SUSY searches with the ATLAS detector at the LHC

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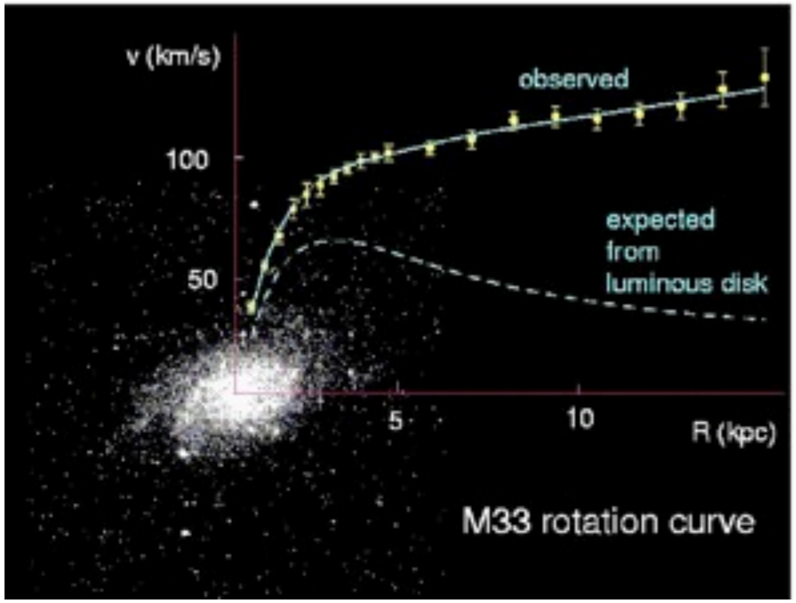
Is the Standard Model enough?

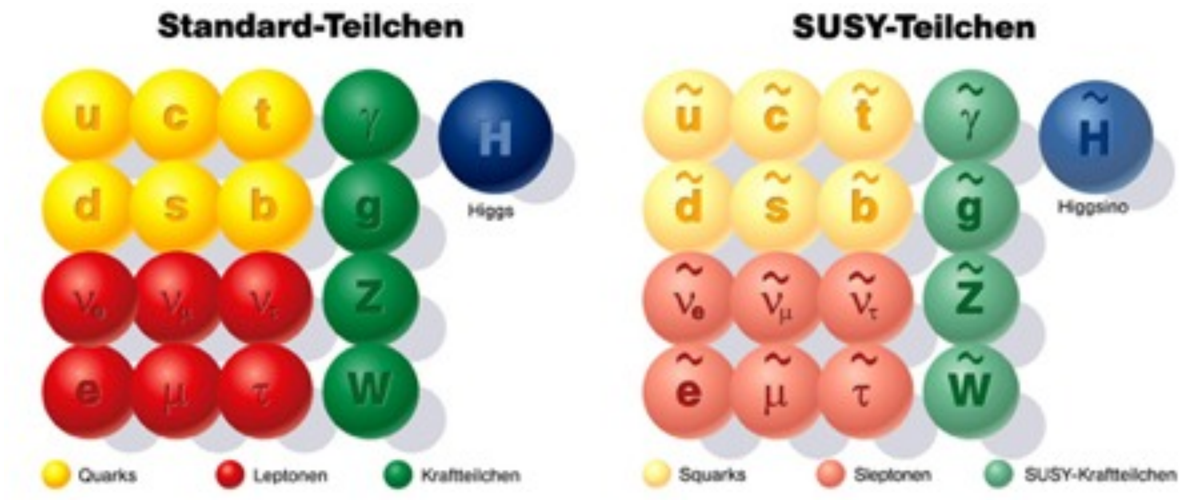
- The Standard Model has accumulated more than 30 years of striking successes in particle physics experiments, but:
  - a) Its Higgs sector suffer from quadratically divergent loop corrections mainly from top (the so called hierarchy problem)
  - b) Cosmological data strongly point to the existence of a dark matter candidate: no such candidate is present in the SM
  - c) No further unification between the EW and QCD possible



- Supersymmetry (SUSY) offers an elegant solution for a), which can simultaneously address b) and c)

Supersymmetry (SUSY)

- SUSY is a spin symmetry that relates bosons and fermions
- In the Minimal Supersymmetric Extension of the Standard Model (MSSM):
  - a new set of fields differing in spin by 1/2 w.r.t. the SM partners (hierarchy problem solved “naturally”)



- Running of coupling constants above the EW scale modified: unification possible
- If R-parity conservation assumed, the Lightest Supersymmetric Particle (LSP) is stable: natural Dark Matter candidate

R-parity = $(-1)^{3(B-L) + 2s}$

-1 for sparticles

1 for particles

Minimal SUSY extension of SM (MSSM)

- If SUSY is unbroken, $M_{sparticle} = M_{particle}$. Since sparticles are not yet observed, SUSY must be (softly) broken:
  - $L_{SUSY} = L_{SUSY\ conserving} + L_{SUSY\ soft\ breaking}$

2 higgs doublets needed → 5 Higgs bosons

MSSM parameters:

SUSY conserving sector	SUSY breaking sector
3 coupling constants for SU(3) xSU(2)sU(1)	5 3x3 hermitian mass matrices (one per EW multiplet)
4 Yukawa couplings per generation	3 complex 3x3 matrices (Higgs trilinear couplings to sfermions)
	3 mass terms for the Higgs sector + 2 additional off-diagonal terms
	Higgs VEV expectation angle β

A total of 124 parameters.
Constraints needed:

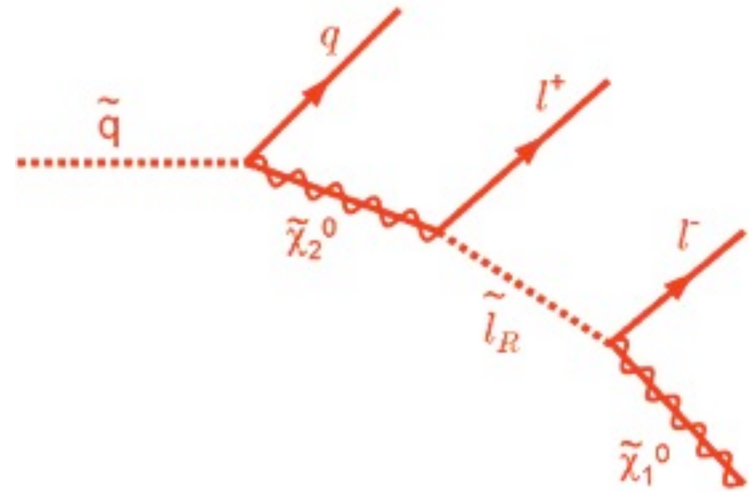
Bottom up: separate lepton number conservation, FCNC suppression, CP violation constrain the MSSM parameters

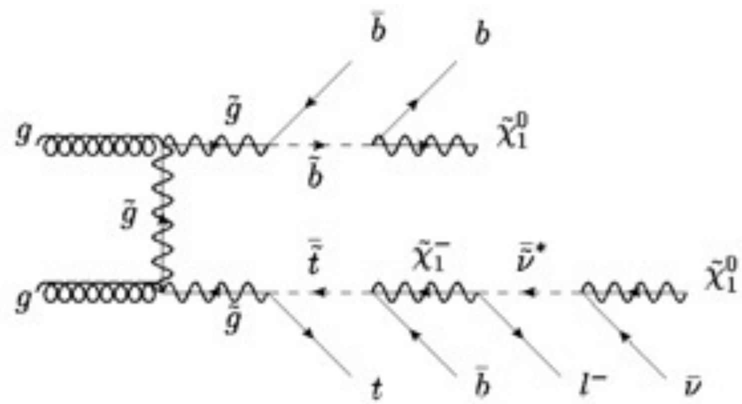
Top-down: Precise assumptions are made on the way SUSY is broken:

- mSUGRA/CMSSM
- GMSB
- AMSB

(R-parity) conserving SUSY phenomenology

- Missing E_T **is the signature**
- General R-parity signatures:
  - The LSP (typically $\tilde{\chi}_1^0$ or $\tilde{\nu}$ in mSUGRA, gravitino in GSMB) is stable and weakly interacting (dark matter candidate) → large missing transverse momentum
  - squarks and gluinos produced in pp collision → large particle multiplicity typically produced in the decay.
- Large jet multiplicities and/or lepton are foreseen in large regions of the parameter space (although not mandatory, e.g. $pp \to \tilde{q}\tilde{q} \to qq\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$)



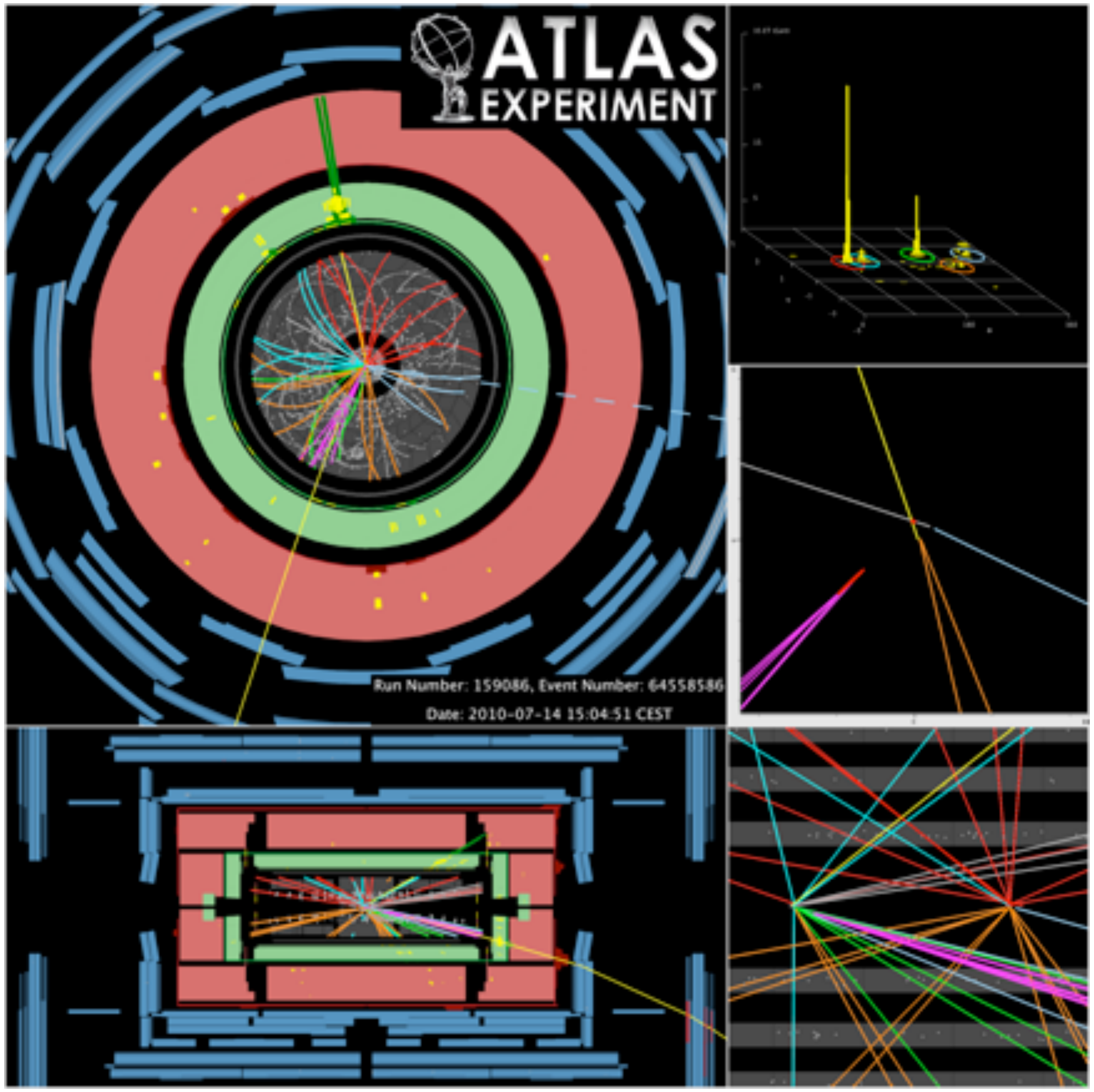


ATLAS - detector and performance

ATLAS in a nutshell

- From inside out:
  - ID made up of three different detectors (Pixel, SCT, TRT):
    - *High resolution tracking down to P_T > o(100) MeV, |η| < 2.5*
  - EM calorimeter - two sections covering up to |η| ≈ 3.2.
    - *High resolution on e/γ objects.*
  - HAD calorimeter - 3 sections covering up to |η|≈5
    - *Good containment, good resolution for jet measurement*
  - Muon system (4 different technologies) covering up to |η|=2.7
- Magnetic field: one solenoid surrounding the ID (2T), three toroids (muon spectrometer - 4T peak)

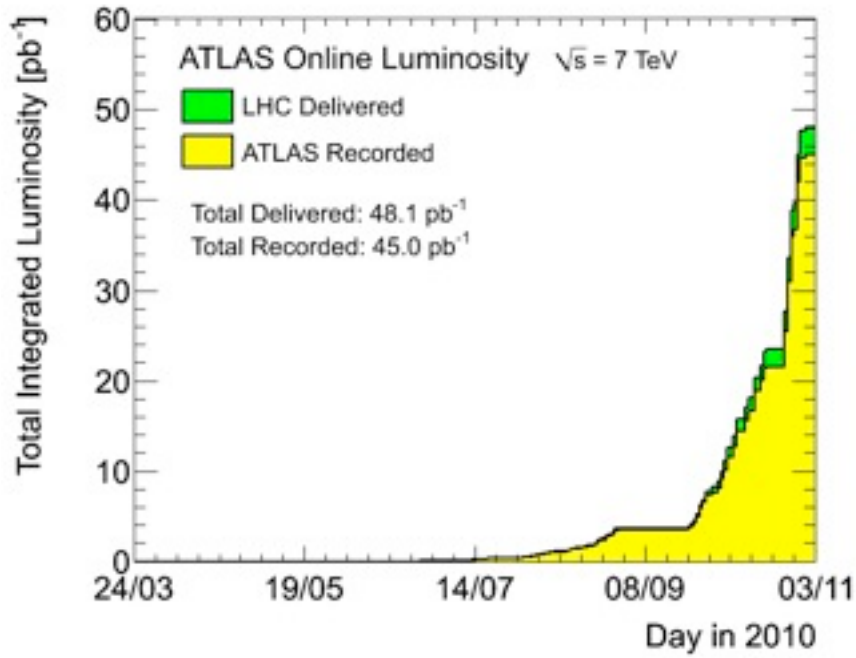
ATLAS in a nutshell (II)



A dileptonic ttbar event candidate

pp data taking in 2010

- First LHC pp collisions in March 2010.
- Maximum instantaneous luminosity: 2 10^{32} $cm^{-2}s^{-1}$. Total integrated luminosity delivered ~48 pb^{-1}



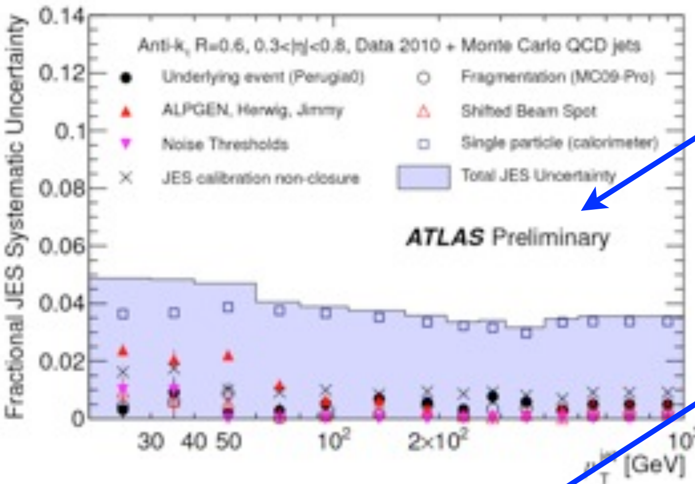
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.2%
SCT Silicon Strips	6.3 M	99.2%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.8%
Hadronic endcap LAr calorimeter	5600	99.8%
Forward LAr calorimeter	3500	99.9%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.8%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	99.1%

- ~95% of delivered luminosity written on tape by ATLAS (@ ~250 Hz)
- Each sub-detector operative for 90/100% of the time, with more than 97% operative channels.

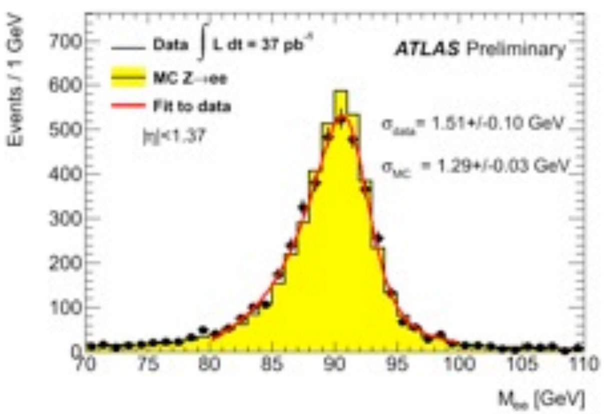
How well is ATLAS performing?

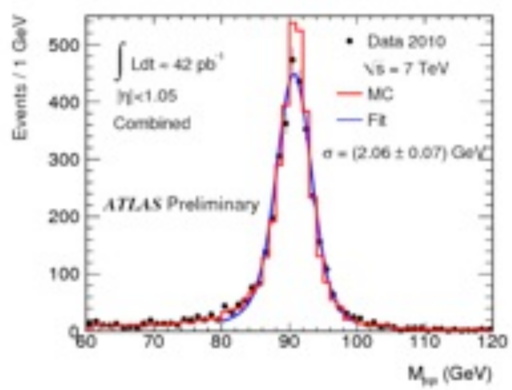
- Very good detector/object reconstruction understanding

Jet energy scale uncertainty down to ~4% for the early Moriond analysis (more later)

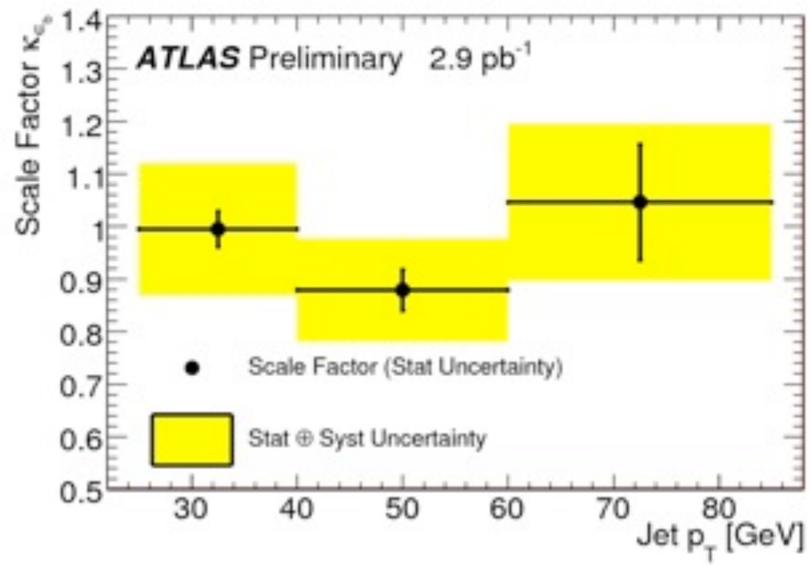


Excellent understanding of lepton reconstruction performance





b-tagging efficiency understood with un uncertainty of ~10%



R-parity conserving SUSY searches

- Generic (but still, exhaustive) SUSY searches:
  - MET and high P_T jets are expected to be present.
  - Depending on the mass hierarchy, final states with and without leptons might be present
  - Third generation squarks are generally expected to be light → b-jets in the final state from $\tilde{b}$ and $\tilde{t}$ decay.
- Define a general set of robust cuts, sensitive to SUSY, able to reject the SM background.

Main searches finalized so far

Inclusive 0-lepton	arXiv:1102.5290 [hep-ex] - submitted to PLB
Inclusive 1-lepton	arXiv:1102.2357 [hep-ex] - accepted by PRL
2-leptons	2 papers - Results approved
b-jets (0 and 1 lepton)	Results approved

Common selection

Common preselection:
- Data quality
- At least 1 vertex with 5 tracks
- Event cleaning

Electrons:
- Identified using shower shape and track matching criteria
- $P_T > 20$ GeV, $|\eta| < 2.5$

Muons:
- Identified with a track matching between the ID and muon spectrometer
- Highly isolated in the ID
- $P_T > 20$ GeV, $|\eta| < 2.5$

JETS:
- Anti-k_T - $\Delta R = 0.4$
- $P_T > 20$ GeV, $|\eta| < 2.5$
- b-tagging done using a lifetime based algorithm reconstructing secondary vertex. Decay length significance $L/\sigma(L)$ cut such that efficiency ~50% on top events. $P_T > 30$ GeV

Missing E_T (MET):
- Reconstructed from the vectorial sum of all jets and leptons. Clusters not belonging to any jets are added to the MET

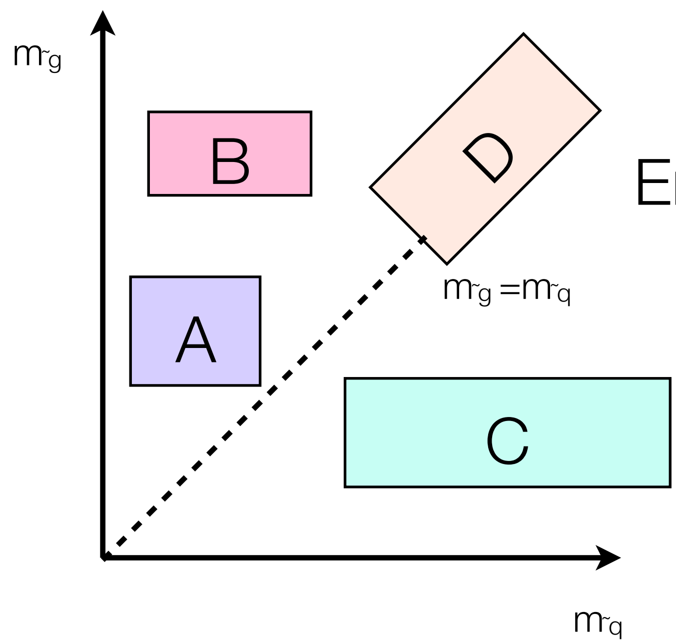
0-lepton inclusive searches

Editors: A.Barr, S.Caron, C.G.Lester, P.J. de Jong

0-lepton inclusive

- Search sensitive to $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production
- Different selections to maximise sensitivity to different processes

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$



Kill QCD

Enhance signal

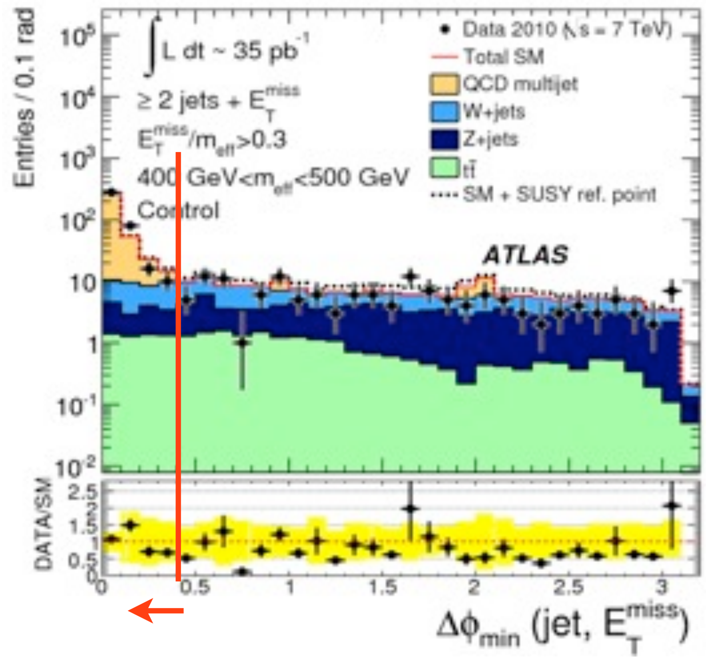
		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{p}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}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

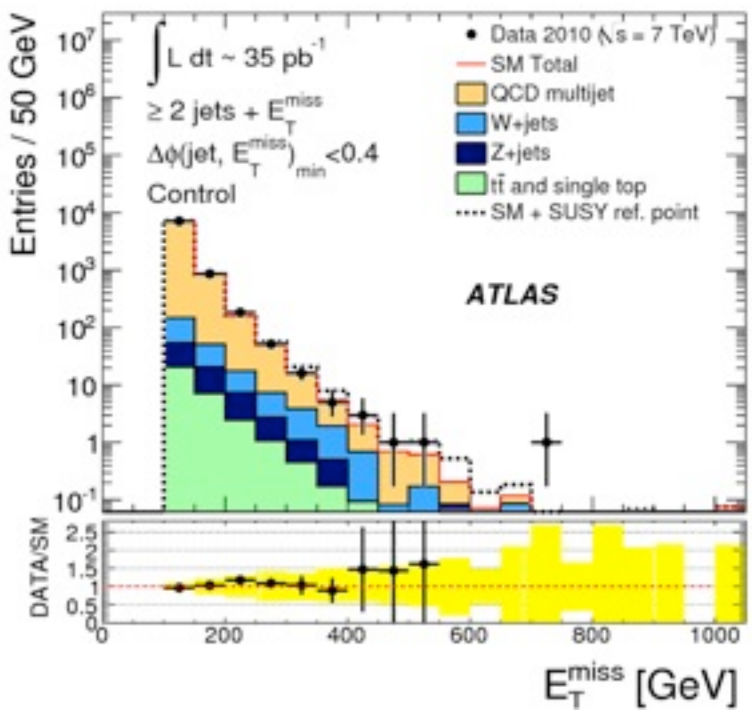
Region A/B: $\tilde{q}\tilde{q}$ production dominates, with $\tilde{q} \rightarrow q\tilde{\chi}_1^0$.
Low jet multiplicity.
Region C: $\tilde{g}\tilde{g}$ production dominates, with $\tilde{g} \rightarrow \tilde{q}q \rightarrow qq\tilde{\chi}_1^0$.
Large jet multiplicity
Region D: $\tilde{q}\tilde{g}$ production dominates. 3 jets expected,
large M_{eff}

Background estimation: QCD multijet

- Large MET in QCD due to one jet mis-measurement or heavy flavour production: in both cases, MET aligned with one jet

- QCD background estimation obtained renormalising PYTHIA and ALPGEN in a control region $\Delta\varphi_{min} < 0.4$





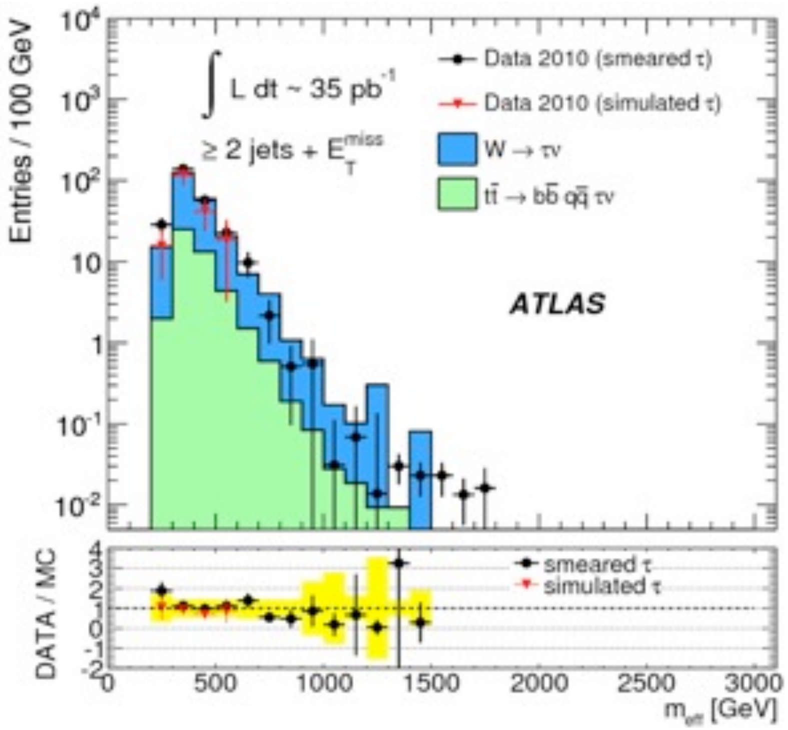
- Alternatively, define CR using MET/m_{eff} cut→consistent results found

- Further check: propagate the measured jet response function

- <u>Residual QCD background not dominant w.r.t. EW and top background (o(5%))</u>

Background estimation - non QCD

- Dominant SM background processes: $W \rightarrow \tau\nu$ ($\tau \rightarrow$ hadrons), $Z \rightarrow \nu\nu$, top production.
- Estimated using MC (ALPGEN with σ_{NNLO} from FEWZ for W, Z; Mc@Nlo with $\sigma_{NLO+NLL}$ for top production)
- Cross checks in CR (for example, $W \rightarrow \mu\nu$ and replacing the μ with τ, or $Z \rightarrow \mu\mu$ and then replace μ with ν).

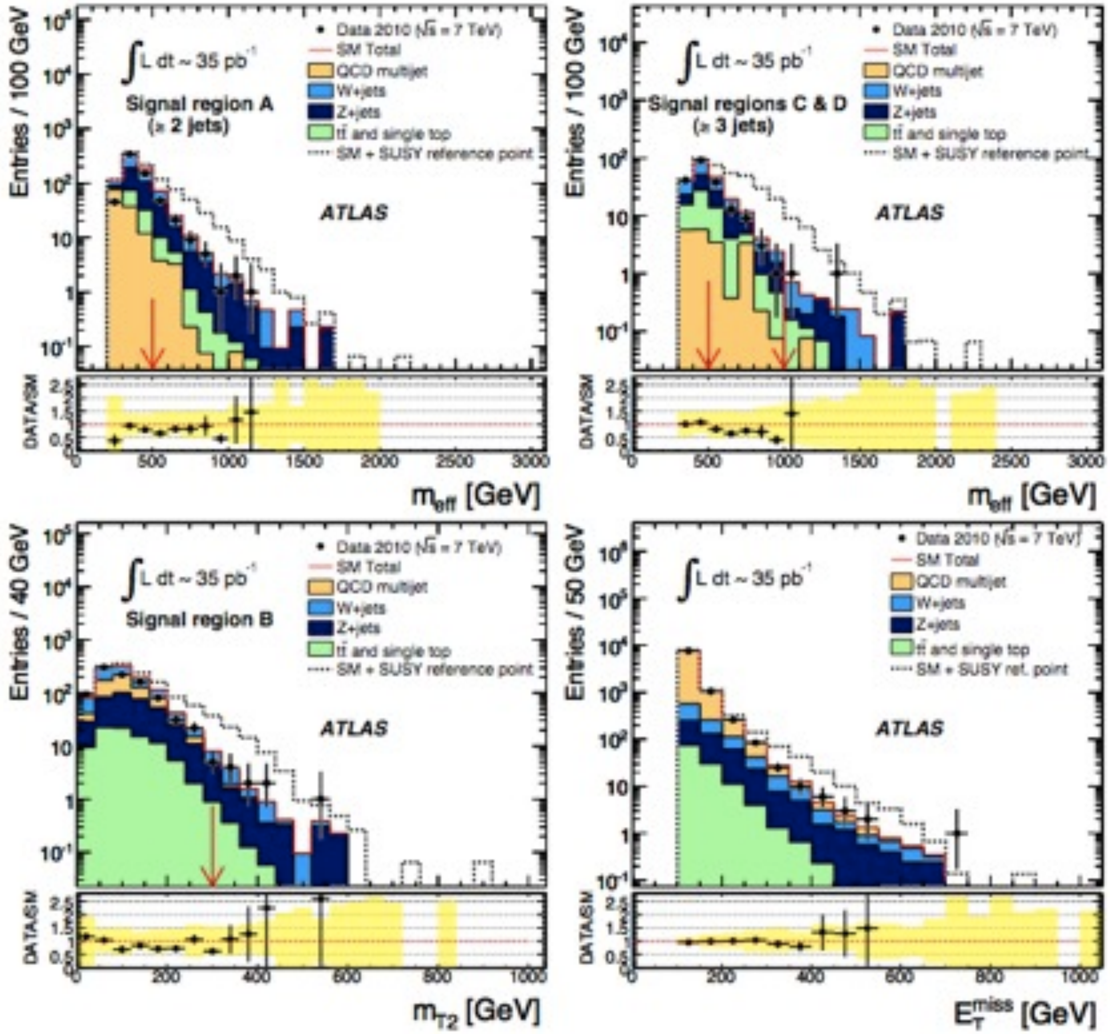


Physics process	$\sigma \cdot$ BR [nb]	
$W \rightarrow \ell\nu$ (+jets)	31.4±1.6	[23, 24, 25]
$Z/\gamma^* \rightarrow \ell\ell$ (+jets)	3.20±0.16	[23, 24, 25]
$Z \rightarrow \nu\nu$ (+jets)	5.82±0.29	[23, 24, 25]
$t\bar{t}$	0.164±0.010	[26, 27, 28]
Single top	0.037±0.002	[26, 27, 28]
Dijet ($\hat{p}_T > 8$ GeV)	10.47×10^6	[29]

After replacement of the μ, the τ response has to be emulated:
- Rerun the full simulation (red dots
- Smear the τ according to its expected response (black dots)

0-lepton results

- Dominant systematic uncertainty: JES uncertainty (j in the table, ~4/5% @ 100 GeV), MC modelling, luminosity (L in the table)
- Results fully consistent with the SM
- A profile likelihood ratio approach is used to set a frequentist 95% CL exclusion limit



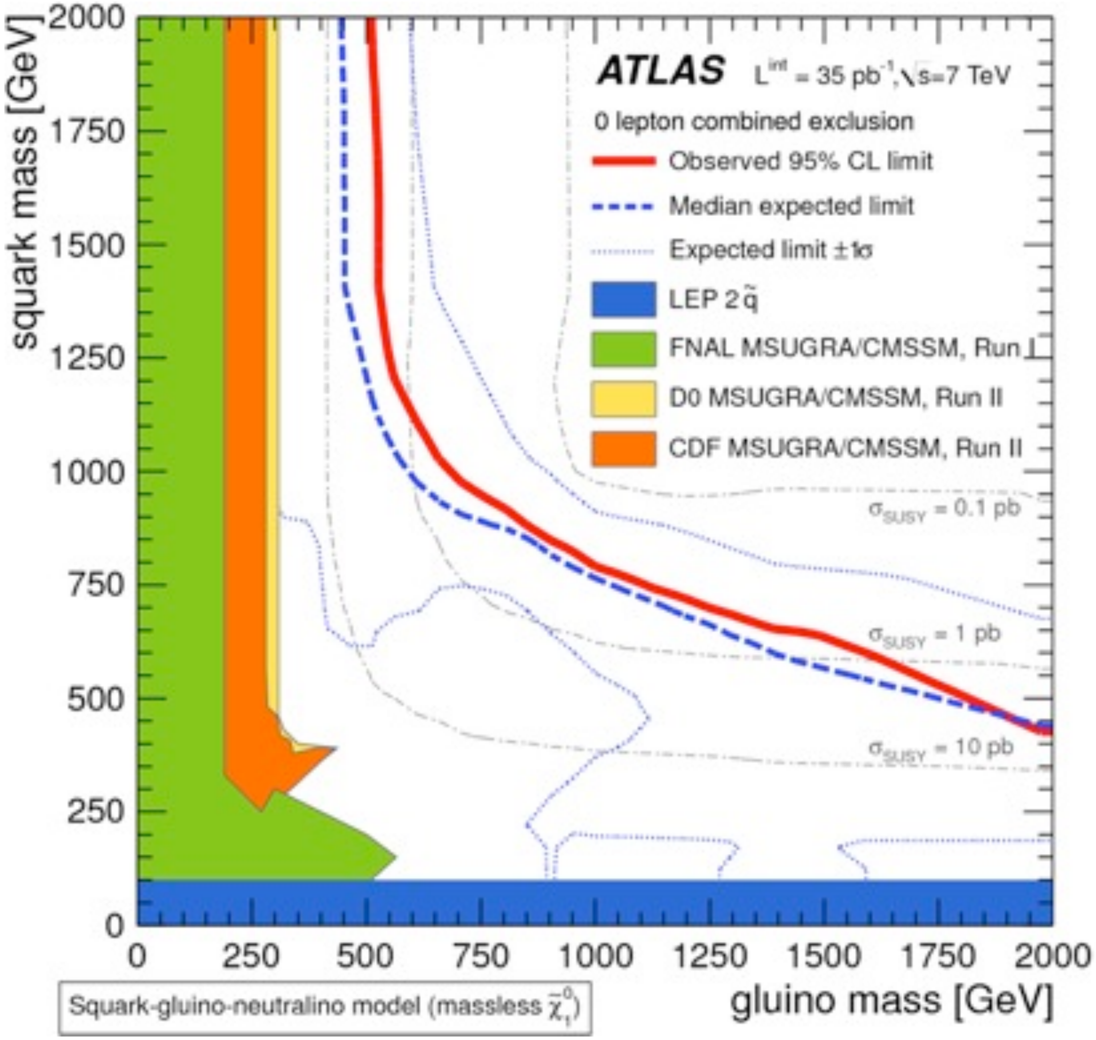
	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}[u+j]$	$0.6\ ^{+0.7}_{-0.6}[u+j]$	$9\ ^{+10}_{-9}[u+j]$	$0.2\ ^{+0.4}_{-0.2}[u+j]$
W+jets	$50 \pm 11[u]\ ^{+14}_{-10}[j] \pm 5[\mathcal{L}]$	$4.4 \pm 3.2[u]\ ^{+1.5}_{-0.8}[j] \pm 0.5[\mathcal{L}]$	$35 \pm 9[u]\ ^{+10}_{-8}[j]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

Table 2: Expected and observed numbers of events in the four signal regions. Uncertainties shown are due to "MC statistics, statistics in control regions, other sources of uncorrelated systematic uncertainty, and also the jet energy resolution and lepton efficiencies" [u], the jet energy scale [j], and the luminosity [$\mathcal{L}$].

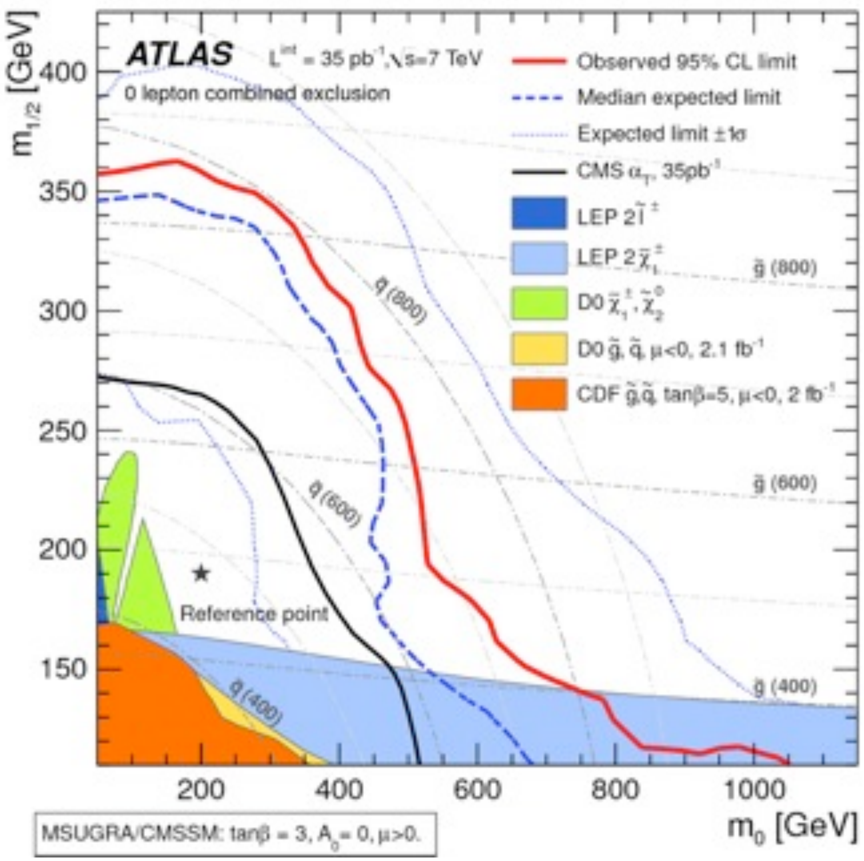
Phenomenological interpretation

- Lightest neutralino mass set to 0. Results studied as a function of the gluino and 1st and 2nd generation squark masses. All other masses set to 5 TeV.
- All 4 searches combined

Gluino masses below 500 GeV are excluded. If $m_{\tilde{q}}=m_{\tilde{g}}$, m < 870 GeV is excluded



mSUGRA/CMSSM result interpretation



- mSUGRA/CMSSM: gravity mediated supersymmetry breaking
- Common masses at GUT scale (assumed to be the Planck scale):
  - m_0 is the common scalar mass
  - $m_{1/2}$ is the common gaugino mass
- 3 additional parameters: common trilinear coupling A_0, higgs mass parameter μ, ratio between the higgs VEVs tanβ
- The RGE predict the mass hierarchy at the EW scale

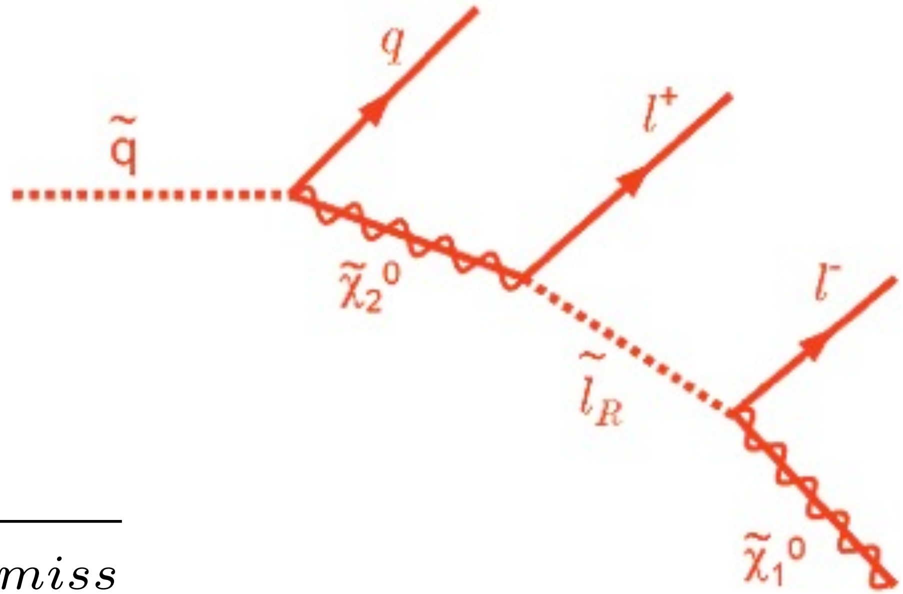
Best limits to date. If $m_{\tilde{q}}=m_{\tilde{g}}$, m < 775 GeV excluded

1-lepton searches

Editors: R.Bruneliere, S.Caron, P.J. de Jong

1-lepton - Motivations

- More complex decay chain of squarks can contain leptons
- Requiring 1 lepton:
  - Better rejection against QCD
  - Additional analysis handles for W/top background rejection



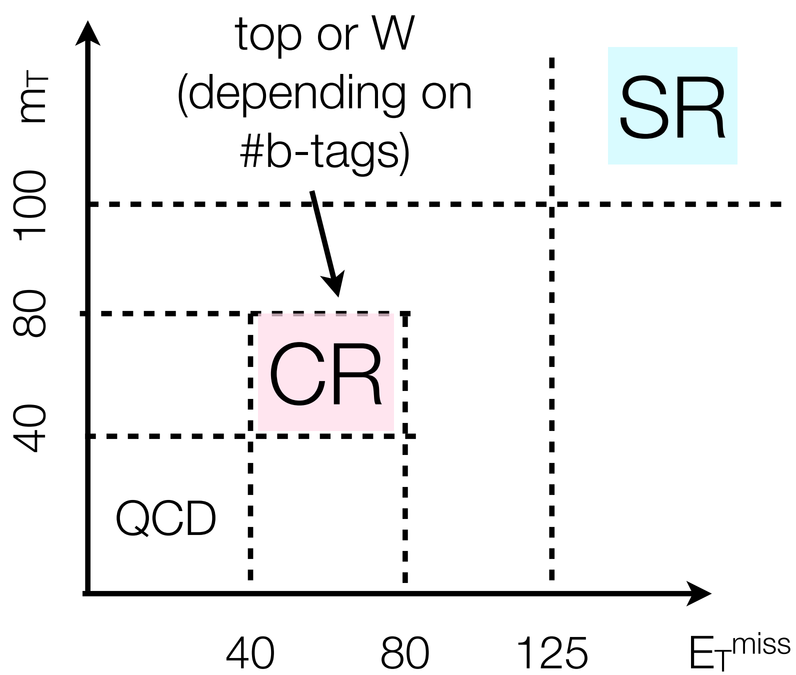
$$m_T = \sqrt{2p_T^l E_T^{miss} - 2\vec{p}_T{}^{\,l} \cdot \vec{E}_T^{miss}}$$

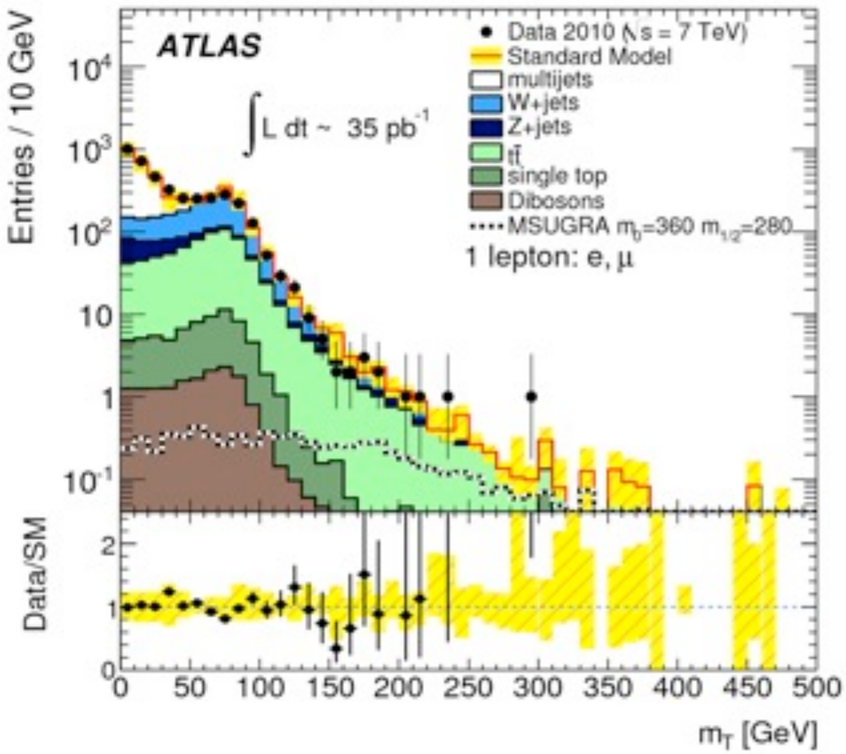
Selection:

- 1 lepton with $P_T > 20$ GeV
- 3 jets (leading with $P_T > 60$ GeV, the others with $P_T > 30$ GeV), MET > 125 GeV
- $\Delta\varphi_{min}>0.2$, MET/$m_{eff}>0.25$ (**further QCD reduction**); $m_T > 100$ GeV (**W, top reduction**)
- SR defined by $m_{eff}>500$ GeV

1-lepton background estimation

- QCD multijet background determined using a CR at low MET/low m_T relaxing the lepton ID criteria (see later the b-jet analysis): found compatible with 0
- W/Z and top determined with a combined fit in 2 CR, assuming shapes from MC:
  - 40 GeV < m_T < 100 GeV and 40 GeV < MET < 80 GeV with (with no) b-tagged jets defines the top (W) CR





1-lepton - Results

Electron channel	Signal region	Top region	W region	QCD region
Observed events	1	80	202	1464
Fitted top events	1.34 ± 0.52 (1.29)	65 ± 12 (63)	32 ± 16 (31)	40 ± 11
Fitted W/Z events	0.47 ± 0.40 (0.46)	11.2 ± 4.6 (10.2)	161 ± 27 (146)	170 ± 34
Fitted QCD events	$0.0^{+0.3}_{-0.0}$	3.7 ± 7.6	9 ± 20	1254 ± 51
Fitted sum of background events	1.81 ± 0.75	80 ± 9	202 ± 14	1464 ± 38

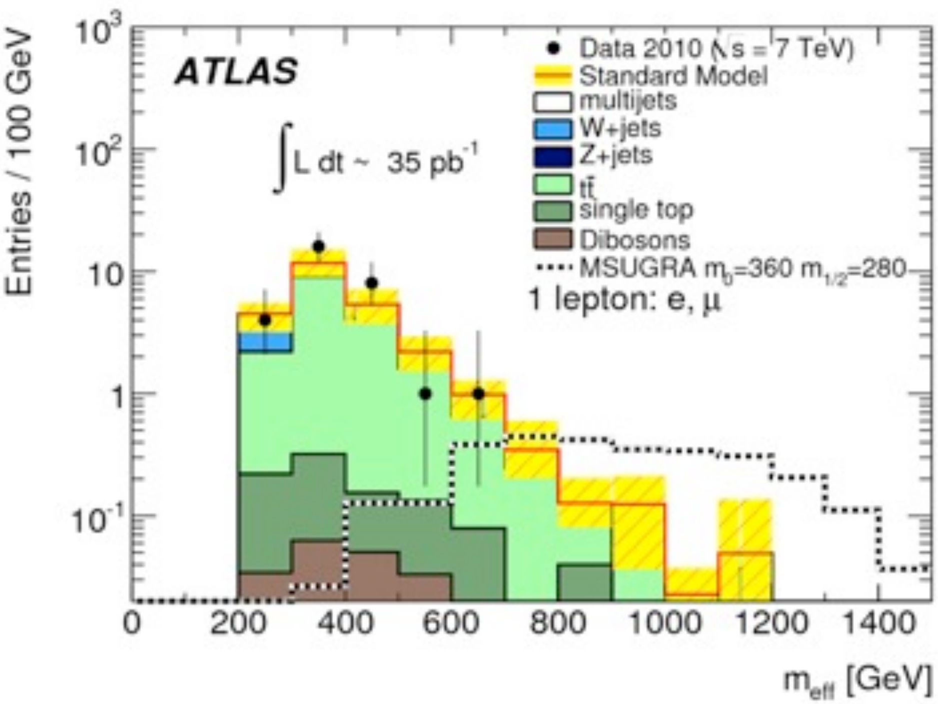
Muon channel	Signal region	Top region	W region	QCD region
Observed events	1	93	165	346
Fitted top events	1.76 ± 0.67 (1.39)	85 ± 11 (67)	42 ± 19 (33)	50 ± 10
Fitted W/Z events	0.49 ± 0.36 (0.71)	7.7 ± 3.3 (11.6)	120 ± 26 (166)	71 ± 16
Fitted QCD events	$0.0^{+0.5}_{-0.0}$	0.3 ± 1.2	3 ± 12	225 ± 22
Fitted sum of background events	2.25 ± 0.94	93 ± 10	165 ± 13	346 ± 19

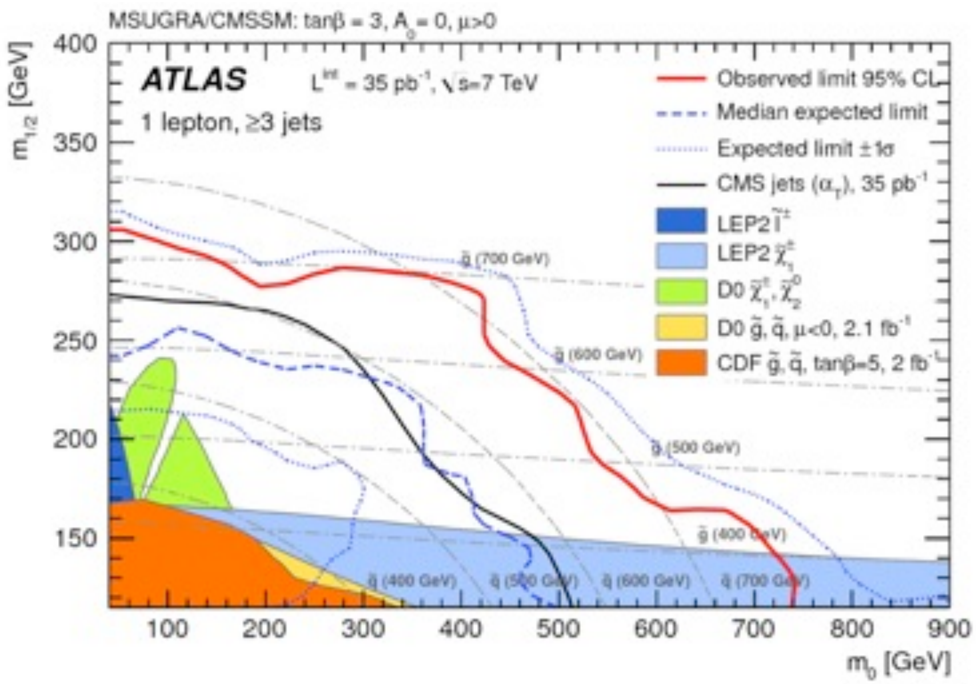
Systematics

- fit uncertainties dominated by modelling of MET and m_T (associated error estimated by varying MC generator and internal parameters)
- Experimental uncertainties (dominated by JES and b-tagging) varied within their range during the fit

1 lepton - Results(II)

- 2 events survive the m_{eff} > 500 GeV cut, in agreement with the SM predictions
- Result interpreted as a 95% CL exclusion limit in a mSUGRA/CMSSM scenario, with tanβ=3, A_0=0, μ > 0
- If $m_{\tilde{q}}=m_{\tilde{g}}$, masses below 700 GeV are excluded.





2-lepton searches

Editors: S.French, G.Polesello, T.Sarangi, D.R.Tovey

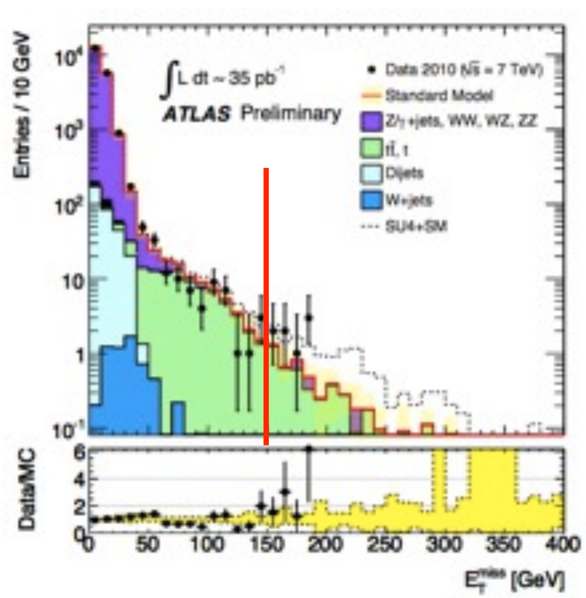
2 leptons

- A further step into complexity: require 2 leptons
  - Sensitive to gaugino decays into weak bosons, slepton production and decay
  - Look both at Opposite Sign (OS) and same sign (SS) lepton pairs
  - Main background: top pair production (fake leptons) for OS (SS) analysis

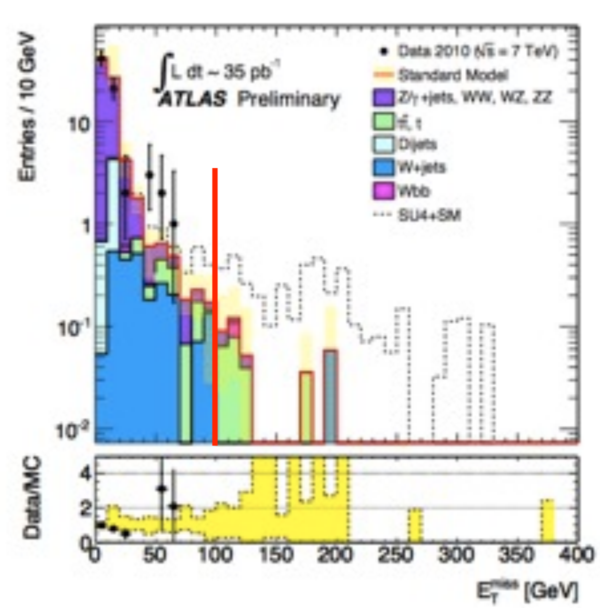
Selection:
- 2 leptons with M_{ll}>5 GeV
- MET > 150 (100) GeV for the OS (SS) analysis

- OS: top estimated in a CR 60 GeV < MET < 80 GeV (kinematics top compatible)
- SS: fake estimate similar to 1-lepton and b-jet analysis

Opposite Sign



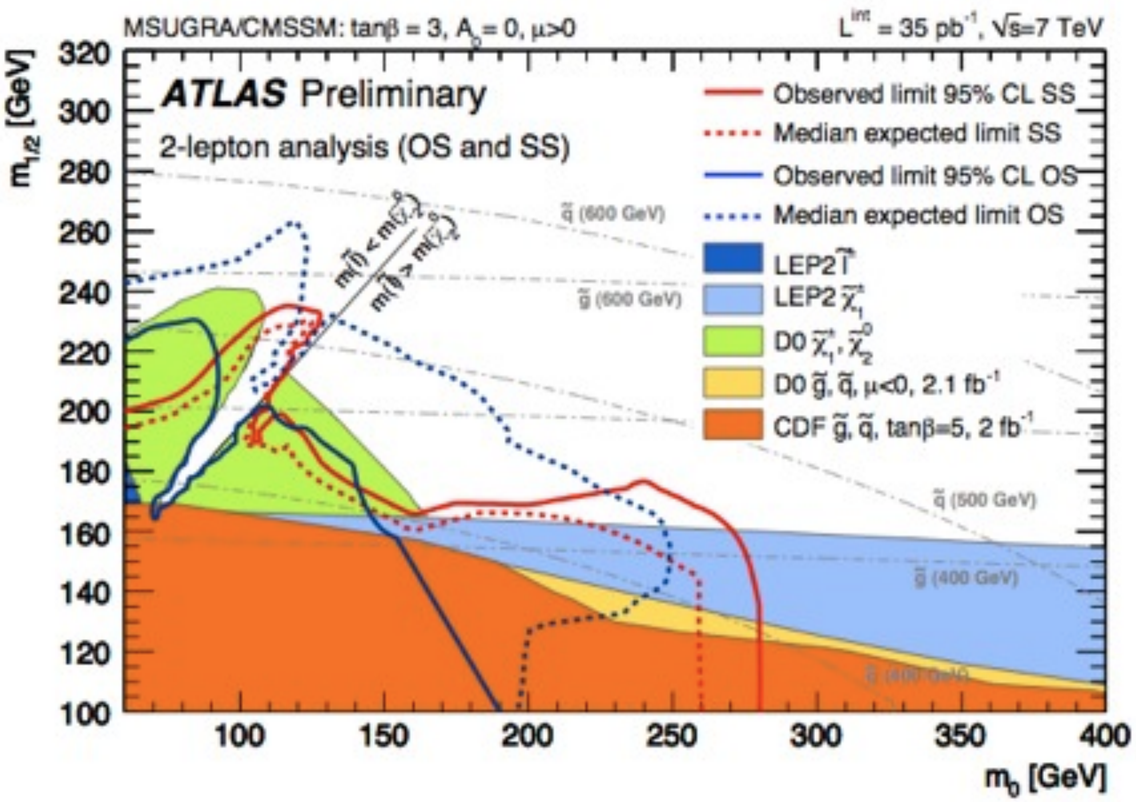
Same Sign



2-leptons results

- Results consistent with SM interpreted in mSUGRA/CMSSM as a 95% CL exclusion limit

	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	0.035 ± 0.012	0.021 ± 0.009
Charge-flip	0.019 ± 0.008	0.026 ± 0.011	-
Cosmic	-	$0^{+1.32}_{-0}$	-
Total	0.15 ± 0.13	$0.09^{+1.32}_{-0.03}$	0.04 ± 0.01
	Opposite Sign, $E_T^{miss} > 150$ GeV		
	$e^{+}e^{-}$	$e^{\pm}\mu^{\mp}$	$\mu^{+}\mu^{-}$
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 ± 0.15	0.08 ± 0.08	0.14 ± 0.17
Fakes	-0.02 ± 0.02	-0.05 ± 0.04	-
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	-	$0^{+1.32}_{-0}$	$0^{+1.32}_{-0}$
Total	$0.92^{+0.42}_{-0.40}$	$1.43^{+1.57}_{-0.59}$	$1.39^{+1.53}_{-0.53}$



- Previously allowed region close to the $m_{\tilde{l}}=m_{\chi 20}$ now exluded
- Results interpreted also in terms of phenomenological models (see backup)

2-leptons, alternative strategy

- The basic idea is to look for an excess of same flavour leptons.
  - Only source of SM background is Z/γ (top to a lesser extent).
  - Subtraction of non opposite flavour reduces systematic uncertainties:
    - Very robust limits can be set
- The variable tested is the excess of same flavour lepton pairs

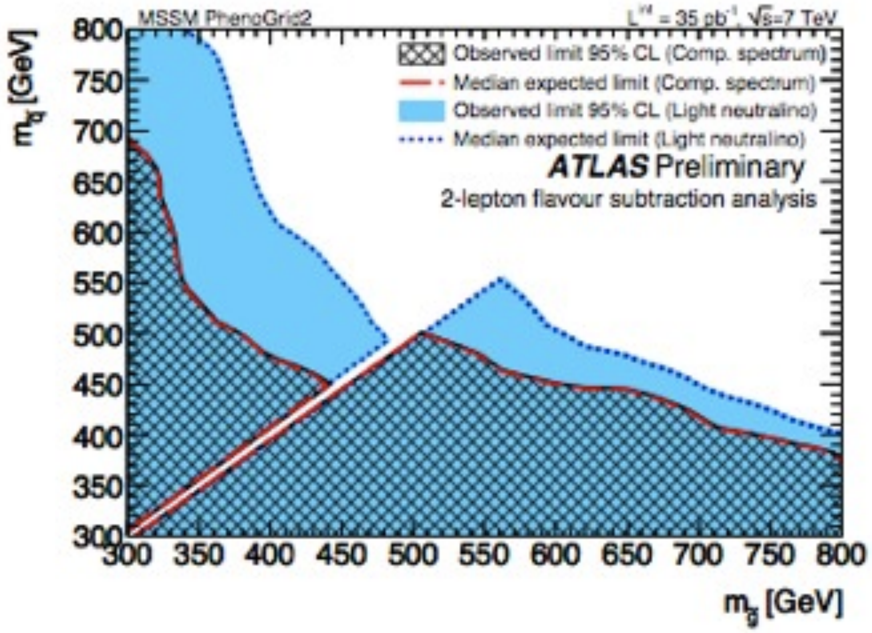
$$\mathcal{S} = \frac{N(e^\pm e^\mp)}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^\pm \mu^\mp)}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^\pm \mu^\mp)}{(1-(1-\tau_\mu)^2)}$$

$$S_{obs} = 1.98 \pm 0.15(\beta) \pm 0.02(\tau_e) \pm 0.06(\tau_\mu)$$

$$S_{exp} = 2.06 \pm 0.79(stat) \pm 0.78(syst)$$

$\beta = \varepsilon_e/\varepsilon_\mu$, with $\varepsilon_{e(\mu)} = e(\mu)$ ID efficiency

$\tau_{e(\mu)}$ = trigger efficiency

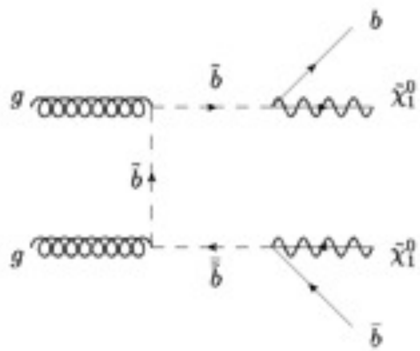


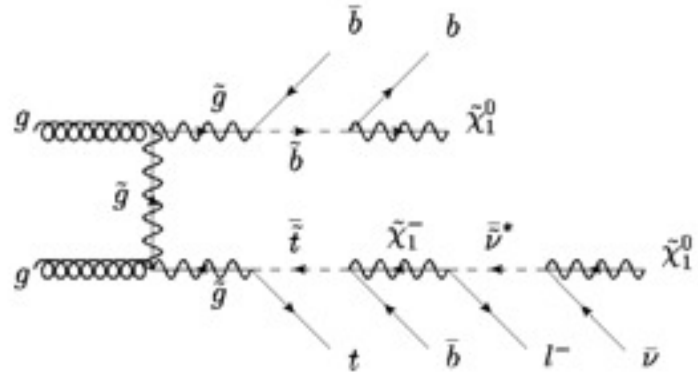
MET + b-jet searches

Editors: D.Costanzo, M.D'Onofrio, K.Jakobs, I.Vivarelli

SUSY with b-jet - Motivations

- Mixing between L and R component of squarks proportional to the fermion partner mass → large mixing for 3rd generation squarks → generally expected to be the lightest squarks
- Large production cross section expected ($\tilde{b}\tilde{b}$($\tilde{t}\tilde{t}$) or via gluino mediated production).





- Signature: large MET, multijet, abundance of b-jets, maybe 1-lepton.
- 2 mutually exclusive analysis developed:
  - 0-lepton channel: lepton veto ($P_T > 20$ GeV), 1-lepton channel: at least 1 lepton with $P_T > 20$ GeV

Event selection

- Trigger:
  - 0-lepton: at L1 ask one jet with P_T > 55 GeV (full efficient on offline P_T > 120 GeV). At HLT, ask MET > 25 GeV (full efficient with offline MET > 100 GeV)
  - 1-lepton: e(μ) with online P_T > 15 (13) GeV

$$\Delta\phi_{min} = \min(|\phi_1 - \phi_{E_T^{miss}}|, |\phi_2 - \phi_{E_T^{miss}}|, |\phi_3 - \phi_{E_T^{miss}}|)$$

$$m_T = \sqrt{2 p_T^{lep} E_T^{miss} - 2\vec{\mathbf{p}}_T \cdot \vec{\mathbf{E}}_T^{miss}}$$

$$m_{eff} = \sum_{i \leq 4} (p_T{}^{jet})_i + E_T^{miss} + \sum_i p_T{}^{lep}$$

0-lepton	1-lepton
Pre-selections cuts: Data Quality, Trigger requirements clean up for misidentified jets: electron fiduciality, ≥ 1 primary vertex with ≥ 5 tracks	
no-lepton ($p_T > 20$ GeV)	≥ 1 lepton ($p_T > 20$ GeV)
jet $p_T > 120, 30, 30$ GeV, $\lvert\eta\rvert < 2.5$	jet $p_T > 60, 30$ GeV, $\lvert\eta\rvert < 2.5$
$E_T^{miss} > 100$ GeV	$E_T^{miss} > 80$ GeV
$E_T^{miss}/m_{eff} > 0.2$	–
At least 1 b-tagged jet (SV0, $L/\sigma(L) > 5.72$, $p_T > 30$GeV, $\lvert\eta\rvert < 2.5$)	
$\Delta\phi_{min} > 0.4$ rad	$m_T > 100$ GeV

On top of these cuts, a signal region is defined with M_{eff} > 600 (500) GeV for the 0(1)-lepton channel

Background estimation

- Due to the large MET cut and the b-jet requirement, the main background is ttbar production for both the 0 and 1 lepton channel

Cut	$t\bar{t}$	$W+$ jets	Wbb	$Z+$ jets	Zbb	single top
$E_T^{miss} > 100$ GeV	3.55 ± 0.02	9.29 ± 0.15	0.1 ± 0.01	4.66 ± 0.14	0.054 ± 0.002	0.30 ± 0.02
$E_T^{miss}/m_{eff} > 0.2$	3.05 ± 0.02	8.36 ± 0.14	0.09 ± 0.01	4.28 ± 0.14	0.047 ± 0.001	0.26 ± 0.02
1 b-tagged jet	2.15 ± 0.02	0.69 ± 0.04	0.06 ± 0.01	0.28 ± 0.03	0.022 ± 0.001	0.16 ± 0.01
$\Delta\phi_{min} > 0.4$	1.60 ± 0.02	0.42 ± 0.03	0.05 ± 0.01	0.19 ± 0.03	0.016 ± 0.001	0.11 ± 0.01
$m_{eff} > 600$ GeV	0.33 ± 0.01	0.11 ± 0.02	0.006 ± 0.002	0.05 ± 0.01	0.0031 ± 0.0003	0.02 ± 0.01

0-lepton
MC predicted
cut flow

Cut	Top	W	Z	QCD	Di–boson production
1 electron with $p_T > 20$ GeV	24.4	3760	631.4	16865	6.2
2 jets ($p_T > 60, 30$ GeV)	17.2	59.6	21.2	590	1.0
$E_T^{miss} > 80$ GeV	4.6	10.4	0.3	6.6	0.2
$m_T > 100$ GeV	1.0	0.38	0.025	0.08	0.0021
1 b-tag	0.70	0.016	3×10^{-4}	0.06	0.0013
$m_{eff} > 500$ GeV	0.18	0.011	–	–	–

1-lepton (electron)
MC predicted cut flow
(similar for muons)

Background estimation (0-lepton)

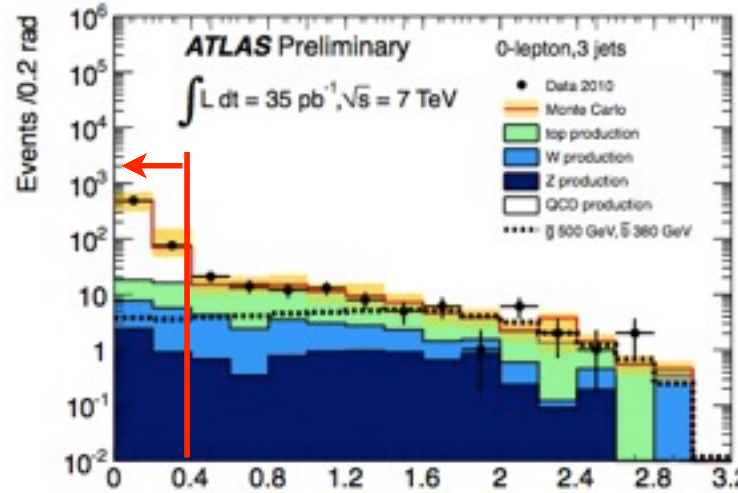
- QCD estimation:
  - Apply all the cuts up to the b-jet requirement.
  - Revert the $\Delta\varphi_{min}$ cut: QCD dominated region. M_{eff} is weakly correlated with $\Delta\varphi_{min}$. Take the M_{eff} shape from $\Delta\varphi_{min} < 0.4$ region.
  - The QCD contribution in the signal region ($\Delta\varphi_{min} > 0.4$, $M_{eff} > 600$ GeV) is

$$N^{SR}_{QCD,DATA} = (N^{CR}_{DATA} - N^{CR}_{nonQCD,MC}) F_{MC} \int_{600\ \mathrm{GeV}}^{\infty} f_{QCD}(\mathrm{m_{eff}})\, d\mathrm{m_{eff}}$$

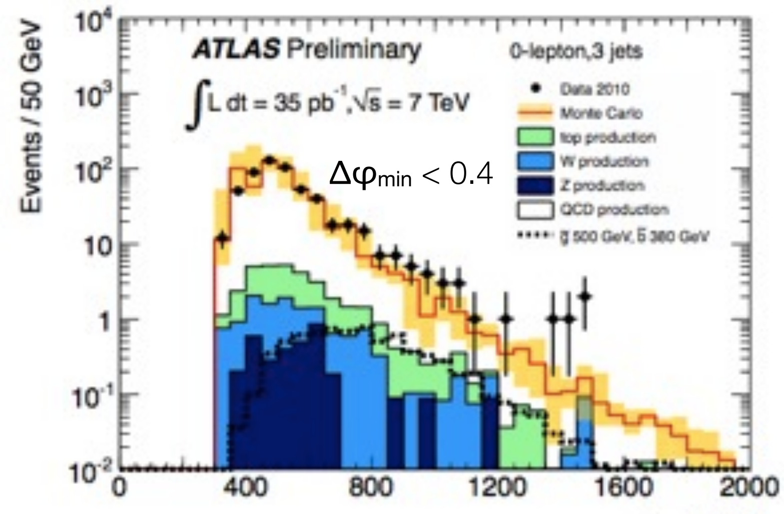
From MC: fraction of QCD events that pass the $\Delta\varphi_{min} > 0.4$ cut

From bottom right plot

- Systematics on F_{MC} include: ME/PS MC differences, possible variations in the b-quark content, MC statistics.



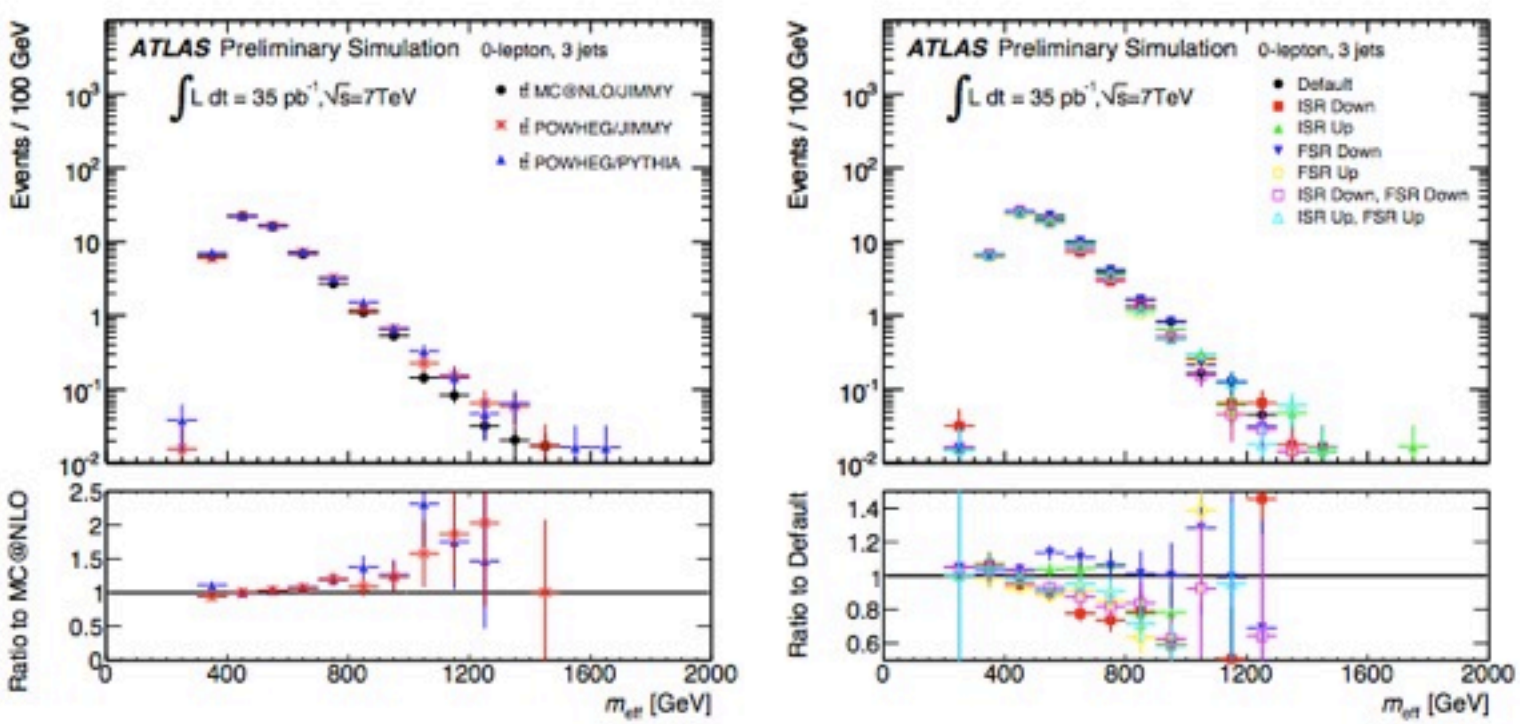
Auxiliary material fig. 2



Auxiliary material fig. 3

Background estimation (0-lepton)

- non QCD (ttbar, Z, W, single top) background estimation done using MC. Systematics include:
  - Common: JES, b-tagging, luminosity, trigger, lepton ID and scale, MC-statistics
  - ttbar: cross section (6%), generator uncertainties (17%), ISR/FSR ($^{+6\%}_{-25\%}$), PDF (6%)
  - W and Z: cross section (5%), PDF (5%), renormalization and factorization scale + PS matching (24%), uncertainty on the W(Z)bb component (100%)

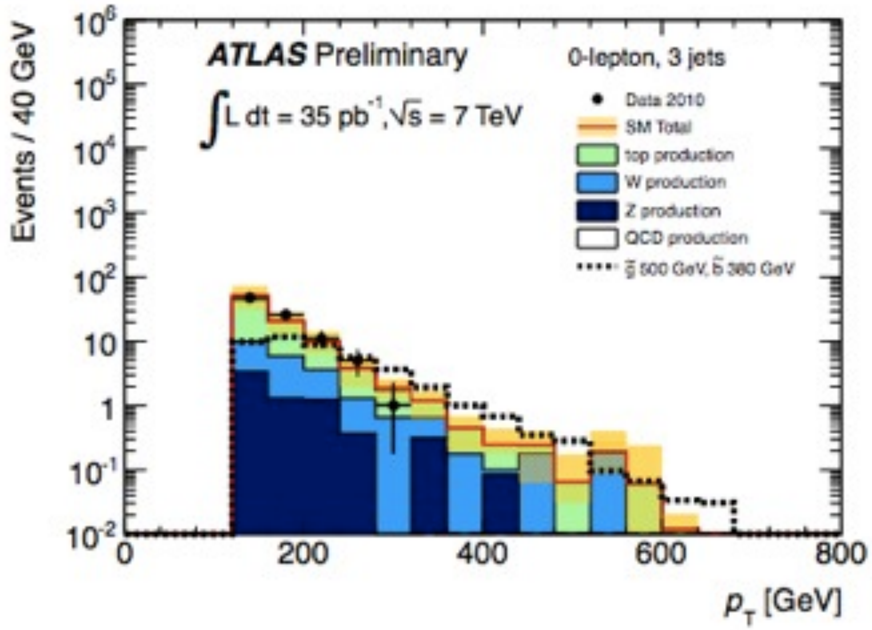


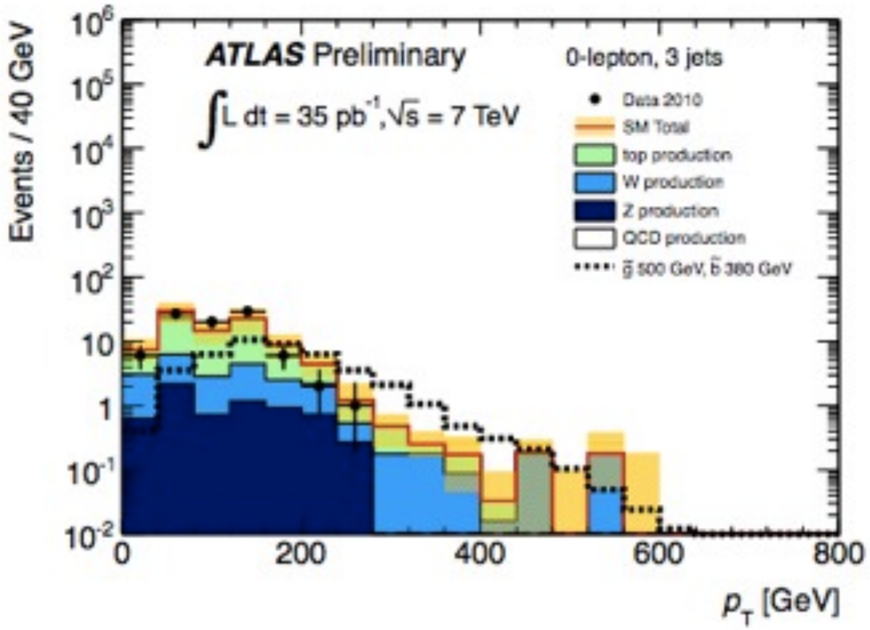
0-lepton channel, data/prediction comparison

Good agreement in the of the data prediction with the theoretical prediction at all levels of the event selection

Selection	Expected events	Observed Events
$E_T^{miss} > 100$ GeV	4800 ± 1600	5834
$E_T^{miss}/m_{eff} > 0.2$	2800 ± 900	3221
b-tag	620 ± 200	656
$\Delta\phi_{min} > 0.4$	90 ± 30	91
$m_{eff} > 600$ GeV	20 ± 7	15

Non-QCD dominated





Background estimation (1-lepton)

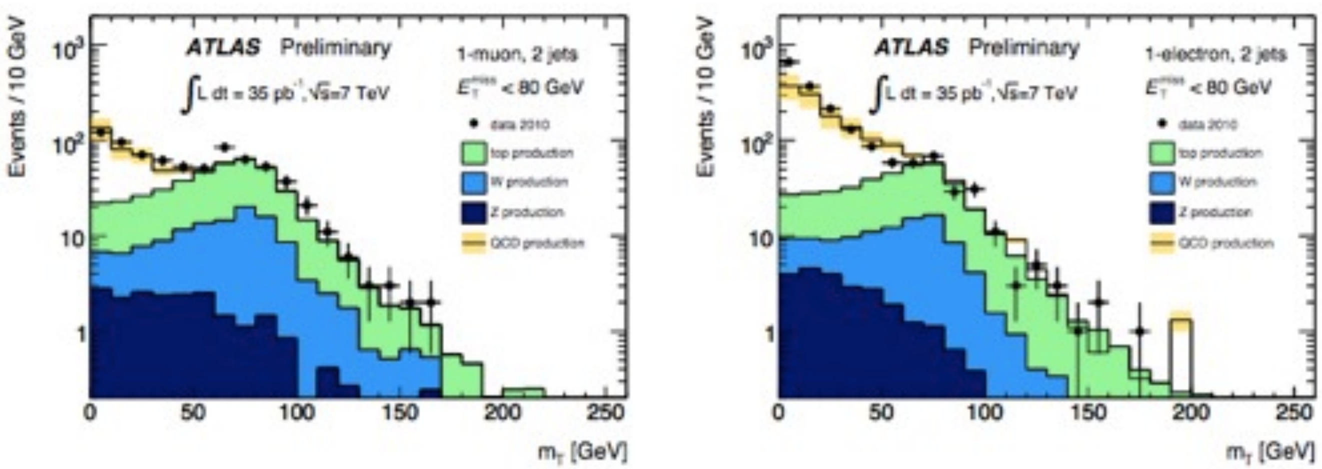
- QCD estimation from a Matrix method relying on 2 data sets differing only in the lepton ID criteria: tight (standard) and loose (relaxed):

$$N_{fake}^{tight} = \frac{\varepsilon_{fake}}{\varepsilon_{real} - \varepsilon_{fake}} (N^{loose} \varepsilon_{real} - N^{tight}).$$

Measured with a Z tag and proble

Measured in a QCD enriched sample

Auxiliary material fig. 5



QCD yield consistent with 0 in the signal region

Figure 5: Distribution of the transverse mass in the QCD control region in the muon channel (left) and in the electron channel (right). The QCD background is estimated using the matrix method. The full systematic uncertainty on the expectation of the QCD multijet background is shown in yellow. The fluctuations in the tails of the distributions are due to the limited Monte Carlo statistics available.

Background estimation (1-lepton)

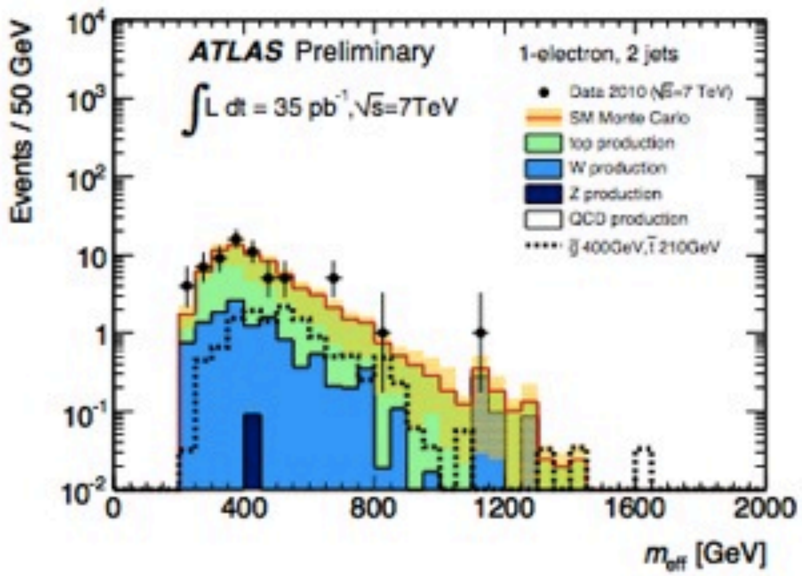
- non QCD background: use an ABCD method relying on the small correlation between the M_T and the M_{eff}:

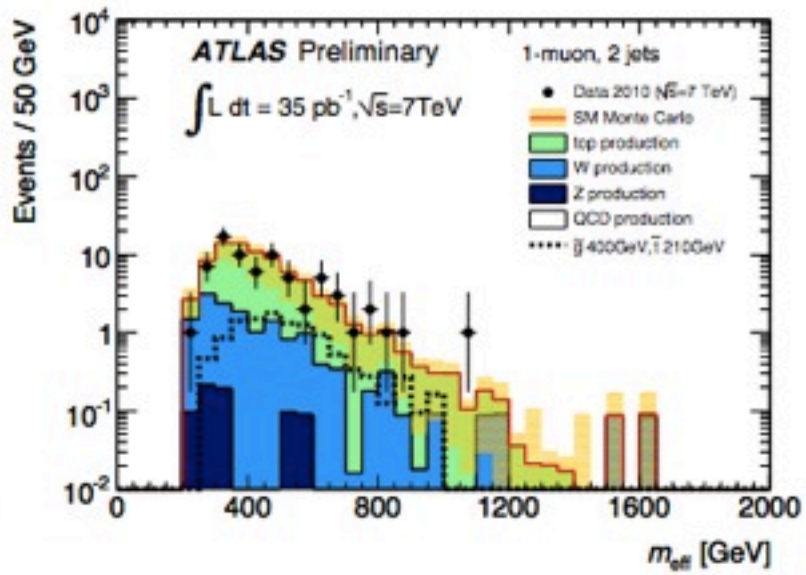
$$N_D^{SM} = N_C/N_A \times N_B$$

- Dominant uncertainty arising from the limited statistics in the CR

Region	Data	Monte Carlo
A: $40 < m_T < 100$ GeV and $m_{eff} < 500$ GeV	103	105.1 ± 1.5
B: $m_T > 100$ GeV and $m_{eff} < 500$ GeV	46	35.9 ± 0.5
C: $40 < m_T < 100$ GeV and $m_{eff} > 500$ GeV	33	40.1 ± 0.8
D: $m_T > 100$ GeV and $m_{eff} > 500$ GeV	9	13.5 ± 0.4
Estimation	14.7 ± 3.7	13.7 ± 0.4
Ratio	(164 ± 41) %	(101.2 ± 2.9)%

40 GeV < M_T < 100 GeV



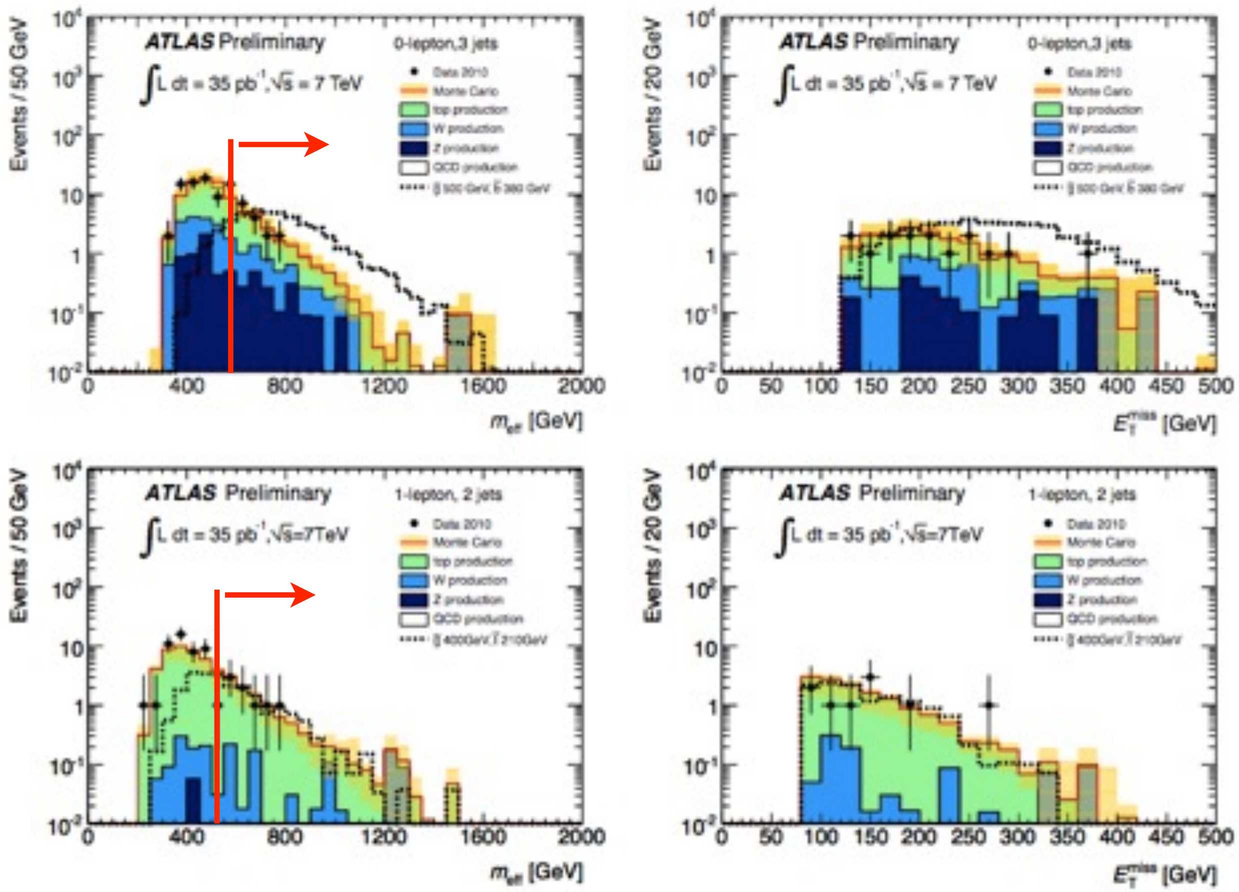


Data/MC agreement in non-QCD background CR

Results

- The number of data events observed both in the 0 and 1 lepton channel is consistent with the SM expectation. Therefore, upper limits at 95% CL exclusion on a new physics event yield in the signal regions can be computed

	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



- A profile likelihood ratio approach has been used. The limit is 10.4 (4.7) events in the signal region of the 0(1)-lepton analysis.

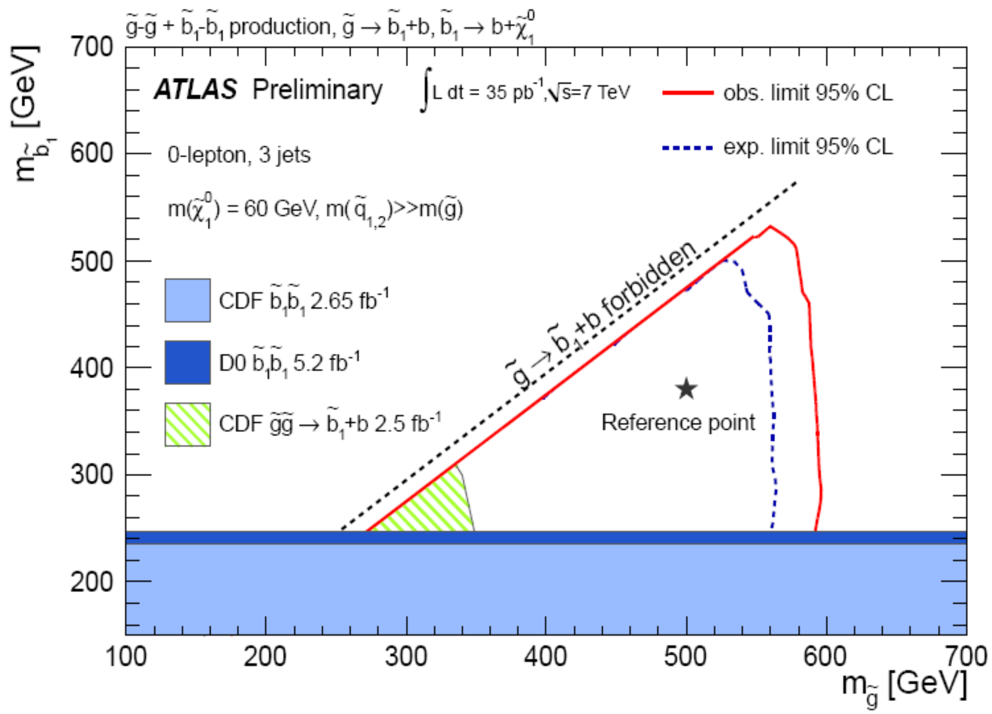
Result interpretation - 0 lepton

- Interpretation of the zero-lepton results in gluino-sbottom scenarios:

$\tilde{g} \rightarrow \tilde{b}_1 b$ (BR=1), $\tilde{b}_1 \rightarrow b + \tilde{\chi}_1^0$ (BR=1)
$m(\tilde{\chi}_1^0) = 60$ GeV

- Signal efficiency (m_{eff}>600 GeV):
  - Varies between 7% and 50% across the (m_g, m_{b1}) plane lowest for large ΔM, where $b_1 b_1$ production dominates

- Systematic uncertainties:
  - Theoretical: renorm/factor scale and PDF: for $\tilde{g}\tilde{g}$: ~16% and 11-25%; for $\tilde{b}_1\tilde{b}_1$: ~30% and 7-16%
  - Experimental: dominant JES and b-tagging



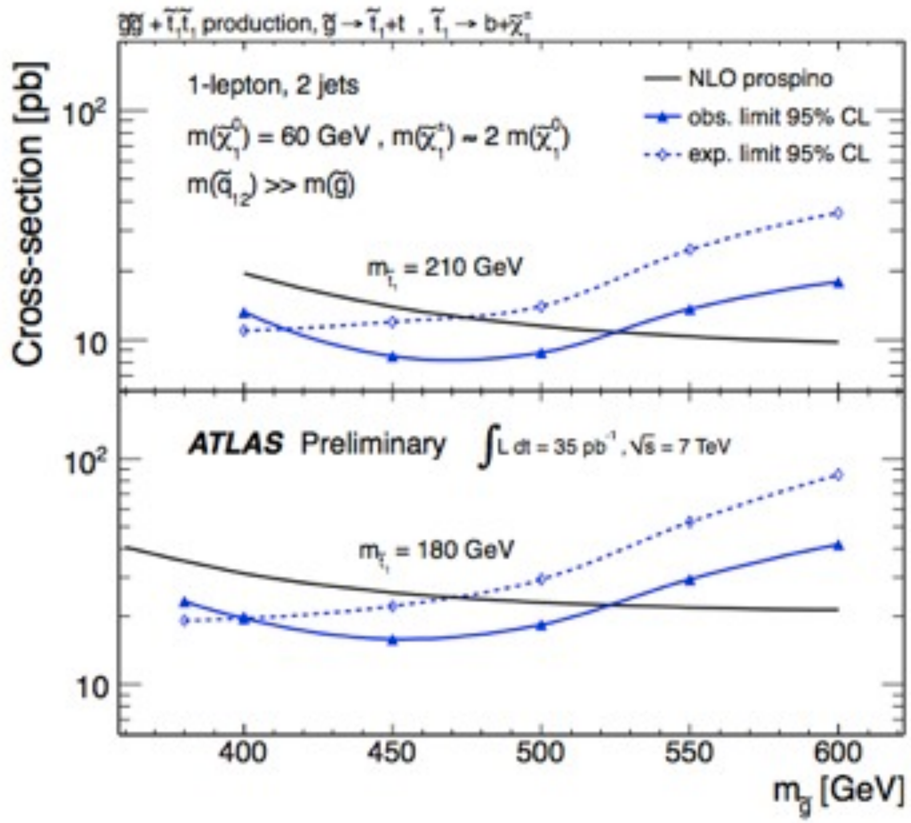
Gluino masses below 590 GeV excluded for sbottom masses below 500 GeV

Result interpretation - 1 lepton

- Interpretation of the one-lepton results in gluino-stop scenarios:
  $\tilde{g} \to \tilde{t}_1 t$ (BR=1), $\tilde{t}_1 \to b + \tilde{\chi}_1^{\pm}$ (BR=1)
  $m(\chi_1^0) = 60$ GeV, $m(\chi_1^{\pm}) \approx 2 \cdot m(\chi_1^0)$

- Signal efficiency (m_{eff}>500 GeV):
Varies between 0.4% and 3% across the (m_g,m_{t1}) plane lowest for large ΔM, where $t_1 t_1$ production dominates

- Systematic uncertainties:
  - Theoretical: renorm/factor scale and PDF: for $\tilde{g}\tilde{g}$: ~16% and 11-25%; for $\tilde{t}_1\tilde{t}_1$: ~30% and 7-16%



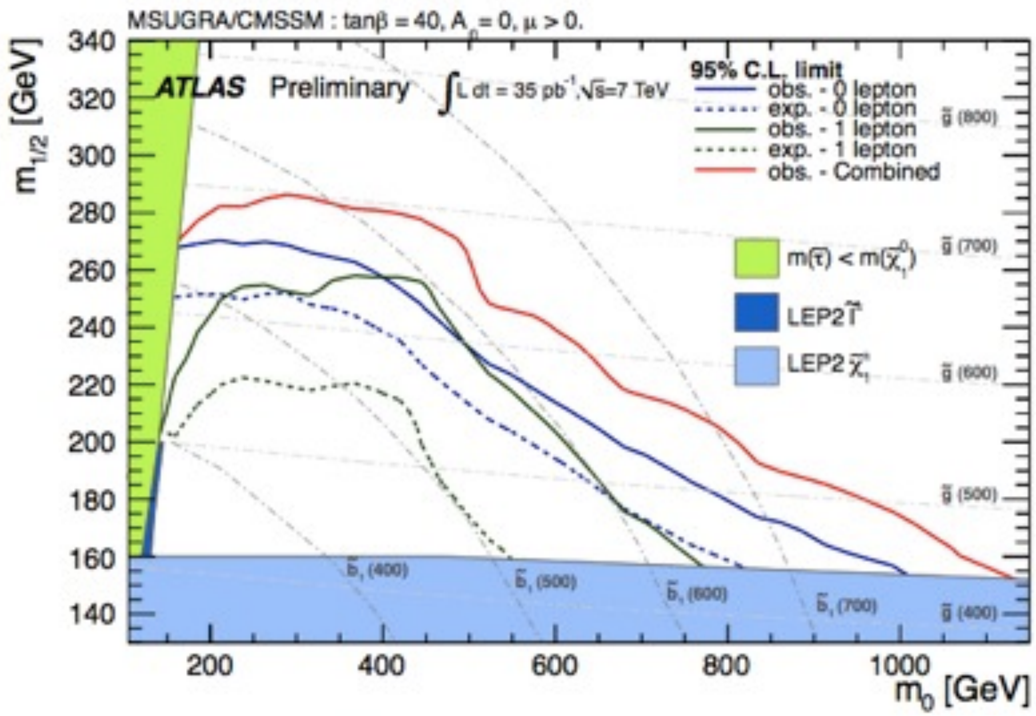
Gluino masses below 520 GeV excluded for stop masses up to the 300 GeV

Result interpretation - mSUGRA/CMSSM

- Interpretation of the zero-lepton and one-lepton results in high tan b mSUGRA scenario: $\tan\beta=40, \mu>0, A_0=0$

- for each $m_0, m_{1/2}$ scenario: sbottom masses reduced w.r.t. low $\tan\beta$, stop masses not so sensitive to $\tan\beta$

- Show interpretation of results from analyses separately and combined.



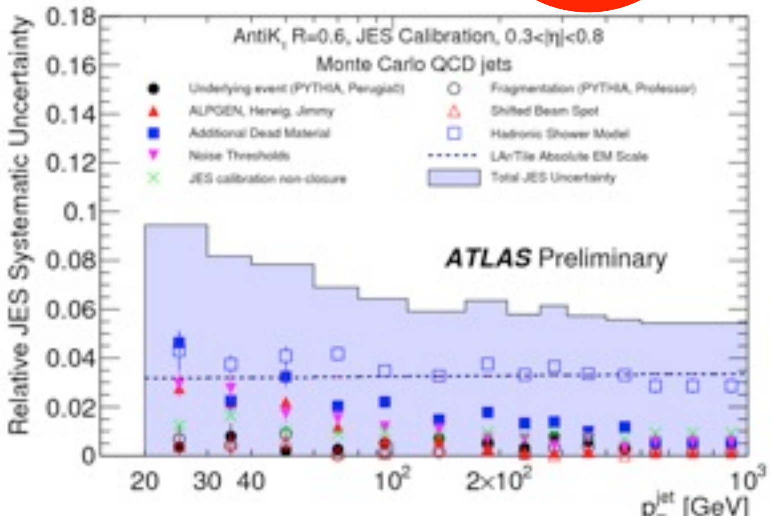
Exclude sbottom masses < 550 GeV, stop masses < 470 GeV, gluino masses < 600 GeV if $m(gl) = m(sq_{1,2})$

Gluino masses < 500 GeV excluded for 100 GeV < m_0 < 1 TeV

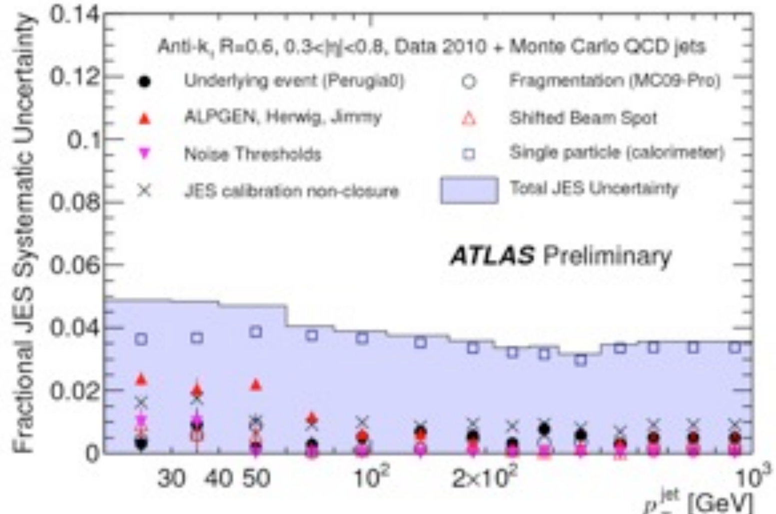
Next future - Outlook

- One of the dominant systematic uncertainties is the one related to Jet Energy Scale.
- Introducing data driven techniques already gave some improvement

Process	MC stat	JES	b-tagging	Lum.	Theor.	Pileup	other (lepton, trigger)	Total
W	±15%	[illegible]	±24%	±11%	±27%	±5%	±3.5%	±43%
Z	±27%	±20%	±25%	±11%	±27%	±5%	±3.5%	±45%
Top	±2.5%	$^{+30\%}_{-23\%}$	$^{+12\%}_{-15\%}$	±11%	$^{+20\%}_{-27\%}$	±5%	±3.5%	±40%



MC driven JES



~data driven JES

Next future - Outlook (II)

- Further improvement expected by the full exploitation of E/p, multijet balance, gamma + jet balance
- JES in central calorimeter region set propagating the single particle response to jets

ATLAS-CONF-2010-052

Editors: M. Duehrssen, N.Kanaya, I.Vivarelli

Single particle response:
- E/p measurement (charged hadrons up to ~ 20 GeV)
- Test beam results (charged hadrons with p > 20 GeV)
- photon scale uncertainty ($\pi^0 \rightarrow \gamma\gamma$)
- Assumptions on pure neutral hadronic component (K^0_L, n)

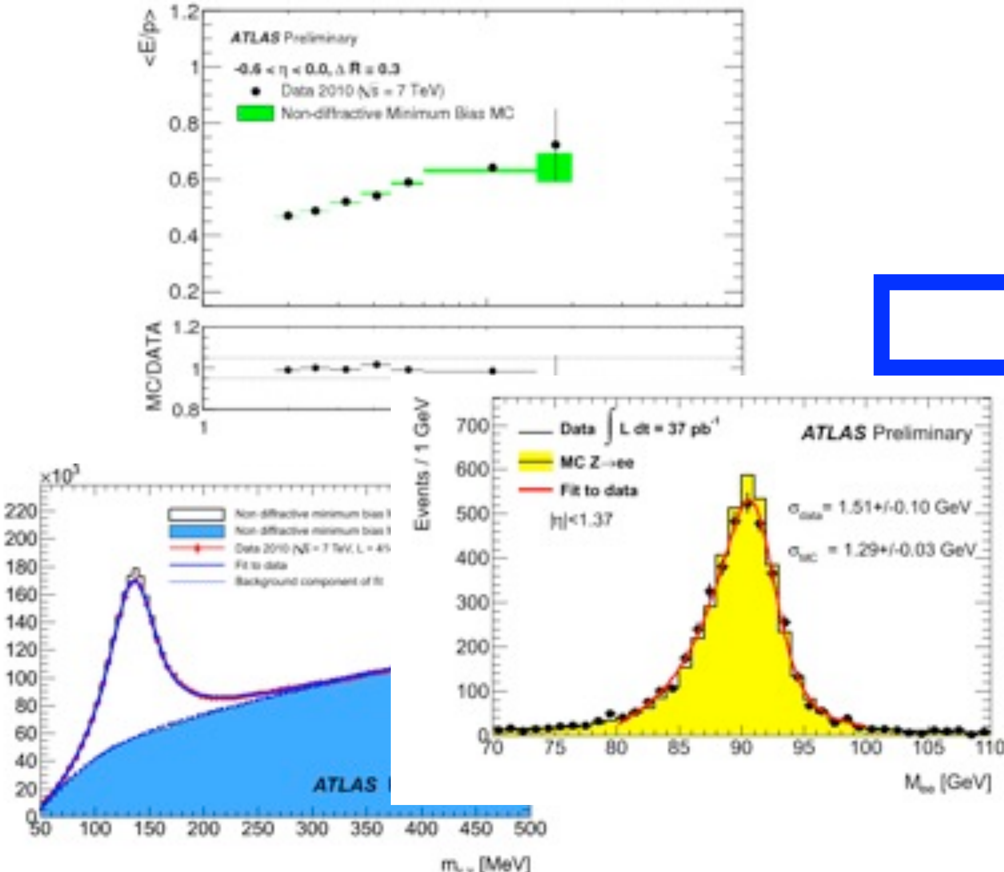
→

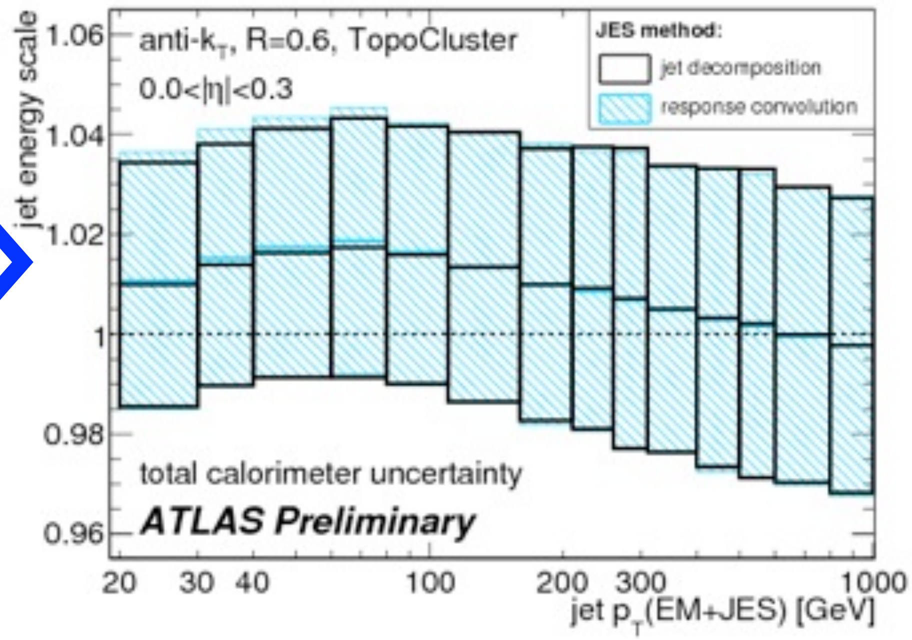
Propagate to jets:
- Use PYTHIA to get the jet composition in terms of particle type and momenta
- propagate the single particle response

→

Predicted calorimeter jet energy scale and uncertainty

Next future - Outlook (III)





- Propagation from the central to the forward regions using multi-jet balance
- Validation of the scale using gamma/jet balance
- Expect to bring the JES down to 2% (in not even 1 year of data taking)

Summary and conclusions

- The ATLAS detector works well. Already with the first 35 pb^{-1} a large physics program has been achieved
- Wide variety of SUSY searches, with general selections that cover a lot of topologies (R-parity violating scenarios not covered):
  - Results are SM compatible → tight exclusion limits (best to date in many cases) determined
- Working hard to optimise the selections for increased luminosity, investigate more topologies, reduce systematic uncertainties.

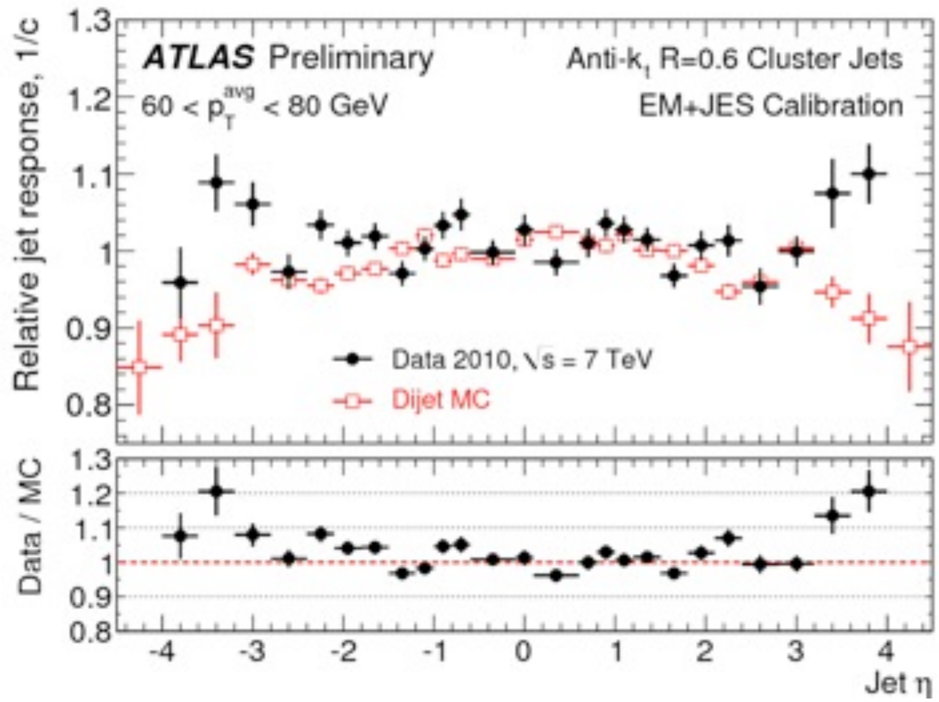
2011 data taking already started → stay tuned!

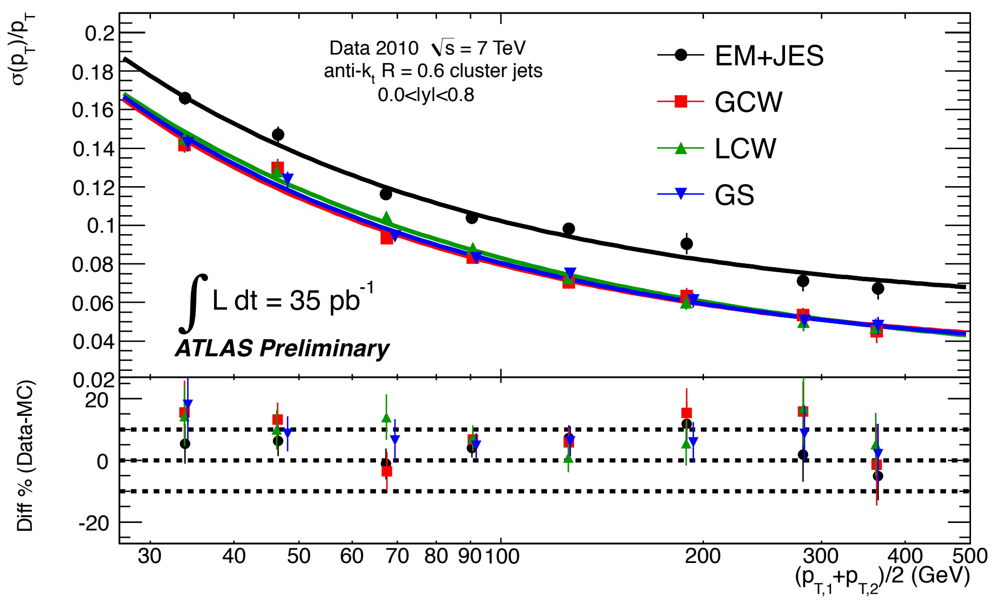
BACKUP

ATLAS

Jet performance

- Scale in the forward region set using the multijet balance
- Overall jet energy scale known at ~5% level in summer
- New results being approved

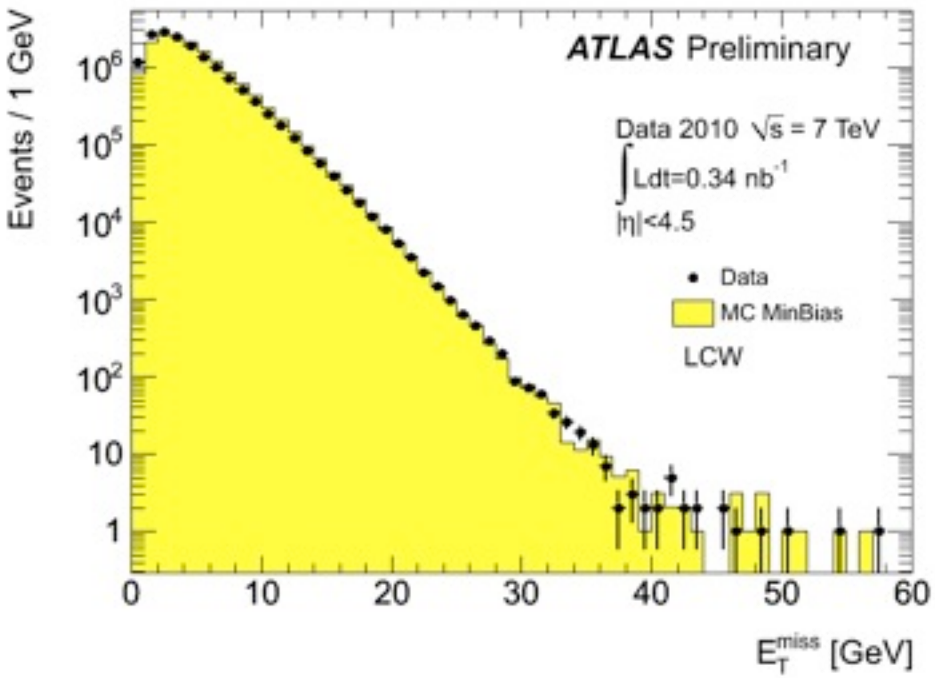


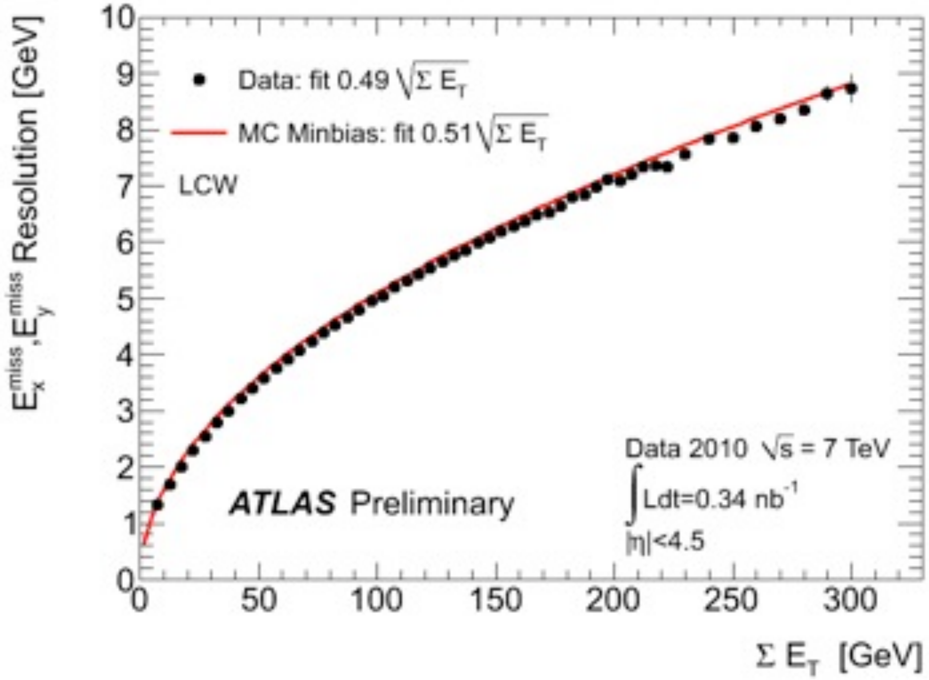


- Jet resolution under control
- Expect improvement when moving to improved hadronic scale corrections

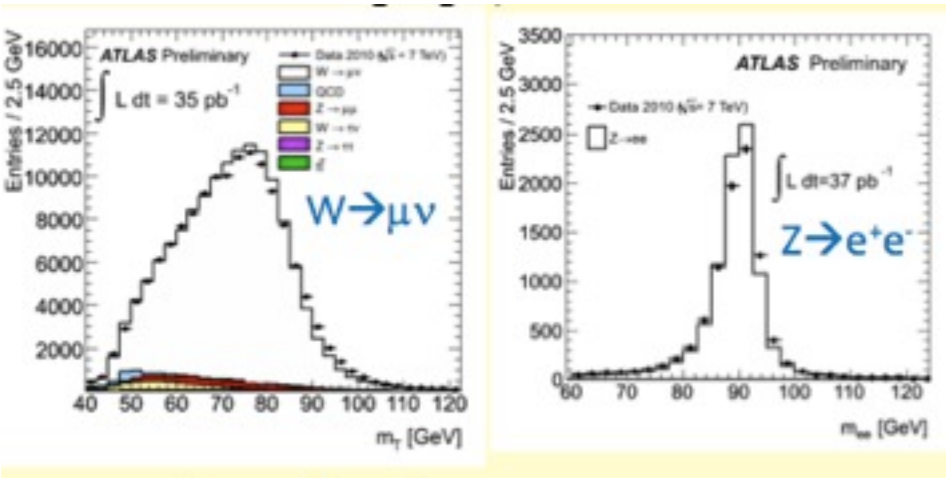
$E_T$miss

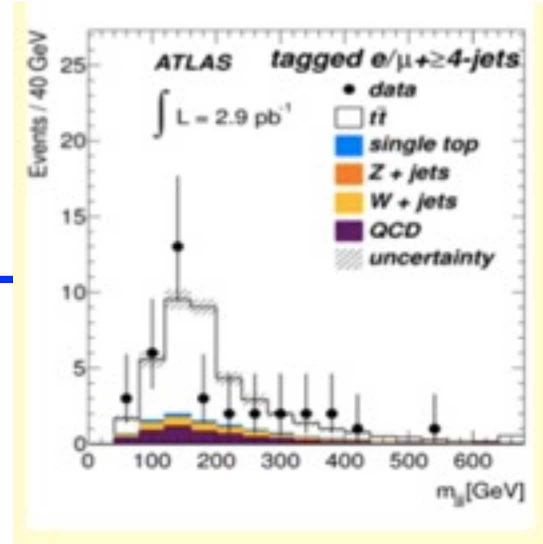
- Nice well understood missing E_T (results shown are a bit old, more being approved)





SM measurement

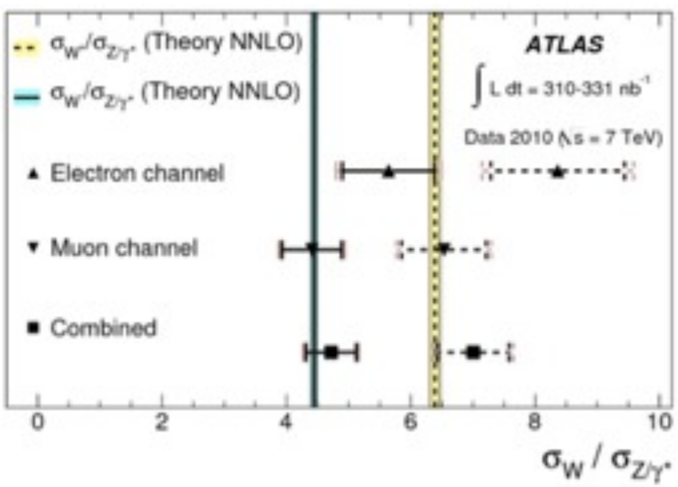


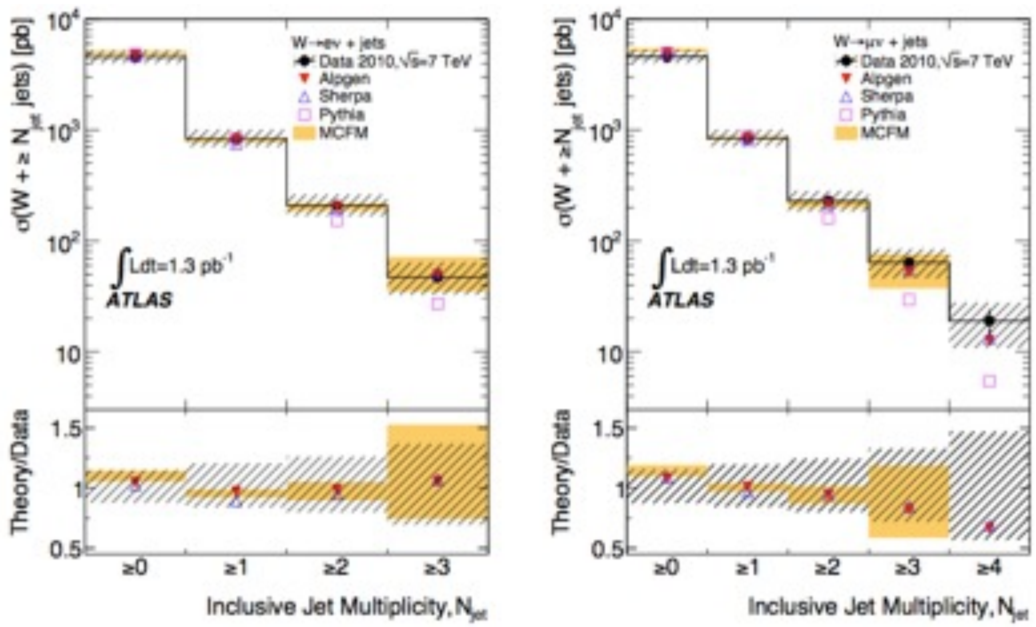


top

W+jets cross section

Inclusive W/Z cross section





Statistical procedure

$$L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \boldsymbol{b}, \boldsymbol{\theta}) = P_{\rm SR} \times P_{\rm CR} \times P_{\rm Syst}$$

$$= P(n_S | \lambda_S(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times \prod_{i \in \rm CS} P(n_i | \lambda_i(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times P_{\rm Syst}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) .$$

$$\lambda_S(\mu, \mathbf{b}, \boldsymbol{\theta}) = \mu \cdot c_{s,\rm SR}(\boldsymbol{\theta}) \cdot s + \sum_j c_{j,\rm SR}(\boldsymbol{\theta}) \cdot b_j ,$$

$$\lambda_i(\mu, \mathbf{b}, \boldsymbol{\theta}) = \mu \cdot c_{s,i}(\boldsymbol{\theta}) \cdot s + \sum_j c_{j,i}(\boldsymbol{\theta}) \cdot b_j .$$

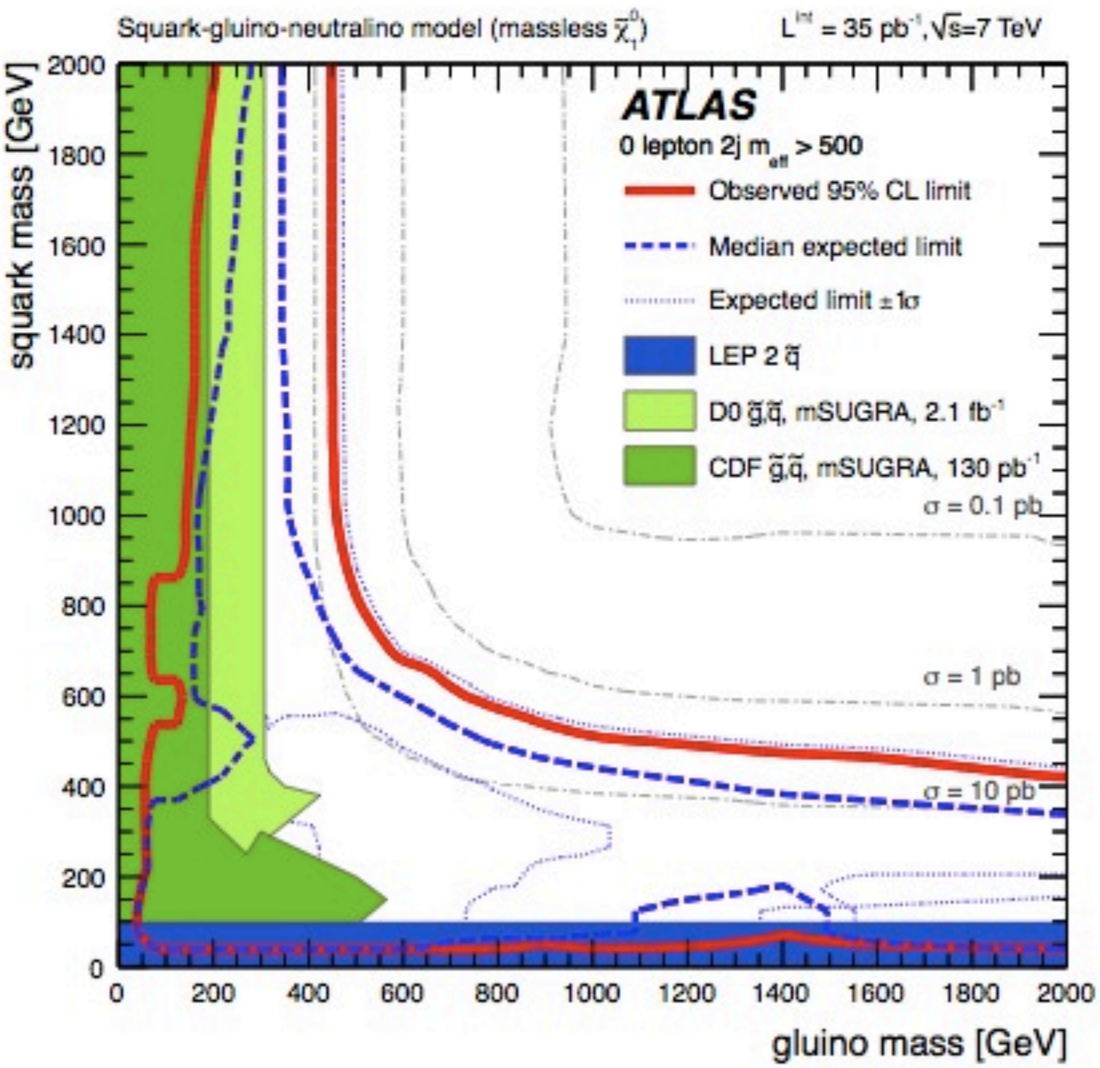
$$P_{\rm Syst}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) = \prod_{j \in \rm SU} G(\theta^0_{\rm j} - \theta_{\rm j}) ,$$

$$c_{\text{process } j, \text{ region } i} = \frac{MC(j,i)}{MC(j,j)} \times \left(1 + \sum_k \Delta_{j,i;k}\, \theta_k\right)$$

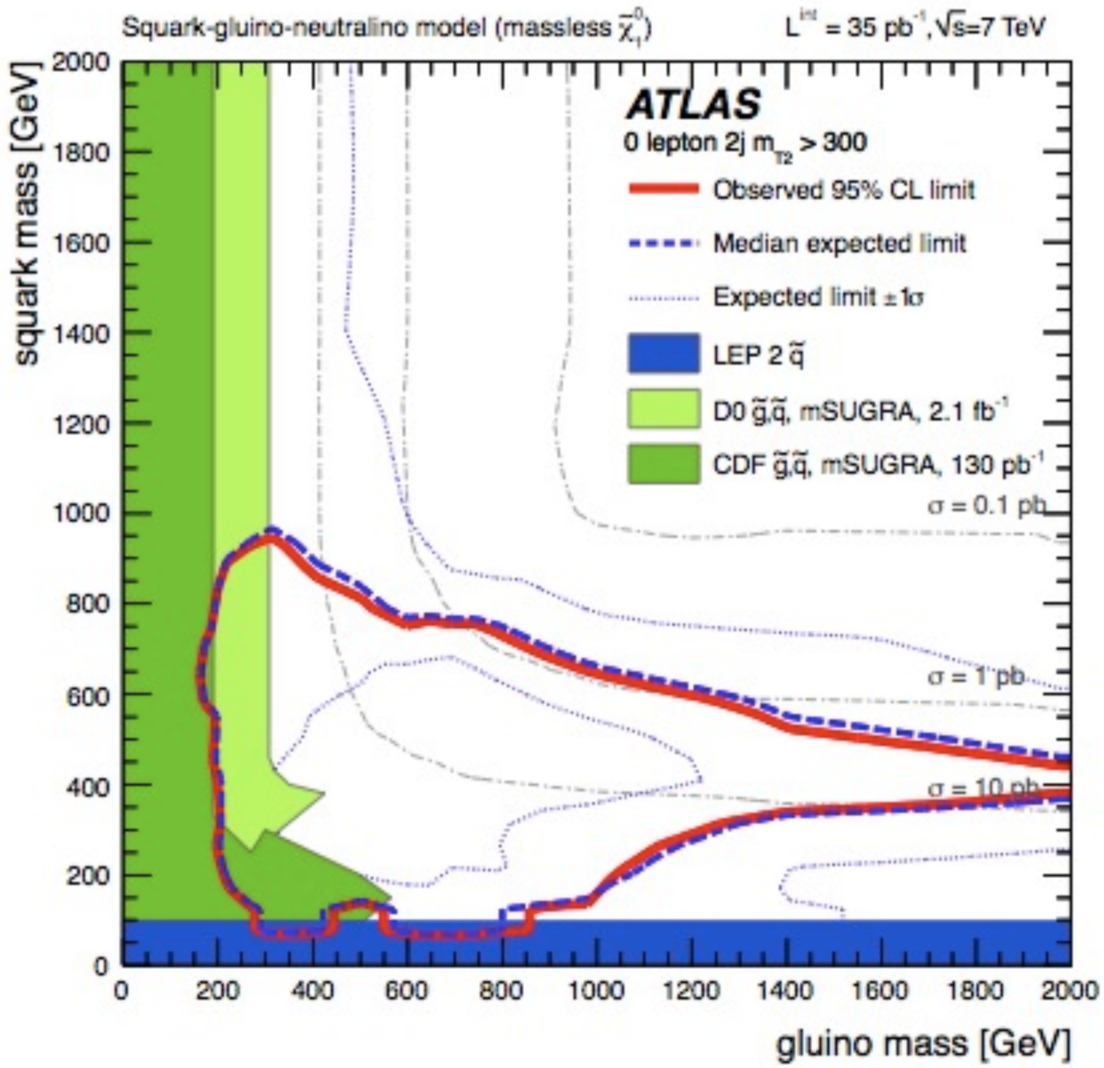
$$\Lambda(\mu) \equiv \Lambda(\mu, \boldsymbol{n}, \boldsymbol{\theta}^0) \equiv -2\left(\ln L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \hat{\hat{\boldsymbol{b}}}, \hat{\hat{\boldsymbol{\theta}}}) - \ln L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \hat{\mu}, \hat{\boldsymbol{b}}, \hat{\boldsymbol{\theta}})\right) ,$$

$$q_\mu \equiv \begin{cases} P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} \geq \mu \\ 1 - P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} < \mu . \end{cases} \quad q_0 \equiv \begin{cases} P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} < 0 \\ 1 - P_{\chi 2}(\Lambda(\hat{\mu})) & \hat{\mu} \geq 0. \end{cases}$$

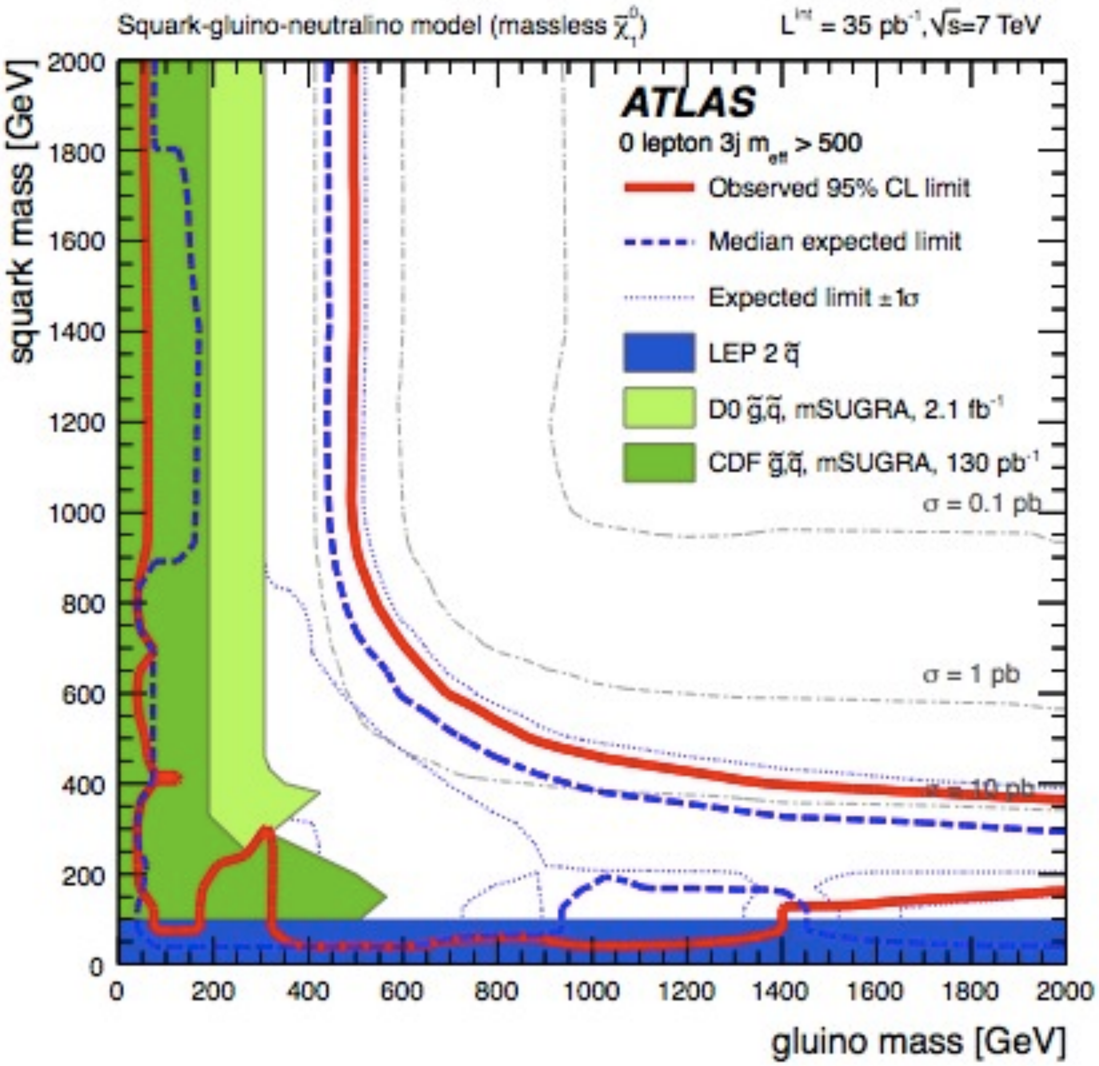
More 0-lepton inclusive plots



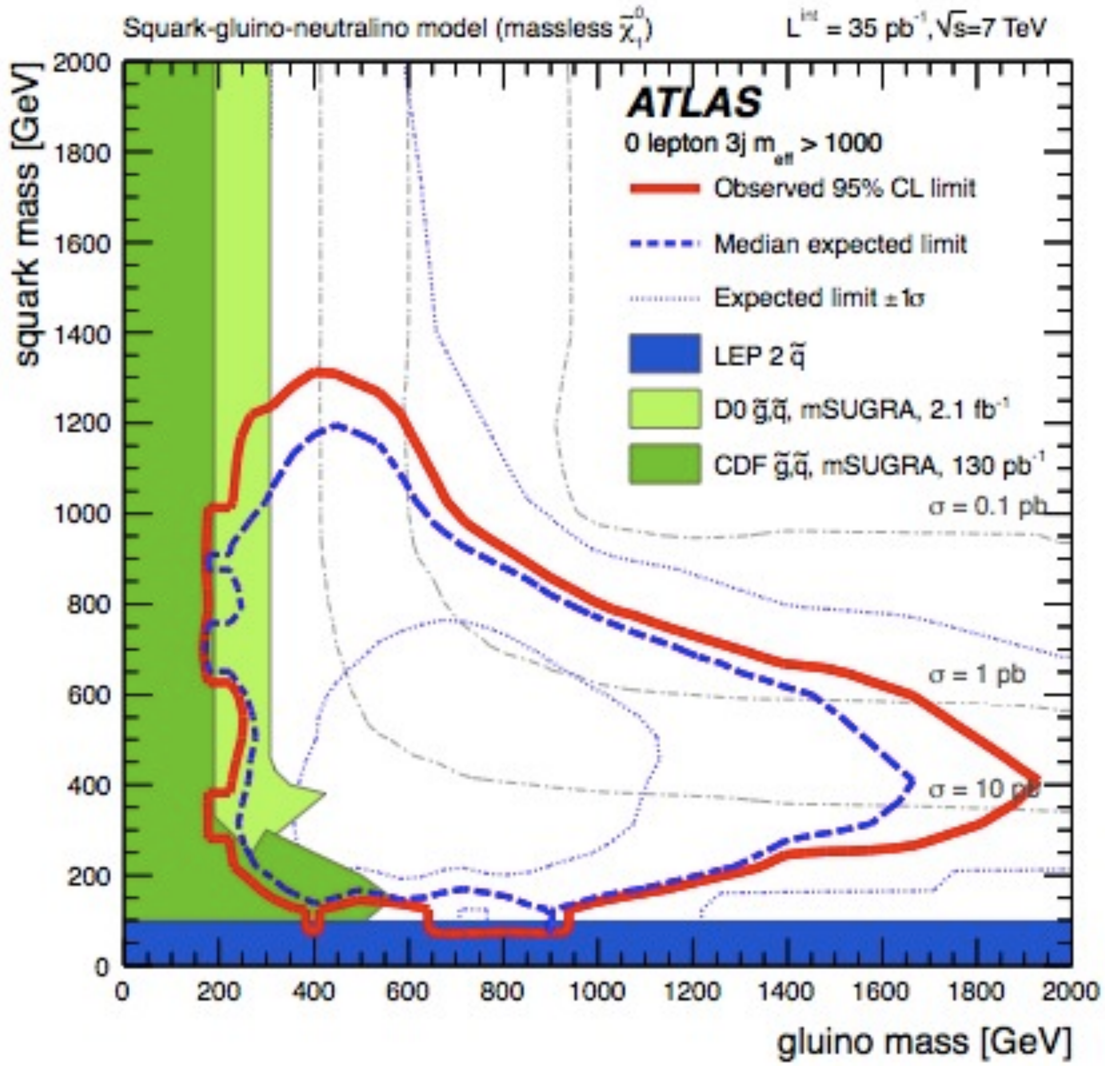
Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
ATLAS
0 lepton 2j m_{eff} > 500
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
LEP 2 $\tilde{q}$
D0 $\tilde{g}$,$\tilde{q}$, mSUGRA, 2.1 fb^{-1}
CDF $\tilde{g}$,$\tilde{q}$, mSUGRA, 130 pb^{-1}
σ = 0.1 pb
σ = 1 pb
σ = 10 pb
squark mass [GeV]
gluino mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000



Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
ATLAS
0 lepton 2j m_{T2} > 300
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
LEP 2 $\tilde{q}$
D0 $\tilde{g}$,$\tilde{q}$, mSUGRA, 2.1 fb^{-1}
CDF $\tilde{g}$,$\tilde{q}$, mSUGRA, 130 pb^{-1}
σ = 0.1 pb
σ = 1 pb
σ = 10 pb
squark mass [GeV]
gluino mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000

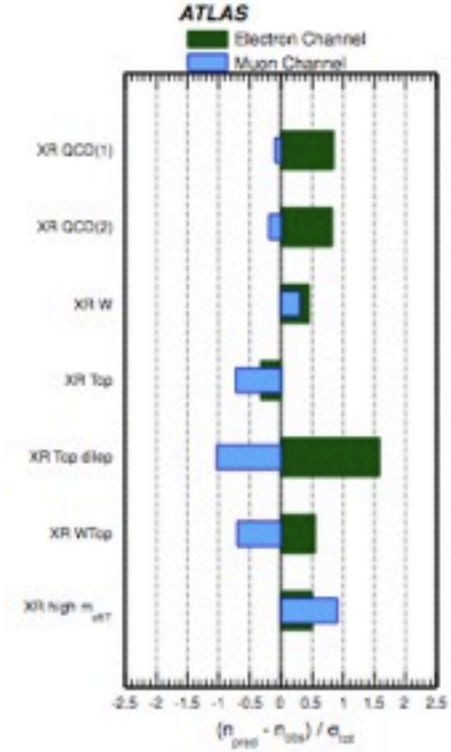


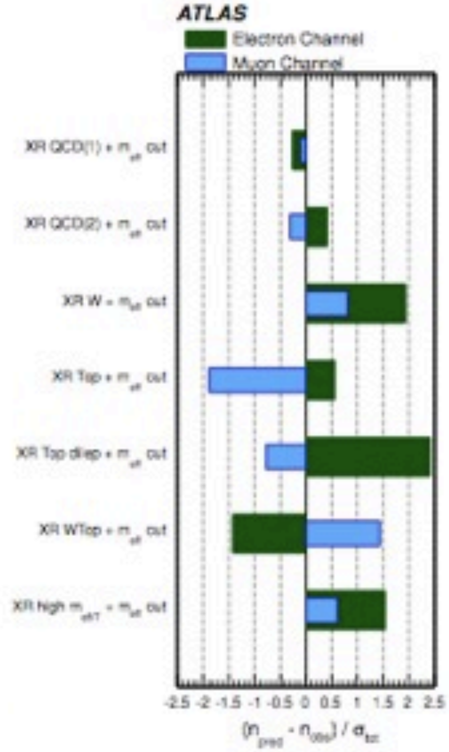
Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
ATLAS
0 lepton 3j m_{eff} > 500
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
LEP 2 $\tilde{q}$
D0 $\tilde{g}$,$\tilde{q}$, mSUGRA, 2.1 fb^{-1}
CDF $\tilde{g}$,$\tilde{q}$, mSUGRA, 130 pb^{-1}
σ = 0.1 pb
σ = 1 pb
σ = 10 pb
squark mass [GeV]
gluino mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000

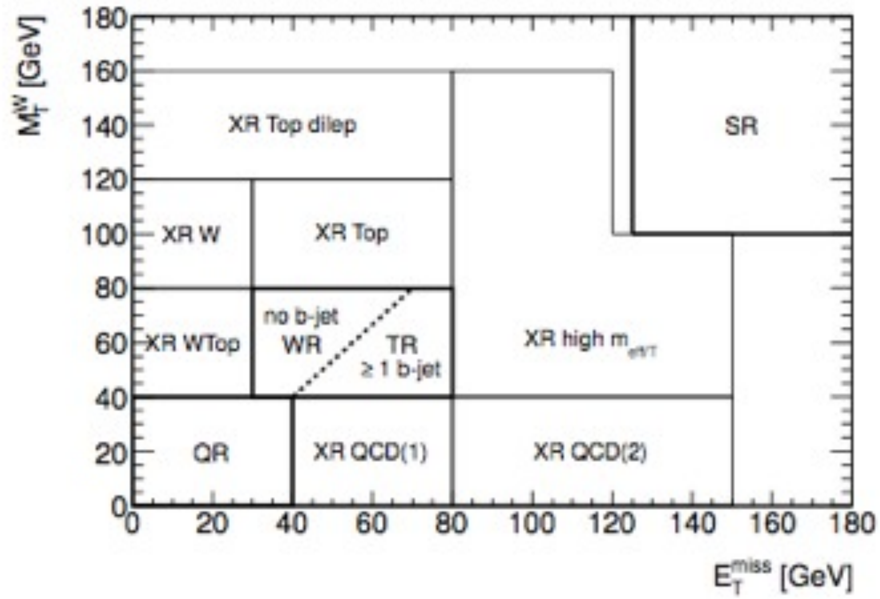


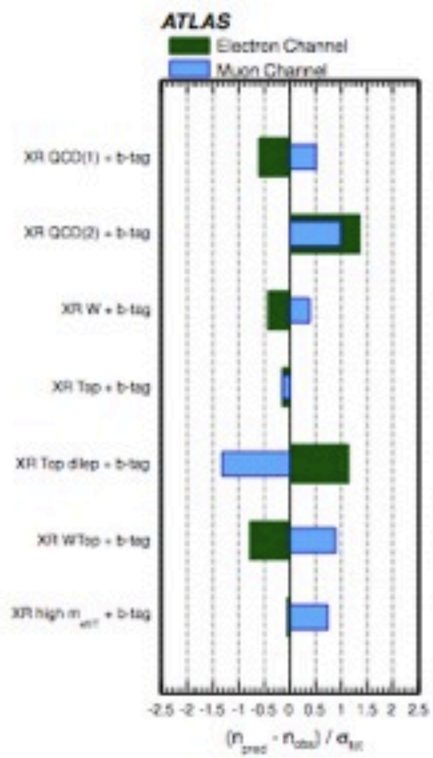
Squark-gluino-neutralino model (massless $\tilde{\chi}_1^0$)
L^{int} = 35 pb^{-1}, $\sqrt{s}$=7 TeV
ATLAS
0 lepton 3j m_{eff} > 1000
Observed 95% CL limit
Median expected limit
Expected limit ±1σ
LEP 2 $\tilde{q}$
D0 $\tilde{g}$,$\tilde{q}$, mSUGRA, 2.1 fb^{-1}
CDF $\tilde{g}$,$\tilde{q}$, mSUGRA, 130 pb^{-1}
σ = 0.1 pb
σ = 1 pb
σ = 10 pb
squark mass [GeV]
gluino mass [GeV]

More 1/2-lepton plots


ATLAS
Electron Channel
Muon Channel
XR QCD(1)
XR QCD(2)
XR W
XR Top
XR Top dilep
XR WTop
XR high m_effT
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
(n_pred - n_obs) / σ_tot


ATLAS
Electron Channel
Muon Channel
XR QCD(1) + m_eff cut
XR QCD(2) + m_eff cut
XR W + m_eff cut
XR Top + m_eff cut
XR Top dilep + m_eff cut
XR WTop + m_eff cut
XR high m_effT + m_eff cut
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
(n_pred - n_obs) / σ_tot


180
160
140
120
100
80
60
40
20
0
M_T^W [GeV]
XR Top dilep
SR
XR W
XR Top
no b-jet
WR
TR
≥ 1 b-jet
XR WTop
XR high m_effT
QR
XR QCD(1)
XR QCD(2)
0 20 40 60 80 100 120 140 160 180
E_T^{miss} [GeV]


ATLAS
Electron Channel
Muon Channel
XR QCD(1) + b-tag
XR QCD(2) + b-tag
XR W + b-tag
XR Top + b-tag
XR Top dilep + b-tag
XR WTop + b-tag
XR high m_effT + b-tag
-2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5
(n_pred - n_obs) / σ_tot

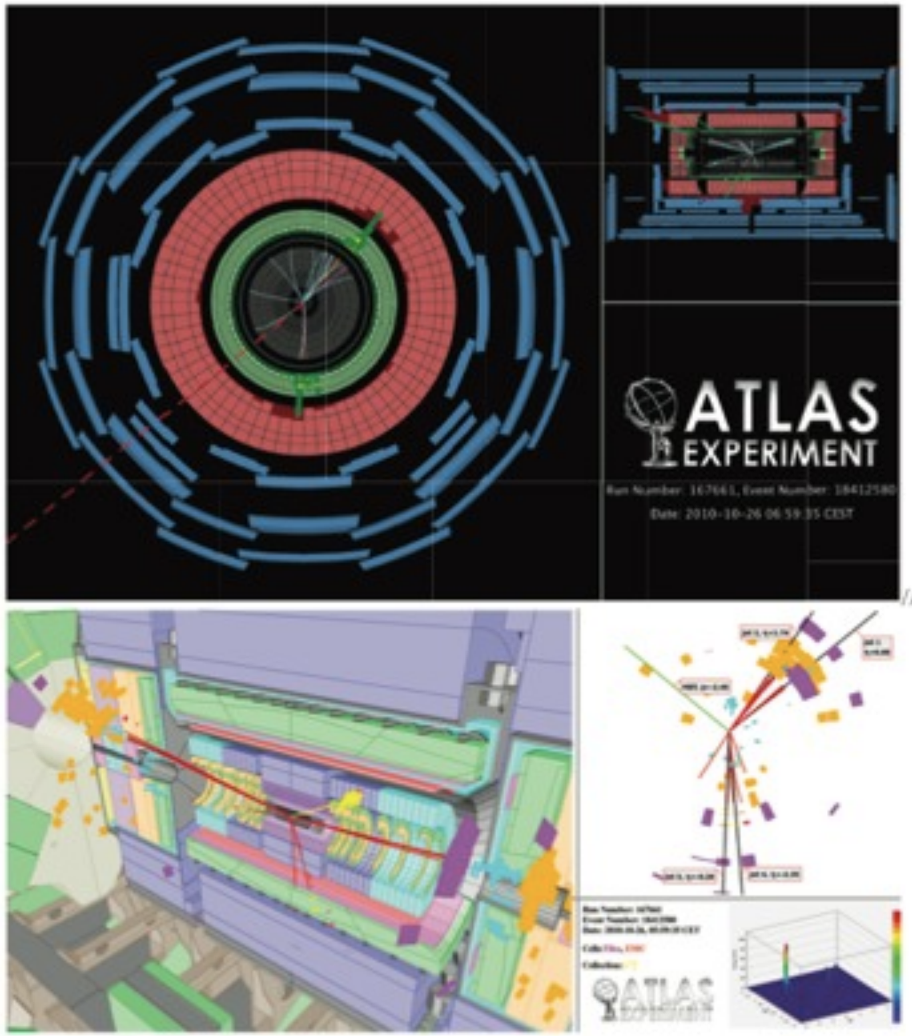
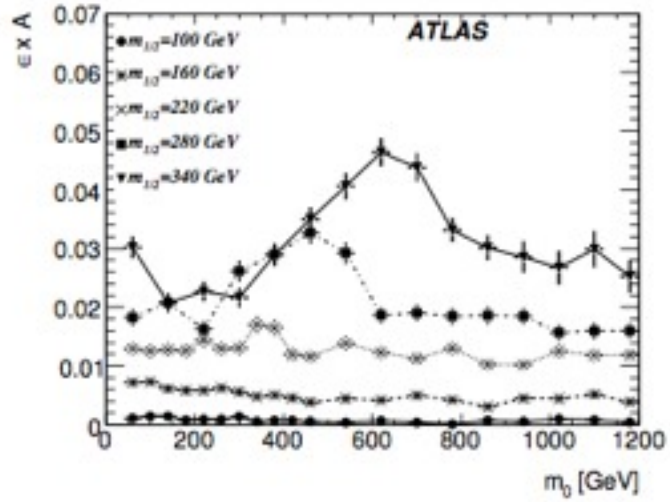
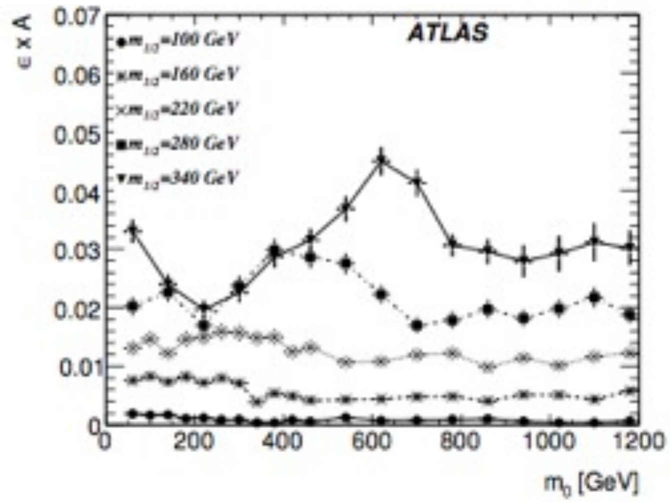


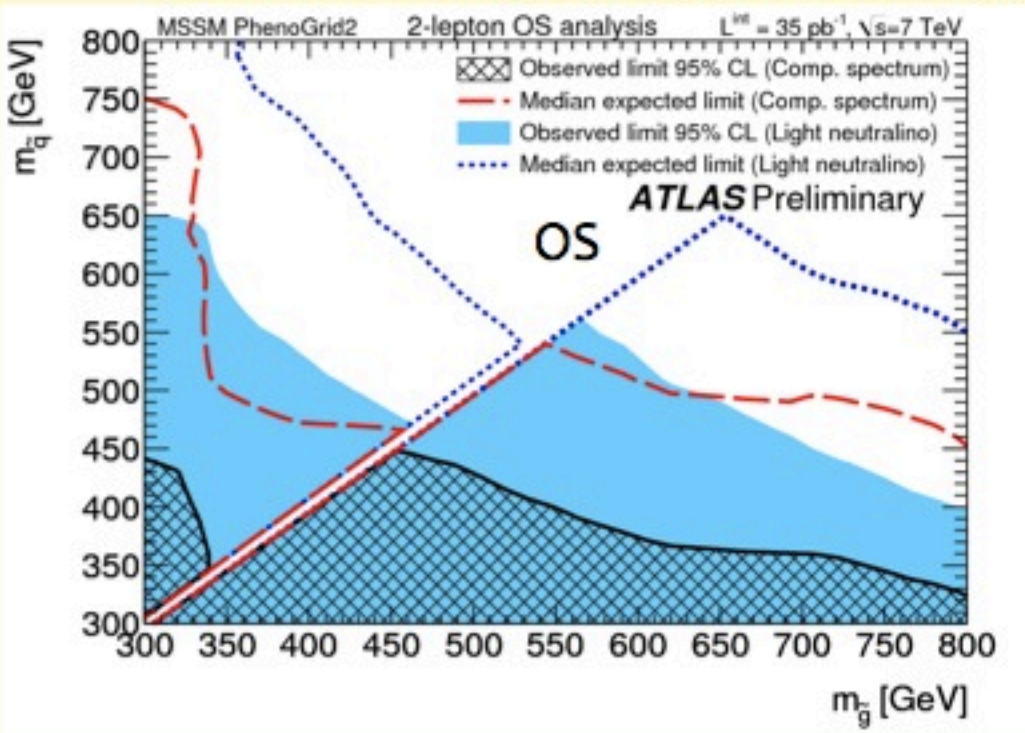
FIG. 9: ATLAS event display of electron event in signal region (run 167661, event 18412580).

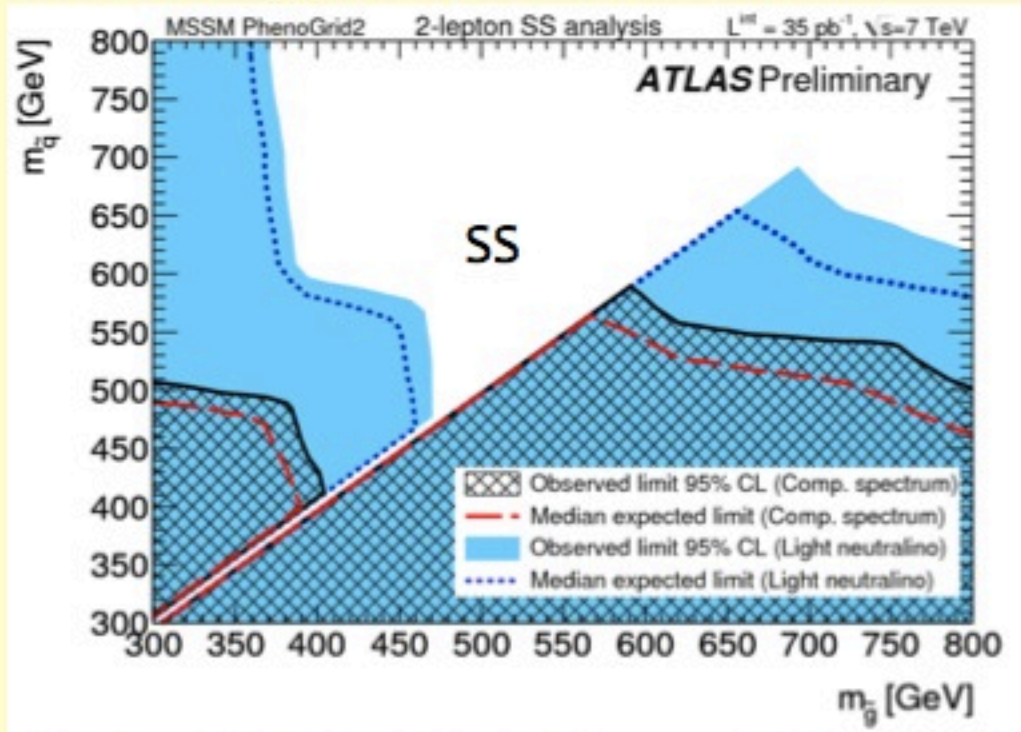




Results (II)

- Consider more general MSSM 24-parameter framework, where sleptons are in the gluino and squark decays chains :
  - m_A=1000 GeV, $\mu=1.5\times\min(m_{gl},m_q)$, $\tan\beta=4$, $A_t=\mu/\tan\beta$, $A_b=A_l=\mu\tan\beta$
  - $m(\tilde{l}_R)=m(\tilde{l}_L)$, $m(\tilde{q}_R)=m(\tilde{q}_L)$, 3rd generation at high mass
- **"compressed spectrum" (CS):** $m(\tilde{\chi}^0_2)$ =M - 50 GeV, $m(\tilde{\chi}^0_1)$=M - 150 GeV, $m(\tilde{l}_L)$=M - 100 GeV, with M=min(m_{gl},m_q) → soft final state kinematics
- **"light neutralino" (LN):** $m(\tilde{\chi}^0_1)$=100 GeV , $m(\tilde{\chi}^0_2)$ =M-100 GeV, $m(\tilde{l}_L)$=M/2 GeV → hard kinematics





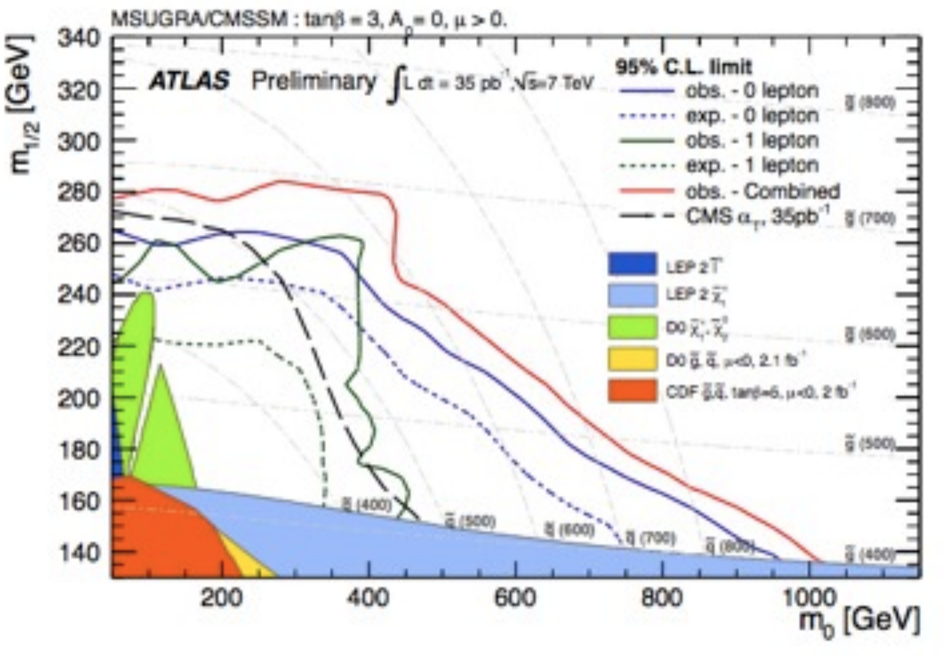
Limits on squark mass for $m(\tilde{g})=m(\tilde{q})$+10 GeV

OS: $m(\tilde{q})$>560 GeV (LN), >450 GeV (CS)
SS: $m(\tilde{q})$>690 GeV (LN), >590 GeV (CS)

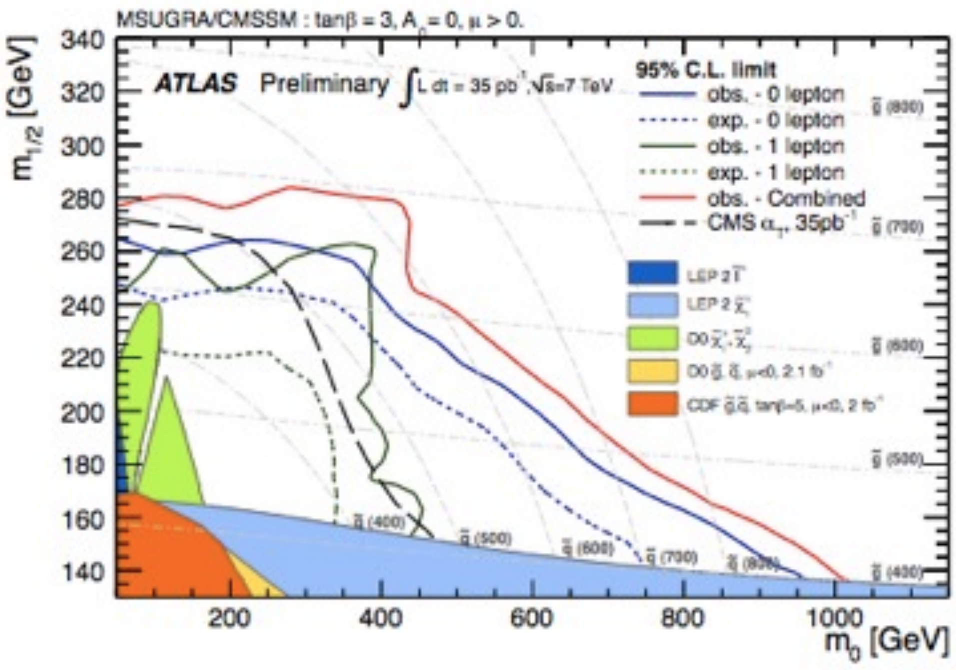
More b-jet plots

Auxiliary mSUGRA low tanβ

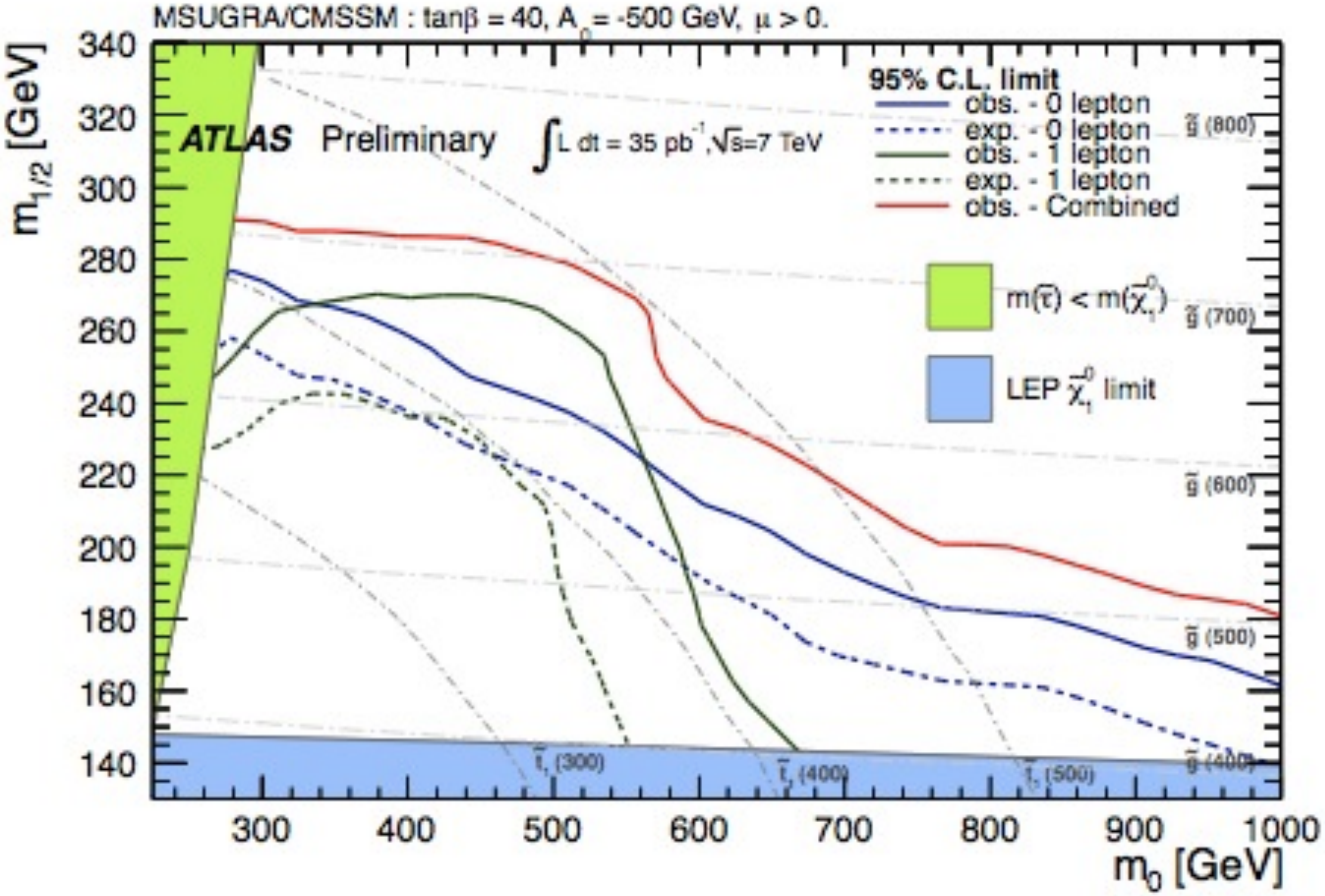
Old



Modified



Auxiliary mSUGRA with tanβ=40, A_0 = -500 GeV



Auxiliary SO(10)

Consider two SO(10) models, HS and DR3, differing on the splitting:

- in DR3, gluino 3-body decay in $bb\chi_0^1$ dominates
- in HS, gluino 3-body decay in $bb\chi_0^2$ dominates

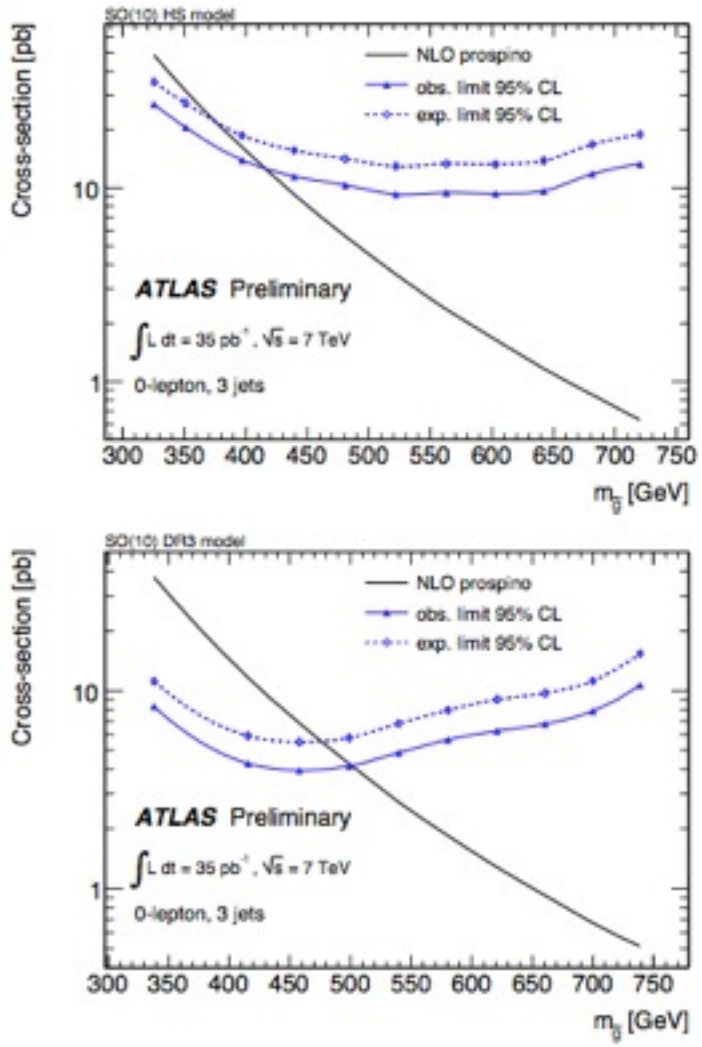


Figure 11: The observed and expected 95% C.L. limit on the production cross sections for the HS (top) and DR3 models (bottom) as a function of the gluino mass, as obtained in the zero-lepton analysis. The theoretical uncertainties on the NLO cross sections are included in the limit calculation.

Excluded gluino masses below 520 (420) GeV for DH3 (HS) mode

Auxiliary 2D gluino-stop plane