SUSY-Searches in the 1 Lepton-Channel

Helmholtz Alliance „Physics at the Terascale“ – Workshop

I Introduction
- The ATLAS-Detector
- Minimal Supergravity (mSUGRA)

II The Analysis
- Data / Triggers
- Signal-Regions
- Control-Regions
- Results for mSUGRA
- Results for simplified models

III Summary / Outlook

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FSP 101 ATLAS

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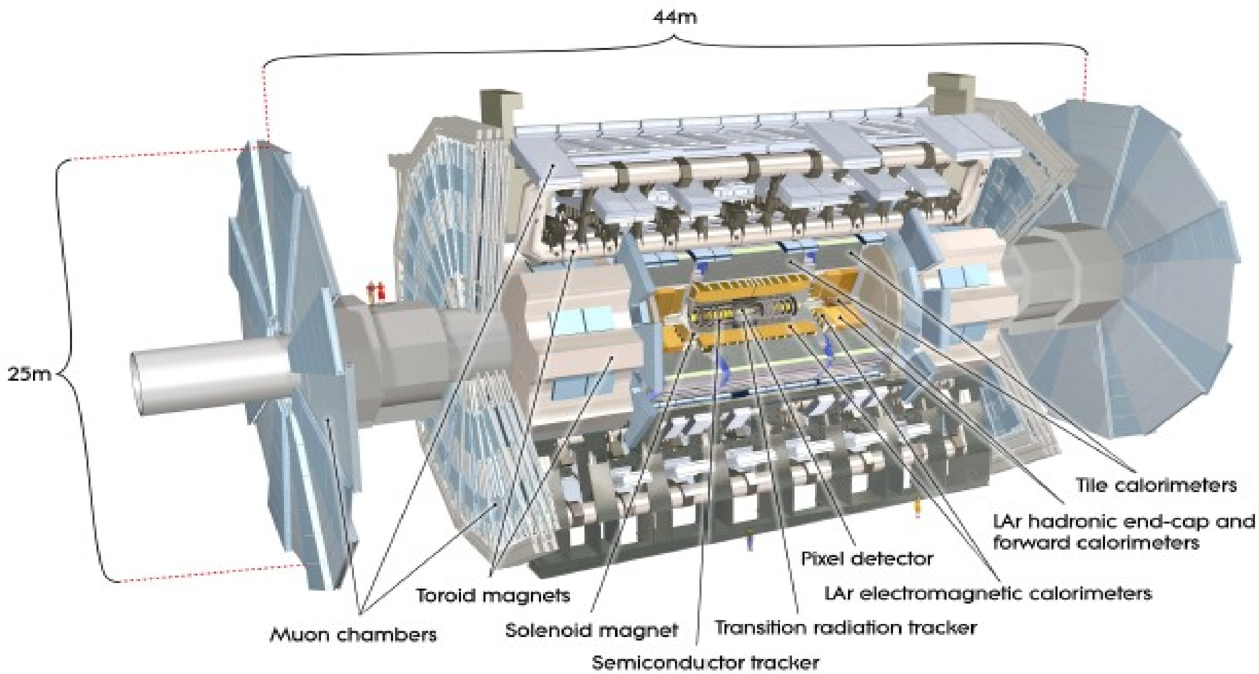
I Introduction

The ATLAS-Detector

- **Multifunctional detector at the** LHC (CERN, Genf)
- pp-collisions at 14 TeV (design-energy) and 7 TeV in the year 2010/2011 → Analysis done for 7 **TeV**
- High precision measurements of energies, momenta and tracks with full 2π-coverage in φ (especially important for E_T^{miss})



Minimal Supergravity (mSUGRA)

Example of a **GUT-SUSY-Theory**

1.) All masses of **scalar** SUSY-particles unify **at the GUT-scale** at a single mass: $\mathbf{m_0}$

2.) All masses of **fermionic** SUSY-particles (**Gauginos**) unify as well: $\mathbf{m_{1/2}}$

3.) All trilinear couplings unify: $\mathbf{A_0}$

5 Parameters left:

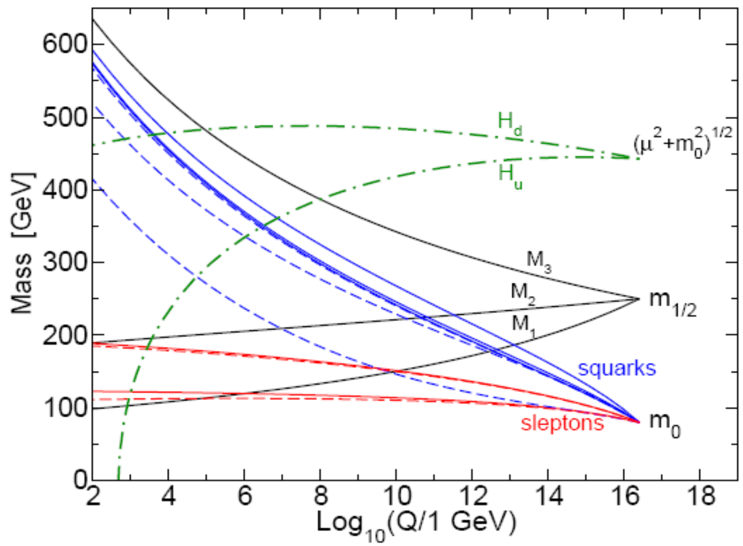
m_0: unified scalar mass

$m_{1/2}$: unified Gaugino-mass

A_0 : unifies trilinear coupling

$\tan(\beta)$: ratio of the VEVs of both higgs-doublets.

sign(μ): higgsino mass-parameter



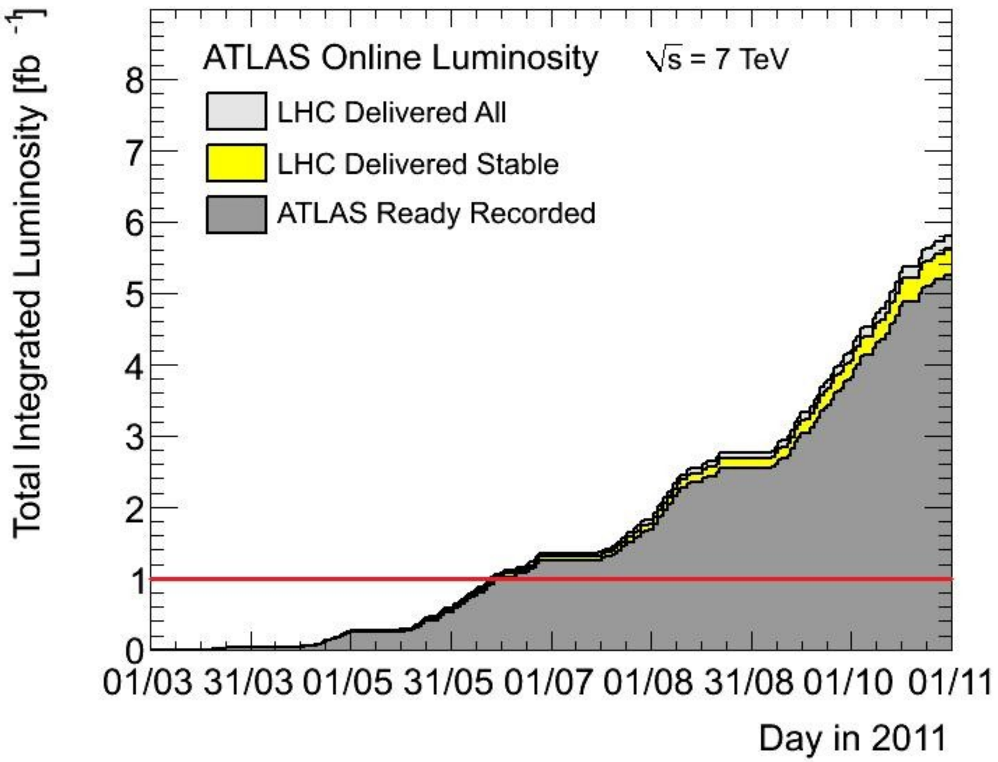
Mass-spectrum of the theory determined by these 5 parameters!

(often a **Grid in m_0 und $m_{1/2}$** for **fixed** A_0, tanβ und sign(μ) generated and studied)

II The Analysis

Data / Trigger

- **Integrated Luminosity:**
- ~ 5 fb^{-1} collected in 2011
- **1.04 fb^{-1}** used for the last publication
  → Talk will present the results on this dataset
- Results on the full 2011-dataset are in the pipeline



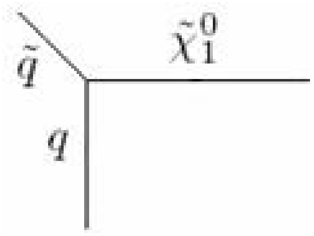
- **Instantaneous luminosity:**
  - ~ 10^{29} cm^{-2} s^{-1} (first runs)
  - ~ 10^{33} cm^{-2} s^{-1} (latest runs)

- **Triggering-criteria based on the 3-level-ATLAS-trigger-system**
  - Ensure that offline – P_T - selection lies in the turn-on-plateau
  - 18 (20) GeV Muons (Electrons) on trigger-level (no prescale)
    → 20 GeV offline Muons / 25 GeV offline Electrons

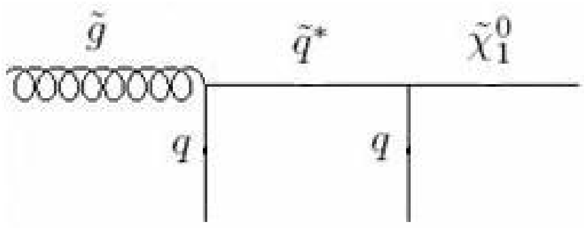
Definition of Signal-Regions I

- **Topology of SUSY-events depend on the masses in the SUSY-decaychain**

1.) Gluino **heavier** than Squarks **($m_0 << m_{1/2}$)**
→ Squarks will decay into a jet and a light gaugino
→ hard 2-body-decays
→ high LSP-boost, **small number of Jets**



2.) Gluino **lighter** than Squarks **($m_0 >> m_{1/2}$)**
→ Squarks will decay into Gluinos
→ Gluinos will decay via 3-body-decays
→ lower LSP-boost, **higher Jet-multiplicity**



- <u>Choice of Signal-regions (SRs) reflect these crucial kinematic differences:</u>
→ Signal-regions containing **at least 3 Jets** (optimized on **region 1**)
→ Signal-regions containing **at least 4 Jets** (optimized an **region 2**)

- <u>For each Jet-multiplicity, define:</u>

1.) One SR with **harsh cuts** (performs well on signal-points with **high-masses / low xsecs)**
2.) One SR with **softer cuts** (performs well on signal-points with **low-masses / high xsecs)**
→ **4 Signal-Regions in total give good coverage of the whole $m_0/m_{1/2}$ - plane**

Definition of Signal-Regions II

- **Kinematic variables used to separate SM-background from SUSY:**

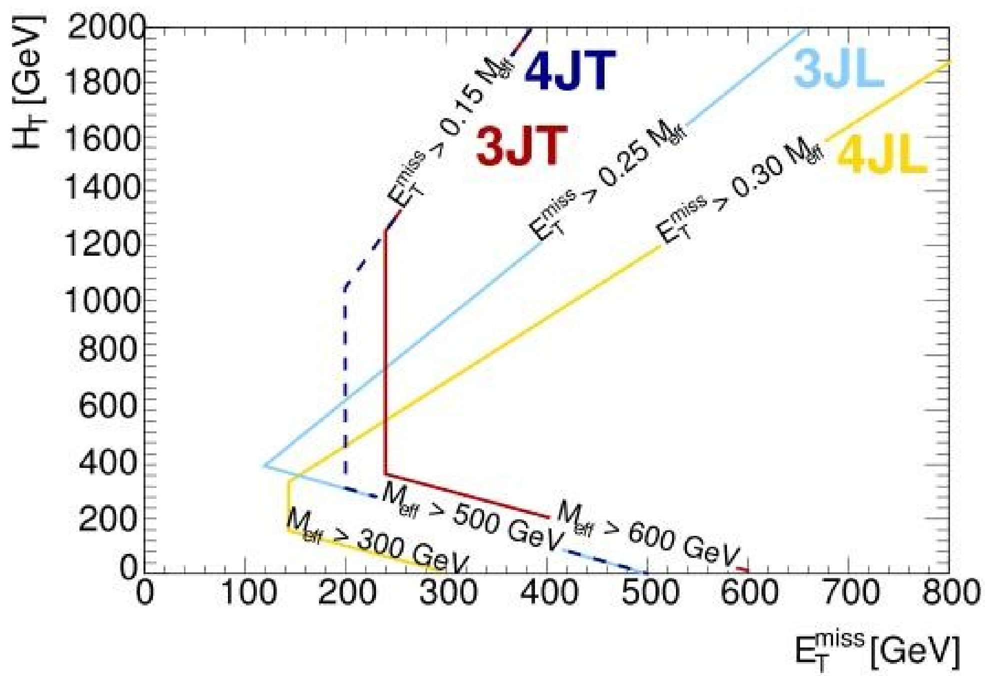
1.) **Transverse mass**
(suppresses W and semilep. Top)

$$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - cos(\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}})))}$$

2.) **„Effective Mass“**
(provides a measure of the total energy/mass in the event)

$$M_{eff} = E_{\mathrm{T}}^{\mathrm{miss}} + H_T = E_{\mathrm{T}}^{\mathrm{miss}} + p_T^{\ell} + \sum_{i=1}^{3} p_T^{jet_i}$$

Selection	Signal Regions 3JL	3JT	4JL	4JT
Number of Leptons	= 1			
Lepton p_{T} (GeV)	> 25(20) for electrons (muons)			
Veto lepton p_{T} (GeV)	> 20(10) for electrons (muons)			
Number of jets	≥ 3		≥ 4	
Leading jet p_{T} (GeV)	60	80	60	60
Subsequent jets p_{T} (GeV)	25	25	25	40
$\Delta\phi(\vec{\mathrm{jet}}_i, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$	[> 0.2 (mod.π)] for all 3 (4) jets			
m_{T} (GeV)	> 100			
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 125	> 240	> 140	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.25	> 0.15	> 0.30	> 0.15
m_{eff} (GeV)	> 500	> 600	> 300	> 500



W / Top Control – Regions

❖ **<u>Basic Idea:</u>**

- Select phasespace enriched with W and Top – events

❖ **<u>Kinematic variables used:</u>**

1.) **M_T:**

W- and Top-events accumulate around the W-mass

→ **40 GeV < M_T < 80 GeV**

2.) **E_T^{miss}:**

W- and Top-events have intermediate E_T^{miss}

(due to the Neutrino-momenta from the **W→lν** – decay)

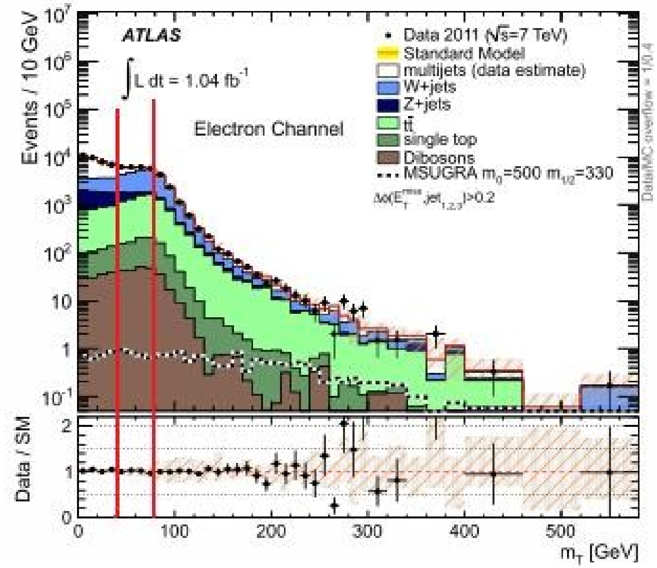
→ **30 GeV < E_T^{miss} < 80 GeV**

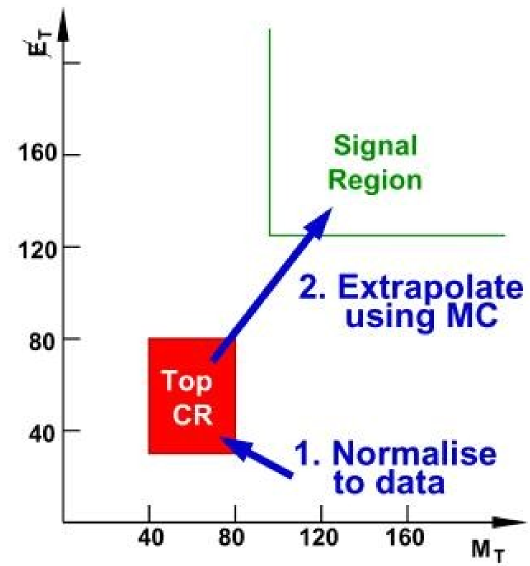
- Separate this Region into a:

1.) **Top-enriched** sub-region (**at least 1 b-tag**)

2.) **W-enriched** sub-region (**no b-tag**)

- Normalize each background in the corresponding control-region to data and extrapolate into the signal-regions





W / Top Control - Regions (Extrapolation)

$$N(t\bar{t}, signal, prediction) = (\boxed{N(Data, control)} - \boxed{N(BG, control, mc)}) * \boxed{\frac{N(t\bar{t}, signal, mc)}{N(t\bar{t}, control, mc)}}$$

Number of measured Data-events

Expected number of BG-events in the control-region

Extrapolation-factor

- **Error on the background-prediction in the signal-region driven by:**
- **Statistical errors in the control-regions**
- **Error on the background-subtraction and SUSY-contamination in the control-regions**
- **Error on the Top/W - mc-expectation in the control- and signal-region**

- SUSY-signal-region selects „extreme“ phase-space (high Jet-activity, large E_T^{miss} …)
  → **High sensitivity to higher order QCD-effects!**

- **Theory uncertainties considered:**
- Change in the renormalization- and factorization-scale
- Different MLM-matching-cutoffs
- Different Hadronization (Pythia vs. Herwig)

Process	Scale	Jet parton matching	Hadronization	NLO Comparison
Top	9%	9%	22%	NA
W+jets	24%	26%	15%	50%

Theory-uncertainties on the extrapolation-factor for the Top- and W+Jets - background

The Combined Fit

- **Fit all backgrounds and the signal-strength (for each SUSY-model) simultaneously in the control- and signal-regions**

- **<u>Processes considered:</u>**

1.) SUSY-signal (dominate the signal-regions)
2.) W+Jets and Z+Jets (dominate the W-CR)
3.) TTBar + Single Top (dominate the Top-CR)
4.) QCD (measured via a Matrix-method)

- **Likelihood-function:**

$$L(\vec{n}|\mu, \vec{b}, \vec{\theta}) = \boxed{P_{\mathrm{SR}}} \times \boxed{P_{\mathrm{WR}}} \times \boxed{P_{\mathrm{TR}}} \times \boxed{P_{\mathrm{QR}}} \times C_{\mathrm{Syst}}$$

- **P** denotes the Poisson-distributions in each control-region (W, Top, QCD) or signal-region (SR)

- A profile **Log Likelihood Ratio** – test is performed to get the best fit-values:

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

- The Limit is extracted using the **CLs - method**

Results

Electron channel	3JL Signal region	3JT Signal region	Top region	W region
Observed events	$\boxed{71}$	$\boxed{14}$	162	565
Fitted top events	56 ± 20 (51)	7.6 ± 3.0 (6.8)	125 ± 16 (112)	64 ± 8 (58)
Fitted W/Z events	35 ± 20 (34)	10.5 ± 6.5 (10.1)	30.1 ± 9.1 (29.3)	425 ± 36 (413)
Fitted multijet events	$6.0^{+2.3}_{-1.4}$	$0.46^{+0.37}_{-0.22}$	7.2 ± 2.6	76 ± 24
Fitted sum of background events	$\boxed{97 \pm 30}$	$\boxed{18.5 \pm 7.4}$	162 ± 13	565 ± 24

Muon channel	3JL Signal region	3JT Signal region	Top region	W region
Observed events	$\boxed{58}$	$\boxed{11}$	166	413
Fitted top events	47 ± 16 (38)	8.9 ± 3.2 (7.3)	142 ± 14 (115)	70 ± 7 (57)
Fitted W/Z events	16.6 ± 9.4 (20.1)	5.0 ± 3.2 (6.1)	19.0 ± 4.8 (23.2)	322 ± 23 (393)
Fitted multijet events	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	5.4 ± 2.2	21.6 ± 5.7
Fitted sum of background events	$\boxed{64 \pm 19}$	$\boxed{13.9 \pm 4.3}$	166 ± 13	413 ± 20

Fit-results for the 3 Jet – Cuts – signal – regions

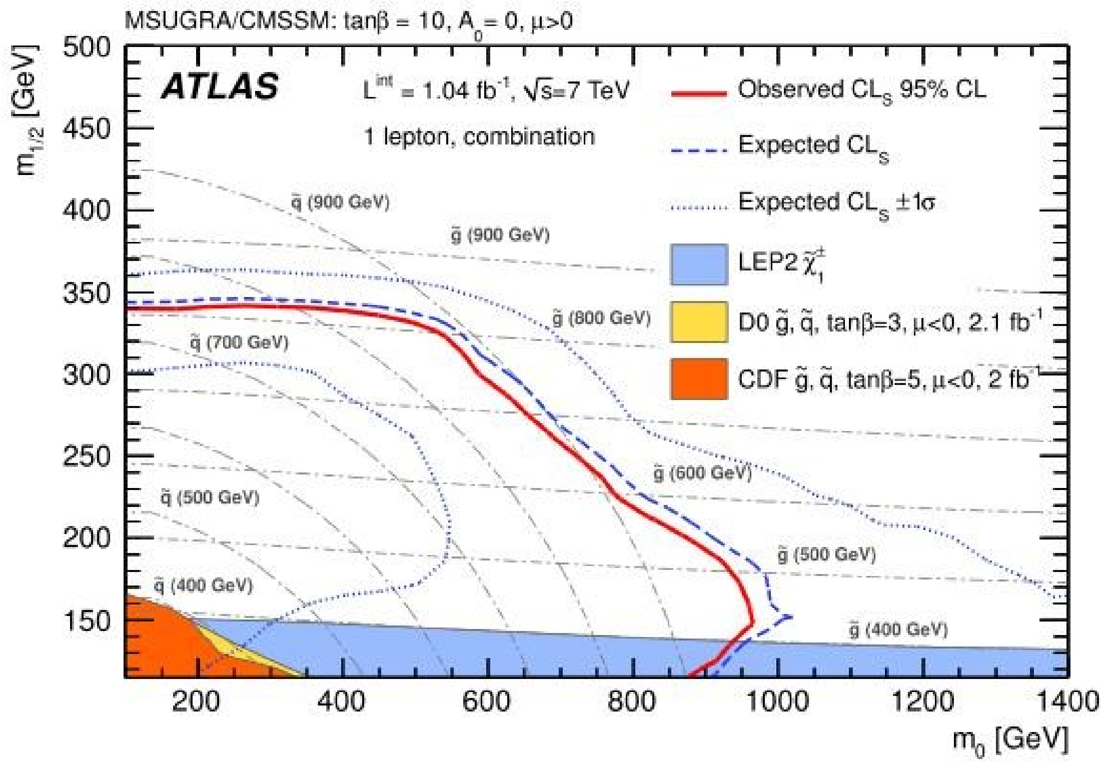
- Number of **observed** and **fitted events** in the signal-regions **agree within errors**
- Same situation for the 4-Jet-signal-regions ☹

→ Agreement between SM-expectation and data used to set **limits on different SUSY-models**

Limits on the mSUGRA - model

- Already with **1fb^{-1}** the exclusion-reach is way above the LEP/TeVatron - limits

- For mSUGRA-points fulfilling $\mathbf{m_{Gluino} \approx m_{Squark}}$, Gluino- ,and Squark-masses up to **~ 800 GeV** can be excluded



Combined limit (e,μ) in the m_0 / $m_{1/2}$ - plane

- Keep in mind that mSUGRA is a very simple model **probably not realized by nature!**
- Is there a way to set limits in a less model-dependant way?
  → **Simplified models**

Limits for simplified models

- **Set Limits on Crosssection for fixed production- and decay-channel varying:**

1.) The **masses** of the produced **SUSY-Particles** (determines **production-xsec**)

2.) The **compression-factor** defined as:

$$X = \frac{m_{Chargino} - m_{LSP}}{m_{Heavy} - m_{LSP}}$$

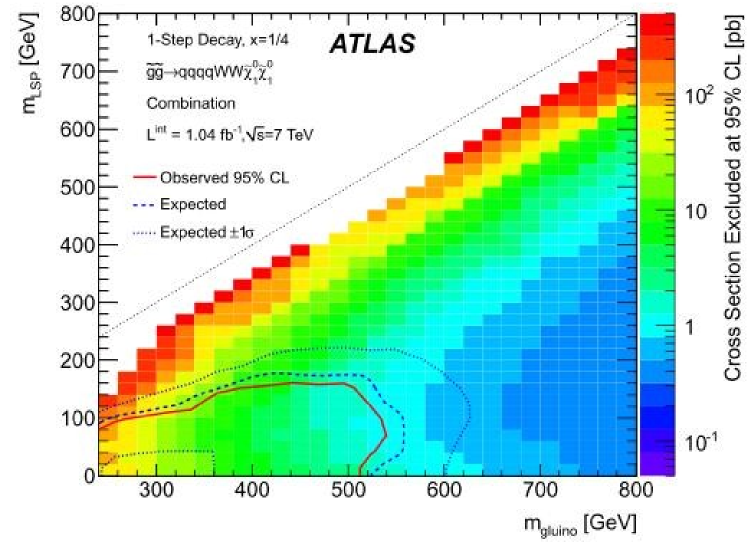
(determines momenta of particles → **selection-efficiency**)

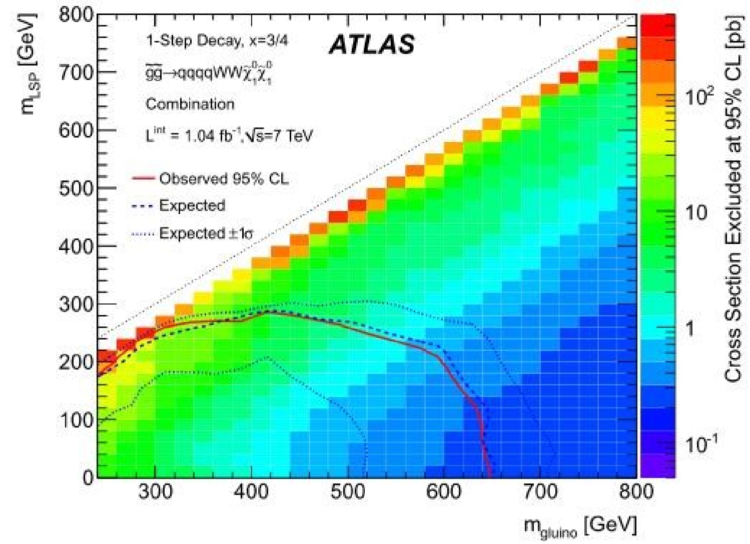
- For each production-, decay-channel and X, a grid in $\mathbf{m_{Heavy}}$ **vs.** $\mathbf{m_{LSP}}$ is generated

- Plots on the right show examples for the process:

$$\tilde{g}\tilde{g} \rightarrow qqqqWW\tilde{\chi}_1^0\tilde{\chi}_1^0$$

for 2 different values of X (1/4 and 3/4)





Summary / Outlook

- The 1-Lepton SUSY-search at ATLAS for **1fb^{-1}** of integrated luminosity was presented

- **No data-excess over the SM-model-prediction was observed**
  → Limits on the benchmark-model (mSUGRA) were strongly improved
  → Limits on simplified models were presented
    → Allows all model-builders out there to check their models against the ATLAS-data

- **Update of the analysis using the full 2011-dataset (~5fb^{-1}) in preparation including several changes:**

1.) Redefinition of the signal-regions to increase sensitivity for higher SUSY-masses
2.) More work on understanding the higher pileup-environment
3.) Profiling systematic uncertainties within the combined fit
→ **Allows to constrain somewhat „arbitrary“ theory-uncertainties**
→ Maybe allows to measure the JES-uncertainty in-situ with high precision

- The air for SUSY is starting to get thinner, but still plenty of scenarii possible, where our searches are not sensitive yet!

Backup

Motivation

- Standardmodel of particle-physics cant be a complete theory of nature:

1.) Only 3 of the 4 known forces of nature included
What about Gravity?

2.) No explanation why the higgs-mass should be in the range of the EW-scale (**Hierarchy Problem**).

3.) Only **~5% of energy-content** of the universe can be explained by matter present in the SM.
~15% Cold Dark Matter
~ 80% Dark Energy

4.) …

Supersymmetry (SUSY)

- New symmetry between Fermions and Bosons:

S |Fermion> ~ |Boson>
S |Boson> ~ |Fermion>

→ SUSY changes the **Spin** of particles by ½
→ **Doubles** natures particle-content!

- New multiplikative Quantum-Number: **R-Parity (P_R)**

- **$P_R = (-1)^{3(B-L) + 2S}$** → SM-particles have P_R = 1, SUSY-particles P_R = -1

- Consequences of a conserved R-Parity:
  1.) SUSY-particles are **produced in pairs.**
  2.) Each cascade-decay of a SUSY-particles ends up with the lightest supersymmetric particle (**LSP**).

Example of a SUSY particle-spectrum

R–Parität = +1			R–Parität = −1			R–Parität = −1		
Teilchen	Symbol	Spin	Teilchen	Symbol	Spin	Teilchen	Symbol	Spin
Lepton	ℓ	$\frac{1}{2}$	Slepton	$\tilde{\ell}_L, \tilde{\ell}_R$	0			
Neutrino	ν	$\frac{1}{2}$	Sneutrino	$\tilde{\nu}$	0			
Quark	q	$\frac{1}{2}$	Squark	$\tilde{q}_L, \tilde{q}_R$	0			
Gluon	g	1	Gluino	$\tilde{g}$	$\frac{1}{2}$			
Photon	γ	1	Photino	$\tilde{\gamma}$	$\frac{1}{2}$			
Z–Boson	Z	1	Zino	$\tilde{Z}$	$\frac{1}{2}$			
W–Boson	$W^{\pm}$	1	Wino	$\tilde{W}^{\pm}$	$\frac{1}{2}$	Neutralino	$\tilde{\chi}_i^0$	$\frac{1}{2}$
Higgs	$H^0, H^{\pm}$	0	Higgsino	$\tilde{H}_1^0, \tilde{H}_2^+$	$\frac{1}{2}$	Chargino	$\tilde{\chi}_i^{\pm}$	$\frac{1}{2}$
	h^0, A^0	0		$\tilde{H}_1^-, \tilde{H}_2^0$	$\frac{1}{2}$			

Graviton	2	Gravitino	3/2

Advantages of SUSY-Theories

1.) If one assumes invariance of the theory under **local** Supersymmetry, a particle with Spin = 3/2 occurs → provides a **potential graviton-partner.**

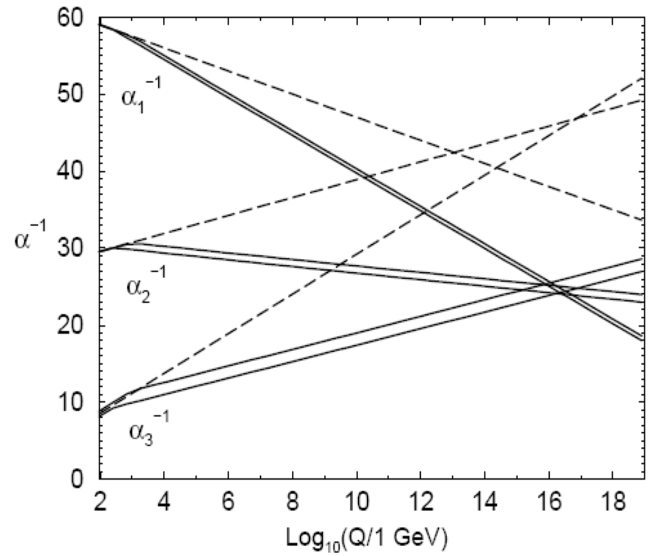
→ **First step towards an inclusion of gravity in particle-physics!**

2.) Loop corrections of the new SUSY-particles stabilize the higgs-mass in the region of the EW-scale → **solution of the Hierarchy-problem!**

3.) A stable and only weak interacting LSP provides a **candidate for cold dark matter**

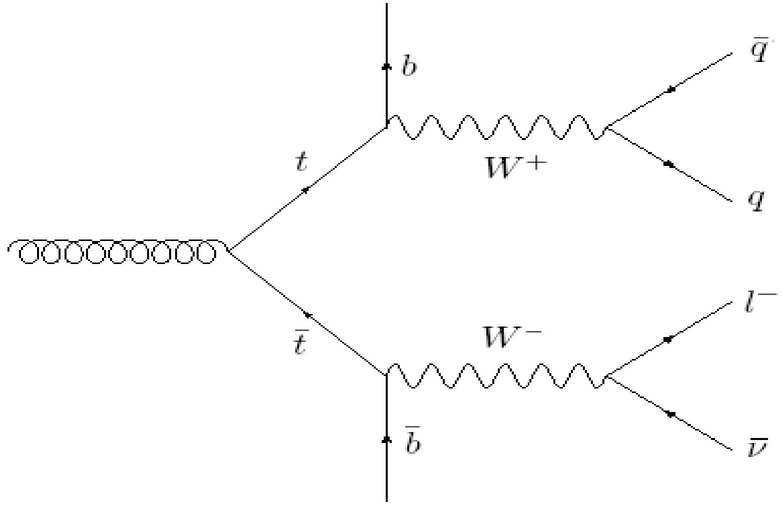
4.) SUSY-GUT-theories **unify the coupling-constants** for sufficiently high energies!

5.) History shows that new symmetries often provide very powerfull tools!

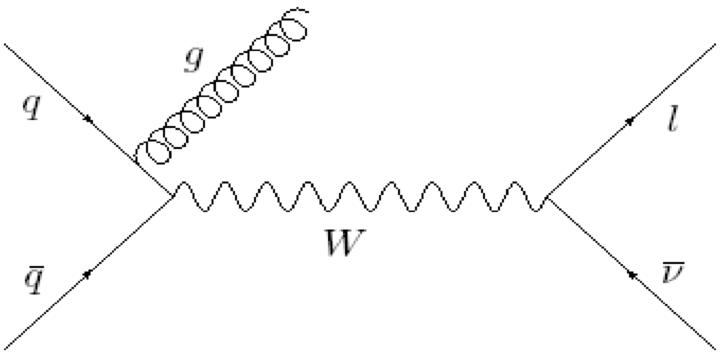


Standardmodel-backgrounds containing one Lepton

- **<u>Top-Quark-pairproduction:</u>**
  (semileptonic decay)
  - 2 hard b-Jets, 2 Jets from the W-decay
  - Lepton with large P_T
  - E_T^{miss} given by the neutrino



- **<u>Production of a W-Boson + ISR</u>**
  - Jets given by gluon-radiation
  - Lepton with high P_T because of the large W-boost and W-mass
  - E_T^{miss} given by the neutrino



- Additional Backgrounds: **QCD**, Diboson-production

Systematics 1 Electron

Electron channel	SR3jL	SR3jT	SR4jL	SR4jT
Total statistical ($\sqrt{N_{\text{obs}}}$)	±8.43	±3.74	±6.40	±3.00
Total background systematic	$^{+30.16}_{-30.16}$	$^{+7.36}_{-7.36}$	$^{+17.86}_{-17.86}$	$^{+3.67}_{-3.67}$
Jet/MET energy resolution	±5.93	±0.47	±4.22	±0.76
Jet/MET energy scale	±18.55	±4.14	±13.55	±2.35
Lepton energy resolution	±0.54	±0.30	±0.05	±0.27
Lepton energy scale	±1.06	±0.27	±0.36	±0.48
b-tagging	±1.21	±0.24	±0.70	±0.15
MC stat top	±5.80	±1.99	±3.78	±1.37
MC stat W	±4.36	±2.30	±2.16	±1.28
QCD fake rate	±1.38	±0.15	±0.21	< 0.1
QCD real rate	±1.48	±0.27	±0.82	±0.14
Theory top	±15.88	±2.11	±9.75	±1.17
Theory W	±19.01	±5.63	±5.07	±1.85
Pile-up	±5.08	±0.99	±2.46	±0.42

Systematics 1 Muon

Muon channel	SR3jL	SR3jT	SR4jL	SR4jT
Total statistical ($\sqrt{N_{\text{obs}}}$)	± 7.62	± 3.32	± 7.07	± 2.65
Total background systematic	$^{+19.27}_{-19.27}$	$^{+4.35}_{-4.31}$	$^{+15.79}_{-15.80}$	$^{+2.71}_{-2.66}$
Jet/MET energy resolution	± 8.99	± 1.06	± 0.92	± 0.52
Jet/MET energy scale	± 6.99	± 0.18	± 9.06	± 1.61
Lepton energy resolution	± 0.00	± 0.00	± 0.00	± 0.00
Lepton energy scale	± 0.75	± 0.26	± 1.42	± 0.54
b-tagging	± 1.00	± 0.19	± 0.87	± 0.12
MC stat top	± 5.39	± 2.12	± 4.01	± 1.40
MC stat W	± 2.52	± 1.37	± 2.57	± 0.65
QCD fake rate	< 0.1	< 0.1	< 0.1	< 0.1
QCD real rate	± 0.53	± 0.14	± 0.44	< 0.1
Theory top	± 12.87	± 2.44	± 9.99	± 1.19
Theory W	± 8.80	± 2.66	± 7.28	± 0.70
Pile-up	± 3.45	± 0.75	± 2.73	± 0.31

QCD Control – Region I (Muons)

- 2 Control-samples for tight (susy object def.) and loose muons (relax isolation):

$$N^{\text{obs}}_{\text{loose not tight}} = N^{\text{obs}}_{\text{loose}} - N^{\text{obs}}_{\text{tight}} = (1/\epsilon^{\text{real}} - 1) \cdot N^{\text{real}}_{\text{tight}} + (1/\epsilon^{\text{fake}} - 1) \cdot N^{\text{fake}}_{\text{tight}}$$

$$N^{\text{obs}}_{\text{tight}} = N^{\text{real}}_{\text{tight}} + N^{\text{fake}}_{\text{tight}}$$

- Solve for the number of tight QCD-fakes:

$$N^{\text{fake}}_{\text{tight}} = \frac{N^{\text{obs}}_{\text{loose not tight}} - (1/\epsilon^{\text{real}} - 1) \cdot N^{\text{obs}}_{\text{tight}}}{1/\epsilon^{\text{fake}} - 1/\epsilon^{\text{real}}}$$

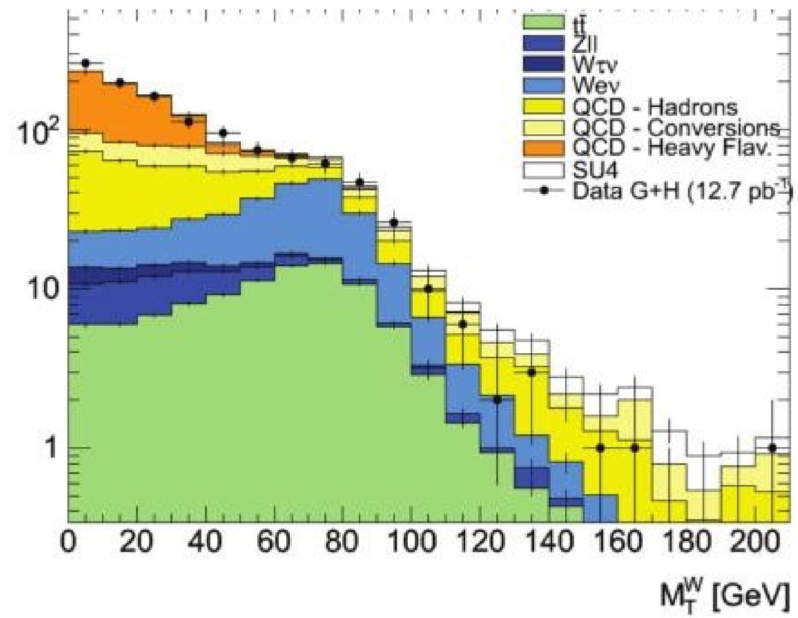
QCD Control – Region II (Electrons)

- **Problem:**
- QCD consists of 3 components **(Conversions, Hadrons, HF)**
- Different components have different shapes for the relavant distributions
  → Components behave different when extrapolating into the signal-region

- Define Control-Regions for each type

QCD control region (RobustLoose electrons)

- Conversions
  - Require $n_{BL} = 0$
- Hadrons
  - $n_{BL} > 0$ and $TRfrac < 0.2$
- Heavy flavor
  - Least important component ⇒ Use MC



- Get a template for each process in the corresponding control-region
- Fit relative components

	Electron channel	Muon channel
SR	< 0.3	< 0.5
WR	9.9 ± 13.7	0.7 ± 1.3
TR	4.1 ± 5.7	0.3 ± 0.5

Object Definitions

❖ Electrons:
- P_T > 25 GeV
- $|\eta|$ < 2.47
- „Tight“ Quality

❖ Muons:
- P_T > 20 GeV
- $|\eta|$ < 2.4
- Isolation
- Cosmic veto

❖ Jets:
- P_T > 30 GeV
- $|\eta|$ < 2.5
- AntiKt4 Algorithm
- JVF > 0.75 (pileup-suppression)

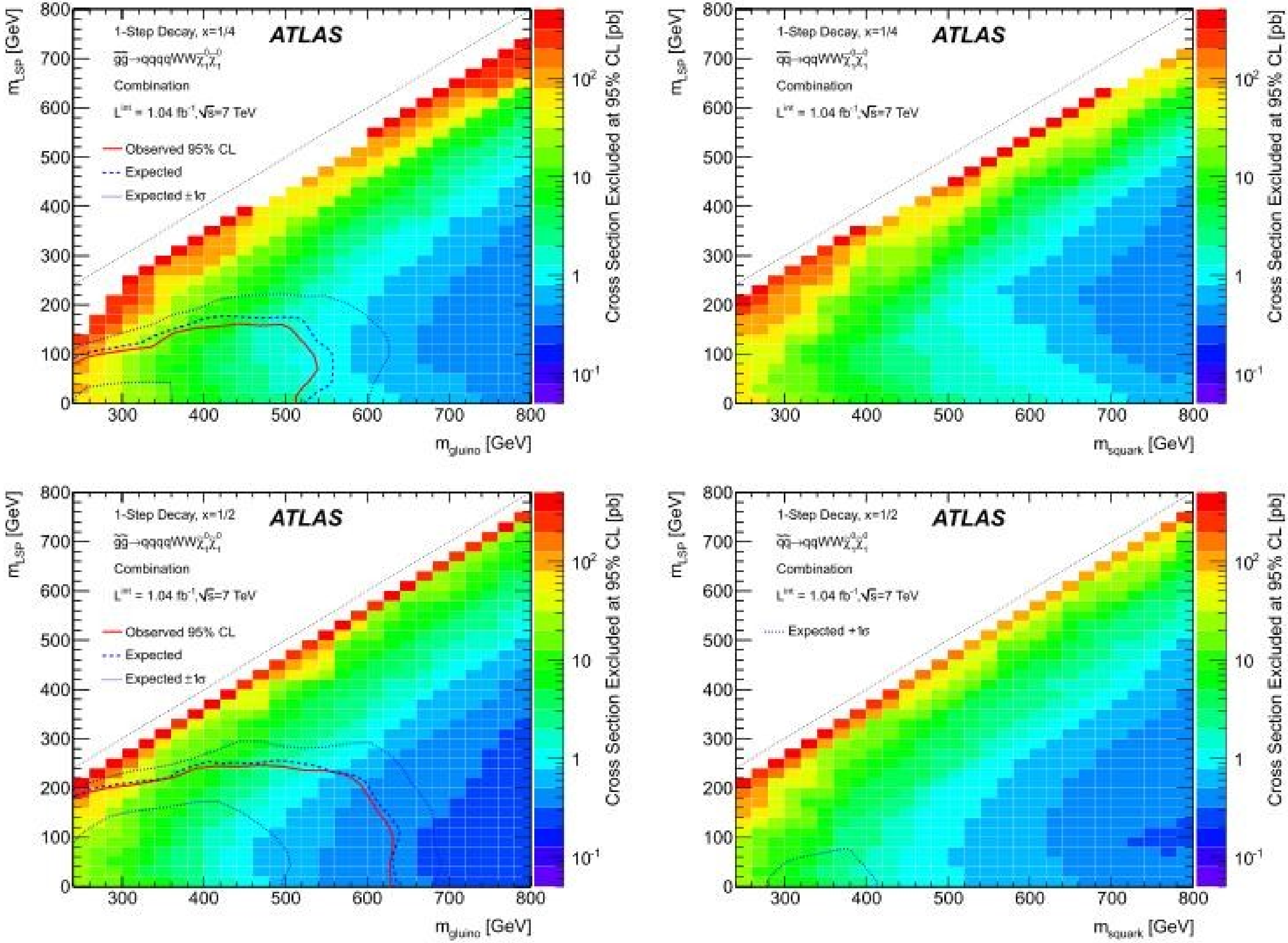
❖ Missing transverse energy:
- Calorimeter based + Muons
- Corrected for selected physics-objects

4 Jet Results

Electron channel	4JL Signal region	4JT Signal region	Top region	W region
Observed events	41	9	1382	1872
Fitted top events	38 ± 15 (34)	4.5 ± 2.6 (4.1)	1258 ± 44 (1138)	391 ± 14 (354)
Fitted W/Z events	9.5 ± 7.5 (9.2)	3.5 ± 2.2 (3.4)	88 ± 21 (86)	1242 ± 89 (1202)
Fitted multijet events	$0.90^{+0.54}_{-0.37}$	$0.00^{+0.02}_{-0.00}$	35 ± 13	239 ± 78
Fitted sum of background events	48 ± 18	8.0 ± 3.7	1382 ± 37	1872 ± 43

Muon channel	4JL Signal region	4JT Signal region	Top region	W region
Observed events	50	7	1448	1623
Fitted top events	39 ± 13 (36)	4.7 ± 2.2 (4.3)	1319 ± 45 (1231)	382 ± 13 (357)
Fitted W/Z events	14.1 ± 8.5 (14.2)	1.4 ± 1.1 (1.4)	91 ± 19 (92)	1169 ± 46 (1185)
Fitted multijet events	$0.0^{+0.0}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	38 ± 10	71 ± 16
Fitted sum of background events	53 ± 16	6.0 ± 2.7	1448 ± 38	1623 ± 40

Simplified models 1



Simplified models 2