
We still believe in supersymmetry
You must be joking

A New Higgs Boson at 96 GeV?!

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

Karlsruhe, 10/2018

- Motivation
- Is SUSY dead?
- A Higgs Boson at ~ 96 GeV?!
- Conclusions

1. Motivation

Fact:

The SM cannot be the ultimate theory!

1. gravity is not included
2. the hierarchy problem
3. Dark Matter is not included
4. neutrino masses are not included
5. anomalous magnetic moment of the muon shows a $\sim 4\,\sigma$ discrepancy

$\Rightarrow$ Time to get ready for BSM physics

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The Future of Particle Physics: A Quest for Guiding Principles

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– Higgs boson mass
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$\Rightarrow$ **good motivation to look at SUSY! :-)**

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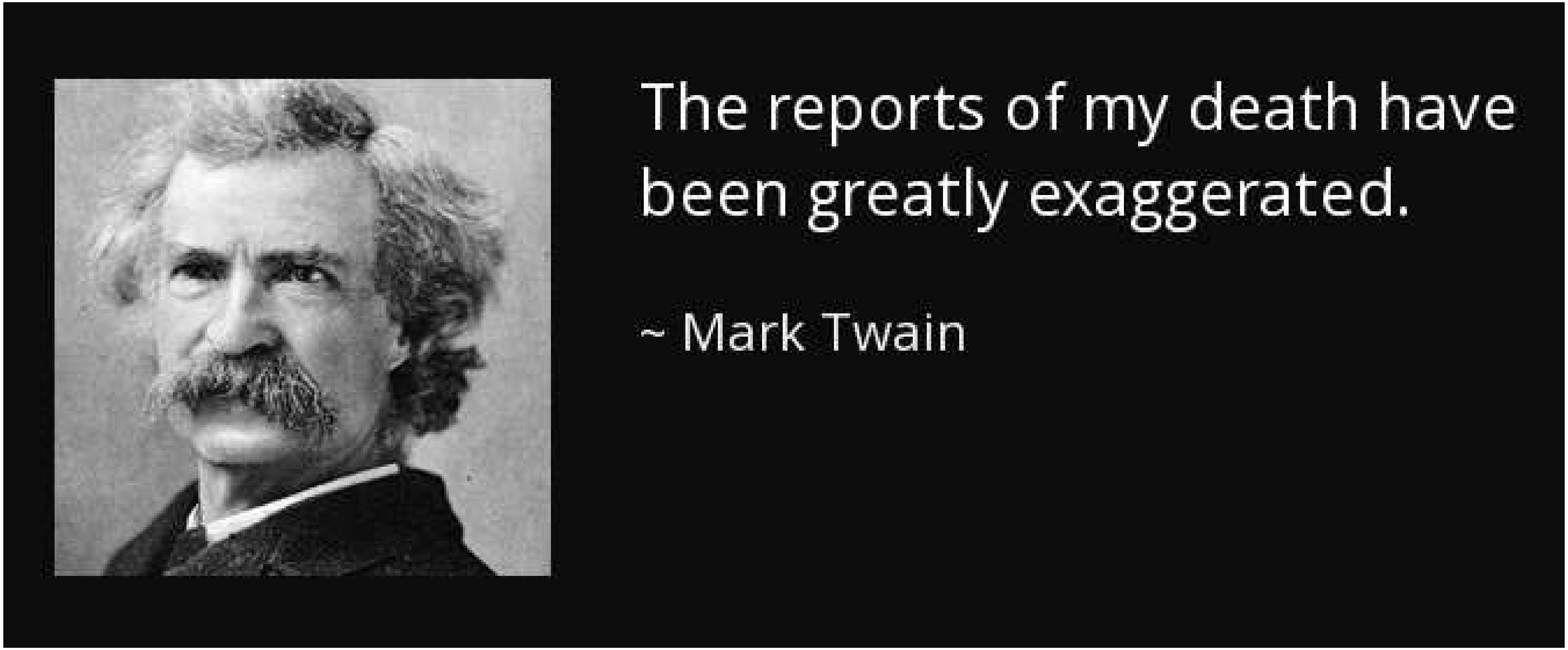

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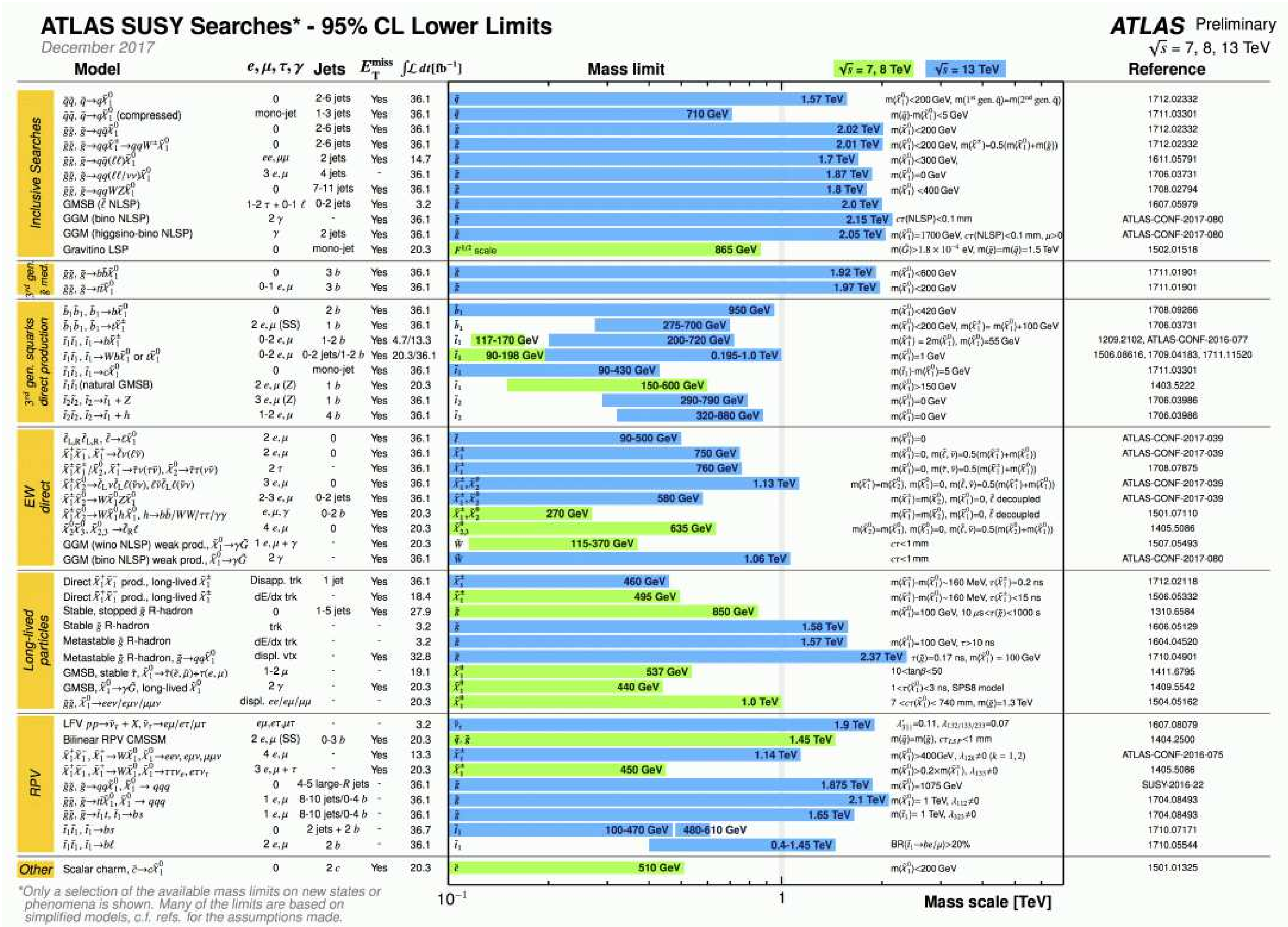
6. ...

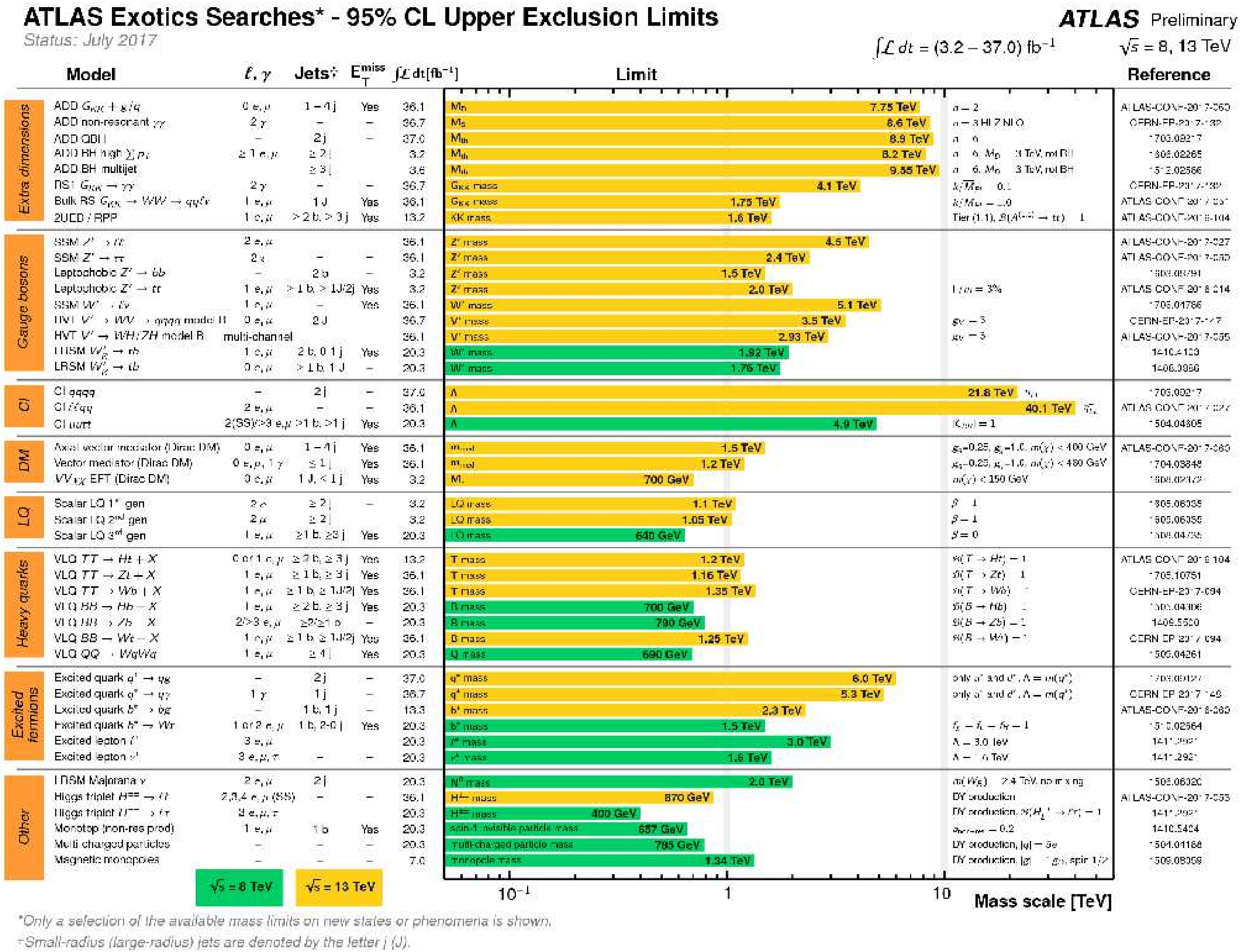
$\Rightarrow$ low-energy SUSY provides the solution(s) (or paves the way)!

$\Rightarrow$ But what about experimental results?

Is SUSY dead? When will I give up on SUSY?



SUSY is as dead (or alive) as ANY OTHER BSM theory



ATLAS and CMS SUSY searches:

Simplified Model Spectra/Analyses

- one production mode
- one decay mode (possibly cascade)
- all other particles "removed" from the spectrum

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– unrealistic situation :-(

– re-interpretation possible :-)
(CheckMate, Smodels, Atom, Fastlim, . . .)

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⇒ do not confuse limits in simplifed models with real limits
on SUSY masses!

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⇒ **focus on the theoretically most appealing theory!**

SUSY is as dead (or alive) as ANY OTHER BSM theory

⇒ focus on the theoretically most appealing theory!

– It is nearly inconceivable that there is no symmetry between bosons and fermions (at low or high energy?)

– SUSY is the only non-trivial extension of (the SM) gauge symmetries

– SUSY gives you coupling constant unification

– SUSY predicted correctly the top quark mass

– SUSY predicted correctly the Higgs boson mass

– SUSY predicted correctly an SM-like Higgs boson

– SUSY predicted correctly DM properties

3. A Higgs Boson at 96 GeV?!

– What was seen in Run I?

– What was seen in Run II?

– What was seen at LEP?

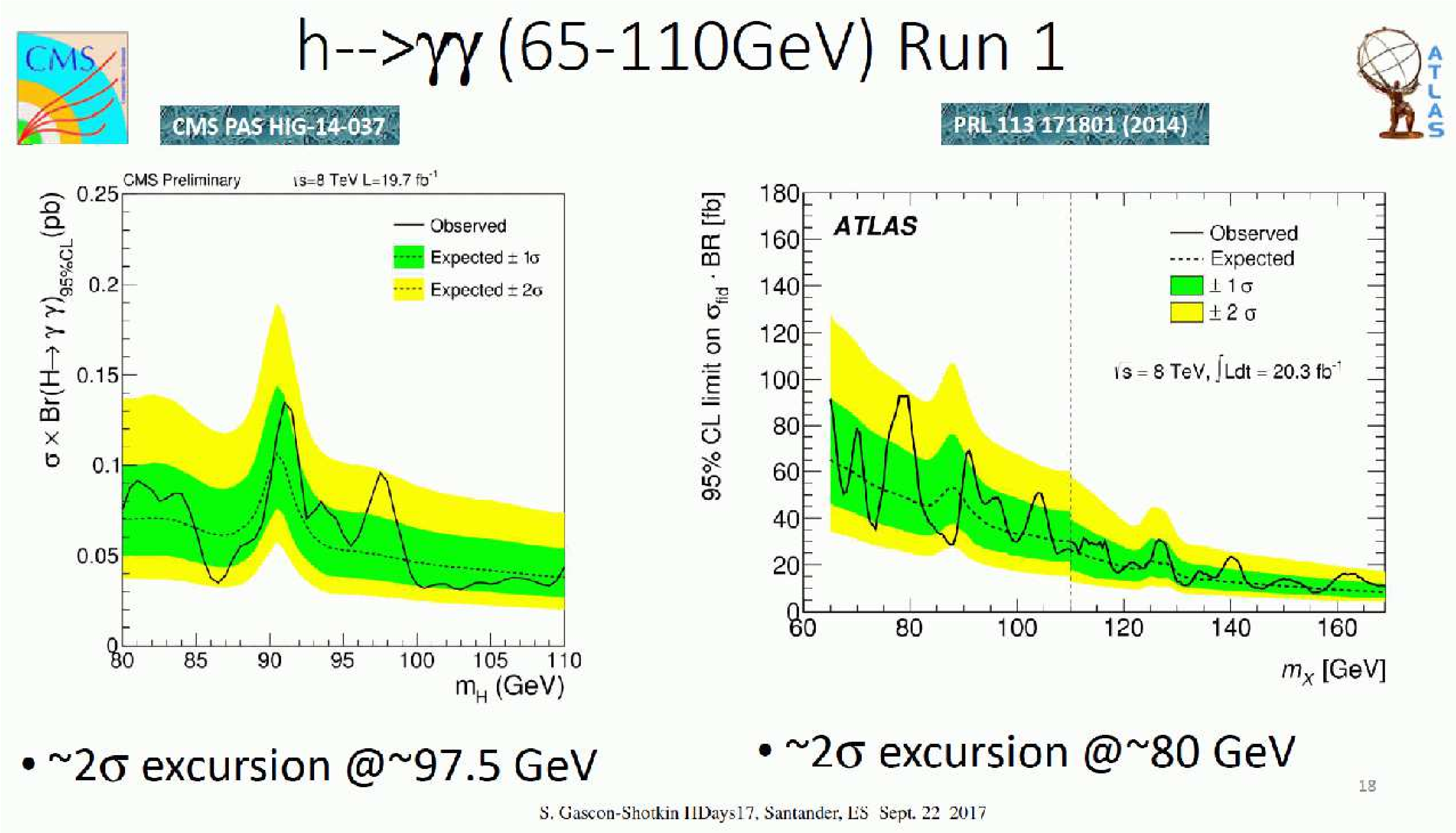
– Should we get excited?

– Which model fits?

– Future projects

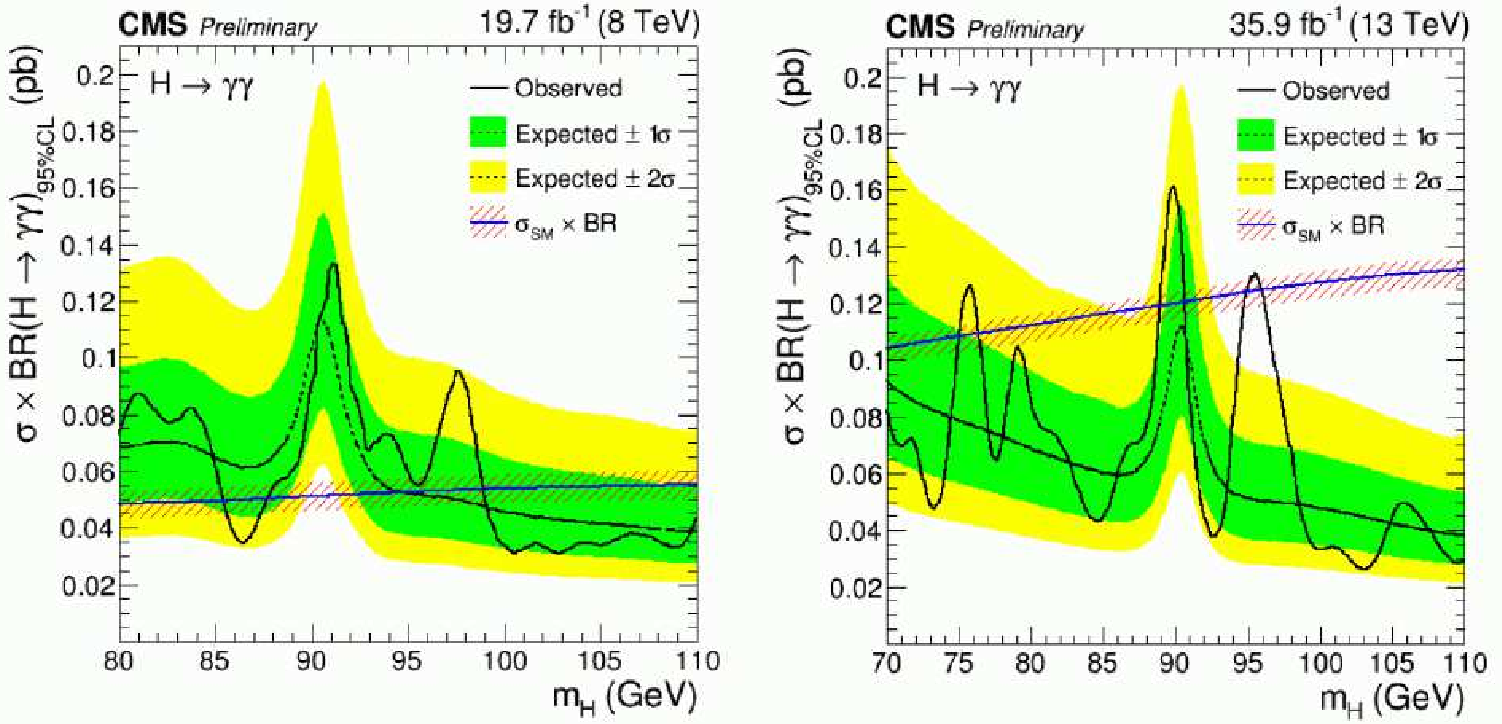
What was seen at Run I?

[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.

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

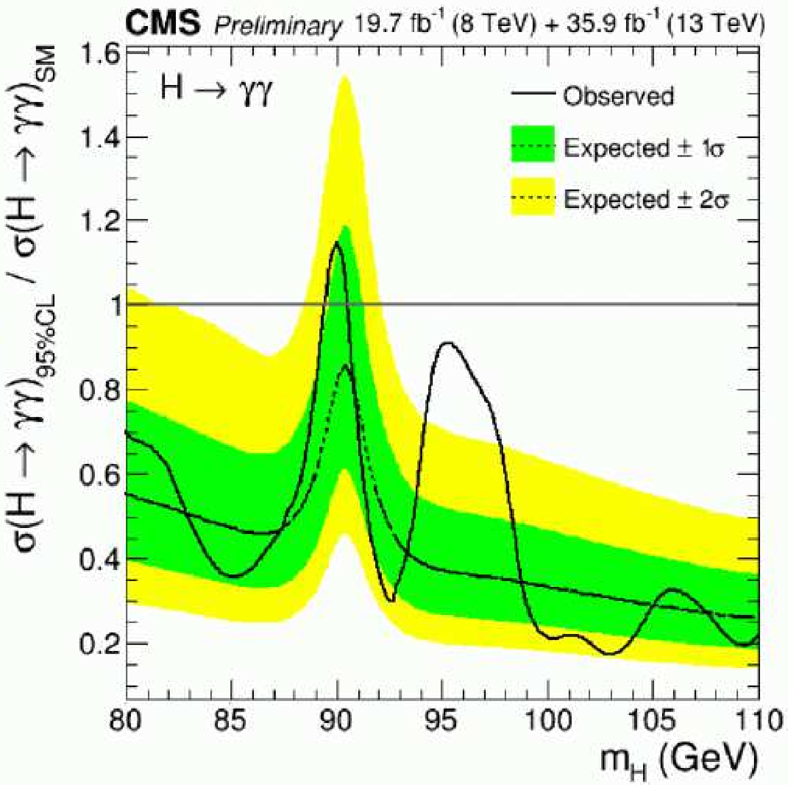
[S. Shotkin, talk at HDays17]

h-->γγ (70-110 GeV) Runs 1+ 2

New!

CMS PAS HIG-17-013

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 $(\sigma \times Br)/(\sigma \times Br)_{SM}$: 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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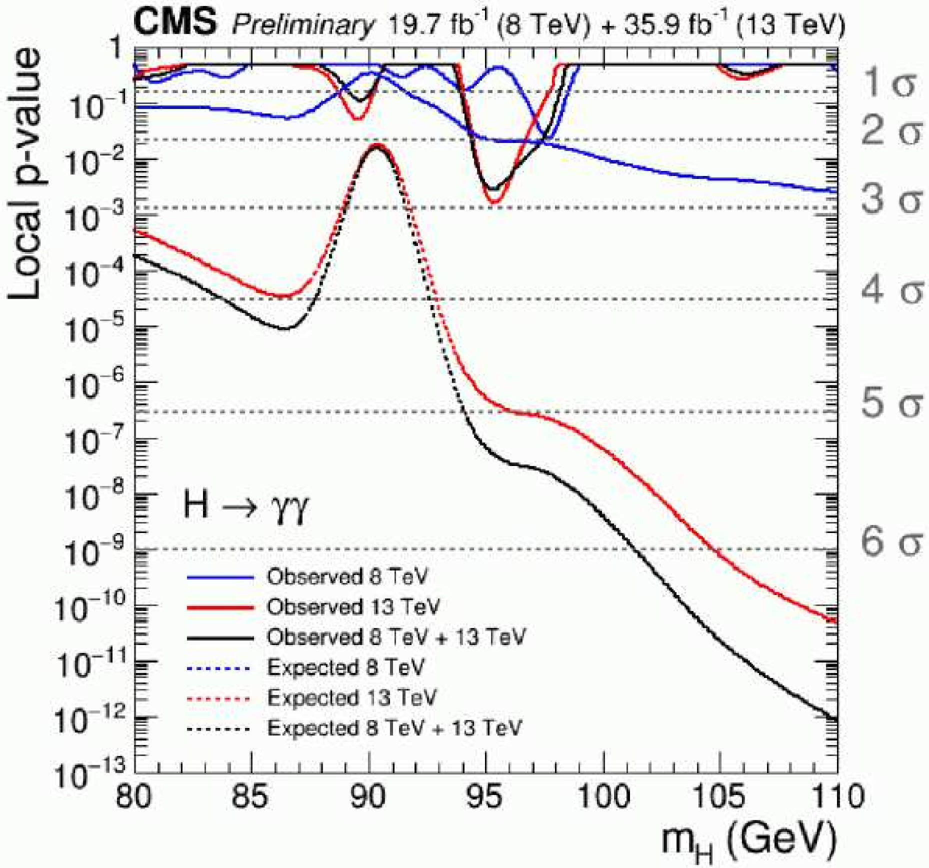

8 TeV: Excess with ~2.0 σ local significance at m=97.6 GeV

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

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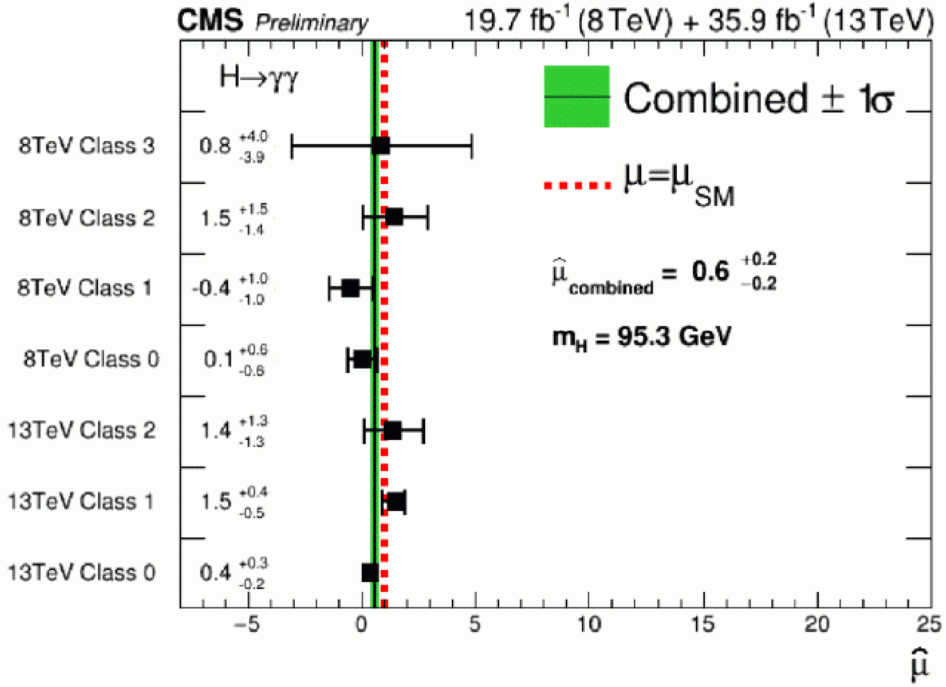
What was seen at Run II?

[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

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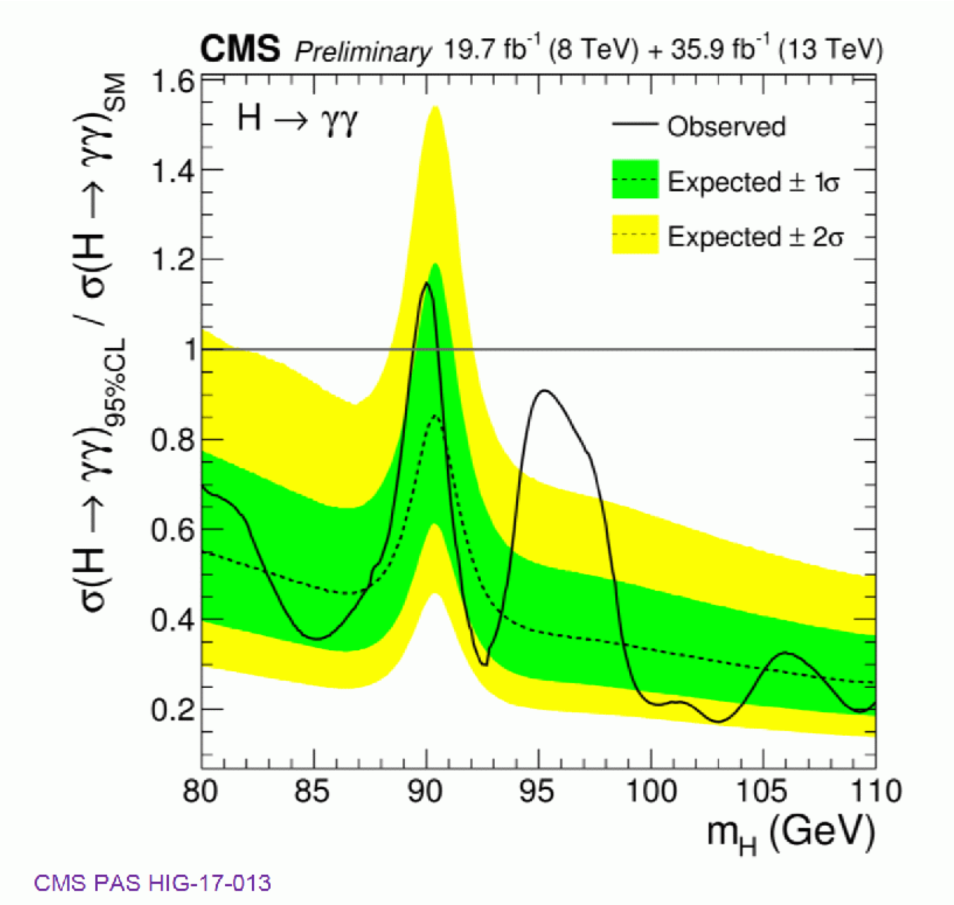
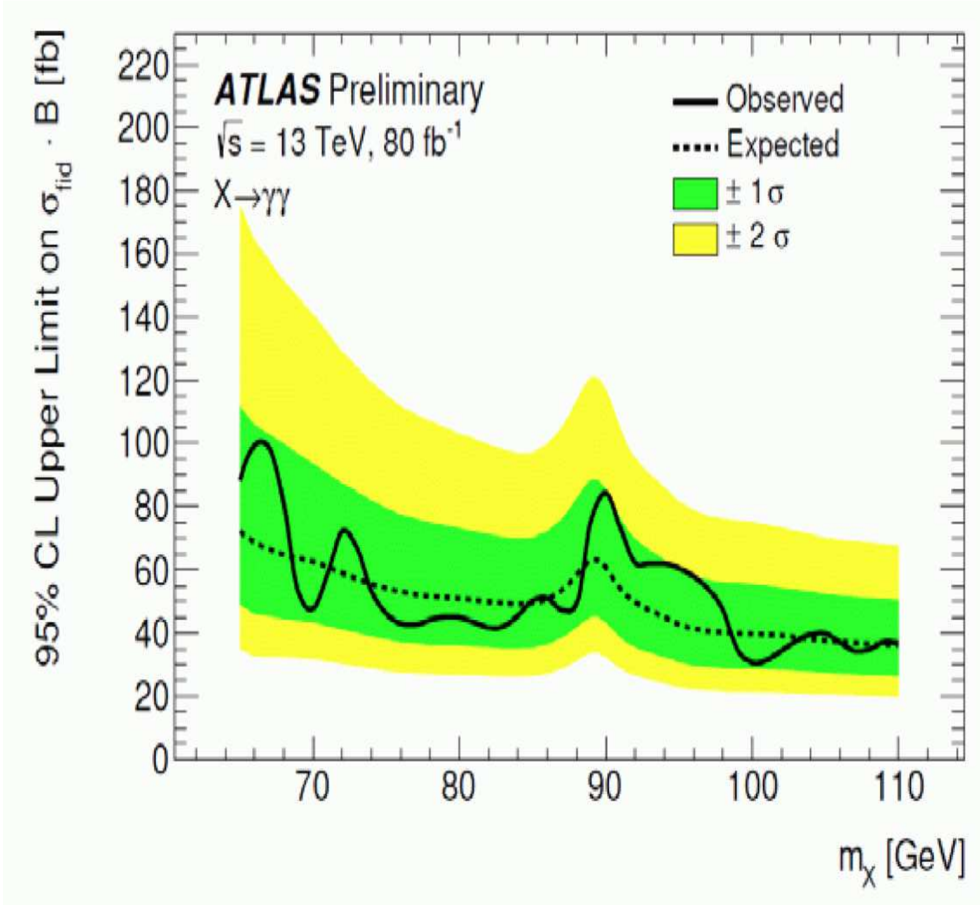
$$\mu_{\text{CMS}}(96\text{ GeV}) = [\sigma(pp \to h_1) \times \text{BR}(h_1 \to \gamma\gamma)]_{\text{exp/SM}} = 0.6 \pm 0.2$$

What about ATLAS?





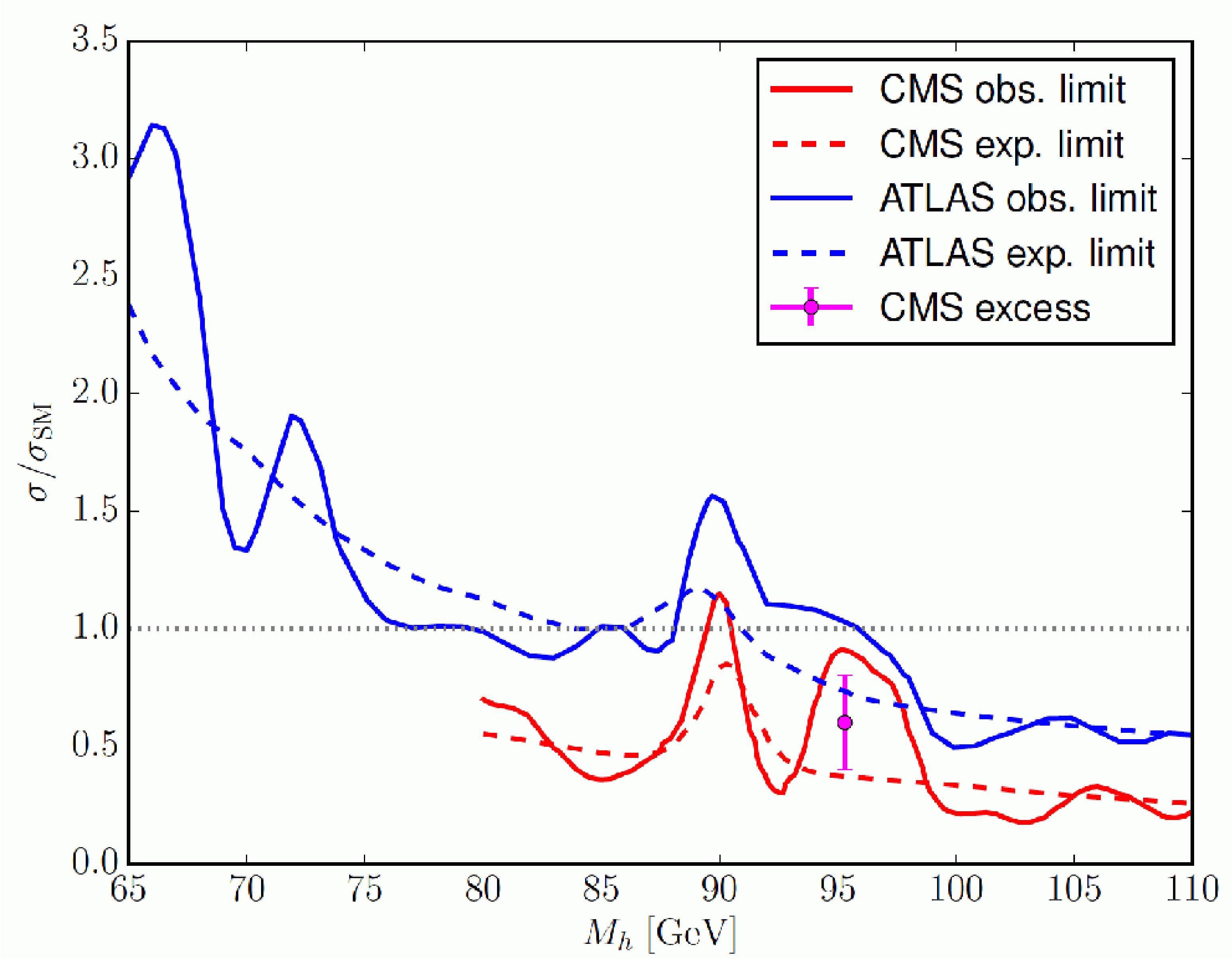
Note: ATLAS gives fiducial cross section! Conversion factor: 1/0.45

$\Rightarrow$ ATLAS and CMS exclusion limit **identical!** (120 fb)

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

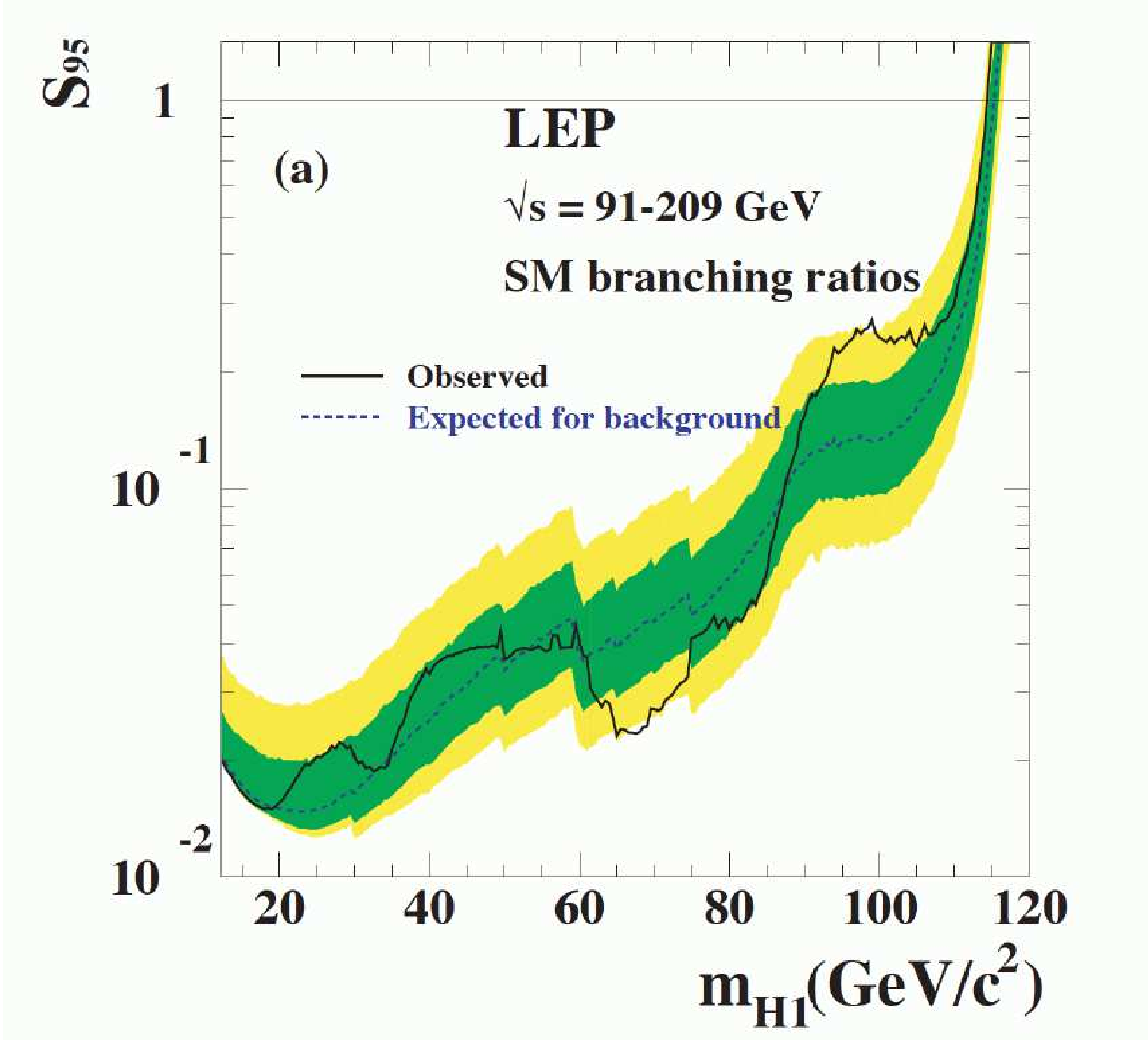
CMS and ATLAS in direct comparison:

[*T. Stefaniak et al. '18*]



⇒ everything well compatible with the excess!

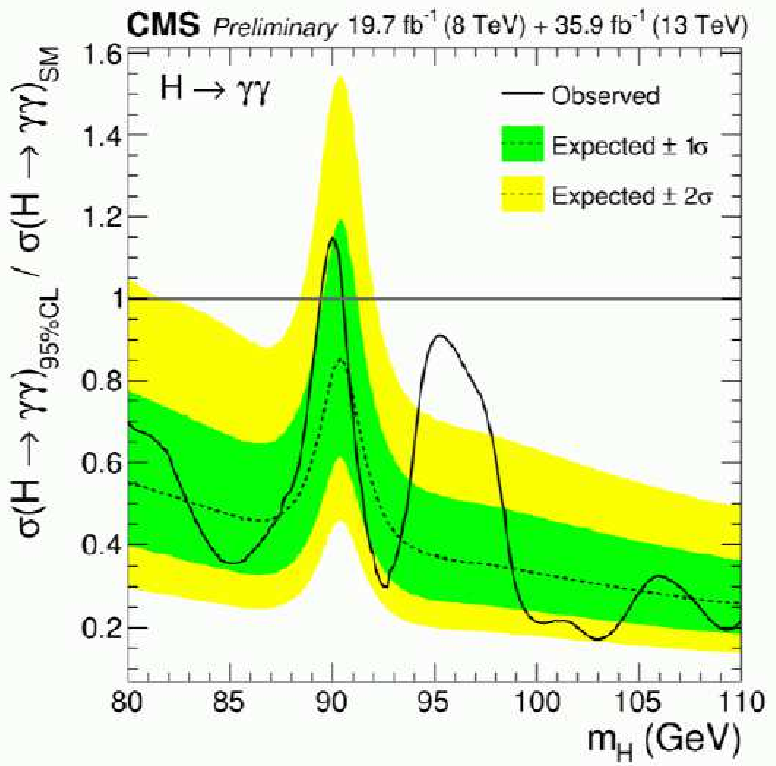
What was seen at LEP?



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

 [*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**



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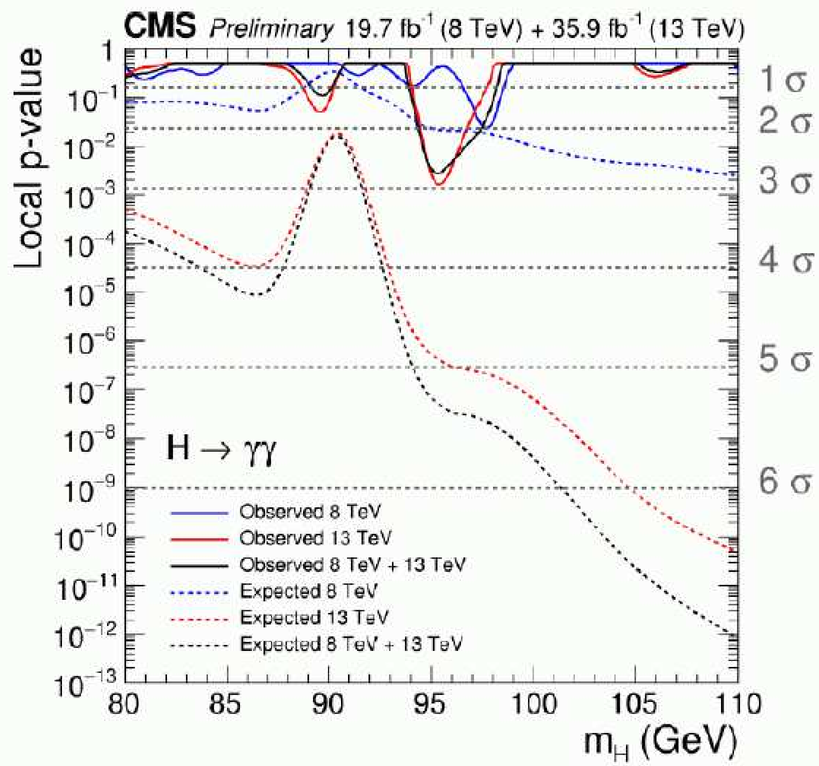
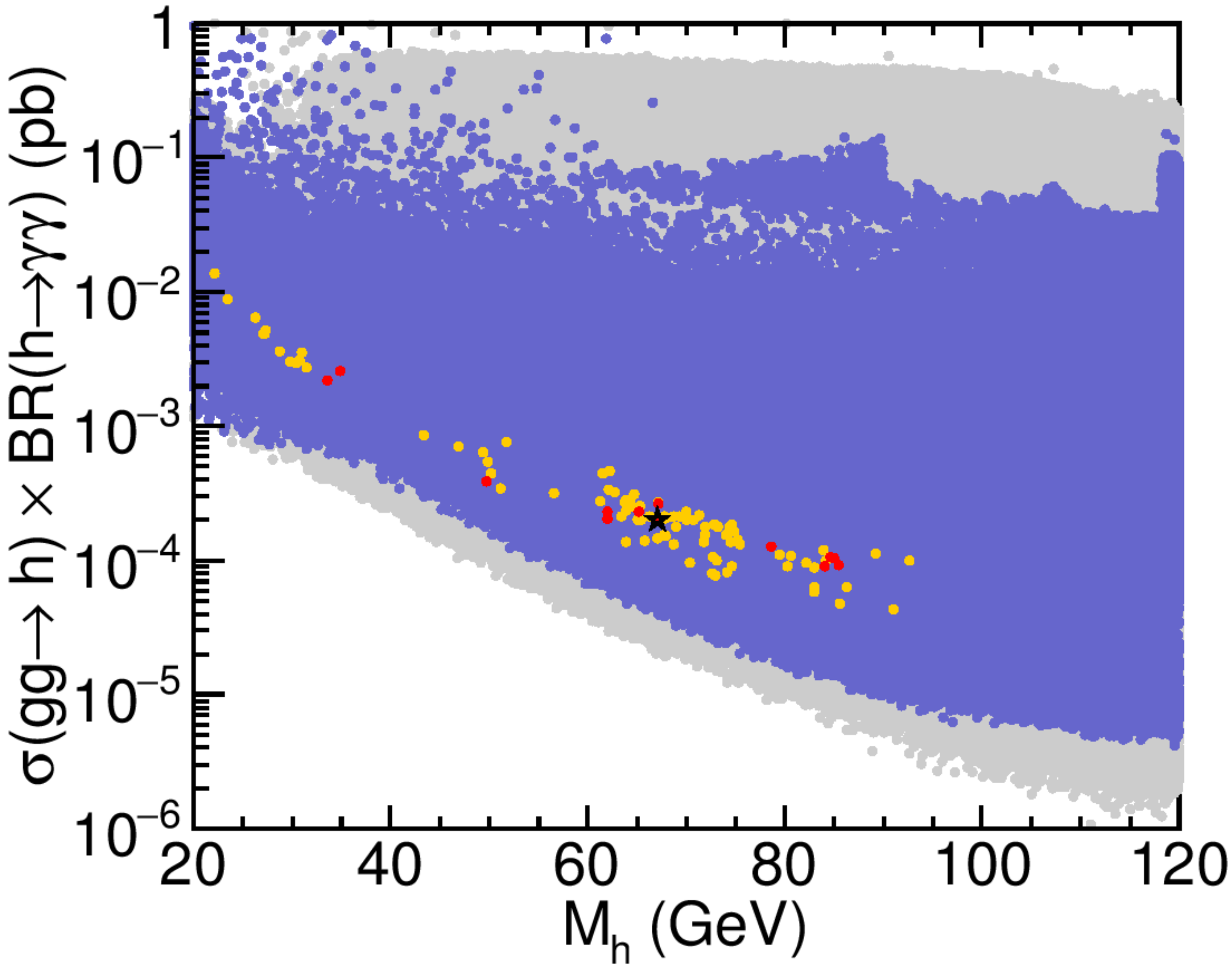


CMS PAS HIG-17-013

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

What about the MSSM?

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



⇒ too small rates!

What about the NMSSM?

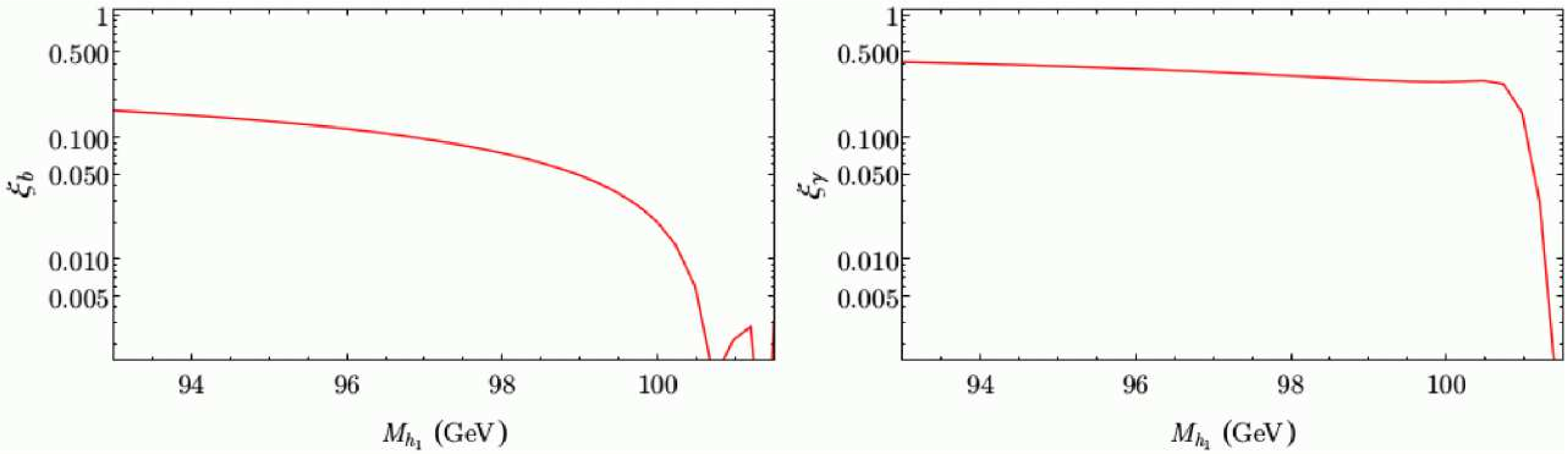
[F. Domingo, S.H., S. Passehr, G. Weiglein '18]

Parameters:

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

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

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



$\Rightarrow$ 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

What about the $\mu\nu$SSM?

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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, arXiv:1712.07475*]

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

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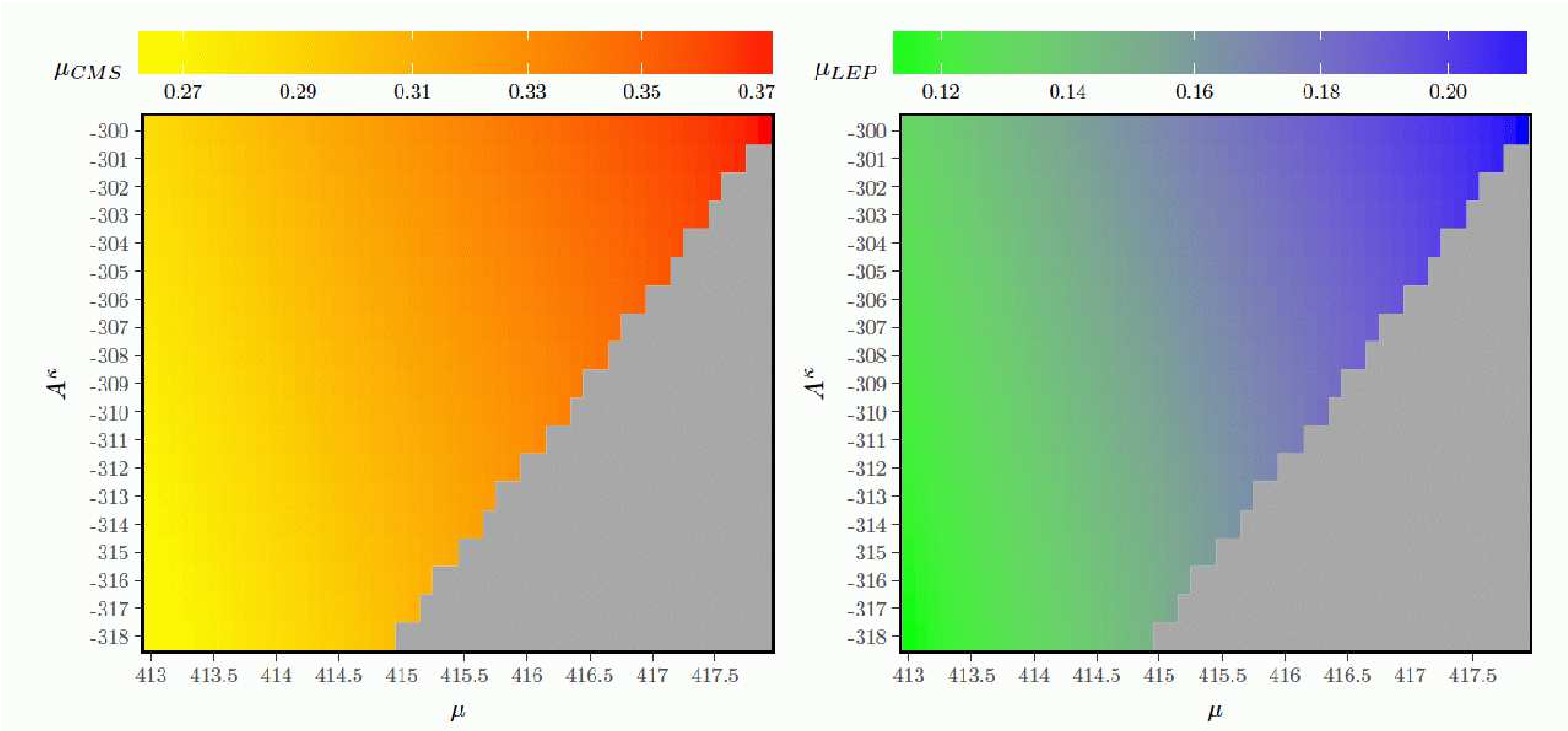
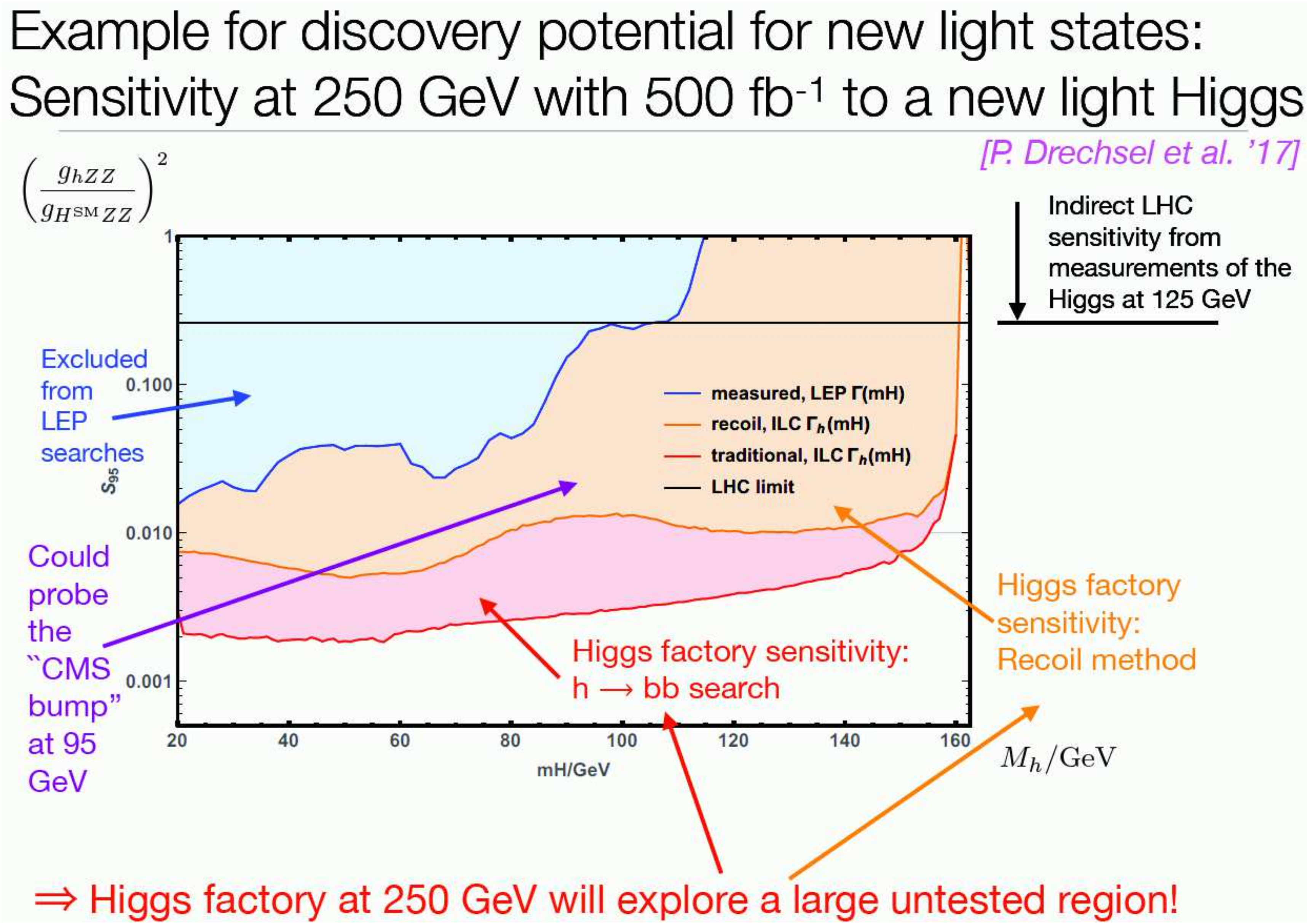


$\Rightarrow$ YES, WE CAN! :-)

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

Next project?

Next project? ILC reach for light Higgs bosons:



[*Taken from G. Weiglein '18*]

4. Conclusinos

- Quest for guiding principles: **experimental data**

  SUSY performs very well $\Rightarrow$ best motivated BSM theory

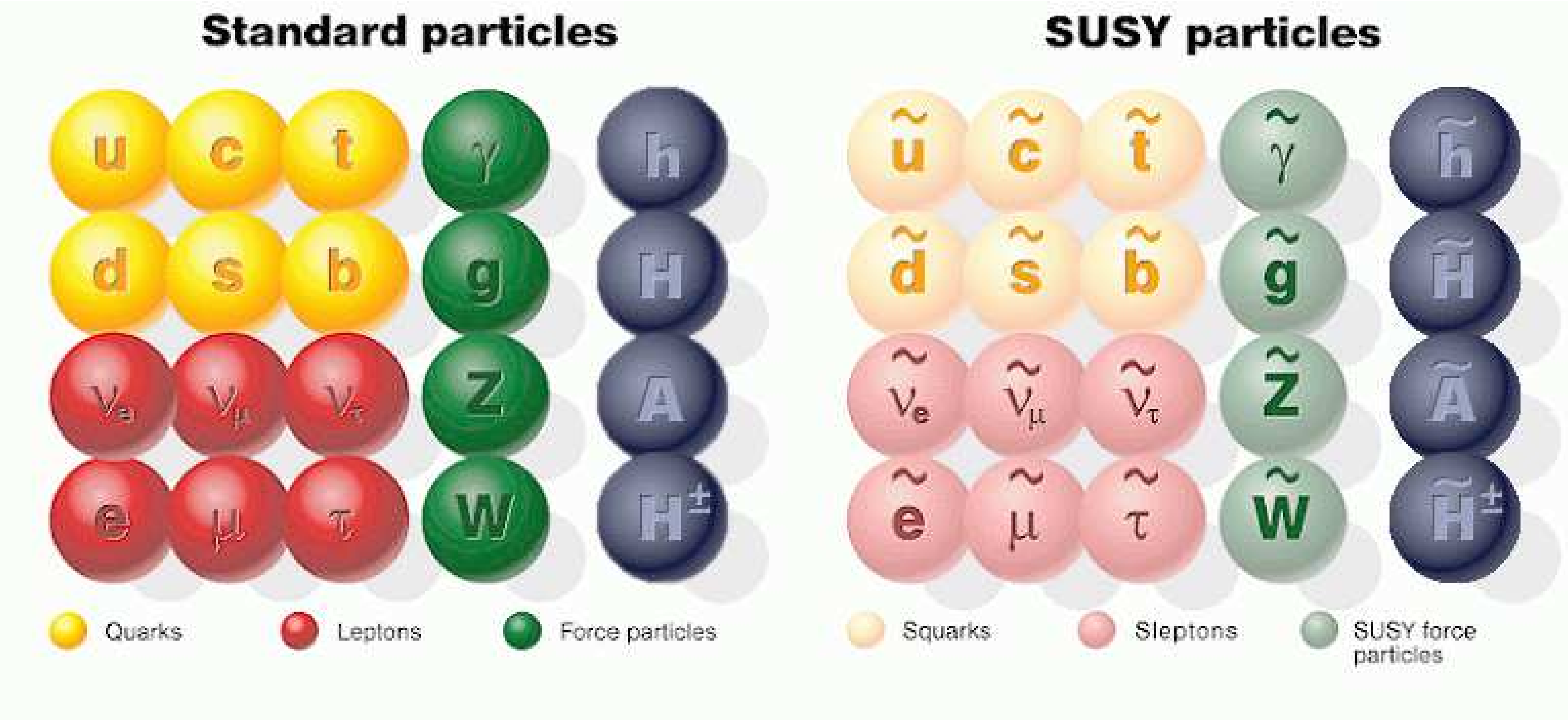
- Do not confuse limits in simplifed models
  with real limits on SUSY masses!

- A new Higgs at 96 GeV?
  - CMS sees excess in $pp \to \phi \to \gamma\gamma$ at 96 GeV
  - ATLAS fails to exclude (interesting "shoulder")
  - LEP sees excess in $e^+e^- \to Z^* \to Z\phi \to Zb\bar{b}$
  - MSSM cannot explain the result (rates too low)
  - NMSSM can explain CMS(/ATLAS) and LEP "excesses"
  - $\mu\nu$SSM can explain CMS(/ATLAS) and LEP "excesses"
  - ILC/FCC-ee/CEPC could easily test/analyze this


Further Questions?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case:

⇒ 105 new parameters: masses, mixing angles, phases

(⇒ many (close to) zero according to experimental data)

⇒ no model missed (within the MSSM)

⇒ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models:

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking

⇒ prediction for soft SUSY-breaking terms
in terms of small set of parameters

⇒ easy to handle

NMSSM Higgs sector (Z_3 invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = (\tilde{m}_1^2 + |\mu \quad |^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \quad |^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

NMSSM Higgs sector (Z_3 invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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$$S = v_s + S_R + IS_I$$

$$V = (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$
$$+ |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\mathcal{CP}\text{–even} : h_1, h_2, h_3$$
$$\mathcal{CP}\text{–odd} : a_1, a_2$$
$$\text{charged} : H^+, H^-$$
$$\text{Goldstones} : G^0, G^+, G^-$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM} : M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM} : \text{"}M_A^2\text{"} = \mu_\text{eff} B_\text{eff}(\tan\beta + \cot\beta)$$

$$\text{with } B_\text{eff} = A_\lambda + \kappa\, s,\ \mu_\text{eff} = \lambda\, s \qquad \Rightarrow \text{ one very light } a_1$$

Mass of the charged Higgs:

$$\text{MSSM} : M^2_{H^\pm} = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

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$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \le M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \ge M_{H^\pm}^{\text{NMSSM,tree}}$

What has been covered by ATLAS/CMS? And what not? And why?

ATLAS and CMS are searching for . . .

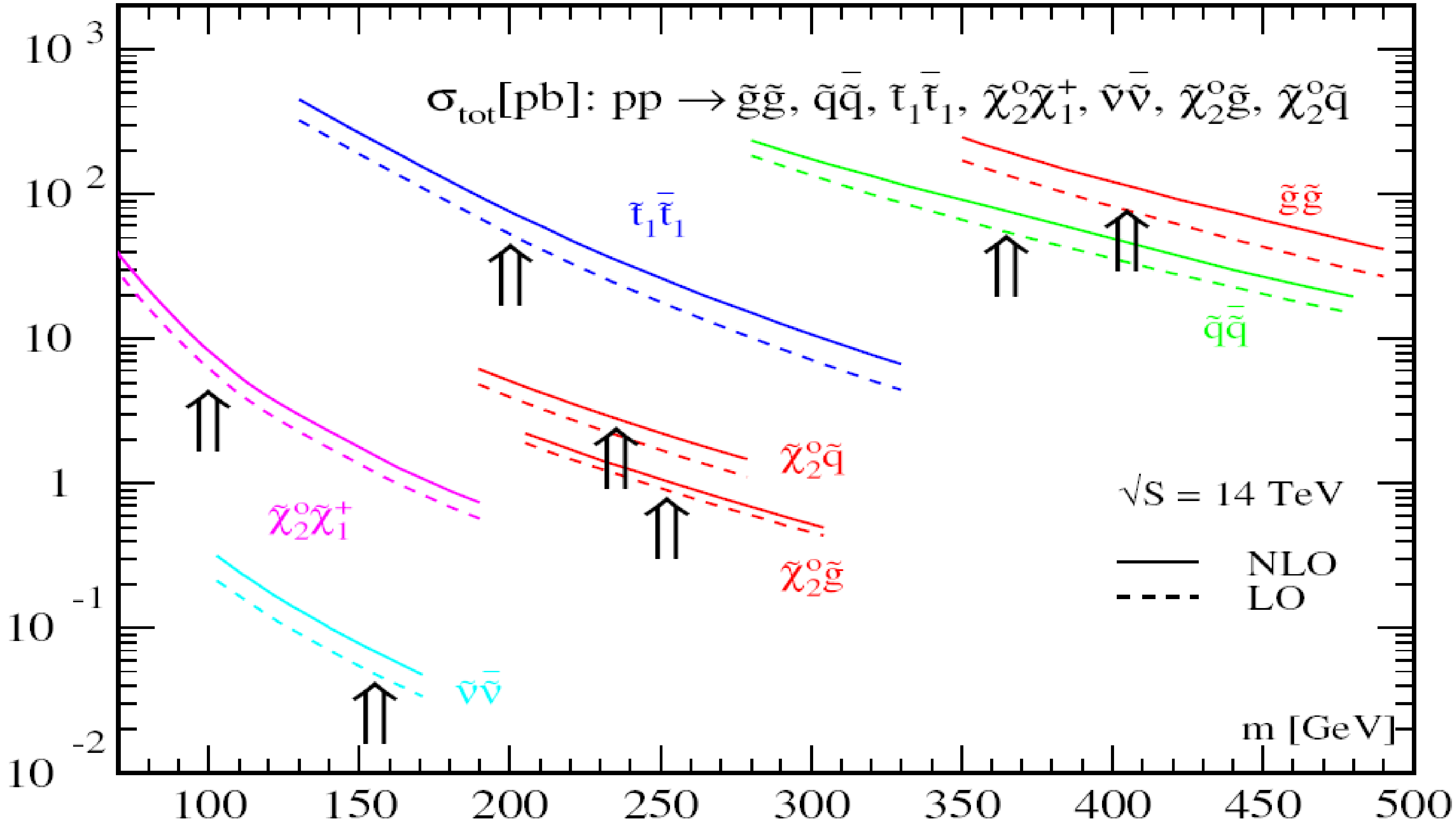
– direct gluino production
– direct squark production
– direct stop/sbottom production
– direct EWino production
– . . .

. . . or in other words:

– 1 jet, 0 leptons, MET
– 2/3/4/. . . jets, 0 leptons, MET
– 1 jet, 1 lepton, MET
– 2/3/. . . leptons, MET
– . . .

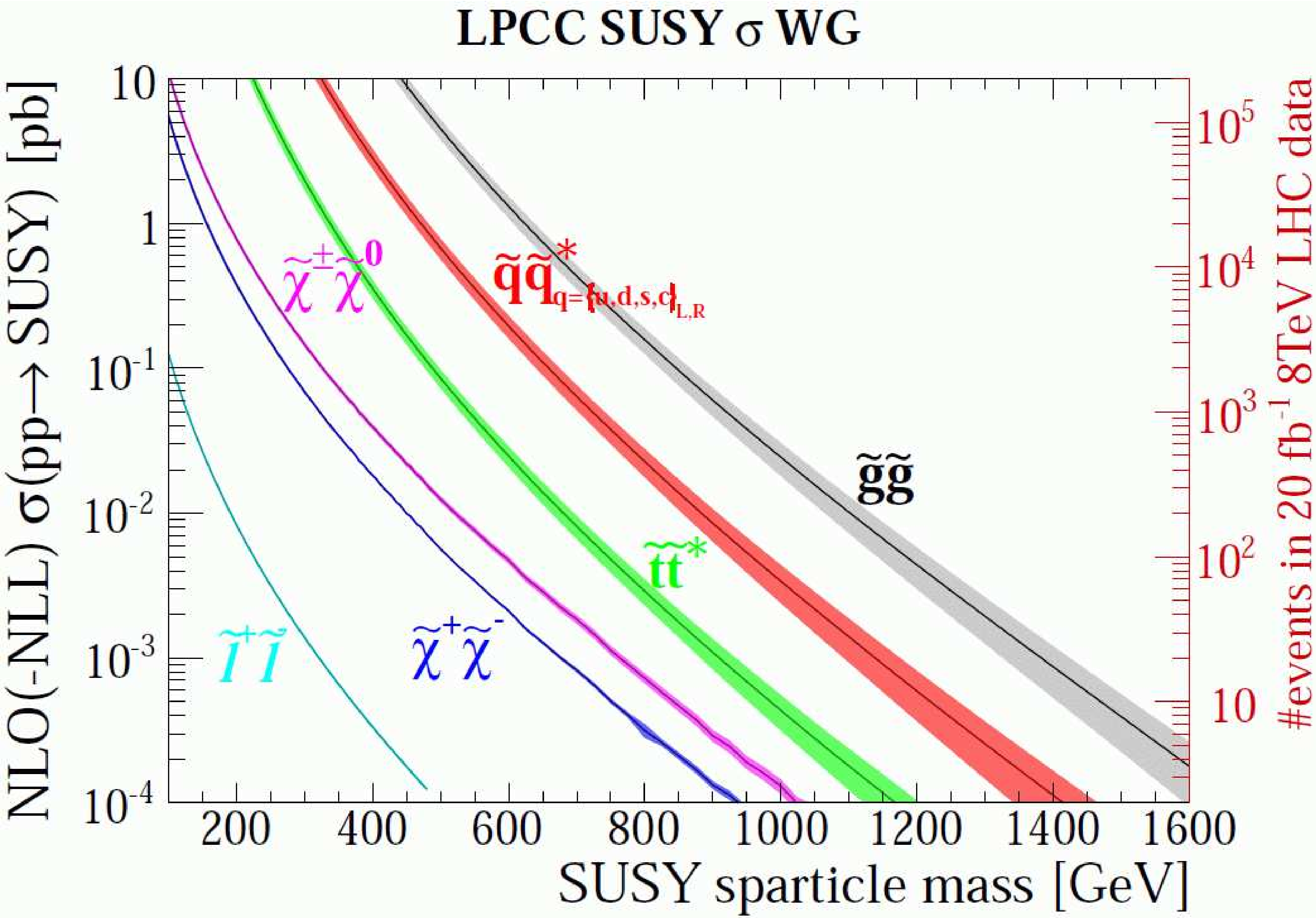
Example for SUSY production:

[*Prospino collaboration*]



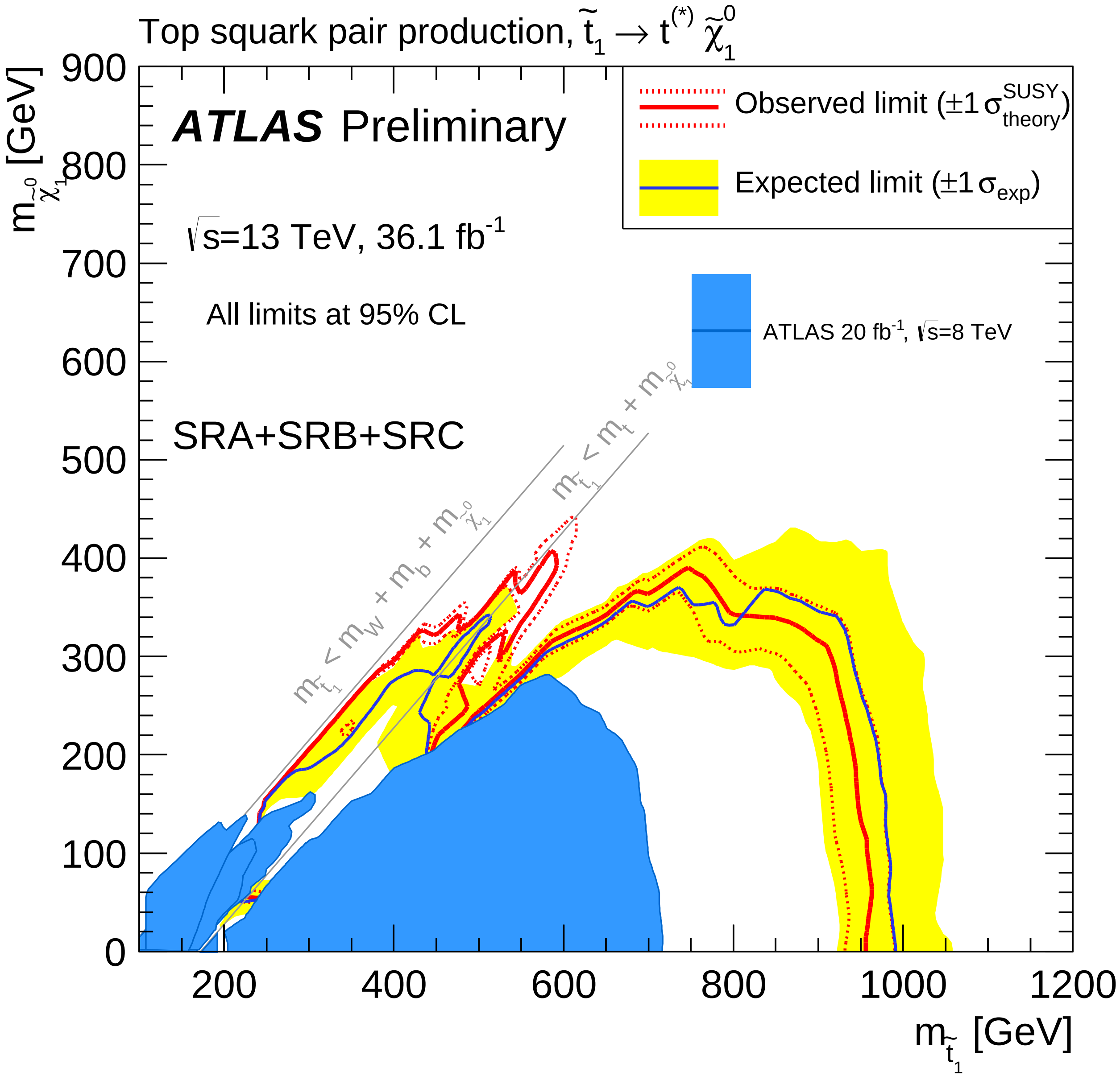
As in QCD: NLO corrections are crucial!

Example for SUSY production:



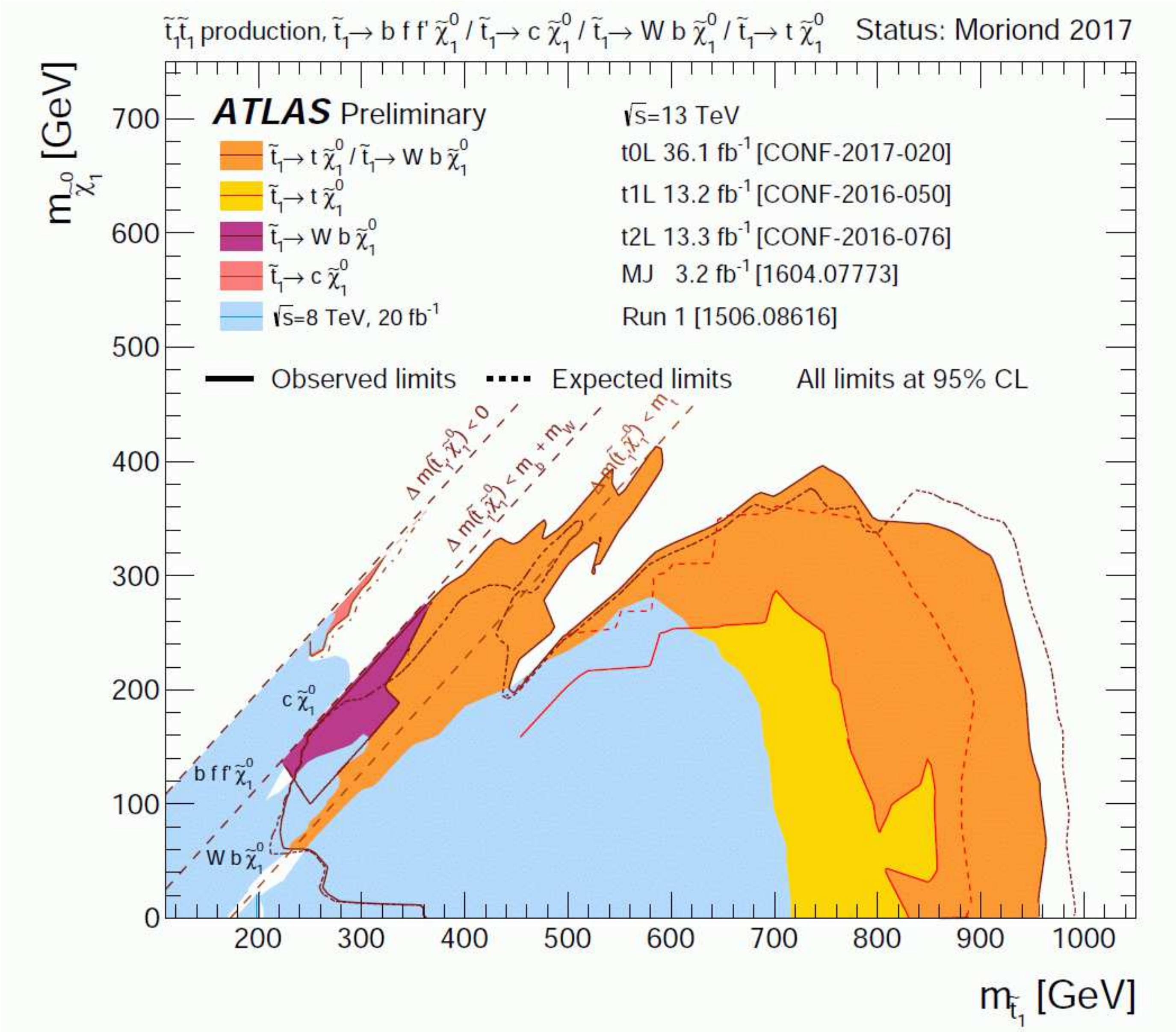
⇒ uncertainties crucial!

Direct stop production:



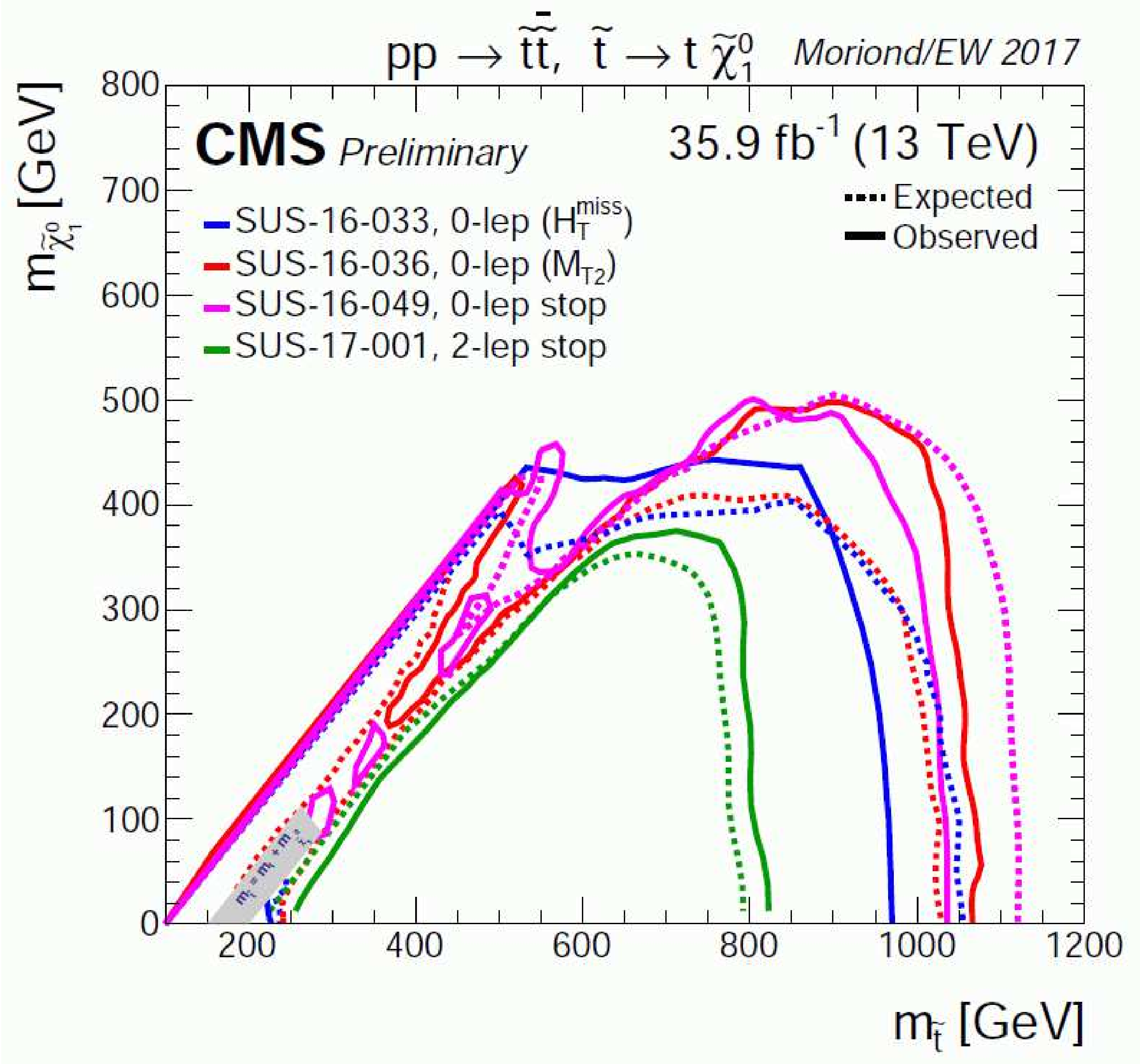
⇒ simplified model, large regions uncovered

Stop overview ATLAS:



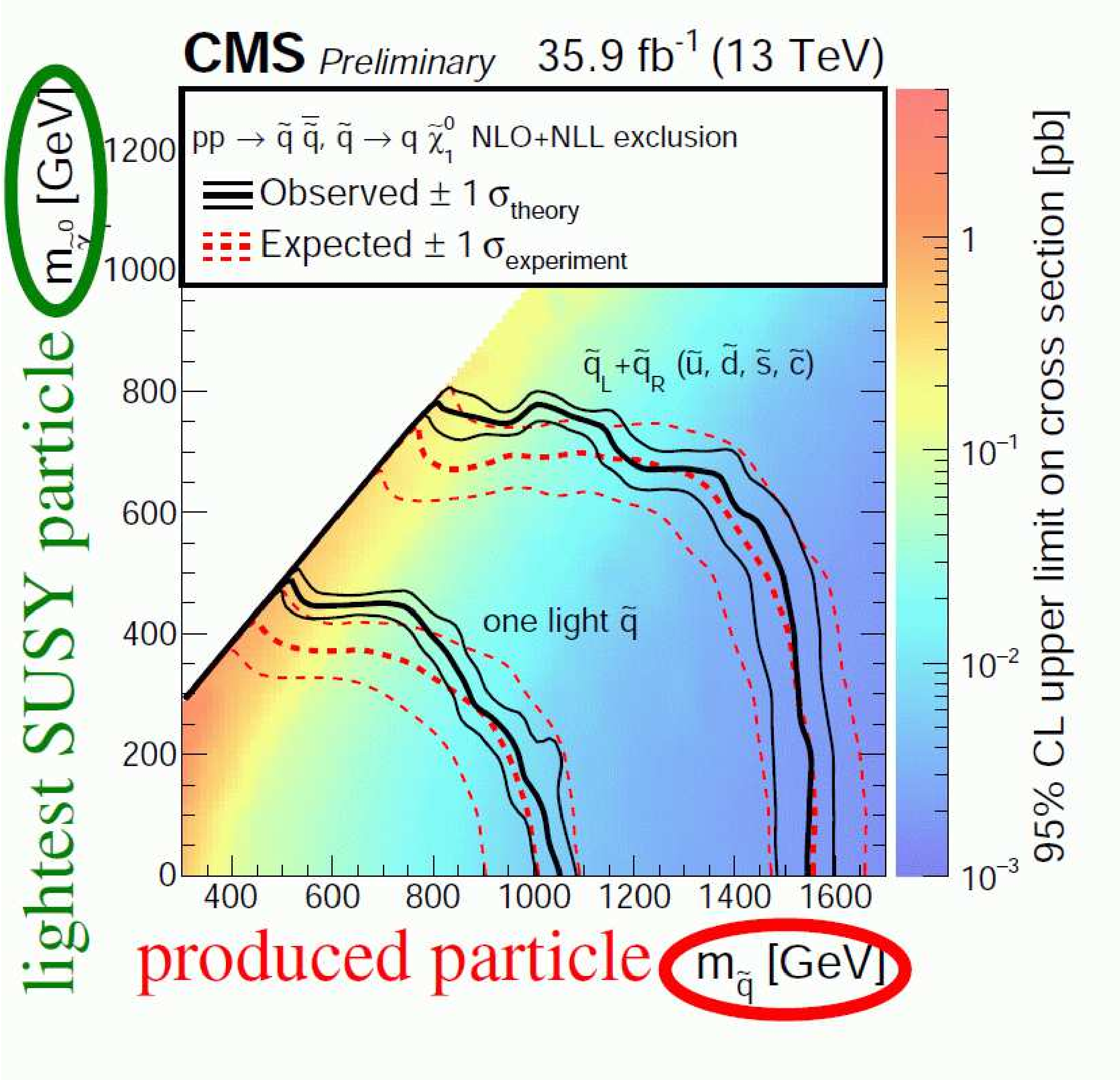
$\Rightarrow$ several simplified models, large regions uncovered

Stop overview CMS:

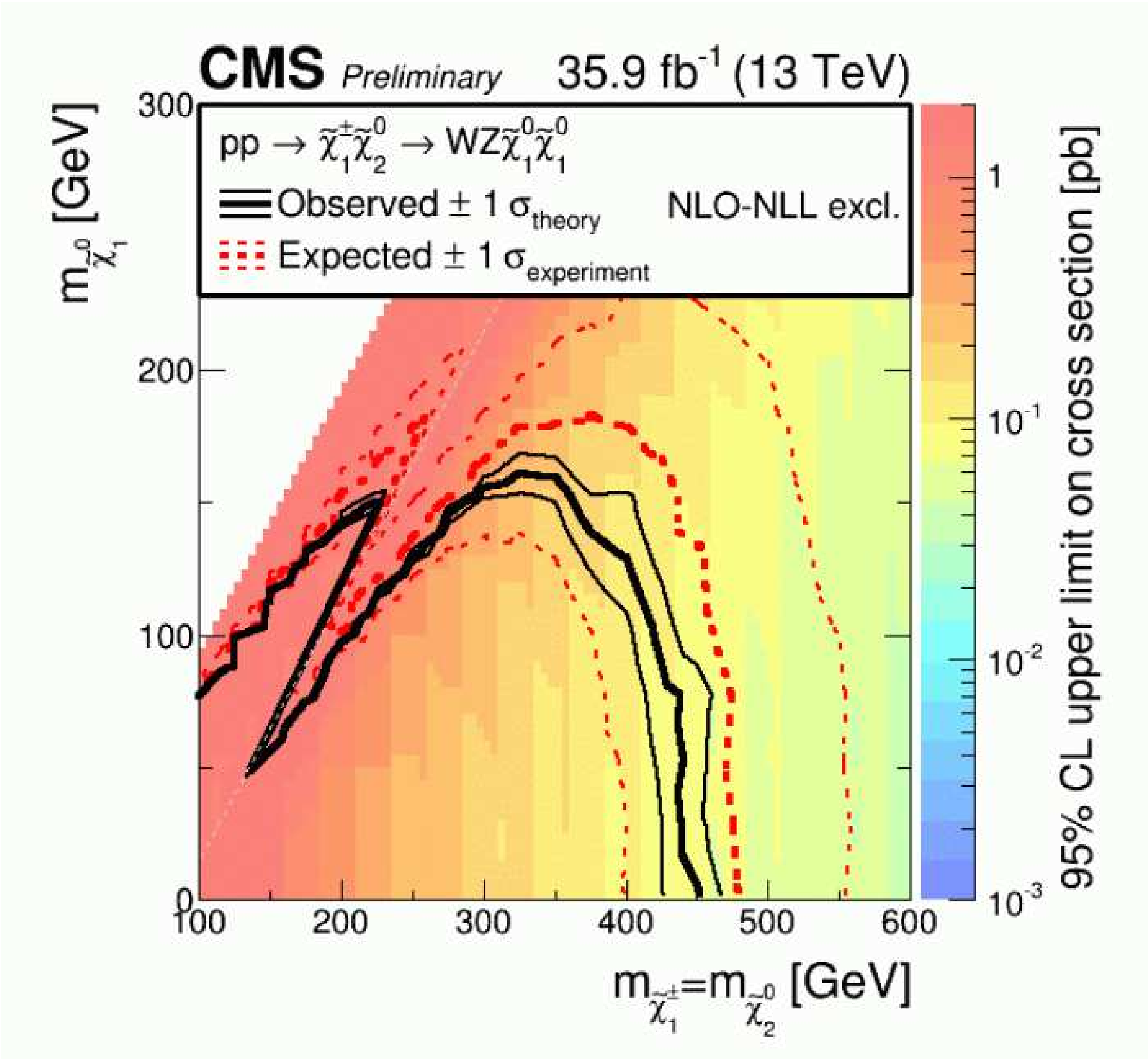


⇒ several simplified models, large regions uncovered

Be aware about squark limits:



Electroweak searches:

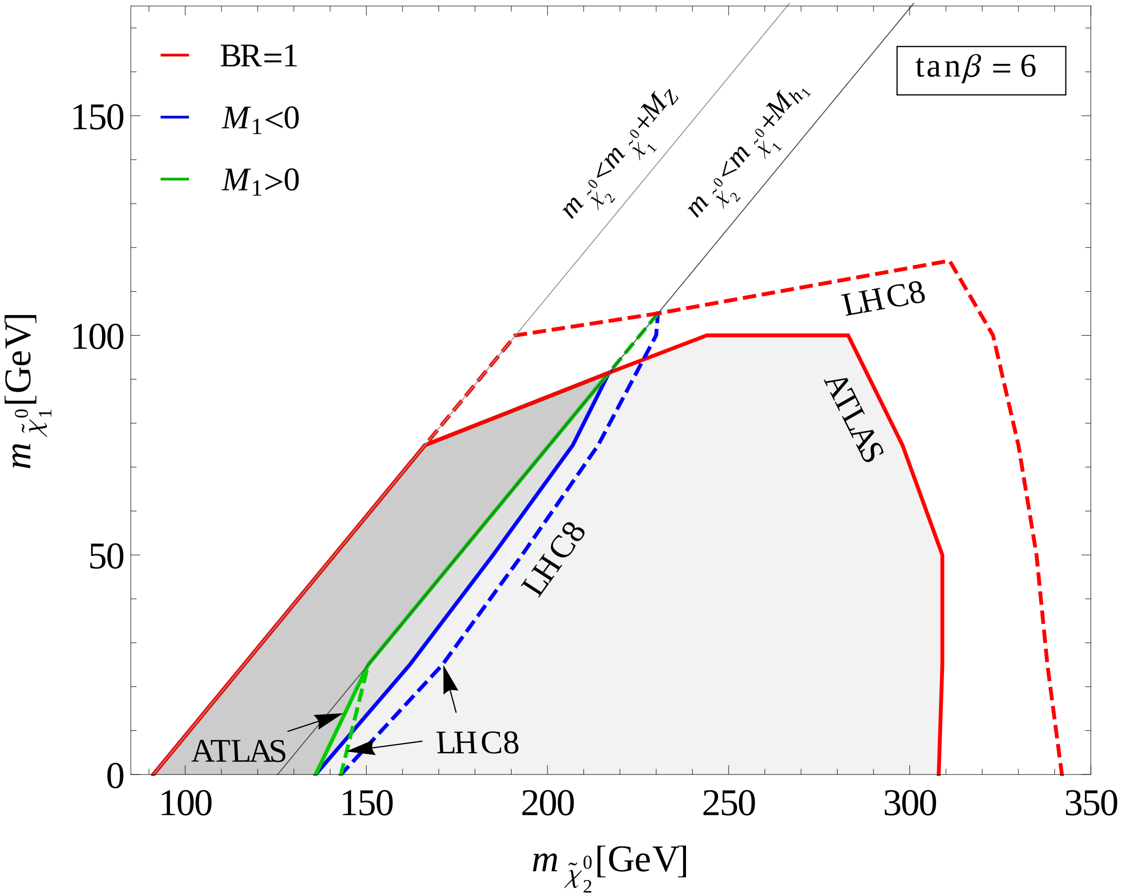


⇒ simplified model! Valid? Where?

LHC is looking for $pp \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, Z\tilde{\chi}_1^0$

Reality: $\mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$ is NEVER correct because $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ is possible

[A. Bharucha, S.H., F. v.d. Pahlen '13]

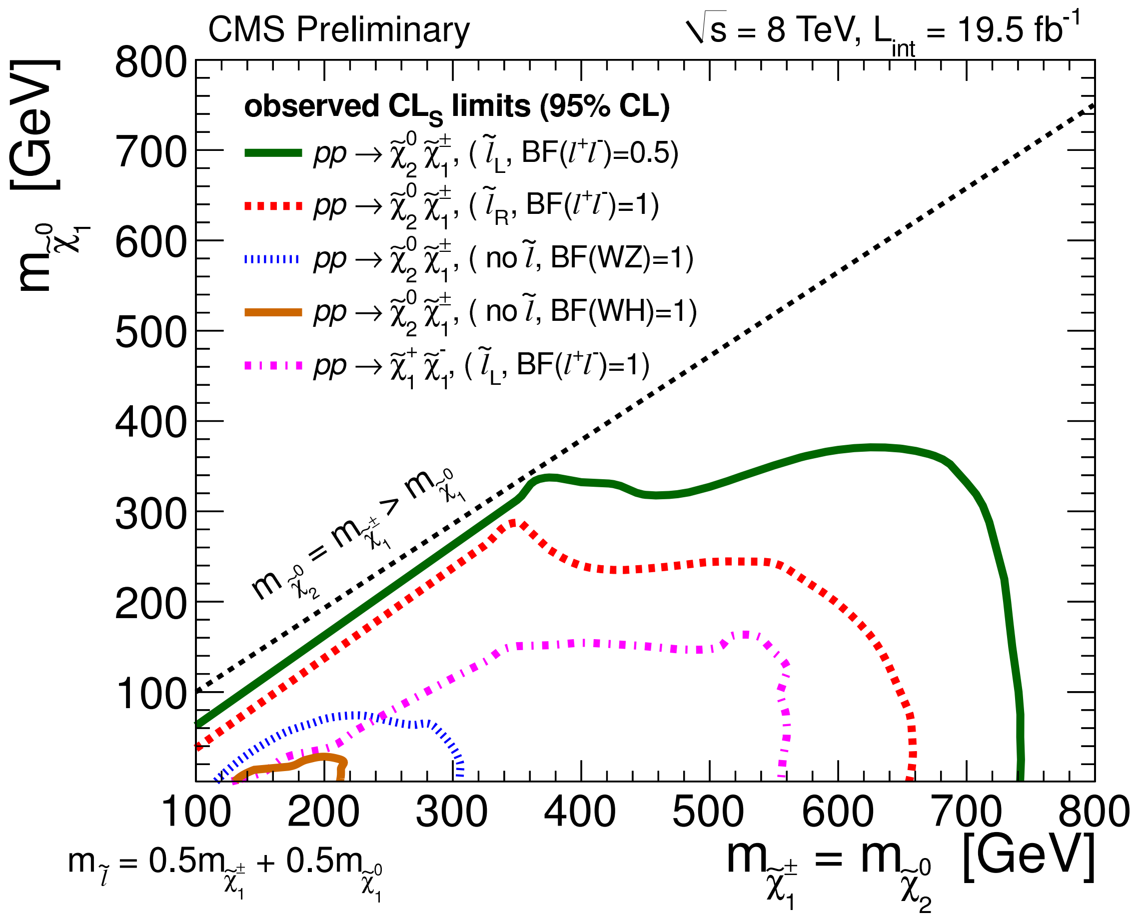


$\Rightarrow$ huge reduction of exclusion region (where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ allowed)

More recently:

ATLAS and CMS are now also searching for

$$pp \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, h\tilde{\chi}_1^0 \to W^{\pm}\tilde{\chi}_1^0\, b\bar{b}\tilde{\chi}_1^0$$



⇒ strongly reduced bounds!

Next project? Theory study confirmed by experimental analysis:

[*Y. Wang et al. '18*]