Long term perspectives and question marks

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DESY

Abingdon, 11 / 2012

- The Higgs-like state at $\sim 126\ \mathrm{GeV}$
- The mechanism of electroweak symmetry breaking
- Further BSM physics
- Conclusions

The Higgs-like state at $\sim 126\ \mathrm{GeV}$

What do we know so far?

What can we find out in the future and how?

Determination of the properties of the state at $\sim 126\ \mathrm{GeV}$

Mass: statistical precision is already impressive, will further improve a lot

$\Rightarrow$ Need careful assessment of systematic effects, e.g. interference of signal and background, ...

Spin: Observation in $\gamma\gamma$ channel $\Rightarrow$ spin 0 or spin 2?

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Spin determination $\Leftrightarrow$ discrimination between distinct hypotheses for spin 0, (1), 2

$\Rightarrow$ Will soon be clarified

$\mathcal{CP}$ ***properties***

$\mathcal{CP}$-properties: experimentally much more difficult
Can be any admixture of $\mathcal{CP}$-even and $\mathcal{CP}$-odd components

Observables investigated up to now ($H \to ZZ^*, WW^*$ and H production in weak boson fusion) involve HVV coupling

General structure of HVV coupling (from Lorentz invariance):

$$a_1(q_1, q_2)g^{\mu\nu} + a_2(q_1, q_2)\left[(q_1 q_2)\, g^{\mu\nu} - q_1^\mu q_2^\nu\right] + a_3(q_1, q_2)\epsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

Pure $\mathcal{CP}$-even state: $a_1 = 1, a_2 = 0, a_3 = 0$,

Pure $\mathcal{CP}$-odd state: $a_1 = 0, a_2 = 0, a_3 = 1$

However, in most BSM models a_3 would be loop-induced and heavily suppressed $\Rightarrow$ Realistic models usually predict $a_3 \ll a_1$

$\Rightarrow$ Observables involving HVV coupling provide little sensitivity to effects of a $\mathcal{CP}$-odd component

$\mathcal{CP}$ ***properties***

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$\Rightarrow$ Channels involving only Higgs couplings to fermions provide much higher sensitivity

Couplings

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data:

Assumptions:

- Signal corresponds to only one state, no overlapping resonances, etc.
- Zero-width approximation
- Only modifications of coupling strenghts (absolute values of the couplings) are considered, no modification of the tensor structure as compared to the SM case

  $\Rightarrow$ Assume that the observed state is a $\mathcal{CP}$-even scalar

Single channel results vs. simultaneous information from several channels

Single channel results: signal strength parameters μ_i for separate search channels

$\Rightarrow$ Most robust information for testing different models

Very useful for confronting theory predictions with experimental results

Adding information from different channels increases sensitivity

But: interpretation of the results is in general more difficult

Analysis in the long run

As long as the SM continues to be (roughly) compatible with the data:

$\Rightarrow$ Use full SM predictions including all available higher-order corrections $+$ anomalous couplings

$\Rightarrow$ Appropriate tools needed

Anomalous couplings would in general change kinematic distributions

$\Rightarrow$ No simple rescaling of MC predictions possible

$\Rightarrow$ Not feasible for analysis of 2012 data set

$\Rightarrow$ Proposal of “interim framework”

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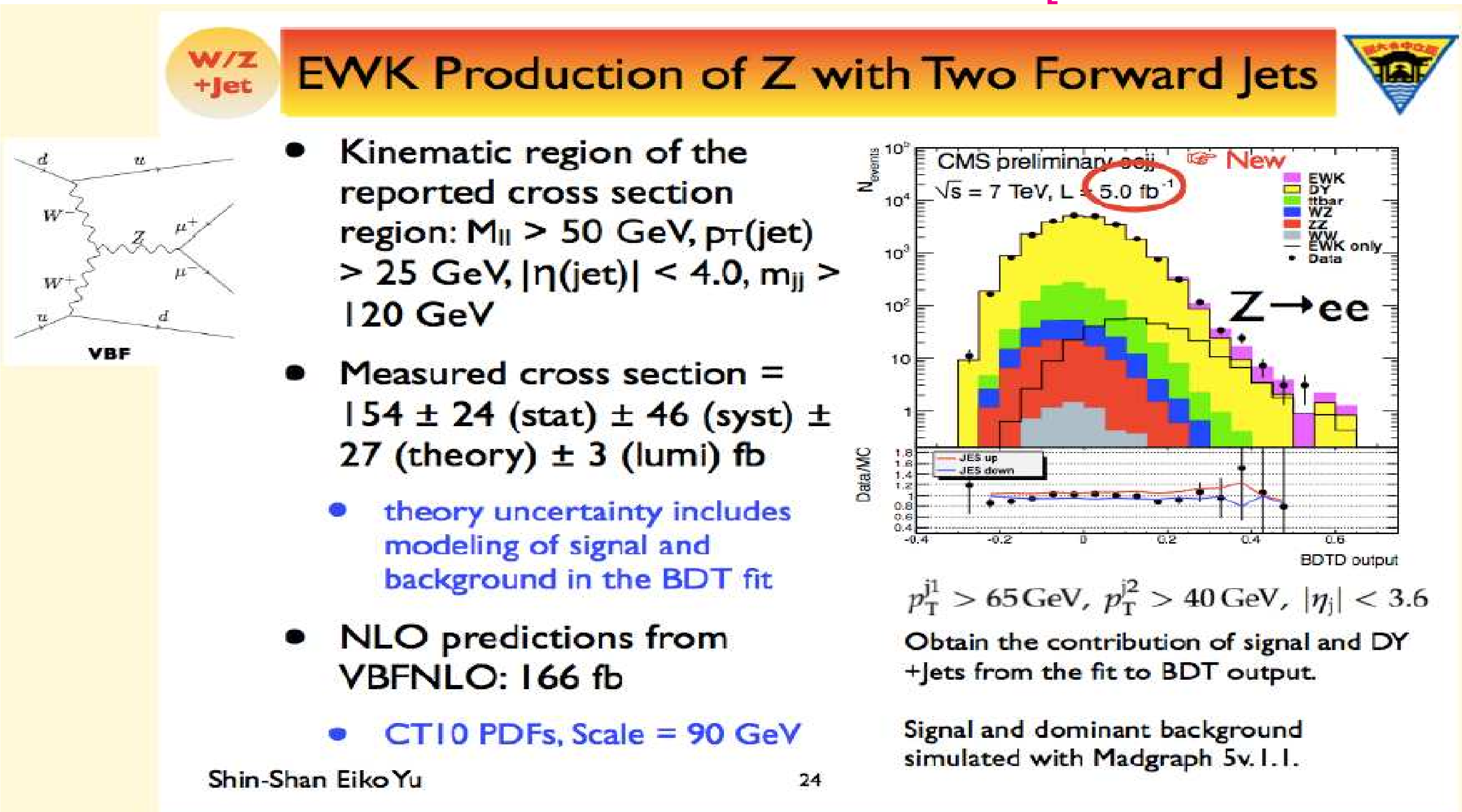
In case SM gets ruled out $\Rightarrow$ Move to other reference model

Recent result that is of interest for Higgs physics: detection of Z production in weak boson fusion

[*CMS Collaboration '12*]



⇒ Reference process for WBF Higgs production?

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

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)

Note: scaling of couplings is in general not possible if higher-order electroweak corrections are included

In the SM: Higgs sector is determined by single parameter $M_{\rm H}$ ($+$ higher-order contributions)

$\Rightarrow$ Once $M_{\rm H}$ is fixed the Higgs couplings are determined and cannot be varied within the SM

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Scaling of couplings $\Leftrightarrow$ test of deviations from the SM

Note: acceptances and efficiencies are assumed to be as in the SM

$\Rightarrow$ This will have an impact on the interpretation in case a sizable deviation from the SM prediction gets established

$\Rightarrow$ Results obtained from the analysis with scaled couplings cannot be interpreted as "coupling measurements"

Recommendations of the LM subgroup of the LHC Higgs XS WG for analyses of 2012 data

Which kind of scaling factors should be considered?

In general, scale factors are needed for couplings of the new state to

t, b, τ, W, Z, $\ldots$

+ extra loop contribution to $\sigma(gg \to H)$, $\Gamma(H \to gg)$
+ extra loop contribution to $\Gamma(H \to \gamma\gamma)$
+ additional contributions to total width, Γ_H, from undetectable final states

Total width Γ_H cannot be measured without further assumptions (otherwise only coupling ratios can be determined, not absolute values of couplings)

Proposed "benchmarks" for scale factors κ_i

Different "benchmark" proposals, based on simplifying assumptions to reduce the number of free parameters

1 parameter: overall coupling strength μ

2 parameters: e.g. common scale factor κ_V for W, Z, and common scale factor for all fermions, κ_F

...

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

Proposed "benchmarks" for scale factors κ_i

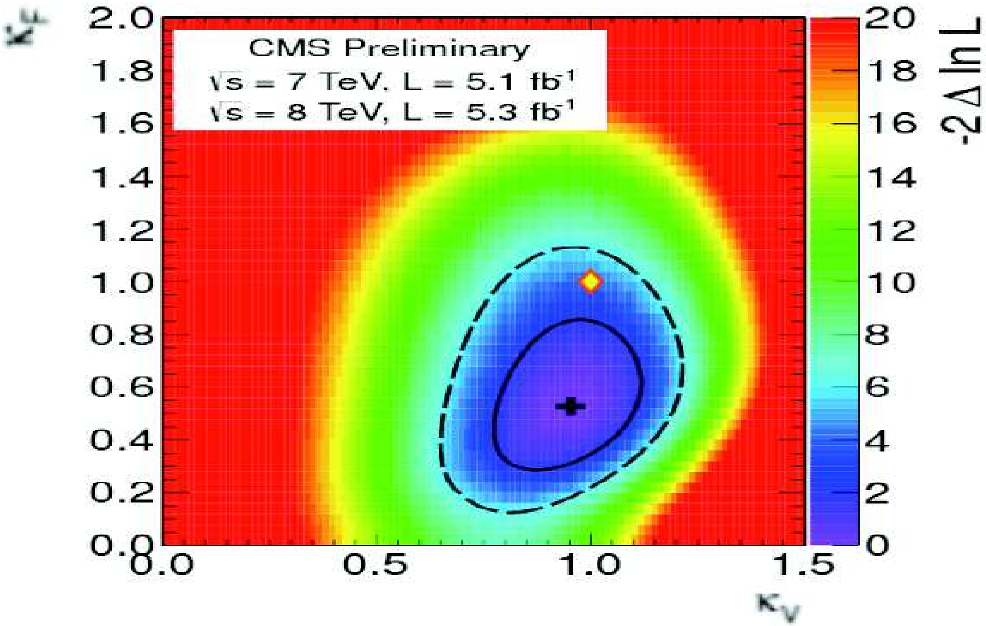
If additional contributions to Γ_H are allowed

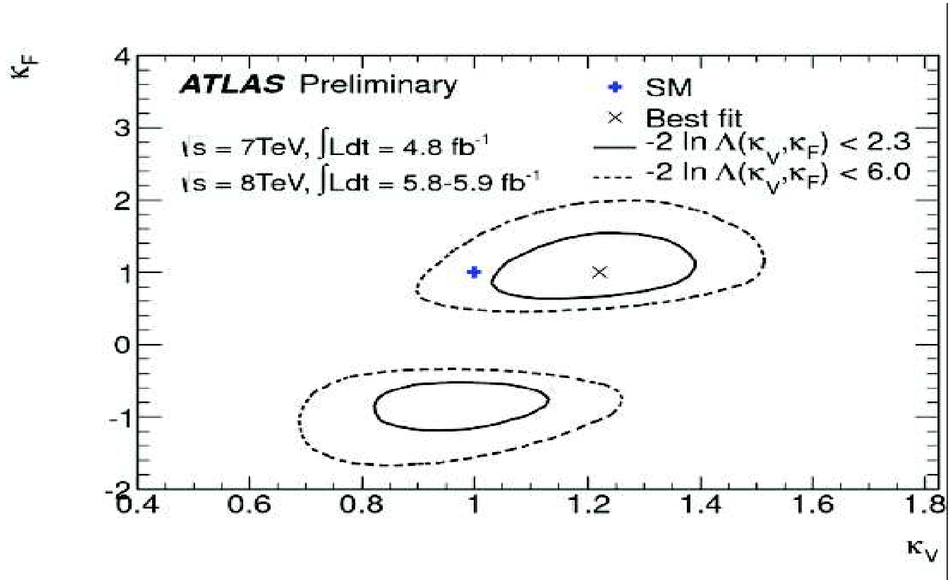
$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

If no additional contributions to $\Gamma(H \to \gamma\gamma)$, Γ_H, $\ldots$ are allowed

$\Rightarrow$ κ_γ can be determined in terms of κ_b, κ_t, κ_τ, κ_W
evaluated to NLO QCD accuracy

Example: κ_V, κ_F analyses from CMS and ATLAS





MSSM interpretation of scale factors κ_i?

- Higgs couplings to up-type and down-type fremions are different $\Rightarrow$ cannot be described in terms of common κ_F
- Large SUSY contributions can affect relation between coupling to $b\bar{b}$ and $\tau^+\tau^-$
- Extra contributions to $\sigma(gg \to H)$, $\Gamma(H \to gg)$, $\Gamma(H \to \gamma\gamma)$: $\tilde{\mathrm{t}}$, $\tilde{\tau}$, $\tilde{\chi}^{\pm}$, ...
- Extra contribution to total width: $H \to$ invisible, ...

It seems difficult to go beyond three free parameters in the near future

$\Rightarrow$ Benchmark scenarios of this kind are in general too restrictive to allow an interpretation within a “realistic” model like the MSSM

Higgs coupling determination at the LHC

Problem: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\rm prod,\, decay} \sim g^2_{\rm prod,\, decay}$):

$$\sigma(H) \times {\rm BR}(H \to a + b) \sim \frac{\Gamma_{\rm prod}\Gamma_{\rm decay}}{\Gamma_{\rm tot}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

$\Rightarrow$ Without further assumtions, total Higgs width cannot be determined

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

What do we need to know?

What we know so far about the new state at ~ 126 GeV still leaves open many possible interpretations

- Many models of physics beyond the SM have a SM-like Higgs over large parts of their parameter space
- Does the new state have the right properties to unitarize $W_L W_L$ scattering?
- Fundamental or composite?

$\Rightarrow$ Need absolute determination of the couplings and the total width with high precision

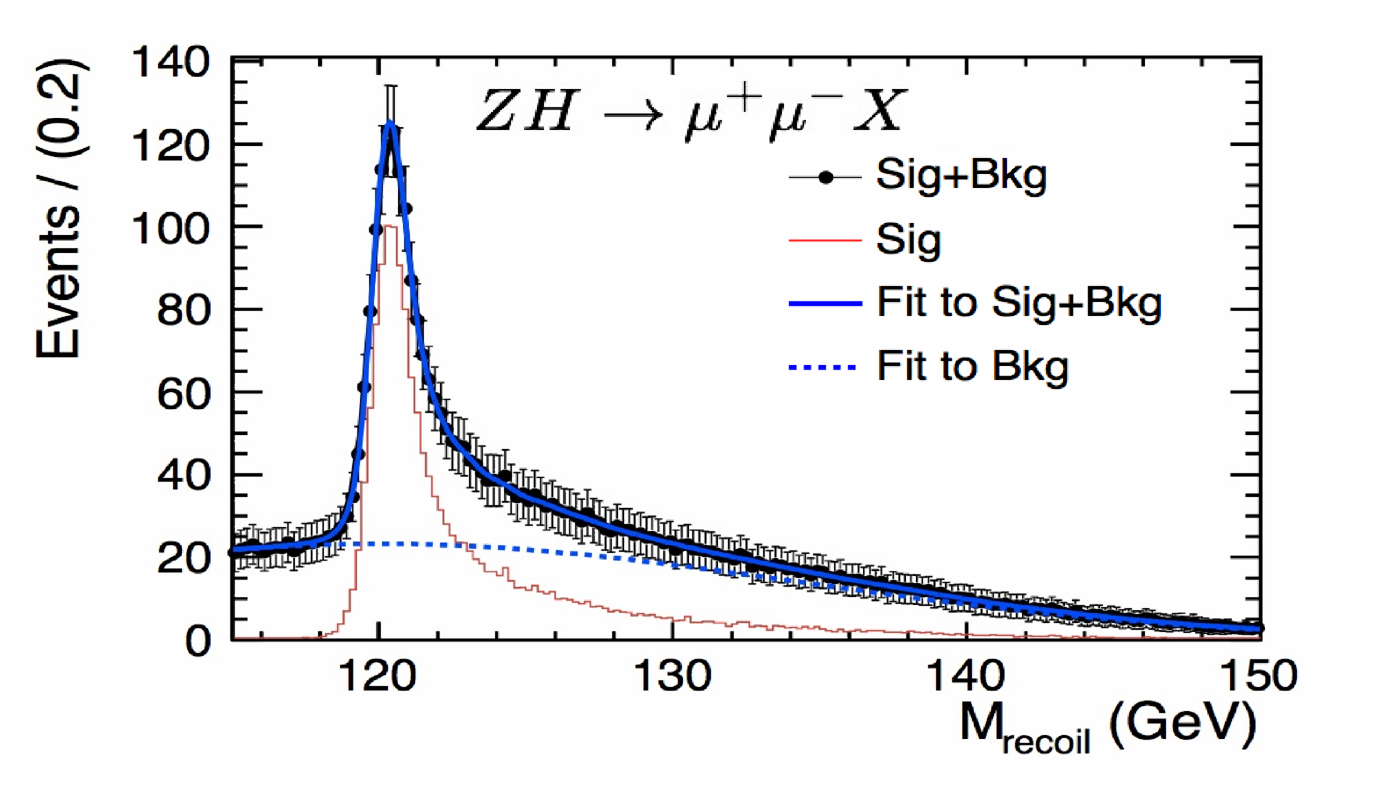
Higgs self-coupling $\Leftrightarrow$ experimental access to Higgs potential

$\Rightarrow$ Strong case for an e^+e^- Linear Collider: “Higgs factory”

Decay-mode independent measurement: “recoil” against Z

LC: high-precision measurements of Higgs properties

"Recoil" method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$ [R. Poeschl et al. '12]



Measurement of mass, couplings, $\mathcal{CP}$ properties, self-coupling, ... + high sensitivity to additional Higgses

⇒ Identification of the underlying nature of electroweak symmetry breaking

The mechanism of electroweak symmetry breaking

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Other possibilities? Dilaton? ...

One would expect to see other signatures of the EWSB dynamics in such a case soon ...

What else? Fundamental or composite?

- Radion
- Composite "pseudo-Goldstone boson", like the pion in QCD $\Rightarrow$ Would imply new kind of strong interaction

  Relation to weakly-coupled 5-dimensional model (AdS/CFT correspondence)

  Discrimination from fundamental scalar

  - Precision measurements of couplings ($\Rightarrow$ high sensitivity to compositeness scale), $\mathcal{CP}$ properties, ...
  - Search for resonances (light Higgs $\Leftrightarrow$ light resonances?)
- ...

SM vs. Supersymmetry

Detection of a SM-like Higgs with $M_{\rm H} \gtrsim 135~{\rm GeV}$ would have unambiguously ruled out the MSSM

$\Rightarrow$ Signal at $\sim 126~{\rm GeV}$ is well compatible with MSSM prediction

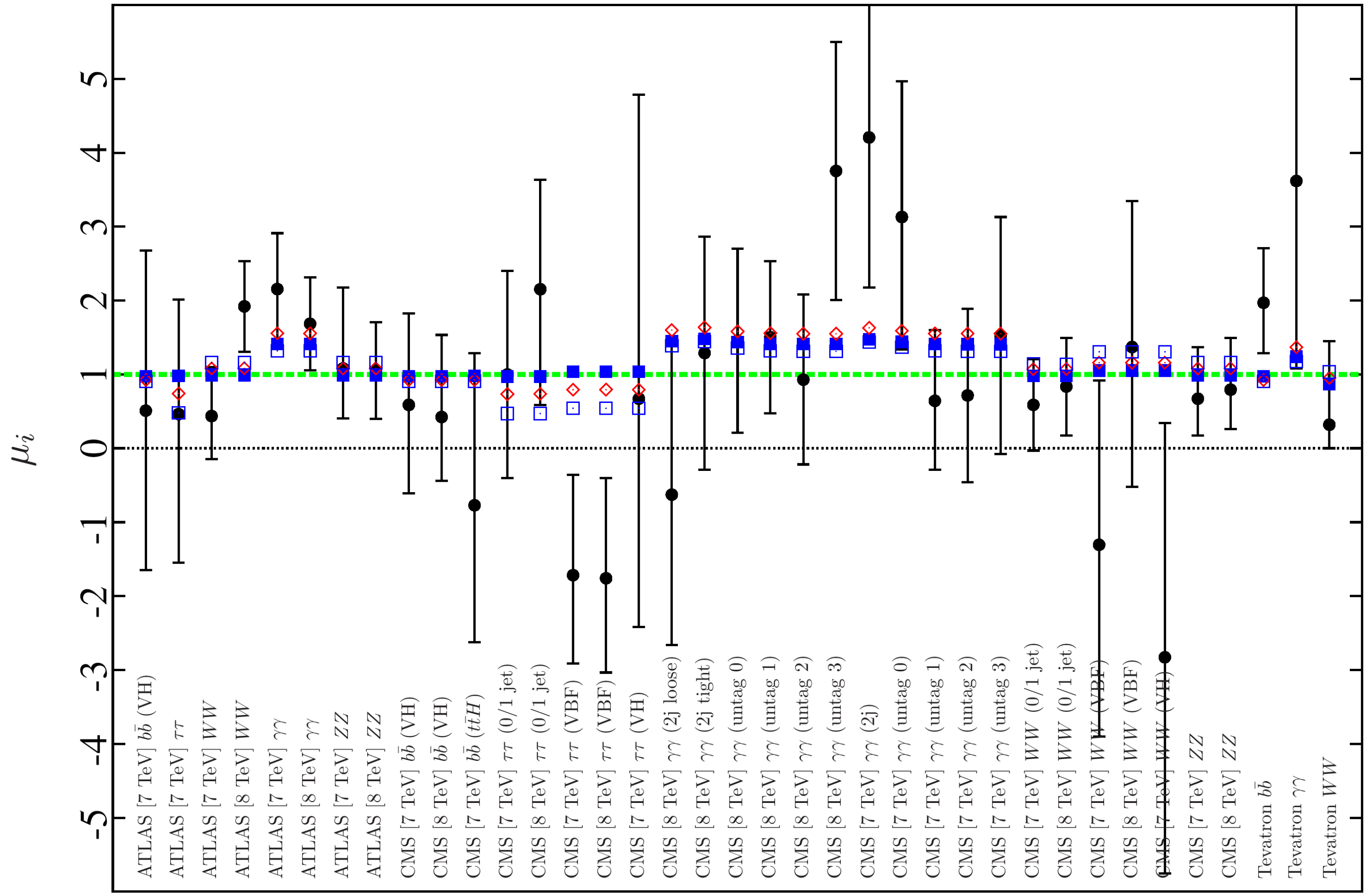
- MSSM can accomodate enhancement of ${\rm BR}(H \to \gamma\gamma)$ (e.g.: additional particles in the loop, light stau, ...), suppression of ${\rm BR}(H \to \tau^+\tau^-)$, ...

- Interpretation of the observed signal at $\sim 126~{\rm GeV}$ is in principle possible both in terms of the lightest (h) and in terms of the next-to-lightest (H) neutral Higgs of the MSSM!

MSSM fit (pre HCP): comparison of SM with MSSM interpretation in terms of light Higgs h

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune ’12*]

- LHC / TeV. data, ■ full fit, ⊡ without TeV., ◇ without low. en. obs.



$\Rightarrow \chi^2$ reduced compared to SM case, better fit probability

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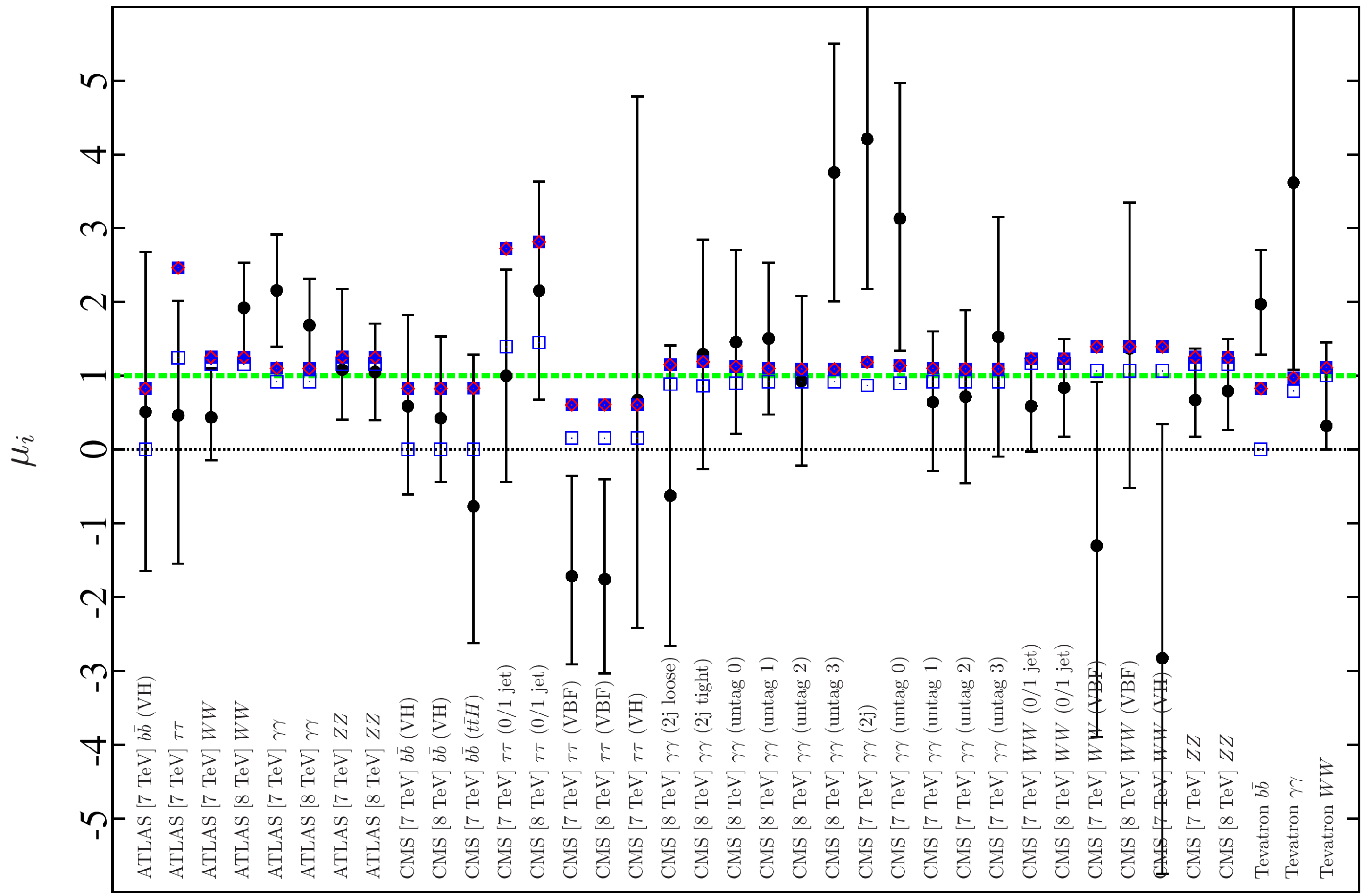


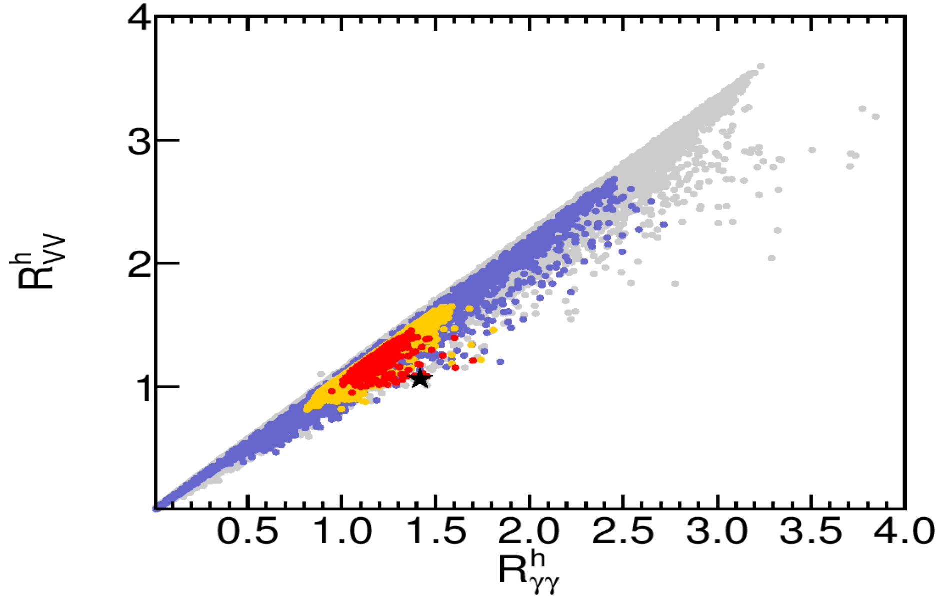
$\Rightarrow$ viable description of data (lower fit quality than MSSM–h)

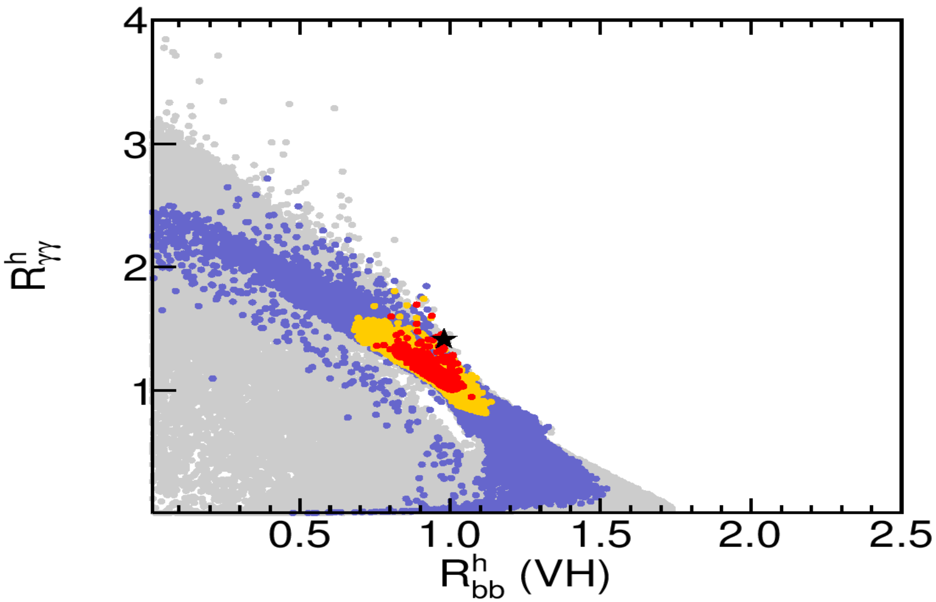
Rates in different channels normalised to the SM

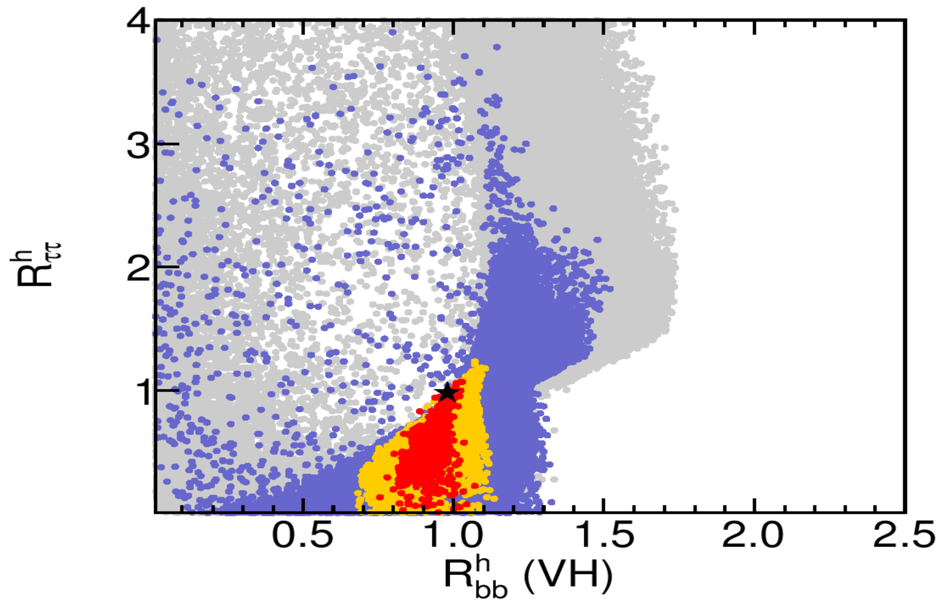
Rate modifiers

- All points: $121 < M_h < 129$ GeV
- Allowed by HiggsBounds
- $\Delta\chi^2 < 2.30$
- $\Delta\chi^2 < 5.99$

$$\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$$

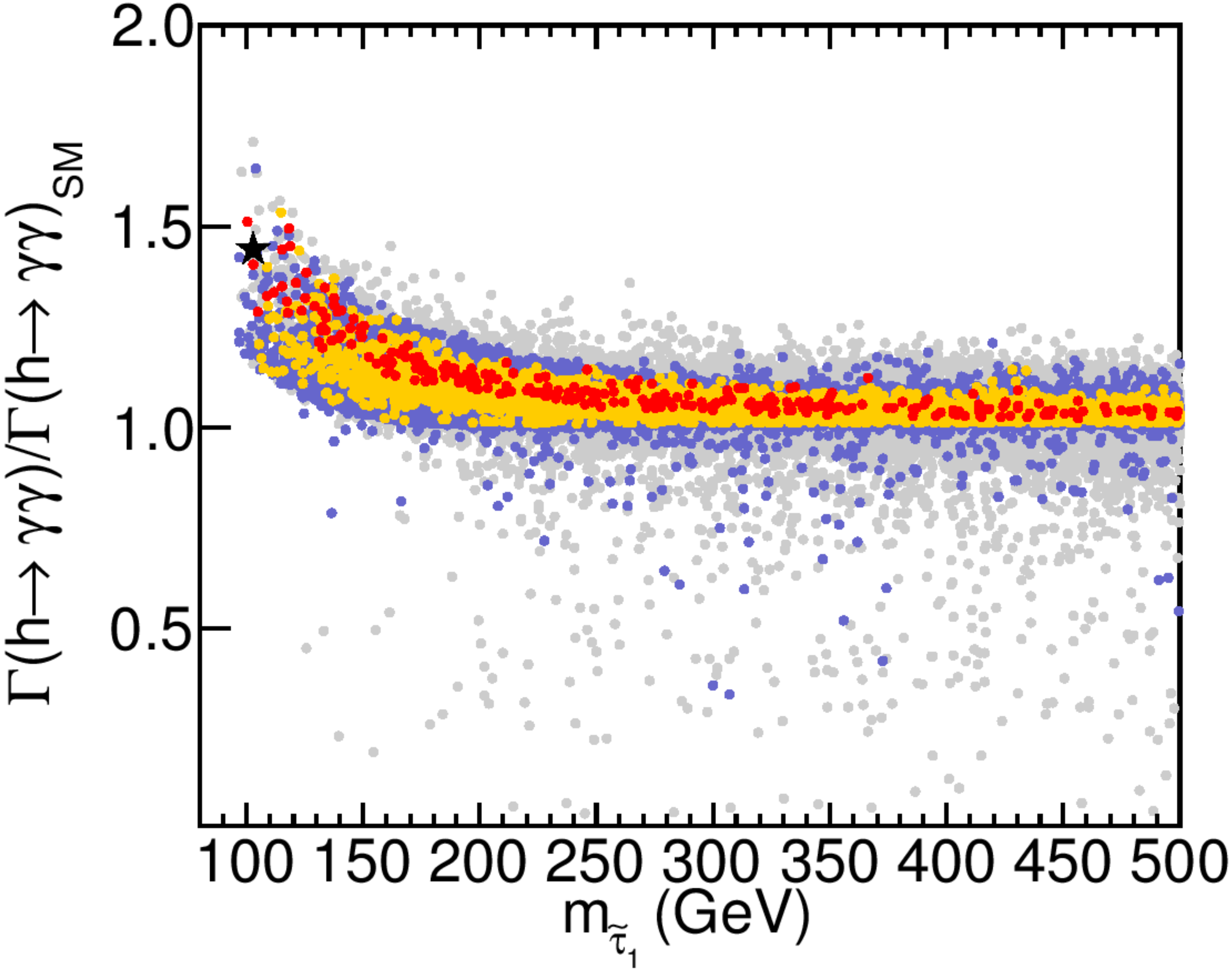






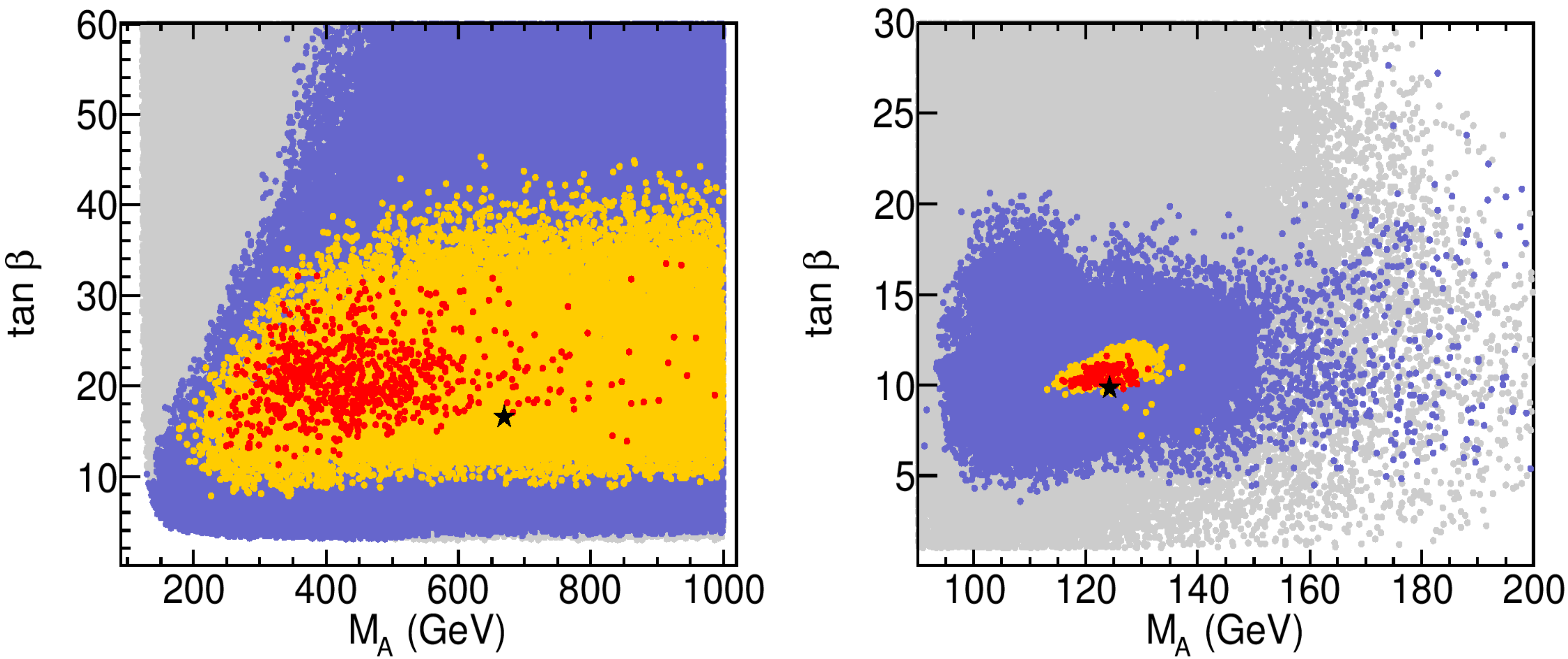
Enhancement of $\gamma\gamma$ partial width from light staus

[*P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. W., L. Zeune '12*]



$\Rightarrow$ Light staus can lead to significant enhancement

Preferred region in $(M_\mathrm{A}, \tan\beta)$ plane for interpretation of observed signal in terms of h (left), H (right), pre HCP



$\Rightarrow$ Effect of limit from $H, A \to \tau^+\tau^-$ searches weaker than in the $m_\mathrm{h}^\mathrm{max}$ scenario

$\Rightarrow$ Need cross section limits from CMS to assess impact of latest HCP results

SUSY interpretation

To what extent is the interpretation of the observed signal at $\sim 126\ \mathrm{GeV}$ in terms of the heavier neutral Higgs H still viable?

$\Rightarrow$ Input from CMS needed

Such an interpretation would imply an additional non-SM like light Higgs, may have mass below the LEP limit of $M_{\mathrm{H_{SM}}} > 114.4\ \mathrm{GeV}$ (with reduced couplings to gauge bosons, in agreement with LEP bounds)

$\Rightarrow$ Observation of a SM-like signal at $\sim 126\ \mathrm{GeV}$ provides a strong motivation to look for non SM-like Higgses elsewhere

$\Rightarrow$ The best way of experimentally proving that the observed state is not the SM Higgs is to find in addition (at least one) non-SM like Higgs!

Further BSM physics

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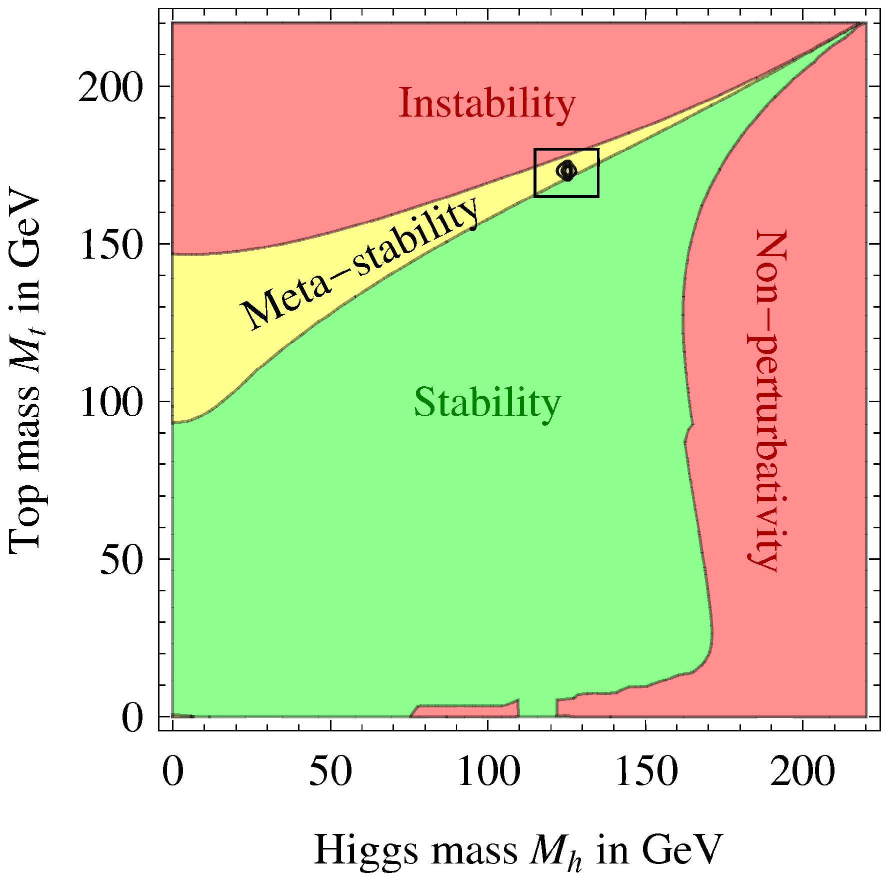
Do we live in a metastable vacuum?

[*G. Degrassi et al. ’12*]



The hierarchy problem: SM Higgs mass is affected by large corrections ($\sim \Lambda^2$) from physics at high scales

Now that a Higgs-like state with a mass of ~ 126 GeV has been discovered, the question what protects its mass from physics at high scale becomes even more pressing

"Hierarchy problem": $M_{\text{Planck}}/M_{\text{weak}} \approx 10^{17}$

How can two so different scales coexist in nature?

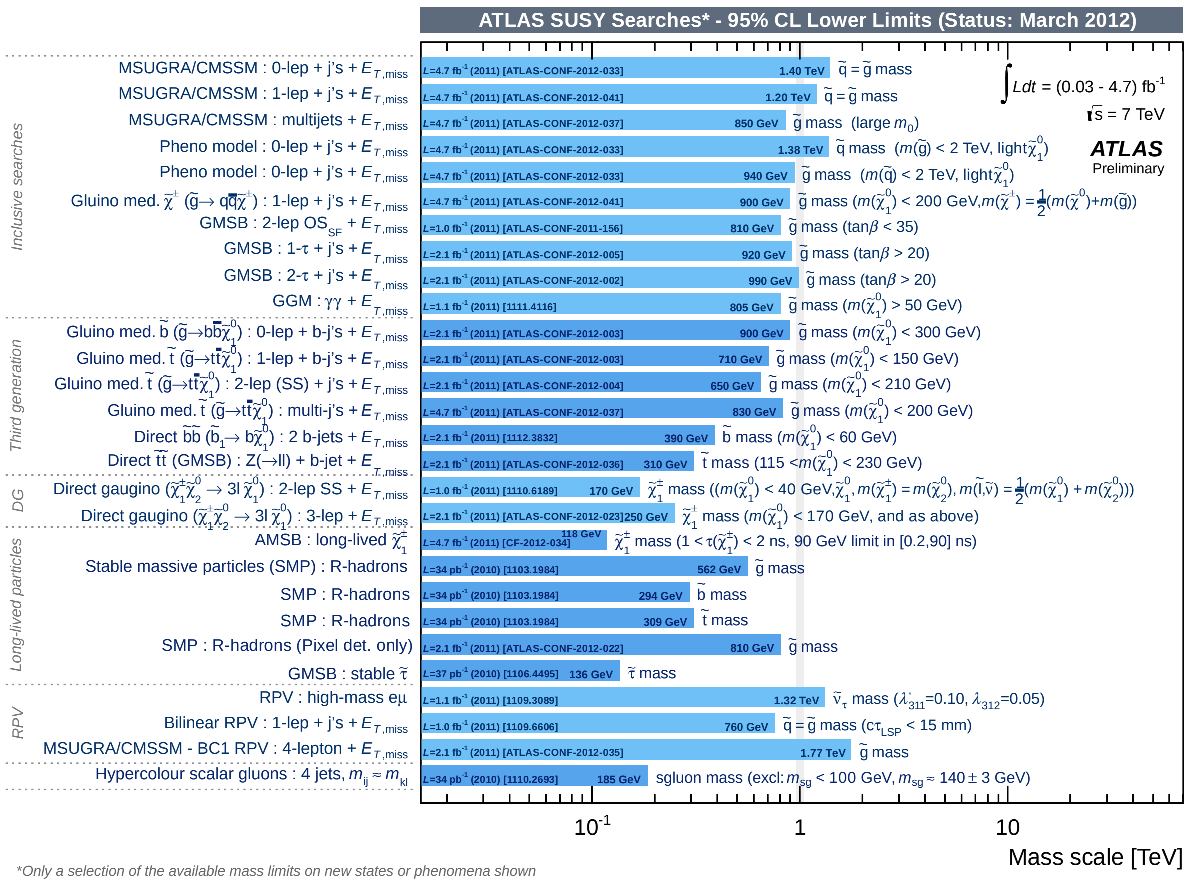
Via quantum effects: physics at M_{weak} is affected by physics at M_{Planck} $\Rightarrow$ Instability of M_{weak}, would imply that all physics is driven up to the Planck scale

$\Rightarrow$ Expect new physics to stabilise the hierarchy

E.g. SUSY: Large corrections cancel out because of symmetry fermions $\Leftrightarrow$ bosons

Where is the new physics that stabilises the gauge hierarchy?

Large number of searches, many limits, . . . [*ATLAS Collaboration '12*]



Interpretation in specific scenarios, e.g. CMSSM, and in "simplified models"

A look back to the pre–LHC days

Global fits in constrained SUSY models (CMSSM, . . .):

Best fit point was close to SPS 1a (LM1, . . .) benchmark point:

Low scale SUSY point

$\Rightarrow$ "plain vanilla" SUSY

$\Rightarrow$ "best case scenario" for LHC and LC

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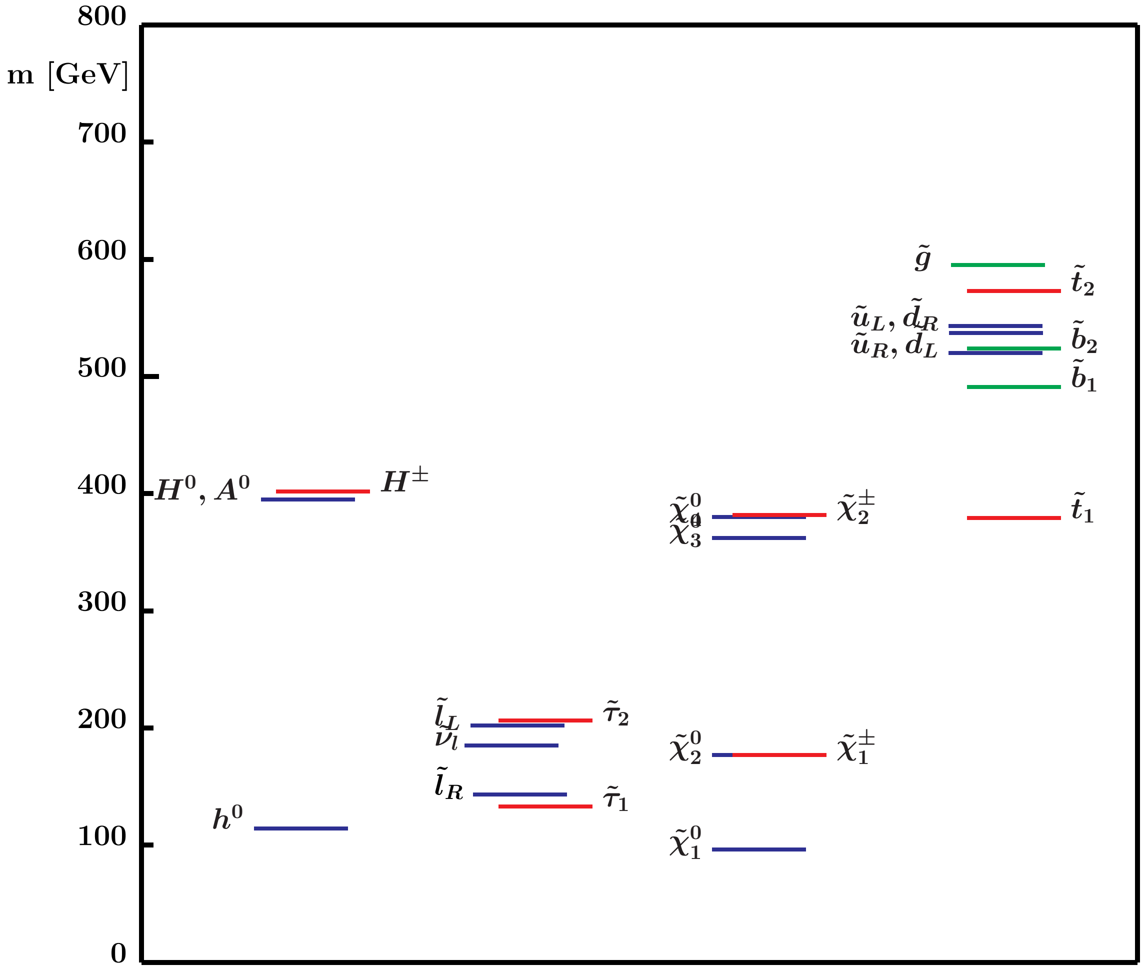
Preference for light SUSY scale was mainly driven by $(g-2)_\mu$

$\Rightarrow$ light $\tilde{e}$, $\tilde{\mu}$, $\tilde{\chi}$, . . . : light electroweak SUSY particles

Particle spectrum of the SPS 1a benchmark point



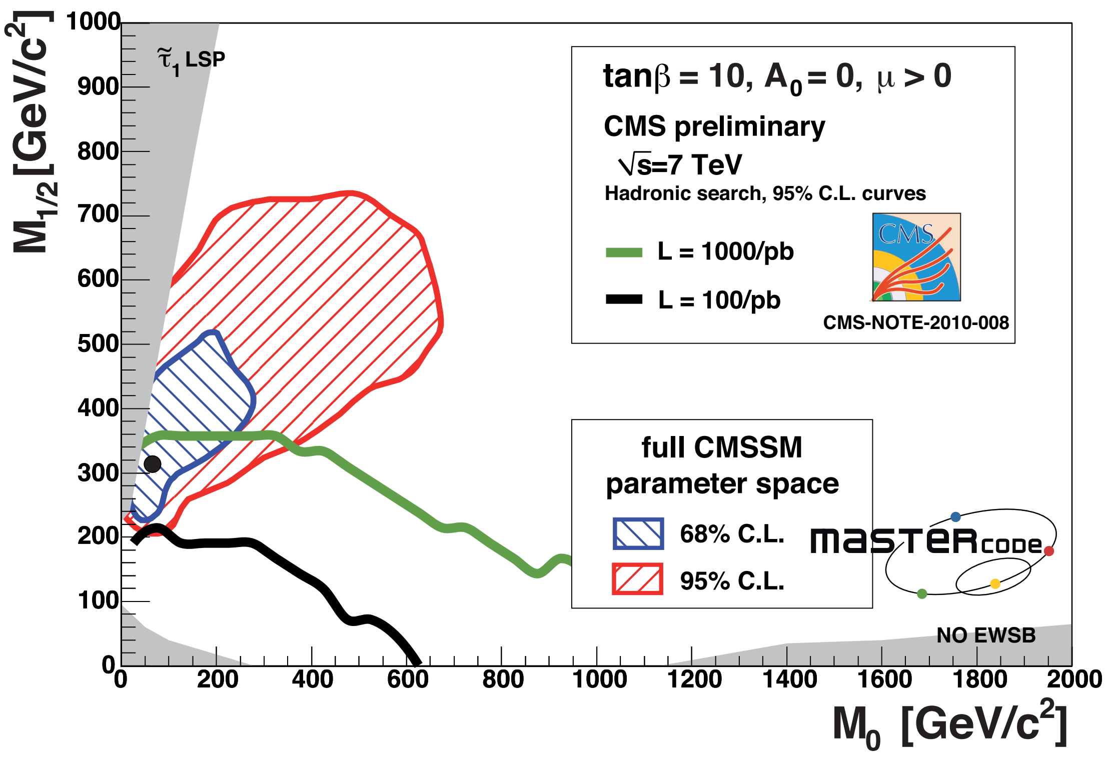
$\Rightarrow$ all SUSY masses below 600 GeV

$\Rightarrow$ “plain vanilla” SUSY at its best

Pre–LHC: Fit results for the CMSSM from precision data

Comparison: preferred region in the m_0–$m_{1/2}$ plane vs. prospective CMS 95% C.L. reach for $0.1, 1\ \text{fb}^{-1}$ at $7\ \text{TeV}$

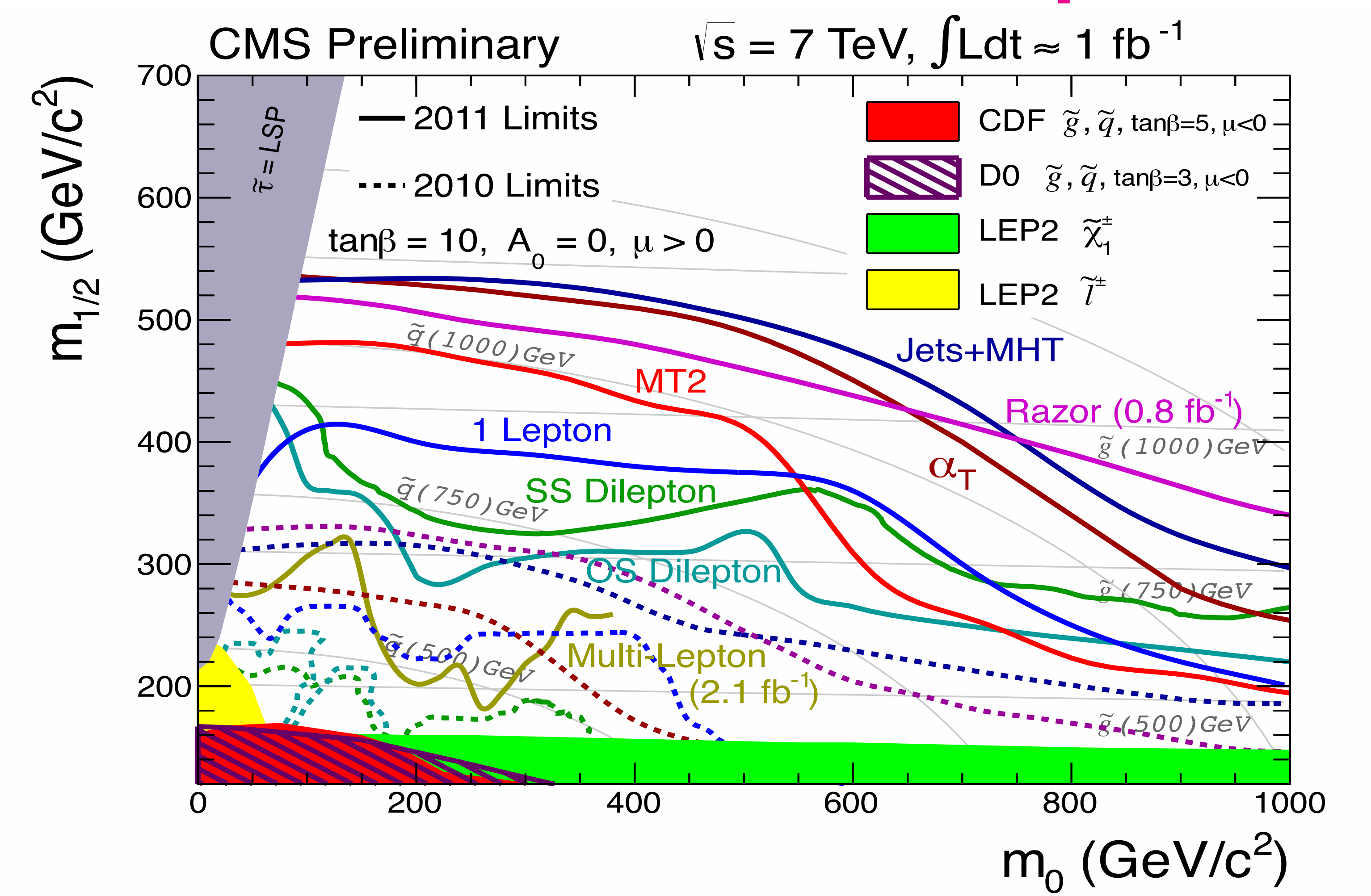
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



⇒ Best fit point was within the 95% C.L. reach with $1\ \text{fb}^{-1}$

Comparison: CMS results with $1\ \text{fb}^{-1}$

[*CMS Collaboration '12*]



⇒ High sensitivity from search for jets + missing energy
Pre–LHC best-fit point excluded

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Do the searches for direct production of third generation squarks and of electroweak SUSY particles have sufficient sensitivity to exclude a "plain vanilla" SUSY spectrum like SPS 1a?

How robust are the limits on squarks of the first two generations?

LHC analyses so far assume that all eight squarks of the first two generations are mass-degenerate

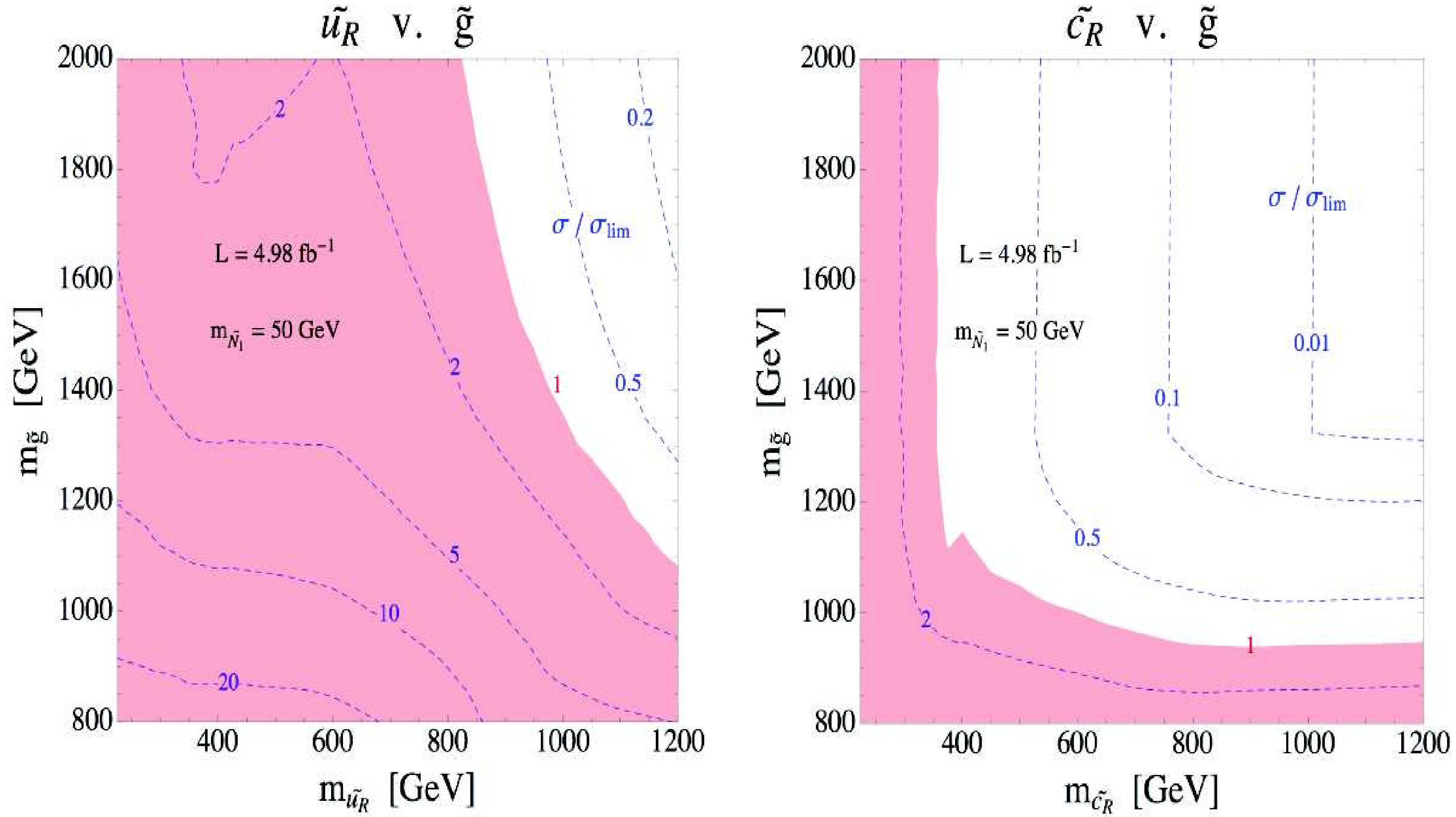
But: Squark spectra can be split within and across generations

$\Rightarrow$ could have important impact on LHC limits

Current limits are optimised for heavy degenerate squarks
Experimental efficiencies sharply deteriorate for lighter squarks

Reinterpretation of the ATLAS and CMS search results ($5\ \mathrm{fb}^{-1}$) for case of non-degenerate squarks (1st, 2nd gen)

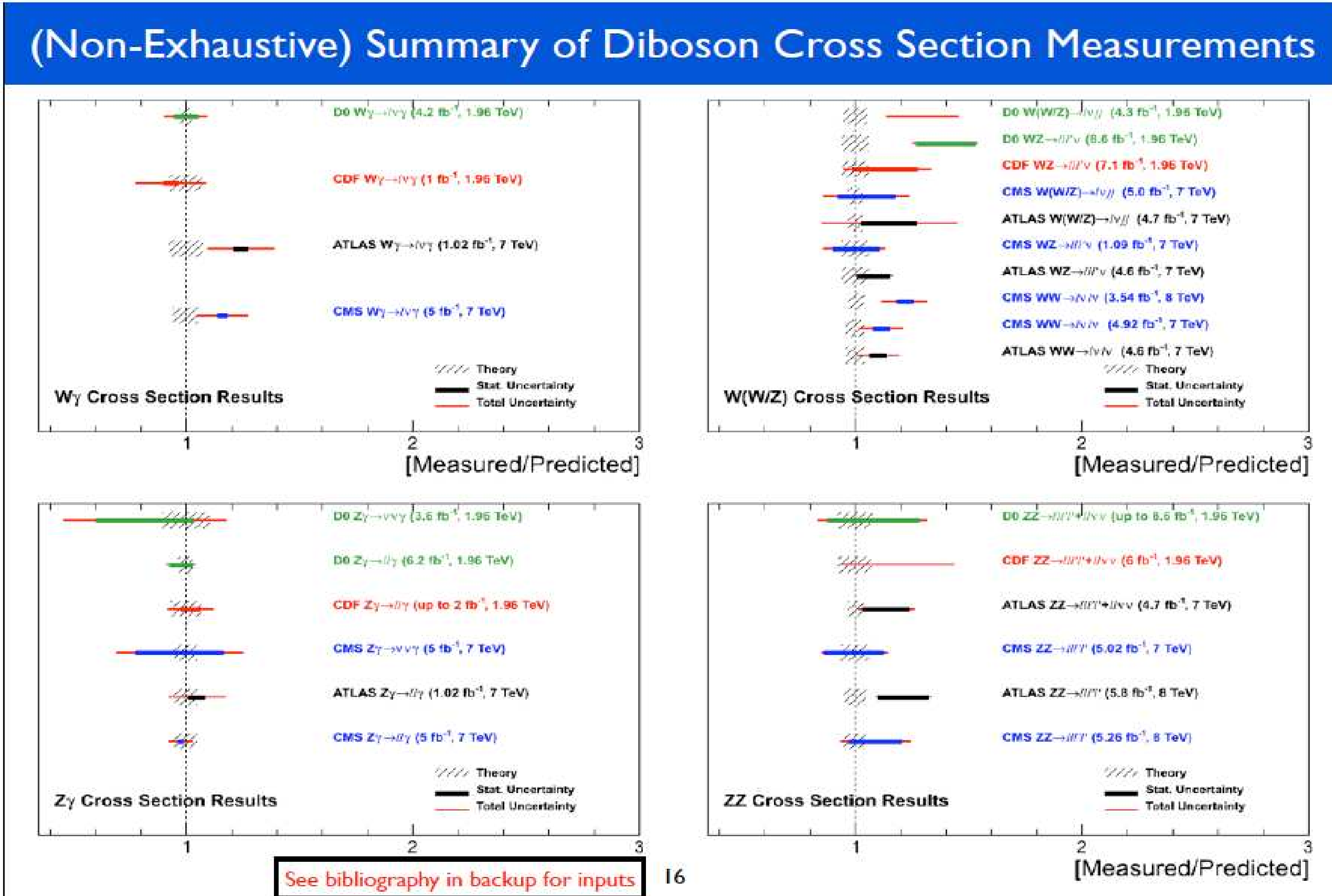
[*R. Mahbubani, M. Papucci, G. Perez, J. Ruderman, A. Weiler '12*]



⇒ Squark limits are drastically weakened compared to the degenerate case

Are there possible hints for effects of new physics elsewhere: how about the WW cross section?

[*D. Evans, HCP 2012*]

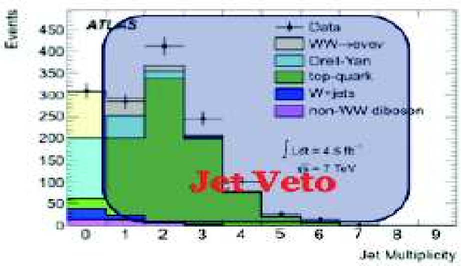


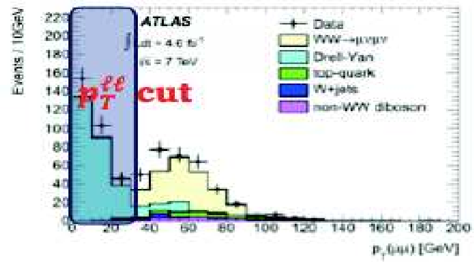
WW cross section: experimental results vs. SM prediction

[*M. Mangano, HCP 2012*]

WW Cross-sections WW cont.

❑ Backgrounds





Jet-veto and other systematics of kinematical origin are greatly reduced in the σ(8TeV)/σ(7TeV) ratio

Future greater statistics in pp→ZZ will allow to greatly reduce such systematics also for the predictions at fixed-energy

❑ Results (CERN-PH-EP-2012-242, CMS PAS SMP-12-005, CMS PAS SMP-12-013)

	$\int L$ (fb^{-1})	$\sigma(pp \to WW) \times B$ (pb)	SM NLO
ATLAS 7TeV	4.6	$51.9 \pm 2.0(stat.) \pm 3.9(syst.) \pm 2.0$(lumi.)	$44.7^{+2.1}_{-1.9}$
CMS 7TeV	4.9	$52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2$(lumi.)	–
CMS 8TeV	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1$(lumi.)	$57.3^{+2.4}_{-1.6}$

⇒ **1.5-2σ off**

❑ Systematics (~8%)

– **Jet Veto efficiency (major), lepton, $E_{T,Rel}^{miss}$, lumi**

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A proposal for BSM interpretations of this discrepancy:

chargino production and leptonic decay

Feigl, Rzehak, Zeppenfeld, arXiv:1205.3468 29

⇒ Will be interesting to watch . . .

Conclusions

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