# Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector

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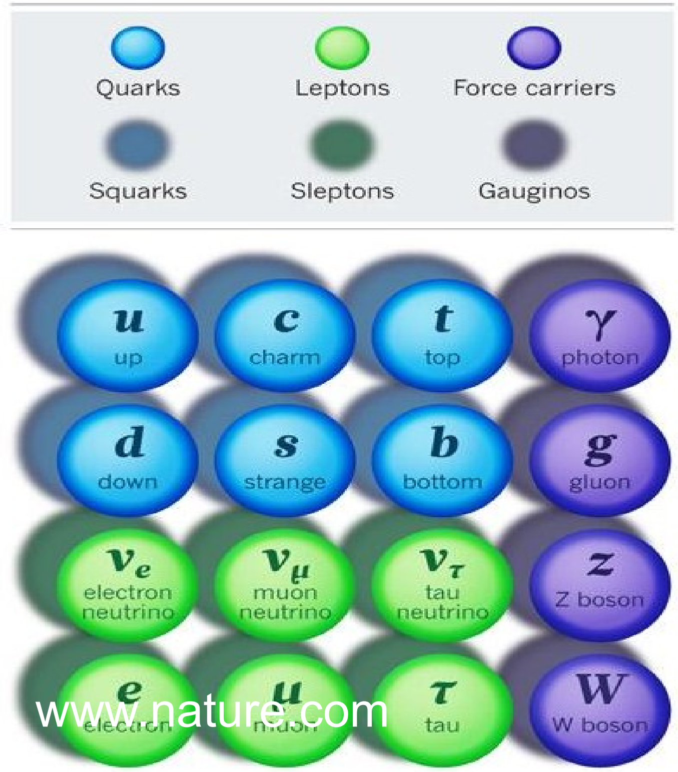
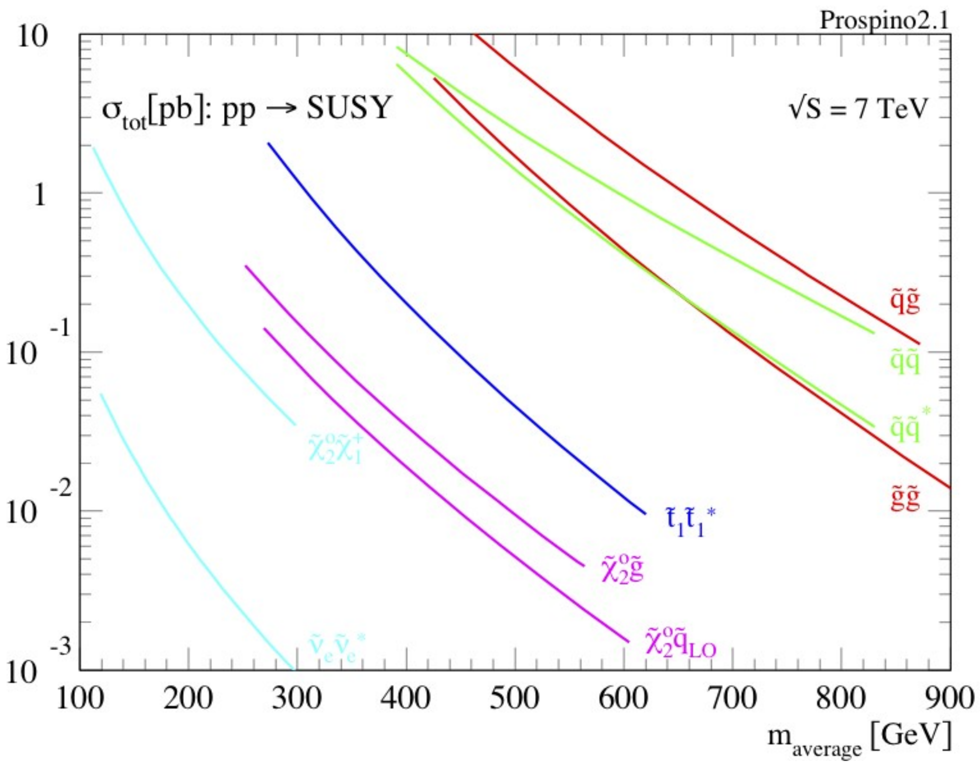
6th Annual Workshop of the Helmholtz Alliance
"Physics at the Terascale"
Hamburg 2012

# Introduction I




- Dominant SUSY particle production at LHC: **gluino-gluino, squark-squark, squark-gluino**

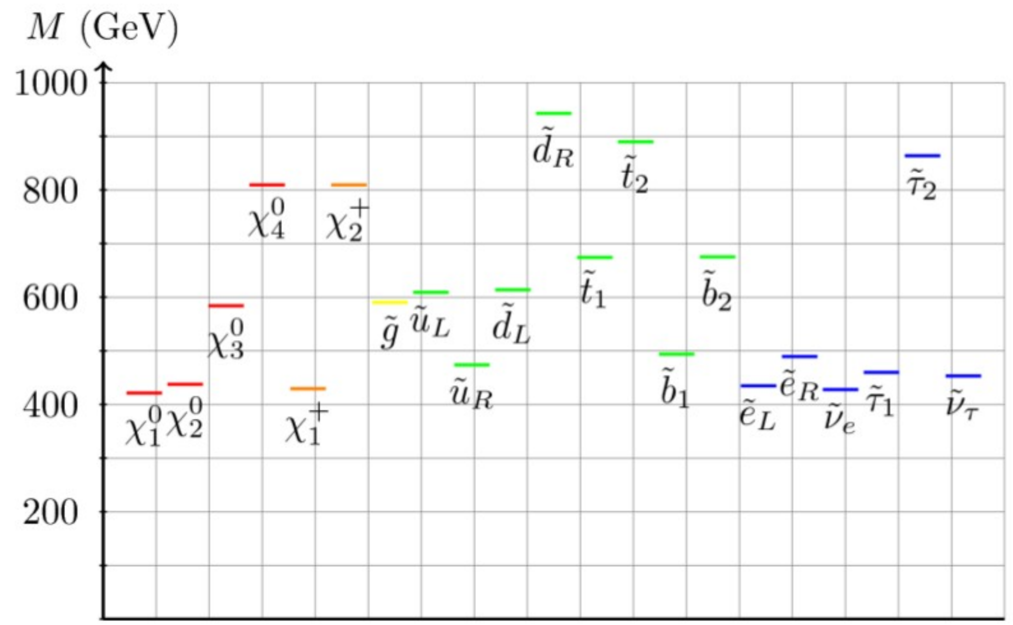


# Introduction II

- Assume ***R-Parity conservation***

  → the **Lightest Susy Particle (LSP)** is stable and escapes the detector unseen

- Event topology depends on masses and mass splittings of particles




- Analysis targeted at decays in more or less complex cascades to **LSP**

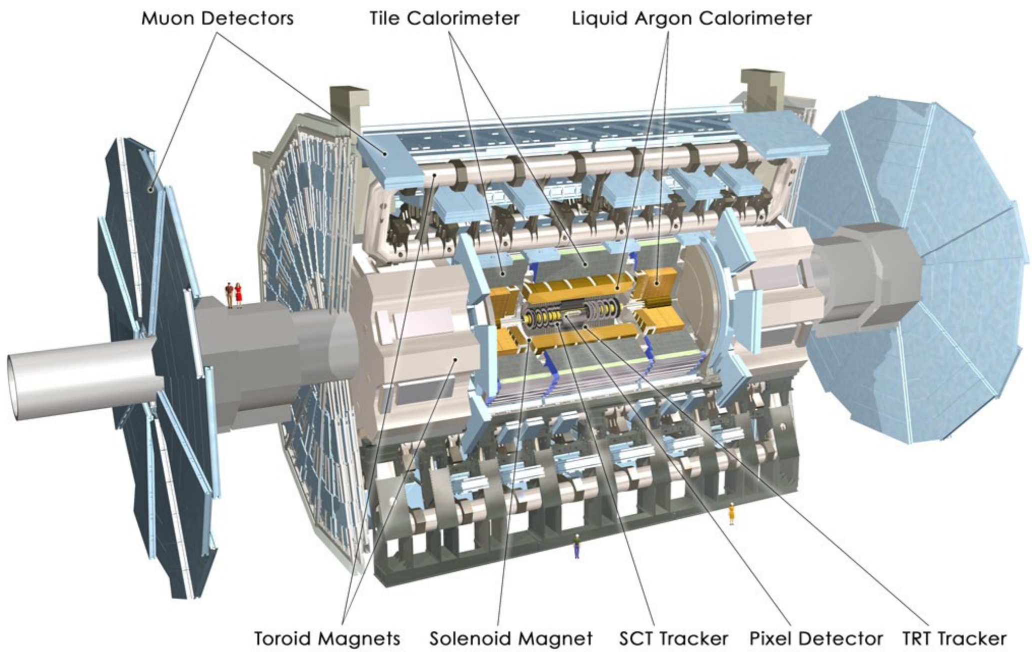
$$\tilde{g} \longrightarrow \tilde{\chi}_1^0 \mathrm{jj} \qquad \tilde{g} \longrightarrow \tilde{\chi}_1^{\pm} jj \longrightarrow W^{\pm}\tilde{\chi}_1^0 \mathrm{jj}$$

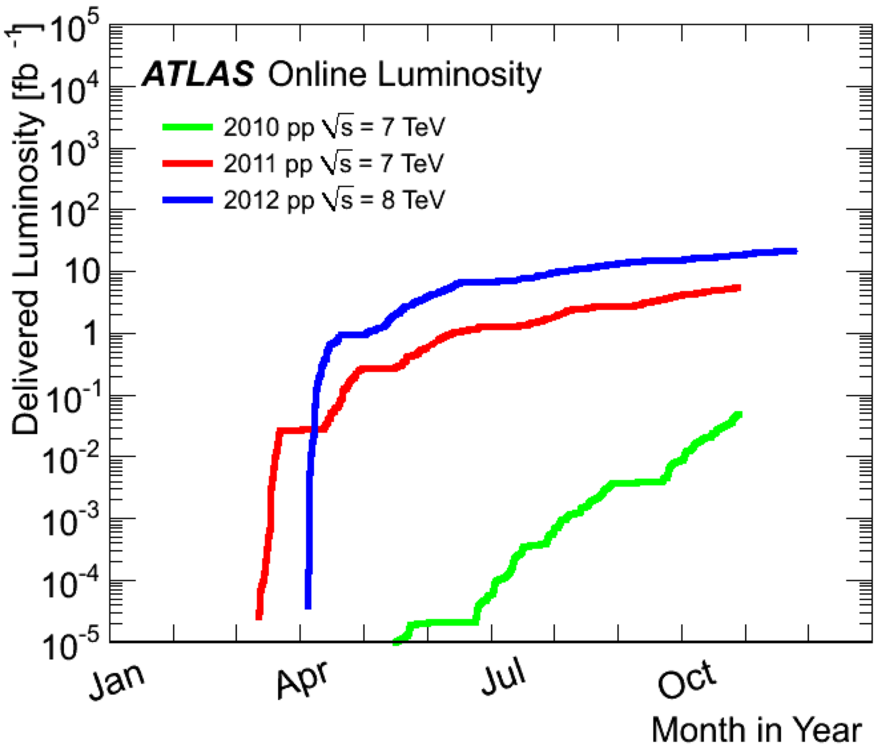
$$\tilde{q} \longrightarrow \tilde{\chi}_1^0 \mathrm{j} \qquad \tilde{q} \longrightarrow \tilde{\chi}_1^{\pm} j \longrightarrow W^{\pm}\tilde{\chi}_1^0 \mathrm{j}$$

more compressed spectra → softer jets spectrum

→ final states with **jets** and **missing transverse momentum**

# Introduction III



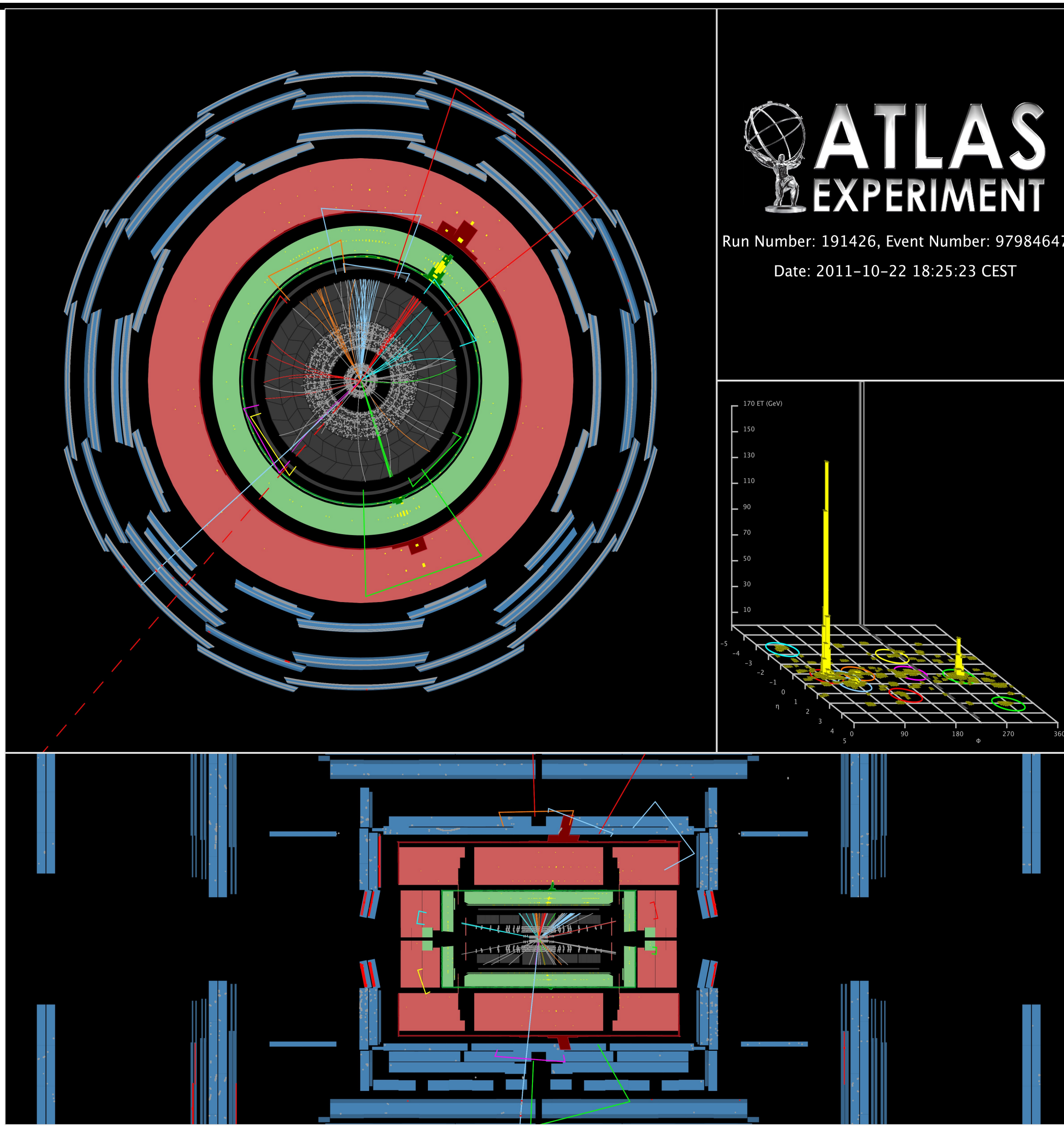




Results presented in this talk correspond to

- **4.7 fb$^{-1}$** of **7TeV** (*arXiv:1208.0949, submitted to PRD )*
- **5.8 fb$^{-1}$** of **8 TeV** (*ATLAS-CONF-2012-109 )*

proton-proton collision data

# Event Display




$E_t^{miss}$ = 984 GeV

**Jet $p_T$** = 974, 276, 146 ,61 GeV .

$$m_{\mathrm{eff}} \equiv \sum_{i=1}^{n} |\mathbf{p}_{\mathrm{T}}^{(i)}| + E_{\mathrm{T}}^{\mathrm{miss}}$$

scalar sum of $E_t^{miss}$ and $p_T$ of jets with $p_T$>40 GeV

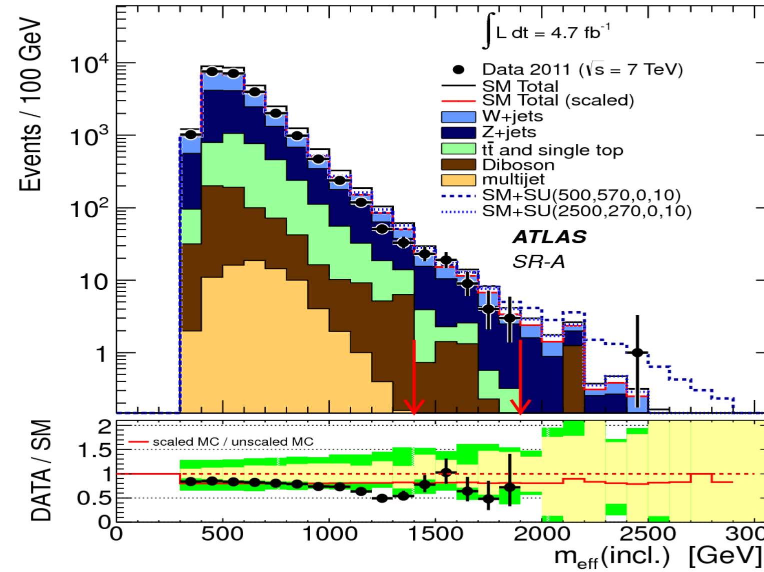
# Analysis strategy

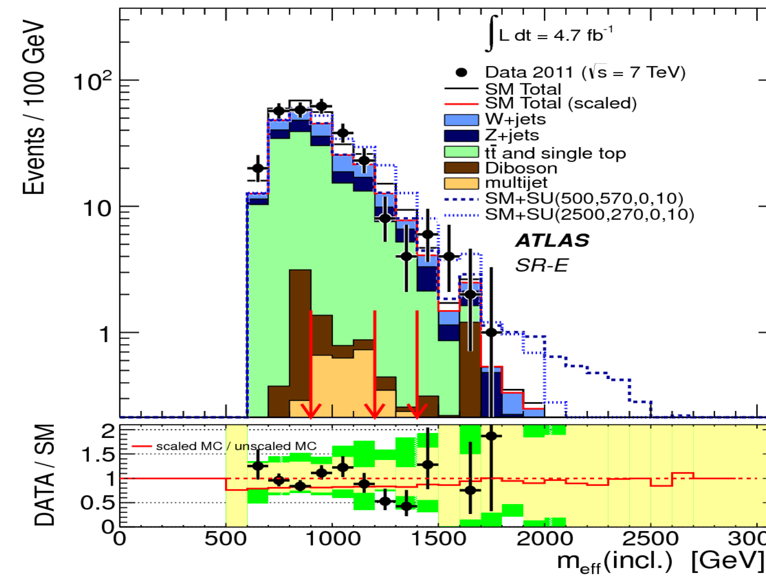
- Inclusive signal regions with different jet multiplicities
- Veto events with one or more e,μ
- Event selection is based on effective mass ($m_{eff}$)

Multi-jets background:
*mis-measured jets or emission of neutrino in heavy flavor decay, potentially high cross section !*

**Analysis designed to reject multi-jets Bkg. efficiently**

| Requirement | Channel | | | | | |
|---|---|---|---|---|---|---|
| | A | A′ | B | C | D | E |
| $E_T^{miss}$[GeV] > | 160 | | | | | |
| $p_T(j_1)$ [GeV] > | 130 | | | | | |
| $p_T(j_2)$ [GeV] > | 60 | | | | | |
| $p_T(j_3)$ [GeV] > | – | – | 60 | 60 | 60 | 60 |
| $p_T(j_4)$ [GeV] > | – | – | – | 60 | 60 | 60 |
| $p_T(j_5)$ [GeV] > | – | – | – | – | 40 | 40 |
| $p_T(j_6)$ [GeV] > | – | – | – | – | – | 40 |
| $\Delta\phi(\text{jet}_i, \vec{P}_T^{miss})_{min}$ [rad] > | 0.4 ($i = \{1,2,(3)\}$) | | | 0.4 ($i = \{1,2,3\}$), 0.2 ($p_T > 40$ GeV jets) | | |
| $E_T^{miss}/m_{eff}$ ($N$j) > | 0.3 (2j) | 0.4 (2j) | 0.25 (3j) | 0.25 (4j) | 0.2 (5j) | 0.15 (6j) |
| $m_{eff}$(incl.) [GeV] > | 1900/1400/– | –/1200/– | 1900/–/– | 1500/1200/900 | 1500/–/– | 1400/1200/900 |




*(from arXiv:1208.0949)*

# Background estimation: QCD multi jets

Targeted at

*mis-measured jets or emission of neutrino in heavy flavor decay*

Jets and $E_T^{miss}$ point into **same direction**

Data driven method**:**

· Measure low-$E_T^{miss}$ events

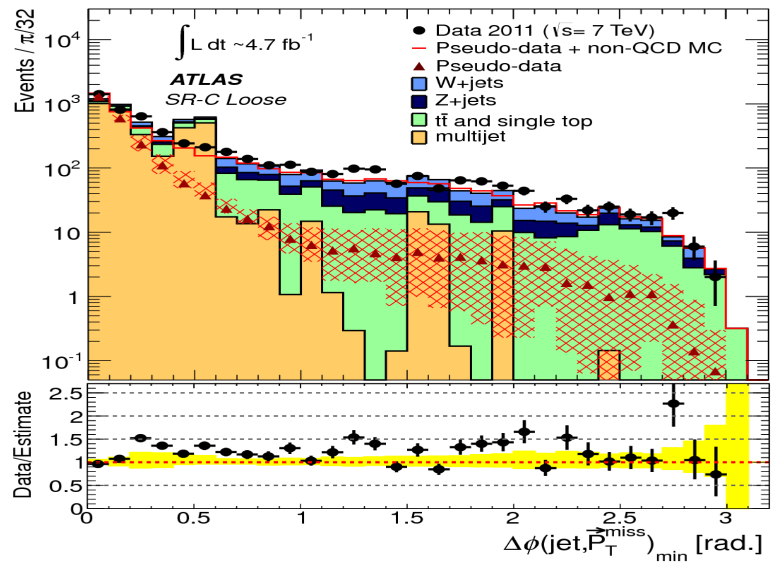
· Response function of calorimeter based on MC simulation

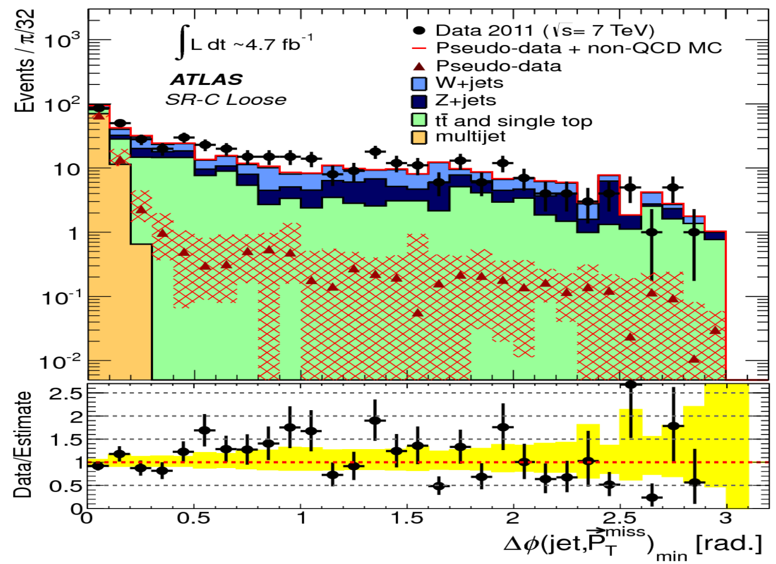
• Smear low-$E_T^{miss}$ events based on response function

**Control region used for normalisation**:

• Cut on angular separation between jets and $E_T^{miss}$ inverted and tightened

• same **meff** requirement as SR



# Background estimation: Z + jets

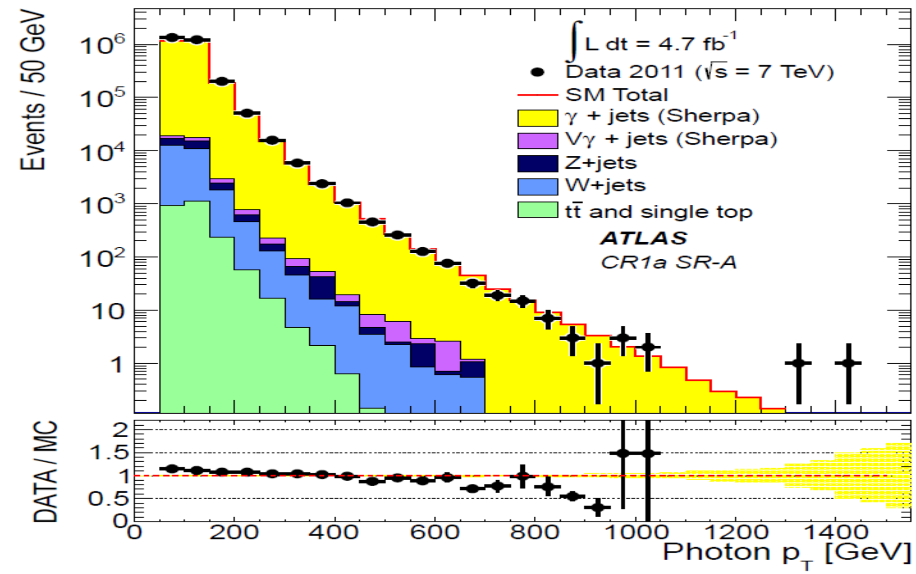
***Irreducible*** *$Z \rightarrow \nu\bar{\nu}$ + jets generates large $E_T^{miss}$*

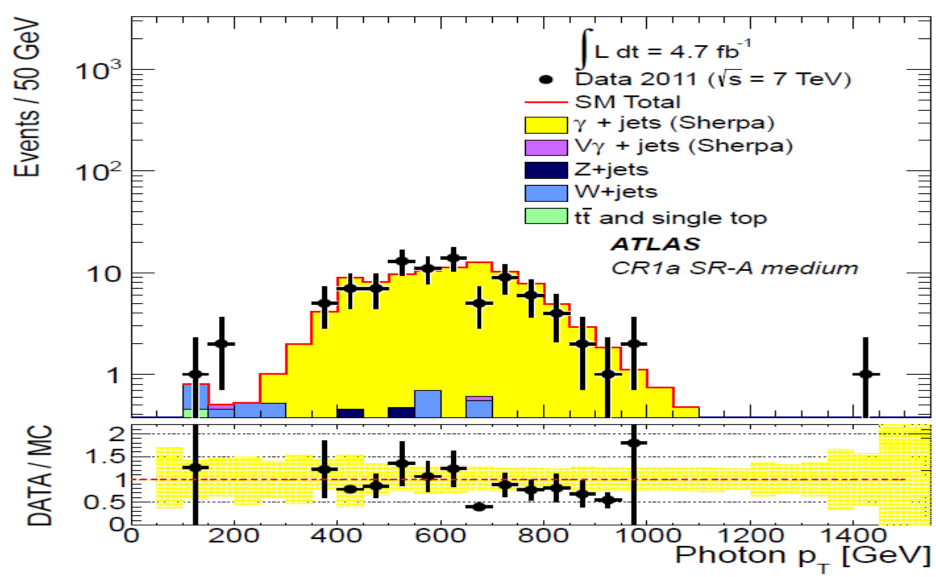
- Isolated **photon + jets** sample as control region
- At large $p_T$ cross sections of γ,Z differ only by coupling constants to quarks

$$R_{Z/\gamma} = \frac{d\sigma(Z + \mathrm{jets})/dp_\mathrm{T}}{d\sigma(\gamma + \mathrm{jets})/dp_\mathrm{T}}$$

- Reconstructed momentum of photon is added to $E_t^{miss}$
- *$Z \rightarrow \nu\bar{\nu}$ + jets in SR :*

$$N^{Z(\rightarrow\nu\bar{\nu})}(p_\mathrm{T}) = N^{\gamma}(p_\mathrm{T}) \cdot \left[ \frac{(1 - f_\mathrm{bkg})}{\varepsilon^{\gamma}(p_\mathrm{T}) \cdot A^{\gamma}(p_\mathrm{T})} \cdot R_{Z/\gamma}(p_\mathrm{T}) \cdot Br(Z \rightarrow \nu\bar{\nu}) \right].$$



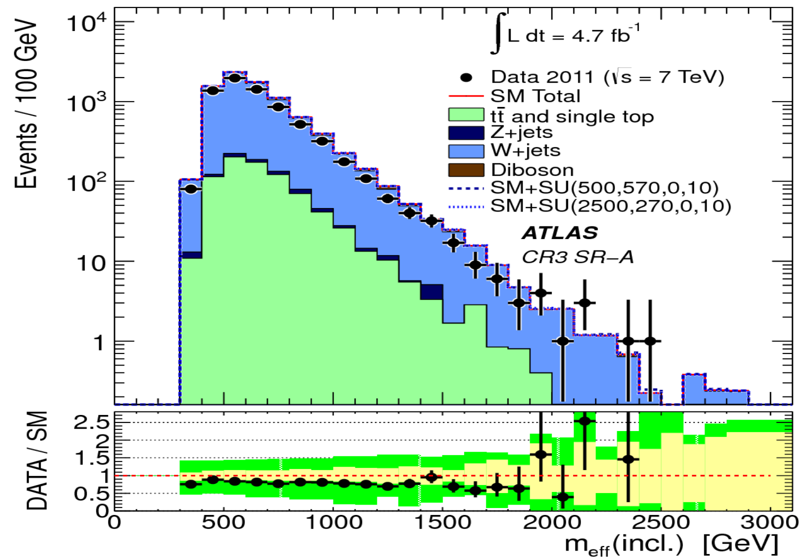
# Background estimation: W + jets

*W → lν + jets with lepton measured as jet*

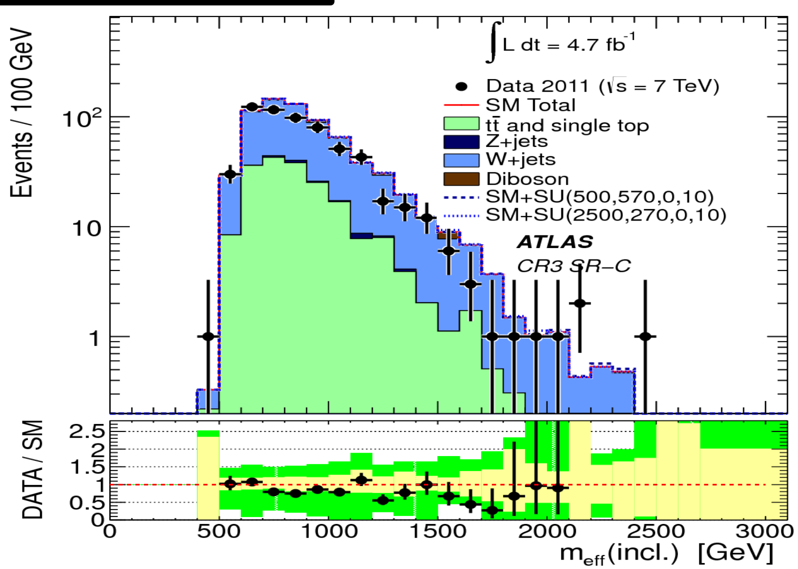
Normalisation region:

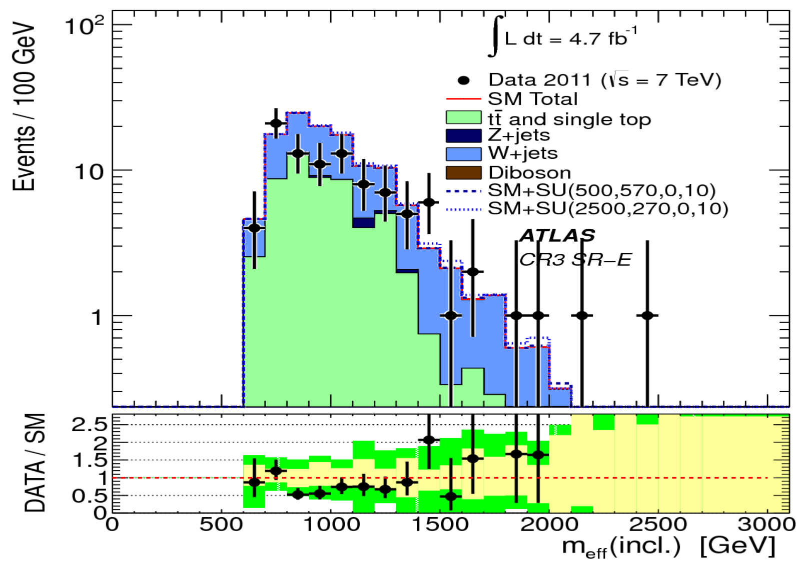
- one lepton
- significant $E_T^{miss}$
- Transverse mass consistent with W
- Veto against b-jets

Lepton is replaced with jet
to estimate kinematic quantities




- Extrapolation(TF) to SR via MC



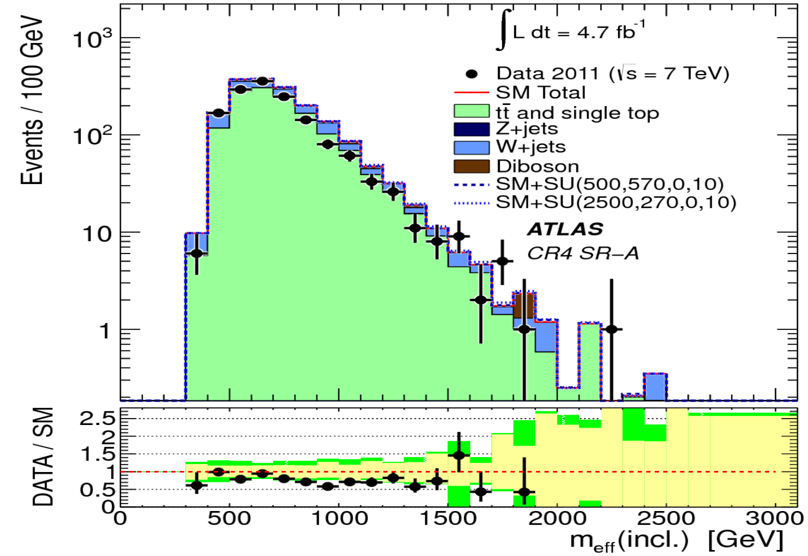



# Background estimation: tt + jets

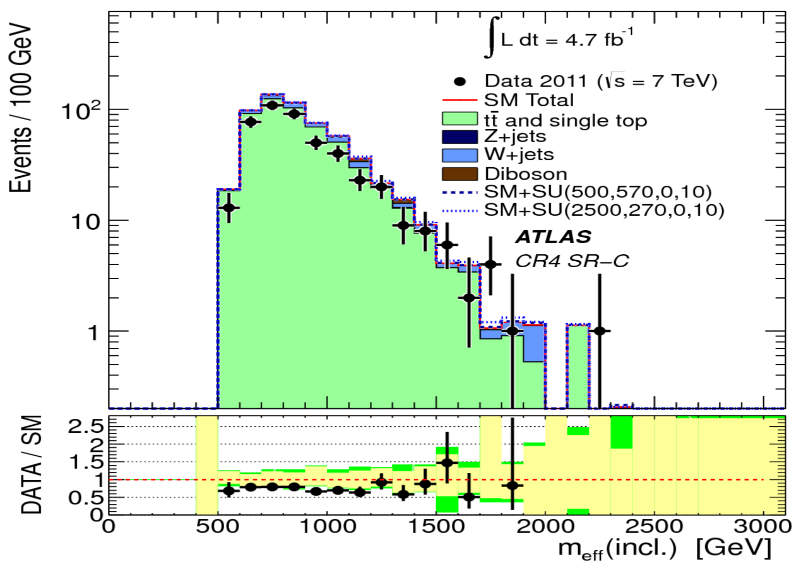
*$t\bar{t}$ + jets and single top,*
*mainly hadronic τ decays in $t\bar{t} \rightarrow b\bar{b}\tau\nu qq$*

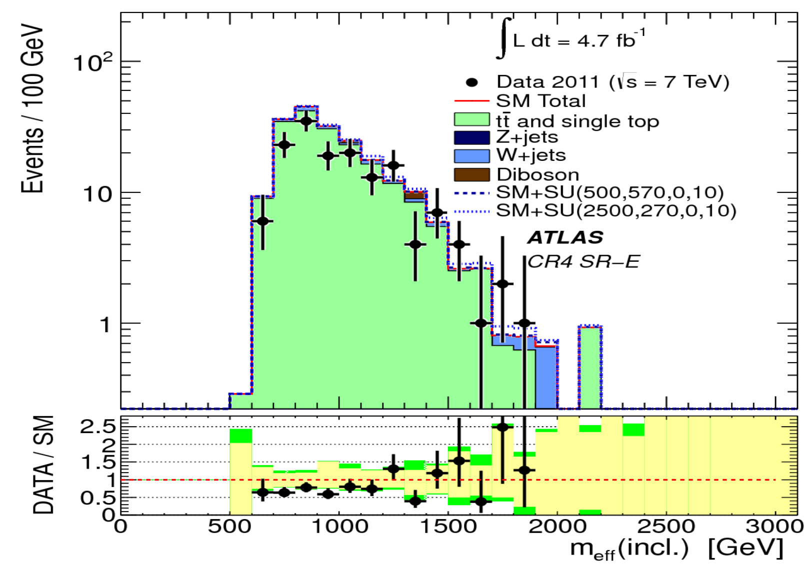
Normalisation region:

- one lepton
- significant $E_T^{miss}$
- Transverse mass consistent with W
- **b-jet requirement**

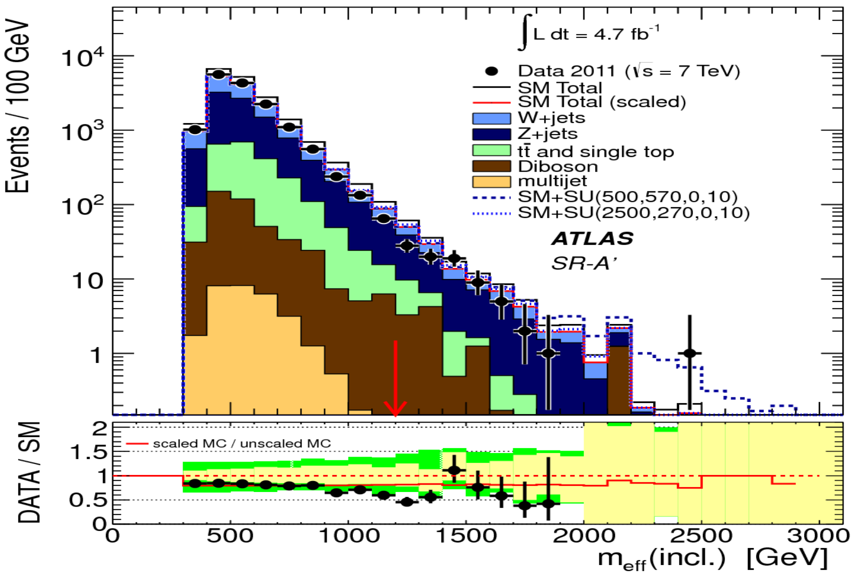


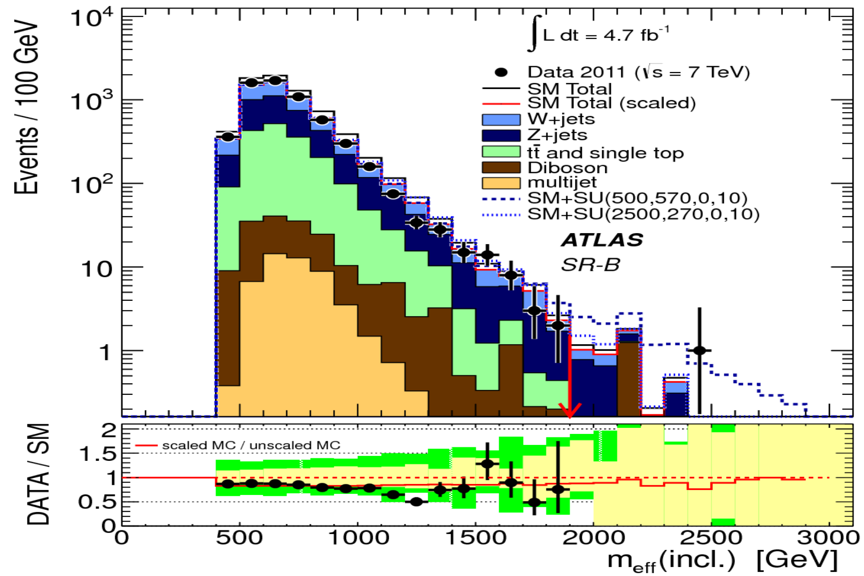

Extrapolation(TF) to SR via MC



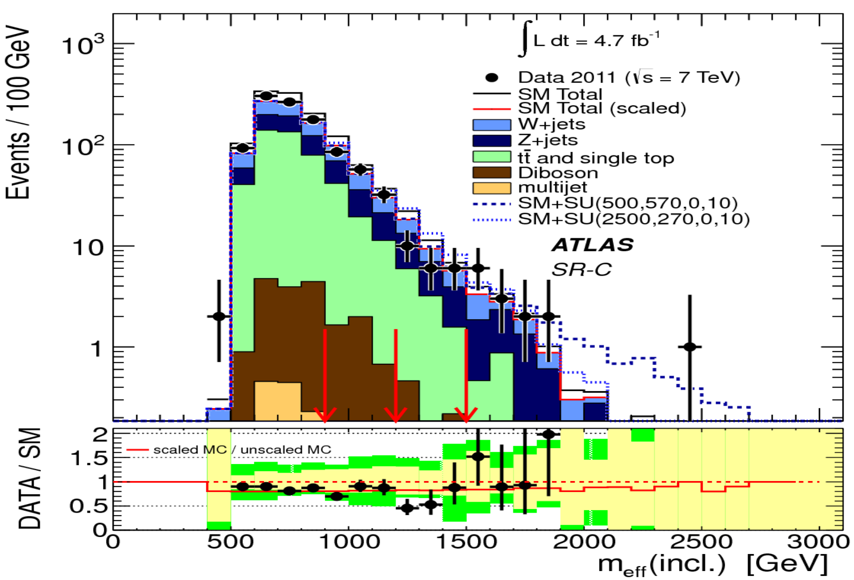



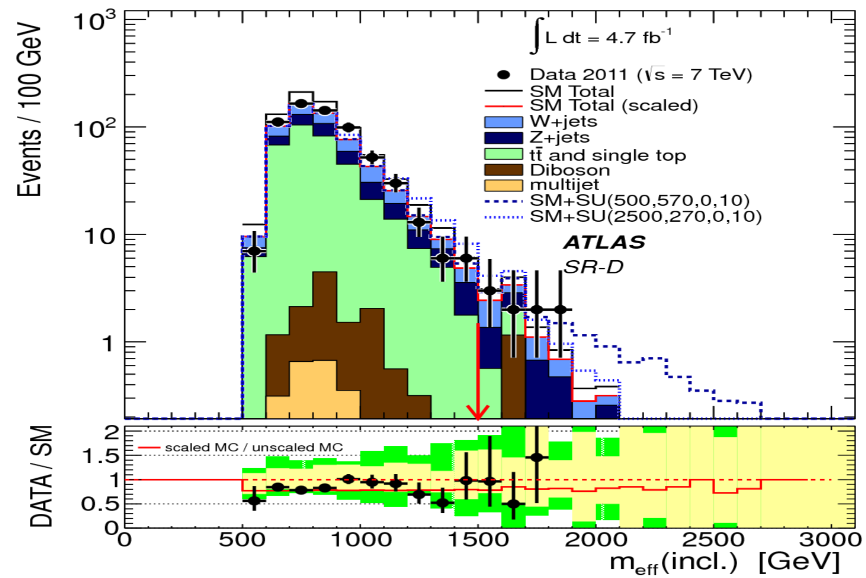
# Results I




**No deviation from SM observed**

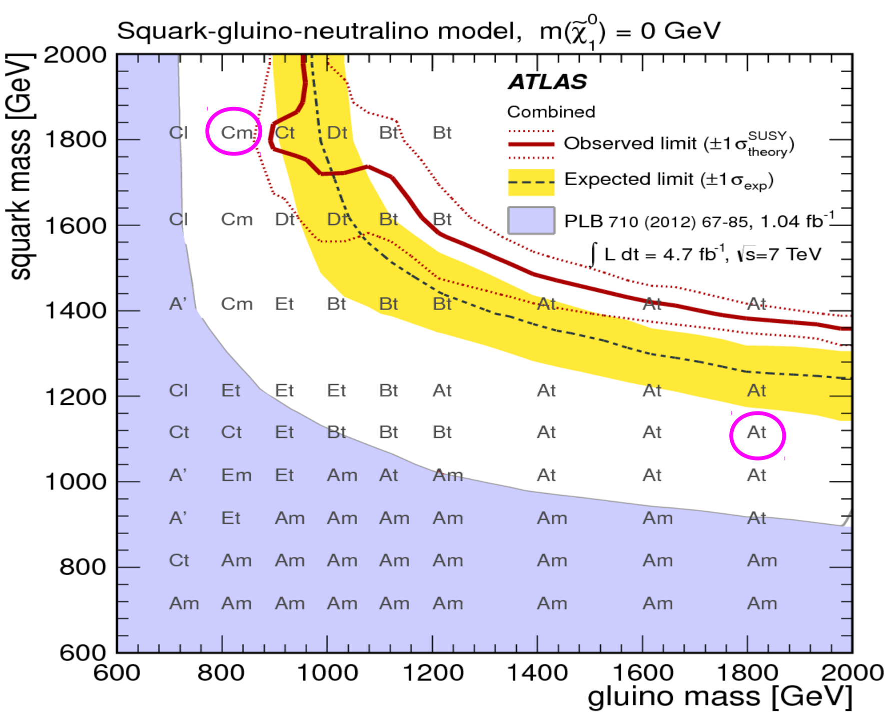


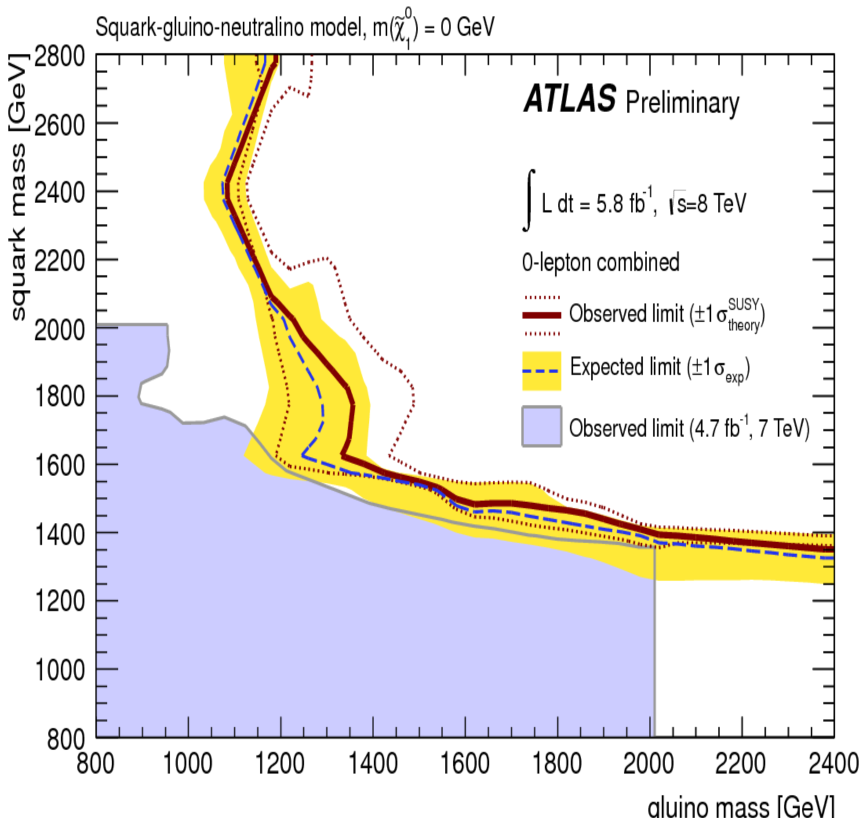
# Results II

Production: **gluino-gluino, squark-squark, squark-gluino (**squark 1.-2. Gen. **)**
**Direct** decay to massless LSP

- 11 SR with different jet multiplic. + $m_{eff}$ cut
- profile log likelihood ratio test statistic
- pick best ***expected*** signal region based on CLs



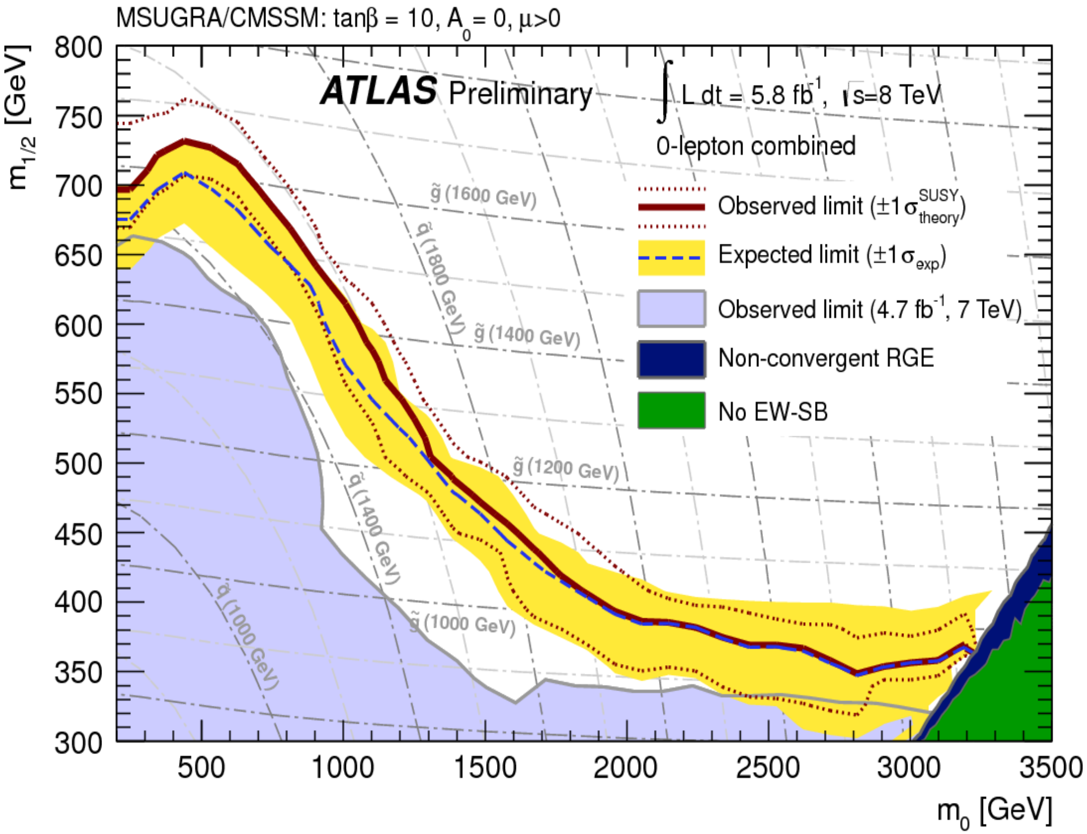

*(from arXiv:1208.0949)* ***7 TeV***

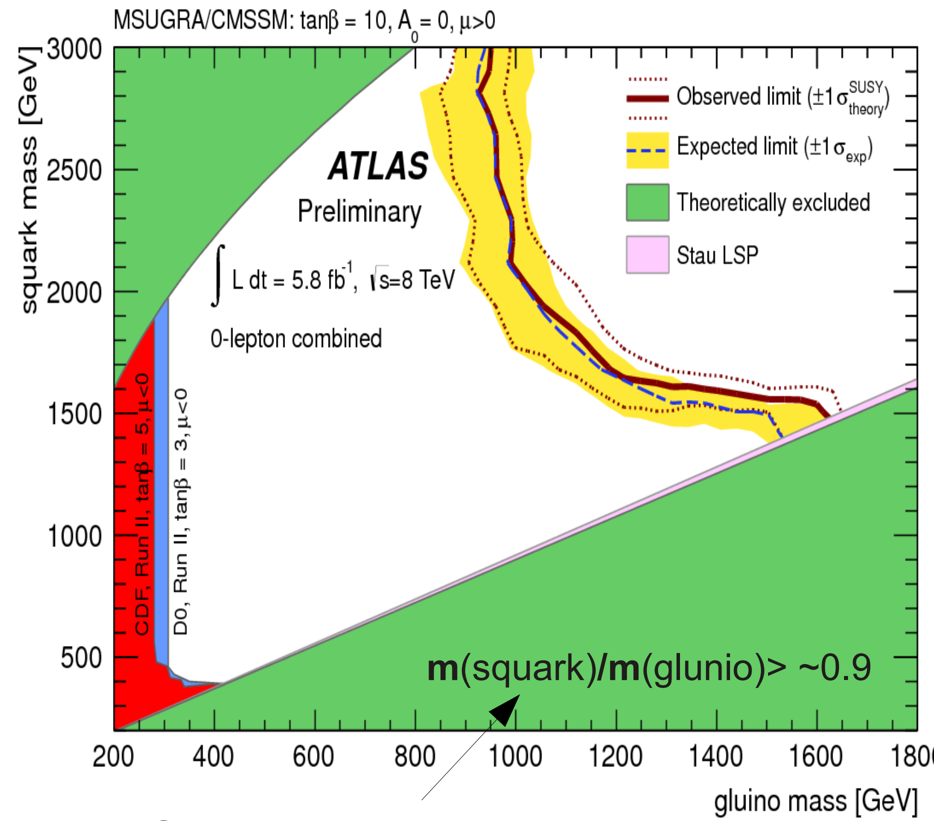



*(ATLAS-CONF-2012-109)* ***8 TeV***

# Results III

Constrained Model: **CMSSM** with $\tan\beta=10$, $A_0=0$, $\mu>0$




**m**(squark)/**m**(glunio)> ~0.9

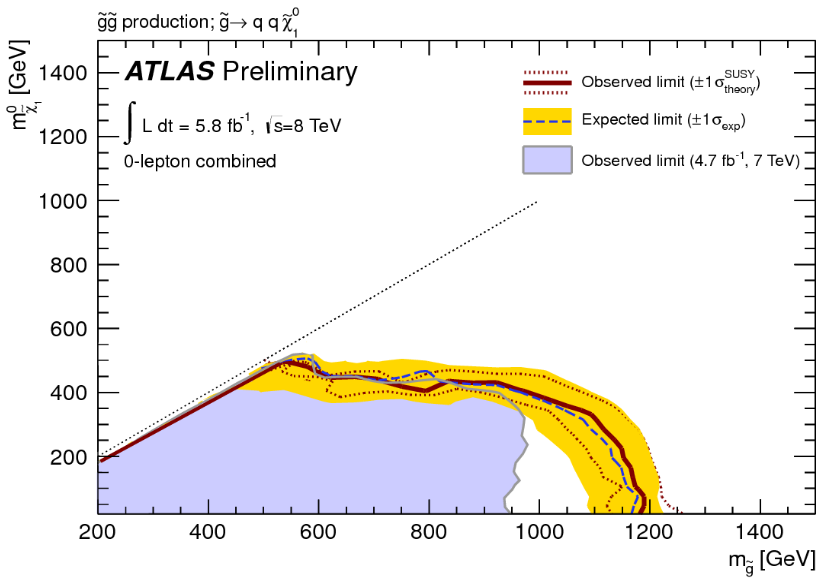
RGE in high scale models

→ **m**(squark) depends on **m**(gluino)

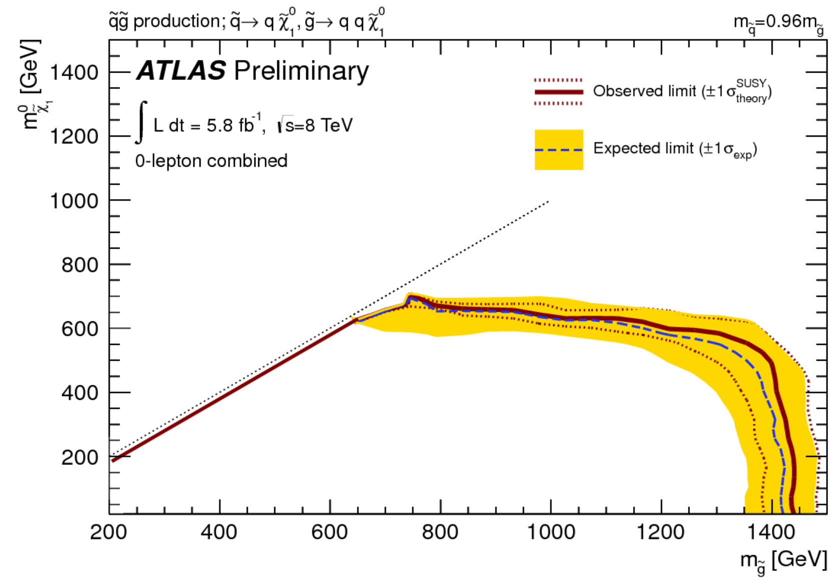
Jäckel et al. *Phys. Rev. D 85, 015015 (2012)*

# Results IV

•1)




• 2)

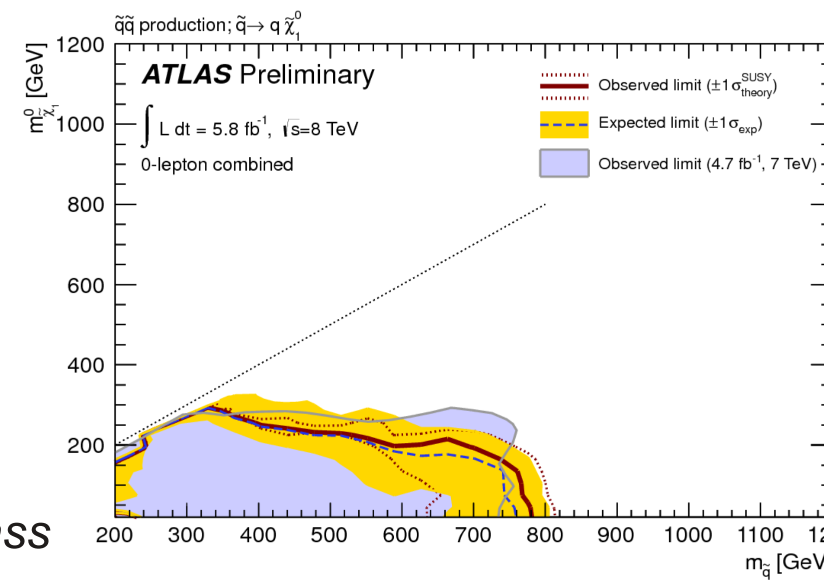



Production:
- **1) gluino-gluino**
- **2) squark-gluino**
- **3) squark-squark**

(squark 1.-2. Gen. )

**Direct** decay to LSP

• 3)




*Limits on 1.-2. gen squark, gluino masses vs LSP mass*

# Summary I

- Analysis of 4.7 $fb^{-1}$ 7 TeV and 5.8 $fb^{-1}$ 8 TeV data

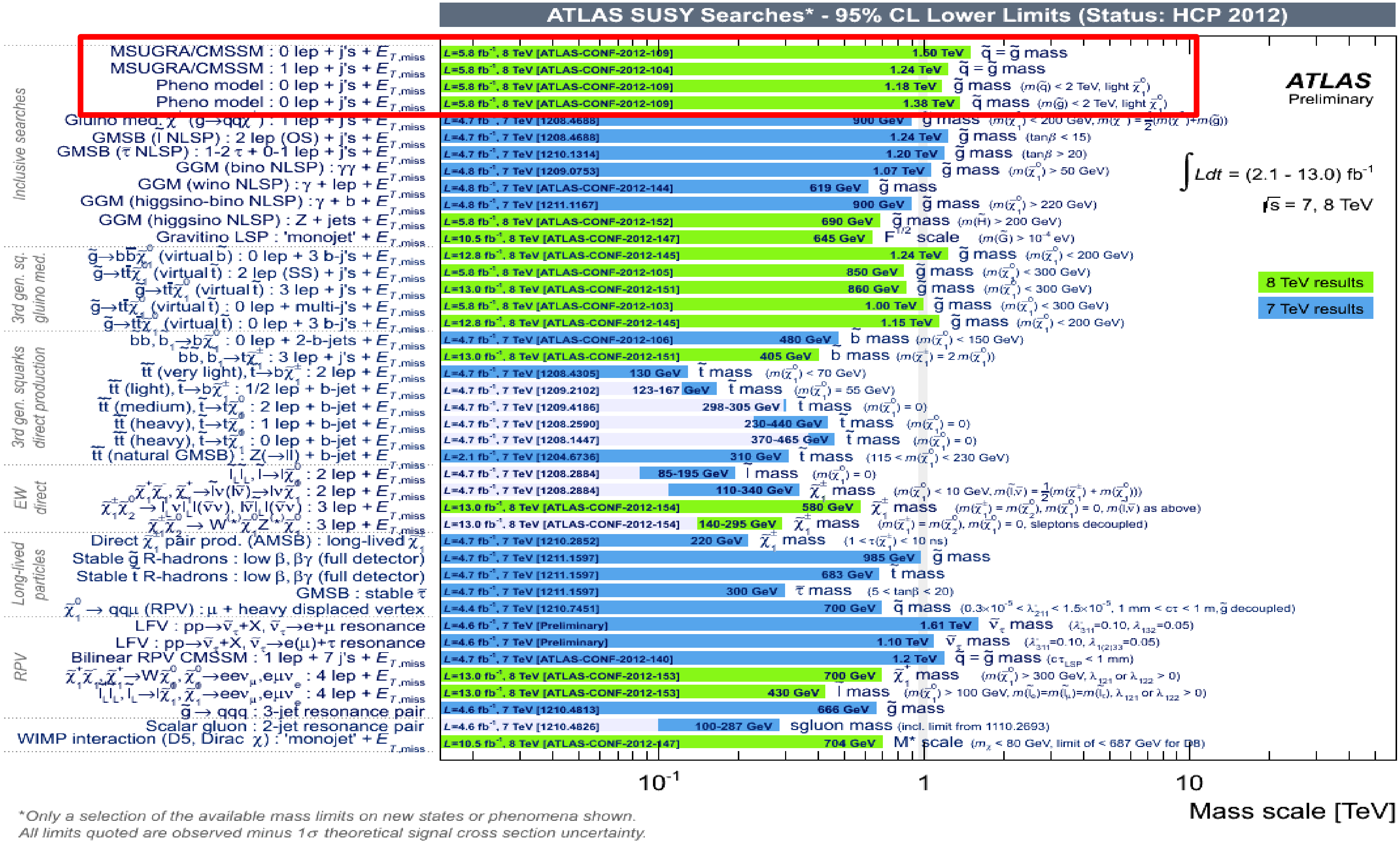
- Inclusive jets + missing transverse momentum final states using different jet multiplicities

- Dominating backgrounds are Z+ jets, W+jets, $t\bar{t}$, dibosons, QCD multi jets

- **No excess seen, observation agrees well with SM**

→ **Set limits on particle masses in specific decay modes**

# Summary II



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS Preliminary
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
1.50 TeV
1.24 TeV
1.18 TeV
1.38 TeV
$\int Ldt$ = (2.1 - 13.0) fb$^{-1}$
$\sqrt{s}$ = 7, 8 TeV
8 TeV results
7 TeV results
3rd gen. sq. gluino med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
$10^{-1}$
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

**BACKUP**

# Background estimation: Overview

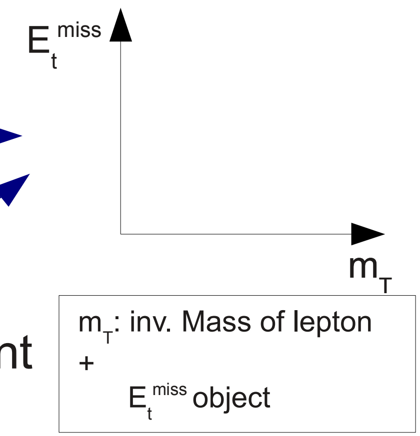
**Transfer function(TF)**: ratio between control and signal region for a given process

Dominant sources of background are:

- **Z + jets:** irreducible $Z \rightarrow \nu\nu$ +jets,
  - fully data driven with $\gamma$ +jets sample,
  - control measurements $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$

- **W+jets :** $W \rightarrow \tau\nu$ and $W \rightarrow l\nu$ where l is not reconstructed
  control measurement via $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ defined
  in $E_t^{miss}$, $m_T$ plane with veto on b-jets

- **Top :** Hadronic $\tau$ decays in $t\bar{t} \rightarrow b\bar{b}\tau\nu qq$ and single top
  control measurement defined in $E_t^{miss}$, $m_T$ plane with b-jet requirement




- **QCD multi jet:** mis-reconstruction leads to fake $E_t^{miss}$, neutrino production in heavy flavour decay
  - data-driven TF by measuring detector response
  - region with inverted angular separation cuts

- **Diboson:**
  WW, WZ, ZZ, $W\gamma*$ estimated via SHERPA

# Results I

| Process | Signal Region | | | | | |
|---|---|---|---|---|---|---|
| | SR-C loose | SR-E loose | SR-A medium | SR-A′ medium | SR-C medium | SR-E medium |
| $t\bar{t}$+ single top | $74 \pm 14$ (75) | $73 \pm 25$ (68) | $6.8 \pm 4.7$ (5.3) | $11 \pm 4$ (10) | $13 \pm 5$ (11) | $19 \pm 6$ (15) |
| $Z$+jets | $71 \pm 19$ (78) | $21 \pm 7$ (17) | $32 \pm 9$ (44) | $66 \pm 18$ (88) | $16 \pm 5$ (20) | $8.4 \pm 3.2$ (5.6) |
| $W$+jets | $61 \pm 11$ (61) | $23 \pm 13$ (23) | $19 \pm 5$ (21) | $25 \pm 5$ (30) | $7.7 \pm 3.0$ (11) | $6.2 \pm 2.6$ (4.7) |
| Multi-jets | $0.9 \pm 1.2$ (0.8) | $8.4 \pm 7.3$ (25) | $0.1 \pm 0.3$ (0.2) | $0.0 \pm 0.1$ (0.5) | $0.03 \pm 0.05$ (0.03) | $1.4 \pm 1.2$ (2.7) |
| Di-bosons | $7.9 \pm 4.0$ (7.9) | $4.2 \pm 2.1$ (4.2) | $7.3 \pm 3.7$ (7.5) | $14 \pm 7$ (16) | $1.7 \pm 0.9$ (1.7) | $2.7 \pm 1.3$ (2.7) |
| Total | $214 \pm 8 \pm 22$ | $129 \pm 8 \pm 30$ | $65 \pm 4 \pm 11$ | $116 \pm 5 \pm 19$ | $39 \pm 3 \pm 7$ | $38 \pm 4 \pm 5$ |
| Data | 210 | 148 | 59 | 85 | 36 | 25 |
| Local p-value (Gauss. $\sigma$) | 0.56(−0.15) | 0.21(0.81) | 0.66(−0.40) | 0.90(−1.3) | 0.61(−0.27) | 0.87(−1.1) |
| Upper limit on $N_{\mathrm{BSM}}$ | $51(55^{\uparrow 42}_{\downarrow 76})$ | $77(67^{\uparrow 49}_{\downarrow 91})$ | $24(28^{\uparrow 20}_{\downarrow 39})$ | $28(42^{\uparrow 31}_{\downarrow 58})$ | $17(19^{\uparrow 14}_{\downarrow 26})$ | $11(16^{\uparrow 12}_{\downarrow 23})$ |
| Upper limit on $\sigma$ (fb) | $11(12^{\uparrow 8.8}_{\downarrow 16})$ | $16(14^{\uparrow 10}_{\downarrow 19})$ | $5.1(5.9^{\uparrow 4.3}_{\downarrow 8.3})$ | $6.0(8.9^{\uparrow 6.6}_{\downarrow 12})$ | $3.6(4^{\uparrow 2.9}_{\downarrow 5.6})$ | $2.2(3.4^{\uparrow 2.5}_{\downarrow 4.8})$ |

| Process | Signal Region | | | | |
|---|---|---|---|---|---|
| | SR-A tight | SR-B tight | SR-C tight | SR-D tight | SR-E tight |
| $t\bar{t}$+ single top | $0.2 \pm 0.2$ (0.1) | $0.3 \pm 0.3$ (0.2) | $2.0 \pm 1.5$ (1.2) | $2.4 \pm 1.7$ (1.4) | $4.2 \pm 4.7$ (3.0) |
| $Z$+jets | $3.3 \pm 1.5$ (4.0) | $2.0 \pm 1.3$ (2.1) | $2.0 \pm 1.0$ (5.6) | $0.9 \pm 0.6$ (3.4) | $3.4 \pm 1.6$ (2.3) |
| $W$+jets | $2.2 \pm 1.0$ (1.9) | $1.0 \pm 0.6$ (0.8) | $1.5 \pm 1.3$ (2.7) | $2.4 \pm 1.4$ (2.5) | $2.8 \pm 1.9$ (1.5) |
| Multi-jets | $0.00 \pm 0.02$ (0.01) | $0.00 \pm 0.07$ (0.02) | $0.00 \pm 0.03$ (0.01) | $0.0 \pm 0.3$ (0.1) | $0.5 \pm 0.4$ (0.9) |
| Di-bosons | $1.8 \pm 0.9$ (2.0) | $1.8 \pm 0.9$ (1.9) | $0.5 \pm 0.3$ (0.5) | $2.2 \pm 1.1$ (2.2) | $2.5 \pm 1.3$ (2.5) |
| Total | $7.4 \pm 1.3 \pm 1.9$ | $5.0 \pm 0.9 \pm 1.7$ | $6.0 \pm 1.0 \pm 2.0$ | $7.8 \pm 1.0 \pm 2.4$ | $13 \pm 2 \pm 6$ |
| Data | 1 | 1 | 14 | 9 | 13 |
| Local p-value (Gauss. $\sigma$) | 0.98(−2.1) | 0.96(−1.7) | 0.016(2.1) | 0.29(0.55) | 0.45(0.14) |
| Upper limit on $N_{\mathrm{BSM}}$ | $3.1(6.4^{\uparrow 4.5}_{\downarrow 9.4})$ | $3.0(5.6^{\uparrow 3.9}_{\downarrow 8.3})$ | $16(9.5^{\uparrow 6.9}_{\downarrow 14})$ | $9.6(8.5^{\uparrow 6.1}_{\downarrow 12})$ | $12(12^{\uparrow 8.4}_{\downarrow 17})$ |
| Upper limit on $\sigma$ (fb) | $0.66(1.4^{\uparrow 0.96}_{\downarrow 2.0})$ | $0.64(1.2^{\uparrow 0.83}_{\downarrow 1.8})$ | $3.4(2.0^{\uparrow 1.5}_{\downarrow 2.9})$ | $2.0(1.8^{\uparrow 1.3}_{\downarrow 2.6})$ | $2.5(2.5^{\uparrow 1.8}_{\downarrow 3.5})$ |

- Inclusive signal regions
  with different jet multiplicities

- Veto events with one or more e,μ

- Event selection is based on
  Effective mass (meff):

| Requirement | Channel | | | | | |
|---|---|---|---|---|---|---|
| | A | A′ | B | C | D | E |
| $E_{\mathrm{T}}^{\mathrm{miss}}$[GeV] $>$ | 160 | | | | | |
| $p_{\mathrm{T}}(j_1)$ [GeV] $>$ | 130 | | | | | |
| $p_{\mathrm{T}}(j_2)$ [GeV] $>$ | 60 | | | | | |
| $p_{\mathrm{T}}(j_3)$ [GeV] $>$ | – | – | 60 | 60 | 60 | 60 |
| $p_{\mathrm{T}}(j_4)$ [GeV] $>$ | – | – | – | 60 | 60 | 60 |
| $p_{\mathrm{T}}(j_5)$ [GeV] $>$ | – | – | – | – | 40 | 40 |
| $p_{\mathrm{T}}(j_6)$ [GeV] $>$ | – | – | – | – | – | 40 |
| $\Delta\phi(\mathrm{jet}_i, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ [rad] $>$ | 0.4 ($i = \{1, 2, (3)\}$) | | | 0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_{\mathrm{T}} > 40$ GeV jets) | | |
| $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ ($N$j) $>$ | 0.3 (2j) | 0.4 (2j) | 0.25 (3j) | 0.25 (4j) | 0.2 (5j) | 0.15 (6j) |
| $m_{\mathrm{eff}}$(incl.) [GeV] $>$ | 1900/1400/– | –/1200/– | 1900/–/– | 1500/1200/900 | 1500/–/– | 1400/1200/900 |

# Why should we test SUSY at the LHC?

- Symmetry between fermions and bosons
- Implies superpartners to SM particles
- Supersymmetry must be broken

- Hierarchy problem → little Hierarchy problem *if masses in range of LHC*
  SUSY could protect the Higgs mass from quantum corrections
- non baryonic dark matter in cosmos,
  SUSY can provide a dark matter candidate
- Unification of coupling constants *if masses in range of LHC*
- Serves as benchmark for BSM colour neutral states → pair production

# Background estimation: Simultaneous normalisation

- Measure the main backgrounds relative to **same phase space (in meff)**
- For each of the SR a likelihood is defined:

$$L(\boldsymbol{n}|\mu, \boldsymbol{b}, \boldsymbol{\theta}) \quad = \quad P_{\mathrm{SR}} \times P_{\mathrm{WR}} \times P_{\mathrm{TR}} \times P_{\mathrm{ZRa}} \times P_{\mathrm{ZRb}} \times P_{\mathrm{QR}} \times C_{\mathrm{Syst}} \, .$$

This ensures:

- **Simultaneous** normalistaion of background processes ( CRs are not pure)
- **Cancellation** of uncertainties
- **Correlation** of uncertainties treated properly
- Potential **signal contamination** correctly taken into account

# Systematic uncertainties

**Dominant systematic uncertainties** on the **background** are
(relative contribution to the total error on the expected event count in signal region):

• Jet Energy Calibration: < 15%

• Jet Energy Resolution: < 10%

• Acceptance* efficiency of $\gamma$ +jets method (20-70)%

• MC modeling W,$t\bar{t}$ :
  - Factorization and renormalization scale variations +additonal jet radiation (20-60)%
  - limited MC statistics (20-50) %

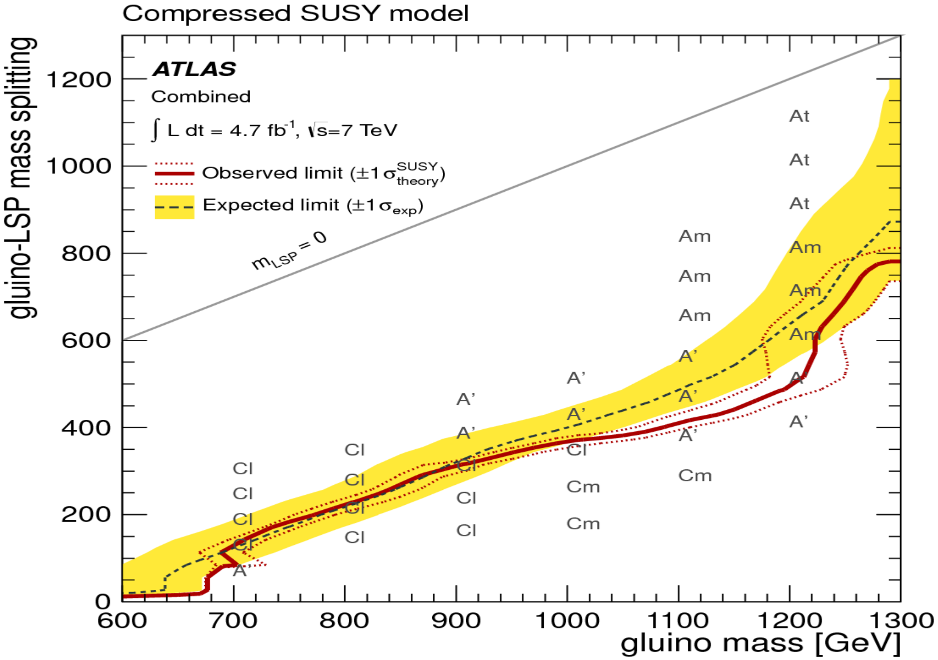
• CR statistics (35 – 50)%

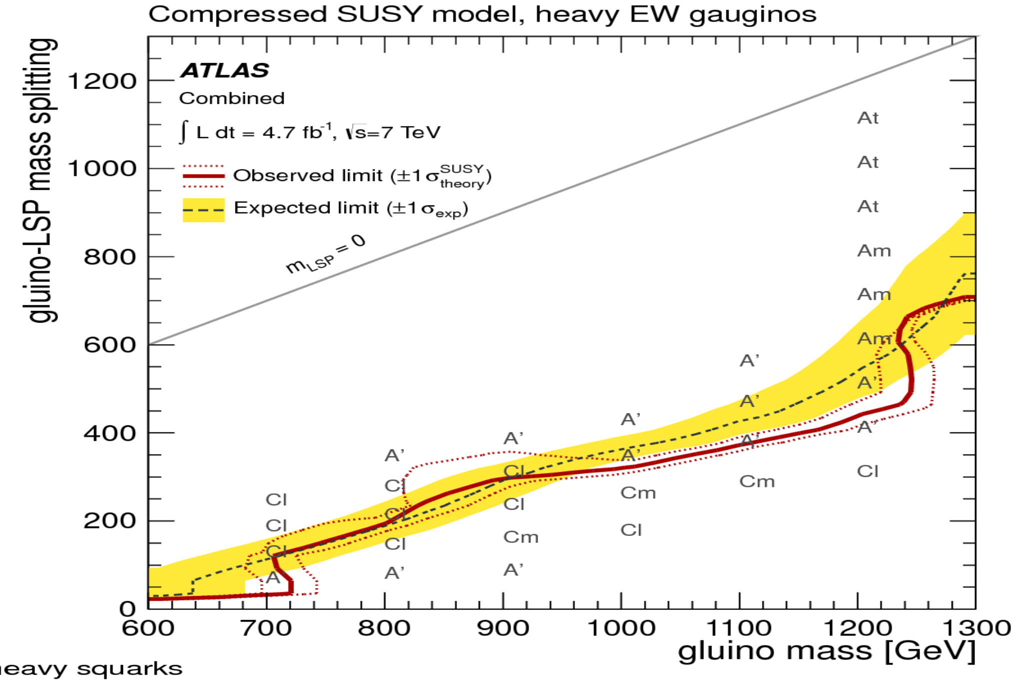
**Systematic uncertainties** on **signal** models( Herwig++ or Madgraph):
•Experimental like JES,JER larger than on background as no cancellation through TF

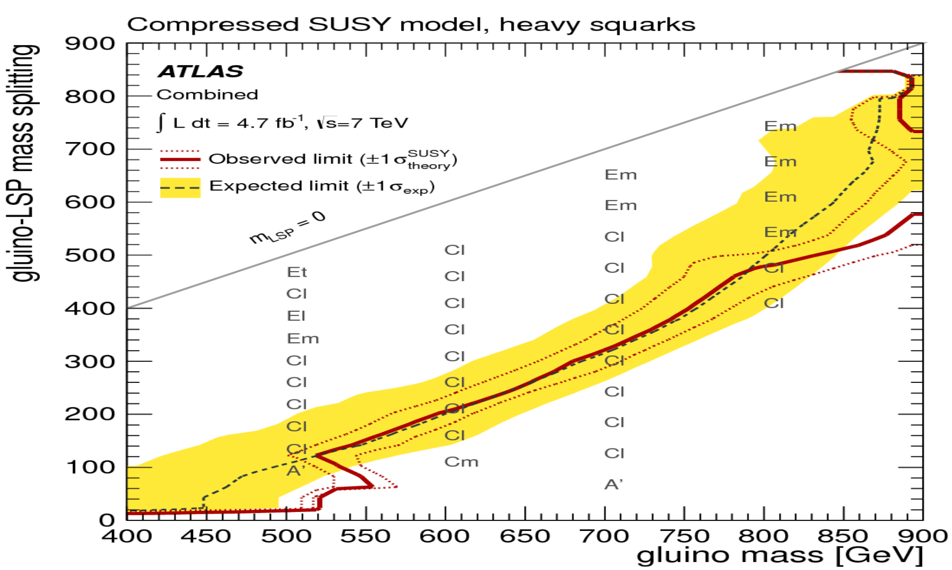
• Factorization and renormalization scale variations

• pdf- MSTW2008 and CTEQ6.6

• ISR (becomes important at small mass splittings) - variations of $\alpha_s$ and Madgraph params

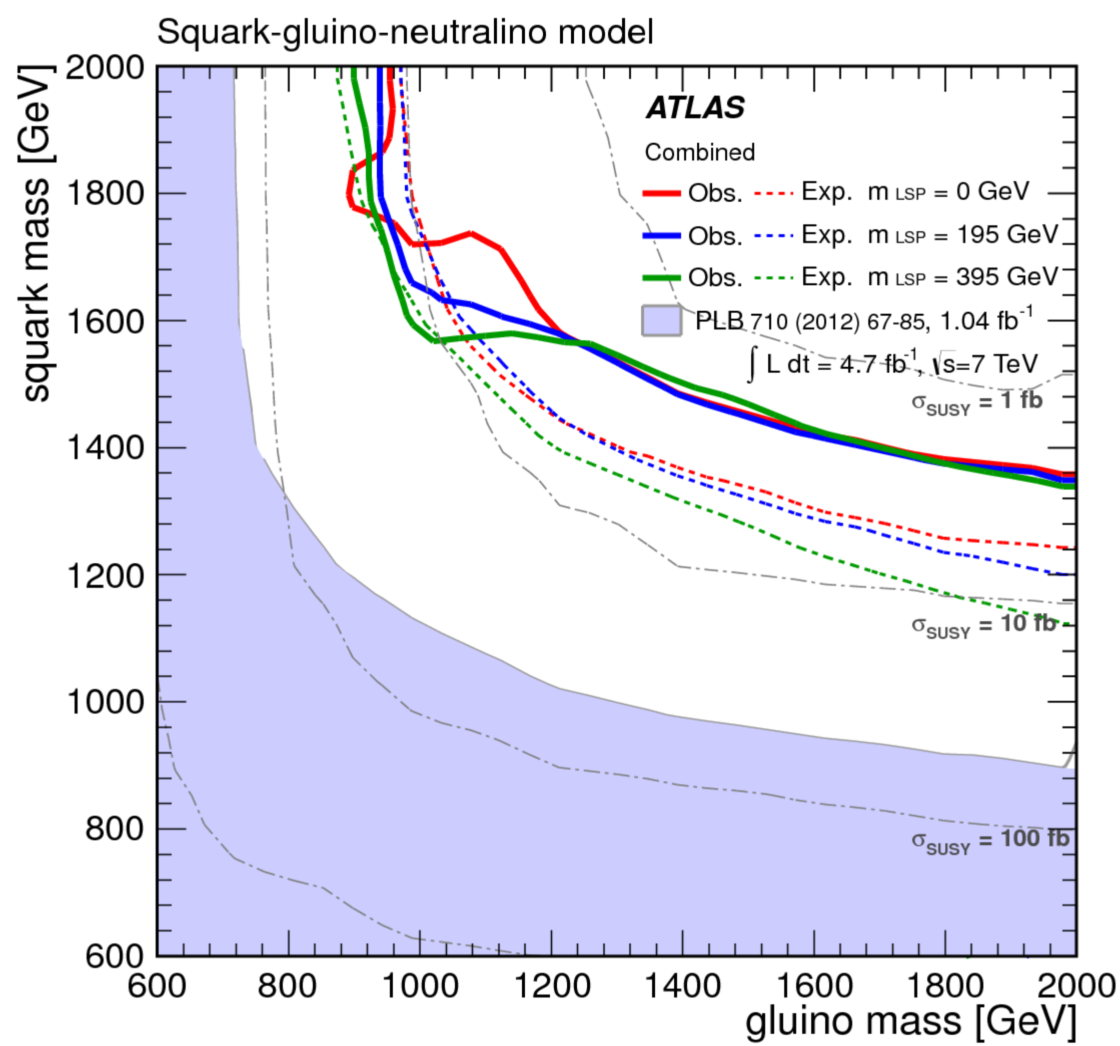



Link to paper:

# Impact on signal models I



| CR | SR Background | CR process | CR selection |
|---|---|---|---|
| CR1a | $Z$+jets | $\gamma$+jets | Isolated photon |
| CR1b | $Z$+jets | $Z(\rightarrow \ell\ell)$+jets | 66 GeV $< m(\ell\ell) <$ 116 GeV |
| CR2 | Multi-jets | Multi-jets | $\Delta\phi(\text{jet}_i, \vec{P}_{\text{T}}^{\text{miss}})_{\text{min}} < 0.2$ rad |
| CR3 | $W(\rightarrow \ell\nu)$+jets | $W(\rightarrow \ell\nu)$+jets | 30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, $b$-veto |
| CR4 | $t\bar{t}$ and single top | $t\bar{t} \rightarrow b\bar{b}qq'\ell\nu$ | 30 GeV $< m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) <$ 100 GeV, $b$-tag |

Trigger:

- at emjes scale jet pT > 75 GeV and  Etmiss > 45-55 depending on instant lumi
- 98 % effiency at  jet pT =130 Gev and Etmiss=160 GeV