# Supersymmetry Searches in the CMS Experiment

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# Overview

- Simplified Models
- Search for Supersymmetry in the single lepton channel
- Latest Results of CMS Searches
- Plans for 2015
- Conclusions

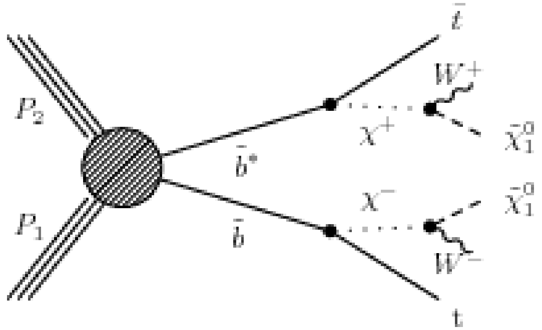
# Simplified Models

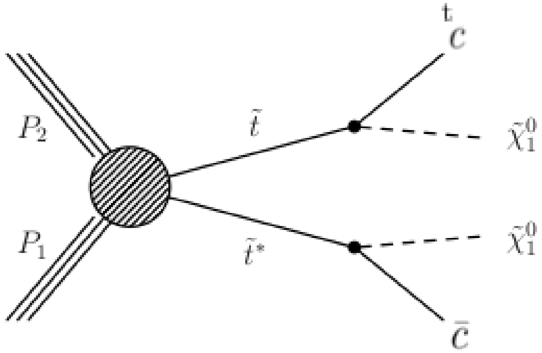
## Simplified Model Spectrums (SMS):

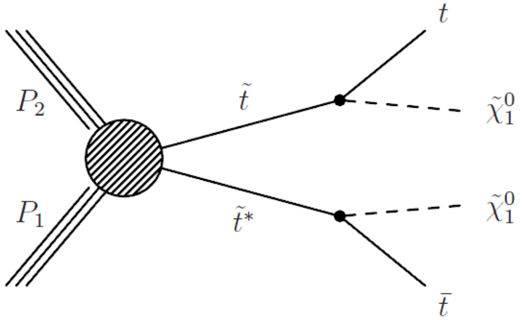
- A simplified model can specify the production and decay of hypothetical particles
- The theoretical predictions of such a model can be compared directly with data
- The simplified model framework can quantify the dependence of an experimental limit on the particle spectrum or a particular sequence of particle production and decay in a manner that is more general than the cMSSM.
- If no excess is found, then for each model a 95% confidence upper limit on the production cross-section is calculated as a function of particle masses

*Source: Phys. Rev. D 88 (2013) 052017*

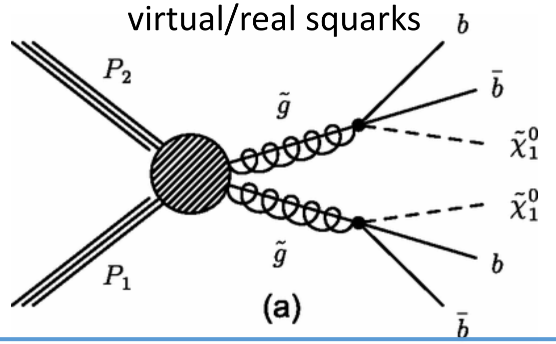
Direct squark pair productions

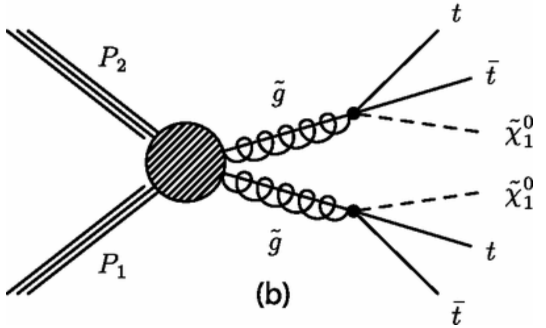


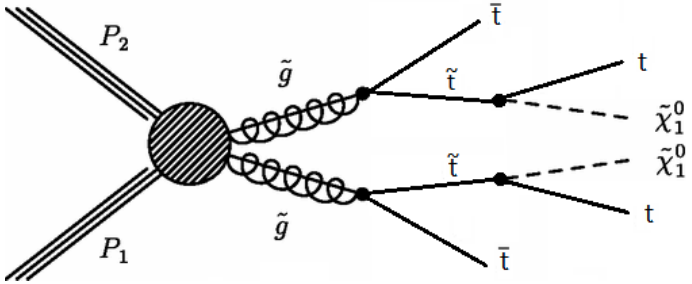




Gluino pair production and decay to virtual/real squarks




Gluino pair production and decay to virtual (off-shell) sbottom/stop

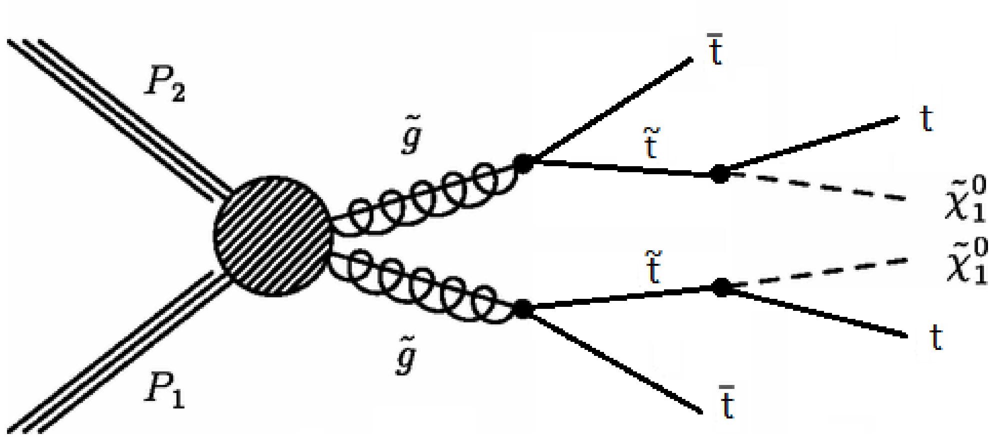



Gluino pair production and decay to on-shell stop

# Event Topology/Selection

Possible SUSY Event topology for $pp \to \tilde{g}\tilde{g}, \tilde{g} \to \tilde{t}\bar{t} \to t\bar{t}\tilde{\chi}_1^0$:

- Missing Transverse Energy (MET)
- Large jet multiplicity
- Lepton(s) coming from the W-decays resulting from decaying tops
  - For this particular model, the four Ws decay to exactly one lepton 40% of the time
- B-tagged jets




Gluino pair production and decay to on-shell stops

Event Selection of the SUSY search we participated in:

- Exactly one isolated lepton - e/μ, with $p_T$ > 10 GeV, |η| < 2.5 (e), 2.4 (μ) veto applied to second leptons
- At least 6 jets
  - At least two of them b-tagged jets
- Large hadronic activity (HT – Scalar sum of Jet $p_T$-s), $H_T$ > 400 GeV

*Source: Physics Letters B 733 (2014) 328-353*

# Background Estimation – LS, MT

## Background composition:

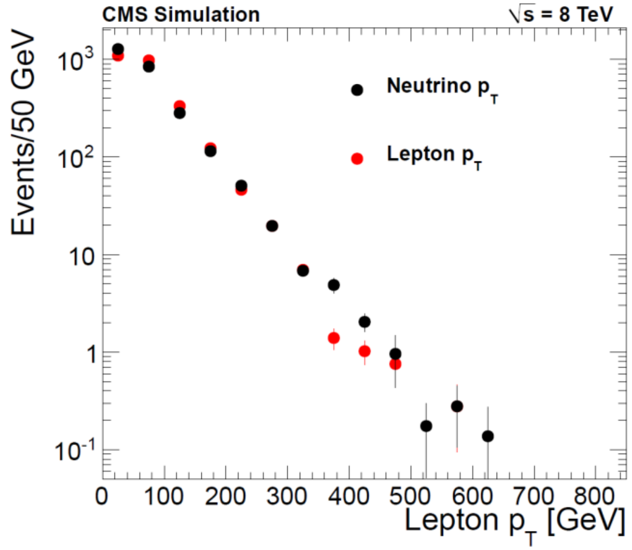
- Top-pair – most dominant bkg, rest of the processes are highly suppressed due to the 6 jet requirement
- Single top
- W + Jets
- Drell-Yan + Jets
- Di-boson

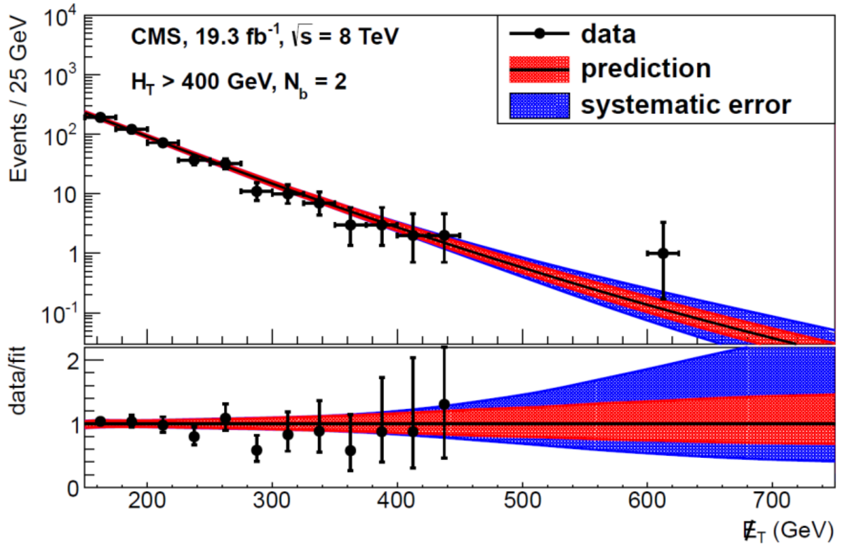
## Estimation Techniques:

- Missing transverse momentum Template (MT) method
  - Fitting a MET model to control regions in data
- Lepton Spectrum (LS) method
  - Uses Lepton $p_T$ spectrum to estimate MET spectrum

→ Estimate the SM backgrounds for events with 2 b-jets, and then extrapolate predictions to ≥3 b-tagged jets

→ Suitable for signals with high MET



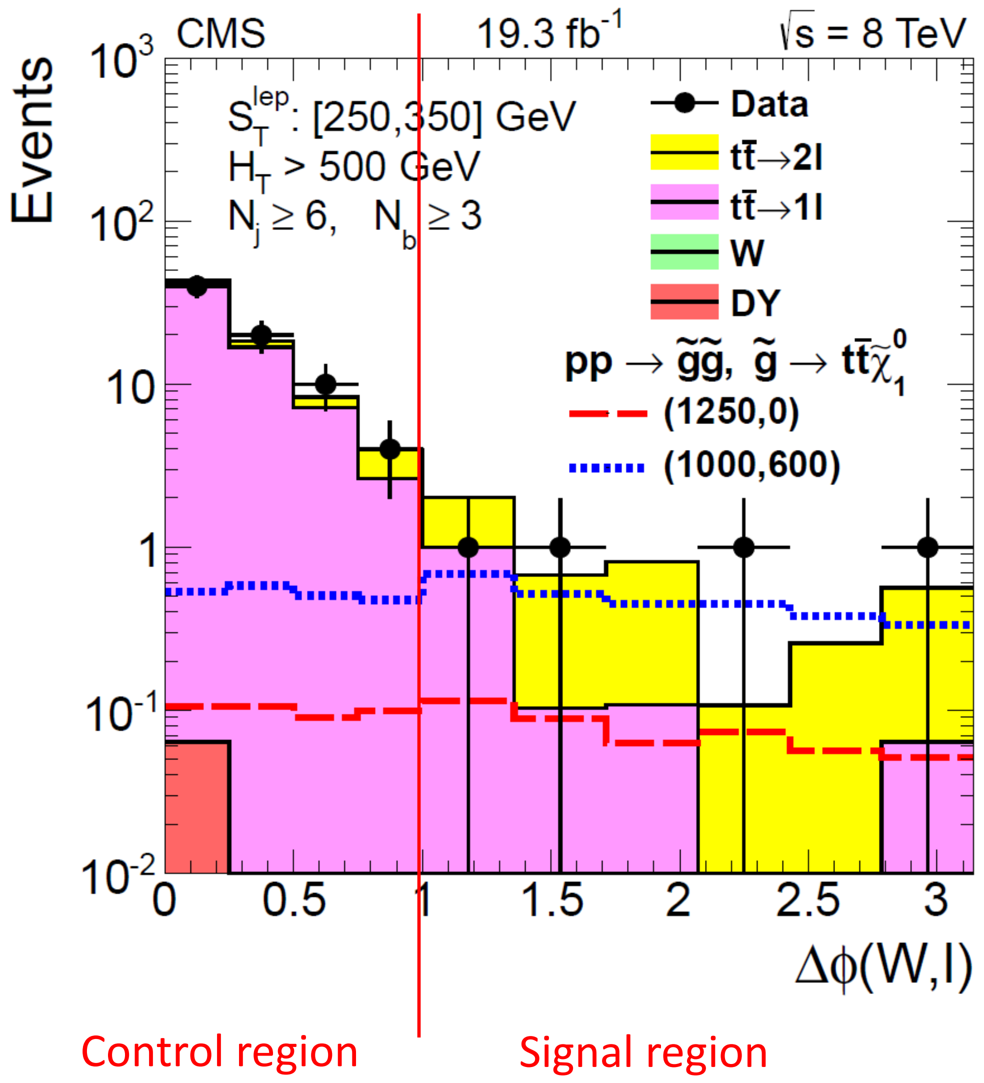
# Background Estimation - DP

## Background composition:

- Top-pair – leading background for dileptonic events, where one lepton is not identified
- Single top
- W + Jets
- Drell-Yan + Jets
- Diboson
- Multijet events

## Estimation Techniques:

- Delta-ϕ (DP) method:
  - Uses the azimuthal angle between the lepton and W boson directions as a discriminating variable
  
  → Strong suppression of single-lepton backgrounds, leaving dilepton ttbar events as the leading SM contribution
  - Search in bins of $S_T^{lep}$: the scalar sum of MET and lepton $p_T$



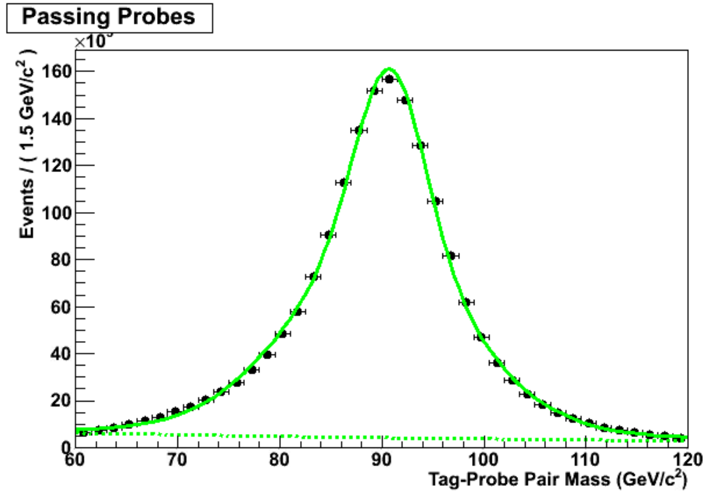
# Evaluation of Systematic Uncertainties

## Sources of Uncertainties:

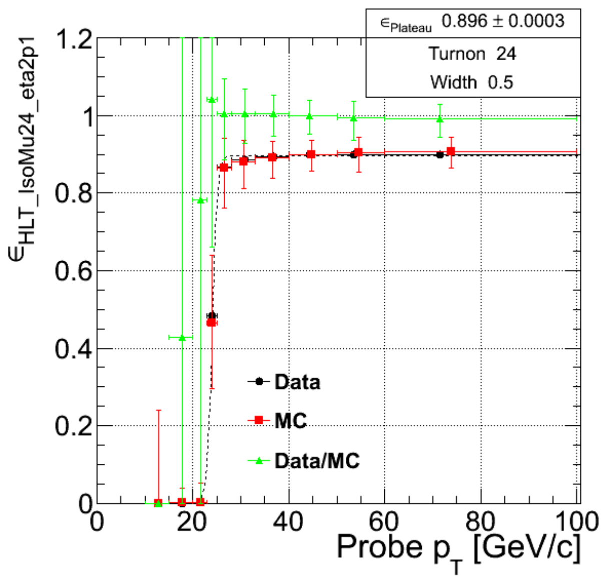
- Jet/MET Energy Scale
- Parton Distribution Functions (PDFs)
- Initial-state radiation
- Pile-up (inelastic proton-proton scatterings present in the same event)
- b-tagging scale factors
- Lepton and trigger efficiencies
  - We measured lepton efficiencies using the Tag-And-Probe method in events with $Z \rightarrow l^+l^-$ decays
  - Measured reconstruction, identification, isolation and trigger efficiencies
  - Mass peak is fitted with a voigtian plus exponential near the Z boson mass for opposite sign lepton pairs
  - After the removal of background the efficiency is the ratio of passing probes to all probes

## Leptonic trigger efficiency with Tag-And-Probe method:

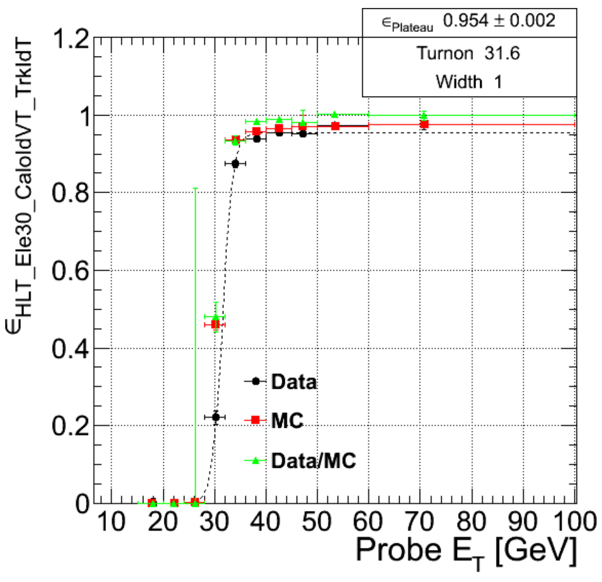
- One of the leptons is required to pass the trigger (Tag), then the efficiency of the other lepton (probe) is measured by checking if it is accepted by the same trigger




Muons




Electrons

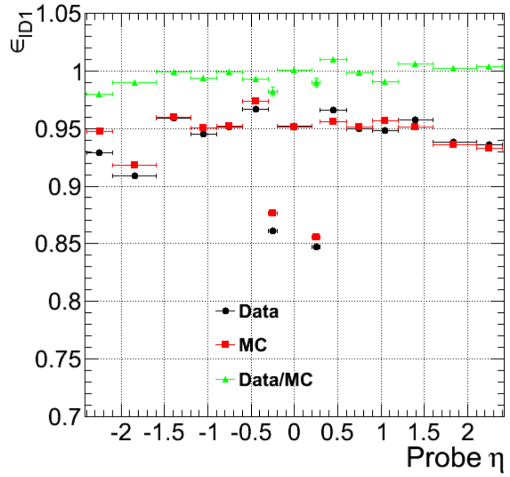


# Lepton efficiencies

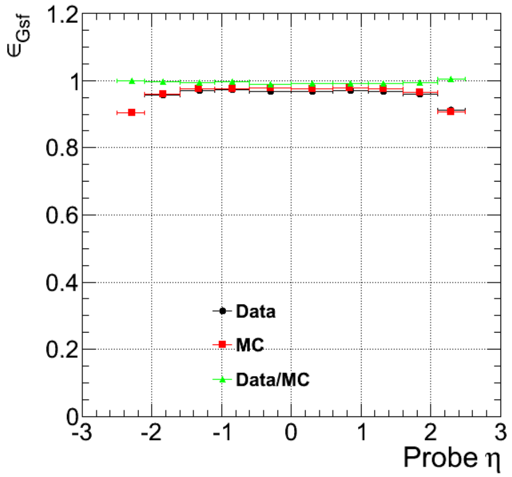
Lepton Efficiencies measurements:

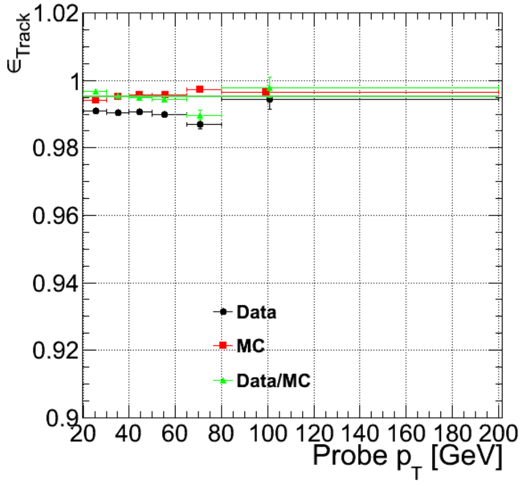
- Muons:
  - Tracking efficiency for muons
  - Muon (ID1) Identification efficiencies
  - Muon Isolation Efficiency (ID2)
- Electrons:
  - Gsf reconstruction efficiency:
    The Gsf algorithm takes into account Bremsstrahlung during the reconstruction of electrons
  - Electron Identification Efficiency (ID)
    - Incorporates isolation efficiency

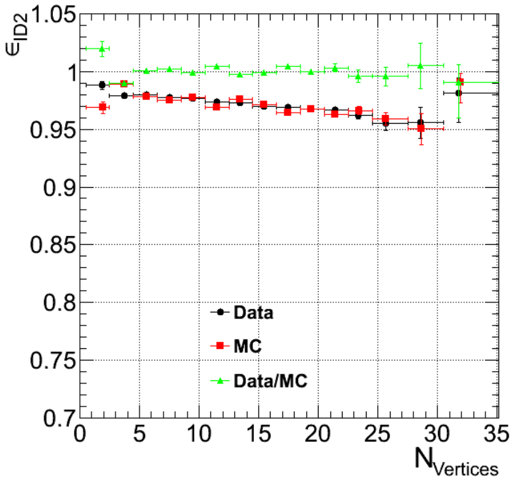
Muons

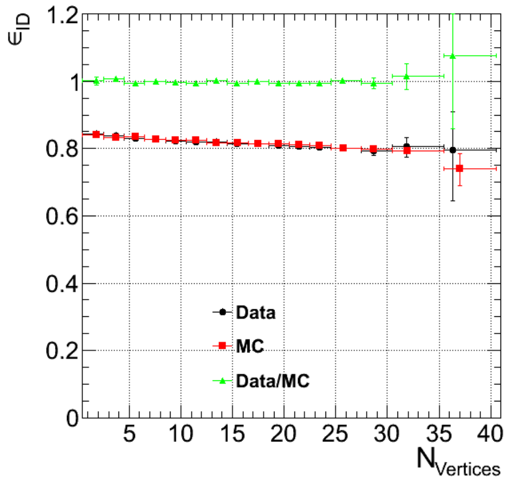



Electrons




*Source: T. Danielson, J. Karancsi,W. Kiesenhofer, V. Veszpremi, "Reconstruction, identification, and trigger efficiencies for SUSY searches in the single lepton channel in 2012", CMS AN AN-13-035*

# Results

No significant excess is seen any of the signal regions

| | | $S_T^{lep}$ [GeV] | $3 \leq N_j \leq 5$ Control | Pred. | Obs. | $N_j \geq 6$ Control | Pred. | Obs. |
|---|---|---|---|---|---|---|---|---|
| $N_b = 2$ | e | [250, 350] | 548 | 34.2±5.4 | 30 | 112 | 3.8±1.8±0.6 | 9 |
| | | [350, 450] | 174 | 5.1±1.9 | 8 | 28 | 2.7±1.9±0.8 | 2 |
| | | >450 | 61 | 5.6±2.1 | 1 | 9 | 0.0±0.4±0.2 | 0 |
| | $\mu$ | [250, 350] | 632 | 41.9±5.6 | 59 | 141 | 6.0±2.2±0.9 | 9 |
| | | [350, 450] | 188 | 8.5±2.4 | 11 | 24 | 1.4±1.1±0.4 | 2 |
| | | >450 | 71 | 2.5±1.3 | 1 | 9 | 0.0±0.7±0.2 | 0 |
| $N_b \geq 3$ | e | [250, 350] | 70 | 3.9±0.9 | 2 | 45 | 1.9±0.9±0.4 | 4 |
| | | [350, 450] | 12 | 0.3±0.2 | 2 | 7 | 0.9±0.7±0.4 | 0 |
| | | >450 | 4 | 0.3±0.2 | 0 | 0 | 0.0±0.1±0.03 | 0 |
| | $\mu$ | [250, 350] | 59 | 3.9±0.8 | 5 | 28 | 1.9±0.8±0.4 | 0 |
| | | [350, 450] | 25 | 1.1±0.4 | 0 | 13 | 0.6±0.5±0.3 | 0 |
| | | >450 | 7 | 0.3±0.2 | 0 | 2 | 0.0±0.2± 0.1 | 0 |

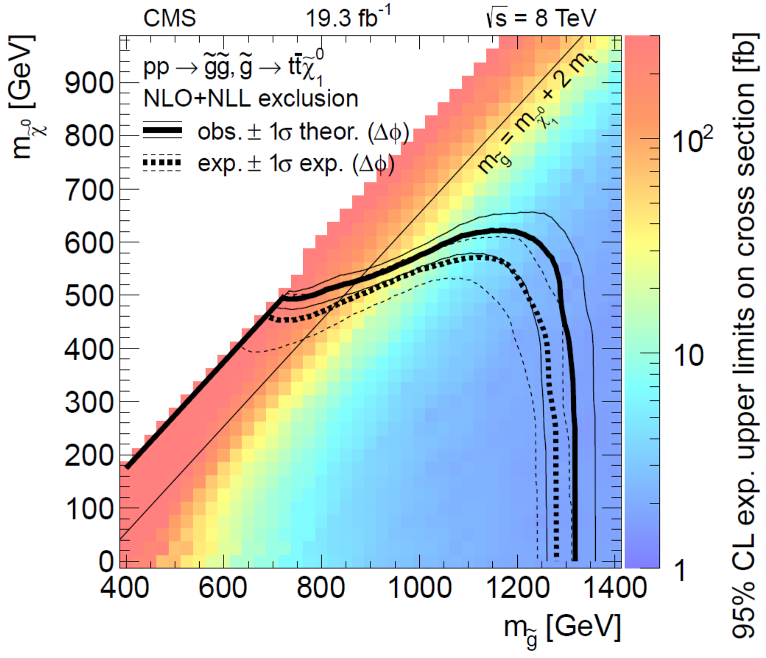
| | $N_b = 2$ Obs. | | Pred. | ± stat. | ± syst. | $N_b \geq 3$ Obs. | | Pred. | ± stat. | ± syst. |
|---|---|---|---|---|---|---|---|---|---|---|
| **$H_T > 400$ GeV** | | | | | | | | | | |
| $150 < \not{E}_T < 250$ GeV | | | | | | 94 | MT | 92 | ± 5 | ± 14 |
| $250 < \not{E}_T < 350$ GeV | | | | | | 16 | MT | 14.5 | ± 1.3 | ± 2.5 |
| $350 < \not{E}_T < 450$ GeV | | | | | | 2 | MT | 2.6 | ± 0.4 | ± 0.7 |
| $\not{E}_T > 450$ GeV | | | | | | 0 | MT | 0.8 | ± 0.2 | ± 0.4 |
| **$H_T > 500$ GeV** | | | | | | | | | | |
| $150 < \not{E}_T < 250$ GeV | 350 | LS | 320 | ± 16 | ± 14 | 84 | LS | 71.1 | ± 3.5 | ± 6.5 |
| $250 < \not{E}_T < 350$ GeV | 55 | LS | 58.1 | ± 7.2 | ± 5.3 | 16 | LS | 12.4 | ± 1.6 | ± 1.5 |
| $350 < \not{E}_T < 450$ GeV | 10 | LS | 15.4 | ± 4.3 | ± 3.1 | 2 | LS | 3.1 | ± 0.9 | ± 0.7 |
| $\not{E}_T > 450$ GeV | 1 | LS | 0.7 | $^{+2.3}_{-0.6}$ | $^{+2.0}_{-0.2}$ | 0 | LS | 0.1 | $^{+0.5}_{-0.0}$ | $^{+0.4}_{-0.0}$ |
| **$H_T > 750$ GeV** | | | | | | | | | | |
| $150 < \not{E}_T < 250$ GeV | 141 | LS | 114.8 | ± 9.4 | ± 6.9 | 37 | LS | 25.9 | ± 2.1 | ± 2.5 |
| | | | | | | | MT | 31.8 | ± 2.7 | ± 4.8 |
| $250 < \not{E}_T < 350$ GeV | 26 | LS | 26.3 | ± 4.9 | ± 2.9 | 12 | LS | 5.9 | ± 1.1 | ± 0.8 |
| | | MT | 37.9 | ± 4.0 | ± 3.5 | | MT | 8.5 | ± 0.9 | ± 1.6 |
| $350 < \not{E}_T < 450$ GeV | 9 | LS | 10.6 | $^{+3.8}_{-3.7}$ | ± 2.4 | 2 | LS | 2.1 | ± 0.7 | ± 0.5 |
| | | MT | 9.4 | ± 1.4 | ± 2.7 | | MT | 1.9 | ± 0.3 | ± 0.6 |
| $\not{E}_T > 450$ GeV | 1 | LS | 0.6 | $^{+3.0}_{-0.2}$ | $^{+1.9}_{-0.2}$ | 0 | LS | 0.0 | $^{+0.7}_{-0.0}$ | $^{+0.4}_{-0.0}$ |
| | | MT | 3.1 | ± 0.7 | ± 1.5 | | MT | 0.7 | ± 0.2 | ± 0.4 |
| **$H_T > 1000$ GeV** | | | | | | | | | | |
| $150 < \not{E}_T < 250$ GeV | 46 | LS | 43.2 | ± 6.1 | ± 3.7 | 14 | LS | 10.4 | ± 1.5 | ± 1.2 |
| | | | | | | | MT | 11.1 | ± 1.6 | ± 1.8 |
| $250 < \not{E}_T < 350$ GeV | 11 | LS | 9.9 | ± 3.1 | ± 1.7 | 4 | LS | 2.4 | ± 0.7 | ± 0.5 |
| | | MT | 15.1 | ± 2.5 | ± 1.9 | | MT | 3.6 | ± 0.6 | ± 0.8 |
| $350 < \not{E}_T < 450$ GeV | 4 | LS | 2.2 | $^{+2.3}_{-1.6}$ | $^{+2.2}_{-0.7}$ | 1 | LS | 0.4 | $^{+0.5}_{-0.3}$ | $^{+0.4}_{-0.2}$ |
| | | MT | 4.7 | ± 0.9 | ± 1.5 | | MT | 0.9 | ± 0.2 | ± 0.4 |
| $\not{E}_T > 450$ GeV | 1 | LS | 0.1 | $^{+2.2}_{-0.1}$ | $^{+3.5}_{-0.1}$ | 0 | LS | 0.0 | $^{+0.4}_{-0.0}$ | $^{+0.7}_{-0.0}$ |
| | | MT | 2.0 | ± 0.5 | ± 1.1 | | MT | 0.5 | ± 0.1 | ± 0.3 |

# Results – Exclusion limits

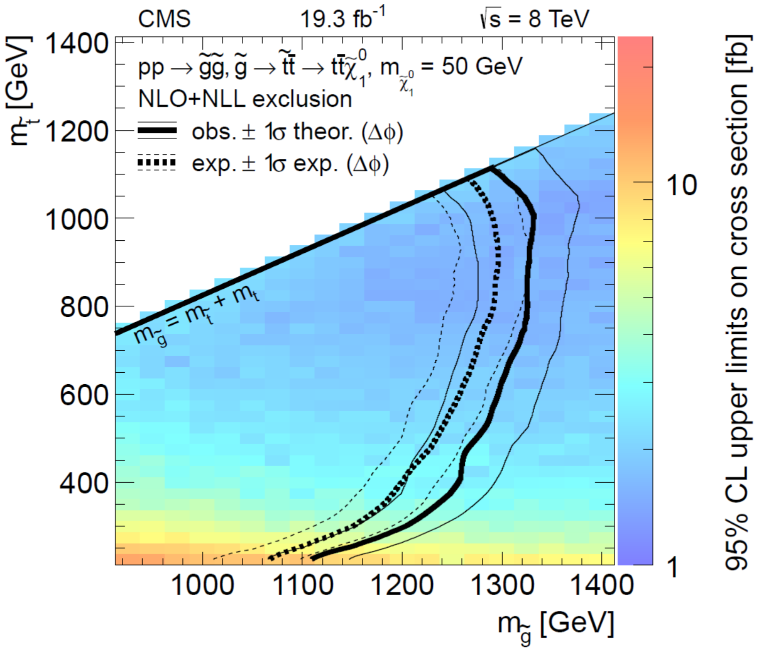
## Interpretation of results:

- Upper limits are set at 95% CL on the product of production cross section and branching fraction
- Three benchmark models of gluino pair production are considered:
  - Gluino decaying into virtual or on-shell stops
  - Each of the two stops decays into a top quark and the lightest supersymmetric particle (LSP)

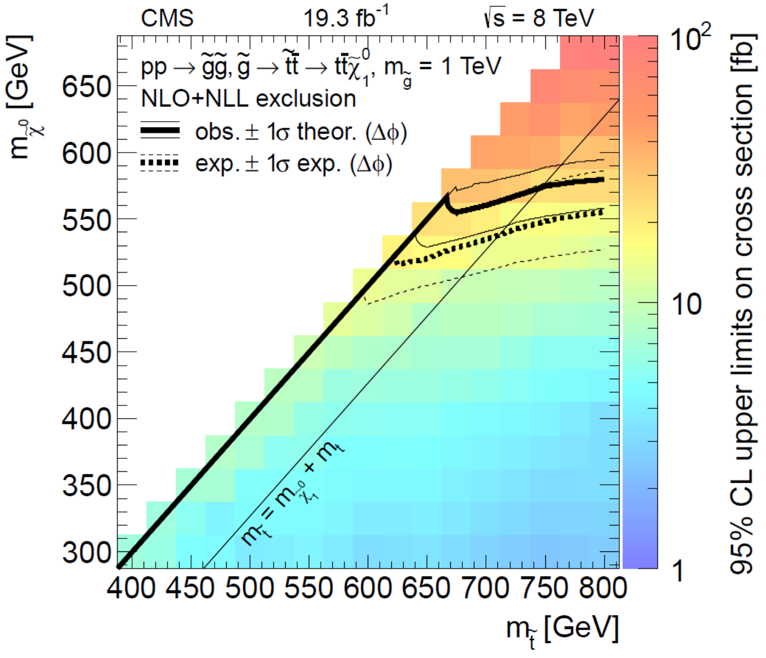
### Virtual stop




### On-shell stop, light LSP




### On-shell stop, 1TeV gluino



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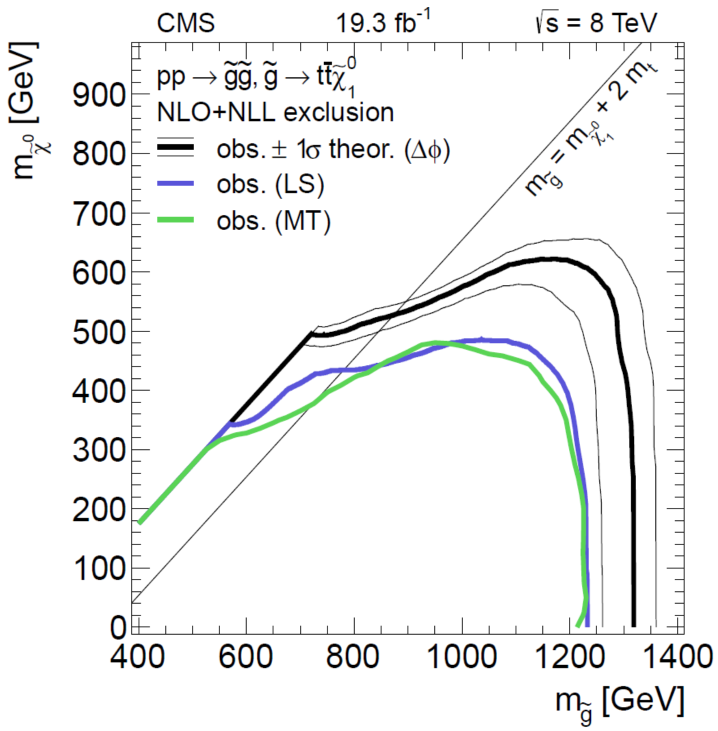
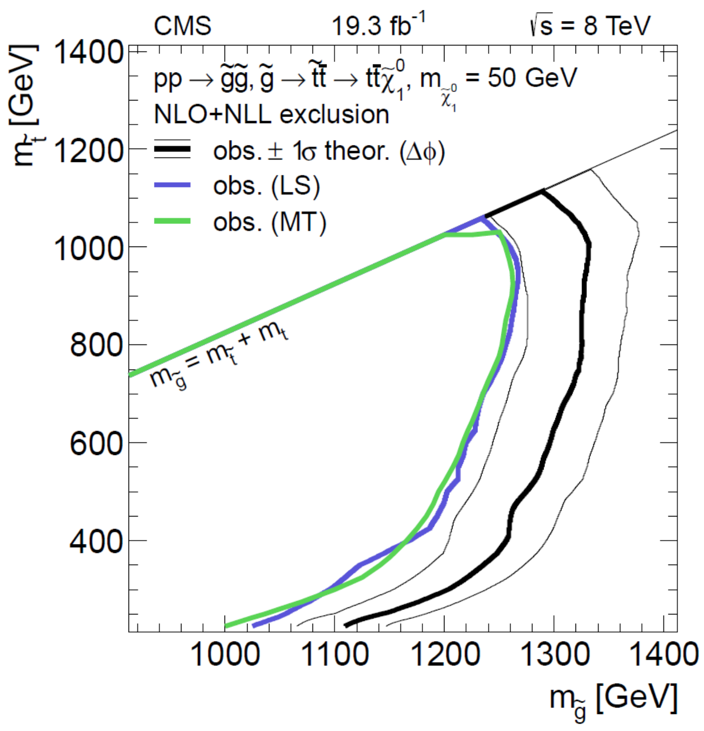
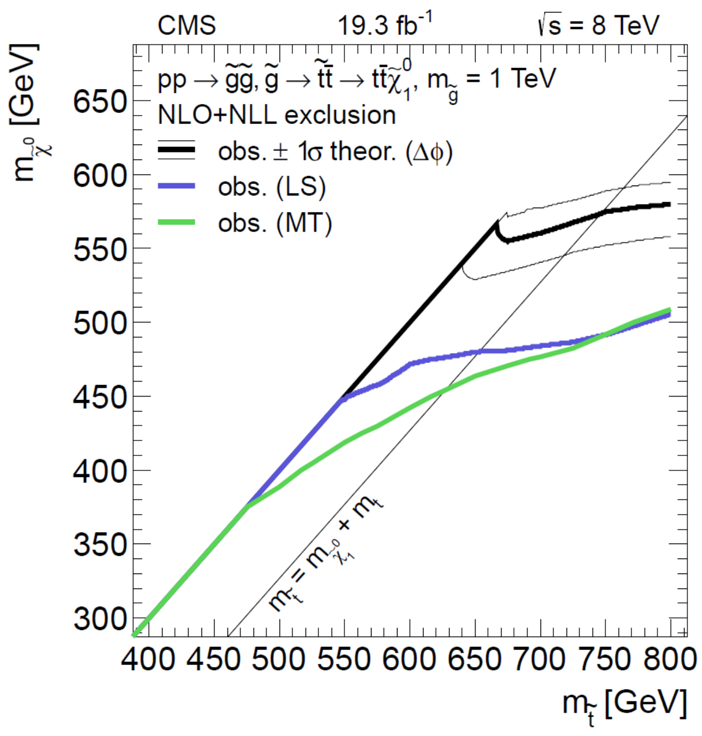
Virtual stop




On-shell stop, light LSP



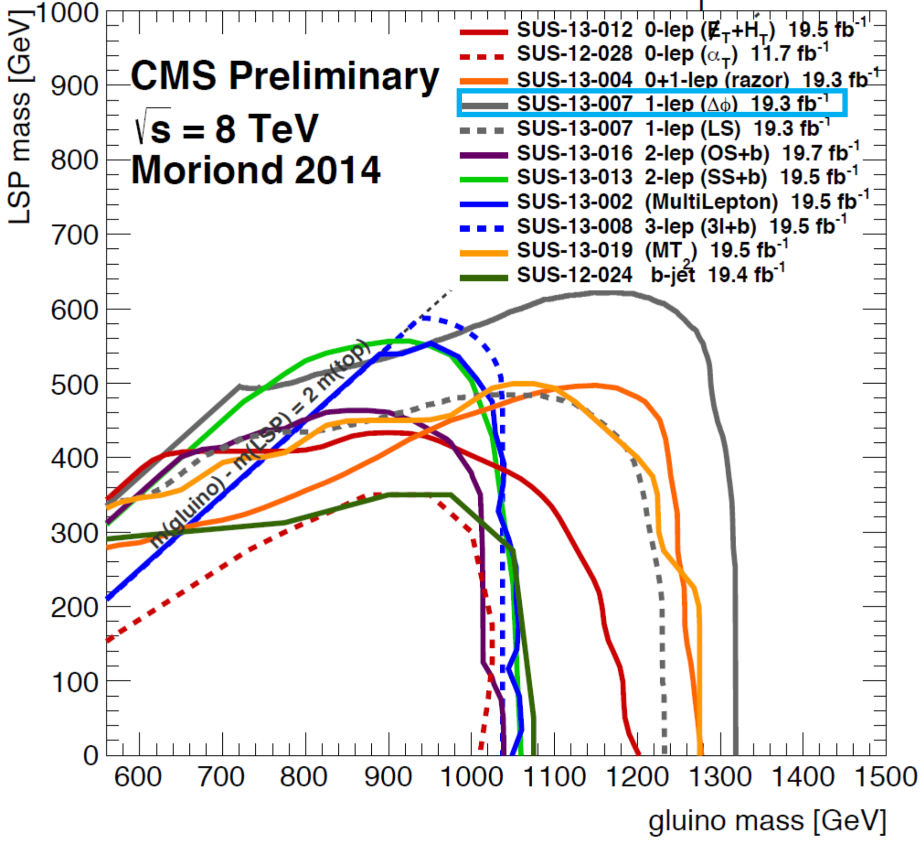

On-shell stop, 1TeV gluino



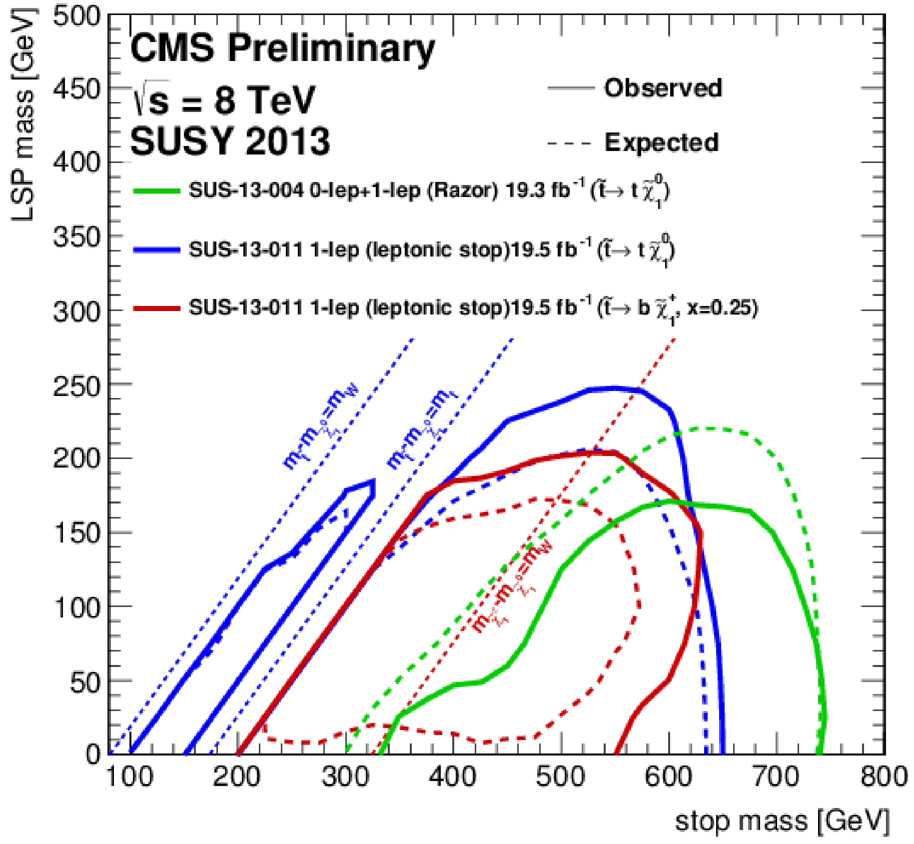
# CMS SUSY Results

- The Single lepton channel with the Δϕ method gave the best sensitivity and the most stringent exclusion limits for the $pp \to \tilde{g}\tilde{g}, \tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ model
- Gluino decays via virtual stops and for light LSPs, gluino masses below 1.26 TeV are excluded

$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \to t\,\bar{t}\,\tilde{\chi}_1^0$




$\tilde{t}$-$\tilde{t}$ production



gluino

squark

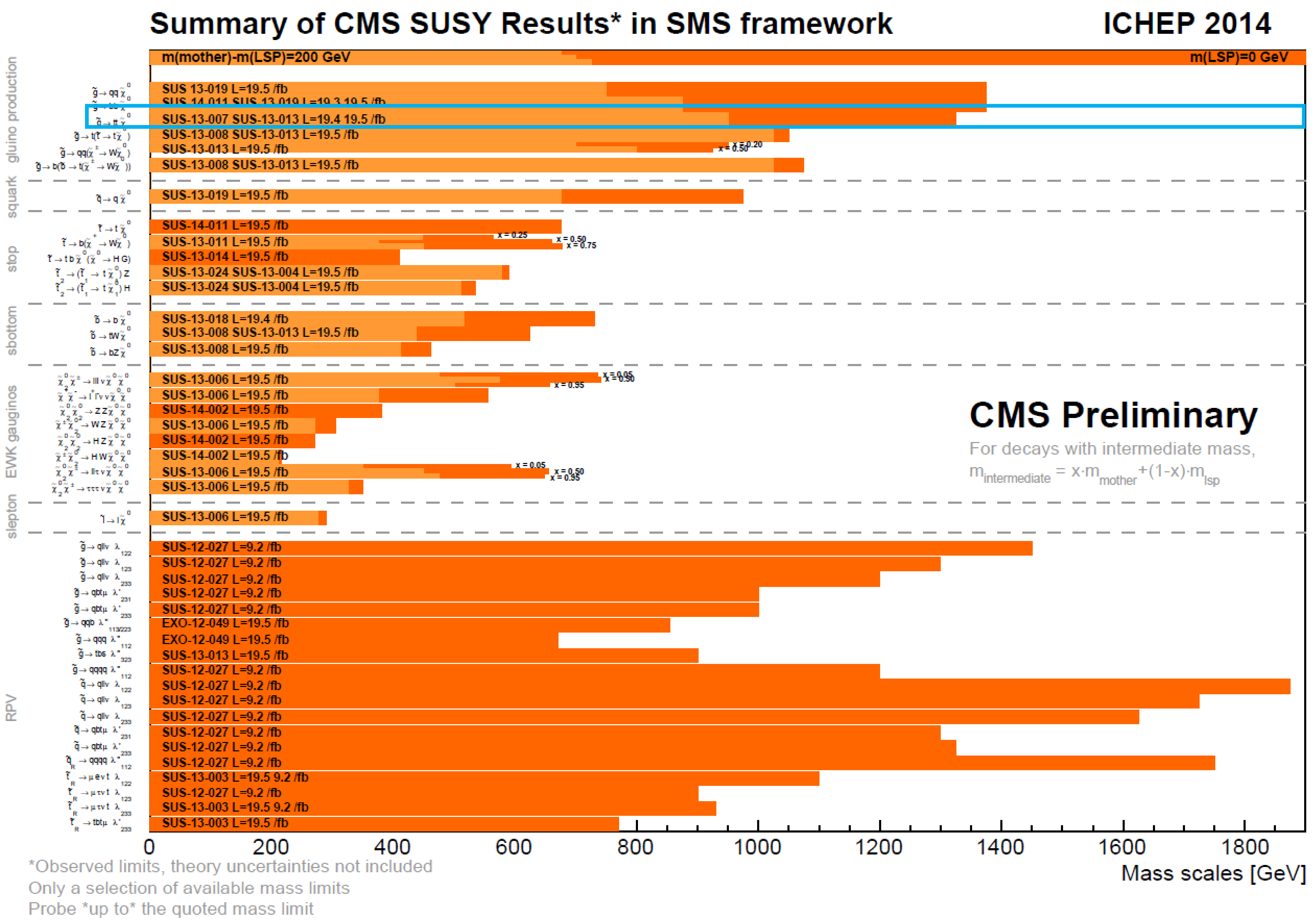
stop

sbottom

EWK gaugino

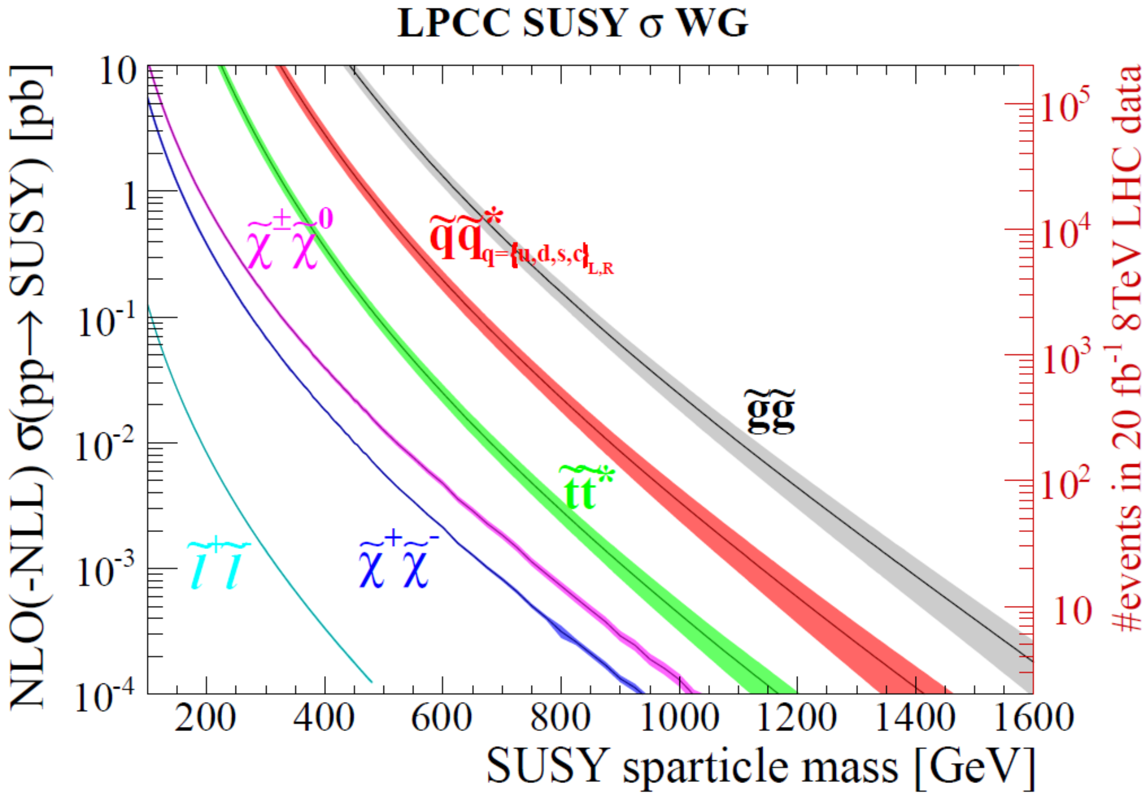
slepton

RPV models

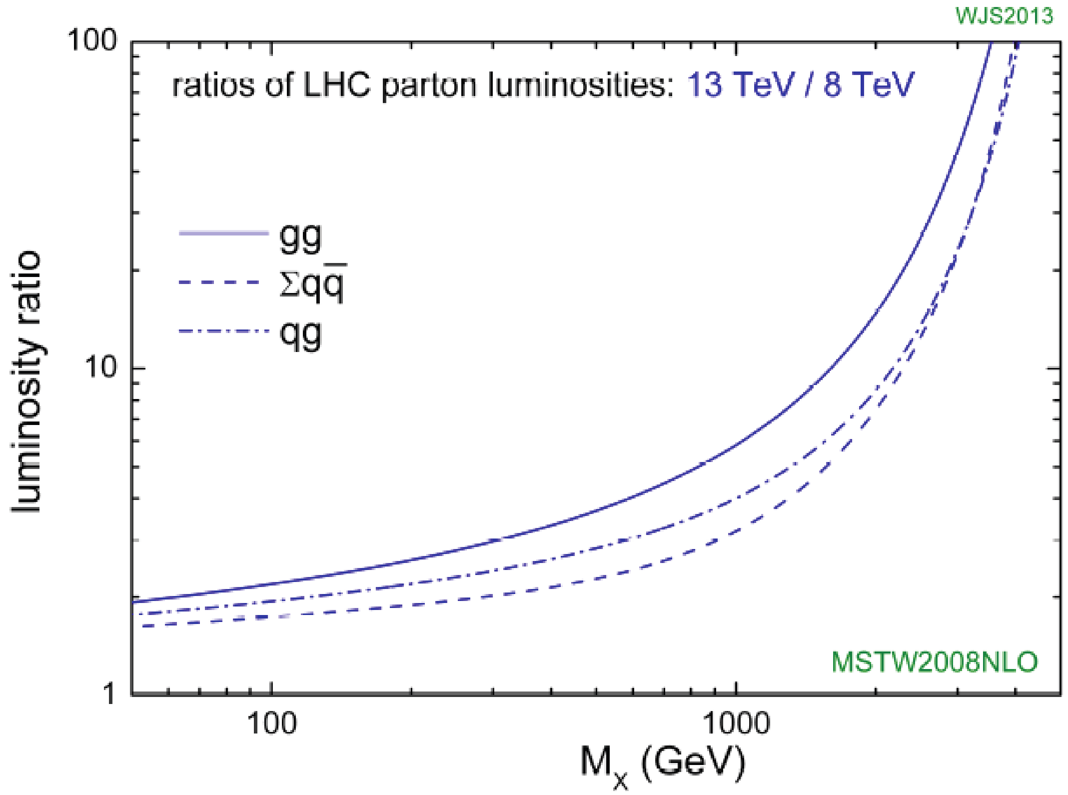


# Plans for 2015

- Cross sections increase by a factor of ~30 for 1.35 TeV gluino, and by a factor of ~9 for a 750 GeV squark
  - Around 1 (or 3) $fb^{-1}$ of data surpasses our best gluino (sbottom/stop) limits
  - Early gluino searches will benefit more from the relative increase in cross section
- Higher energy may give rise to unseen physicsal phenomena




https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections arXiv:1206.2892




*Source: J. Stirling, http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html*

# Conclusions

- Simplified models proved to be very useful for analyses
  - They are  more general than constrained SUSY models
  - There are many directions one can go
- In the single lepton channel, no significant excess was seen in the 8TeV data
- Clever choice of a discriminator to reduce background contributions proved to give very good sensitivities
- In 2015, increased cross-sections on 13TeV Energy give an opportunity:
  - to reach and go beyond current limits
  - possibly to explore new physics in uncharted territories

# Conclusions

Thank you for your attention!