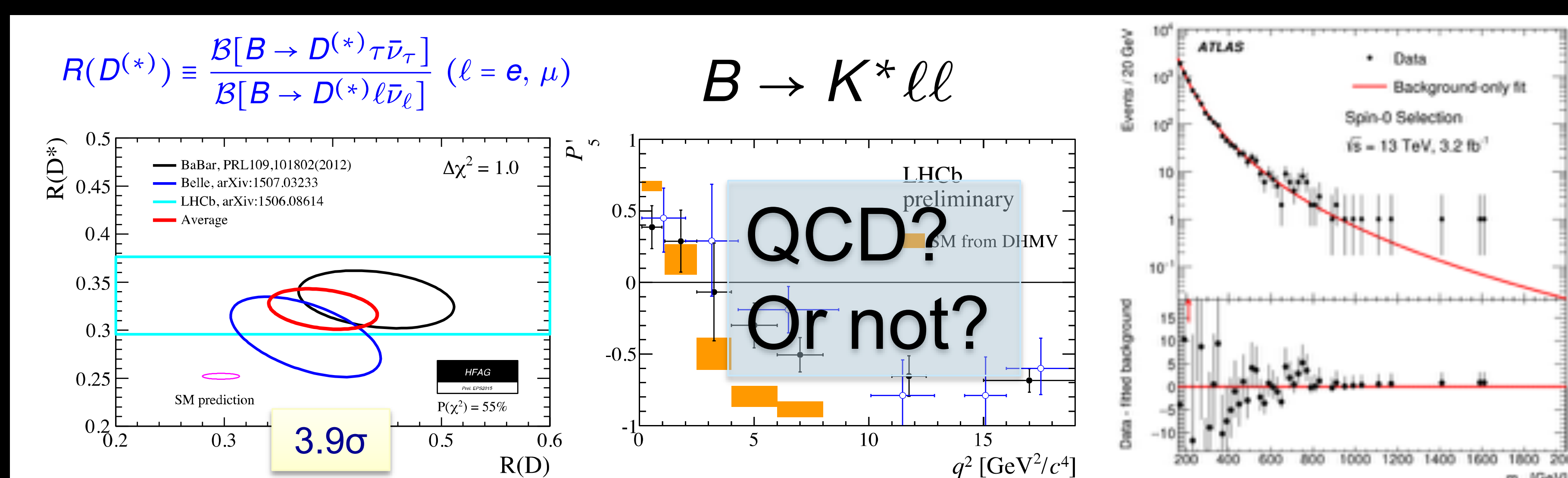
TOMMASO LARI, INFN MILANO

SUPERSYMMETRY BETWEEN HOPE AND DESPAIR

STANDARD MODEL

- The SM has predicted correctly measurements done at colliders for the last 40 years
  - Electroweak precision measurements, top and higgs masses and properties, CP violation, precision flavor physics, LHC cross sections etc.
  - Tensions exist at any given moment - currently : g-2, some flavor physics observables, 750 GeV bump. But no evidence of BSM at colliders yet



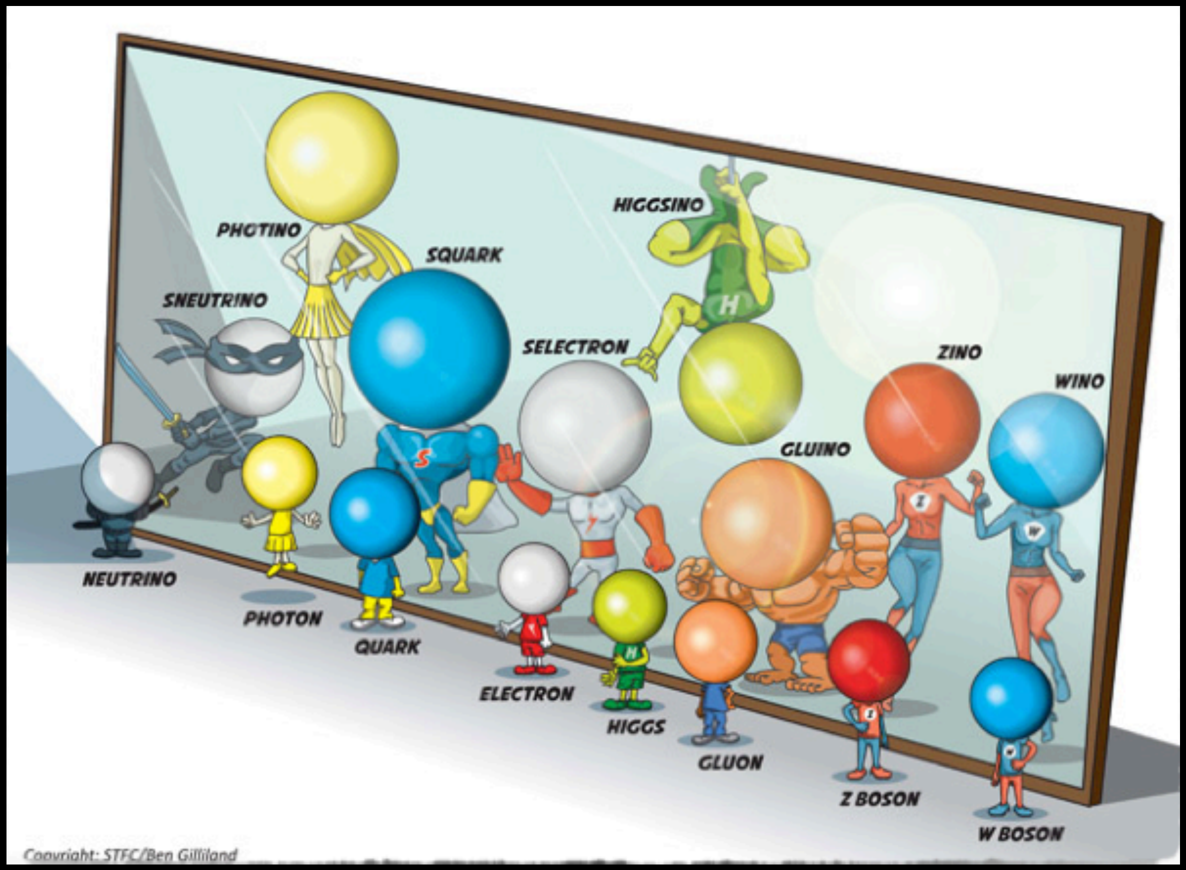
STANDARD MODEL

- The SM is however doing very badly to describe the real world…
  - No Dark Energy
  - No Dark Matter
  - No matter (should have annihilated with antimatter)
  - No neutrino masses
  - No gravity
  - Electroweak scale

None of this is predicted by the SM !

SUPERSYMMETRY

- symmetry between bosons and fermions, doubles the spectrum
- two Higgs doublets, giving a five Higgs bosons and their spin 1/2 partners
- Minimum particle content :
  - gluinos (degenerate octet)
  - scalar quarks and leptons
  - colorless neutral ($N^0_{1,2,3,4}$) and charged ($C^+_{1,2}$) states, from mixing of higgsinos, photino, winos, zinos
- All masses and interactions predicted by the symmetry to be the same as those of the SM (!!)

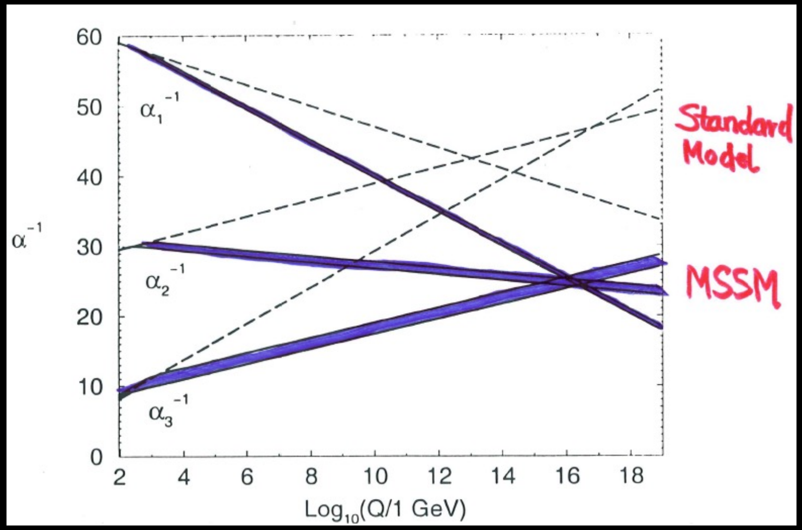


SUSY BREAKING

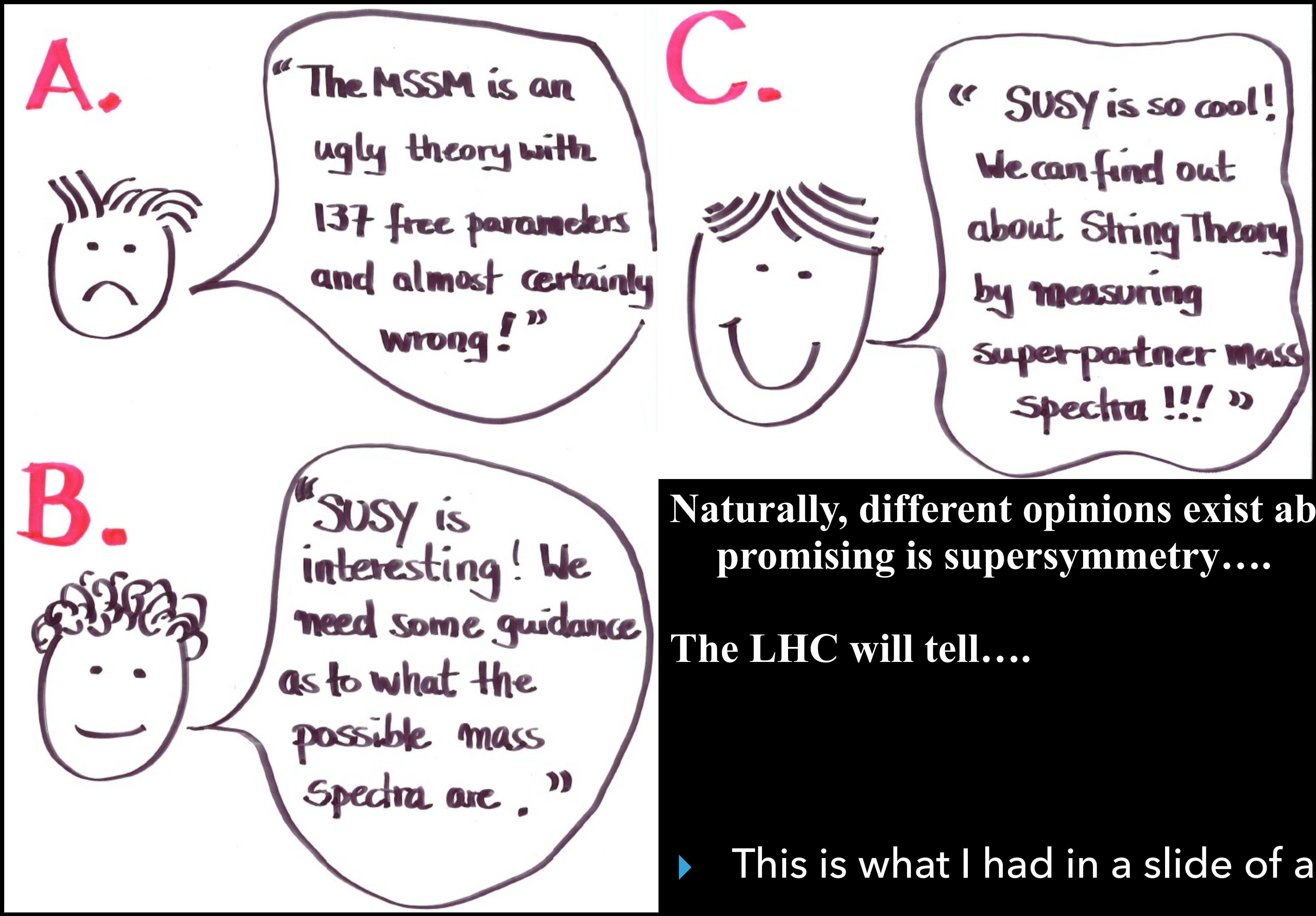
- One needs to introduce new particles and interactions in order to have a viable spontaneous breaking of supersymmetry
- We don't really know how this might be realized, so there are two choices :
  - Assume a specific mechanism of SUSY breaking, giving a predictive model with few parameters, much might be wrong
  - Write the more general weak-scale lagrangian, which has ~120 free parameters. As there are very strong flavor physics constraints on sfermion mixing angles and CP phases, one can set all of them to zero, but we still have at least ~20 free parameters relevant for collider phenomenology

QUITE A FEW ADVANTAGES

- Cancelation in the radiative contributions to the Higgs mass between SUSY and SM particles. It solves the hierarchy problem, if super-partner masses are at the Higgs mass scale.
- If R-parity is conserved, the lightest SUSY particle is stable providing a Dark Matter candidate.
- Unification of gauge couplings. The unification of couplings was taken as a strong hint that SUSY was right.
- Electroweak spontaneous breaking is predicted in SUSY, has to be assumed in the SM.



CERTAINLY DIFFERENT VIEWS OF SUSY EXISTED…



Naturally, different opinions exist about how promising is supersymmetry….

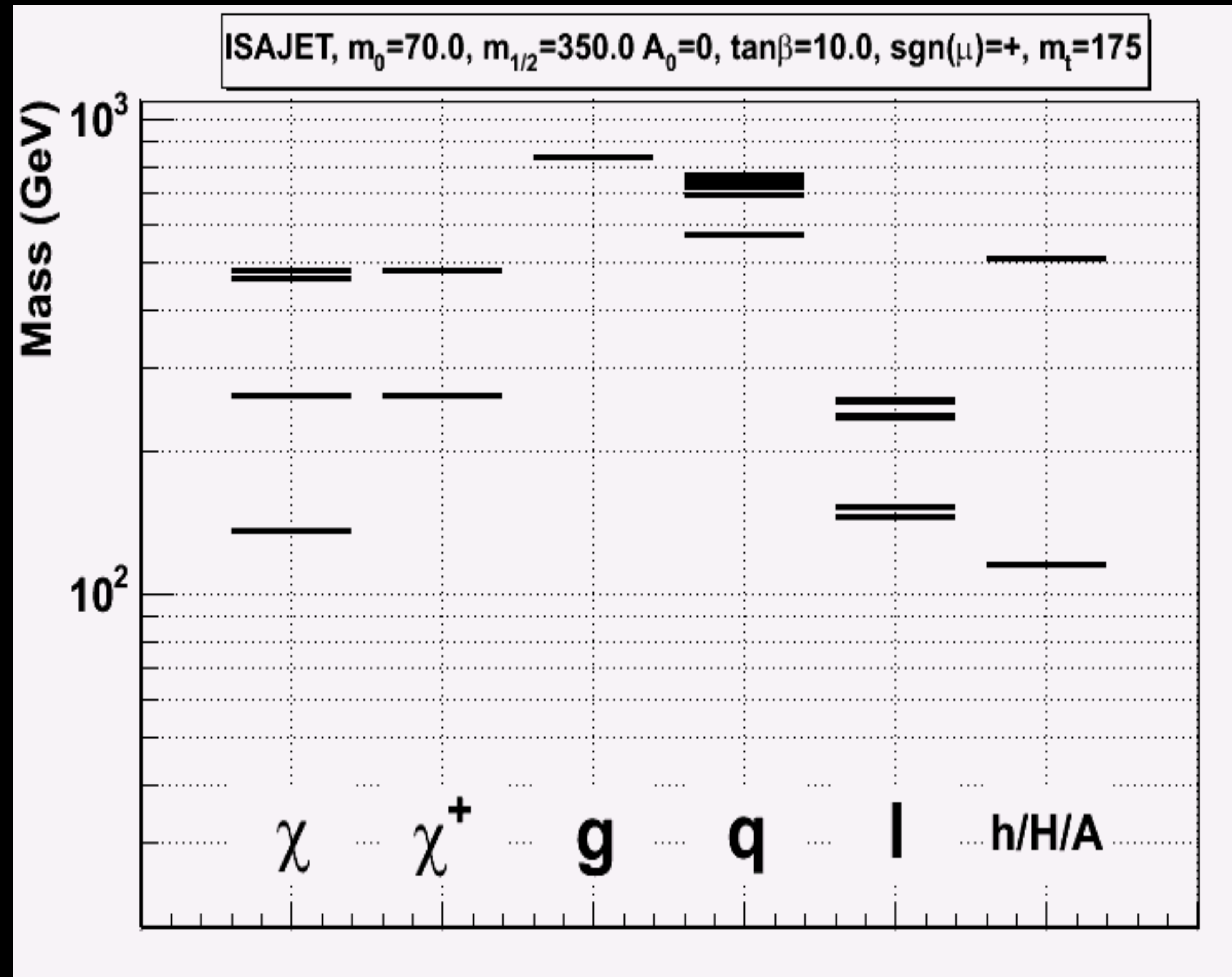
The LHC will tell….

- This is what I had in a slide of a seminar in 2007

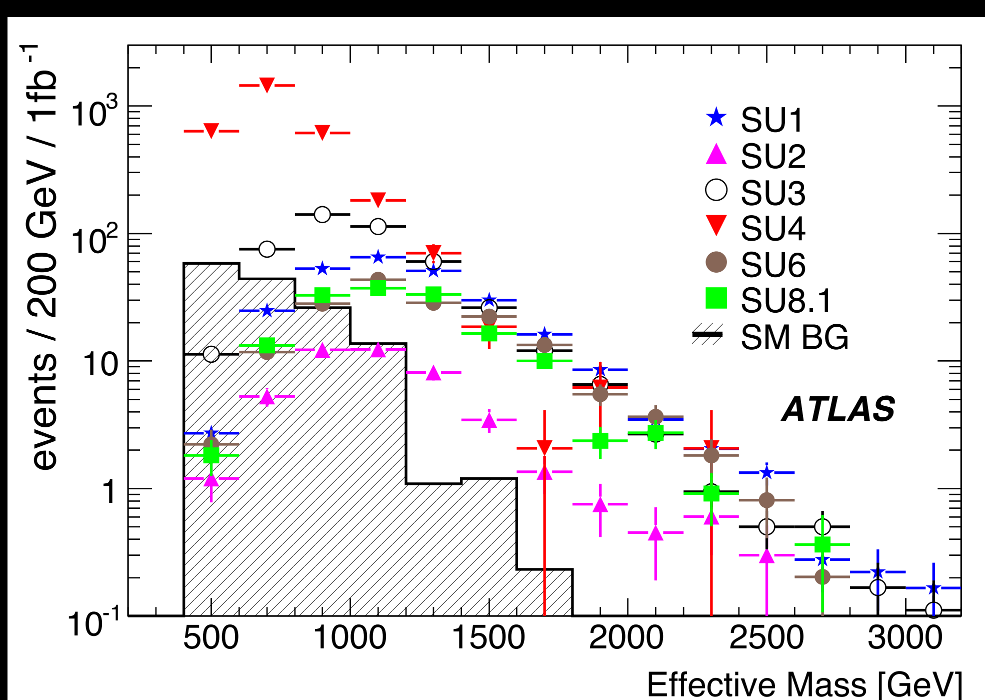
BUT PREDICTIONS WERE CLEAR ENOUGH AND TESTABLE

- Lightest CP-even Higgs boson lighter than the Z mass.
  - Radiative corrections actually can raise its mass up to 130 GeV maximum for large tan b, stop mass and mixing.
- Superpartners at the same mass scale of the Z (order of magnitude) to ensure naturalness
- It was reasonable to expect the observation of both the Higgs boson and SUSY particles at LEP. But should that fail, SUSY particle (if they existed) would show up pretty early at LHC, with the Higgs taking a bit more time

GREAT EXPECTATIONS



Sample	$M_{\rm eff} > 400$ GeV		$M_{\rm eff} > 800$ GeV		$M_{\rm eff} > 1200$ GeV	
	Events	Z_n	Events	Z_n	Events	Z_n
Standard Model BG	144		42		2	
SU1	260	7.6	232	12.3	114	18.0

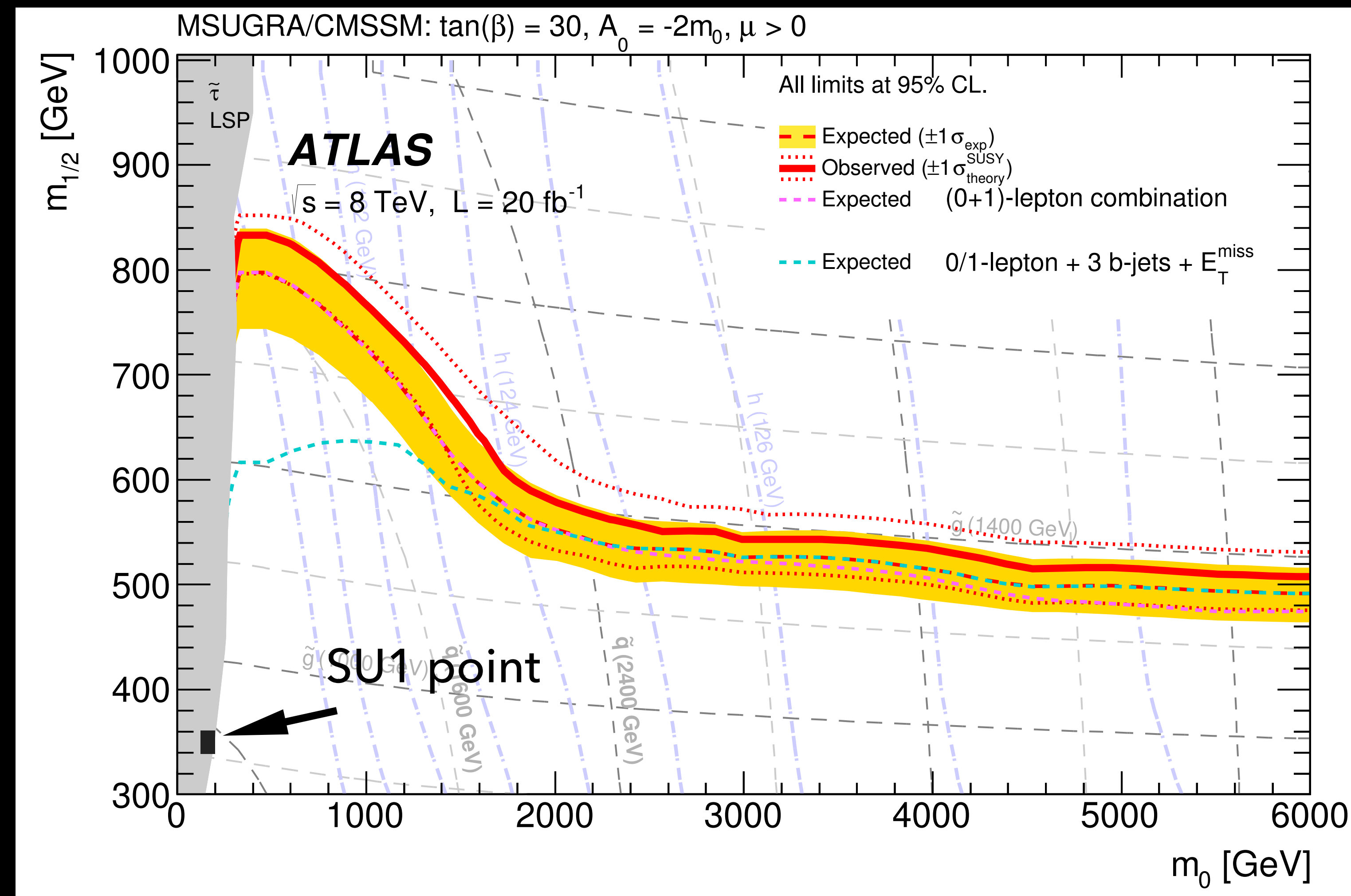


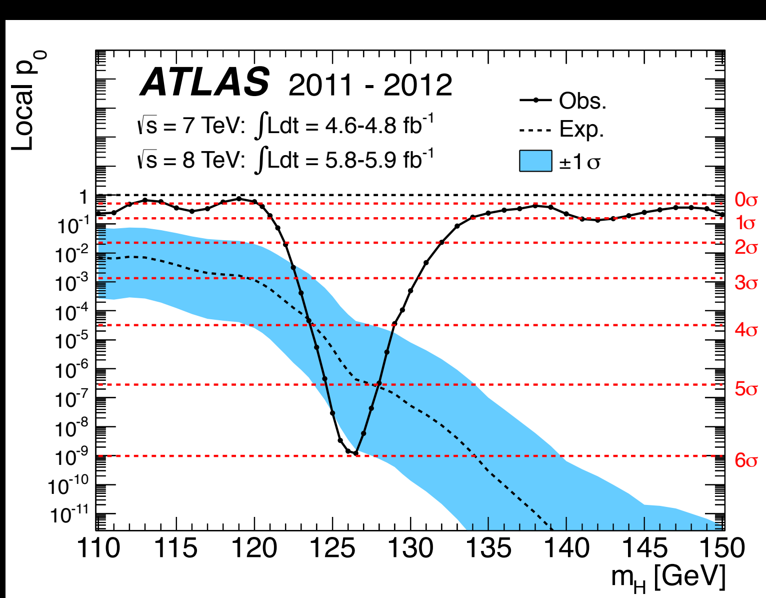
- A significance of 18 standard deviations was expected with 1 fb^{-1} at 14 TeV in the 1-lepton channel, for the "SU1" point (which wasn't the easiest one)

REALITY CHECK…

- plot shows the limit on the (former) most popular gravity-mediated SUSY breaking model
- squarks bound to be heavier than about 1600 GeV. The stop mass is related to that of other squarks, which makes the model not very natural (top loop to the Higgs is not well canceled, ~1% fine tuning or worse remain)
- We don't even bother to generate mSUGRA simulated samples these days..

http://arxiv.org/abs/1507.05525





- SM-like Higgs at 125 GeV, this is ok. A bit heavy but still within the range predicted by SUSY.
- The hierarchy problem is more actual than ever. DM is still there too.

REACTIONS

I ALWAYS KNEW SUSY WAS WRONG

Still needs some BSM which evades LHC constraints

LET'S FORGET ABOUT NATURALNESS

SUSY with heavy squarks still addresses DM and unification.

LHC signatures : EWKinos production, possibly long-lived gluinos

multiverse plus anthropic selection ? UV-less SM extensions somehow ?

SUSY IS JUST A BIT SHY

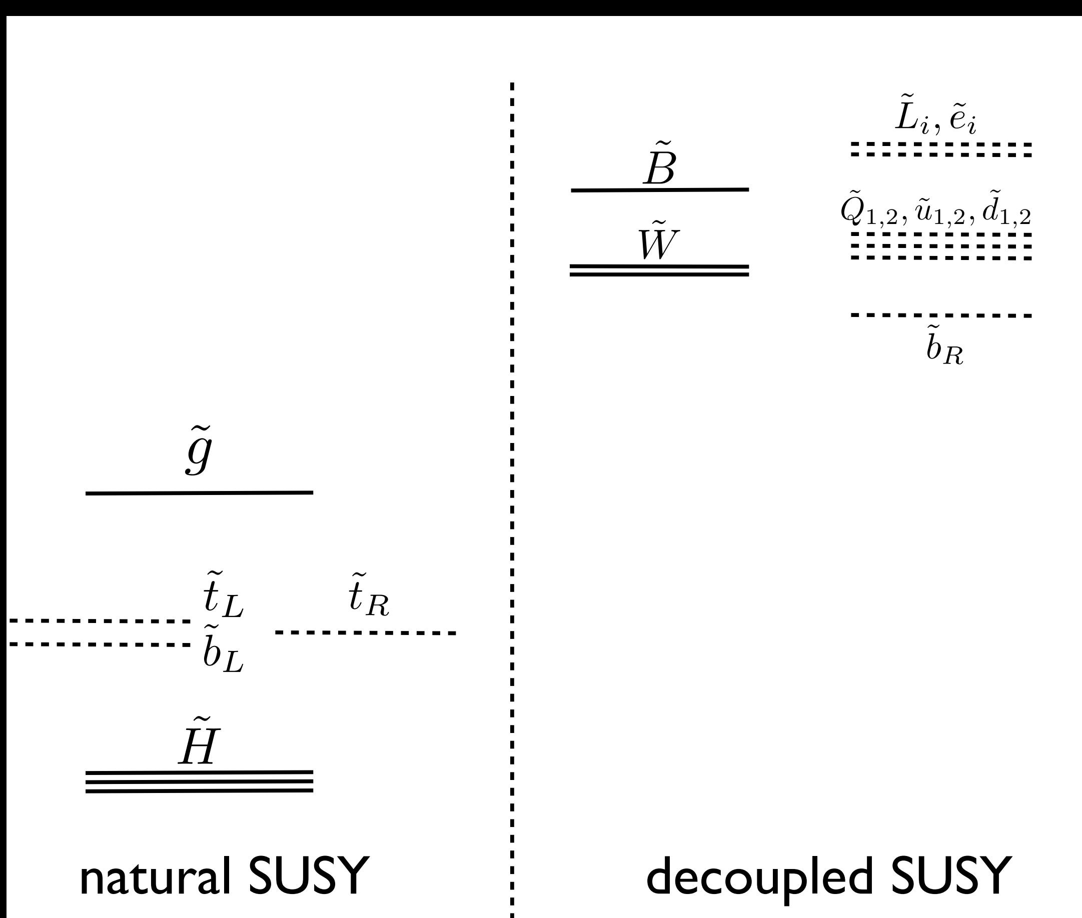
- Typically relies on ways to reduce E_T^{Miss} at LHC : R-parity violation (need something else for Dark Matter!) with UDD coupling harder to find, compressed mass spectra, stealth SUSY…
- LHC signatures : monojet, soft leptons, RPV searches

NATURAL SUSY IS PERFECTLY FINE

- Beware of how fine tuning is calculated
- Beware of assumptions in LHC limits
- You never believed in mSUGRA, did you ? SUSY can be a lot more complicated - could accomodate a natural spectrum still

NATURALNESS AS A GUIDE

- The higgsinos, stop and gluino are related to the Higgs mass at tree level, 1-loop, 2-loop respectively. For a natural scenario, these particle *must be* light, the others *might be* light.



$$\Delta = \left| \frac{\partial \ln m_Z^2}{\partial \ln \theta} \right|$$

$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2 \quad \Rightarrow \quad \Delta \sim 5\left(\frac{\mu}{200GeV}\right)^2$$

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right) \quad \Rightarrow \quad \Delta \geq 30\left(\frac{m(\tilde{t}_1)}{TeV}\right)^2\left(\frac{\log(\Lambda/TeV)}{3}\right)$$

$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2 \ln^2\left(\frac{\Lambda}{TeV}\right) \quad \Rightarrow \quad \Delta \sim 5\left(\frac{m(\tilde{g})}{TeV}\right)^2\left(\frac{\log(\Lambda/TeV)}{3}\right)^2$$

NATURALNESS – CAVEATS

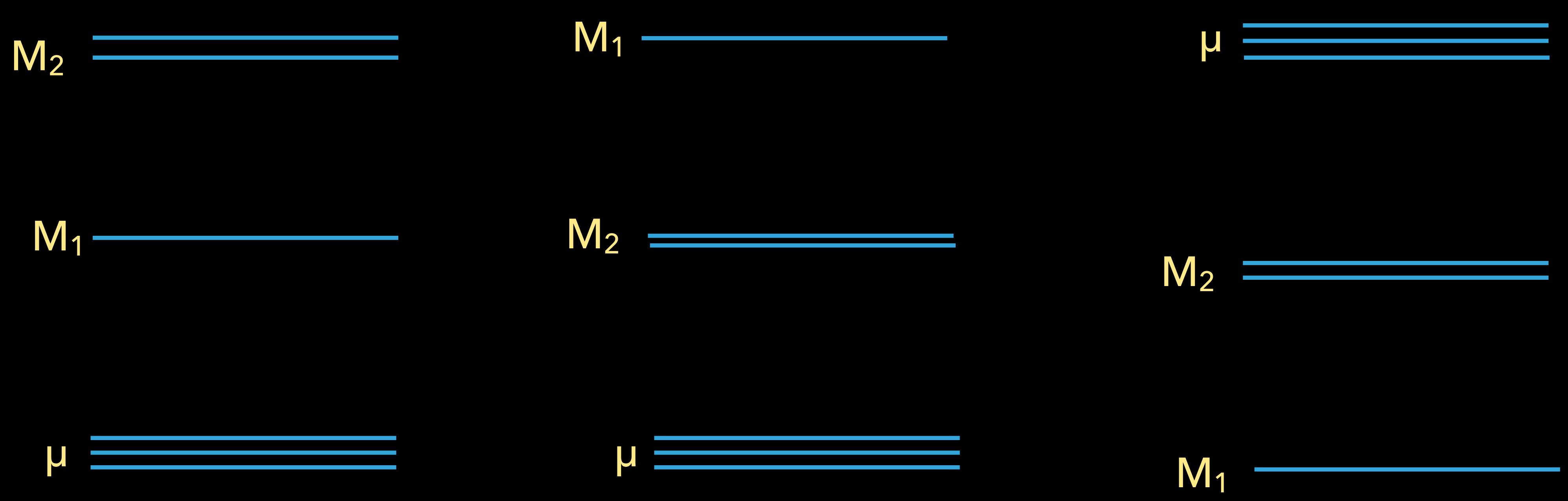
- The formulas of the previous slides consider the sensitivity of the Z mass of the electroweak scale effective susy mass parameters, but these are not the fundamental parameters of the theory, but derived from the unknown susy breaking parameters. “Accidental” cancellations might not be accidental any more, but a consequence of the SUSY breaking.
  - 1 = A - B, with B=A-1, is not fine tuned no matter how large A is !
  - higgsino has to be light in a natural theory. But the large fine tuning from high stop and gluino mass could be an apparent one.
- In any case, interpretation of the naturalness bound is subjective. How much fine tuning are you prepared to accept ? Is 5% acceptable ? 1% ? 0.1% ?

Mean apparent size from Earth:

Sun 32.1′, Moon 31.5′

2% fine-tuning.

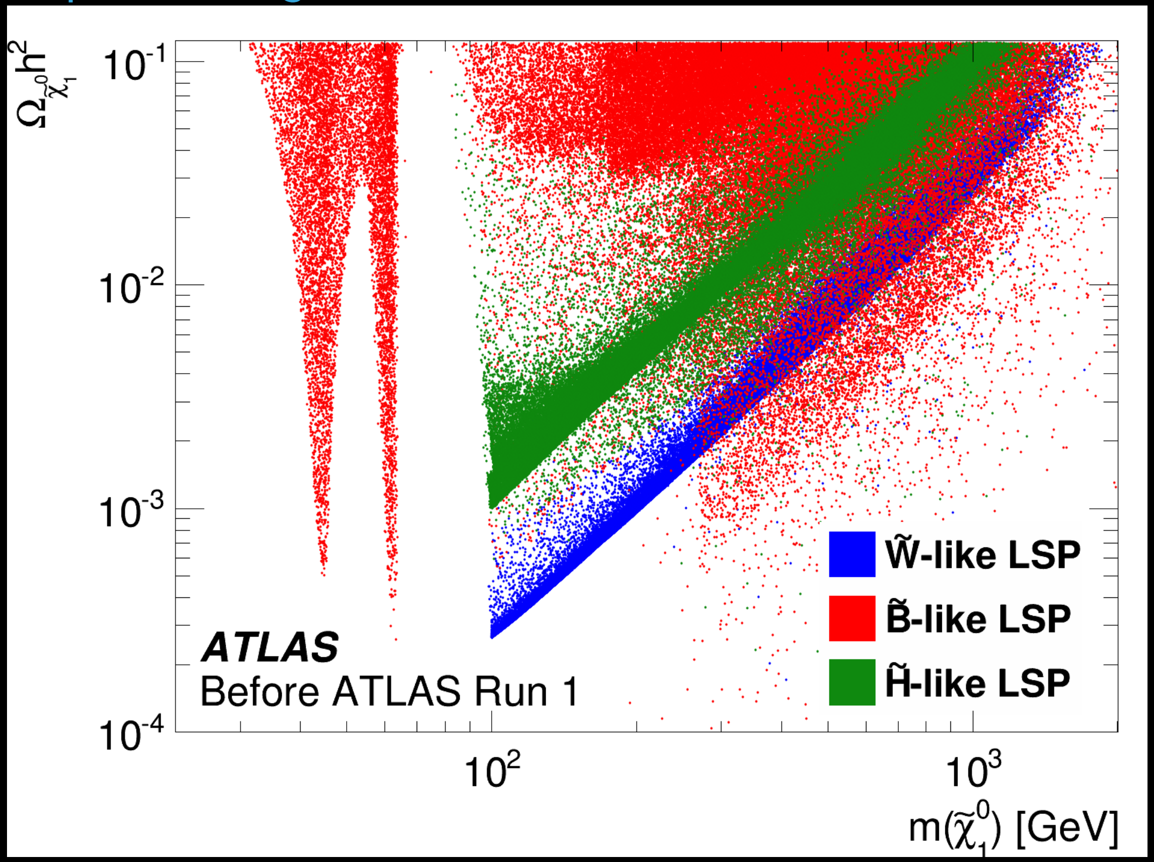
ELECTROWEAK SECTOR



- μ should be light. M_1 and M_2 might or might not be.
- mSUGRA predicts the third spectrum, still the most used in search limits (stuff which decays directly to the LSP is a simple signature)
- N_i => N_j Z or N_jh, Ci => Nj W
- If there are intermediate sleptons, decay through leptons easily dominate, 2/3/4 leptons in all events, very easy. But leptons do not need to be light either…

LET'S NOT FORGET DARK MATTER

http://arxiv.org/abs/1508.06608

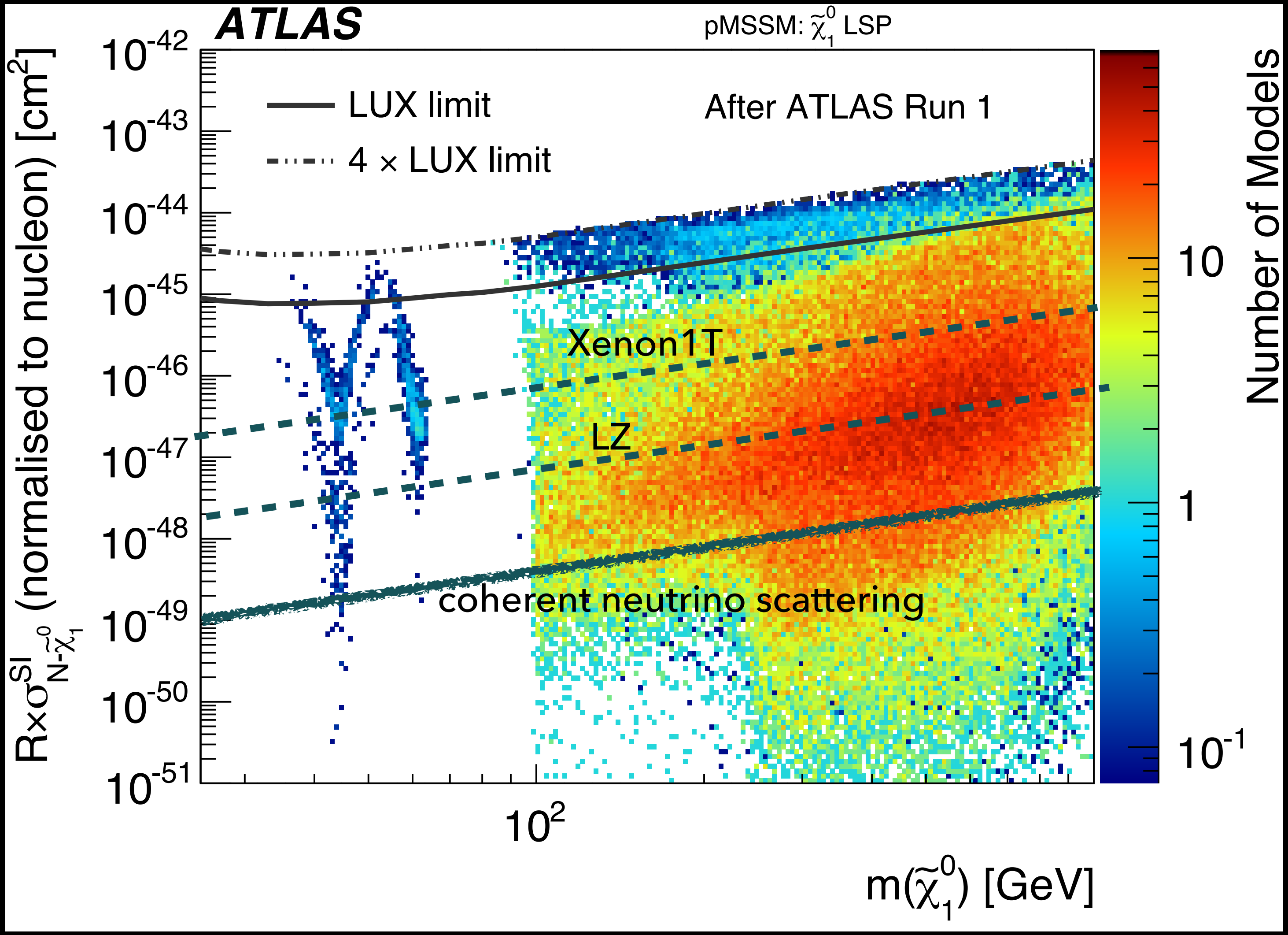


The plot is for a scan of the 19-dimensional pMSSM space, to evaluate constraints from ATLAS searches and complementarity with non-LHC constraints

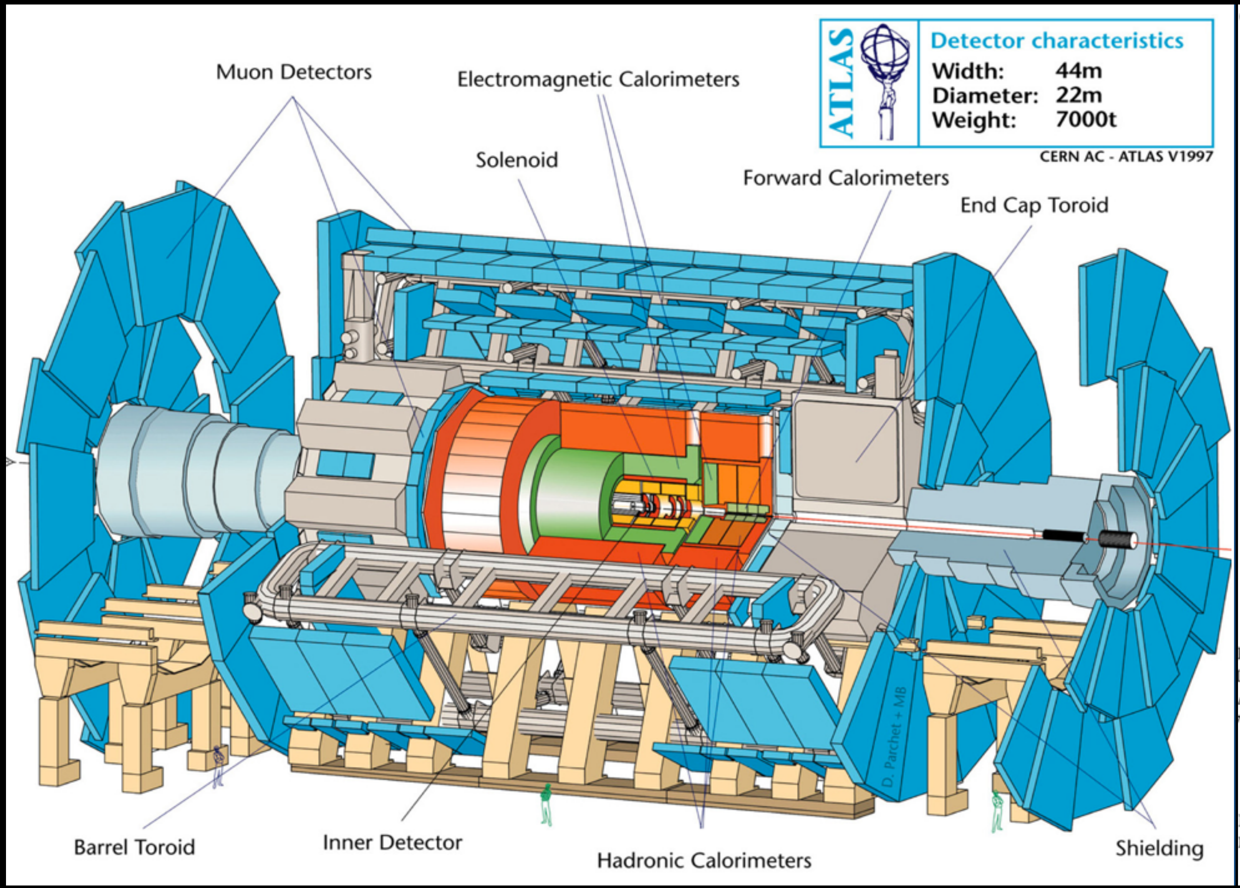
- Relic density is a tough constraints on SUSY models. Getting it right requires :
- bino like ($M_1 << M_2,\mu$) would be too abundant, need annihilation mechanism to reduce density in early universe: half the Z/H/A mass for s-channel annihilation, or close in mass (few 10s of GeV) to an other particle (squarks, sleptons)
- well tempered neutralino (careful mixture of bino, wino, higgsino => M_1, M_2, μ should be within 100 GeV)
- heavy higgsino or wino (TeV scale, bad for LHC, not natural)
- light higgsino or wino, other Dark Matter from something else (like axion)

DARK MATTER DIRECT DETECTION

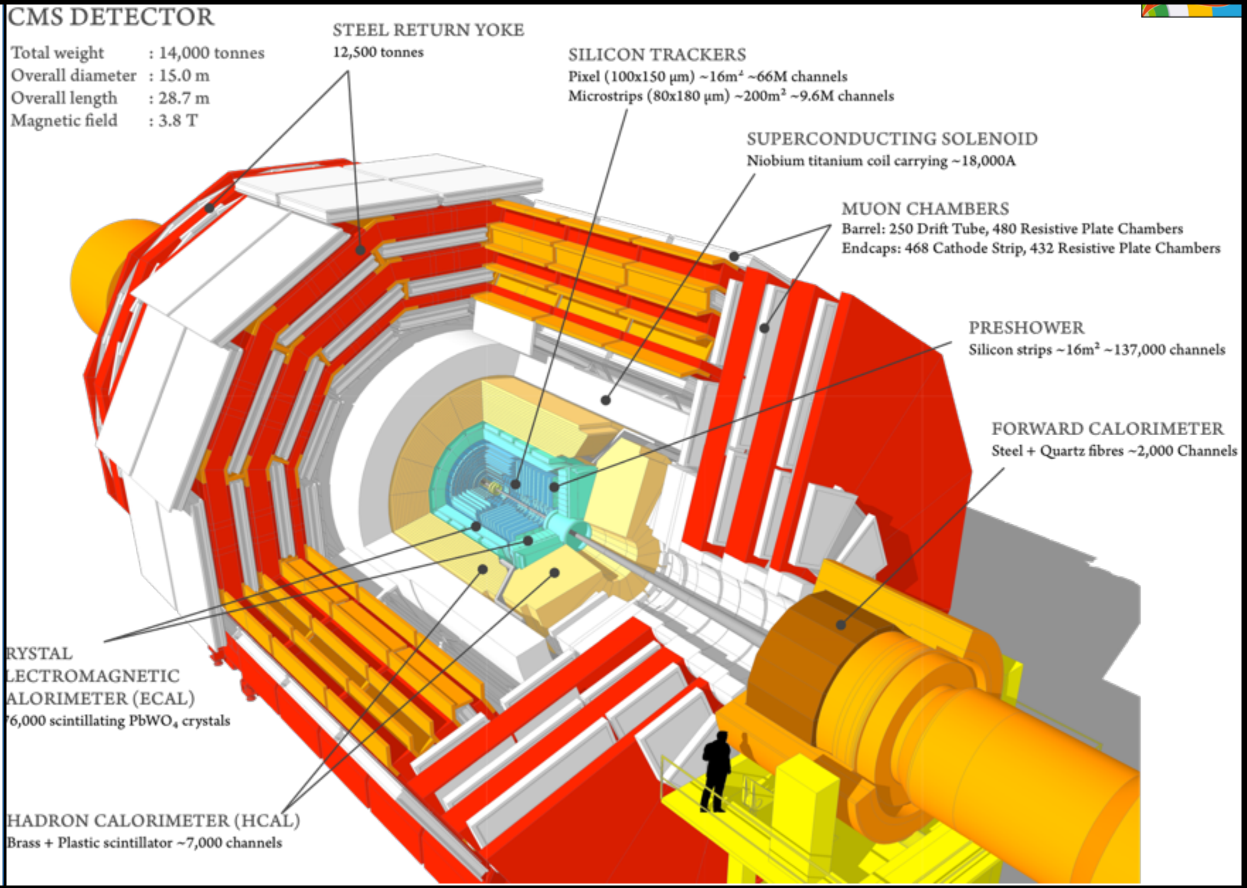
http://arxiv.org/abs/1508.06608



OK, LET'S GO TO LHC SEARCHES

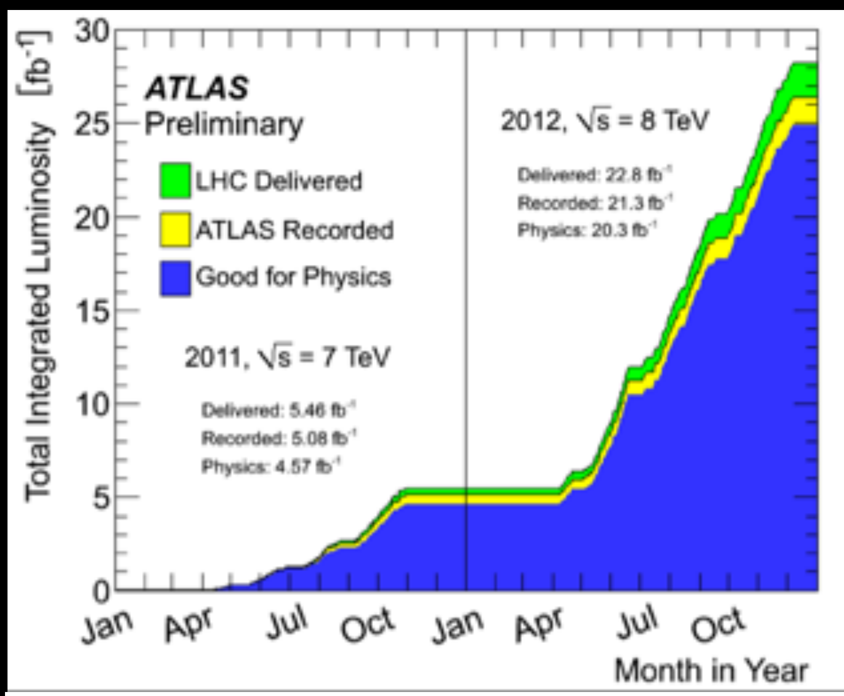


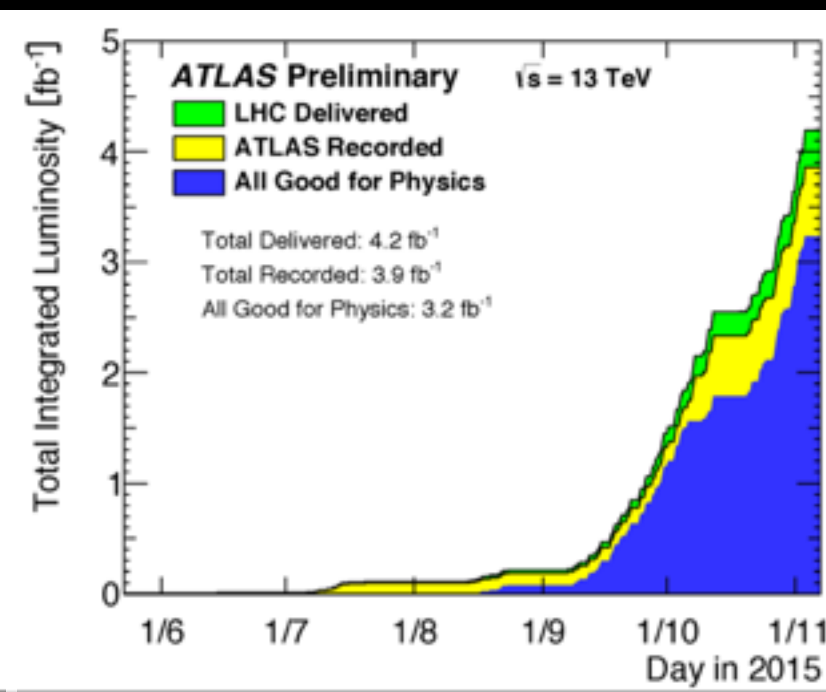
A ToroidaL ApparatuS

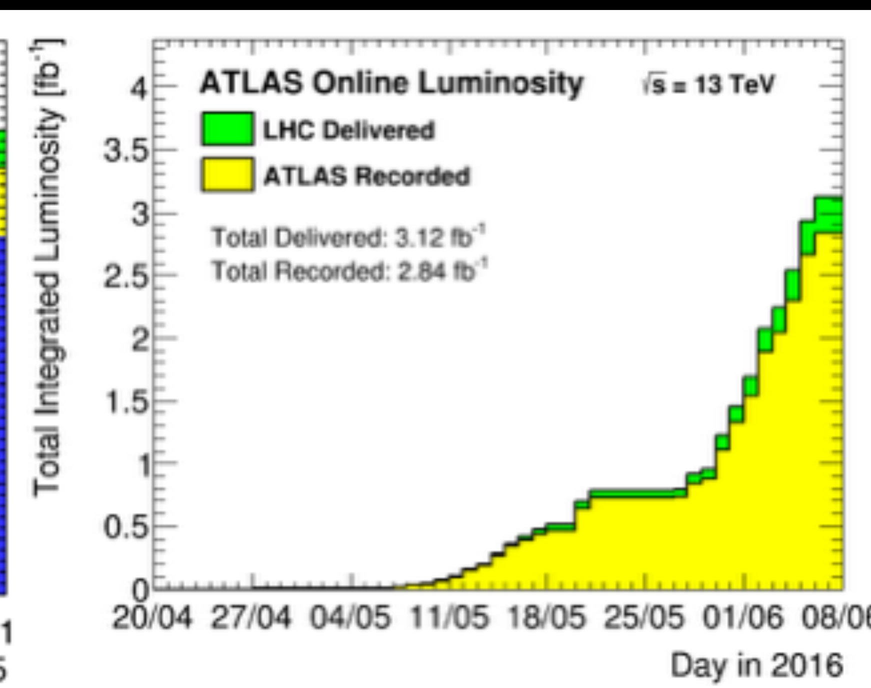


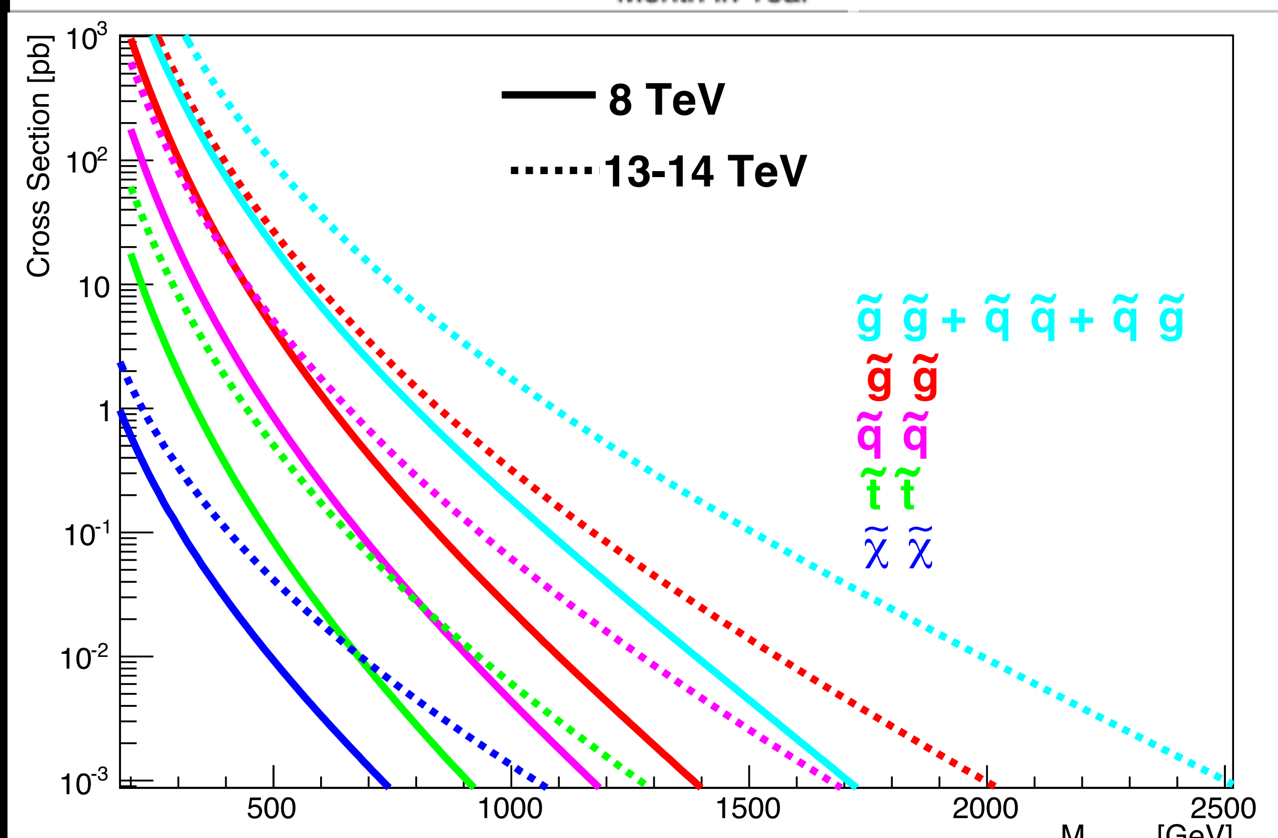
Compact Muon Spectrometer

AVAILABLE DATA









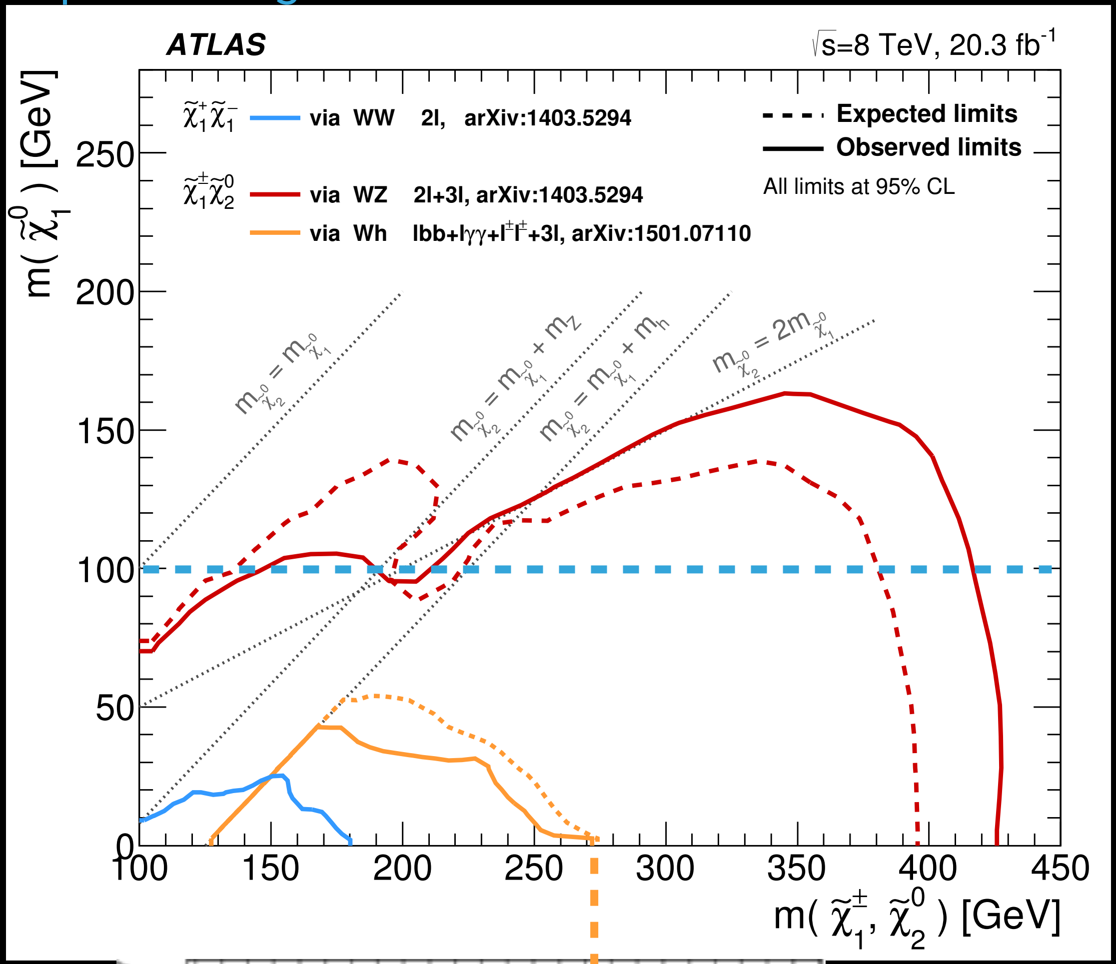
- Cross section for strong production (gluino, squarks) of heavy particles rise with energy more than that of weak production (charginos, neutralinos, sleptons) of light particles.

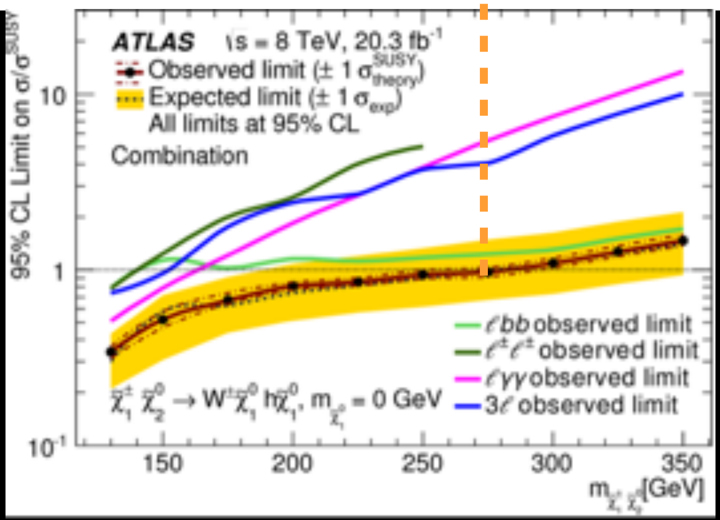
- 2015 data have placed strong constraints on the already tight limits on strongly interacting particles. Electroweak search limits are still from run1 (but they will benefit the most from integrated luminosity)

EWKINOS WITHOUT SLEPTONS

- Limits on C_1N_2 production decaying via either WZ or WH (the case of both decays competing is not shown).
- WH mode limit will improve fast with luminosity (best channel is 1Lbb+MET, BR limit only weakly dependent on mass)
- WZ mode limit from 3L+MET, 2L+2J+MET channels. Very clean signature for large $\Delta M(N_2,N_1)$, more difficult for $\Delta M \sim m_Z$ (signal similar to SM WZ background) and for $\Delta M << m_Z$ (soft leptons from decay via virtual W,Z) .
- Only bino-like can be lighter than 100 GeV, then limits on the NSLP in the 200-400 GeV range, depending on the decay mode.
- For LSP heavier than 100 GeV, very weak limits, and no limits for ΔM < 30 GeV in any case.

http://arxiv.org/abs/1509.07152

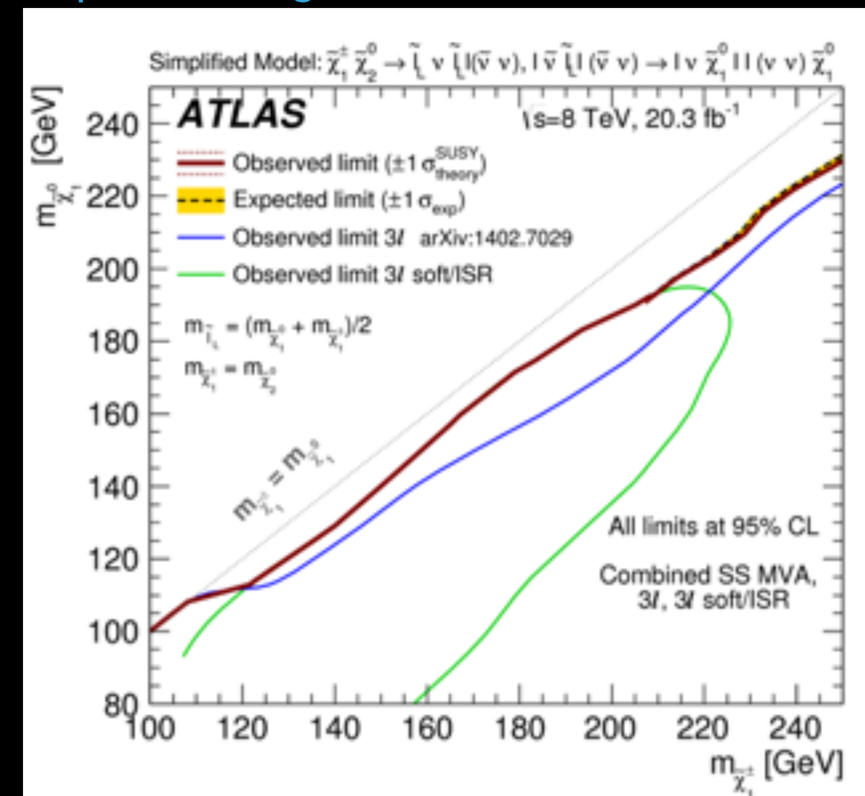




http://arxiv.org/abs/1501.07110

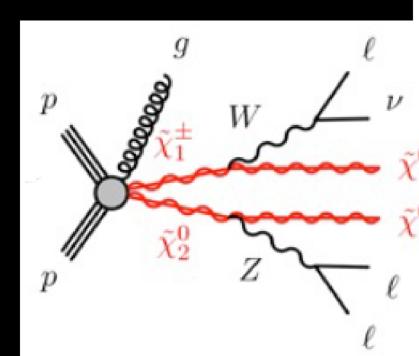
COMPRESSED SPECTRA

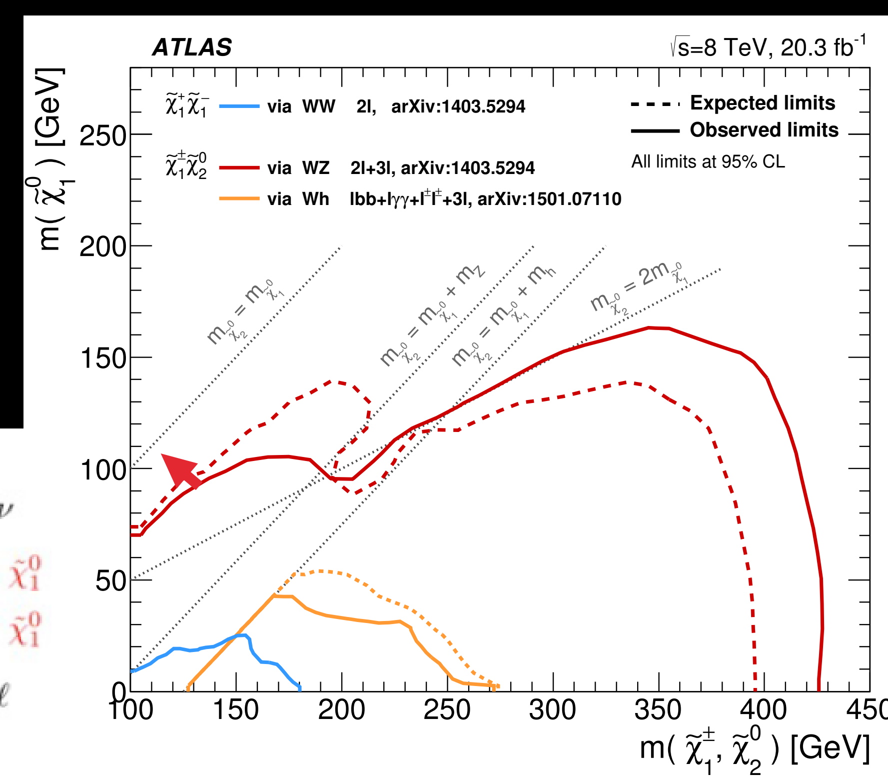
http://arxiv.org/abs/1509.07152



- The worst for LHC, but still natural scenario, is a light higgsino with decoupled bino/wino. Then there is only a triplet of degenerate higgsino states, with $\Delta M \sim M^2_W/2(\min(M_1,M_2)+-\mu)$
- Dark matter requires additional contributions to relic density
- Compressed spectra has been accessed in run1 for decays via leptons (which is easier). Signature is ISR+2/3 soft leptons +MET. Need to trigger on either ISR or soft leptons.
- No run2/run3/HL-LHC projections. Moderate mass splitting likely accessible with luminosity, unlikely to reach few GeV mass differences (without intermediate sleptons)

Light higgsinos have not, and won't, be excluded by LHC (independently of assumptions on other particles). They provide a good physics case for a linear collider.

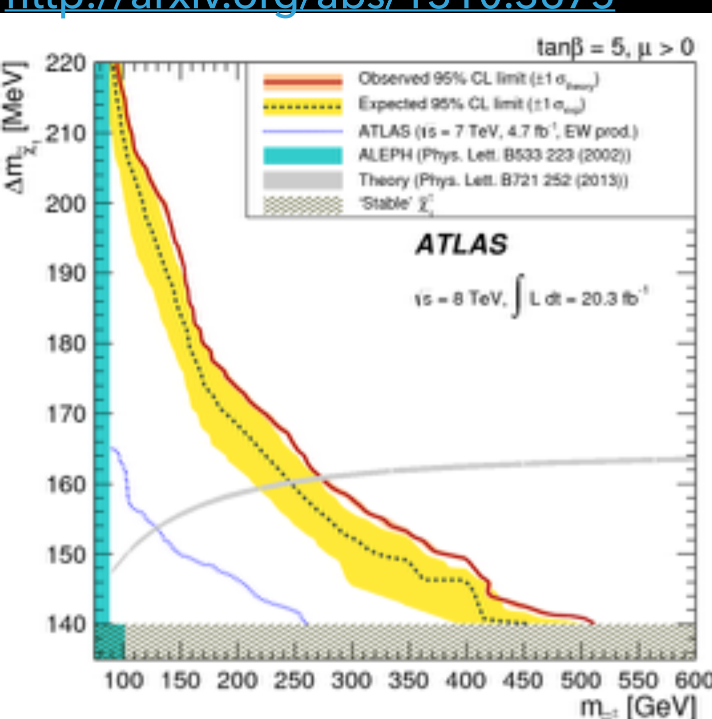


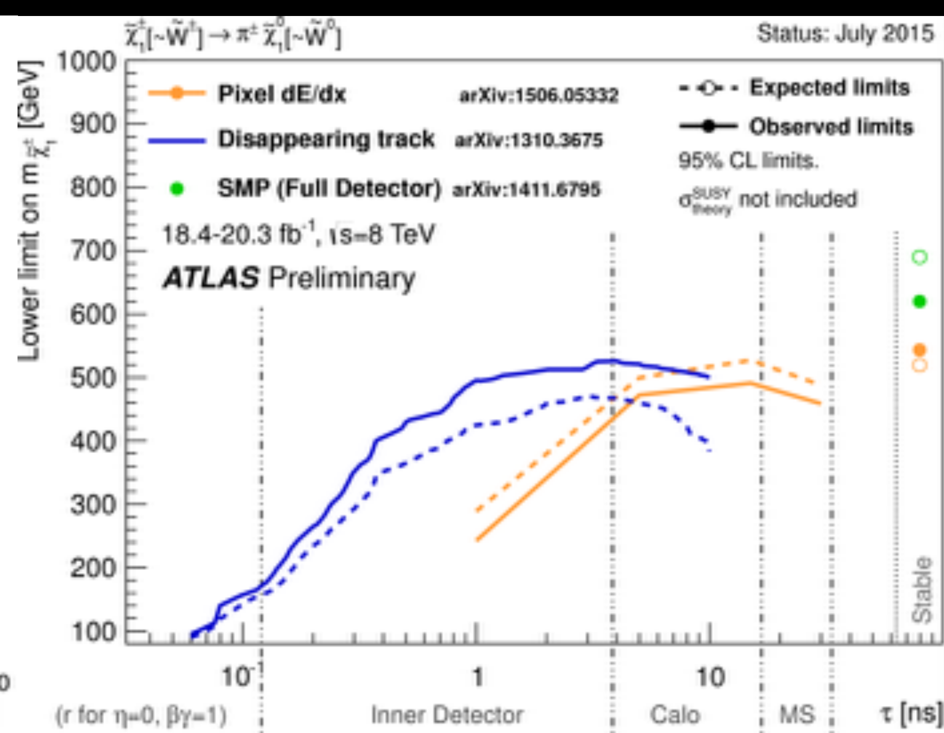


VERY COMPRESSED EWKINOS

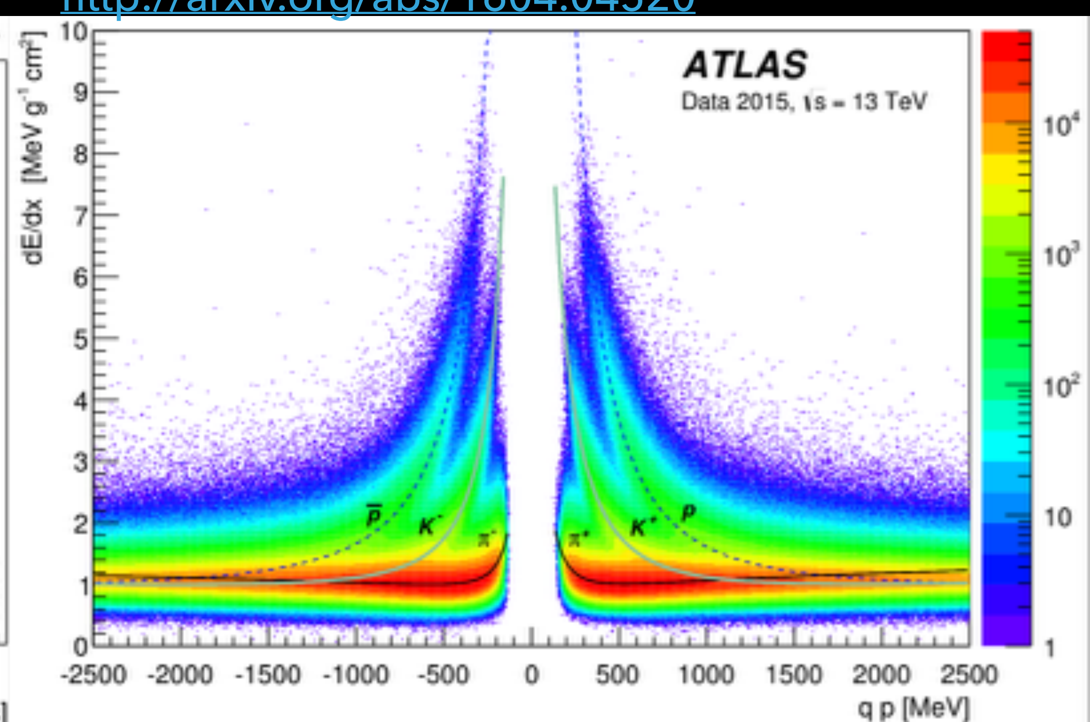
- If very small chargino-neutralino mass splitting, the chargino becomes long lived.
- Good sensitivity from disappearing tracks (seen only by inner layers of tracker) and slow heavily ionizing massive particles searches (seen with dEdx measured in pixel detector).
- Expected for pure wino LSP (~0.2 MeV mass splitting from SM radiative corrections). Pure higgsinos have ~0.4 MeV minimum mass splitting, lifetime is too short.

http://arxiv.org/abs/1310.3675





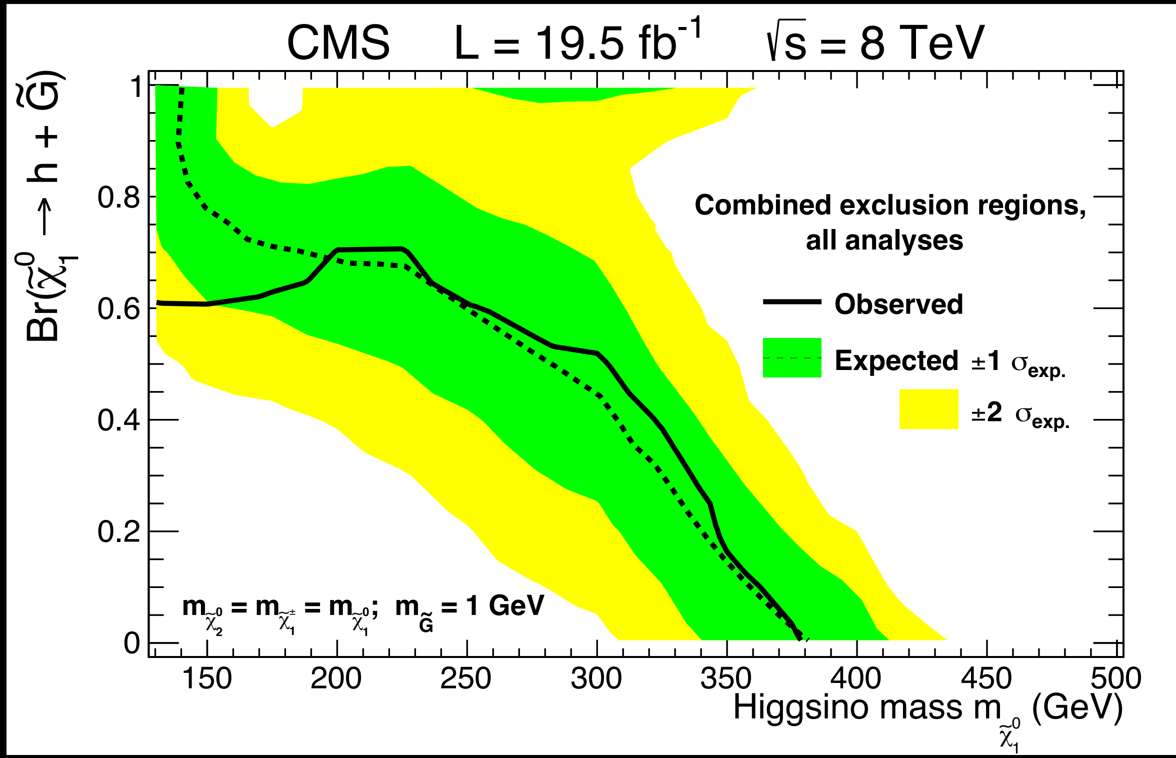
http://arxiv.org/abs/1604.04520

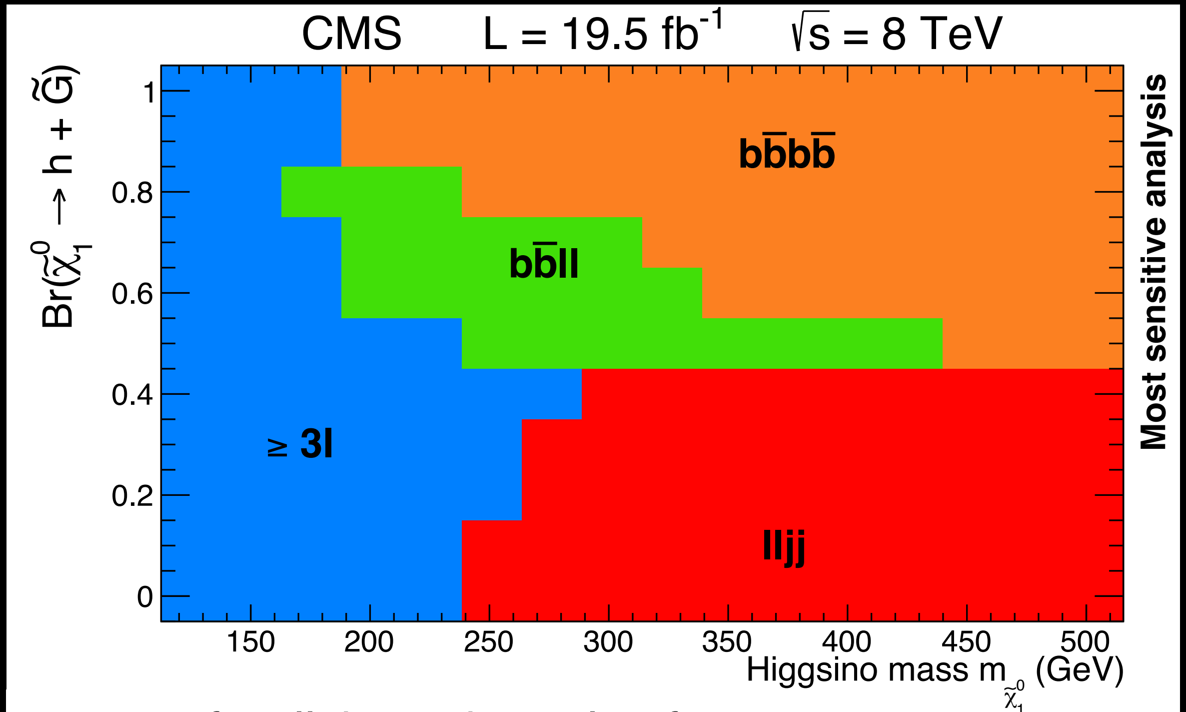


LIGHT HIGGSINO TO GRAVITINO

- If gravitino LSP and neutralino decays promptly to the gravitino, it's much more difficult for light higgsino to hide!
- Neutralino decays to gravitino and Z,h, or photon.
- Significant limits from run1. Probably run2 will probe the entire natural range,
- …as long as the neutralino is not long lived (which then becomes pretty much like neutralino LSP for the LHC…)
- displaced decays analyses important, as they probe the intermediate lifetimes case

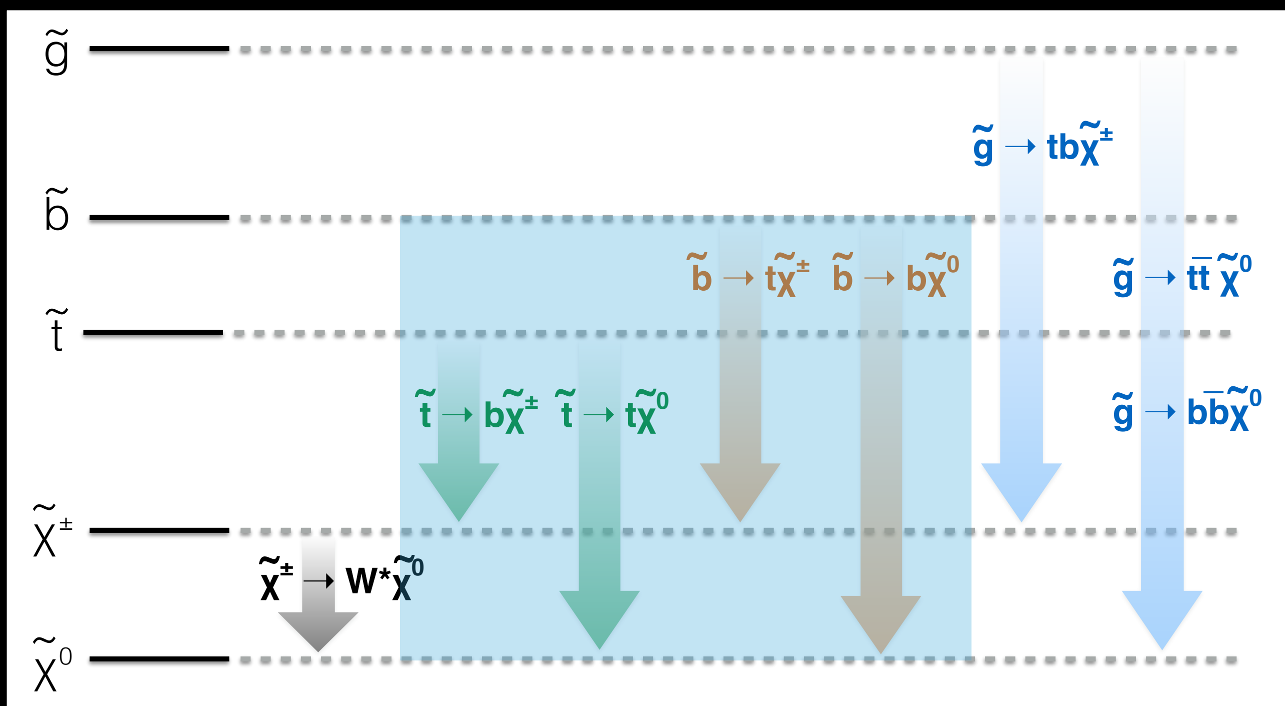
http://arxiv.org/abs/1409.3168

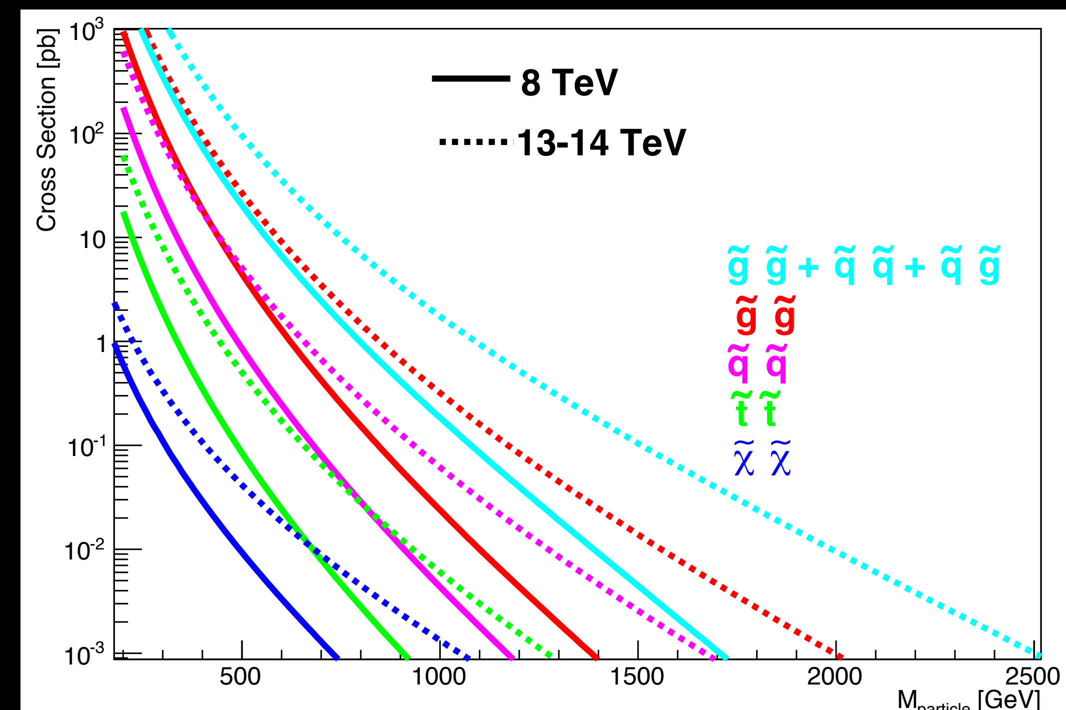


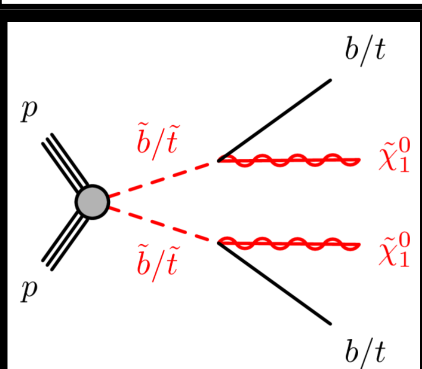


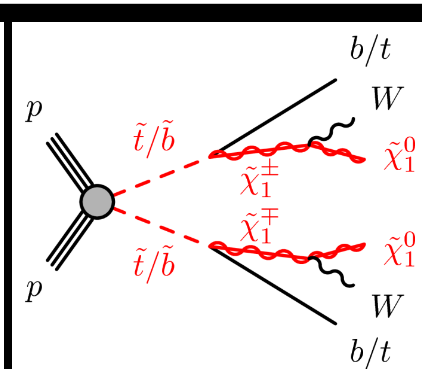
+ETMISS for all these channels, of course

STOP PHENOMENOLOGY







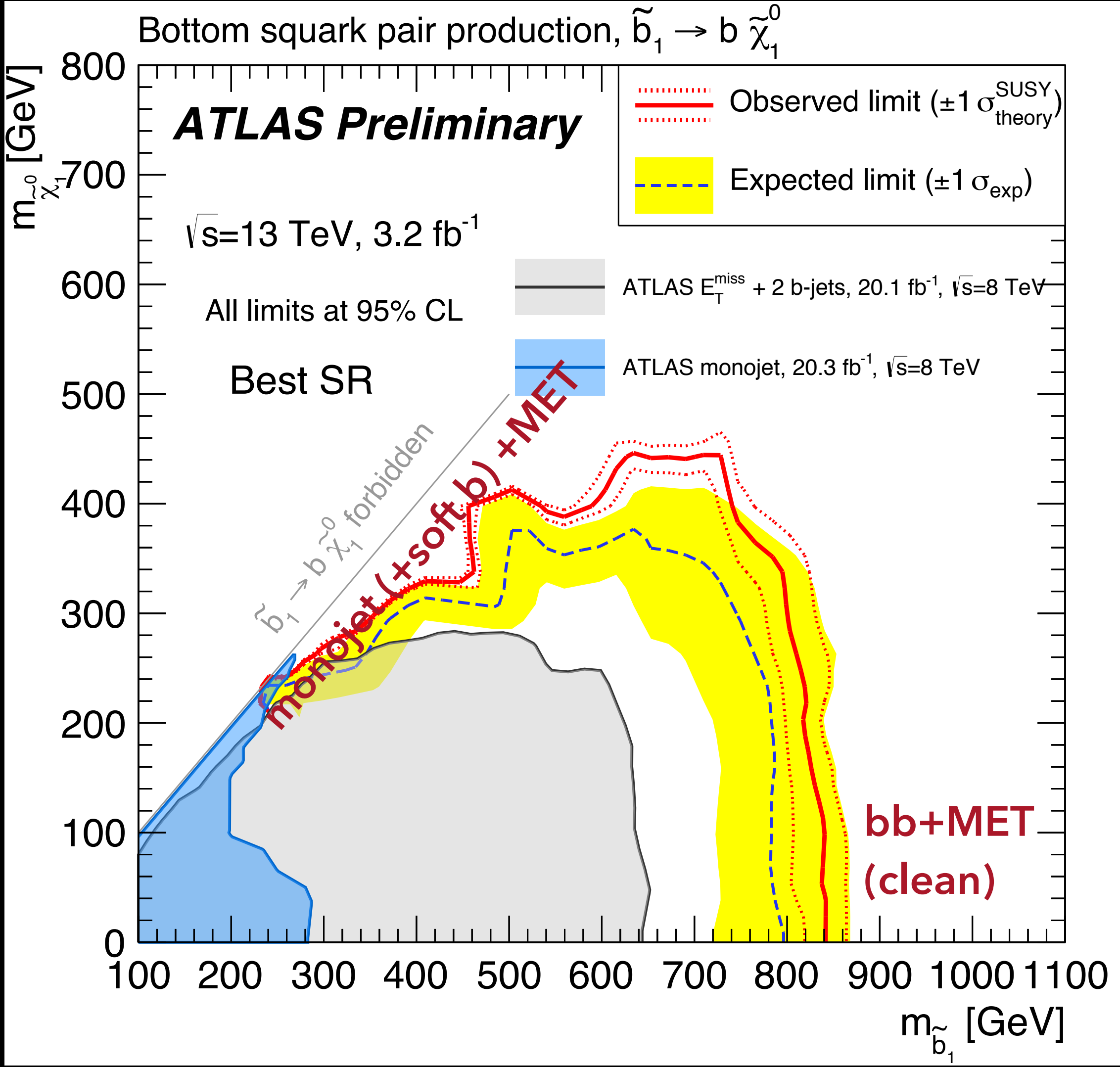


- Large cross section at low mass (but more similar to SM backgrounds)

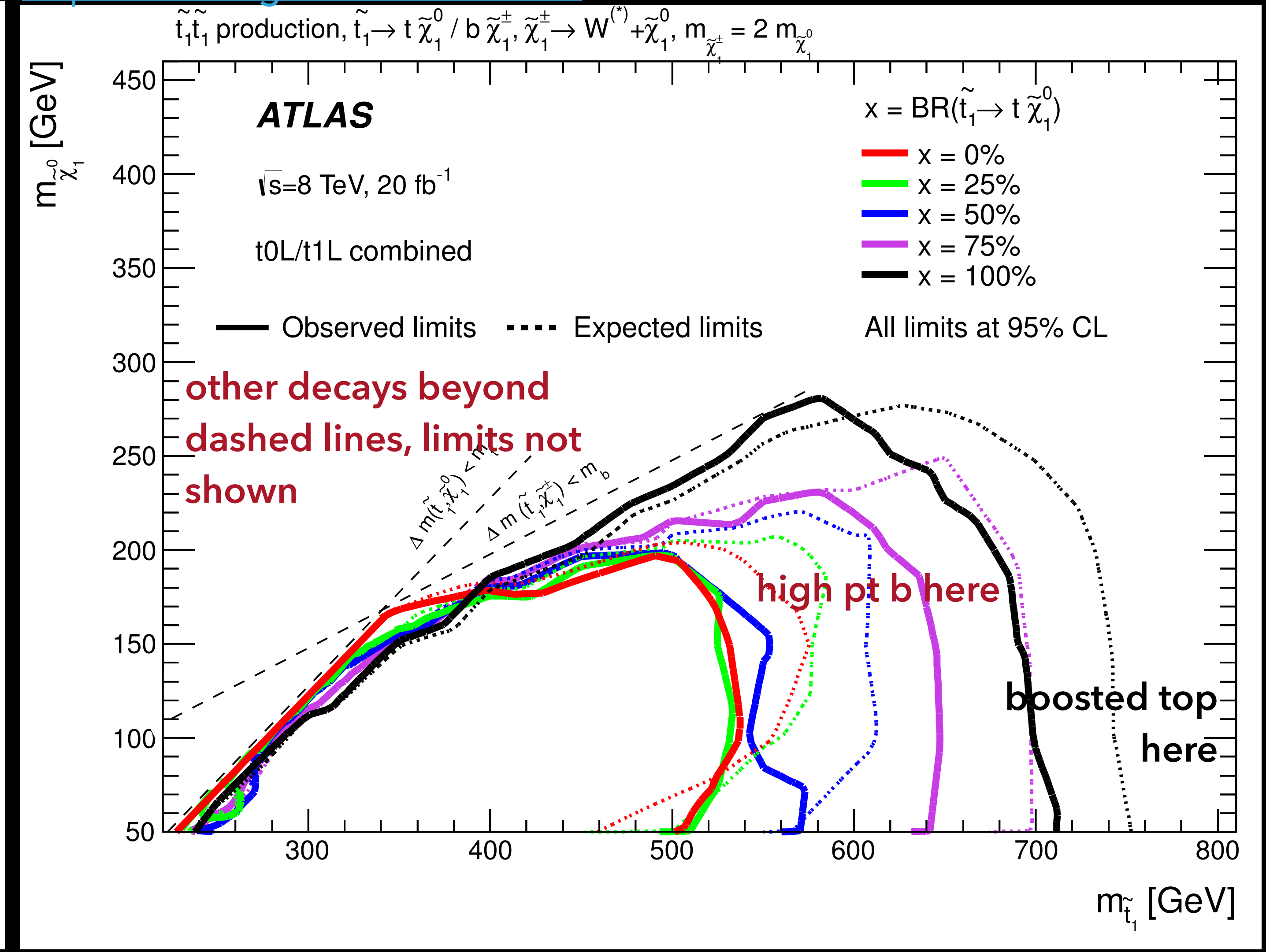
- ~t decays give bWbW+MET final state (without or with on-shell top)
- ~b decays give bb+MET or ttWW+MET final states
- ~b/~t to an higgsino triplet would give a mix of bb+MET, tt+MET, bt+MET (ignoring soft decay products from ~H+ => ~H0+ff')

SIMPLIFIED MODEL LIMITS

ATLAS-CONF-2015-062



http://arxiv.org/abs/1506.08616

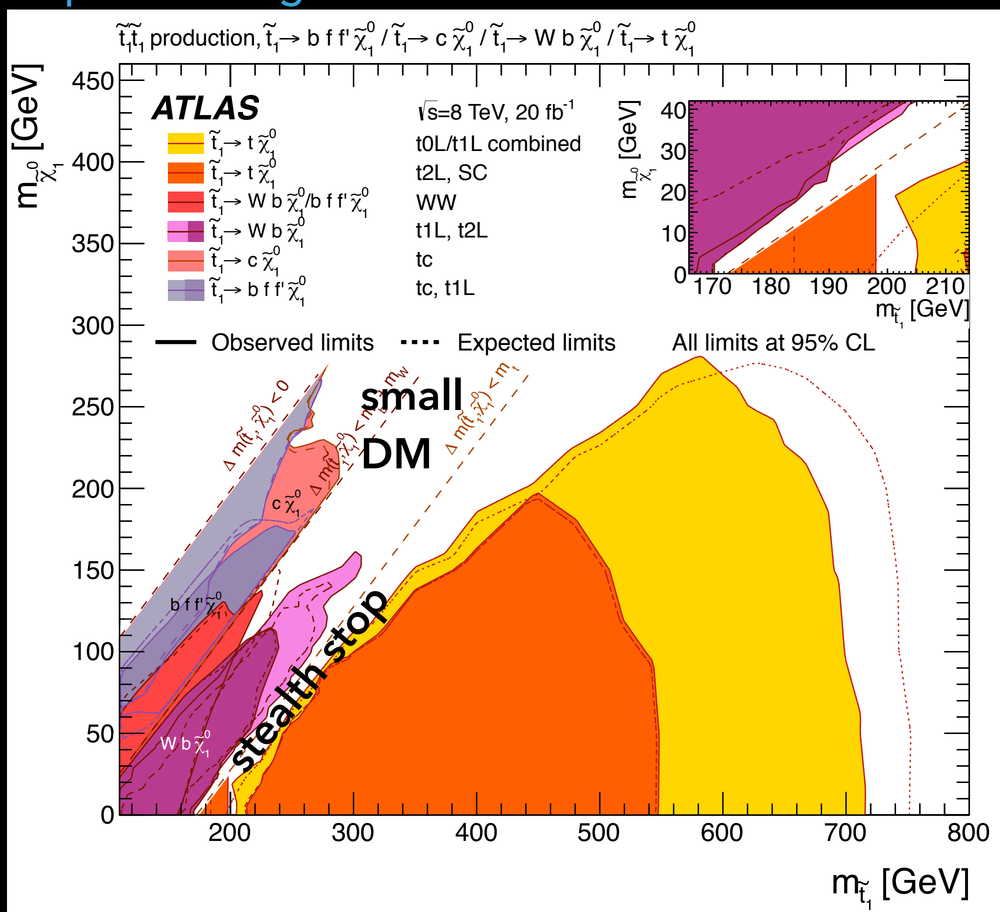


- The 100% BR can occur in a sbottom - bino only spectrum, (unlikely and unnatural) or for m(sbottom-LSP) < mtop (coannihilation scenario, more interesting)
- Signature can happen with reduced BR (sbottom to neutral higgsino, ~25% bb+MET), cross section limits within the 100% excluded line are a major part of the result

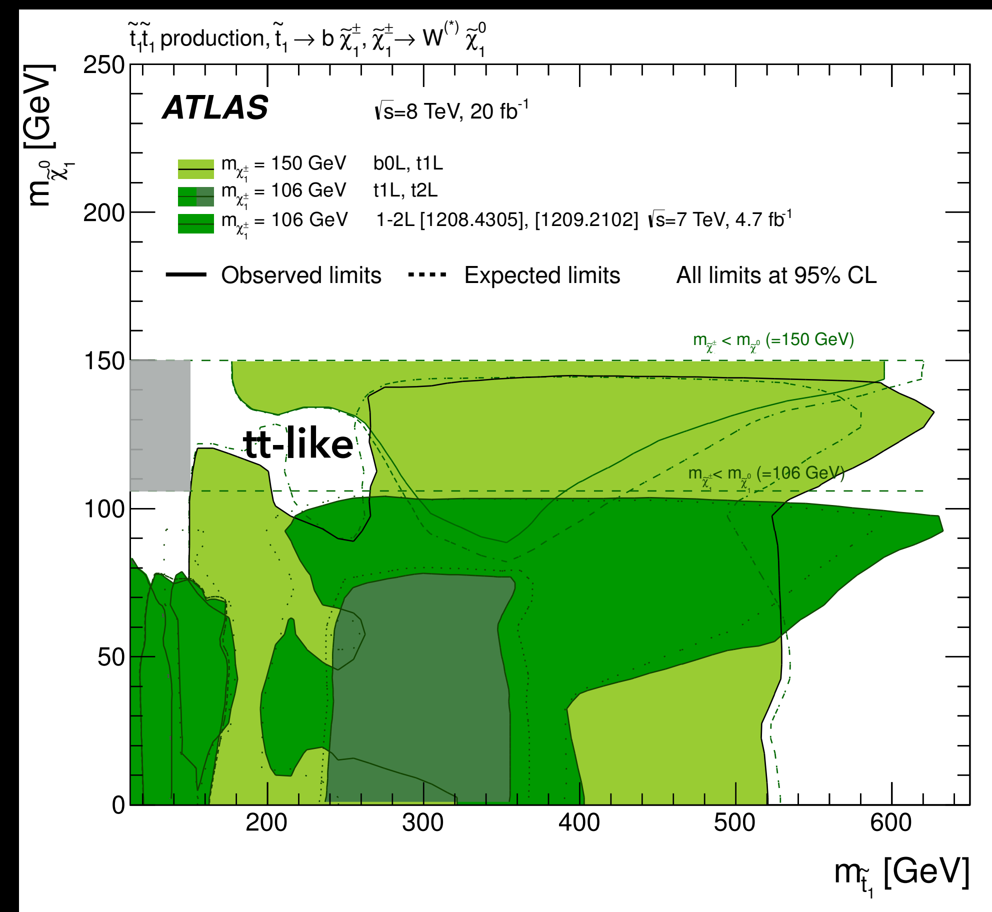
- Limits as a function of masses and BR of stop in neutralino and chargino. Assumes chargino mass twice the neutralino one.
- Still a simplified model - expect also ~t => tN_2 => tZN_1 decays with comparable BR to chargino if stop-wino-bino or stop-higgsino-bino spectrum
- Gives an idea of the dependence of limits on decays - here changing between 500 and 700 GeV depending on BR

DIFFICULT CORNERS

http://arxiv.org/abs/1506.08616



http://arxiv.org/abs/1506.08616

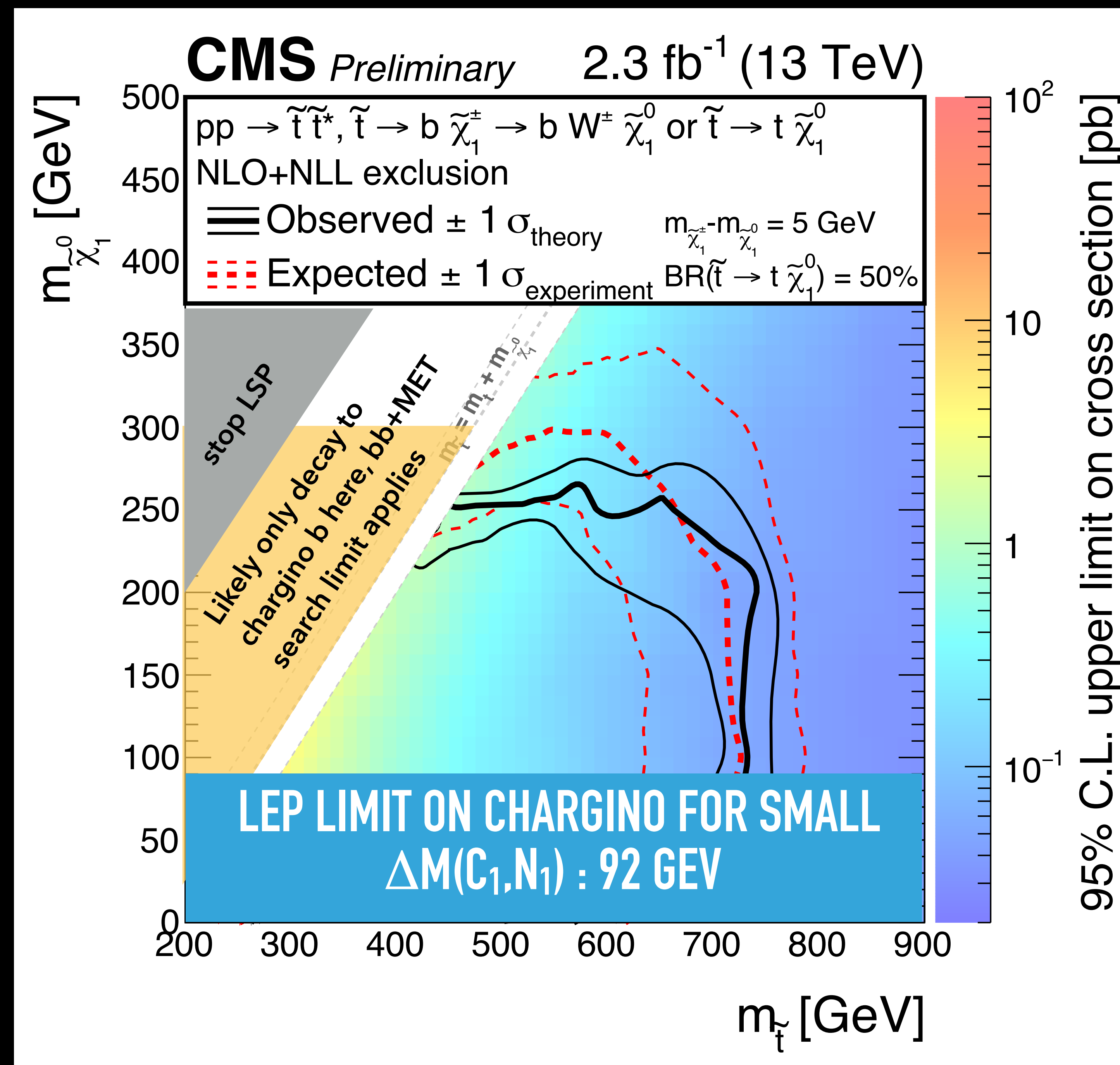


- Even for 100% BR scenarios, there are difficult corners, allowing low mass stops :
  - Small ΔM, soft decay products. ISR jet + (soft charm or leptons) + MET covering up to 250 GeV mass
  - ΔM ~ mt, "stealth stop" very similar to SM ttbar production (soft neutralinos). Can be probed with boosted stop production at run2 energy and enough luminosity
  - stop -chargino -neutralino mass combination resulting in final state similar to SM ttbar (mass differences close to top and W mass)

STOP TO HIGGSINOS

- Small ΔM(C_1,N_1) simplified model with mixed decays is a good approximation of a stop-higgsino model
- Not exact, the BR won't be 50% independent of mass (different phase space for top neutralino decays)
- More complex decays if other EWKinos are around (wino-higgsino motivated by relic density after all)

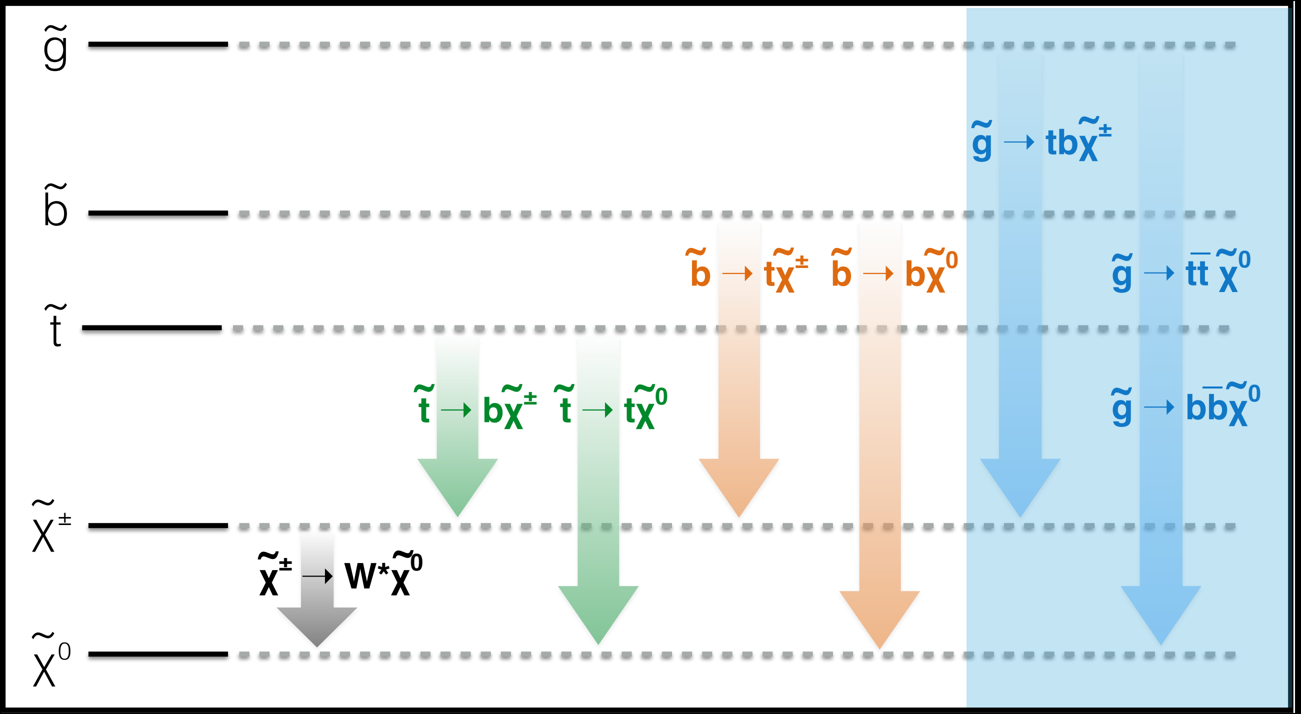
CMS-SUS–2016-007



But I would dare say that scenarios with both an higgsino lighter than 250 GeV and a stop lighter than 700 GeV would have problems with LHC limits.

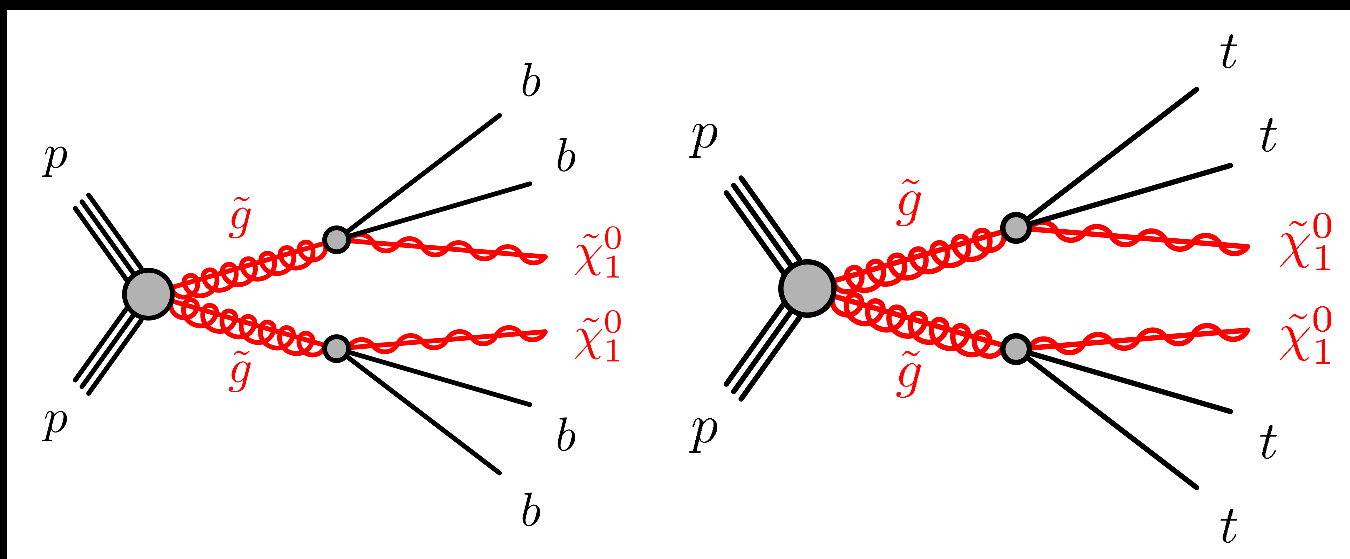
GLUINO SEARCHES

- Octet of strongly interacting states, high cross section
- Inspiring many searches : long lived R-hadrons, multijet (RPV), jets +X+MET, with X=nothing.leptons, taus, photons, …
- Because of high cross sections, difficult to hide - 1 TeV limits even for RPV case.
- Decays to the LSP via stop and sbottom is the final state motivated by the natural spectrum.

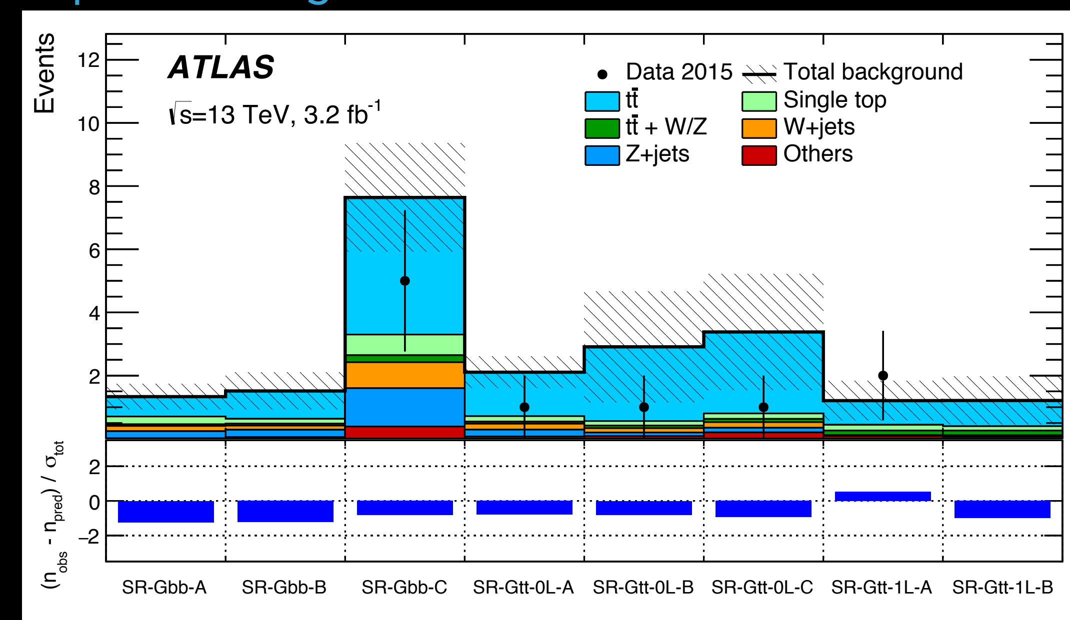


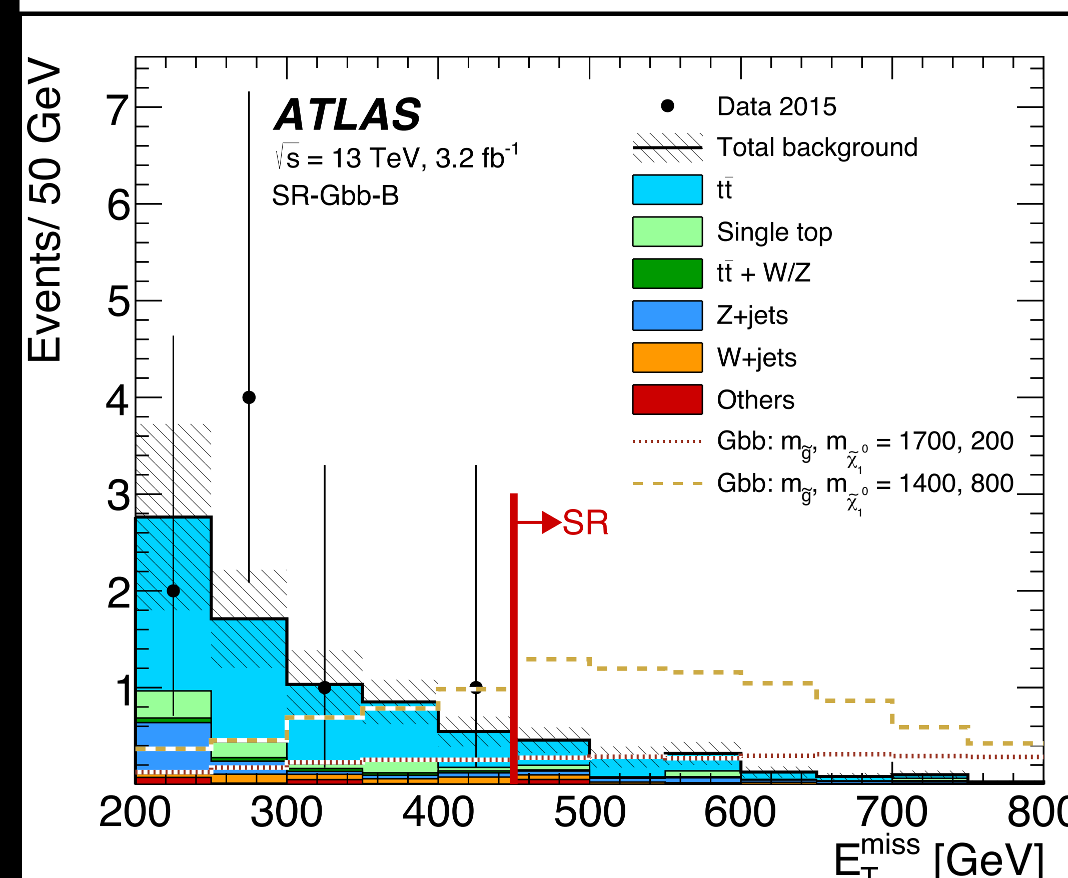
- Decays to higgsinos via stop/sbottom would yield a mixture of tt+MET, bt+MET, bb+MET states.

OUR GBB/GTT SEARCH



https://arxiv.org/abs/1605.09318

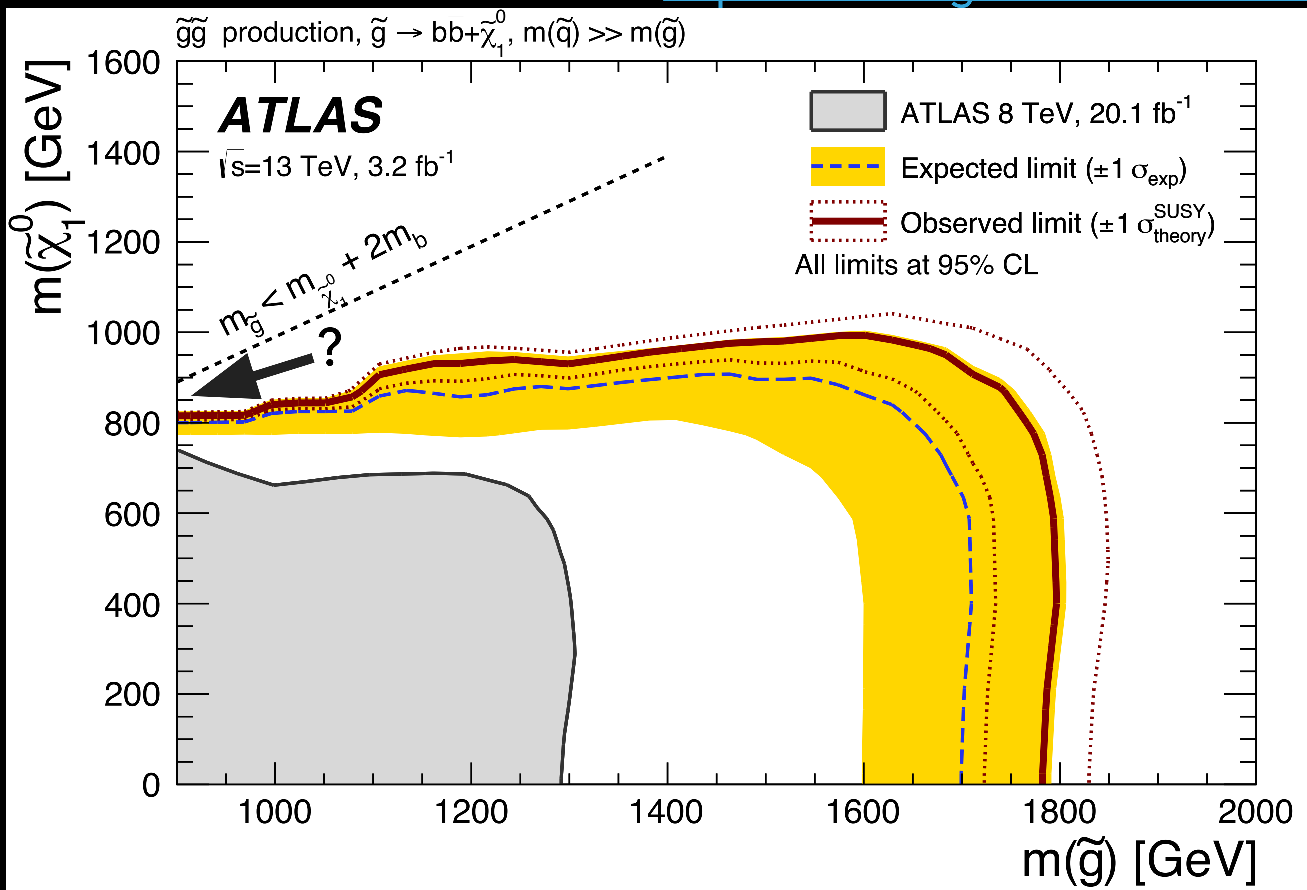


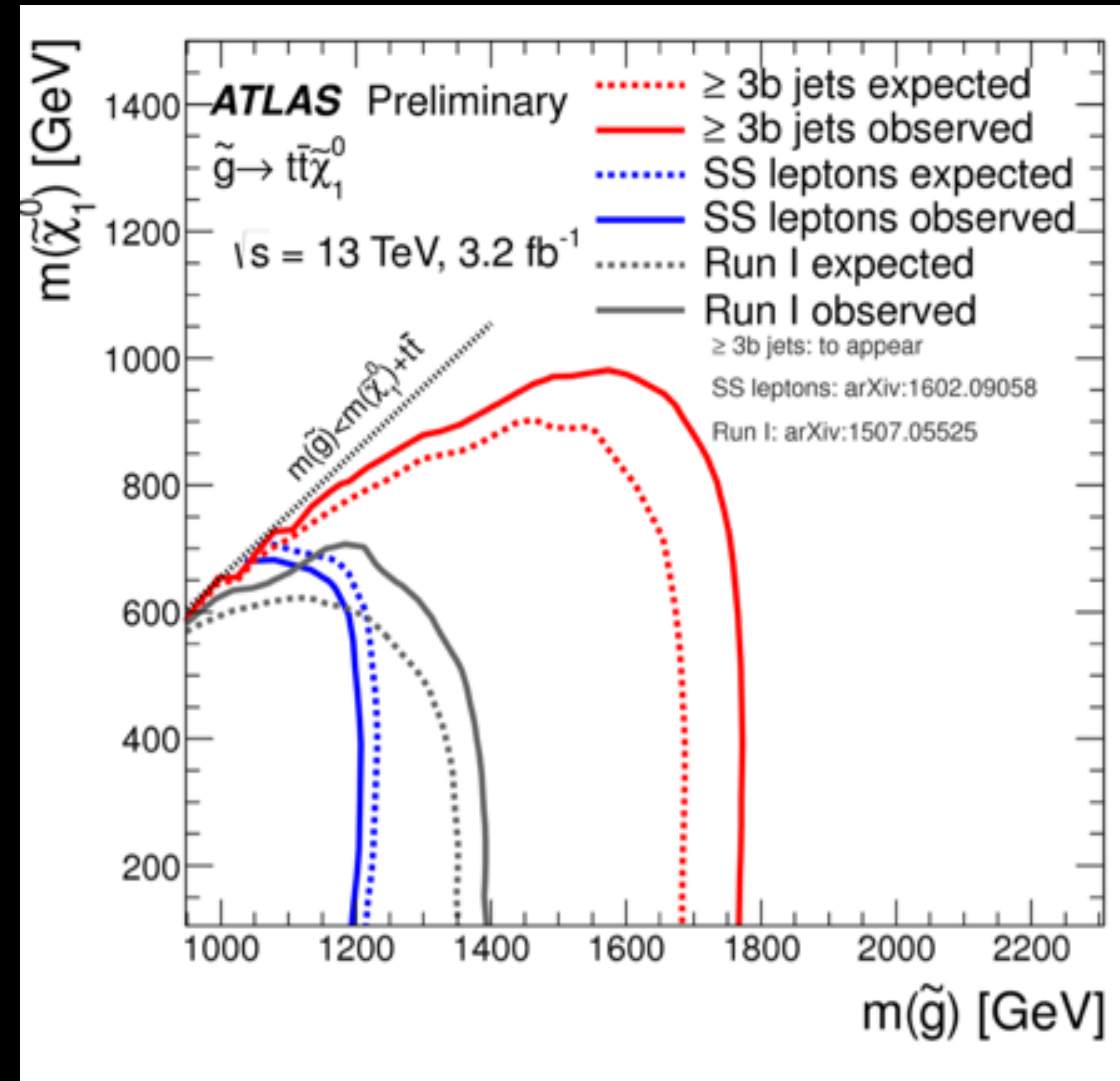


- Best ATLAS channel is the search requiring three identified b jets and large missing momentum.
- Selection targeting top decays also require 0 lepton and additional jets, 1 lepton with large M_T(lep, MET), or 2 same sign or 3 leptons.
- No excess…

LIMITS

https://arxiv.org/abs/1605.09318



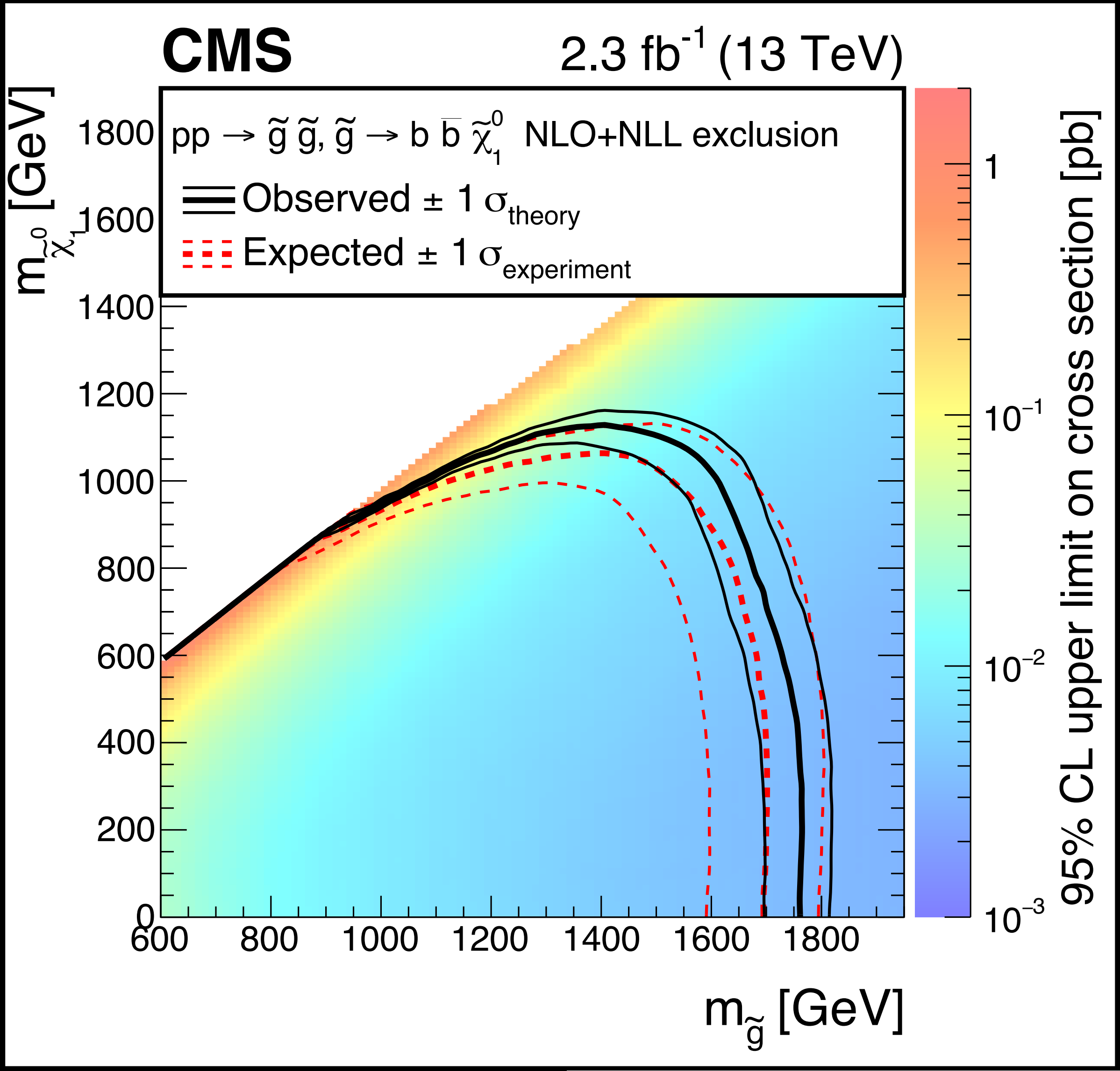


- For a light neutralino, the limit is now close to 1.8 TeV.
- Somewhat smaller masses are probably possible for a mix of final states, but not much smaller (see later)
- What about compressed mass spectra ?

COMPRESSED GLUINO

- If small ΔM(gluino,neutralino), jets from the decay are too soft to be detected. But boosted gluino production still gives ISR jets + MET from the invisible gluino decay.
- The CMS search looks in bins of jet and b-jet multiplicity (starting from one and zero), H_T (scalar sum of jet p_T), M_{T2} and goes all the way to the diagonal.
- Since we don't detect the gluino decay, limits at the diagonal itself are independent of the gluino decay mode

https://arxiv.org/abs/1603.04053



Basically, we get a lower limit of 900 GeV on a gluino-higgsino mass degenerate combination, which is actualy <u>less</u> natural than a 200 GeV higgsino and 1800 GeV gluino.

PMSSM SCANS

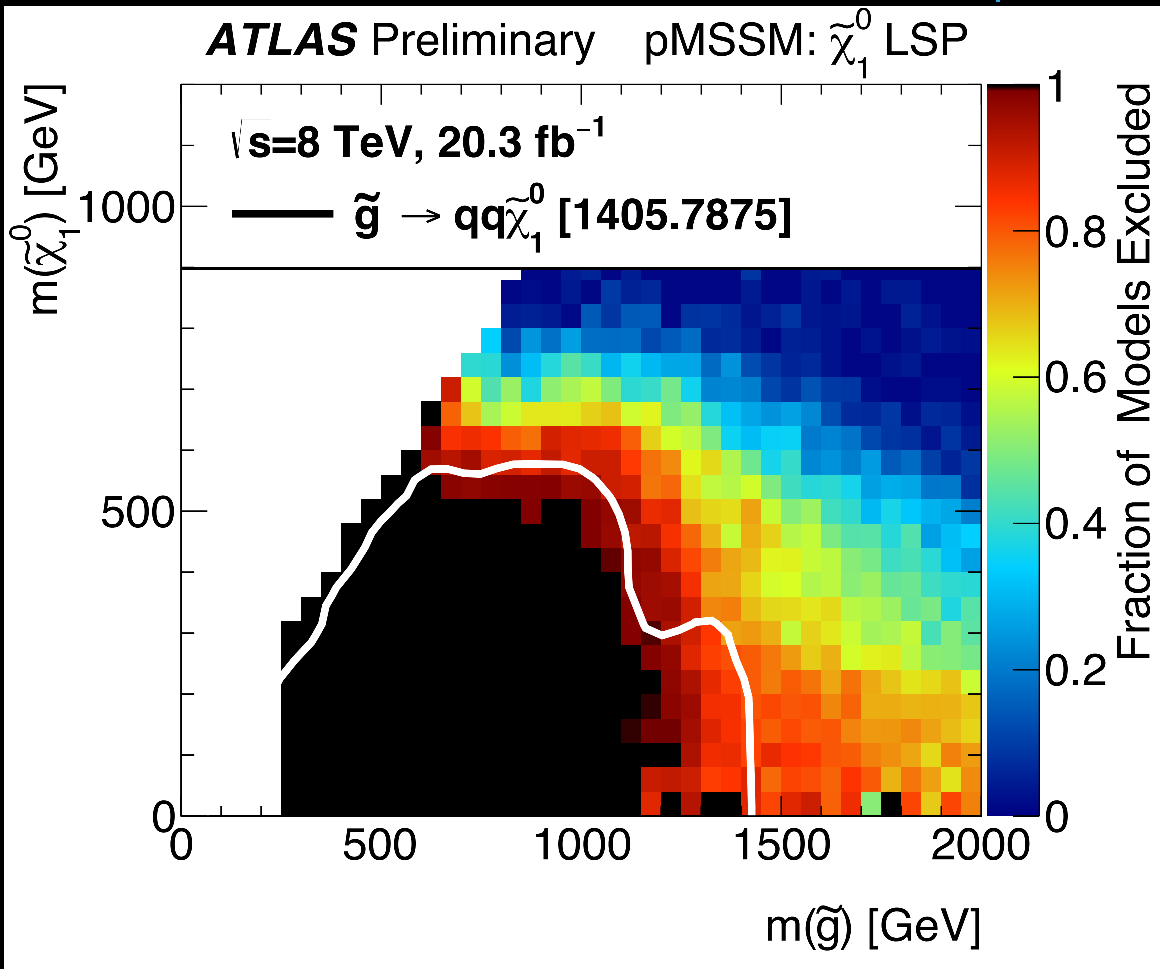
- In order to check how well the simplified model limits hold when more realistic scenarios with multiple production and decay processes take place, ATLAS and CMS have performed scans of the 19-dimensional pMSSM parameter space and evaluated the limits from several run1 searches.

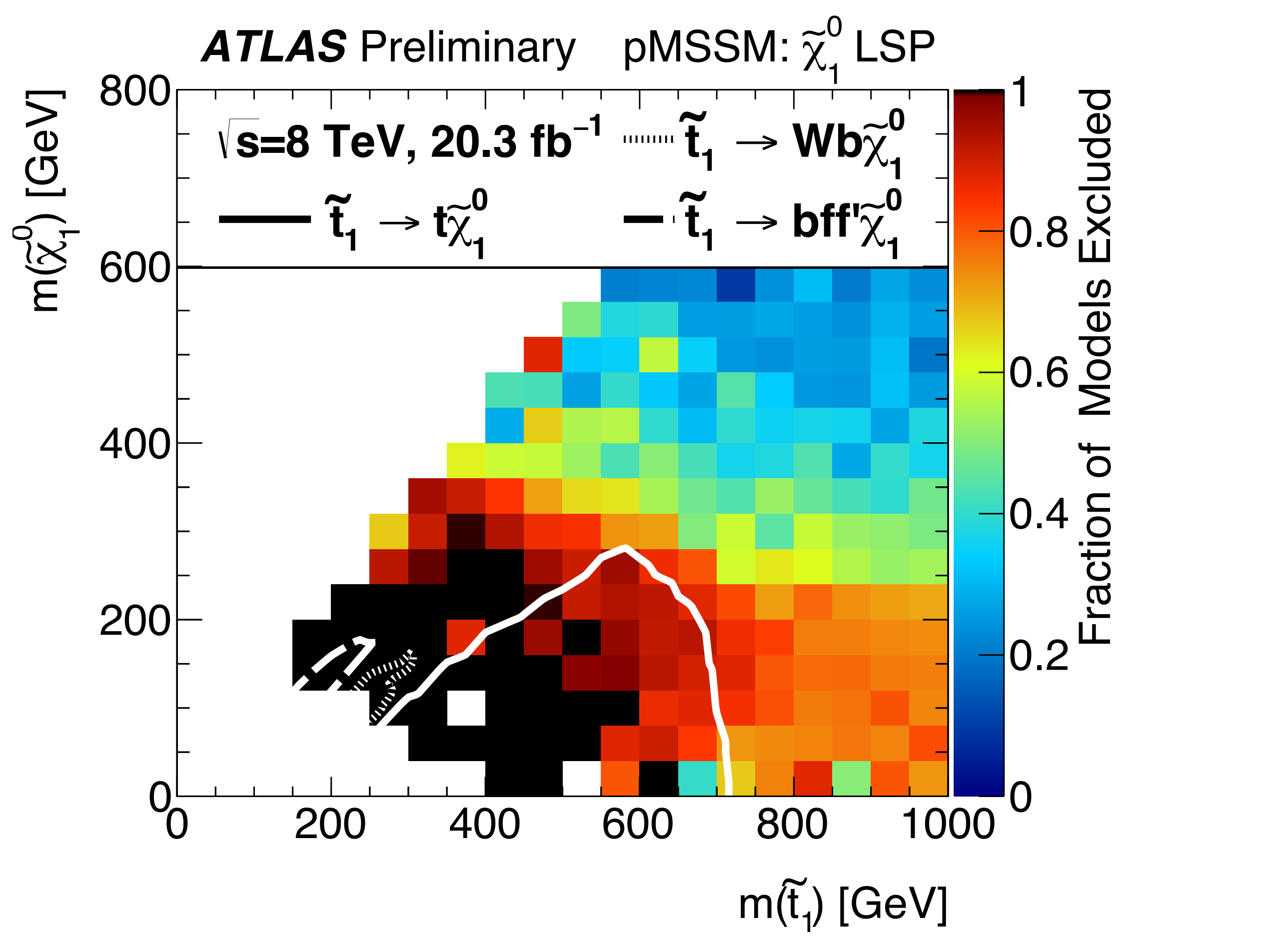
- The ATLAS scan considers 500 million model points, 310,000 of which survive Dark Matter and previous collider constraints. 22 searches are considered.

Inclusive	0-lepton + 2–6 jets + E_T^{miss}
	0-lepton + 7–10 jets + E_T^{miss}
	1-lepton + jets + E_T^{miss}
	$\tau(\tau/\ell)$ + jets + E_T^{miss}
	SS/3-leptons + jets + E_T^{miss}
	0/1-lepton + 3b-jets + E_T^{miss}
	Monojet
3rd generation	0-lepton stop
	1-lepton stop
	2-leptons stop
	Monojet stop
	Stop with Z boson
	2b-jets + E_T^{miss}
	$tb+E_T^{miss}$, stop
Electroweak	ℓh
	2-leptons
	2-τ
	3-leptons
	4-leptons
	Disappearing Track
Other	Long-lived particles
	$H/A \to \tau^+\tau^-$

PMSSM RESULTS

http://arxiv.org/abs/1508.06608

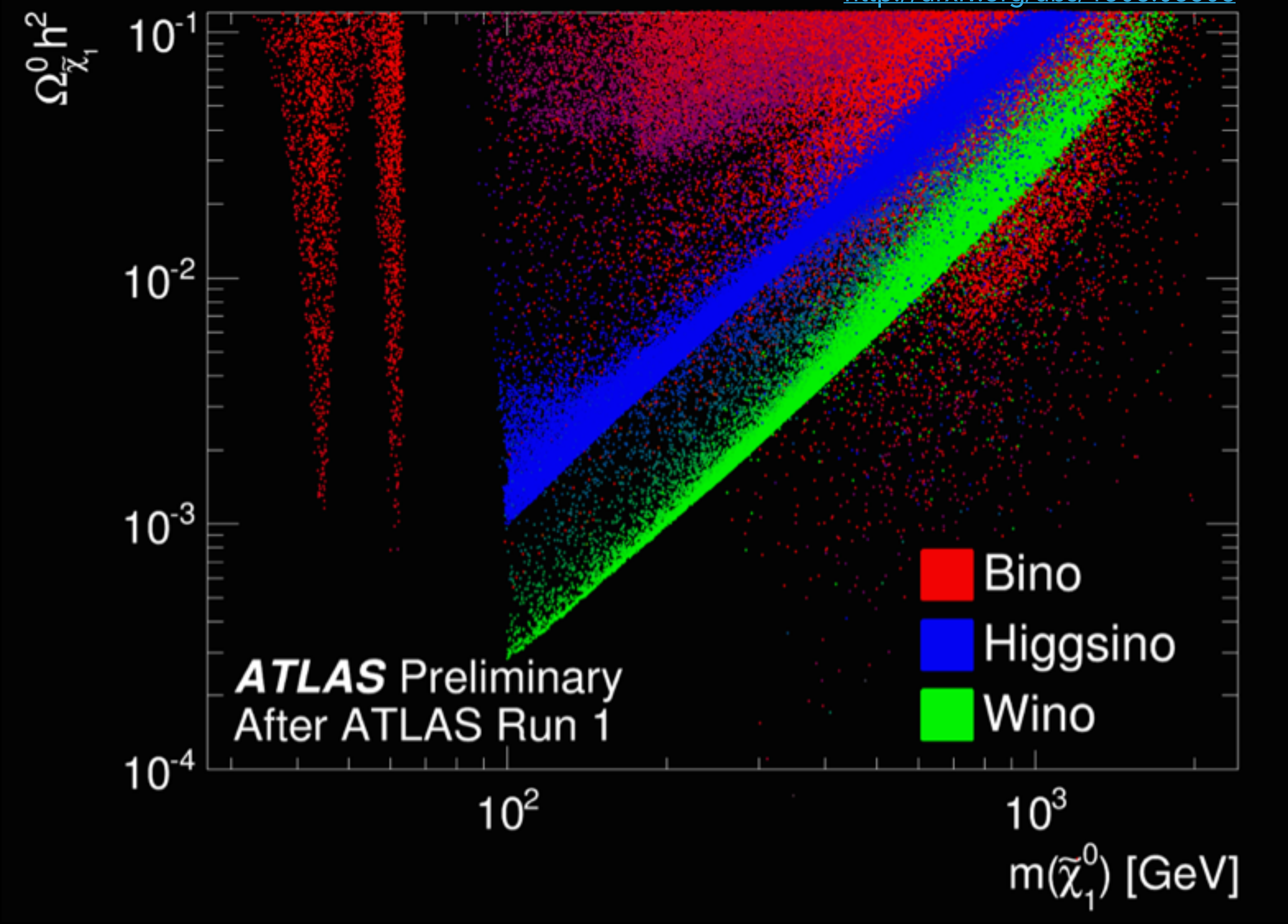




- The limit itself have been superseded by run-2 result, but the good correlation between the simplified (white line) and general limit is still interesting
- Correlation is somewhat worse for the (stop, neutralino) plane.

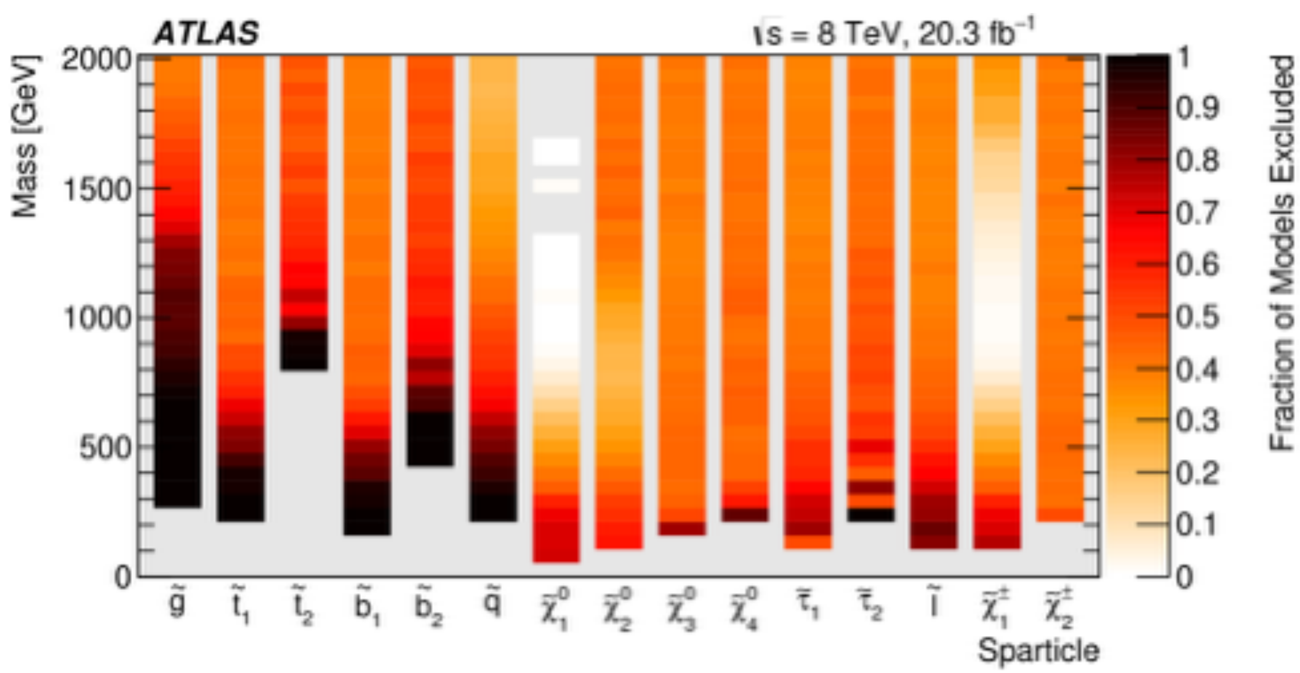
PMSSM: DARK MATTER

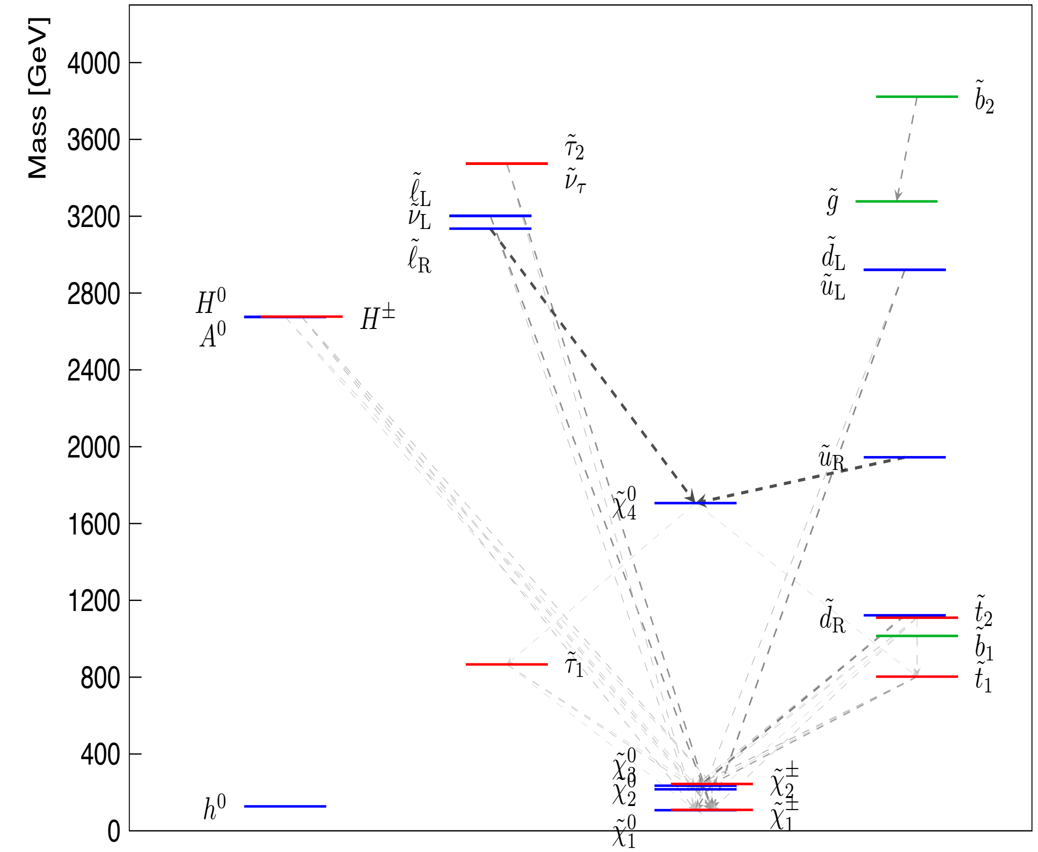
http://arxiv.org/abs/1508.06608



PMSSM OVERALL SUMMARY

http://arxiv.org/abs/1508.06608





(a) Point 18898934 (fine-tuning 56)

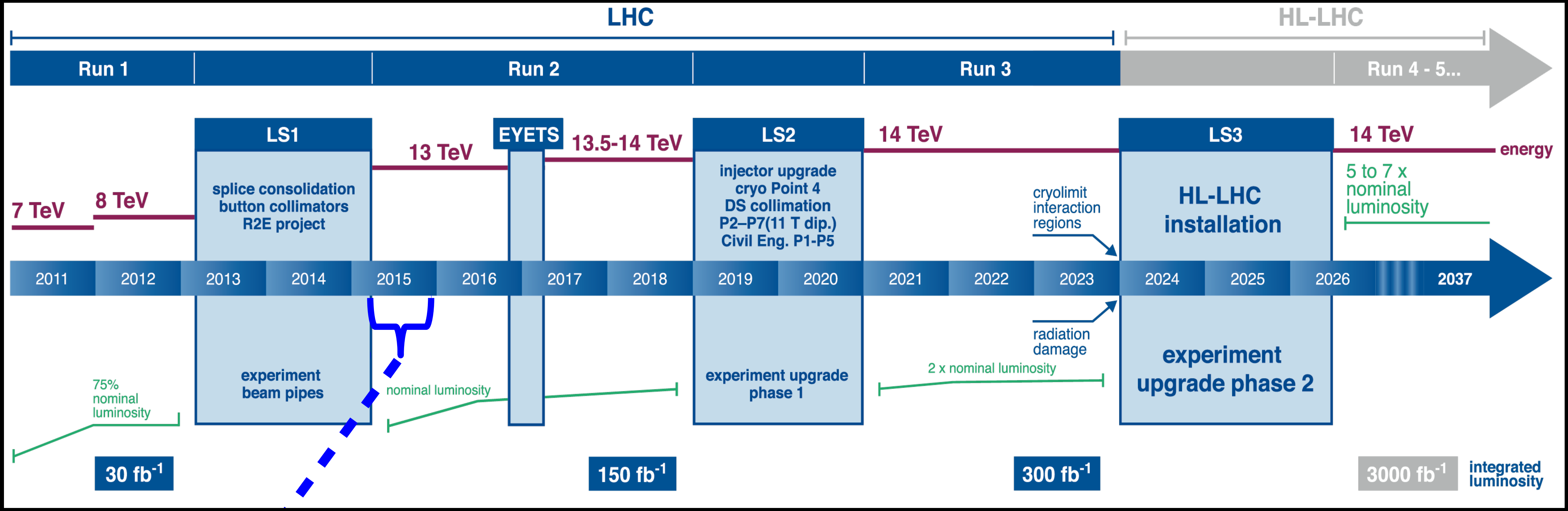
- The least fine-tuned pMSSM point surviving run1 constraints
- Fine tuning is actually driven by the Higgs mass constraint (which could be evaded in extensions of the model) rather than the direct searches

OK, WHERE DO WE STAND ?

Fine tuning bars based on formulas from arXiv:1110.6926 with m(t1)=m(t2), xt=0, tan β large, $\Lambda = 10^3$ TeV. Use with care - other calculations proposed, possible dependence on the fundamental parameters of SUSY breaking.

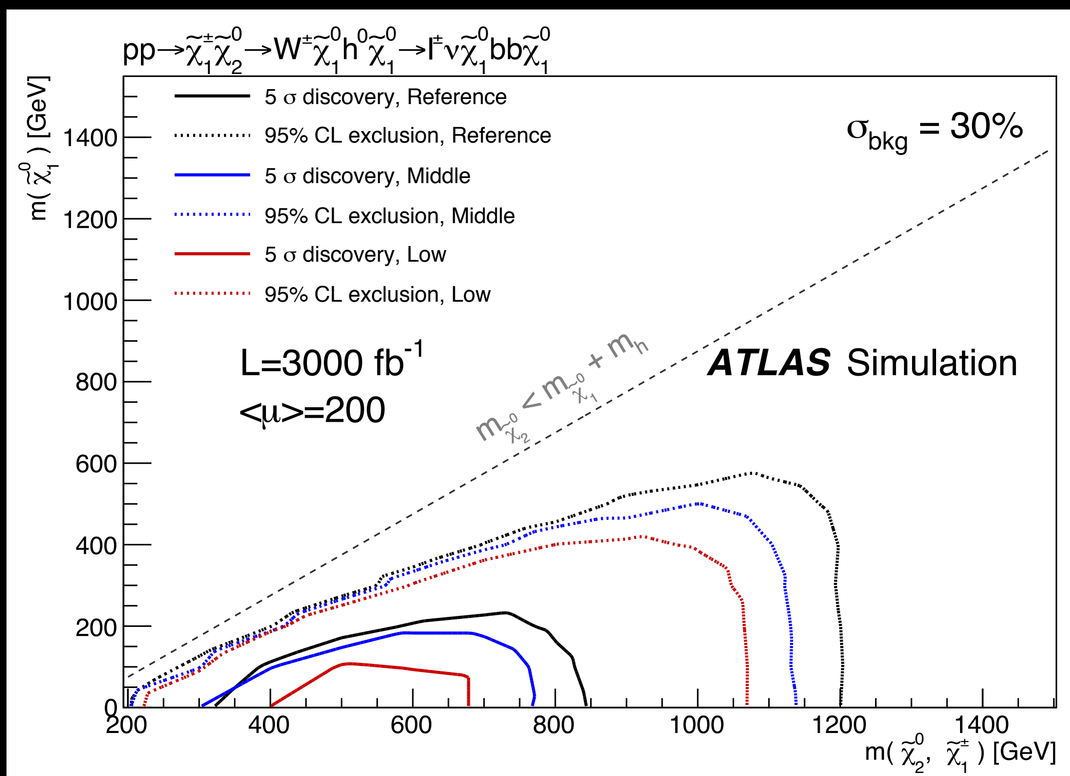
- Significant constraints from LHC results, but still plenty of room for light natural supersymmetry

FUTURE PROSPECTS

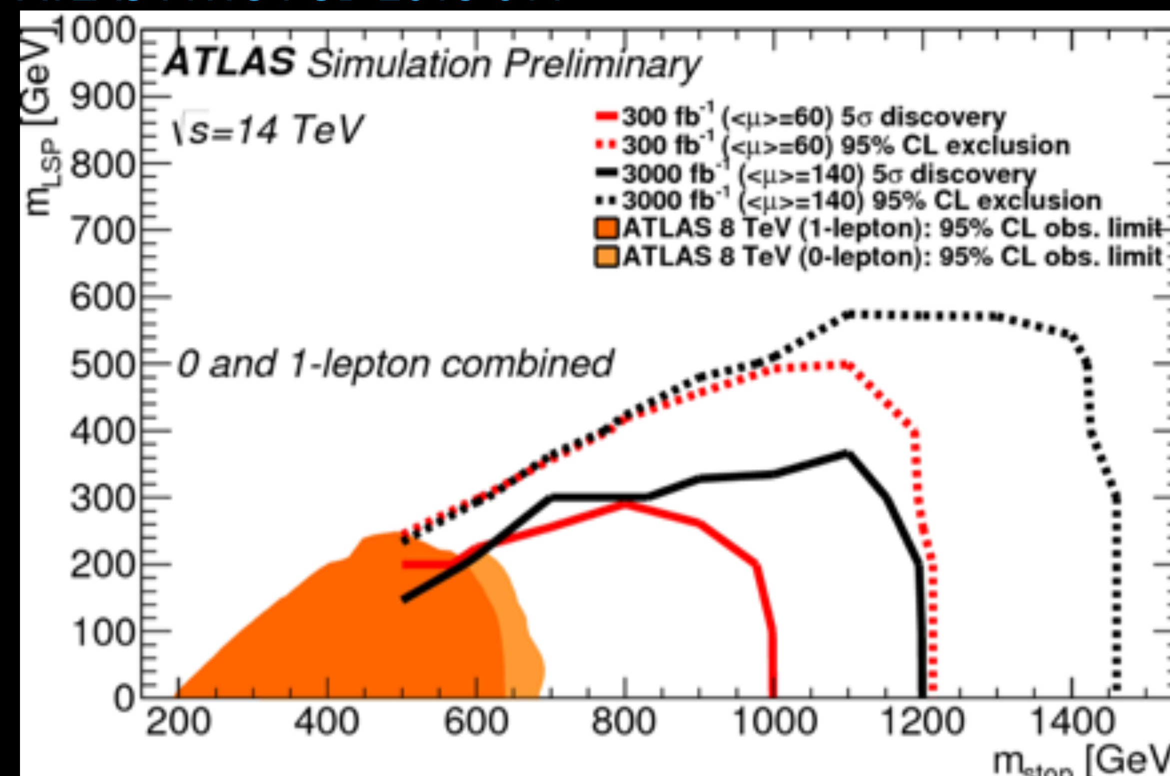


- 4 fb^{-1} delivered in 2015
- 3 fb^{-1} delivered in 2016 so far, 30 fb^{-1} expected for the end of the year
- ultimately, 3000 fb^{-1} by the end of the year
- In other words, factor of 10 increases in integrated luminosity in 5 months, 7 years, and 20 years all giving comparable gains in sensitivity

FUTURE PROSPECTS, NATURAL SUSY



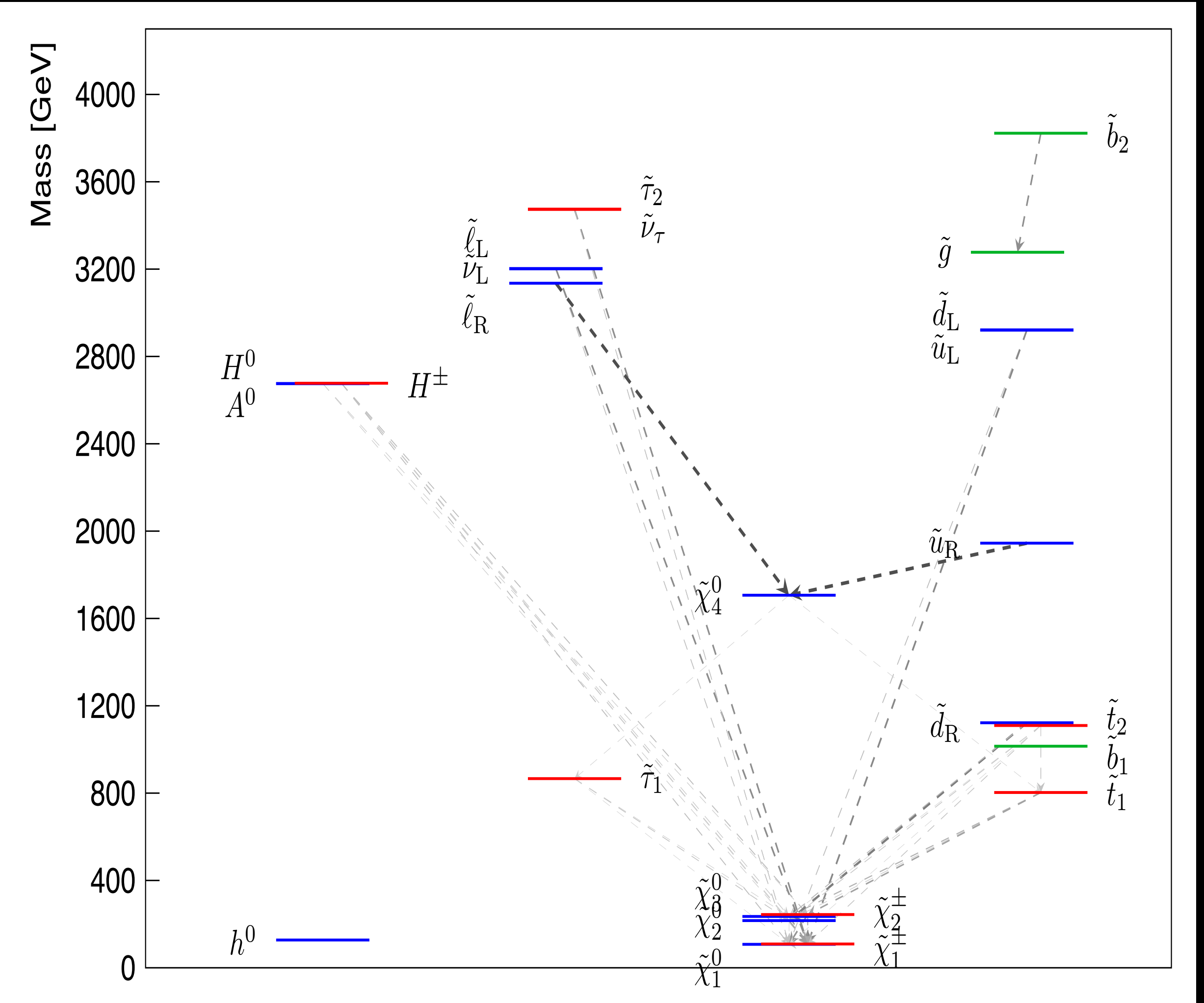
ATLAS-PHYS-PUB-2013-011



- Good coverage for EWkinos with moderate to large mass differences up to 1 TeV NLSP mass, independently of having friendly (lepton-rich) decay modes. No study of compressed scenarios though (analysis is more complicated)
- stop (expected) limits should hit 1 TeV this year already, ultimately 1.4 TeV. Again, official projections from compressed scenarios are lacking. Theory papers suggest good sensitivity using boosted stop production (feasible with enough energy and luminosity).
- gluino searches have the spotlight now, but will saturate 13 TeV PDF reach this year. HL-LHC increase sensitivity to gluinos for light LSP from ~2.4 to ~2.8 TeV (higher masses probed if squarks are around). Compressed mass spectra sensitivity more difficult to asssess, as it depends critically on the level of systematic uncertainty achieved in monojet+MET analysis.

FUTURE PROSPECTS, PERSONAL MUSINGS

- Higgsino-wino mixture with moderate mass splitting (natural and DM friendly) should be accessible at LHC in soft lepton channels.
- pure very compressed higgsino won't, but direct detection searches will probe most of parameter space.
- stop and gluinos will be probed up to ~1.5 TeV and 3 TeV respectively - compressed scenarios at lower mass would be allowed but even less natural
- Models like the one on the right should give a signal in run2 already. Likely true for "most" natural SUSY scenarios still allowed.

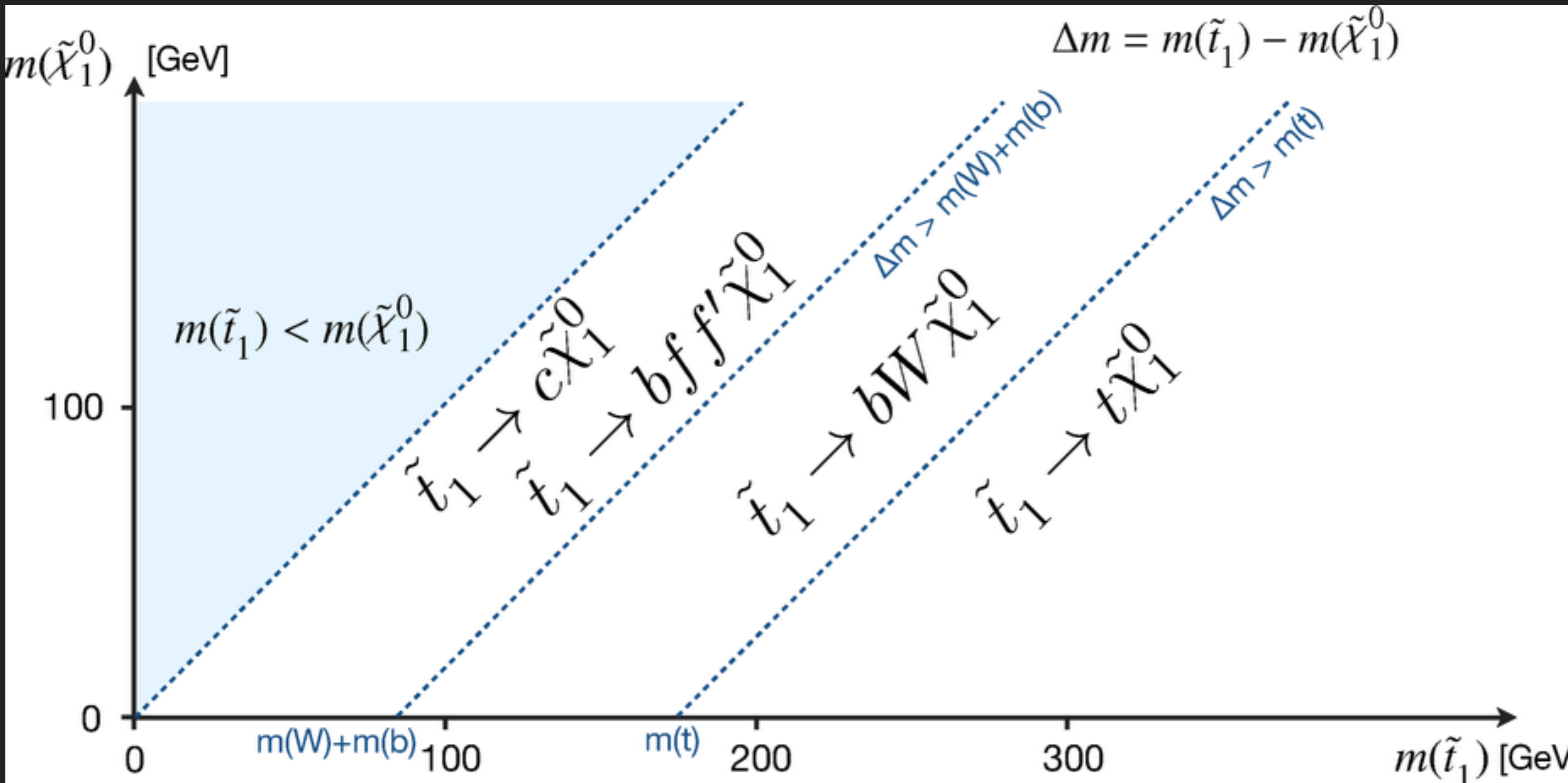


(a) Point 18898934 (fine-tuning 56)

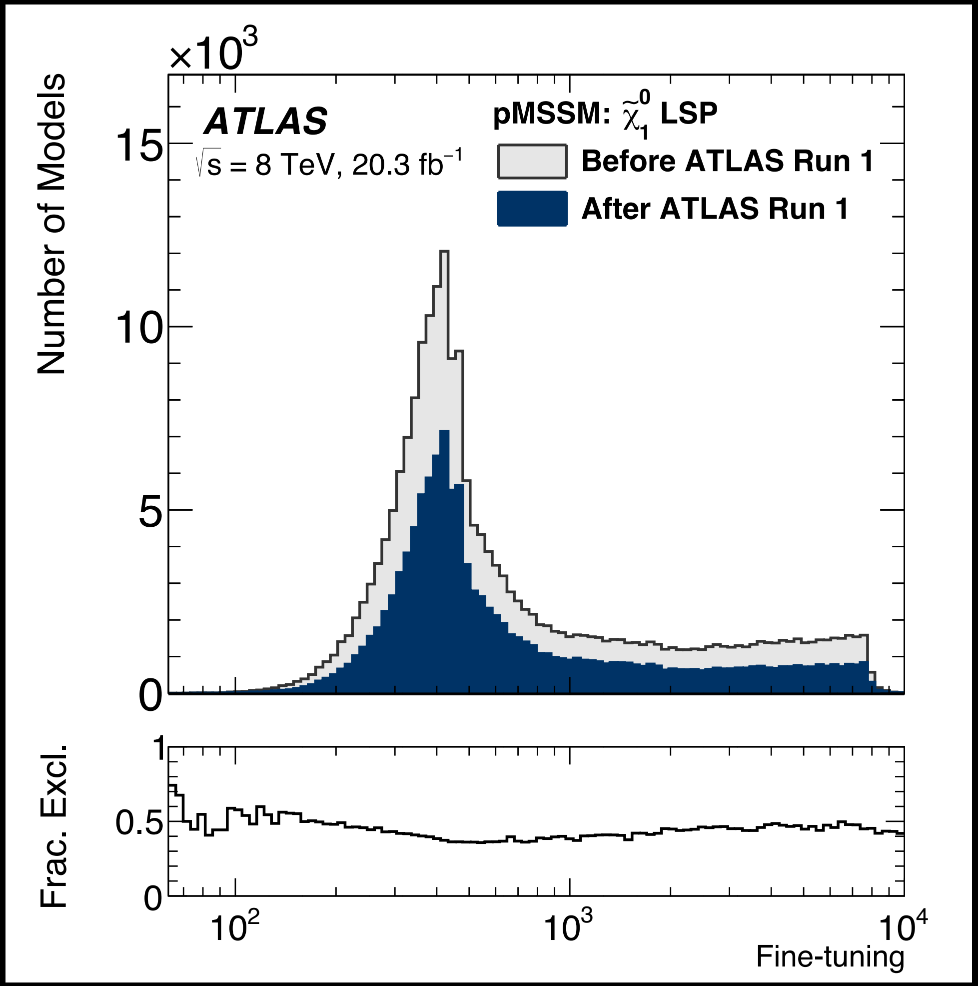
CONCLUSIONS

- SUSY wasn't the low hanging fruit expected before the LHC startup
- Tight constraints from run1, still not compromising a SUSY solution to Dark Matter and naturalness though
- Good prospects for future LHC detection, with 2016 providing a sizeable chunk of the ultimate reach improvement.
- No signal at either the HL-LHC and direct detection experiments would put SUSY (as solution of Dark Matter and fine tuning) in a tight spot indeed.

BACKUP



$\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{t}_1) < m(\tilde{\chi}_1^0)$
100
0
$\tilde{t}_1 \to c\tilde{\chi}_1^0$
$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$
$\tilde{t}_1 \to bW\tilde{\chi}_1^0$
$\tilde{t}_1 \to t\tilde{\chi}_1^0$
Δm > m(W)+m(b)
Δm > m(t)
m(W)+m(b)
m(t)
0
100
200
300
$m(\tilde{t}_1)$ [GeV]


ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
pMSSM: $\tilde{\chi}_1^0$ LSP
Before ATLAS Run 1
After ATLAS Run 1
Number of Models
$\times 10^3$
15
10
5
0
Frac. Excl.
1
0.5
0
10^2
10^3
10^4
Fine-tuning

OUTLINE

- standard model and susy
- predictions and observations
- reactions…
- naturalness theme
- electroweak searches
- third generation searches
- gluino searches
- where do we stand ?
- prospectives