Higgs and Top interplay!

Rohini M. Godbole
Centre for High Energy Physics, IISc, Bangalore, India

- Various ways top properties affect Higgs physics!

- Observation of a SM like Higgs leads to strong conclusions about the SM and BSM! two examples.

- Measurements which will explore and utilize the interplay to probe SM and the BSM; some focus on top spin observables!

Particle physics finds itself in a place somewhat similar to the one found by classical physicists at the end of 19th century.

Statement number 1:

"In the present state of physical science, therefore, a question of extreme interest arises: Is there any principle on which **an absolute thermometric scale** can be founded?"

Statement number 2:

" There is nothing new to be discovered in physics now, All that remains is **more and more precise measurement**."

The rest is History as the saying goes!

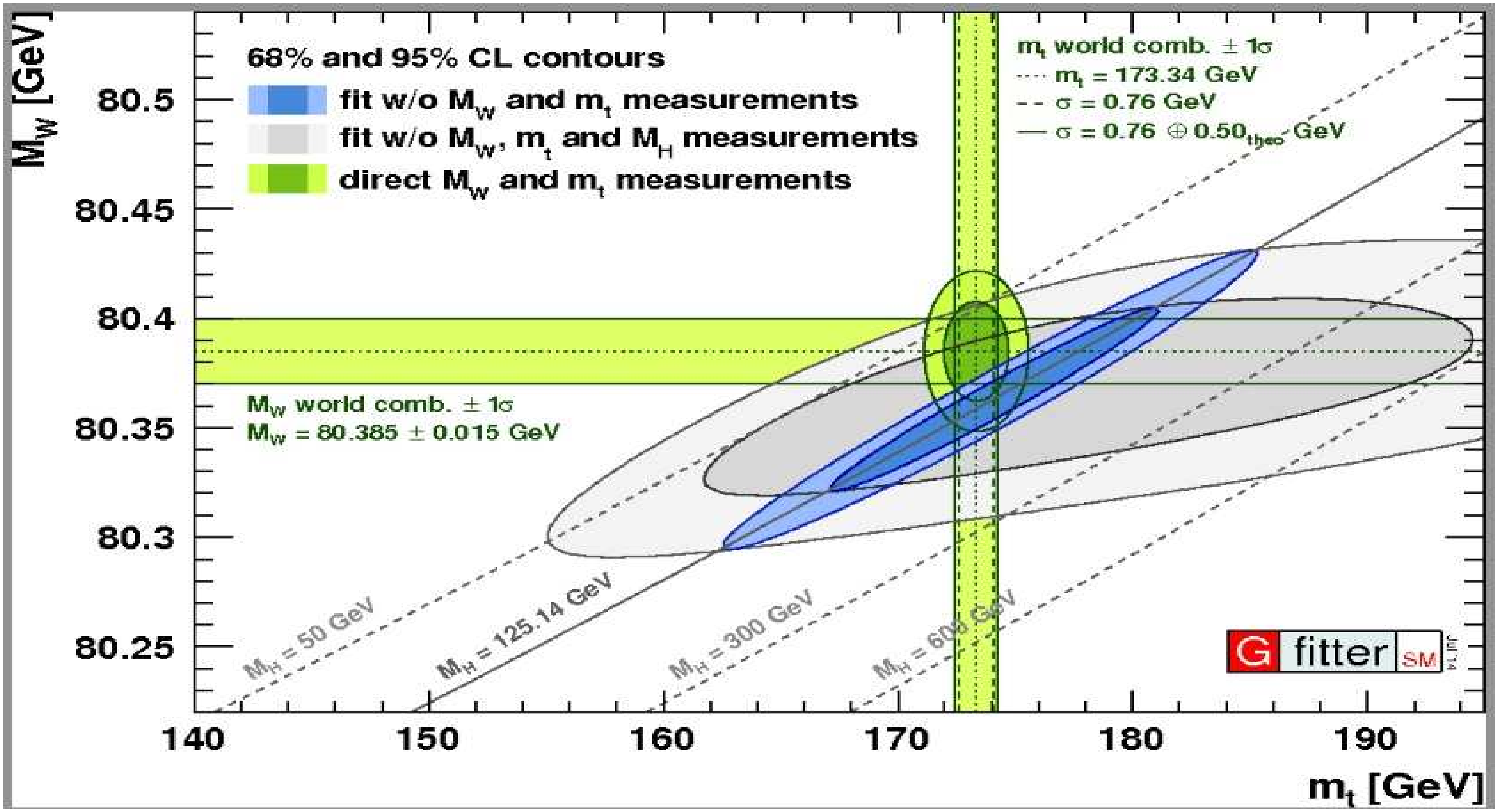
1. Existence of a EW scale **stable under radiative corrections** revealed.Is there a guiding principle on which the stability can be founded? We 'thought' we knew!..may be our thinking is right but...may be not!

2. All that remains is **more and more precise measurement** of the Higgs and top properties! *OR Higher and higher energies?*

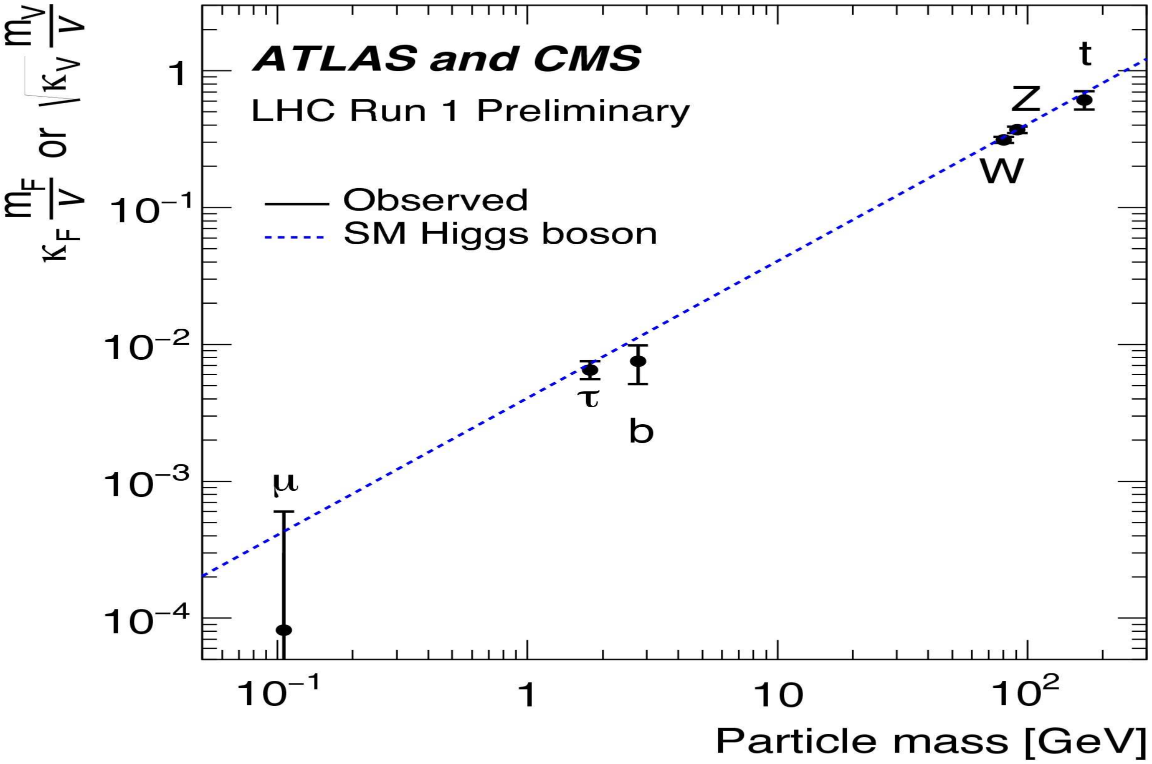
The rest (we hope) is future of HEP and the story of hunt for fundamental principles of nature!

Why did we believe the Higgs signal when it came first even if it was somewhat tenuous?

The signal had all the connections with the top that we expected the SM Higgs to have.



SM rocks! *At LOOP level* **Connection with top absolutely essential**



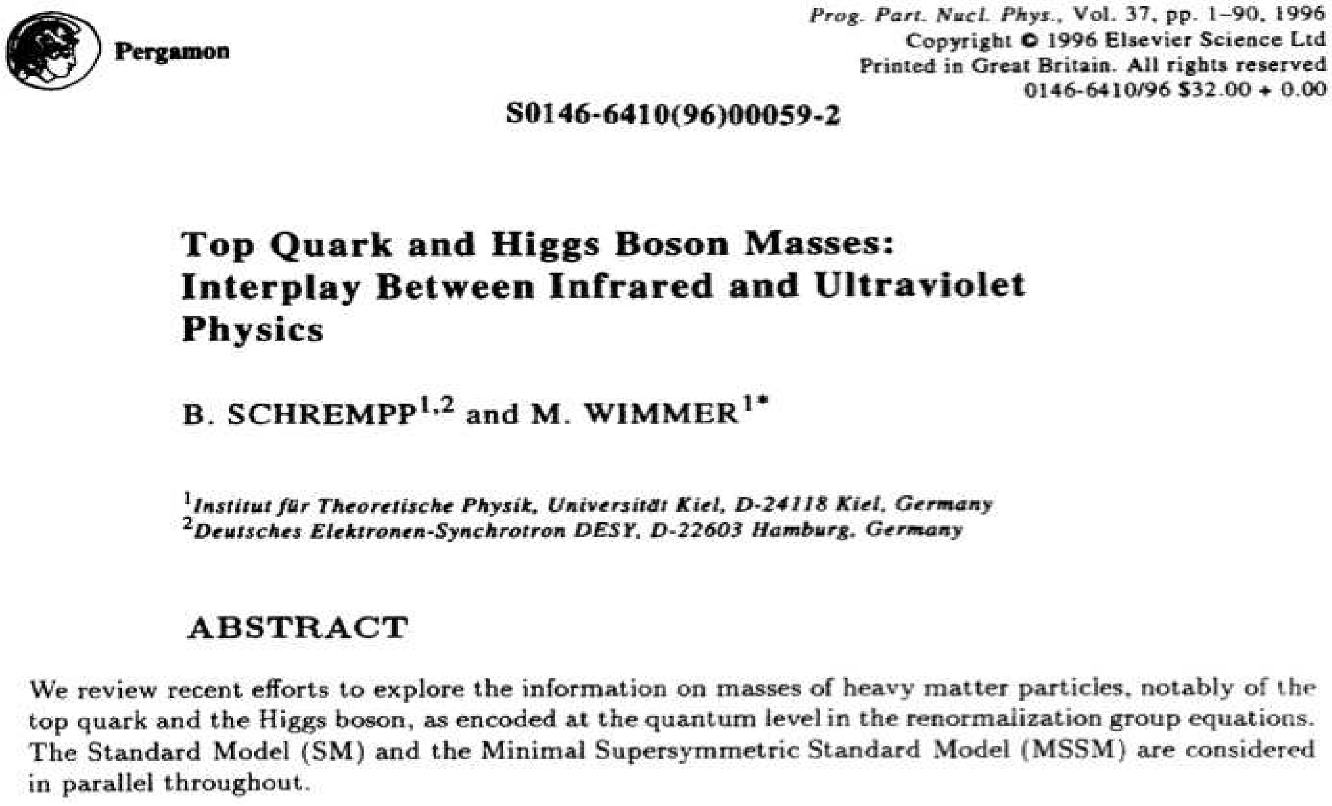
The production rates in both the $\gamma\gamma$ channel and ZZ^* channel were *almost* compatible with the SM predictions. It has the right couplings!. Agree with SM predictions to within 20%. Again top played an important role along with W/Z.

A 'light' Higgs found but **BUT NO BSM at all: ex. SUSY**.

This agony is also due to a connection between the top and the Higgs!

Interplay between the top and the Higgs is all important has led to big ideas about new physics, helps in testing those ideas and further may now help to explore those ideas experimentally, indirectly!

From the beginning!



Pergamon

Prog. Part. Nucl. Phys., Vol. 37, pp. 1–90, 1996

Copyright © 1996 Elsevier Science Ltd
Printed in Great Britain. All rights reserved

0146-6410/96 $32.00 + 0.00
S0146-6410(96)00059-2

Top Quark and Higgs Boson Masses: Interplay Between Infrared and Ultraviolet Physics

B. SCHREMPP[1,2] and M. WIMMER[1*]

[1]*Institut für Theoretische Physik, Universität Kiel, D-24118 Kiel, Germany*
[2]*Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany*

ABSTRACT

We review recent efforts to explore the information on masses of heavy matter particles, notably of the top quark and the Higgs boson, as encoded at the quantum level in the renormalization group equations. The Standard Model (SM) and the Minimal Supersymmetric Standard Model (MSSM) are considered in parallel throughout.

A very nice (early) discussion of these connections The times when t had just been discovered and h was far in future. Knowledge on mass of M_t was still stabilizing! Essentially through Renormalisation Group Equations.

We now know:

$M_h, M_t \sim \mathcal{O}(v)$.

$\lambda = \frac{M_h}{\sqrt{2}v} = 0.36, y_t = \frac{M_t\sqrt{2}}{v} \sim 1$

The heaviest two particles : h, t.

Generically, if there ever is any dynamical understanding of the observed values of these couplings, then these should be related.

Different connections:

Effect of top loops on M_Z, M_W, M_h

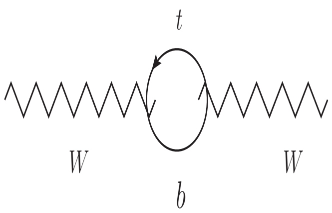
Effect of top loops on Higgs couplings

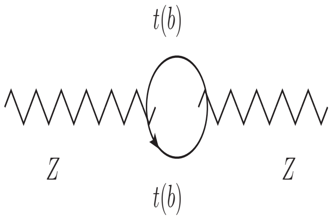
Effect of top loops on production rates of multi-higgs

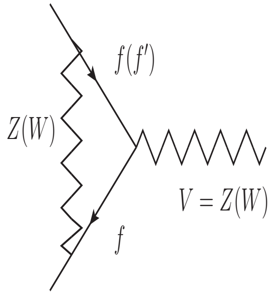
Effect of top coupling on rates of associated production of Higgs with top

Probing Higgs sector through properties of the top produced in association with Higgs bosons : $t\bar{t}h, th, h\text{jet}, H^{\pm}t$ OR produced in H/A decays!

Before top discovery!







$$\rho_{corr} = 1 + \Delta\rho$$

$$\Delta\rho \simeq \frac{3G_F M_t^2}{8\pi^2\sqrt{2}} = 0.01$$

There is also a diagram with h in the loop.

EW precision measurements of $M_W, \sin^2\theta_W \Rightarrow$ constrained first M_t

An analysis of EW precision observables put a limit on M_h: rather weak due to the logarithmic dependency on M_h, but none the less a good limit. Of course it depended on M_t

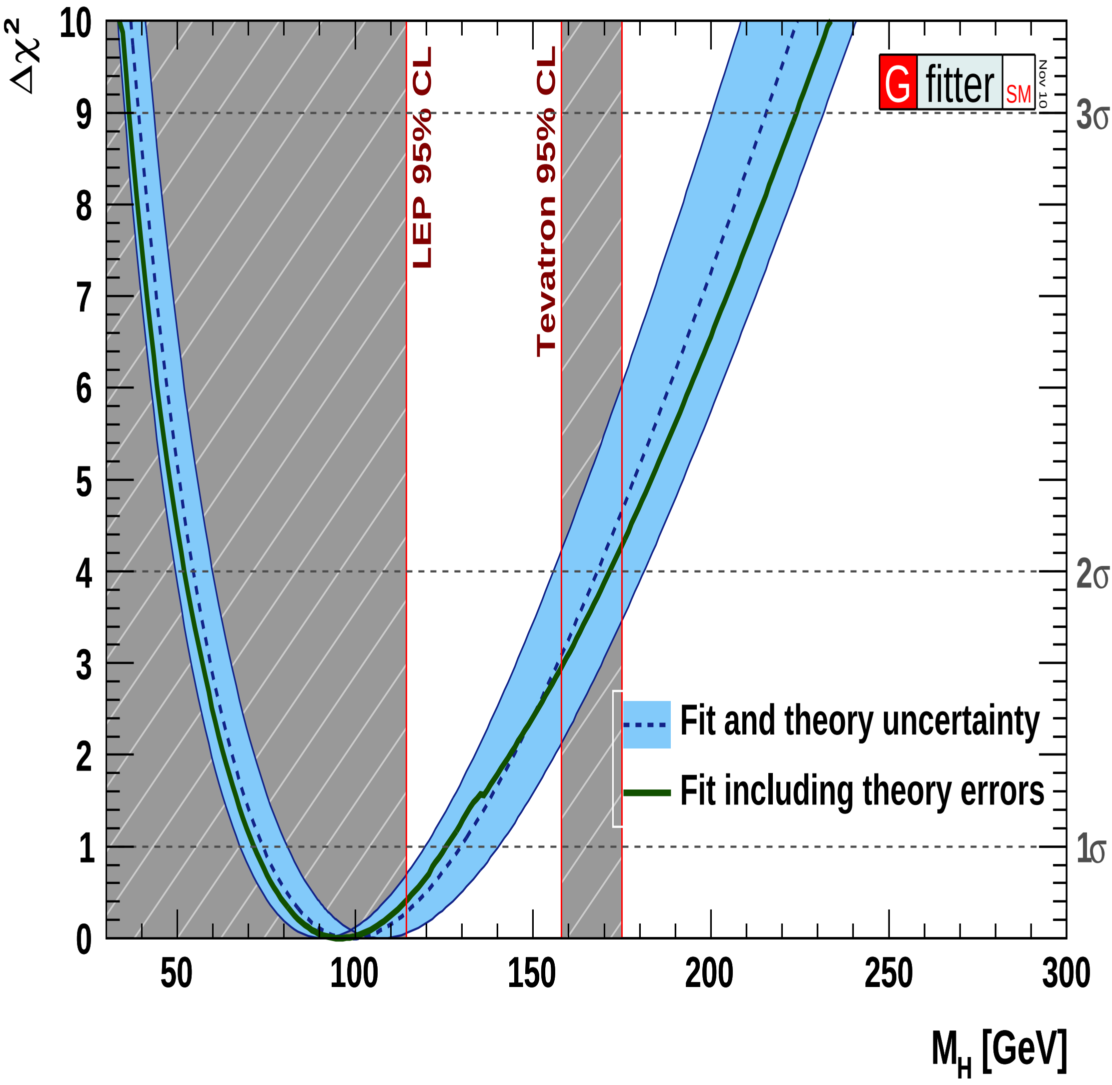
Before the Higgs discovery

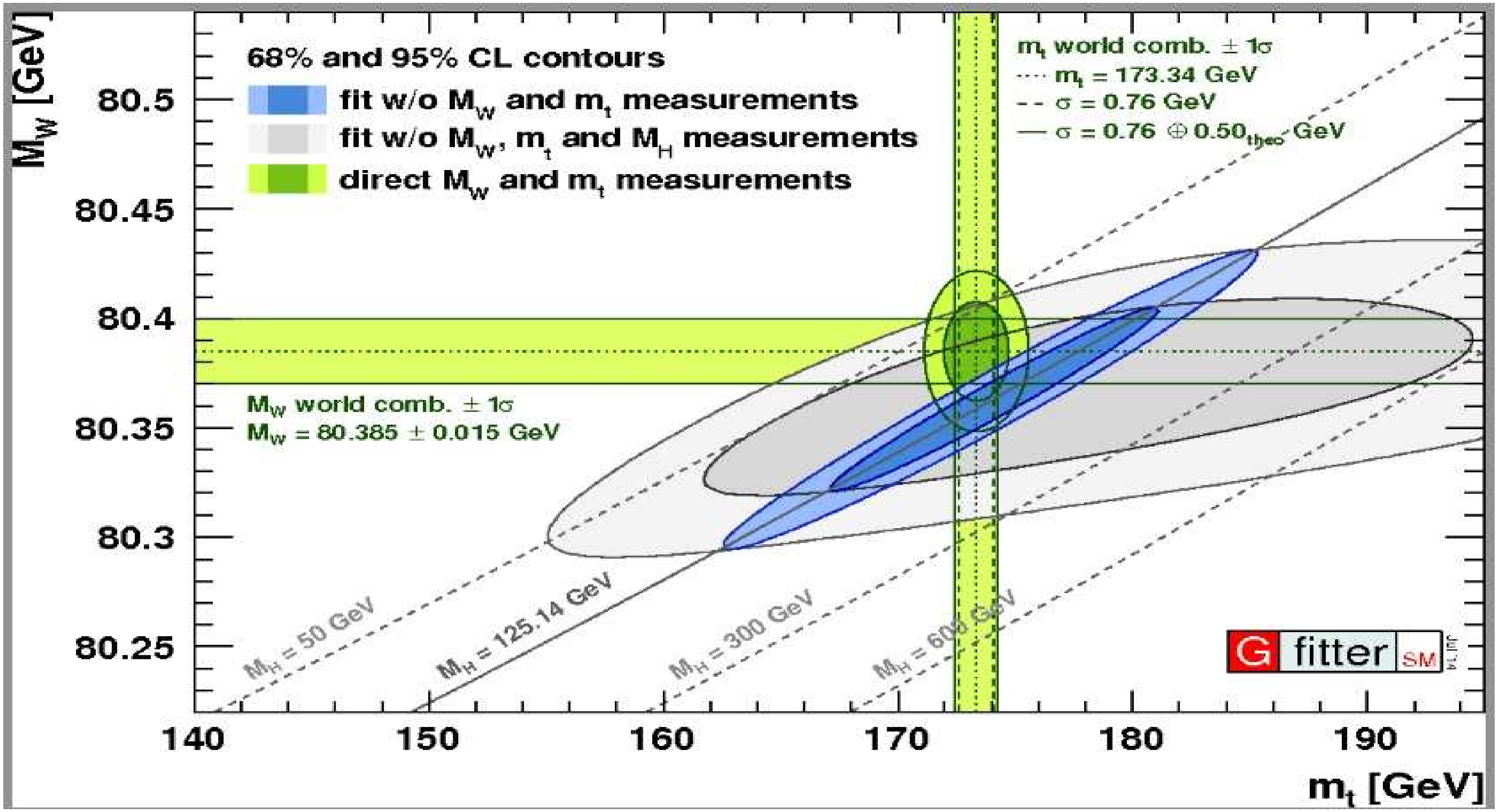
A slide from 2011:

The loop corrections depend on the Higgs mass. Since that is the only unknown these measurements indirectly constrain the Higgs mass.

If all the current information is put together the Higgs mass should be less than 150 GeV. (**indirect experimental limit!**)

From the Gfitter web page.





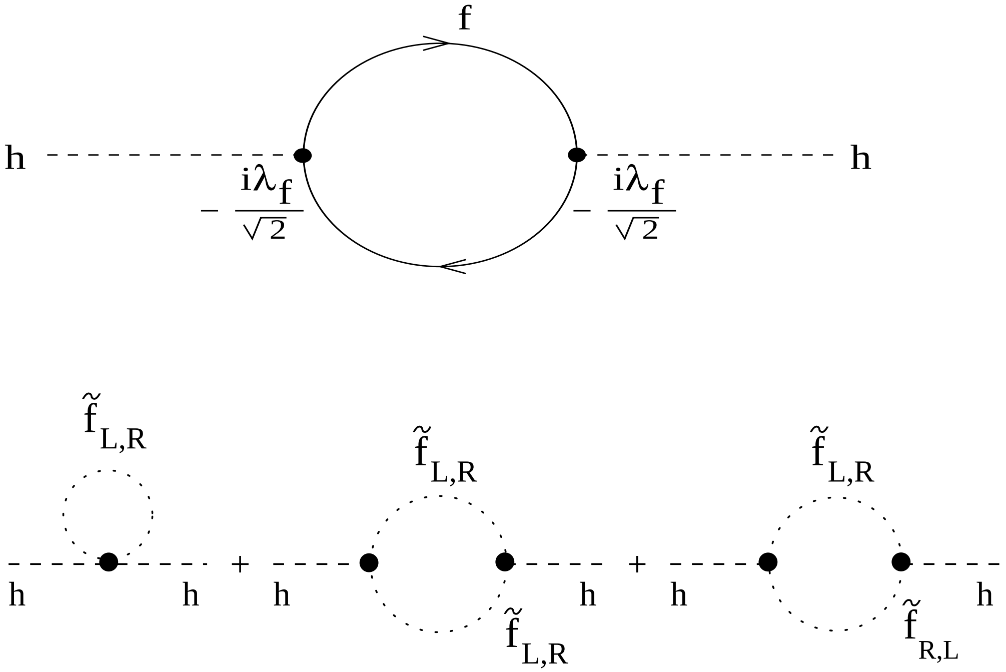
The interplay between Higgs and top is clear!

Top loops induce corrections to Higgs mass

If, $m_{\mathsf{h}}^2 = m_{\mathsf{bare}}^2 + \delta m_{\mathsf{h}}^2$ the top loop (e.g.) gives

$$\delta m^2_{\mathsf{h|top}} \sim -\frac{3G_{\mathsf{F}}}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2.$$

The radiative corrections destabilize the Higgs mass. Stabilising it at the EW scale requires extra input



Thus the sparticle loops cancel the large self energy corrections and keep the higgs mass 'naturally' small. Not just that, there is a theoretical UPPER limit on the Higgs mass **different from the limits if the SM was an effective theory!**

The limit is robust and variation with SUSY model and model parameters is not very large!

The mass of the observed state very very interesting!

Small enough to keep us still thinking of a mechanism like SUSY to stabilize it.

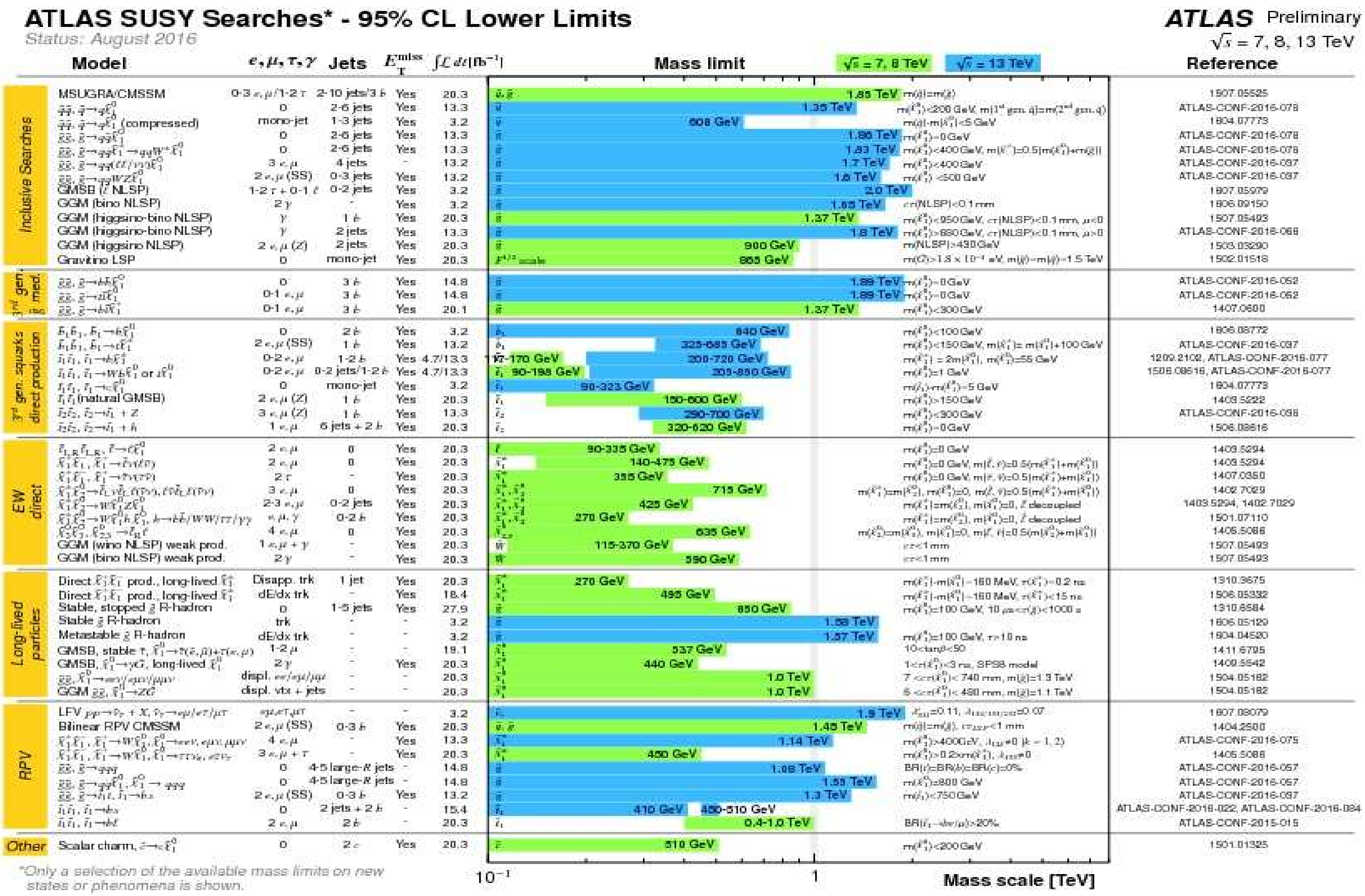
But large enough to already provide some interesting constraints on SUSY breaking ideas.

$M_h = 125$ GeV points at large values of SUSY scale and large mixing in the stop sector and large A_t values.

In fact GMSB which was theoretically very attractive, for various reasons, can not work as the large A_t values required problematic in GMSB! Ie. way too much fine tuning.

One logical implication of the interplay between the t and higgs.

But no SUSY


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\, dt\, [fb^{-1}]$
Mass limit
$\sqrt{s}$ = 7, 8 TeV
$\sqrt{s}$ = 13 TeV
Reference
Inclusive Searches
3rd gen. $\tilde{g}$ med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
1.85 TeV
1.35 TeV
608 GeV
1.86 TeV
1.83 TeV
1.7 TeV
1.6 TeV
2.0 TeV
1.65 TeV
1.37 TeV
1.8 TeV
900 GeV
865 GeV
1.89 TeV
1.89 TeV
1.37 TeV
840 GeV
325-685 GeV
117-170 GeV
200-720 GeV
90-198 GeV
205-850 GeV
90-323 GeV
150-600 GeV
290-700 GeV
320-620 GeV
90-335 GeV
140-475 GeV
355 GeV
715 GeV
425 GeV
270 GeV
635 GeV
115-370 GeV
590 GeV
270 GeV
495 GeV
850 GeV
1.58 TeV
1.57 TeV
537 GeV
440 GeV
1.0 TeV
1.0 TeV
1.9 TeV
1.45 TeV
1.14 TeV
450 GeV
1.08 TeV
1.55 TeV
1.3 TeV
410 GeV
450-510 GeV
0.4-1.0 TeV
510 GeV
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.

Pre LHC:

Why must the LHC agenda include more than finding a 'light' Higgs?

The hierarchy problem:

The EW theory has been tested at 1-loop level. The Higgs mass which is a free parameter in the SM, receives large quantum corrections and the mass will approach the cutoff scale of the theory.

The light higgs is 'natural' then only if $\Lambda_{NP} \sim$ TeV.

Searches for light 'stops' an issue of lot of attention. So far -ve results.

Stop searches involve top final states crucially. Polarisation of the top produced in the stop decay plays a crucial role and can even affect to some extent conclusions about exclusion.

Polarisation of the $\tilde{t} \to t\tilde{\chi}_1^0$ and $\tilde{b} \to t\chi_1^{\pm}$ can give us information about the SUSY: mixing in the stop sector and in the chargino/neutralino sector.

The t produced in $\tilde{g} \to \tilde{t}_1 t$ can be polarised if $M_{\tilde{t}_2} - M_{\tilde{t}_1}$ is large. This polarization is directly proportional to the mixing in the stop sector!

Again t can play a useful role!

Normally polarization of t :

1)has well defined relationships with SUSY model parameters in the rest frame of decaying particle.

AND

2)extracted from angular correlations of the decay products of the t in the rest frame of the t.

1)But usually decaying sparticle is NOT produced at rest! Useful to have an idea of expected t polarization in the laboratory frame.

AND

2)Neither is the top at rest! So useful to have laboratory frame observables to track the top polarisation.

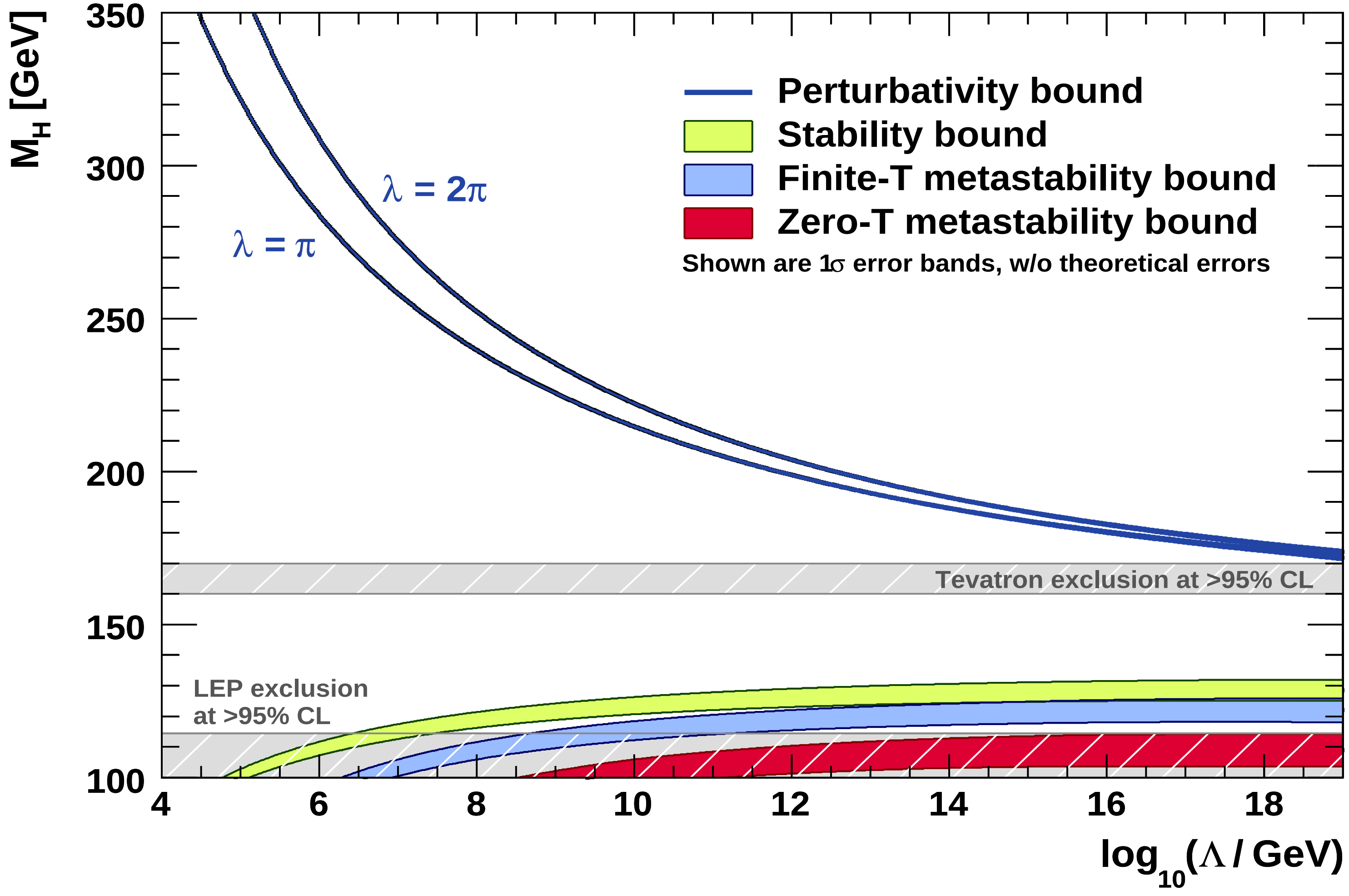
Advertisement: With Ritesh Singh, Arunparasath,we have done this.

We will later see also use of t polarization in th and $tH^{\pm}$ analysis.

Vacuum stability bounds imply that unless M_h is large enough SM will become inconsistent at some large scale Λ!

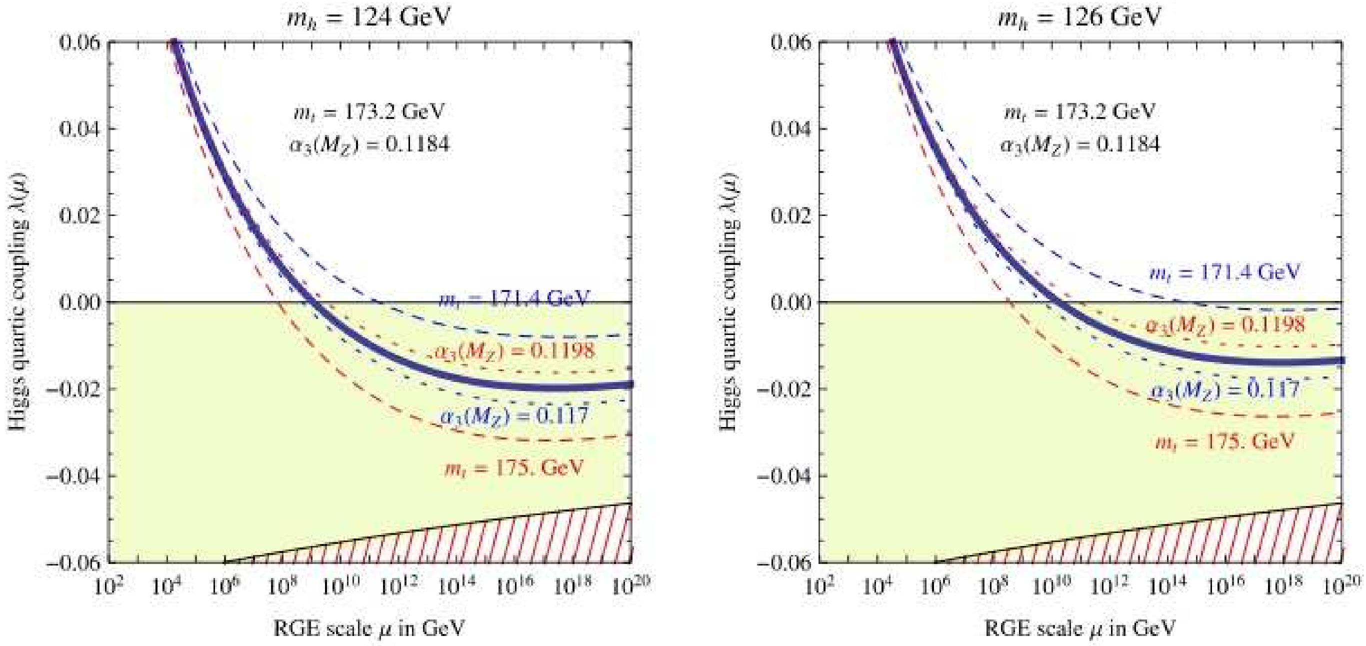
The mass is just large enough to make us suspect that SM is all there is! ie. it **may** remain consistent all the way to Planck scale!

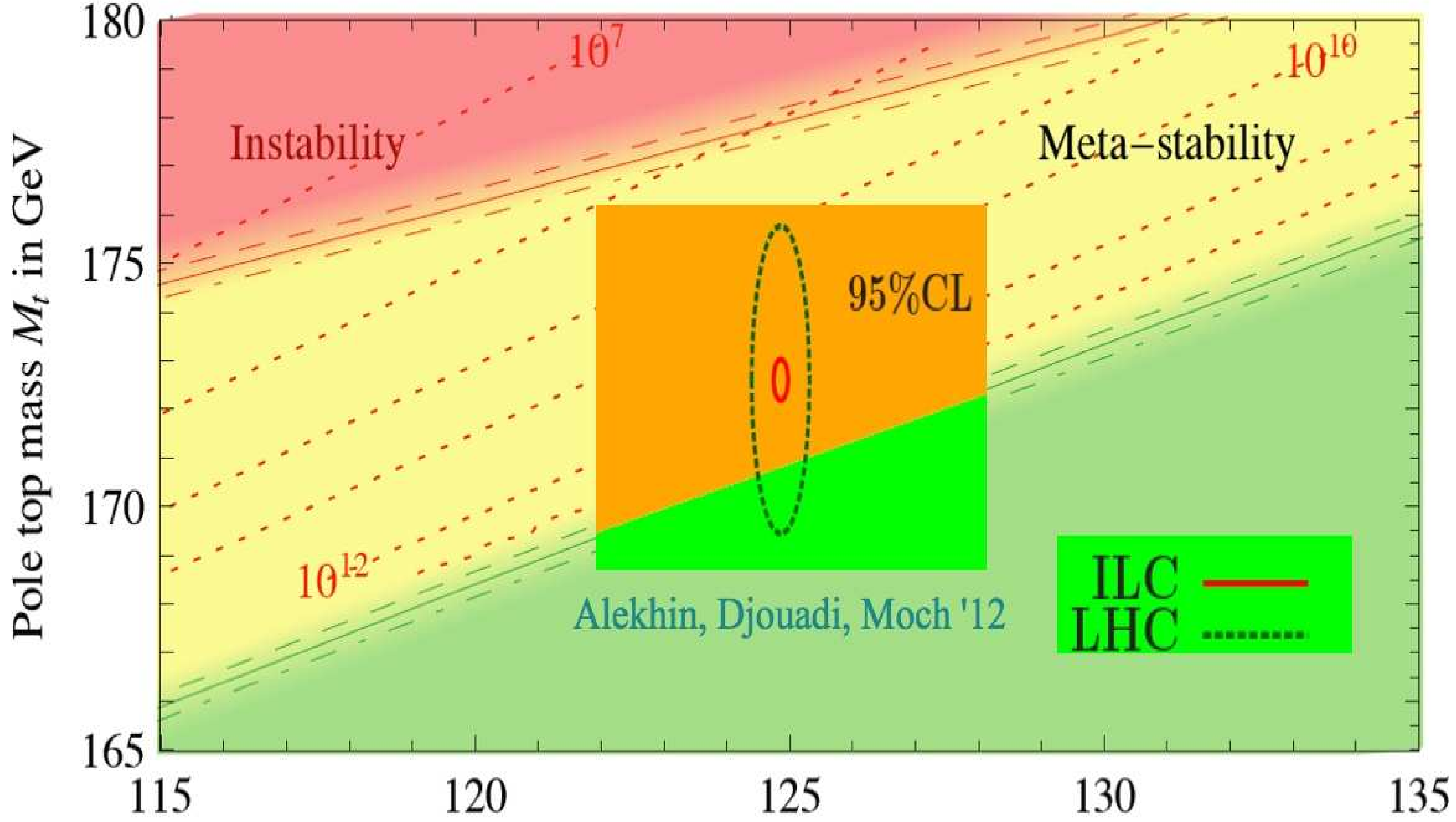
$M_h = 125$GeV is really critical, in all senses of the word. Knowledge of M_t crucial here.


M_H [GeV]
350
300
250
200
150
100
4
6
8
10
12
14
16
18
$\log_{10}(\Lambda / \mathrm{GeV})$
$\lambda = 2\pi$
$\lambda = \pi$
Perturbativity bound
Stability bound
Finite-T metastability bound
Zero-T metastability bound
Shown are 1σ error bands, w/o theoretical errors
Tevatron exclusion at >95% CL
LEP exclusion
at >95% CL

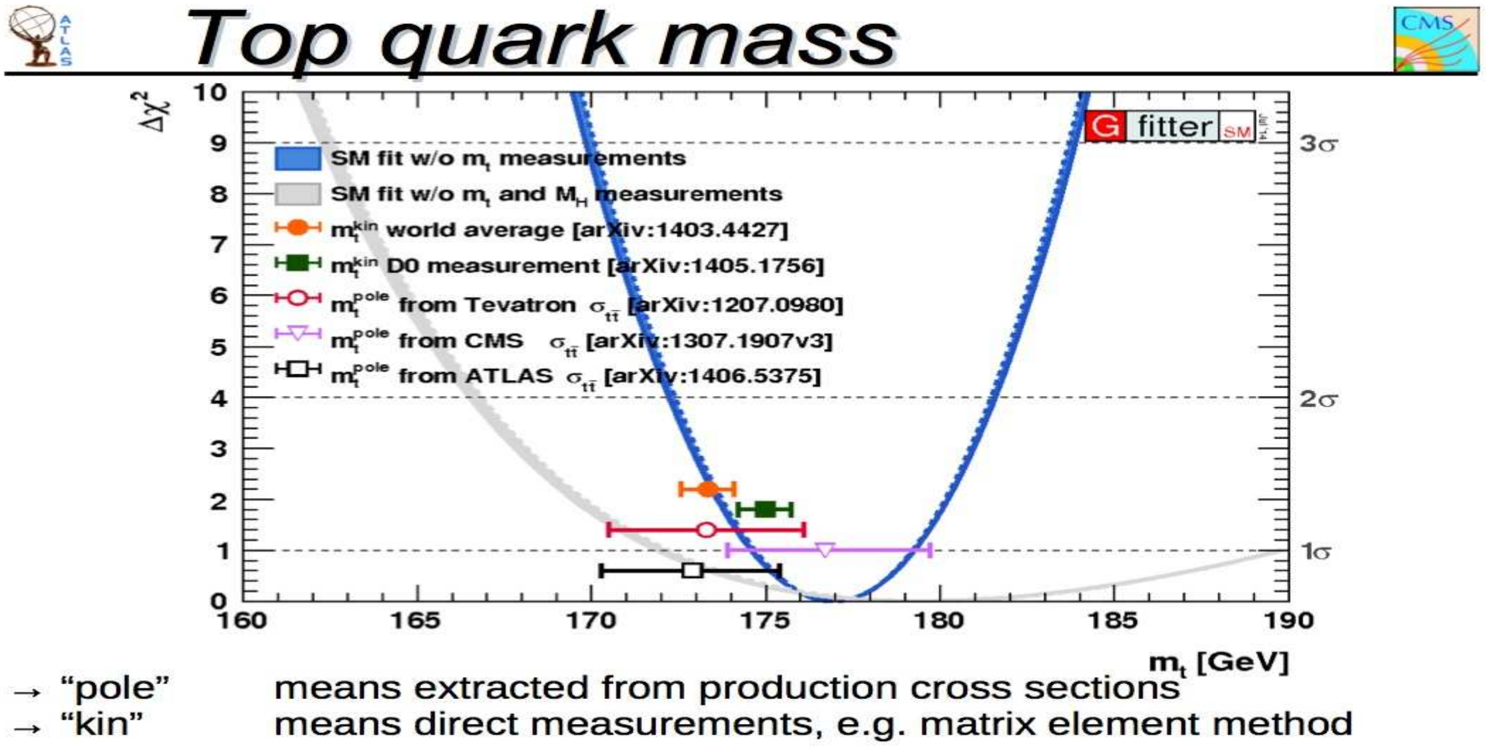
Vacuum stability limit on M_h depends on M_t

J. Elias-Miró et al. / Physics Letters B 709 (2012) 222–228 223





M_h value indeed critical.

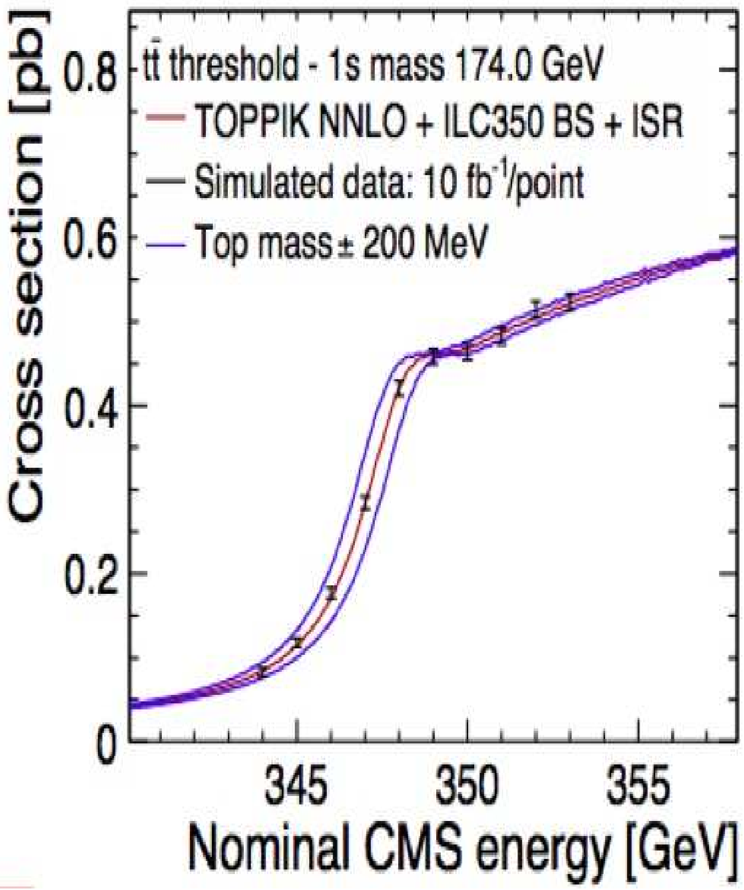


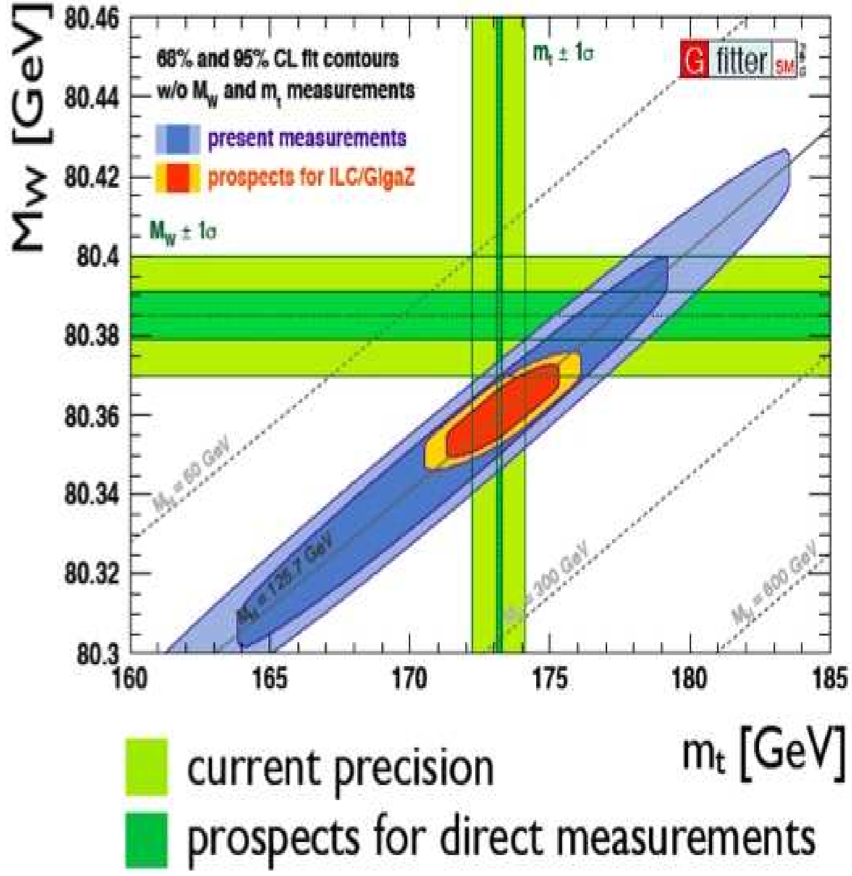
Top quark mass

→ "pole" means extracted from production cross sections
→ "kin" means direct measurements, e.g. matrix element method

Precision at LHC (With 80 million top pairs) : 500 MeV, Ultimately 200 MeV may be possible!

Theoretical precision to relate pole mass to measured cross-sections is high! But cross-section predictions at leptonic colliders more accurate than at hadronic colliders



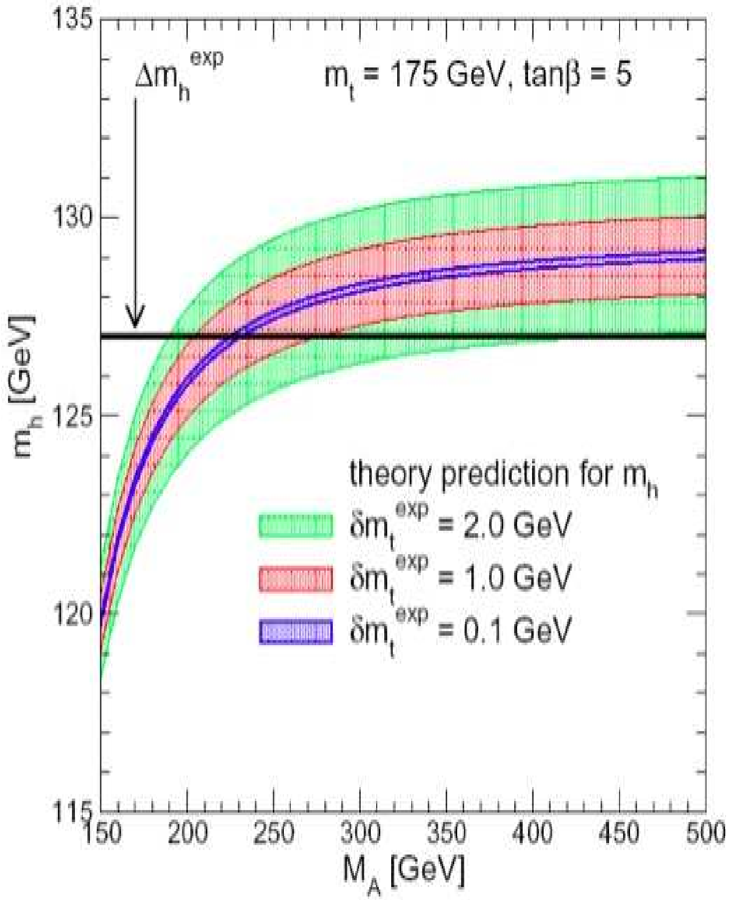


Precision: $\simeq$ 100 MeV!

In fact this can be an excellent way to look for BSM!

100 MeV precision on M_t would be required to match the precision on $\sin^2\theta_W$ and M_W at ILC/Giga Z.

100 MeV precision on M_t can be used to better exploit the LHC (and ILC) precision measurement on M_h.



One more t–h connection.

a)t effects on loop induced Higgs couplings

b)tree level processes affected by t Yukawa couplings

Sensitive observables:

Loop:

$h \to \gamma\gamma$, $gg \to h$

Tree level:

$\sigma(pp \to t\bar{t}h)$

$\sigma(pp \to W + b + X \to t + h)$ (fabio),

$\sigma(pp \to thj)(S.Rindani)$, $\sigma(pp \to hh)$.

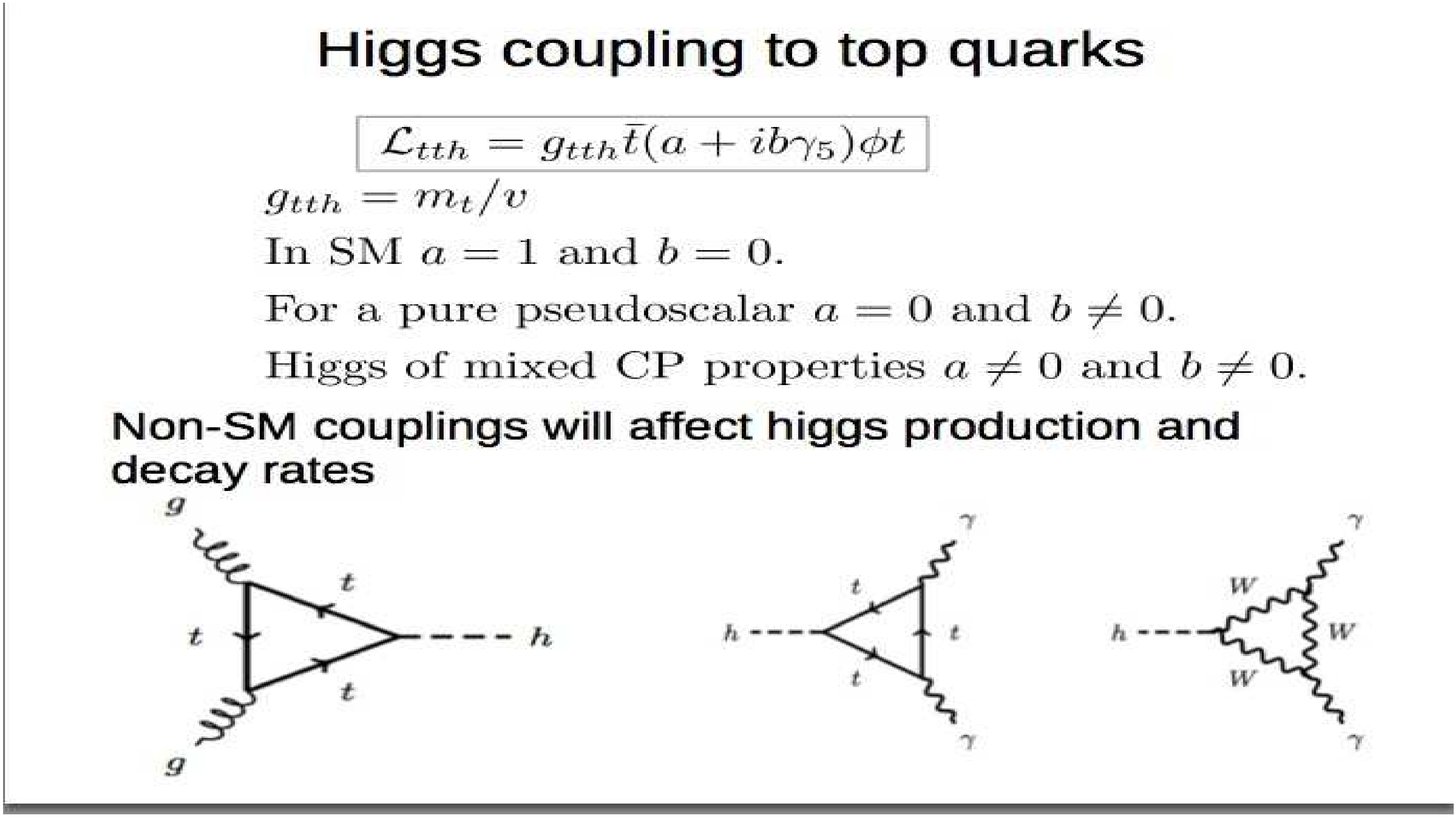
First and foremost: a 'direct' measurement of the strength of this coupling (lot of work and discussions!)

Check CP property of the coupling :

a)Use cross-section and kinematical observables for tth.

b)Use cross-sections for th and $t\bar{t}h$

c)Use polarization information for th



Higgs coupling to top quarks

$$\boxed{\mathcal{L}_{tth} = g_{tth}\bar{t}(a + ib\gamma_5)\phi t}$$

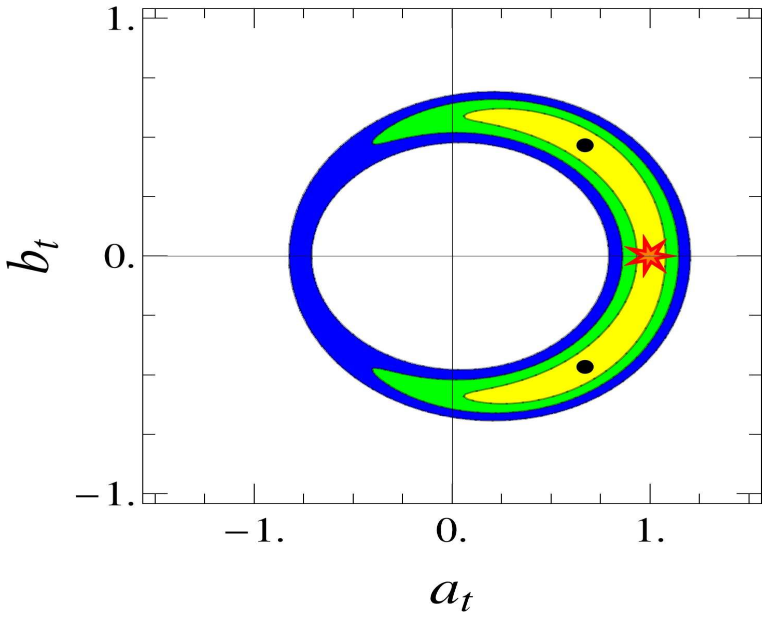
$g_{tth} = m_t/v$

In SM $a = 1$ and $b = 0$.

For a pure pseudoscalar $a = 0$ and $b \neq 0$.

Higgs of mixed CP properties $a \neq 0$ and $b \neq 0$.

Non-SM couplings will affect higgs production and decay rates



All the other couplings other than the t are taken to be SM couplings.

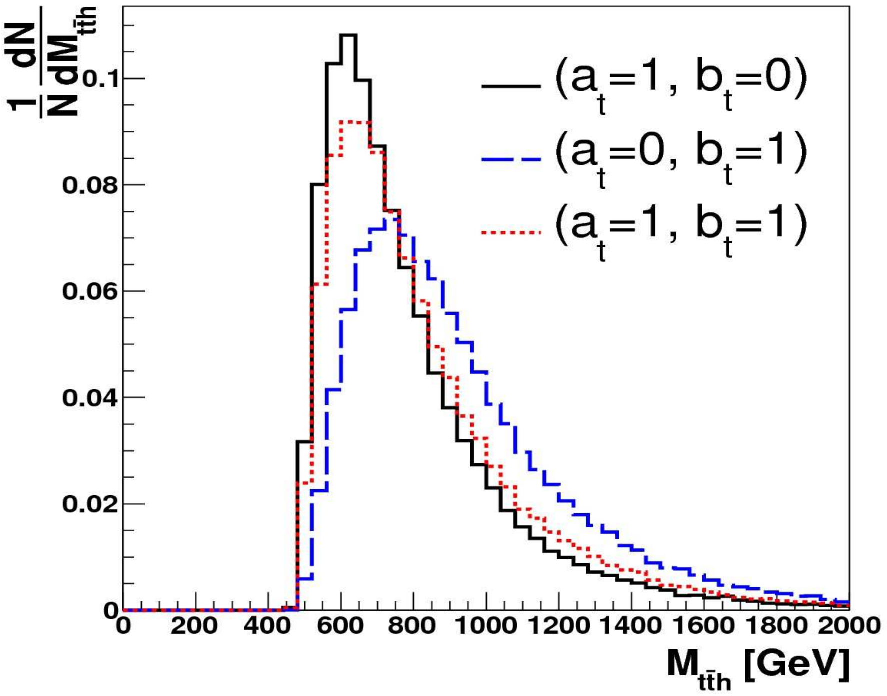
Rates are more sensitive to the pseudo scalar part b_t than a_t Does allow $b_t \neq 0$ and will continue for a while!

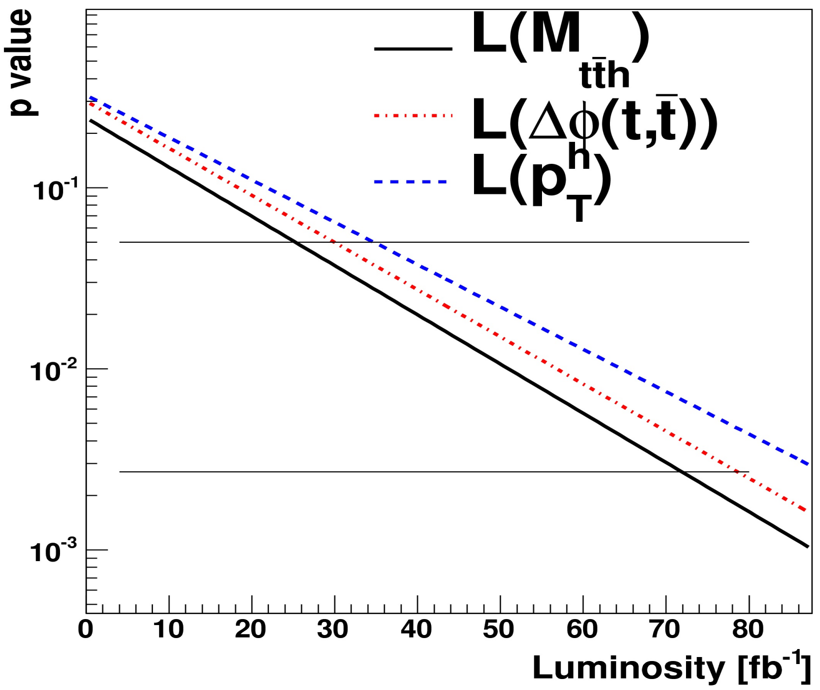
The $t\bar{t}h$ c.section is more sensitive to the scalar part than the pseudo scalar part.

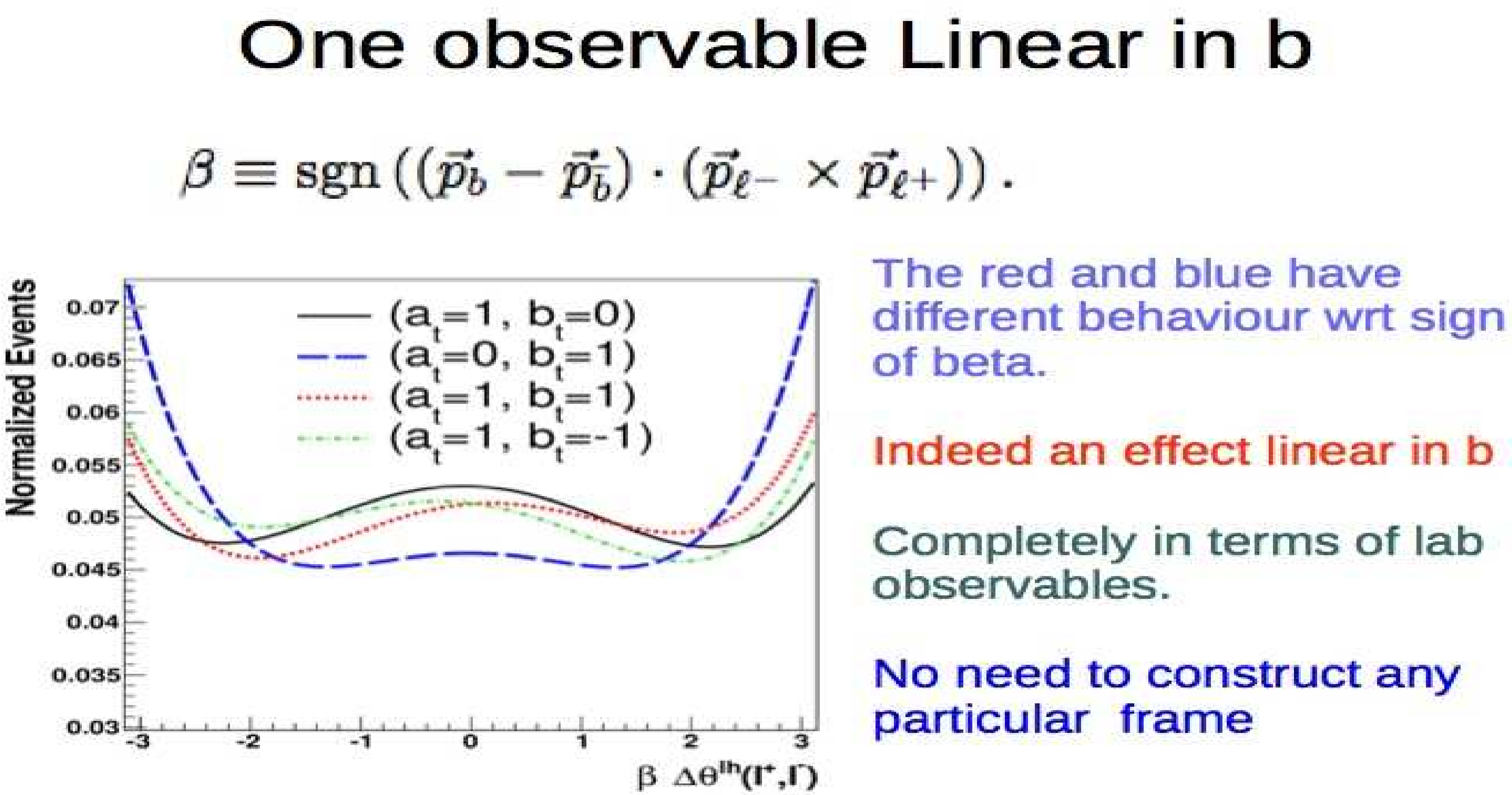
Distributions in $p_T^h, \Delta(\phi)^{t\bar{t}}$ and $m_{t\bar{t}h}$ are sensitive to CP mixing.

But distributions depend on b_t^2. Not linear in b_t

$m_{t\bar{t}h}$


$\frac{1}{N}\frac{dN}{dM_{t\bar{t}h}}$
0
0.02
0.04
0.06
0.08
0.1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
$M_{t\bar{t}h}$ [GeV]
$(a_t=1, b_t=0)$
$(a_t=0, b_t=1)$
$(a_t=1, b_t=1)$


p value
10^{-3}
10^{-2}
10^{-1}
0
10
20
30
40
50
60
70
80
Luminosity [fb^{-1}]
$L(M_{t\bar{t}h})$
$L(\Delta\phi(t,\bar{t}))$
$L(p_T^h)$



One observable Linear in b

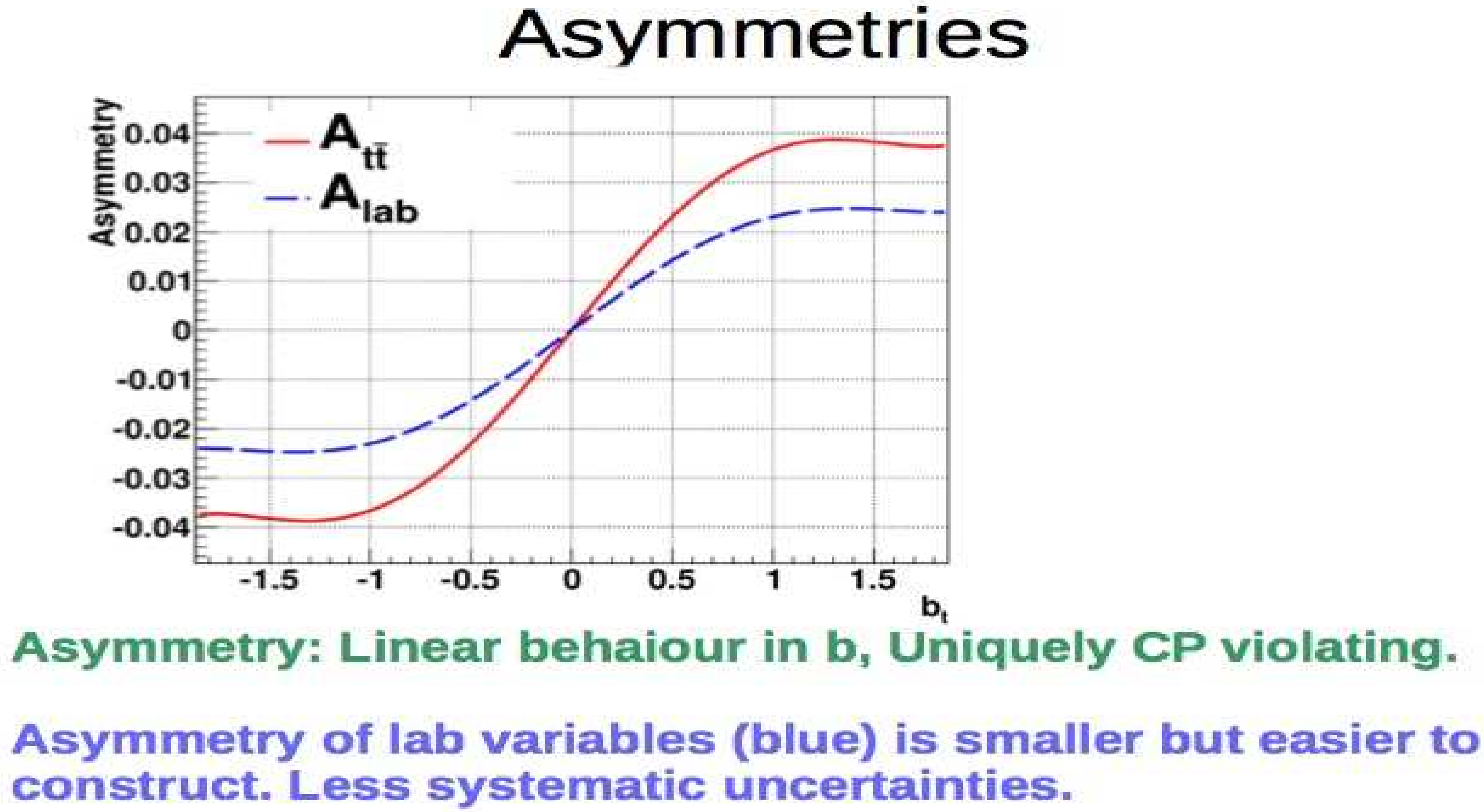
$$\beta \equiv \mathrm{sgn}\left((\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})\right).$$

The red and blue have different behaviour wrt sign of beta.

Indeed an effect linear in b

Completely in terms of lab observables.

No need to construct any particular frame



Asymmetries

Asymmetry: Linear behaiour in b, Uniquely CP violating.

Asymmetry of lab variables (blue) is smaller but easier to construct. Less systematic uncertainties.

There exist a lot of paper and analyses

Latest ones:

The latest is arXiv:1606.03107 . It is a comprehensive analysis.

CP violating observables: : arXiv:1603.03632

Soft gluon resummation: 1609.01619

th cross-section:

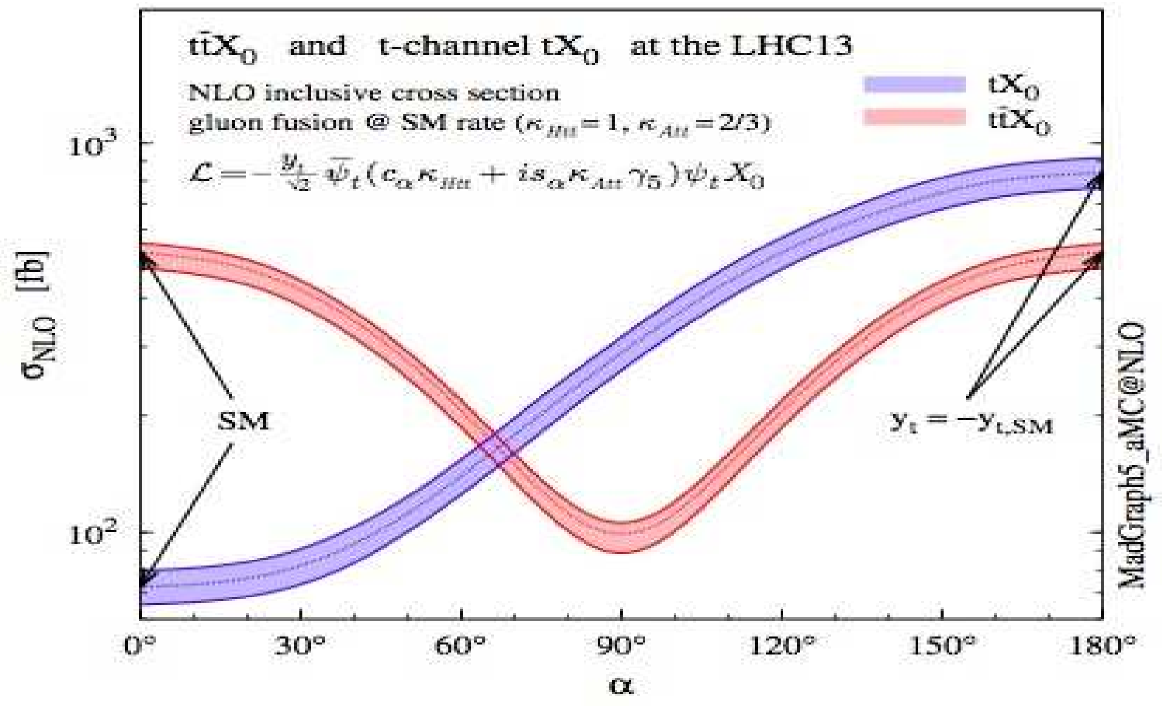


Fig. 12 NLO cross sections (with scale uncertainties) for $t\bar{t}X_0$ and t-channel tX_0 productions at the 13-TeV LHC as a function of the CP-mixing angle α, where κ_{Htt} and κ_{Att} are set to reproduce the SM GF cross section for every value of α

α measures the CP admixture: X_0 a scalar with indeterminate CP.

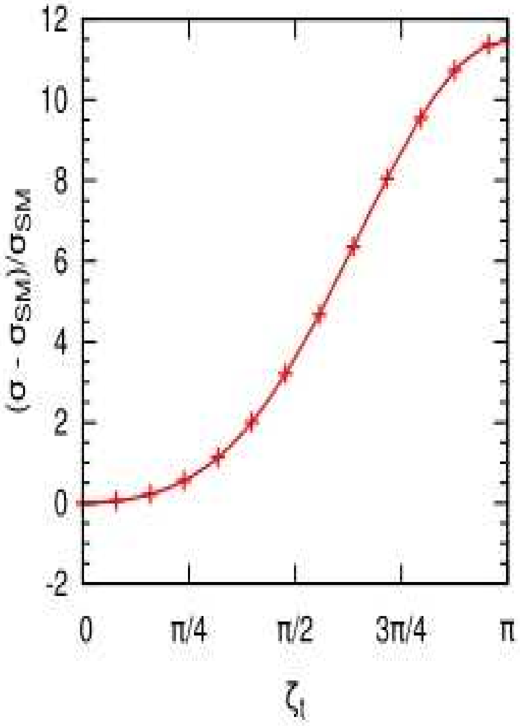


Fig. 2. The fractional deviation of the cross section from the SM value as a function of CP phase ζ_t in the $t\bar{t}h$ coupling for thj process at LHC14.

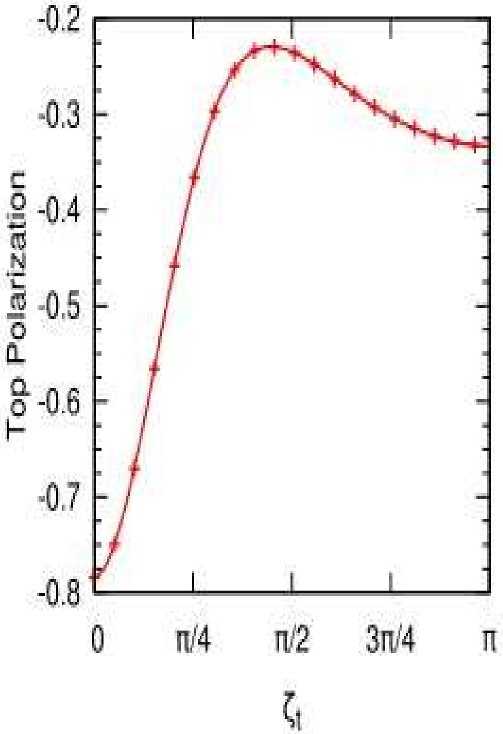
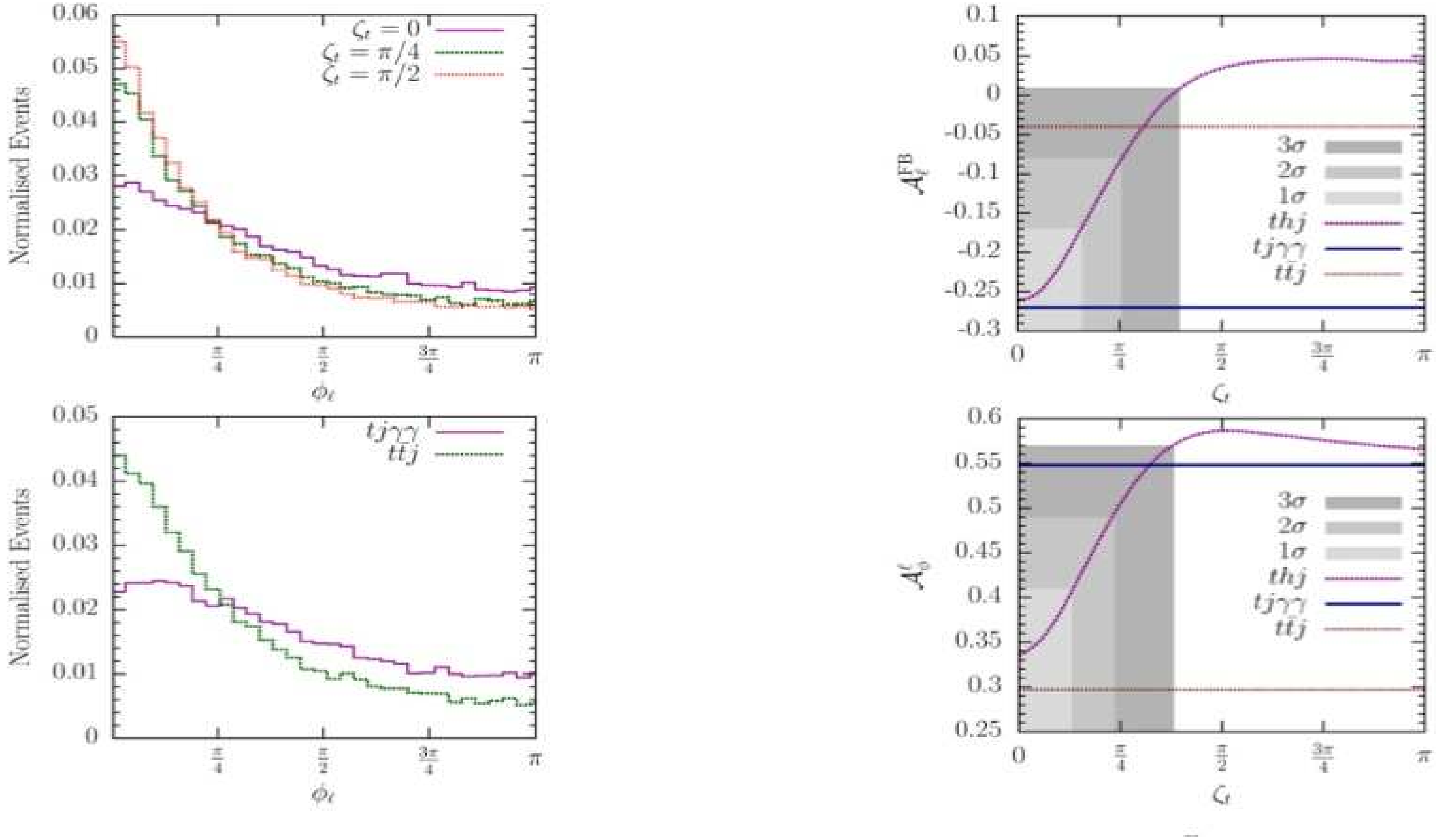


Fig. 3. Top polarization in $pp \to thj$ at LHC14 as a function of the CP phase ζ_t of the tth coupling.

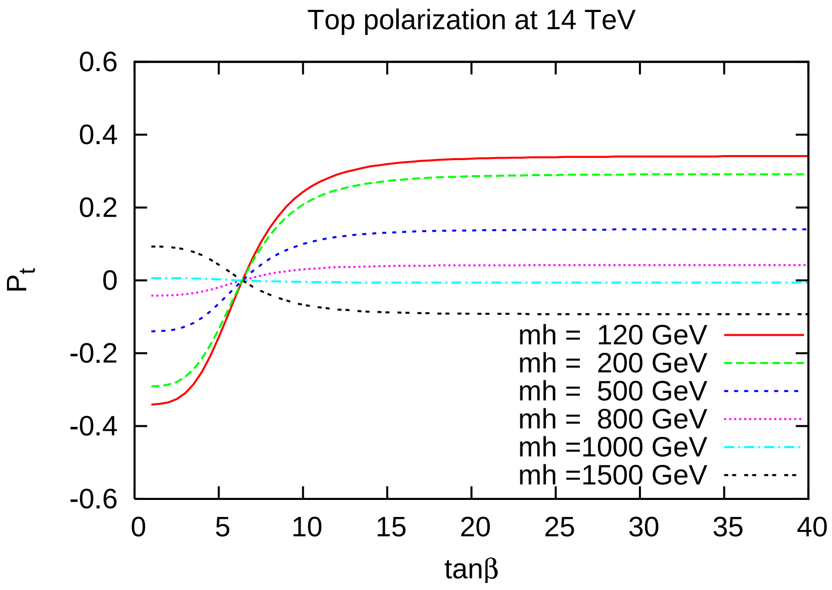
Sensitivity of c.section and polarization complimentary. (S.Rindani, P. Sharma)

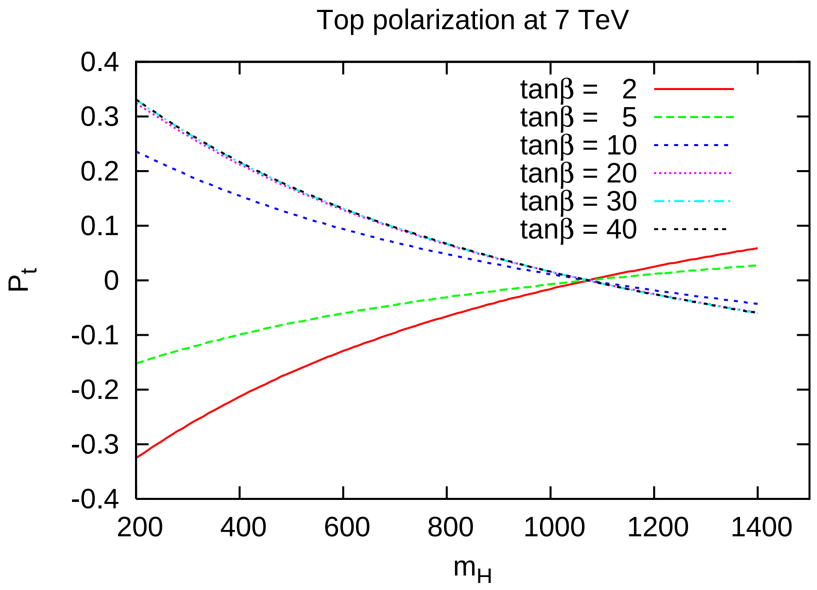


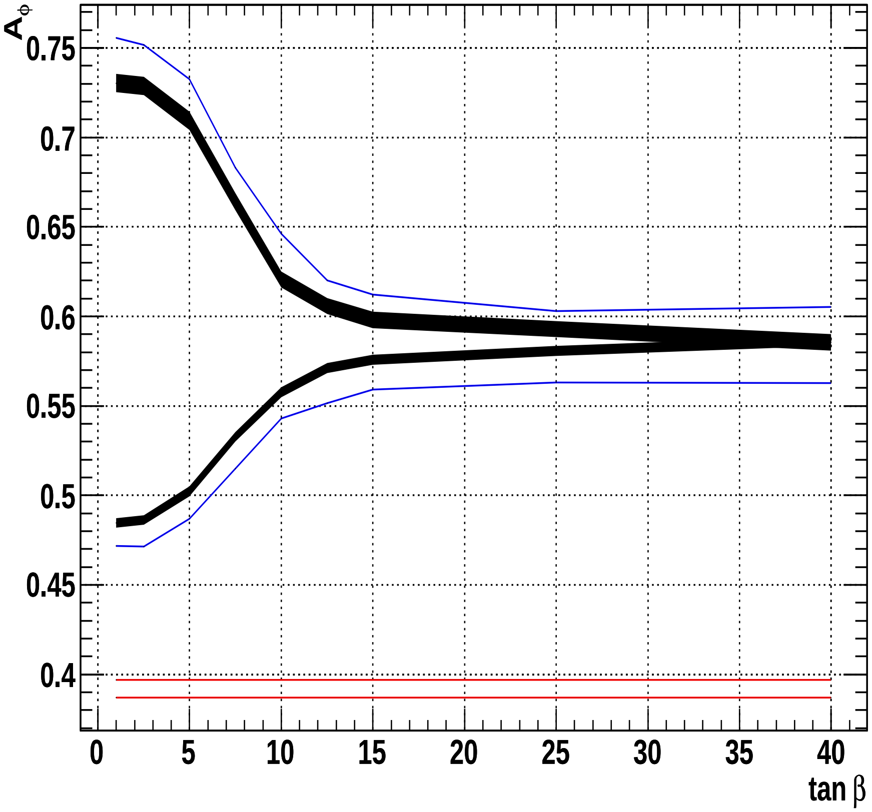
Sensitivity of c.section and polarization complimentary. (S.Rindani, P. Sharma)

$W^{-}t$ production : t will be left polarised, $H^{-}t$ production: t polarisation depends on $\tan\beta$, and m_t.

Extracting charged higgs couplings: K. Huitu, S. Kumar Rai, K. Rao, S. D. Rindani and P. Sharma, JHEP **1104**, 026 (2011), [arXiv:1012.0527 [hep-ph].


Top polarization at 14 TeV


Top polarization at 7 TeV



Separation between $W^- t$ and $H^- t$ for this observable is clear.

Thin line: LO result, thick black: NLO.

$M_{H^-} = 200$ lower curves, $M_{H^-} = 1500$ upper curves.

Constant contours at the bottom $W^- t$.

Correspond to different schemes to adjudge the effect of interference effects at NLO. Only if the two are close is the isolation of $W^- t$ considered free of these ambiguities.

Polarisation tracked through azimuthal asymmetries (With C. White, L. Hartgring and I. Niessen:

Top and Higgs intimately related. Precision measurements of t properties can only help pinpoint the Higgs properties further.

Together their precise knowledge will help us answer some big questions.

They are our window for any physics beyond the SM and understanding/utilising the interplay is extremely important.