



# Searches for SUSY Signals with Leptons at LHC

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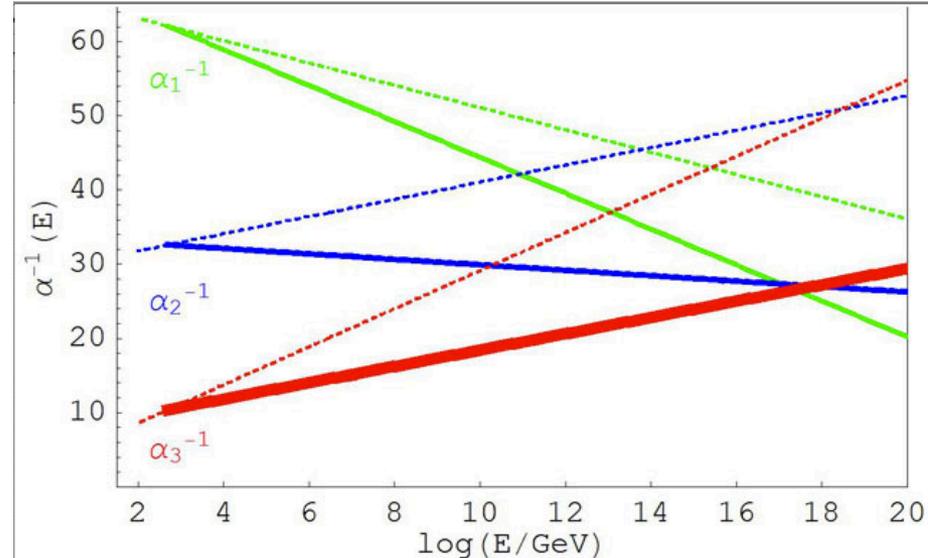
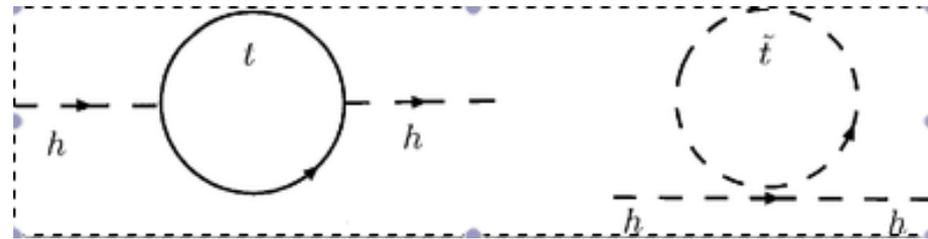
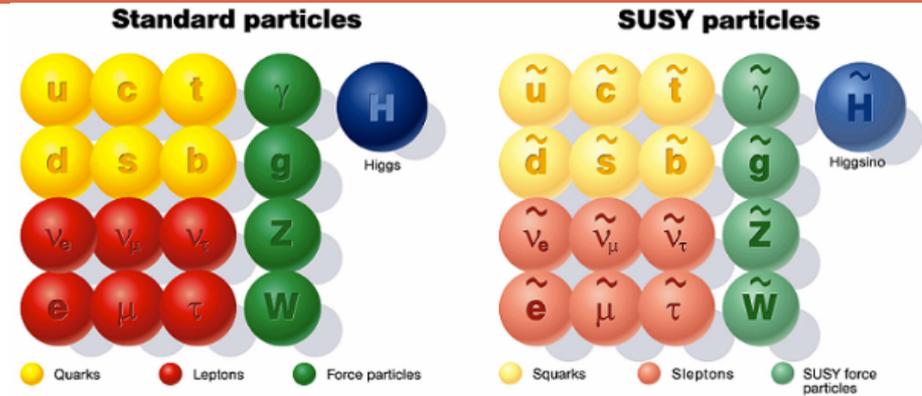


Beyond The Standard Model of Particle Physics  
Quy Nhon, Vietnam July 15-21, 2012



# SUperSYmmetry

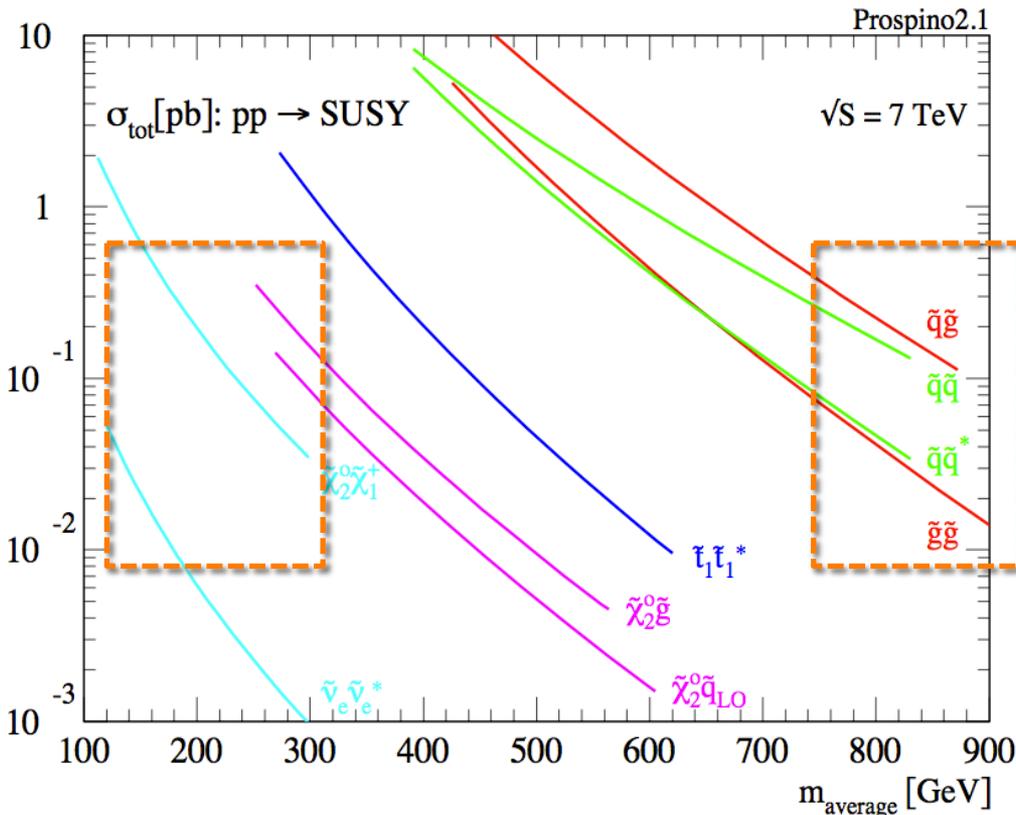
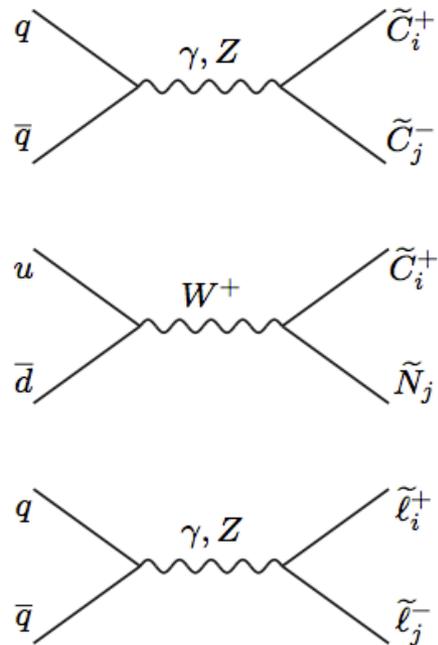
- Most popular theory beyond the Standard Model
- Introduces SUSY partners to each SM particle with spin different by 1/2
- Regularizes electroweak scale
  - **Stop must be similar to top in mass**
  - **Gauginos coupling to the Higgs sector should be light**
- Unification of gauge couplings at GUT scale
  - Mass unification at GUT in parallel  
Implies  $M_1:M_2:M_3 \sim 1:2:7$  at EW
- Higher GUT scale ( $\sim 1e17$  GeV) prevents GUT-mediated proton decays
- R-parity conserving models can provide dark matter candidate
  - **Pair production**
  - **Large  $E_T^{\text{miss}}$  collider signature**



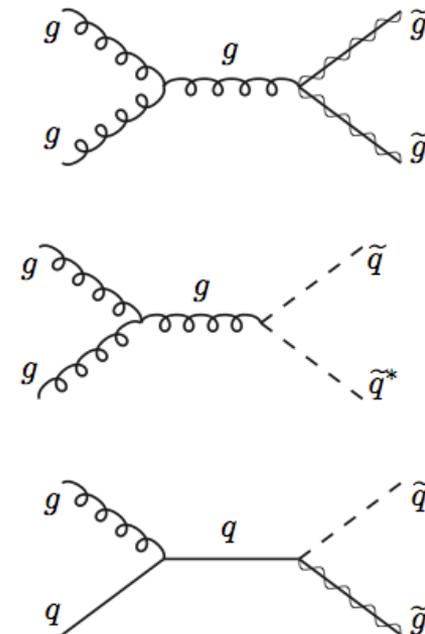
# Production of SUSY Particles

- Strong production is dominant unless squark and gluino masses are large
- Stop has to be light to solve hierarchy problem (next talk by Sudarshan)
- Gaugino masses expected to be light as they couple to the Higgs sector
- **Weak production could be the dominant production, accessible in leptonic final states**

## Weak Production



## Strong Production



# SUSY Breaking Models

- **mSUGRA (CMSSM)**
- **SUSY breaking through gravitational-strength interactions**
- **Five parameters at GUT scale**  $m_0, m_{1/2}, A_0, \tan \beta, \text{sgn } \mu$

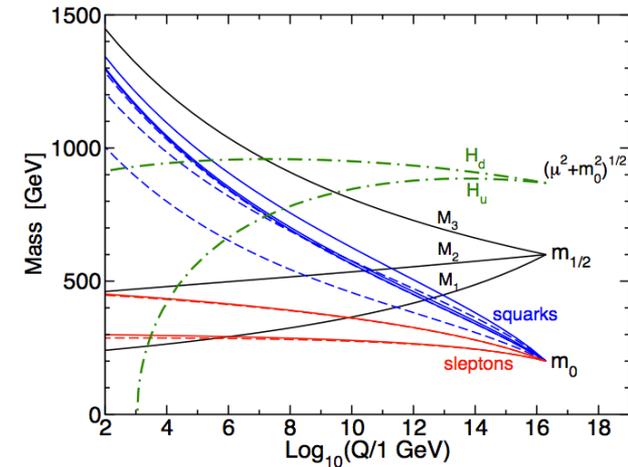
$$M_3 = M_2 = M_1 = m_{1/2},$$

$$m_Q^2 = m_U^2 = m_D^2 = m_L^2 = m_E^2 = m_0^2 \mathbf{1}, \quad m_{H_u}^2 = m_{H_d}^2 = m_0^2,$$

$$\mathbf{a}_u = A_0 \mathbf{y}_u, \quad \mathbf{a}_d = A_0 \mathbf{y}_d, \quad \mathbf{a}_e = A_0 \mathbf{y}_e,$$

$$b = B_0 \mu,$$

- **RG equation provide spectrum at EW scale**
- **Usually Neutralino LSP**



- **GMSB**
- **Gauge Mediated Supersymmetry Breaking**
- **Six parameters:**
  - $\Lambda$  - SUSY breaking mass scale
  - $N_5$  and  $M$  - number and mass of SU(5) messenger fields
  - $\tan \beta$  and  $\mu$  - Higgs vev ratio and mixing parameter
  - $C_{\text{grav}}$  - scale factor of gravitino mass
- **Gravitino LSP**

# Phenomenological Models

- **pMSSM**: number of free parameters reduced to 19 (from 105) by the following assumptions
  - CP conservation (removes all phases)
  - minimal flavour violation (removes off-diagonal terms in mass matrices)
  - negligible trilinear couplings for 1st and 2nd generation
  - degenerate 1st and 2nd generation sfermion masses
- Heavy squarks, gluinos and left-handed sleptons.  $\tan\beta=6$ .  $m_A=500\text{GeV}$
- Right-handed slepton masses  $m_{\tilde{\ell}_R} = (m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0})/2$
- **Free parameters remain: M1, M2,  $\mu$**

*SUSY model, charginos and neutralinos direct production*

- **Simplified models**
  - For generic optimization of searches
  - Framework for understanding the implication of NP searches
  - Model defined by a TeV scale effective lagrangian describing its particle content and interactions
- Mass degenerate Chargino1 and Neutralino2, wino like
- Neutralino1, bino like
- BR into sleptons and sneutrinos set to 50% (ATLAS)
- BR into sleptons 100% (CMS)
- **Free parameters: Chargino and neutralino masses**
- Other particle masses are set to high values

$$m_{\tilde{\nu}} = m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm})/2$$
$$m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm})/2$$

*SUSY inspired model, chargino1-neutralino2 direct production*

# Outline

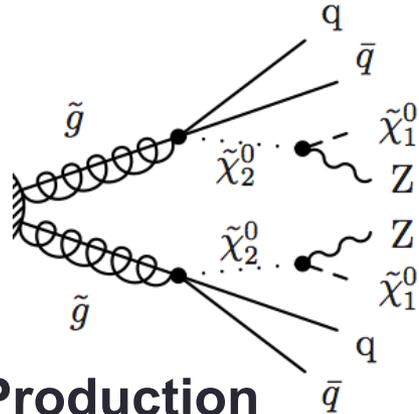
Results obtained using ~5/fb of 7 TeV pp collision data collected in 2011

Channel	mSUGRA (RPC & RPV)	GMSB / GGM	pMSSM (Weak Prod)	Simplified Models
2 Light Leptons	✓	✓	✓	✓
2 Taus	✓	✓		✓
3 Leptons	✓	✓	✓	✓
4 Leptons	✓	✓		✓

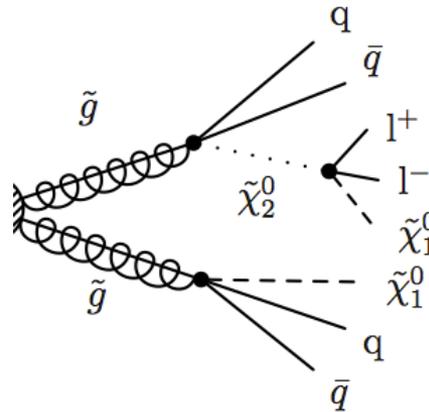
# 2-Lepton Analyses

- Strong Production**

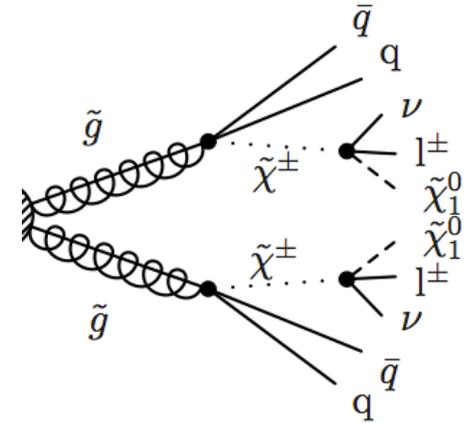
Neutralino through Z



Neutralino through Slepton

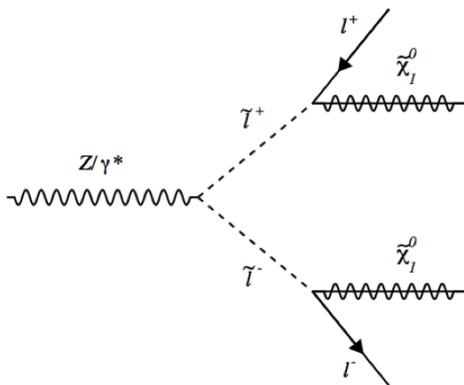


Chargino

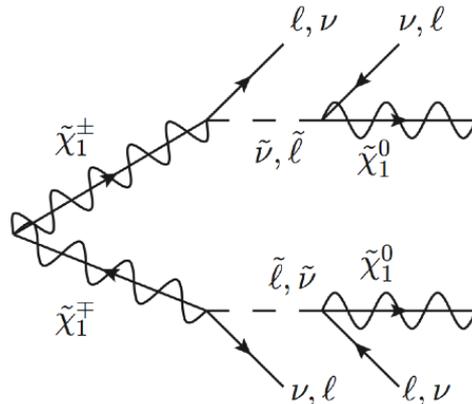


- Weak Production**

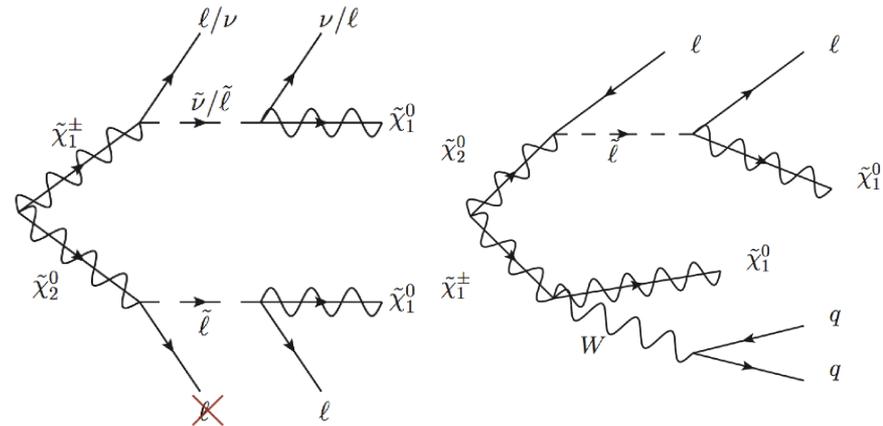
Direct Sleptons



Direct Charginos



Direct Chargino Neutralino



# Z+Jets+E<sub>T</sub><sup>miss</sup> Searches



$$\tilde{g} \rightarrow \text{jets} + \tilde{\chi}_2^0 \rightarrow \mathbf{Z} + \tilde{\chi}_1^0$$

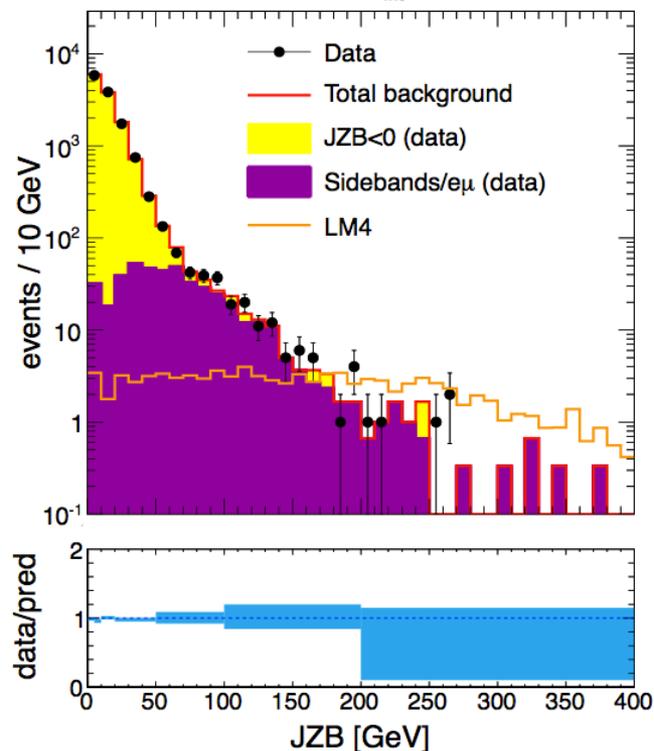
$$\mathbf{Z} \rightarrow \ell^+ \ell^- \quad (\ell = e, \mu)$$

## • Jet-Z Balance method

- sensitive to models where the Z boson and LSP are decay products of a heavier particle

$$\text{JZB} = \left| \sum_{\text{jets}} p_T \right| - \left| \vec{p}_T^{(Z)} \right|$$

CMS,  $\sqrt{s} = 7 \text{ TeV}$ ,  $L_{\text{int}} = 4.98 \text{ fb}^{-1}$

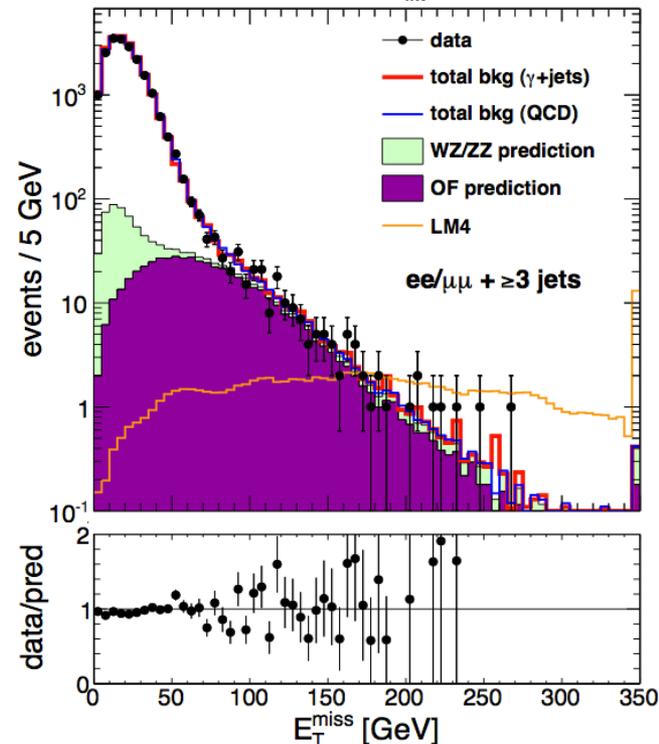


## • E<sub>T</sub><sup>miss</sup> template method

- distribution modeled using a control sample with no true E<sub>T</sub><sup>miss</sup> and a similar hadronic system as in Z + jets events
- **γ + jets or QCD multijet events** of the same jet multiplicity and scalar sum of jet transverse energies, normalized to unit area

- In SUSY JZB asymmetric
  - strength of correlation dependent on the SUSY mass spectrum
- In Z + jets events, JZB distribution approximately symmetric about zero
  - Z+j estimated from the negative JZB tail
- Top background from opposite flavor lepton data in both methods

CMS,  $\sqrt{s} = 7 \text{ TeV}$ ,  $L_{\text{int}} = 4.98 \text{ fb}^{-1}$

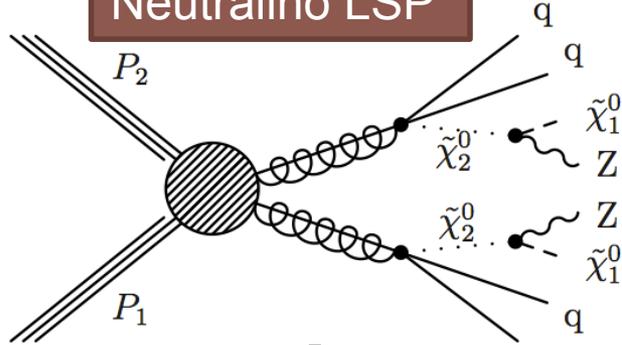


CMS arXiv:1204:3774

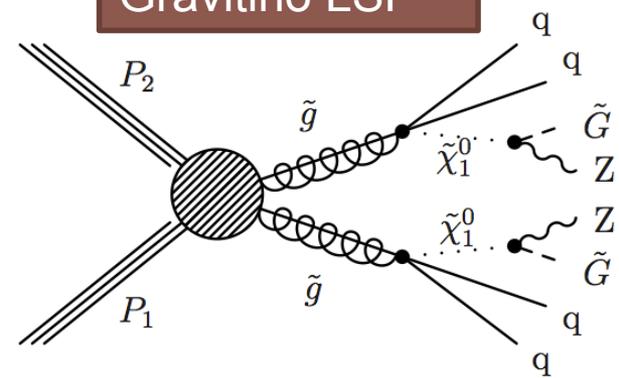
# Z+Jets+Met Interpretations



Neutralino LSP



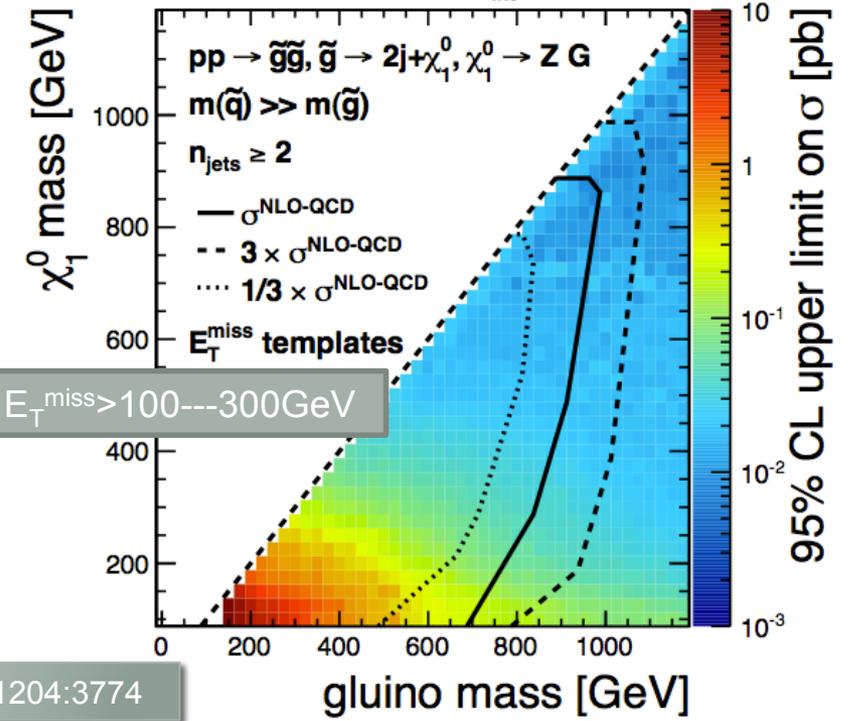
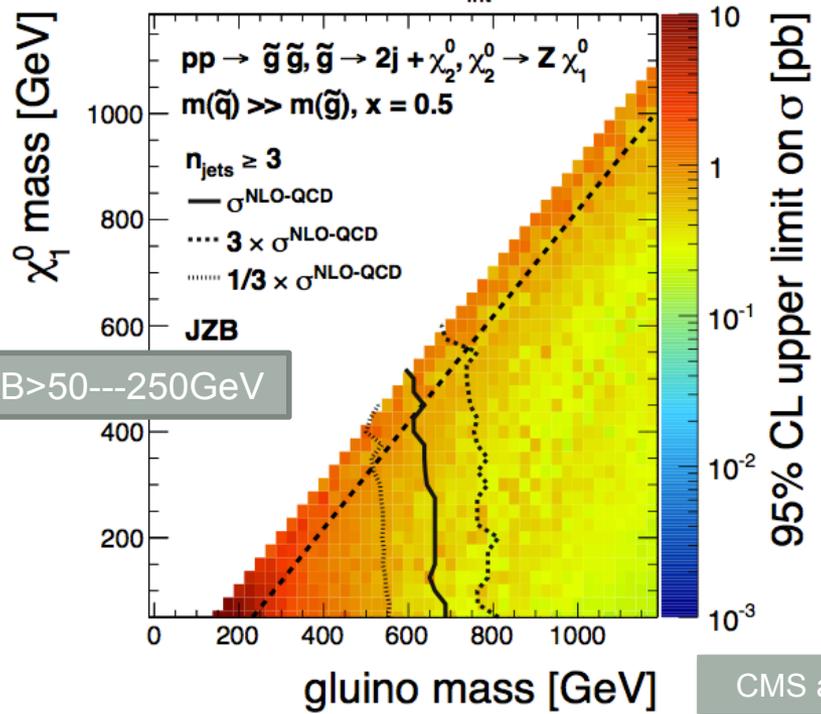
Gravitino LSP



$$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + \max \left[ 0.5(m(\tilde{g}) - m(\tilde{\chi}_1^0)), m(Z) \right]$$

CMS,  $\sqrt{s} = 7 \text{ TeV}$ ,  $L_{\text{int}} = 4.98 \text{ fb}^{-1}$

CMS,  $\sqrt{s} = 7 \text{ TeV}$ ,  $L_{\text{int}} = 4.98 \text{ fb}^{-1}$



CMS arXiv:1204:3774

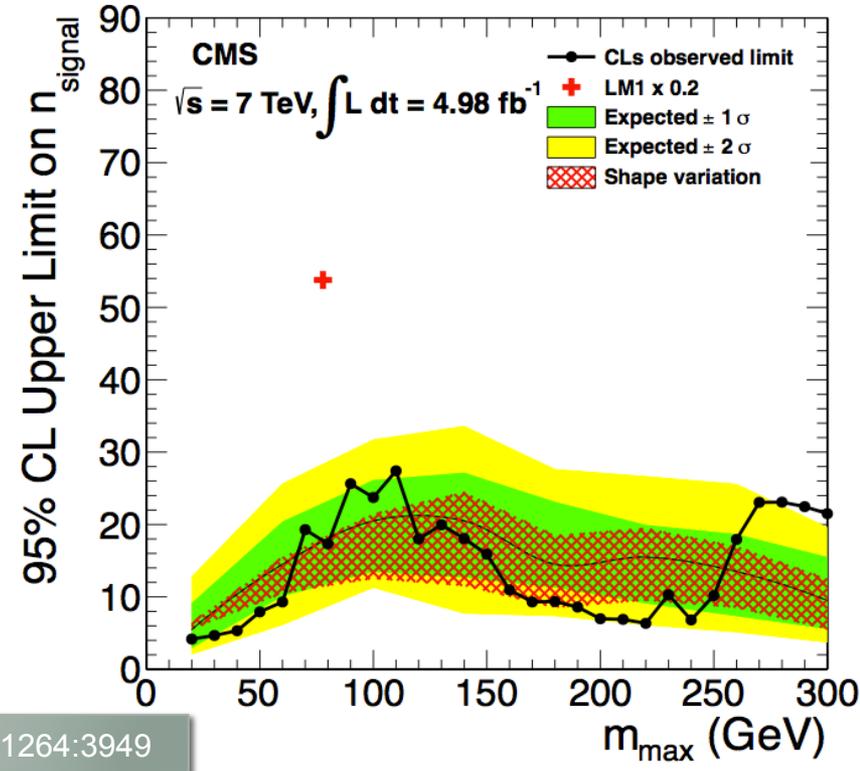
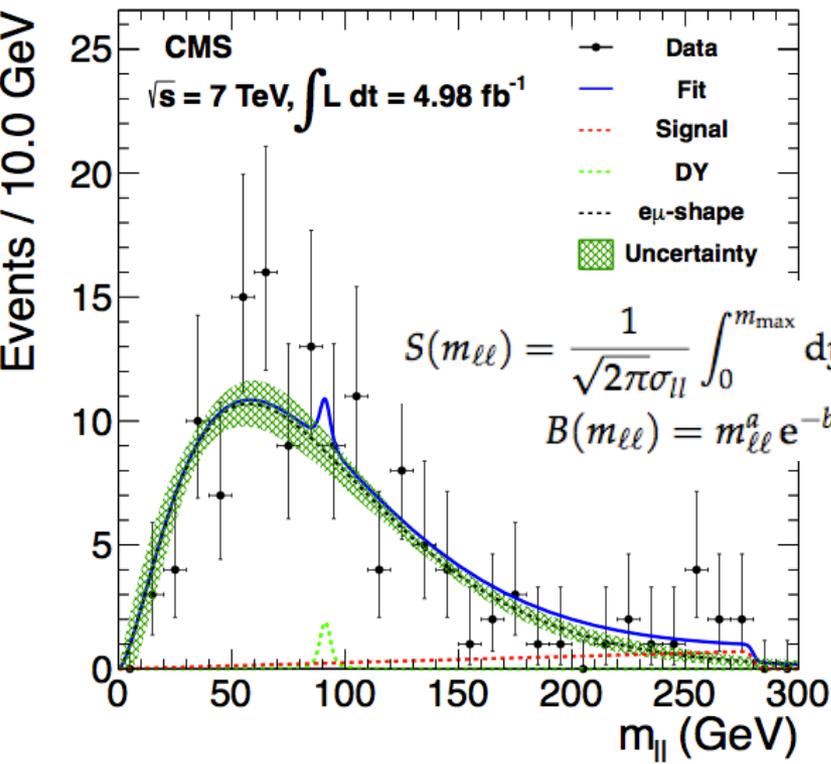
# OS Leptons with Edge Method



- Search for a kinematic edge (end-point) in the dilepton mass distribution for same-flavor lepton pair

$$\tilde{\chi}_2^0 \rightarrow \tilde{l} \rightarrow \tilde{\chi}_1^0 l^+ l^-$$

- #jets>2,  $H_T > 300\text{GeV}$  and  $E_T^{\text{miss}} > 150\text{GeV}$  to suppress DY
- Shape of backgrounds with leptons of un-correlated flavor extracted from events with OF lepton pairs
- **Simultaneous, extended, unbinned maximum likelihood fit to the distribution of dilepton mass for events containing ee,  $\mu\mu$  (signal, DY and background model), and  $e\mu$  pairs (background model only)**

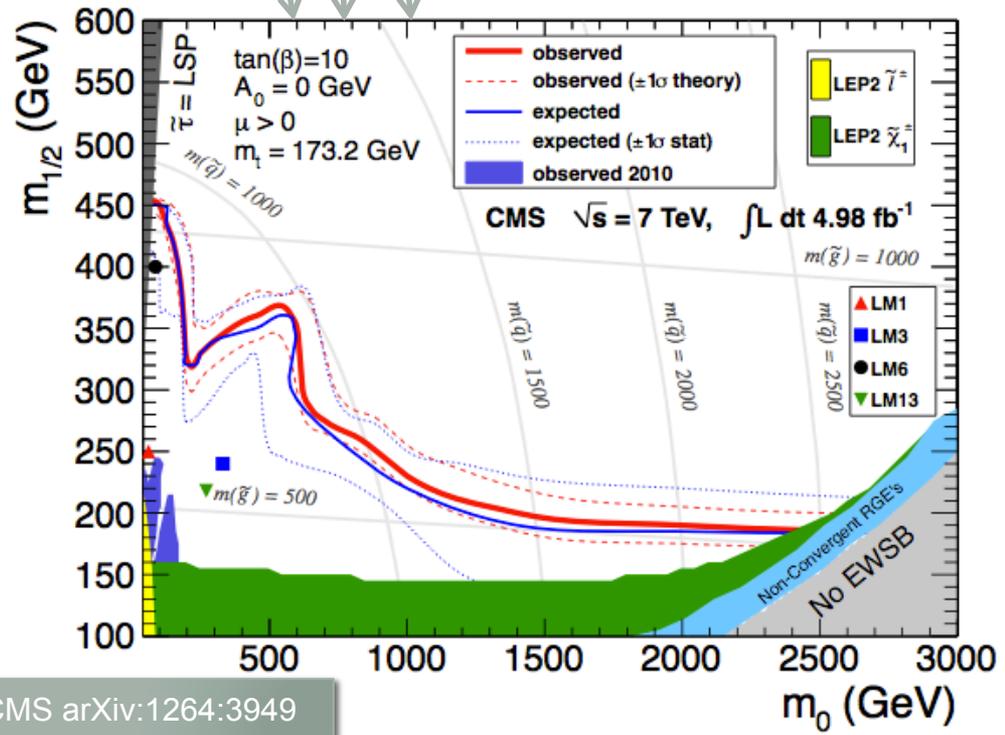
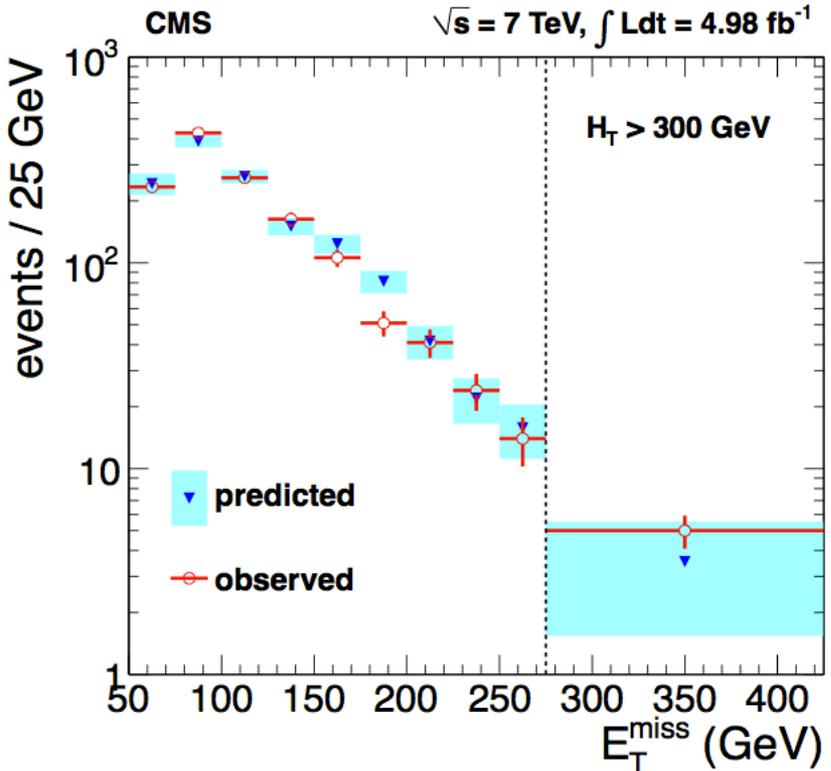
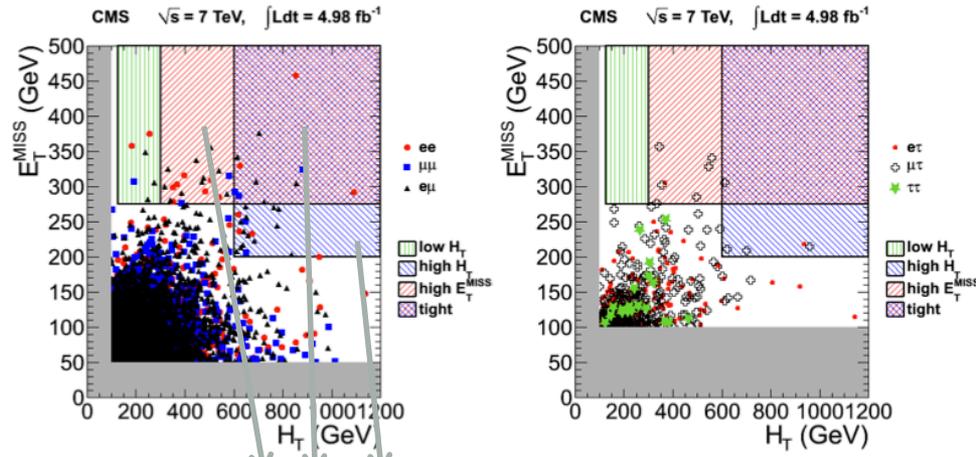


CMS arXiv:1264:3949

# OS Leptons Counting Method



- OS + 2 or more jets, Z veto, including taus
- Top pair production dominant
  - In dilepton events,  $p_T(l_l)$  and  $p_T(\nu\nu)$  approximately uncorrelated on an event-by-event basis
  - Observed  $p_T(l_l)$  distribution models the  $p_T(\nu\nu)$  and  $E_T^{\text{miss}}$  distribution

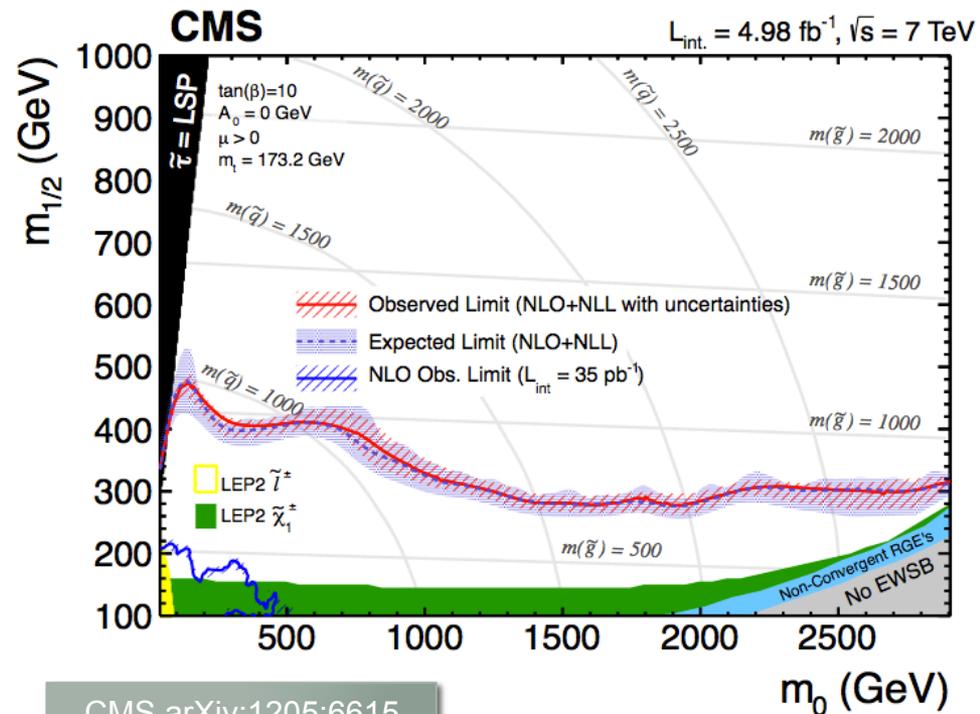
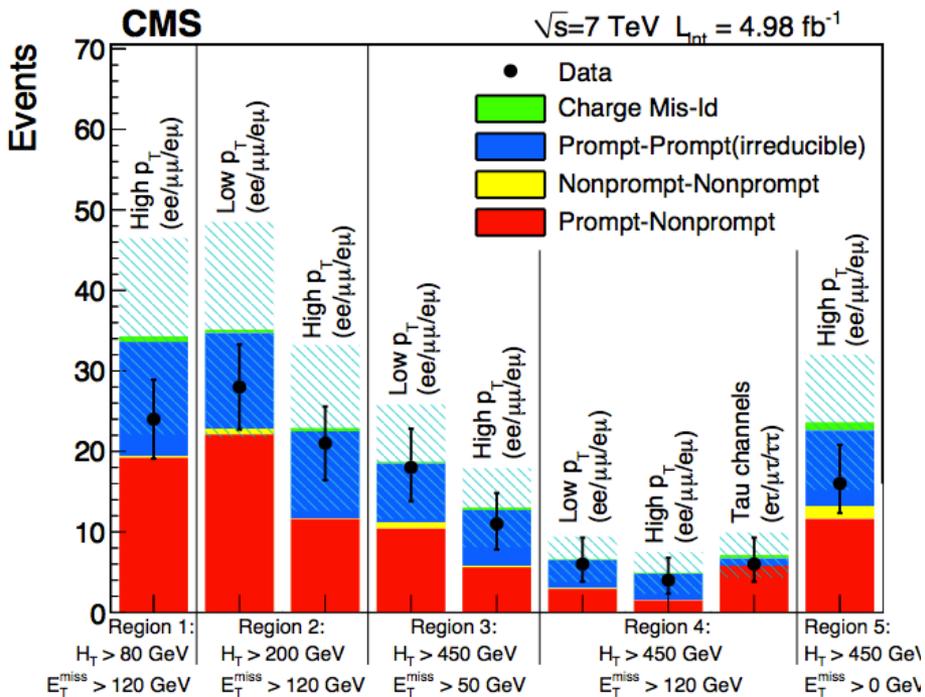


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# Same-Sign Leptons



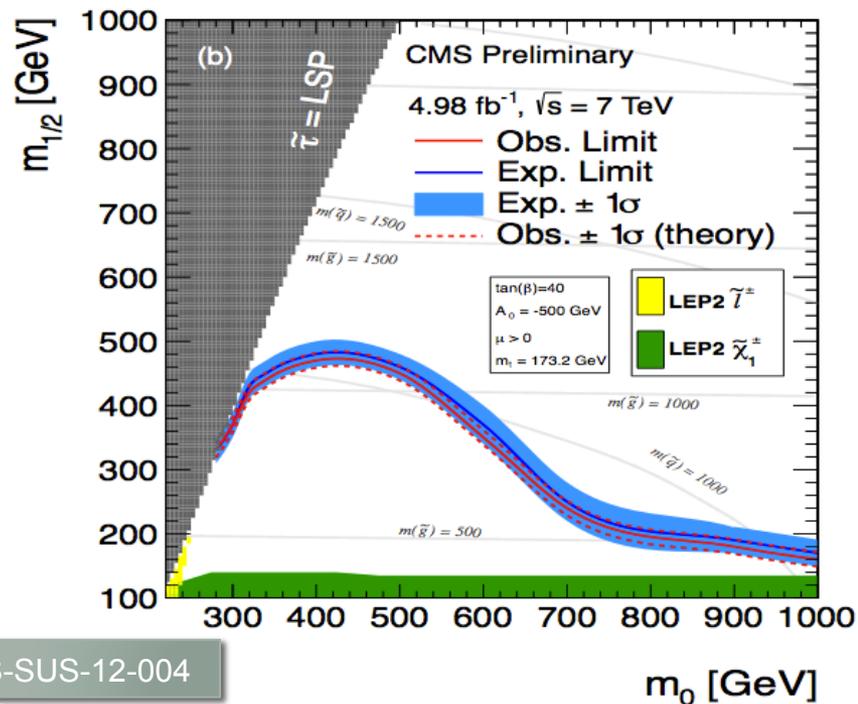
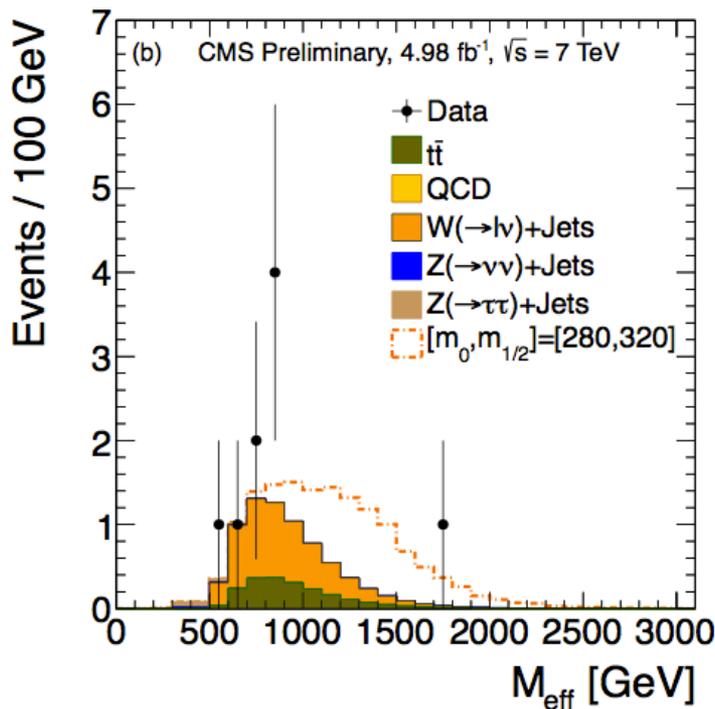
- Two same Sign leptons & at least 2 jets
  - Including hadronic taus  $\tau_h$
  - As low as 5,10,15 GeV for  $\mu$ ,  $e$ ,  $\tau_h$
- Multiple search regions in the  $(H_T, E_T^{\text{miss}})$  plane
  - Background from non-prompt leptons measured in data using side-bands
  - Irreducible background from MC
  - Charge flip from  $Z \rightarrow ee$  and  $Z \rightarrow \tau\tau$



# 2 Tau Searches

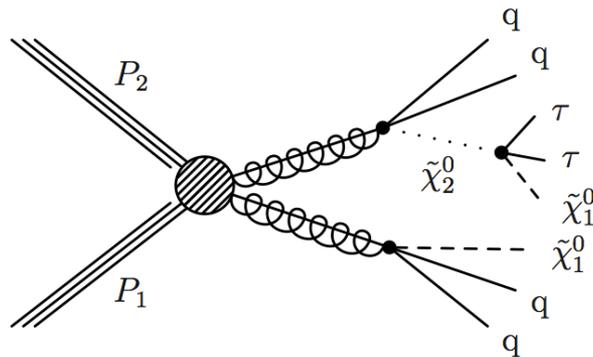


- Stau produced via charginos and neutralinos in cascade decays of colored SUSY particles
  - to allow the NLSP to coannihilate with the LSP in the early universe leading to the current dark matter density in the universe,  $\Delta M$  between the NLSP (stau) and the LSP (neutralino) of approximately 5-15 GeV
  - Di tau analysis (single tau analysis) for large (small) mass splitting
  - 2 or more taus, 2 jets  $p_T > 100$  GeV and  $\cancel{E}_T = |-\sum \vec{p}_T^{jet}| > 250$  GeV
  - Data driven estimates of all backgrounds, W+jets and tbar dominated background

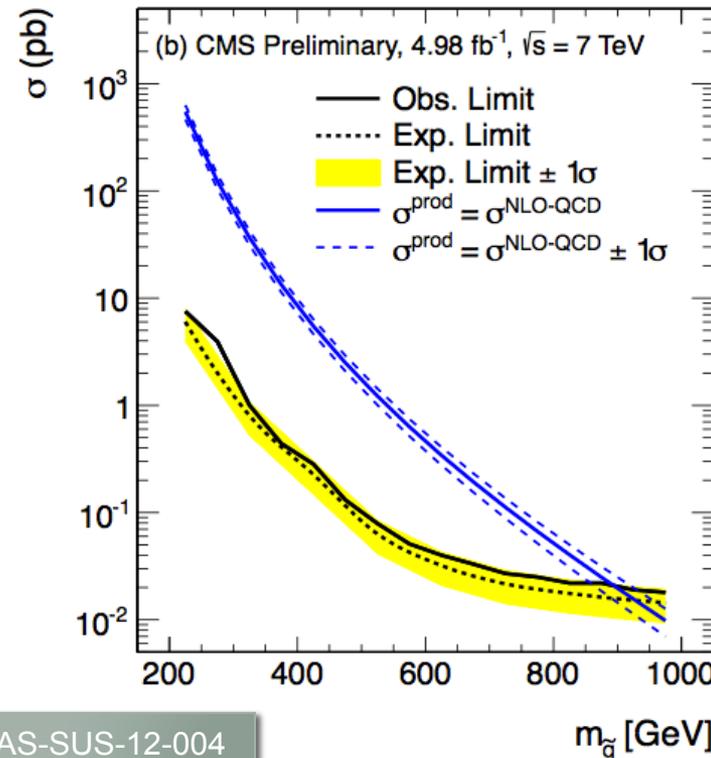
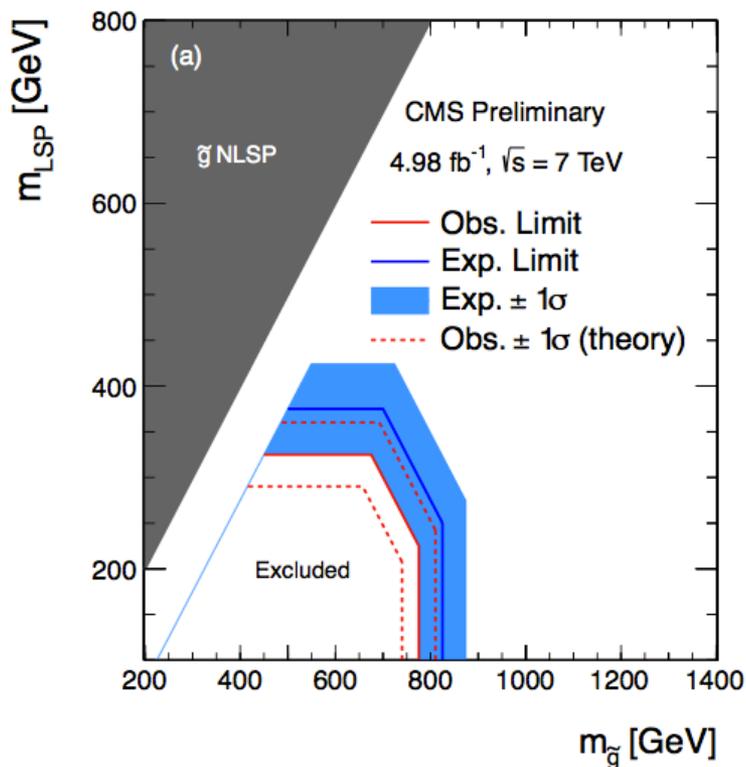


CMS PAS-SUS-12-004

# Interpretations in Simplified Models



- Simplified GMSB
- Stau is the NLSP and decays to a  $\tau$ -lepton and a gravitino,  $G_{\tilde{}}$ , with a mass of the order of  $\sim$  keV
- Assumed both gluinos decay to  $\tau$ -lepton pairs with a branching fraction of 100%

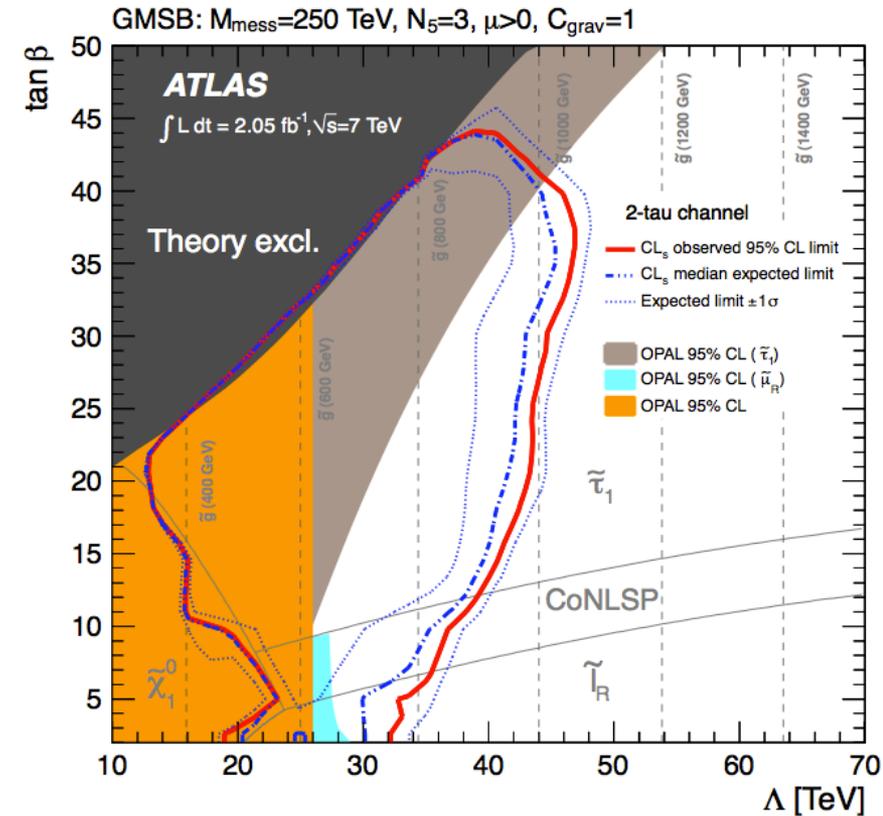
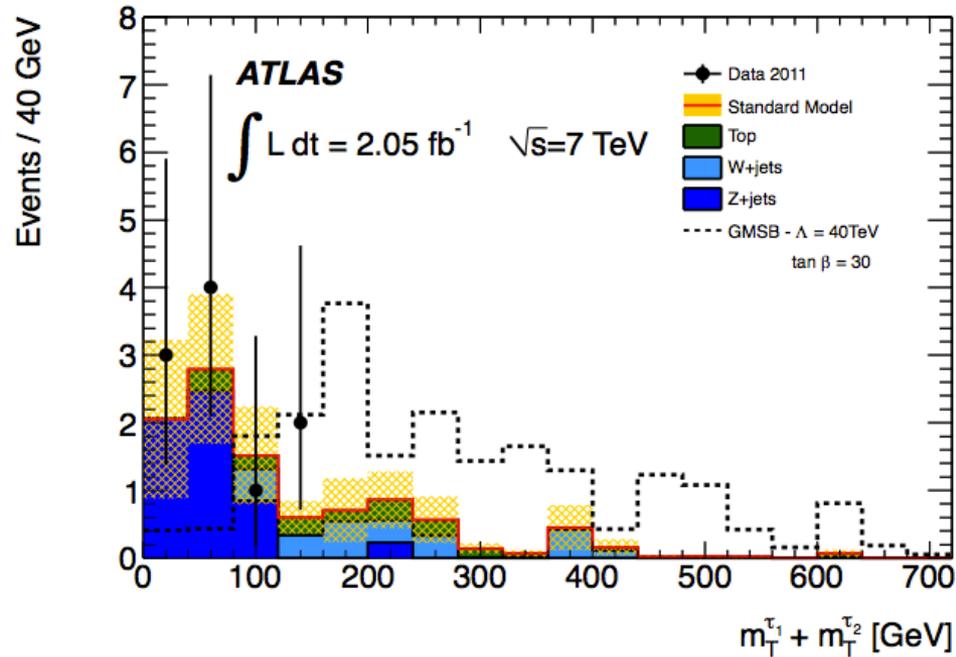


CMS PAS-SUS-12-004

# 2 Tau GMSB Searches

arXiv:1203.6580

- Light gravitino LSP
- Stau NLSP for most of the parameter space
- At least 2 hadronically decaying taus
- 2 jets,  $m_{\text{eff}} > 700 \text{ GeV}$ ,  $m_{T1} + m_{T2} > 80 \text{ GeV}$
- Reducible backgrounds estimated from data,  $m_{\text{eff}} < 700 \text{ GeV}$
- Irreducible from MC

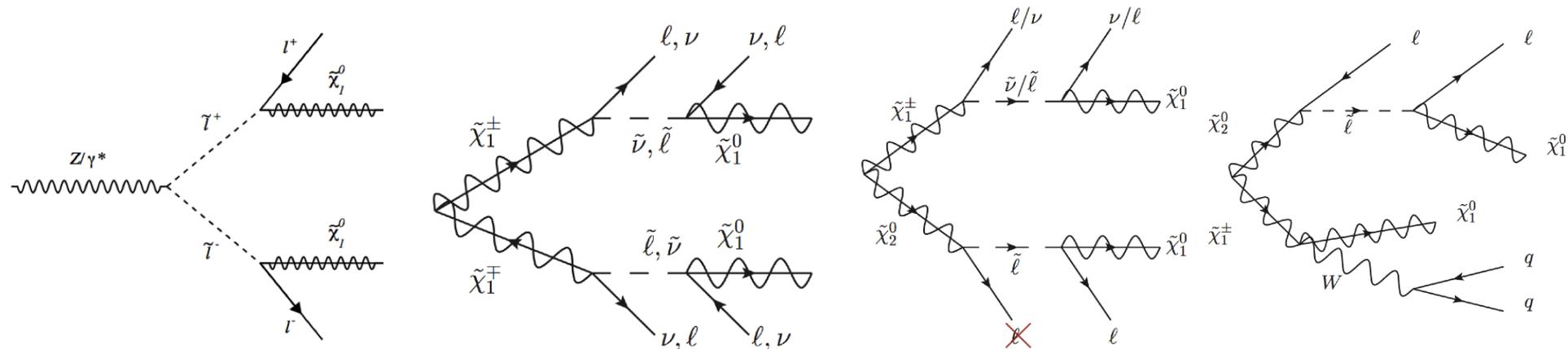


# 2 Leptons (Weak Production)

- Four SR optimized for direct slepton production and different Chargino/Neutralino decay modes.

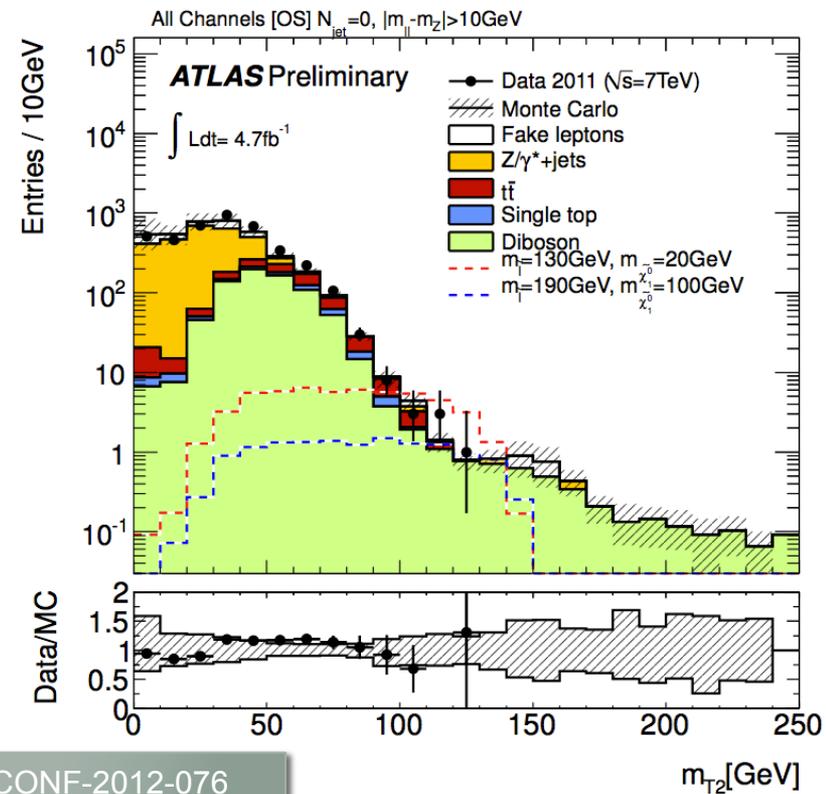
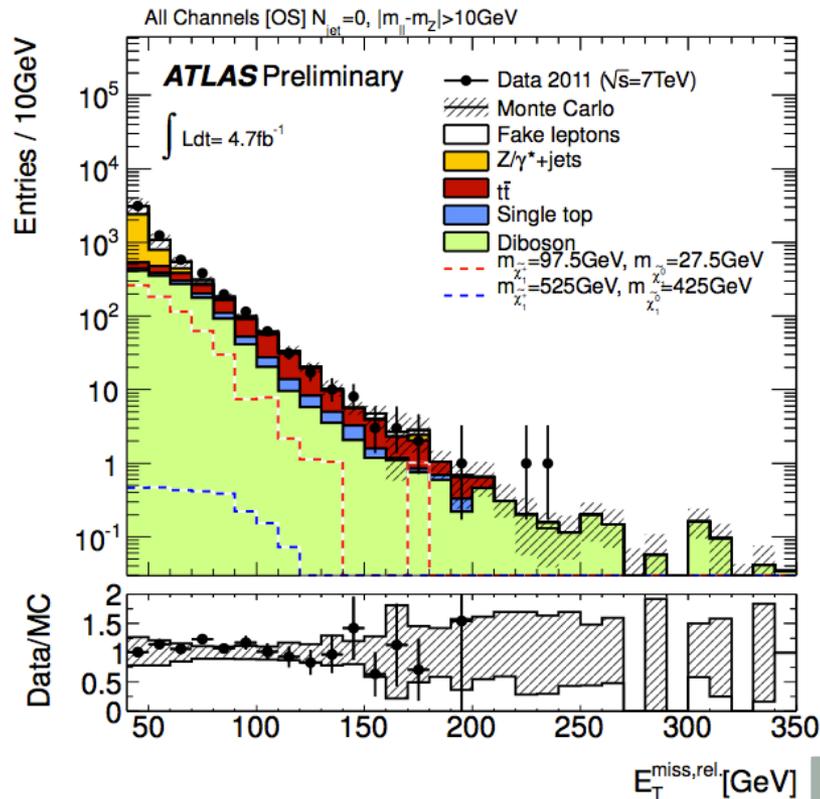
ATLAS-CONF-2012-076

SR-	$m_{T2}$	OSjveto	SSjveto	2jets
charge	OS	OS	SS	OS
flavour	any		any	SF
$m_{ll}$	Z-veto	Z-veto	-	Z-veto
signal jets	= 0	= 0		$\geq 2$
signal $b$ -jets	-	-		= 0
$E_T^{\text{miss,rel.}}$	> 40	> 100		> 50
other	$m_{T2} > 90$	-		$m_{CT}$ -veto



# Direct Slepton Production

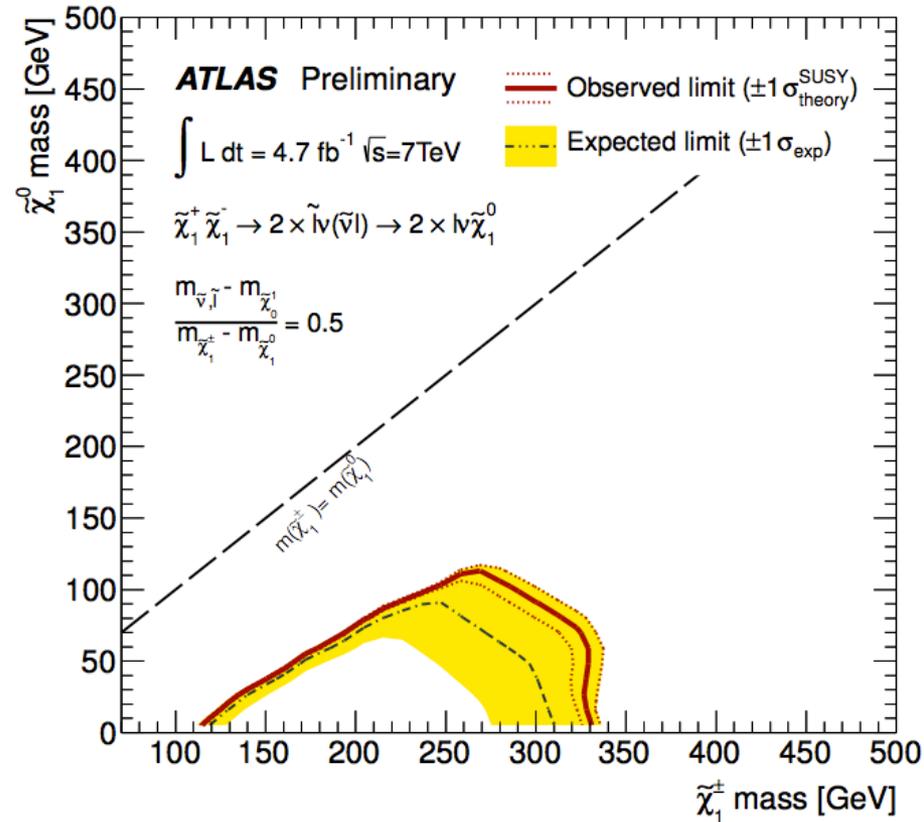
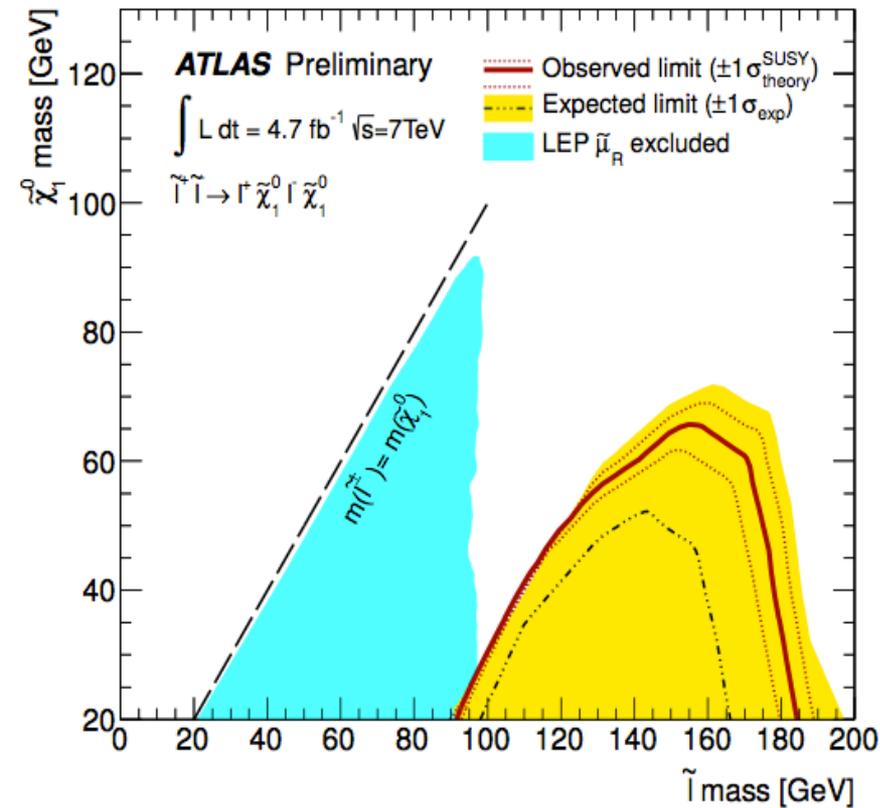
- $m_{T2}$  signal region
  - $t\bar{t}$ ,  $Z+j$  normalized to data in control regions
  - $WW$  from MC
  - reducible background ( $W+j$ , and QCD) from loose lepton sample using the loose to tight efficiency



ATLAS-CONF-2012-076

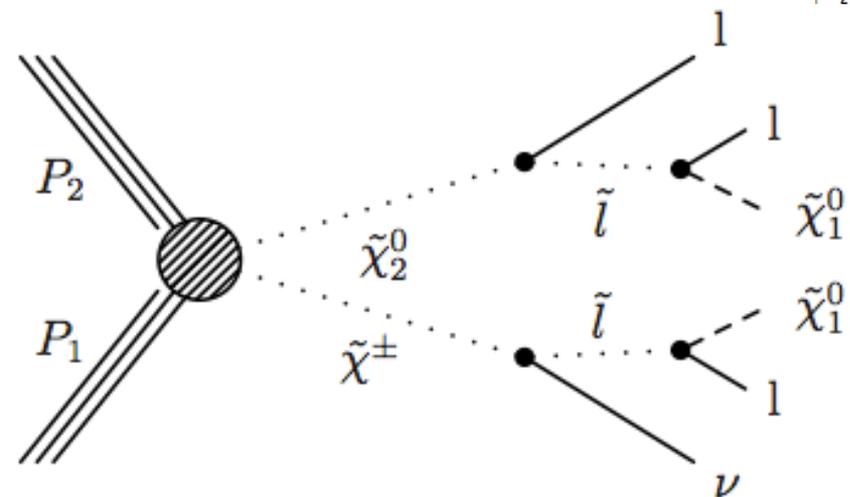
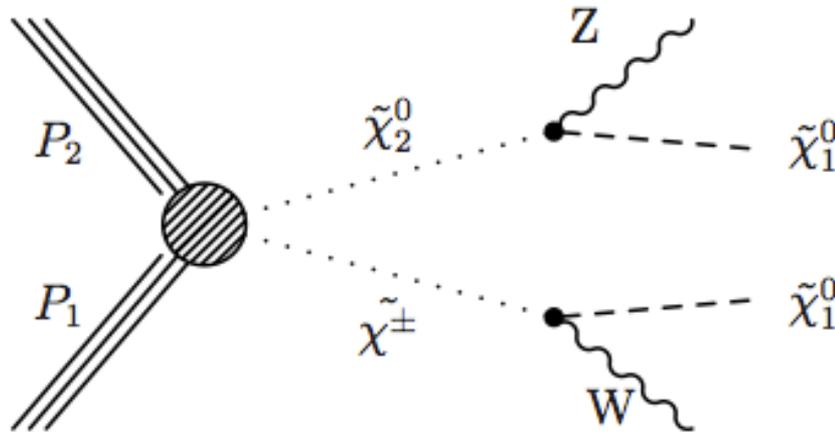
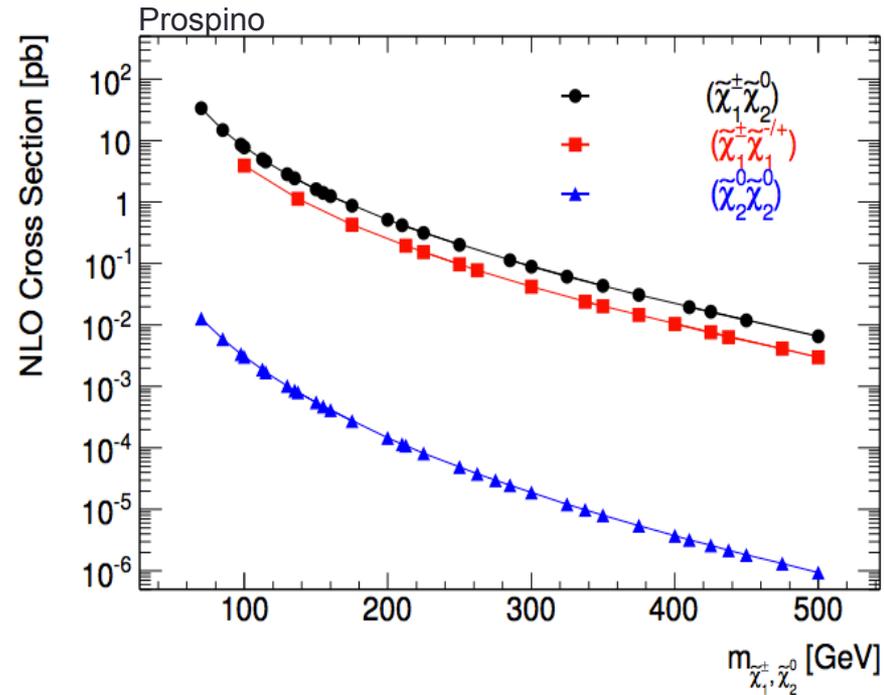
# Direct Slepton and Chargino Limits

- $m_{T2}$  signal region
- Direct sleptons within the pMSSM model
- Direct Charginos with Simplified Models, Chargino1 and Neutralino1 masses



# 3 Lepton Searches

- Targeting Chargino Neutralino direct production
- Both decays via intermediate slepton and gauge bosons
- ATLAS targeting models with either small or large mass splitting
- CMS: general search
  - Including final states with up to 2 taus



# ATLAS 3 Lepton Search

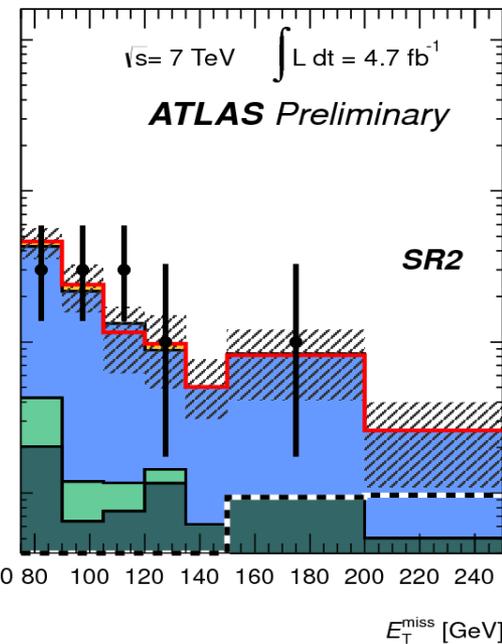
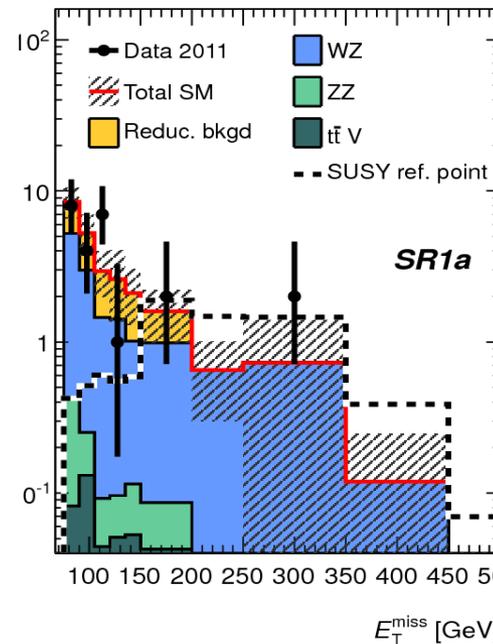
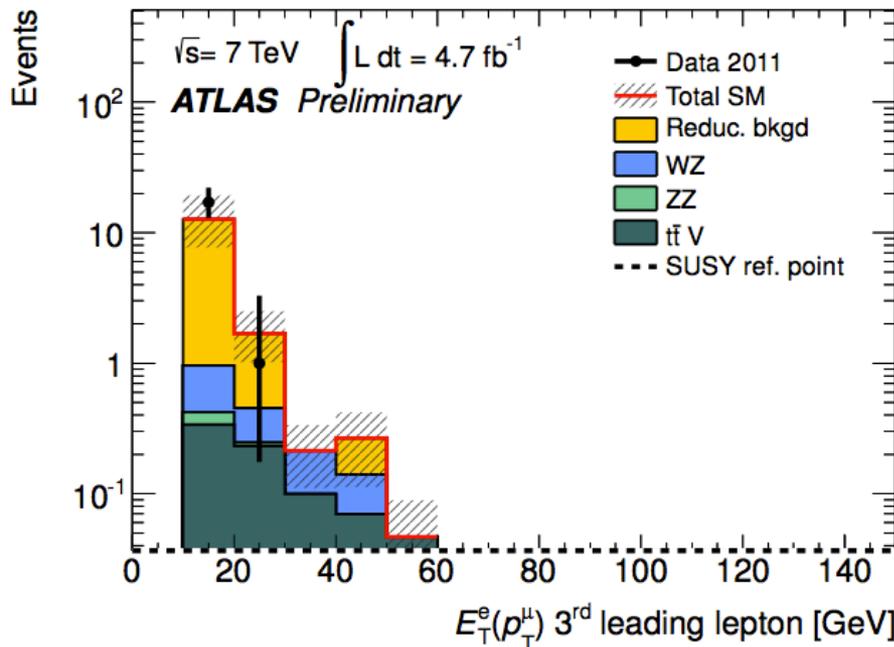
- Z-depleted signal region
  - Low mass splitting between N1 and N2
  - High mass splitting
- Z-enriched for decays via gauge boson
- WZ normalized to data in CR via simultaneous fit accounting for potential signal contamination
- Irreducible with data-driven matrix method

$E_T^{\text{miss}}$	> 75 GeV		
$m_{\text{SFOS}}$	Z-veto	Z-veto	Z request
N b-jets	0	0	any
$m_T$	any	> 90 GeV	> 90 GeV
$p_T \ell_3$	> 10 GeV	> 30 GeV	> 10 GeV

ATLAS-CONF-2012-077

Top validation region

Z depleted SR (low lepton  $p_T$ ); Z enriched SR





# 3 Lepton Interpretations

ATLAS-CONF-2012-077

## Simplified model

Decay via intermediate sleptons

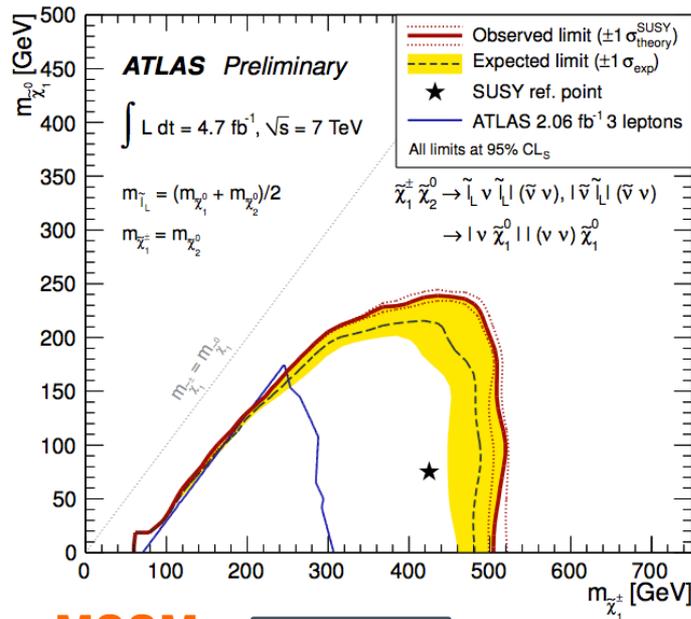
Based on SR targeting large mass splitting

(BR of  $N_2$  into slepton = 50%)

First LHC limit on pMSSM

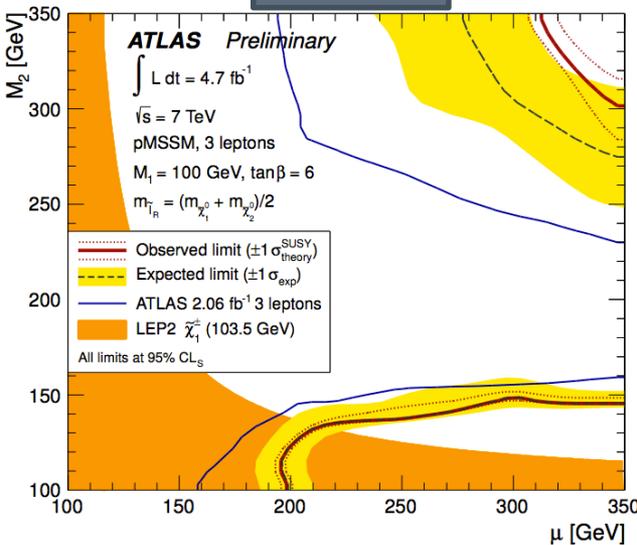
with  $M_1=140$  and  $250$  GeV

Based on SR targeting small mass splitting

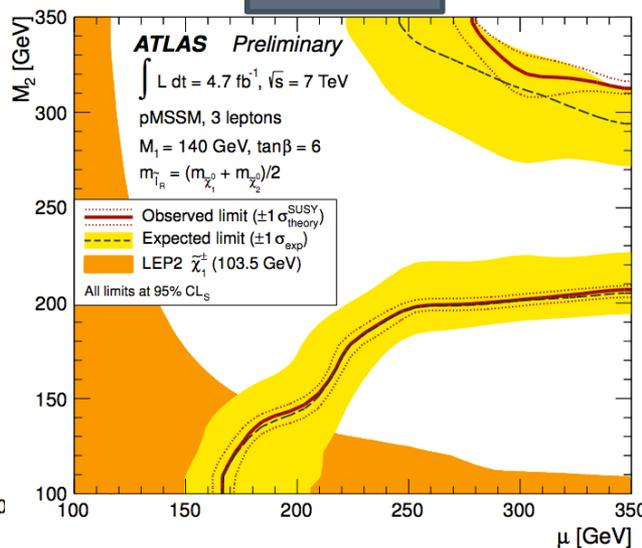


## pMSSM

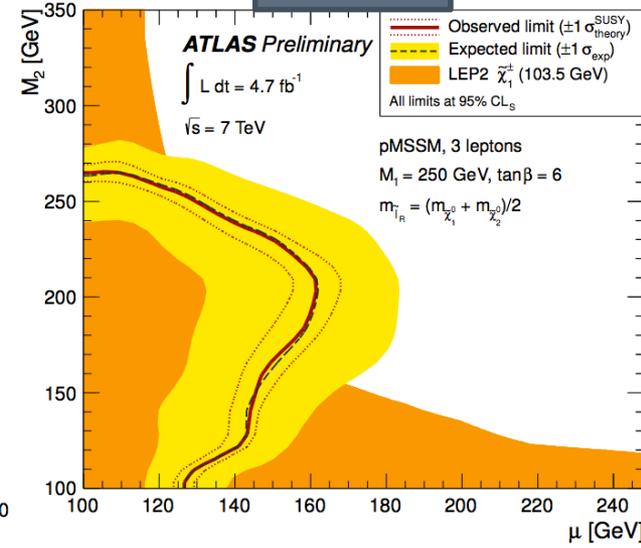
$M_1=100\text{GeV}$



$M_1=140\text{GeV}$



$M_1=250\text{GeV}$



# mUED and GGM Interpretations

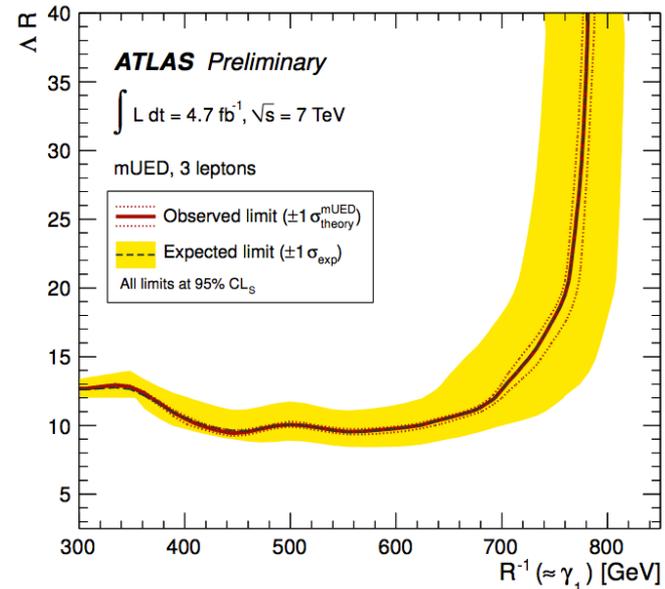
ATLAS-CONF-2012-077

## mUED

- 1 extra dimension,  $S^1/Z_2$  orbifold of size  $R$
- $\Lambda$  cut-off scale of the effective theory
- KK-photon is the lightest stable KK-particle

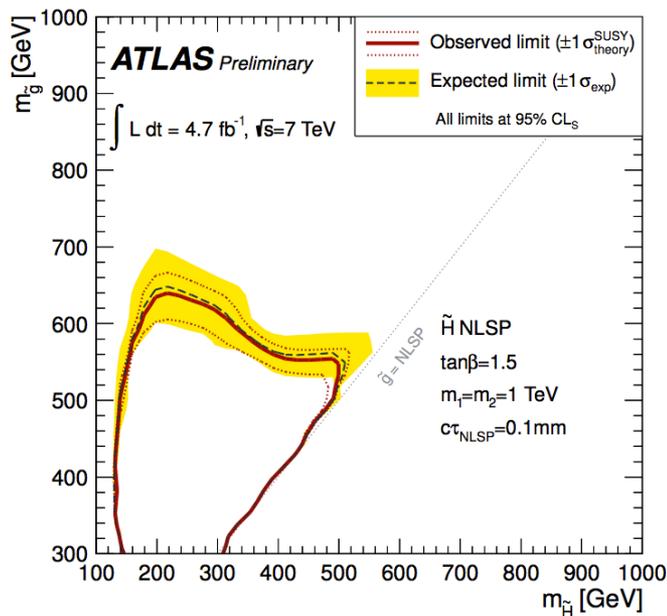
## GGM

- Strong production through gluinos
- LSP  $\sim$  massless Gravitino
- NLPS Higgsino (left),
- Wino-like Chargino1, Neutralino1 (right)



$$\tilde{H} \rightarrow \gamma \tilde{G}$$

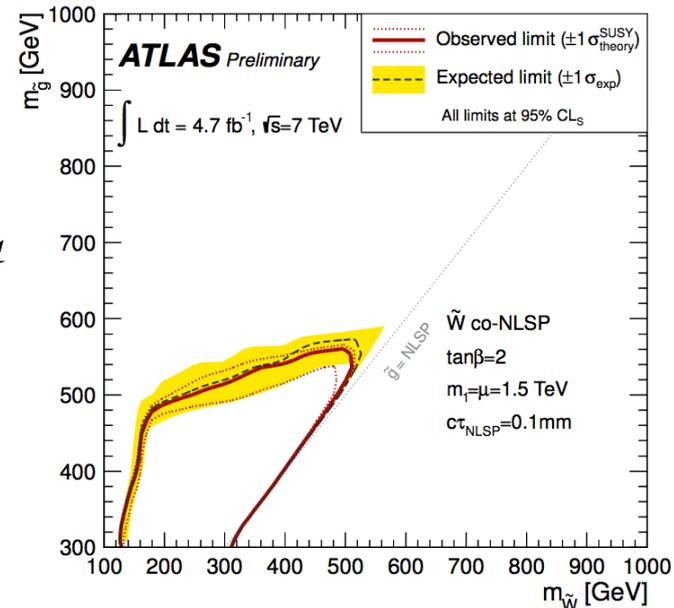
$$\tilde{H} \rightarrow Z \tilde{G}$$



$$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$$

$$\tilde{\chi}_1^0 \rightarrow Z \tilde{G}$$

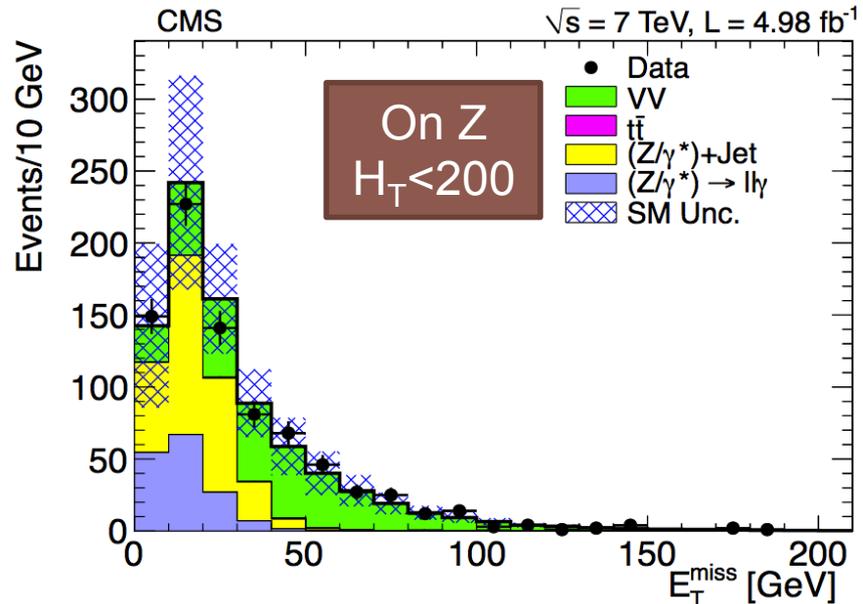
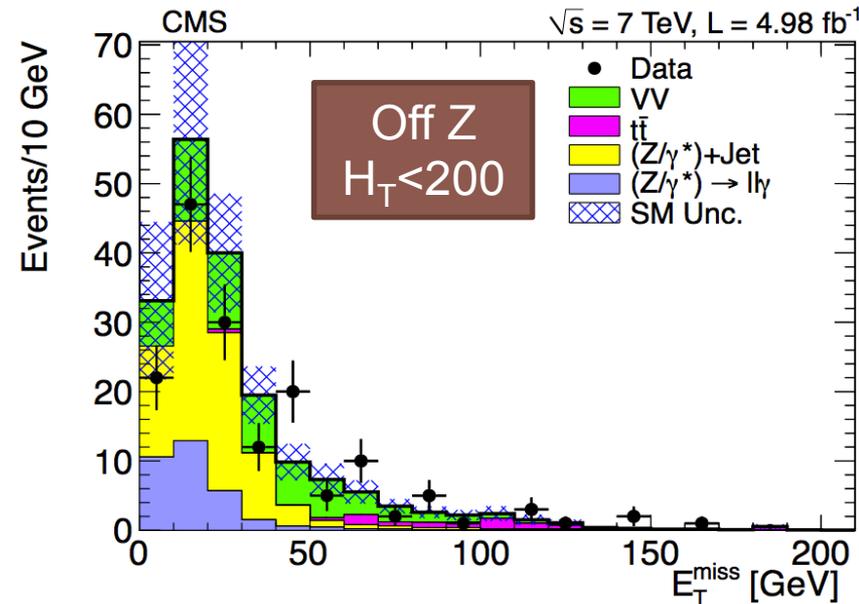
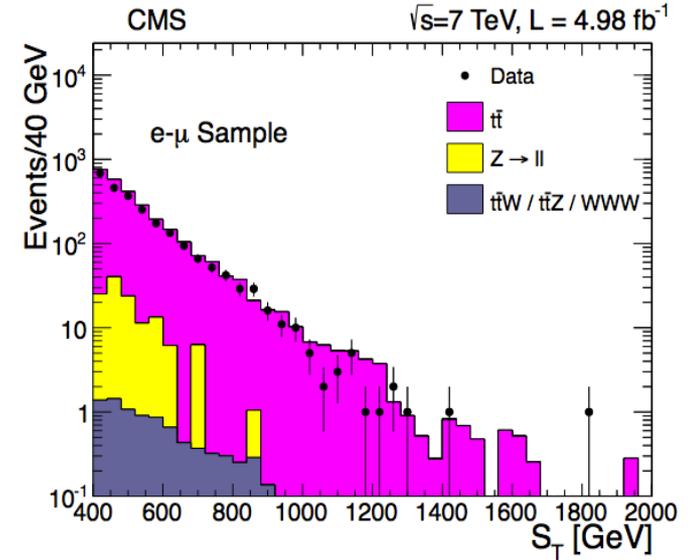
$$\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$$



# CMS 3-4 Lepton Search



- 0,1,2 hadronic taus
- 52 channel  $E_T^{\text{miss}} \leftrightarrow 50$  GeV,  $H_T \leftrightarrow 200$  GeV
- 54-channel  $S_T \leftrightarrow 300, 600$  GeV (RPV)
- on- and off-shell Z
- Signal (low-bkgnd) and control (high bkgnd) channels treated uniformly.
  - Data driven estimate of the reducible background
  - $t\bar{t}$  and irreducible from MC

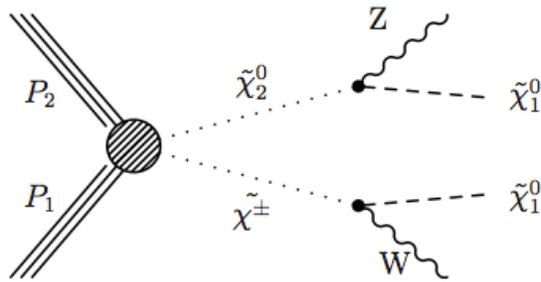


CMS arXiv:1204.5341, EXO11045/SUS11013

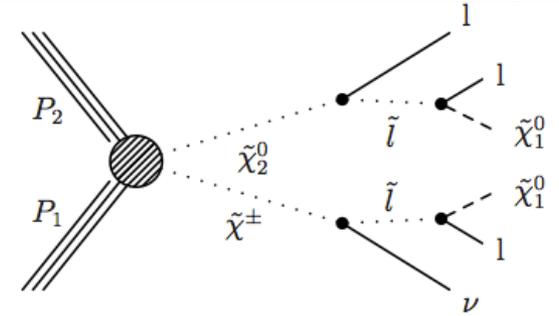
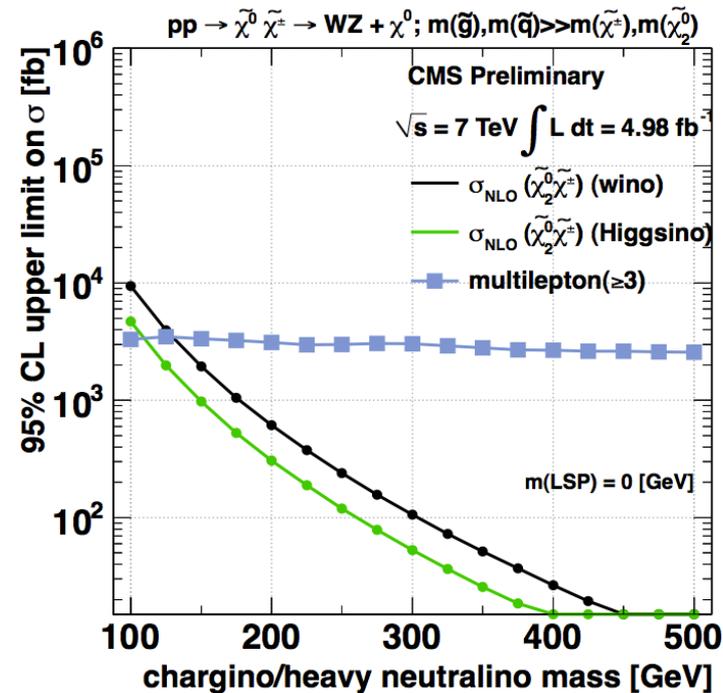
# Direct Production Simplified Models



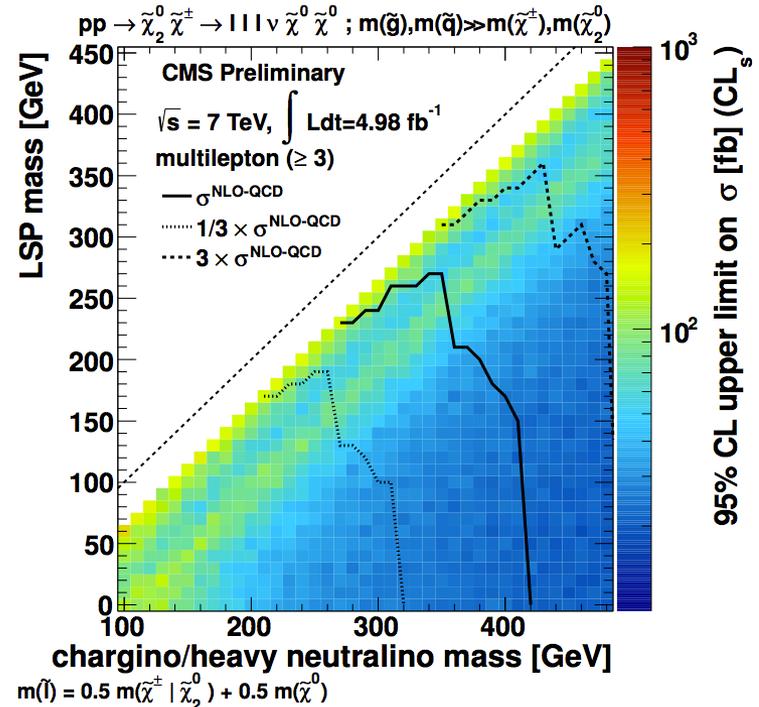
CMS PAS-SUS-11-016



First LHC limit on gaugino decay via W and Z bosons



Decay via intermediate sleptons (BR of Neutralino into slepton = 100%)



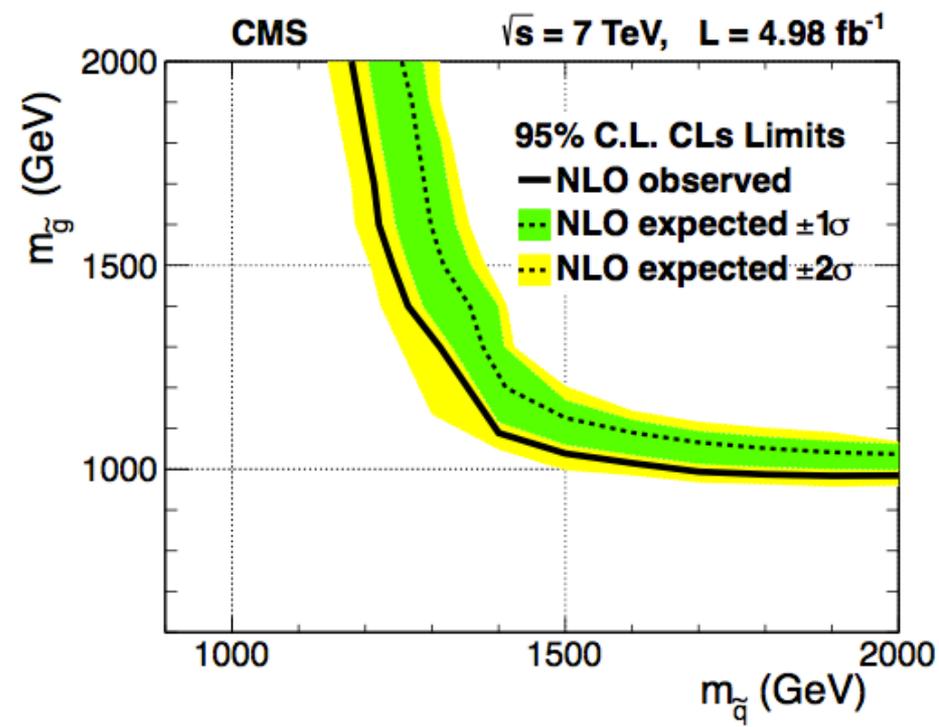
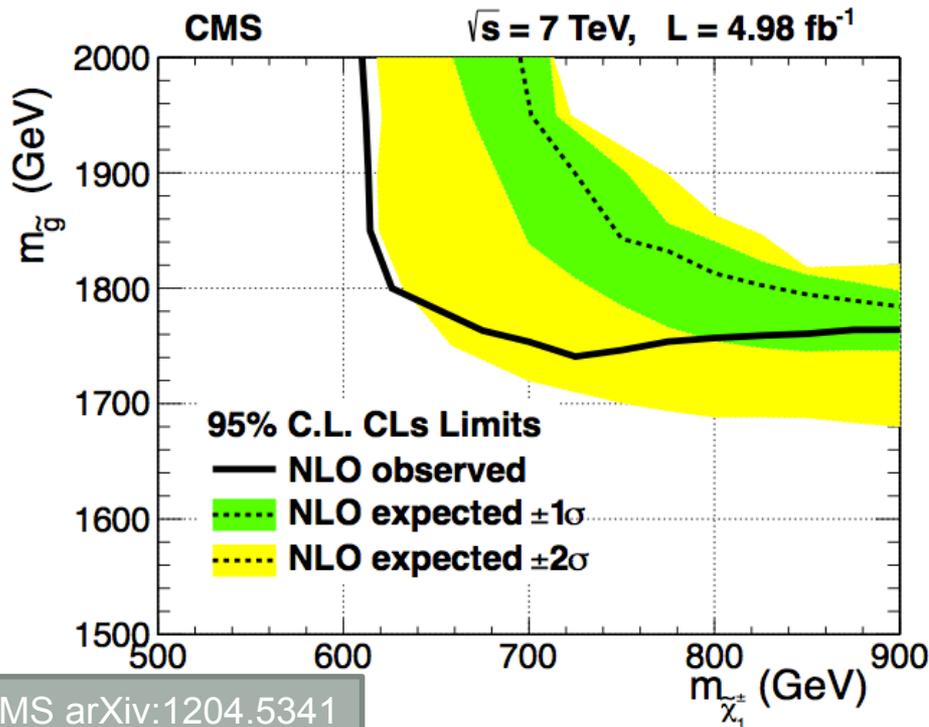
# GMSB and RPV Interpretations



- GMSB, gravitino LSP
- Right handed sleptons co-NLSP
- Neutralino decays to 2 leptons + gravitino (through sleptons)
- Strong production
- $E_t^{\text{miss}} / H_T$  binned signal regions

$$W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- L-RPV  $\lambda_{ijk} \neq 0$
- Neutralino LSP decays to 2 leptons and neutrino
- Strong production
- $S_T$  binned signal regions



# 4 Leptons, RPV mSUGRA

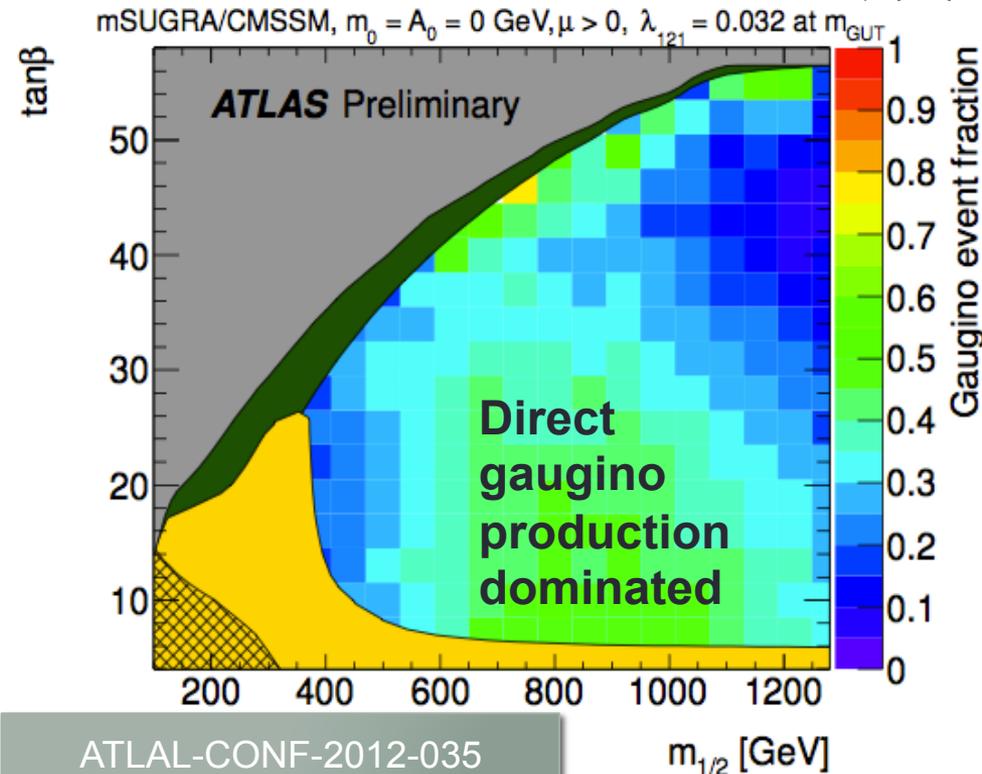
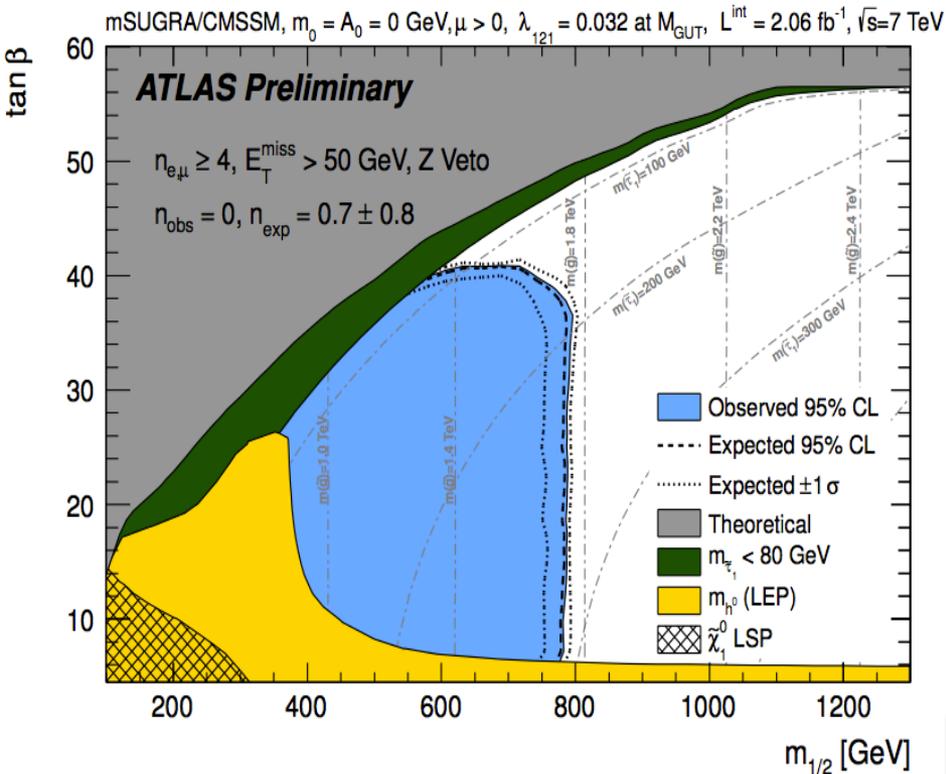
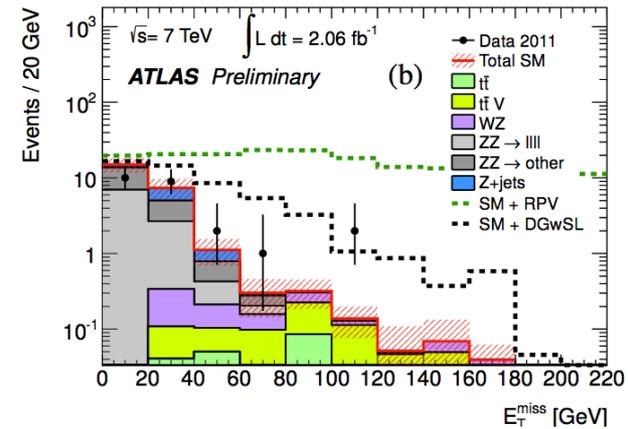
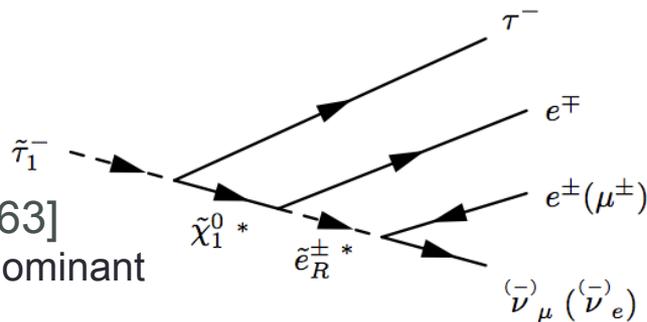
## Signal regions

- $E_{T,miss} > 50$  GeV veto Z
- $E_{T,miss} > 50$  GeV with Z

## RPV with stau LSP:

- mSUGRA/CMSSM
- BC1 point [hep-ph/0609263]
  - gaugino pair production dominant

ATLAS-CONF-2012-001

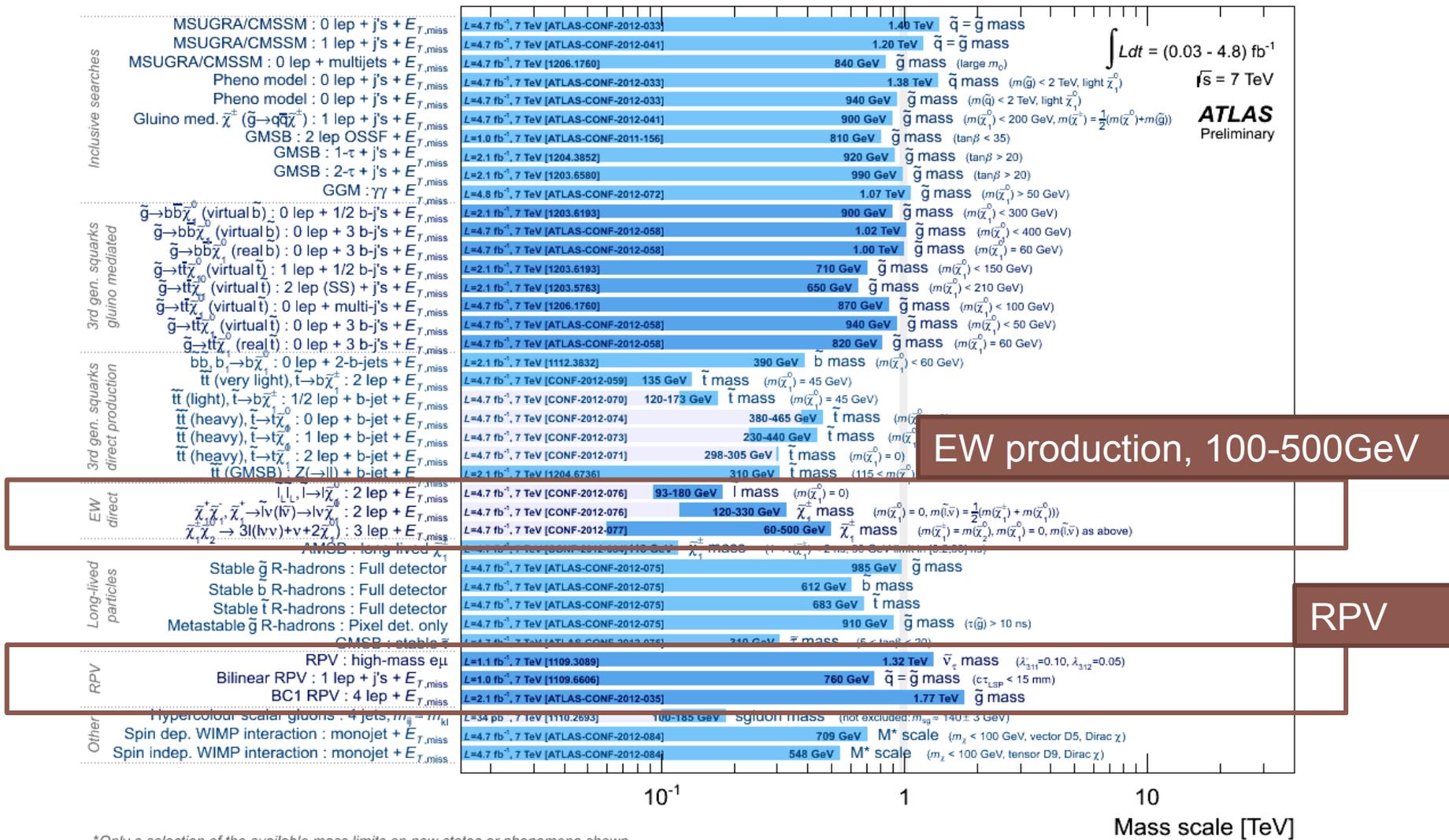


ATLAS-CONF-2012-035



# ATLAS Grand Summary

## ATLAS SUSY Searches\* - 95% CL Lower Limits (Status: ICHEP 2012)

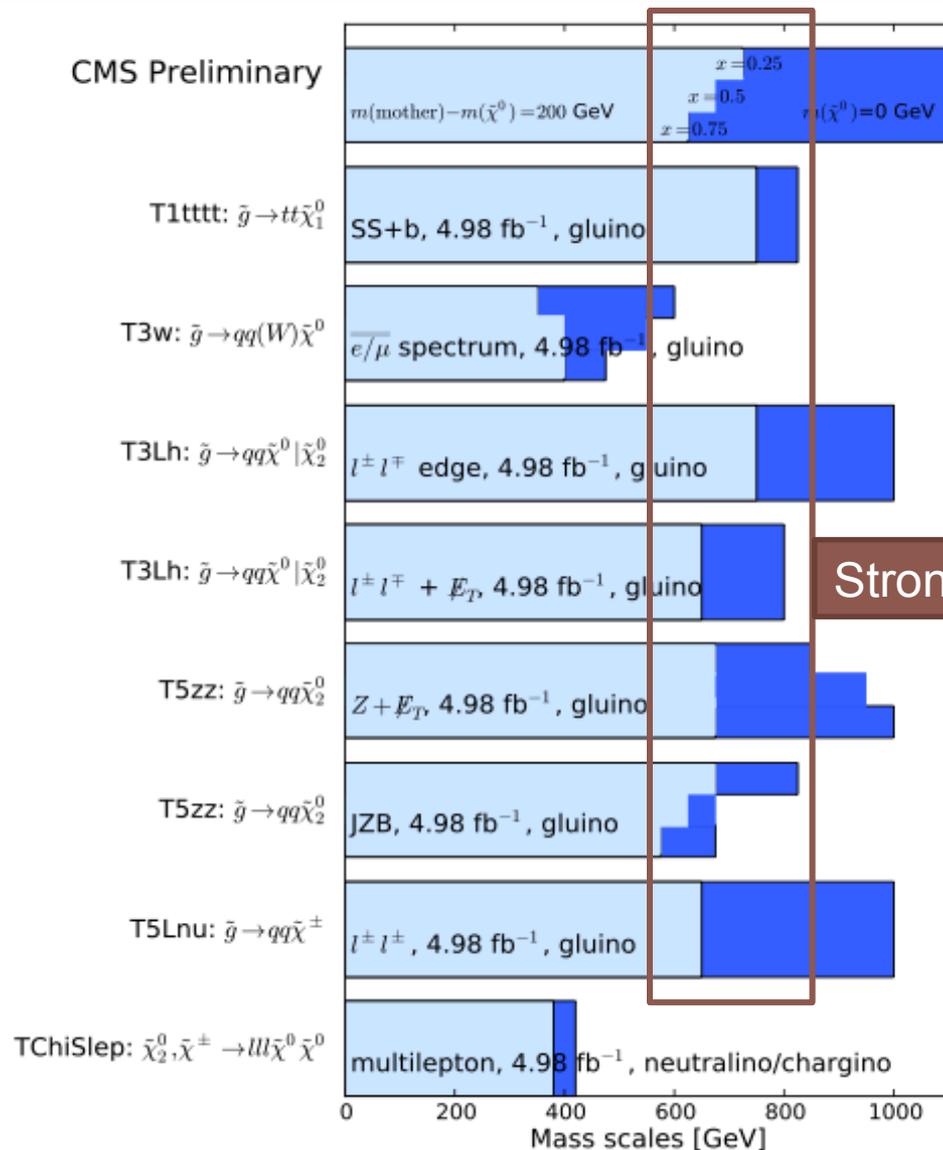


\*Only a selection of the available mass limits on new states or phenomena shown

# CMS Grand Summary



- Range of excluded mass scale in Simplified Model Spectra from CMS Leptonic SUSY searches



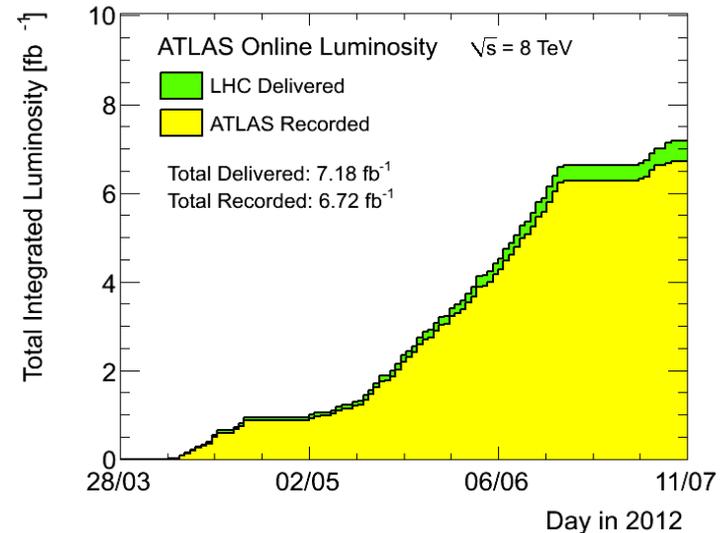
Strong production, gluino ~700GeV

Chargino/neutralino ~400GeV

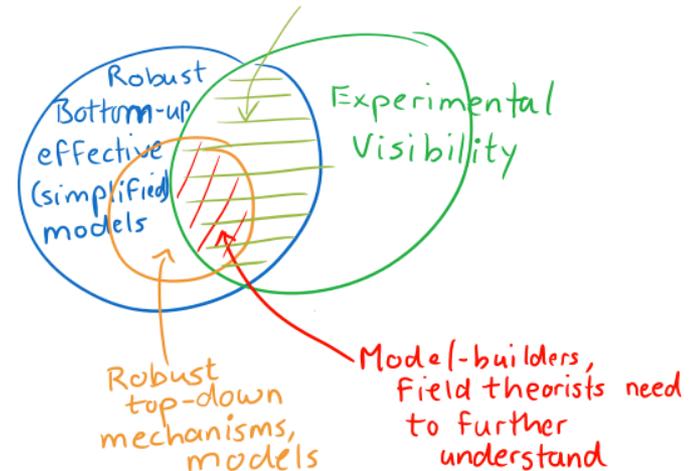
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>

# Summary and Outlook

- **Excellent performance of LHC, ATLAS and CMS in 2011**
- Broad spectrum of SUSY leptonic searches carried out
- **Most limits set at or beyond TeV scale!**
- **New Physics was not just around the corner!**
- More data already available from the 8 TeV run, expected  $\sim 20/\text{fb}$  by end of the year
- Both CMS and ATLAS adjusting their search strategy
  - Extend to higher masses
  - Focus on processes preferred by naturalness
  - Explore further final states



IT AIN'T OVER TILL I SAY VENN  
where we must act, now



from R. Sundrum ICHEP2012