principles of Minimal Flavour Violation, thus the limits from FCNC are compatible with a relatively low energy scale for New Physics

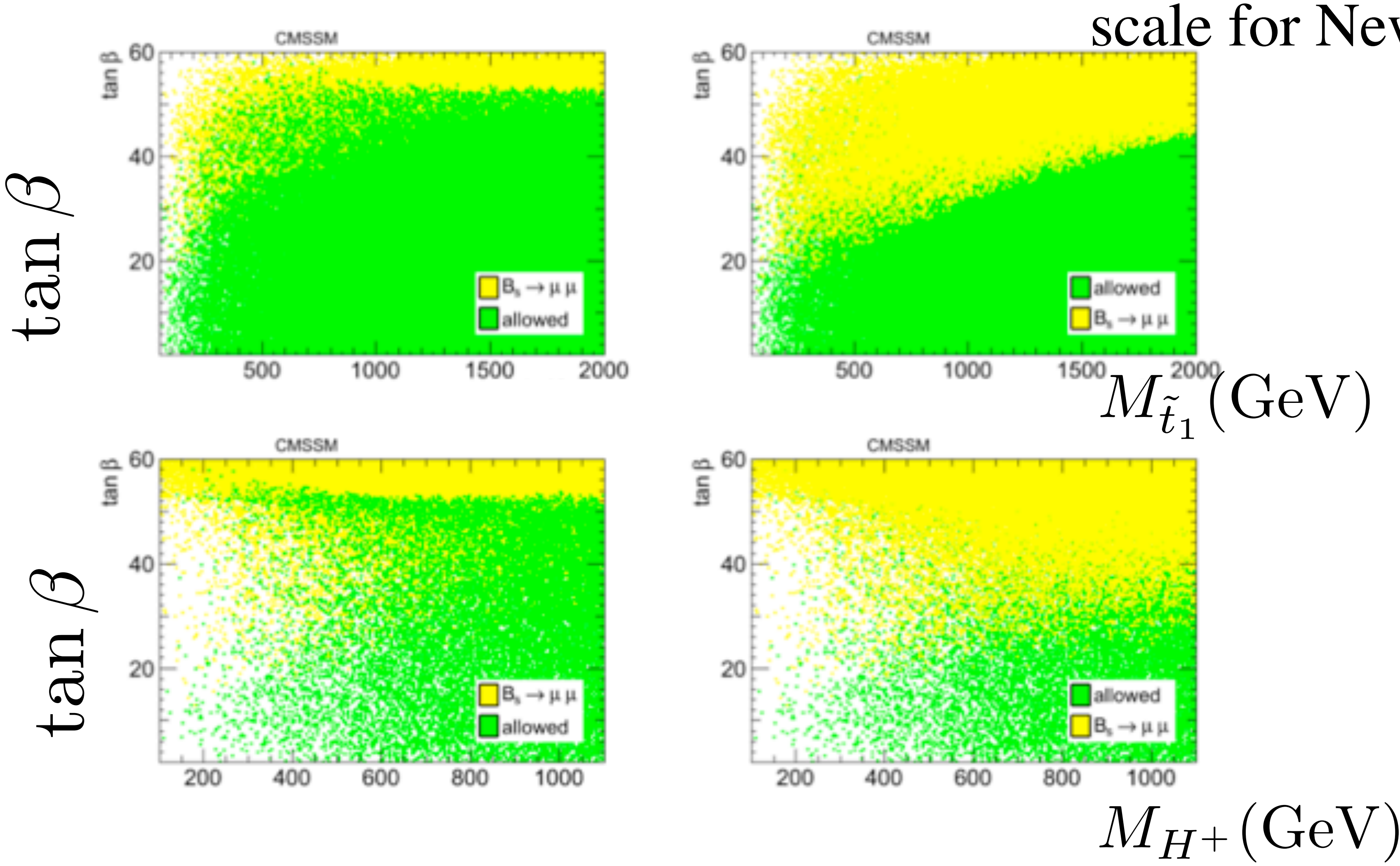


Figure 1: Constraint from BR($B_s \to \mu^+\mu^-$) in the CMSSM plane ($M_{\tilde{t}_1}$, $\tan\beta$) in the upper panel and ($M_{H^\pm}$, $\tan\beta$) in the lower panel, with the allowed points displayed in the foreground in the left and in the background in the right.

3. META-STABILITY OF VACUUM ?

If M_h is too small:

- SM: the quartic coupling constant is driven to zero in the UV by the t-quark mass
- a stable minimum develops at a high-energy scale Λ,
- the electroweak minimum, and the present vacuum, is unstable
- stability region depends upon M_t and Λ

N. Cabibbo, L. Maiani, G. Parisi, R. Petronzio, Nucl. Phys. **B 158** (1979) 295, Leading Order; recent analysis at NNLO: G.Degrassi, S.Di Vita, J.Elias-Miro, J.R.Espinosa, G.F.Giudice, G.Isidori and A.Strumia,JHEP {\bf 1208} (2012) 098

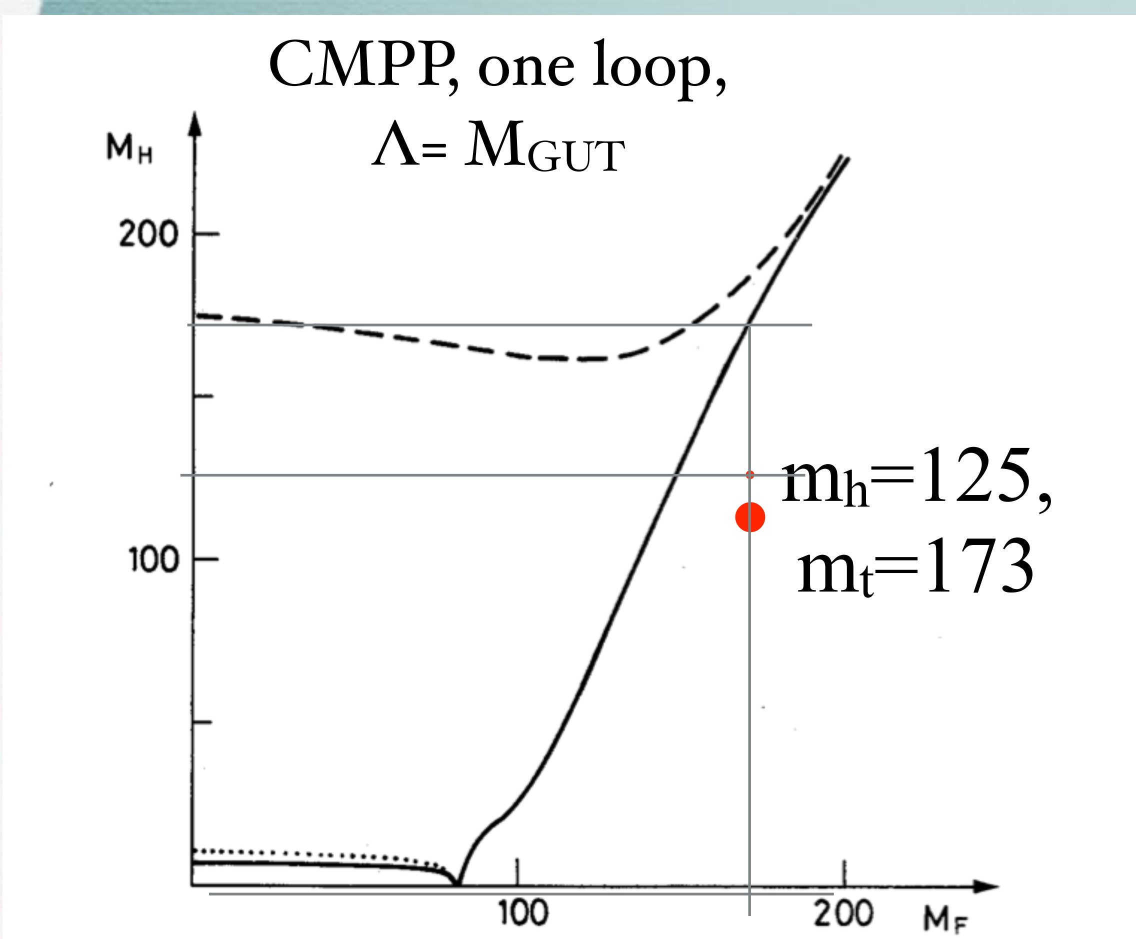
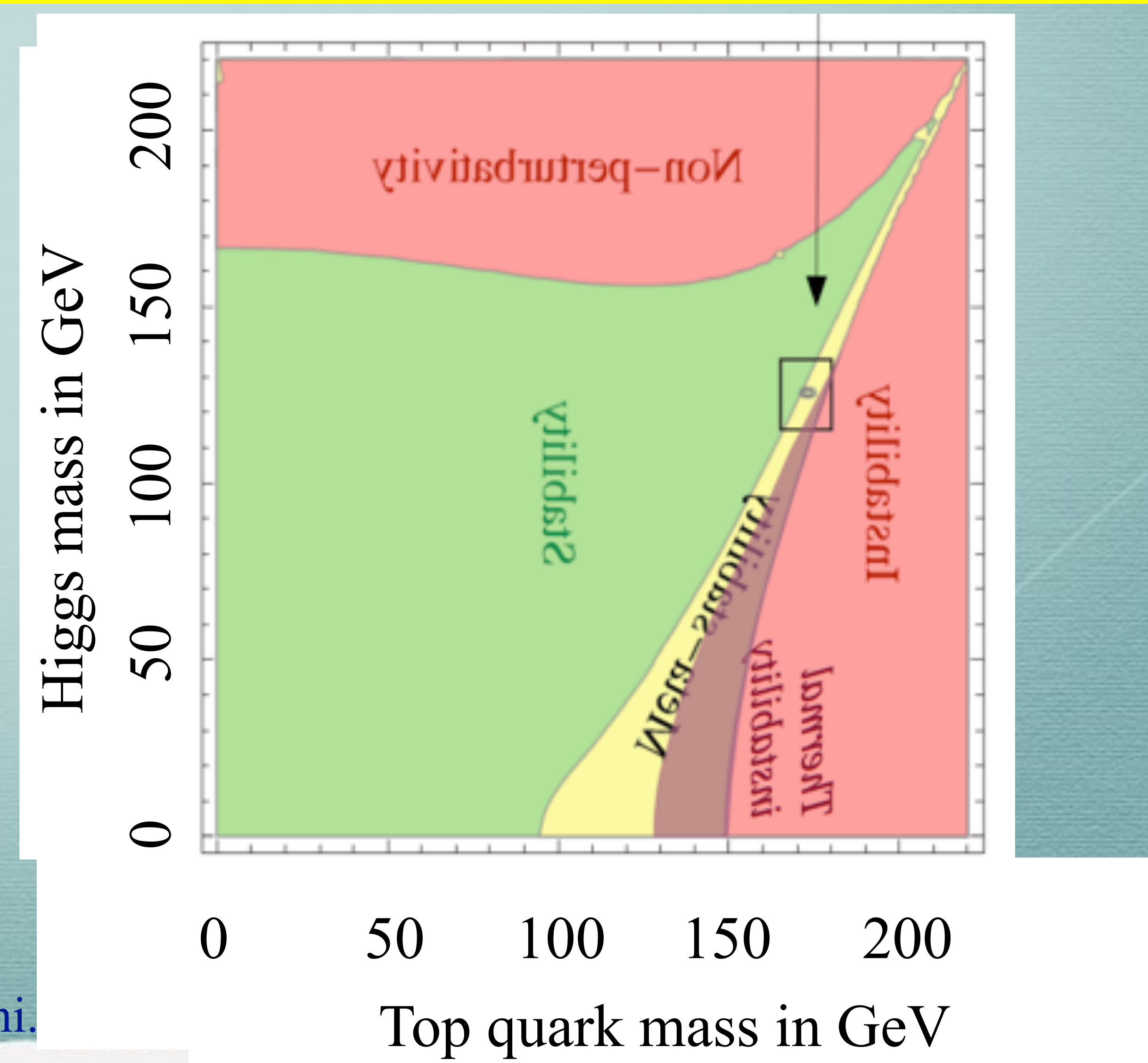
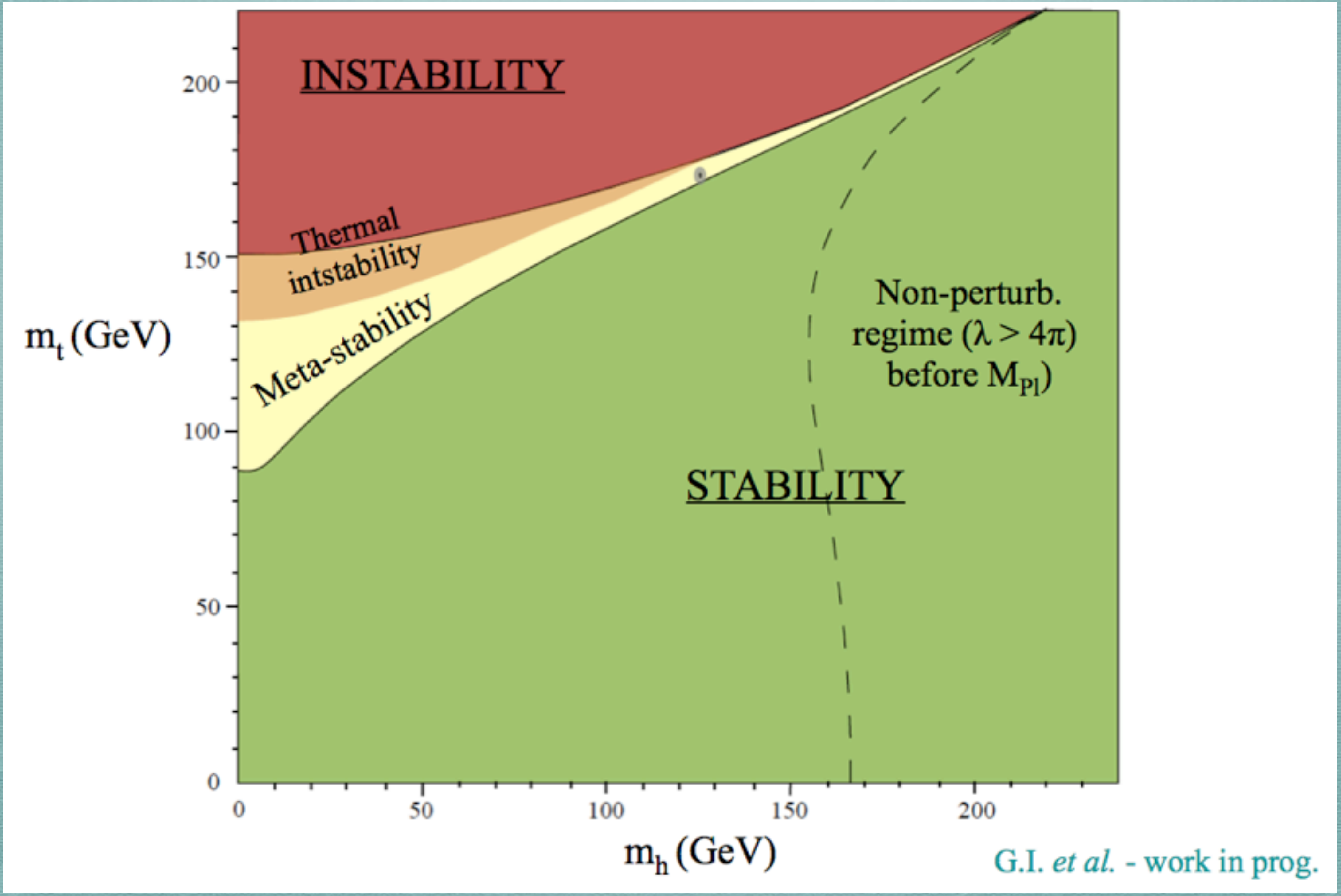
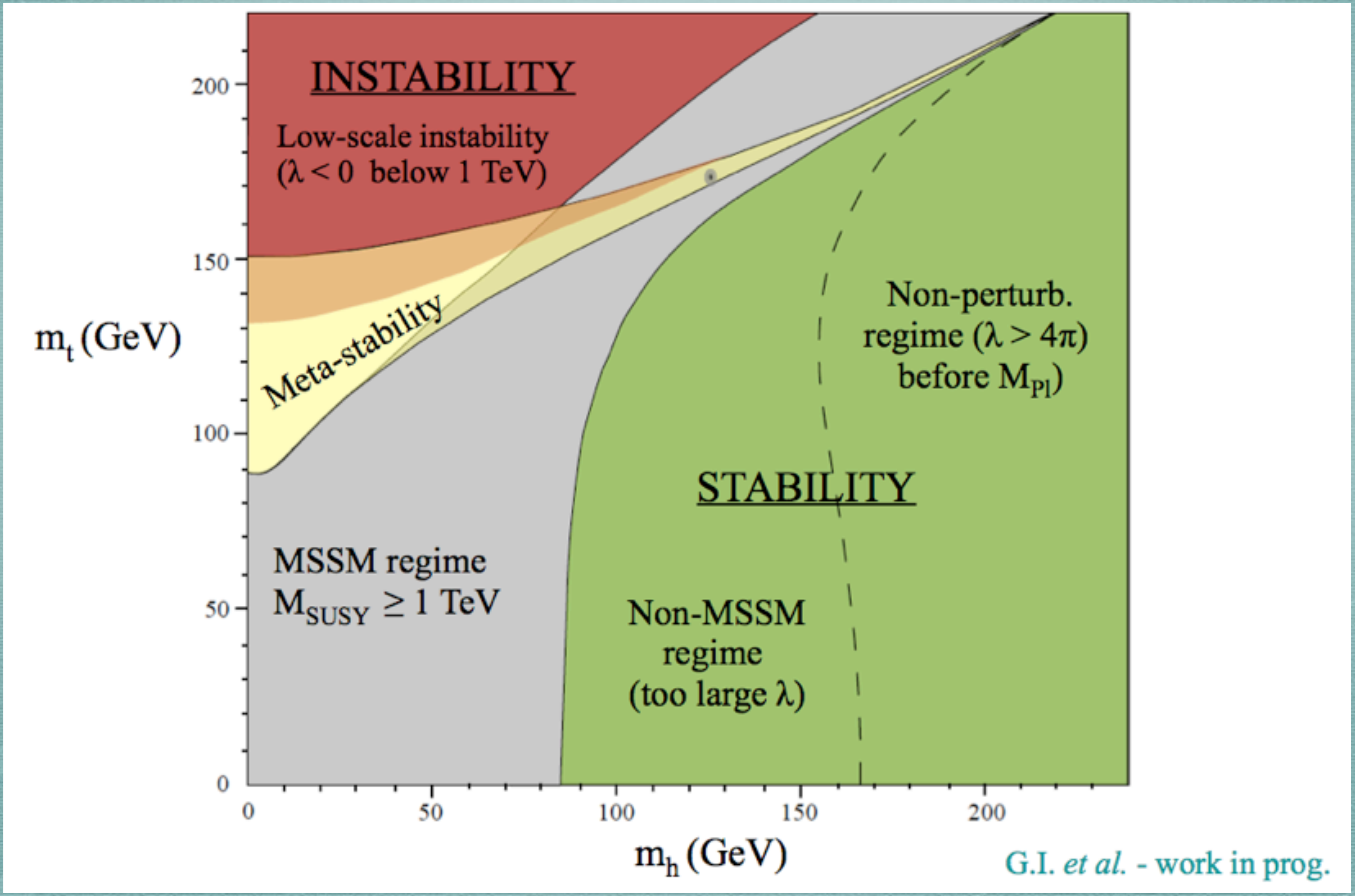


FIG. 1

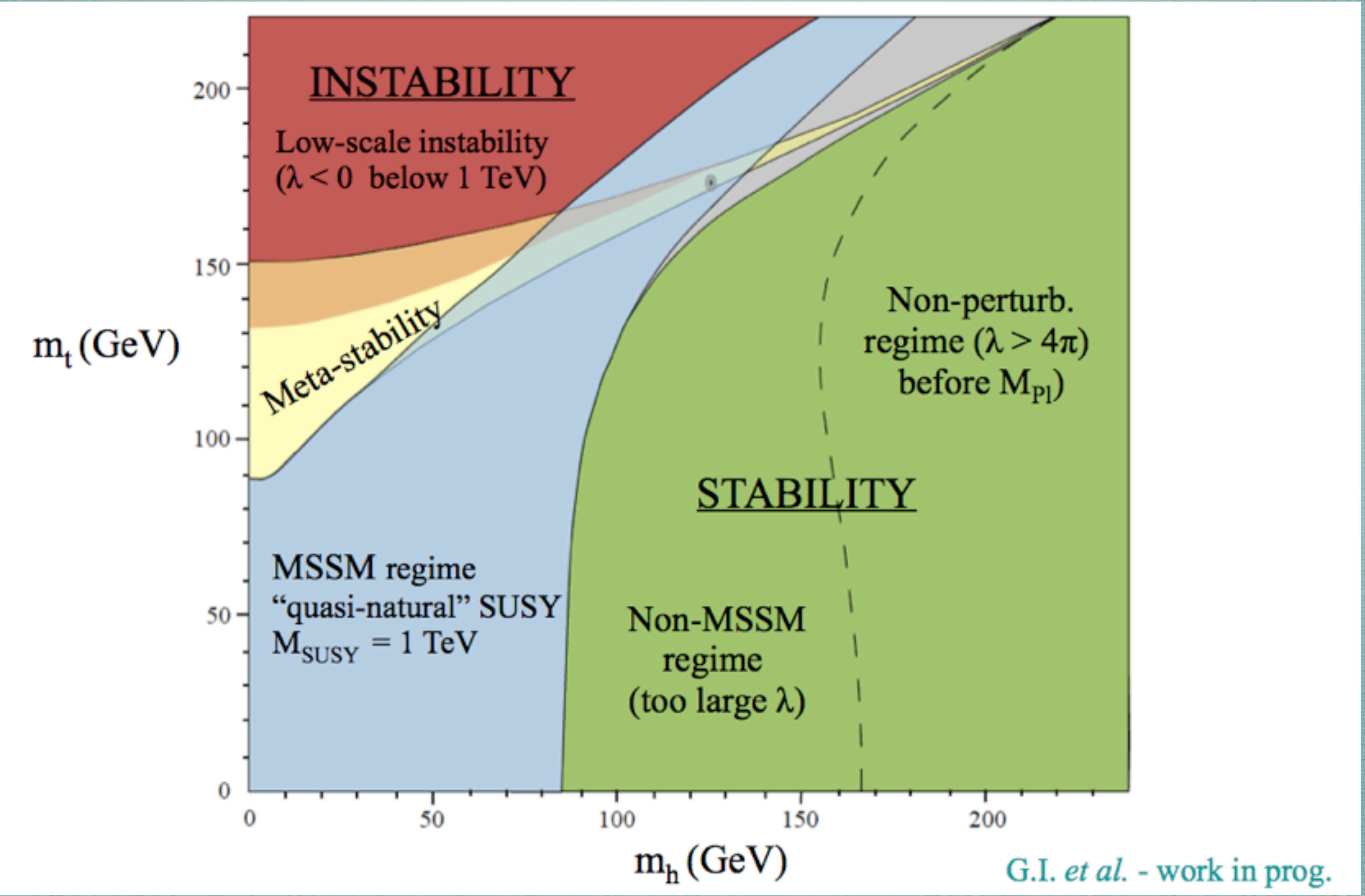


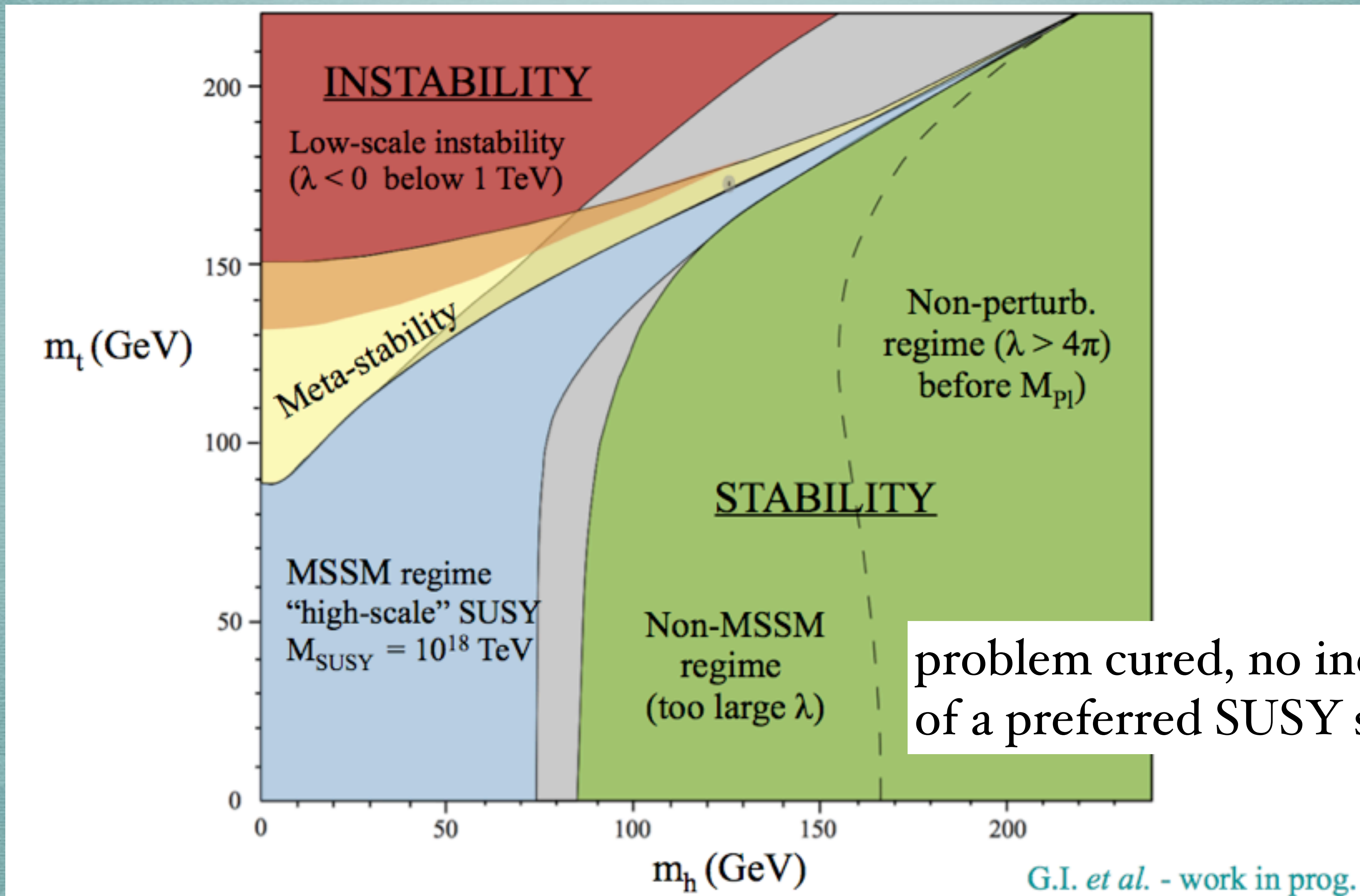
THE OF CASE OF MINIMAL SUSY HAS BEEN DISCUSSED BY ISIDORI IN ORSAY A WEEK AGO!





INSTABILITY
Low-scale instability
(λ < 0 below 1 TeV)
Meta-stability
MSSM regime
$M_{SUSY} \geq 1$ TeV
STABILITY
Non-MSSM
regime
(too large λ)
Non-perturb.
regime (λ > 4π)
before M_{Pl})
m_t (GeV)
m_h (GeV)
0
50
100
150
200
G.I. *et al.* - work in prog.


INSTABILITY
Low-scale instability
(λ < 0 below 1 TeV)
Meta-stability
Non-perturb.
regime (λ > 4π)
before M_Pl)
STABILITY
MSSM regime
"quasi-natural" SUSY
M_SUSY = 1 TeV
Non-MSSM
regime
(too large λ)
m_t (GeV)
m_h (GeV)
0
50
100
150
200
G.I. et al. - work in prog.



problem cured, no indication of a preferred SUSY scale

4. PROBING SUSY IN THE HIGGS SECTOR

L. Maiani, A.D. Polosa , V. Riquer, New J. Phys. **14** (2012) 073029.:

ORSAY-ROMA Collab.: A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon1 , V. Riquer, EPJ C in press, arXiv: 1307.5205

•Two Higgs doublets required (Dimopoulos & Giorgi): H_u, H_d

$$\langle 0|H_u^0|0\rangle = v\sin\beta; \quad \langle 0|H_d^0|0\rangle = v\cos\beta; \quad 0 < \tan\beta < +\infty$$

$$v^2 = (2\sqrt{2}G_F)^{-1} = (174\ \text{GeV})^2$$

Recent work:
P.Giardino, et al.arXiv:1303.3570 [hep-ph];
A.Djouadi, J.Quevillon,arXiv:1304.1787 [hep-ph];
NMSSM model:
G.~Belanger et al., JHEP **1301**(2013) 069;
R.Barbieri, et al., arXiv:1304.3670 [hep-ph];
Two Higgs Doublets:
B.Grinstein,P.Uttayarat,arXiv:1304.0028 [hep-ph];
O.~Eberhardt et al., arXiv:1305.1649 [hep-ph].

Physical H bosons: $h: \ 125\ \text{GeV}$

$H,\ A,\ H^{\pm}\ \ ???$

• h, H mass matrix contains M_Z, M_A, tanβ , δ

$$\mathcal{M}_S^2 = M_Z^2 \begin{pmatrix} \cos^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \sin^2\beta \end{pmatrix} + M_A^2 \begin{pmatrix} \sin^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \cos^2\beta \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2\beta} \end{pmatrix}$$

•EW interactions control the quartic potential, hence M_Z

•δ embodies the leading radiative corrections related to the top-sector and summarizes all details and variations of the MSSM;

•absence of the beauty-sector contribution: a very mild assumption for tan β<10;

•with M_h=125 GeV, we can obtain δ= δ(M_A, tan β) and determine all quantities in the Higgs sector as function of M_A, tan β, or M_H, tan β.

CHECKS

A. Djouadi *et al*.

$$\Delta\mathcal{M}^2_{22} = \frac{M_h^2(M_A^2+M_Z^2-M_h^2) - M_A^2 M_Z^2 c^2_{2\beta}}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2} = \frac{\delta}{\sin^2\beta}$$

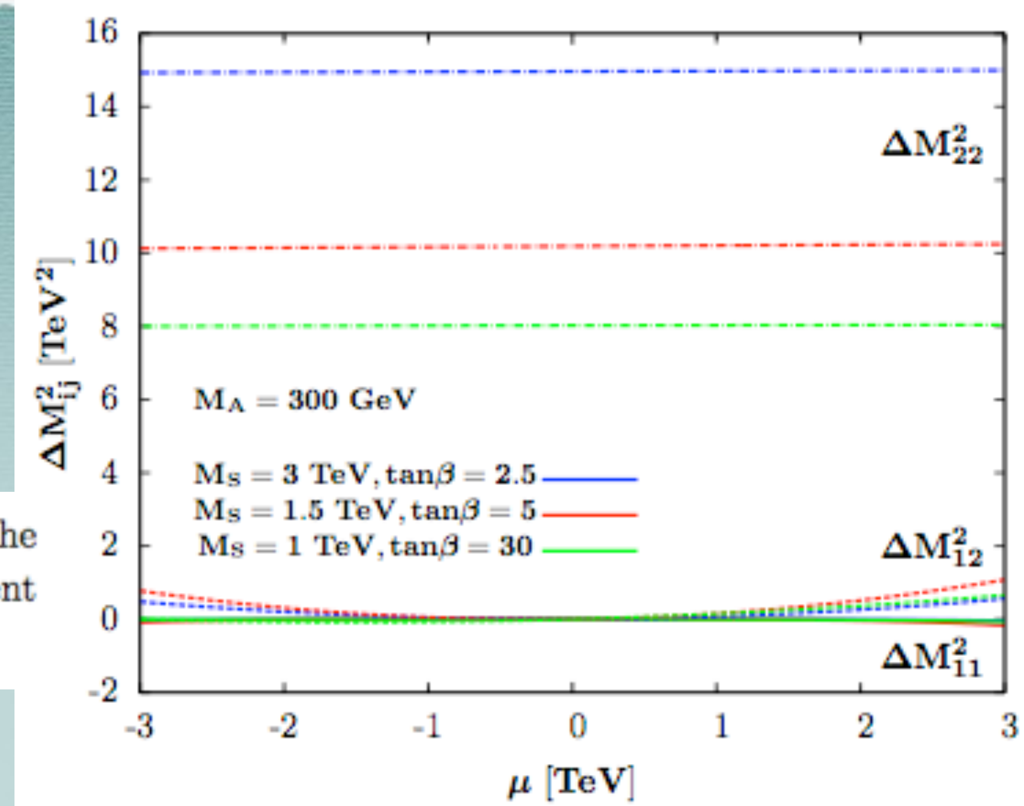


Figure 1: The entries $\Delta\mathcal{M}^2_{11}$ (solid), $\Delta\mathcal{M}^2_{12}$ (dashed), and $\Delta\mathcal{M}^2_{22}$ (dotted-dashed lines) of the radiative corrections matrix as functions of μ with a fixed $M_A = 300$ GeV for three different $(M_S, \tan\beta)$ sets and A_t such that it accommodates the mass range $M_h = 123$–129 GeV.

$$H = \cos\alpha H_d^0 + \sin\alpha H_u^0 \text{ and } h = -\sin\alpha H_d^0 + \cos\alpha H_u^0$$

$$M_H^2 = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2c_\beta^2+M_A^2s_\beta^2) - M_A^2M_Z^2c^2_{2\beta}}{M_Z^2c_\beta^2+M_A^2s_\beta^2-M_h^2}$$

$$\alpha = -\arctan\left(\frac{(M_Z^2+M_A^2)c_\beta s_\beta}{M_Z^2c_\beta^2+M_A^2s_\beta^2-M_h^2}\right)$$

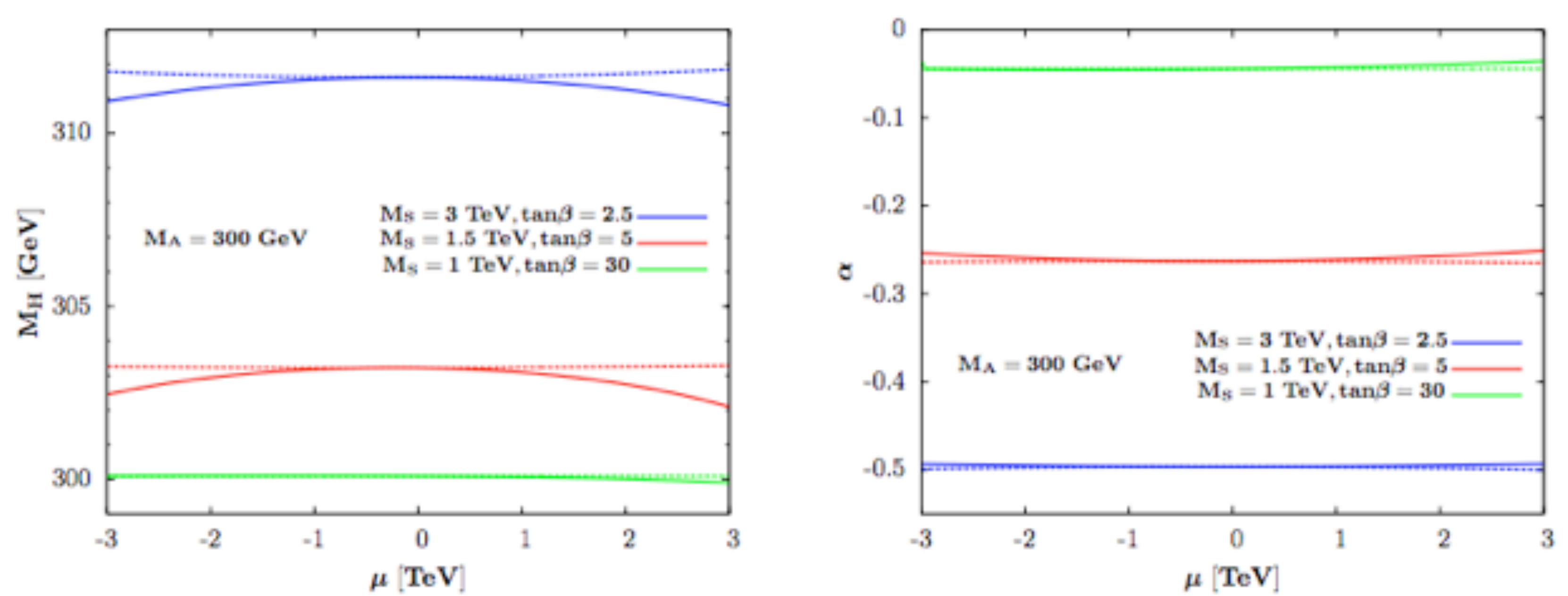


Figure 2: The mass of the heavier CP–even H boson (left) and the mixing angle α (right) as a function of μ with (solid lines) and without (dashed) the off–diagonal components components for $M_A = 300$ GeV and three $(M_S, \tan\beta)$ sets. A_t is such that $M_h = 123$–129 GeV and $A_b = 0$.

CHECKS

A. Djouadi *et al*.

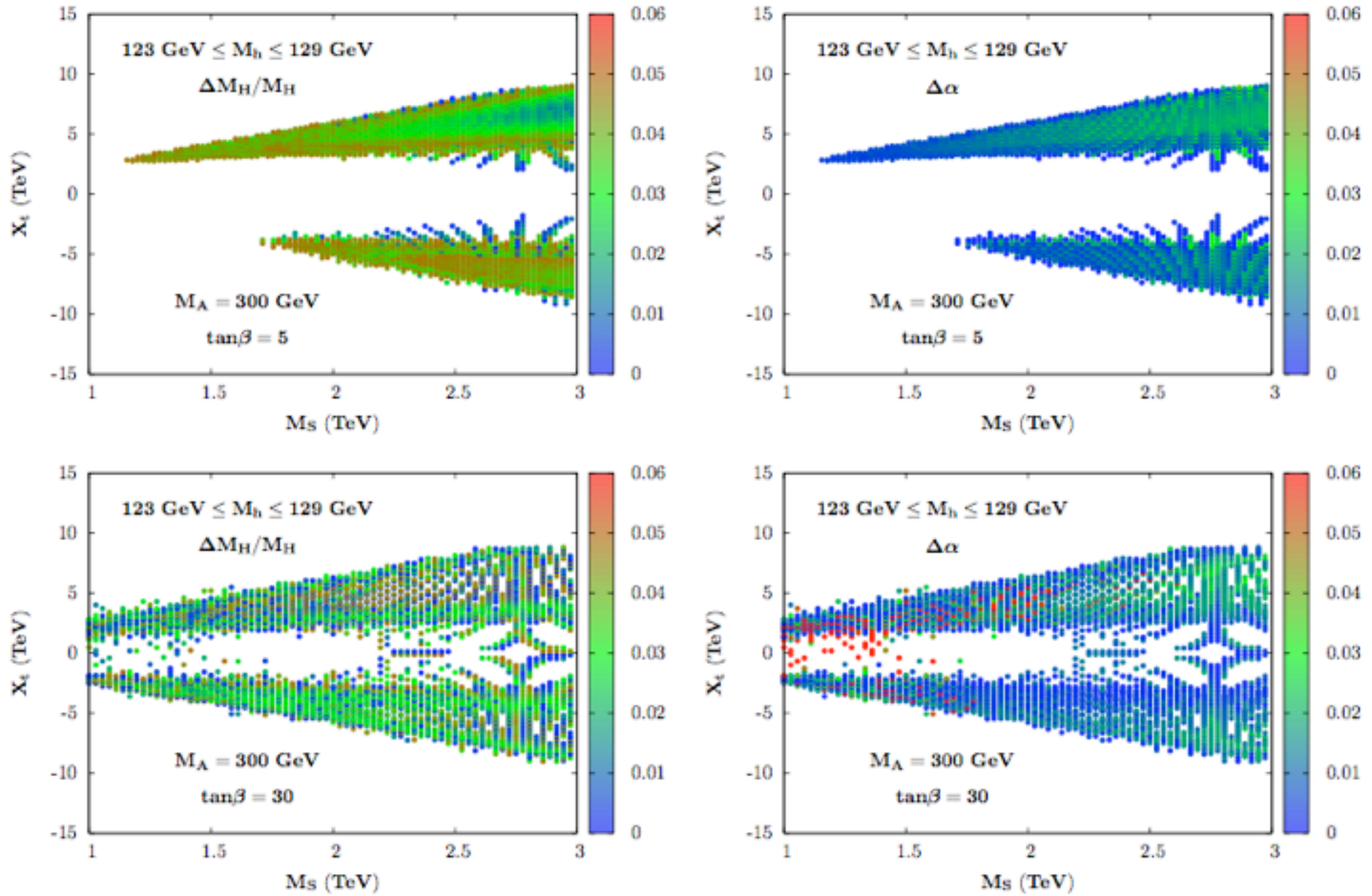


Figure 3: The variation of the mass M_H (left) and the mixing angle α (right), are shown as separate vertical colored scales, in the plane $[M_S, X_t]$ when the full two loop corrections are included with and without the subleading matrix elements $\Delta\mathcal{M}^2_{11}$ and $\Delta\mathcal{M}^2_{12}$. We take $M_A = 300$ GeV, $\tan\beta = 5$ (top) and 30 (bottom) and the other parameters are varied as described in the text.

MIXING COEFFICIENTS AND COUPLINGS

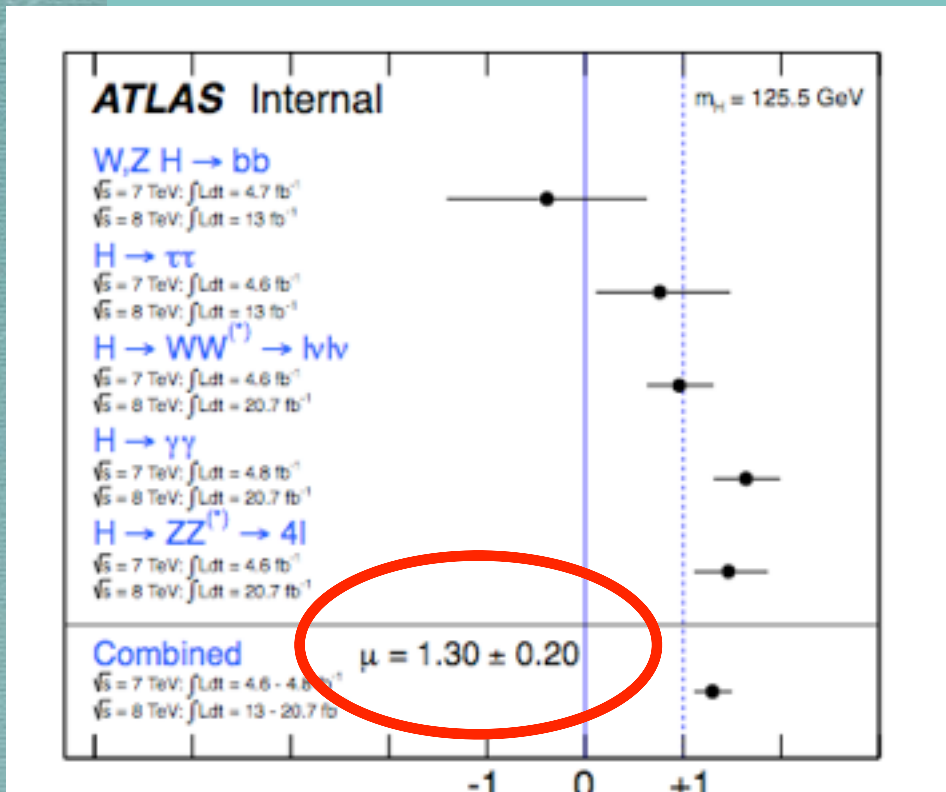
- tree level SUSY suggests a fit to h data with three couplings, in alternative to the usual c_V, c_F fit:

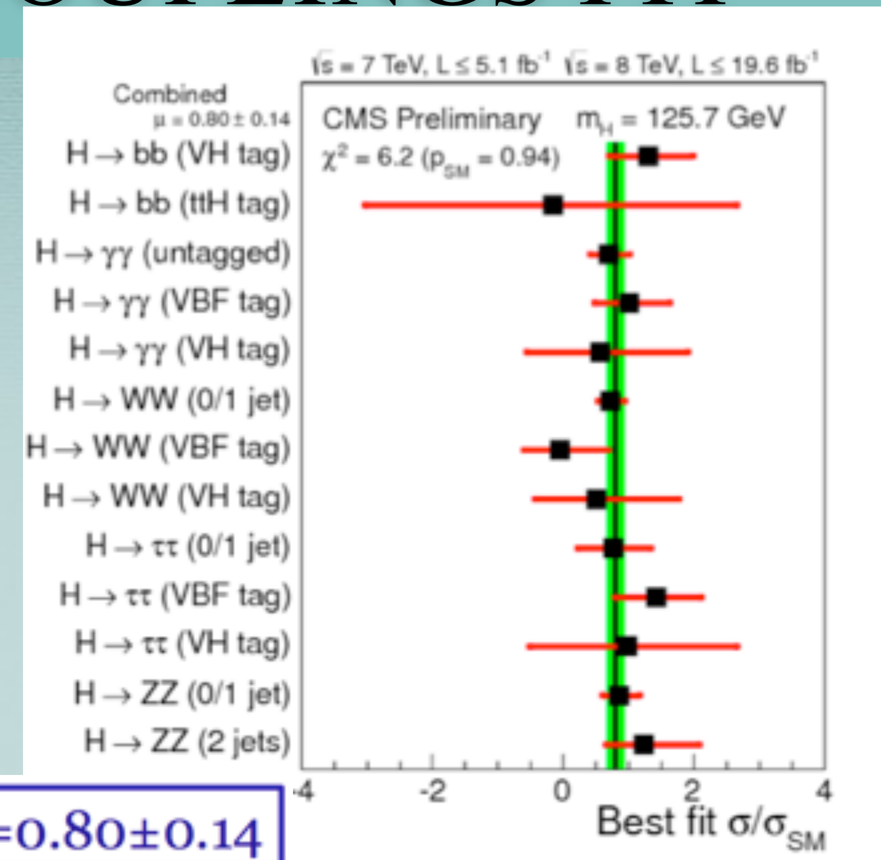
$$c_V^0 = \sin(\beta - \alpha), \qquad c_t^0 = \frac{\cos\alpha}{\sin\beta}, \qquad c_b^0 = -\frac{\sin\alpha}{\cos\beta}$$

$$c_c^0 = c_t^0, \; c_\tau^0 = c_b^0$$

- corrections to c_t and c_b from s-top and s-bottom exchange could be appreciable (few to 10 percent) and are discussed in our Orsay-Roma paper
- most exact: 5 couplings
- at present: c_c only in total widths, τ branching ratio known to 40% error
- a three-coupling fit is meaningful: c_V, c_t , c_b

4. DATA AND THREE-COUPLINGS FIT

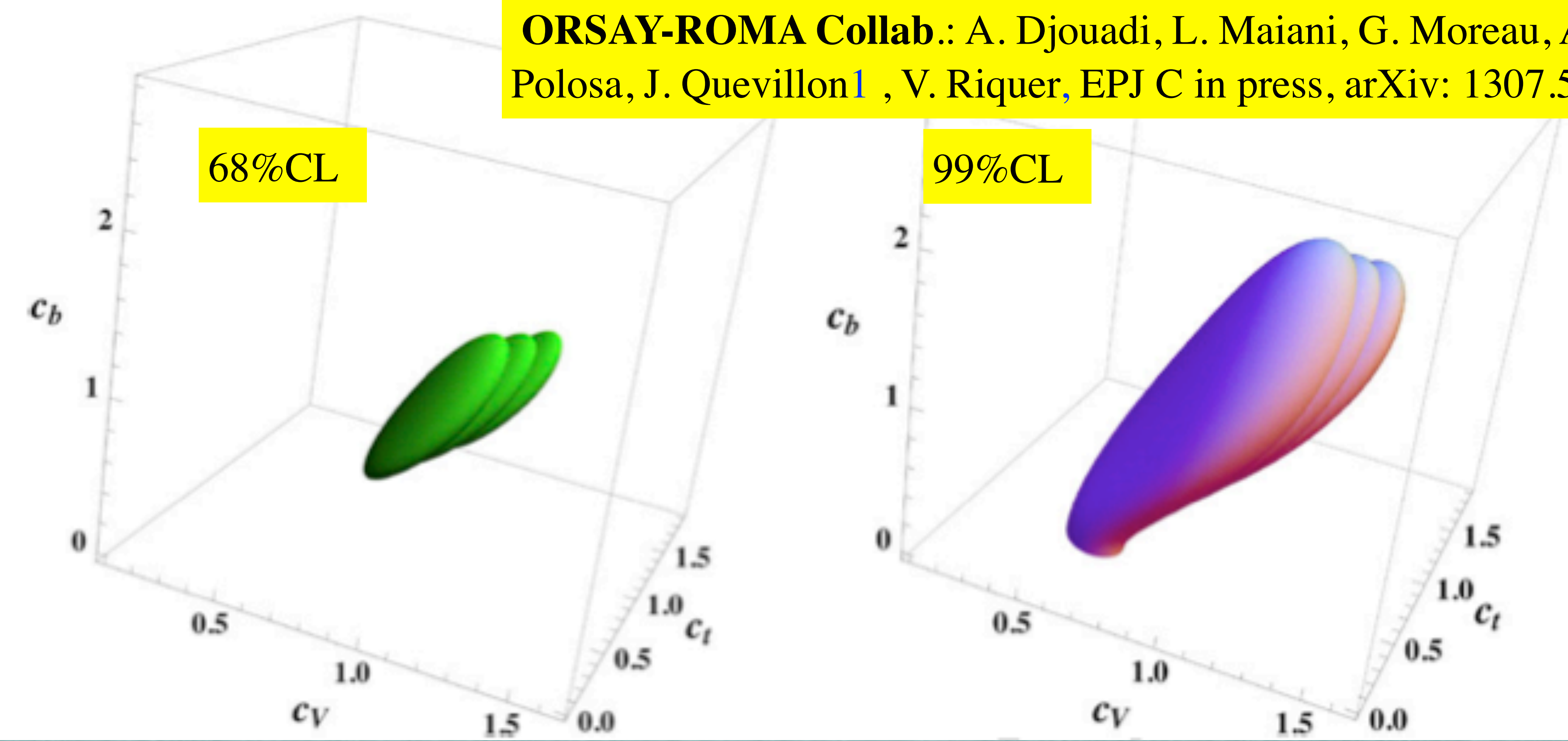




μ=0.80±0.14

Fig. 4 Best-fit regions at 68 % CL (*green*, *left*) and 99 % CL (*light gray*, *right*) for the Higgs signal strengths in the three-dimensional space $[c_t, c_b, c_V]$. The three overlapped regions are associated to central and two extreme choices of the theoretical prediction for the Higgs rates

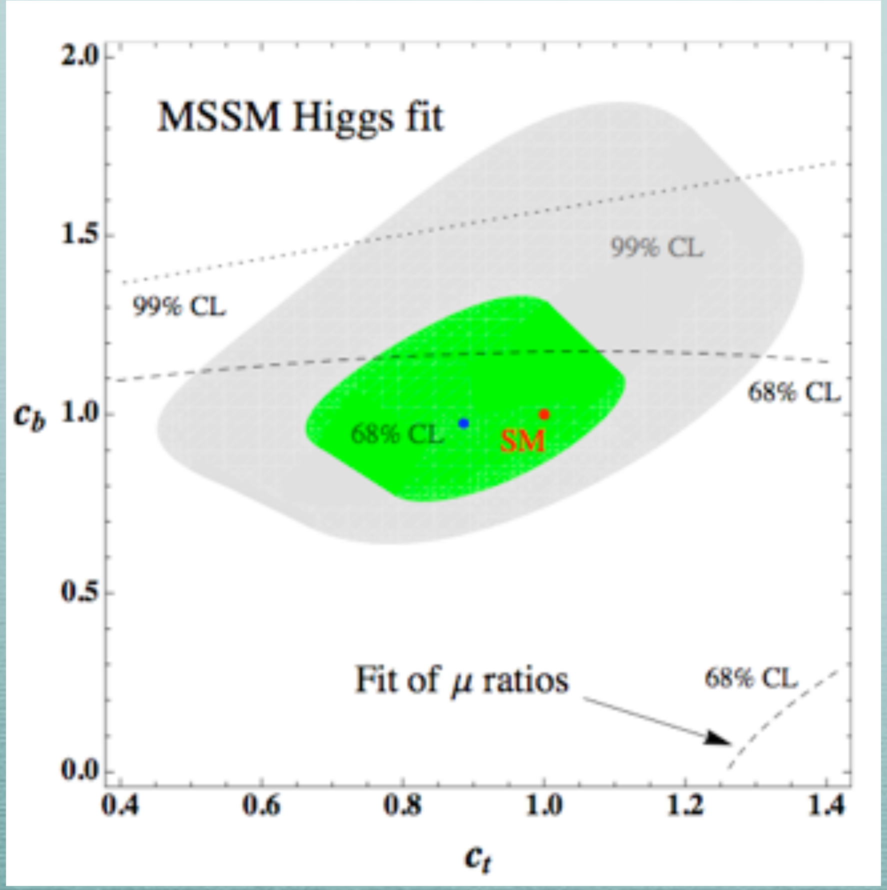
ORSAY-ROMA Collab.: A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon1 , V. Riquer, EPJ C in press, arXiv: 1307.5205



•in scenarios where the direct corrections are not quantitatively significant (i.e. considering either not too large values of μ tan β or high stop/sbottom masses), one can use the MSSM relations to reduce the number of effective parameters down to two.

•e.g. one can express c_V in terms of the other two and fit data in the c_t-c_b plane

•Note that although for the best-fit point one has $c_b < 1$, actually $c_b > 1$, as required by SUSY, in most of the 1σ region.



•fixing M_h to the measured value $M_h \approx 125$ GeV, one can even perform a fit in the plane [tan β, M_A].

•the fit can give only lower bounds, since the SM point (tan β, $M_A \rightarrow \infty$) is compatible with data

•the figure on the right superimposes the lower limits from direct A search by ATLAS and CMS

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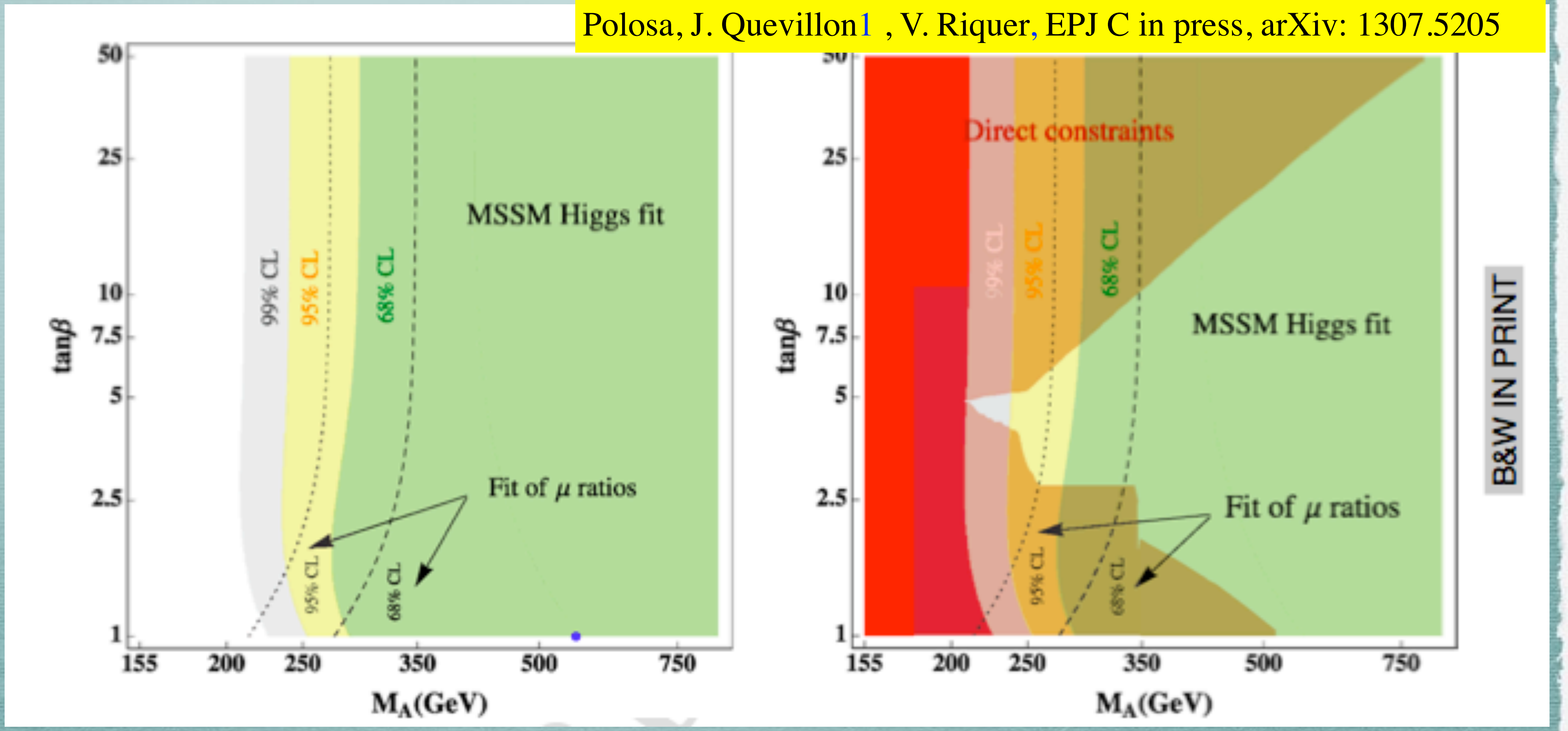
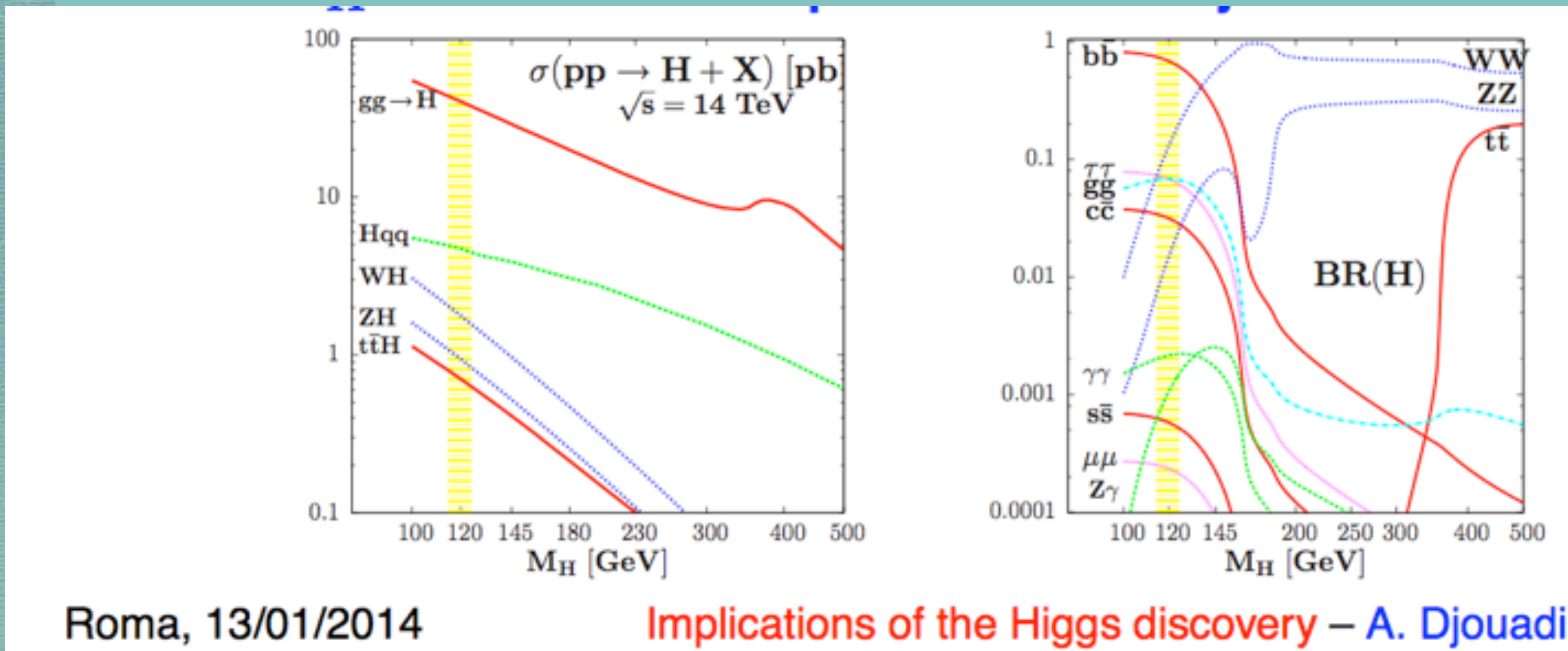
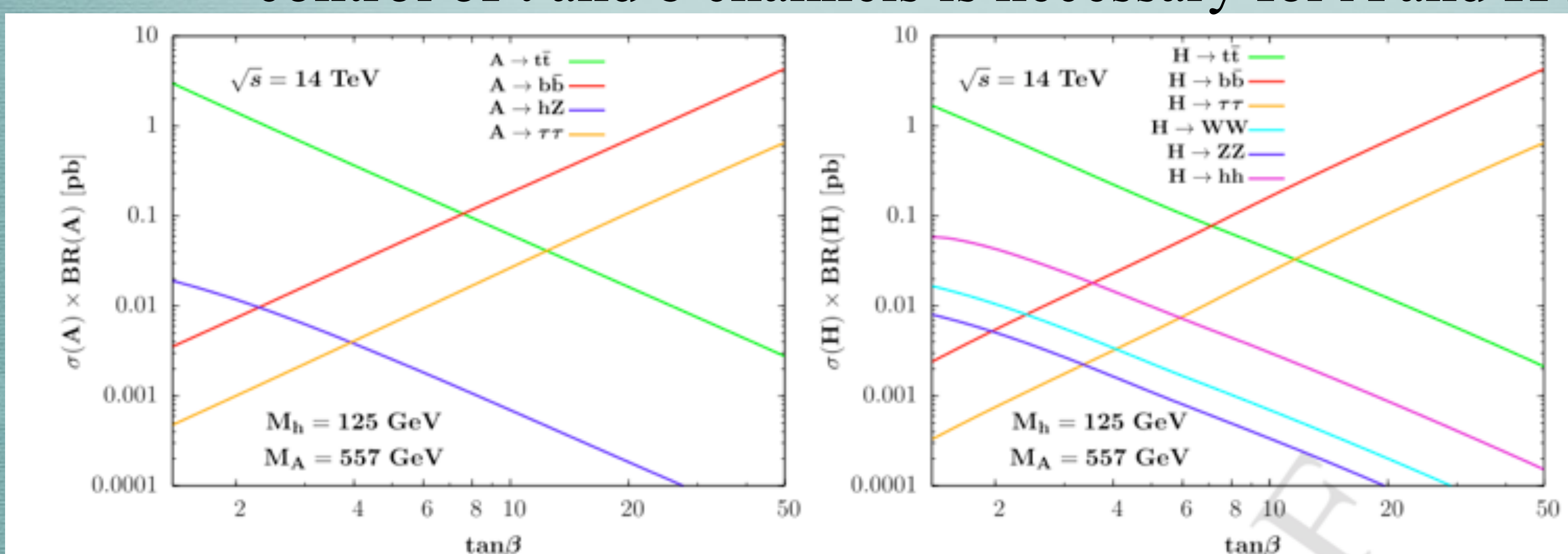


A AND H SIGNALS



- high energy run can be decisive
- control of t and b channels is necessary for A and H search



5. POST LHC@ 8-13 TEV PROJECTS

- high Luminosity LHC (10xluminosity = 1.5 energy)
- International Linear Collider, e^+e^- @ 0.5 TeV:
    - -site approved in Japan (Kitakami) + one reserve site (Sefuri):

- Proton-proton Collider @100 TeV:
- CERN? FermiLab? China?

6. CONCLUSIONS

• An "intermediate decoupling" region:

- $\tan\beta$=1-10,
- M_H in few 100 GeVs,
- scalar top below 1 TeV

is not excluded by present data on h(125) and by limits from Flavor Changing Neutral Currents;

• it entails 10-20% deviations of down fermions from ST: a better determination of h couplings, in particular to b and τ is crucial;

• three coupling fit to data very effective in mapping the allowed region;

• the fit is sensitive to the esperimental cuts: a fit made directly by tthe LHC collaborations would be very useful;

• the search for SUSY signal to continue in the next experimental round.

Look everywhere, no time to give up