# Search for Supersymmetry at the LHC

GK Workshop Bad Liebenzell 2014 – Part II

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# Recap

Yesterday we discussed:

- Introduction to Supersymmetry
- Challenges in data analysis
- Detailed example for a SUSY search

Today and tomorrow:

- Overview over other SUSY searches
- Outlook

# Overview on searches

In the following hour we will discuss the following analyses:

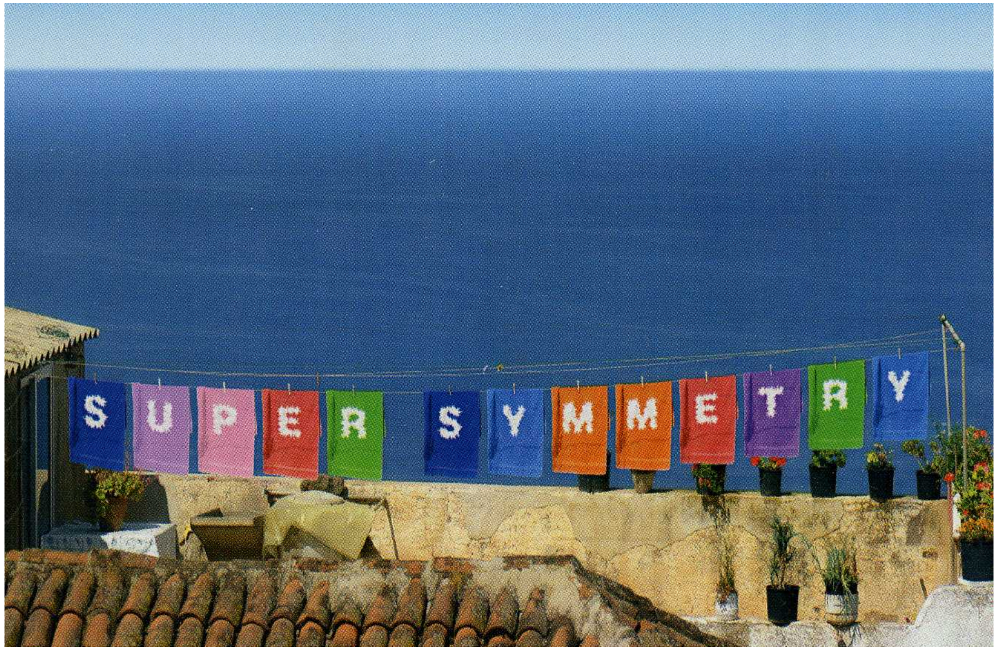
- Gluinos and 1st/2nd generation squarks
- Third-generation squarks

Tomorrow:

- Electroweak SUSY sector
- Escape routes:
  - R-parity violation
  - Long-lived particle searches
  - Beyond MSSM signatures

# Outline for today

- **Gluinos and 1$^{st}$/2$^{nd}$ generation squarks**
  - Full-hadronic searches
  - Single-lepton searches
  - Di-leptonic searches
  - Multilepton searches
- Third-generation squarks



# Gluino, 1st/2nd Generation Squarks

Gluinos and squarks can leave many different signatures in the detector, but we can distinguish **two classes of signals** depending on the underlying SUSY model:

- **Massive LSP = $\tilde{\chi}_1^0$:**
  - Cascade decays to jets and MET → Jets + MET signature
  - Cascade decays + leptonic gaugino/slepton decay → Isolated lepton + jets + MET signature, 2-leptons (OS or SS) + jets +MET
  - Cascade decays to t or b quarks + MET (through on- or off-shell stop/sbottom)
- **~Massless LSP = $\tilde{G}$** (interpretation in GMSB/GGM)
  - Cascade decays in GMSB/GGM model typically include photons

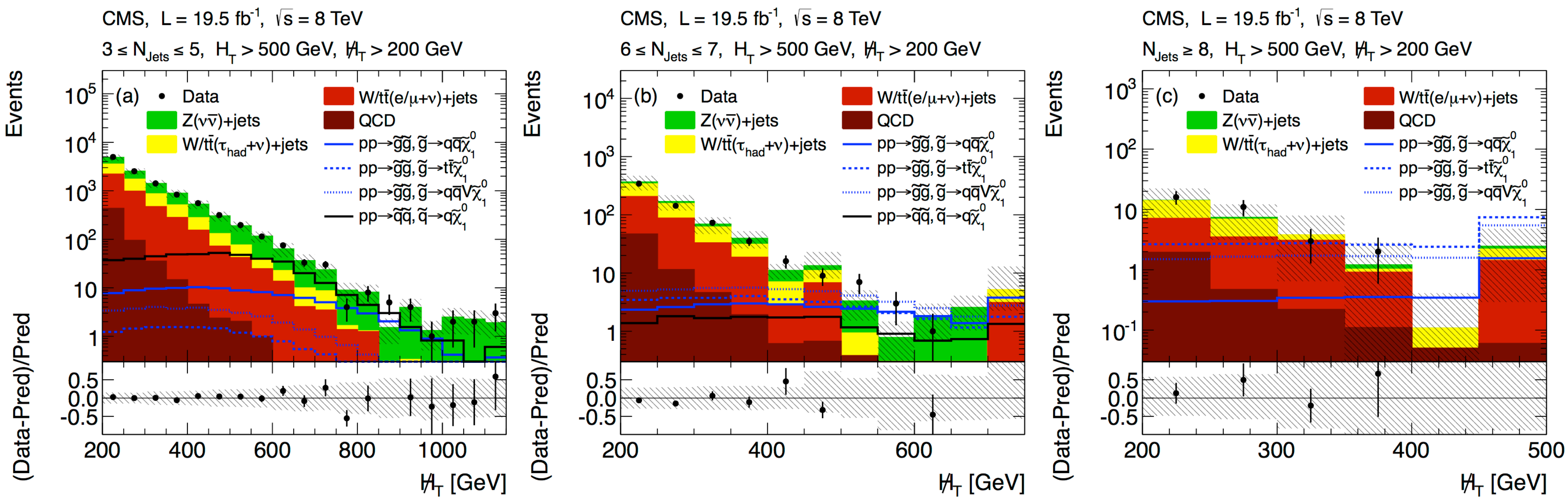
→ **signatures depend critically on the investigated model!**

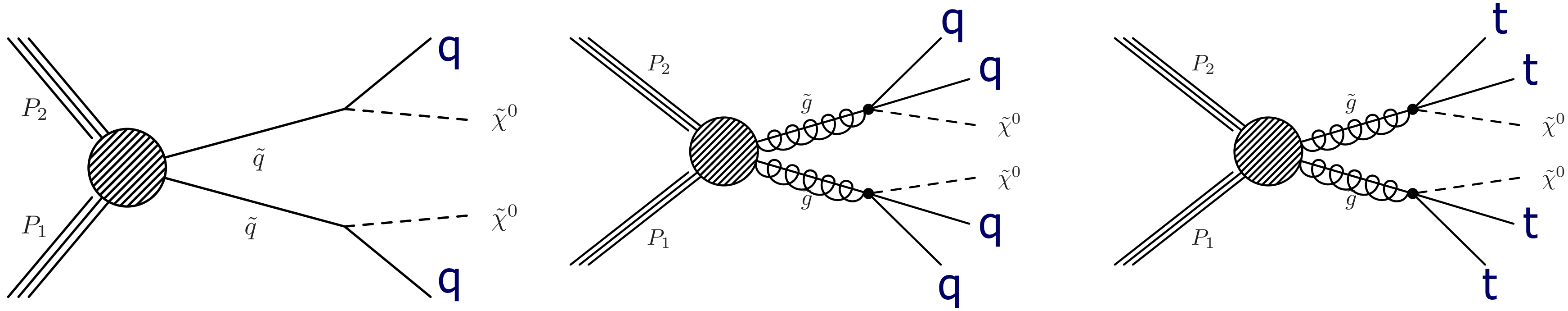
# Inclusive All-Hadronic Search: Results

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Result measured in bins of **$H_T$, $H_T^{miss}$ and Njets**

Different search regions sensitive to different signals

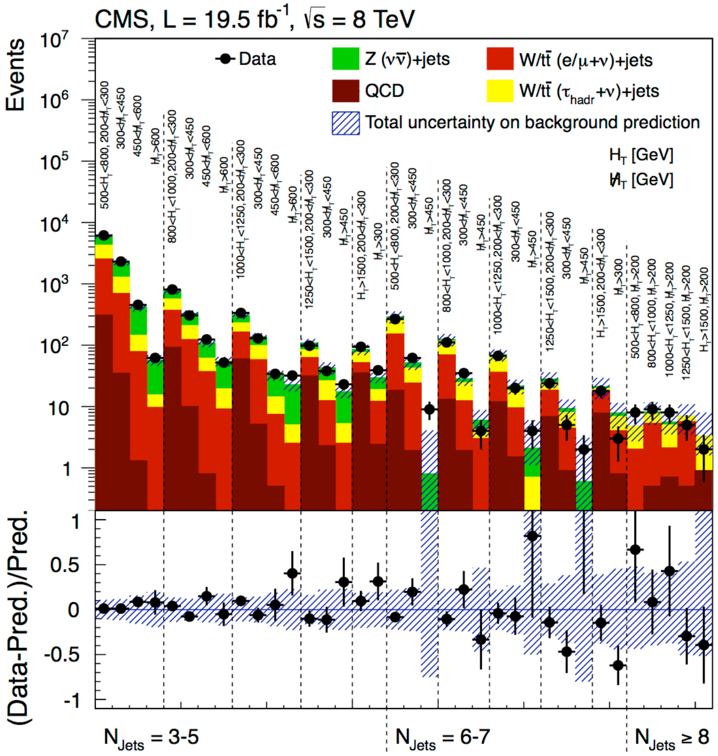


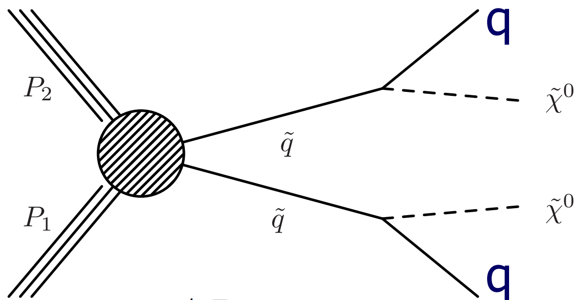



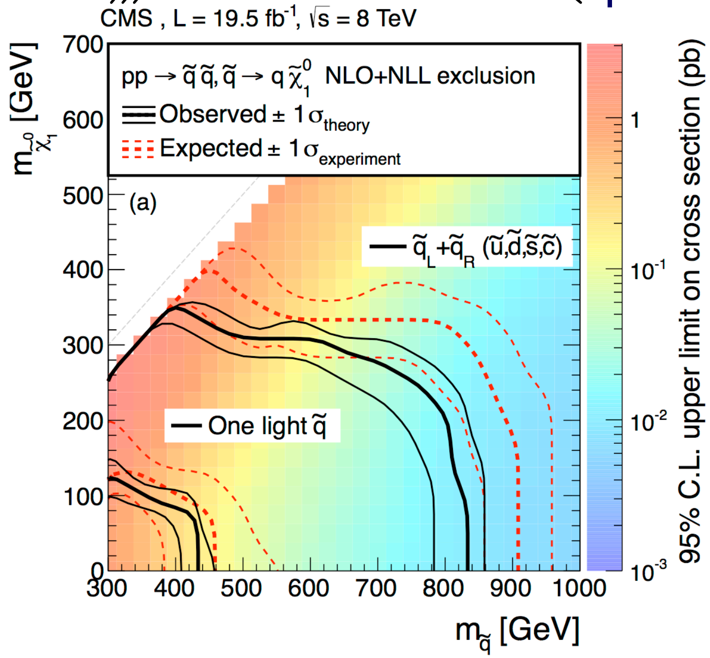
# Inclusive All-Hadronic Search: Interpretation

SUS-13-012
JHEP 06 (2014) 055
arXiv:1402.4770

Interpretation in simplified models:




**Squark masses excluded up to**

- **800 GeV** (assuming all 1st and 2nd generation masses degenerate)
- **400 GeV** (assuming only one light squark)

# Inclusive All-Hadronic Search: Interpretation

SUS-13-012
JHEP 06 (2014) 055
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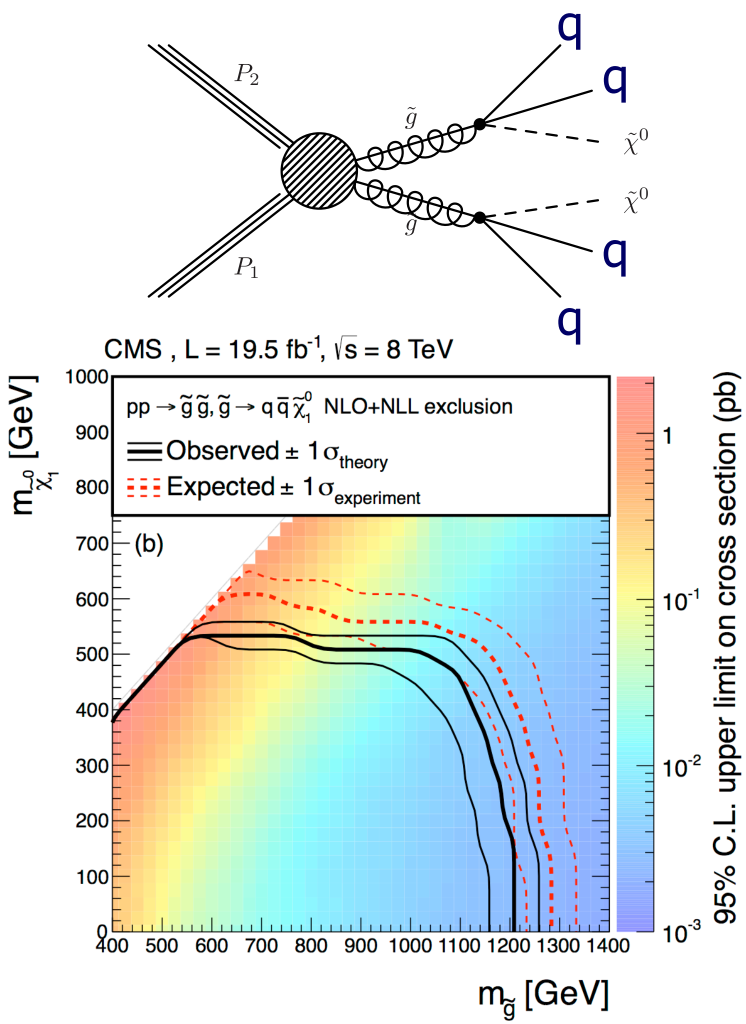
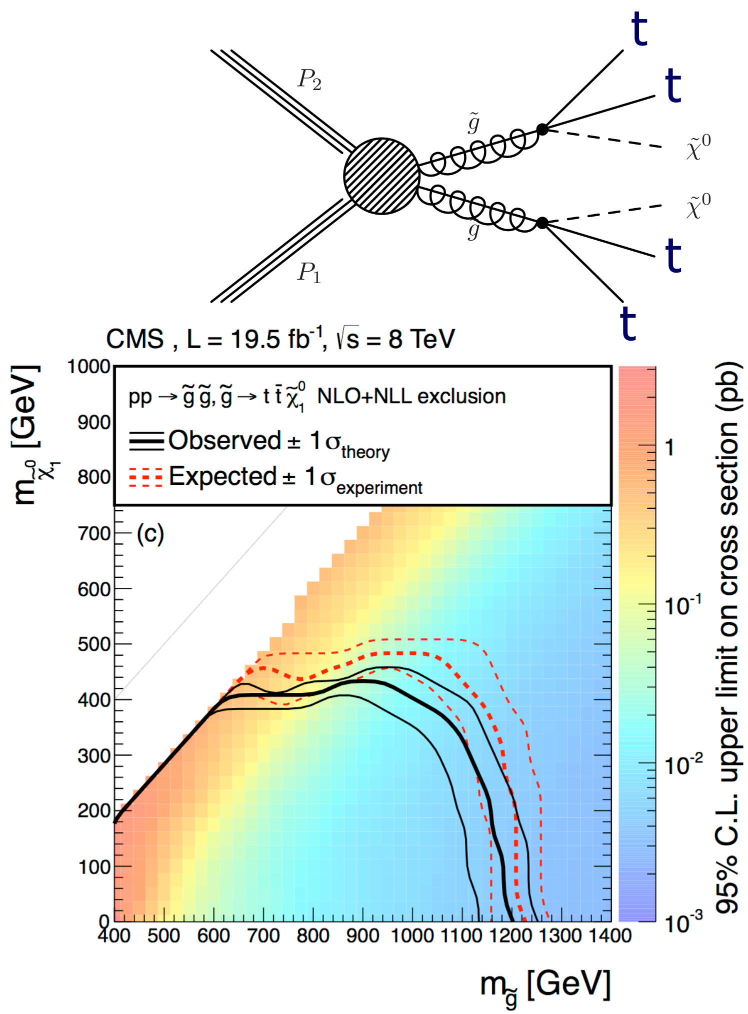


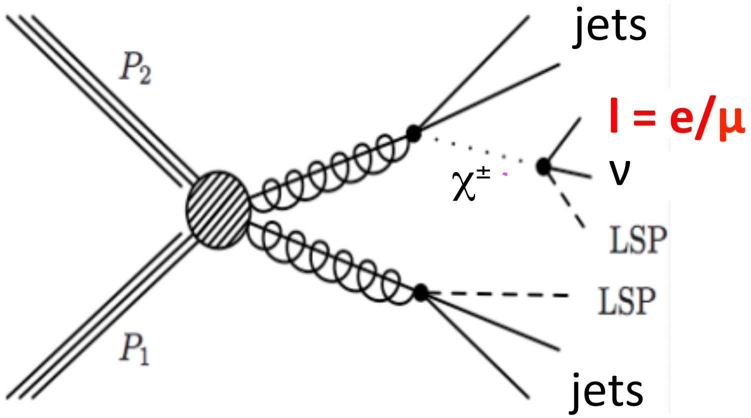

**Gluino masses excluded up to 1.2 TeV!**
**Constraint on neutralino mass stronger in case of 4q finals state**

# Single-Lepton Search

SUS-13-007
PLB 733 328 (2014)
arXiv:1311.4937

Advantage of single lepton analysis compared to full-hadronic:

→ QCD background reduced by 1 lepton requirement



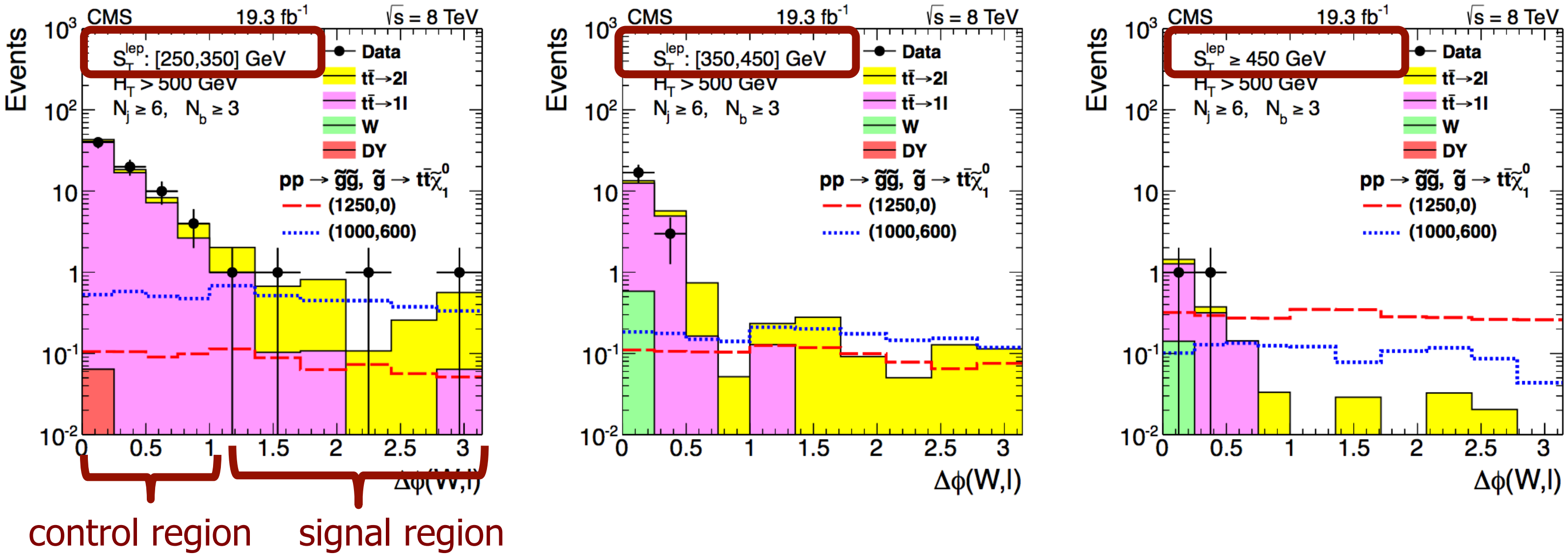

Background estimation methods make use of lepton and MET

→ **Method 1:** predict MET spectrum from lepton spectrum (assuming that BG events contain mainly MET from W → $l\nu$)

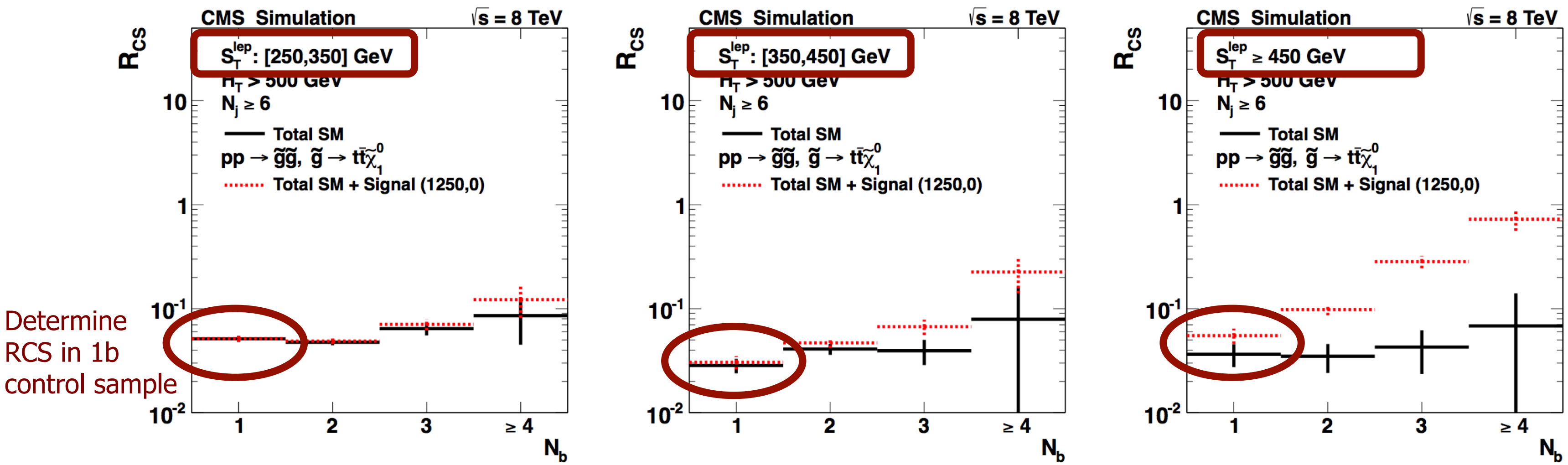
→ **Method 2:** predict main background from $\Delta\Phi$, the azimuthal angle between the W-boson candidate and the lepton, analysis binned in $S_T = p_T$ (lepton) +MET

# Single-Lepton Search: Background Estimation

SUS-13-007
PLB 733 328 (2014)
arXiv:1311.4937



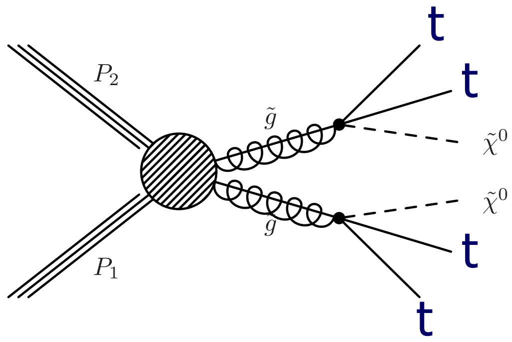

Method relies on signal being significant only on >= 2b-tag channel



# Single-lepton search – Results

SUS-13-007
PLB 733 328 (2014)
arXiv:1311.4937

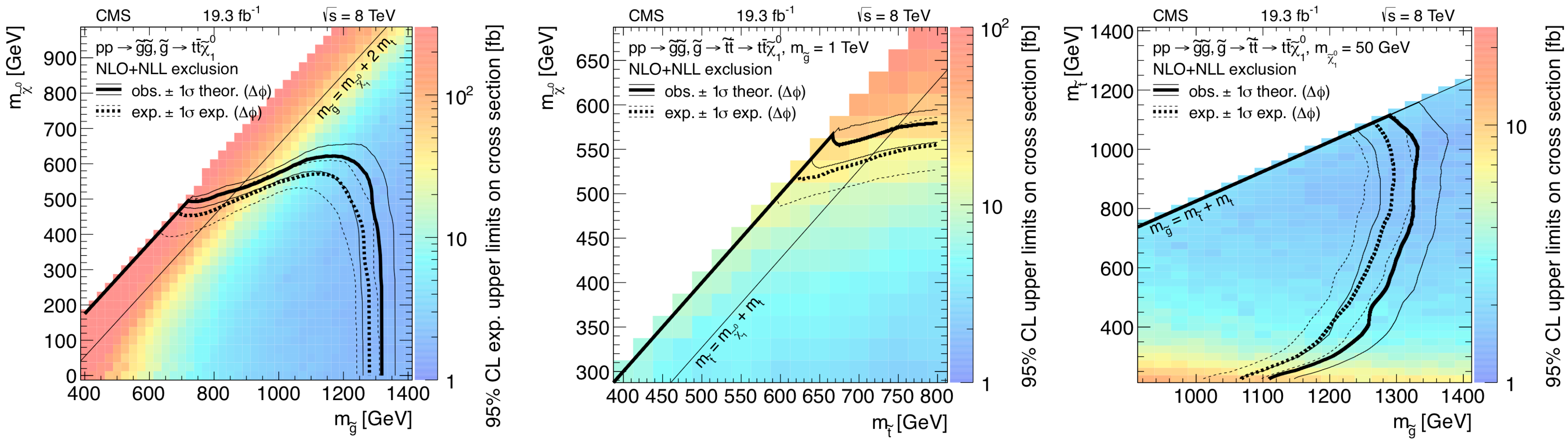
Interpretation for gluino → stop top N1:




m(gluino)>m(stop)

m(gluino)=1TeV

m(N1) = 50 GeV



**Strong constraints on gluino mass up to 1.3 TeV!**
**Stronger constraints on stop (up to 800 GeV) as in direct stop searches (under the assumption that gluino is in reach…)**

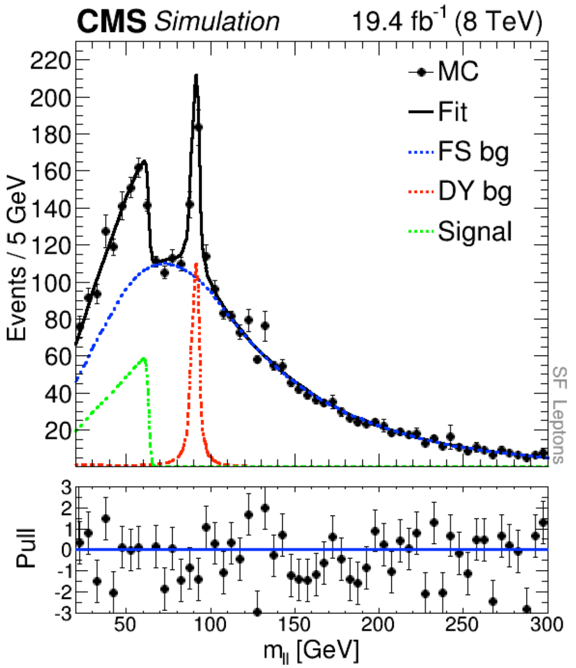
# Di-lepton search

SUS-13-013
SUS-12-019

Leptons can be

- same-flavor (SF) or different flavor (DF)
- opposite-sign (OS) or same-sign (SS)

search for mass edge in SF events

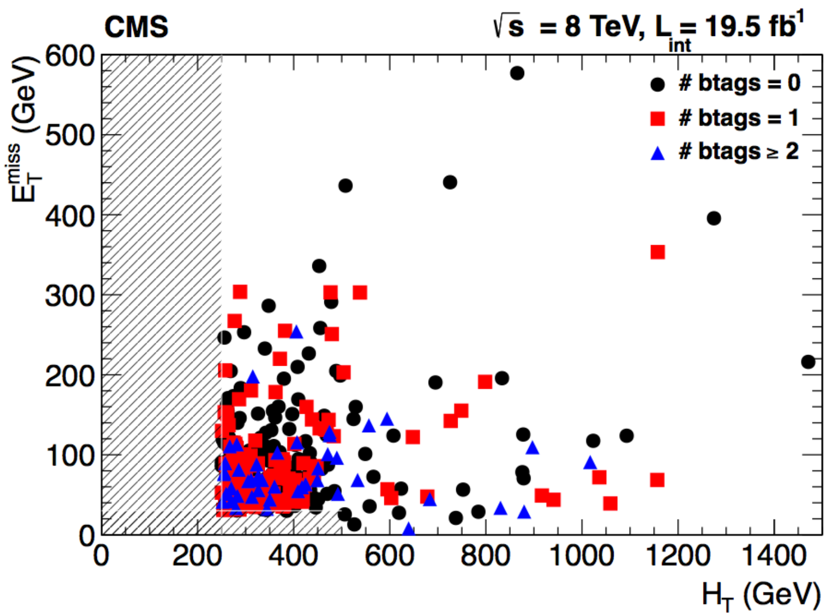


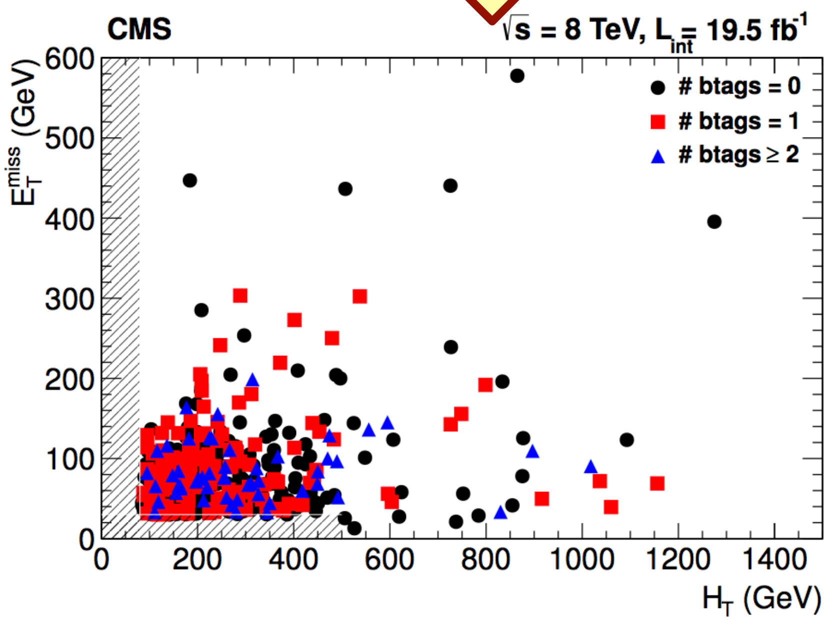

low SM background
only rare processes

SUS-13-013
JHEP 01 (2014) 163
arXiv:1311.6736

# Same-Sign Di-leptons

- MET > 30 GeV (if $H_T$ < 500 GeV)
- Signal regions binned in N(b-jets)
- Two signal selections:
  - Low-$p_T$ leptons ($p_T$ > 10 GeV), $H_T$ > 250 GeV
  - High-$p_T$ leptons ($p_T$ > 20 GeV), $H_T$ > 80 GeV

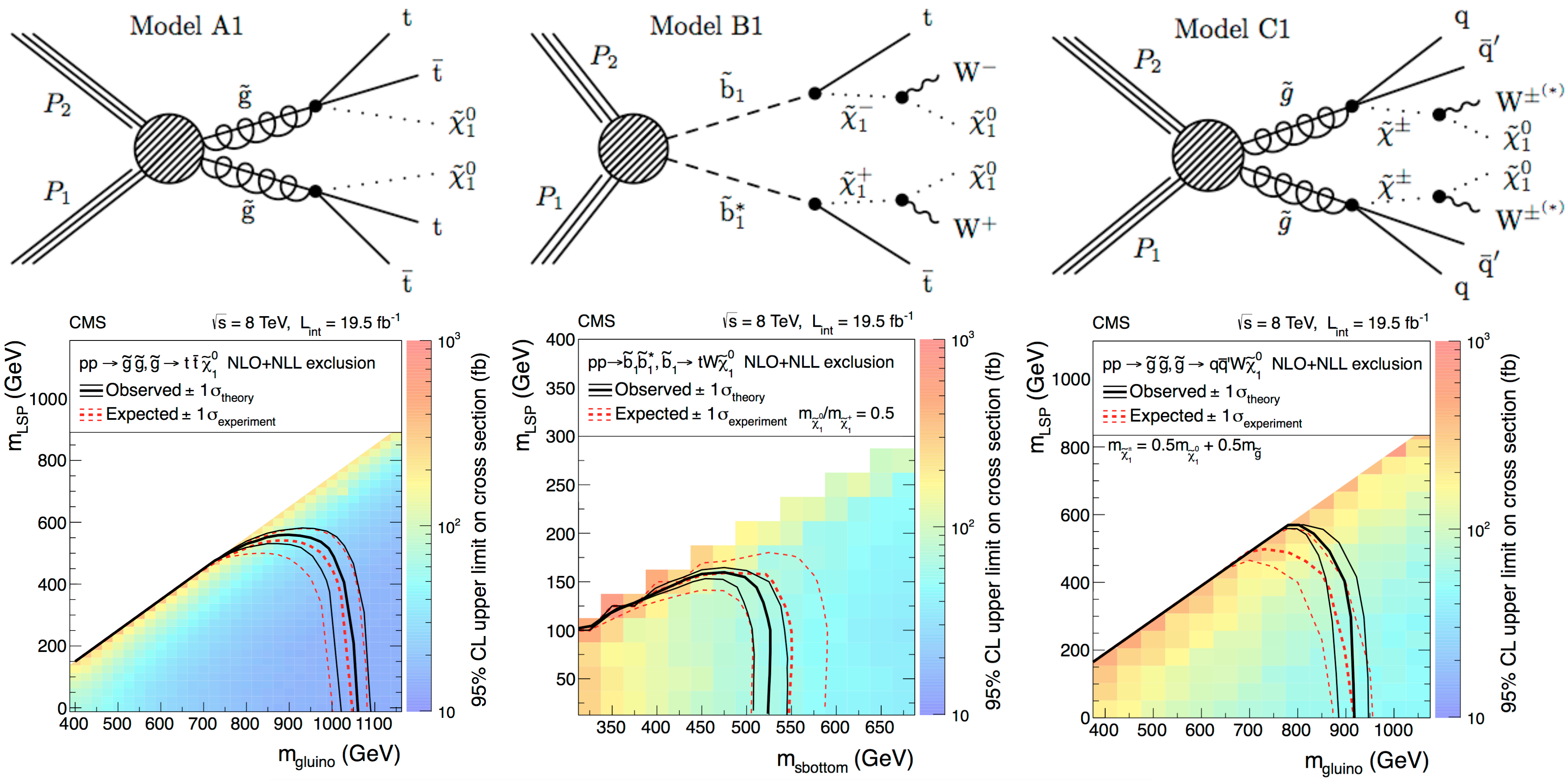



- Many interpretations possible…

# Same-Sign Di-leptons

## Examples for interpretations

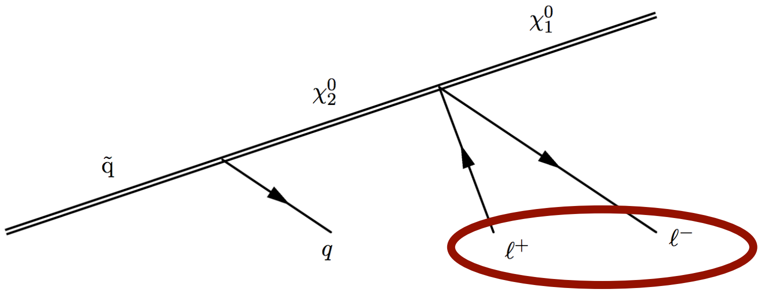


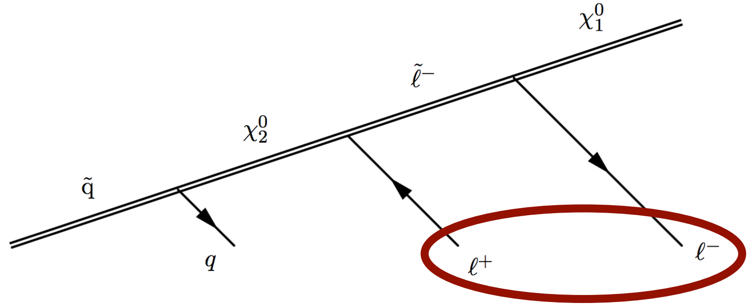

→ **Gluino masses excluded up to 1 TeV**
→ **Sbottom masses excluded up to 500 GeV**

SUS-12-019

# Opposite-Sign Dileptons

- Search for a mass edge



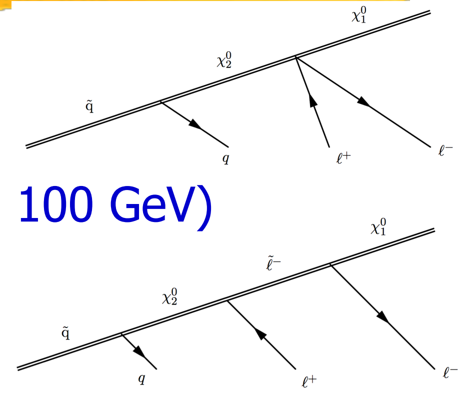

- For $m(\tilde{\chi}^0{}_2)$ > m(slepton) > $m(\tilde{\chi}^0{}_1)$ expect mass edge:

$$m_{\mathrm{edge}} = \sqrt{\left(\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}}\right)\left(m^2_{\tilde{l}} - m^2_{\tilde{\chi}^0_1}\right)\right) / m_{\tilde{l}}}$$

SUS-12-019

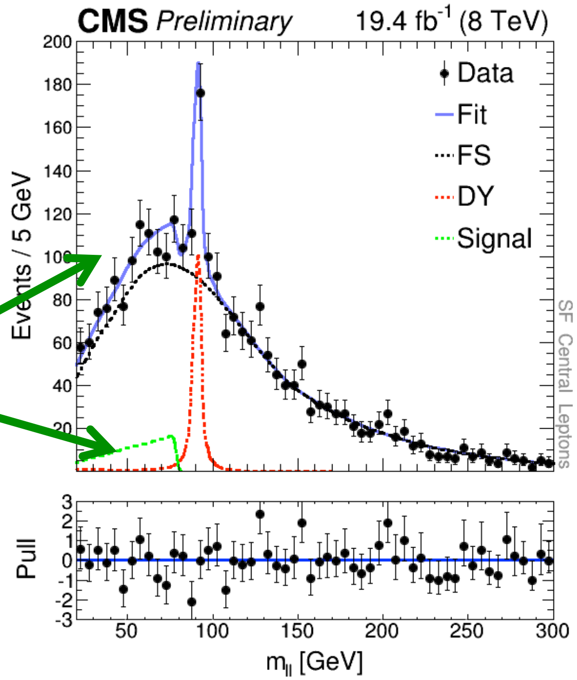
# Opposite-Sign Dileptons

- $N_{lep} \geq 2$ ($p_T > 20$ GeV, $|\eta| < 2.4$)
- $N_{jets} \geq 2$ ($p_T > 40$ GeV, $|\eta| < 3.0$)
- ($N_{jets} \geq 2$ & MET > 150 GeV ) .OR. ($N_{jets} \geq 3$ & MET > 100 GeV)
- **Central region (both leptons within $|\eta| < 1.4$)**
- Forward region (at least one lepton $|\eta| > 1.4$)

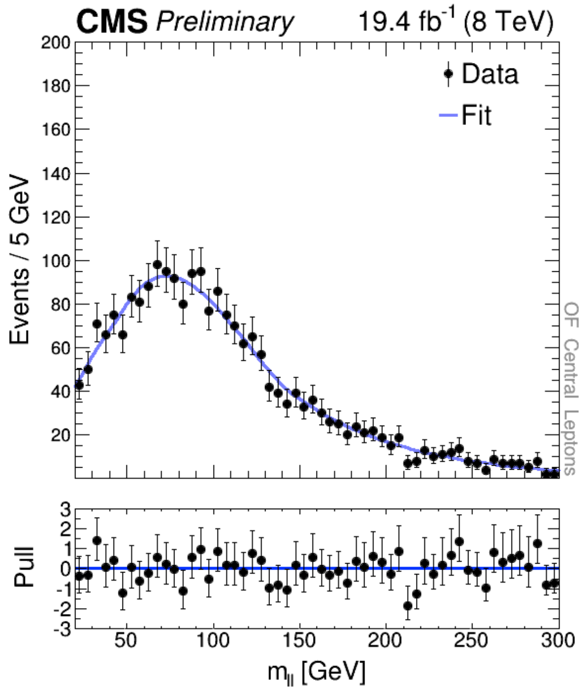



signal ???

central, same flavor



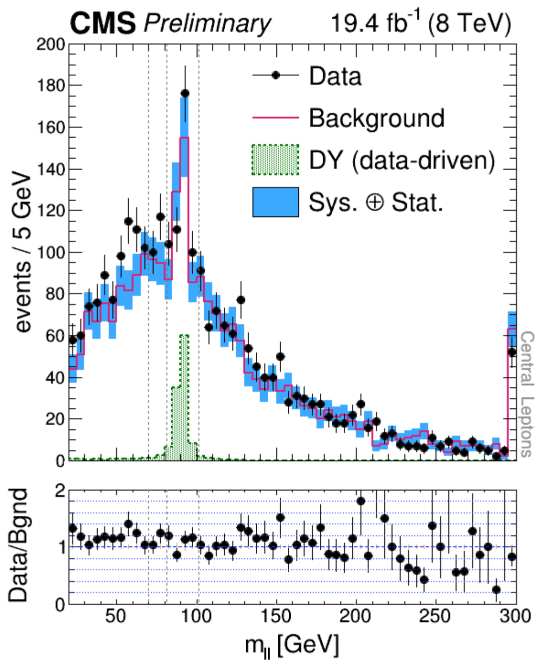

central, different flavor



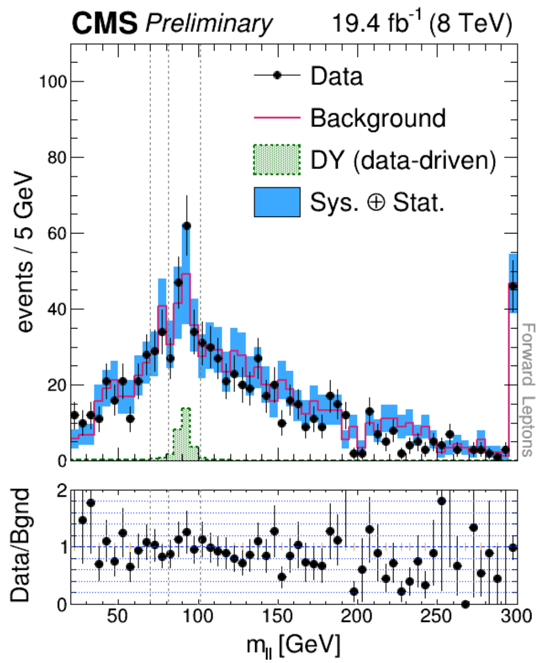
# Opposite-Sign Dileptons

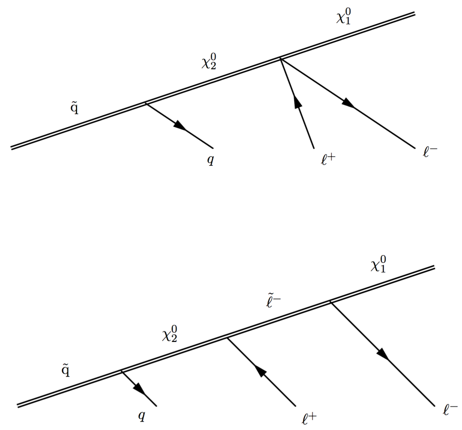
- Assume that signal is more central
- Cross check: comparison for background estimation from control region instead of fit

Central




Forward



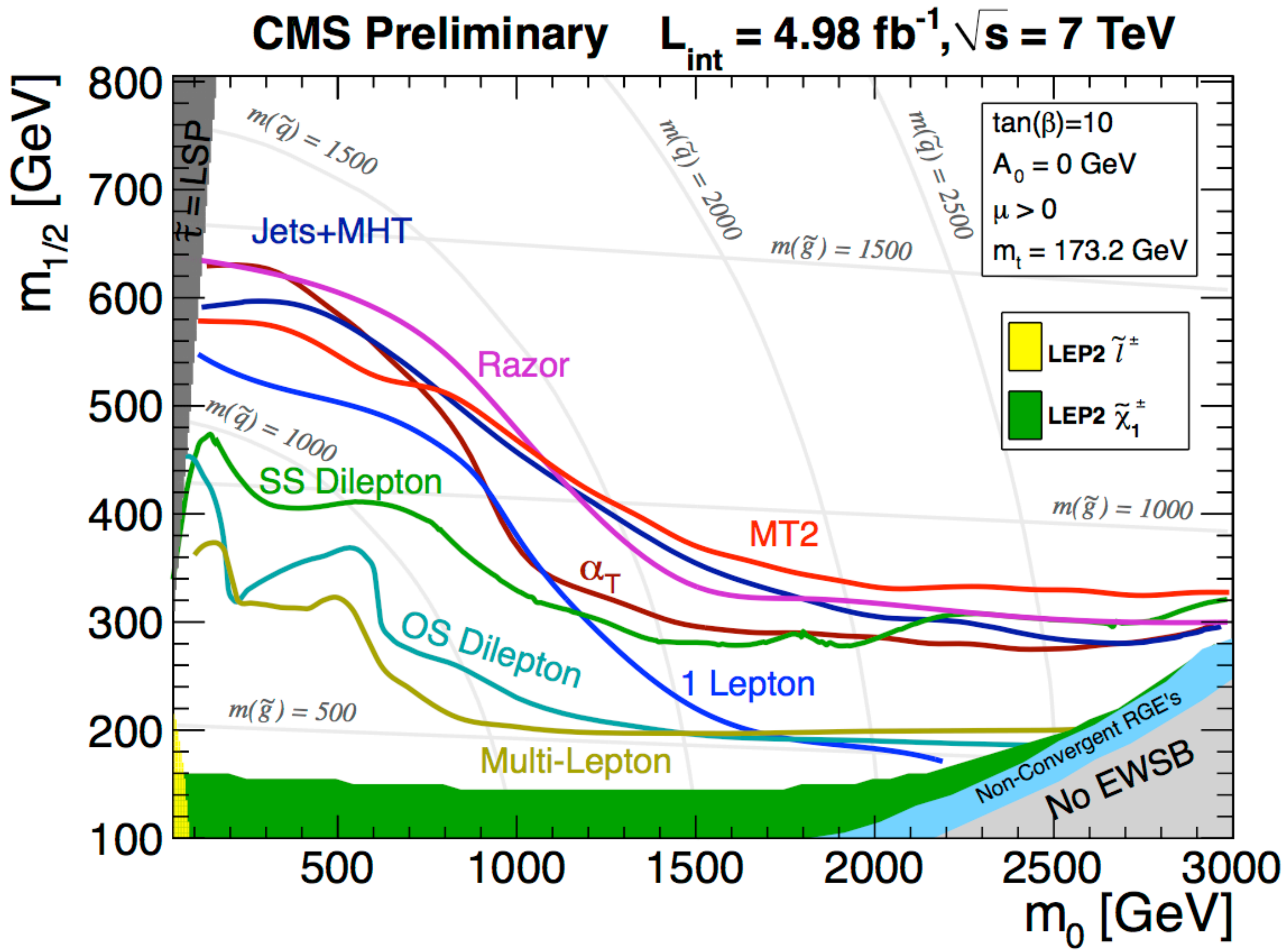



Total yield in window 20 < $m_{ll}$ < 70 GeV leads to:

→ Local significance of **2.6σ** (central) and 0.3σ (forward)

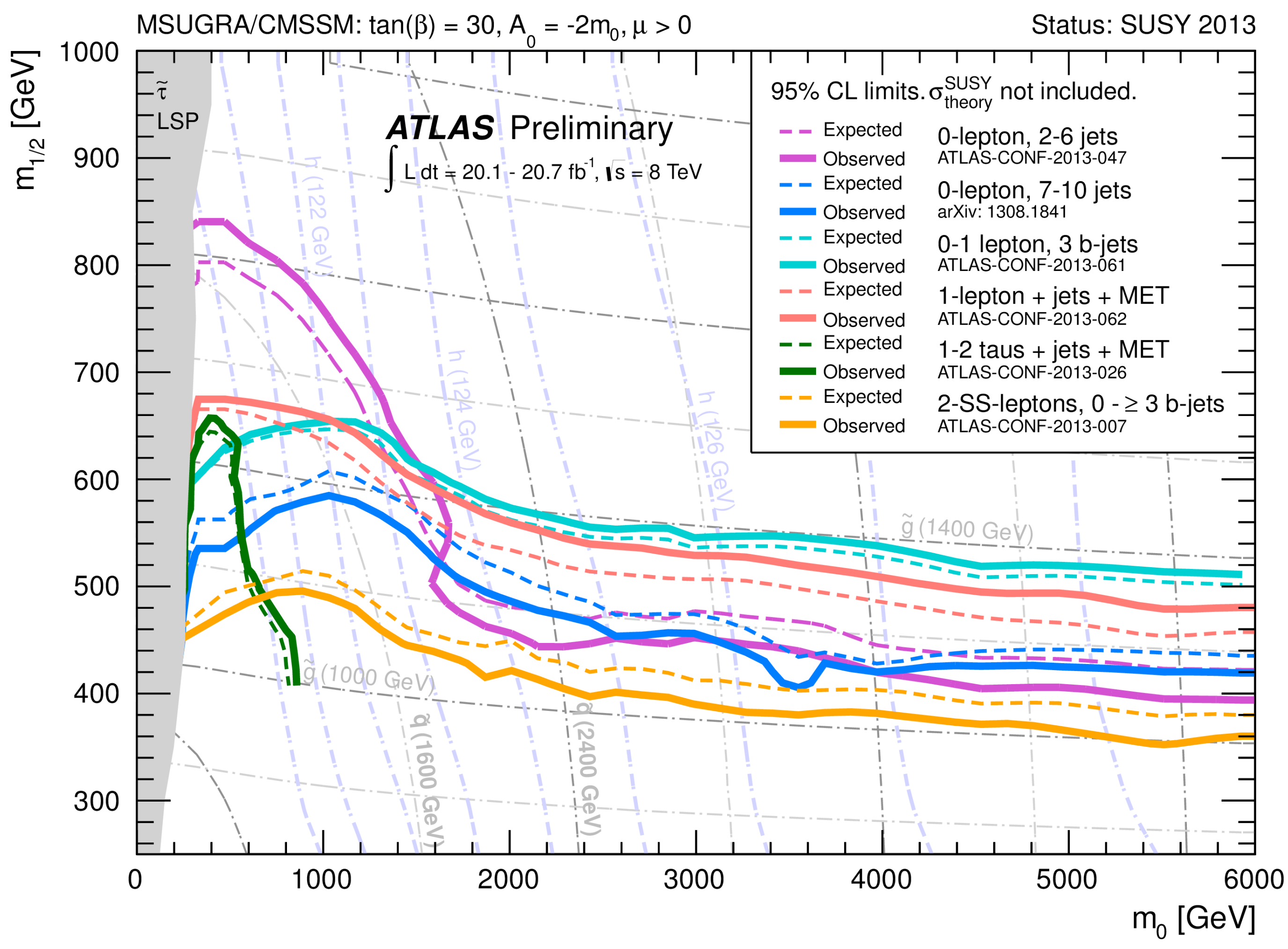
# CMSSM Summary plot

Interpretation in CMSSM by CMS for 7 TeV only…



# CMSSM Summary plot

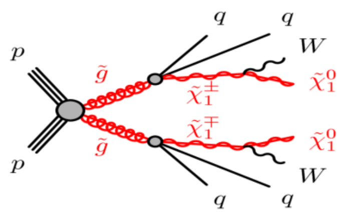
ATLAS did 8 TeV as well

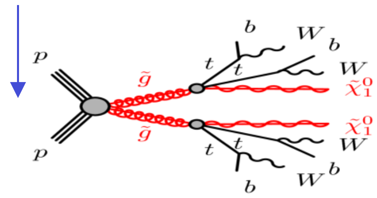


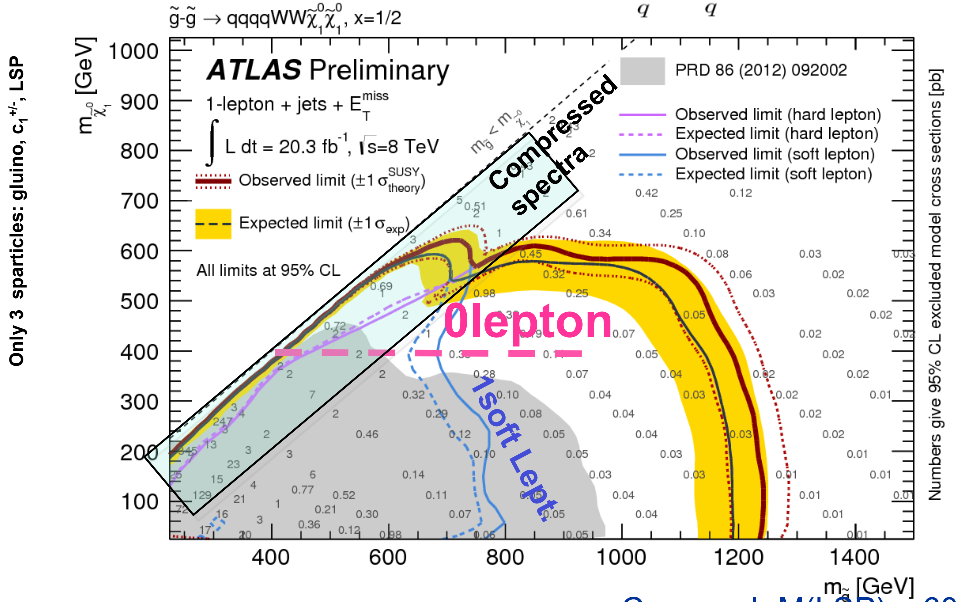
# Compressed spectra

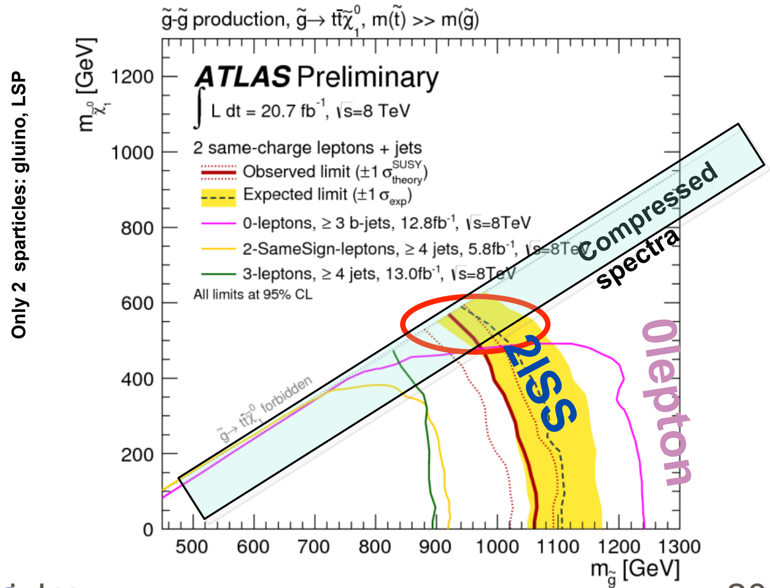
Special analyses required if $\Delta M$ between SUSY particles is small
→ called compressed spectra

- Dedicated analysis using ISR jet : "Monojet"
- Analyze parked data
- Relax kinematic constraints on $H_T$ and MET by requiring 1 soft lepton or 2 same-sign leptons







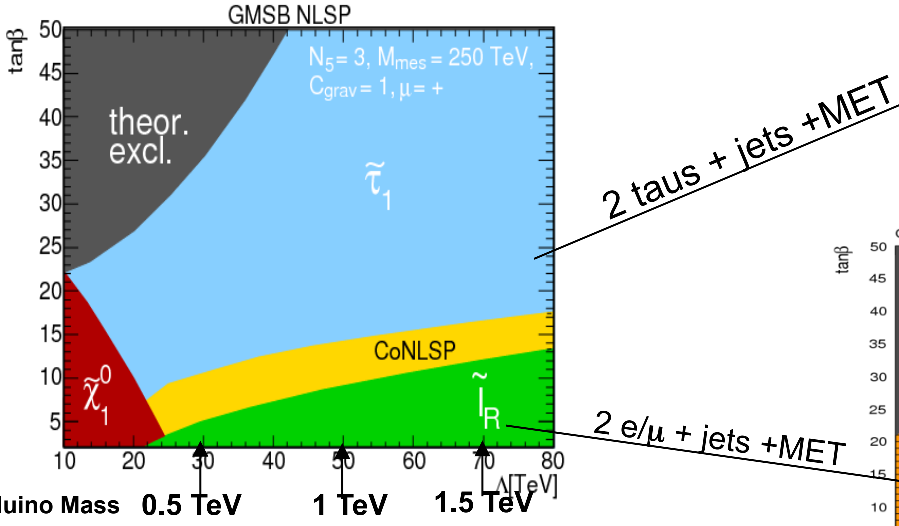



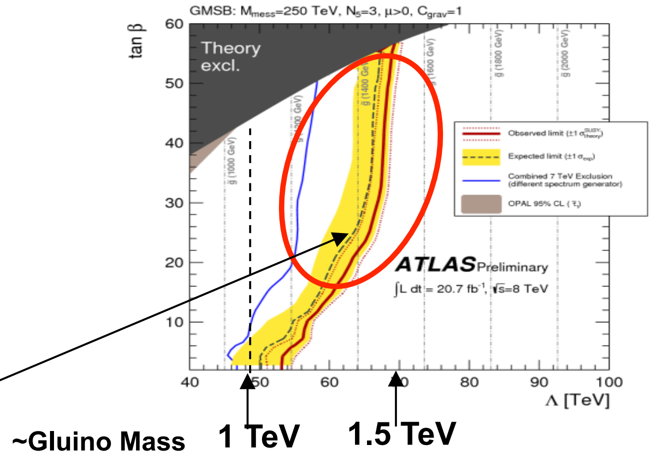

Can reach M(LSP) ~ 600 GeV

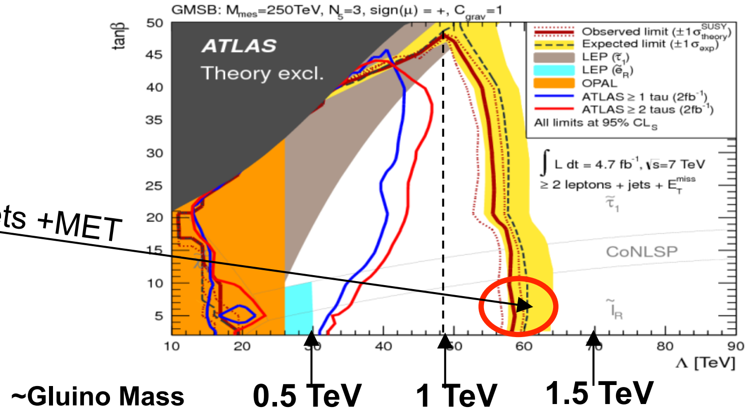
# Gluino, 1st/2nd Generation squarks in GMSB

GMSB (reminder: Gauge Mediated SUSY Breaking): Gravitino is LSP

- Next-to-Lighest LSP (NLSP) determines the event final states
- NLSP = slepton
  - Number of leptons (taus) enhanced



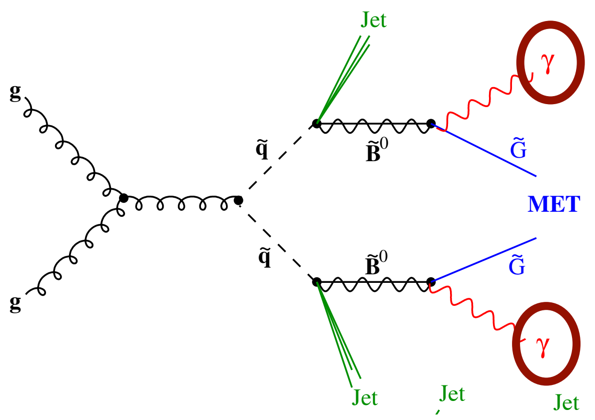



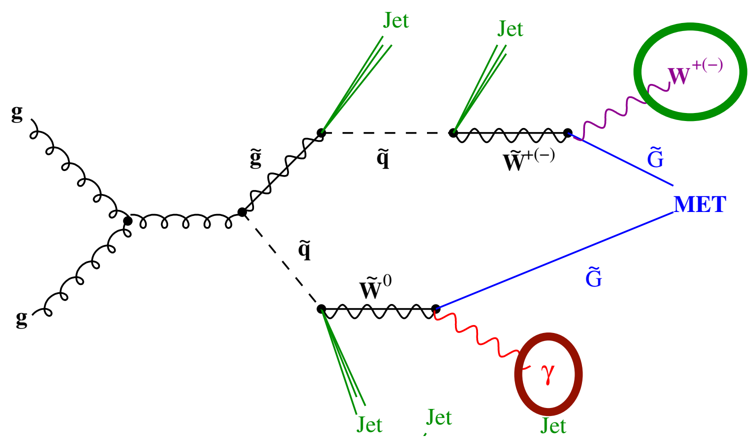
# Gluino, 1st/2nd Generation squarks in GMSB

GMSB (reminder: Gauge Mediated SUSY Breaking): Gravitino is LSP

- Next-to-Lighest LSP (NLSP) determines the event final states
- NLSP = $\tilde{\chi}_1^0$
  - $\tilde{\chi}_1^0$ bino-like: $\gamma\gamma$ final states
  - $\tilde{\chi}_1^0$wino-like: $\gamma$+e or $\gamma$+ jets final states




→ Di-photon analysis




→ Single-photon analysis

# Searches with Photons: Event Selection

- **Di-photon analysis:**
  - At least 2 photons in barrel with $p_T^{\gamma 1} > 40$ GeV, $p_T^{\gamma 2} > 25$ GeV
  - At least 1 jet with $p_T > 30$ GeV, $|\eta|<2.6$
  - *Signal region:* $E_T^{miss} > 100$ GeV

- **Single photon analysis:**
  - Exactly 1 photon in barrel with $p_T^{\gamma} > 110$ GeV (due to trigger)
  - $H_T > 500$ GeV (also from trigger)
  - At least 2 jets with $p_T > 30$ GeV, $|\eta|<2.5$
  - *Signal region:* $E_T^{miss} > 100$ GeV (6 intervals)

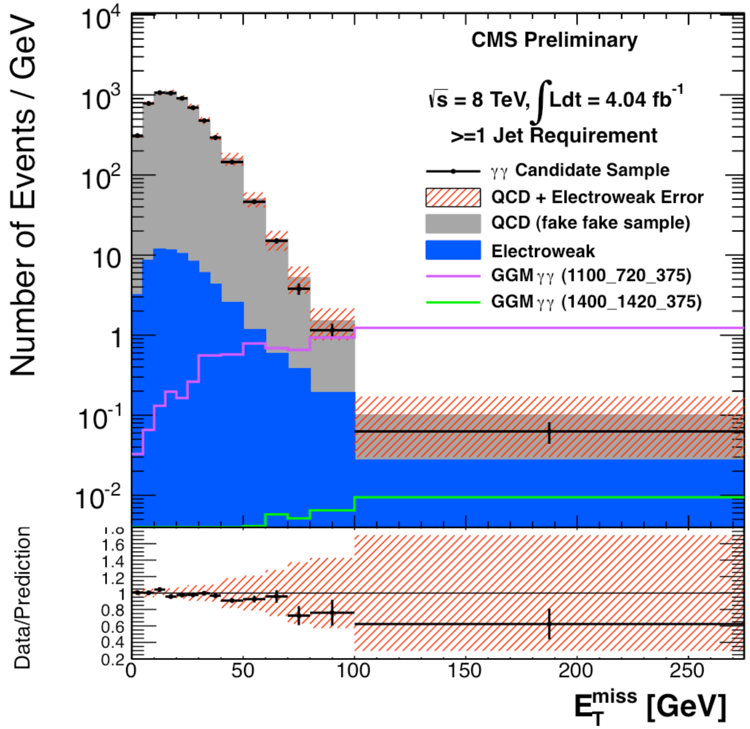
# Searches with Di-Photons: Background Determination

**QCD background (no true $E_T^{miss}$)**

- Mis-measurement of $E_T^{miss}$ in QCD processes and/or photon mis-identification:
  - Direct di-photon production
  - $\gamma$+jets and multijets, with jets mimicking photons
- Background determined from samples with 2 loose $\gamma$ (or electrons)

**Electroweak background with true $E_T^{miss}$**

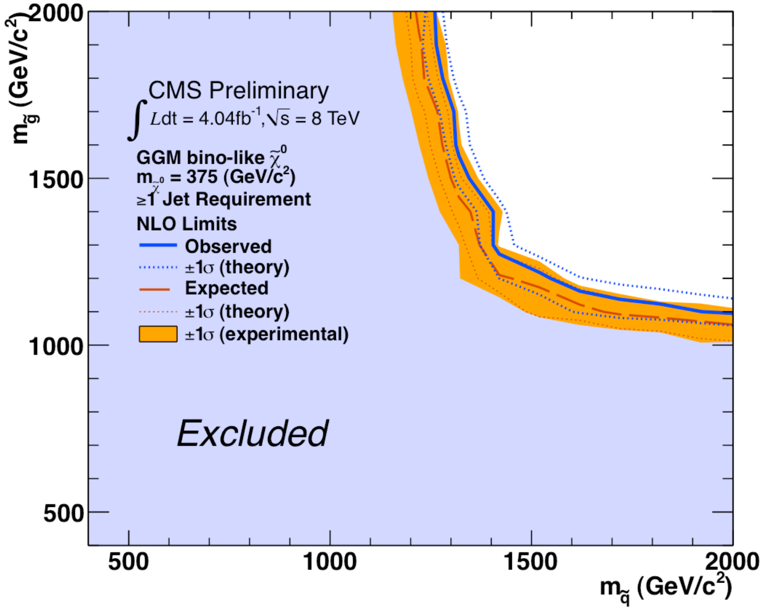
- Background from events with real or fake photon and W → $\nu$e (where e is misidentified as $\gamma$)



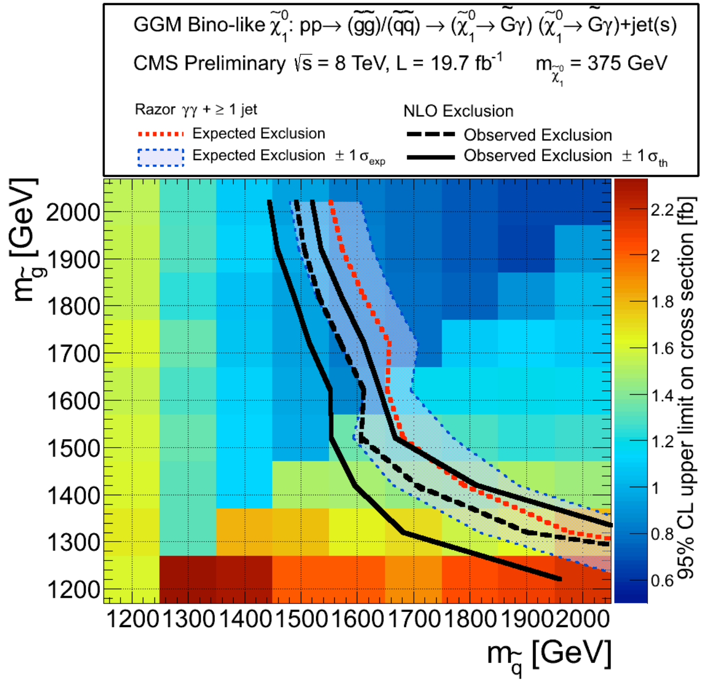
# Searches with Di-Photons: Results

Excluded regions in **gluino-squark plane** for $m_{\chi^0}$=375 GeV

analysis described here




limit with Razor analysis

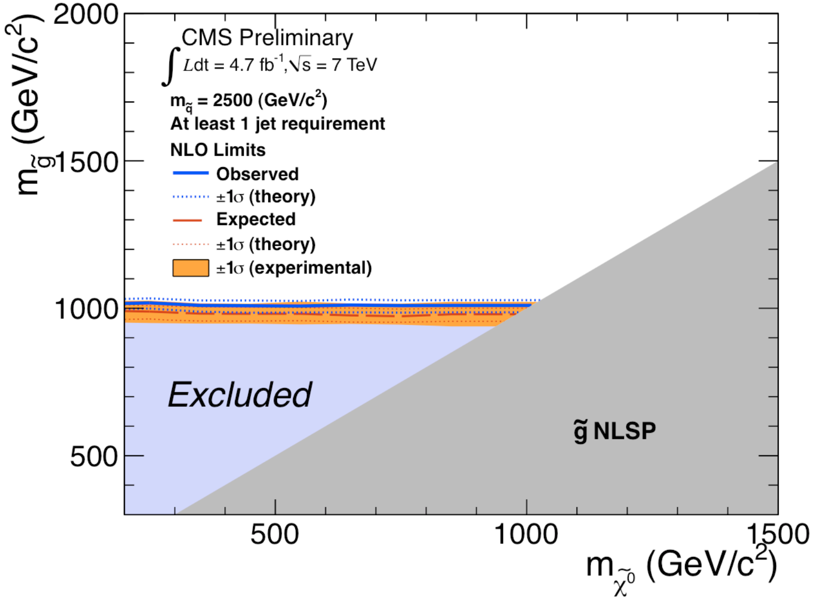



**Strong limit on squarks up to 1.45 TeV and gluinos up to 1.2 TeV for neutralinos of 375 GeV**

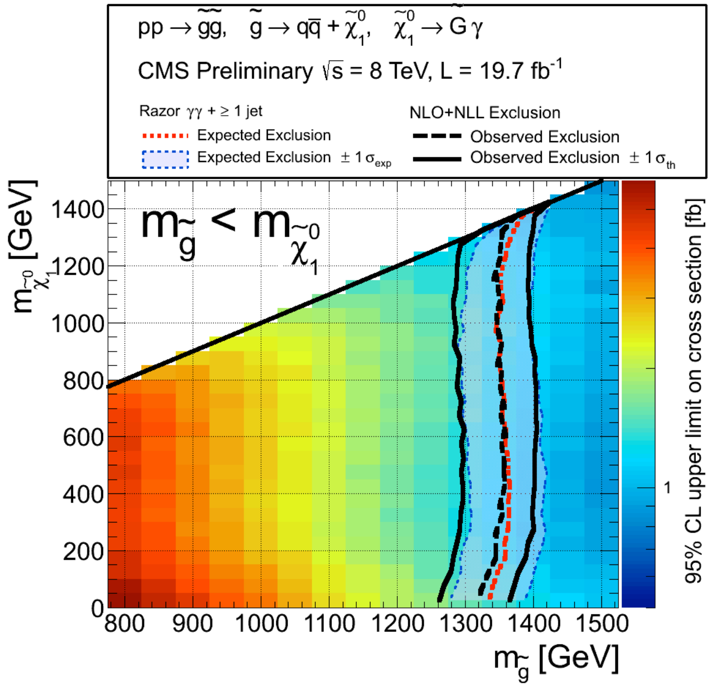
# Searches with Di-Photons: Results

Excluded regions in **gluino-neutralino plane** for $m_{squark}$=2.5 TeV

analysis described here




limit with Razor analysis




**Strong limit on gluinos up to 1.25 TeV and neutralinos up to 1.2 TeV for squarks of 2.5 TeV**

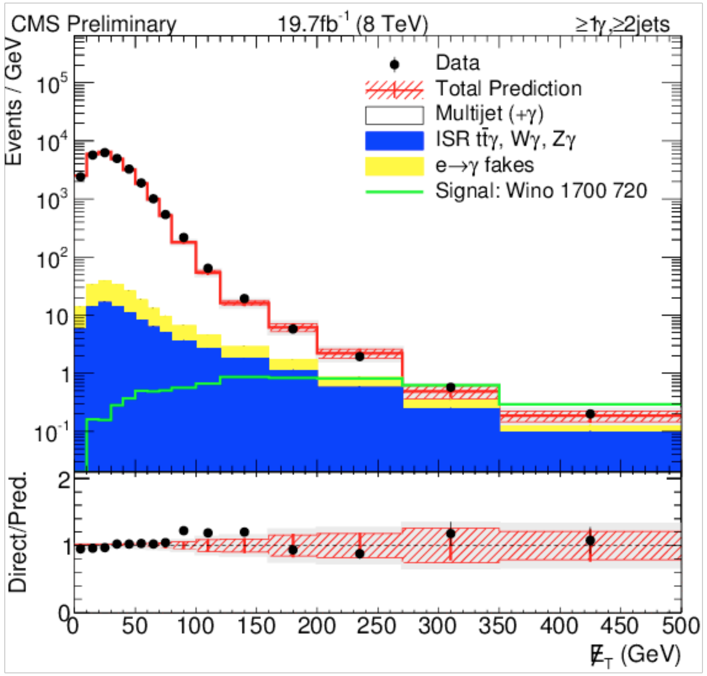
# Searches with Single Photons: Background Determination

CMS PAS SUS-12-001

Background determination similar to di-photon case

Additional backgrounds: initial state radiation (ISR) and final state radiation (FSR) of photons:

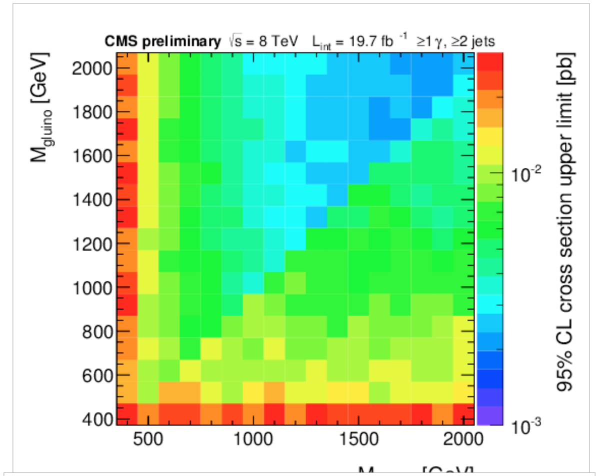
- ISR and FSR in events with electrons in final state covered by EW background prediction from data
- Remaining contributions from SM process are very small – taken from Monte Carlo simulation with a systematic uncertainty of 100%.

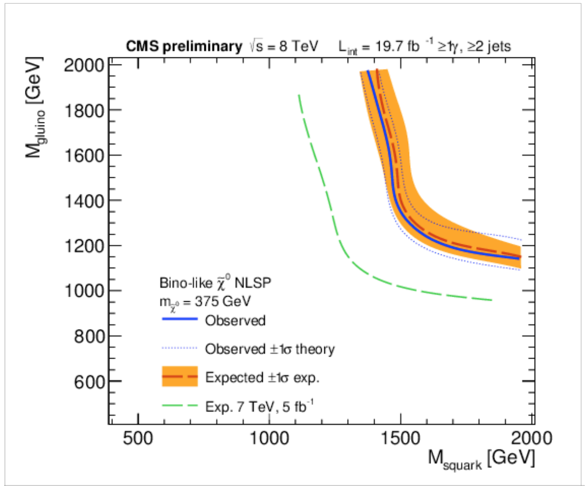


# Searches with Single Photons: Results

95% CL upper limit in gluino-squark mass space

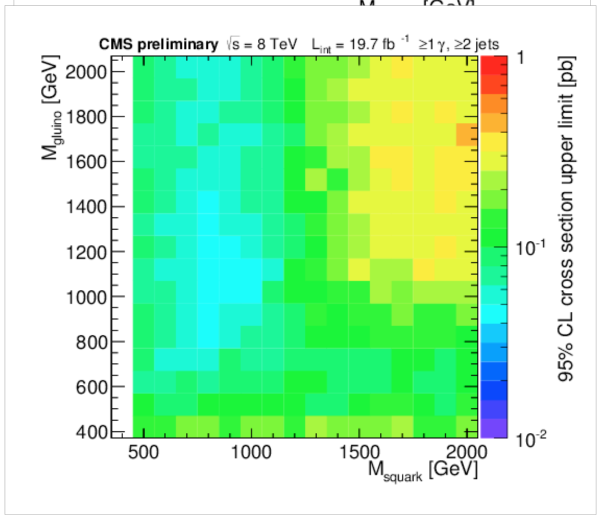
95% CL exclusion contours in gluino-squark mass space

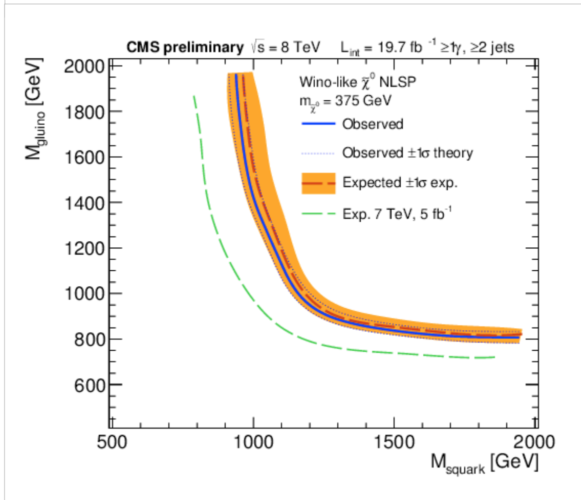



**Bino-like**

Exclude squark masses below 1.5 TeV and gluino masses below 1.2 TeV




**Wino-like**

Exclude squark masses below 1 TeV and gluino masses below 800 GeV

# Outline for today

- Gluinos and 1st/2nd generation squarks
- **Third-generation squarks**
  - Full-hadronic sbottom search
  - Di-leptonic sbottom search
  - Stop searches

# Third Generation Masses in SUSY

Mass eigenstates are calculated from gauge eigenstates, e.g. $f_1 = f_L \cos(M_f) + f_R \sin(M_f)$, where the mass matrix $M_f$ depends on:

- $M_1$, $M_2$, $\tan\beta$, $\mu$: SUSY masses and breaking
- MZ, $\sin^2\theta_W$: EWSB mixing: B,W → Z, $\gamma$

Stop mass:

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{LL}^2 & m_{LR}^* m_t \\ m_{LR} m_t & m_t^2 + m_{RR}^2 \end{pmatrix},$$

stop mass can be small due to top mass in non-diagonal matrix elements

$$\begin{aligned} m_{LL}^2 &= \widetilde{M}_Q^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right), \\ m_{RR}^2 &= \widetilde{M}_U^2 + \frac{2}{3} m_Z^2 \cos 2\beta \, \sin^2\theta_W, \\ m_{LR} &= \boxed{A_t - \mu^*} \cot\beta, \end{aligned}$$

Coupling of h and $\tilde{t}$

Large mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ possible

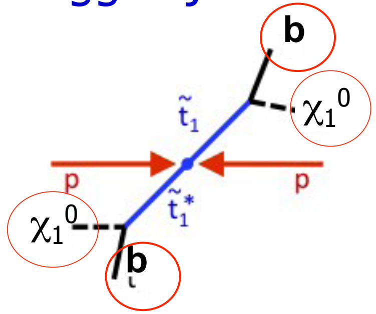
Sbottom and stau:

- Mass can be small due to large tan $\beta$
- $\tilde{b}_L$ can be small even in models with small large tan $\beta$ due to large top Yukawa coupling being part of the doublet containing $\tilde{t}_L$

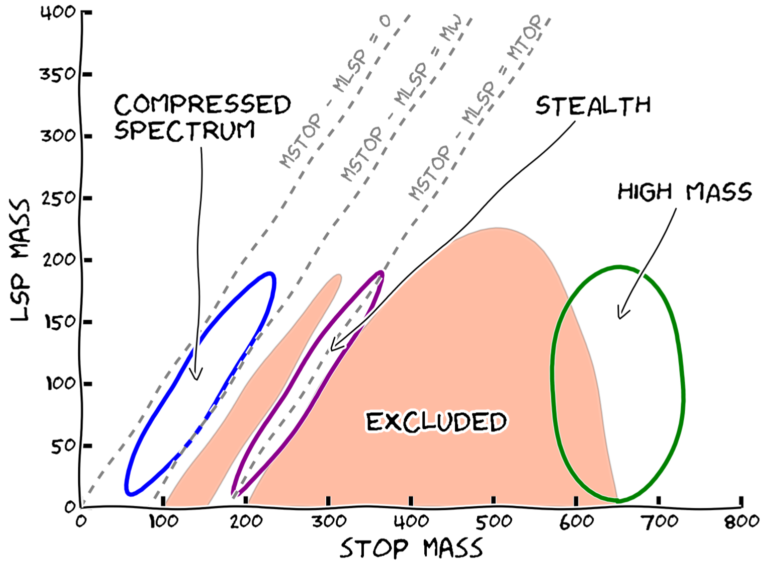
# Third-Generation Searches

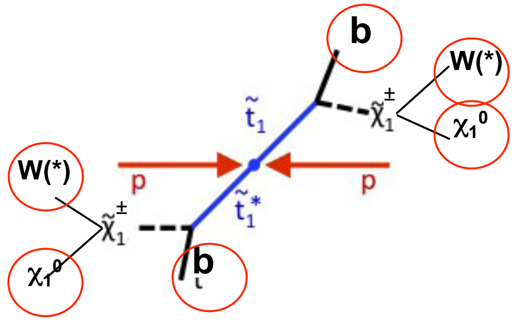
**Natural solution to hierarchy problem: light stops and sbottoms!**

- Powerful sbottom search: $\tilde{b}_L\tilde{b}_L$ with $\tilde{b}_L \rightarrow b\,\tilde{\chi}_1^0$ ➔ 2 b-tagged jets + MET
- Other searches (not discussed here in detail):
  - $\tilde{b}_L\tilde{b}_L$ with $\tilde{b}_L \rightarrow t\,\tilde{\chi}_1^{+-}$ ➔ 2 b + 4 W+ MET
  - $\tilde{b}_L\tilde{b}_L$ with $\tilde{b}_L \rightarrow b\,\tilde{\chi}_2^0$ ➔ 2 b + 2 h + MET



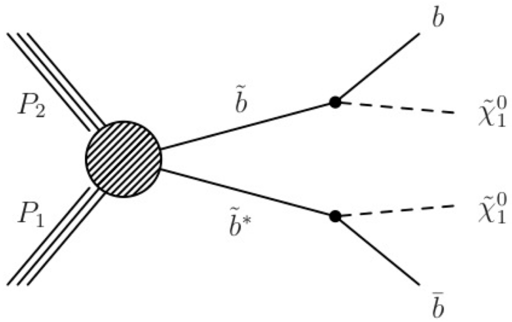

- Stop searches depend on investigated parameter space



# Full-Hadronic sbottom Search

**Exclusive 2b-jet analysis:**

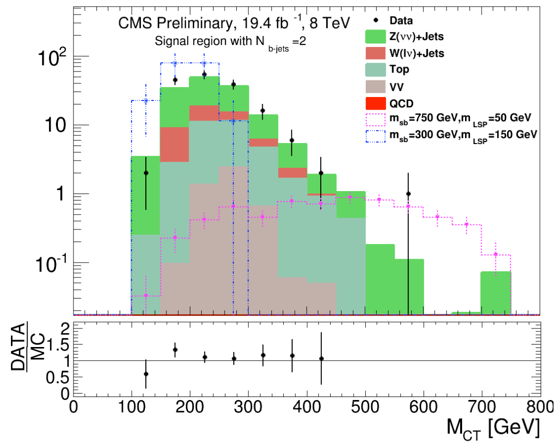



- 2 jets with $p_T$ > 70 GeV and $|\eta|$ < 2.4
- veto 3rd jet with $p_T$ > 50 GeV and $|\eta|$ < 5
- Veto leptons
- $\Delta\Phi$ (jet1, jet2) < 2.5 to veto QCD events
- 1 or 2 b-tags
- $H_T$ > 250 GeV
- MET > 175 GeV
- $M_T = \sqrt{[E_T(J_2) - E_T^{miss}]^2 + [\mathbf{p_T}(J_2) - \mathbf{E_T^{miss}}]^2}$ > 200 GeV (kinematic edge at the mass of the top quark when the jet and MET originate from semileptonic top decay)
- Contransverse mass $$M_{CT}^2(J_1, J_2) = [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p_T}(J_1) - \mathbf{p_T}(J_2)]^2 = 2p_T(J_1)p_T(J_2)(1 + \cos\Delta\phi(J_1, J_2)),$$

  with endpoint at $(m(\tilde{b})^2 - m(\tilde{\chi}_1^0)^2)/m(\tilde{b})$

**Main backgrounds:**

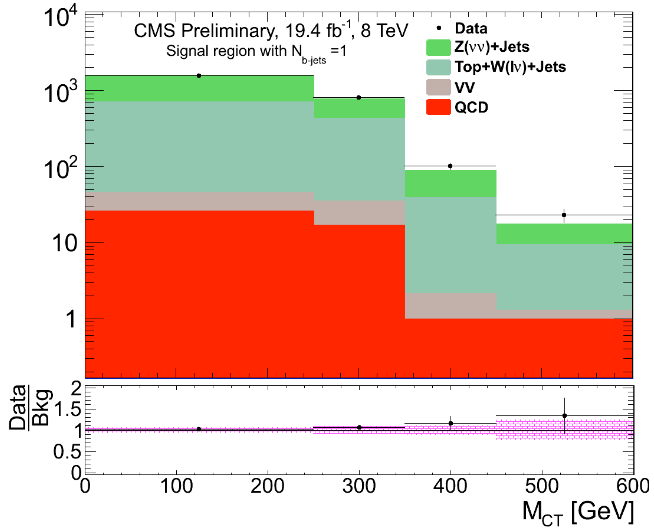
- Z → invisible (as most hadronic searches)
- W + jets
- ttbar

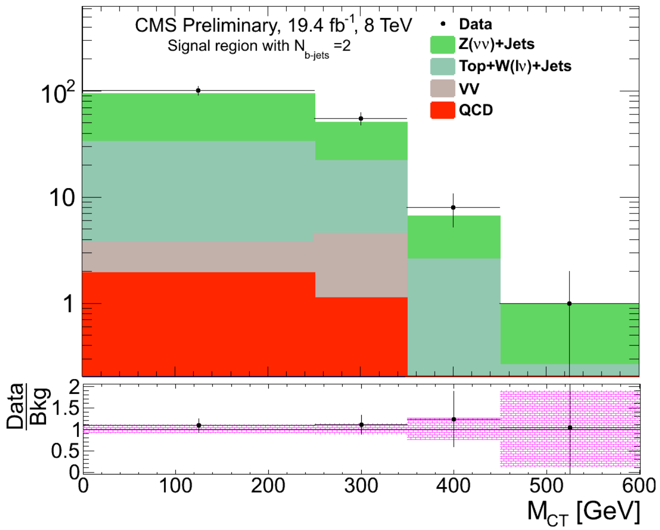


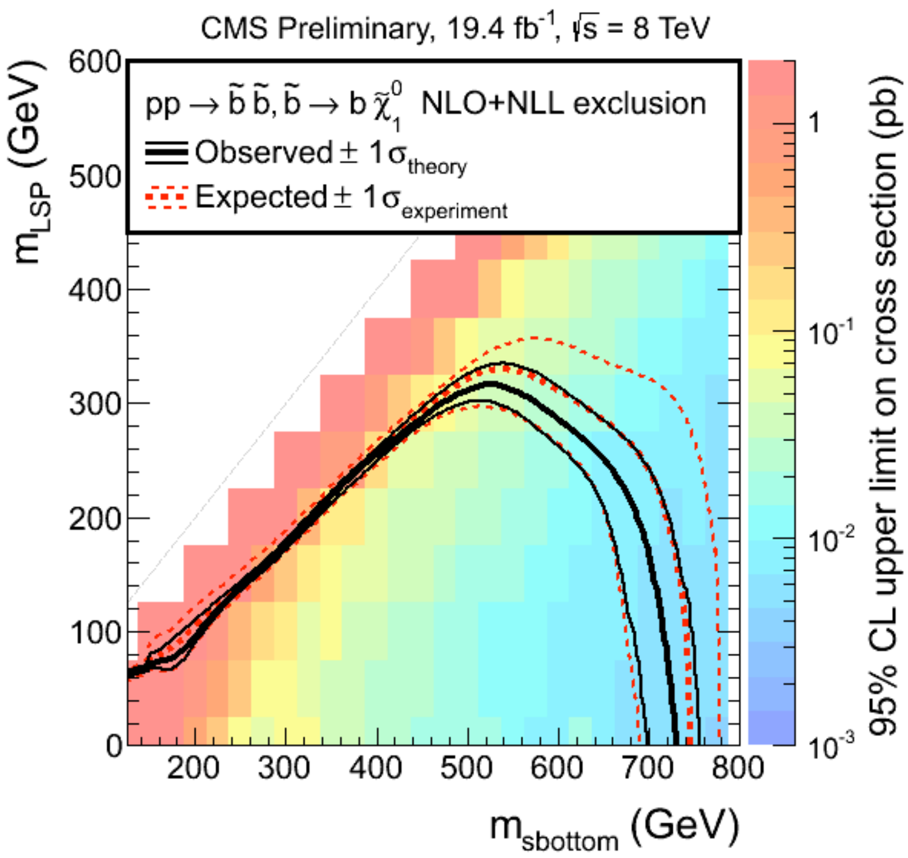
SUS-13-018

# Full-Hadronic sbottom Search

Results binned in N(btag) and MCT




**Exclude sbottom masses below 700 GeV**

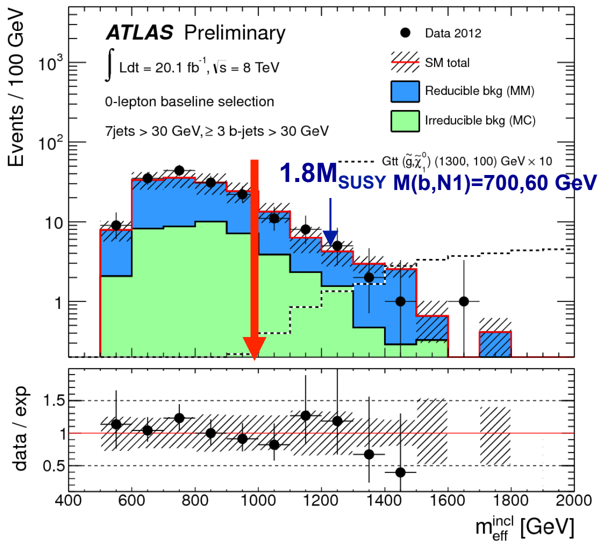
ATLAS-CONF-2013-061

# Di-leptonic sbottom Search

What if sbottom decays mainly as: $\tilde{b}_L\tilde{b}_L \rightarrow bb\,\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow$ 2b+2h(bb,WW)+MET

- Search in 3b + jet +MET (as H→bb is ~60%)

## After all cuts




## Remaining background

**Irreducible:**

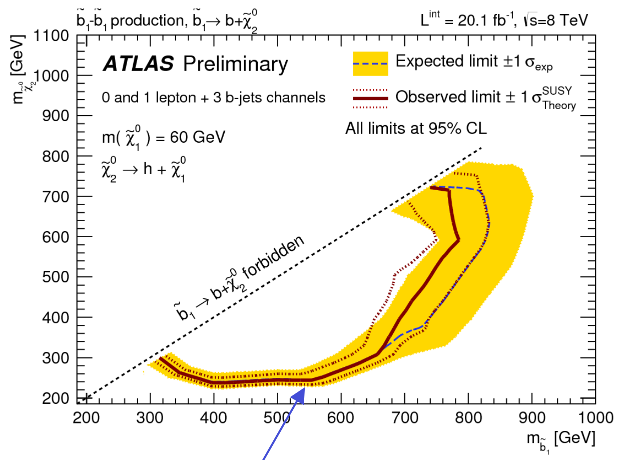
- ttbar+H/Z(bb) : $\sigma$~0.1 pb
- ttbar+b/bb : $\sigma$~0.1 pb

→ Estimated w Monte Carlo

**Reducible:**

- ttbar with $\tau$-jet, c-jet mistagged as a b-jet

→ Estimated w matrix method

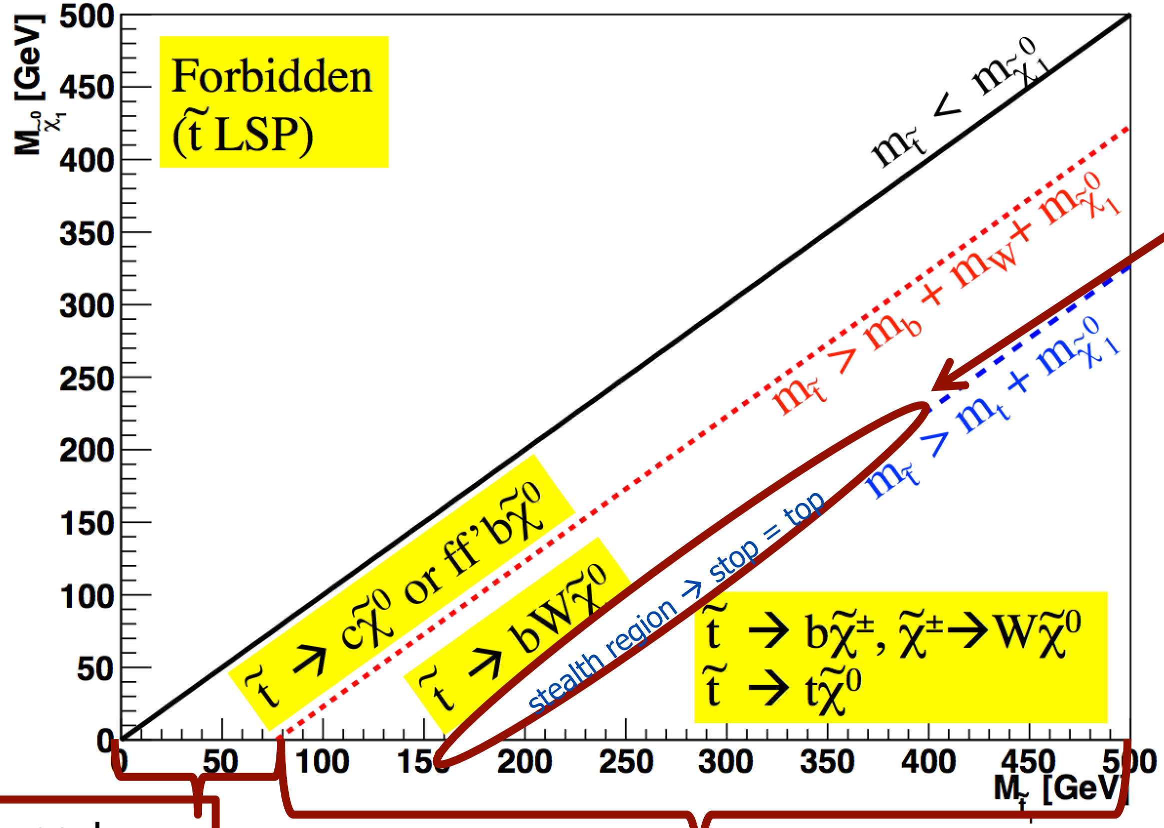



bjets from Higgs very soft

**Exclude sbottom masses up to 700 GeV**
**No constraint for neutralino masses below 250 GeV**

# Stop Search

Different final states → different search strategies for different mass ranges




**search for $\tilde{t}_1$ in $\tilde{t}_2$ decay**

Compressed spectra soft objects essentially invisible
→ **Monojet search**

**2b + 2W + MET search**

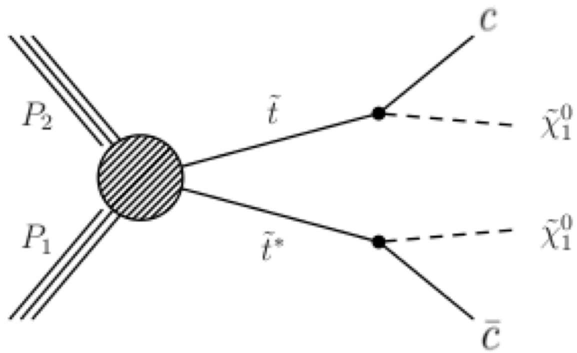
SUS-13-009

# Stop Search with Monojets

For a very **compressed spectrum** the stop decay products, e.g. $\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$, are very soft, and thus hard to detect.

⇒ Exploit the possible presence of a **hard ISR jet** and large MET

- MET > 250 GeV
- pT (j1) > 110 GeV
- veto 2nd jet with $p_T$ >60 GeV
- no leptons
- $\Delta\Phi$(jet1, jet2) < 2.5

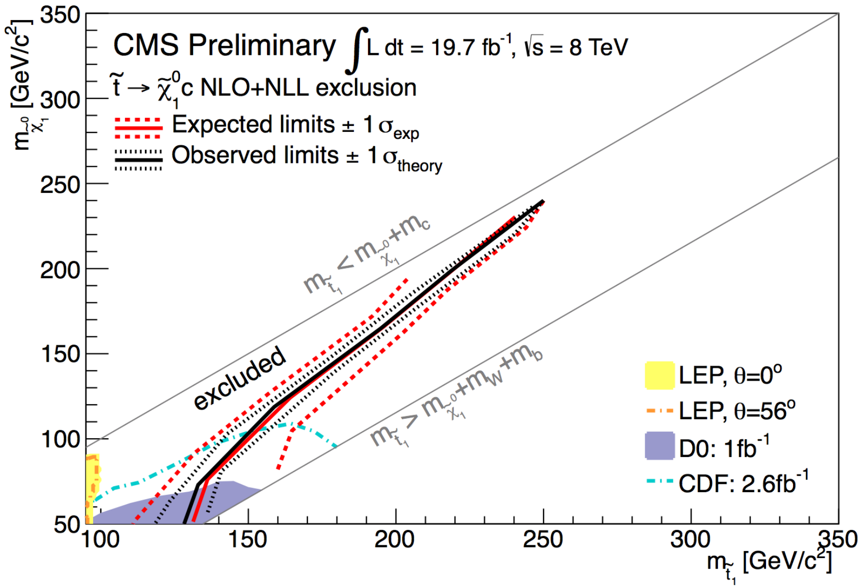



**Main backgrounds:**

- $Z \rightarrow \nu\nu$+jets
- $W \rightarrow l\nu$+jets

**Stop masses up to 250 GeV are excluded for $m_{stop} - m_{\chi_1^0} < 10$ GeV**

Results can be generalized to $\tilde{t}_1 \rightarrow x\tilde{\chi}_1^0$, where x is any decay product invisible to the monojet selection

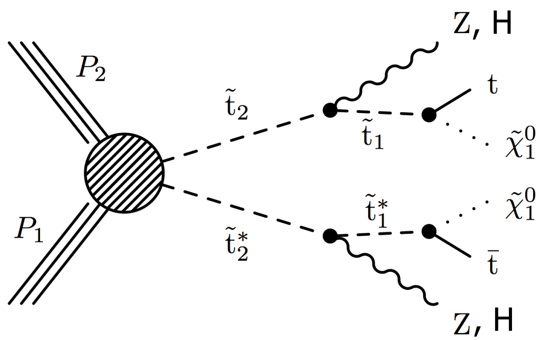


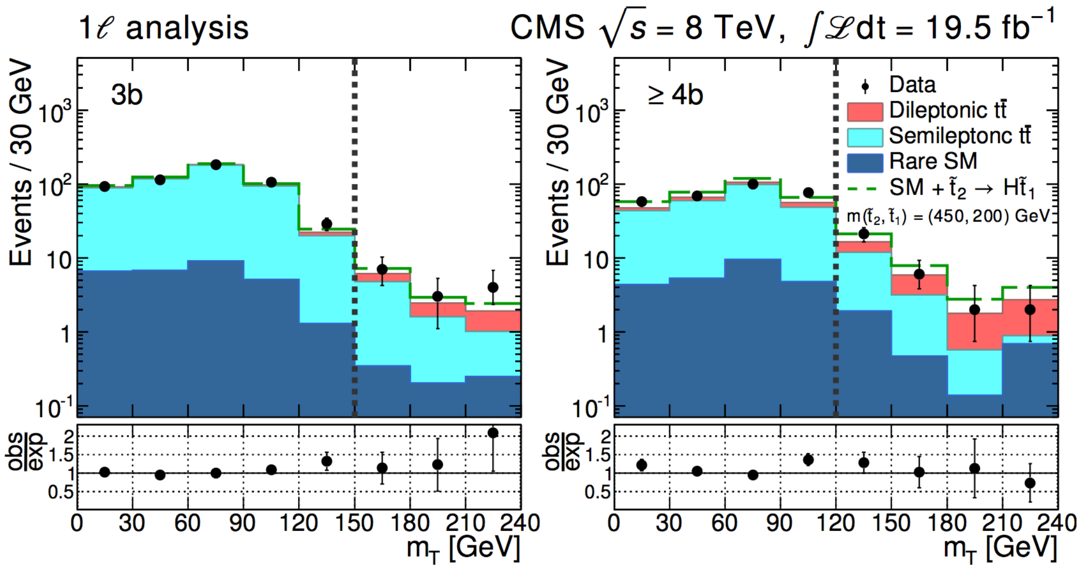
# Stealth Stop Search

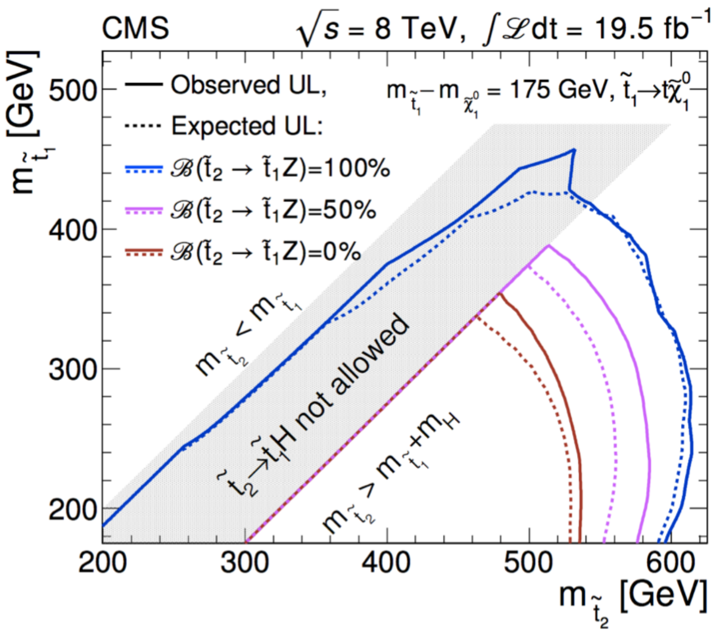
SUS-13-024

If $\tilde{t}_2$ light enough to be produced, use it to target region with $m(\tilde{t}_1)-m(\tilde{\chi}^0{}_1) = m(t)$

- Use searches with 1, 2, >=3 leptons
- b-tags for H→bb signature







- 3 lepton region mostly sensitive

**Exclude $\tilde{t}_2$ masses below 575 GeV for $\tilde{t}_1$ masses below 400 GeV**

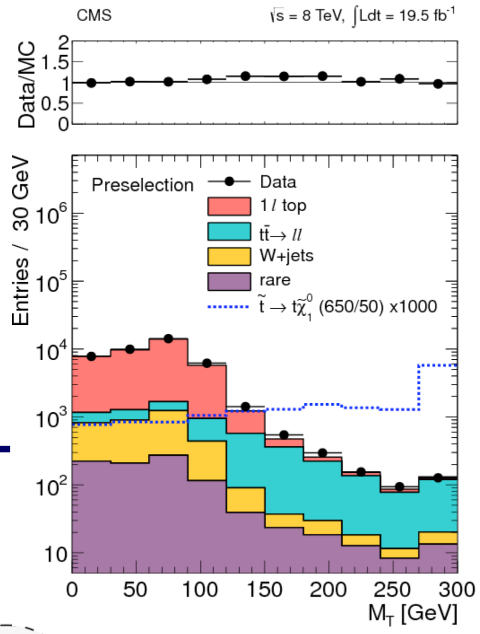
# Search for stop → top neutralino

SUS-13-011
EPJC 73 (2013) 2677
arXiv:1308.1586

## Need to reduce large background that looks similar to the signal:

Baseline selection:

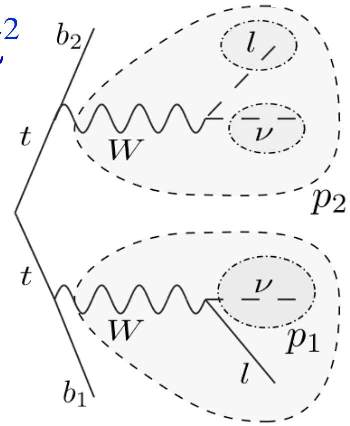
- >= 4 jets
- >= 1 b-jet
- 1 lepton
- MET > 100 GeV
- $M_T$ > 120 GeV

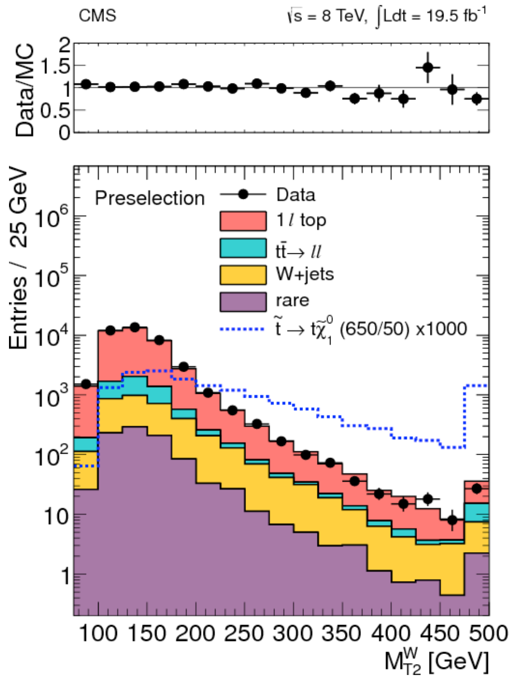



## Multivariate analysis with BDT

## BDT signal regions:

- MET
- Hadronic top $\chi^2$
- $H_T$ ratio
- b-jet $p_T$
- min ($\Delta\Phi$)
- $M_{T2}{}^W$

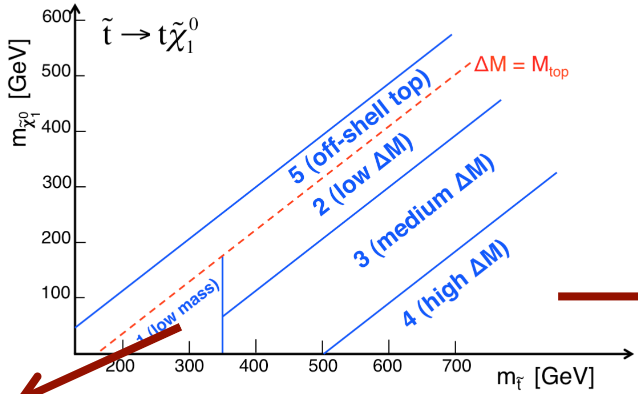


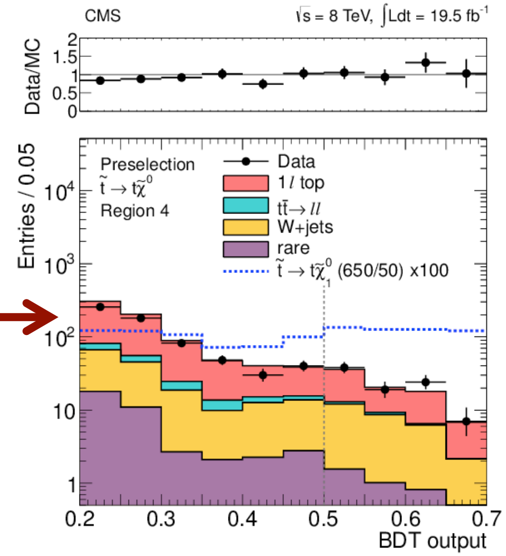



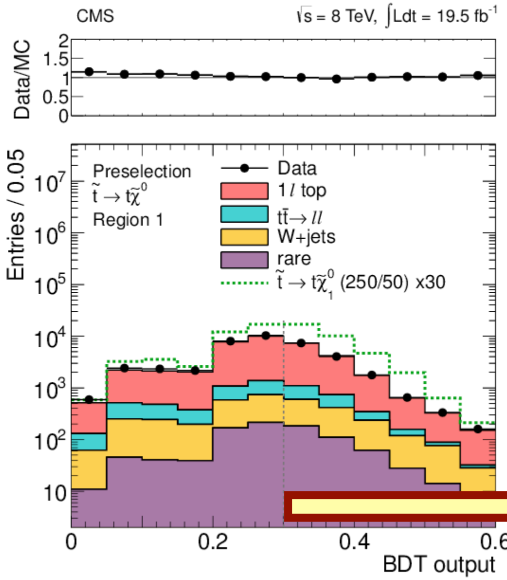
# Single Lepton Stop Search with BDT

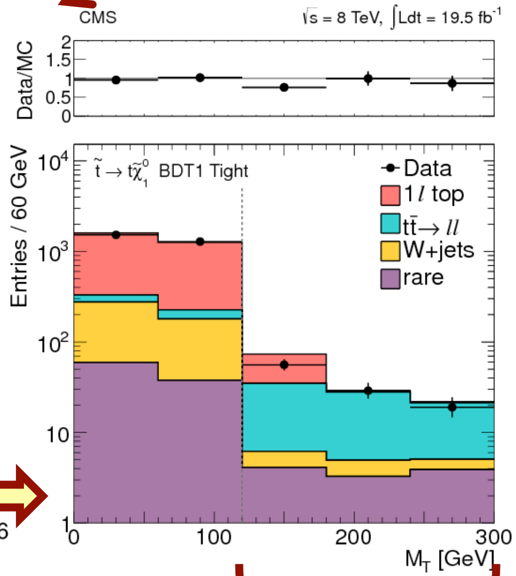
SUS-13-011
EPJC 73 (2013) 2677
arXiv:1308.1586

BDT training regions



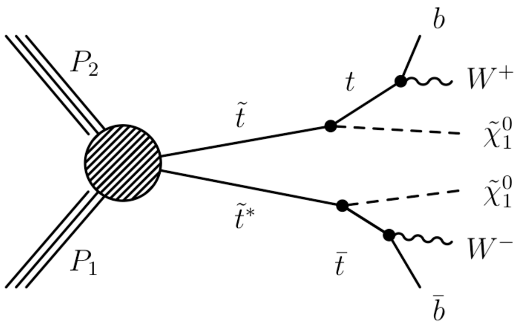



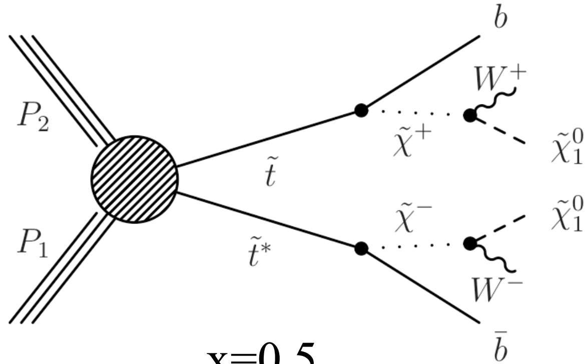

SR

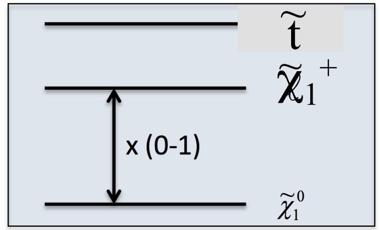
# Single Lepton Stop Search with BDT

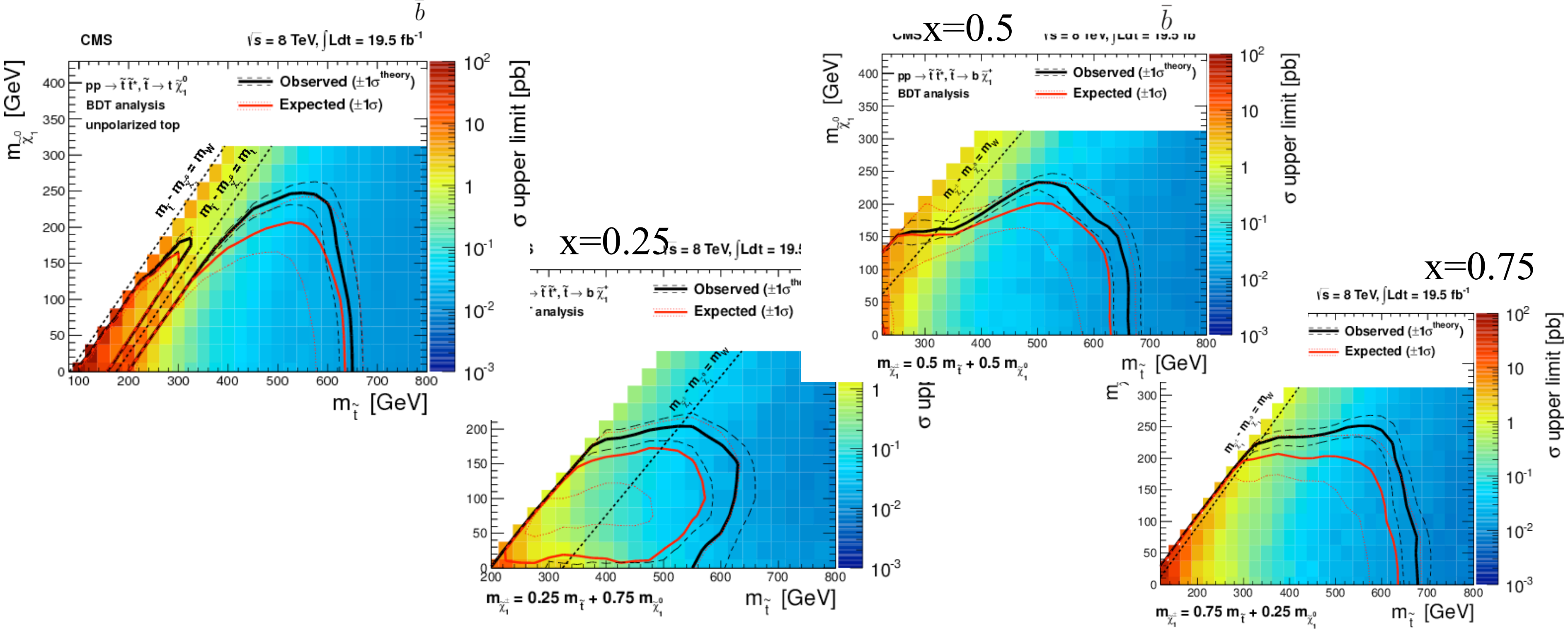
SUS-13-011
EPJC 73 (2013) 2677
arXiv:1308.1586

Results for different simplified models



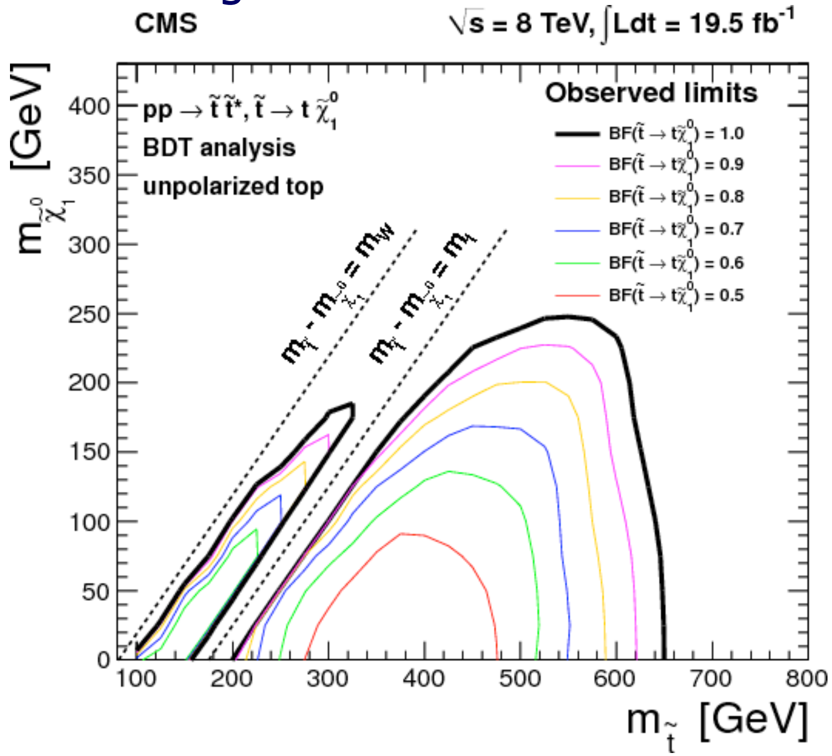



# Search for stop → top neutralino Influence of Branching Ratio

SUS-13-011
EPJC 73 (2013) 2677
arXiv:1308.1586

Considering no acceptance for other decay chains in the investigated channel in case of smaller branching ratio

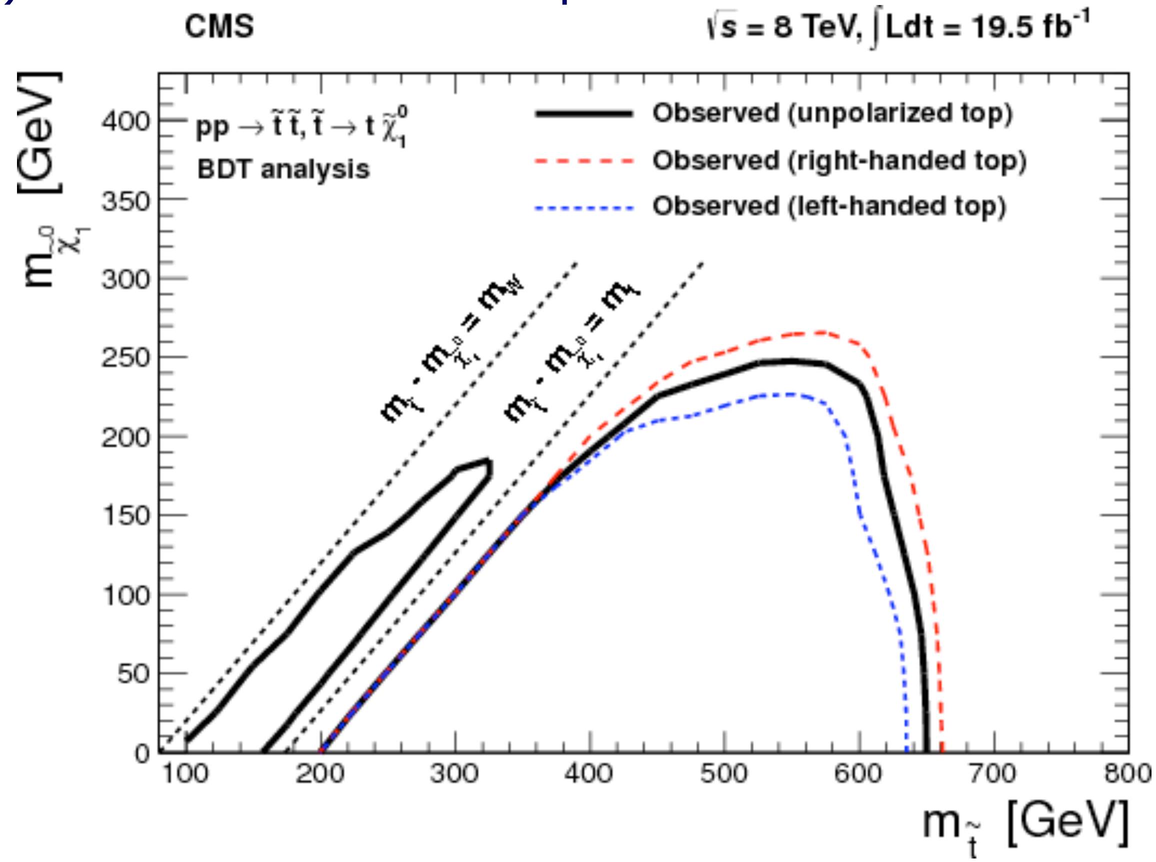



**50% branching ratio reduces discovery range from m(gluino) = [200,750] GeV, m(neutralino) < 250 GeV to m(gluino) = [275,475] GeV, m(neutralino) < 90 GeV**

# Search for stop → top neutralino Influence of Polarization

SUS-13-011
EPJC 73 (2013) 2677
arXiv:1308.1586

Polarization of the top quarks (inherited from left/right mixing of the top squarks) has an influence on acceptance → limit

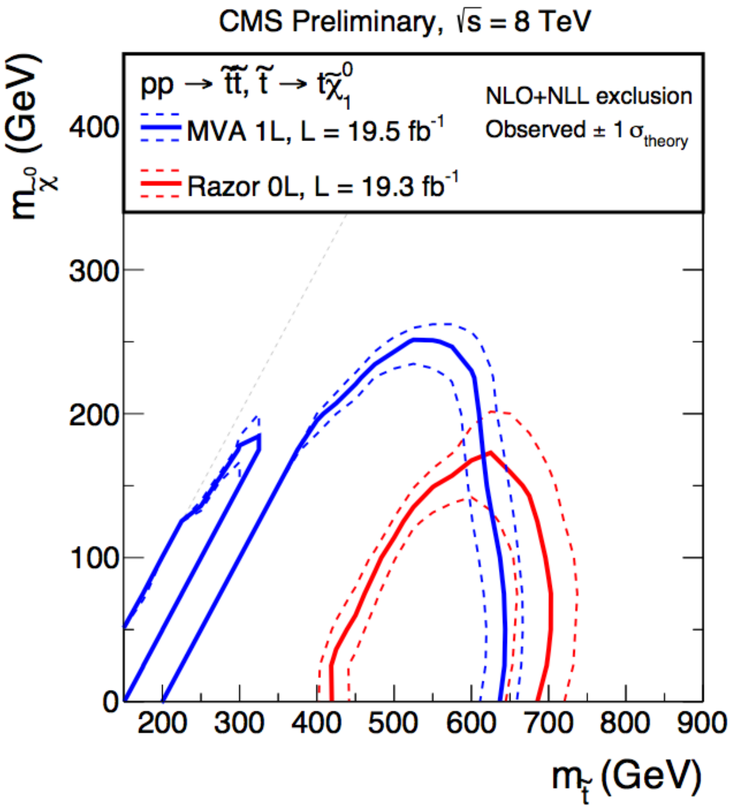



**Gain (loss) of 25 GeV for right (left)-handed top quarks**

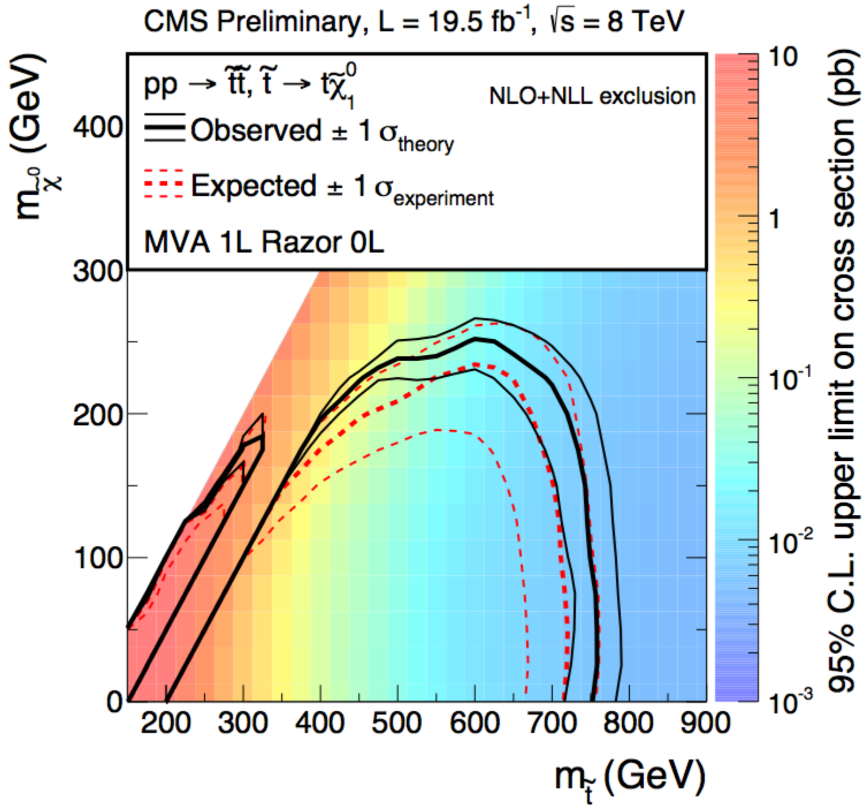
SUS-13-011
SUS-13-004
SUS-14-011

# Search for stop → top neutralino

Single lepton stop search combined with Razor hadronic box



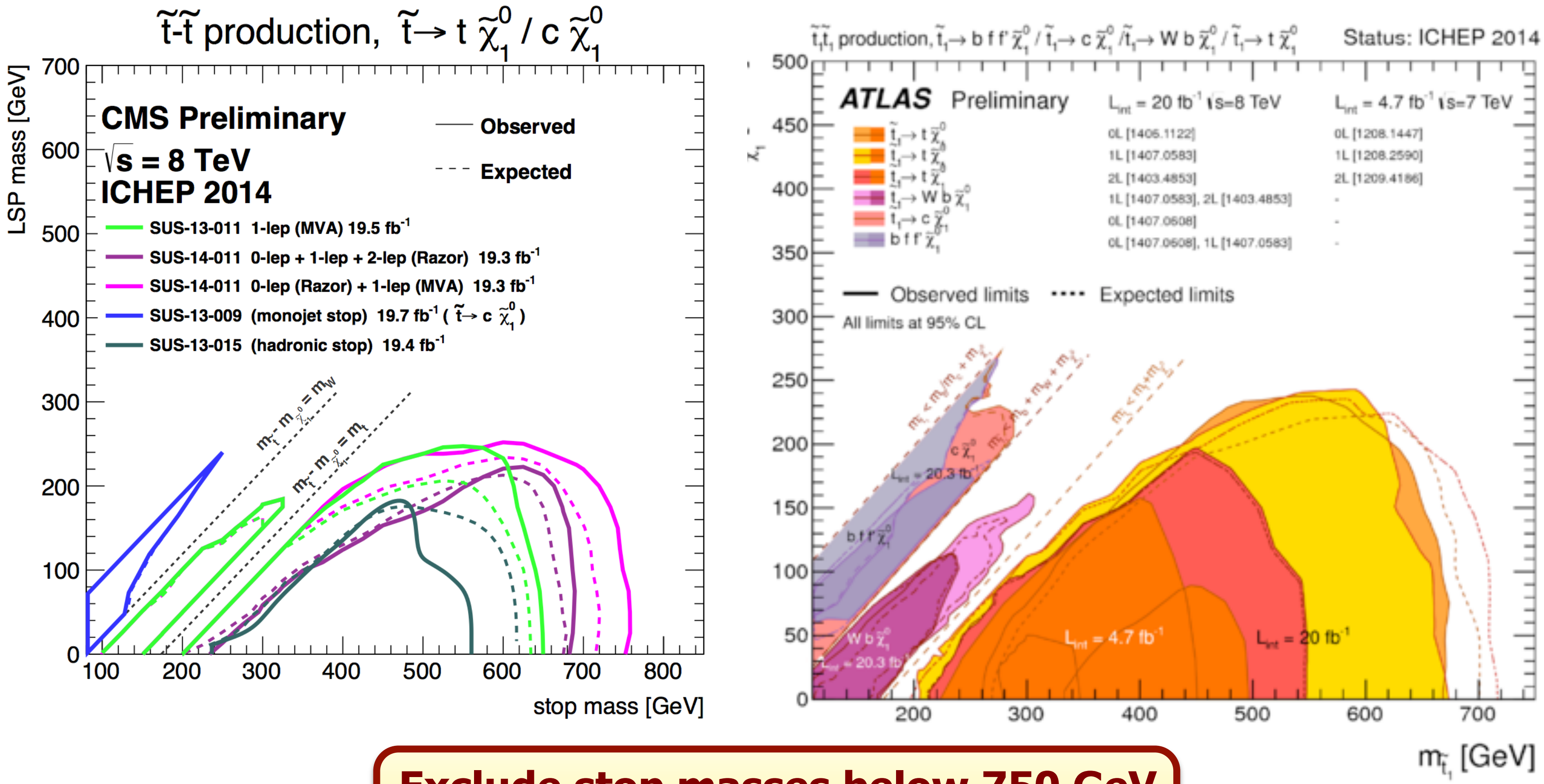

⇒




**Exclude stop masses below 750 GeV**
**No acceptance in stealth region**

# Search for stop - Summary

SMS limits including other decay channels



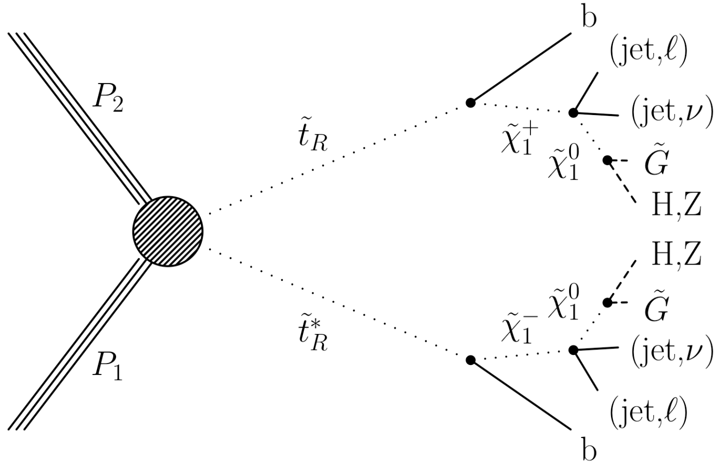

**Exclude stop masses below 750 GeV**
**No acceptance in stealth region**

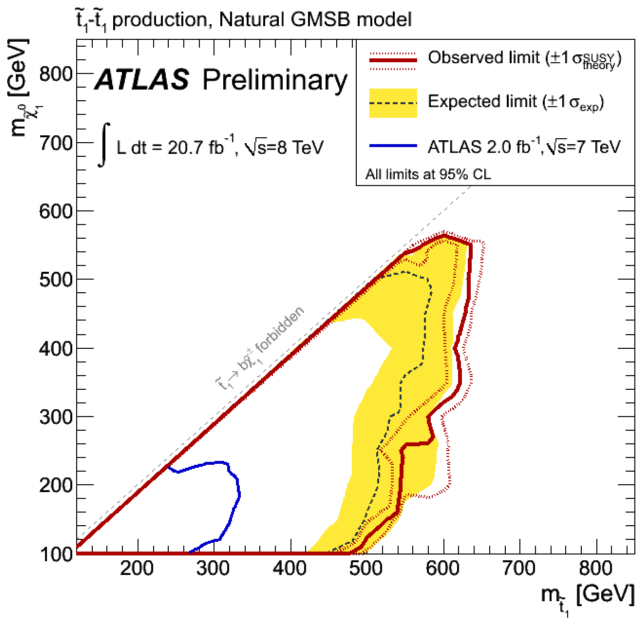
ATLAS-CONF-2013-025
CMS-PAS-SUS-13-002

# Stops in GMSB

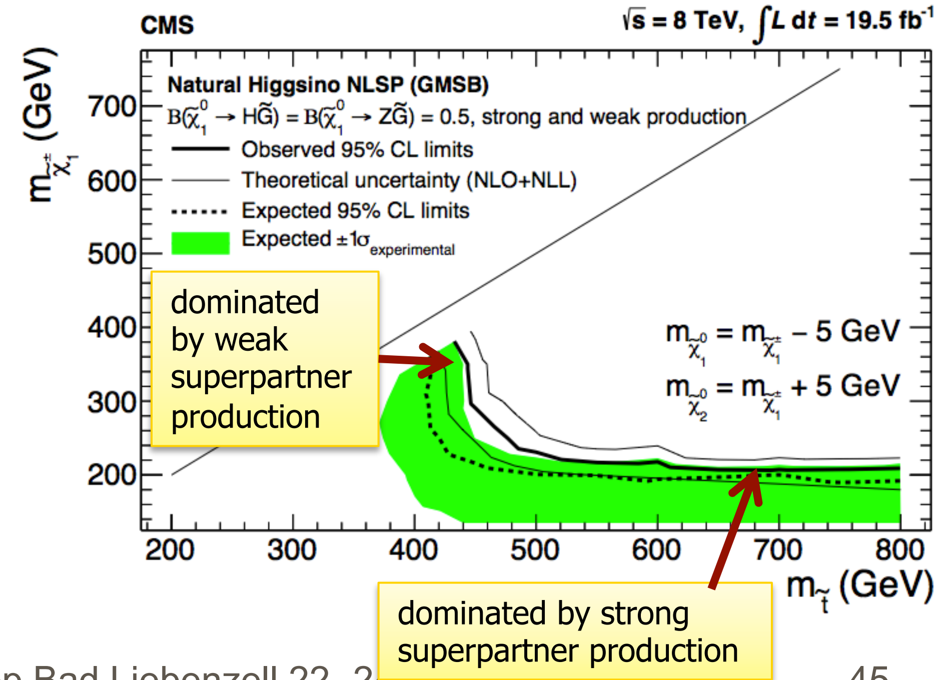
If $\tilde{\chi}_1^0$ NLSP and higgsino-like: decay via Z or h

→ Search for ttZZ/hh or bWZZ/bWhh




ATLAS has stronger limits due to assumption of BR ($\tilde{\chi}_0^1 \to Z\tilde{G}$)=1



## Summary on Stop

Plain vanilla scenarios for 'natural' stop and sbottom almost all excluded

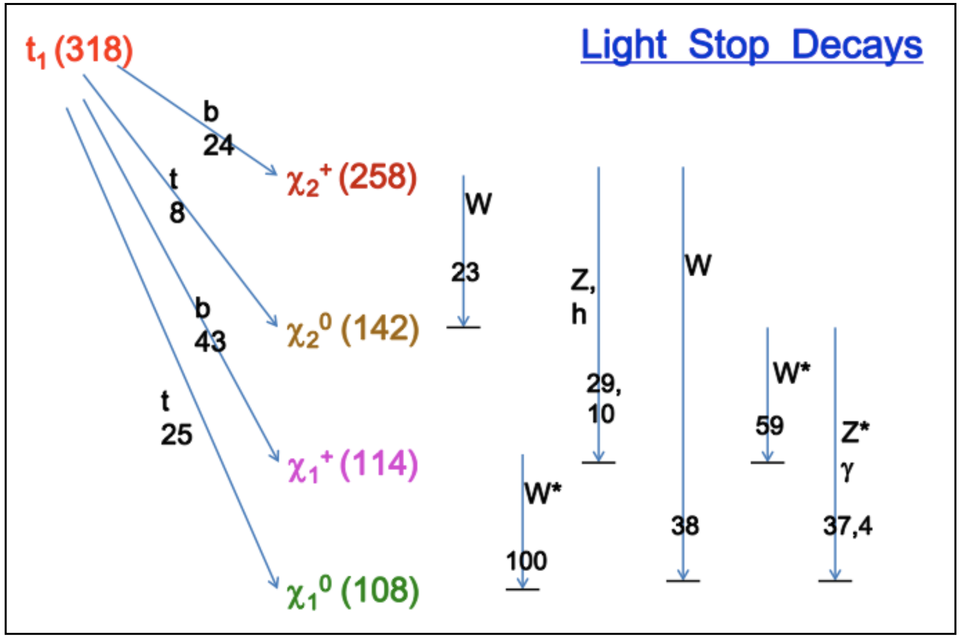
- Second SUSY crisis after no Higgs found at LEP2?
- Generate lots of new ideas to evade these constraints

**Naturalness guide not applicable to Higgs?**

**Higgs mass stabilized by other mechanism?**

**SUSY fine-tuned?**

Clearly the situation can be **more complex and signal may well hide**…



# Recap

Today we discussed:

- Gluinos and 1$^{st}$/2$^{nd}$ generation squarks
- Third-generation squarks

Next:

- Electroweak SUSY sector
- Escape routes:
  - R-parity violation
  - Long-lived particle searches
  - Beyond MSSM signatures
- Outlook