Discussion

starting from an experimentalist point of view….

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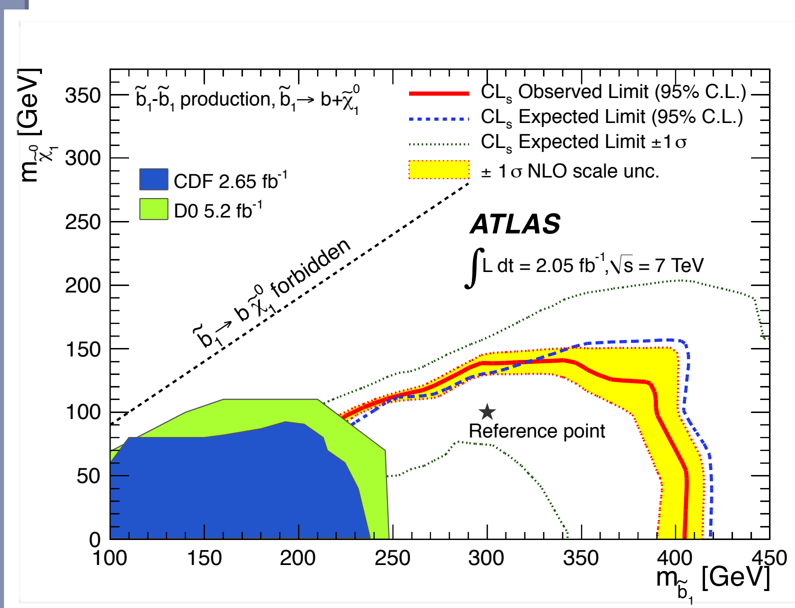
…Long time ago, they told us SUSY was just around the corner. It might still be true. We just need to find the right one …

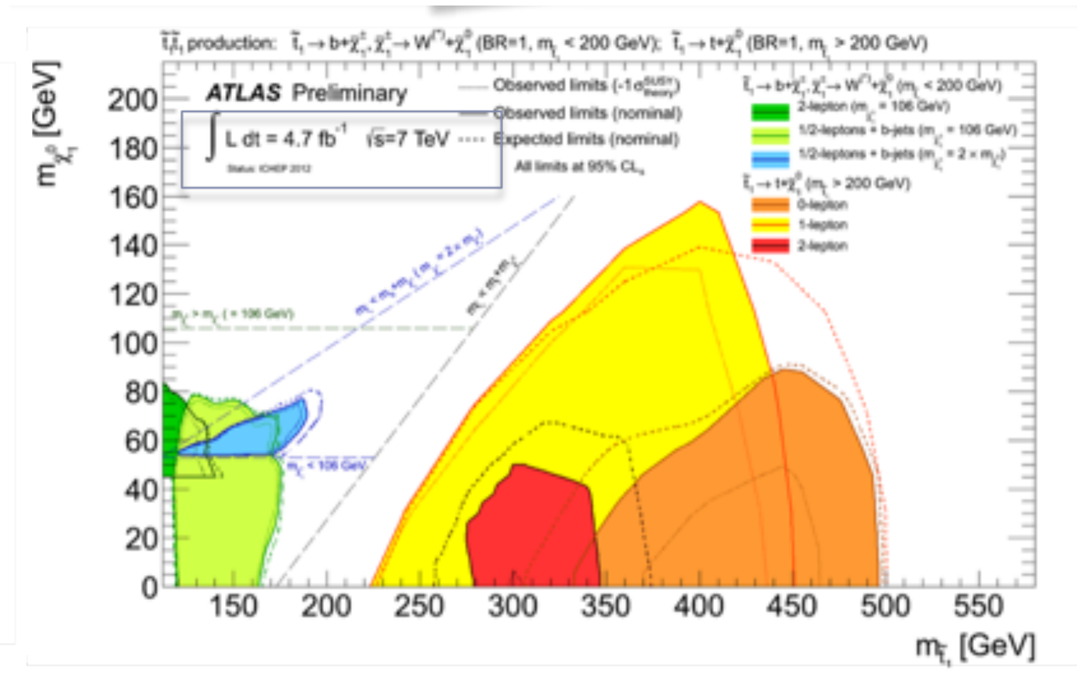
14/11/2014

SUSY @ the LHC

- At the beginning was mSUGRA / cMSSM - squarks, gluinos
- Then, focus also on third generation squark searches, inspired by Naturalness…

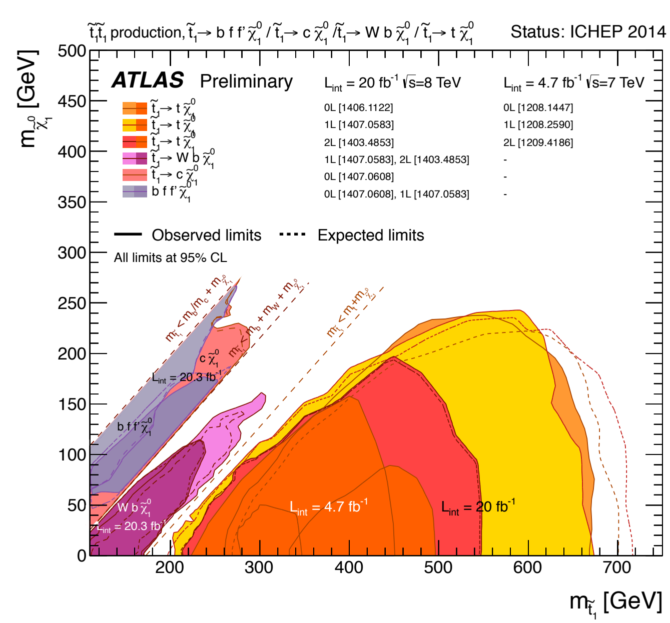
ICHEP 2012: First ATLAS stop summary plot with ~5/fb data at √s=7 TeV.

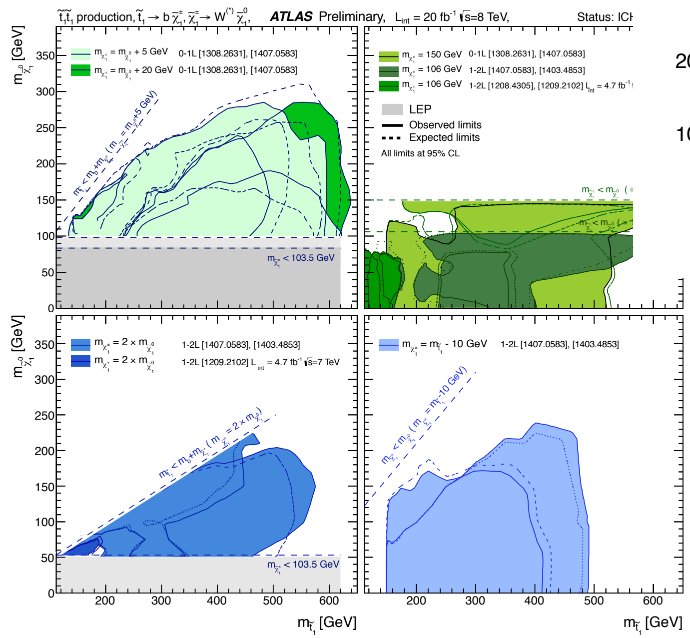


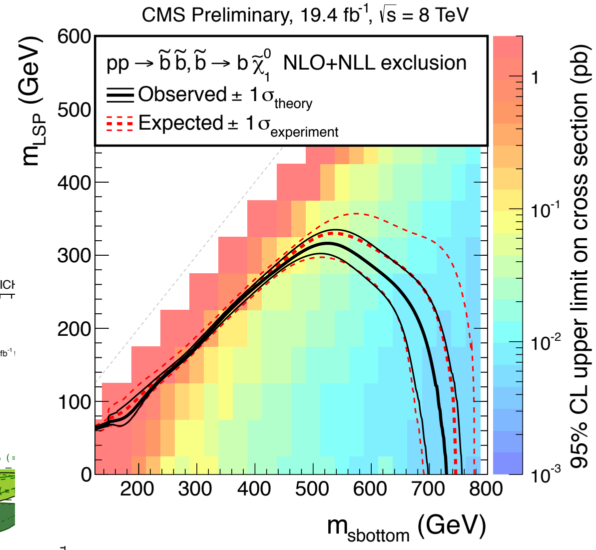


SUSY @ the LHC

- At the beginning was mSUGRA / cMSSM - squarks, gluinos
- Then, focus also on third generation squark searches, inspired by Naturalness, and EWK SUSY …
- 2013 – 2014: many more searches, very complete search program from ATLAS and CMS







And much more on EWK scenarios with higgs in final states

What we learnt on SUSY @ the end of Run 1

- Projections made in the past were more conservative than what we actually achieved → creativity, improvement in theoretical calculations and experimental techniques, hard work made this possible!
- Most simplistic version of SUSY under stress
  - Partially true also for 'Natural' SUSY, although depends *e.g.* on level of fine-tuning
- Still, lot of open points for us to chase. A few examples:
  - top squarks up the TeV range → not yet fully covered
  - If there are such 'light' stops, gluinos might be in the 2-3 TeV range → not yet reached
  - Decays of sparticle in most of SUSY models are complex:
    - Limitations on our limits: often valid only if a sparticle decays 100% in one mode
  - High scalar masses (O(10 TeV)) foreseen in several and still natural models
    - E.g. model of focus point SUSY ? EWK sector to be explored more !
  - Strictly speaking, there is much more to be done on the EWK sector: Low higgsino mass scenarios lead to "compressed" SUSY spectra (low ΔM Next-LSP – LSP) → difficult to corner because of low cross sections + low acceptances
  - R-parity violation or non-prompt sparticle production not yet fully covered:
    - Lack of handles such as missing transverse momentum, complex phenomenology, experimental challenges

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  - Should we better complement the simplified models approach ?
- **The real question (and biggest nightmare): are we missing something ?**

... and are we searching in the right way (if there is one)?

  - Maybe should explore more on naturalness of the Higgs mass and its implication (more in Marumi's discussion)
  - Move to NMSSM or other beyond-MSSM scenarios: does this imply a radical change in experimental approach?
    - Probably not in several cases (e.g. maximally natural susy models)
  - Should exploit more possible indications from indirect constrains?
- What are the prospects for (classic) Natural SUSY searches

  And until which point can we talk about 'Natural' searches ?

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Natural SUSY

- **Experimentalists or at least, the SUSY ones, like (some) guidance in searching for new physics**
  - **Natural SUSY seem to offer a 'paradigm' on sparticle masses:**
    - Some of the sparticles must be 'light' for the higgs mass to be at O(100 GeV)
- **Fine tuning** → quantified in terms of stability of EWK scale (MZ) wrt model parameters (NP B306(1987))

$$m_Z^2 = -2\mu^2 + 2\frac{m_{H_d}^2 - \tan^2\beta \, m_{H_u}^2}{\tan^2\beta - 1} \qquad max_{a_i}\left(\left|\frac{a_i}{m_Z^2}\frac{\partial m_Z^2(a_i)}{\partial a_i}\right|\right) < \Delta$$

model parameters (a_i)

tolerated fine tuning (Δ)

What is usually said and used as guidance

Low level of fine tuning → Natural scenarios

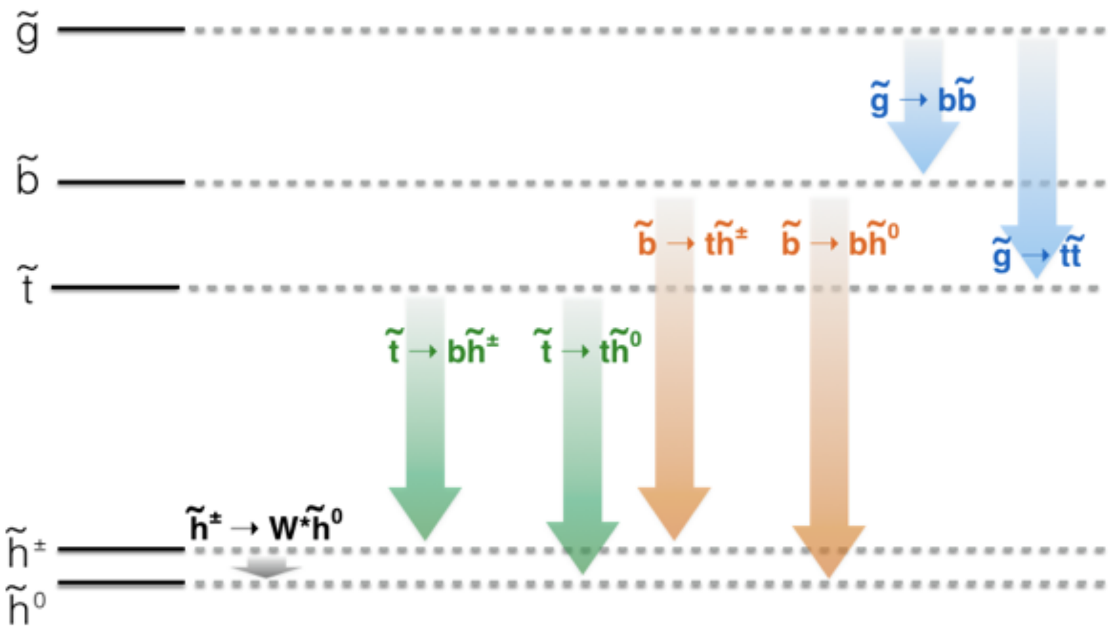
Relevant parameters a_i:

- μ (higgs mass parameter) → enters at tree level → higgsino masses
- A_t, M_{Q3}, M_{u3} → related to stop masses
- M_3 → gluino masses (entering at second order via stop mass corrections)

what we typically search for

- Inspired by a large number of papers and discussions, the 'model' is:
  - Low mass higgsinos
  - Low mass stop (and sbottom?)
  - Low mass gluinos

M. Dine et al. arXiv:hep-ph/9304299
P. Pouliot and N. Seiberg, arXiv:hep-ph/9308363
R. Barbieri, L. J. Hall and A. Strumia, arXiv:hep-ph/9504373
S. Dimopoulos, G. F. Giudice hep-ph/9507282
A. Pomarol and D. Tommasini, arXiv:hep-ph/9507462
R. Barbieri, G. R. Dvali and L. J. Hall, arXiv:hep-ph/9512388
A. G. Cohenet al., arXiv:hep-ph/9607394
R. Barbieri, L. J. Hall and A. Romanino, arXiv:hep-ph/9702315
R. Sundrum, arXiv:0909.5430 [hep-th]
R. Barbieri et al. arXiv:1004.2256 [hep-ph]
R. Barbieri et al. arXiv:1011.0730 [hep-ph]
N. Craig, D. Green, A. Katz, arXiv:1103.3708 [hep-ph]
T. Gherghetta, B. von Harling, N. Setzer, arXiv:1104.3171 [hep-ph]
M. Papucci, et al., arXiv:1110.6926 [hep-ph] 4



Of course, the SUSY program is wider, but this is the **Natural SUSY ground**

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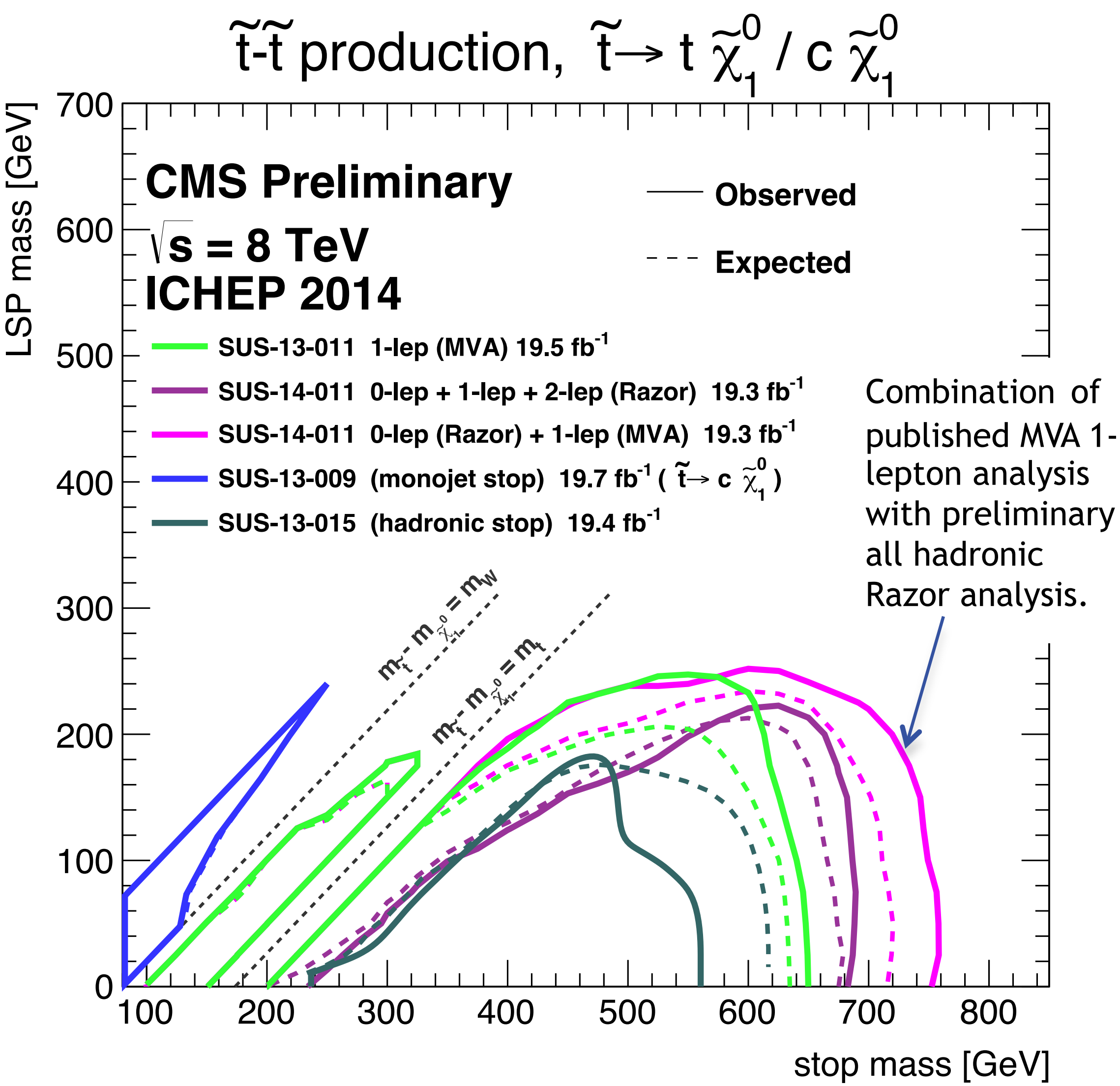
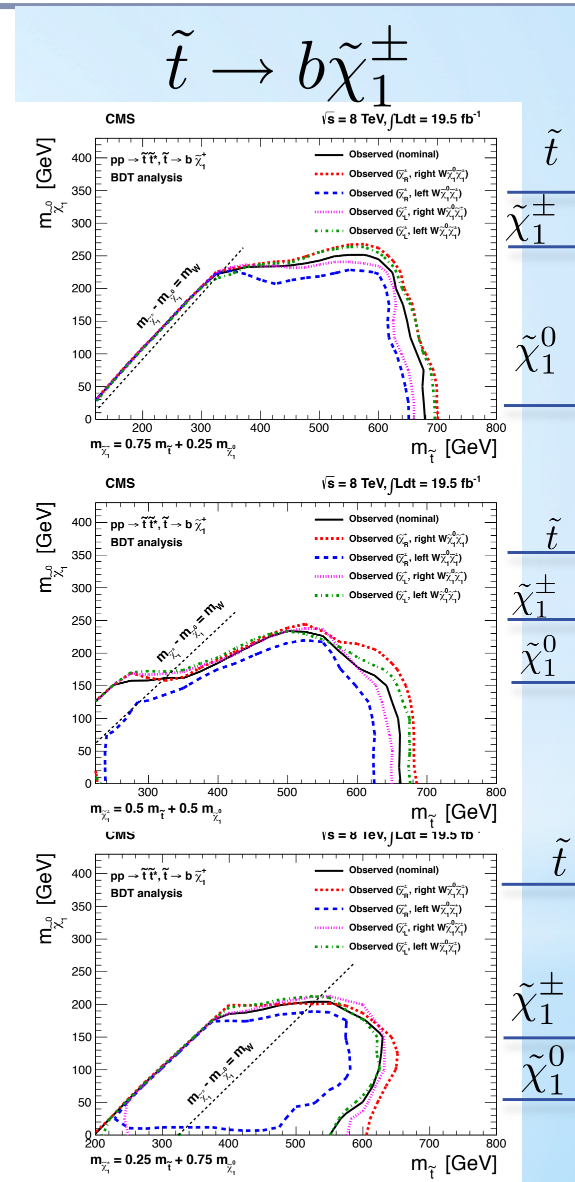
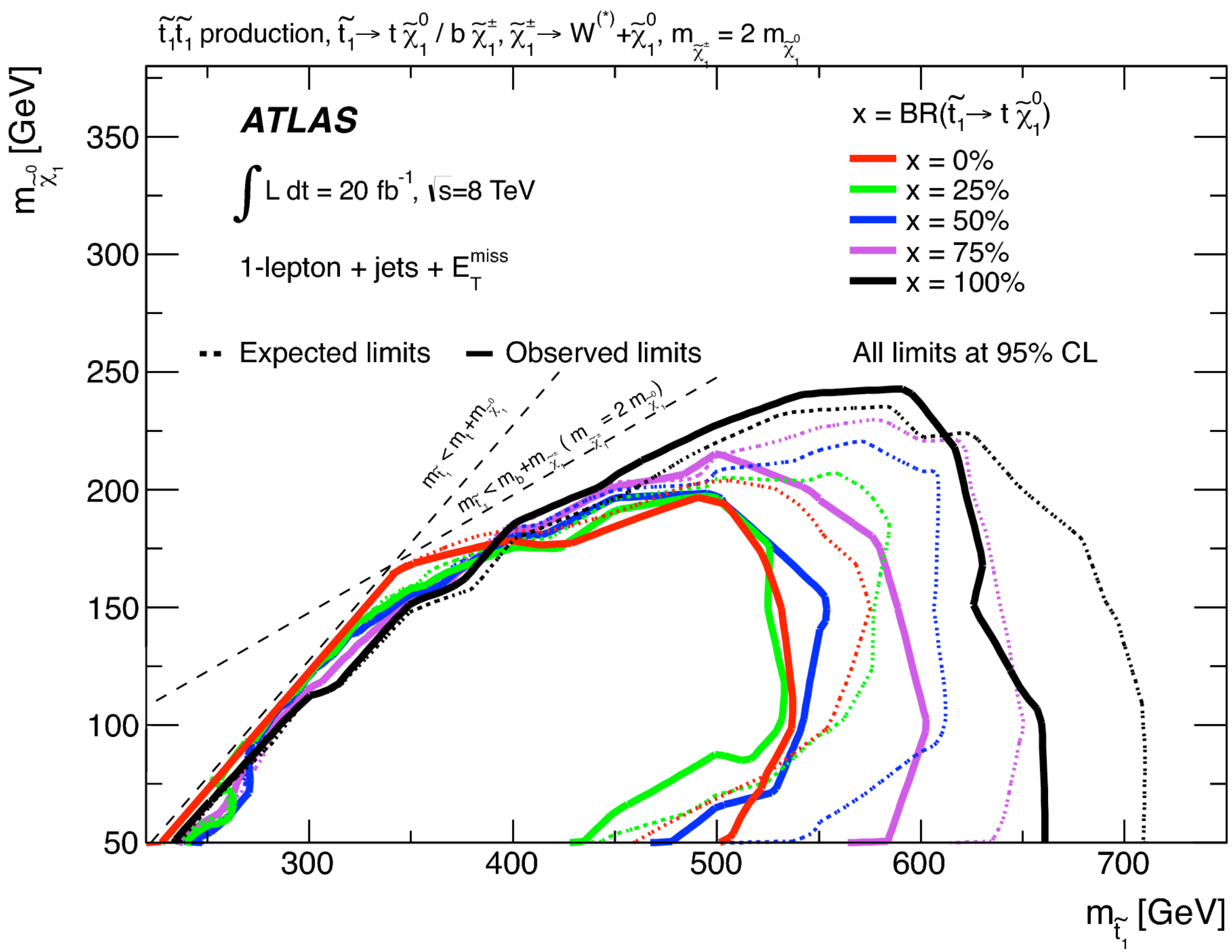
True: we use simplified models – but large variety!





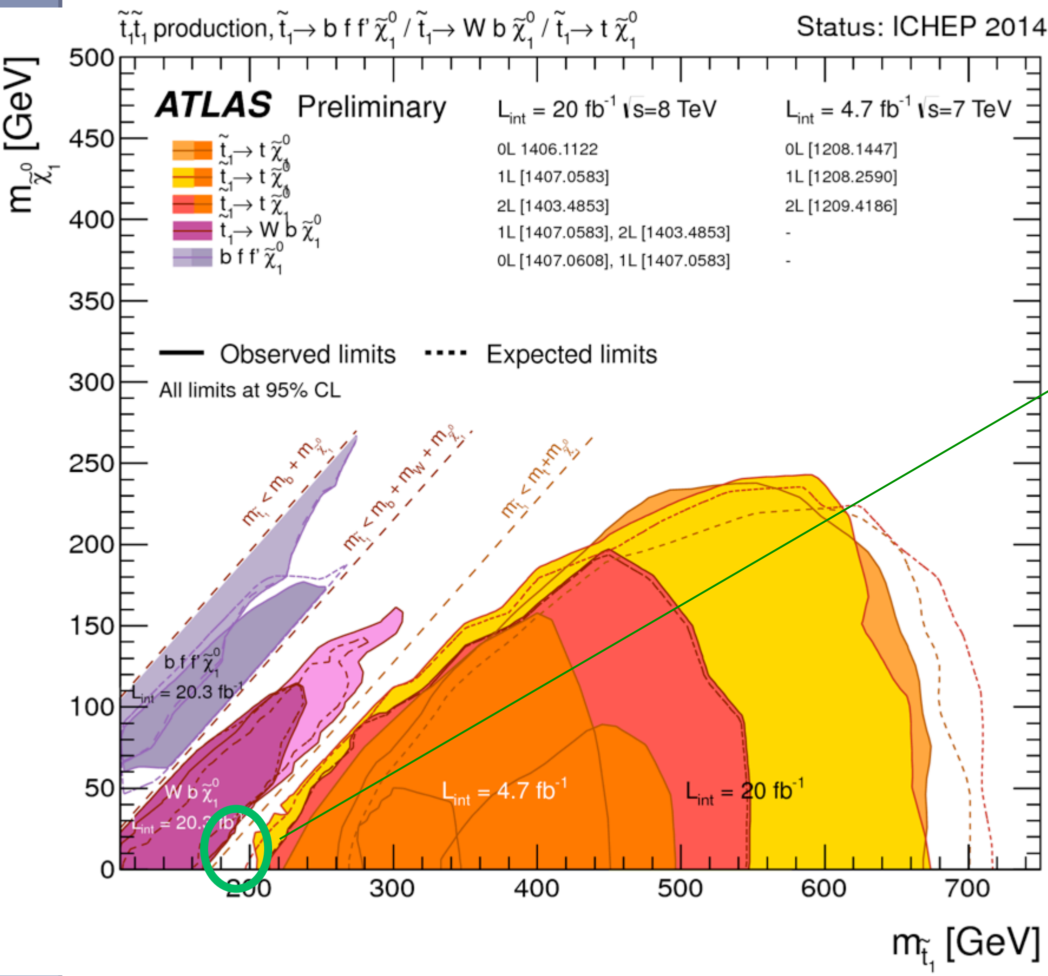
increasing complexity of simplified models

We also go beyond strong BR assumptions → mixture!



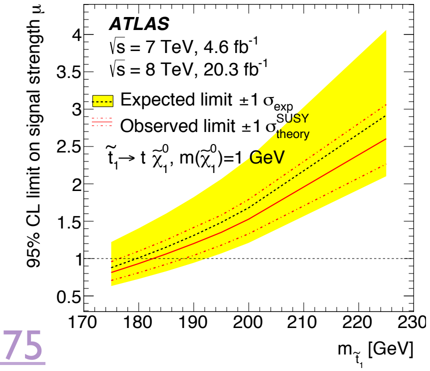
we look at deviation in SM measurements

More on compressed scenarios in Frank's talk



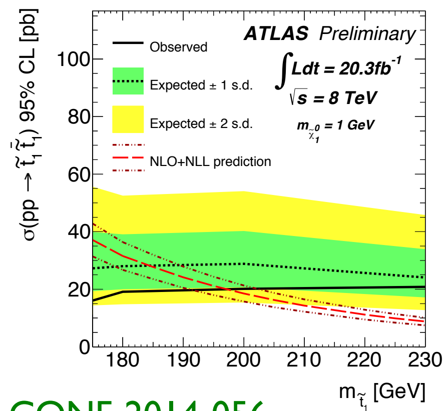
M(stop) ~ m(top):

- Constraints from $\sigma(t\bar{t})$ measurement



1406.5375

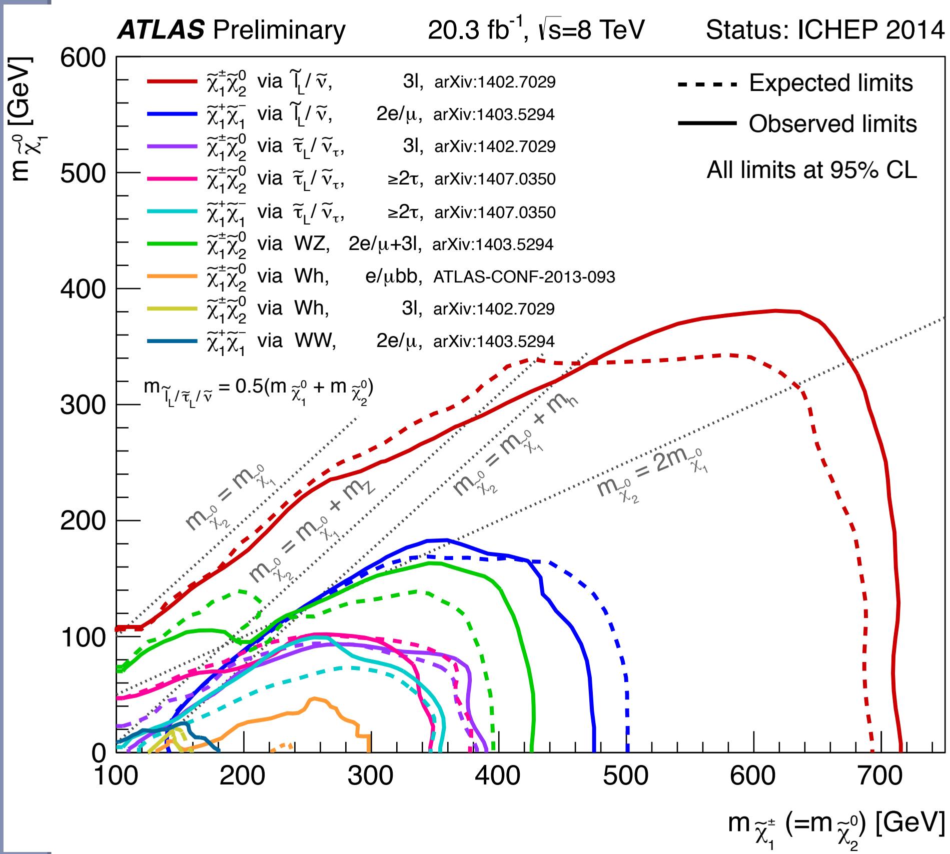
- Constraints from top-antitop spin correlations (exploit that stop is scalar)

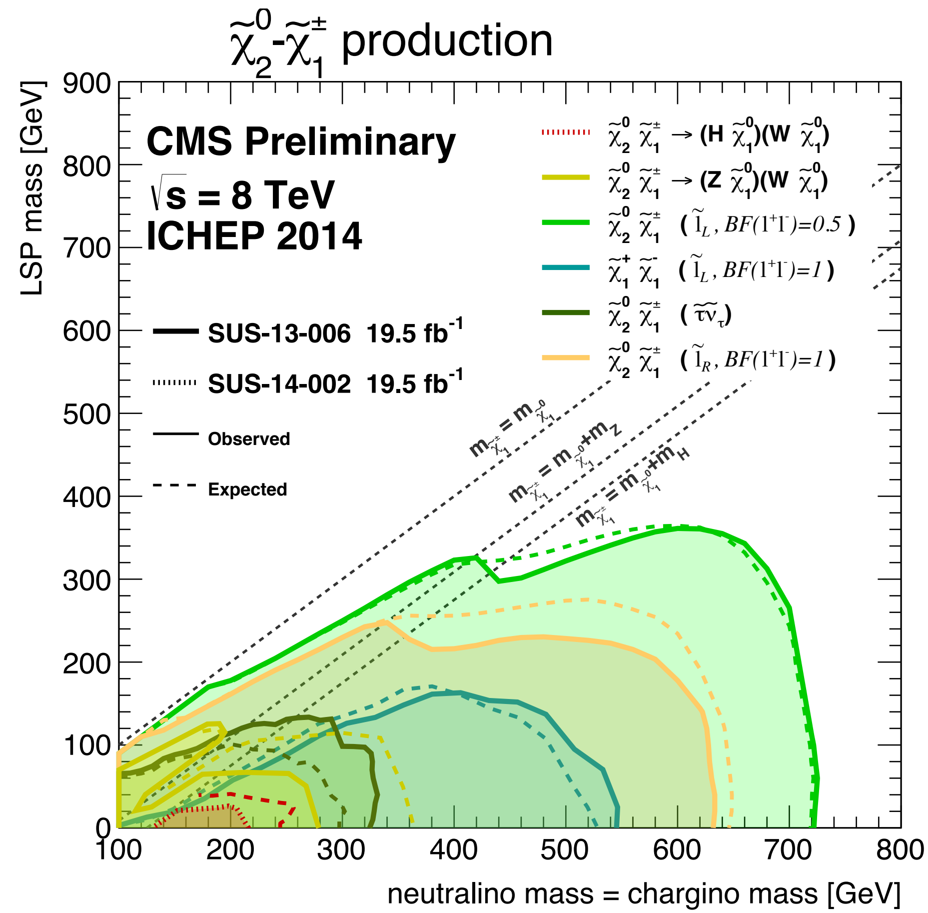


ATLAS-CONF-2014-056

ATLAS: 1403.5222 (Z-mode)
CMS:1405.3886 (Z/H modes)

again, many models in EWK sector



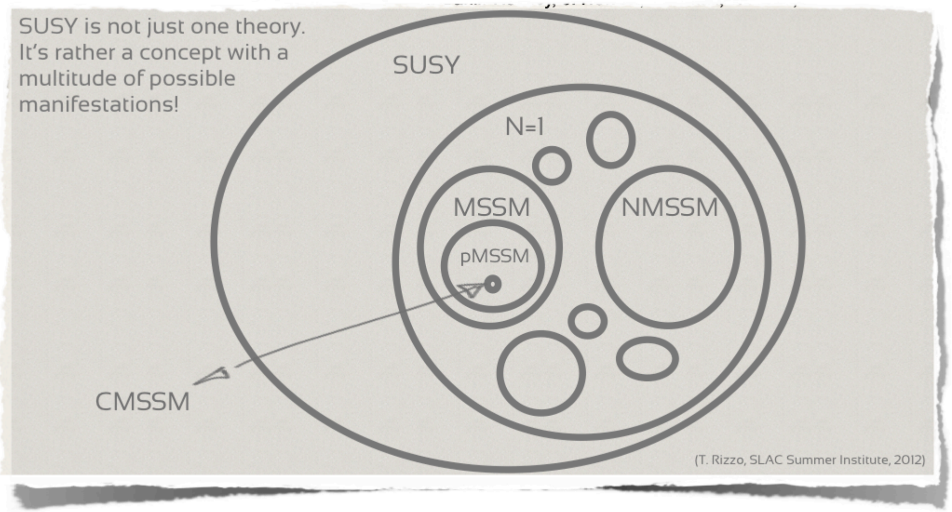


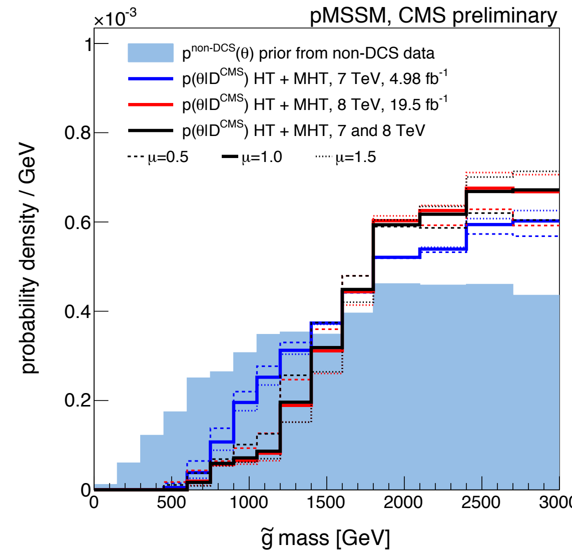
- Constraints on chargino/next-to-lightest neutralinos up to 720 GeV (if decays are mediated by sleptons); up to ~ 450 GeV for WZ-decays; but maybe not even so 'Natural' EWK SUSY ..
- **Great emphasis** on decay channels involving the higgs boson

Beyond Simplified Model: pMSSM or more?

Use pMSSM to 'generalize' the results and identify loop-holes
→ intrinsically covers a wide diversity of topologies.

SUS-13-020

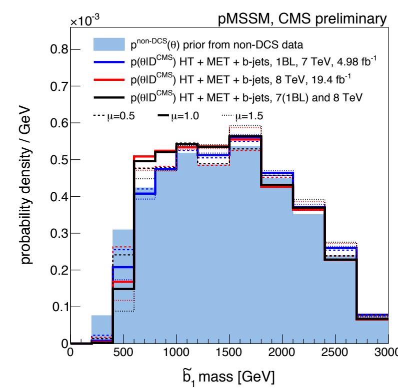


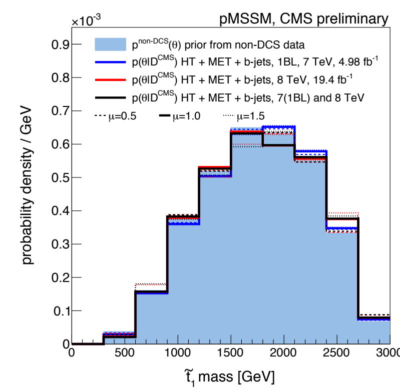


- draw conclusions that are more generic than , and complimentary to, those derived in more constrained or in simplified models

CMS pMSSM studies:

e.g. m(gluino)<1.2 TeV strongly disfavored – small impact of the searches explored on stop and sbottom

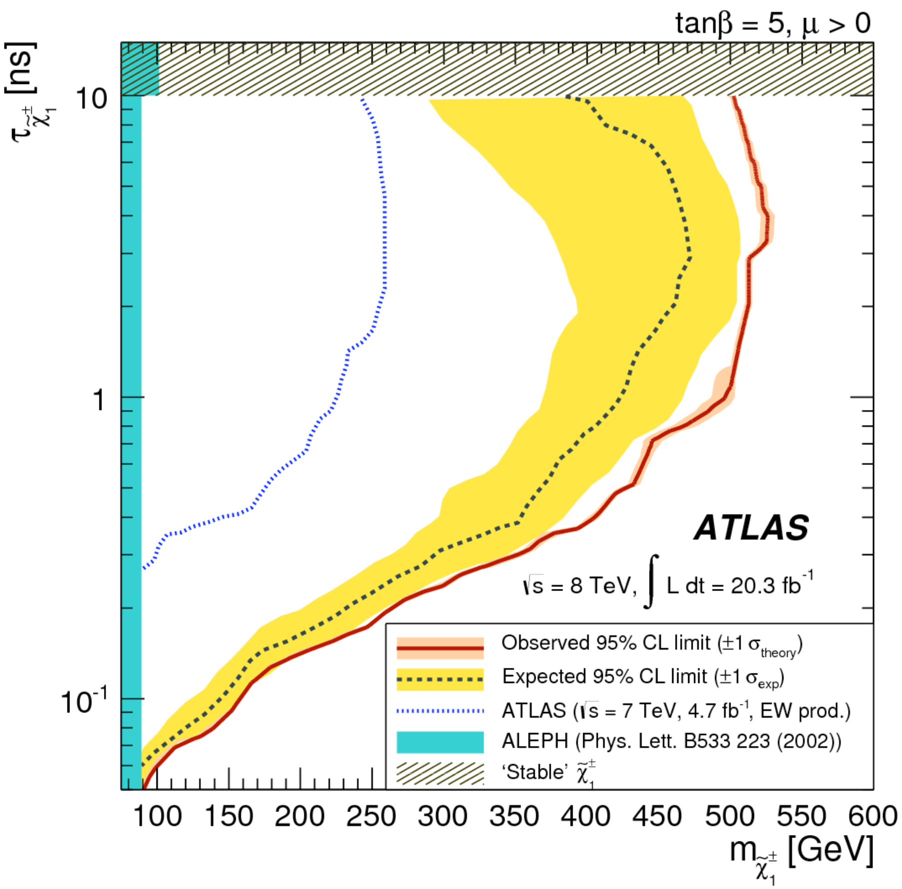


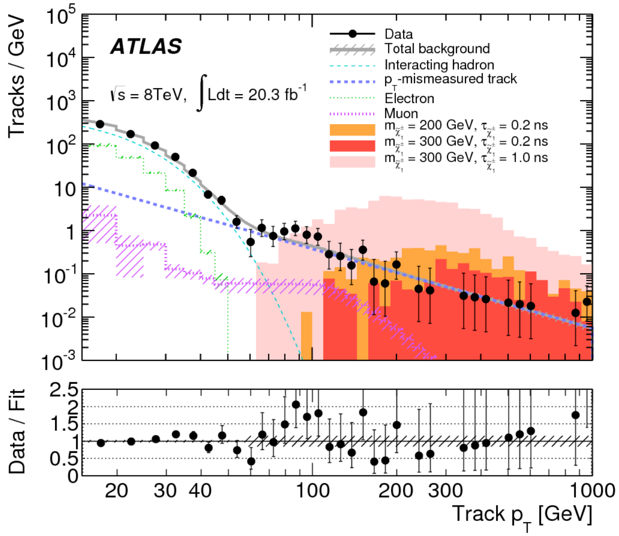


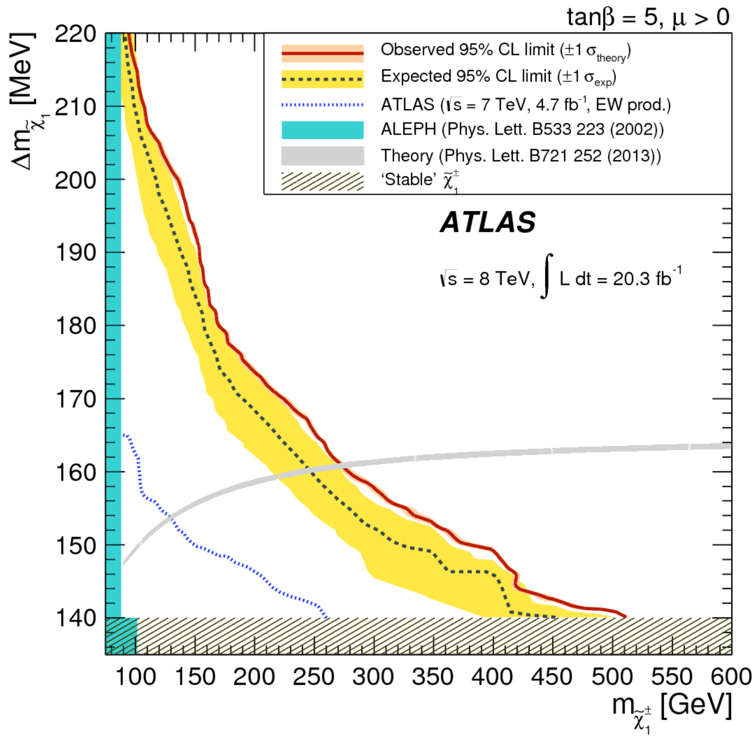
- Still - constrained → e.g. $c\tau(\chi\pm)$ < 10 mm

Again: complementarity

- Non-prompt chargino searches
  - Although scenarios are different







1310.3675

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SM background estimates

- Searching for BSM physics means understanding SM background contributions (*)
  - Search kinematic phase space usually different from SM measurements (tail of distributions at high p_T)

(*) For long-lived particle searches, need more specialized techniques

Irreducible SM backgrounds →

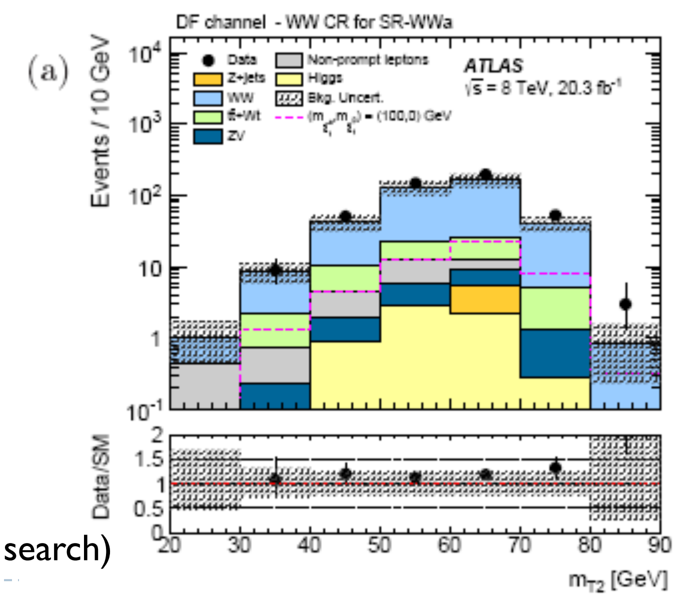
'Semi' data-driven methods

- Normalisation done in dedicated Control Regions (CR) enriched in specific bkg. E.g.: ttbar, W+jets…
- Compromise between closeness to SR, statistics and handling of uncertainties

Reducible SM background → *Data-driven methods*

Validation of Background estimates in dedicated samples (VR)

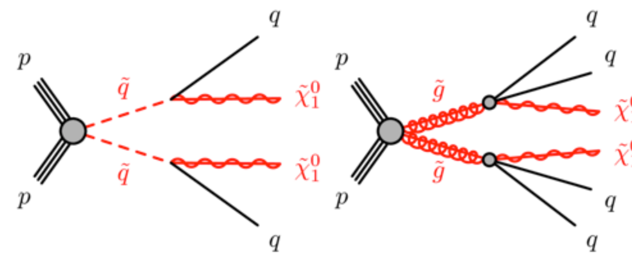
Still – when we 'normalize' SM bkg from MC to data in CR, are we biased?



WW CR (ex. for SR-WWb/c in 2L ATLAS search)

many signal regions!

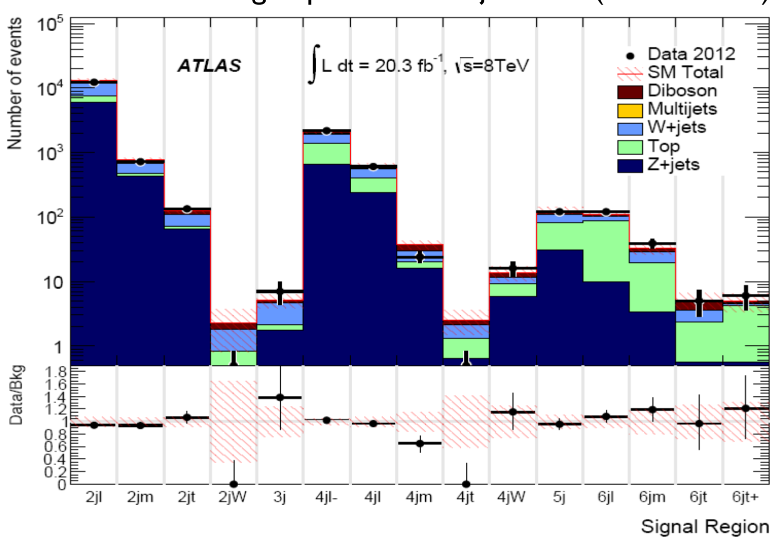
- E.g. inclusive searches focusing on 1st / 2nd generation squarks and gluinos, but quite general
- Possibly complex final states, great variety of signatures → main target of inclusive searches with several jets, possibly leptons and large E_T^{Miss}
- *Example:* Inclusive jets+E_T^{Miss} analyses:



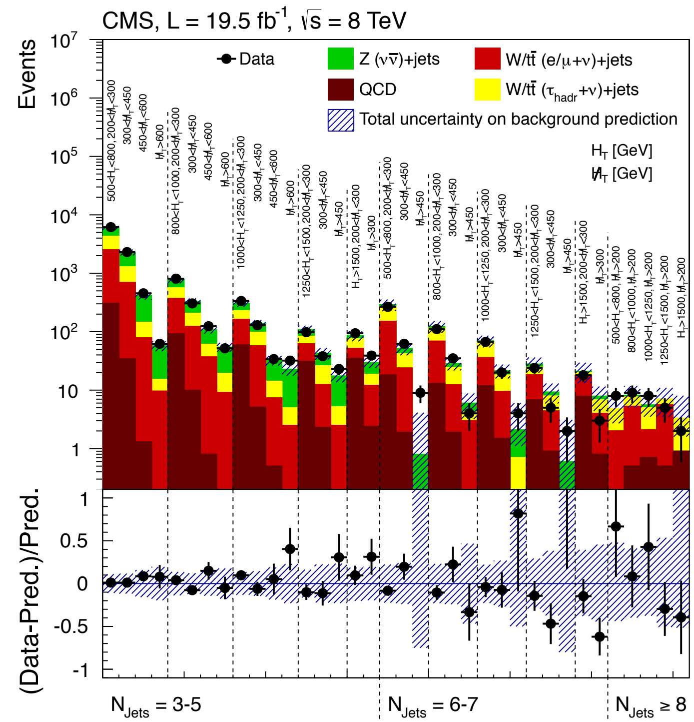
CMS: 1402.4770

ATLAS: 1405.7875

- Minimum Jet multiplicity (2 to >=6j)
- Use **Effective Mass** (M_{eff}= E_T^{Miss} +Sum p_T jets)
  - Thresholds from 800 GeV to 2.2 TeV
- But also: presence of boosted W→qq'
  - Also merged products → jet mass (60-100 GeV)

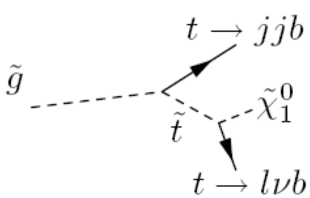


- Three jet multiplicity categories:(3–5, 6–7, and 8 jets)
- Selections in E_T^{Miss} and HT (Sum p_T jets)



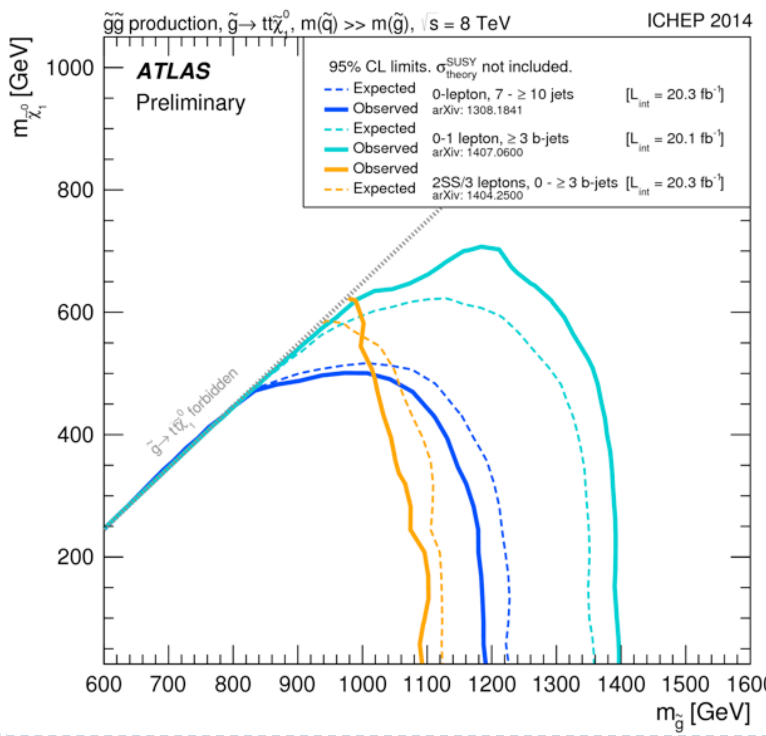
complementary searches for gluinos

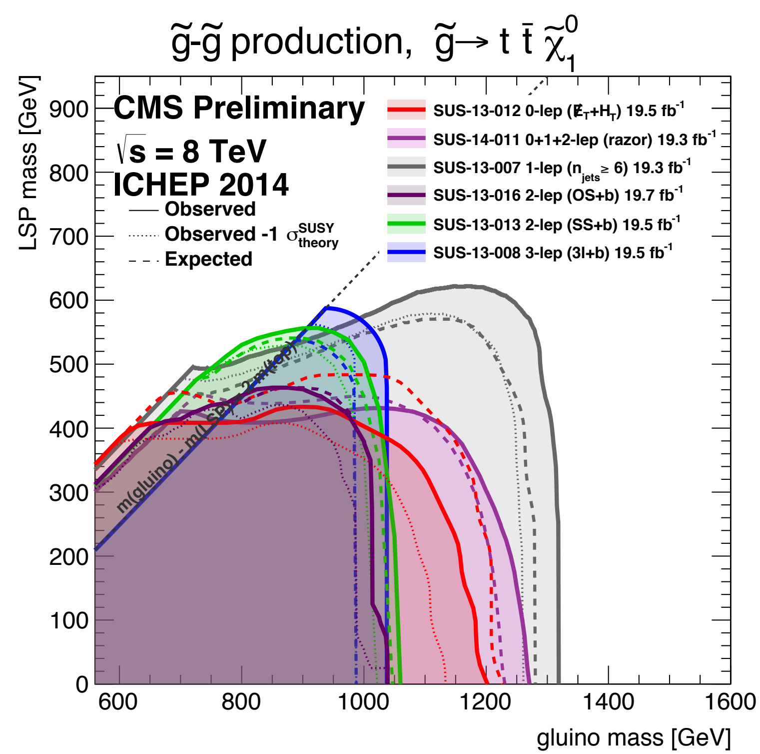
- Diversity !! Search for in gluino-mediated and direct pair production of third generation squarks considering different and complementary scenarios. E.g.: **Gluino-mediated stop:**



Various analyses exploiting the complexity of the final states including up to 4 tops.

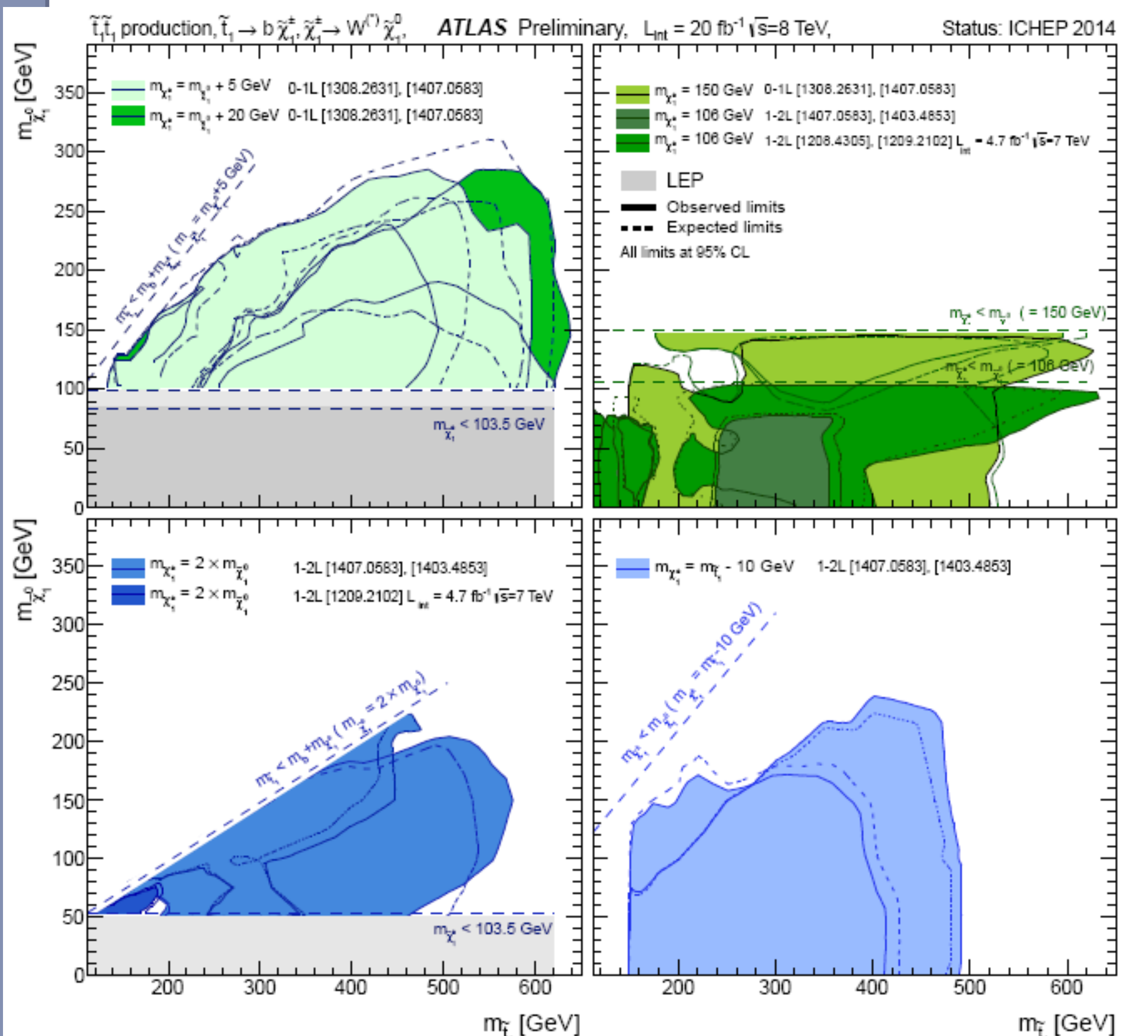
0 lepton + multijets (7-10j)
Same-sign /3 leptons + jets (b-jets)
0/1 or 2 leptons + 3- or 4bjets ..

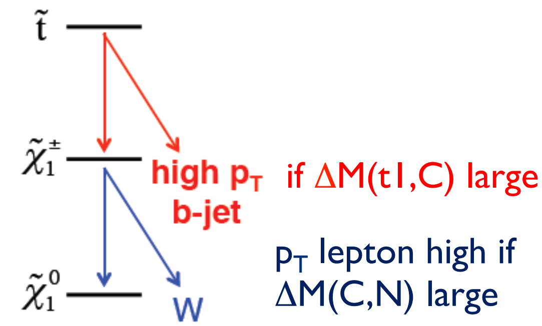




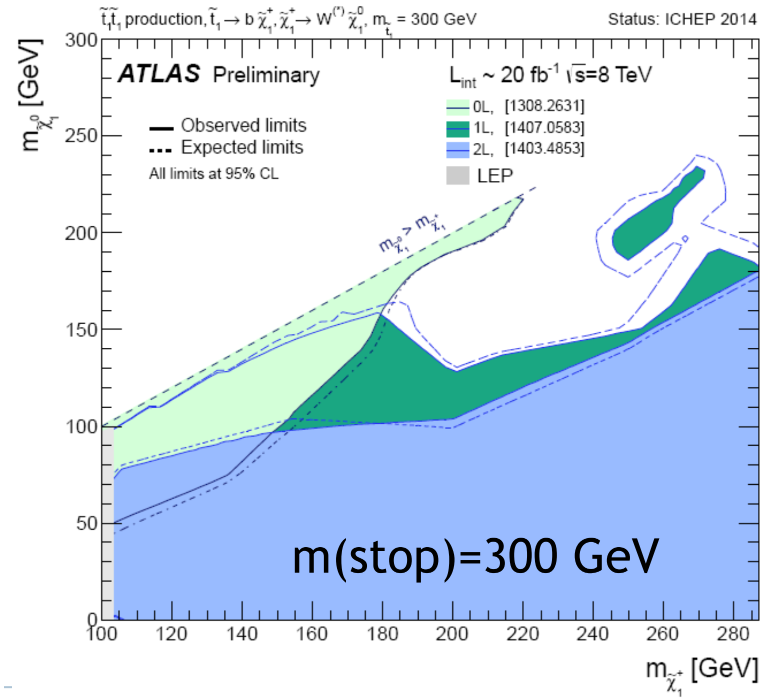
complementary searches for stop..

- Various assumptions of ΔM(stop-chargino) and ΔM(chargino-neutralino)





Fixed mass stop, function of chargino-neutralino mass



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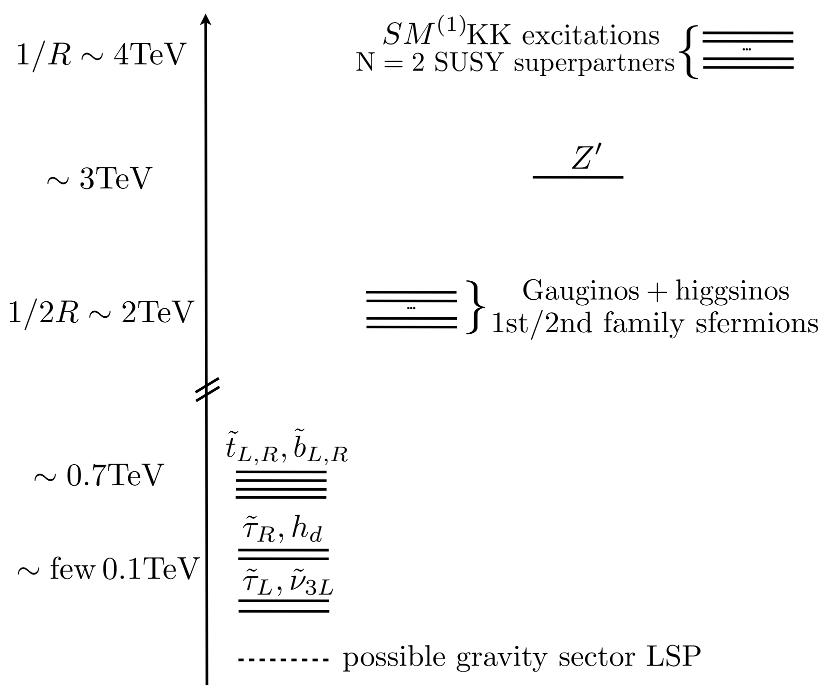
maximally natural SUSY

1404.7554

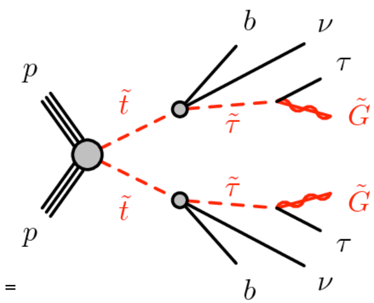
- Typical spectra:

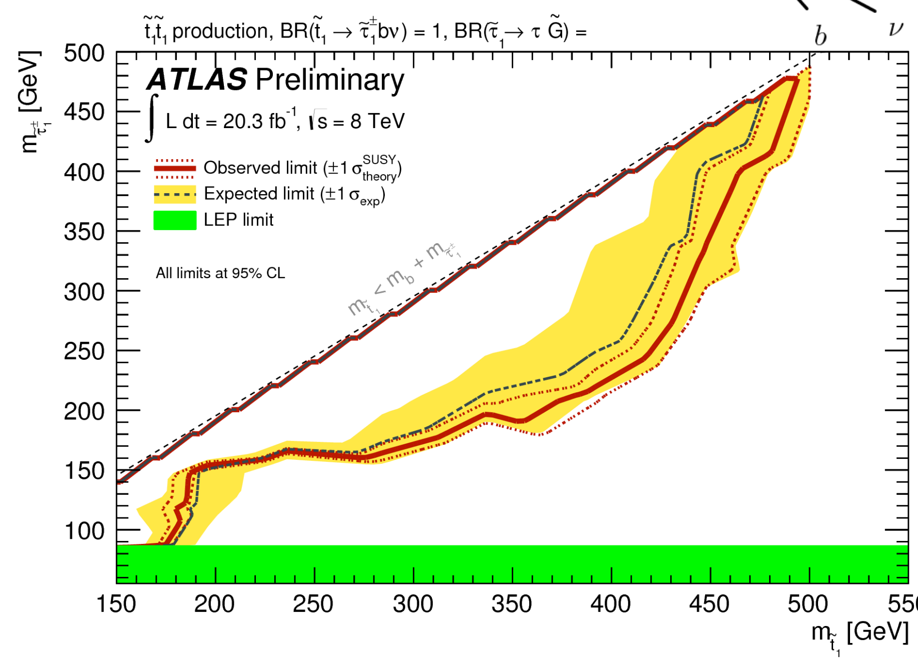


Stau or stau neutrino LSP

Decays of stop/sbottom in tau-enriched final states

Can reinterpret or improve existing searches. E.g.





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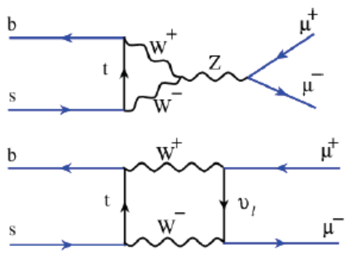
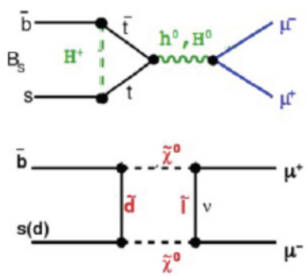
Indirect constraints

- $B_s \rightarrow \mu\mu$: constrain MSSM at large tan β
- BR Enhancement from many BSM models

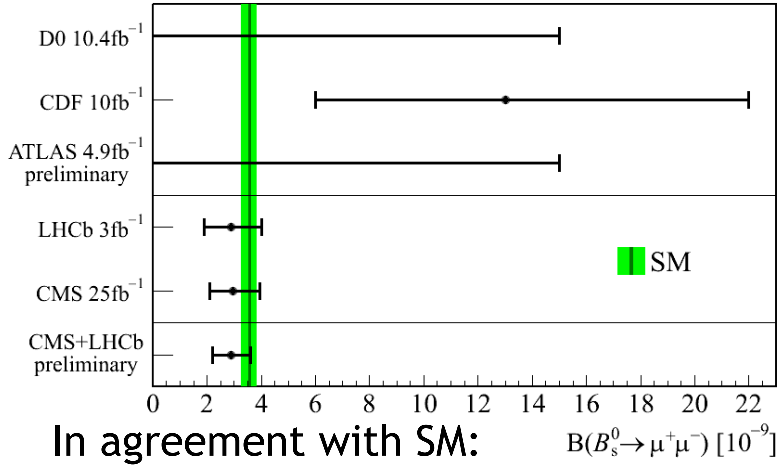
In SM:



In BSM:

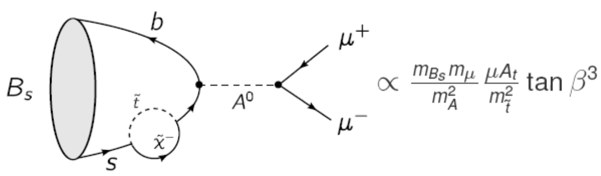


The CMS and the LHCb Collaborations have obtained a combined preliminary value of the Bs→μμ branching fraction of $(2.9\pm0.7)\times10^{-9}$



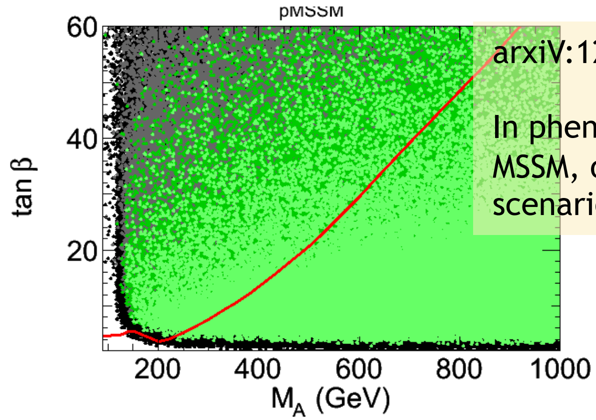
In agreement with SM: BR=$(3.56\pm0.30)\times10^{-9}$

What can this tell us about SUSY?



Large tan β with light pseudoscalar Higgs disfavoured **BUT**
'Natural' (small fine tuning) MSSM scenarios barely affected

- SUSY-BR(Bs→μμ) is ~ to SM-BR or even smaller in some scenarios



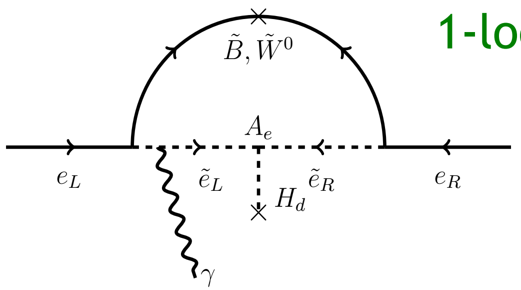
arxiV:1212.4887

In phenomenological MSSM, only < 20-30% scenarios are excluded

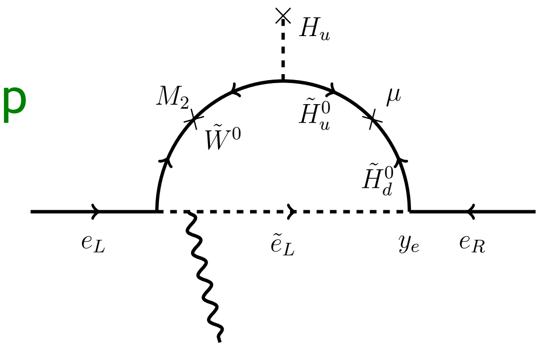
Indirect constraints (II)

- **EDM:** As other BSM theories, SUSY predict small – yet measurable electron electric dipole moment (d_e)
  (In SM, $d_e \sim 10^{-44}$ *e* cm)

1-loop

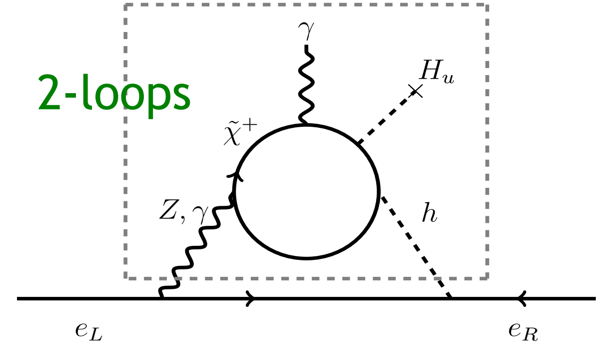


Bino-higgsino/Selectron

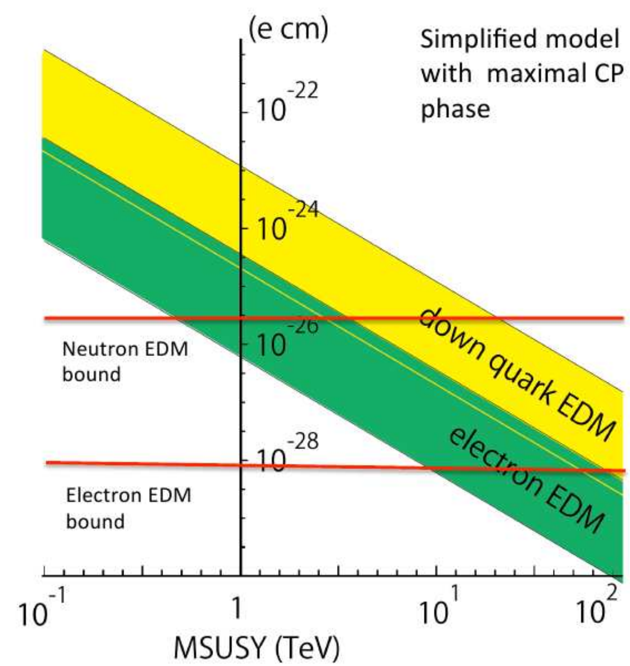


Selectron-electron-higgsino interaction

2-loops



(Hisano @ Moriond EW 2014)



ACME collaboration (arXiV:1310.7534):

- d_e = -2.1±3.7(stat)±2.5(syst) x 10^{-29} *e* cm
- $|d_e| < 8.7 \times 10^{-29}$ *e* cm
  - for models where 1- (2-loop) diagrams produce d_e, bound on CP violation at energy scales **Λ ~ 3(1) TeV**

→ **Small CP phases ←→ decoupling:** Might indicate preference for **1st generation squark/slepton masses** at O(10) TeV

(preserves EWK sector / naturalness)

Indirect constraints (III)

$\left(a_\mu := \frac{g_\mu - 2}{2}\right)$

- Anomalous magnetic moment: Muon g-2

$a_\mu^{SM} = (116\,591\,828 \pm 49) \times 10^{-11}$

$a_\mu^{exp} = (116\,592\,089 \pm 63) \times 10^{-11}$

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (26.1 \pm 8.0) \times 10^{-10}$$

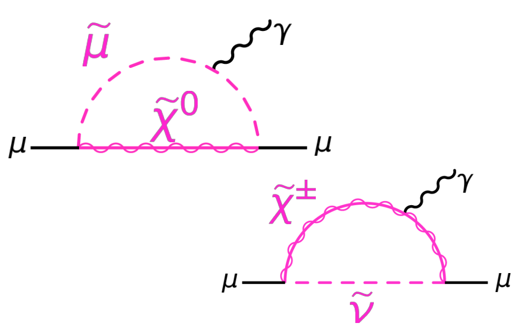
3.3 σ discrepancy → New Physics ? SUSY ?

$$\delta a_\mu \sim (\alpha_{\mathrm{NP}}/4\pi) \times (m_\mu^2/m_{\mathrm{NP}}^2)$$

Coupling constant of new particles to the muon

Typical scale of new particle mass

SUSY contributions to g-2:
neutralino-smuon and chargino-sneutrino loop diagrams

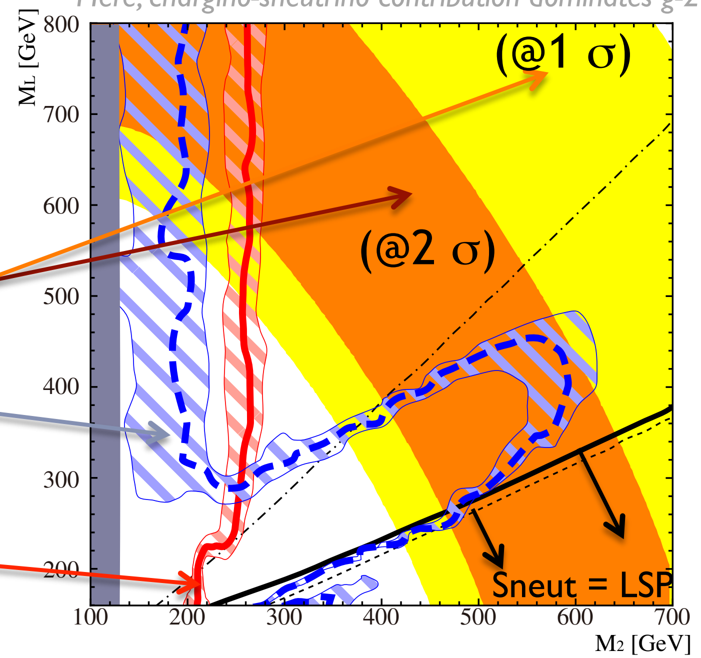


- SUSY explains g-2
- LEP searches
- Excluded by LHC-lepton searches
- Excluded by LHC Jet searches

M_1, M_2=bino, wino masses
μ = higgsino mass
m_L = slepton (LH component) mass

JHEP01(2014)123
LHC and g-2 constraints

Here, chargino-sneutrino contribution dominates g-2



(a) $\mu = M_2$, $m_R = 3$ TeV

For discussion

- Let's make a step backward:
  - What experimentalists like about 'Natural' SUSY ?
  - And what do we mean by searching for Natural SUSY ?
- We saw nothing so far: what's wrong? Are we using a too simplistic approach in our searches ?
  - Should we better complement the simplified models approach ?
- **The real question (and biggest nightmare): are we missing something ?**

… and are we searching in the right way (if there is one)?

  - Maybe should explore more on naturalness of the Higgs mass and its implication (more in Marumi's discussion)
  - Move to NMSSM or other beyond-MSSM scenarios: does this imply a radical change in experimental approach?
    - Probably not in several cases (e.g. maximally natural susy models)
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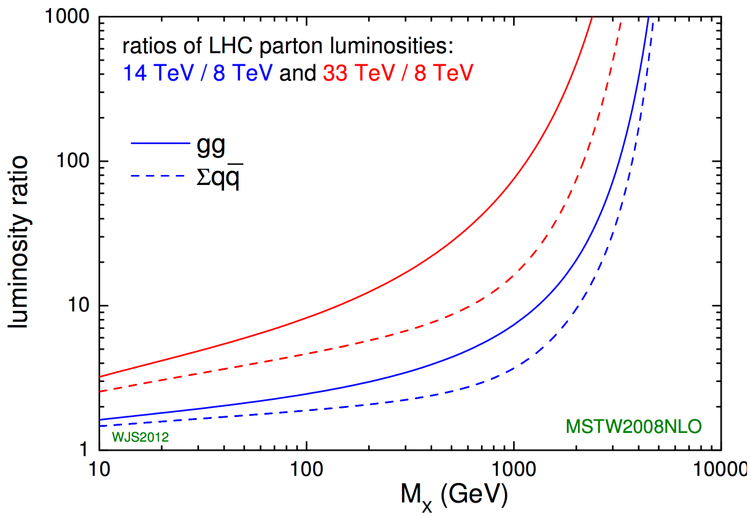
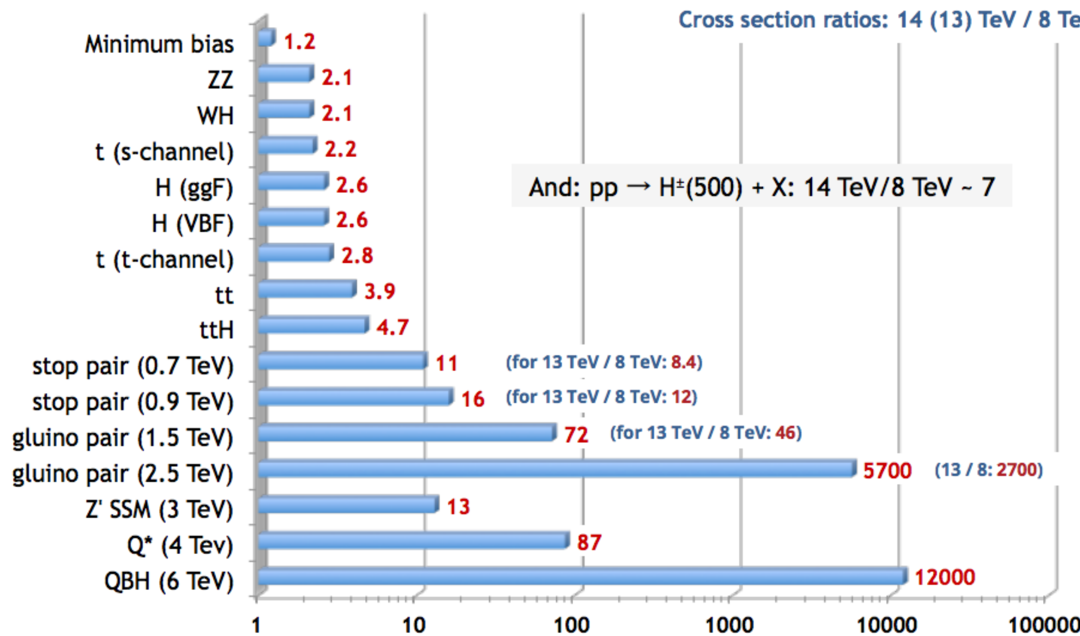
  And until which point can we talk about 'Natural' searches ?

The next steps for the LHC

- **LHC Runs 2 and 3**, up to 300 fb^{-1} at $\sqrt{s}$ = 13/14 TeV
  - Huge increase in sensitivity wrt Run 1 in multi-TeV region



Cross section 14 TeV / 8 TeV	gg	$\Sigma q\bar{q}$
M_X = 2 TeV	~20	~10
M_X = 3 TeV	~70	~30
M_X = 4 TeV	~400	~160



- **High Luminosity (HL)-LHC:**
  - up to 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV → factor of 10 luminosity crucial for new physics processes with low cross section (e.g. EWK SUSY, 3^{rd} generation squarks)

Squark/gluinos reach at HL-LHC

- Compare the search reach with 300 and 3000 /fb at 14 TeV

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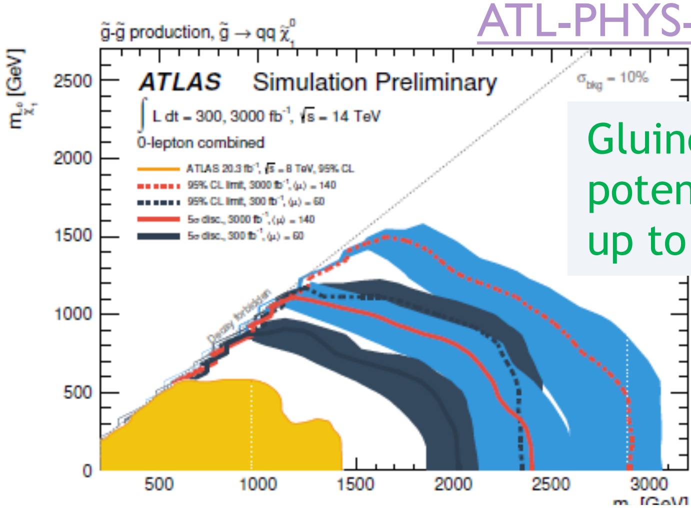
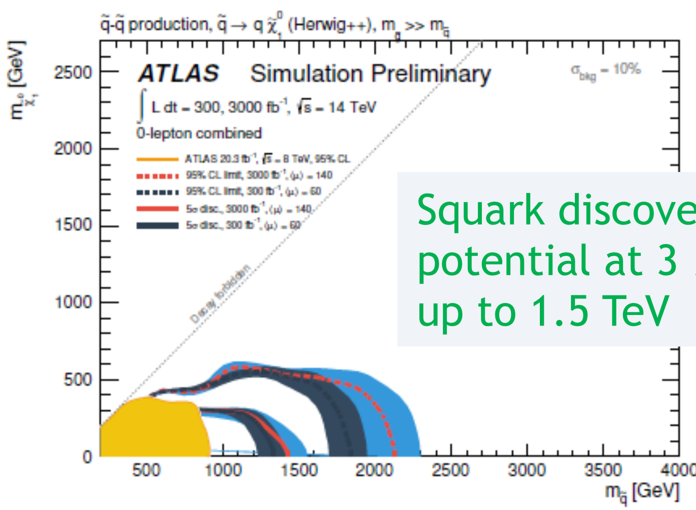
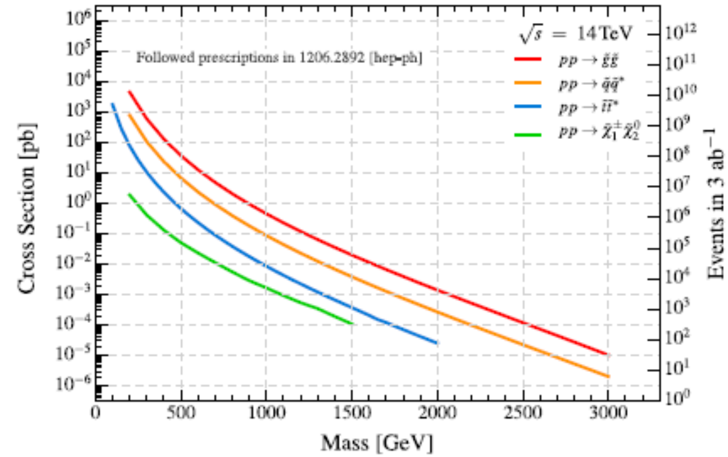


Gluinos discovery potential at 3 /ab up to 2.5 TeV

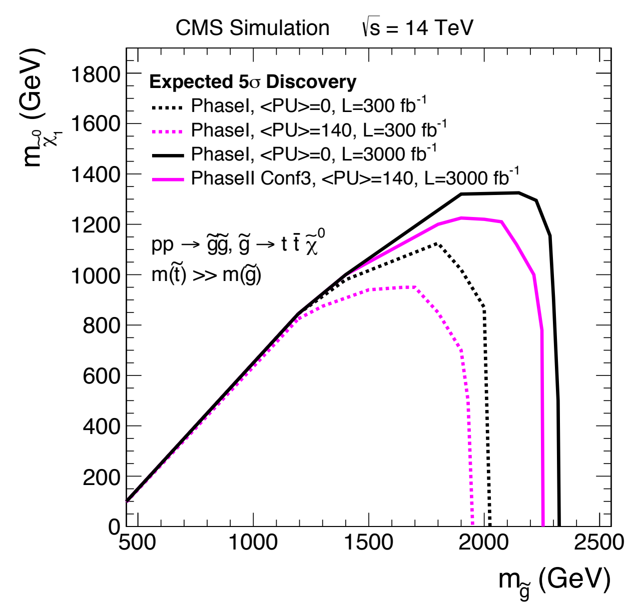


Squark discovery potential at 3 /ab up to 1.5 TeV

Discovery reach up to 2.5-3 TeV



CMS PAS FTR-13-014

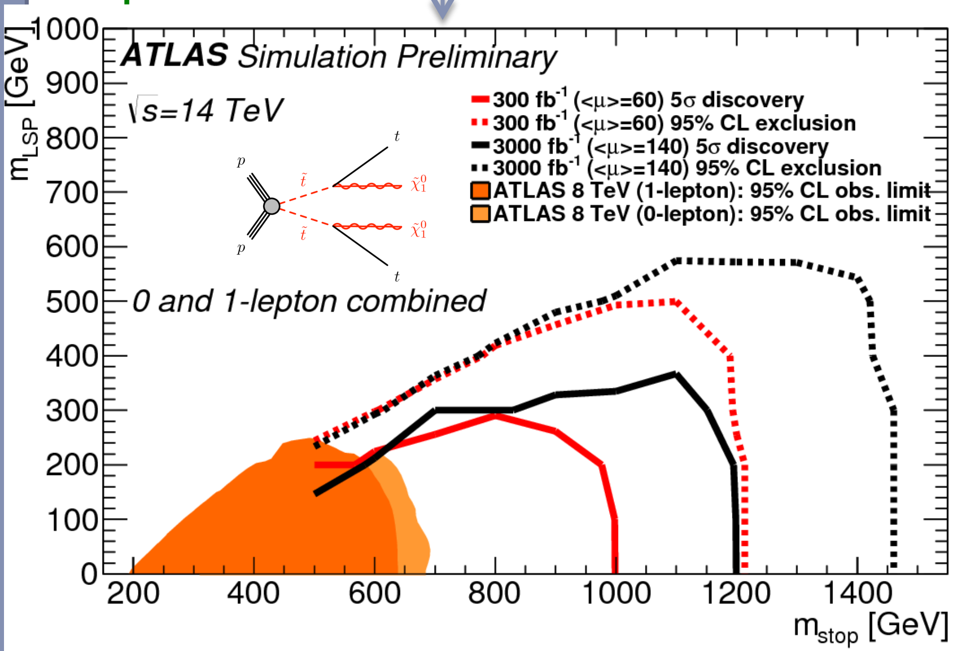


Third generation squarks

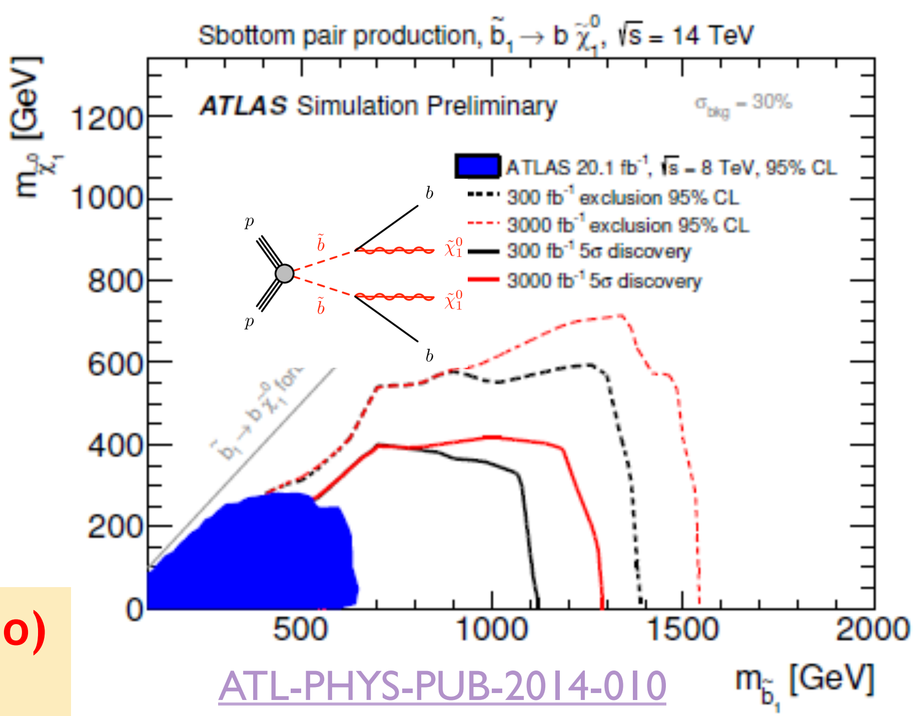
- Top and bottom squarks
  - Direct production, feasibility studies only for standard cases (b/t+LSP)
  - Predictions for 'compressed' scenarios more difficult → need complex analyses, good level of knowledge for systematic uncertainties

stop

ATL-PHYS-PUB-2013-011



sbottom



Discovery reach up to 2.5 TeV (gluino) and above 1 TeV (stop/sbottom)

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EWK SUSY at the HL-LHC

- Chargino and neutralino production

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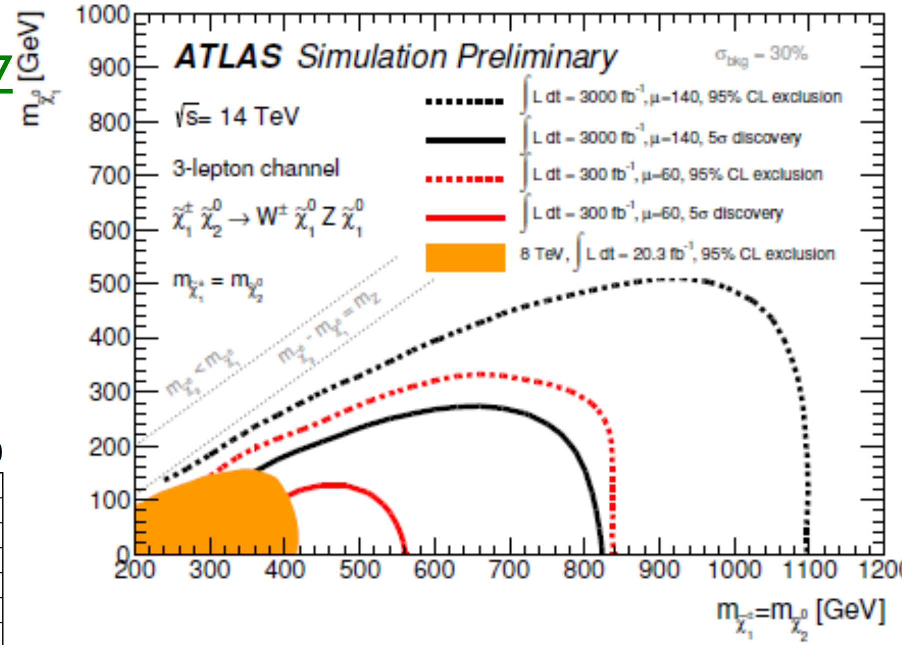
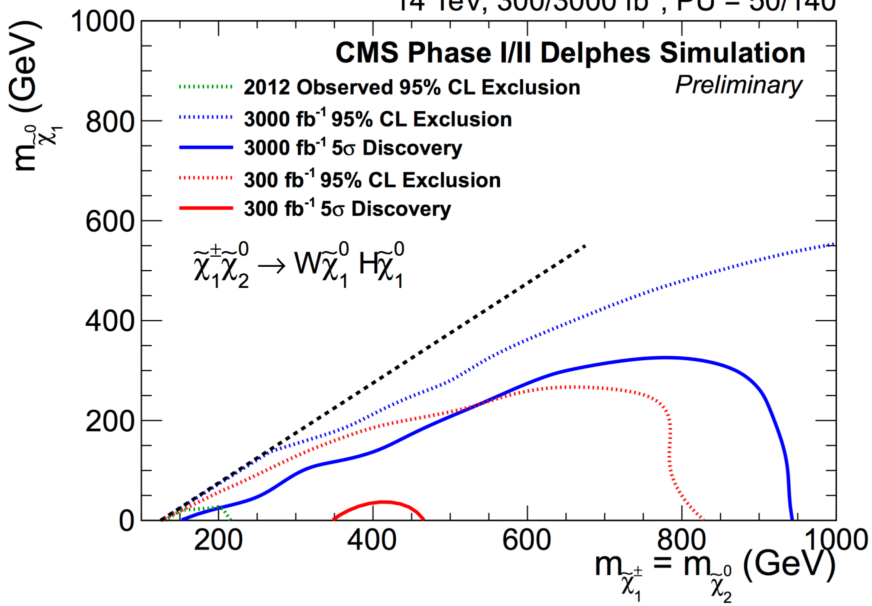
Via WZ



Via WH, with higgs in WW*, ττ

CMS PAS SUS-14-012



Charginos/Neutralinos discovery potential at 3/ab up to 800(600) GeV depending on decays mode

Very challenging even with 3 /ab

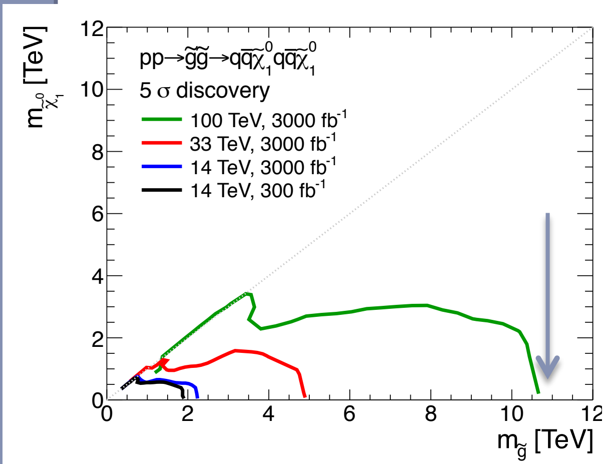
Even more prospects: High Energy colliders

- **Higher Energy hadron colliders** of course provide an exciting playground for SUSY with possibility of reaching high sparticle masses!
  - 50-70 TeV *pp* collider (SppC)
  - 100 TeV *pp* collider (FCC-hh)

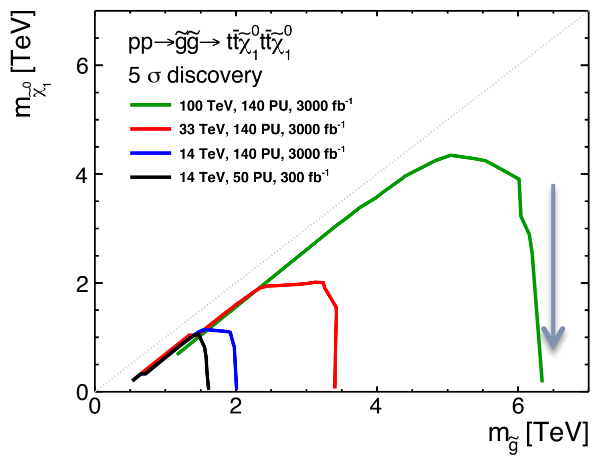
Rule of thumb: at fixed Lumi, discovery reach scales as 2/3 E_{beam}
X 5 from 14 to 100 TeV

Gluino pair production @ 100 TeV

Simple feasibility studies: several jets + ETMiss searches

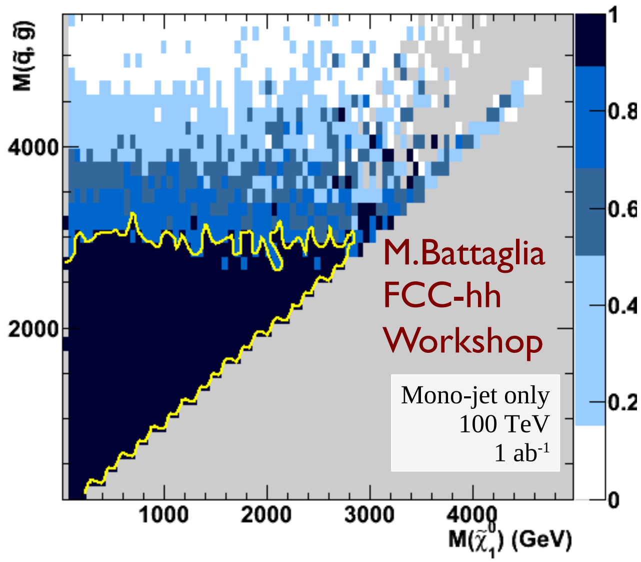


→ Discovery reach up to 11(6) TeV depending on decay mode



arXiV:1310.0077
(Snowmass '13 studies)

Feasibility studies: mono-jet searches (relevant for compressed scenarios)

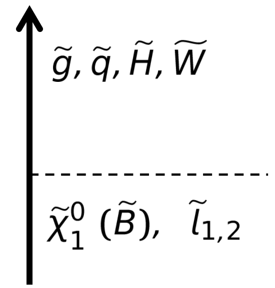


M.Battaglia FCC-hh Workshop

FCC-hh to operate **at the same time of FCC-he and FCC-ee: great complementarity**

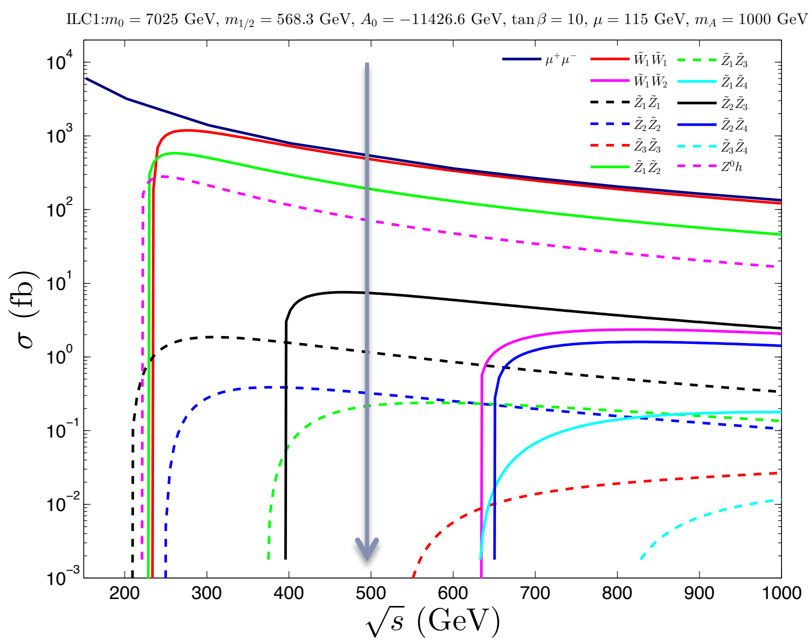
electron-positron machines

- Various proposals under study:
  - Linear e+e- colliders: ILC, CLIC
  - Circular e+e- colliders: FCC-ee (was TLEP), CEPC
- Why are they interesting for SUSY ?



Sensitive to EWK process
Compressed scenarios in 'Natural' SUSY

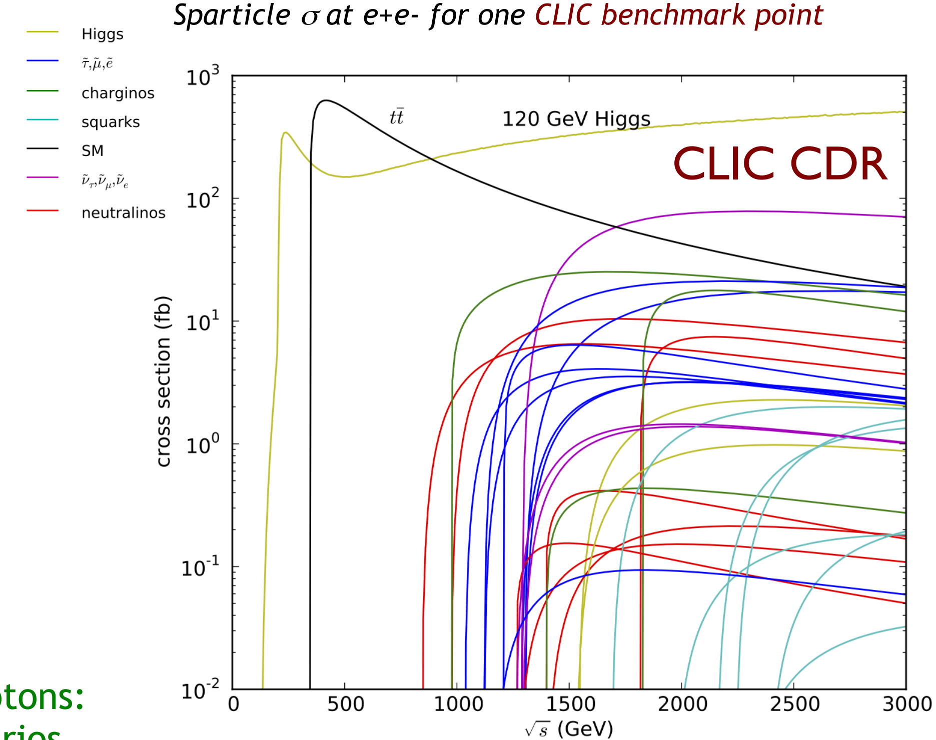
Sparticle σ for unpolarized beams at e+e- for ILC benchmark



arXiV:1404.7510

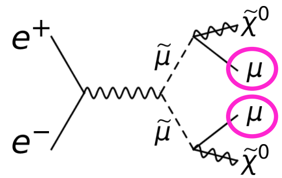
High cross section for $\chi^{\pm}_1$ and χ_0 production and sleptons: clean environment to access very compressed scenarios

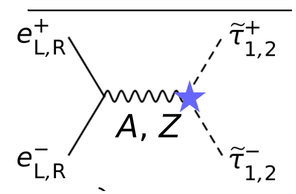
Sparticle σ at e+e- for one CLIC benchmark point

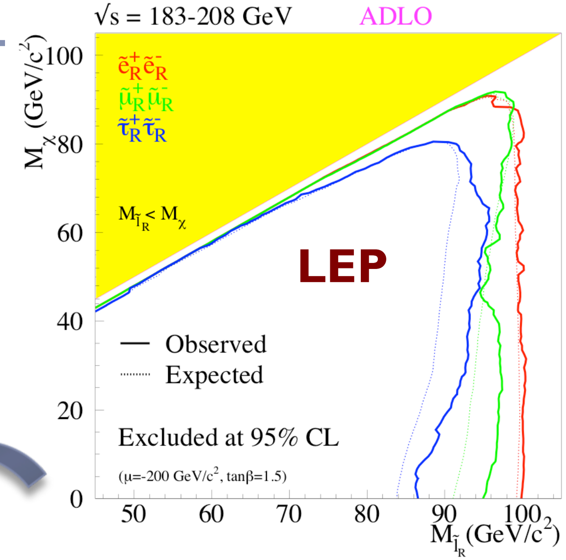


electron-positron machines (II)

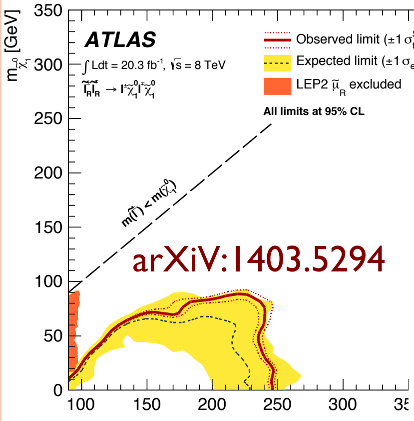
- In EWK SUSY sector, some of the LEP limits are still the most stringent up to date.
- *Example:*
  - slepton pair production

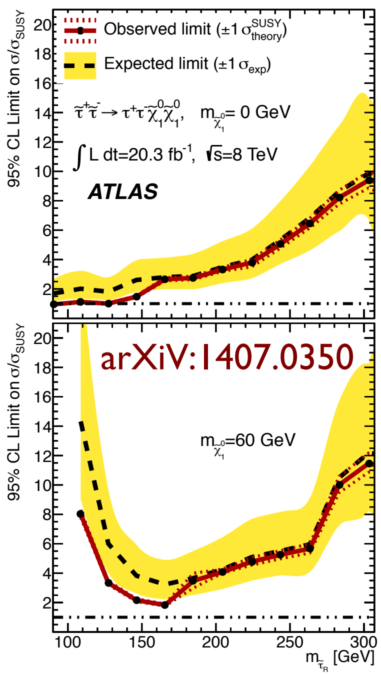






LHC current results





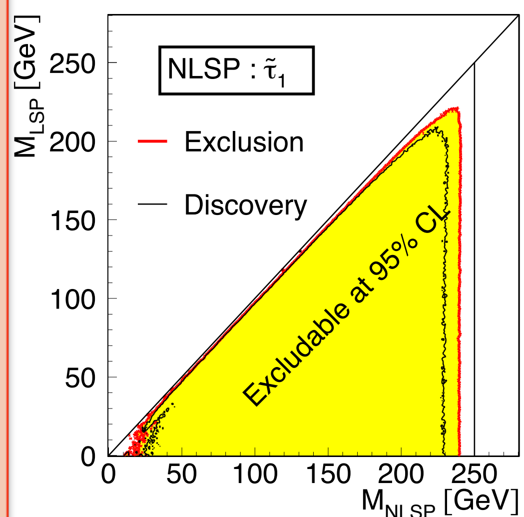
$\tilde{e}/\tilde{\mu}_R$ mass

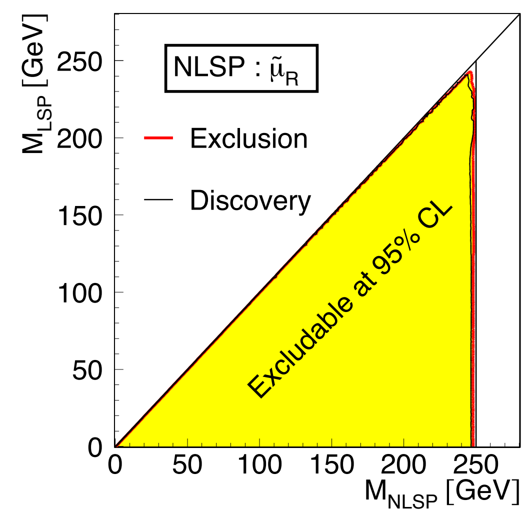
$\tilde{\tau}_1$ mass

Difficult to probe regions with ΔM(Next LSP-LSP)<100 GeV

ILC (500 GeV)

arXiV:1307.5248

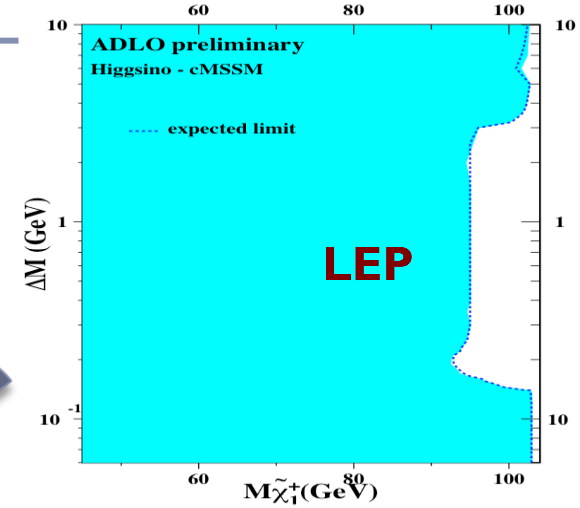




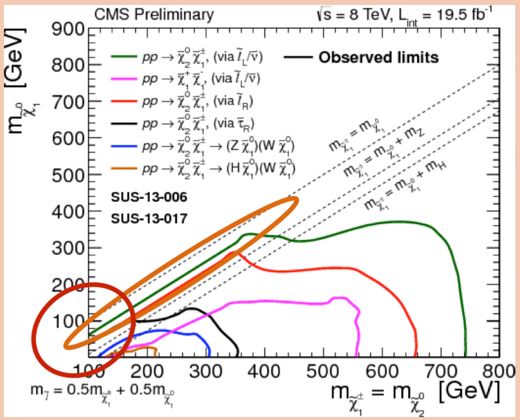
Similar studies in progress for circular colliders

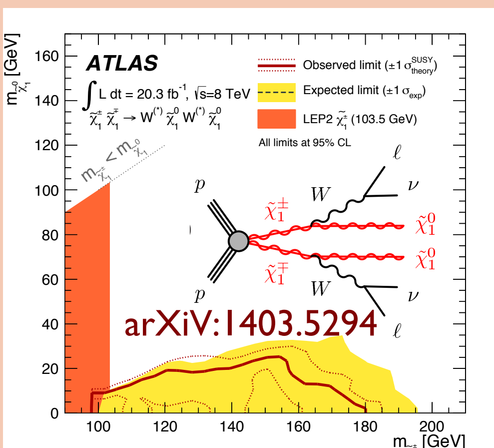
electron-positron machines (III)

- **Chargino/neutralino pair production**
- Very challenging at hadron colliders if no intermediate sleptons and/or in compressed scenarios



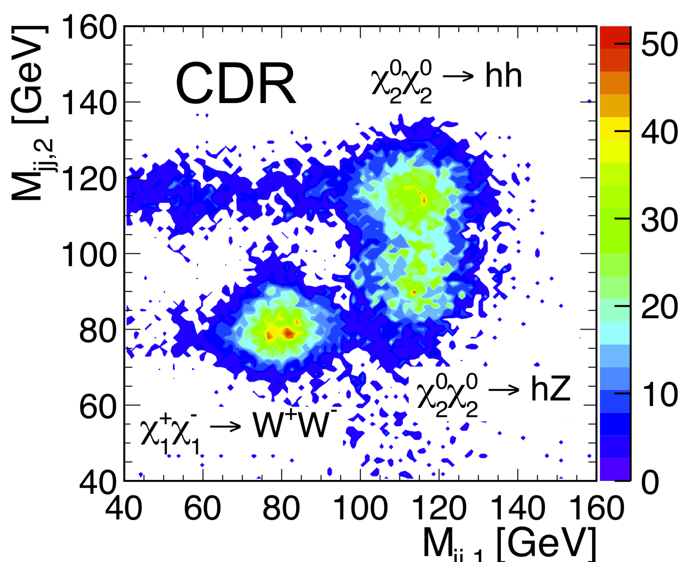
LHC current results





→ LEP limits are still the most stringent for model- independent chargino mass!

CLIC (Stage 2: 1.4 TeV)



$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$

$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to hh\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0 \to Zh\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

Precision on the measured chargino/neutralino masses (few hundred GeV): 1 - 1.5%

(M(charg/neut2)=487 GeV)

Similar studies in progress for circular colliders

For discussion

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  And until which point can we talk about ‘Natural’ searches ?

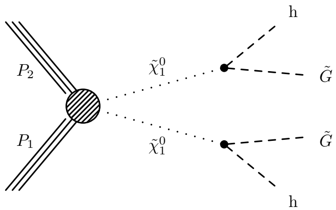
Bonus slides

Searches for EWK SUSY with higgs

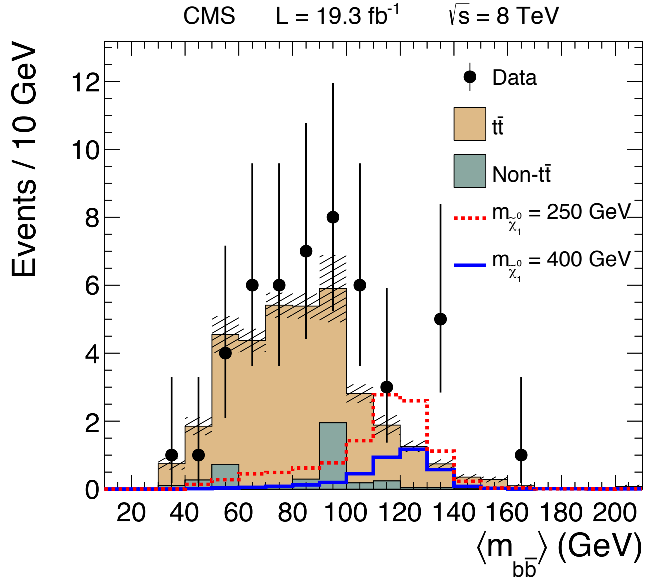
Higgs discovery opens up new branches of searches:

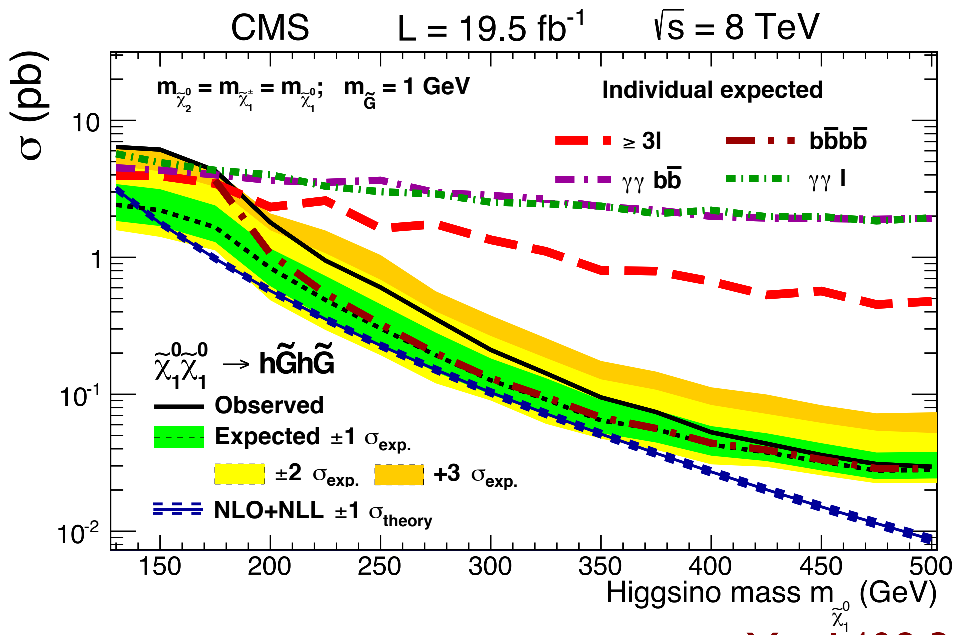
- Lightest neutral CP-even higgs expected to be SM-like, if others are heavy
- Charginos and neutralinos can decay to h+LSP

- CMS: Comprehensive set of searches for Zh, hh and hW final states
  - higgs in $\gamma\gamma$, bb, ZZ* and WW*
  - Example for neutralino pair production in Gauge Mediated Models:



hh→bbbb mode

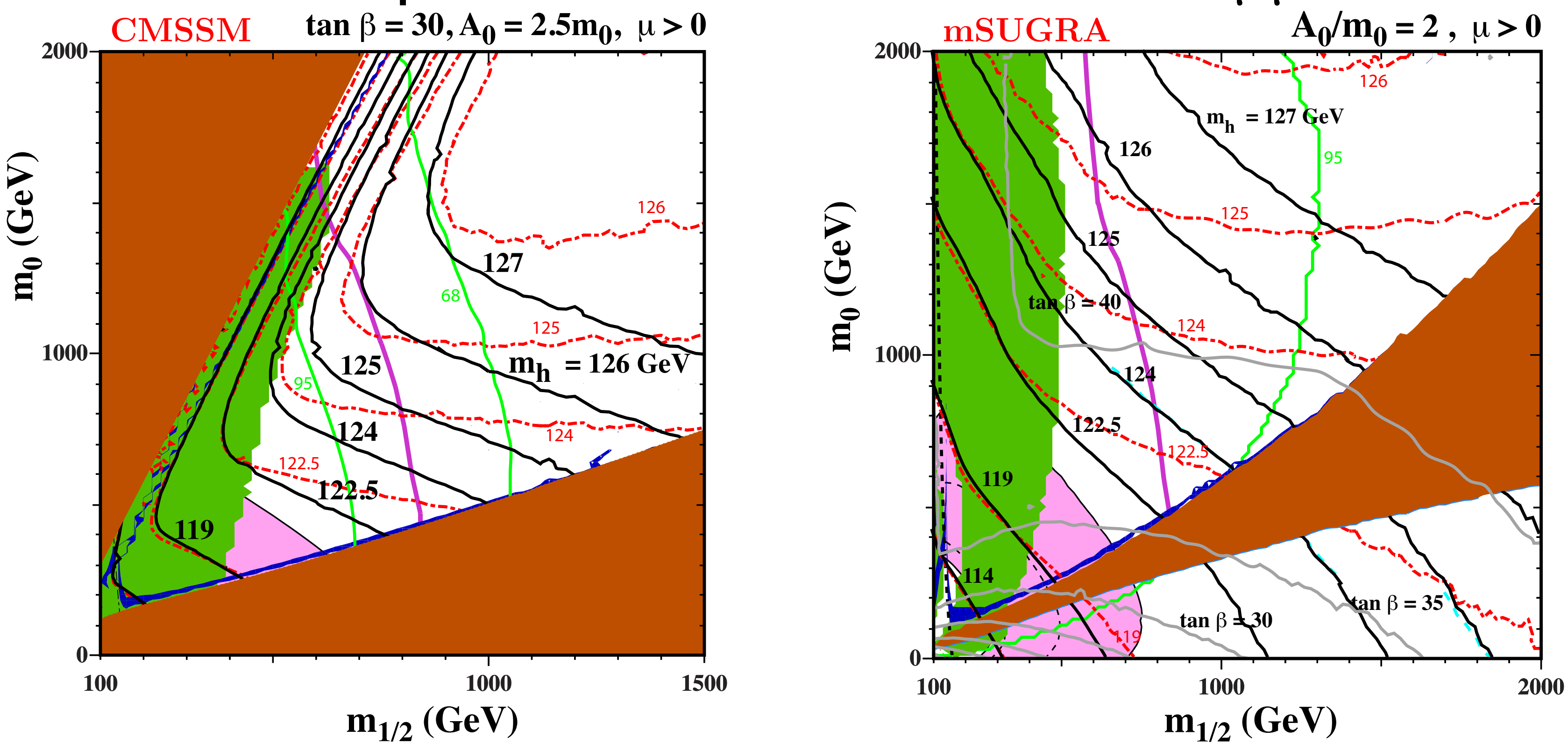




arXiv:1409.3168

Constraints from Bs

- Other examples of constraints from Bs→μμ



green lines – bounds from $B_s \to \mu^+\mu-$ (CMS & LHCb 2013, exclusion to the left)

purple lines – ATLAS 95%CL bounds from $\not{E}_T+$ jets

green shaded – excluded by $b \to s\gamma$

brown shaded – charged LSP

pink shaded – SUSY helps with $g-2$

blue strips – favoured by $\Omega_{\rm DM}$

arXiv:1312.5426