Searching for SUSY at ATLAS

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SUSY mass scale: *a priori* knowledge

Upper mass scale constrains	Lower mass scale constrains
Unification of couplings if mass scale is not too large	Bounds from low energy experiments
Fine tuning problem less severe if mass scale is not too large	Tevatron bounds (e.g gluino and squark mass)
Perfect DM candidate if mass scale not too large	Bounds from LEP (e.g. chargino, slepton, neutralino)

Are there SUSY particles at a scale of 0.2 - few TeV ?

SUSY mass scale: *a priori* knowledge

Upper mass scale constrains

- Unification of couplings if mass scale is not too large
- Fine tuning problem less severe if mass scale is not too large
- Perfect DM candidate if mass scale not too large

Lower mass scale constrains

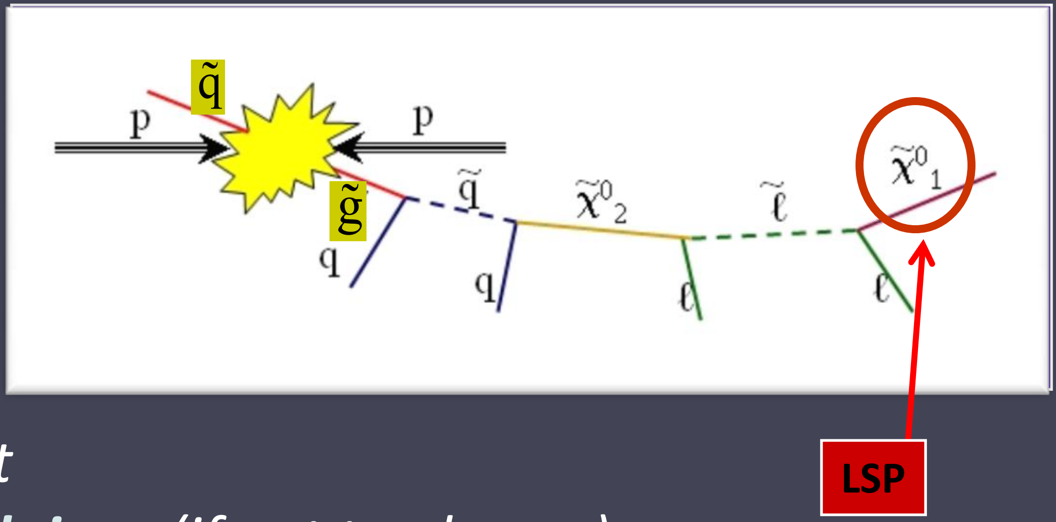
- Bounds from low energy experiments
- Tevatron bounds (e.g gluino and squark mass)
- Bounds from LEP (e.g. chargino, slept
neutralin

Are there SUSY particles at a scale of 0.2 - few TeV ?

SUSY searches at LHC will teach us if this story is correct

SUSY and the LHC : Signal

If R-Parity is conserved then SUSY particles are pair produced



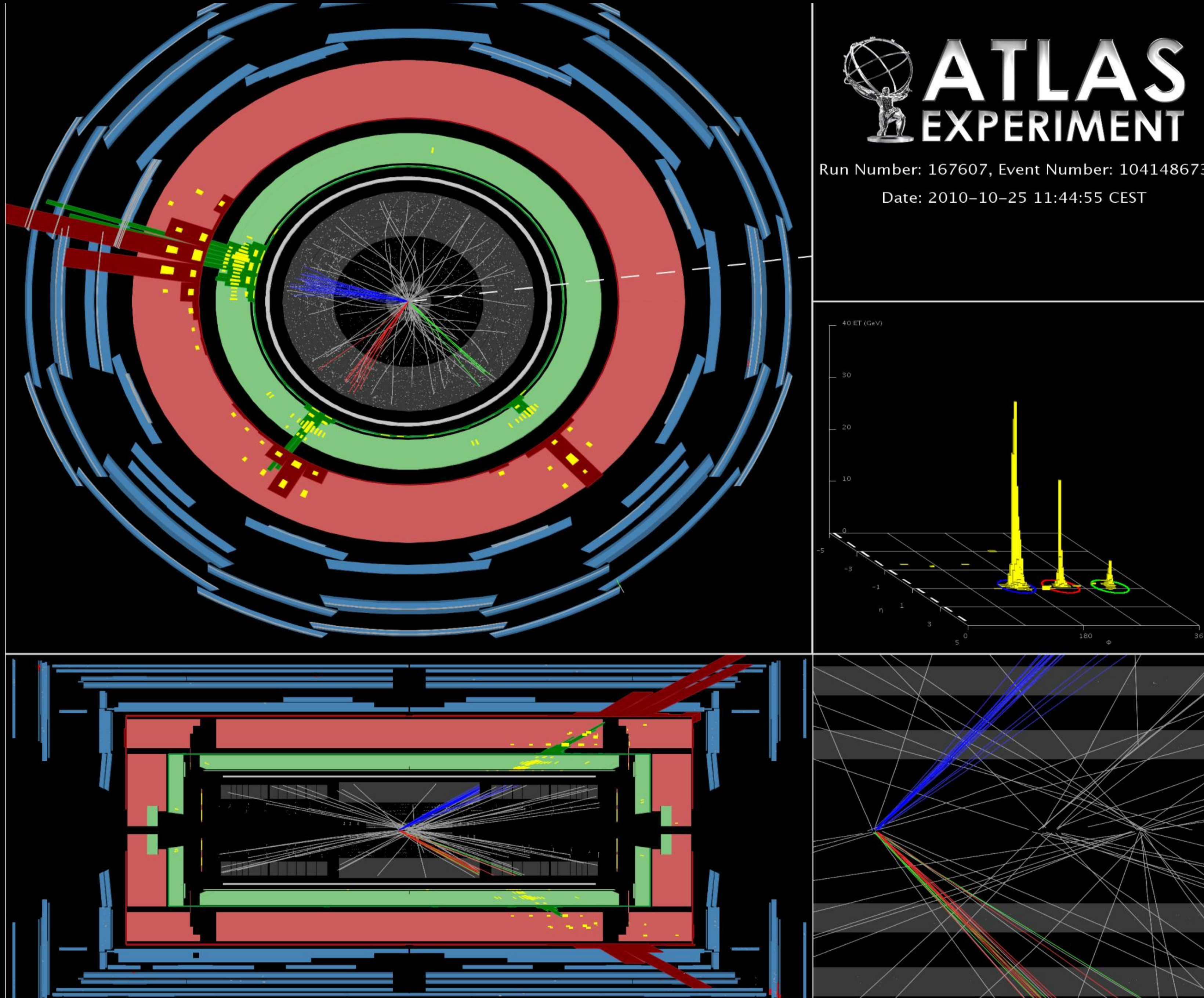
LHC:

Due to strong force dominant production of ***squarks*** *and* ***gluinos*** *(if not too heavy)*
Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

Mass pattern in general SUSY unknown ! Searches need to be quite general and model-parameter-independent

3 jets with p_T of approximately 400 GeV, 120 GeV, 60 GeV and E_t^{miss} of approximately 420 GeV

Event found in signal region of jet+ E_t^{miss} analysis



Searches presented today

Jets + lepton + E_t^{miss}	**PRL paper**
Jets + E_t^{miss}	**submitted to PLB**
Jets + b-tag + E_t^{miss}	**preliminary/paper soon**
Dilepton + E_t^{miss}	**preliminary/papers soon**
Multileptons + E_t^{miss}	in pipeline
Photons + jets + E_t^{miss}	(UED published 3.1 pb-1)
e mu	**preliminary/paper soon**
Slow Moving Particle	**submitted to PLB**

Similar conclusions /channels for Universal Extra Dimension, ADD, Little Higgs, ...

See YSF talk by Jeanette Lorenz

Jets + lepton + E_t^{miss}

- First ATLAS SUSY paper

arXiv:1102.2357 **Accepted by PRL**

- Expected to be less effected by potentially "dangerous" QCD background, main background W and top pairs
- Analysis cuts follow quite closely previous ATLAS MC studies
- 1 electron or muon with p_T>20 GeV

  3 jets with p_T> 60,30,30 GeV

  E_t^{miss} > 125 GeV and E_t^{miss} > 0.25 * M_{eff}

  Transverse mass > 100 GeV

  M_{eff} > 500 GeV

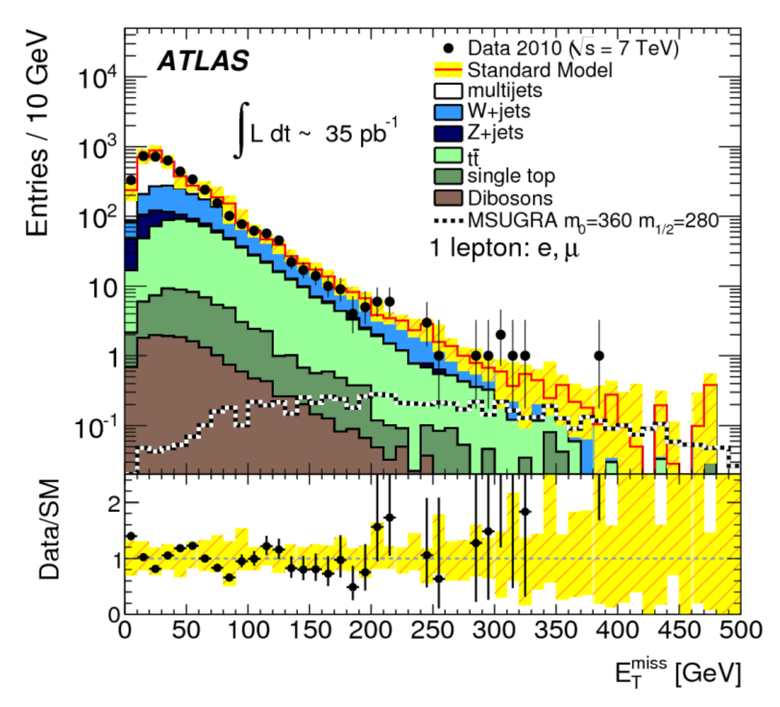
Definition of **W and top control regions:**

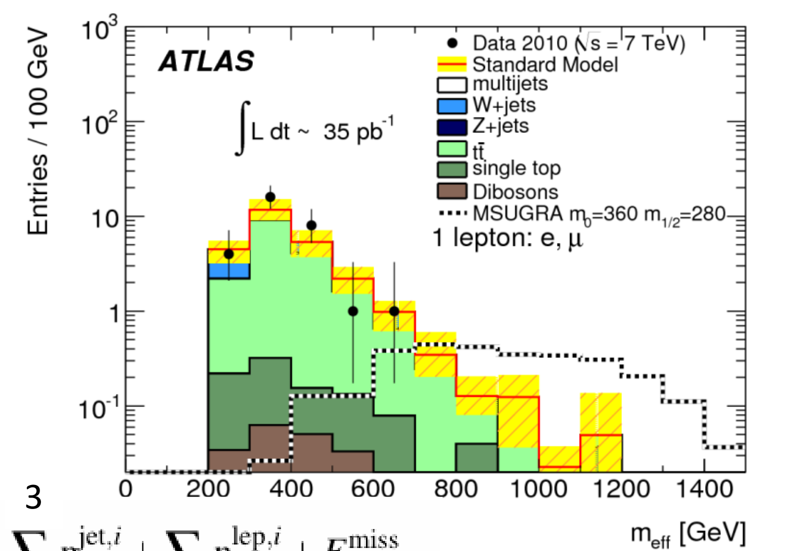
30< E_t^{miss} < 80 GeV

40< transverse mass < 80 GeV

→Veto b-tag : W control region

→Apply b-tag : top pair control regions





$$M_{\rm eff} \equiv \sum_{i=1}^{3} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_{\rm T}^{\rm miss}$$

Jets + lepton + E_t^{miss}

- Fits to control regions predict the number of Top, W and QCD events in the signal region
- Several cross checks performed (e.g. tests with alternative control regions)

Electron channel	Signal region
Observed events	1
Fitted top events	1.34 ± 0.52 (1.29)
Fitted W/Z events	0.47 ± 0.40 (0.46)
Fitted QCD events	$0.0^{+0.3}_{-0.0}$
Fitted sum of background events	1.81 ± 0.75

Muon channel	Signal region
Observed events	1
Fitted top events	1.76 ± 0.67 (1.39)
Fitted W/Z events	0.49 ± 0.36 (0.71)
Fitted QCD events	$0.0^{+0.5}_{-0.0}$
Fitted sum of background events	2.25 ± 0.94

Profile likelihood ratio test + toys

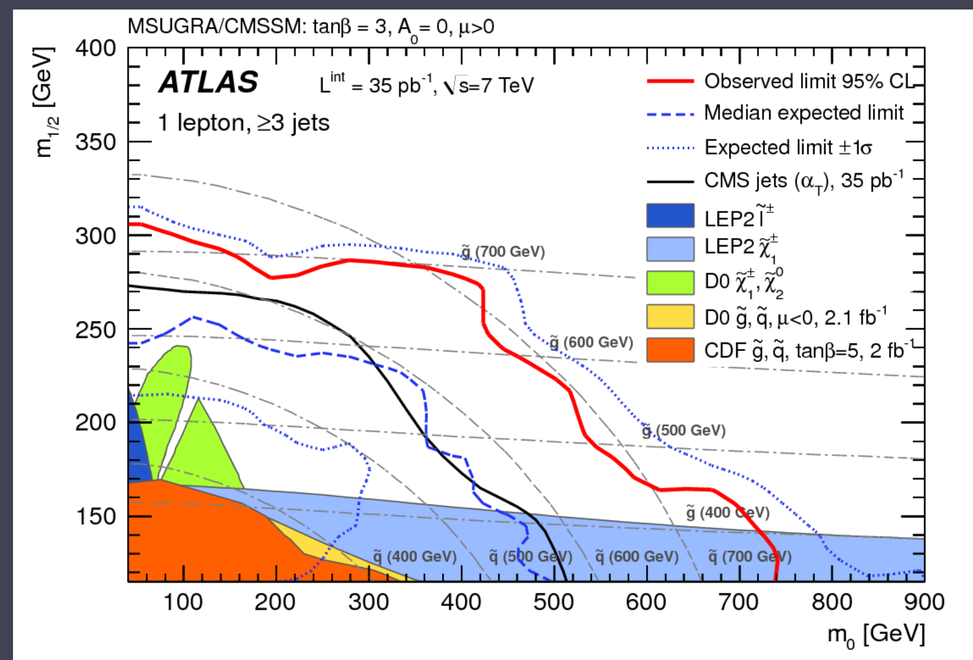
$$\Lambda(\mu) = -2(\ln L(n|\mu, \hat{\hat{b}}, \hat{\hat{\theta}}) - \ln L(n|\hat{\mu}, \hat{b}, \hat{\theta}))$$

Main result: Table and 95% CL

Limits on Cross section * Acceptance *effi.

Electron channel: 0.065 pb

Muon channel: 0.073 pb



Jets + E_t^{miss}

The signal regions A,B,C,D are inclusive

		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–

TABLE I: Criteria for admission to one of the four signal regions A to D. All variables are defined in the text.

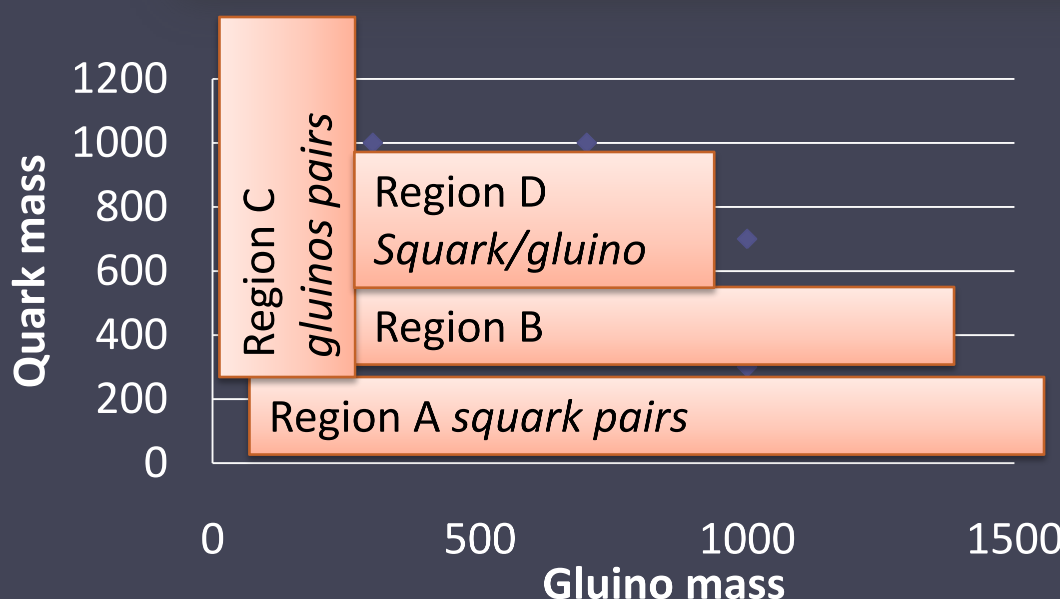
Very simple model-independent classification of signal regions:

Low and high mass dijets (squarks→ quark neutralino)

Region **A and B**

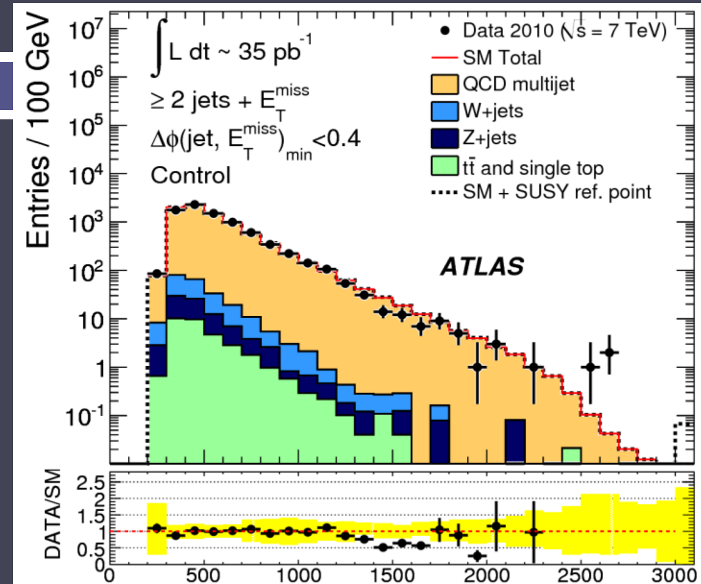
Low and high mass 3-jets (associated squark/gluino and gluino pair production):

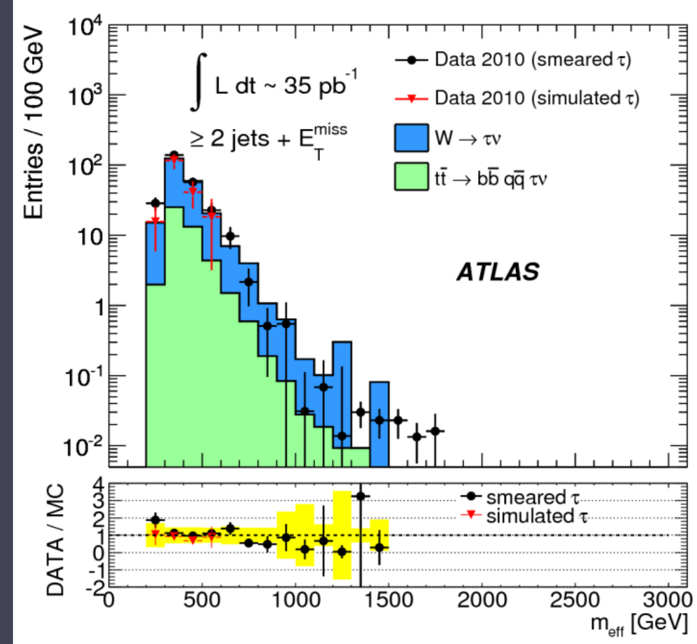
Region **C and D**



Trigger efficiency close to 1 for all signal and control regions

Jets + E_t^{miss} : Background evaluation





Main work:

Typically 2-4 control region measurements or "data driven" methods performed for each background (and each signal region)

Examples:

- QCD : control regions with inverted cuts e.g. δϕ(jet,MET), determination without MC but smearing data with the measured detector response.
- Z+ jets: Z➔μμ, Z➔ee and W control regions
- W+ jets: W➔μν and W➔eν control regions, tau embedding
- Top pairs: Top control regions with or without lepton, and W embedding

Jets + E_t^{miss} : Results

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\,^{+8}_{-7}$[u+j]	$0.6\,^{+0.7}_{-0.6}$[u+j]	$9\,^{+10}_{-9}$[u+j]	$0.2\,^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm\ 5[\mathcal{L}]$	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	$35 \pm\ 9$[u] $^{+10}_{-\ 8}$[j] $\pm 4[\mathcal{L}]$	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm\ 6[\mathcal{L}]$	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] $\pm 0.5[\mathcal{L}]$	27 ± 12[u] $^{+10}_{-\ 6}$[j] $\pm 3[\mathcal{L}]$	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] $\pm 0.1[\mathcal{L}]$
$t\bar{t}$ and t	$10 \pm\ 0$[u] $^{+\ 3}_{-\ 2}$[j] $\pm\ 1[\mathcal{L}]$	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] $\pm 0.1[\mathcal{L}]$	$17 \pm\ 1$[u] $^{+\ 6}_{-\ 4}$[j] $\pm 2[\mathcal{L}]$	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] $\pm 0.0[\mathcal{L}]$
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] $\pm 12[\mathcal{L}]$	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] $\pm 1.0[\mathcal{L}]$	88 ± 18[u] $^{+26}_{-18}$[j] $\pm 9[\mathcal{L}]$	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] $\pm 0.2[\mathcal{L}]$
Data	87	11	66	2

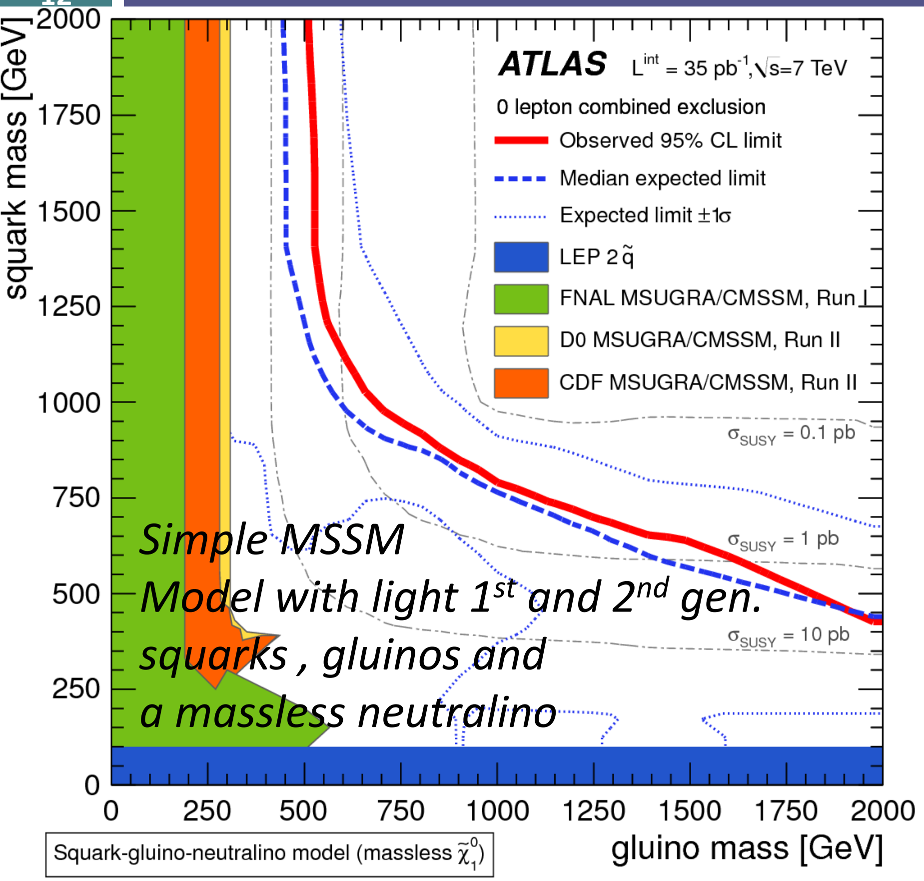
Signal region A, B, C, D exclude non-SM process within acceptance*effi. of 1.3, 0.35, 1.1 and 0.11 pb respectively at 95% confidence.

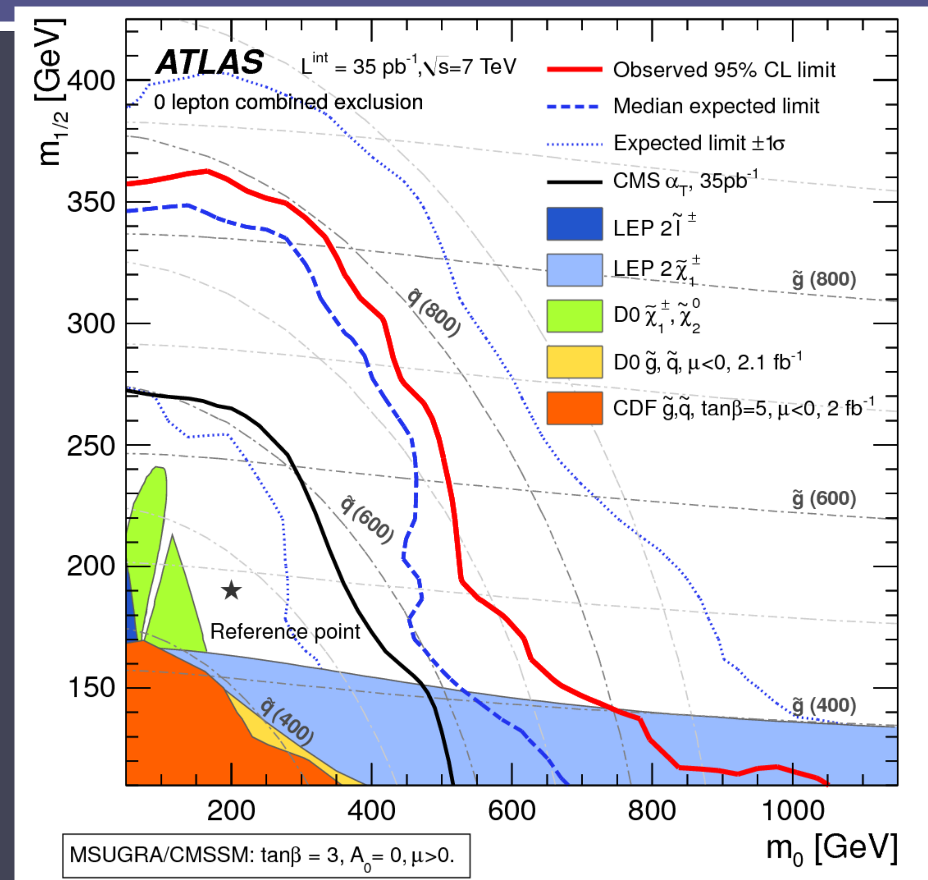
SUSY model-independent search

➔ Interpretation: Take the signal region with the largest expected sensitivity

➔ Show reach of the search for 2 examples

Jets + E_t^{miss} : Results

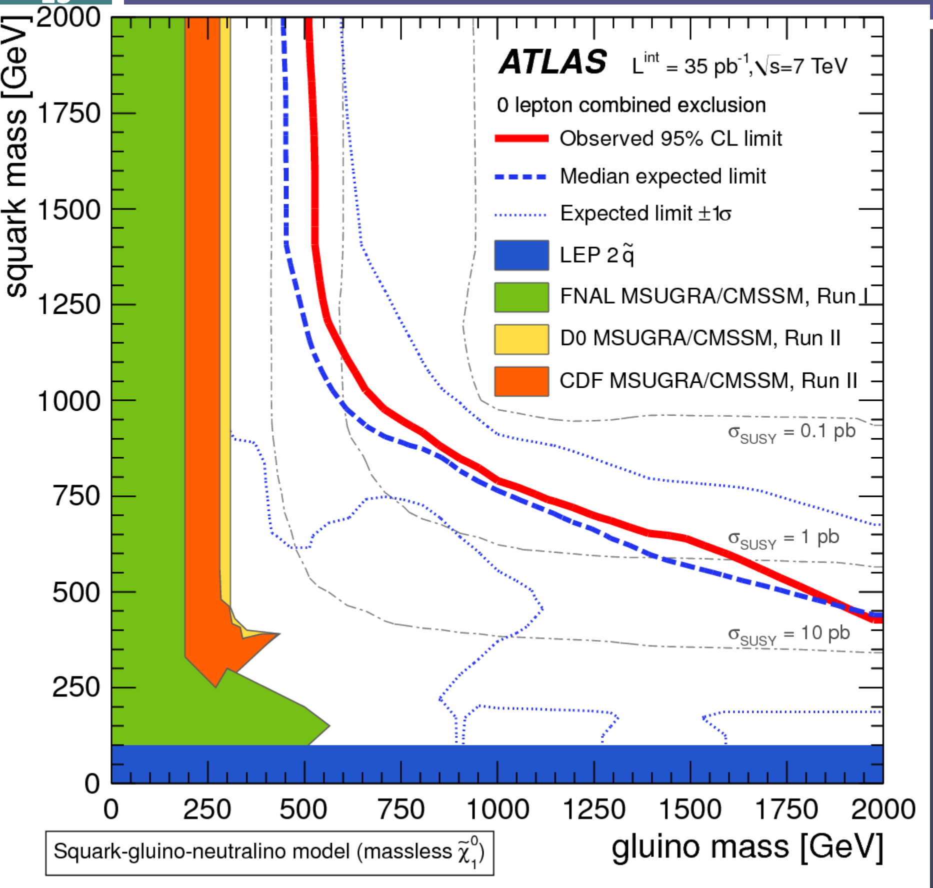


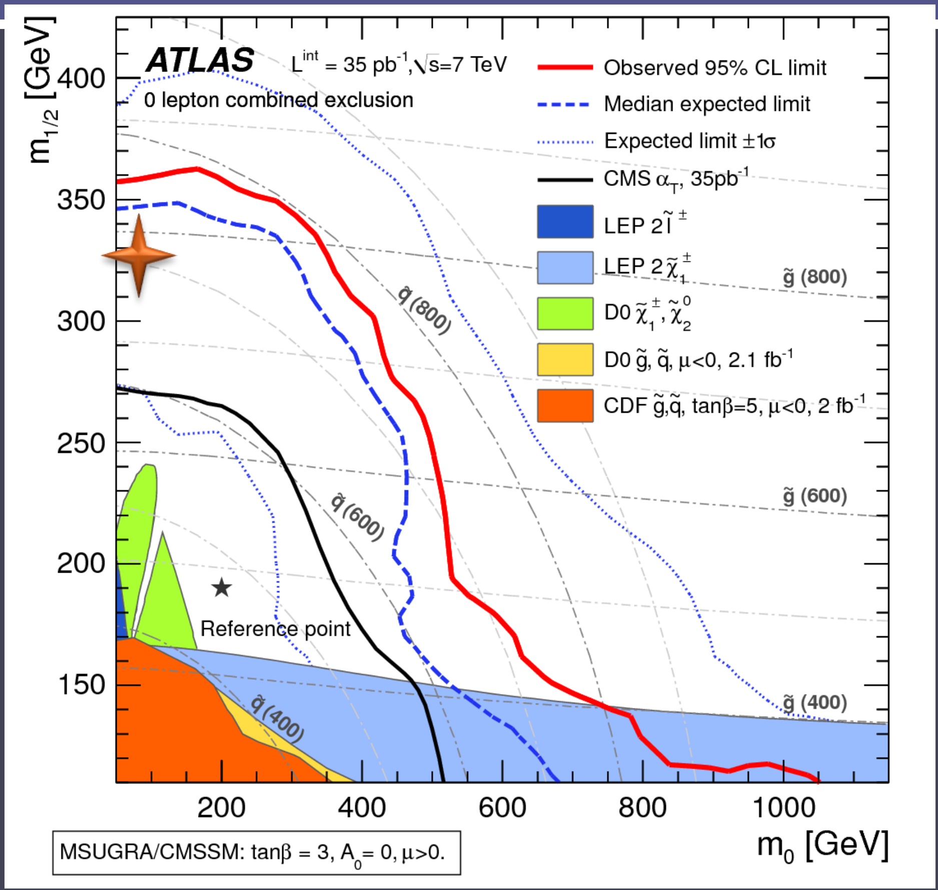


1 sigma total experimental uncertainty band shown (*shows roughly the 1 and 3 sigma exclusion*)

Exclusion reach not strongly sensitive to sign(mu), tan beta and A_0

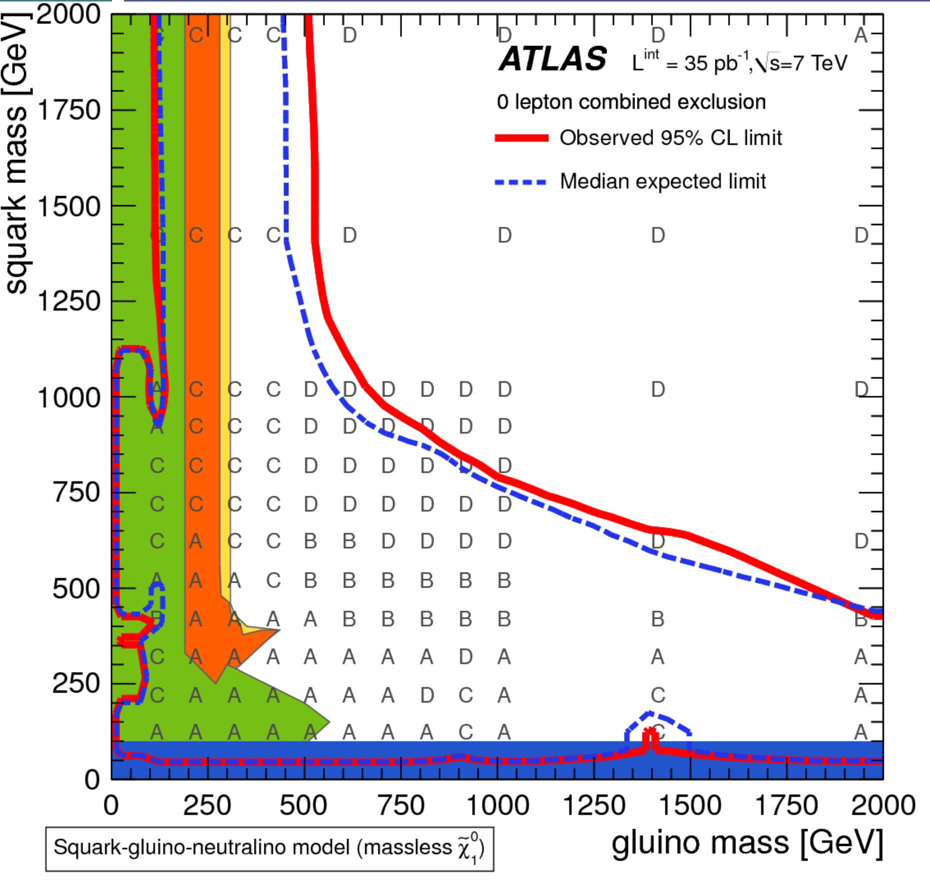
Jets + E_t^{miss} : Results

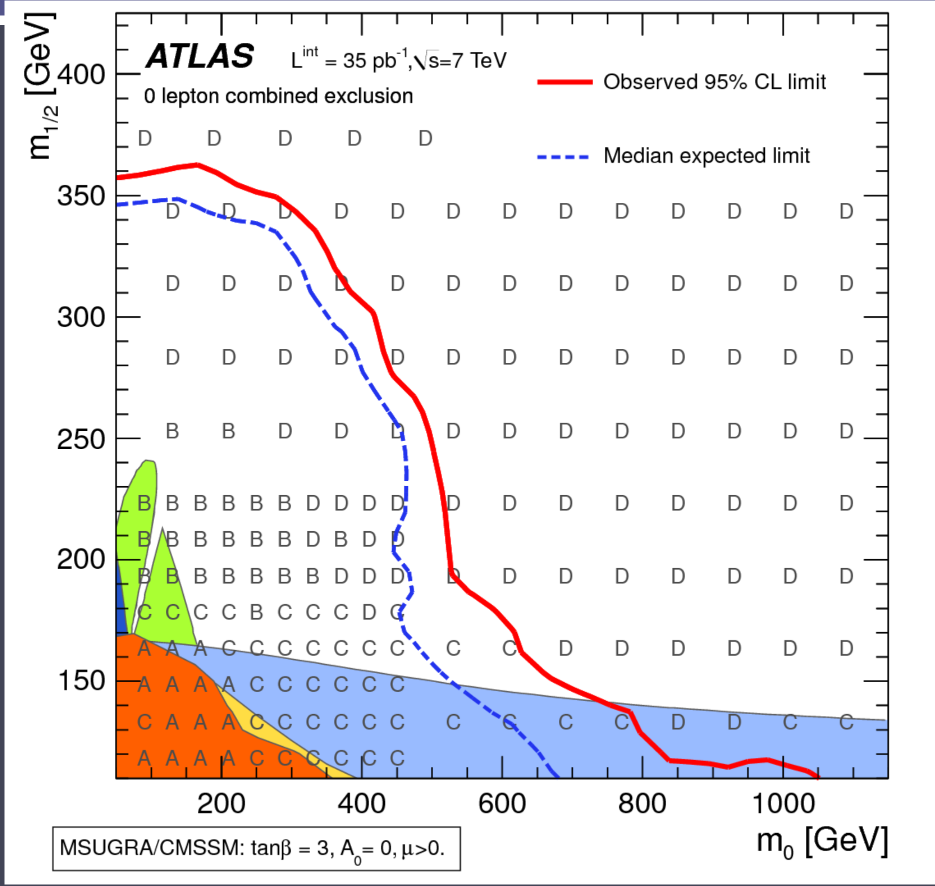




- Shows best mSUGRA fits to low energy data ➔ excluded
(here arxiv 1102.4693, M0=75, M1/2=329 GeV)

Jets + E_t^{miss} : Results



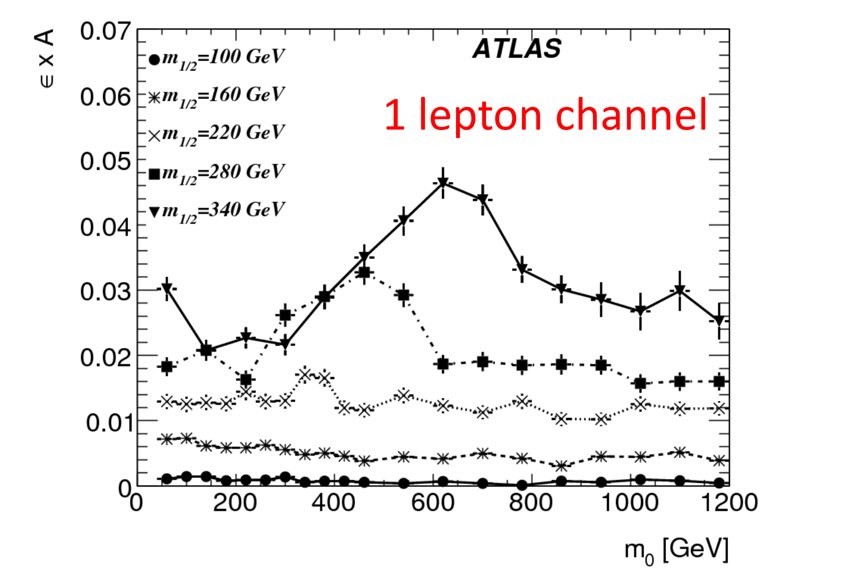


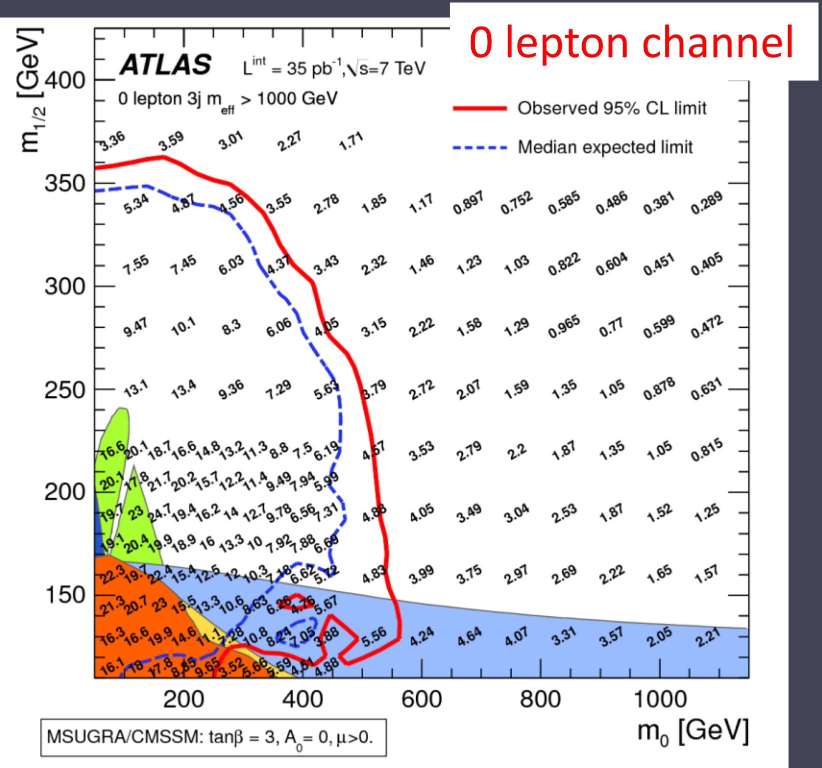
Consider the signal region with the best <u>expected</u> upper limit.
Automatically chosen by limit setting algorithm

Other Interpretations possible !

Example:

How can a theorist use these data ?





Signal efficiency * acceptance provided for each signal region and analysis channel *(see ATLAS public SUSY results webpage)*
Les Houches Accord SUSY steering files provided

Validate your "local" setup

➔ Interpret the data with your favored model.

Jets + E_t^{miss} with b-tag

0 and 1-lepton channel also studied for events with b-tag to enhance sensitivity to 3rd generation

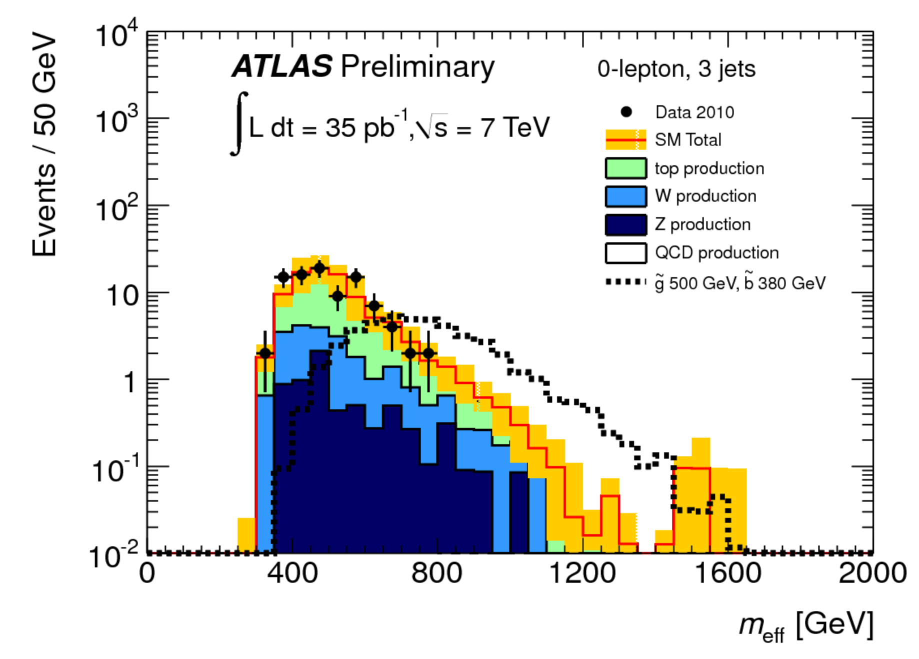
Slightly modified selection criteria

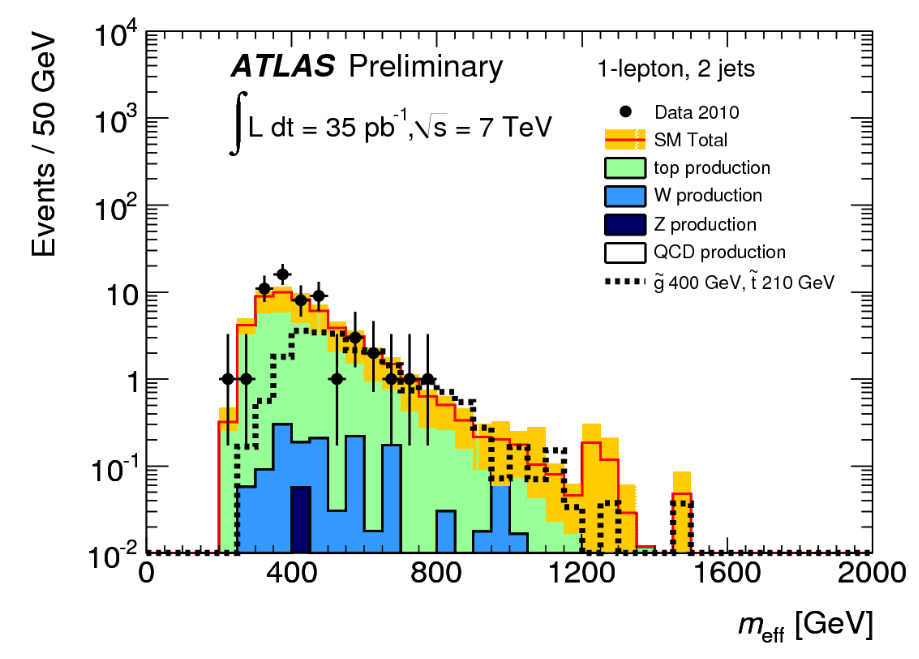
Aim is here to maximize sensitivity to e.g.

0l : $\tilde{g} \to \tilde{b}_1 b$ and $\tilde{b}_1 \to b\tilde{\chi}_1^0$

1l : $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu$

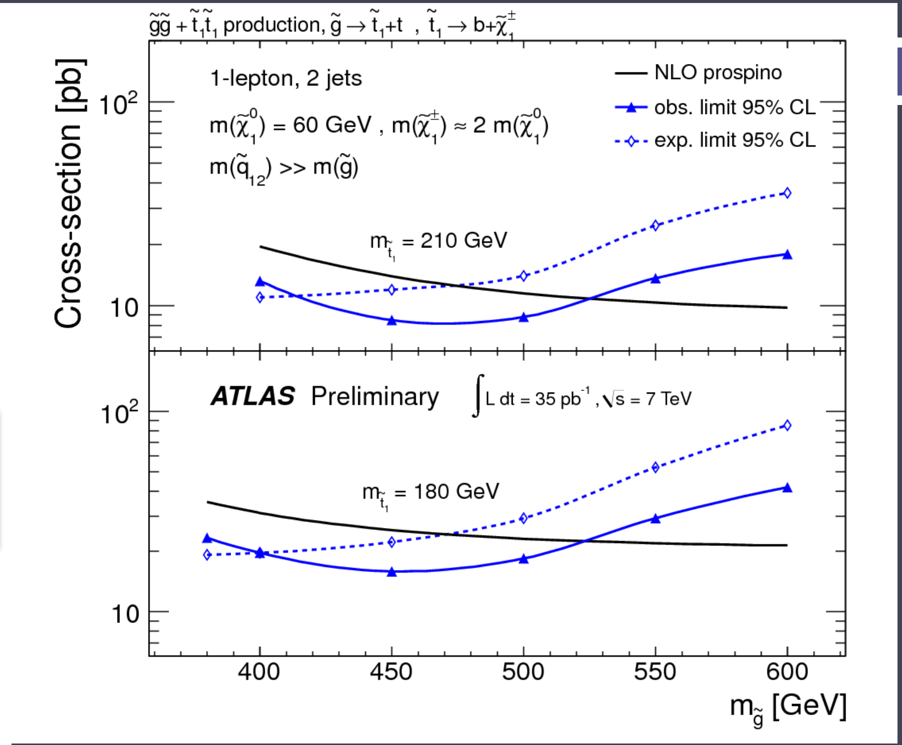
	0-lepton	1-lepton Monte Carlo	1-lepton data-driven
$t\bar{t}$ and single top	12.2 ± 5.0	12.3 ± 4.0	14.7 ± 3.7
W and Z	6.0 ± 2.0	0.8 ± 0.4	-
QCD	1.4 ± 1.0	0.4 ± 0.4	$0^{+0.4}_{-0.0}$
Total SM	19.6 ± 6.9	13.5 ± 4.1	14.7 ± 3.7
Data	15	9	9



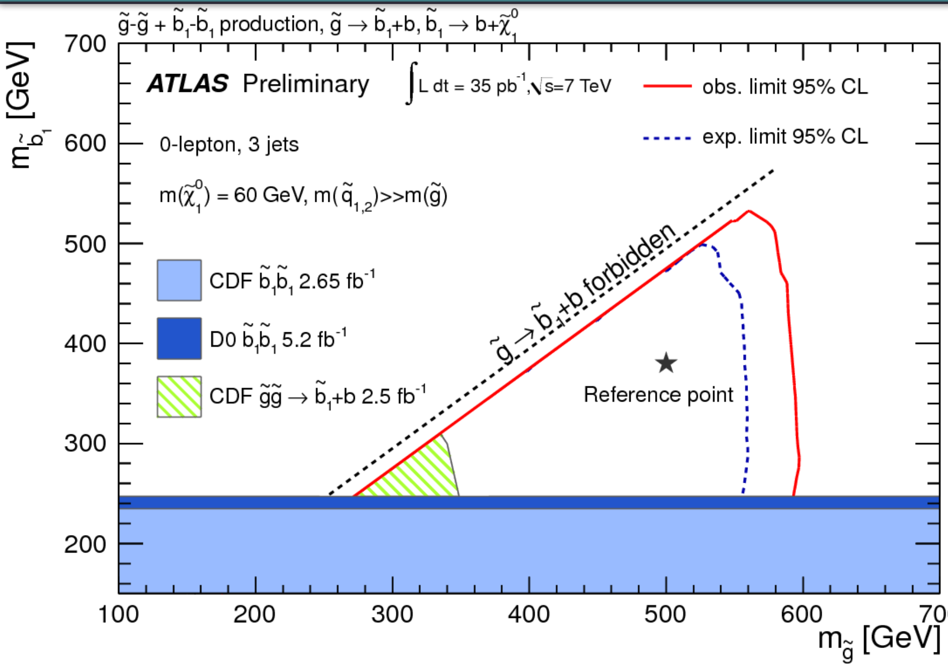


Jets + E_t^{miss} with b-tag

Here $\tilde{t}_1$ is the lightest quark and produced in 100% of the gluino decays (or directly produced) and the stop decays via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$



Exclusion of gluinos below 520 GeV for stops in in the range 160-240 GeV



Sbottom_1 produced via gluino or directly and decay via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0,$

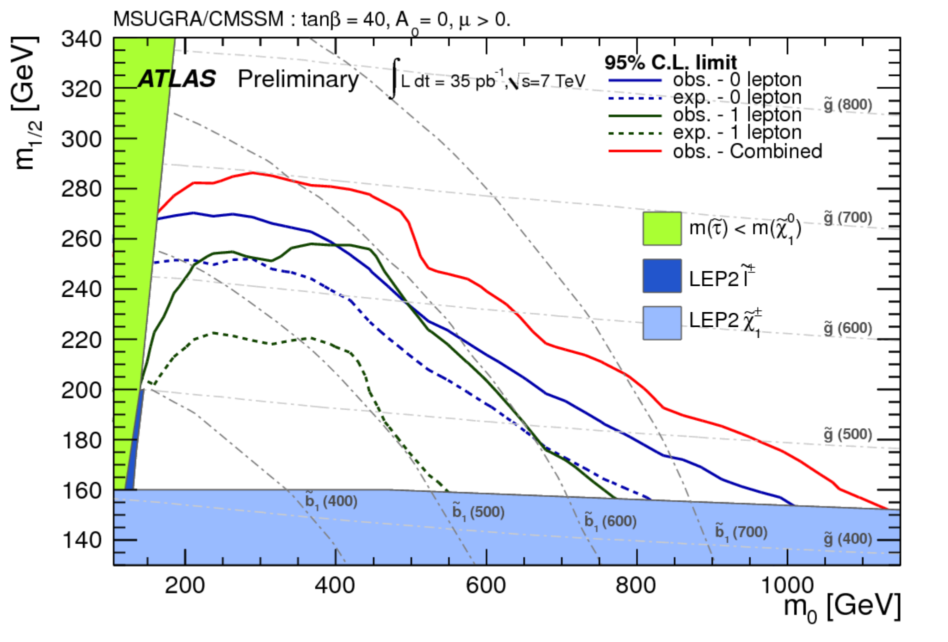
➔ Limit on gluino mass of 590 GeV

Jets + E_t^{miss} with b-tag

Interpretation within mSUGRA

Combination of 0 and 1 lepton channel with b-tag

Also here strong limits in mSUGRA phase space (here shown at high tan beta)

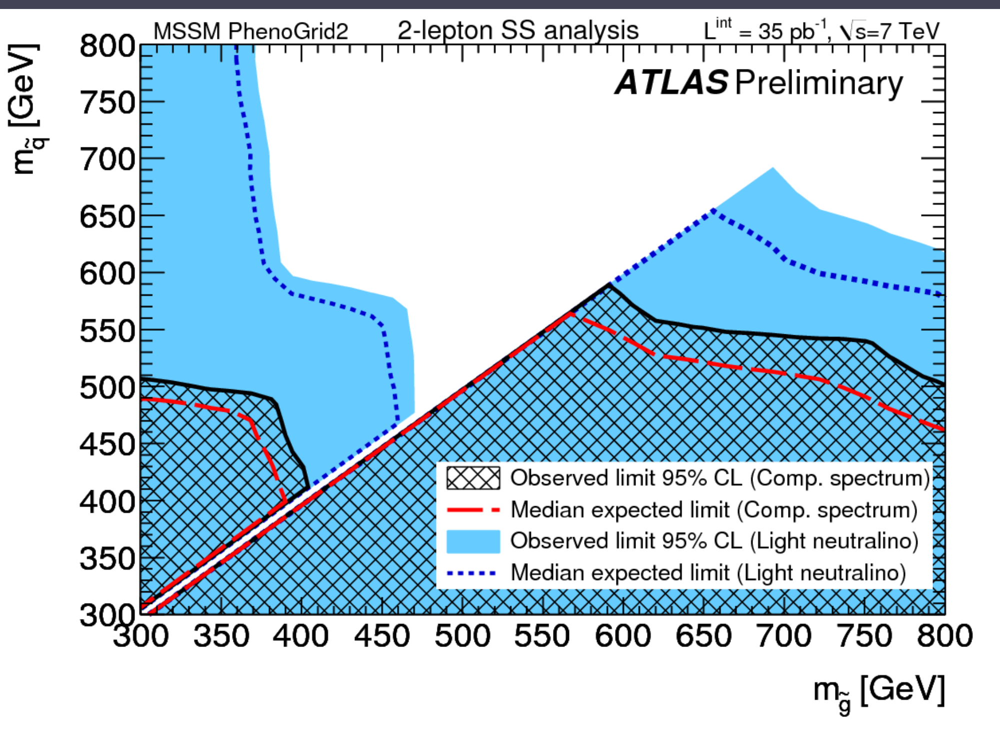


Dilepton + E_t^{miss} (OS/SS)

2 leptons with pT > 20 GeV + E_t^{miss} cut

- Fake background estimation by solving linear equations to get the fake probability for a "tight" lepton selections via a "loose" selection
- Top background estimated with control region

Same Sign, $E_T^{miss} > 100$ GeV			
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Data	0	0	0
Fakes	0.12±0.13	0.03±0.026	0.014±0.01
Di-bosons	0.015±0.005	0.021 ±0.009	0.035 ±0.012
Charge-flip	0.019±0.008	0.026 ±0.011	0
Opposite Sign, $E_T^{miss} > 150$ GeV			
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Data	1	4	4
$t\bar{t}$	$0.62^{+0.31}_{-0.28}$	$1.24^{+0.62}_{-0.56}$	$1.00^{+0.50}_{-0.45}$
Z+jets	0.19 ± 0.11	0.08 ± 0.08	0.14 ± 0.17
Fakes	-0.02 ± 0.02	-0.05 ± 0.04	0
Single top	0.03 ± 0.05	0.06 ± 0.08	0.10 ± 0.07
Di-bosons	0.09 ± 0.03	0.06 ± 0.03	0.15 ± 0.03
Cosmics	0	$0^{+1.32}_{-0}$	$0^{+1.32}_{-0}$
Total	$0.91^{+0.39}_{-0.37}$	$1.37^{+1.49}_{-0.64}$	$1.39^{+1.44}_{-0.55}$



Exclusion plot shown for a phenomenological MSSM scenario which allows sleptons in the decay chains

M(Squark/gluino) > M(chi2) > M(slepton) > M(chi1)

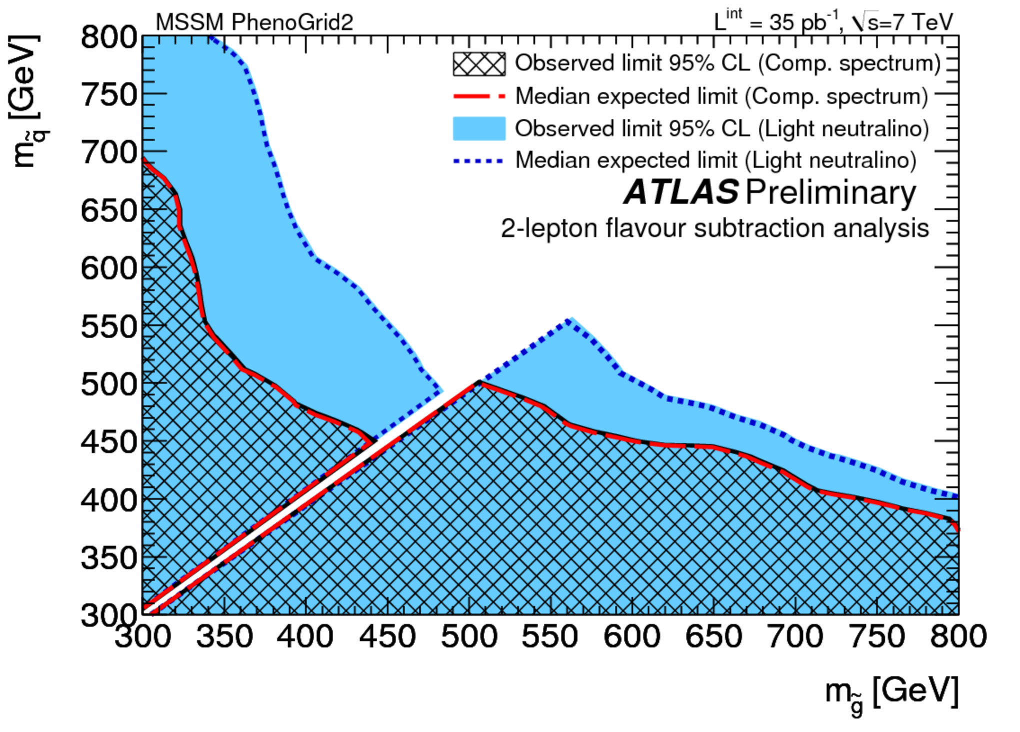
Shown is a compressed ("soft" particles) and a favorable scenario ("harder"particles)

Dilepton + E_t^{miss} (flavour substraction)

Search for events with E_t^{miss} , opposite charge and identical flavour (ee, μμ)

SM processes do equally produce ee+μμ and emu events

➔ Background can be subtracted !



In SUSY events the production of the two leptons can be correlated

$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^{\mp}\ell^{\pm} \rightarrow \tilde{\chi}_1^0\ell^{\pm}\ell^{\mp}$$

due to lepton flavor conservation in the decays.

$$\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{(1-(1-\tau_\mu)^2)}$$

$$\mathcal{S}_{obs} = 1.8 \pm 0.2(\beta) \pm 0.01(\tau_e) \pm 0.01(\tau_\mu)$$

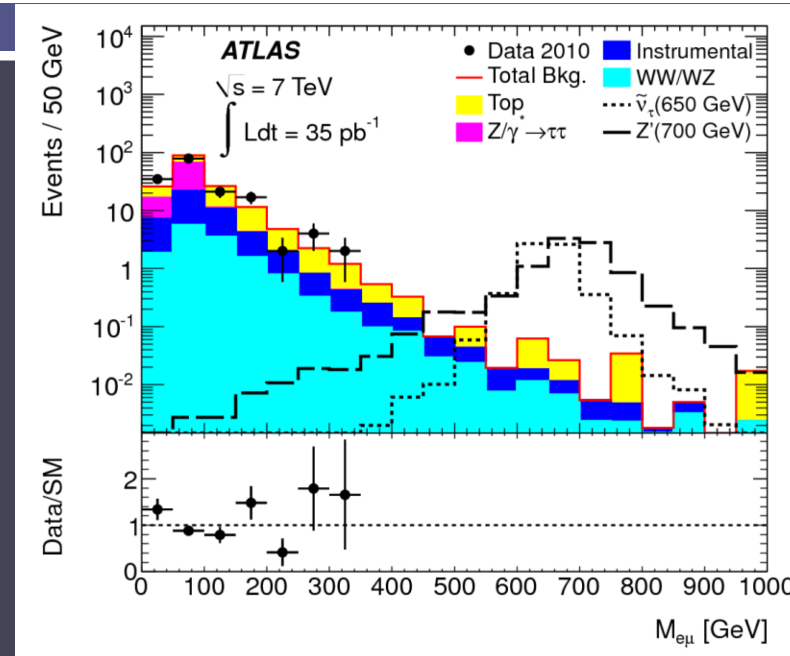
$S_{expected}$ = $1.98 \pm 0.79(stat.) \pm 0.78(sys.)$

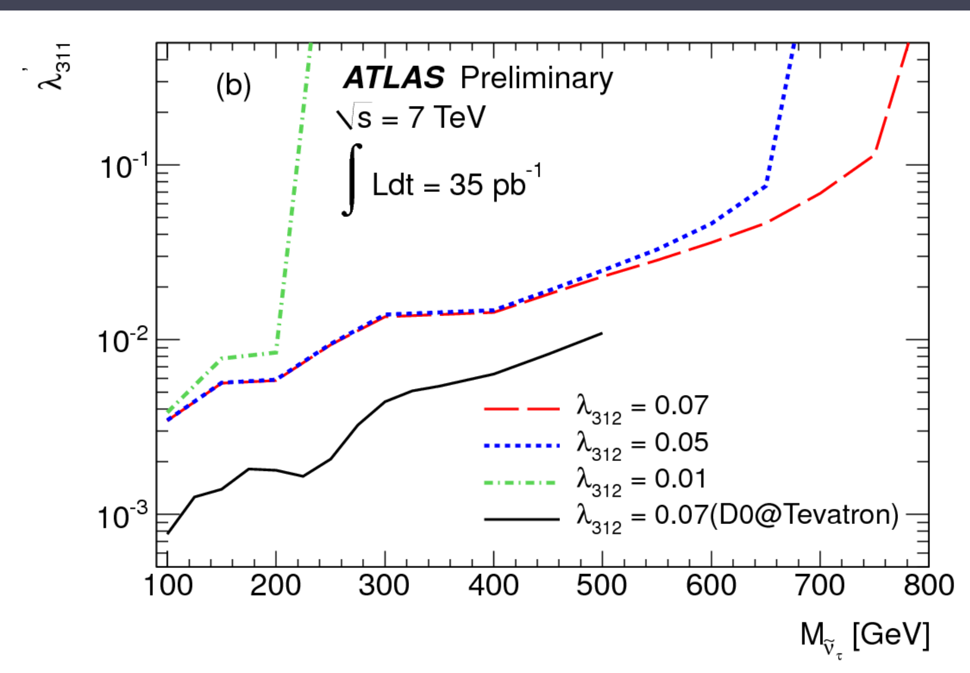
Electron Muon Resonance

Generic Search for a electron muon resonance

Selection: e and mu of opposite charge
$p_{T,lepton}$ > 20 GeV and not cut on MET

Determination of the instrumental (single and double fake) again via soft/tight equations





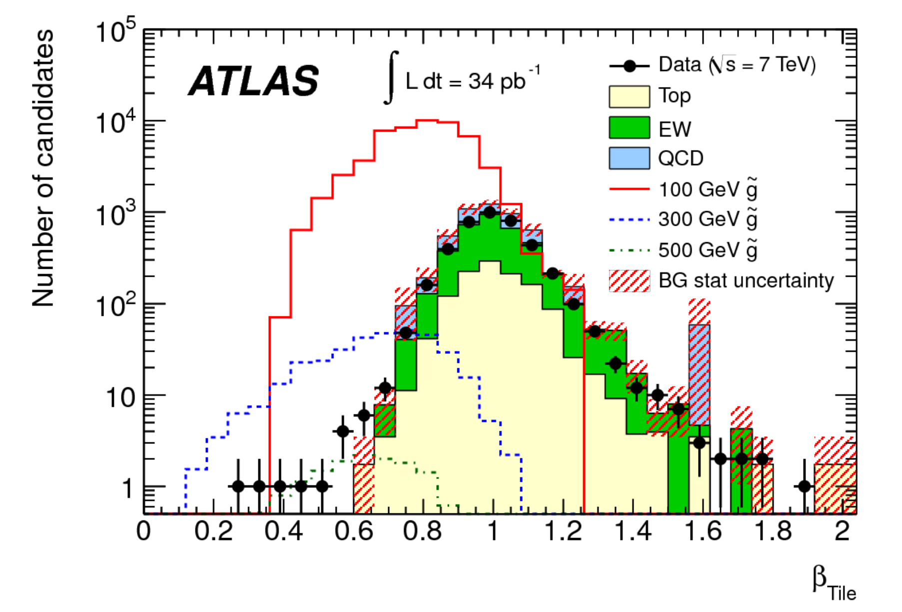
Limits on R_P violating $\tilde{\nu}_\tau$ production extending previous searches at high mass

Stable Massive Particle Search

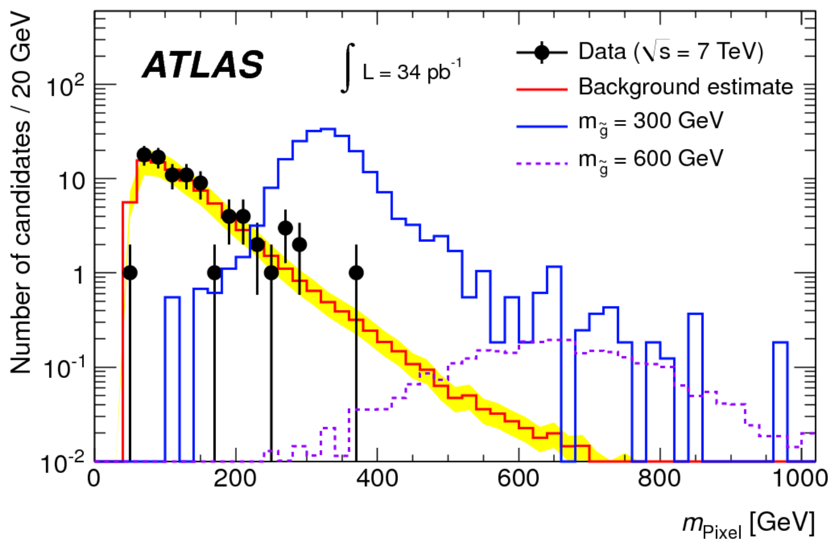
- Search for R-hadrons (stable hadrons including a stable gluino, stop or sbottom)
- Selection: E_t^{miss} >40 GeV for triggering + track with p_T > 50 GeV
- Two complementary subsystems used to measure SMPs

1. **Tile sampling calorimeter**
   iron+plastic scintillators, time resolution of 1-2 ns, calibrated with muons from Z decays
2. **Pixel detector:**
   dE\dx is measured
   with the charge loss of clusters formed with the pixels

Background estimates and signal distributions for the pixel and tile mass measurements



Stable Massive Particle Search

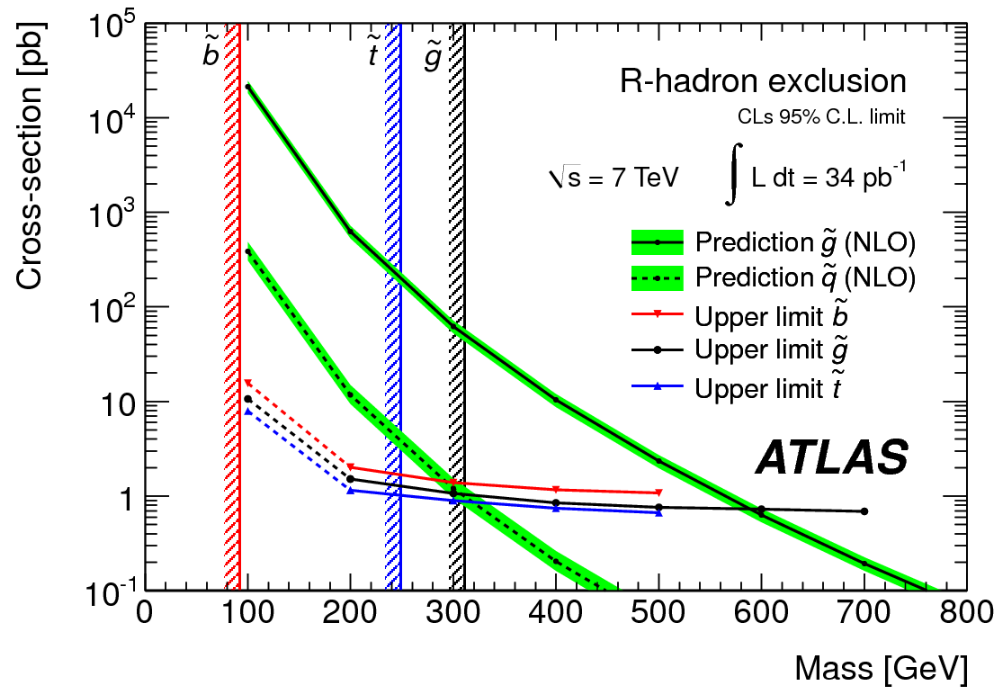


Measure dE/dx to determine βγ via Bethe/Bloch formular for Pixel and beta of the tile calorimeter
➔Transform these measurement into mass via M = p / βγ
Background determined via random picking of momentum, tile, pixel information

Final signal regions defined by requiring cuts on both mass measurements

No events after final selections
➔New strongest limits
limits on stable the masses of

$\tilde{g}\bar{\tilde{g}}$, $\tilde{t}\bar{\tilde{t}}$ and $\tilde{b}\bar{\tilde{b}}$

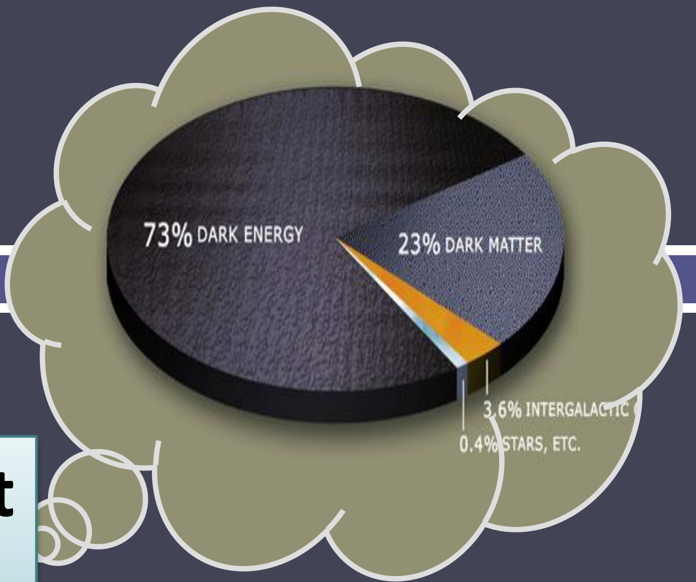


Summary and Conclusion

- The search has begun
- SUSY seems not to lie "just around the corner" of the LEP/Tevatron reach
- ATLAS has presented the most stringent limits to date in various scenarios
- mSUGRA: $M_{squark} = M_{gluino} > 775$ GeV
- Expect sensitivity beyond 1 TeV already for 2011

EXTRA SLIDES

Why SUSY ?



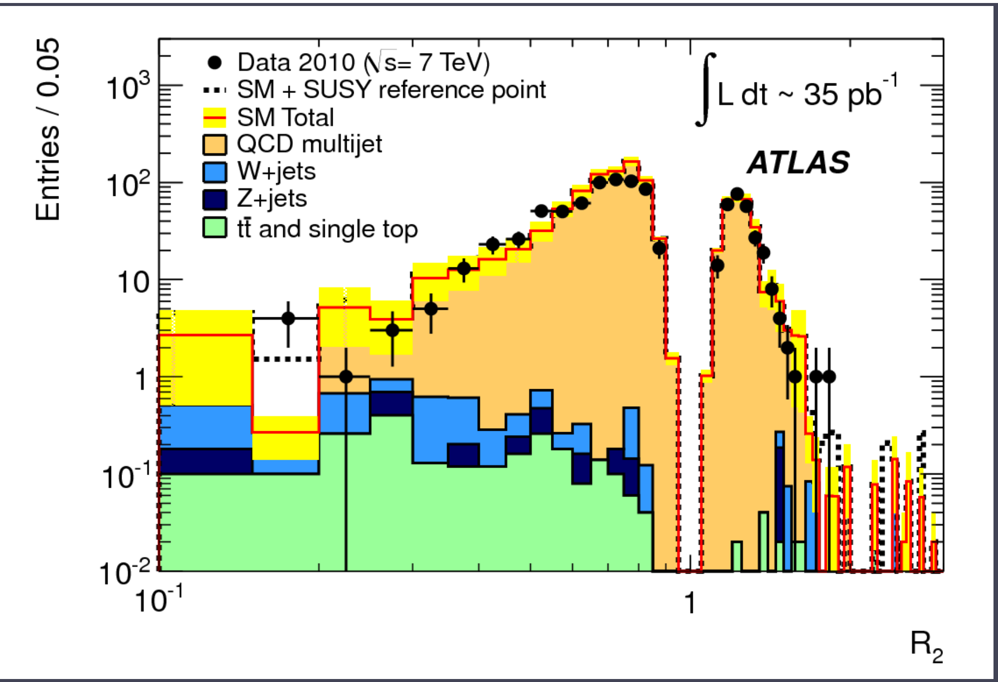
Most studied new physics theory at LHC for several reasons :

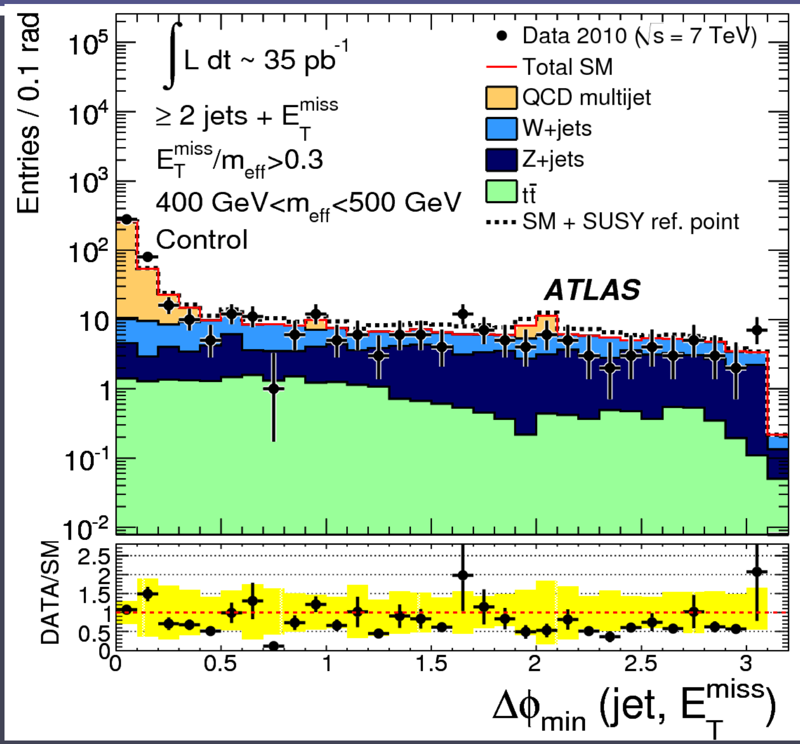
-Fermion and Boson loops protect the Higgs mass at large energies (reduces "fine tuning")

-SUSY is a broken symmetry and thus offers (with R-parity conservation) perfect candidates for Dark Matter with a WIMP mass of O(100) GeV

-Gauge couplings unification, "radiative" EWSB, …

0 lepton background determination

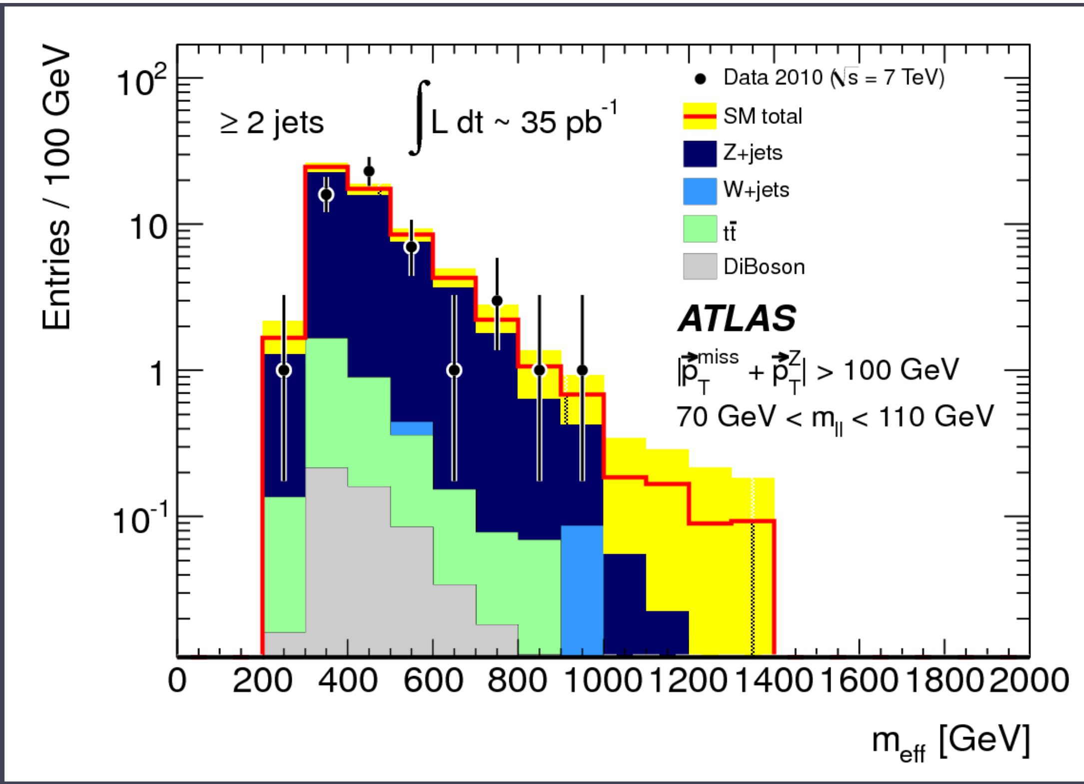




Non gaussian tail of the jet response function

R_2 = (p_T.(p_T+p_T^miss))/|p_T + p_T^miss|.
Events in which requirements have been used to associate the source of the P_T^miss with only one of the jets. The Gaussian core of the jet response function is removed by the selection requirements on E_T^miss. For each p_T bin the tails at low R_2 are subsequently used, together with the central Gaussian part of the response function (measured separately), and a set of low-E_T^miss seed events to form the fully data-driven QCD determination

0 lepton background determination



Distribution of m_eff in the dileptonic Z+jets control region for the >=2-jet selection.
Pre-selection requirements have been applied.
The missing transverse momentum requirement has been applied using the value that would be obtained if the leptons were not observed, |p_T^miss + p_T(l^+) + p_T(l^-)| > 100 GeV. In addition a requirement on the dileptonic invariant mass 70 GeV < m_ll < 110 GeV

0 lepton - Signal variables detail

Effective mass The scalar sum of transverse momenta defined by:

$$M_{\text{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\text{T}}^{(i)}| + E_{\text{T}}^{\text{miss}} \tag{2}$$

where n is the number of jets (two or three) defining the analysis channel, $\mathbf{p}_{\text{T}}^{(i)}$ is the transverse momentum of the i^{th} jet (ordered descending in $|\mathbf{p}_{\text{T}}|$), and $E_{\text{T}}^{\text{miss}}$ is defined in (1). The effective mass is sensitive to the centre-of-mass energy of the parton–parton collision. Selections demanding progressively larger M_{eff} tend to give sensitivity to progressively heavier coloured sparticles.

Stransverse mass The m_{T2} variable is the generalization of the transverse mass to pair decays [40]. For a final state consisting of two visible objects with transverse momenta $\mathbf{p}_{\text{T}}^{(1)}$ and $\mathbf{p}_{\text{T}}^{(2)}$ respectively, and with missing transverse momentum $\not{\mathbf{p}}_{\text{T}}$, it is defined by

$$m_{\text{T2}}\left(\mathbf{p}_{\text{T}}^{(1)}, \mathbf{p}_{\text{T}}^{(2)}, \not{\mathbf{p}}_{\text{T}}\right) \equiv \min_{\not{\mathbf{q}}_{\text{T}}^{(1)} + \not{\mathbf{q}}_{\text{T}}^{(2)} = \vec{E}_{\text{T}}^{\text{miss}}} \left\{\max\left(m_{\text{T}}\left(\mathbf{p}_{\text{T}}^{(1)}, \not{\mathbf{q}}_{\text{T}}^{(1)}\right), m_{\text{T}}\left(\mathbf{p}_{\text{T}}^{(2)}, \not{\mathbf{q}}_{\text{T}}^{(2)}\right)\right)\right\} \tag{3}$$

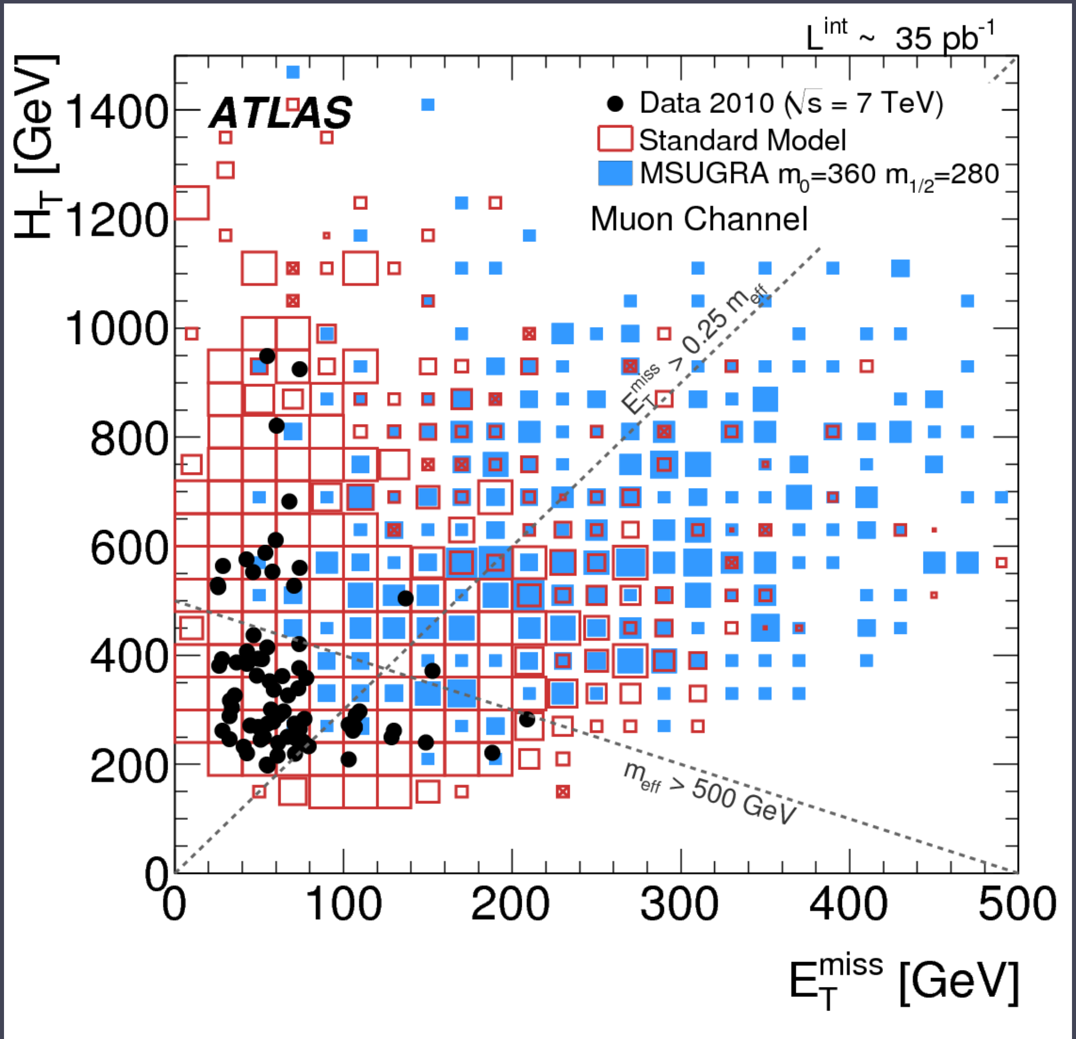
where m_{T} is the transverse mass[7]

$$m_{\text{T}}^2\left(\mathbf{p}_{\text{T}}^{(i)}, \not{\mathbf{q}}_{\text{T}}^{(i)}\right) \equiv 2|\mathbf{p}_{\text{T}}^{(i)}||\not{\mathbf{q}}_{\text{T}}^{(i)}| - 2\mathbf{p}_{\text{T}}^{(i)} \cdot \not{\mathbf{q}}_{\text{T}}^{(i)}, \tag{4}$$

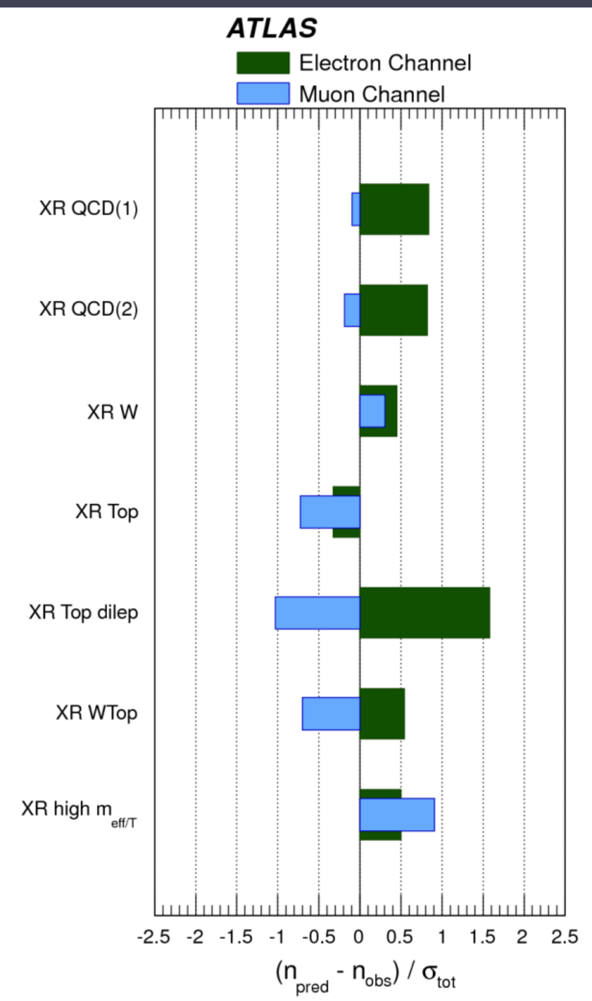
and the minimization is over all values of the two undetectable particles' possible missing transverse momenta $\not{\mathbf{q}}_{\text{T}}^{(1,2)}$ consistent with the $\vec{E}_{\text{T}}^{\text{miss}}$ constraint. This variable gives the largest possible event-by-

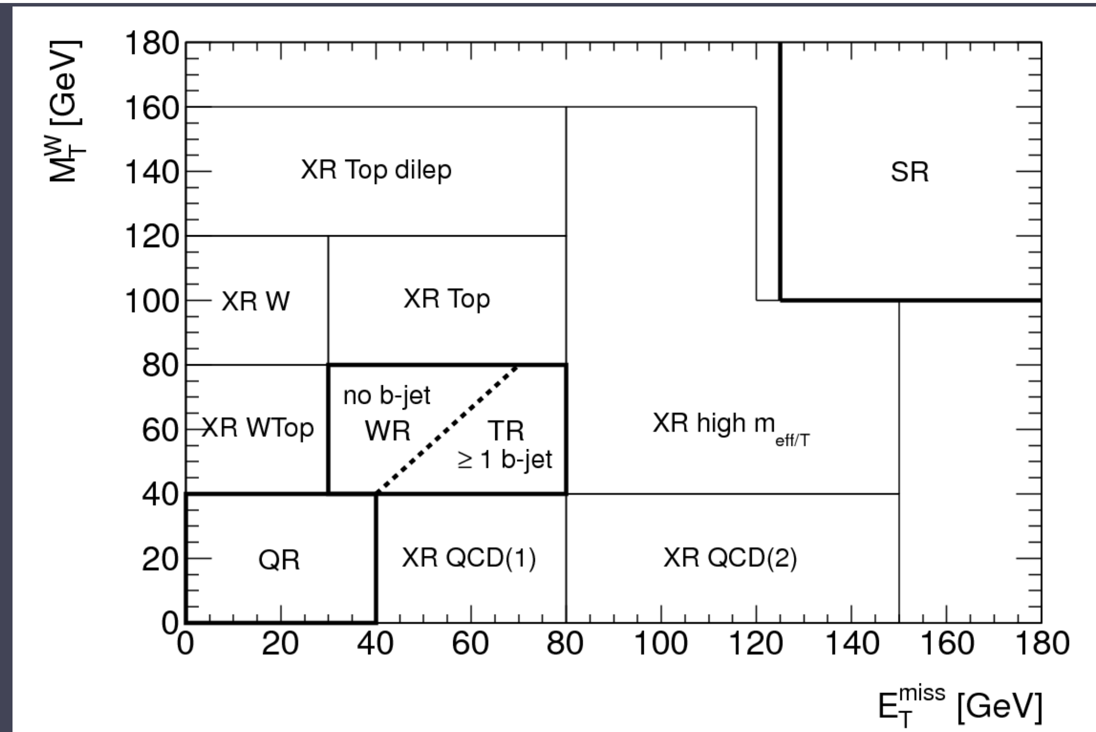
1 lepton channel details

Selection criteria



1 lepton channel details





Fits to alternative control regions

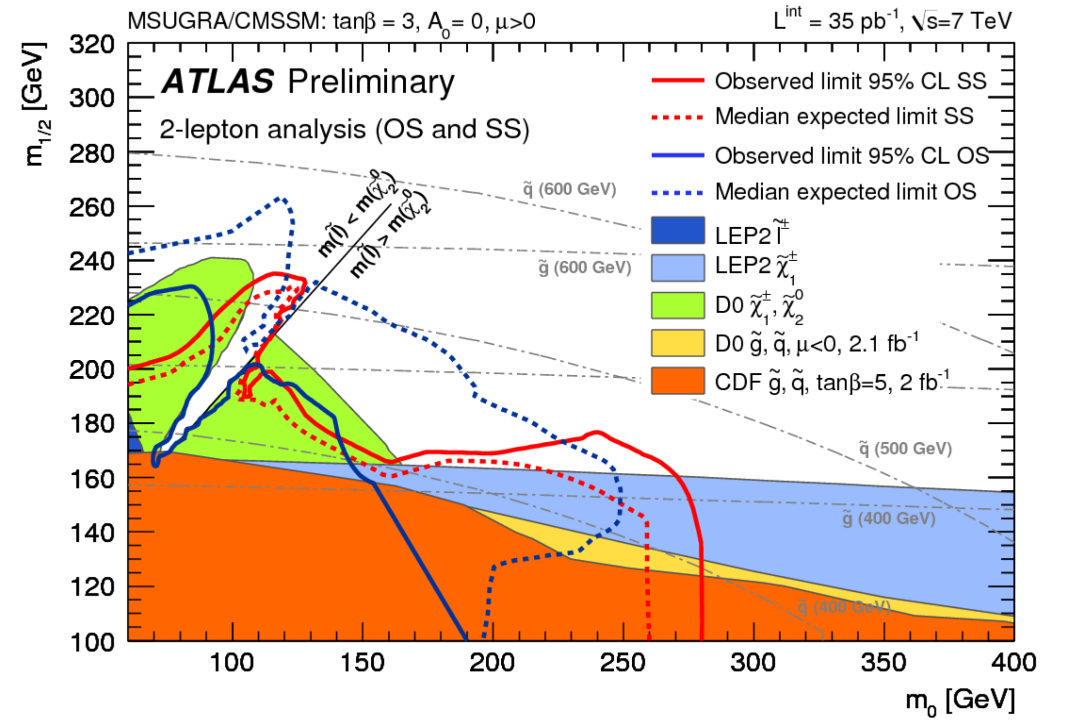
Grid 2 lepton

The Phenogrid2 allows the presence of sleptons in the gluino and squark decays chains:
m(3rd generation)=2000 GeV,
m(slepton_R)=m(slepton_L),
m(squark_R)=m(squark_L).

Two scenarios are considered:
a less favourable scenario, PhenoGrid2a with a very compressed spectrum yielding softer values of the discriminant variables, defined by m(chi_2^0)=M-50 GeV, m(chi_1^0)=M-150 GeV and m(slepton_L)=M-100 GeV, where M is the minimum of the gluino and squark mass

and a more favourable one, PhenoGrid2b with m(chi_2^0)=M-100 GeV, m(chi_1^0)=100 GeV and m(slepton_L)=M/2 GeV

2 lepton SS/OS msugra limit



SMP search

No correlations between the measurements of momentum, dE/dx (Pixel), and Beta (Tile)

➔ Exploited to estimate the amount of background arising from instrumental effects.

Estimates for the background mass distributions from dE/dx (Pixel) and beta (Tile) are obtained by independently combining random momentum values (from the momentum distribution obtained after all kinematic cuts) with random measurements of dE/dxPixel and beta Tile respectively to yield mass estimates.

SMP search

- Signal region and 2d plots