Looking for Supersimmetry (SUSY for friends)

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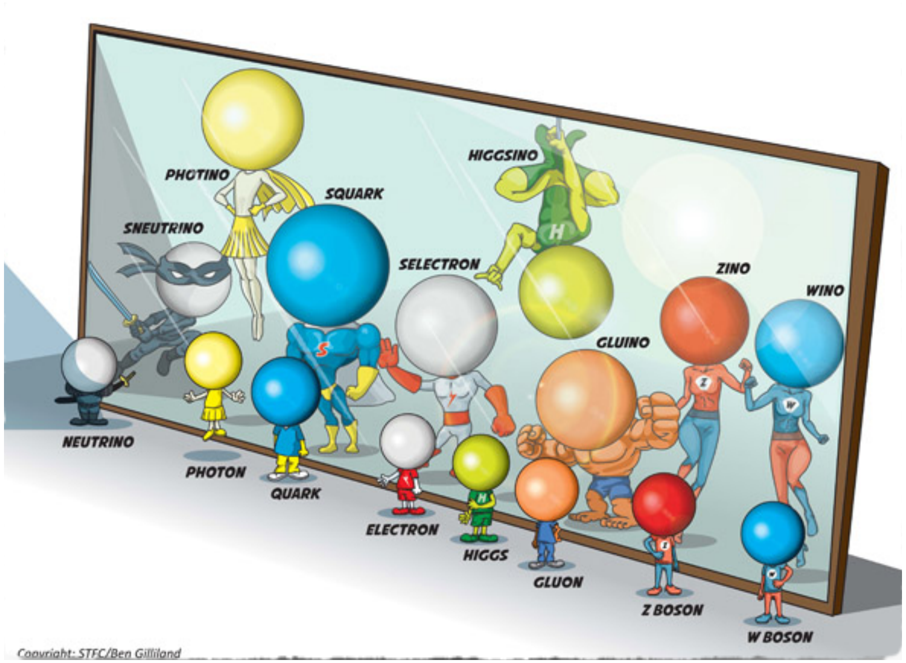
What is in this lesson

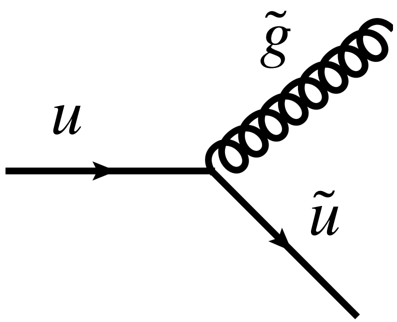
- In the lesson of Prof. Jaeger you have learned what Supersymmetry is: the motivations, how to build the Lagrangian, the particle content etc.
- The theory predicts the existence of *at least* 35 new particles (4 other Higgs bosons, 12 scalar leptons, 12 scalar quarks, 6 neutralinos e charginos, the gluino)
- Today I will tell you about the searches of these particles at LHC

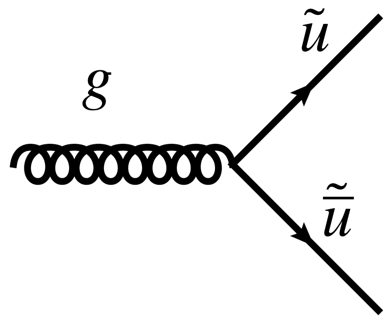
- Production of SUSY particles in *pp* collisions
- Decays of SUSY particles
- What the detector measure
- How to separate signal from backgrounds
- Something different: long-lived (s)particles, R-parity violation
- Future prospects

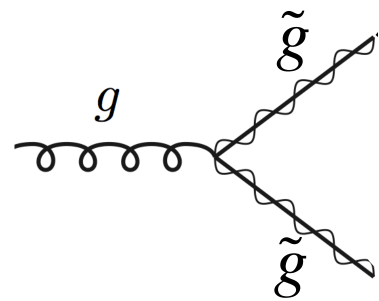


Production of SUSY particles

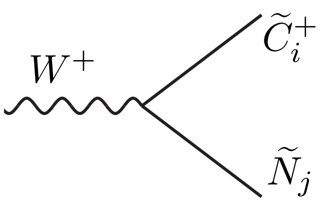
- We start from gluons and quarks
- Because of the symmetry, SUSY diagrams are obtained from SM ones adding tilde on two of the particles
  - **Two for R-parity conserving processes**

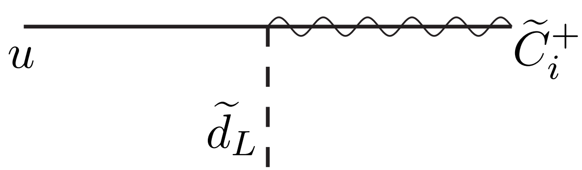






Strong interaction examples





Weak interaction examples

WWZ triple vertex

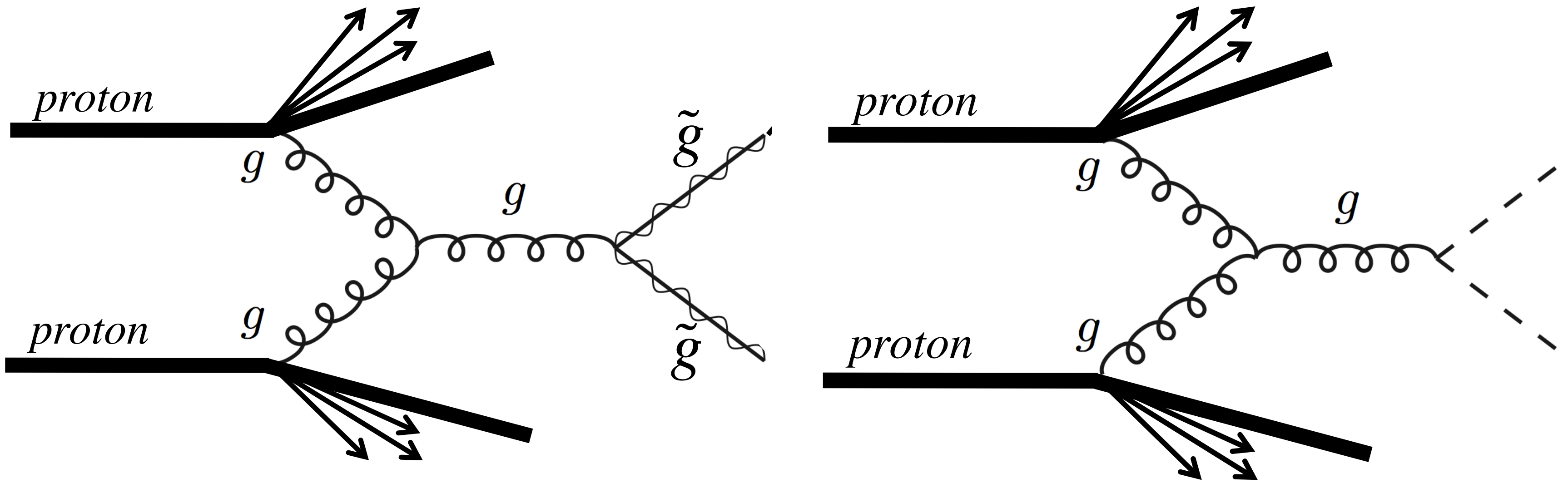
W => qq'

Corresponding SM process

R-parity = (-1)$^{3(B-L)+2S}$ = +1 for SM particles; -1 for SUSY particles

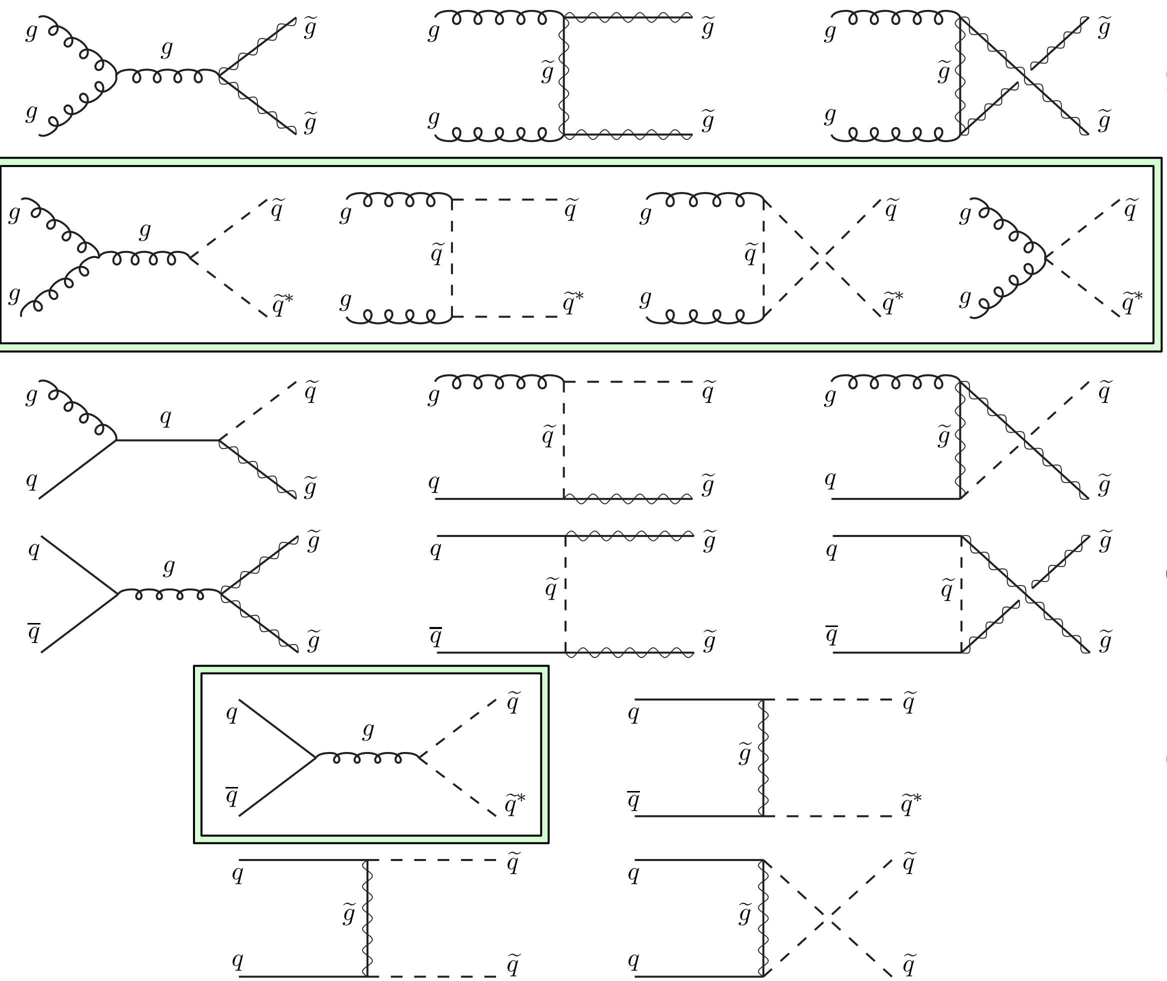
- Guarantees proton is stable
- Provides DM candidate

Scalar quark and gluon interactions



- Here we take a gluon as the colliding constituent of each proton
- The merge into a third virtual gluon (this is called an s-channel process) to produce a pair of gluinos (left) or a pair of squarks (right)

Scalar quark and gluino production



gluon-gluon ⇨ **gluino pair**

gluon-gluon ⇨ **squark antisquark**

gluon-quark ⇨ **squark gluino**

quark-antiquark ⇨ **gluino pair**

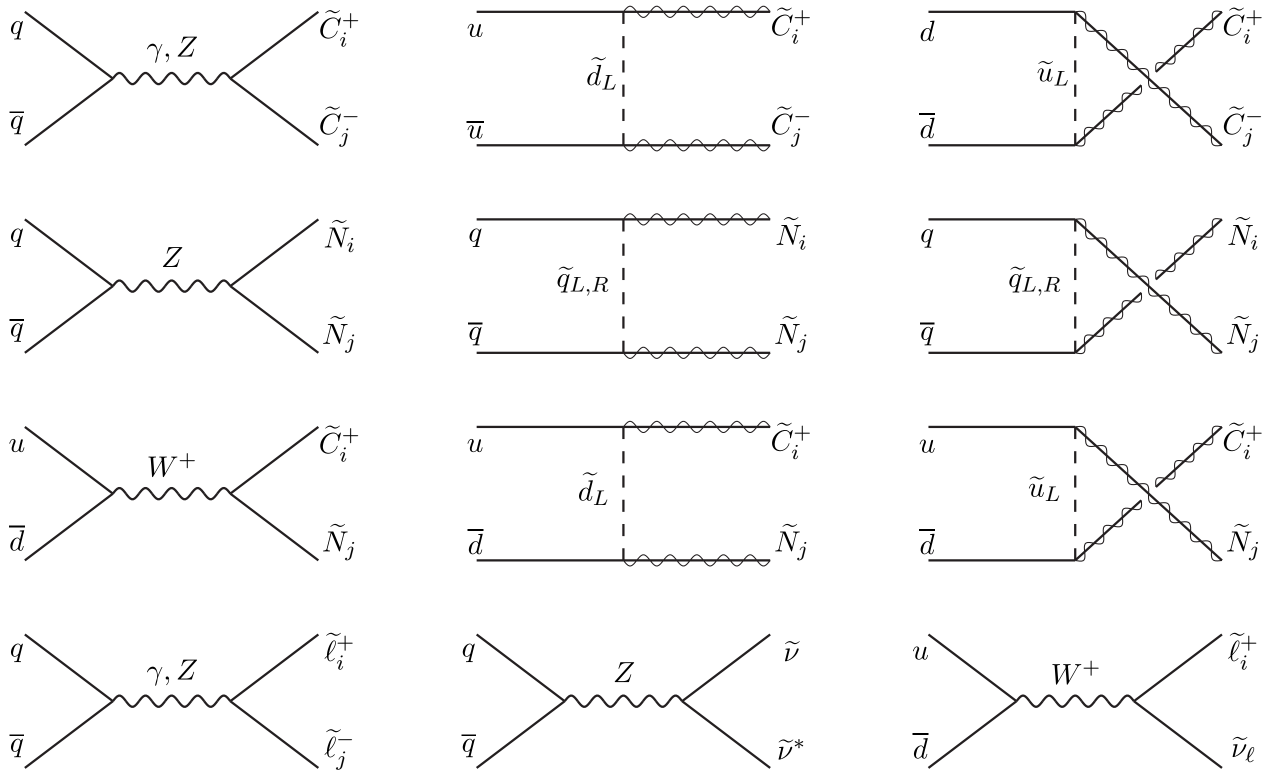
quark-antiquark ⇨ **squark antisquark**

quark-quark ⇨ **squark pair**

There are few bottom and no top quarks in the proton, because of their mass.
Thus, third generation scalar quarks are only produced by boxed diagrams

Electroweak production

N^0_1 or χ^0_1 = neutralino-1 $C^{\pm}_1$ or $\chi^{\pm}_1$ = chargino-1



Pairs of charginos

Pairs of neutralinos

Chargino neutralino

Slepton pairs
Sneutrino pairs
Sneutrino-slepton

These production processes are suppressed compared to those of slide 5

- Only quarks in the initial state
- At least two vertices involving the electromagnetic or weak coupling…

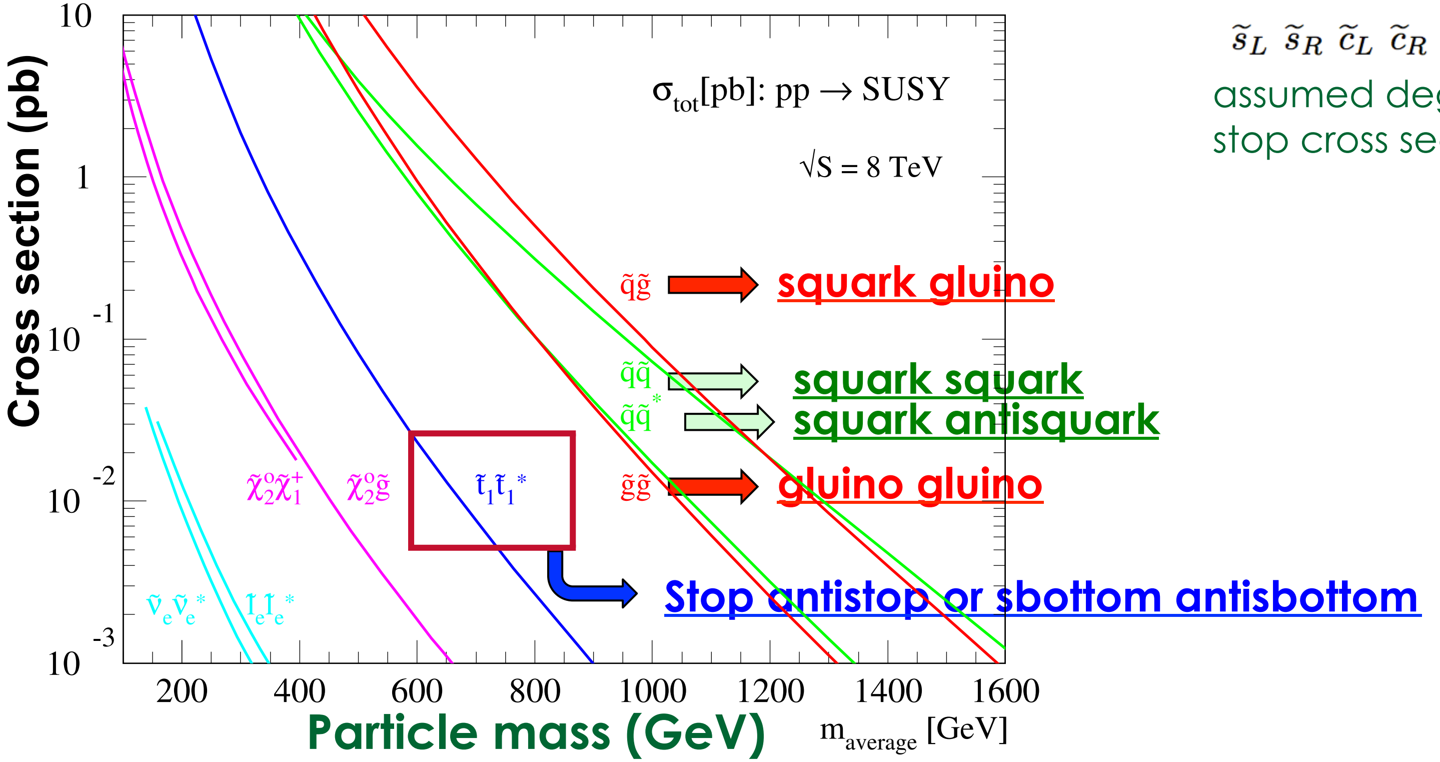
Cross sections

Squark cross section is the sum over

$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$

$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$

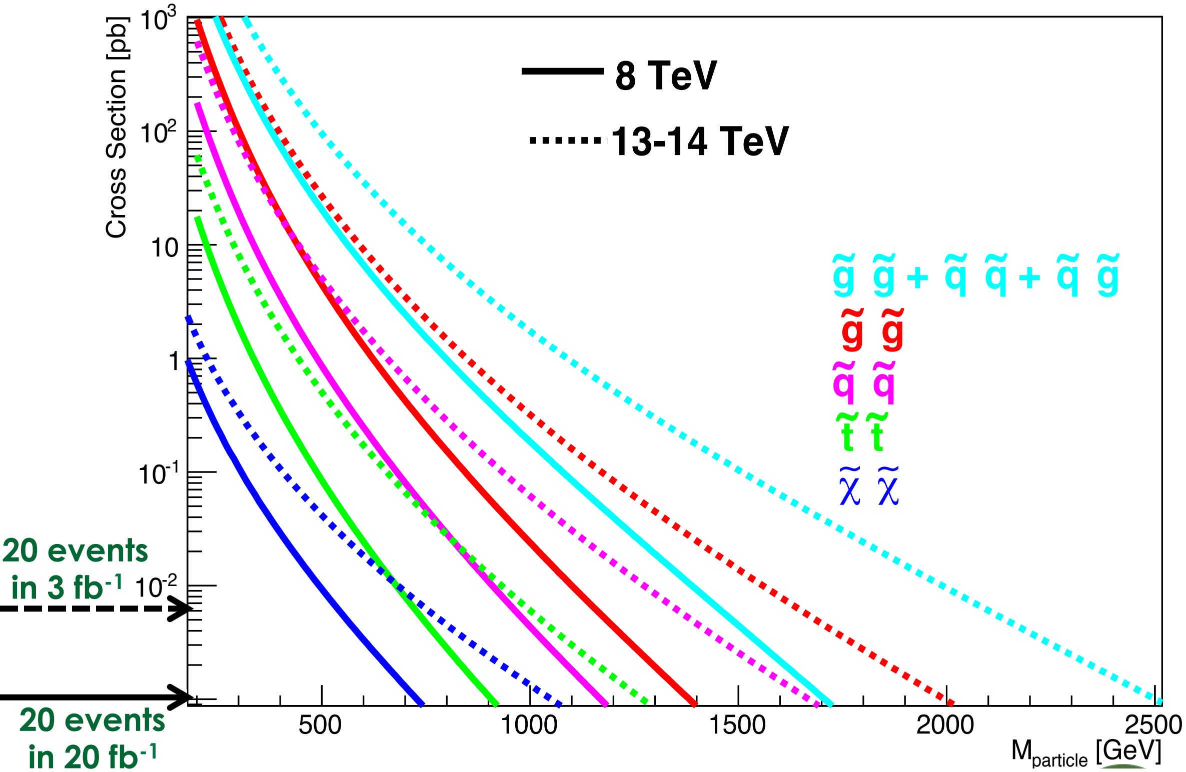
assumed degenerate in mass. The stop cross section is only one state.



- For the same mass, cross section is **much larger** for particles produced trough strong interaction (squark and gluinos)
- It's also larger for first generation squarks (more production diagrams)
  - High cross section means strong existing limits : we are now looking at higher masses

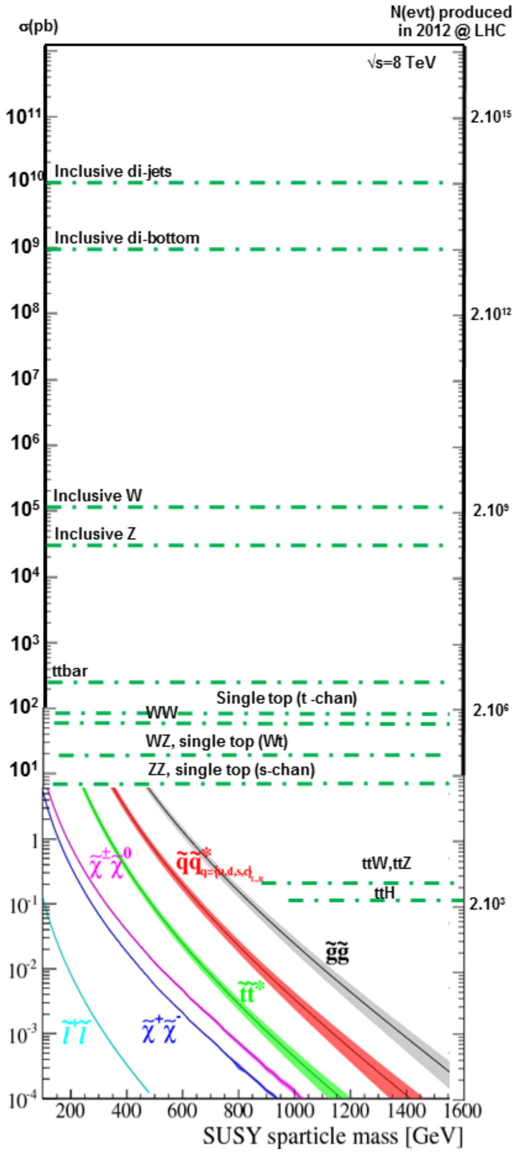
Energy and luminosity

	E_{CM} [TeV]	L [fb^{-1}]
Tevatron run2 (2002-2011)	1.96	10
LHC run1 (2010-2012)	8	20
LHC 2015	13	3
LHC run2 (2015-2018)	13	100



- Increased E_{CM} = increased cross section. Increase is much larger for high mass states.
- Increased luminosity = sensitivity to smaller cross section
- LHC 2015 has smaller luminosity and higher energy compared to run1. Sensitivity gain for high mass (cross section times luminosity increase) : strong production searches
- LHC run2 and beyond (same energy more luminosity) will probe lower cross sections

Other cross sections

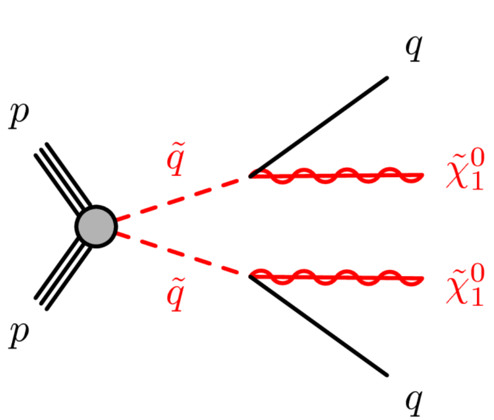


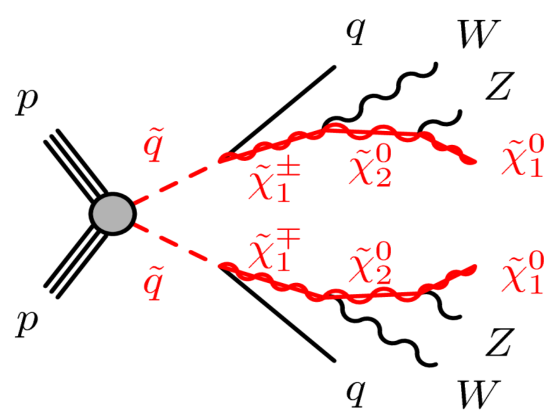
Even the SUSY processes with "high" cross are a tiny fraction of the total collisions.
Out of 1 billion collisions per second, *less than one* will produce SUSY particles.

Disk and CPU constraints imply only one collision in 40,000 can be registered – the first selection of signal candidates is done by the data acquisition software *(trigger)*

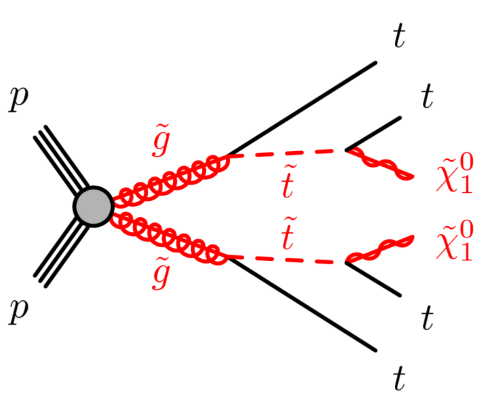
Squark and gluino decays

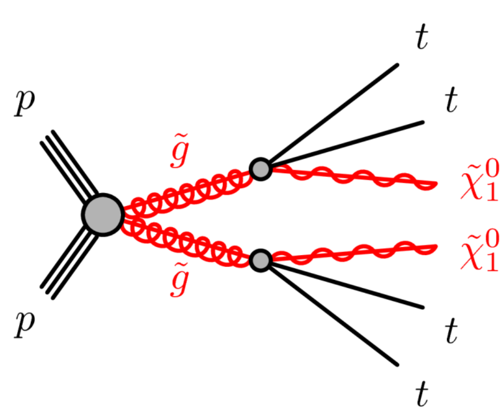
Assuming R-parity conservation and the χ^0_1 as the lightest SUSY particle. More on other scenarios later.





- If $m(\tilde{q}) > m(\tilde{g})$, $\tilde{q} \rightarrow \tilde{g}q$ via strong interaction
- Otherwise, $\tilde{q} \rightarrow q\tilde{\chi}^0$ or $q\tilde{\chi}^\pm$ via EW interaction

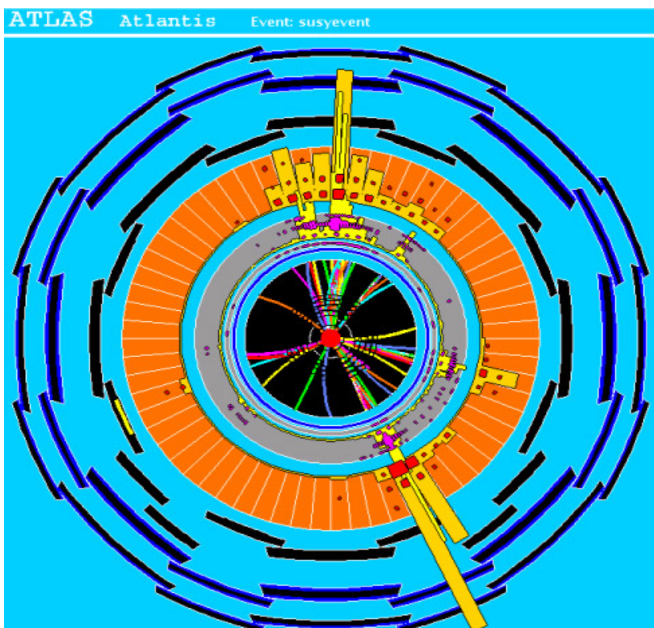




- If $m(\tilde{g}) > m(\tilde{q})$ the gluino decays to squark-quark.
- Otherwise, a 3-body decay via virtual squark is expected

Observable final state: jets

- The top decays to bW before forming hadrons. All other quarks will be observed as a jet of collimated hadronic particles
- The neutralinos are not seen directly, but their momentum in the plane transverse to the beam has to match that of all visible particles (as it's 0 in the initial state) => **missing transverse momentum**
  (also called missing energy as most momenta are reconstructed from energy measurements in the calorimeters)

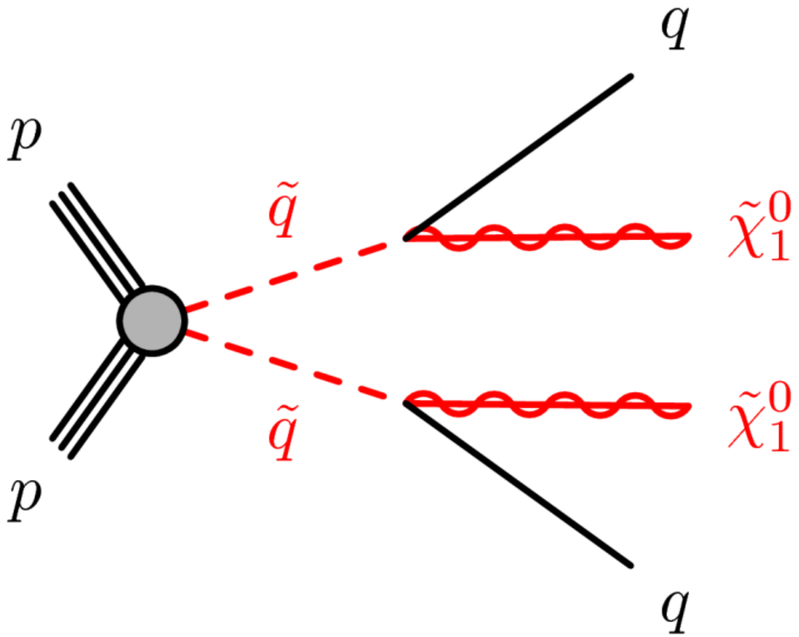


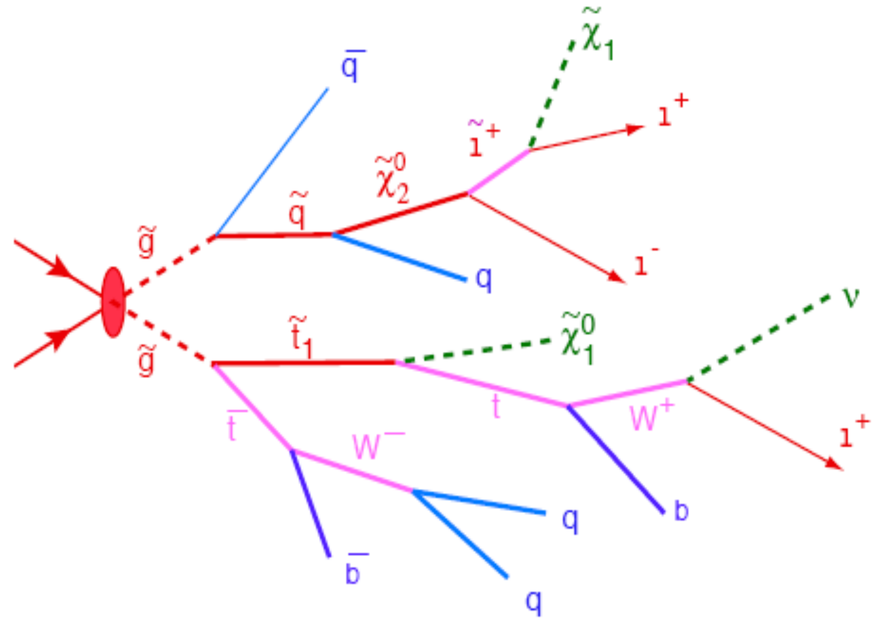
A proton proton collision with three jets

An other type of jet

Possible SUSY events

Assuming strong production. More on electro-weak production later.



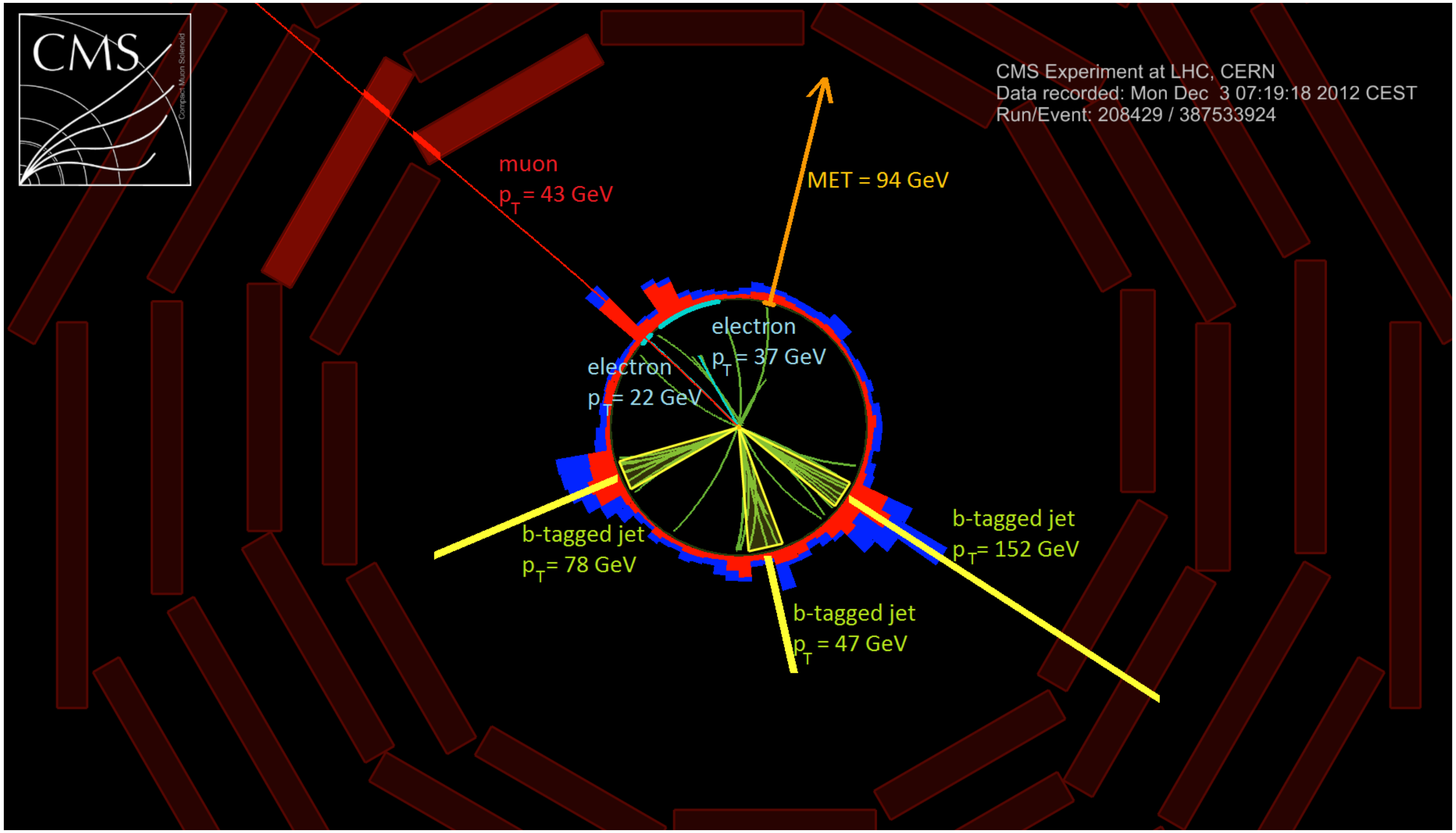


➔Two hadronic jets (from the quarks) and missing momentum (from the two weakly interacting particles)

➔ Six jets, three leptons, and missing momentum

- R-parity conservation and squark and gluinos lighter than about 2 TeV means events with **jets and missing momentum**
- The *number* of jets, and whether leptons are also produced, depend on the (unknown) details of mass spectrum and decay chains.

A signal event ?



Maybe… but while pretty rare, an handful of events like this is expected from SM processes.

Search strategies

In R-parity conserving scenarios

- SUSY particles are produced in pairs
- The lightest one one is stable and weakly interacting.

Since there are two unmeasured particle in the final state it is not possible to measure all decay products of a SUSY particle and reconstruct invariant mass.

The simplest SUSY search proceed as follows:

- Count the number of collisions satisfying a given selection (say "six jets with p_T > 60 GeV and missing transverse momentum larger than 150 GeV")
- Compute the number of background events expected to pass the selection
- Compare the observed number of events with the expected background rate. An excess of the former indicates the presence of a signal.

The key difficulties are:

- How we determine the selection criteria, since we do not know the masses and decays of SUSY particles ?
- How do we compute the expected background rate in such a reliable way that we can attribute an higher observed rate to a non-Standard Model process ?

A typical analysis

Using a specific example I will try to show you the basic building blocks of a SUSY search analysis

- **Choice of selection criteria**
- **Comparison of simulated and real data in appropriate control selections**

Make sure that simulation describes real data within uncertainties!

- **Determine the uncertainty** on the background level in signal candidates sample. Example of uncertainties:
  - Experimental: jet energy calibration
  - Computational: number of simulated events (constrained by available CPU and disk space…)
  - Theoretical: cross sections, hadronization model, PDF, …
- **"Open the box"**

Observed number of events becomes known at this point

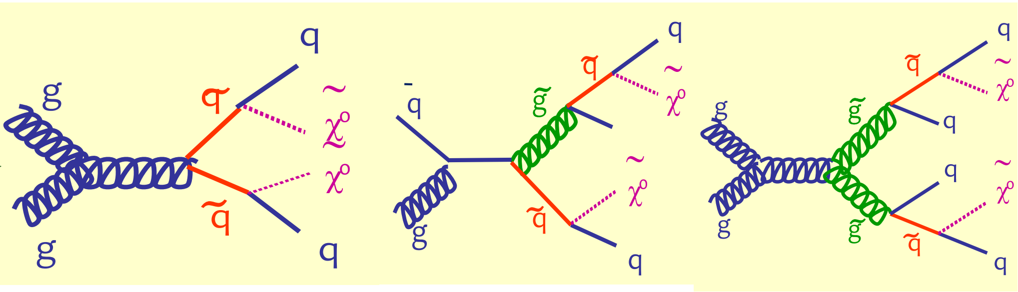
- No signal ? =>  => **derive limits**

Mass ranges for SUSY particles which are excluded (in disagrement with observed rate)

Choice of selection criteria

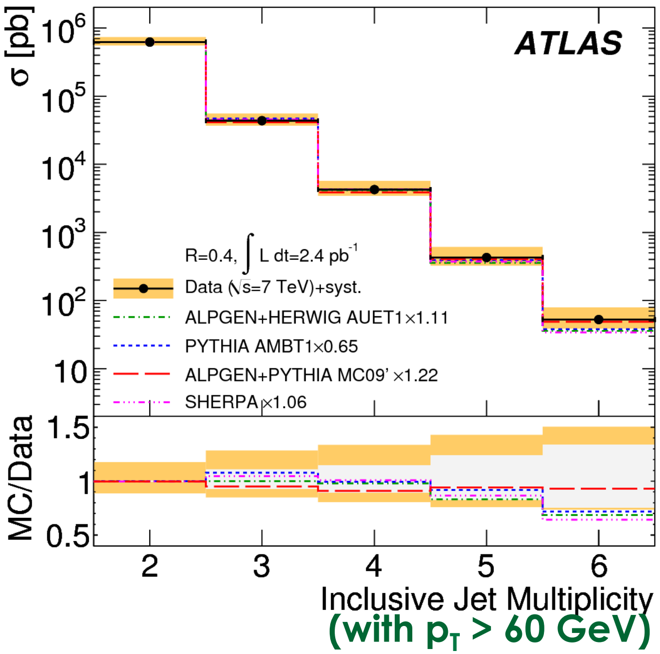
Following ATLAS logic here. CMS logic a bit different – more on this later.

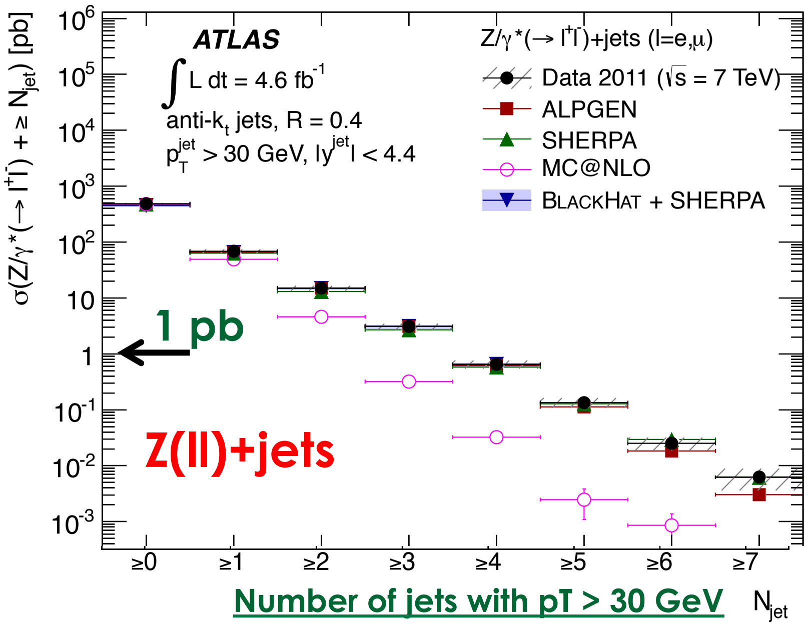
- Typically, we choose the signal to be targeted. Each choice defines an analysis and the set of all analysis is supposed to target all possible signal processes.
- Say we target squark or gluinos decaying to the LSP plus jets:



- We still do not know masses and decay chains
  - Gluinos give more jets than squark production
  - Long decay chains give more jets than decays directly to the LSP
  - If the mass difference ΔM between the produced particle and the LSP is small, the jet momenta and missing momentum will be smaller
- The selection criteria need to accommodate all scenarios
  - One can define a set of criteria for each scenario: 2,3,4,5,6,…9 jet selections, for each number of jets have a set of cuts for large ΔM and one for low ΔM, etc.
  - In alternative, we can use the shape of 2-3 key distributions (say, number of jets and missing transverse momentum) and compare the data with the expected background in all bins.

Discriminating variables





- Most common process: multi-jet production
- Many jets, but no missing momentum, unless a jet momentum is mismeasured or a particle in the jet decays producing neutrinos (B ➔D l ν)

But then missing momentum is aligned with a jet, which is not the case for signal

- Once we get rid of multi-jets, we are left with Z+jets, W+jets, top pairs
- Z(νν)+jets is an irreducible background (it looks like the signal) but the cross section decreases rapidly with the number (and momentum) of jets

Selections, one example

Requirement	Channel									
	A (2-jets)		B (3-jets)		C (4-jets)		D (5-jets)	E (6-jets)		
	L	M	M	T	M	T	–	L	M	T
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] >	160									
$p_{\mathrm{T}}(j_1)$ [GeV] >	130									
$p_{\mathrm{T}}(j_2)$ [GeV] >	60									
$p_{\mathrm{T}}(j_3)$ [GeV] >	–		60		60		60	60		
$p_{\mathrm{T}}(j_4)$ [GeV] >	–		–		60		60	60		
$p_{\mathrm{T}}(j_5)$ [GeV] >	–		–		–		60	60		
$p_{\mathrm{T}}(j_6)$ [GeV] >	–		–		–		–	60		
$\Delta\phi(\mathrm{jet}_i, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\min}$ >	0.4 ($i = \{1, 2, (3$ if $p_{\mathrm{T}}(j_3) > 40$ GeV$)\}$)				0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_{\mathrm{T}} > 40$ GeV jets)					
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj)$ >	0.2	–[a]	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
m_{eff}(incl.) [GeV] >	1000	1600	1800	2200	1200	2200	1600	1000	1200	1500

• $m_{eff} = E_T^{miss} + H_T \sim 1.8(M_{SUSY}^2 - M_{LSP}^2)/M_{SUSY}$ [hep-ph/0006276]

Alternative selections, from 2 to 6 jets

One jet with p_T > 160 GeV, missing momentum > 130 GeV★

Further jets

These kills most of the multi-jets

"effective mass", scalar sum of transverse momenta of jets and missing transverse momentum.

It peaks at a value correlated with the mass of produced particles (hence the name)

Loose/medium/tight cuts. Overall, 10 alternative selections

★ Match the trigger event selection criteria

• $m_{eff} = E_T^{miss} + H_T \sim 1.8(M_{SUSY}^2 - M_{LSP}^2)/M_{SUSY}$ [hep-ph/0006276]

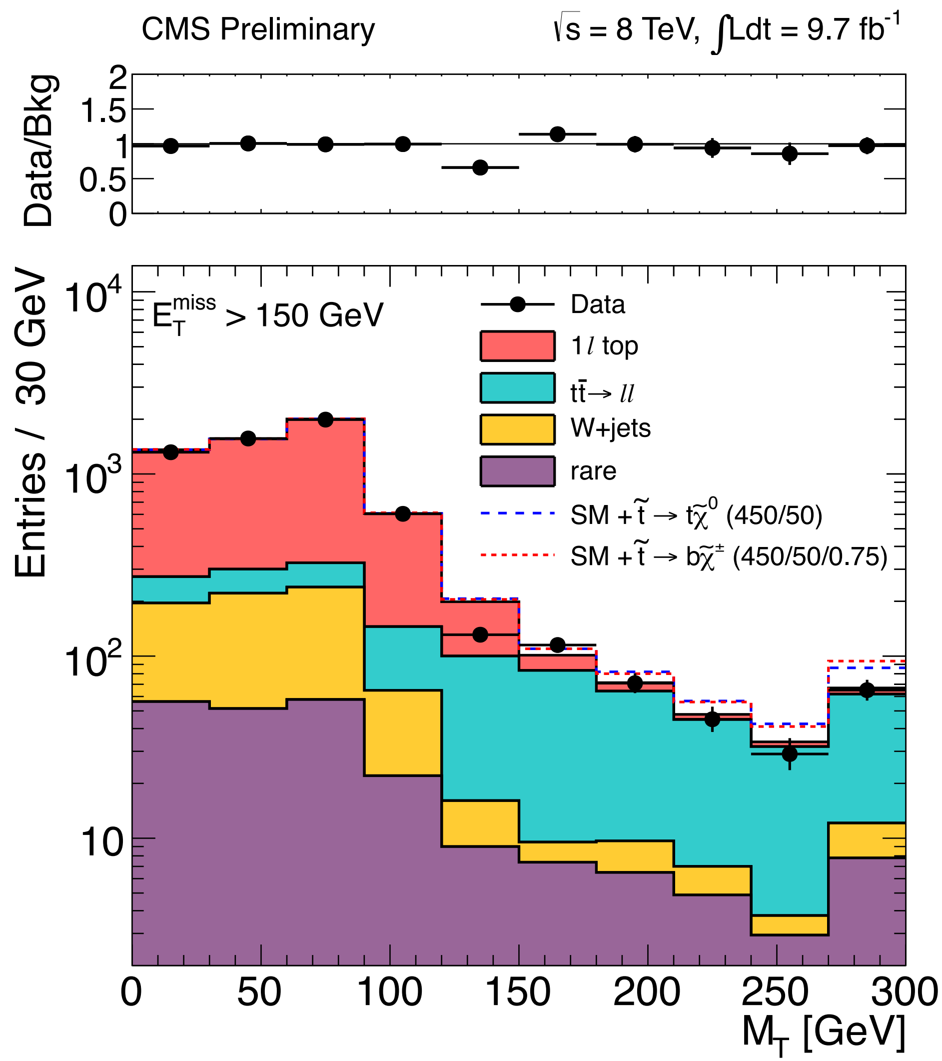
S/B separation, an other example

For search channels with one lepton:

$$M_T(l,\nu) = \sqrt{2p_T(l)p_T(\nu)\left[1-\cos(\phi_l-\phi_\nu)\right]}$$

- In Background the invariant mass of the lepton and missing momentum (the neutrino) is the W mass, and the transverse mass is lower than that.
- Signal has two extra invisible particles and some signal events will have $M_T > M_W$

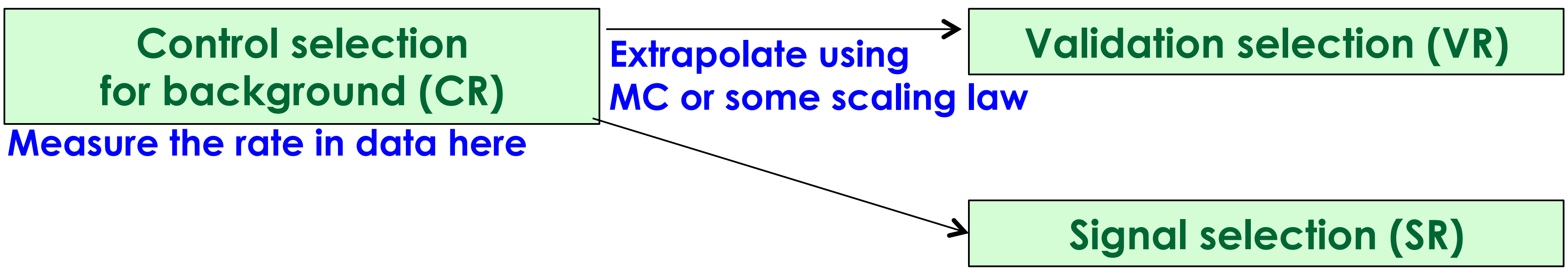
In fact, top antitop **both** decaying to blν is the main background at large M_T.



Step 2: estimate of backgrounds

Background rates can be estimated using MonteCarlo simulation, but is the physics and detector description in the simulation reliable ?

Remember: any excess in data compared to expectation must be confidently attributed to non-Standard Model processes, we need to be super-confident about our background estimate !



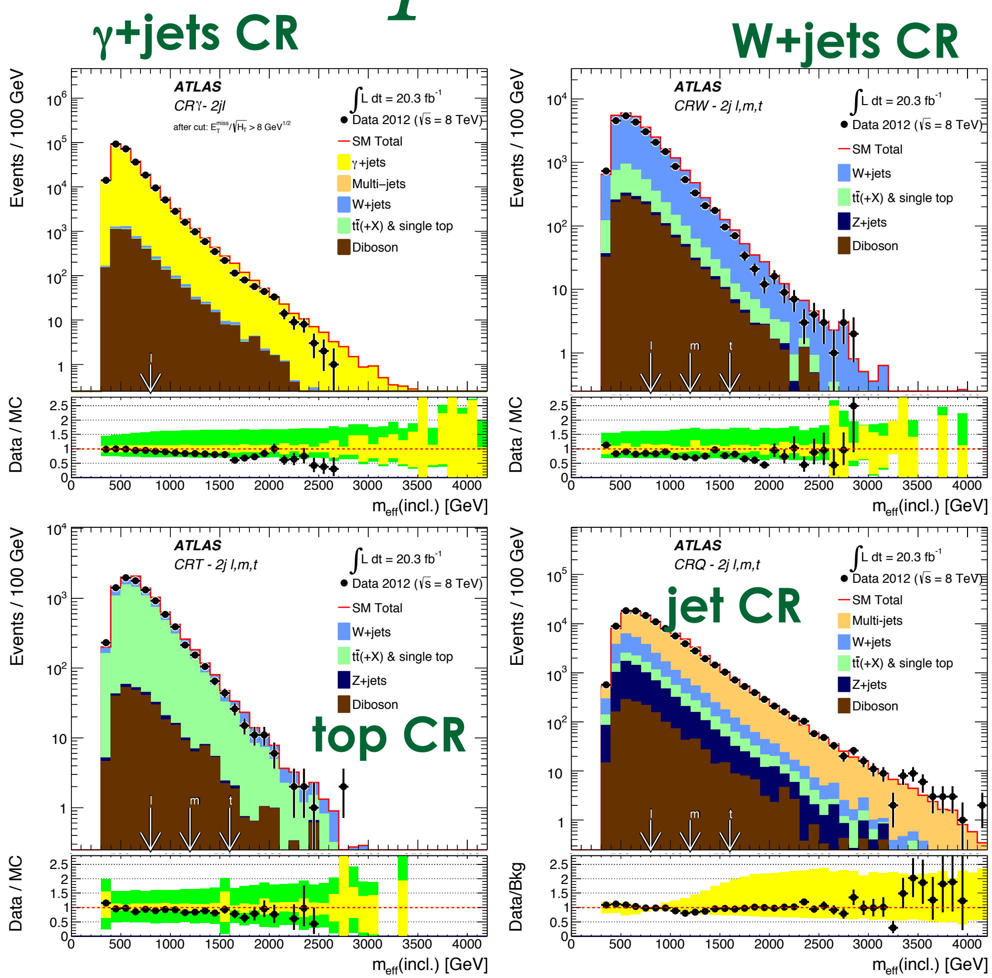
Typically, we measure the rate in a set of control selections

- One control selection for each major background
- CR (and VR) are designed so that the target signal is negligible there
- All selections which are difficult to model are common for the CR and the SR

Example

- Use γ+jets as a control process for $Z(\nu\nu)$+jets
  - The kinematics of the two processes is similar for large boson momenta (>> m_Z)
  - The cross section of γ+jets is larger than Z+jets (good statistics in the control sample)
  - Asking a photon and veto large missing transverse momentum ensure negligible contribution of the targeted signals in the control sample
- Procedure:
  - Ask a photon, and add the photon transverse momentum to measured missing transverse momentum (=> pretend the observed photon was an invisible decaying Z)
  - Apply the full signal selection (using the new missing momentum)
  - The $Z(\nu\nu)$ background estimate is the observed rate, corrected for the difference in γ+jets and Z+jets cross sections, photon identification efficiency, and any difference between γ+jets and Z+jets
  - The last piece comes from theory/MonteCarlo but it is a relatively well known and small correction

Control plots



- ➢ Effective mass distributions in some control selections
- ➢ The agreement between data and MC (the histograms) is shown, but only the data counts contribute to the background estimate

CR	SR background	CR process	CR selection
CRγ	$Z(\to \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	Multi-jets	Multi-jets	SR with reversed requirements on (i) $\Delta\phi(\text{jet}, \mathbf{E}_{\text{T}}^{\text{miss}})_{\text{min}}$ and (ii) $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}(N_{\text{j}})$ or $E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$
CRW	$W(\to \ell\nu)$+jets	$W(\to \ell\nu)$+jets	30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \to b\bar{b}qq'\ell\nu$	30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, b-tag

Opening the box

- The decision of the selections, the estimation of the background, and all the cross-checks are done with the signal candidates "blinded", without having access to them in data
- Once one has the final estimate of expected background and uncertainty, the signal candidates are "unblinded"
- So far, the rate in data has always been in agreement with the Standard Model expectation

Signal Region	**4jl-**	**4jl**	**4jm**	**4jt**
MC expected events				
Diboson	175	70	7.2	0.34
Z/γ^*+jets	885	333	30	2.9
W+jets	832	284	16	1.2
$t\bar{t}$(+EW) + single top	764	167	4.0	0.62
Fitted background events				
Diboson	180 ± 90	70 ± 34	7 ± 4	0.34 ± 0.17
Z/γ^*+jets	660 ± 60	238 ± 28	16 ± 4	$0.65^{+0.78}_{-0.65}$
W+jets	560 ± 80	151 ± 28	10 ± 4	0.9 ± 0.4
$t\bar{t}$(+EW) + single top	730 ± 50	167 ± 18	3.8 ± 1.9	0.6 ± 0.6
Multi-jets	$1.7^{+3.9}_{-1.7}$	$0.73^{+1.57}_{-0.73}$	–	–
Total bkg	2120 ± 110	630 ± 50	37 ± 6	2.5 ± 1.0
Observed	2169	608	24	0
$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	13	4.5	0.52	0.15
$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb] (asymptotic)	13	4.3	0.45	0.12
S^{95}_{obs}	273	91	10	3.1
S^{95}_{obs} (asymptotic)	268	87	9.2	2.5
S^{95}_{exp}	244^{+91}_{-66}	103^{+34}_{-29}	16^{+6}_{-4}	$4.0^{+1.8}_{-0.9}$
S^{95}_{exp} (asymptotic)	242^{+87}_{-65}	97^{+35}_{-25}	15^{+6}_{-4}	$4.0^{+2.4}_{-1.4}$
p_0 (Z)	0.35 (0.4)	0.50 (0.0)	0.50 (0.0)	0.50 (0.0)

MC prediction of background

Actual background prediction (using CR observations)

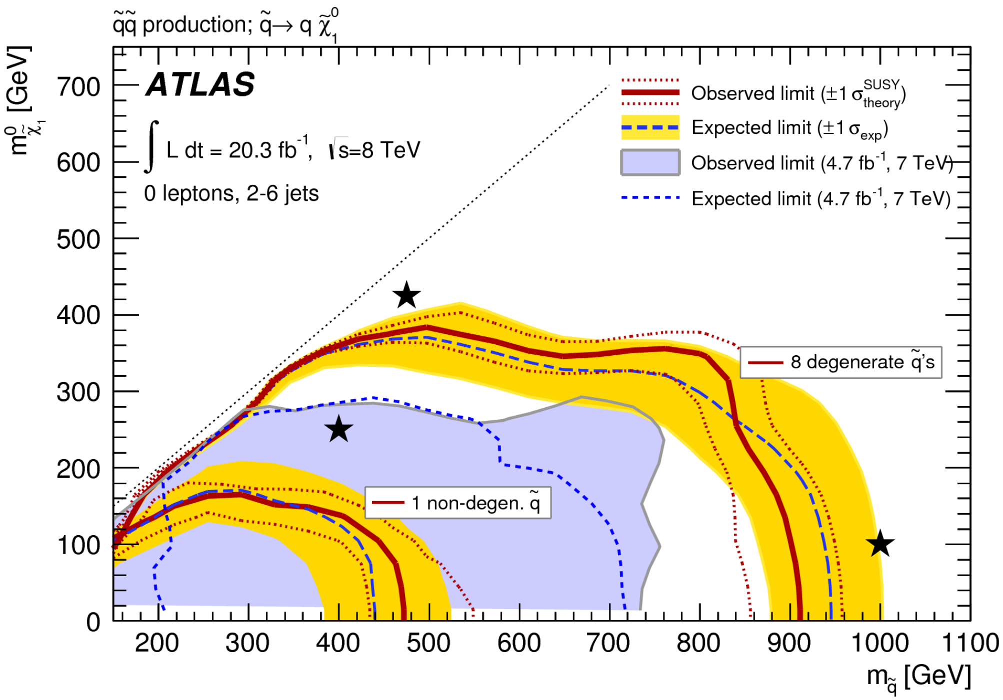
Observed event counts

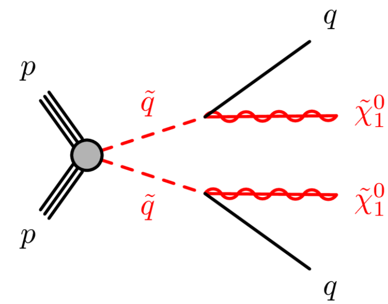
Limit on signal rates: for average signal rate larger than this, the probability of having as few (or fewer) events as observed is < 5%

Compatibility with Standard Model

Limits on SUSY models

Given a negative result, the theory parameter space incompatible with the observation is derived.
Problem: SUSY has O(100) free parameters (at least) but we can made only 2D plots and simulate pp-collisions for a few thousands of different signal hypothesis at best.
Solution: for each production process and decay chain produce a 2D limit plot.





Limit on squark and neutralino mass, assuming all squark are degenerate in mass and the branching ratio of the decay in the diagram is 100%

A bit of warning on LHC limits..

- It’s likely there are multiple competing decay modes for each SUSY particle – the 100% BR limit curve is not the only result, cross section limits at nominally excluded mass points are also important
- We have lots of exclusion plots, but they will never cover all possible diagrams – we provide cutflows, acceptance maps etc. so that theorists can implement our selections and produce their own limits on other models
- We say we look for squarks and gluinos, but the signature is a strongly interacting pair-produced particles decaying to a DM particle each. Should we see a signal, we won’t be able to tell wether it’s SUSY or something else for a long time.

The other side of the ring…

- Several selections, by binning in discriminating variables

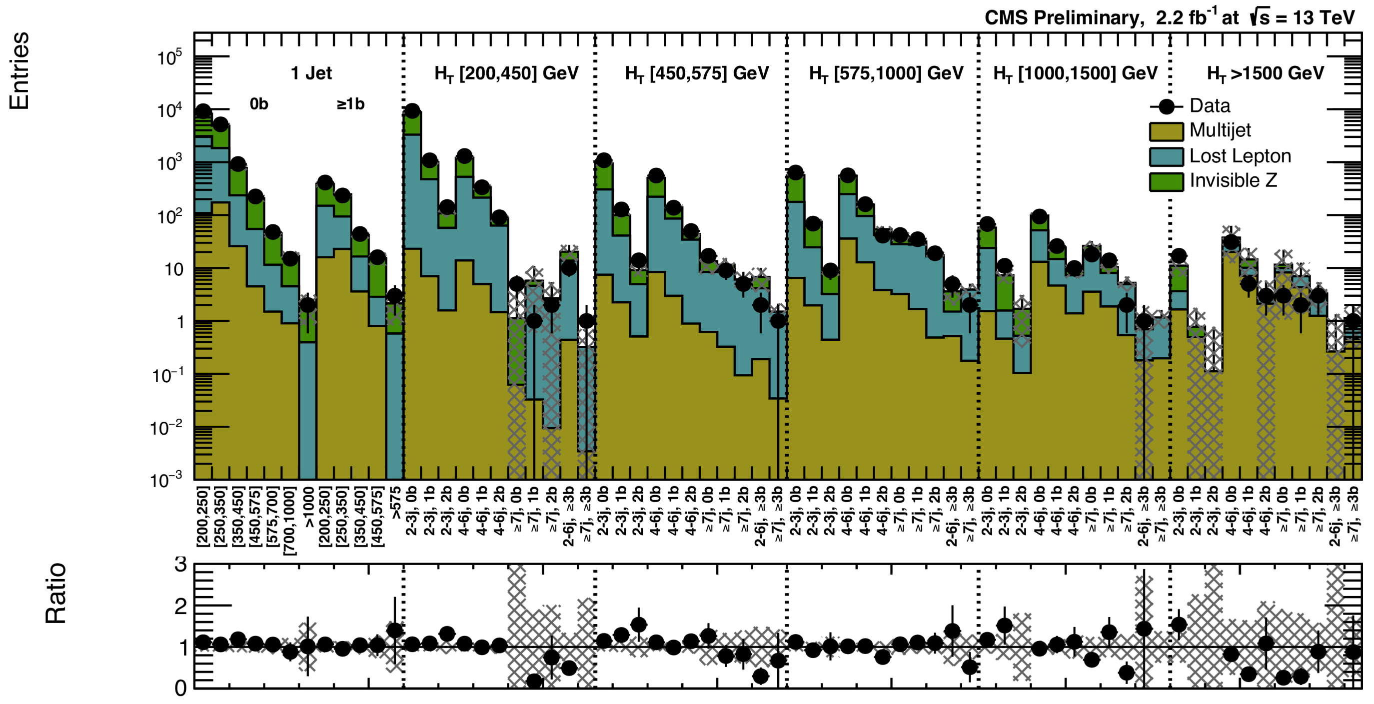
> - 5 bins in H_T: [200,450], [450, 575], [575, 1000], [1000, 1500], [1500,∞]
>   These bins are also referred to as very low H_T, low H_T, medium H_T, high H_T, and extreme H_T regions.
> - 11 bins in N_j and N_b: 2–3j 0b, 2–3j 1b, 2–3j 2b, 4–6j 0b, 4–6j 1b, 4–6j 2b, $\geq$7j 0b, $\geq$7j 1b, $\geq$7j 2b, 2–6j $\geq$3b, $\geq$7j $\geq$3b
>
> Each bin defined by the H_T, N_j, N_b requirements above is referred to as a *topological region* and we further divide each topological region in bins of M_{T2}.
>
> - 3 bins in M_{T2} at Very Low H_T: [200,300], [300,400], [400,∞]
> - 4 bins in M_{T2} at Low H_T: [200,300], [300,400], [400,500], [500,∞]
> - 5 bins in M_{T2} at Medium H_T: [200,300], [300,400], [400,600], [600,800], [800,∞]
> - 5 bins in M_{T2} at High H_T: [200,400], [400,600], [600,800], [800, 1000], [1000,∞]
> - 5 bins in M_{T2} at Extreme H_T: [200,400], [400,600], [600,800], [800,1000], [1000,∞]

162 selections !

What is M_{T2} ???

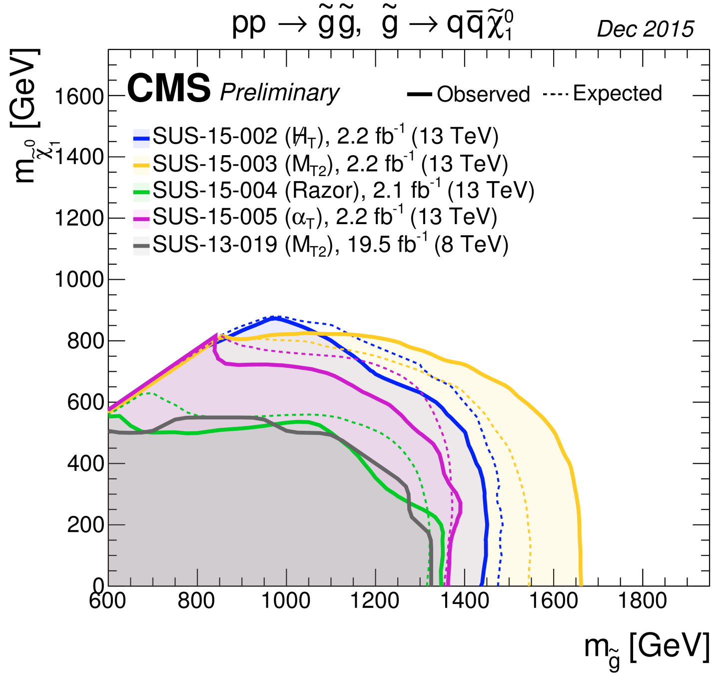
- Uhm. Where is that blackboard ?

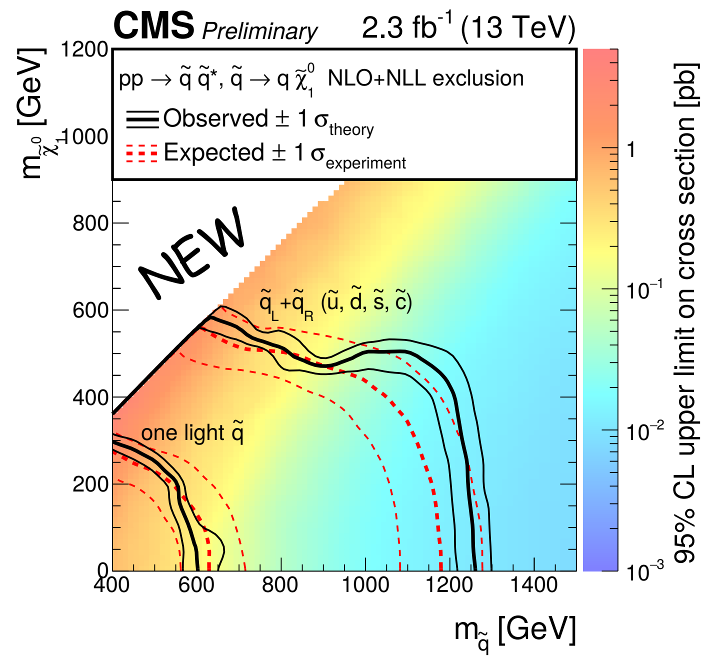
SUSY searches with many bins



- All selections are statistically combined, building a joint likelihood of data against the SM and the SM+SUSY hypothesis
  - Better discrimination than any single cut, and you don't need to worry what is the best cut value (which is model dependent)
  - You need to worry about correlations between systematics uncertainties in the various bins
  - The combination requires a known signal model – works for excluding simplified models, problematic for finding an unknown signal

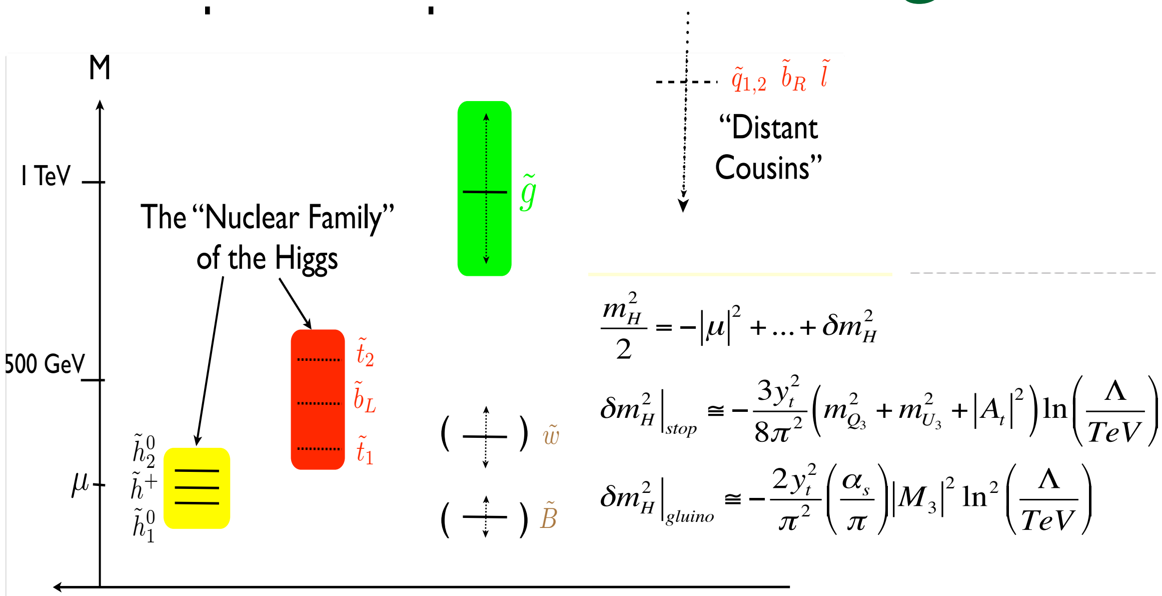
Status of squark and gluino limits





- Depending on the mass of the lightest SUSY particle and on the decay chain, lower limits of 600-1200 GeV (800-1700 GeV) are placed on the masses of squarks of the first two generations (gluinos).
- A single squark eigenstate (say c_L) might be lighter
- **But is this a problem for the Supersymmetric theory ?**

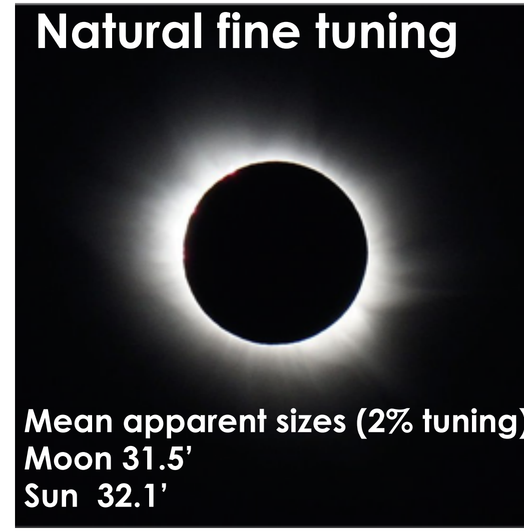
Naturalness as a guide ?



$$\frac{m_H^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2\Big|_{stop} \cong -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{TeV}\right)$$

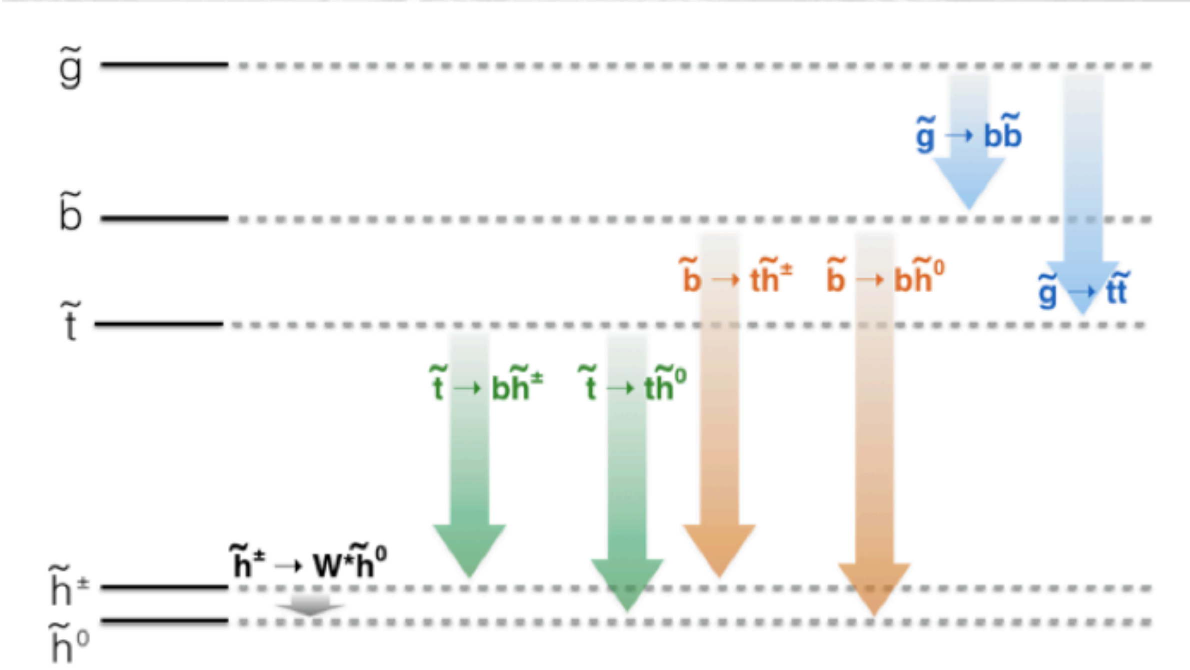
$$\delta m_H^2\Big|_{gluino} \cong -\frac{2y_t^2}{\pi^2}\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\ln^2\left(\frac{\Lambda}{TeV}\right)$$



- The scalar top, the lightest neutralino, and the lightest chargino should be well below 1 TeV mass.
- The gluino should be not much heavier
- Other particles might be light or heavy (specific models of SUSY breaking will make specific predictions)

- One does not get hard numbers though…
  - What is "natural enough" ? Is 5% natural ? 1% ?
  - SUSY breaking will make the weak scale masses dependent on each other, so "accidental" cancellations won't be accidental any longer...

Searches for natural SUSY

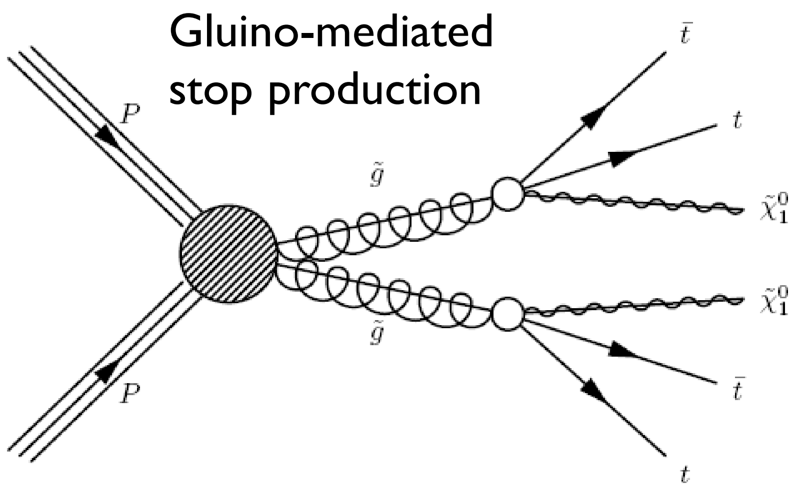


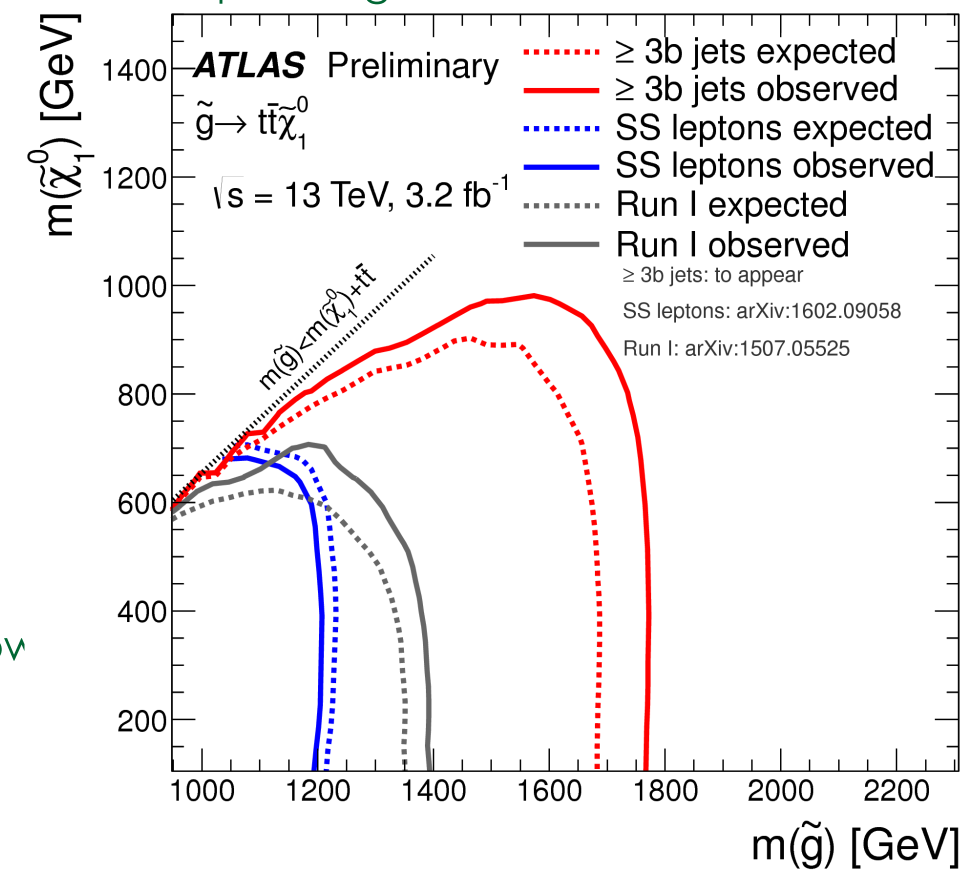
Given the natural mass spectrum, priority searches are

- Gluino pairs decaying into third generation squarks
- Direct production of scalar top and bottom quarks
- Direct production of neutralinos and charginos (but difficult if only the minimal natural spectrum : small mass splitting)

Gluino to top stop

Gluino excluded up to 1100-1750 GeV depending on the neutralino mass



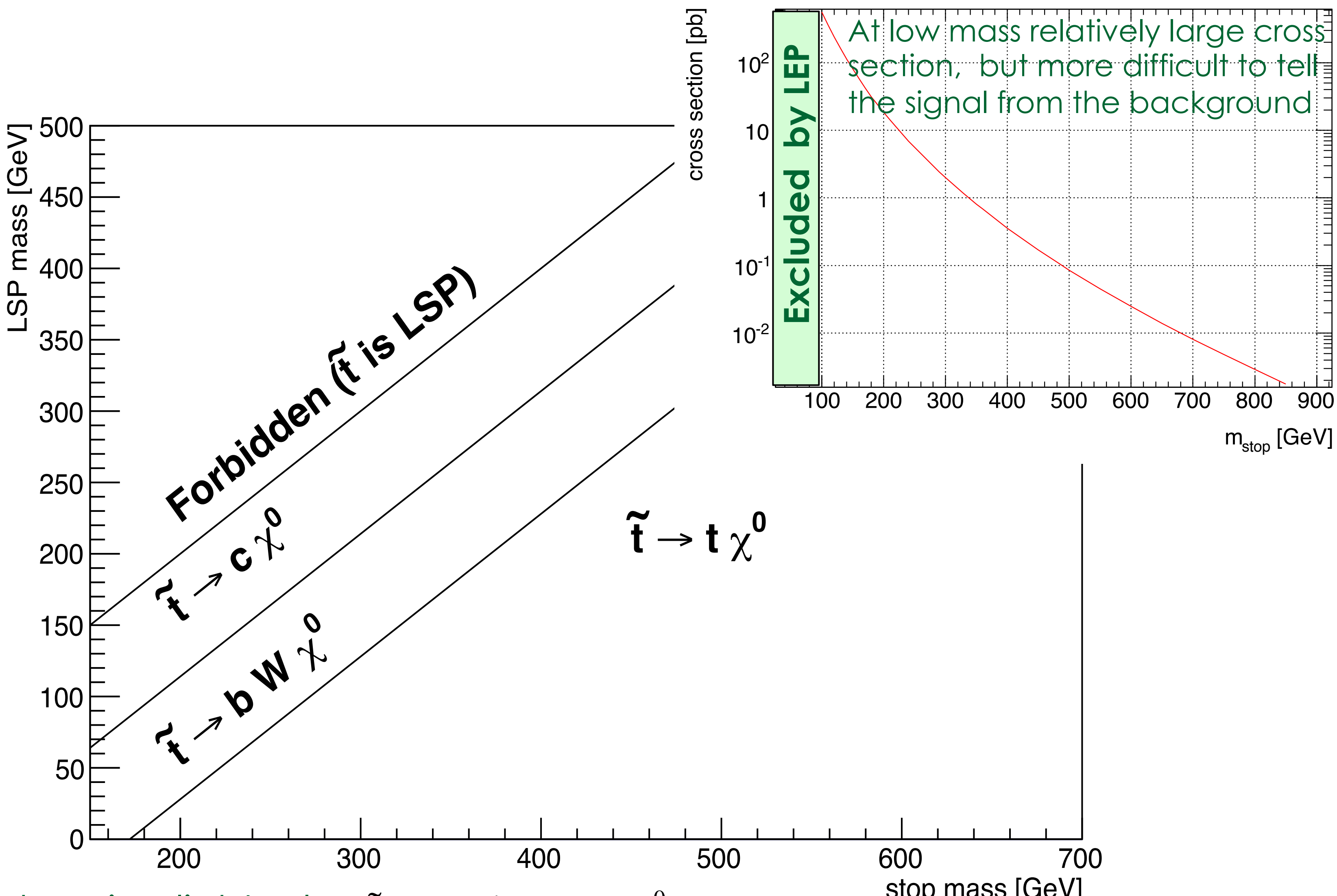


Four W boson and four b-jets !

Takled with 3b+jets+(0 or 1)leptons and 2 same sign leptons, both of which have low SM backgrounds

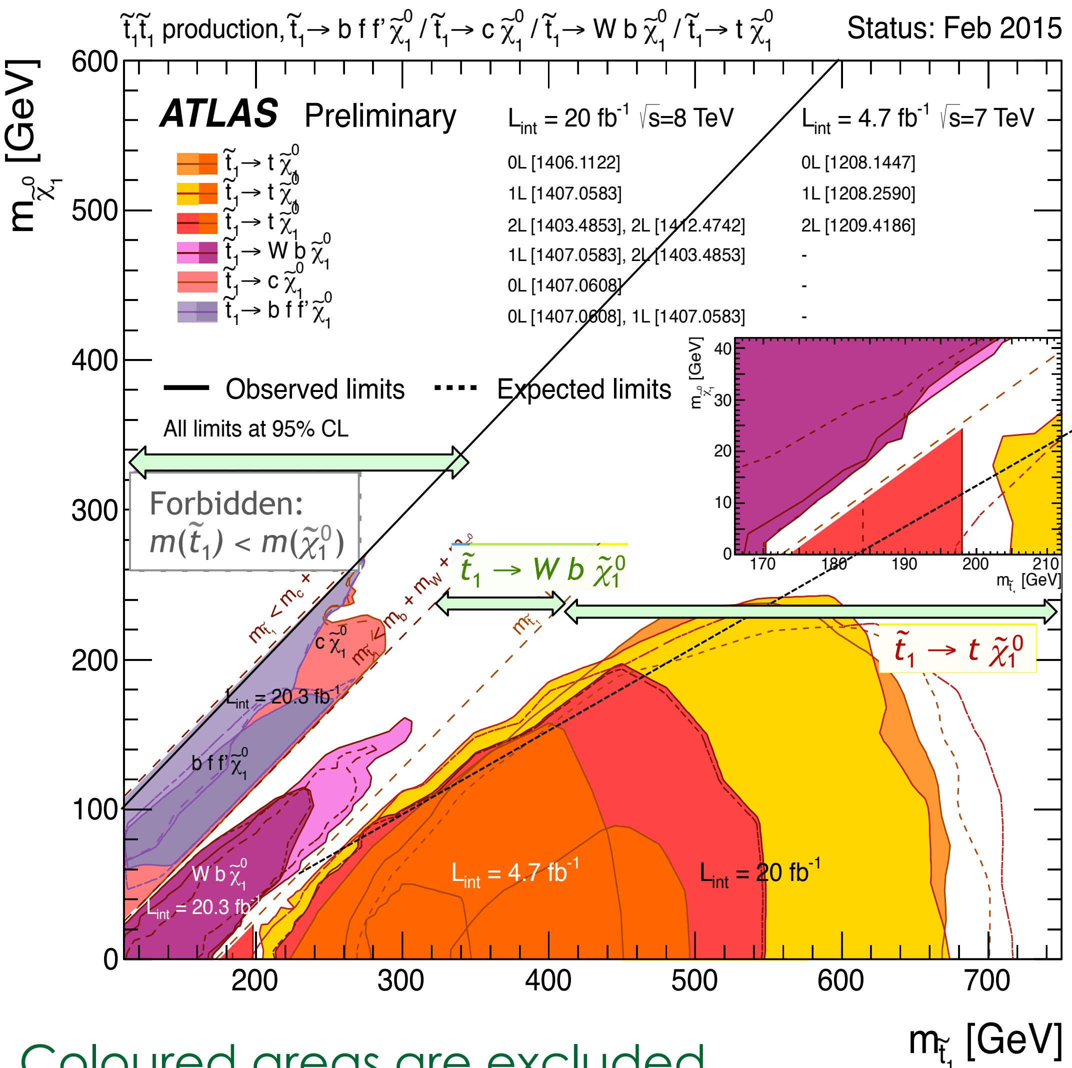
Here each curve is a different search (final state), everything on the left of *any* curve is excluded

Stop quark pair production



If chargino light, also $\tilde{t} \to b\chi^{\pm} \to bW\chi^{0}$

Scalar top limits



Coloured areas are excluded

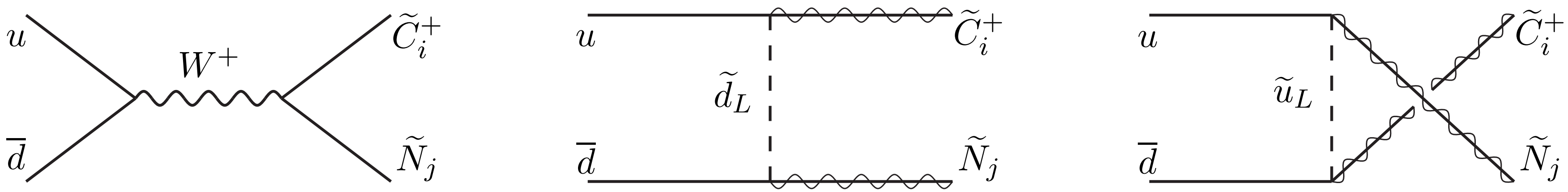
- The plot refer to the case of the stop decaying directly to the lightest neutralino.

What's happening here ?

- The stop decays to top N_1.
- mstop-mtop-mN_1 is ≈ 0 : N_1 is at rest in the stop reference frame. Final state very similar to ttbar, little MET from N_1, low cross section
- We expect sensitivity in run2 with ISR+tt production : boost of stop gets transferred to N_1

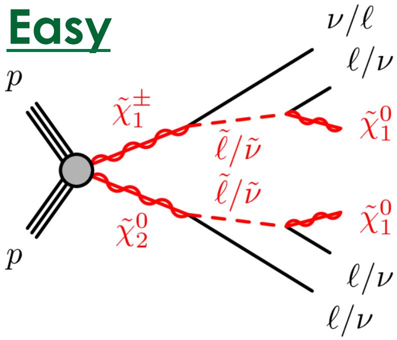
Direct pair production of EWKinos

- The production cross section is quite small, as it doesn't occur via strong interaction
- Similar Standard Model processes: WW, WZ, ZZ, WH, ZH production (only the first three have been observed so far)
- If the charginos and neutralinos decay hadronically, the (strong interaction produced) background is just too large
- If there are leptons in the decay, the dominant backgrounds are vector boson production and this can be handled.
- Typical signature is leptons, missing momentum, and **no jets**.
- Let's focus on just the example of N_2C_1 production



N_2C_1 *final states*

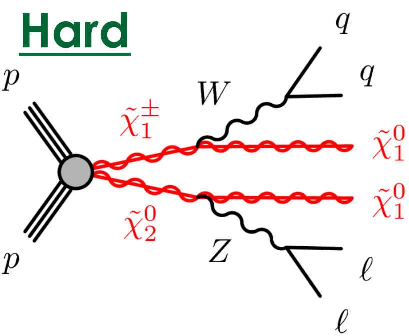
Easy



- If they can, the gauginos will decay to sfermion fermion. In practice only sleptons can be lighter than gauginos because of squark direct production limits. *Uhm…*
- Easy case : three leptons in 100% of the events

Signature : three leptons, missing energy, no jets

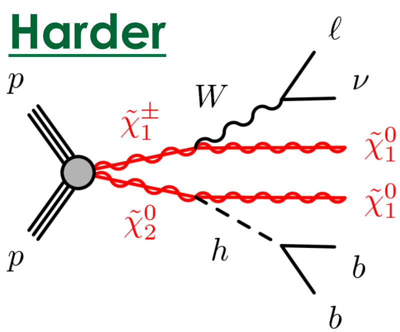
Hard



- If sleptons are heavy, things get more difficult.
- Only 3.3% of the events have three leptons because BR($Z \rightarrow l^+l^-$) = 3 x 3.3% BR($W \rightarrow l^+\nu$) =1/3

Signature : three leptons, missing energy, no jets

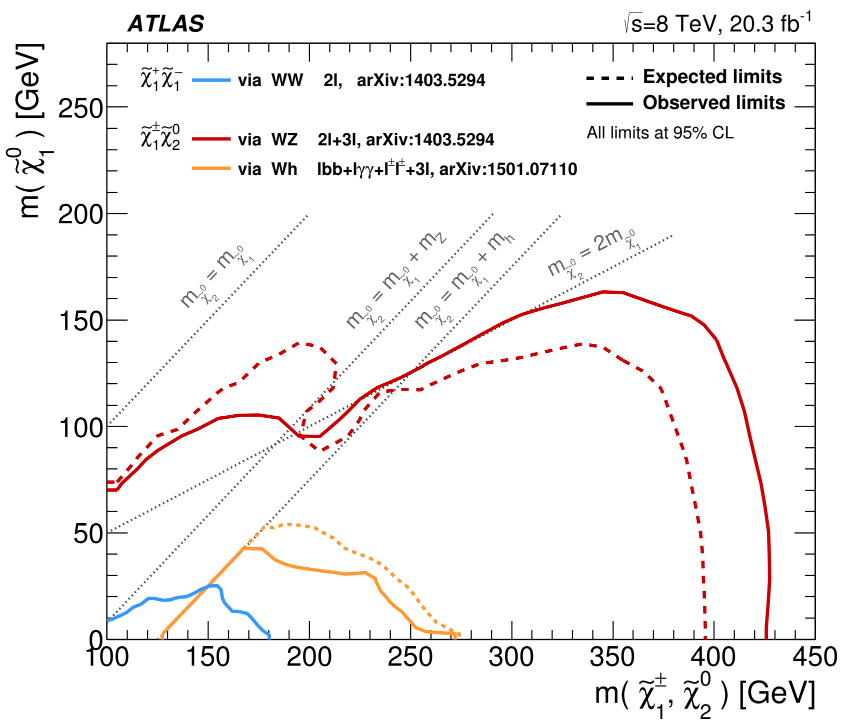
Harder



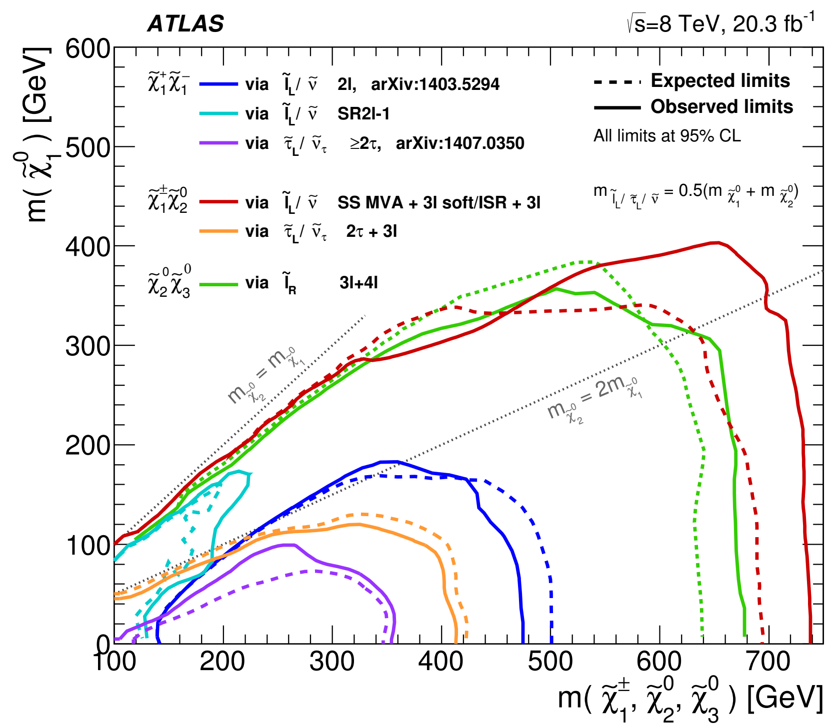
- If $m(N_2)$-$m(N_1)$ > $m(h)$, and depending on the neutralino mixing, the Higgs decay might be dominant.
- Similar to WH production, with comparable cross section at best, and with two extra undetected particles

Signature depend on H decay. Tackled in SS leptons, 3 leptons, 1Lbb, 1L$\gamma\gamma$ (plus MET in all cases)

Direct gaugino limits



Decays via WZ or WH

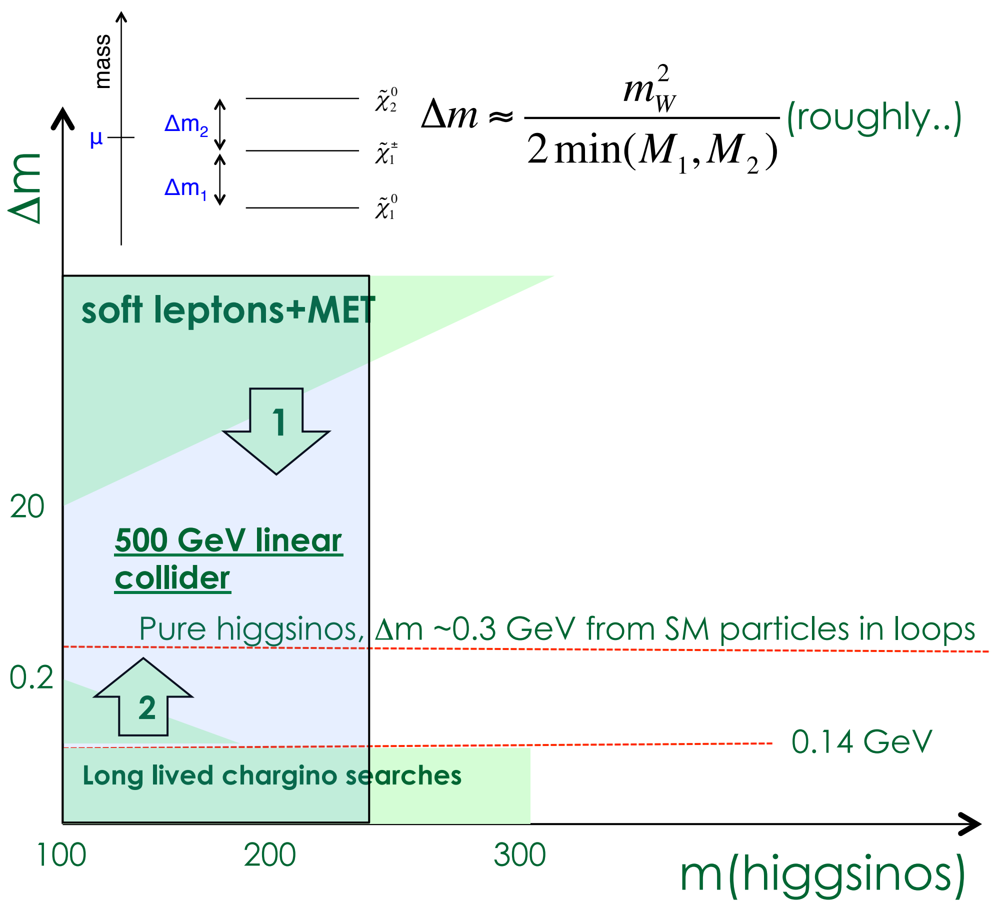


Decays via sleptons

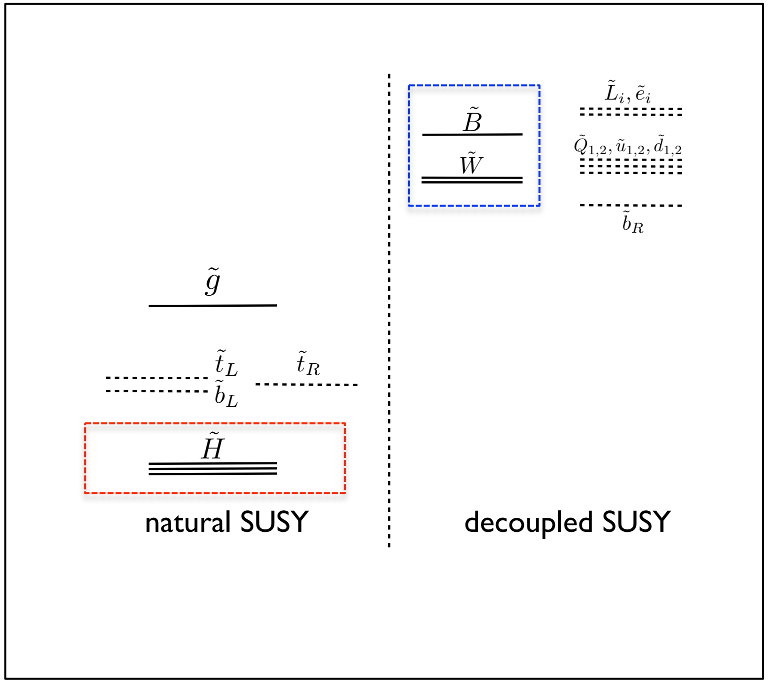
- Charginos cannot be lighter than 100 GeV, they would have been seen at LEP
- No limits if sleptons heavy and $\Delta M(C_1,N_1) < 30$ GeV
    - Case of $\mu \ll M_1,M_2$ gives an higgsino mass triplet (N_1,N_2,C_1) which would escape all electroweak searches…

Compressed electroweak searches

Naturalness calls for a mass spectrum like this



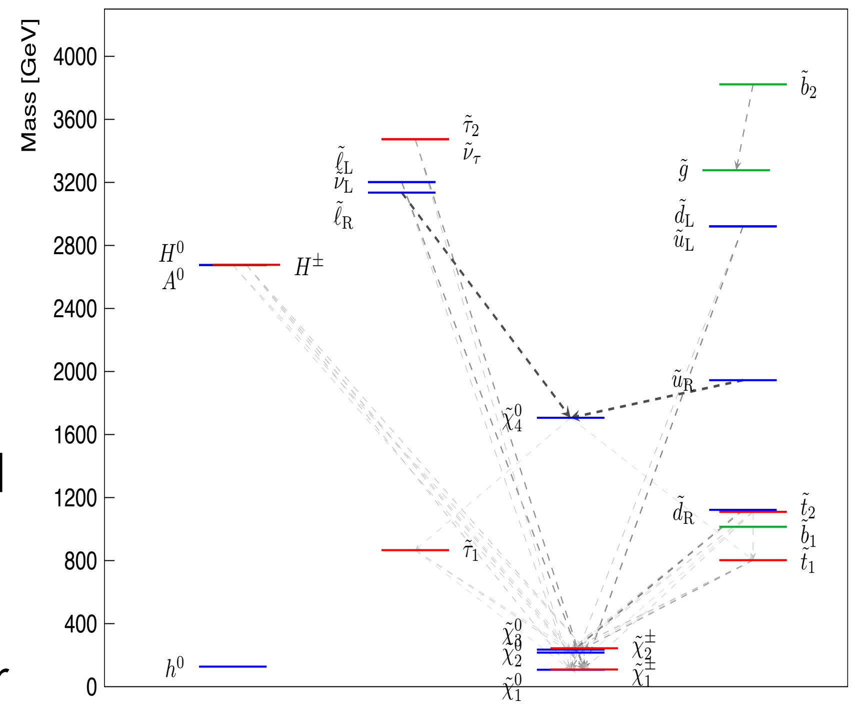
Papucci et. al., "Natural SUSY endures", 35 JHEP 2012



1. Can push soft lepton searches to lower Δm by lowering the lepton pT (require jet from ISR to trigger on) – maybe to a few GeV with large luminosity ?
2. Can push disappearing track searches to large Δm by using shorter tracks (but not going to reach 0.3 GeV which is ~1 cm decay length)

Tackling the (p)MSSM

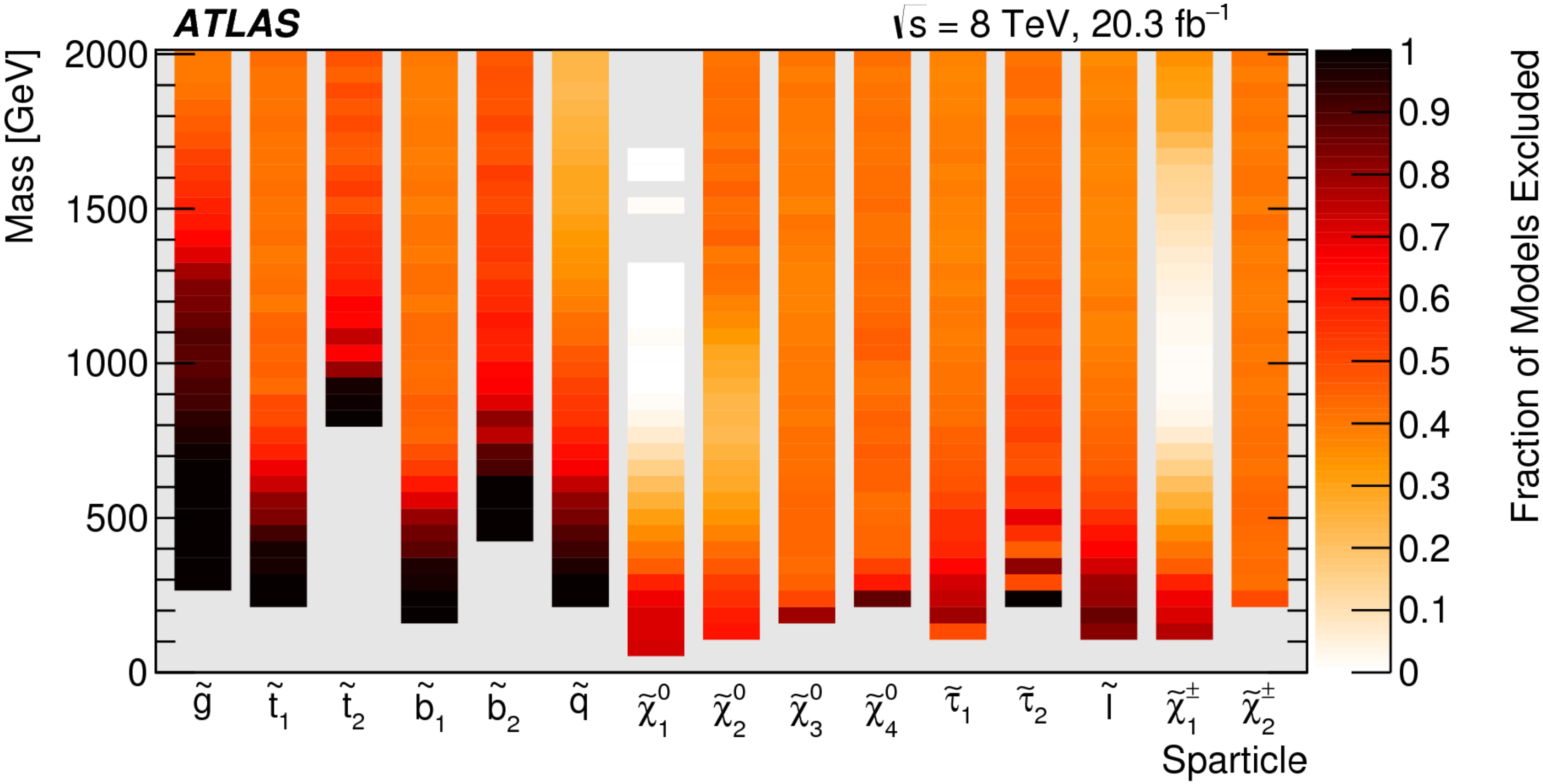
- Are the limits on simplified models realistic ? What are the values of susy masses allowed when there are many production and decay modes ?
- In the MSSM, masses and decays are largely determined by 19 parameters (still a lot!)
- ATLAS and CMS both made random scan of this parameter space.
- ATLAS : limits from 22 papers evaluated on 300 thousand models (passing Higgs, DM, flavour physics, etc. constraints)



(a) Point 18898934 (fine-tuning 56)

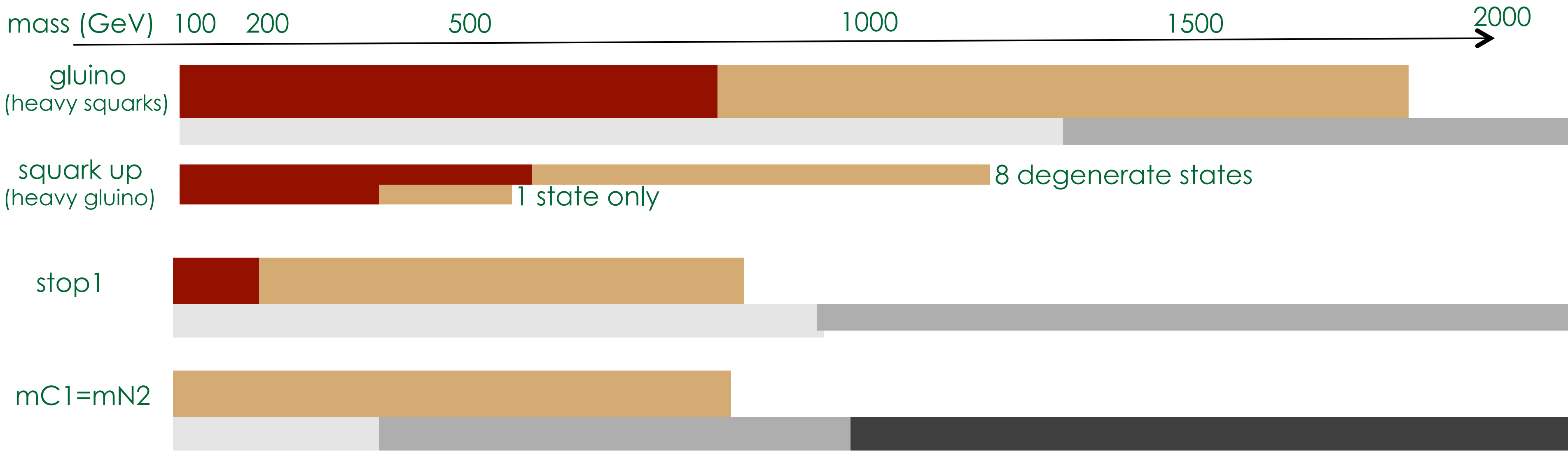
Two stop, one sbottom, and two light squarks below 1.2 TeV, decaying to three neutralinos and two charginos.

pMSSM limits



Fraction of models excluded as a function of particle mass

My own hand-made summary…



difficult to evade limits | limits dependent on assumptions | no constraint

Fine tuning: < 10; 10-100; > 100

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}.$$

Fine tuning bars based on formulas from arXiv:1110.6926 with m(t1)=m(t2), xt=0, tan β large, Λ = 10³ TeV. Use with care - other calculations proposed, possible dependence on the fundamental parameters of SUSY breaking.

gravitino LSP scenarios

- The lightest SUSY particle might actually be a nearly massless gravitino
- If so, SUSY particles are expected to decay to the next lightest particle (NLSP) which then decays to gravitino, possibly with a long lifetime (from femtoseconds to *years*)

NLSP is..

$\tilde{\chi}^0_1$

- Decays to γG, hG, or ZG (depending on mixing)
- Like normal SUSY, but with a bit less MET and two extra photons, Z, or Higgs in every event

Interesting things happen here

- Like normal SUSY – we will never realize (with LHC alone) this is not a model with neutralino LSP

$\tilde{t}_1$

- Decays to tG
- Like normal SUSY with stop => top N1

- "Stable" strongly interacting particle (see next slides)

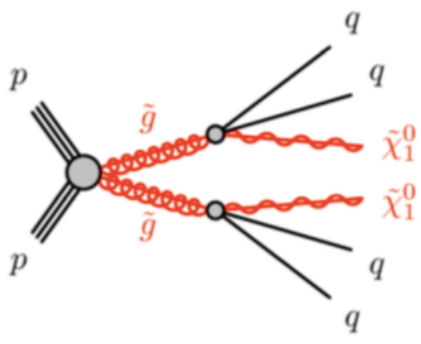
short (< ns)

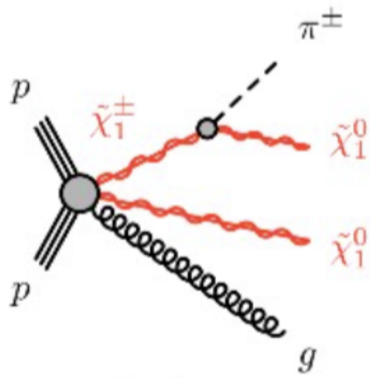
long (> μs)

lifetime

Long lived particle searches

- Long lived particles (other than the neutral LSP) can easily arise in SUSY
  - Decay through heavy virtual particles
  - Small decay phase space
  - Small couplings (decay to gravitino)
- Long lived means long enough for direct detection by the detector, and/or decaying inside the detector
- Clean signatures (no irreducible backgrounds) but can be challenging – this is not what the detectors have been designed for !

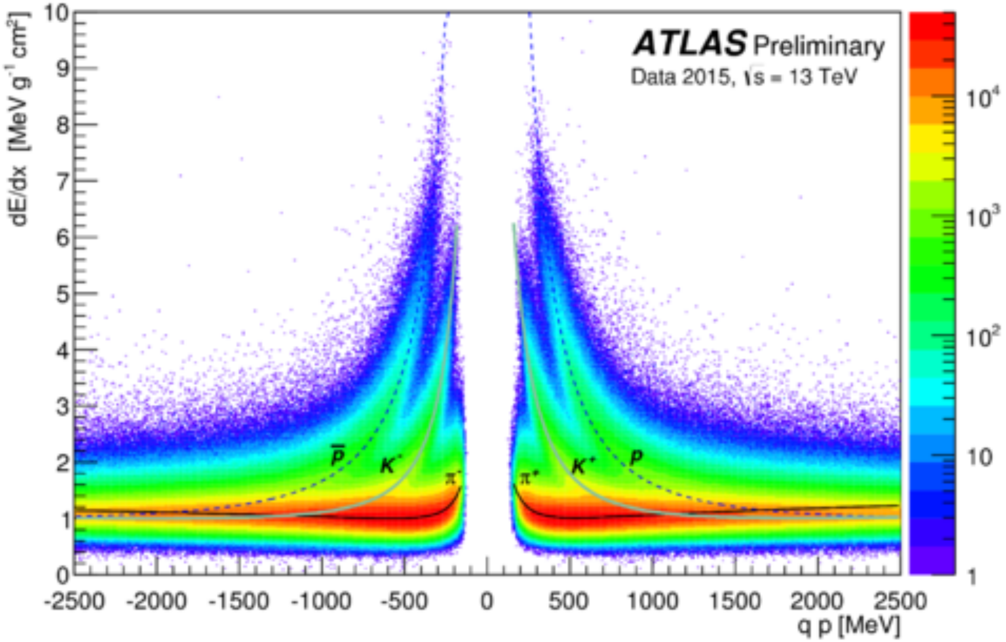


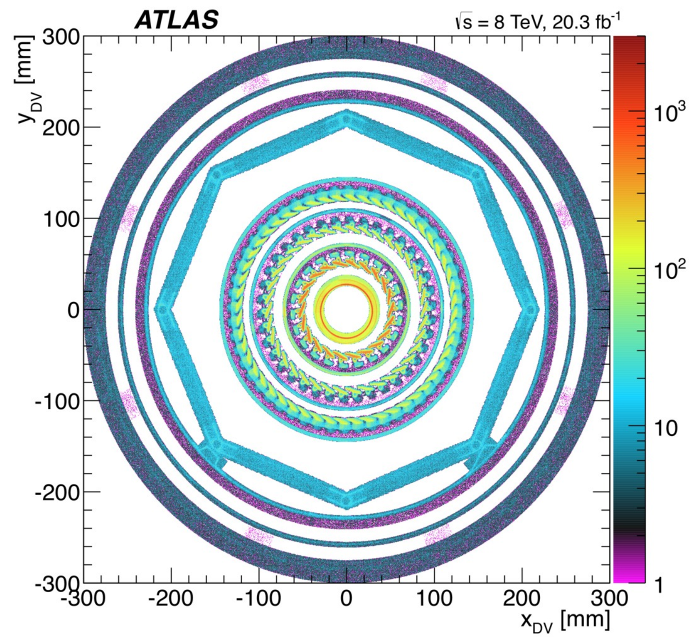


Long lived particle searches

- A long-lived chargino/slepton is like an heavy muon
  - Slow and heavily ionizing (Bethe-Block)
- A long-lived gluino/squark hadronizes but still interacts pretty much like an heavy muon
  - Exchanged momentum at every hadronic interaction is of the order of LQCD, small compared to the particle momentum (which is hundreds of GeV)
- Signatures are
  - Muon-like particle arriving late (time measured by calorimeters and muon spectrometer)
  - Muon-like particle heavily ionizing (dEdx measured by trackers)
  - Disappearing track (only seen in inner tracker, because it has decayed)
  - Decay vertex into charge particle explicitly reconstructed
  - Displaced photons (not from interaction vertex) from $N_1 \Rightarrow \gamma\tilde{G}$

Two beautiful plots

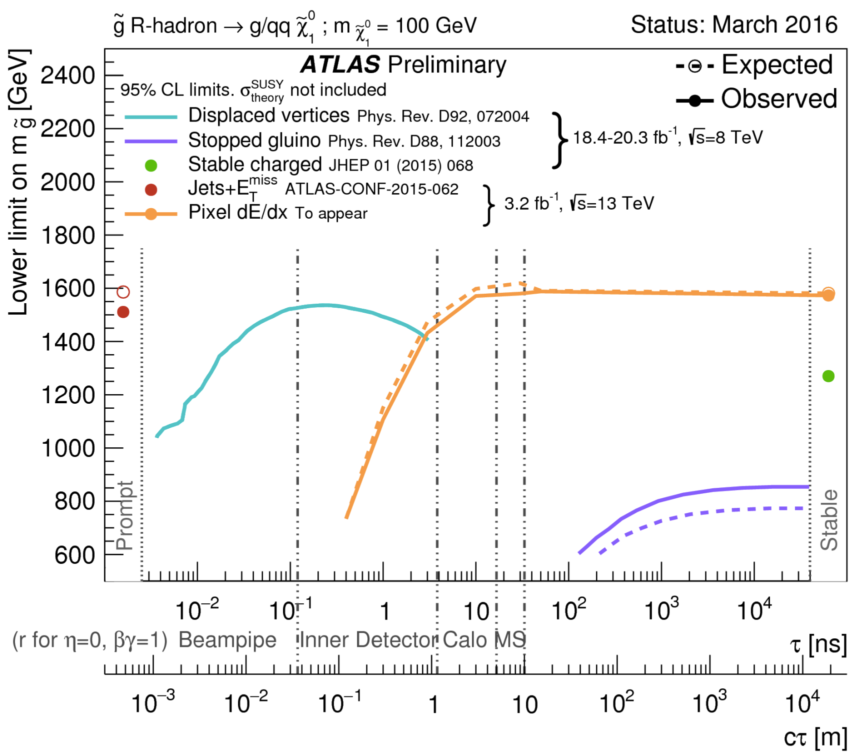


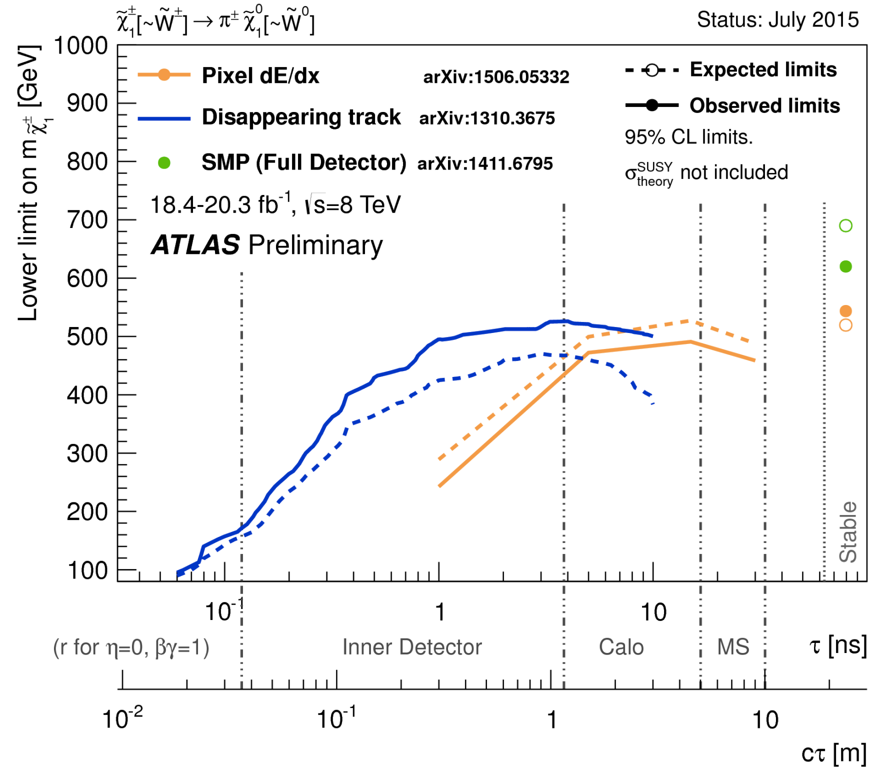


Bethe-block measured by ATLAS pixel detector (dEdx vs track momentum)

Reconstructed position of vertices from hadronic interactions, maps the detector material.

Long lived particle limits





gluino

Chargino
(no limit for prompt decay)

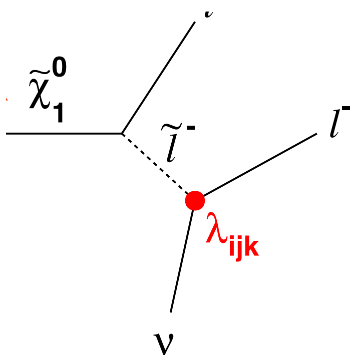
R-parity violating SUSY

- No Dark Matter candidate
- The LSP is not stable : less missing momentum, higher particle multiplicity in the final state
- Several possible R-parity violating terms in the Lagrangian, giving many different experimental signatures:

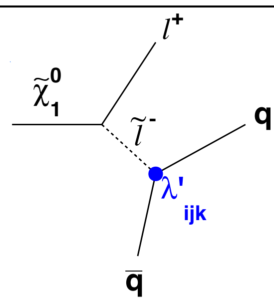
$$W_{RPV} = \underbrace{\boxed{\lambda_{ijk} L_i L_j \bar{E}_k} + \boxed{\lambda'_{ijk} L_i Q_j \bar{D}_k}}_{\text{Lepton Violating}} + k_i L_i H_2 + \underbrace{\boxed{\lambda''_{ijk} \bar{D}_i \bar{D}_j \bar{D}_k}}_{\text{Baryon Violating}}$$

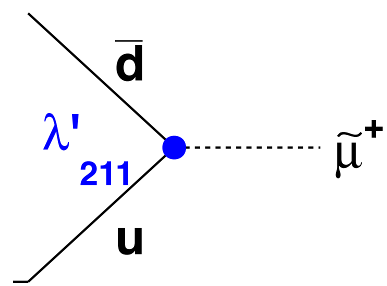
- Multi-jet resonances
- Many jets but with little ETMiss

High lepton multiplicity, from LSP decays like:

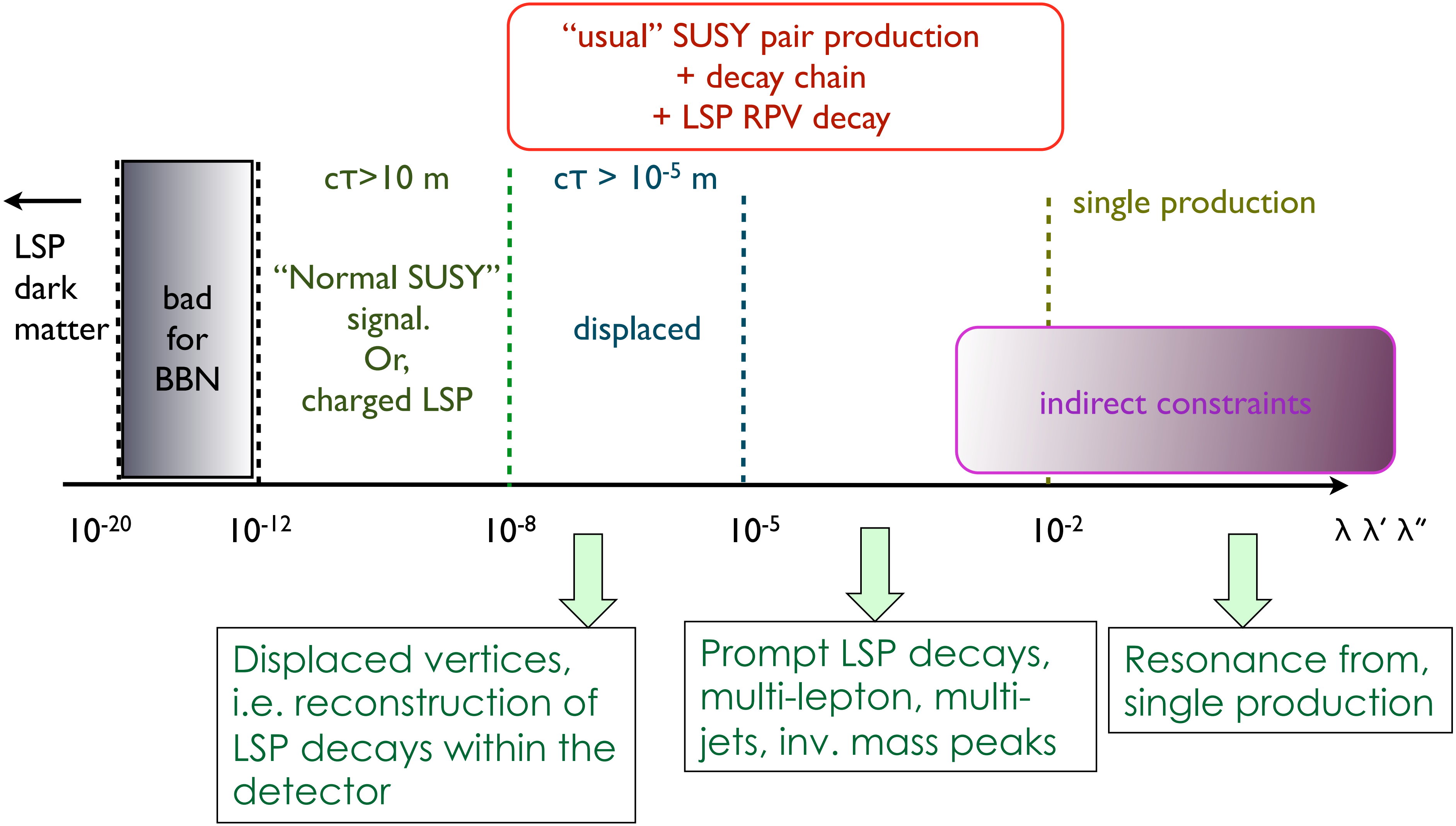


- Additional leptons and jets from LSP decay
- Single production of sleptons?





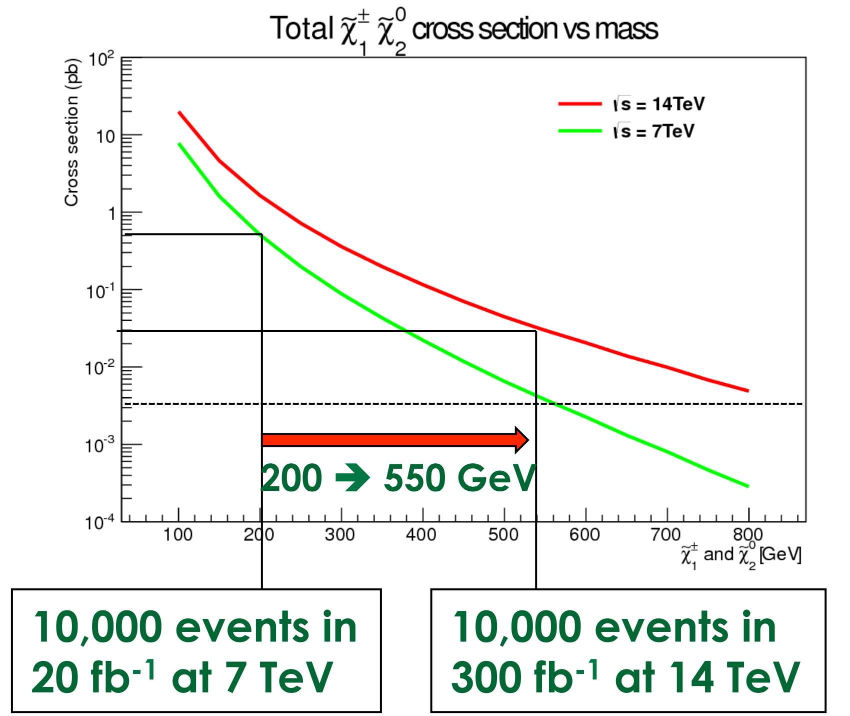
Size of R-parity violating couplings



Outlook

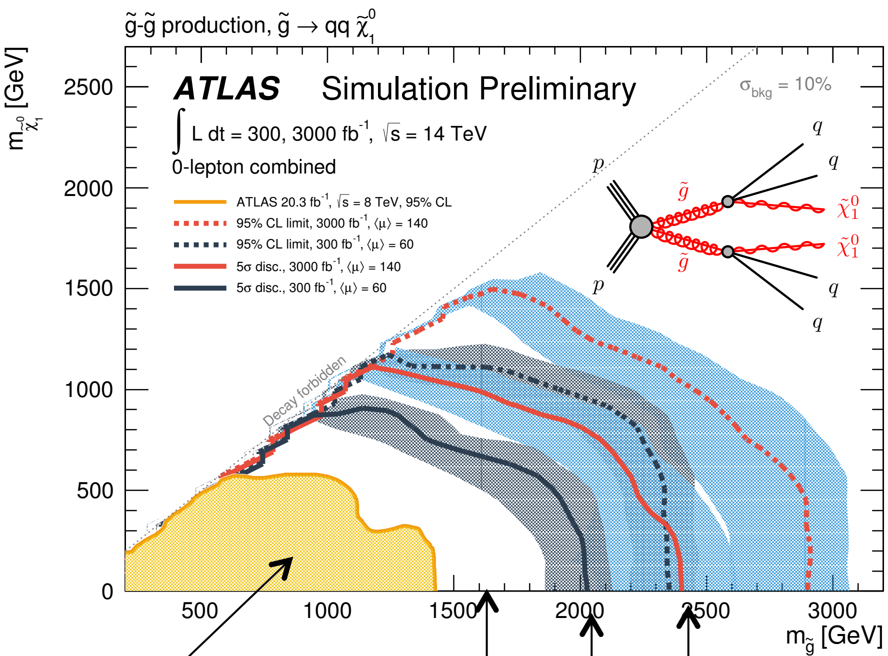
- We currently have a mere 3 fb^{-1} at 13 TeV collision energy
- ~300 fb^{-1} foreseen by 2021
- Proposal to further increase luminosity and collect 3000 fb^{-1} afterwards

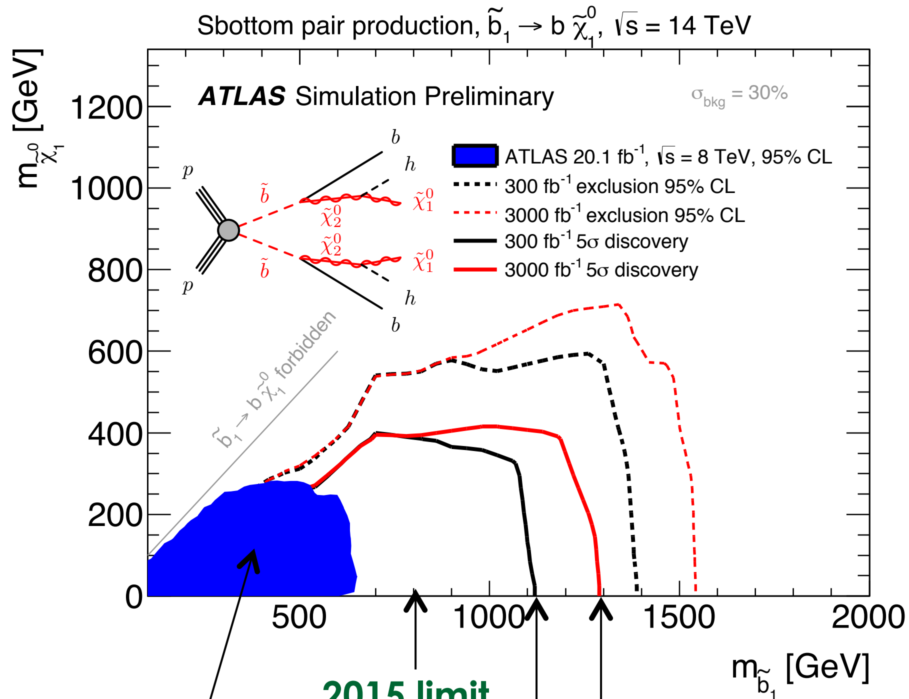
> ➢ Current run2 data sensitivity to electroweak production less than in run1, but with more luminosity the electroweak searches will benefit the most



Electroweak production benefits from increased luminosity (and energy)

Outlook: strong production





2015 limit

run1 limits

5σ (discovery) sensitivity for 300/3000 fb^{-1}

2015 limit

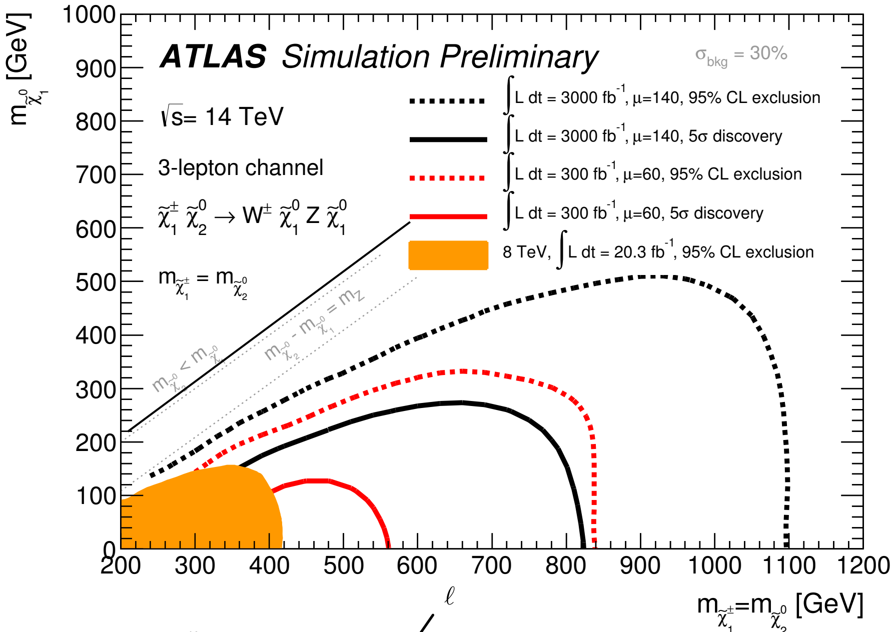
run1 limits

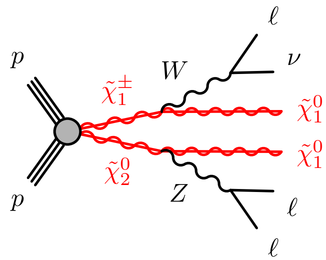
5σ (discovery) sensitivity for 300/3000 fb^{-1}

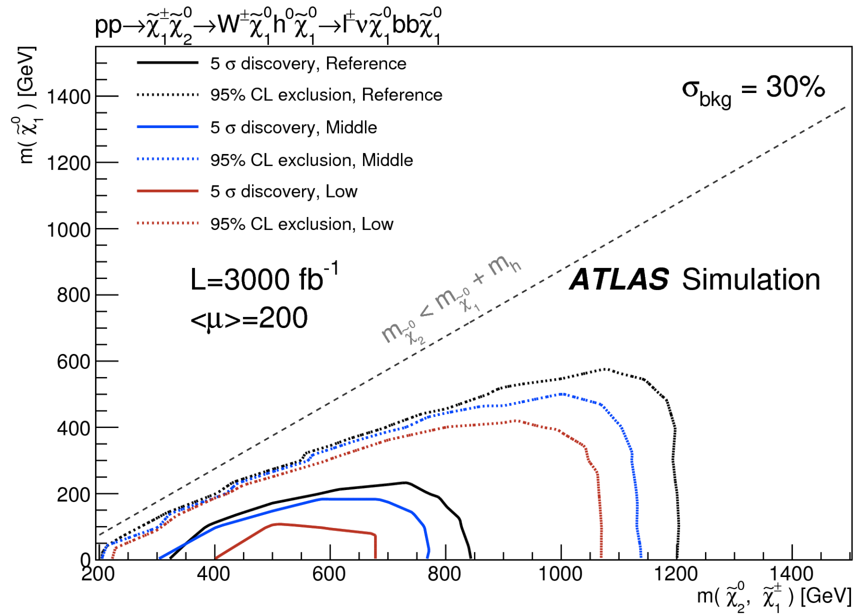
Gluino pair production

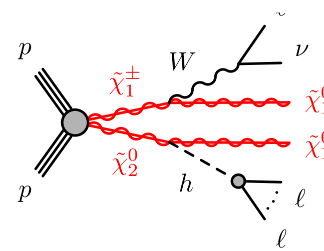
sbottom pair production

Outlook: electroweak production









Conclusions

- I hope I gave you the feeling that searches for new particles at colliders are interesting…
- Supersymmetry has been considered for some decades one of the most promising extensions of the Standard Model (which we know ***must*** be extended)
- The negative results from the first 3+1 years of LHC data put **new strong constraints** on the supersimmetric particle masses
- Obviously what we would like is to find some signal… looking forward for the new collision data and hoping for the best