ATLAS SUSY searches with lepton(s), jets and Etmiss

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BNL SUSY Workshop

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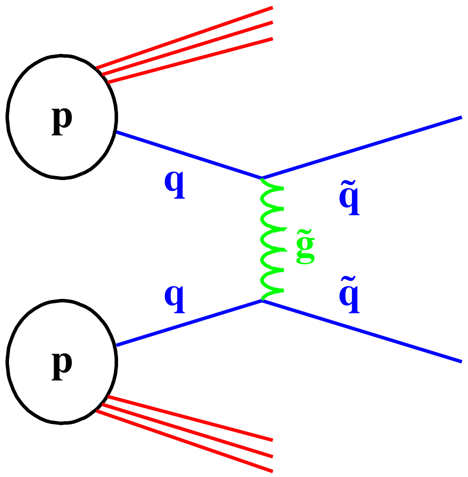
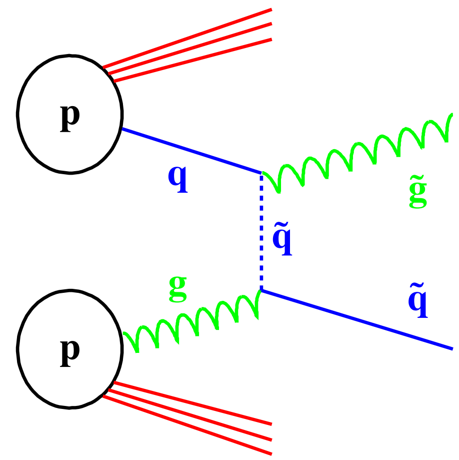
(On behalf of the ATLAS collaboration)

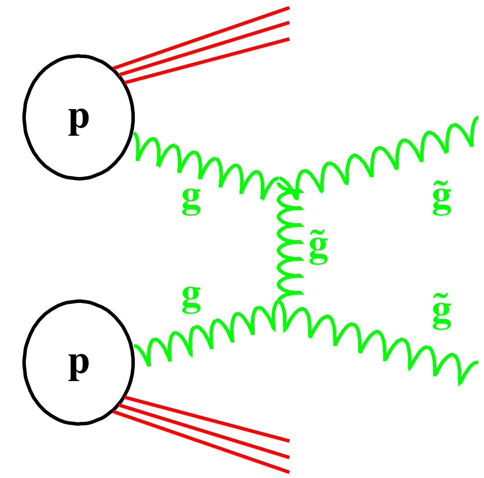
SUSY with strong production at LHC



$\tilde{q}\tilde{q}$

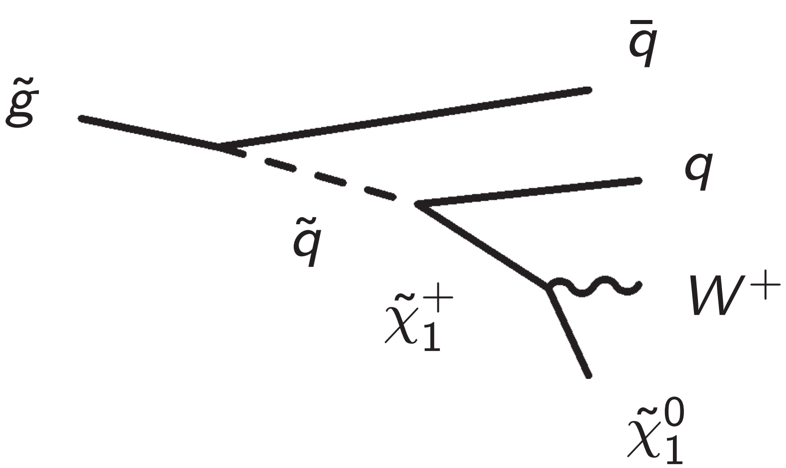


$\tilde{q}\tilde{g}$



$\tilde{g}\tilde{g}$

- R-parity conservation results in the pair production of SUSY particles
- Production of strongly interacting particles should be abundant



- The final state with leptons is one of the cleanest ways to discover SUSY/new physics
- Leptons are produced along with high-pT jets and high missing transverse momentum (Etmiss)

- The squarks can also be from 3rd generation depending upon the mass of the gluino

Analysis that will be covered

❖ **ATLAS Analysis with final states :**

- 1-lepton + jets + Etmiss
  - High cross-section x branching ratio
  - Covers a wide range of SUSY models
  - ATLAS analysis : ATLAS-CONF-2012-041 (4.7 fb^{-1})

- Two leptons with same-sign + jets + Etmiss
  - One of the cleanest channels to discover SUSY
  - Covers gluino mediated decays with high signal significance
  - ATLAS analysis : arXiv:1203.5763 (2 fb^{-1})

1-lepton + jets + Etmiss

ATLAS-CONF-2012-041

Int. Lumi = 4.7 fb^{-1}

Selection of leptons, jets and Etmiss

- Leptons (electrons and muons) are divided into two categories
- "Hard" and "Soft" (Recovers phase space with compressed SUSY spectrum)
  - electron:
    - pT > 25 GeV (**Hard**), $|\eta| < 2.47$
    - 7 < pT < 25 GeV (**Soft**), $|\eta| < 2.47$
  - muon:
    - pT > 20 GeV (Hard), $|\eta| < 2.4$
    - 6 < pT < 20 GeV (Soft), $|\eta| < 2.4$
  - Jets:
    - pT > 25 GeV, $|\eta| < 2.5$
    - 75% of $\sum$pT of tracks inside a jet should come from tracks associated with a primary vertex *deals with pileup effects at high lumi.*
  - Etmiss:
    - Calculated using all the objects in the event and with jets of pT > 20 GeV and $|\eta| < 4.5$
  - Trigger:
    - Single lepton (electron, muon) based trigger used
    - To recover efficiency at higher lumi., electron trigger with looser shower shape selection
    - Etmiss based trigger is used which has a plateau at Etmiss > 180 GeV

Event Selection for 1-lepton Analysis

- Two main variables that defines the selection
  - Transverse mass (lepton and Etmiss)

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi(\vec{\ell}, \vec{p}\!\!\!/_{\mathrm{T}})))}$$

  - Effective mass (scalar sum pT of the lepton, jets and Etmiss in the event)

$$m_{\mathrm{eff}}^{\mathrm{inc}} = p_{\mathrm{T}}^{\ell} + \sum_{i=1}^{\mathrm{N_{jet}}} p_{\mathrm{T,i}} + E_{\mathrm{T}}^{\mathrm{miss}}$$

- Other variables :
  - Etmiss, Etmiss/m_{eff}

	3-jet	4-jet	soft-lepton
Trigger	Single electron or muon (+jet)		Missing E_{T}
N_{lep}	1	1	1
p_{T}^{ℓ} (GeV)	> 25 (20)	> 25 (20)	[7,25] ([6,20])
$p_{\mathrm{T}}^{\ell_2}$ (GeV)	< 10	< 10	< 7 (6)
N_{jet}	≥ 3	≥ 4	≥ 2
p_{T}^{jet} (GeV)	> 100, 25, 25	> 80, 80, 80, 80	> 130,25
$p_{\mathrm{T}}^{jet\ 4}$ (GeV)	< 80	—	—
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 250	> 250	> 250
m_{T} (GeV)	> 100	> 100	> 100
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	> 0.2	> 0.3
$m_{\mathrm{eff}}^{\mathrm{inc}}$ (GeV)	> 1200	> 800	—

- 3,4-jet signal region is optimized based on CMSSM, aim for large mass differences
- soft-lepton signal region covers signals with compressed mass spectra

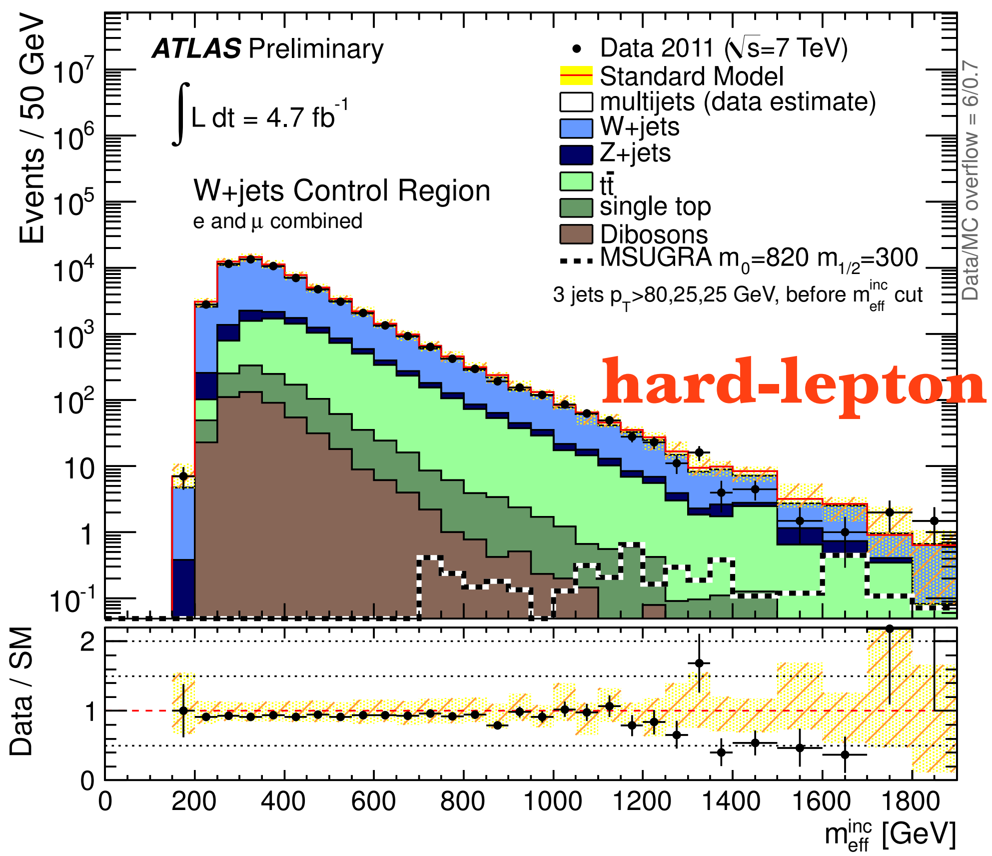
SM Backgrounds

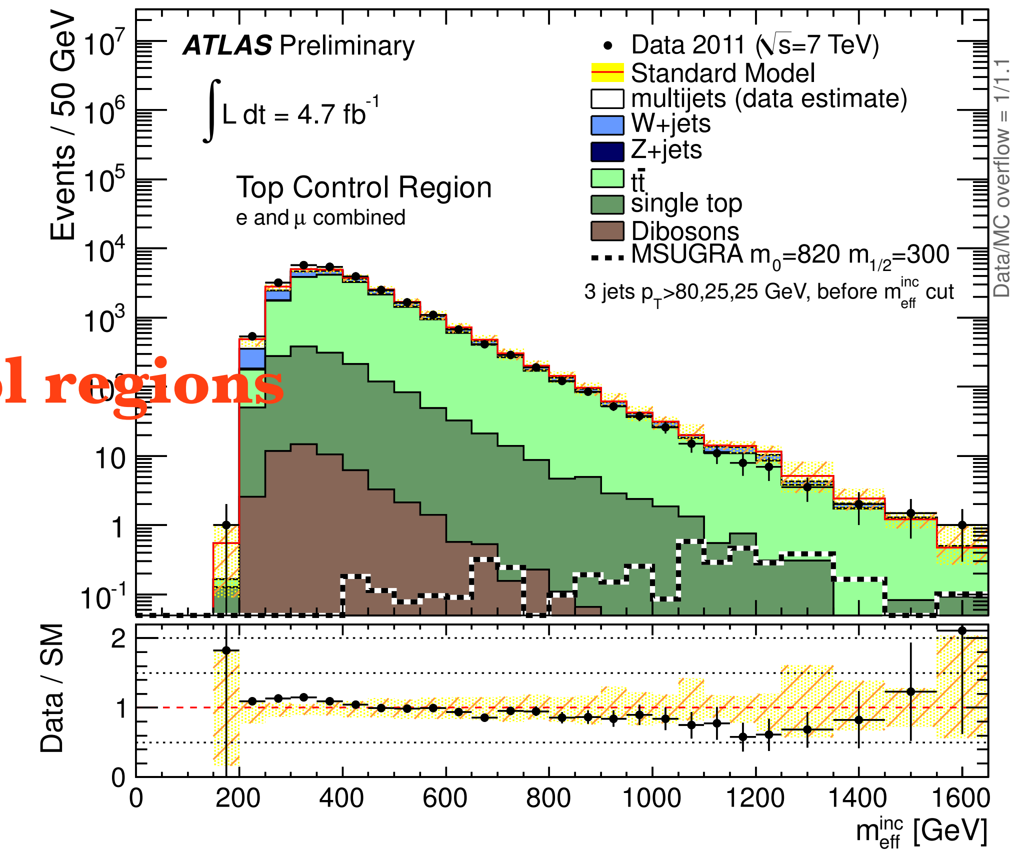
- Minor sources:
  - Z+jets, QCD multijets, single-top and dibosons
    - QCD multijets background is estimated using a data-driven method
    - Others are estimated using MC simulation

- Dominant background sources:
  - semi/fully-leptonic ttbar events, W+jets
    - These backgrounds are obtained using specific control regions
    - Main discriminants are Etmiss and mT
    - Events with b-tag/veto separates ttbar from W+jets in control regions

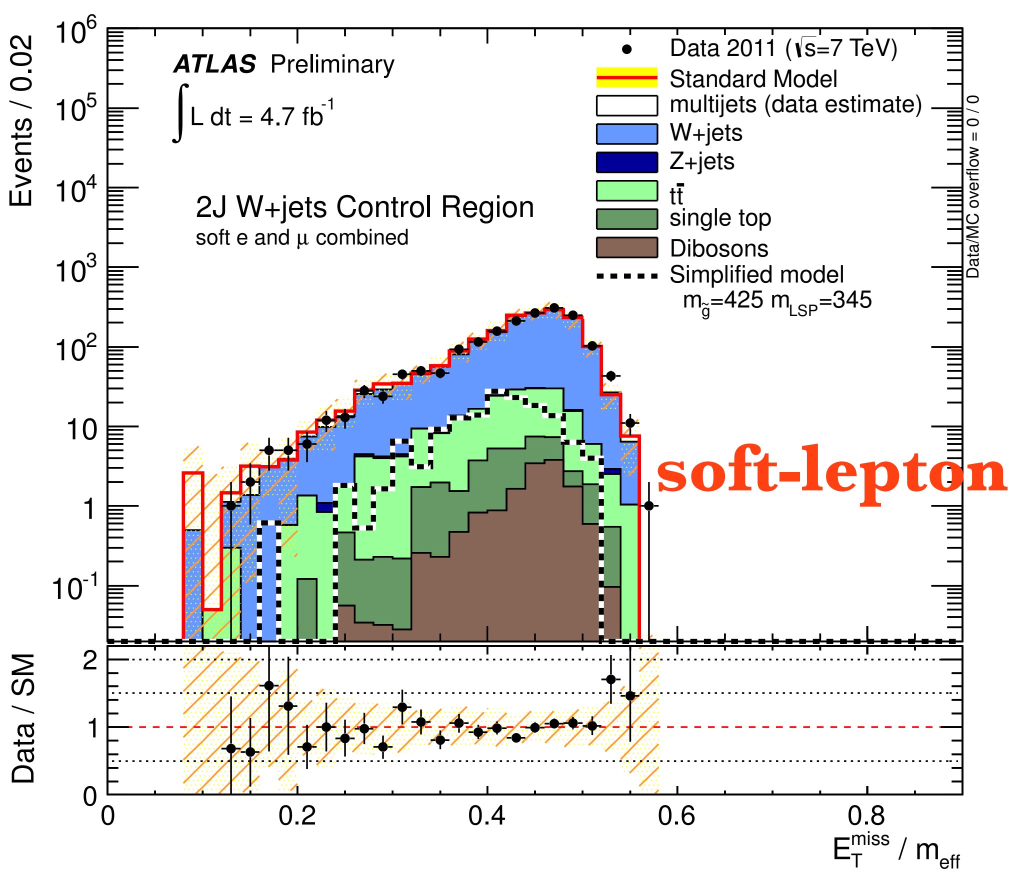
	3- and 4-jet W control	**3- and 4-jet $t\bar{t}$ control**	**soft-lepton W control**	**soft-lepton $t\bar{t}$ control**
N_{jet}	≥ 3	≥ 3	Same as signal region	
p_T^{jet} (GeV)	$> 80, 25, 25$	$> 80, 25, 25$	Same as signal region	
N_{jet} (b-tagged)	0	≥ 1	0	≥ 1
E_T^{miss} (GeV)	[30,120]	[30,120]	[180,250]	[180,250]
m_T (GeV)	[40,80]	[40,80]	[40,80]	[40,80]
$m_{\mathrm{eff}}^{\mathrm{inc}}$ (GeV)	> 400	> 400	—	—

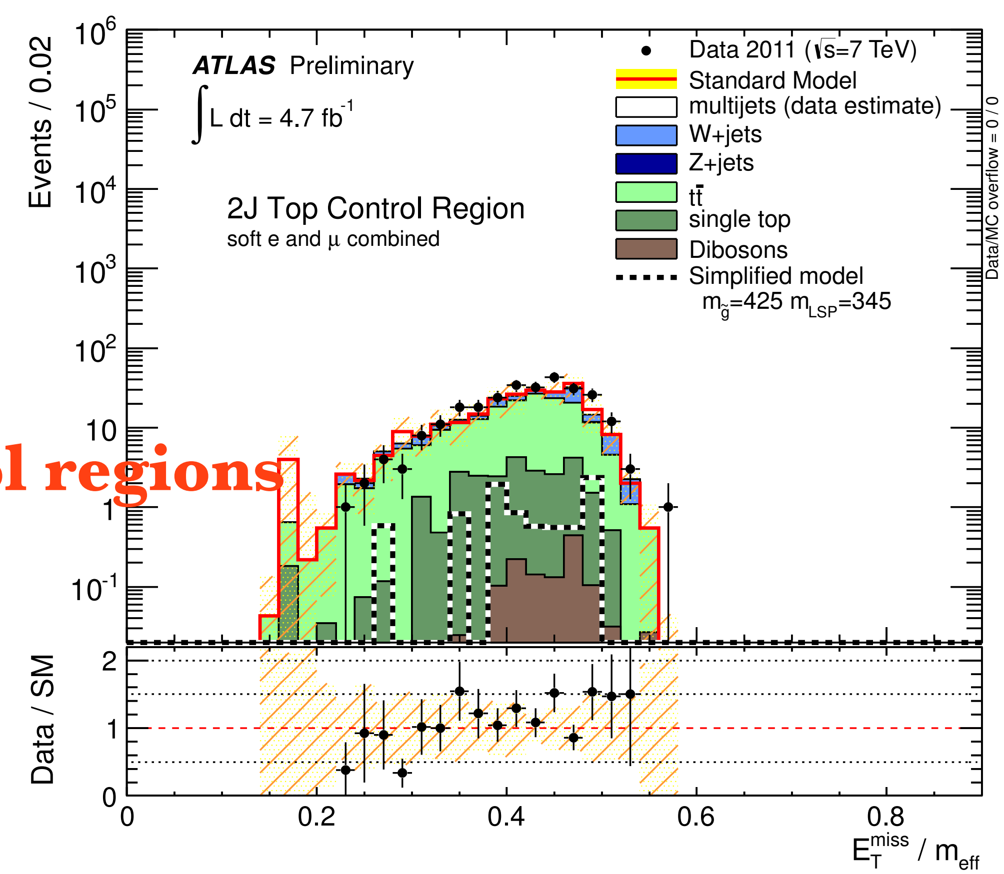
W+jets and ttbar control region





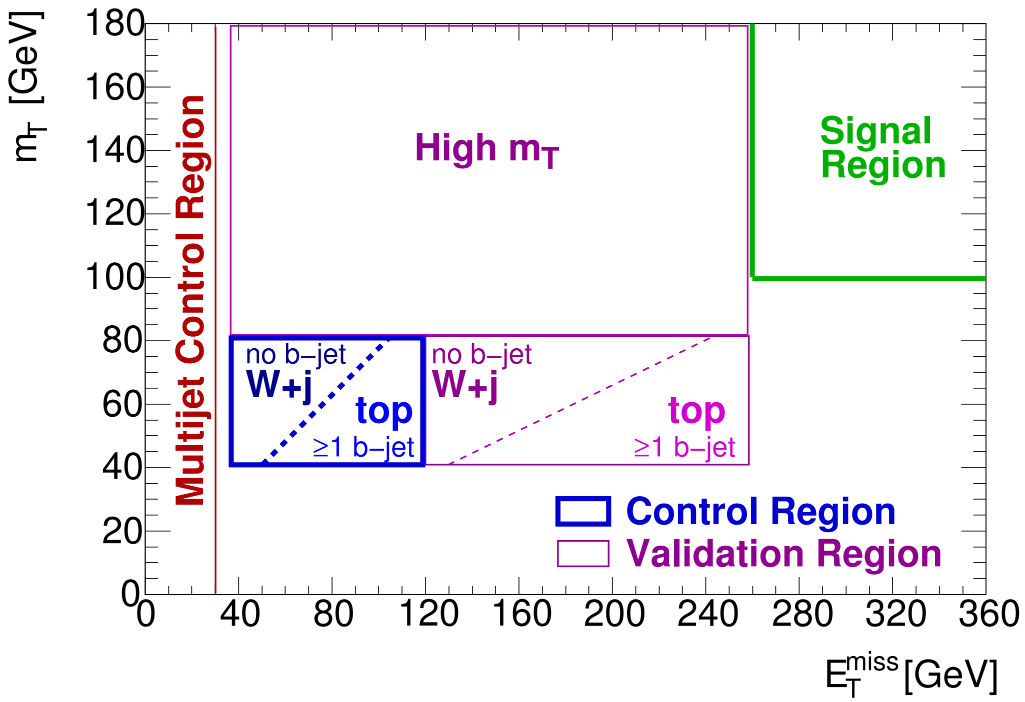
hard-lepton control regions





soft-lepton control regions

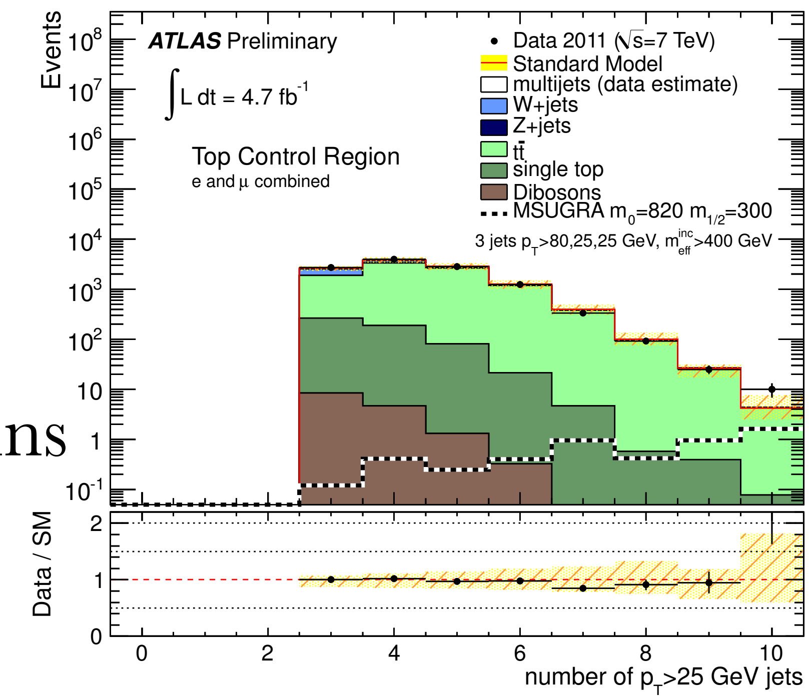
Estimation using Background Fit



SM background in the signal region is estimated using a fit based on profile likelihood method

Input to the fit

- N_{evt} in the W/top control regions in data and MC separated into several jet multiplicity bins



- Transfer factors (TF; Data, MC ratio) from the control regions are used to extrapolate to signal regions
  - Accounts for contamination from other SM processes and signal contamination

Parameters in the fit

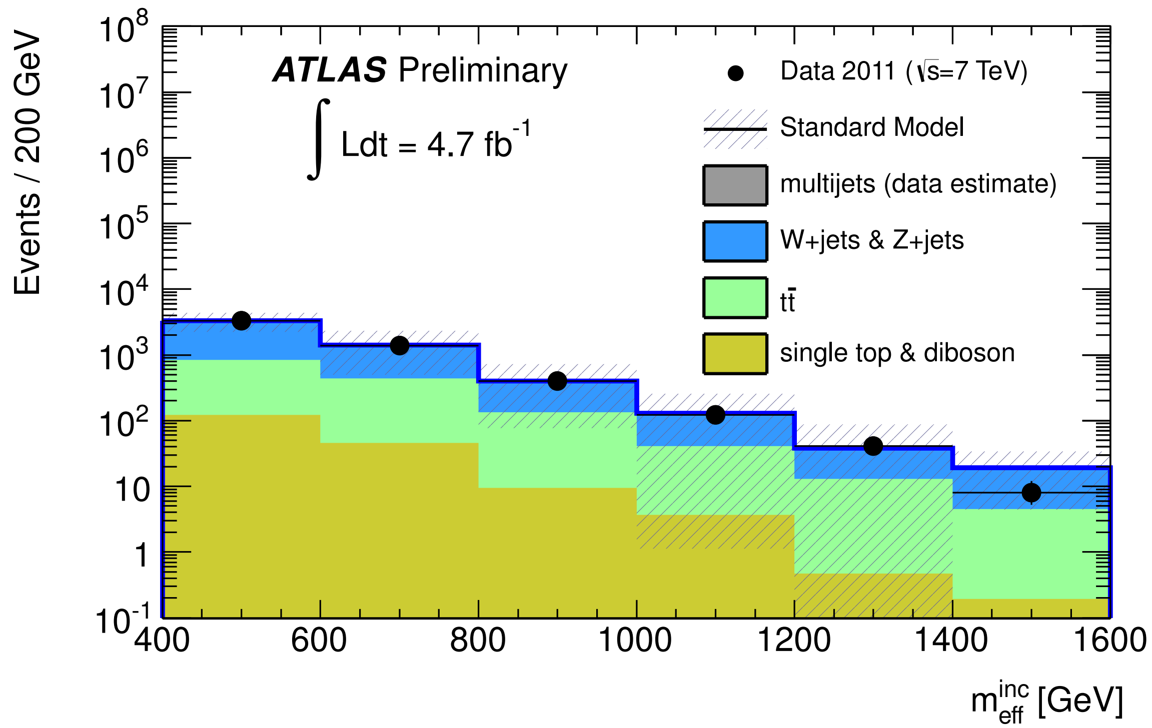
- Normalizations for the W+jets and top background
- Nuisance parameters are the ALPGEN matching scale kT_{fac} and MLM matching parameter $pT,_{min}$

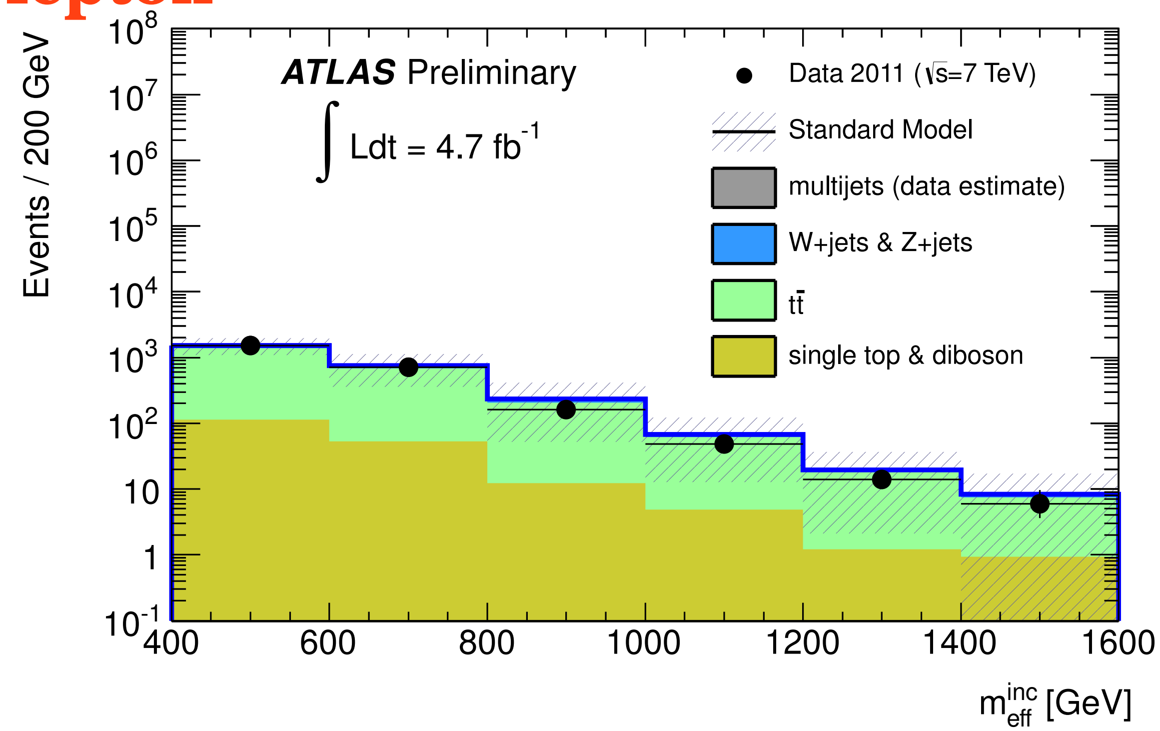
Validation Regions for the fit

- Fit results are validated using moderate Etmiss or mT cuts in the control regions

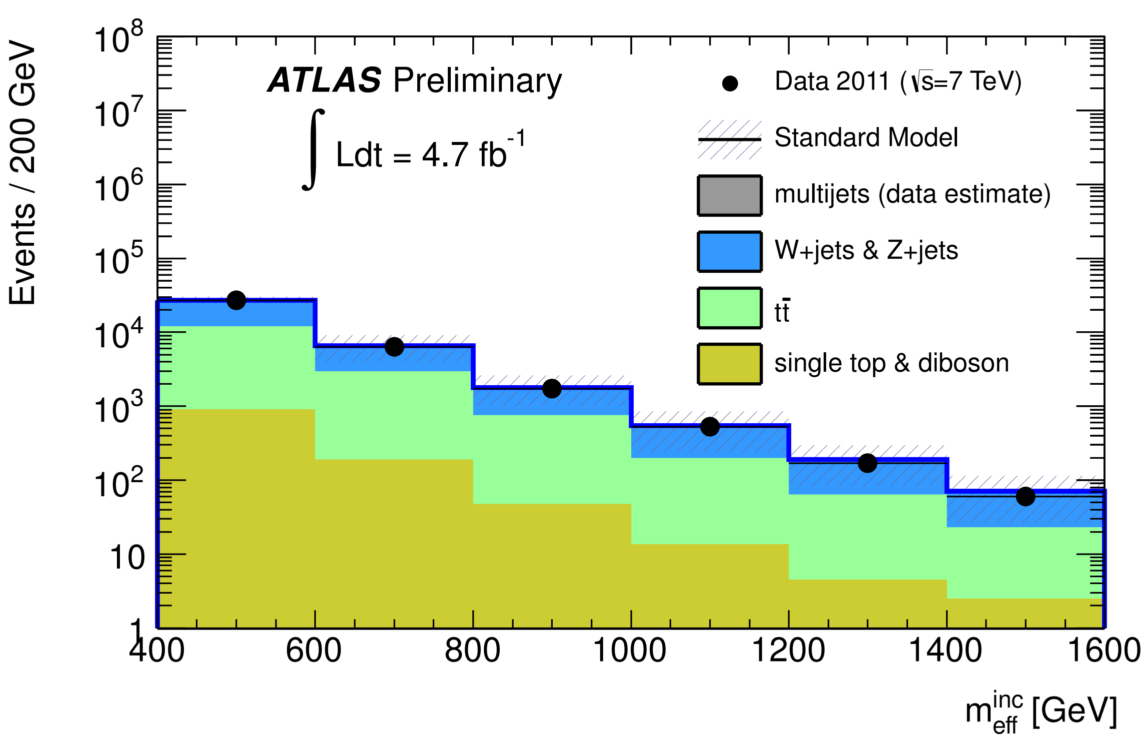
Validation of the BG Fit

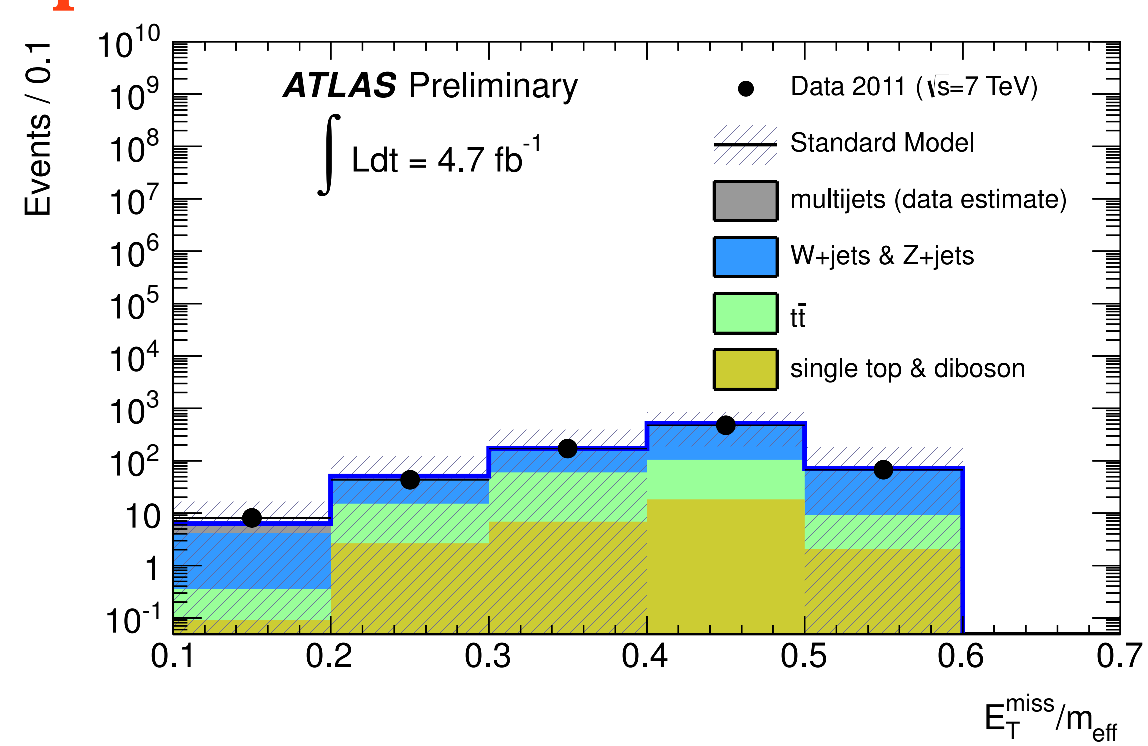
hard-lepton





soft-lepton





Validation of the BG Fit

3- and 4-jet channels	W+jets validation	$t\bar{t}$ validation	High m_T validation	$t\bar{t}$ control	W+jets control
Observed events	5281	2458	36041	11143	21324
Fitted bkg events	5300 ± 1000	2600 ± 400	37000 ± 5000	11140 ± 140	21320 ± 150
Fitted top events	1200 ± 220	2180 ± 350	15000 ± 2200	8900 ± 500	4100 ± 500
Fitted W/Z+jets events	3800 ± 900	230 ± 50	18800 ± 2900	1150 ± 120	15000 ± 1100
Fitted other bkg events	181 ± 27	186 ± 22	1170 ± 100	580 ± 60	450 ± 50
Fitted multijet events	9 ± 80	7 ± 50	1300 ± 1600	500 ± 400	1800 ± 1300
MC exp. SM events	5700	2600	39000	11220	22900
MC exp. top events	1290	2220	15500	9000	4300
MC exp. W/Z+jets events	4200	250	20700	1240	16400
MC exp. other bkg events	181	183	1170	560	440
Data-driven multijet events	9	7	1300	400	1700

Soft lepton channel	Validation Region	$t\bar{t}$ Control	W+jets Control
Observed events	764	271	1794
Fitted bkg events	810 ± 230	268 ± 17	1800 ± 50
Fitted top events	160 ± 40	169 ± 24	143 ± 32
Fitted W/Z+jets events	600 ± 200	55 ± 10	1550 ± 60
Fitted other bkg events	30 ± 8	30 ± 4	40 ± 5
Fitted multijet events	30 ± 40	14 ± 16	60 ± 70
MC exp. SM events	820	237	1810
MC exp. top events	160	157	164
MC exp. W/Z+jets events	600	43	1540
MC exp. other bkg events	29	25	41
Data-driven multijet events	31	12	60

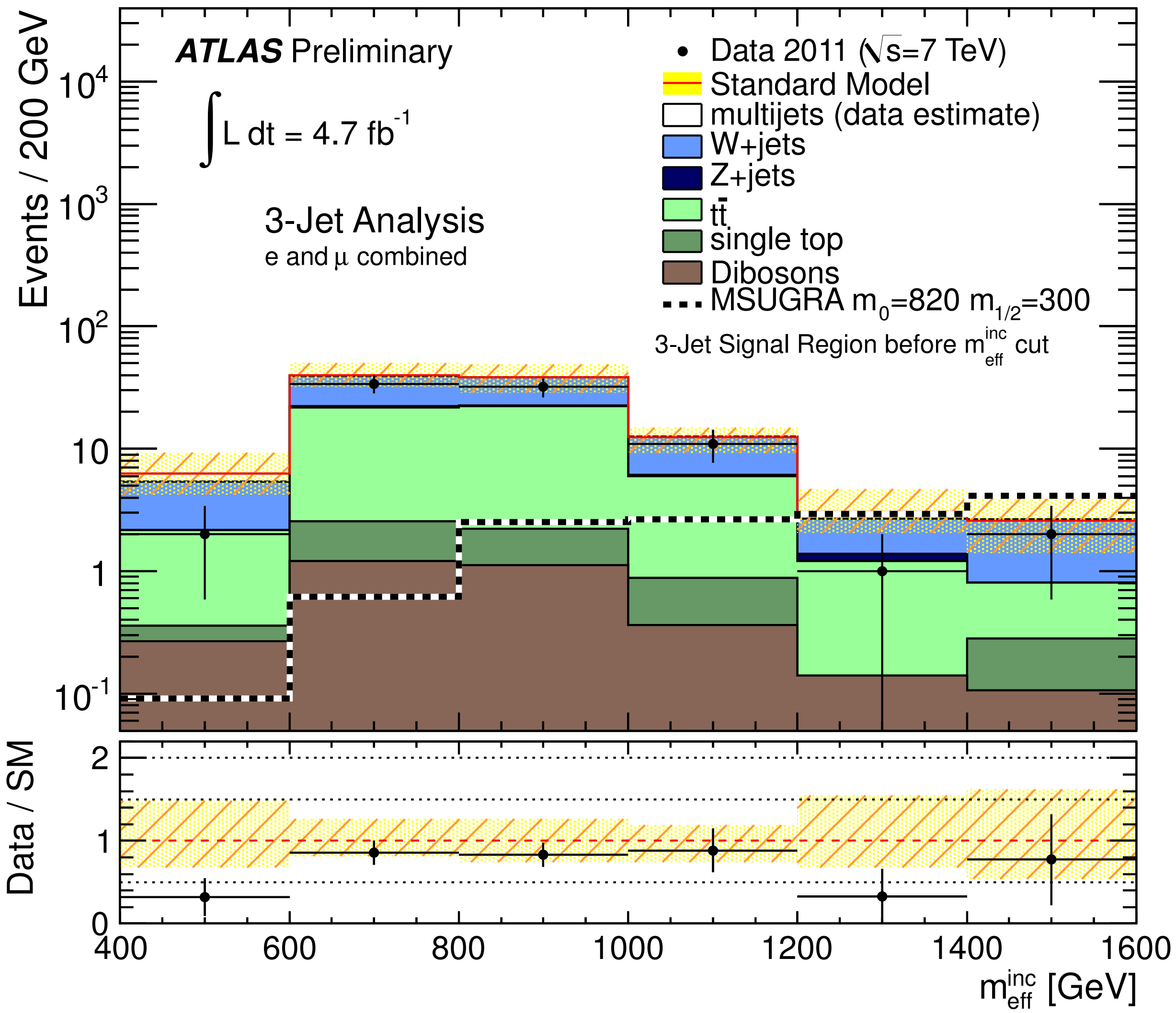
Results

	3-jet	4-jet	soft lepton
Observed events	3	6	26
Fitted bkg events	5.7 ± 4.0	8.3 ± 3.1	32 ± 11
Fitted top events	2.0 ± 1.5	5.3 ± 2.1	8.6 ± 3.4
Fitted W/Z+jets events	2.9 ± 2.1	2.0 ± 0.7	15 ± 7
Fitted other bkg events	0.5 ± 0.7	0.9 ± 0.8	0.62 ± 0.24
Fitted multijet events	0.3 ± 0.4	0.17 ± 0.30	8 ± 4
MC exp. SM events	5.6	7.9	32
MC exp. top events	1.9	5.0	8.6
MC exp. W/Z+jets events	3.1	2.0	15
MC exp. other bkg events	0.3	0.7	0.62
Data-driven multijet events	0.3	0.17	8

Model Independent Limit (CLs)

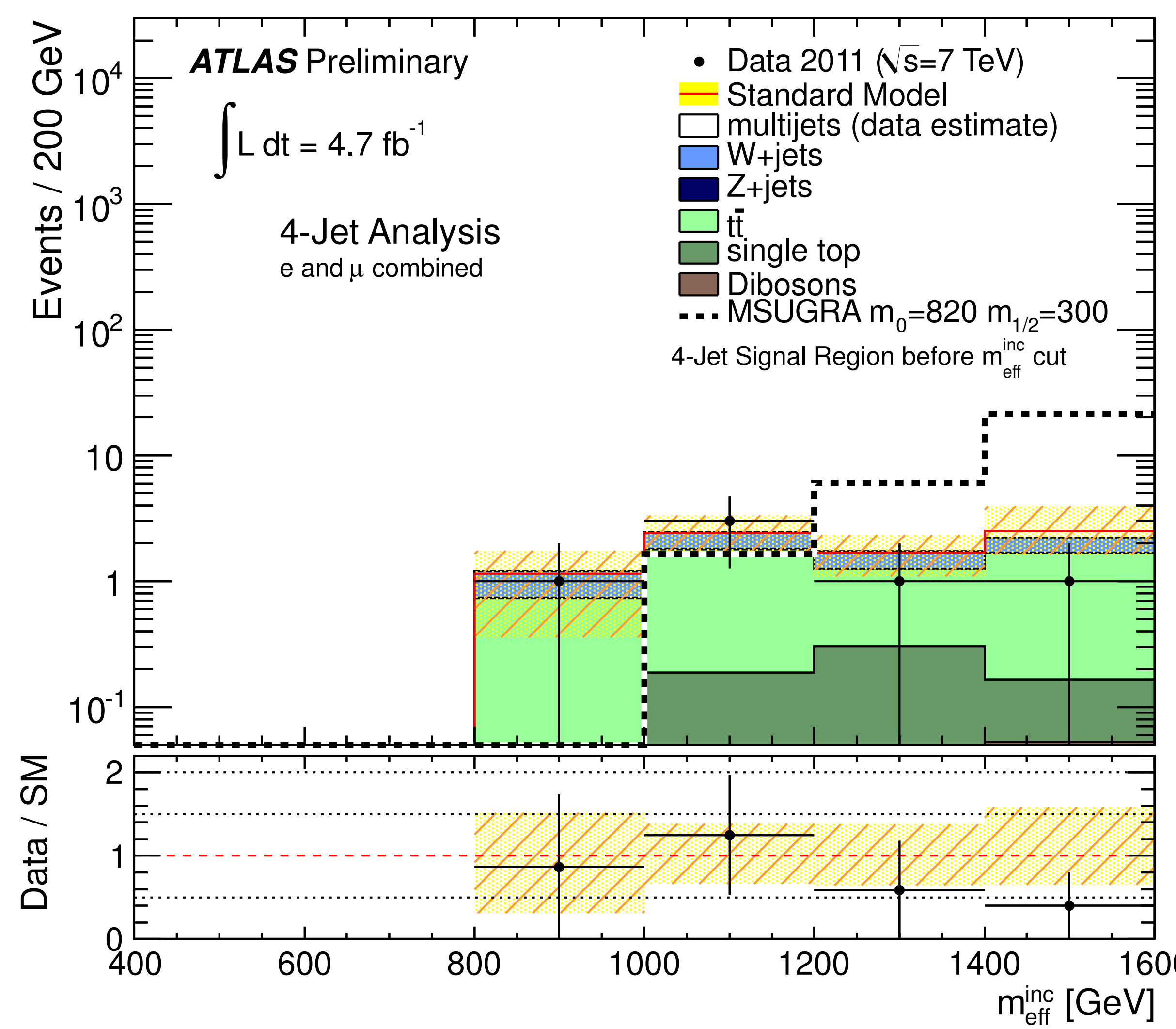
Signal channel	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$[fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B
3-jet	1.3	6.1	$7.2^{+3.0}_{-2.1}$	0.31
4-jet	1.5	7.2	$8.0^{+3.5}_{-2.4}$	0.36
soft-lepton	3.7	17.2	20^{+7}_{-5}	0.32

Results including Signal shape



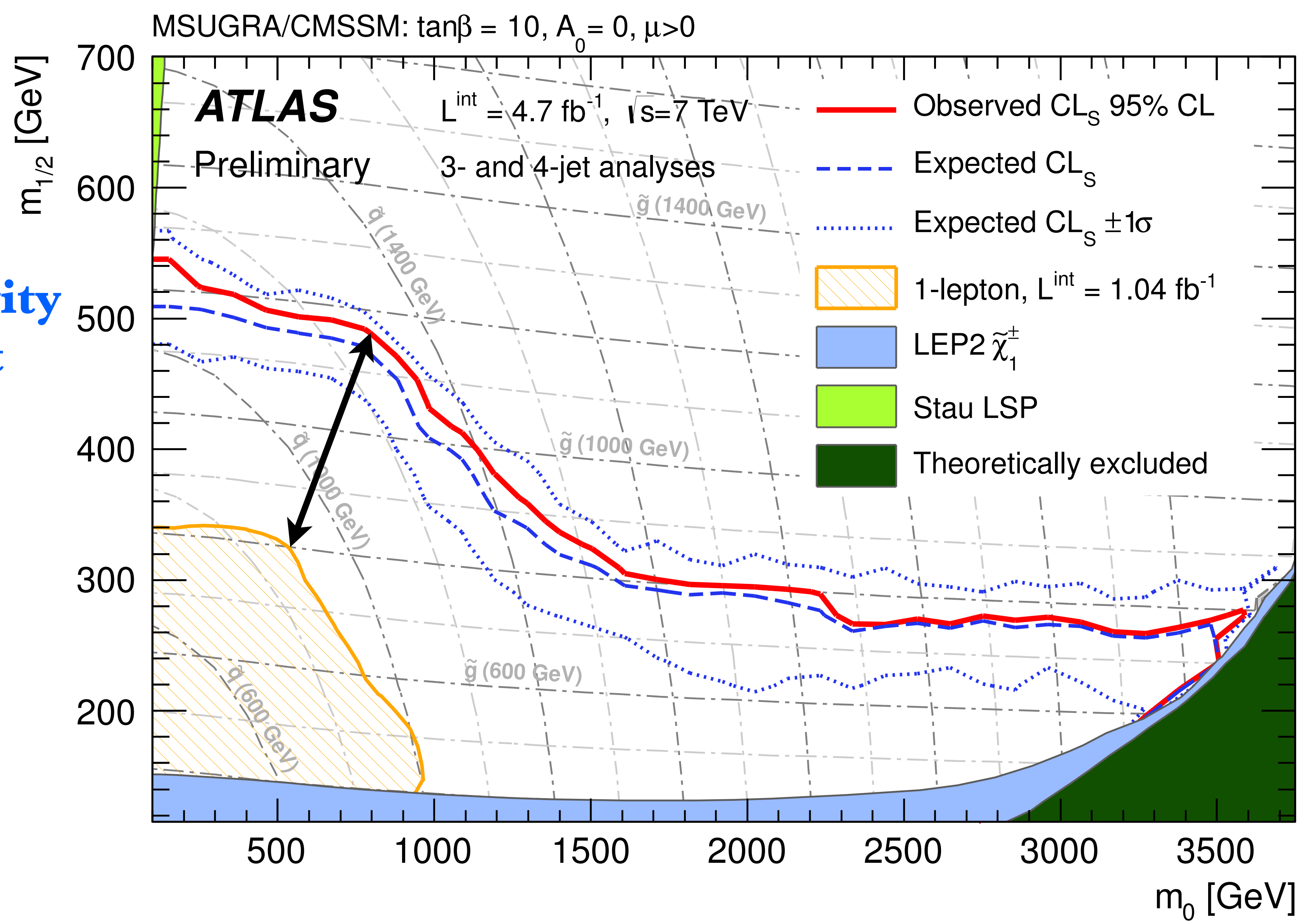
- For exclusion of a particular signal, shape information of M_{eff} is used in the fit (additional discrimination)

- The likelihood is extended to include the bin-by-bin information of the shape
- It also accounts for the signal contamination in the control regions



Interpretation (CMMSM)

Big increase in sensitivity as a result of the BG fit and optimization for CMSSM models



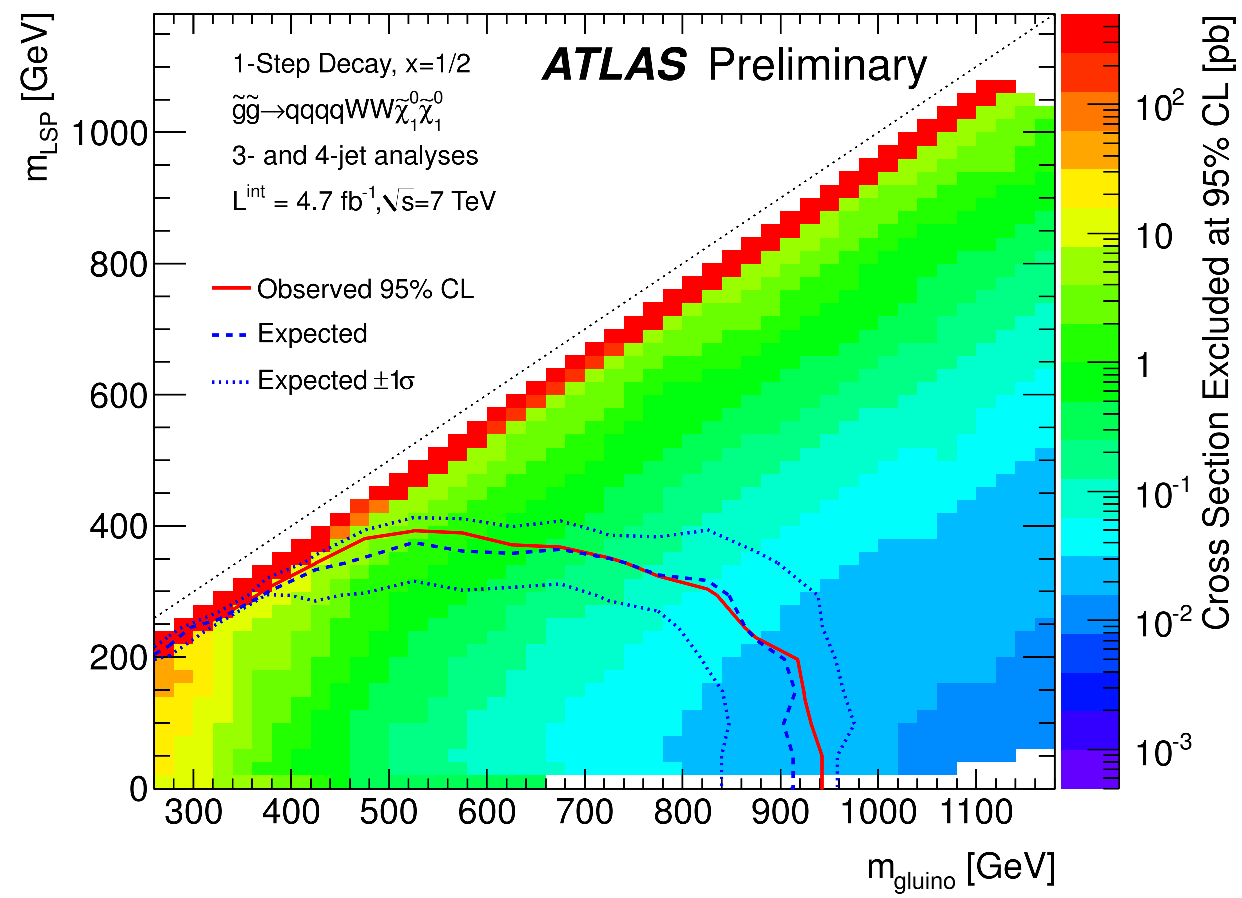
- Statistically combine the 3- and 4-jet analysis
- Masses below 1200 GeV is excluded at 95% CL

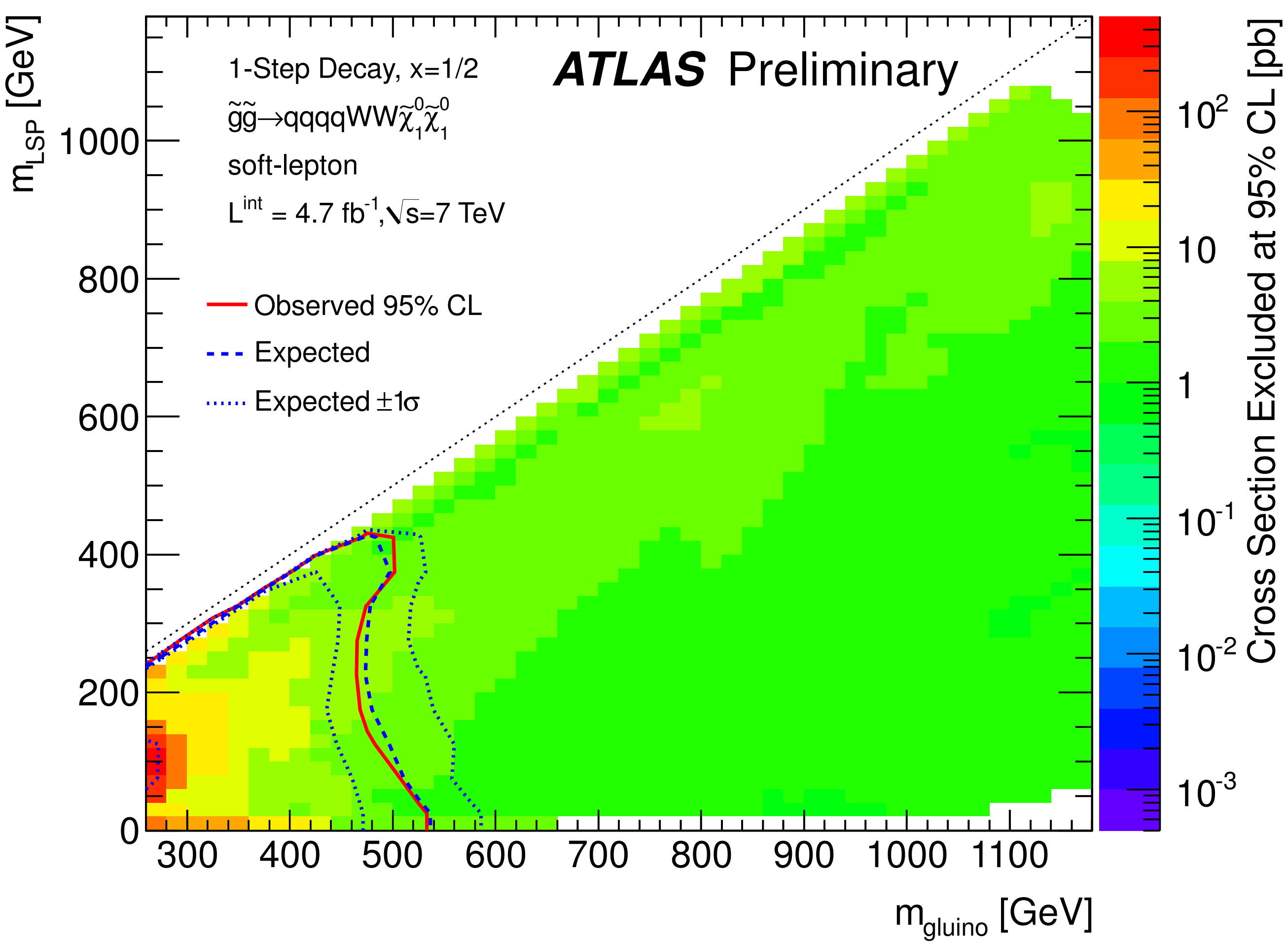
Interpretation (Simplified Model)

- Use one step gluino decay in a g˜g˜ production mode with the following assumptions :

$$\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^{\pm} \rightarrow q\bar{q}'W^{\pm}\tilde{\chi}_1^0$$

$$m_{\tilde{\chi}_1^{\pm}} = \frac{1}{2}(m_{\tilde{g}} - m_{\tilde{\chi}_1^0})$$





- Statistical combination of 3- and 4-jet analysis
- Soft lepton complements in the diagonal region for very compressed spectra of particles

m(g˜) ~ 900 GeV excluded for m(LSP) ~ 200 GeV

2-lepton same-sign + jets + Etmiss

arXiv:1203.5763

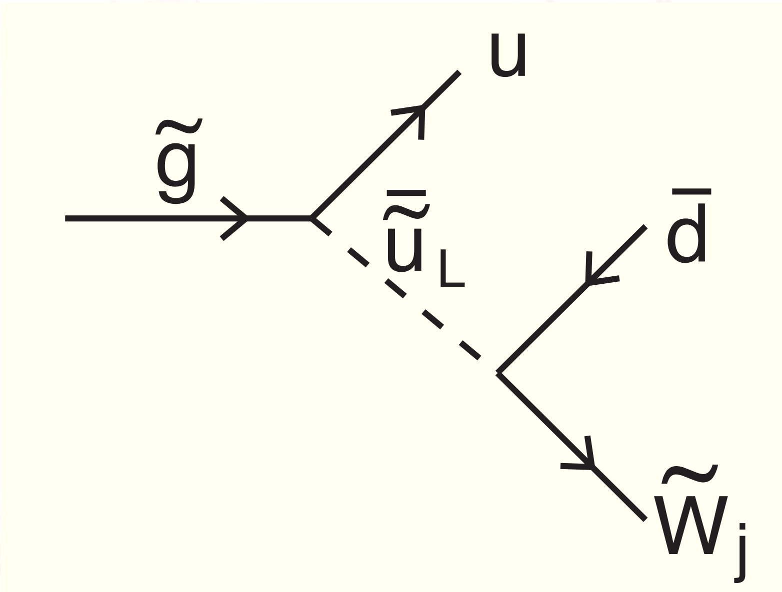
Int. Lumi = 2.0 fb^{-1}

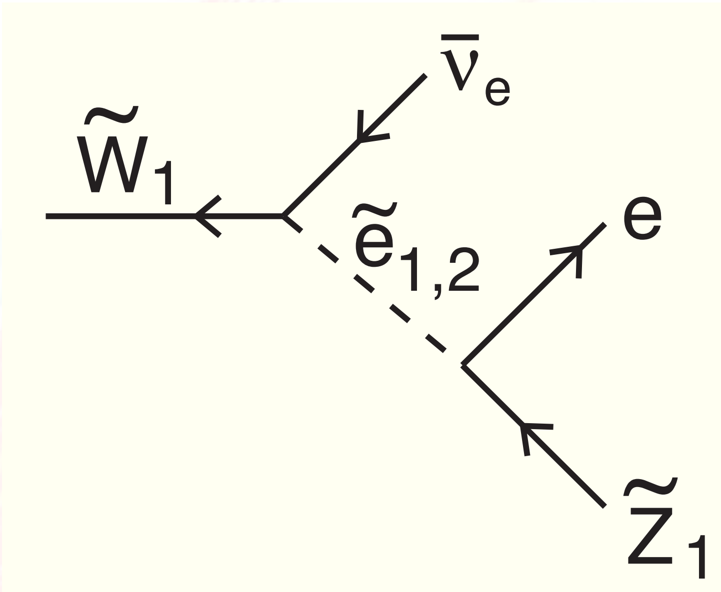
Gluinos with two same-sign leptons

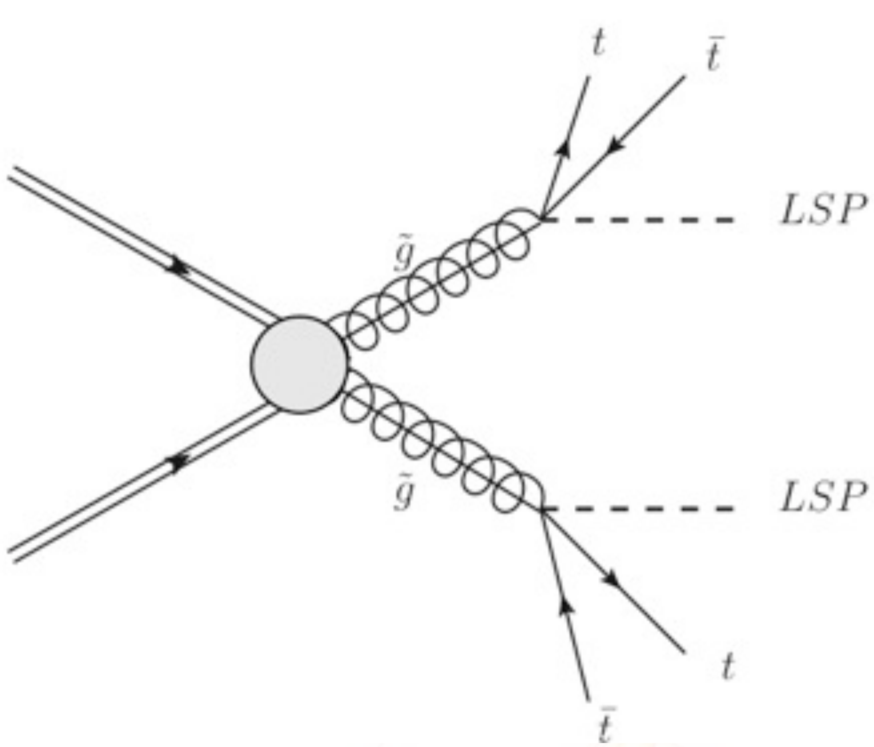
- Gluino is assumed to be Majorana in nature
- A pair produced gluino has equal probabilities to decay to a pair of leptons with same charge (same-sign) and opposite charge

- Signature with two same-sign (SS) leptons are clean and sensitive for a SUSY/new physics discovery
  - **Motivation:**
    - The contribution from the SM processes are much smaller compared to the signal expectation
    - Observation of a new signal would be clean and significant

Gluino mediated productions







- Leptons are produced via cascade decays of gluino to squarks and via sleptons or chargino decay

- If gluino is heavier than the top quark, it produces a stop-top pair

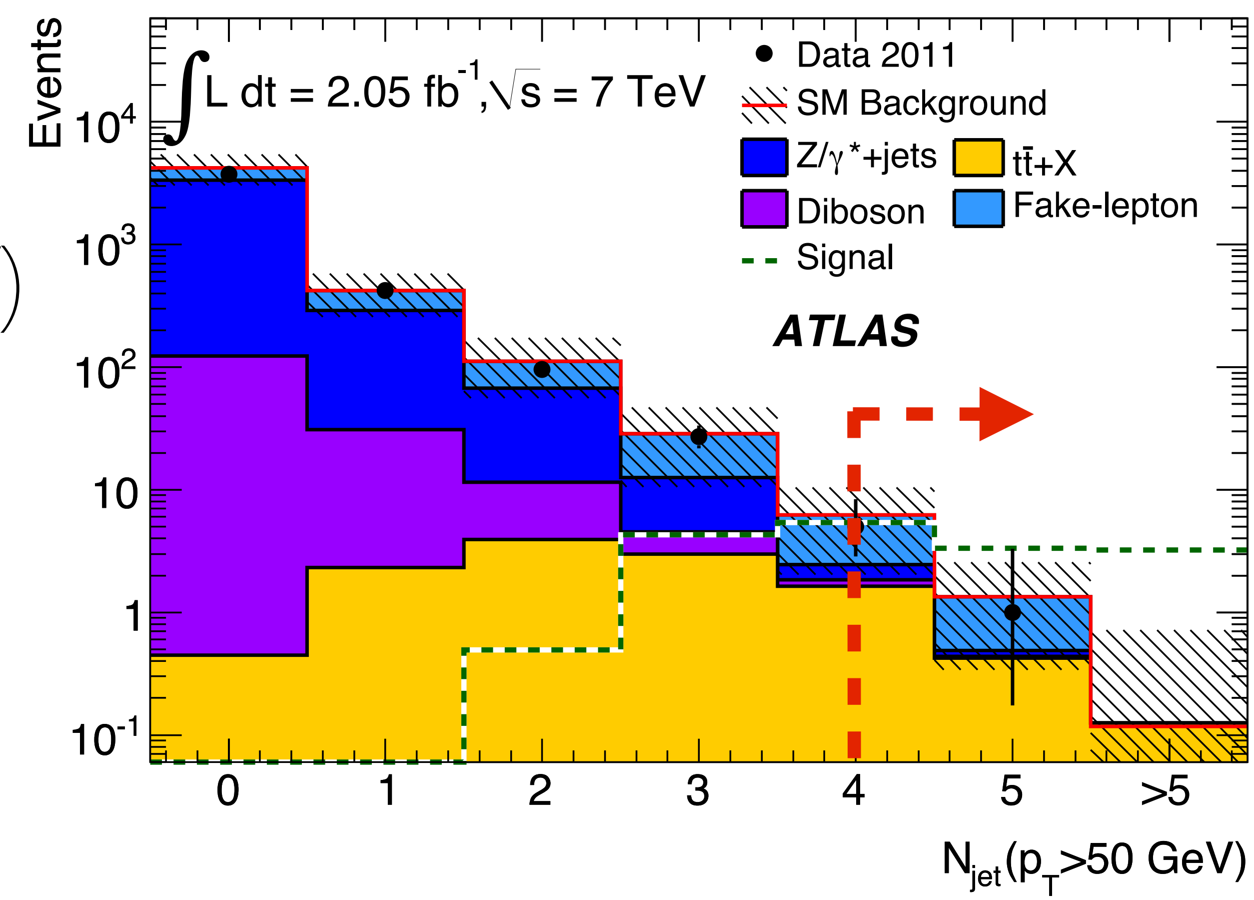
- Leptons can be produced from the decays of top, enhancing the production rate for SS leptons

Selection Criteria

In these decays, high-pT jets and high ETmiss are produced in a signal event along with two or more leptons (with at least a pair of SS leptons)

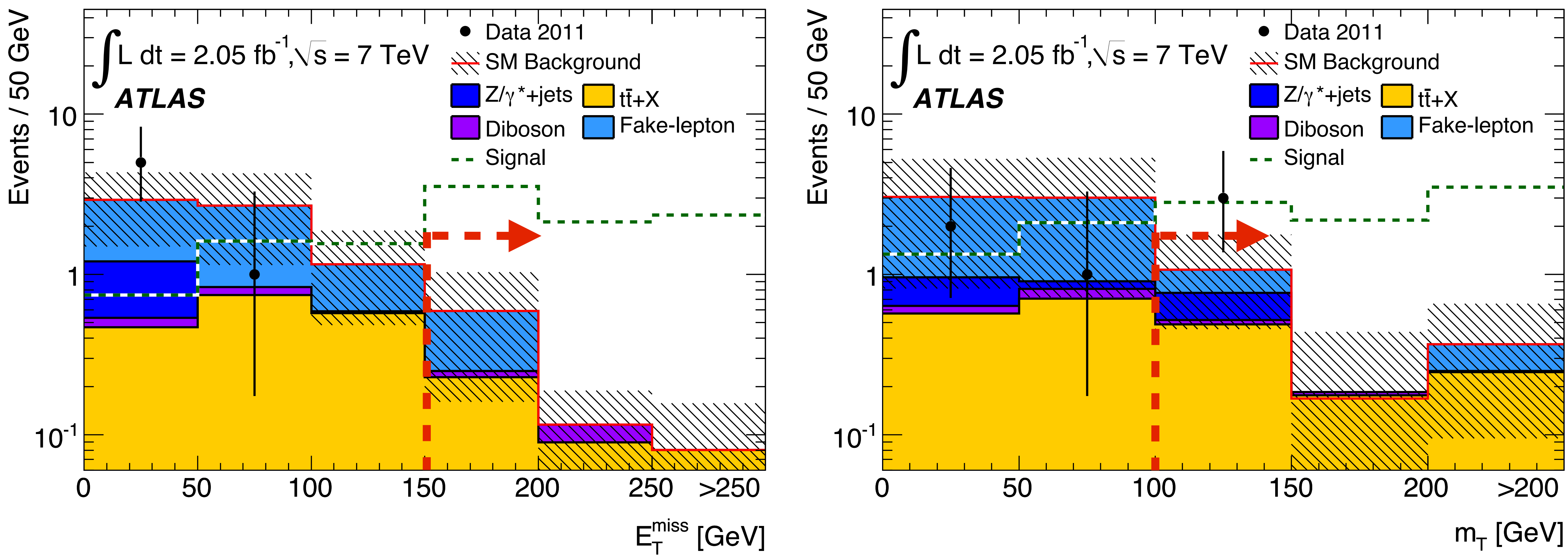
Selection criteria :

- ≥ 2 SS leptons (pT > 20 GeV)
- ≥ 4 jets (pT > 50 GeV)
- Signal Region :
  - (1) ETmiss > 150 GeV
  - (2) M_T > 100 GeV



A typical signal (gluino mediated stop-top decay) has been considered : m(gl) ~650 GeV, m(LSP)~150 GeV

Variables defining Signal Regions



- A cut on ETmiss reduces most of the SM backgrounds

- Some of the irreducible backgrounds are further suppressed by a cut on the Transverse mass (M_T) of the leading lepton and ETmiss system

SM processes as background

The background in SS dilepton analysis due to SM processes can be divided into three categories

1)Fake-lepton background

- Originates from processes that produces at least 1 lepton from a jet-fake-lepton or non-isolated source
- Processes : ttbar + jets, W+jets, QCD-bb, single-top etc…

2)Electron charge mis-identification

- Originates when a real electron goes through a hard bremsstrahlung producing a photon that converts into a pair of electrons
- One of these converted electrons with another lepton from the parent particle creates a same-sign pair
- Processes : Z+jets, dileptonic-ttbar, Diboson

3)Irreducible background

- Real leptons and real ETmiss
- Processes : $W^{\pm}W^{\pm}qq$, ttbar production with associated gauge bosons (ttW, ttZ, etc…)
- Some of these processes are not experimentally observed yet

How do we measure them ?

Fake-lepton background is measured by a data-driven process (aka 'Matrix method')

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

- N_{RF}, N_{FR} and N_{FF} are obtained by inverting the matrix
- N_{TL}, N_{LL} are the number of events obtained after loosening at least one/two out of two leptons
- ***'r'*** and ***'f'*** are the efficiency to obtain a real and fake leptons
- The efficiencies are obtained using dedicated control samples in data
- Estimation method is then validated in regions with looser event selection criteria (based on pT of jets, ETmiss)

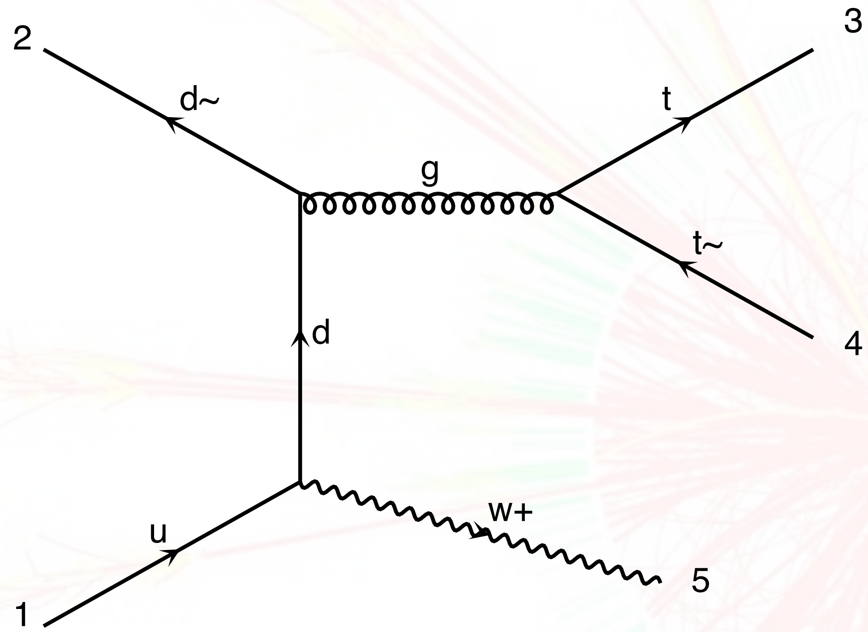
- Backgrounds due to **charge misidentification** is obtained using a semi-data driven method

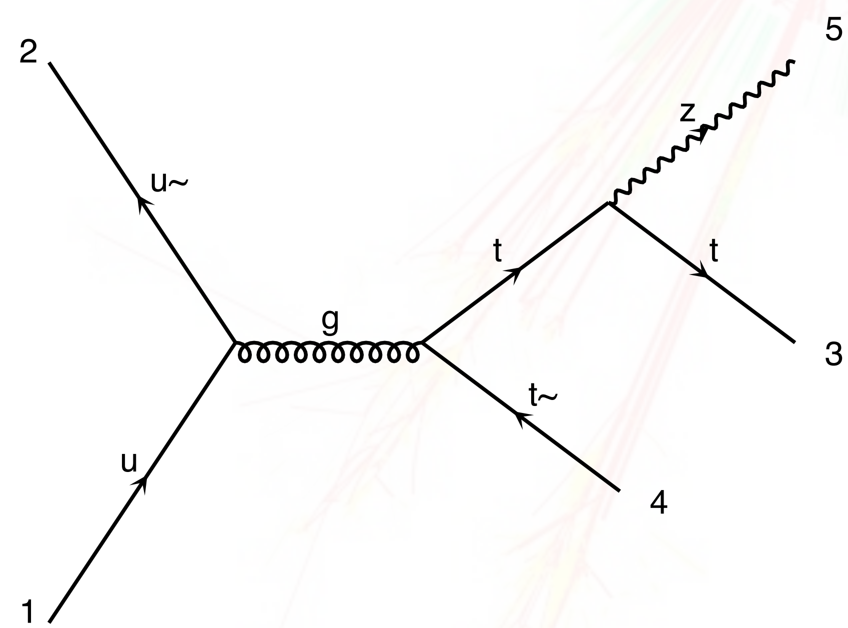
- Control samples using Z(ee) decay are used to obtain the charge misid in MC and data

- Major contribution of charge misid in the signal region comes from dileptonic ttbar+jets events, where both leptons originate from W decay and one of them is misid

- The misid rate from Z(ee) control region is applied to dileptonic-ttbar with lepton pT and Eta dependence

Irreducible background processes are **tt+X (X=W, Z)**





- These are rare productions, so MC simulation is used to derive the rate of these processes in the signal region
- Careful and extensive studies of MC uncertainties are made to ensure the validity of the estimation
- Dominant uncertainties are mainly on theoretical cross-sections of these samples

Background Estimation Results

SR1	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
$t\bar{t}$ +X	0.13 ± 0.09	0.16 ± 0.11	0.09 ± 0.06
Diboson	0.009 ± 0.010	0.017 ± 0.004	0.02 ± 0.02
Fake-lepton	0.09 ± 0.08	< 0.1	0.25 ± 0.15
Charge mis-ID	0.041 ± 0.008	0.039 ± 0.008	negligible
Total SM	0.27 ± 0.12	0.22 ± 0.15	0.36 ± 0.16
Observed	0	0	0

SR2	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
$t\bar{t}$ +X	0.05 ± 0.03	0.11 ± 0.11	0.06 ± 0.05
Diboson	0.001 ± 0.001	negligible	0.02 ± 0.02
Fake-lepton	< 0.1	< 0.1	< 0.1
Charge mis-ID	0.023 ± 0.006	0.016 ± 0.004	negligible
Total SM	0.07 ± 0.11	0.12 ± 0.13	0.08 ± 0.11
Observed	0	0	0

Interpretation with 2 fb^{-1} of ATLAS data

In background compatible observation, limit is set at 95% CL :

1) The visible cross-section of a new signal independent of any signal model
2) Using several signal models

	SR1	SR2
$t\bar{t}$ +X	0.37 ± 0.26	0.21 ± 0.16
Diboson	0.05 ± 0.02	0.02 ± 0.01
Fake-lepton	0.34 ± 0.20	< 0.17
Charge mis-ID	0.08 ± 0.01	0.039 ± 0.007
Total SM	0.84 ± 0.33	0.27 ± 0.24
Observed	0	0
$\sigma_{\mathrm{vis}}^{\mathrm{obs}}$ [fb]	<1.6	<1.5
$\sigma_{\mathrm{vis}}^{\mathrm{exp}}$ [fb]	$<1.7^{+0.5}_{-0.1}$	$<1.6^{+0.2}_{-0.1}$

With zero observation, a limit on the visible cross-section with 2 fb^{-1} integrated luminosity : 3 signal counts correspond to 1.5 fb

Interpretation using signal models

(1) Simplified Gluino ($\tilde{g}$) mediated stop-top($\tilde{t}t$) production
Use decays of stop($\tilde{t}$) and put limits on masses of different particles, m($\tilde{g}$), m($\tilde{t}$) and m(LSP)

(2) Constrained MSSM/MSUGRA
5 parameters : m_0, $m_{1/2}$, $\tan\beta$, A_0, $\mathrm{sgn}(\mu)$
Fix 3 of these parameters and scan other two

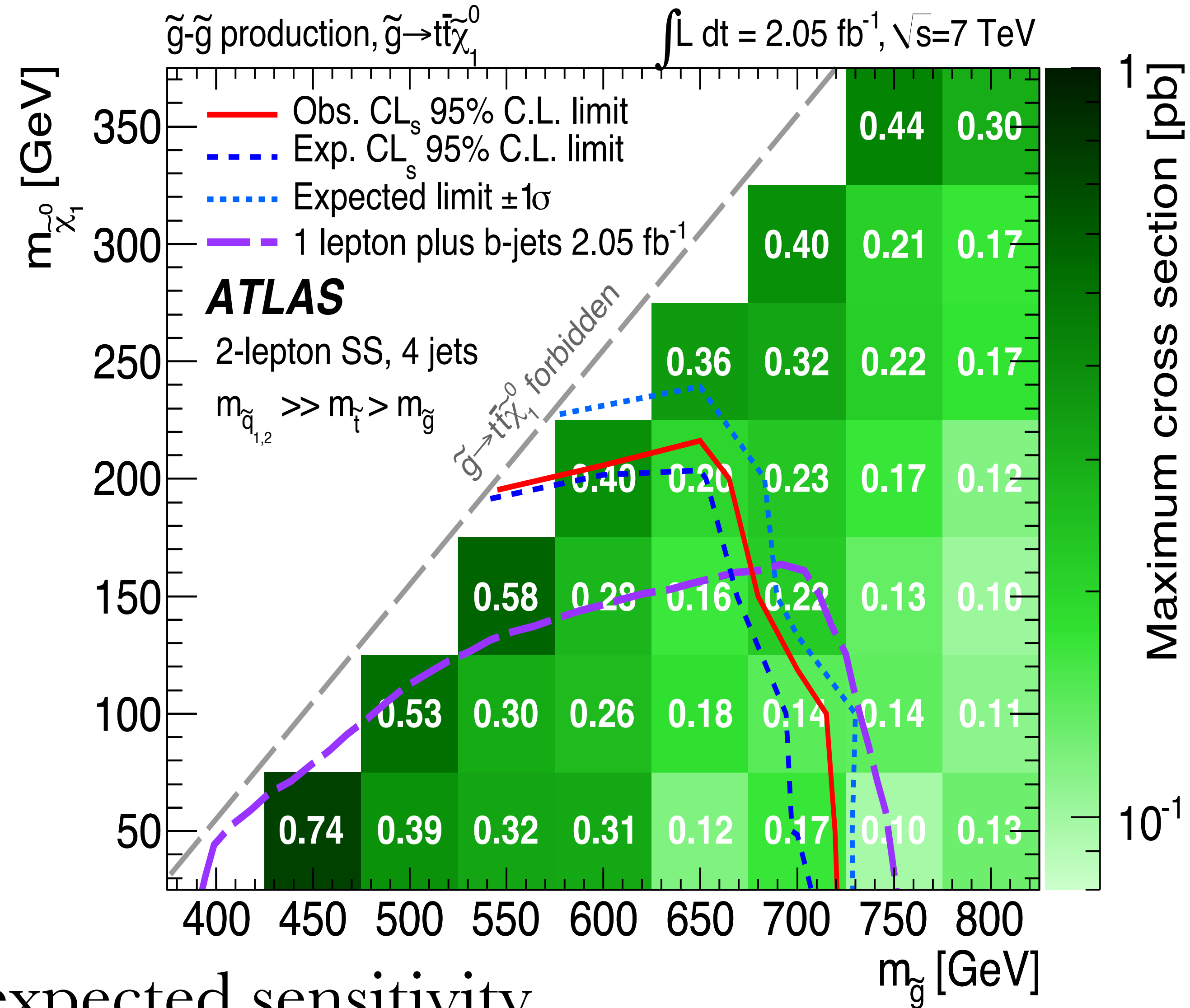
Simplified Model with $\tilde{g}\tilde{g}$ production

Mass Spectrum

- $m(\tilde{g}) < m(\tilde{t}) \sim 1.2$ TeV
- Other squarks are heavier

Decays

- $BR(\tilde{g} \rightarrow tt\tilde{\chi}_1^0) = 1$



- Signal Region (2) provides the best expected sensitivity
- Limit is produced as $f\,[\,m(\tilde{g}), m(\tilde{\chi}_1^0)\,]$
  - Gluino masses below 650 (720) GeV for neutralino masses below 215 (100) GeV are excluded
- Maximum 95% CL upper cross section limit for each model are also shown
  - Better sensitivity in most part of the parameter space compared to 1-lepton+b-jet search for same signal

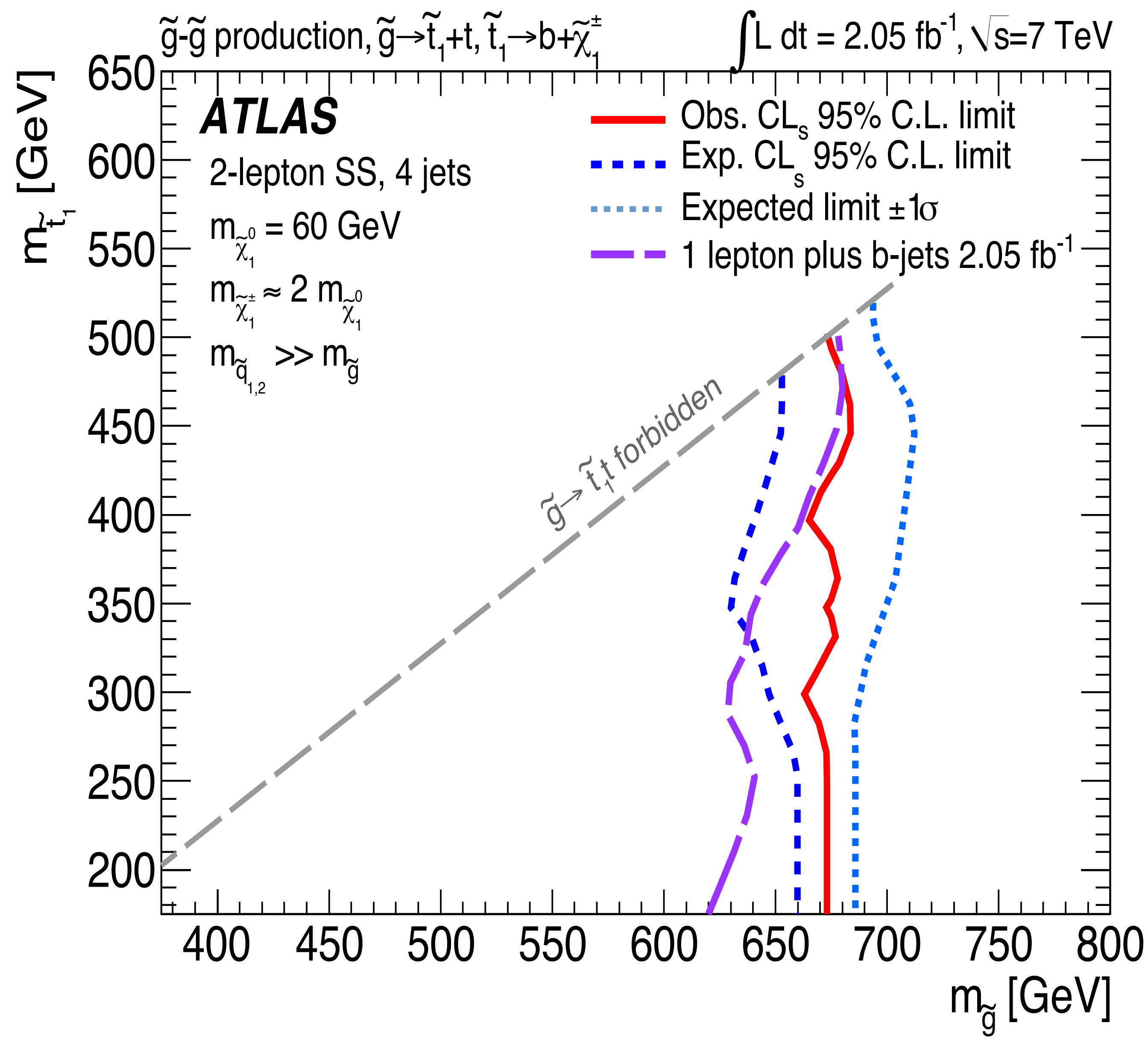
Interpretation with MSSM-24 scenario

Mass Spectrum

- Consider g˜g˜ and t˜t˜* production
- All squarks are heavier than gluino except stop with
  - m(g˜) > m(t˜) + m(t)
  - $m(\tilde{\chi}_1^{\pm}) \sim 2m(\tilde{\chi}_1^0)$
  - $m(\tilde{\chi}_1^0) = 60$ GeV

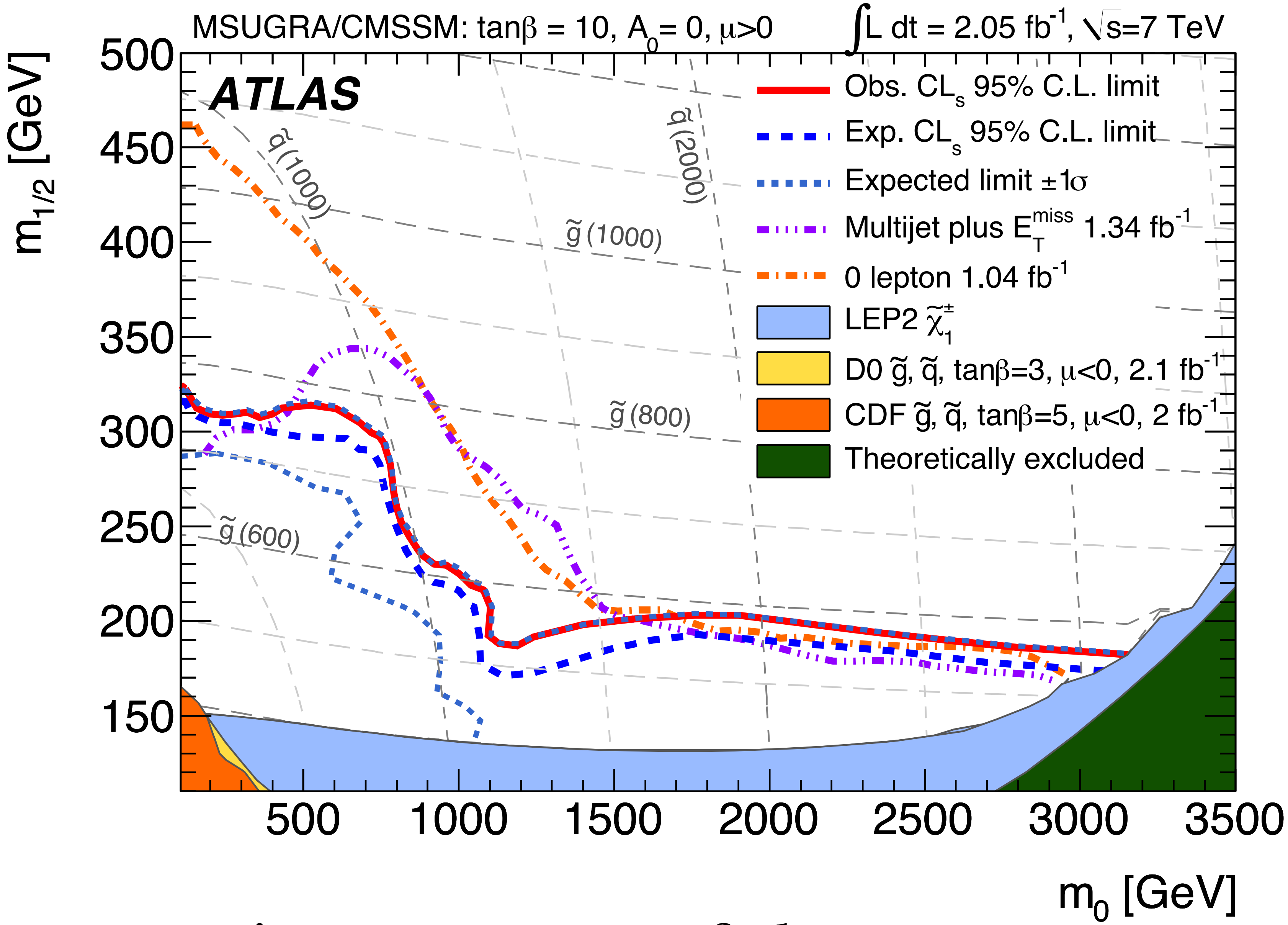
Decays

- $BR(\tilde{g} \rightarrow t\tilde{t}) = 1$
- $BR(\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}) = 1$
- $BR(\tilde{\chi}_1^{\pm} \rightarrow \ell\nu\tilde{\chi}_1^0)$



- Signal Region (2) provides the best expected sensitivity
- Limit is produced as *f* [m(g˜), m(t˜)]
  - Gluino masses below 670 GeV for stop masses below 460 GeV are excluded
  - Similar sensitivity compared to 1-lepton+b-jet search for same signal

CMSSM/MSUGRA limits



- Result improves in some areas of the parameter space and competitive with other searches
- Limit:
  - $m_0 < 700$ GeV is excluded for $m_{1/2} < 300$ GeV
  - $m_0 \sim 2$ TeV is excluded for $m_{1/2} < 180$ GeV

SUMMARY

- Strong-SUSY is being heavily constrained by the searches at the LHC
- The leptonic searches look for corners that are not covered
  - Compressed spectra of SUSY particles
  - Decay via third generation

- With the updated 1-lepton + jets + Etmiss searches, ATLAS provides one of the best limits in CMSSM with 4.7 fb^{-1}
  - A new analysis is done with soft-lepton scenario that complements the default hard-lepton case
    - Masses of strongly produced particles are excluded up to 1.2 TeV for CMSSM model
    - $m(\tilde{g}) < 900$ GeV is excluded for m(LSP) ~ 200 GeV for the simplified model considered

- Same-sign dilepton search is clean and very sensitive for new physics, especially for gluino production modes
  - Decay via 3^{rd} generation squarks are extremely important and can be exploited using this channel
    - $m(\tilde{g}) \sim 670$ GeV is excluded up to $m(\tilde{t}) \sim 460$ GeV