

# SUPERSYMMETRY

## Searches for supersymmetry with the CMS detector at LHC

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**on behalf of the CMS Collaboration**

**National Centre for Nuclear Research  
(NCB) – Warsaw )**

**Cracow Epiphany Conference**  
**On the physics after the first phase of of the LHC**  
**7-9 January 2013, Cracow, Poland**



# SUSY at CMS



## OUTLINE:

Short intro

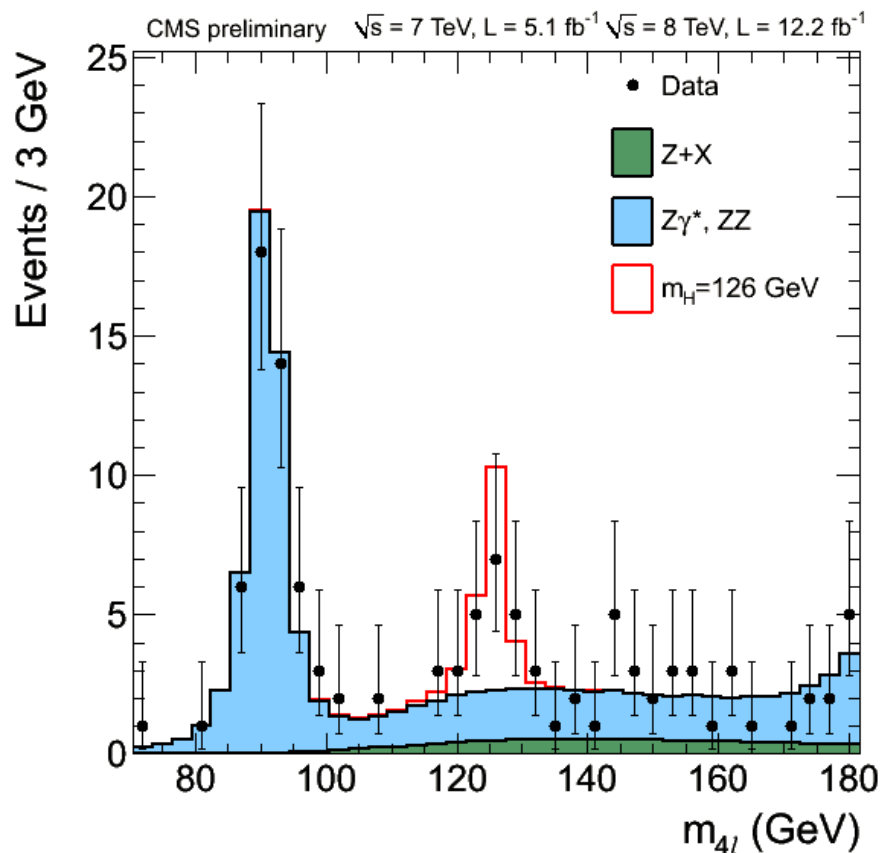
- Background for searches:
  - **HIGGS BOSON DISCOVERY!**
  - SM precise measurements
  - Motivation for SUSY

Main part

- **Review of SUSY searches**
  - New results from CMS data collected in 2011 (5/fb at 7 TeV) and 2012 (9 - 12/fb at 8 TeV)



# Higgs discovery



- The newly discovered particle is a boson with spin 0 or 2  
Spin 1 is ruled out by the Landau-Yang theorem, as it can't decay into two photons
- The coupling structure has been confronted to the **SM predictions**  
→ **Overall very good agreement observed**
- No evidence for non-standard higgs production or decay is found in several models  
(hints from  $b$  and tau channels)

**CMS average:**

**$m_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$**

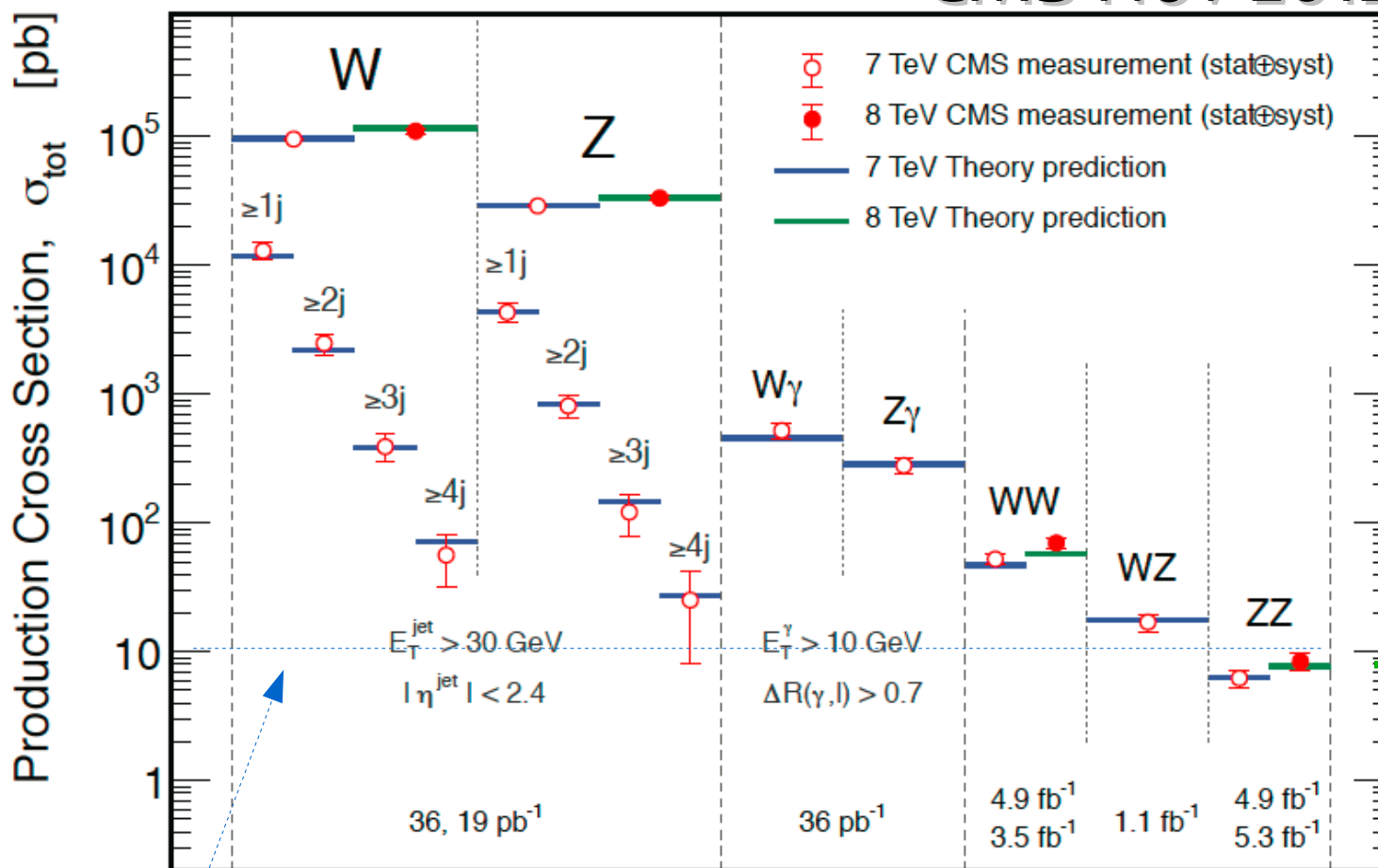
CMS-PAS-HIG-2012-045



# Standard Model



CMS Nov 2012

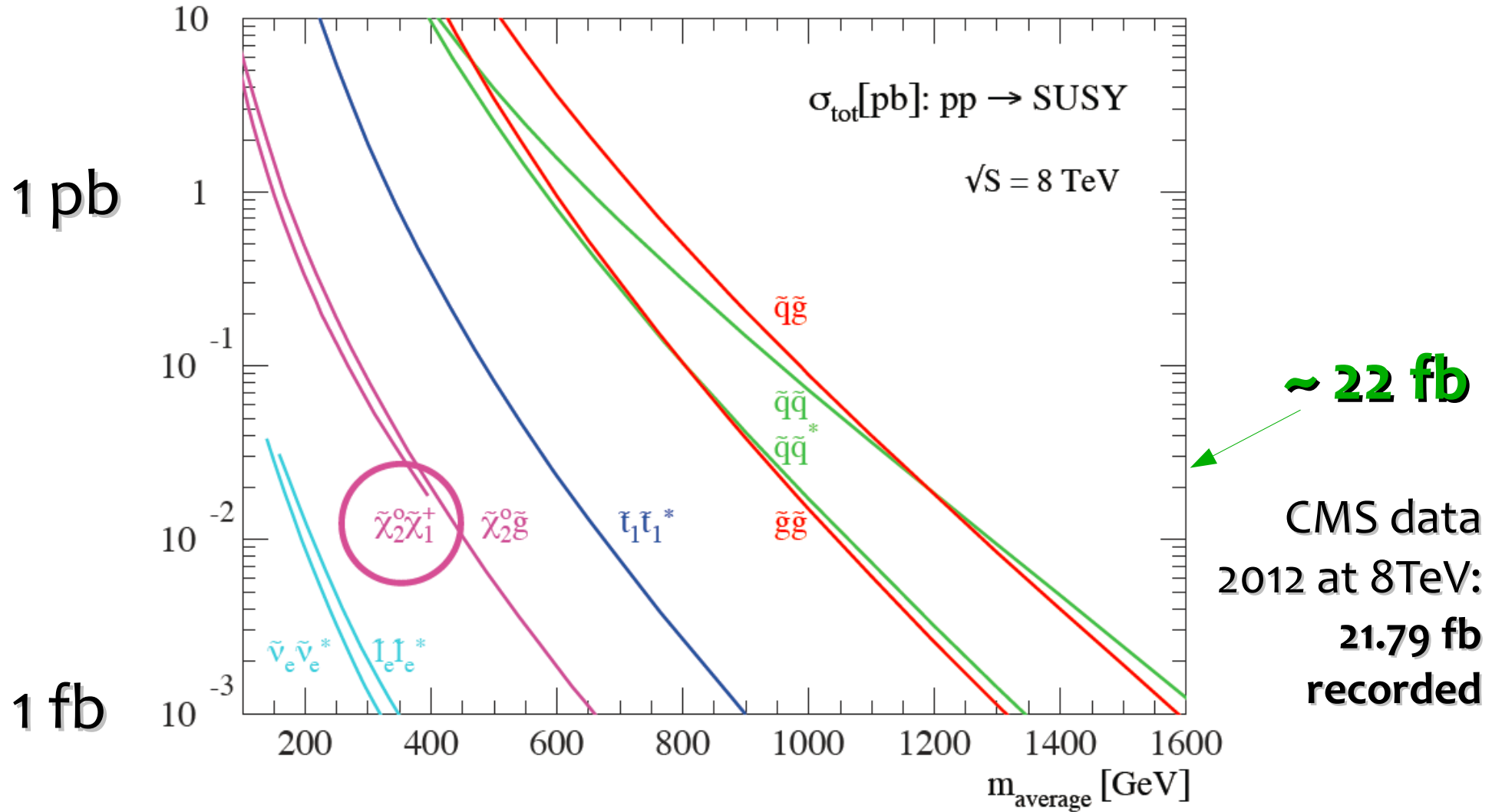


Higgs  
gluon-gluon  
fusion  
( $\sim 125 \text{ GeV}$   
 $\sigma \sim 19/\text{fb}$ )

- **SUSY**: typical cross sections below 10 pb



# SUperSYmmetry



- SUSY:** typical cross sections below 10 pb

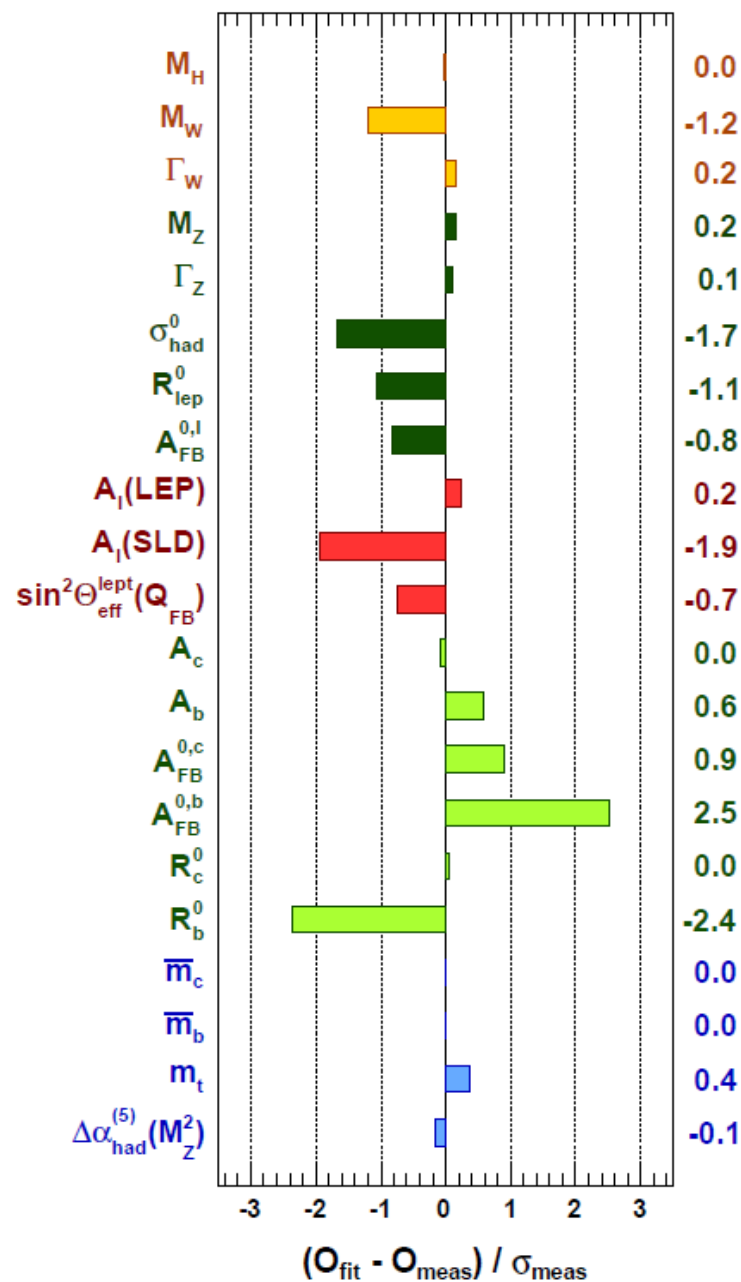


# SM tested to per mil level

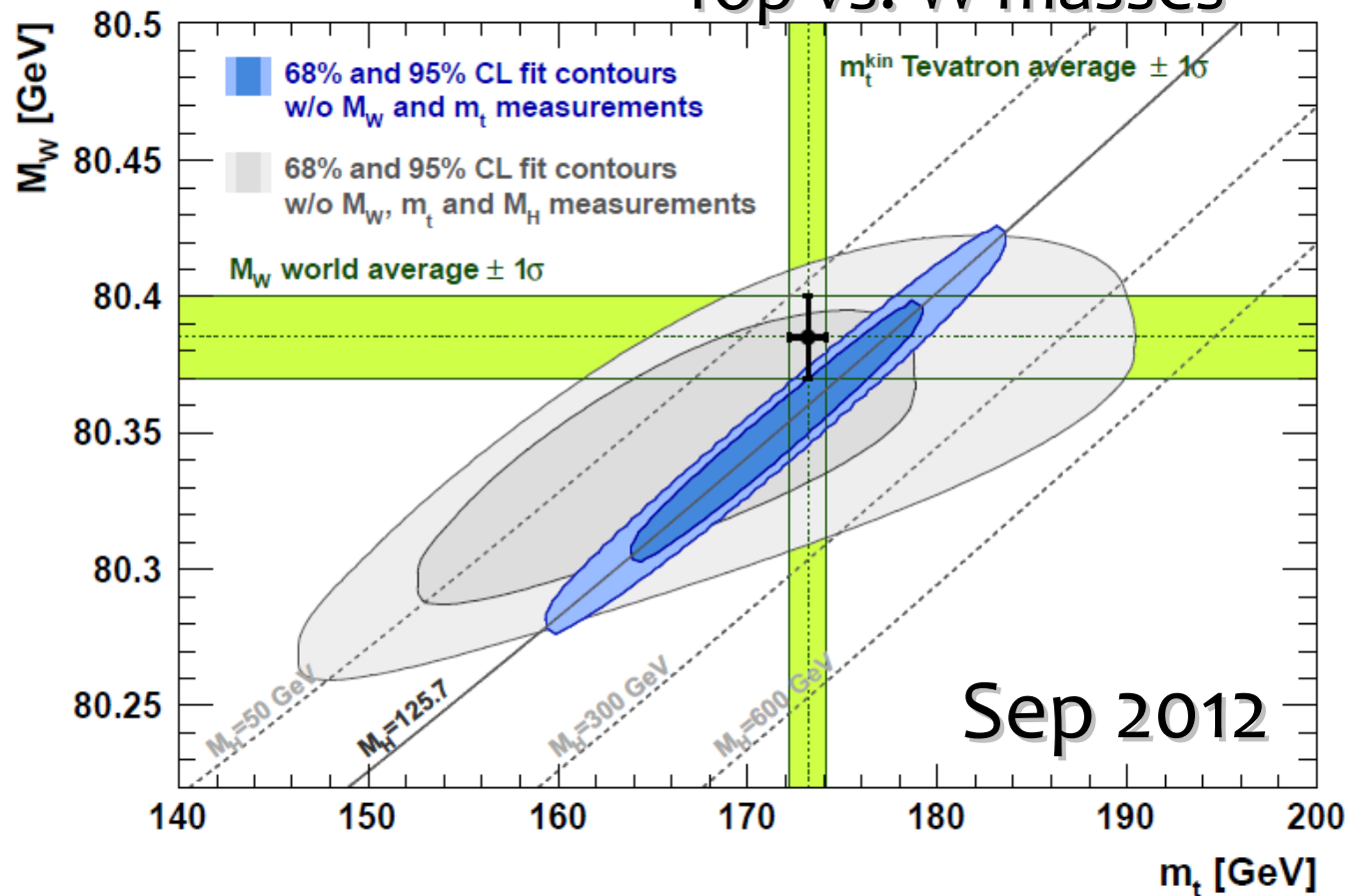


arXiv: 1209.2716

- Precise measurements give hints to Higgs properties and shows windows to New Physics



## Top vs. W masses





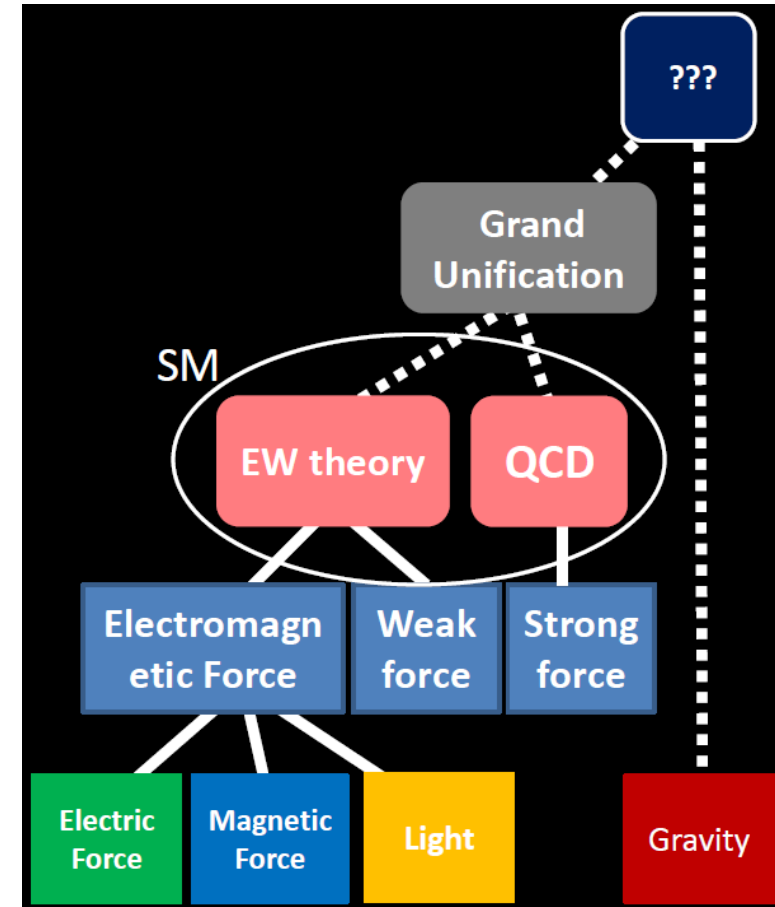
# We still have a lot of questions



- **SM is a successful theory!**

**BUT:**

- What is the Dark Matter?
- Why the Higgs boson is so much lighter than the Planck mass?  
(hierarchy problem)
  - Do fermions have spin-integer partners?
  - Maybe Higgs partners are around corner?
- Why gravity is so weak?
- ...

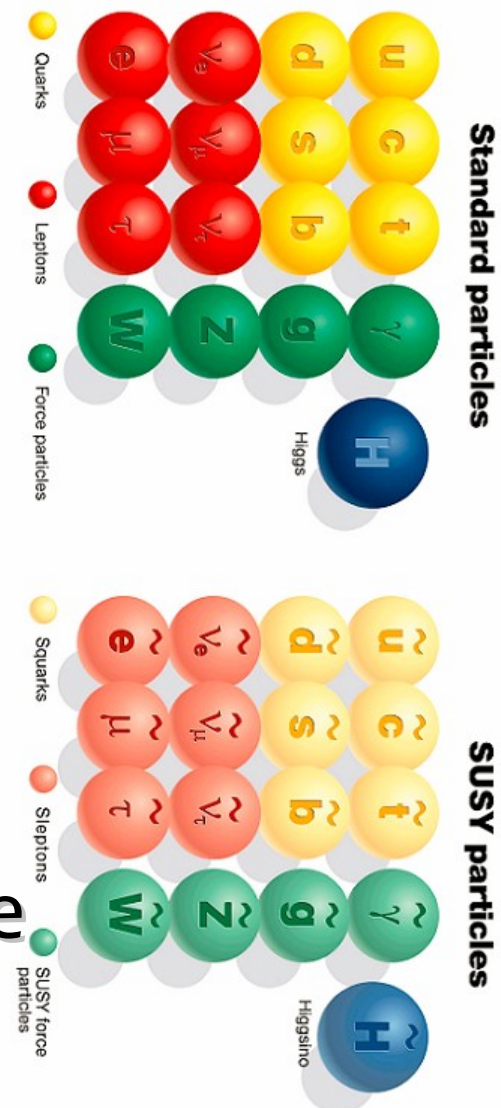




# Attractive Supersymmetry



- SUSY provides a solution to the Higgs mass hierarchy problem
  - SUSY contribution cancels SM divergence in  $m_h$  radiative corrections
- SUSY allows unification of gauge couplings
  - In SM, the couplings “run” but do not cross each other at the same energy while in SUSY they do
- SUSY can predict a Dark Matter candidate
  - R-parity conservation: Lightest SUSY Particle can be the WIMP



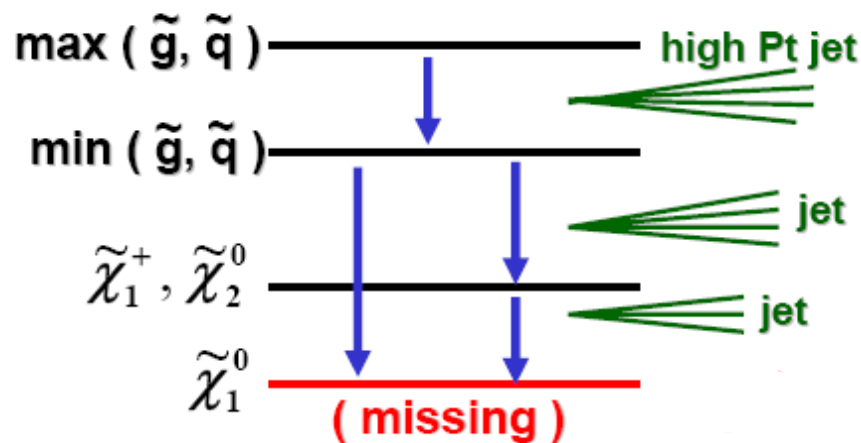




# Signatures of SUSY



- PRODUCTION of SUSY event at the LHC:



- MAIN SIGNATURE:

**large MET** + **multi-jets**

- MAIN BACKGROUND:

QCD,  $t\bar{t}$ /W/Z associated with jets

- Basic search CHANNELS:

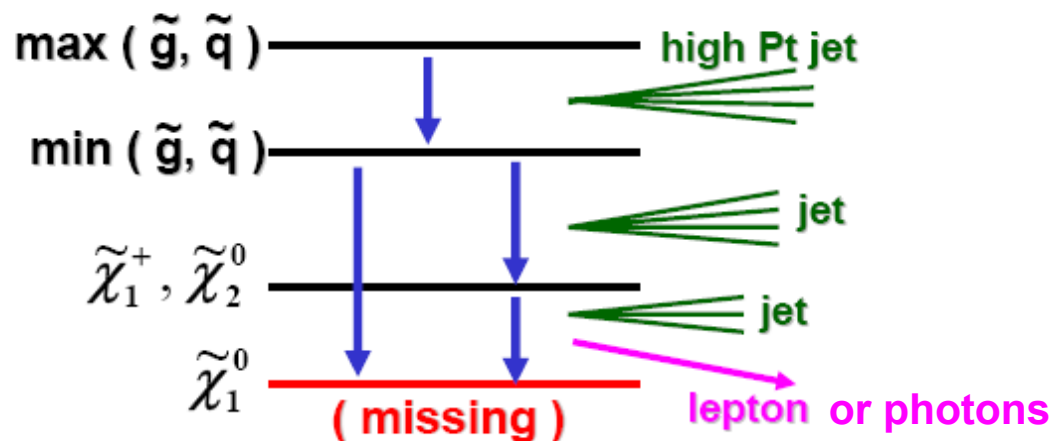
0-leptons
Jets + MET



# Signatures of SUSY



- PRODUCTION of SUSY event at the LHC:



- MAIN SIGNATURE:

**large MET** + **multi-jets** + **(multi-leptons or photons)**

- MAIN BACKGROUND:

~~QCD~~,  $t\bar{t}$ ,  $W/Z$  associated with jets

- Basic search CHANNELS:

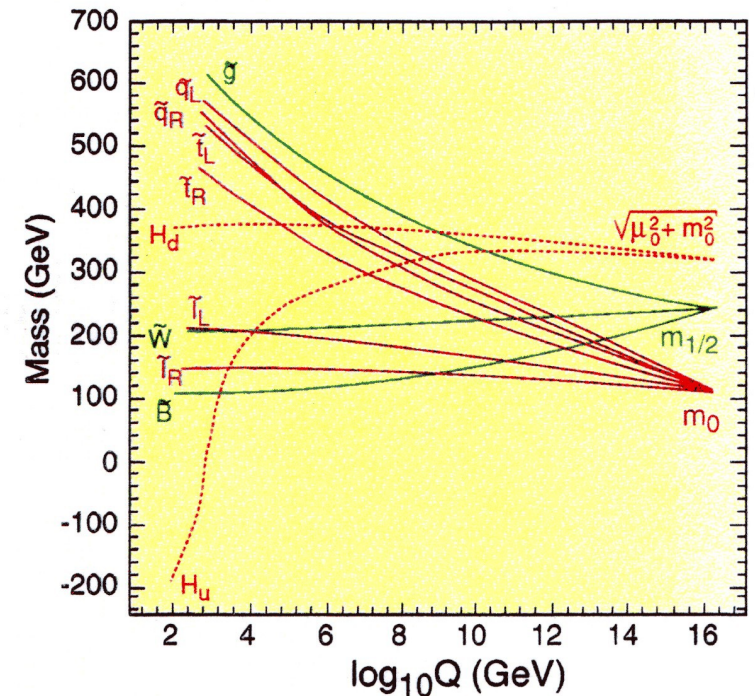
0-leptons	1-lepton	OSDL	SSDL	$\geq 3$ leptons	2-photons	$\gamma$ +lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET



# Popular framework for SUSY BEGINNING



- **MSSM**: the most popular Minimal Supersymmetric extension of the Standard Model
  - too many free parameters...
- assuming simple scenario of SUSY breaking:
  - **Constrained MSSM**
  - $[m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu]$
  - Typically:
    - gluino mass =  $\sim 2.7 m_{1/2}$
    - squark mass =  $\sqrt{(\sim 6 m_{1/2}^2 + m_0^2)}$

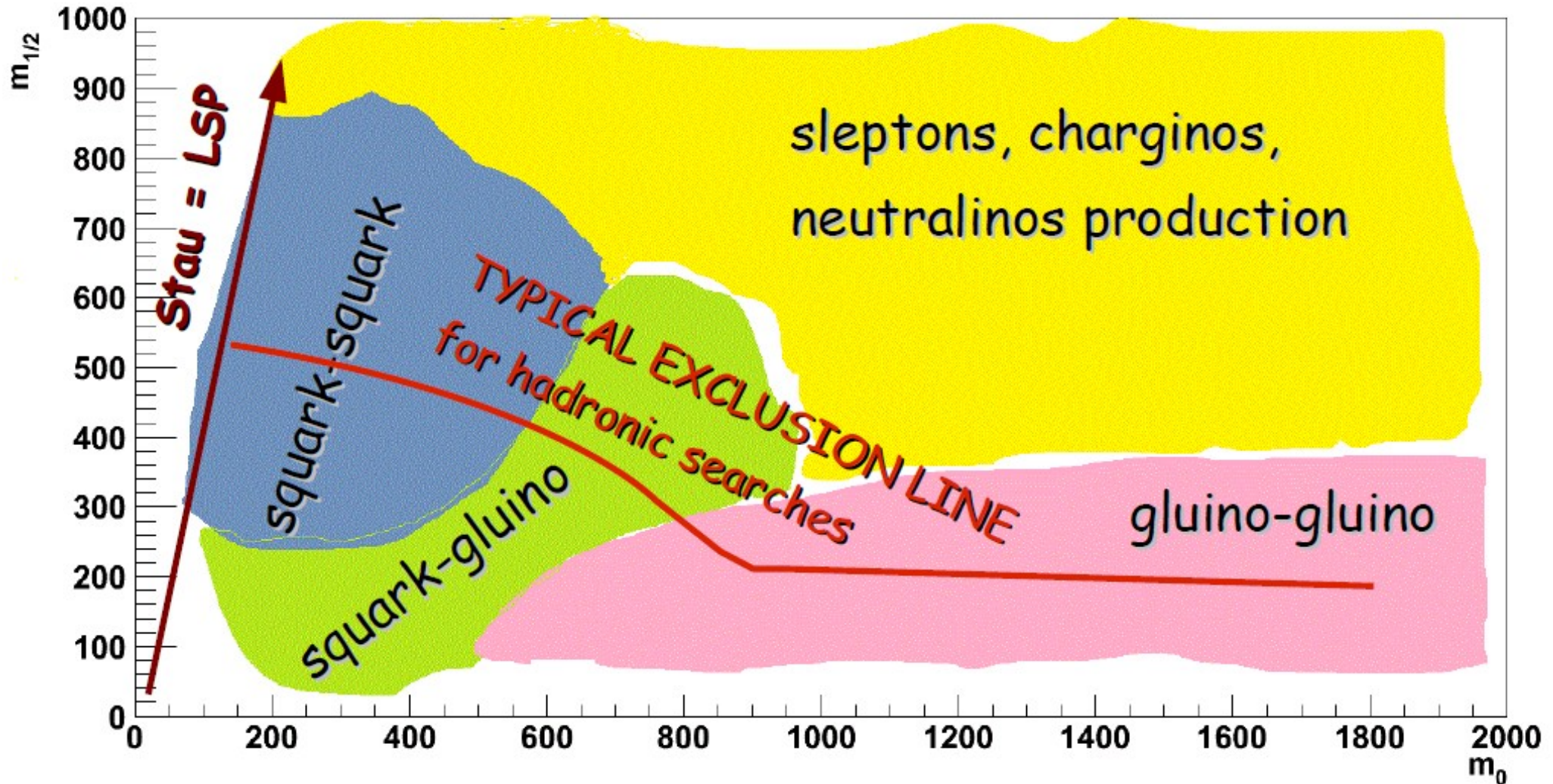




# Anatomy of CMSSM



- Dominant processes of SUSY events production at LHC

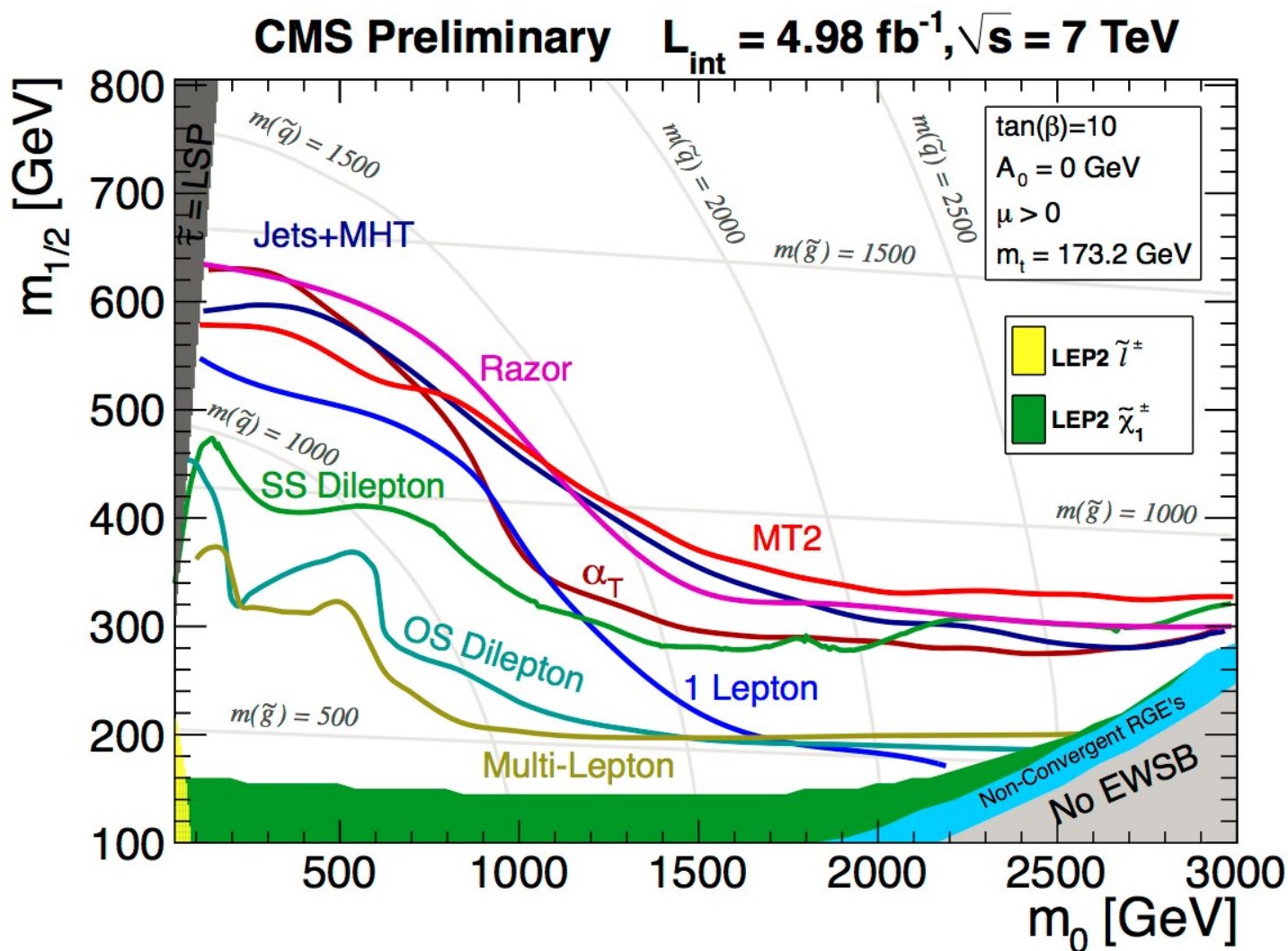




# CMS Spaghetti



- Observed limits from 2011 CMS SUSY searches plotted in the CMSSM  $(m_0, m_{1/2})$  plane



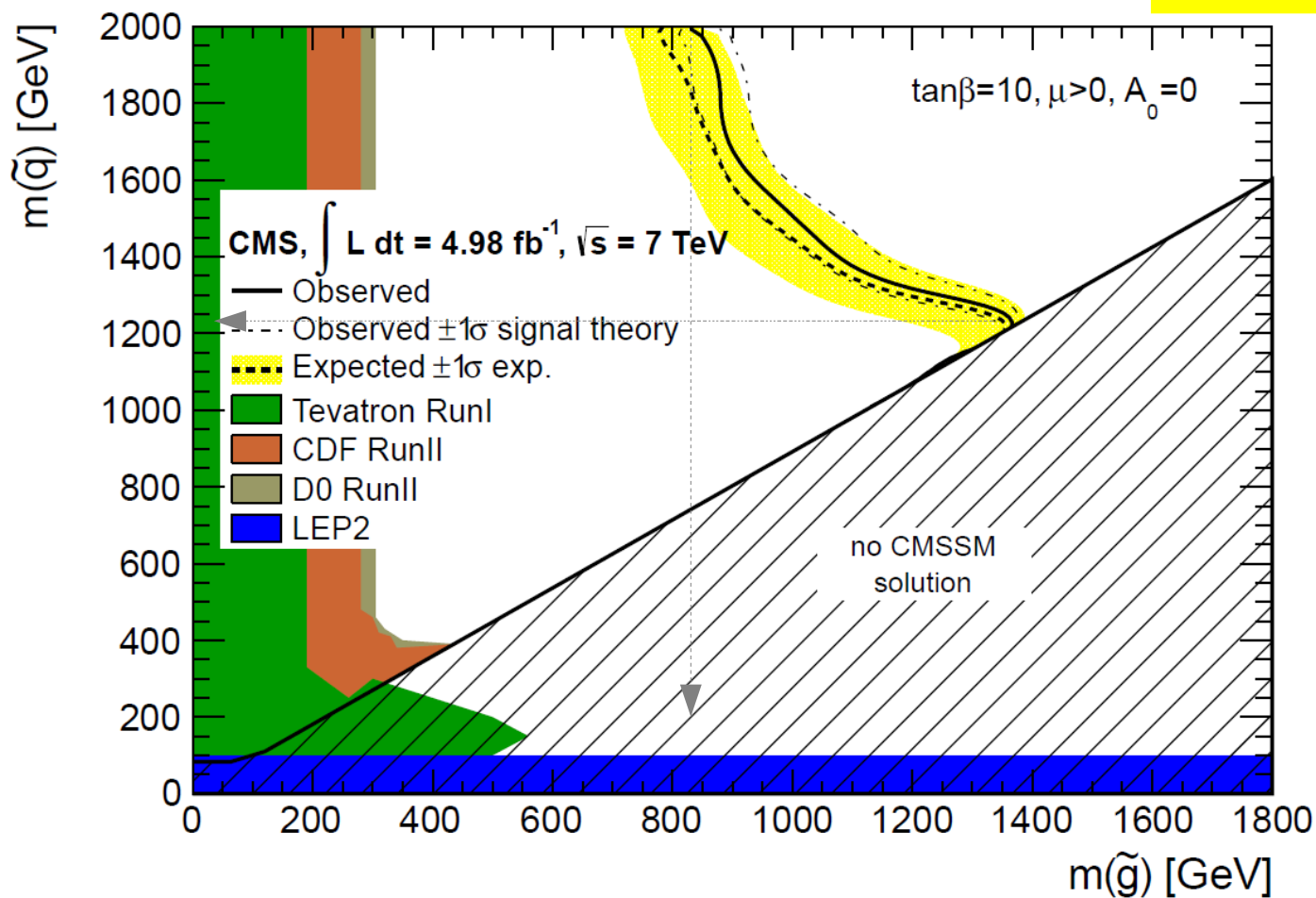


# CMSSM Limits on Sparticles



- Limits in terms of squark and gluino masses

CMS-PAS-SUS-2012-011  
PRL 109, 171803





# SUSY/CMSSM under pressure

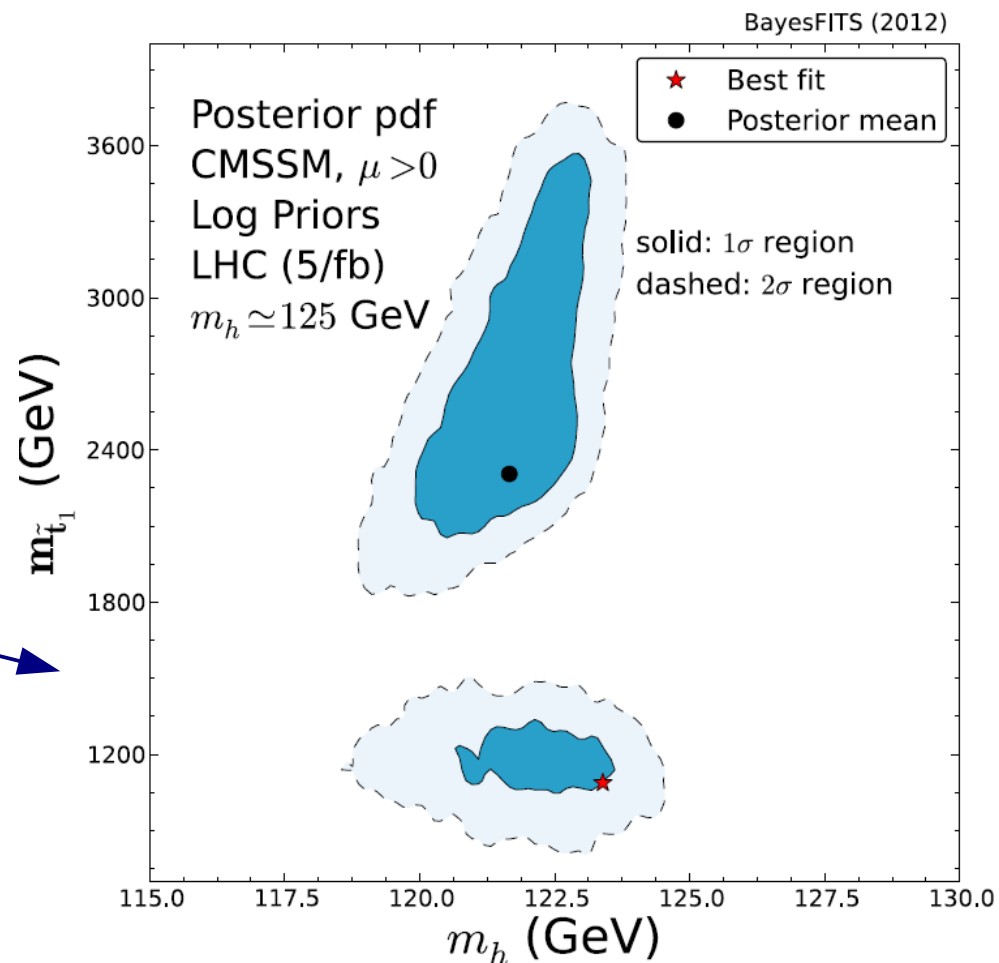


- Strong constrains from direct searches
- Allowed phase space is getting squeezed

Update of  
Phys.Rev. D86  
(2012) 075010

- Flavour physics (recent result from LHCb  $B_s \rightarrow 2 \mu$ ) remains in good agreement with SM

- **Light Higgs-like boson at high end of CMSSM preference**



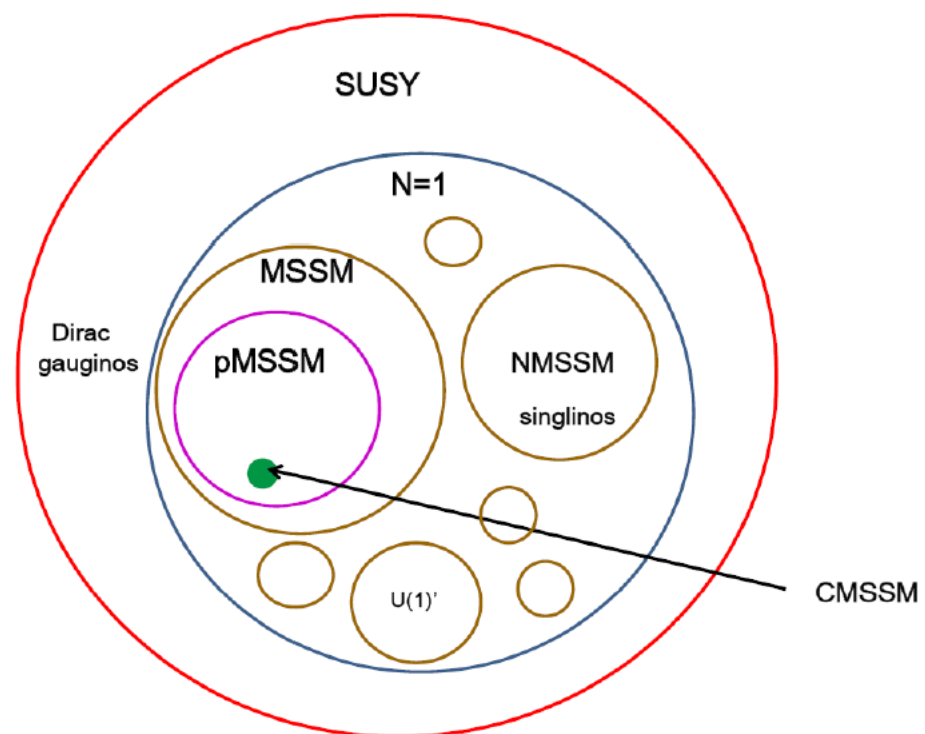


# SUSY – not just one model



- Many possible variations
- SUSY breaking mechanism: gravity-, gauge-, anomaly-mediated,
  - Long lived sparticles ?
- Is R-parity =  $(-1)^{3(B-L)+2S}$  conserved?
  - If not, RPViolating models
- **Wide range of possible signatures** for SUSY to be searched for and **many ways to hide**
- The goal is to find hints of SUSY particles in the LHC range  
→ **New interpretation of results preferred**

SUSY Theory phase space



T. Rizzo (SLAC Summer Institute, 01-Aug-12)



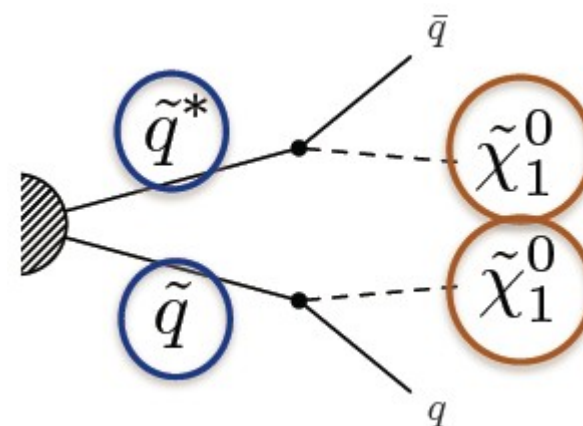


# Simplified Model Spectra (SMS)



- Final state kinematics from SUSY particle production fixed mostly by pdfs and decay amplitudes
- **SMS limited to a few particles, 2-3 body decay chains**
- **Topological signatures group large sectors of phase space**
- **SMS limits can be used as reference and translated to different theoretical models:**

- Mass limits assume SUSY cross section production
- **Illustrate sensitivity independently of SUSY-breaking model**



Model T2



# SUSY search strategies



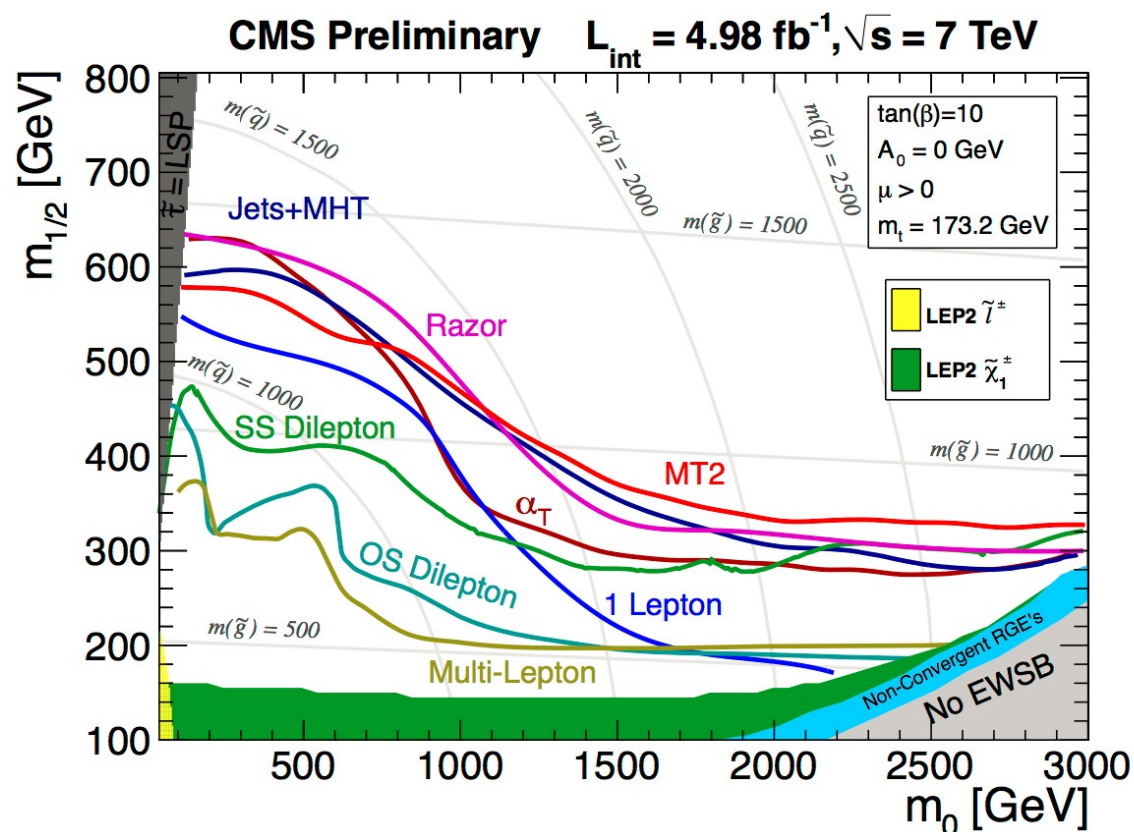
- Highest sensitivity for fully hadronic final states
- Searches based on kinematical variables:

- **Jets + MHT**

- **AlphaT**

- **Razor**

- **MT2**





# AlphaT



- **AlphaT**: For events with 2 (pseudo-) jets:

$$\alpha_T = E_T^{j2} / M_T = E_T^{j2} / \sqrt{H_T^2 - \cancel{H}_T^2}$$

less energetic jet

transverse mass of di-jet system

- **HT**: **Scalar sum** of the transverse energy of jets

$$H_T = \sum_{i=1}^{N_{\text{jet}}} E_T$$

- **MHT**: **Magnitude of the vector** sum of the transverse momenta of jets

$$\cancel{H}_T = \left| \sum_{i=1}^{N_{\text{jet}}} \vec{p}_T \right|$$

- **$\alpha_T$**  is used as the **main discriminator**

between events with **genuine and misreconstructed MET**

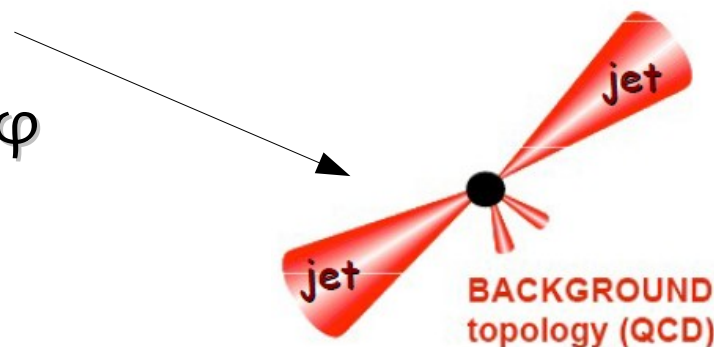


# AlphaT behaviour



- $\alpha_T = 0.5$

For a perfectly measured dijet event with  $ET^{j1} = ET^{j2}$  jets are back-to-back in  $\varphi$  in the limit of large jet momenta compared to their masses

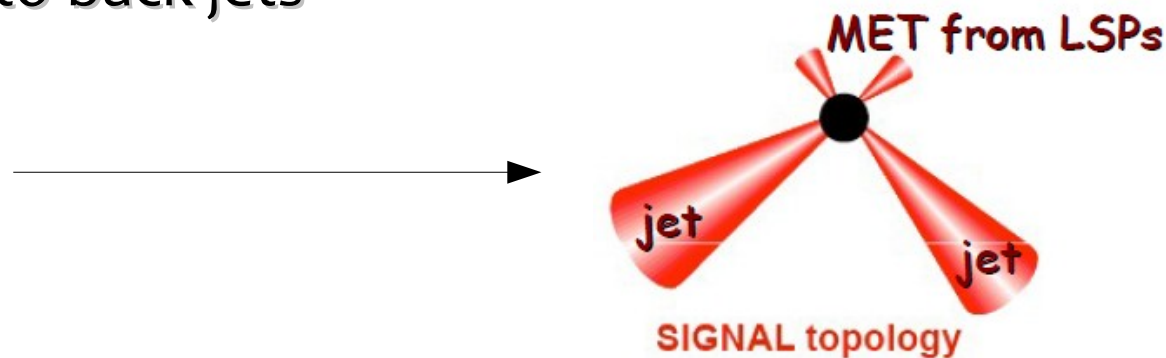


- $\alpha_T$  is smaller than 0.5

in the case of an imbalance in the measured ETs of back-to-back jets

- $\alpha_T$  is greater than 0.5

when the two jets are not back-to-back and balancing genuine MET



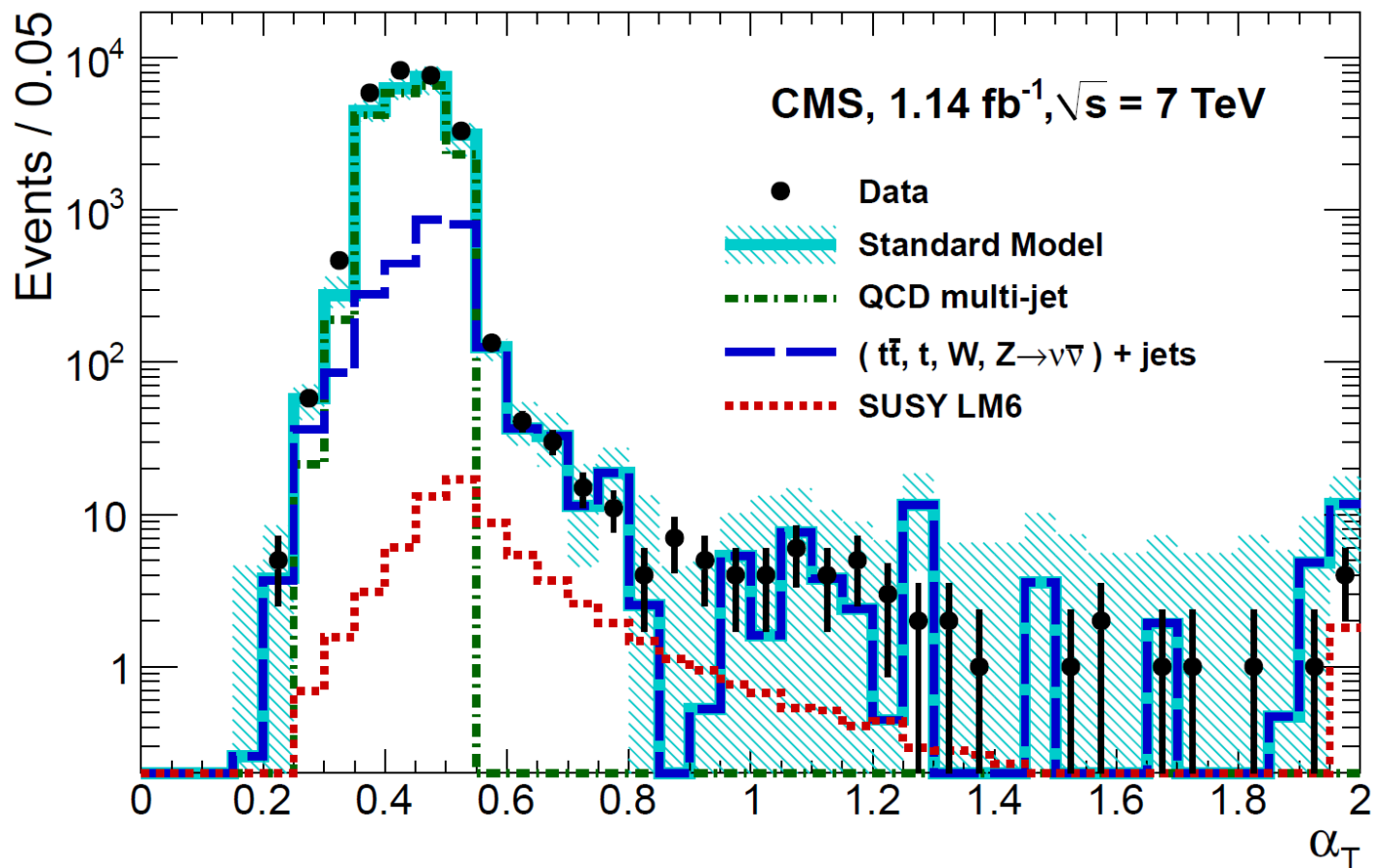


# AlphaT behaviour



Final selection:  $\alpha_T > 0.55$  makes background QCD free

CMS-PAS-SUS-2011-003





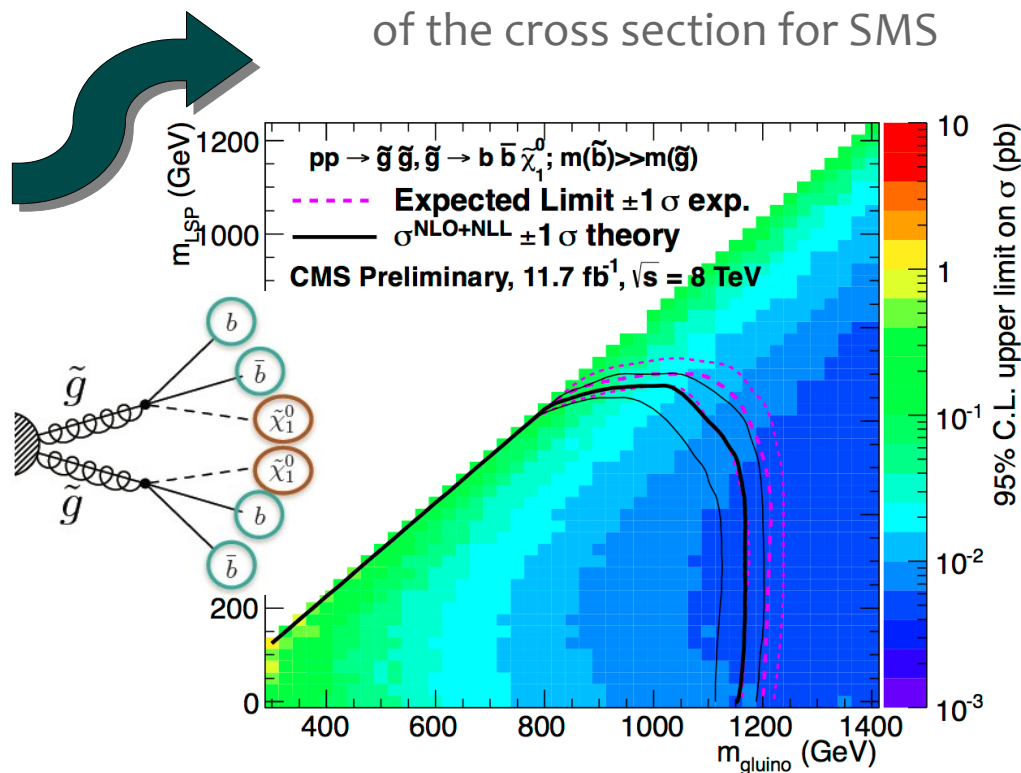
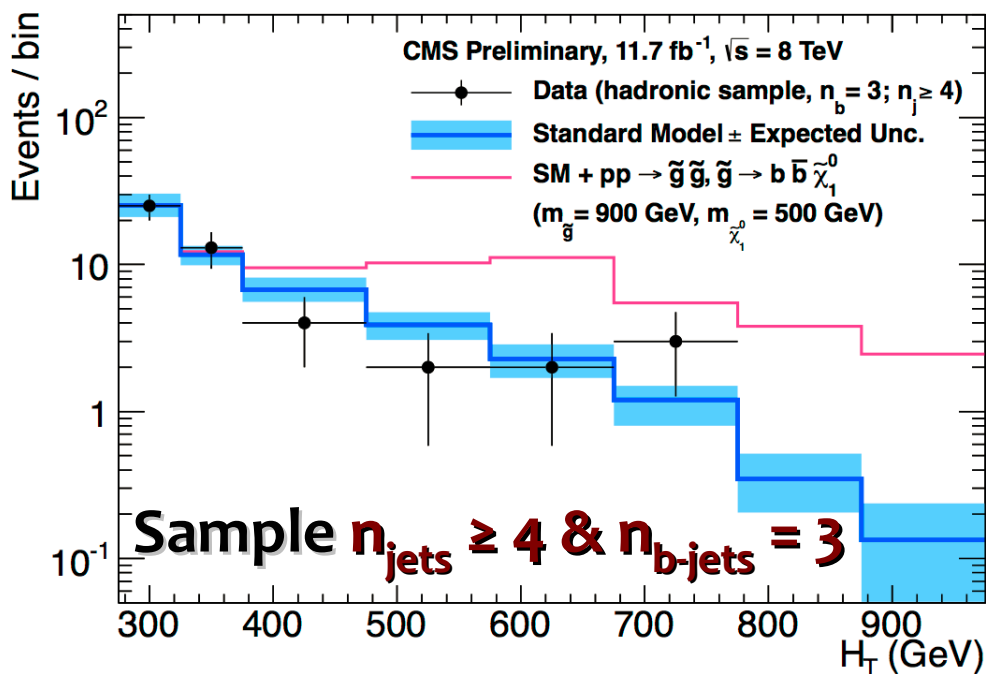
# Gluino searches with $\alpha_T$ (SMS)



- Hadronic events: veto if jet  $p_T > 50$  GeV &  $|\eta| > 3$ , isolated lep ( $\gamma$ )  $p_T > 10$  (25) GeV
- **Signal regions** for  $\alpha_T > 0.55$  and  $HT > 275$  GeV in **HT bins** and for **n (b-tag) jets**

Color index is upper limit on cross section  $\sigma = N_{\text{upper}} / (L \cdot \epsilon)$

Exclusion curve, is interpretation of the cross section for SMS

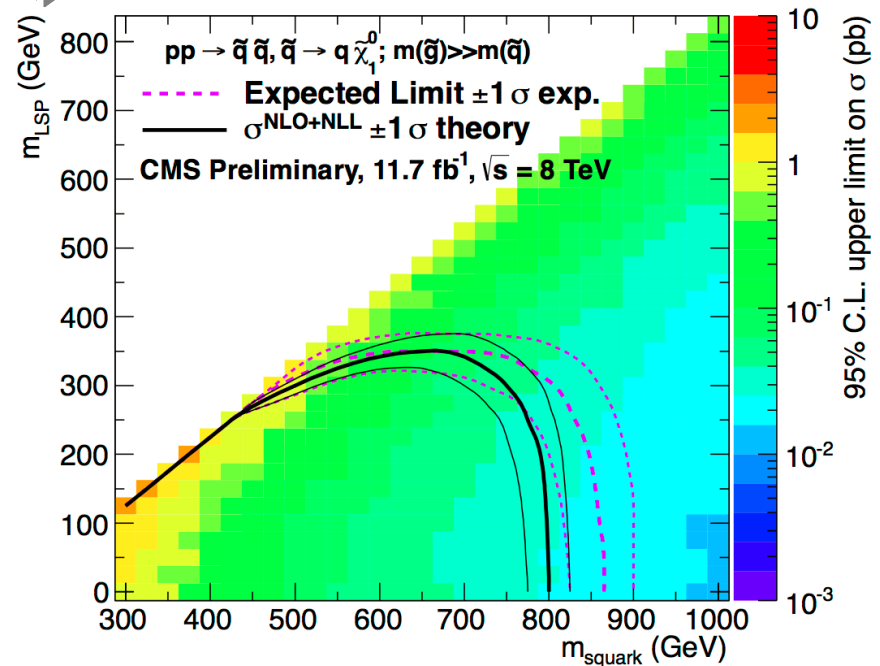
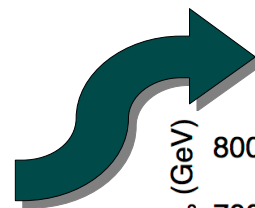
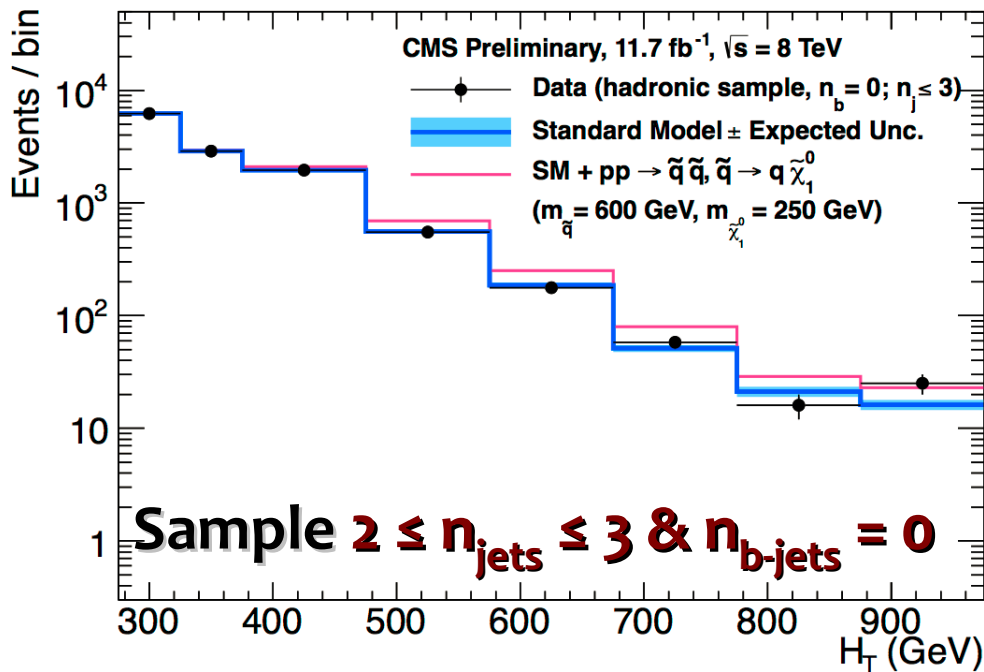
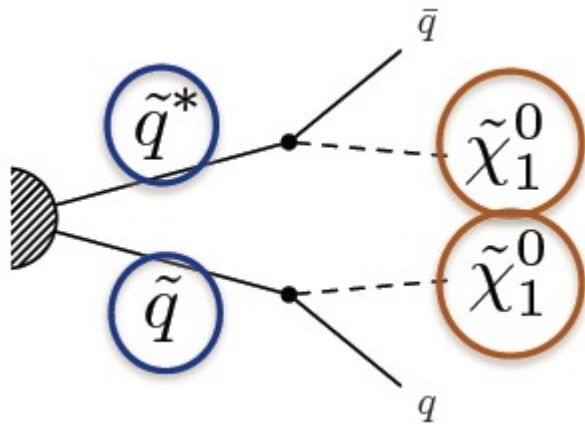


CMS-PAS-SUS-2012-028

- Probed gluino up to  $\sim 1.2$  TeV for T1bbbb SMS models



# Squark searches with $\alpha_T$ (SMS)



CMS-PAS-SUS-2012-028

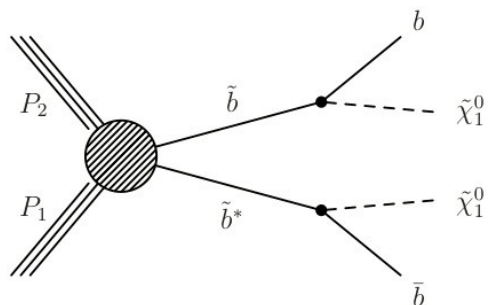
- Probed squark up to  $\sim 800$  GeV for T2 SMS models



# Sbottom/Stop searches with $\alpha_T$

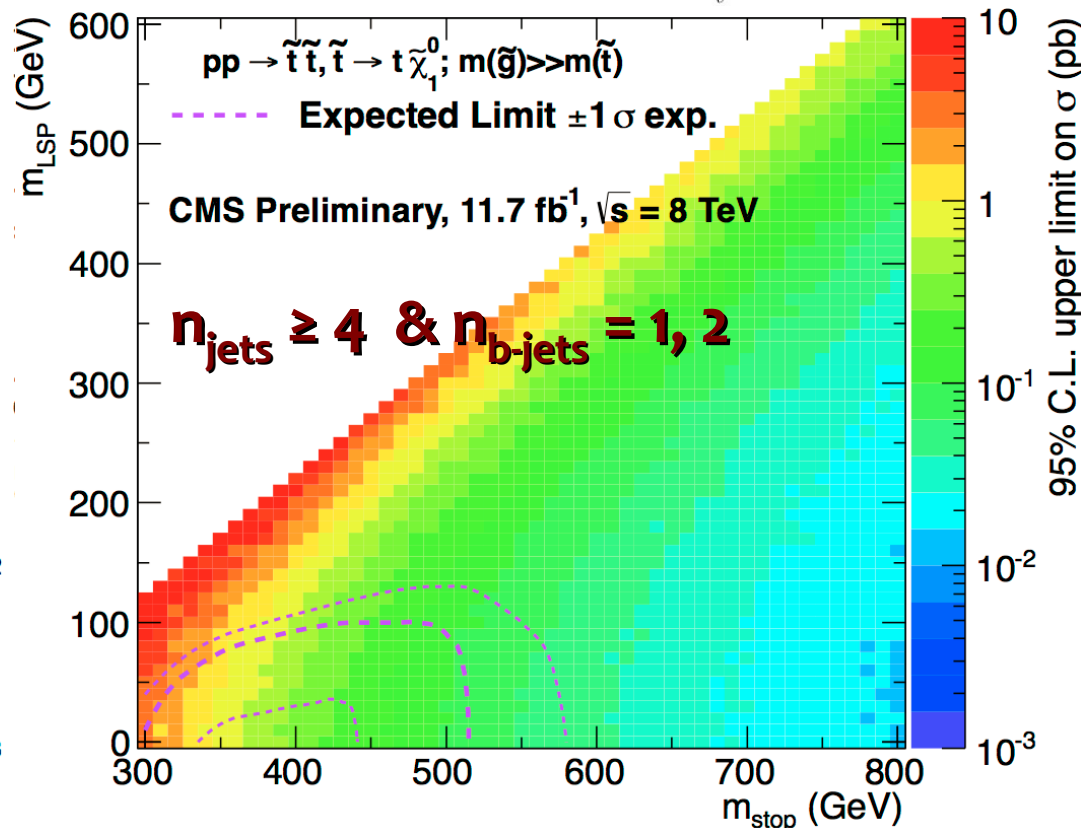
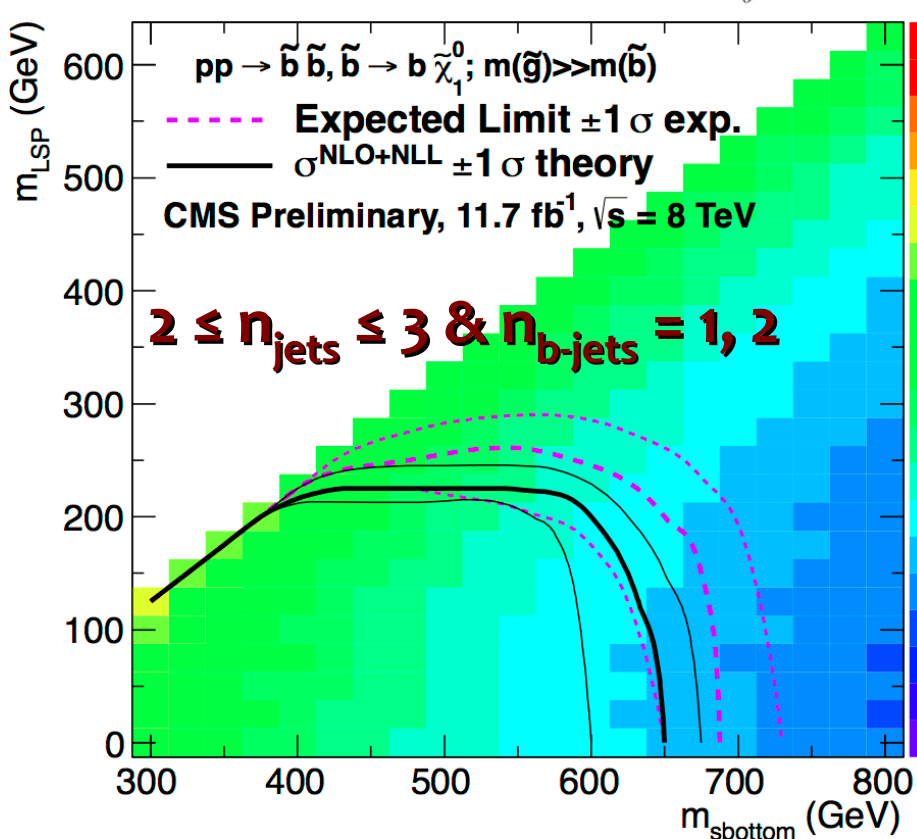
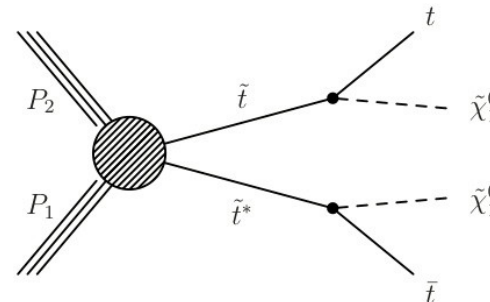


SMS: T2bb



CMS-PAS-SUS-2012-028

SMS: T2tt



- Probed sbottom quark up to  $\sim 650 \text{ GeV}$

- No observed exclusion is possible for the considered mass parameter space

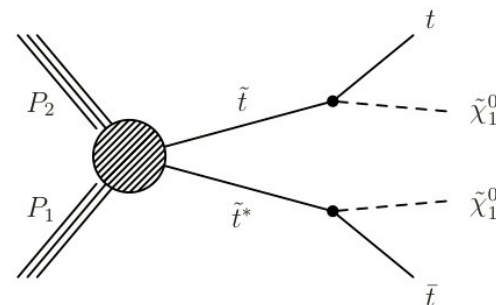




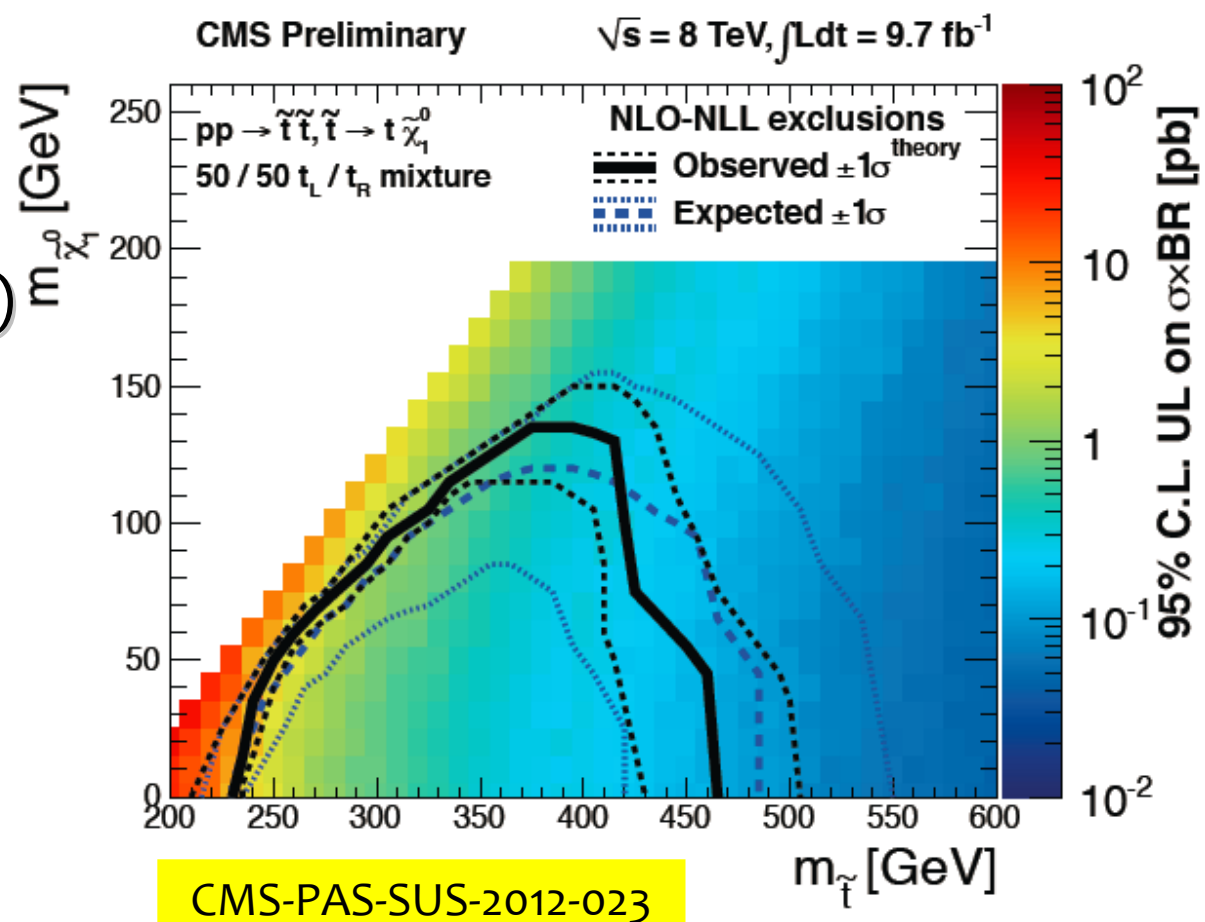
# Stop search in 1 lep channel



- **Signal** looks like “tt + MET” from the LSPs
- **Single lepton channel:**  
1 e/μ + ≥ 4 jets (2 b-jets) + MET
- **Background:**  
semi-leptonic ttbar and W+jets  
(MC & data control samples)
- Results probe **stop** masses in the range ~230-460 GeV for neutralino masses less than ~130 GeV



SMS: T2tt

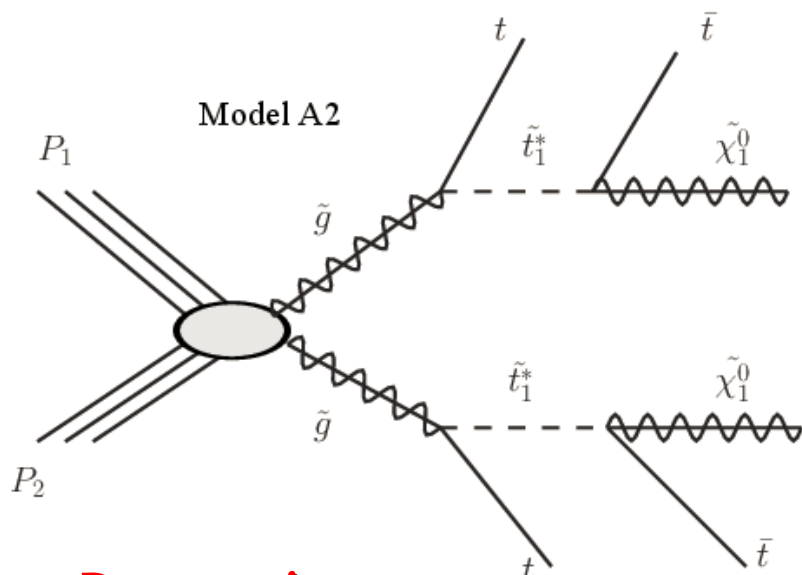




# Leptonic (SS) searches

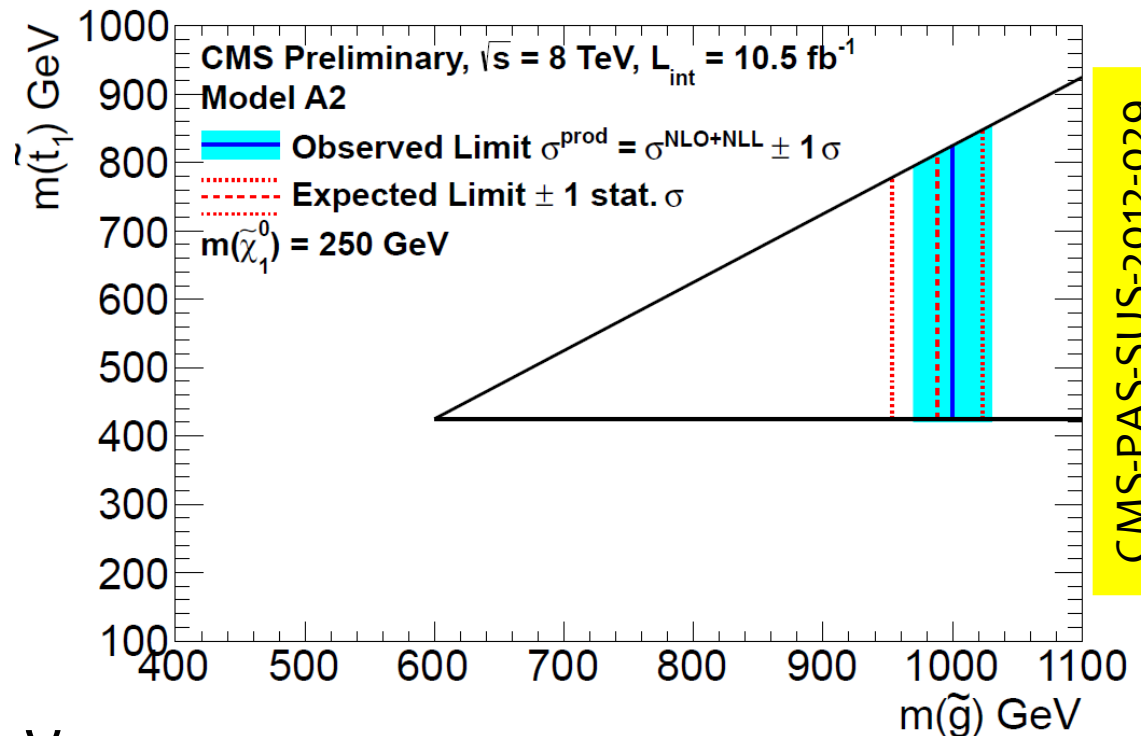


- Same sign di-lepton (SS) events **extremely rare in SM**
- **Signal search:** SS di-lepton (e or  $\mu$ ),  $\geq 2$  b-jets, binned in Nb-jets, Njets, high HT & MET
- **Background:** mis-ID/non-prompt leptons (T&P), ttW/ttZ (simulation)



• **Decay via stop**

• Probed gluino up to  $\sim 1$  TeV



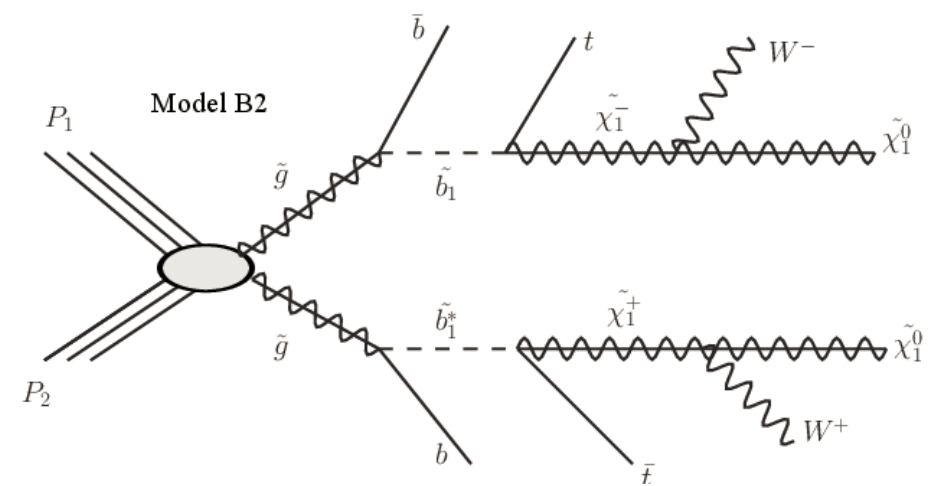
CMS-PAS-SUS-2012-029



# Leptonic (SS) searches

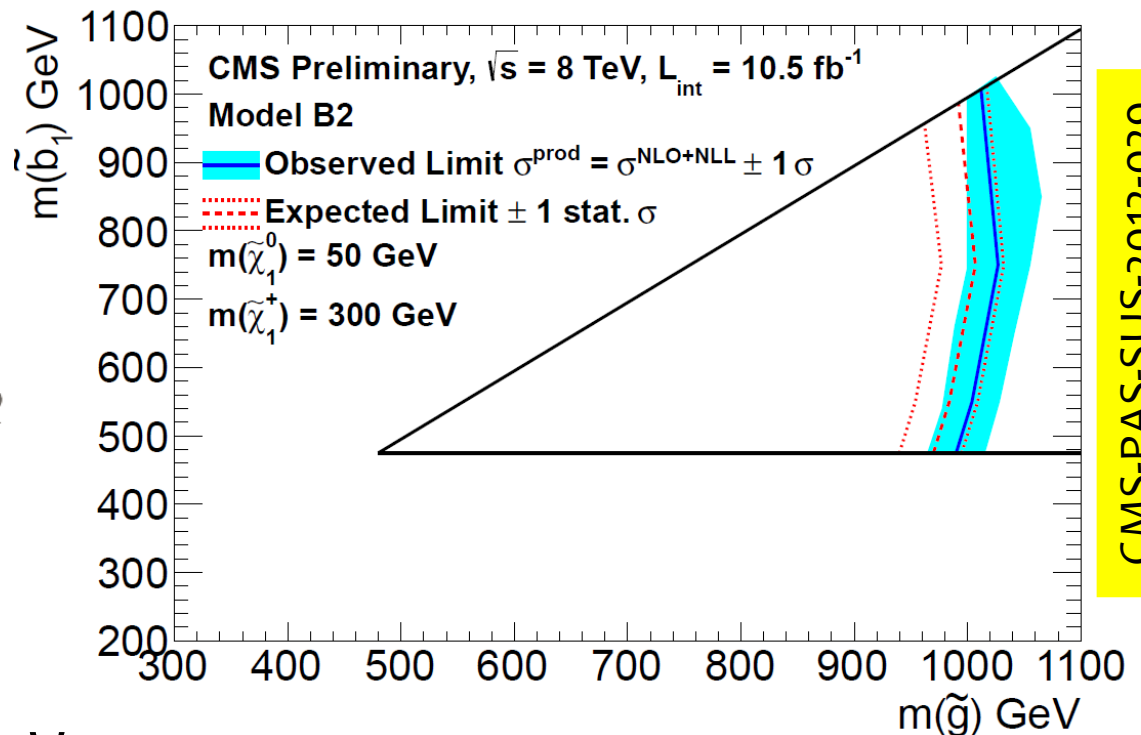


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- **Background:** mis-ID/non-prompt leptons (T&P), ttW/ttZ (simulation)



• **Decay via sbottom**

• Probed gluino up to  $\sim 1$  TeV



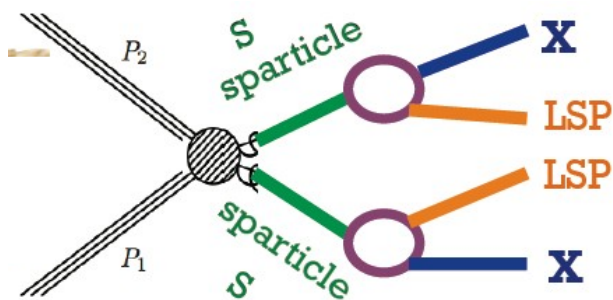
CMS-PAS-SUS-2012-029



# RAZOR



- **Razor variables R and  $M_R$**  designed for final state topology characteristic of R-parity SUSY
- **Selection:**  
Group all final state objects (jets, leptons) into **two mega-jets**



In simple case:  
**S = squark**  
**X = jet**

$$M_R = \sqrt{(|\vec{p}_{j1}| + |\vec{p}_{j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

$$M_R = M_\Delta = \frac{M_S^2 - M_{LSP}^2}{M_S}$$

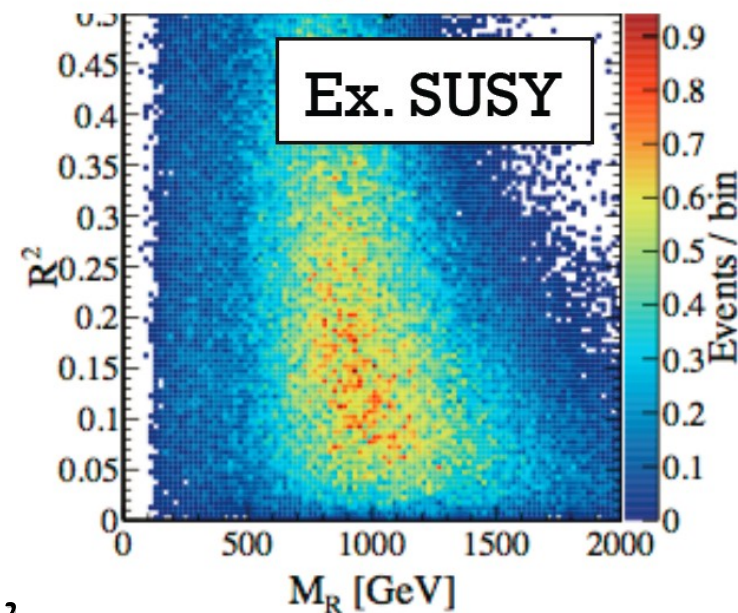
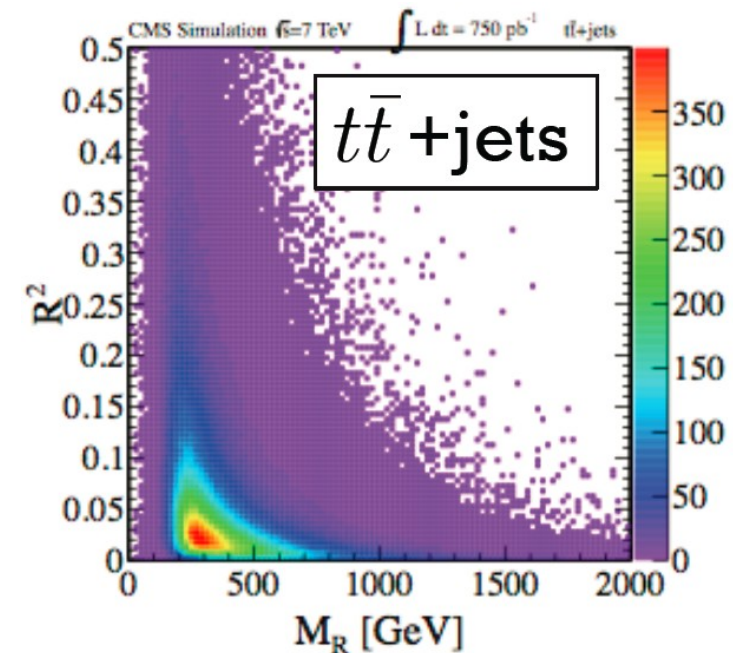
Peaks at

$$M_T^R = \sqrt{\frac{E_T^{miss} (p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

Edge at  $M_\Delta$

$$R = \frac{M_T^R}{M_R}$$

Ratio of two estimators of SUSY scale – describes transverse shape of event





# RAZOR Analysis



- Selection classify final states into exclusive boxes
- Background functionally extrapolated to signal region
- 2D fit performed independently for BOXes
- New analysis: **RAZOR applied to SUSY with  $\tau$  + jets in the final state**

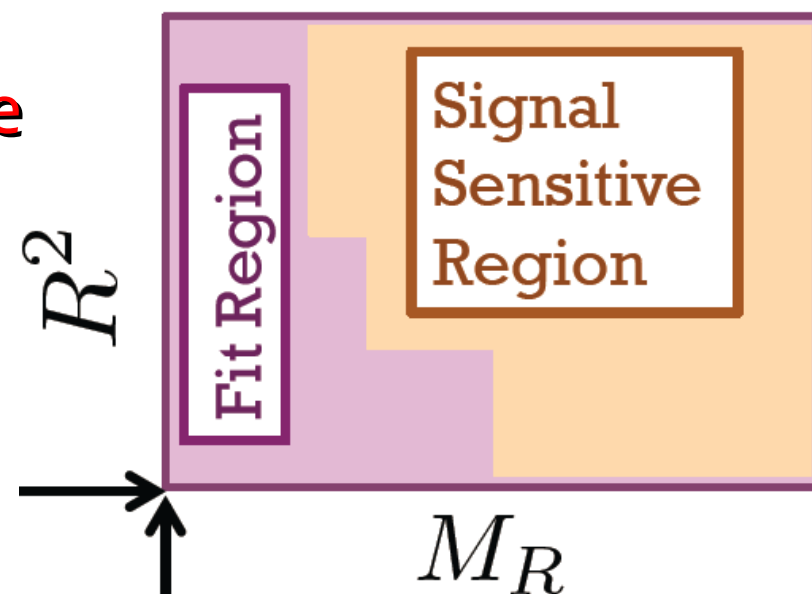
- **4 exclusive boxes:**

1<sup>st</sup> : MU-TAU  $\tau \geq 1$  &  $\mu \geq 1$  &  $0 e$

2<sup>nd</sup> : MU **all the other events w/  $\mu \geq 1$**

3<sup>rd</sup> : ELE-TAU  $\tau \geq 1$  &  $e \geq 1$  &  $0 \mu$

4<sup>th</sup> : ELE **all the other events w/  $e \geq 1$**

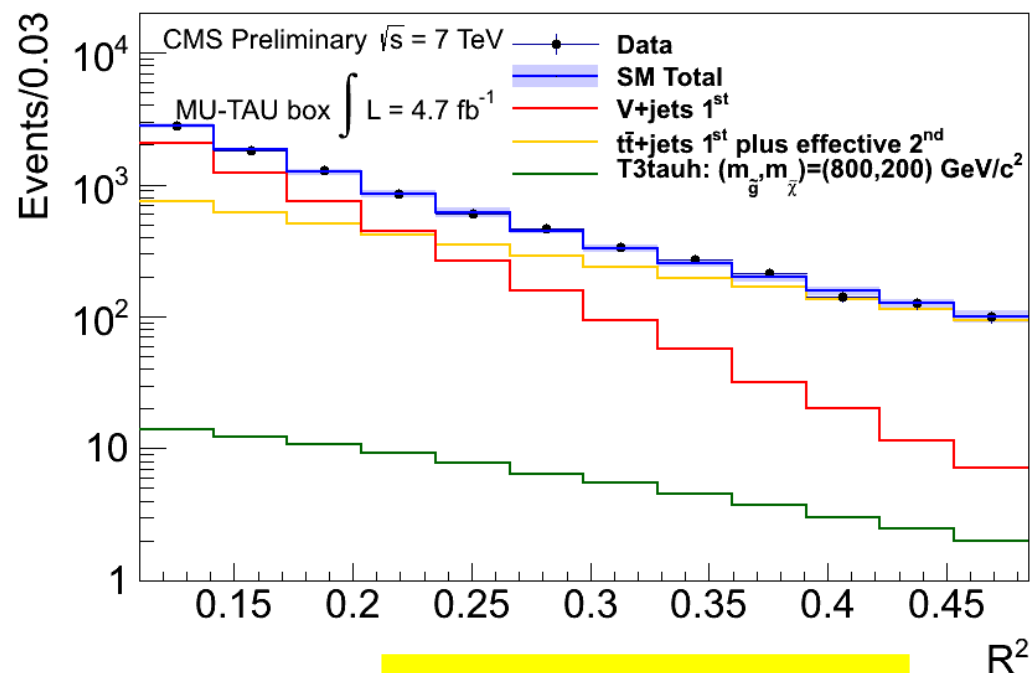
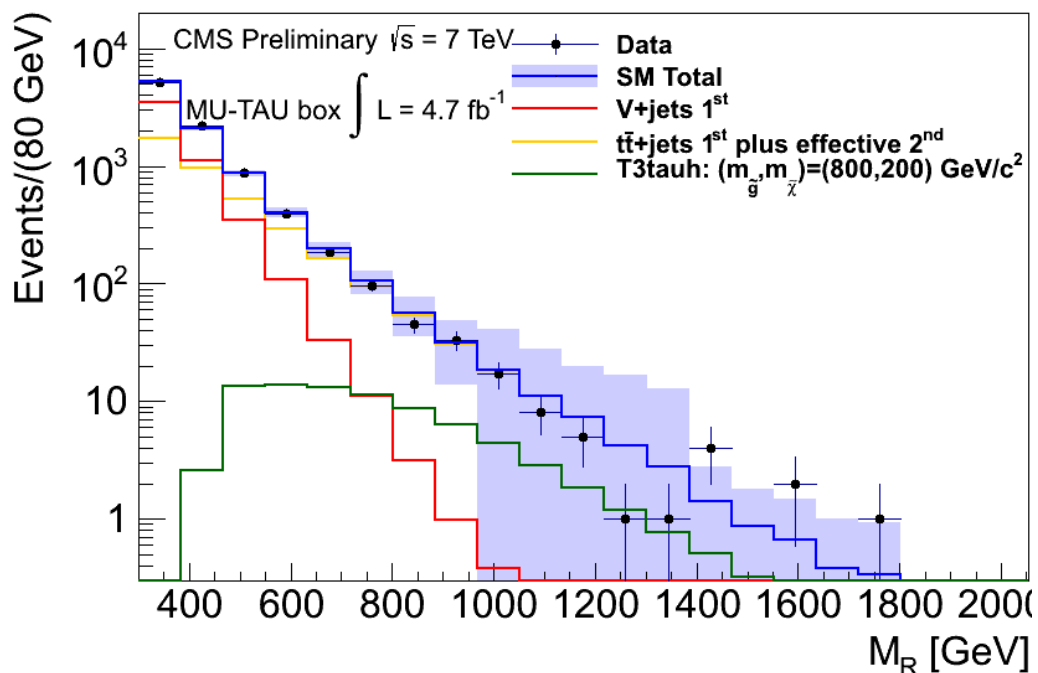




# RAZOR for SUSY with $\tau$ 's



1D projections of 2D Fit in  $R^2$  and  $M_R$  plane



CMS-PAS-SUS-2011-029

Results from one box MU-TAU

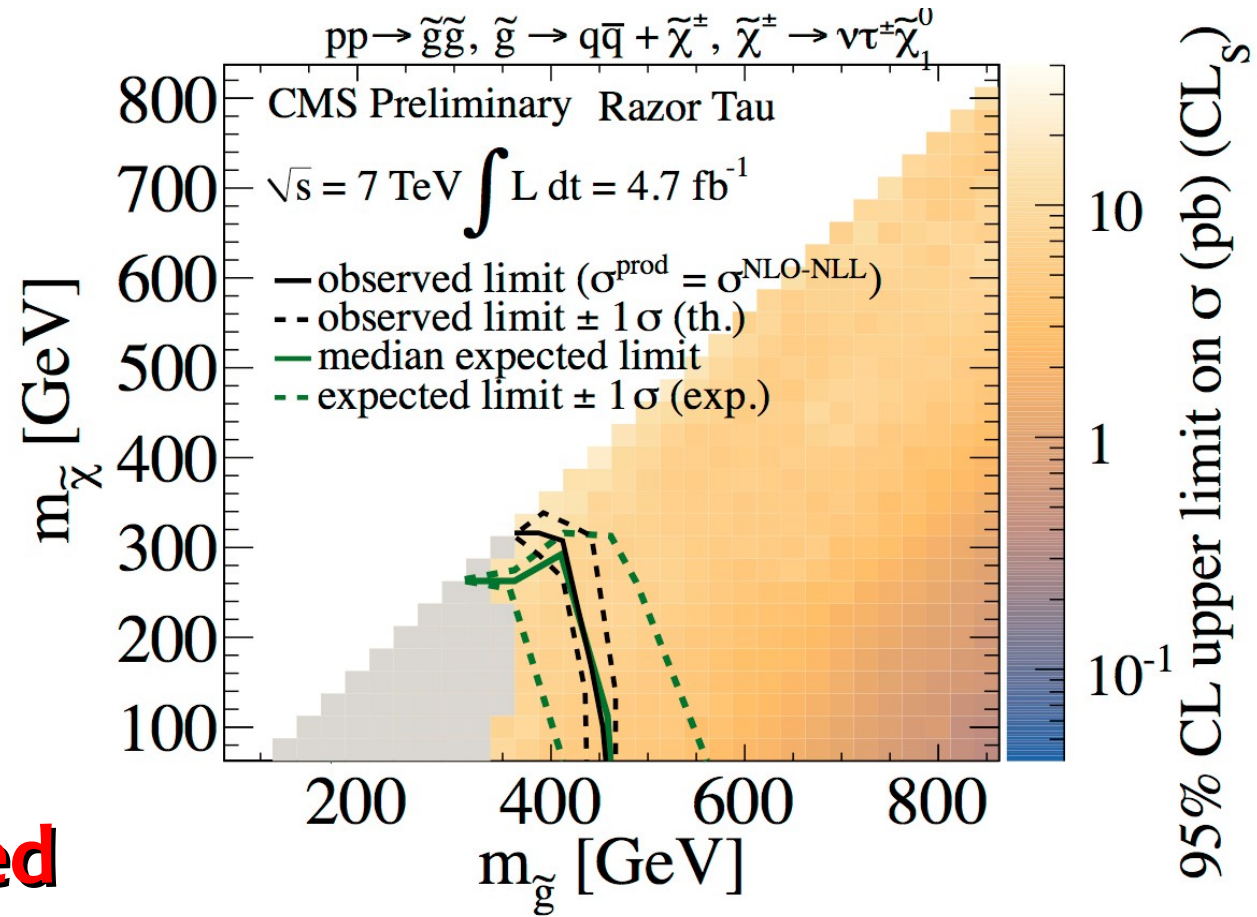
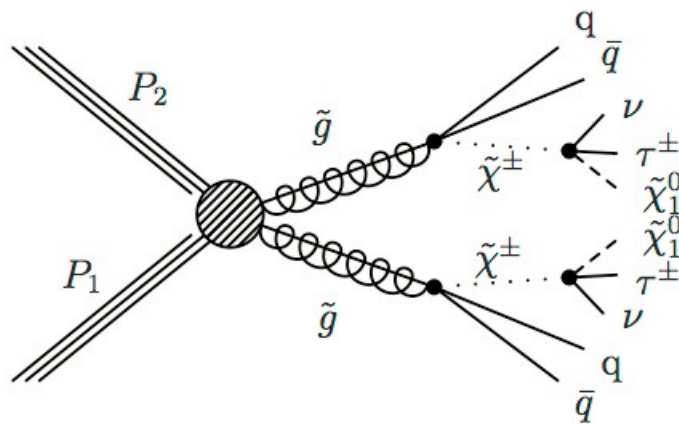
**Observations consistent with SM expectations**



# RAZOR for SUSY with $\tau$ 's



Interpretation of results in SMS: T3tauH



**Limit for tau-enriched SUSY events**

CMS-PAS-SUS-2011-029

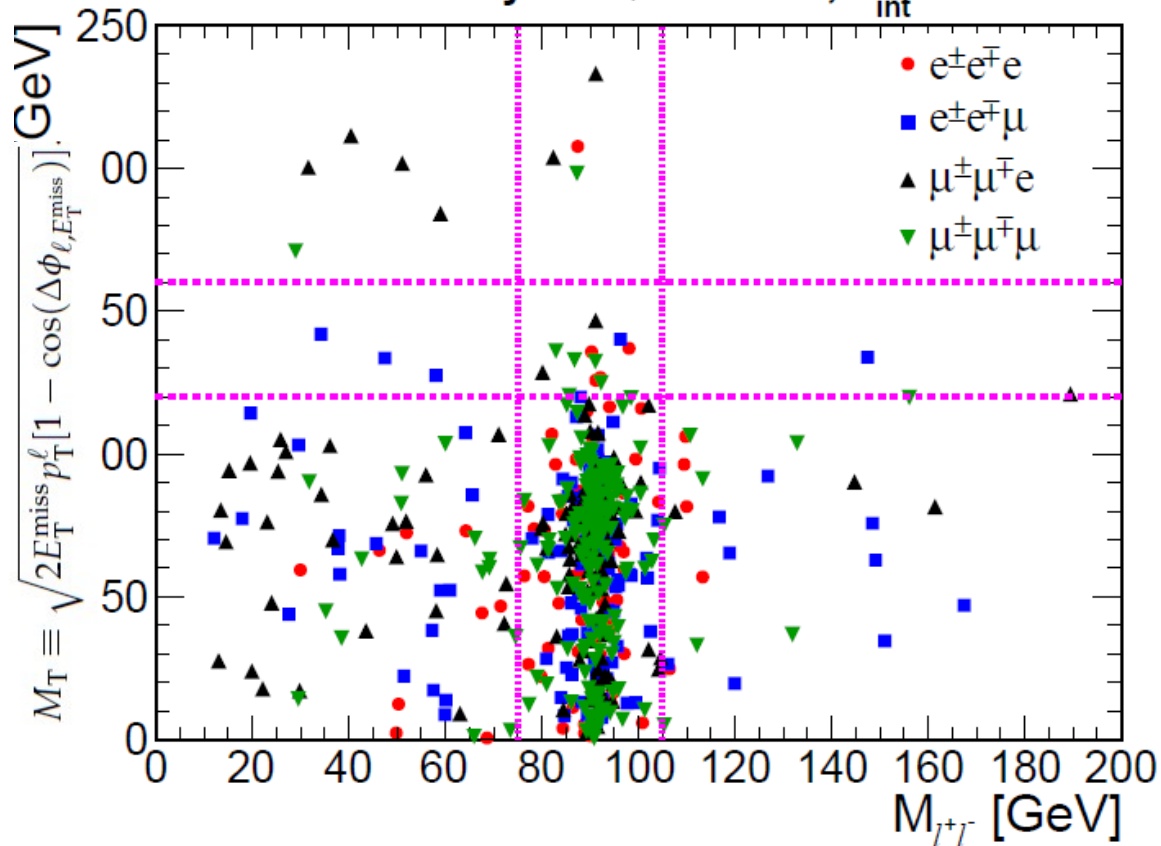


# Search for neutralino-chargino



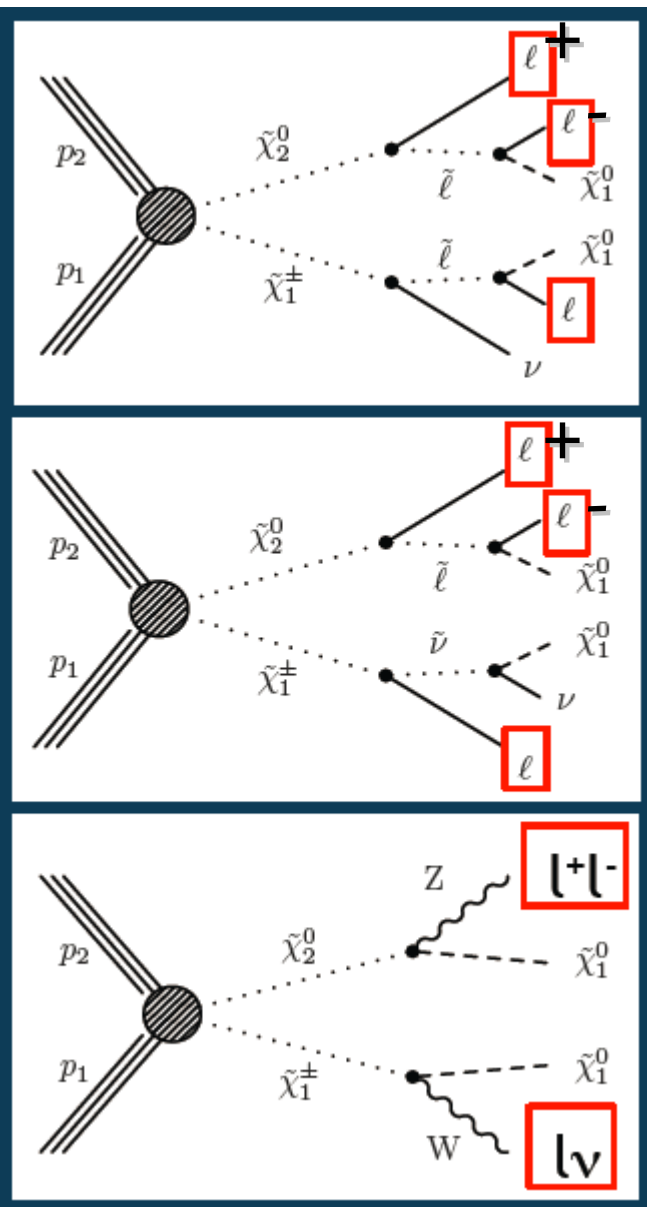
CMS-PAS-SUS-2012-022

CMS Preliminary  $\sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 9.2 \text{ fb}^{-1}$



Three-lepton events with an  $ee$  or  $\mu\mu$  OSSF dilepton pair, where the third lepton is either an electron or a muon

$M_T$ (GeV)	$E_T^{\text{miss}}$ (GeV)	$M_{\ell\ell} < 75 \text{ GeV}$		$75 \text{ GeV} < M_{\ell\ell} < 105 \text{ GeV}$	
		total bkg	observed	total bkg	observed
$> 160$	50 – 100	$2.1 \pm 0.5$	4	$3.3 \pm 0.5$	3
	100 – 150	$1.7 \pm 0.4$	0	$1.8 \pm 0.2$	1
	150 – 200	$0.8 \pm 0.3$	1	$0.63 \pm 0.16$	1
	$> 200$	$0.25 \pm 0.20$	0	$0.58 \pm 0.19$	1





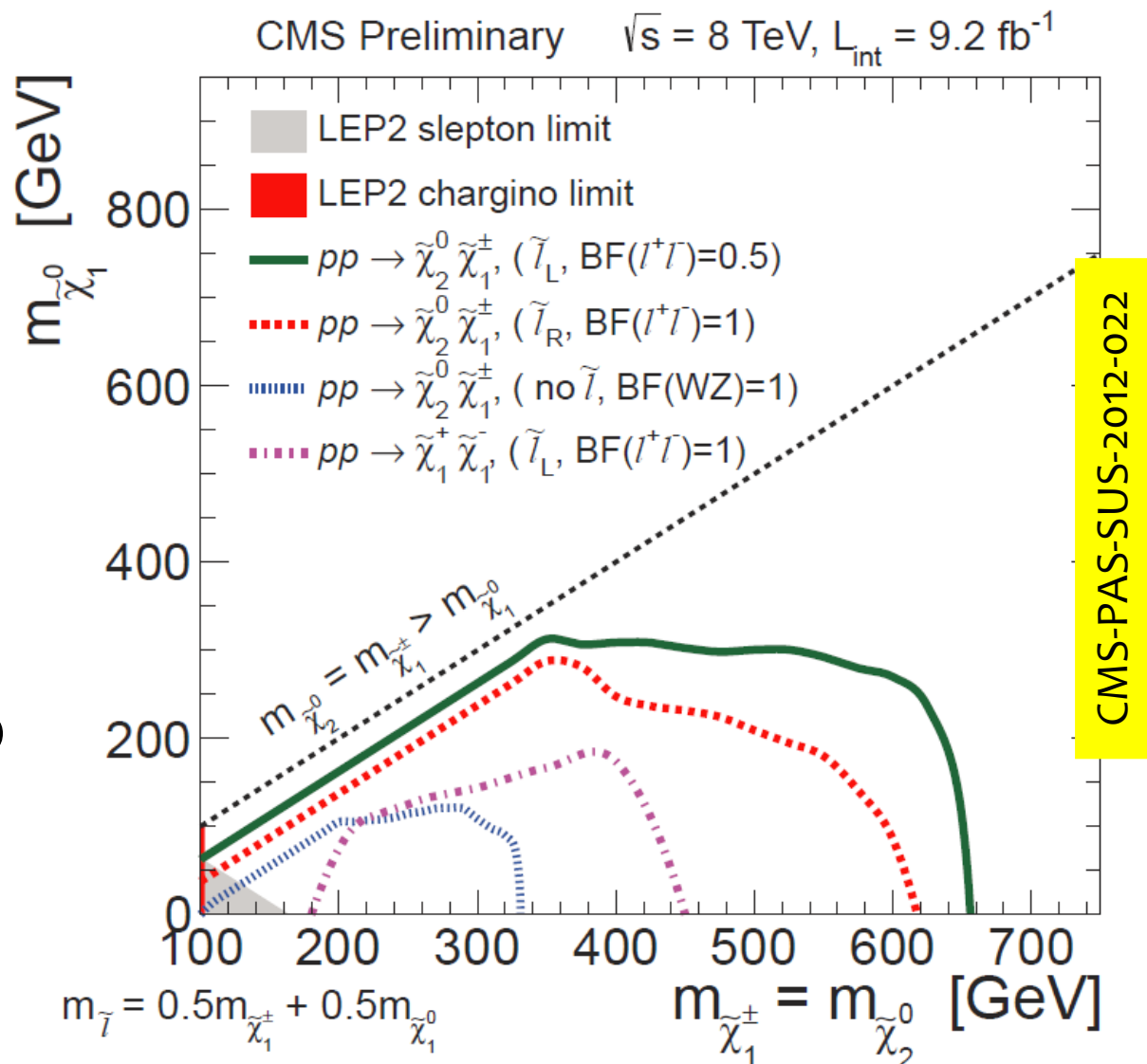


# Search for neutralino-chargino



- Summary of results for chargino-neutralino production with decays to left-handed sleptons, right-handed sleptons, or direct decays to vector bosons, and chargino-pair production

- **Chargino-neutralino limits extended up to ~ 650 GeV**





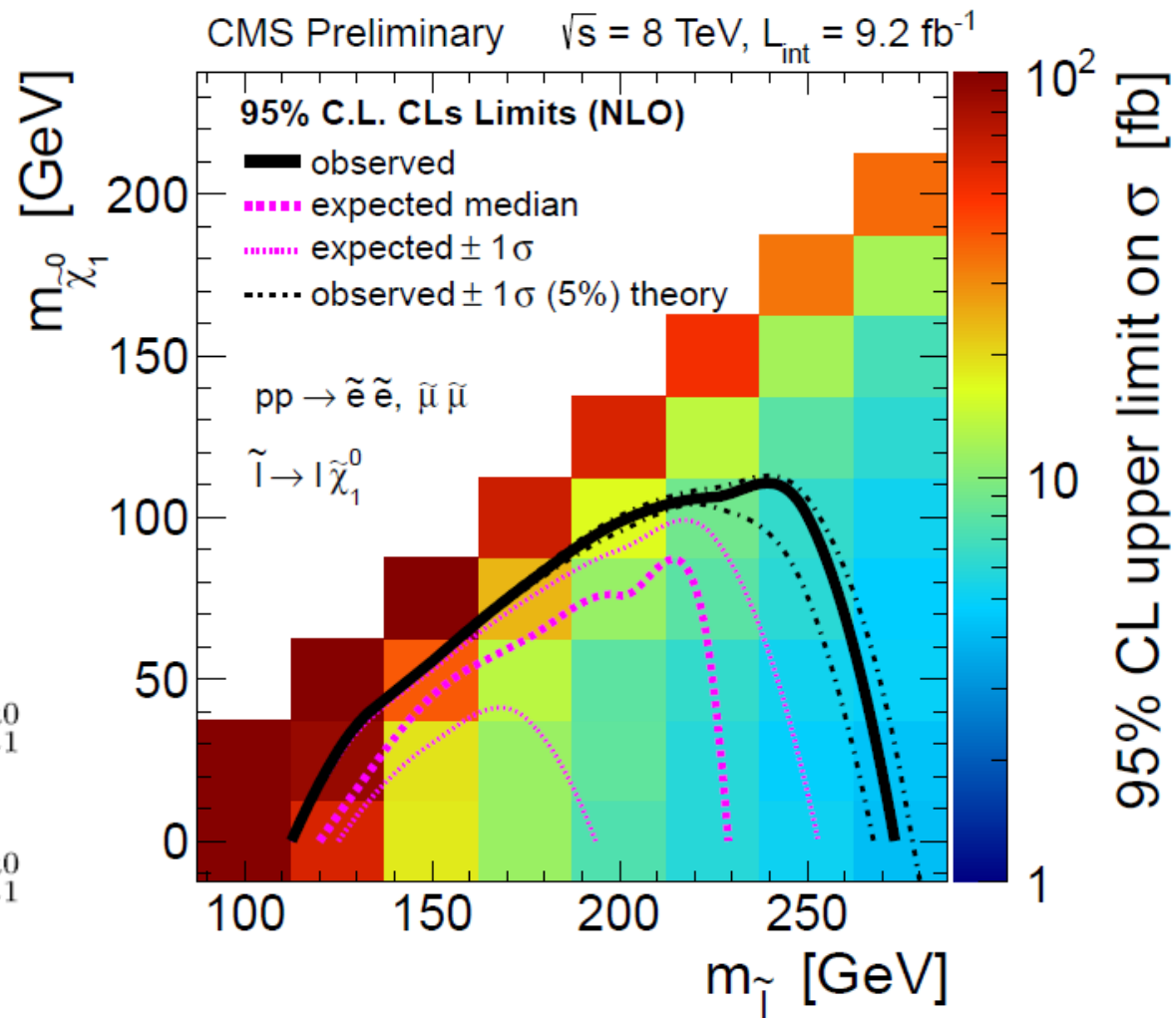
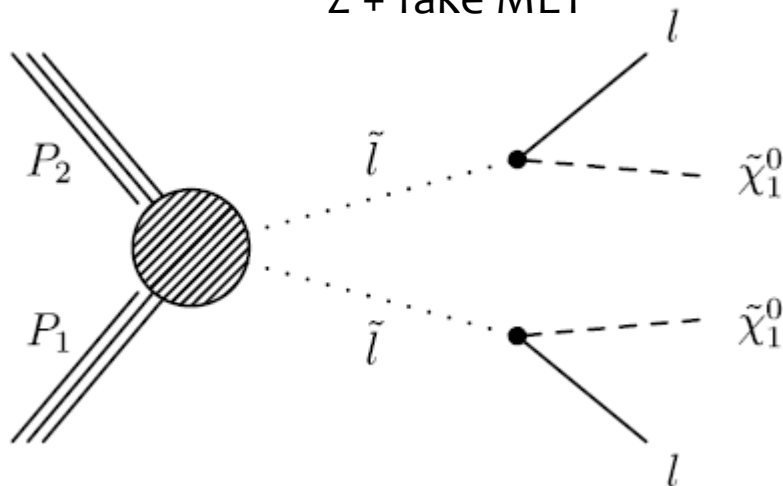
# Search for slepton pair



- First limit on slepton pair production

- Search for OS (SF+DF)

- Main bkg:  $Tt\bar{b}$   
 $WW \rightarrow l\nu l\nu$   
 $ZZ \rightarrow 2l 2\nu$   
 $Z + \text{fake MET}$



- Slepton mass limited up to  $\sim 275 \text{ GeV}$

CMS-PAS-SUS-2012-022

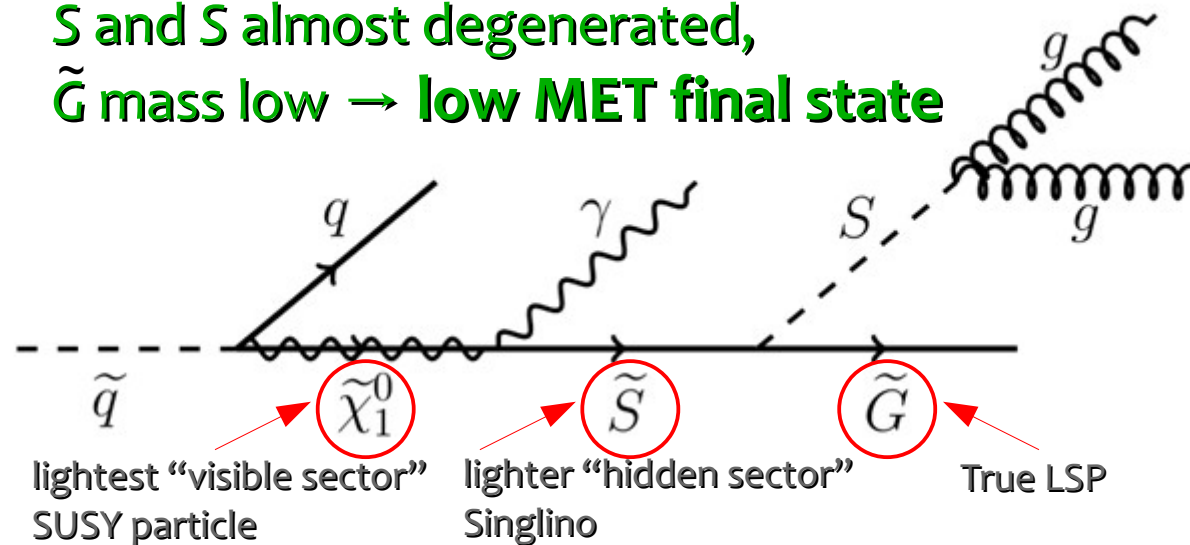


# Stealth SUSY ( $2\gamma$ )



- “Stealth” SUSY has a **new hidden sector** and **low energy SUSY breaking**

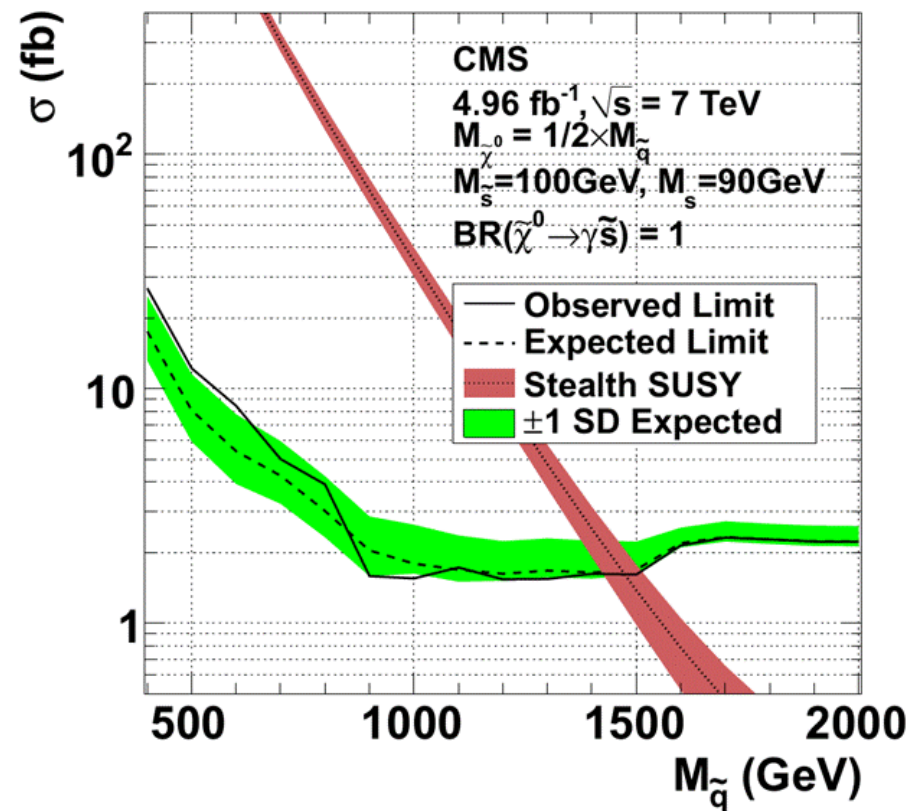
$S$  and  $\tilde{S}$  almost degenerated,  
 $\tilde{G}$  mass low  $\rightarrow$  **low MET final state**



**Signal searched in:** two photons  
 ( $p_T > 40, 25$  GeV),  
 $\geq 4$  jets ( $p_T > 20$  GeV) and **low MET**

**Background:** SM production of  $2\gamma + \geq 4$  jets (QCD)  
 estimated using ST shape,  $ST = \Sigma p_T^{\text{jets}} + \Sigma p_T^\gamma + MET$

CMS-PAS-SUS-2012-014



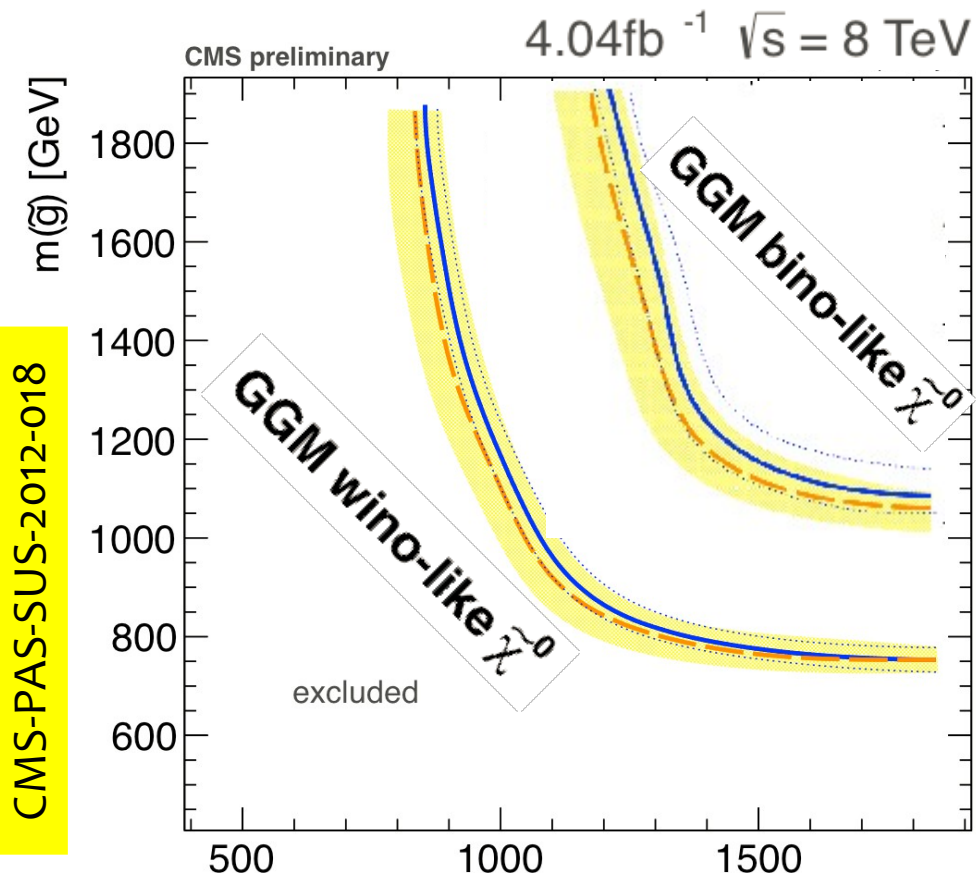
- **In the context of stealth SUSY, squark masses excluded  $< 1430$  GeV**



# GMSB – Highlights



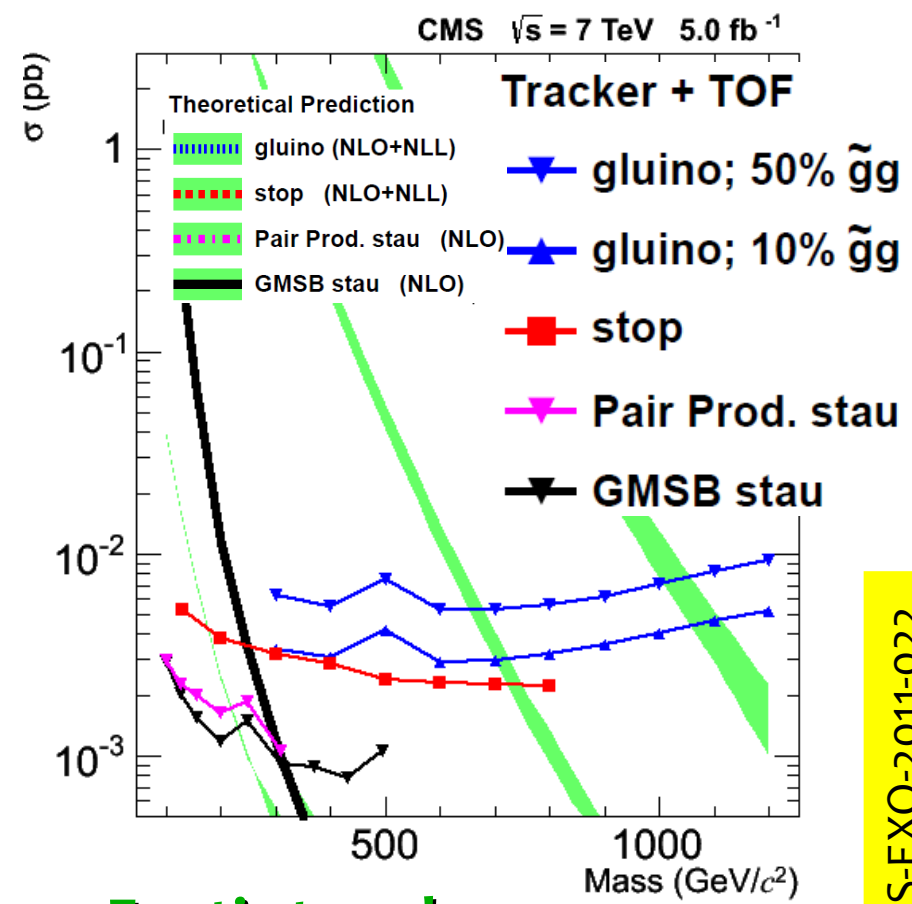
- Gauge Mediated SB: Gravitino is LSP, (co-)NLSP neutralino or slepton



CMS-PAS-SUS-2012-018

$m_{\tilde{\chi}_0^0} = 375 \text{ GeV}$   
 — Observed  
 ..... Observed  $\pm 1\sigma$  signal theory  
 - - - Expected  $\pm 1\sigma$  exp.

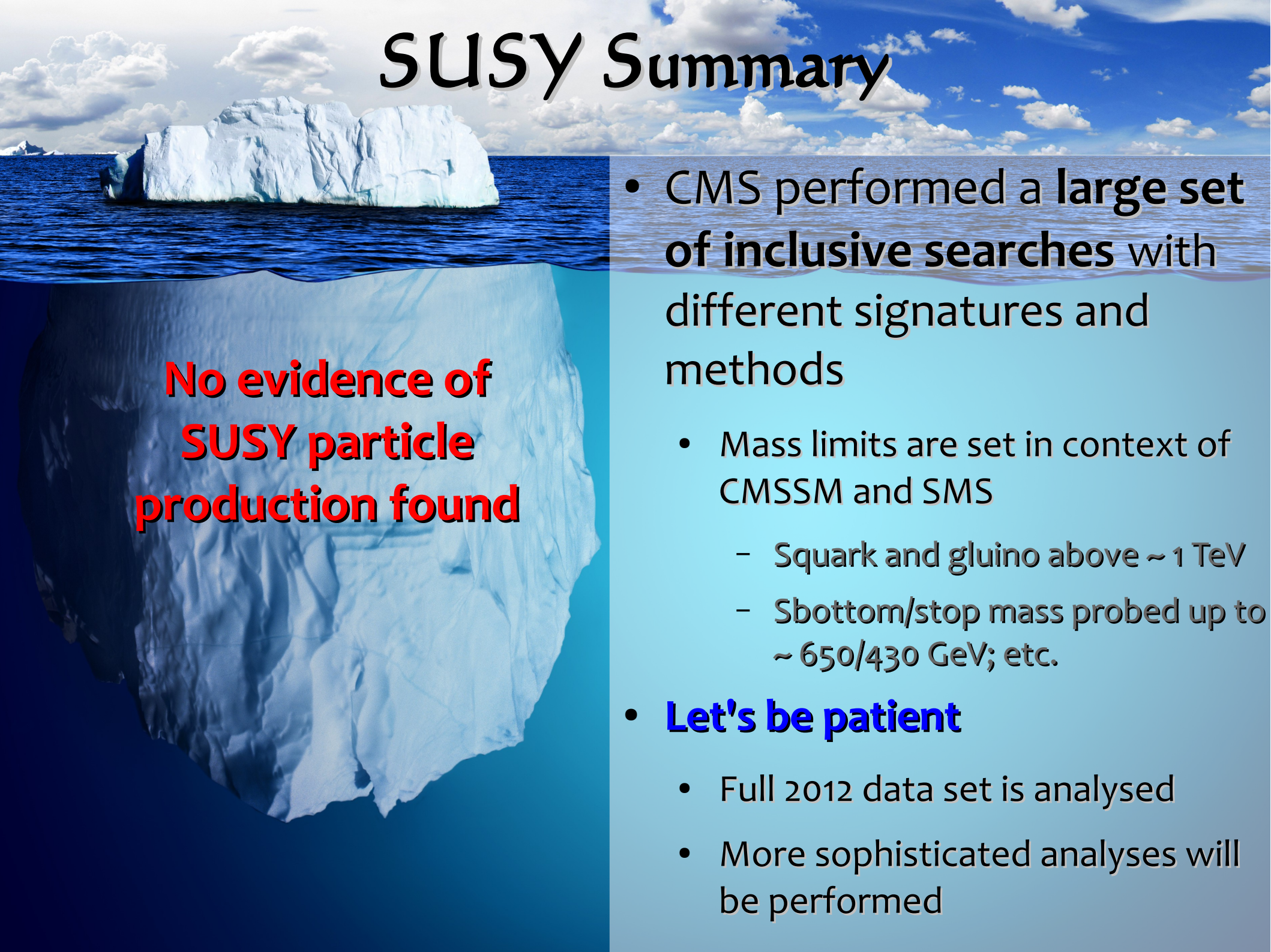
$\geq 1 \gamma, \geq 2 \text{ jets}$   
 (80 GeV), (30 GeV)  
**& HT > 450 GeV**



**Exotic topology:**  
**dE/dx** and **TOF** measured  
**long-lived GMSB stau**  
 excluded below **~300 GeV**

CMS-PAS-EXO-2011-022

# SUSY Summary

A large iceberg floats in the ocean under a blue sky with white clouds. The iceberg is mostly submerged, with only a small portion visible above the water. The text "No evidence of SUSY particle production found" is written in red on the submerged part of the iceberg.

**No evidence of  
SUSY particle  
production found**

- CMS performed a **large set of inclusive searches** with different signatures and methods
  - Mass limits are set in context of CMSSM and SMS
    - Squark and gluino above  $\sim 1$  TeV
    - Sbottom/stop mass probed up to  $\sim 650/430$  GeV; etc.
- **Let's be patient**
  - Full 2012 data set is analysed
  - More sophisticated analyses will be performed

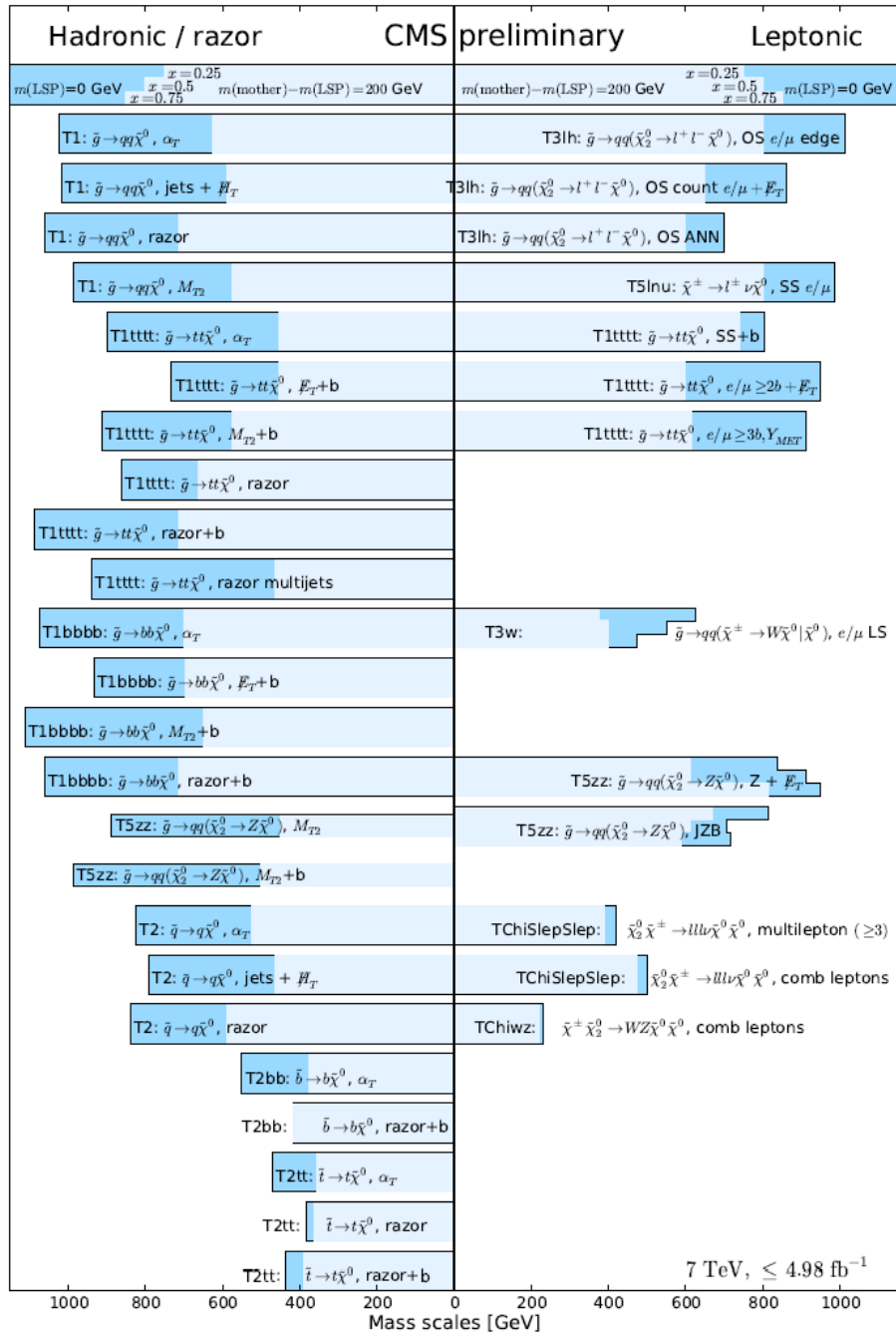


# References:

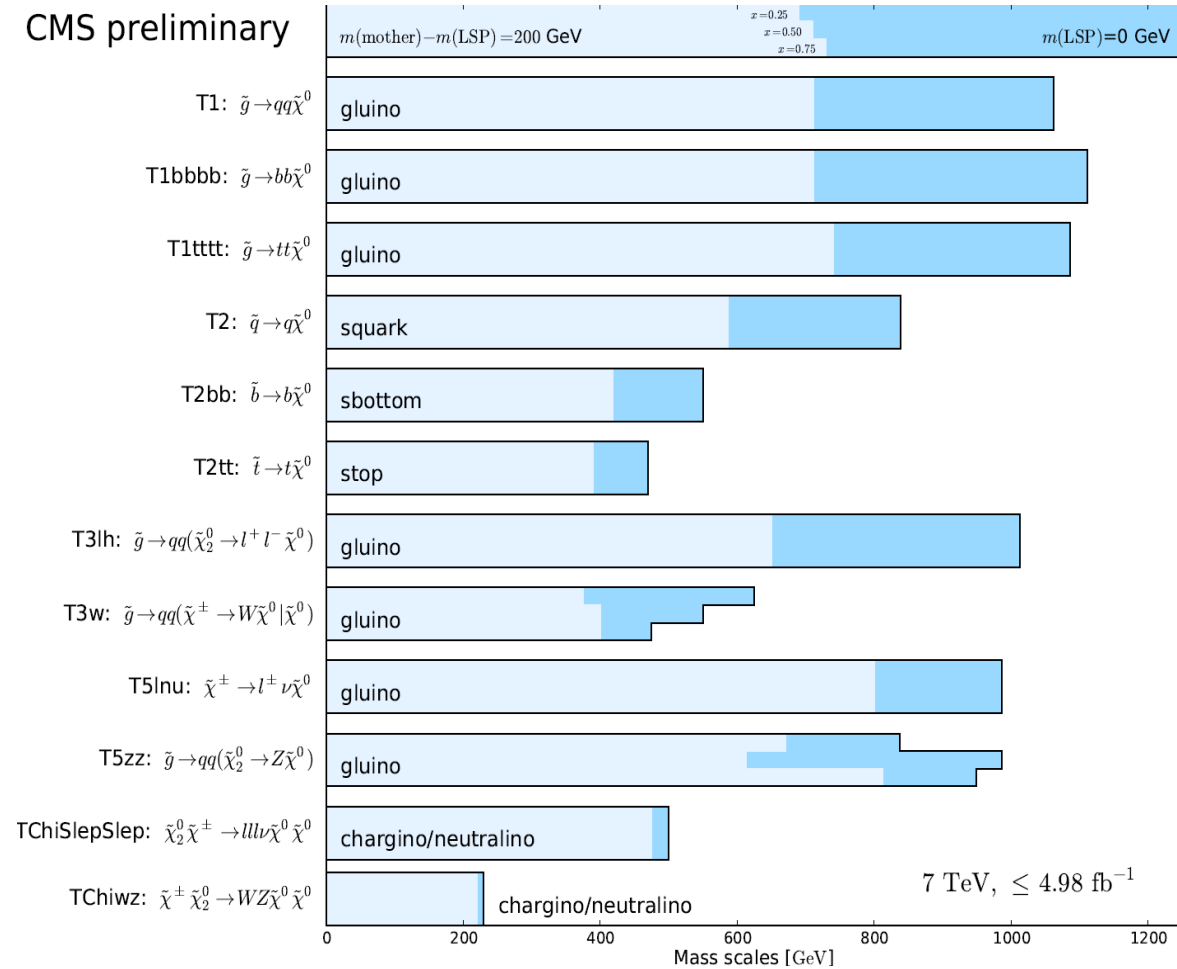
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS>



# SUSY in Simplified Models



## CMS preliminary



- Limits from 2011 data