CMS Results on SUSY

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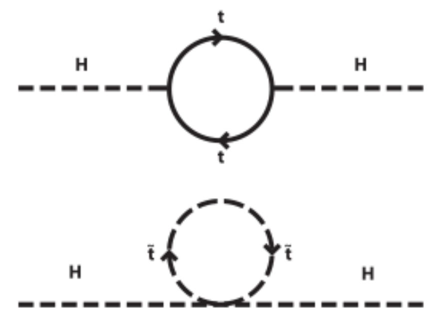
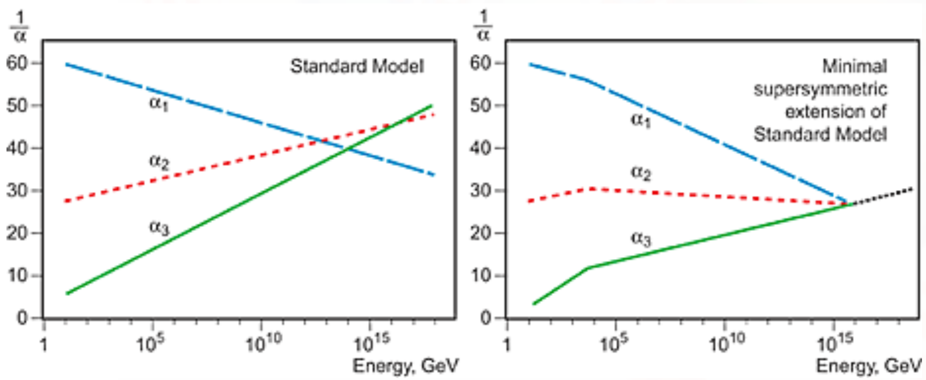
Motivation for Supersymmtery (SUSY)

Solution to hierarchy problem

- Resolves the hierarchy problem of the SM by stabilizing the Higgs boson mass via additional quantum loop corrections from the top super-partner (top squark),which compensate the correction due to the top quark





Unification of Gauge Couplings

- SUSY particles modify running coupling constant and ensure unification of gauge couplings (unification of the electroweak and strong forces at high energies)

Dark Matter in the Universe

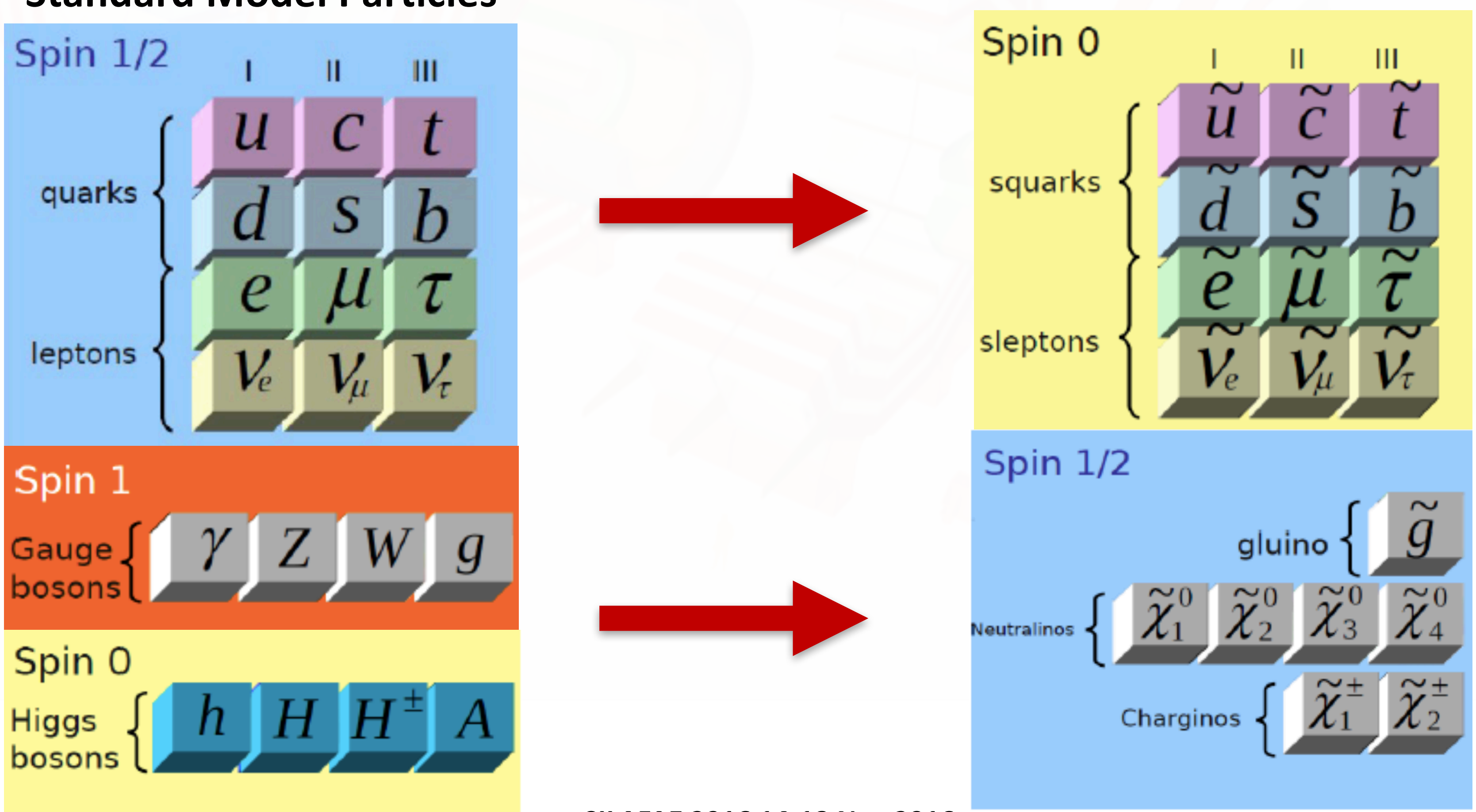
- If R-parity is conserved the lightest state predicted by the theory is stable and potentially massive, providing a candidate for dark matter.– a stable neutral particle

SUSY particle spectrum

- **SUSY is a symmetry between fermions and bosons**
- **To make the SM Lagrangian supersymmetric requires each bosonic particle to have a fermionic superpartner and vice-versa**

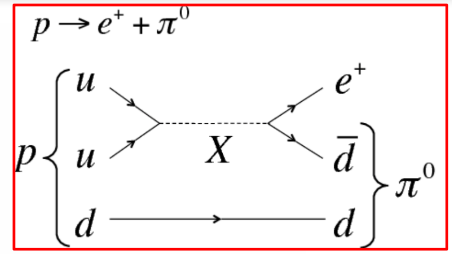
Standard Model Particles

Supersymmetric Particles

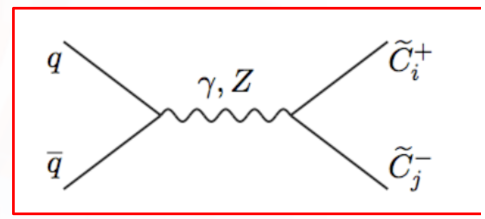


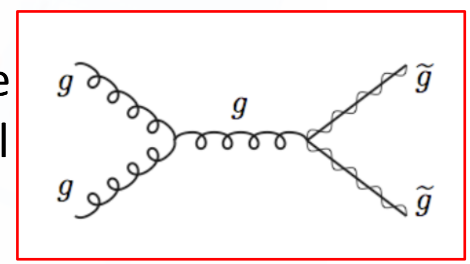
About SUSY

- SUSY allows for proton decay to occur and the lifetime is predicted to be very short
- BUT proton decay experiments have established proton life to be
  > 1.6 x 10 ^{33} years
- A new discrete symmetry called R-parity conservation is invoked to deal with proton long life time
  - All SM particles have even R-parity (R = 1)
  - All SUSY particles have odd R-parity (R= -1)
  - Protons can not decay in R-parity conserving SUSY models
- A consequence of R-parity conservation is that the Lightest Supersymmetric Particle (LSP) is stable (its decay would be R-parity violating)
- The LSP would thus make a very good dark matter candidate if it is neutral and non-strongly interacting, many models are popular in which the LSP is the lightest neutralino
- SUSY particles are produced they always cascade down to the massive but stable LSP (which shows up only as missing energy – the canonical SUSY signature)
- Can only produce (or annihilate) SUSY particle pairwise
- No evidence yet of SUSY since it was proposed ~ 40 years

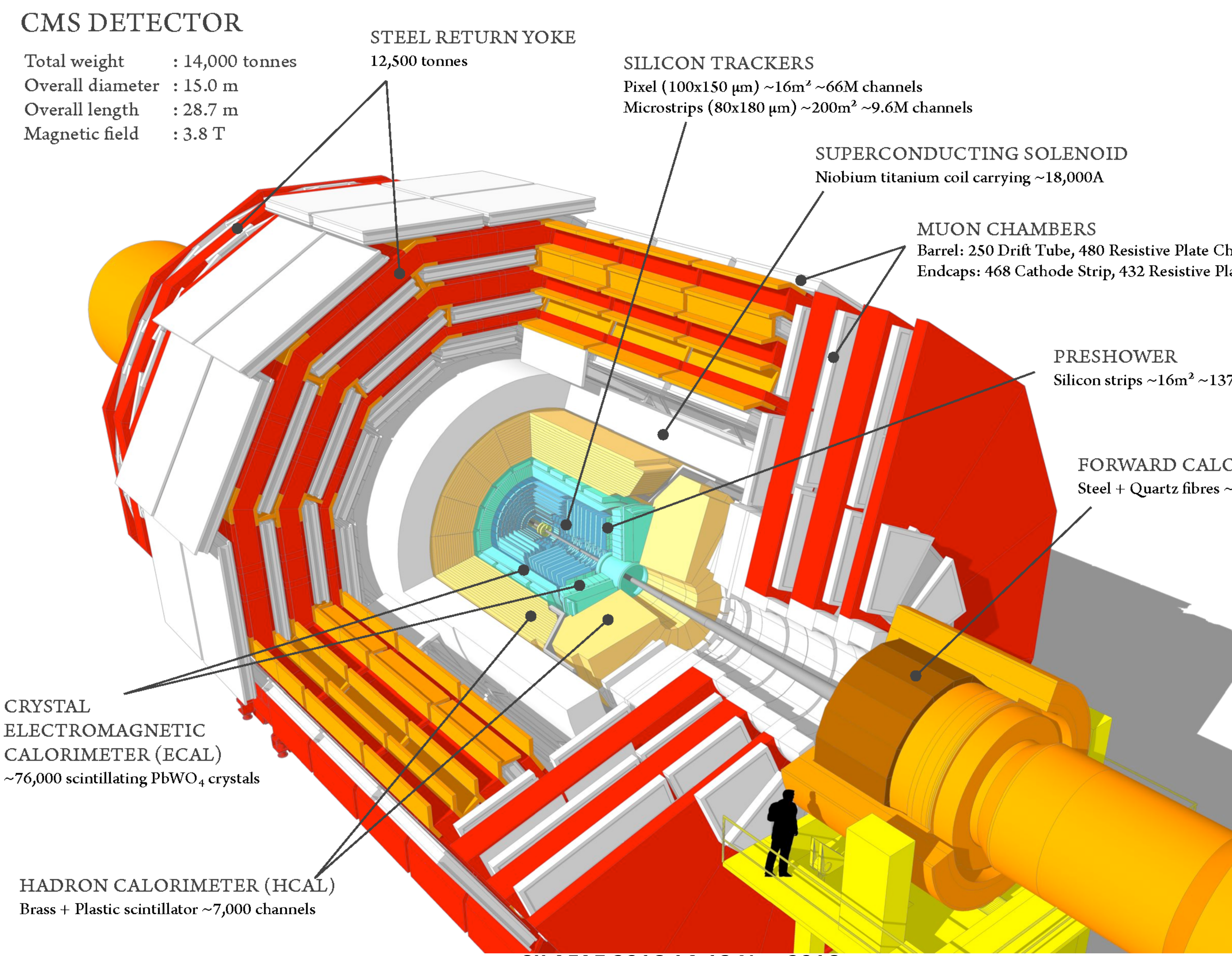


$$R = (-1)^{2S+3B+L}$$

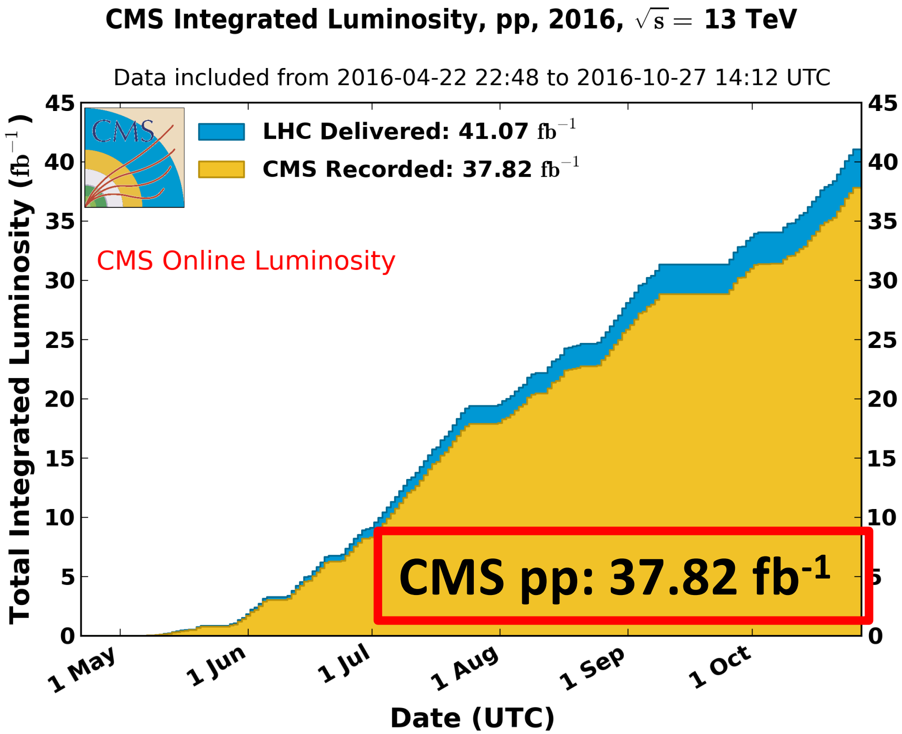


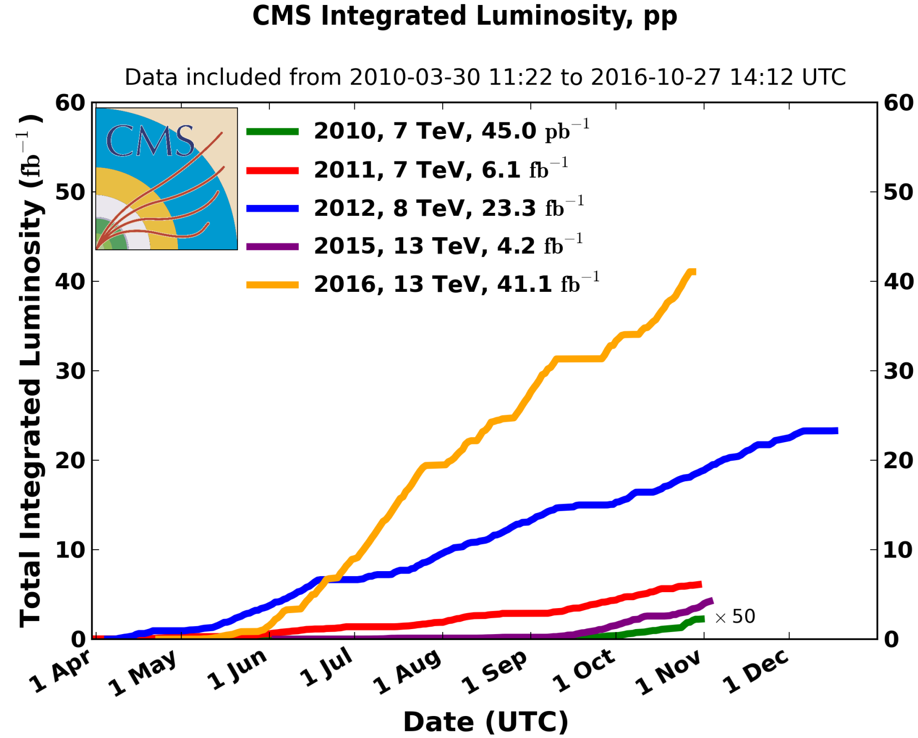


Compact Muon Solenoid (CMS) Detector



CMS Run 2



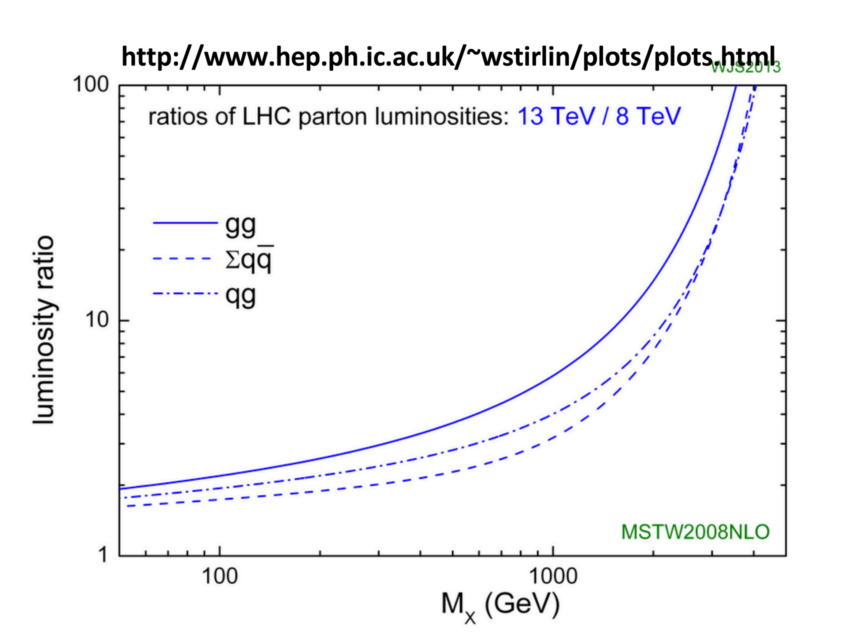


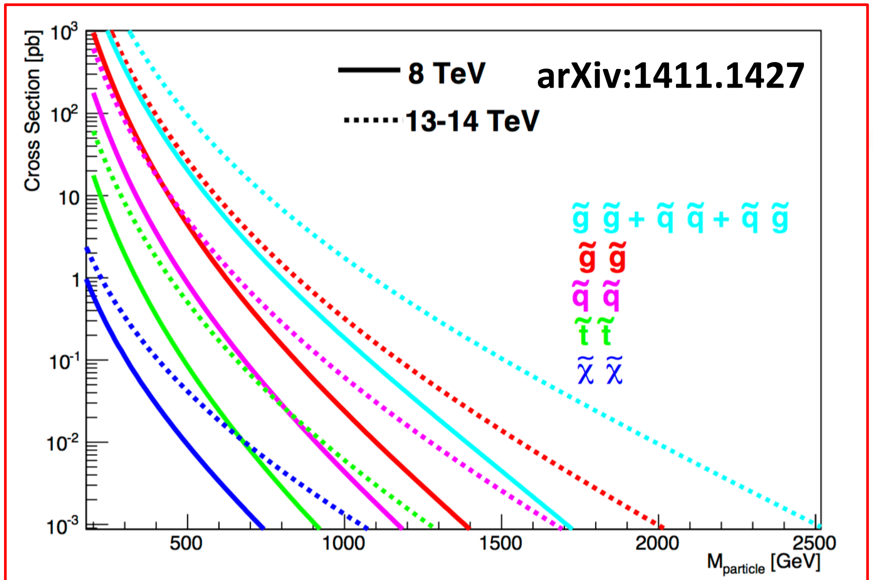
CMS in excellent shape to explore BSM

- LHC exceeded design goals
- Goal for 2016 was 25 fb^{-1}
- LHC had much higher availability
- CMS recording efficiency > 92%

Analysis shown here are based on 12.9 fb^{-1}, a factor of ~5 increase in statistics with respect to 2015

Search for SUSY at 13 TeV

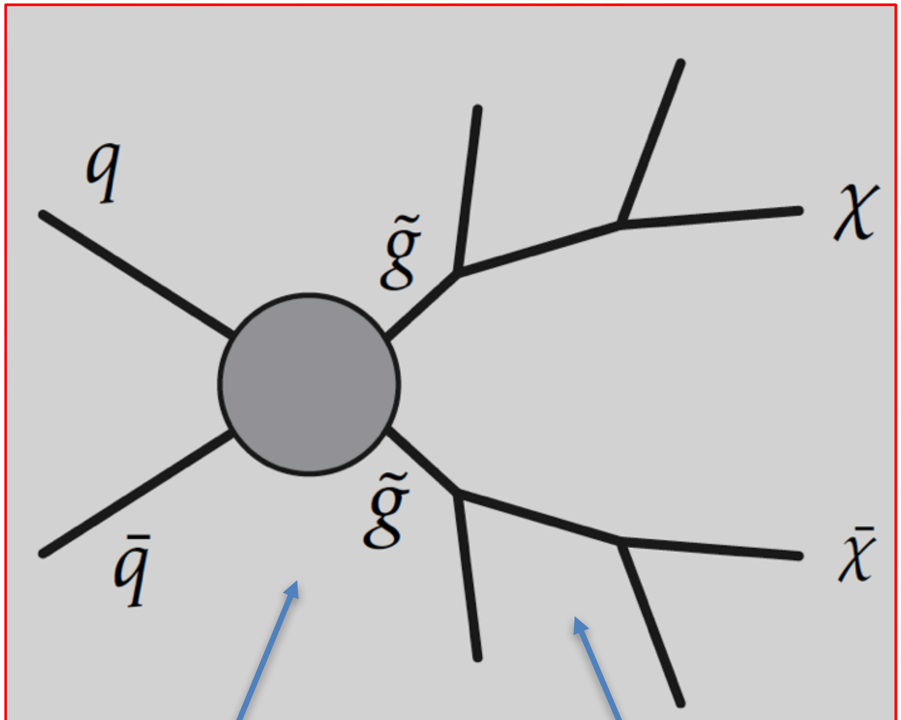




- Large increase of the cross-sections (w.r.t. Run 1) of massive particles at 13 TeV:
  - gluino: x 30 for mass = 1.4 TeV
  - stop: x 8 for mass = 700 GeV
  - chargino: x 4 for mass = 500 GeV
  - ttbar: 3.3
- Increasing luminosity and increased collision energy leads to probing higher mass scales by searching for signatures in the far tails of SM distributions
- Experimental challenge:
  - Keep trigger rates under control at increasing luminosity
  - Increasing number of simultaneous collisions
  - Follow data-taking conditions with on(off)line calibrations (particularly important for SUSY measurements – high object multiplicities, select tails of distributions)

SUSY production at LHC

A typical SUSY production at LHC predicted by SUSY models with conserved R-parity



Each cascade decay chain ends with the LSP, invisible and causes missing transverse momentum (MET)

SUSY particles will be pair-produced

Each SUSY particle successively decays to another SUSY particle and SM particle (the cascade decay)

The final states contain large MET, jets, and possibly leptons or photons

SUSY flavors

The potential SUSY parameter space is enormous:

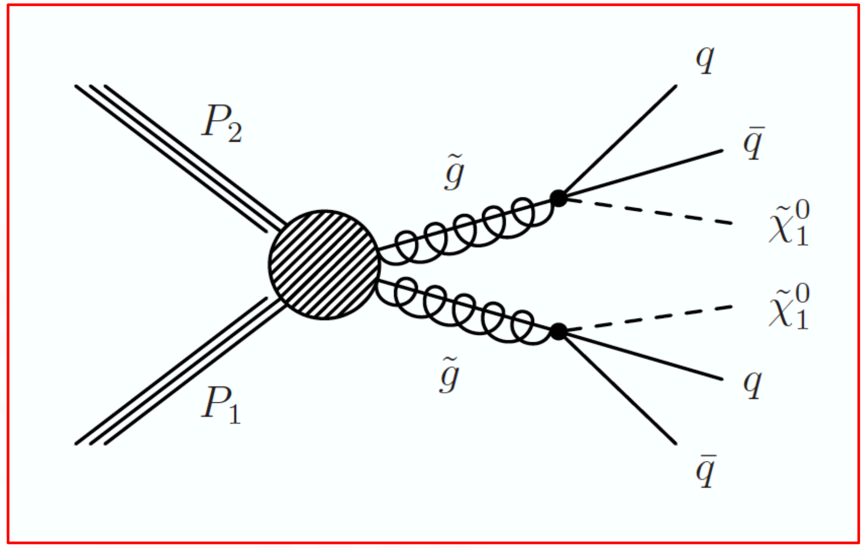
- cMSSM (4+1), pMSSM (19), MSSM (105), NMSSM, …

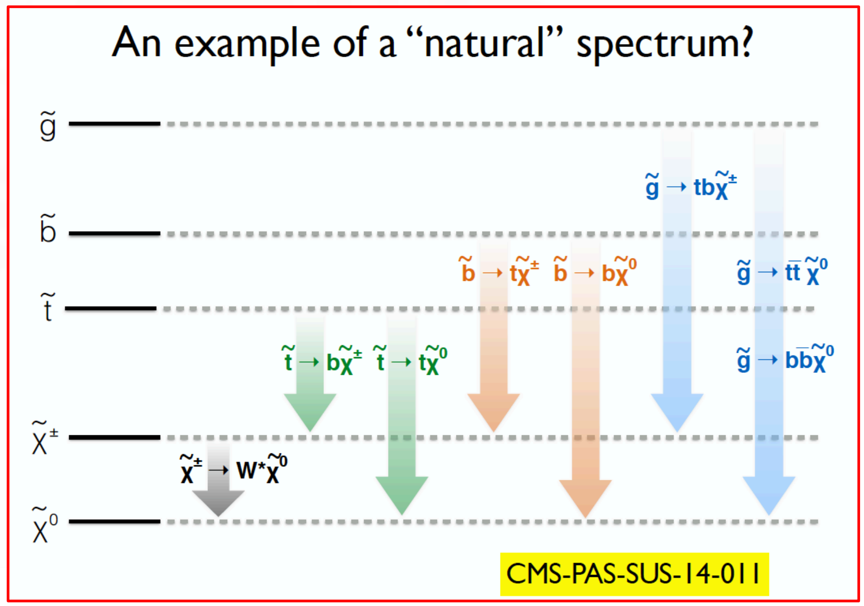
Some scenarios are privileged in our searches:

- R-Parity conserved with lightest SUSY particle (LSP) $\tilde{\chi}_1^0$
  - Provides Dark Matter candidate
  - Classical SUSY signature with high transverse missing energy (MET)
  - Strong or electroweak production
- Gauge mediated symmetry breaking (GMSB)
  - Decay chain terminated with low mass and invisible particles
  - Typical signature: MET from $\tilde{G}$, photons or *Z* from last decay step
- R-Parity violating
  - Coupling strongly constrained (proton stability)
  - Loose MET handle for background reduction
  - Alternative signature, like high jet multiplicity

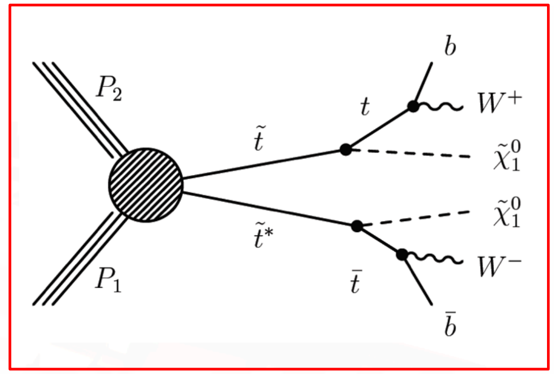
Simplified Model Spectra (SMS)

- A SMS contains two (or three) new particles in addition to the SM particles
- New particles are named after sparticles with the same quantum numbers, e.g., gluinos, neutralinos
- The heavier particles are produced in pair. Each decay chain ends with the lighter particle (LSP).
- The masses of the new particles are the only new parameters if the couplings are specified by a particular SUSY model
- We use the data to exclude the possible range of the masses of the new particles in SMS as long as the data agrees with the SM predictions
- Relevant for "natural" SUSY models, in which only a few particles are light enough to be produced at LHC
- Very useful to define the signal regions (as closely related to experimental observables) and to interpret the results. Usually the masses of SUSY particles are scanned in 2 dimensions





Search for SUSY?



- Select you preferred signal, with its associated decay. It can be classified as a function of the lepton number : 0l, 1l, 2l, ...

- Play with the different observables to enrich S/B
  - Standard SM objects: isolated leptons, jets, b-jets, **MET** = |-Σ(particle) $\mathbf{p_T}$|
  - Composite, boosted objects: topness, boosted W and top taggers, jet substructure
  - Kinematic variables to reconstruct mass of intermediate states: $\mathbf{m_T}$ of (**l, MET**) or (**b, MET**), $\mathbf{m_{T2}}$, $\mathbf{m_{CT}}$
  - Hadronic/total energy: $\mathbf{H_T}$ $\mathbf{M_{HT}}$ $\mathbf{m_{eff}}$
  - Event kinematics: hemispheres, razor, recursive jigsaw reconstruction,…

- Optimize your selection depending on the parameter space: High Δm, compressed spectra, … → several signal regions (SR)

- Different approaches can be used: multi-variate (with BDT) or cut&count.In Run2 mainly cut&count approach

Common variables

Common variables used to define search regions or categories

- HT - a measure of how energetic the event was

$$H_T = \sum_{i \in \text{jets}} \left| \vec{p}_{Ti} \right|$$

$$\vec{H}_T^{\text{miss}} = \vec{\not{H}}_T \qquad \vec{E}_T^{\text{miss}} = \vec{\not{E}}_T$$

- MET - sensitive to the presence of invisible particles and their total p_T

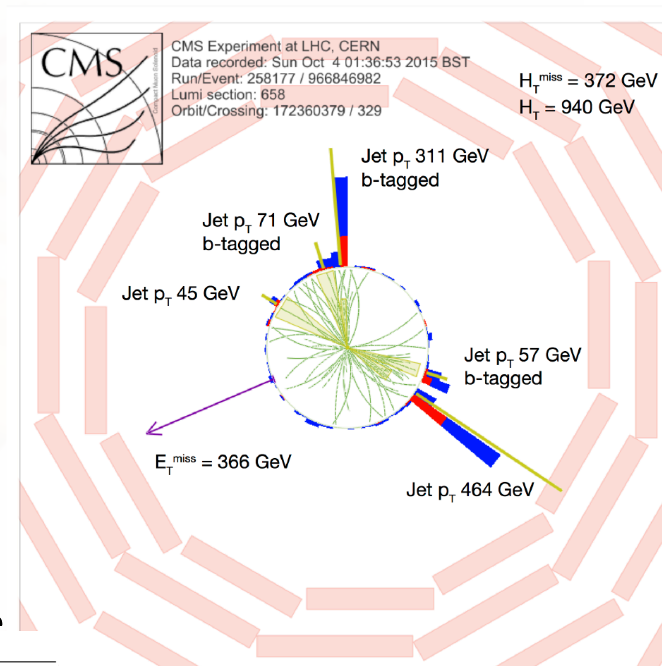
$$\vec{\not{E}}_T = -\sum_{i \in \text{particles}} \vec{p}_{Ti}$$

- M_{HT} - alternative to MET, defined only by jet p_T

$$\vec{\not{H}}_T = -\sum_{i \in \text{jets}} \vec{p}_{Ti}$$

$\Delta\phi$ - the azimuthal angle between jet p_T and M_{HT} (or MET)

Jet multiplicity n_{jet} , b-jet multiplicity n_b



$\alpha_T = E_T^{j2}/M_T$ where E_T^{j2} is the transverse energy of the less energetic of the

M_T is the transverse of the di-jet system defined as

$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}$$

$$m_{T2}^2 = \min_{\mathbf{p}_{1T}+\mathbf{p}_{2T}=\mathbf{E}_T^{\text{miss}}} \left\{ \max\left(m_T^2(l_1, p_1), m_T^2(l_2, p_2) \right) \right\}$$

$$m_{CT}^2 = [E_T(l_1) + E_T(l_2)]^2 - [\mathbf{p}_T(l_1) - \mathbf{p}_T(l_2)]^2$$

$$m_{eff} = H_T + E_T^{miss}$$

$$m_T \equiv \sqrt{2E_T^{\text{miss}}\, p_T^l (1 - \cos(\Delta\phi))}$$

Background estimation

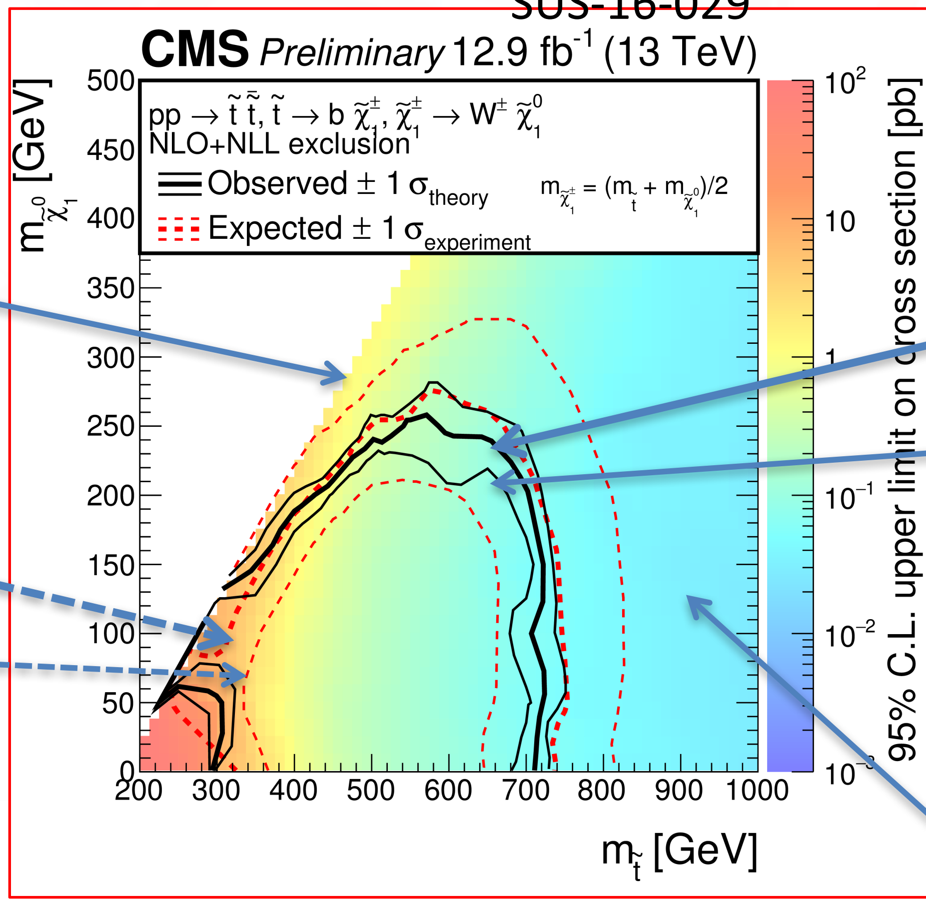
- SUSY analyses can not rely on perfect modeling in MC to estimate background yields in Signal Region (SR).
- Major backgrounds are estimated with data-driven techniques using orthogonal control regions (CR), typically by varying the lepton multiplicity or the b-jet multiplicity.
  - Otherwise stay as close as possible to the signal regions (~ same binning)
  - If statistically limited, an integration over some variables is done
  - Use of Transfer Factors (Control region → Signal region)
- Yields of rare backgrounds are taken from simulation
  - reweighted to the most accurate cross-section and to known mis-modeling of the simulation (ex: PU)
  - all uncertainties (theory – experimental) are taken into account

Interpretation of the results

If no excess is observed in data, limits are derived based on the different SR (with the possibility to also have aggregated SR)

example: the stop pair production

SUS-16-029



Kinetic limits

Observed mass limit, and with 1σ variation on the production cross section

Expected median mass limit at nominal production cross section, and with 1σ variation due to stat+syst

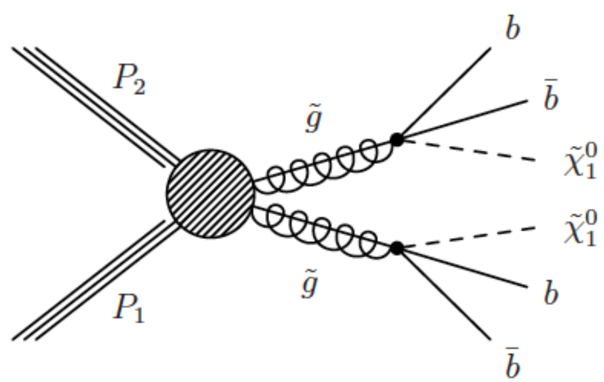
Map of observed cross-section limits

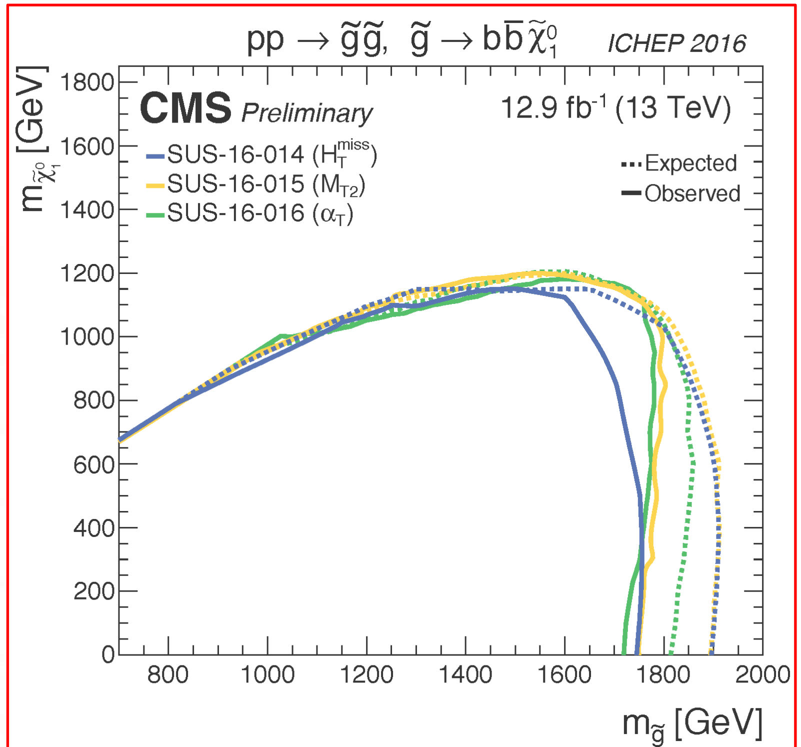
Gluino pair production

Gluino decays to bb $\tilde{\chi}_1^0$

R-parity conserved, LSP = $\tilde{\chi}_1^0$

CMS-SUS-16-014
CMS-SUS-16-015
CMS-SUS-16-016





- Gluinos: highest SUSY production cross section
- All Hadronic inclusive searches
- Can give access to other sparticles via decay chains
- Here we consider decays to two quarks and the LSP
- Extensive categorization used and wide phase space covered.

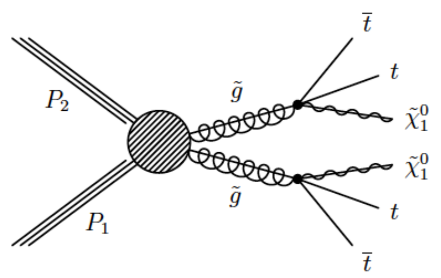
- Sensitive to many different new physics scenarios:
  - Light/heavy flavors, low/high jet multiplicity
- Key variables:
  - **n_{jet}, n_b, H_T^{miss}, M_{T2}, α_T**

Gluino masses excluded up to ~1.75 TeV

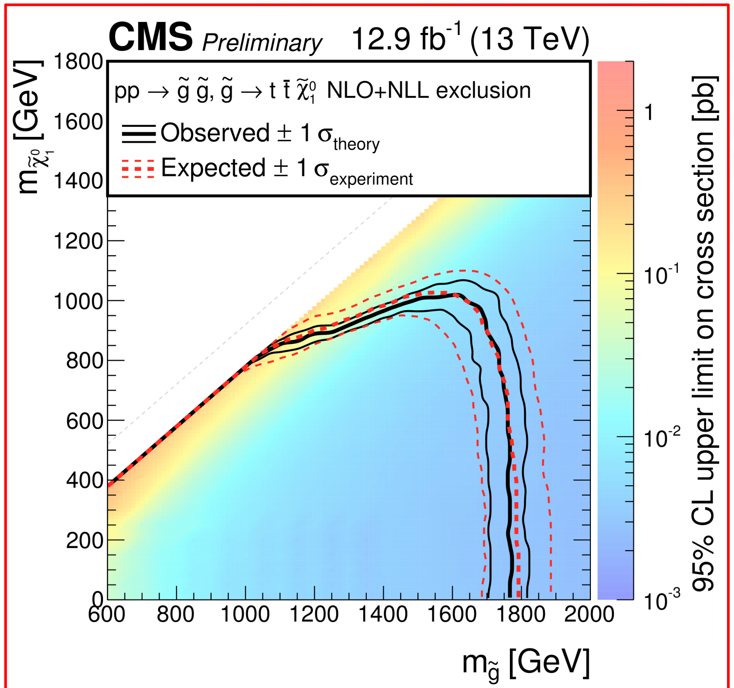
Gluino decays to tt $\tilde{\chi}_1^0$

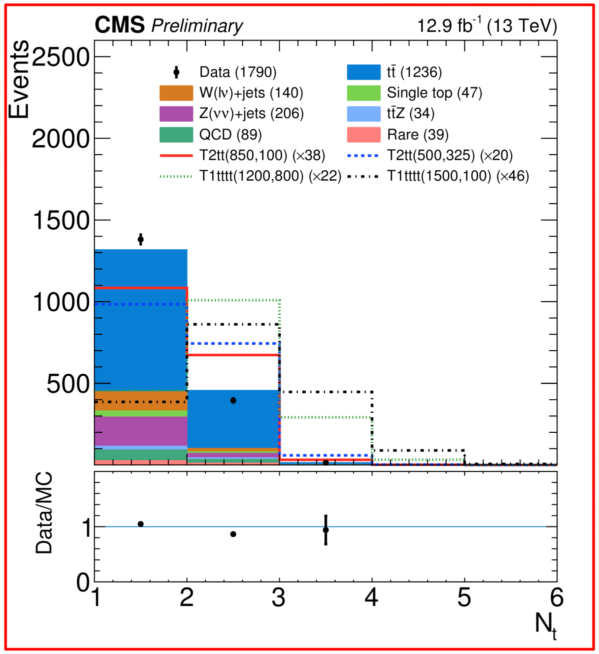
R-parity conserved, LSP = $\tilde{\chi}_1^0$

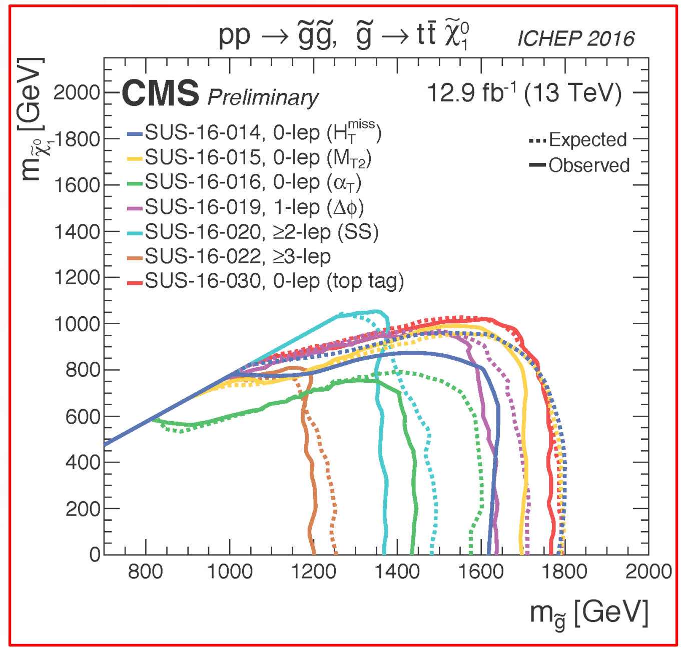
- Dedicated search using top-tagging techniques.
- Key variables: $\mathbf{n_b, n_{top}, E_T^{miss}}$, $\mathbf{M_{T2}}$
- Top tagging in CMS
  - Target hadronically decaying tops: tri-jet (fully resolved), di-jet (boosted) and mono-jet (very boosted) candidates considered
  - Number of b-tag sub-jet, W and top mass constraints are used
  - Efficiency ~80% at high top p_T (~20% mis-tag probability)



CMS-SUS-16-030



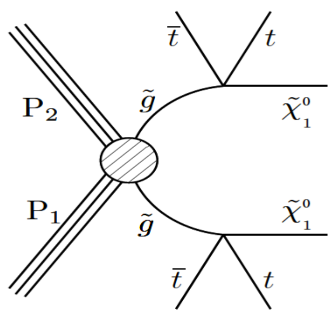




Gluino masses excluded up to ~1.8 TeV

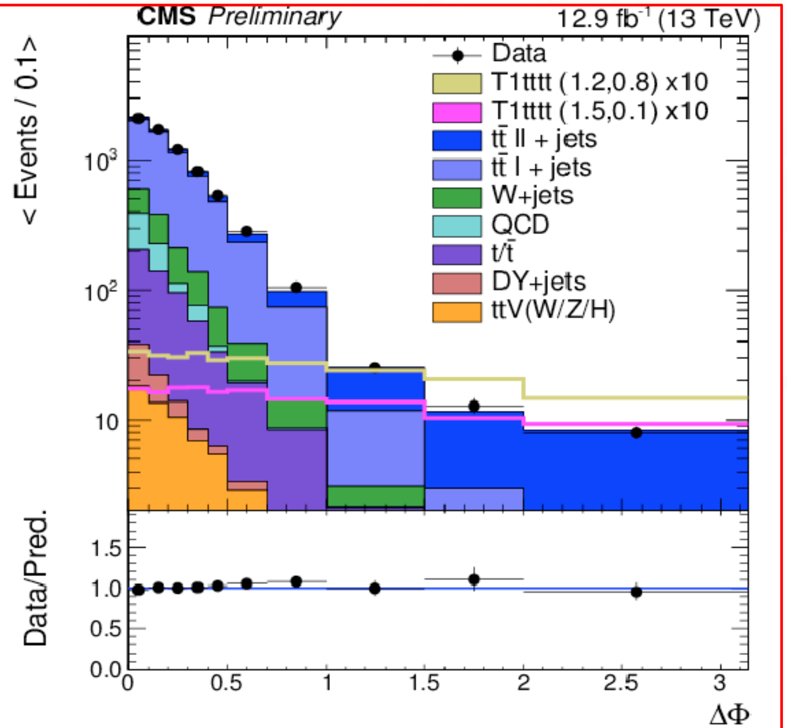
Gluino decays to tt $\tilde{\chi}_1^0$ (1-lepton)

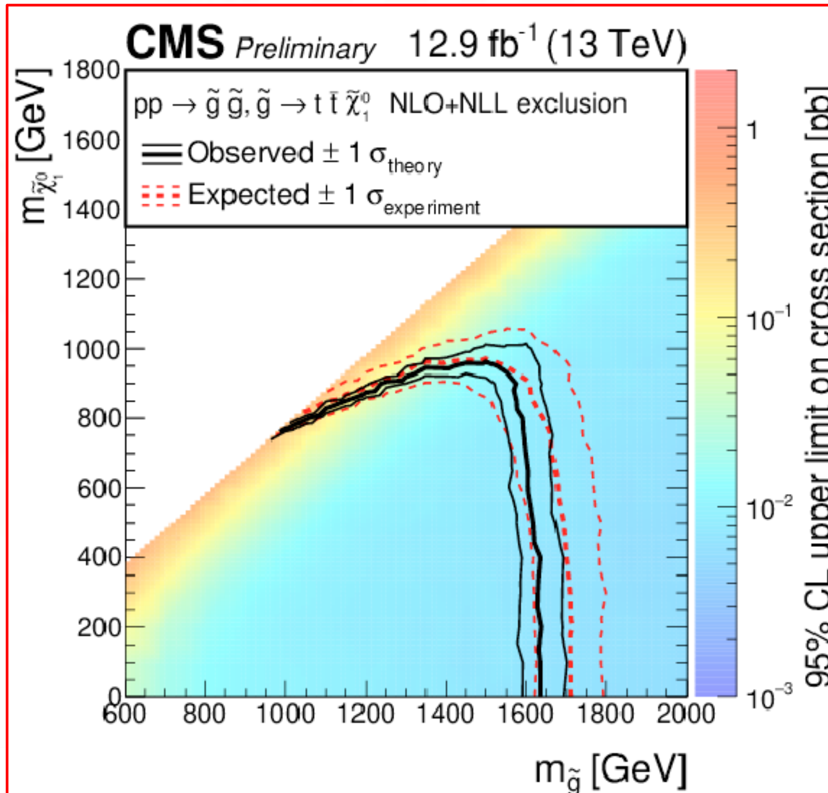
R-parity conserved, LSP = $\tilde{\chi}_1^0$



- Require 1-lepton (e,μ), significant jet activity (H_T), significant leptonic activity (L_T) and b-tags.
- $\Delta\phi(W(p_T),lep(p_T))$ is used to further discriminate between signal and backgrounds

CMS-SUS-16-019

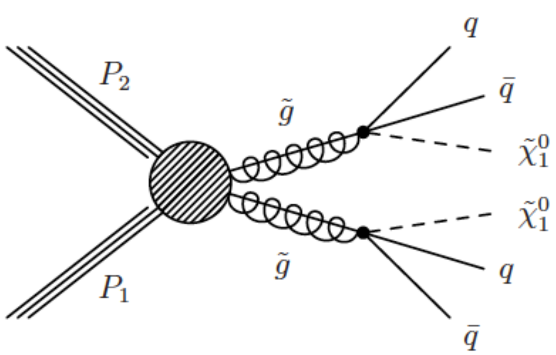




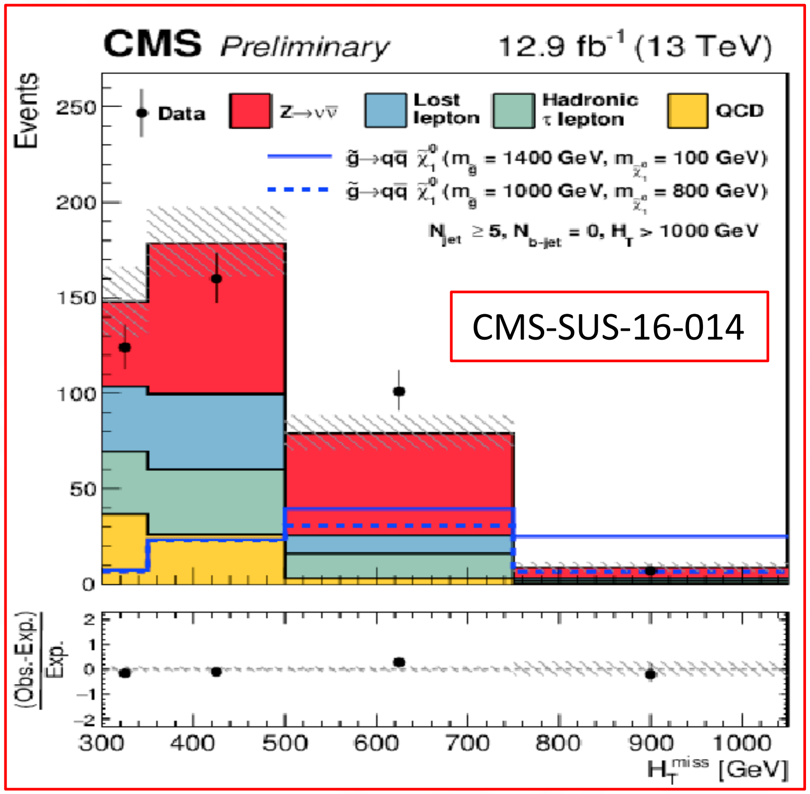
Gluino masses excluded up to ~1.6 TeV

Gluino decays to light flavors

R-parity conserved, LSP = $\tilde{\chi}_1^0$



- 2 all-hadronic inclusive searches
- Key variables: $\mathbf{n_{jet}, n_b, H_T, H_T^{miss}, M_{T2}}$



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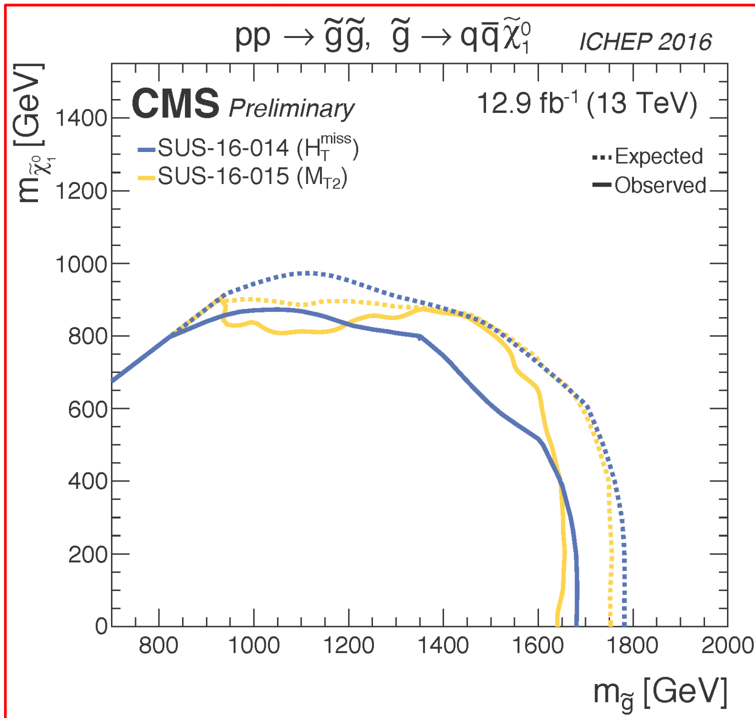
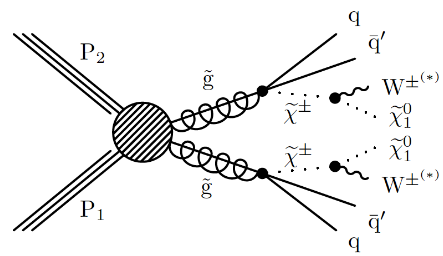


Gluinos masses excluded between around 1620 and 1750 GeV depending on the assumed gluino decay mode

Gluino decay to chargino (leptonic)

R-parity conserved, LSP = $\tilde{\chi}_1^0$



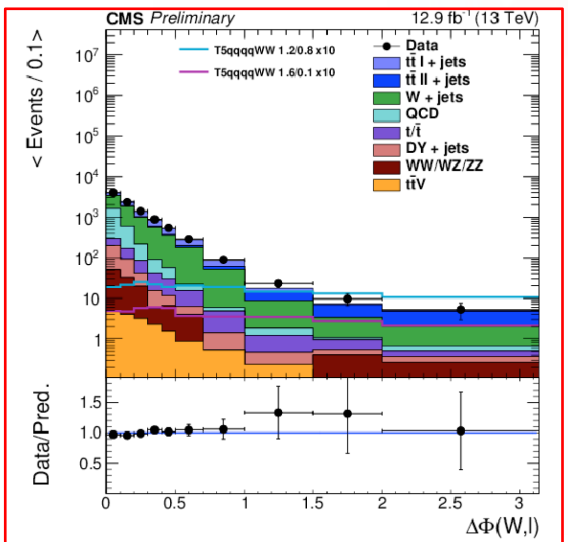
Single lepton search

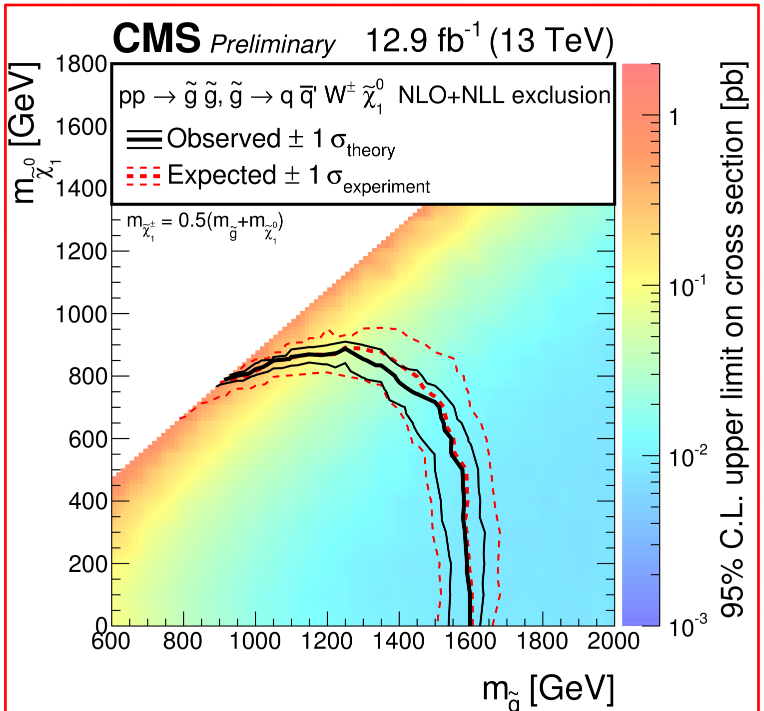
- 1 lepton, jets, (here no) b-jets
- key variables: H_T, MET, "W" p_T, and $\Delta\phi$("W",lep)

Same-sign dileptons

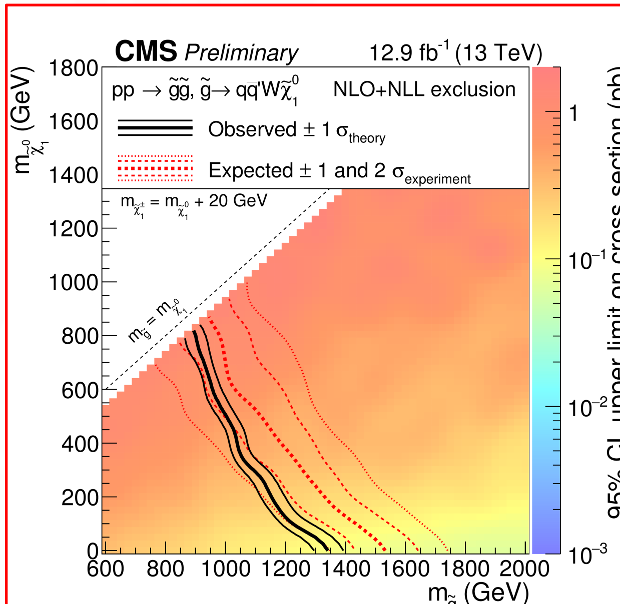
- small SM backgrounds (multi-boson fake leptons, charge flip)
- binned in p_T(l), m_T, MET, H_T, #jets

CMS-SUS-16-019





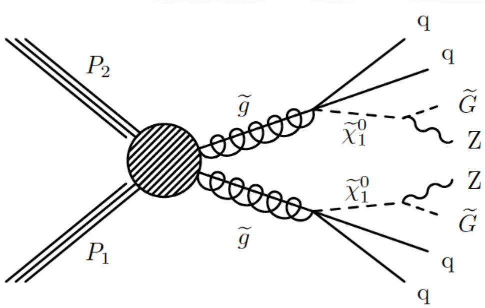
CMS-SUS-16-020



Gluino masses excluded up to ~1.6 TeV

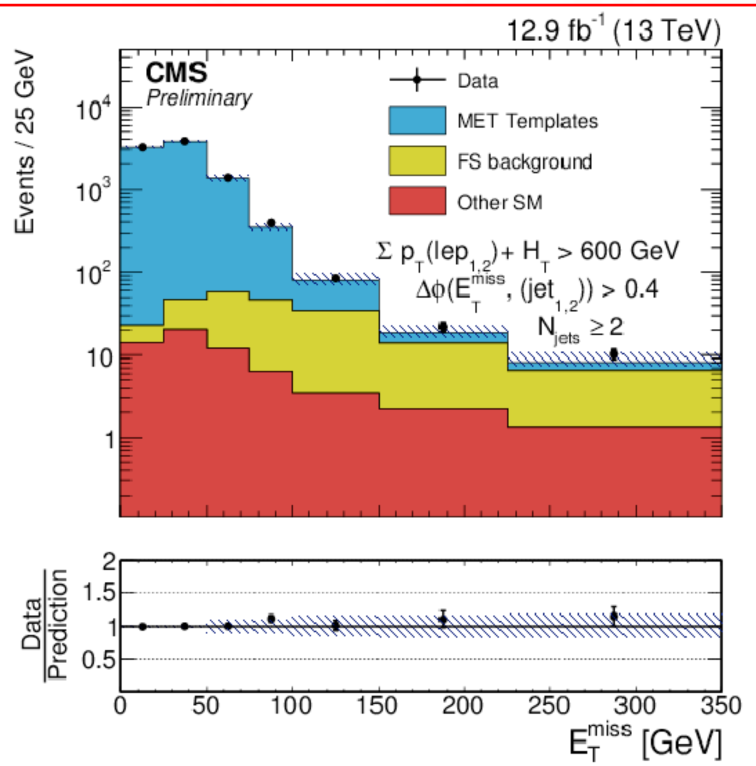
Gluino-induced Z/γ+gravitino

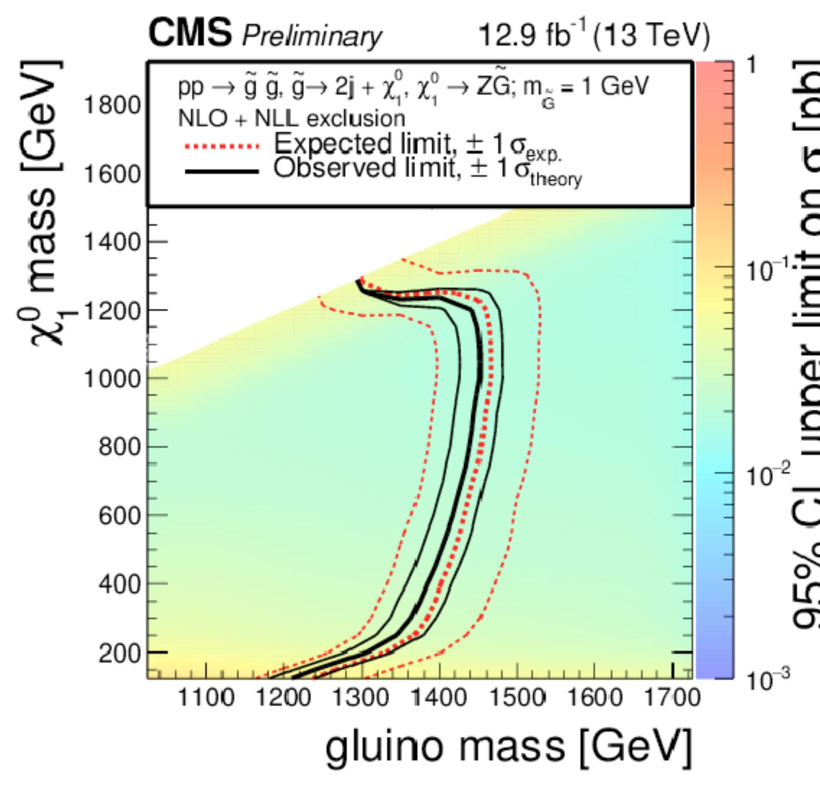
R-parity conserved, LSP = $\tilde{G}$



CMS-SUS-16-021

- Search with 2 leptons (Opposite Sign, Same Flavour →on-Z), jets, MET
- Key variables: #jets, #b-jets, HT, MET + 1 SR



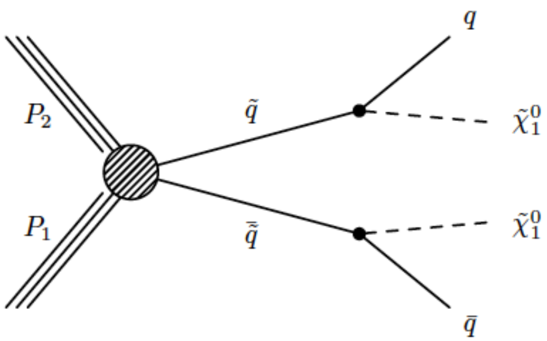


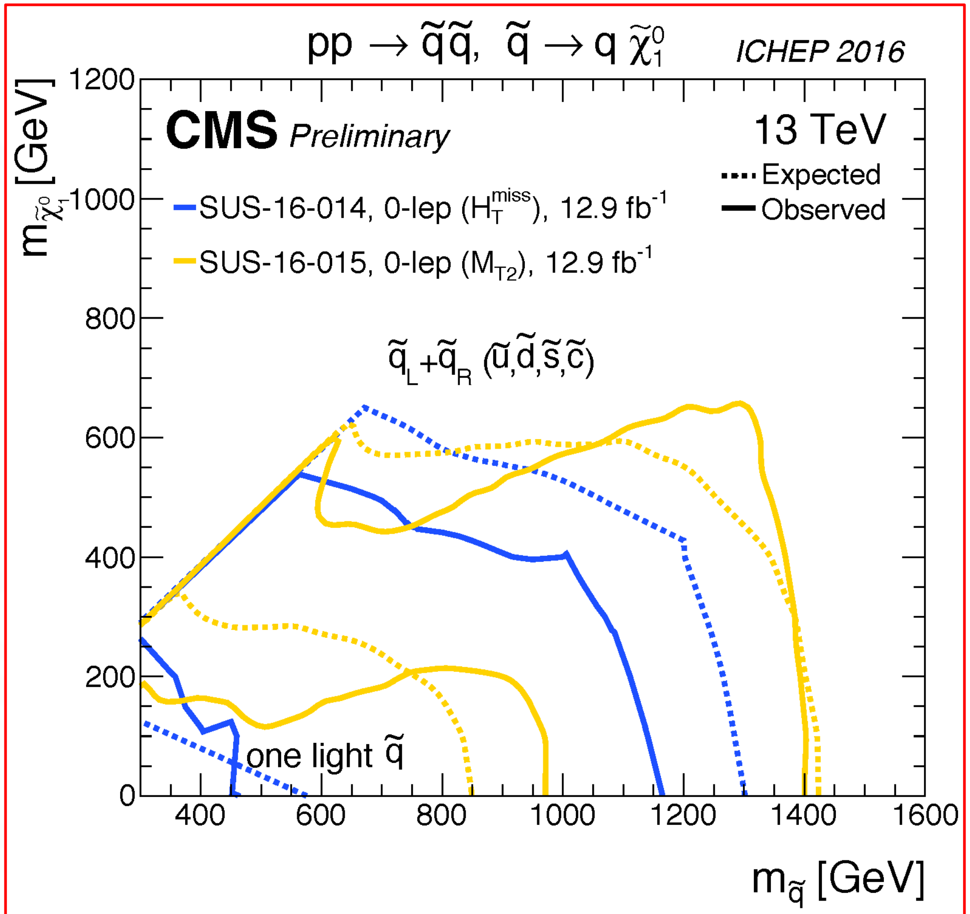
Gluino masses below 1200 TeV for high/low neutralino masses, and 1450 TeV for medium neutralino masses have been excluded

Squark pair production

Light squarks

CMS-SUS-16-014
CMS-SUS-16-015

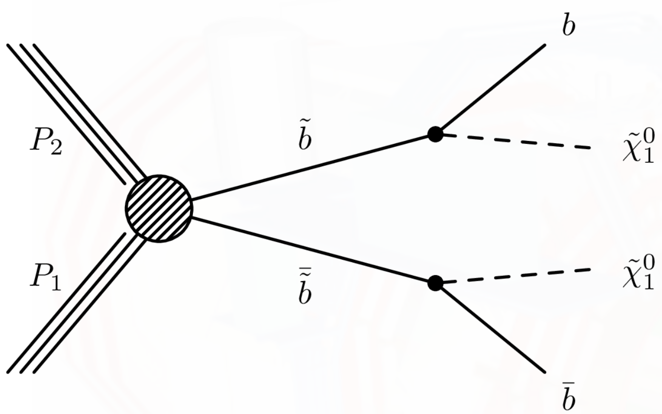




- All-hadronic inclusive searches: $n_{jet}, n_b, H_T, H_T^{miss}, M_{T2}$
- Modest excess ($\lesssim 2\sigma$) seen by the two analysis

Light squark masses excluded up to ~1.4 TeV

Sbottom



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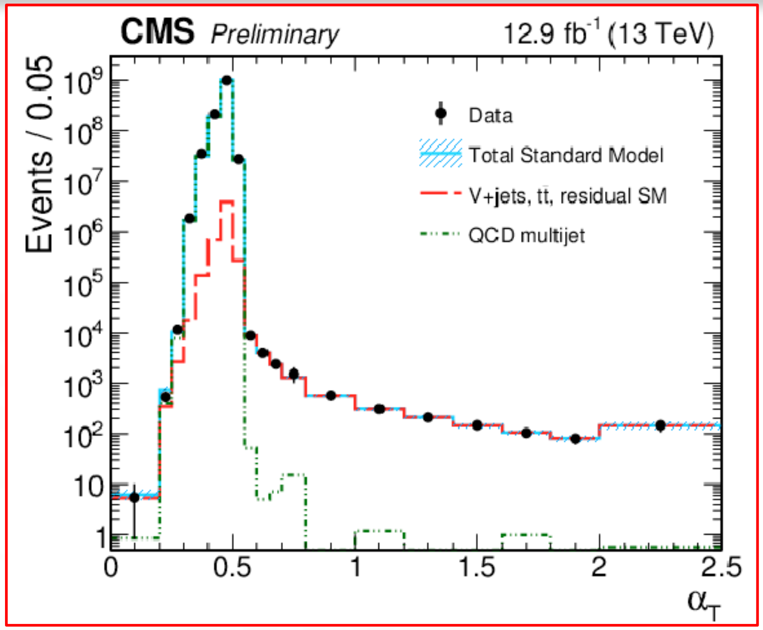
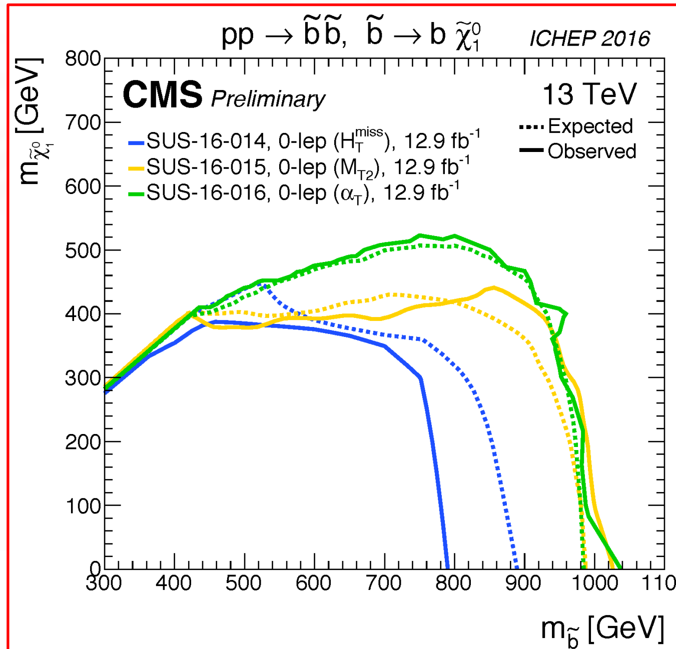


3 all-hadronic inclusive searches:
n_{jet},n_b,H_T,H_T^{miss} ,M_{T2} , α_T

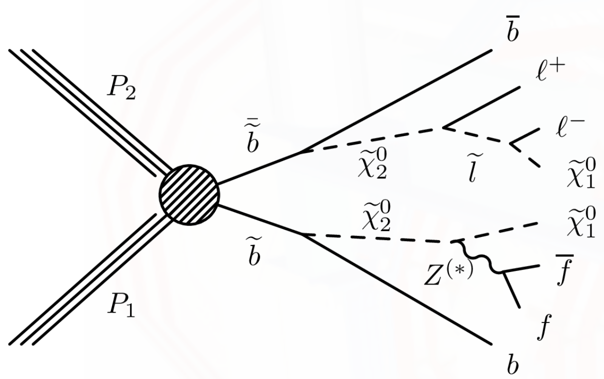


- Low-thresholds (trigger) used, unique phase space covered
- Use $\Delta\phi_{min}^*$ = minimum $\Delta\phi$ jet and H_T^{miss} computed without the jet to keep multi-jet background at a negligible level
- Extensive categorization: n_{jet},n_b,H_T, H_T^{miss}

Sbottom masses excluded up to ~1 TeV

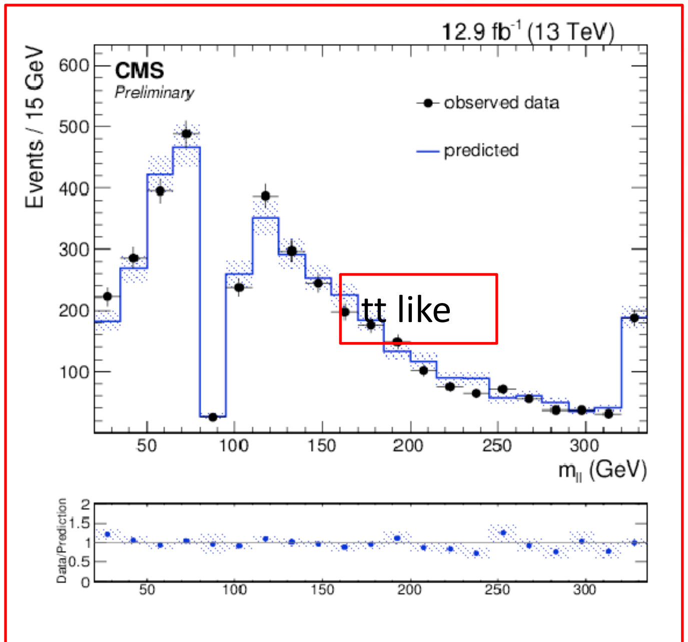
Sbottom

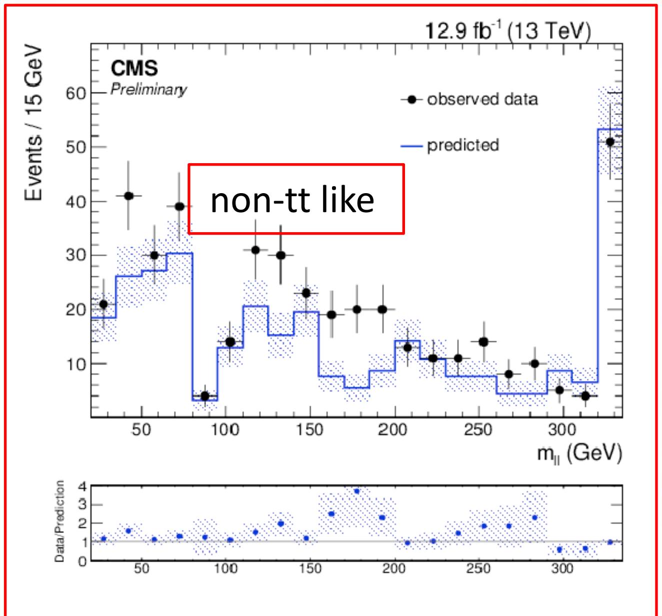
CMS-SUS-16-021

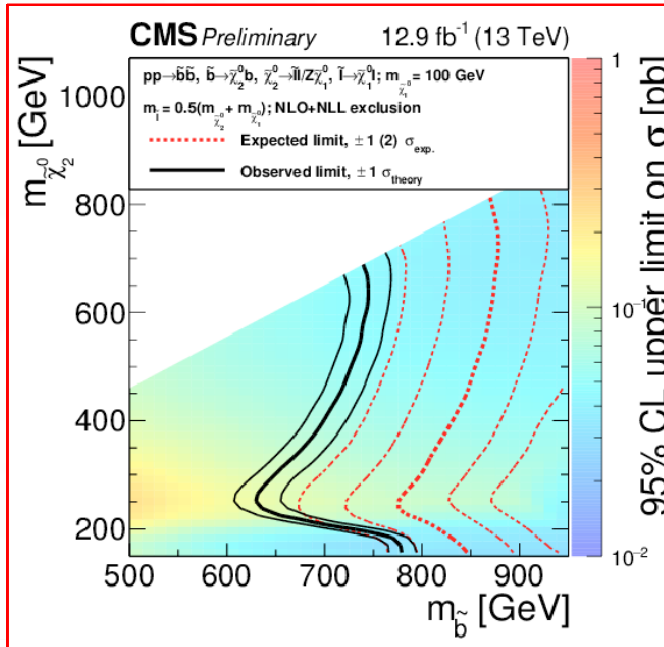


Opposite-sign dilepton search (dilepton mass edge)

- Opposite-sign ee or μμ pair with jets and MET
- Here: off-Z regions targeting kinematic edge in decay chain
- dominant flavor-symmetric backgrounds estimated from data
- SRs binned according to tt discriminator, #jets, #b-jets, MET



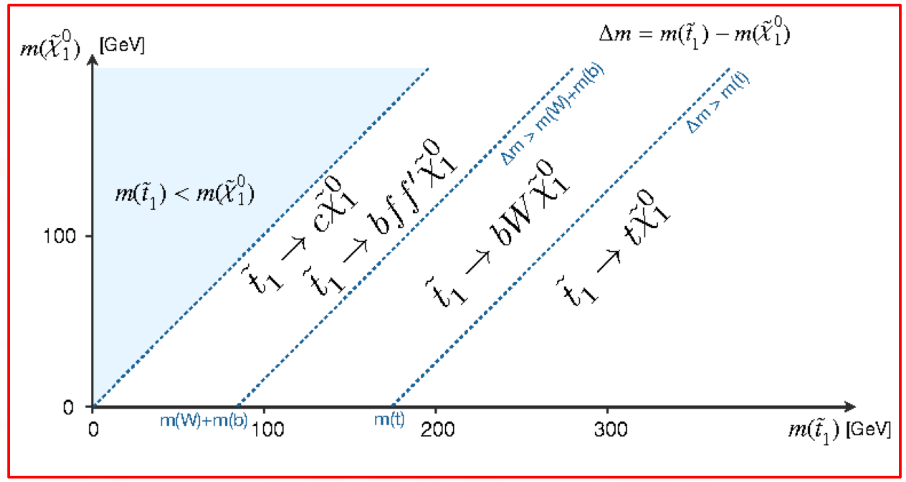




Sbottom masses excluded up to 800 and 625GeV depending on $\tilde{\chi}_2^0$ mass

Stop search

- Low-mass top squarks required for natural SUSY models could be the NLSP (and the first detectable sparticle at the LHC)
- Several final states explored (0,1,2 leptons)
- Different topologies depending on $\Delta m = m_{stop} - m_{LSP}$



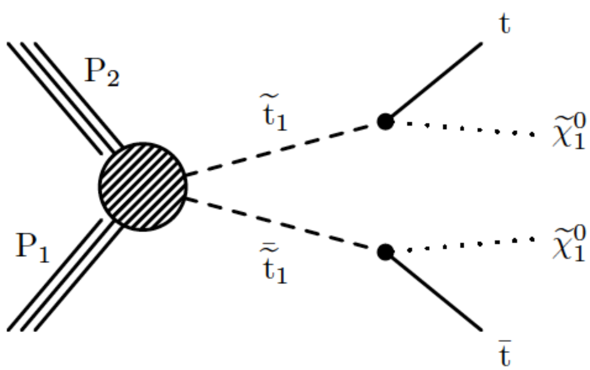
Signature

- favored decay via t(*) and LSP: final states classified according to W decay mode
- approaches SM tt signature for $\Delta m \approx m(t)$ and low LSP mass

R-parity conserved, LSP = $\tilde{\chi}_1^0$

Stop (hadronic)

CMS-SUS-16-029
CMS-SUS-16-030



Experimental signatures

Typical signal topology:

- Multiple jets, potentially b-tagged jets
- Missing transverse momentum (MET) from neutralinos
- Potentially leptons from W decay
- More challenging as mass splitting becomes smaller (less jets, MET, …)

Typical backgrounds :

0-lepton

- Lost leptons from ttbar or W+jets: higher MET than expected from hadronic events
- (ttbar) Z→νν + jets: provides MET
- QCD: very large cross section, MET from mismeasured jets, b-tagged jets from gluon splitting or mistag

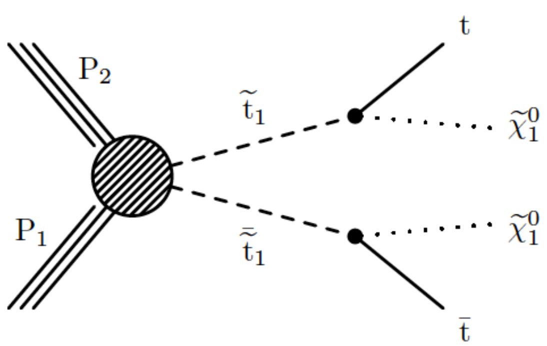
1-lepton

- Lost leptons from ttbar or single top: higher MET, m_T(lepton,MET) $\nless m_W$
- Off-shell W boson decays
- (ttbar) Z→νν + jets: provides MET

Stop (hadronic, 0-lepton)

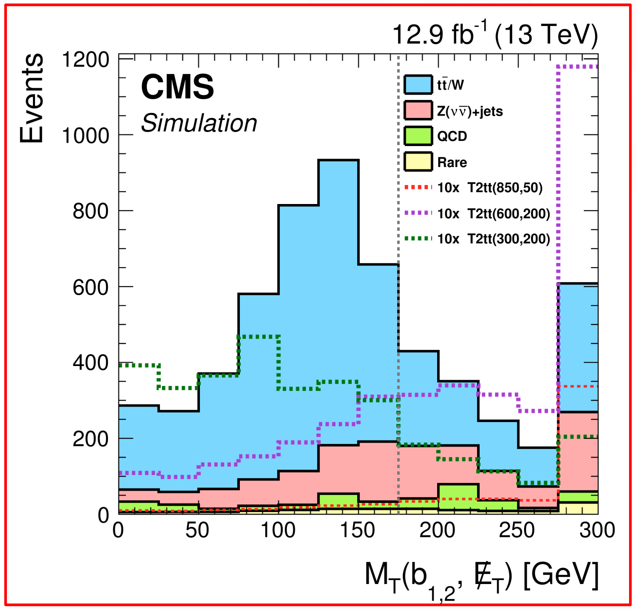
CMS-SUS-16-029

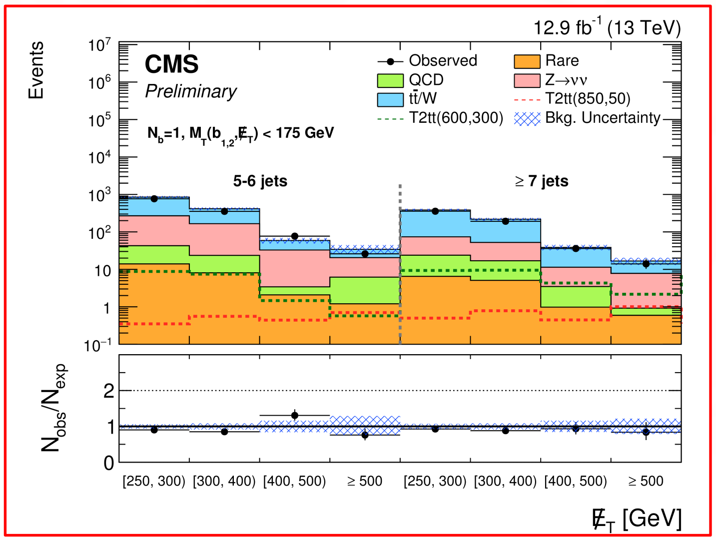
Direct stop

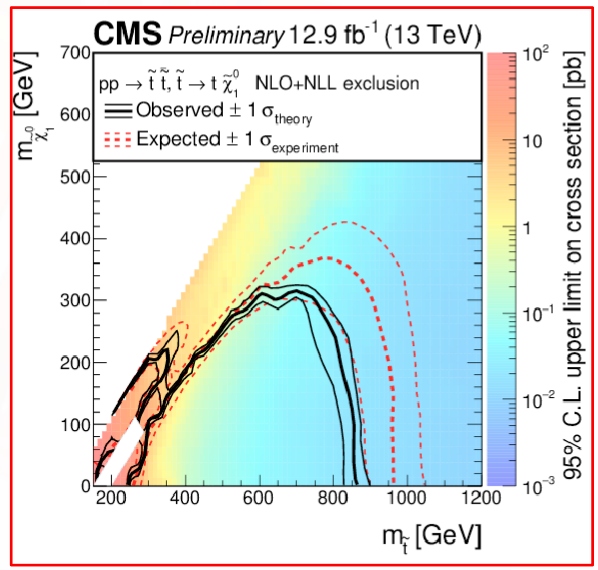


Hadronic search (0-lepton)

- Optimizations for low and high ΔM (stop, neutralino)
- High ΔM : (using W and top tagging) #jets, #b-jets, m_{Tb}, and MET; #tops and #Ws from jet substructure
- Low ΔM: Soft top squark decay products (4-body decay), rely on ISR-tag

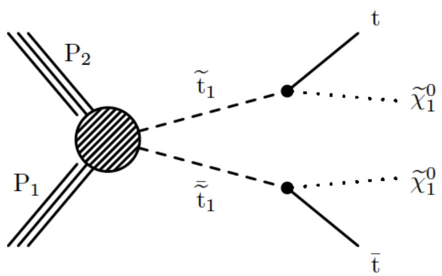






Exclude top squark masses up to 860 GeV and neutralino masses up to 320 GeV,

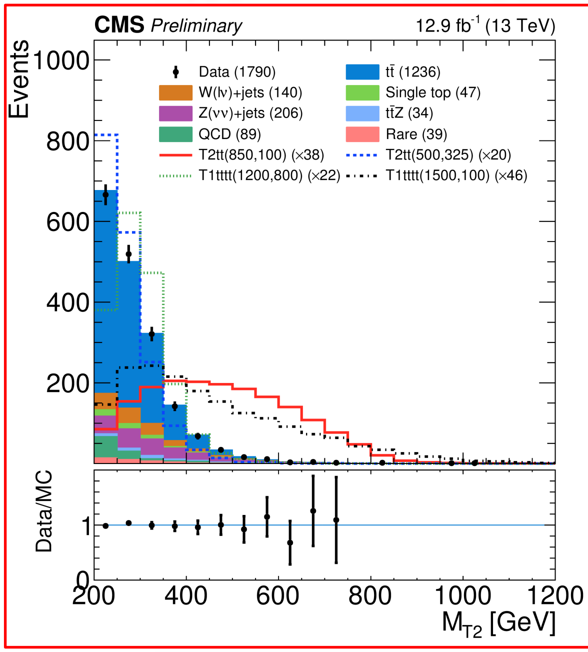
Stop (hadronic, 0-lepton)

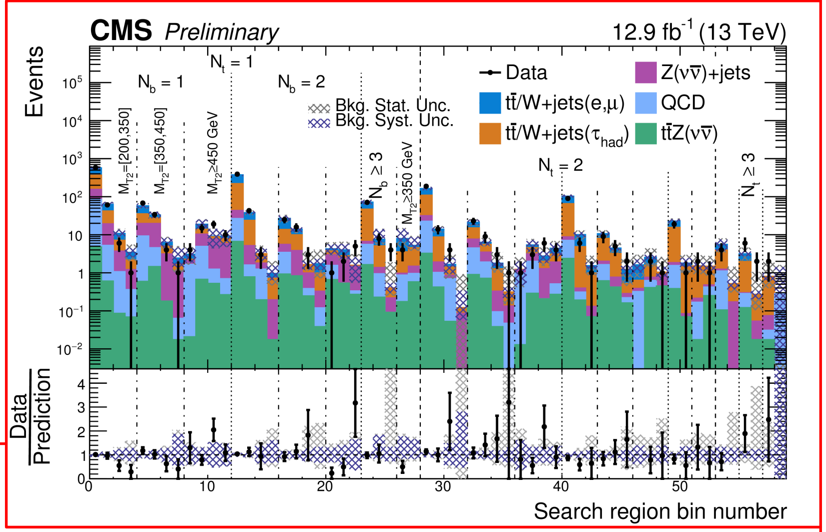


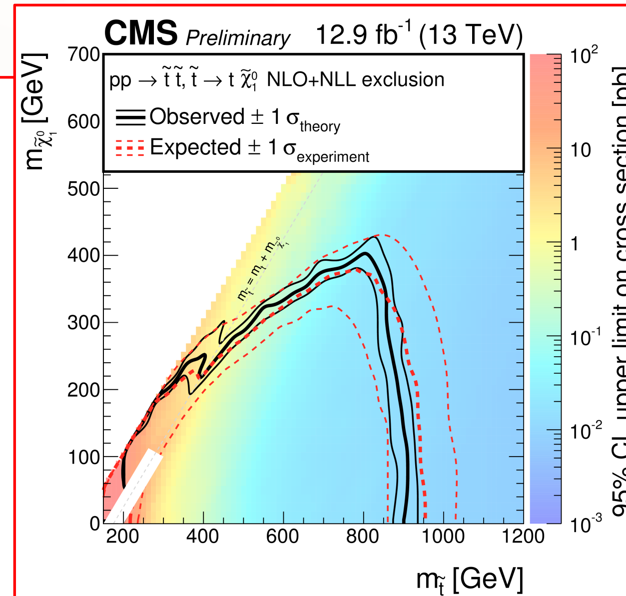
With top tagging

CMS-SUS-16-030

- 3rd generation SUSY often comes with top quarks, up to 2 for direct production, up to 4 for gluino-mediated production
- Use top tagging to identify number of top quarks in an event
- n_{jets}, n_{b-}, m_{Tb}, $\Delta\varphi(j_{123},MET)$ and MET, no leptons or isolated tracks, M_{T2}, H_T
- 59 signal region binned in MET, M_{T2}, N_b and N_t



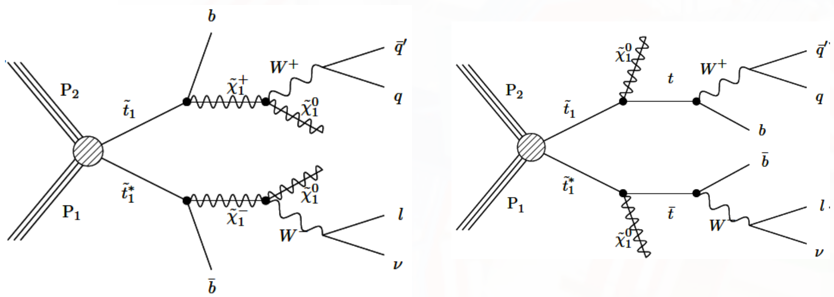




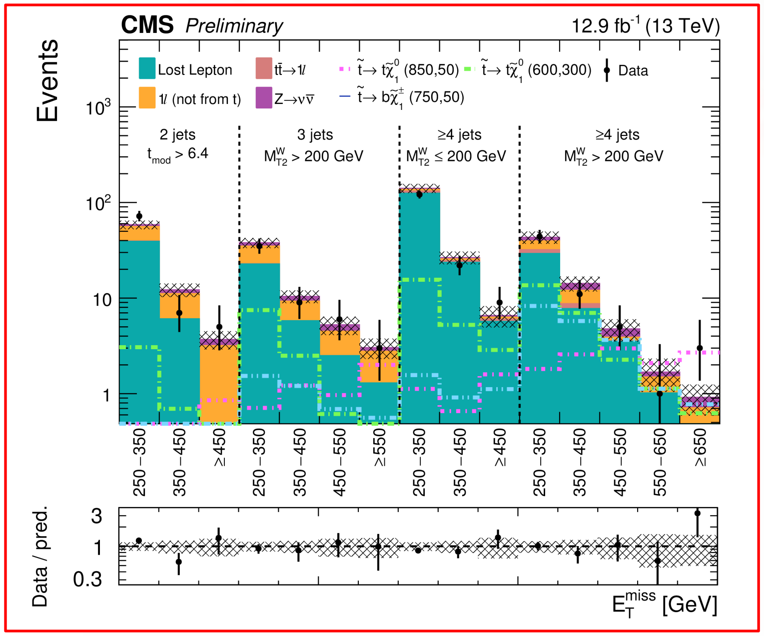
Exclude top squark masses up to 910 GeV for neutralino masses up to 400 GeV

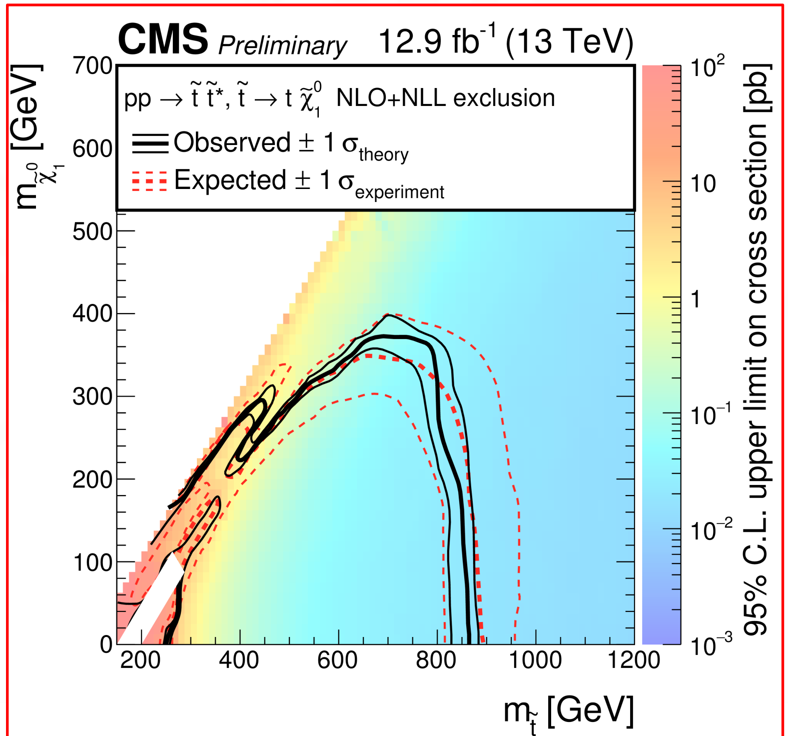
Stop (1-lepton)

CMS-SUS-16-028



- 1 lepton, veto on 2nd lepton or isolated track
- n_{jets}, n_{b}-, m_T, min $\Delta\varphi(j_{12}$,MET) and MET
- M_{T2}^{W} (minimal mother mass compatible with W mass and MET constraints for a ttbar(2l) event topology)

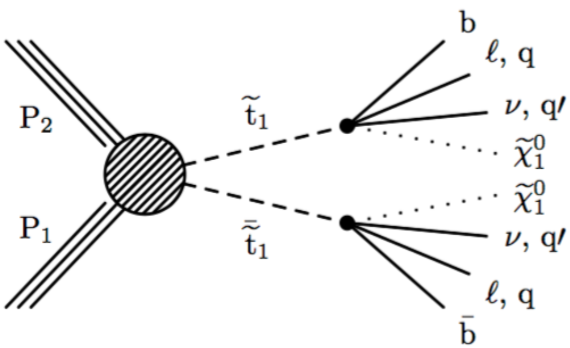




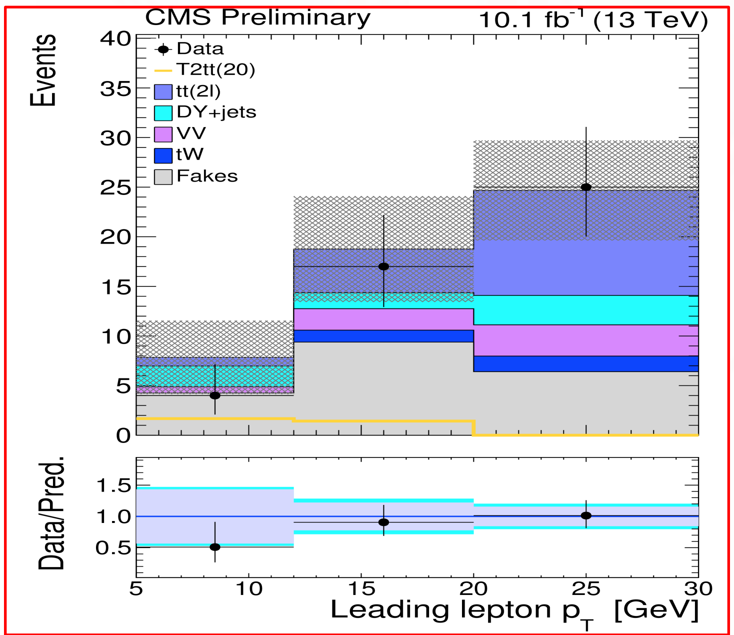
Exclude top squark masses up to 860 GeV for neutralino masses up to 380 GeV

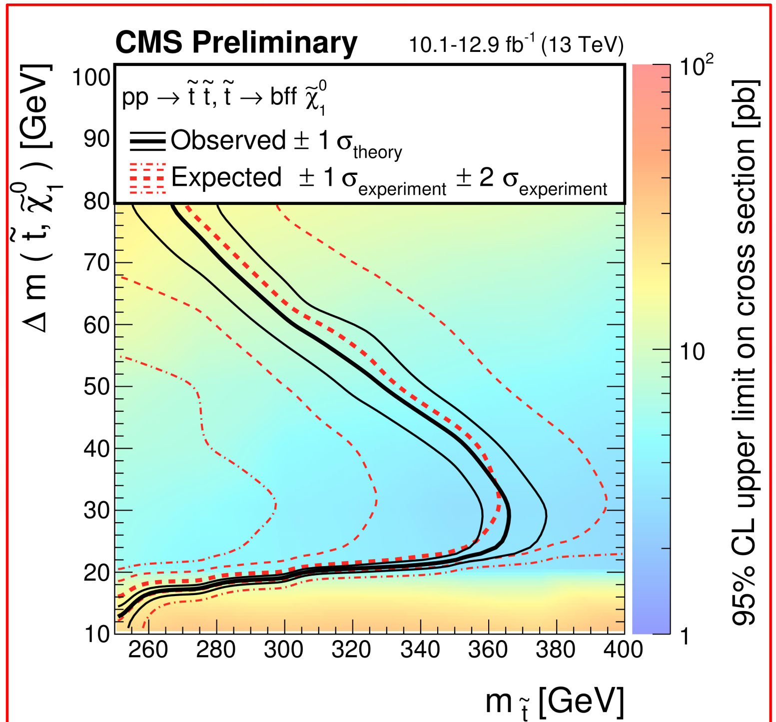
Stop (2-lepton)

CMS-SUS-16-025



- Dedicated search for compressed spectra
- Requires presence of 2 soft leptons with opposite sign
- n_b to suppress ttbar, one jet in final state



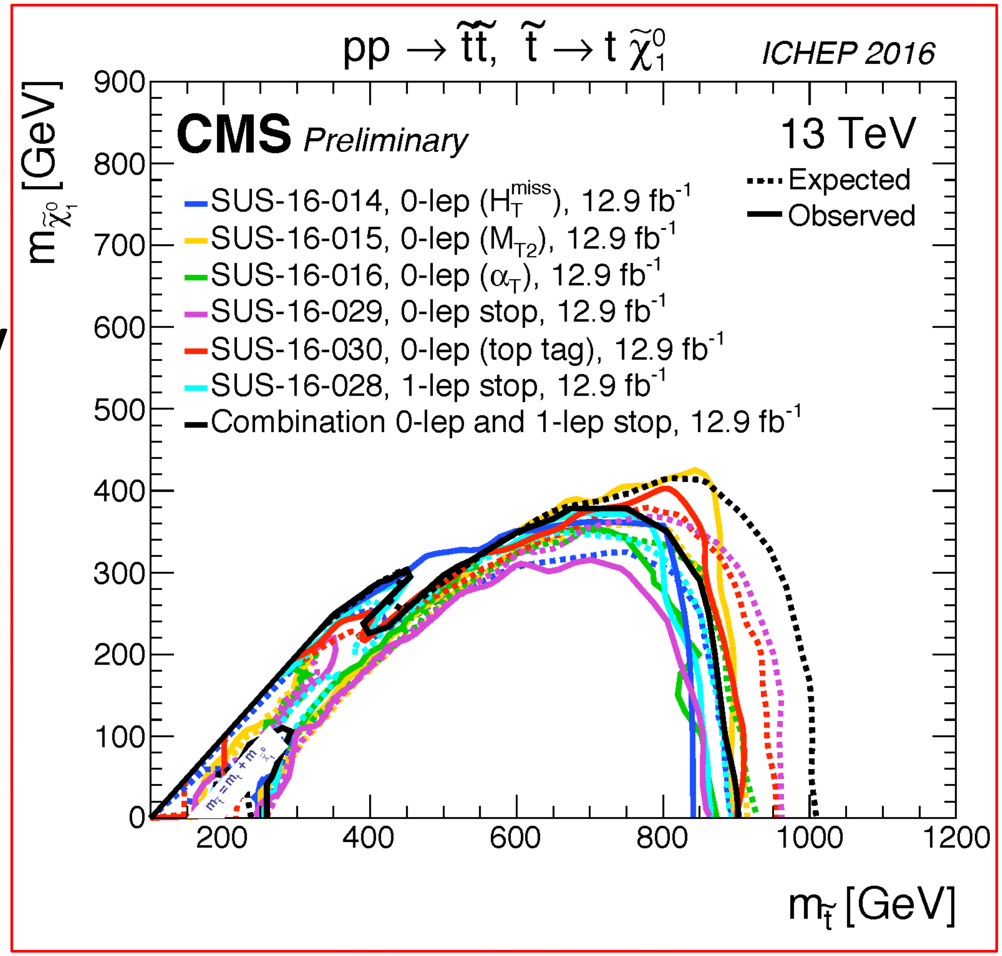


Exclude top squark masses up to 360 GeV, for ΔM($\tilde{t}$, LSP) of 30 GeV

Stop summary

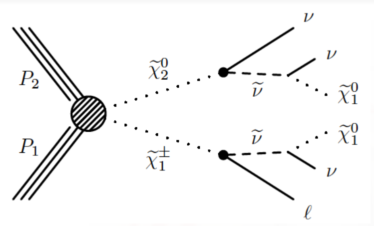
CMS: best exclusion from the combination of 0-1 lepton channels for 2-3 body decays

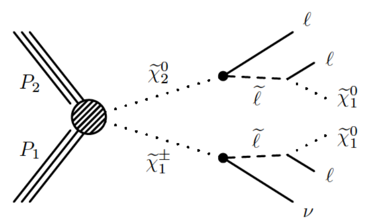
- Stop masses up to ~ 900 GeV are excluded for small LSP masses
- At small Δm stop masses of ~400 GeV are excluded (At m_{LSP}~250 GeV)



Electroweak production

Chargino/neutralino production



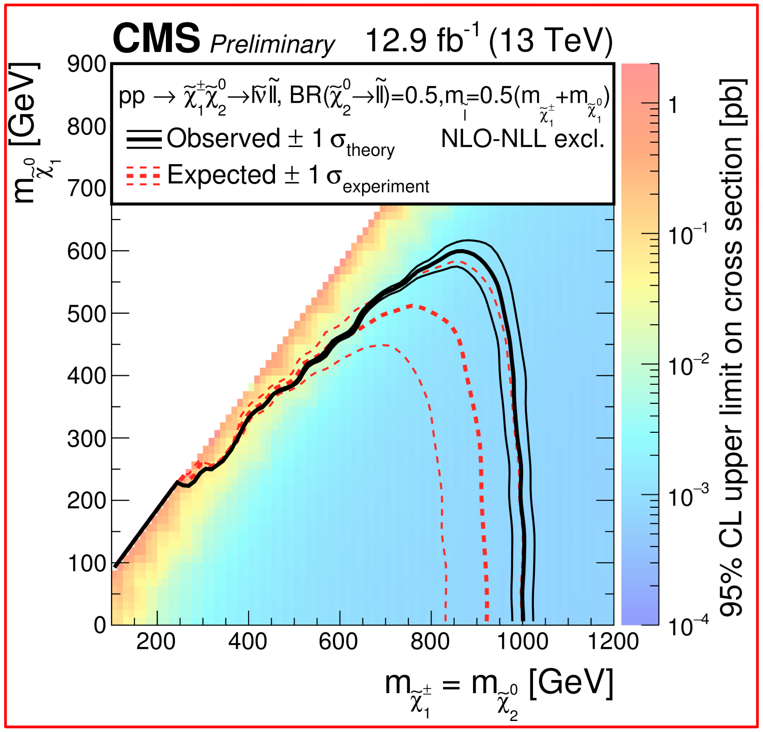


Direct production of "electroweakino" pairs

- decays via sleptons / sneutrinos
- using benchmarks to illustrate different scenarios (depend on mixings and nature of lightest slepton)

Multilepton searches

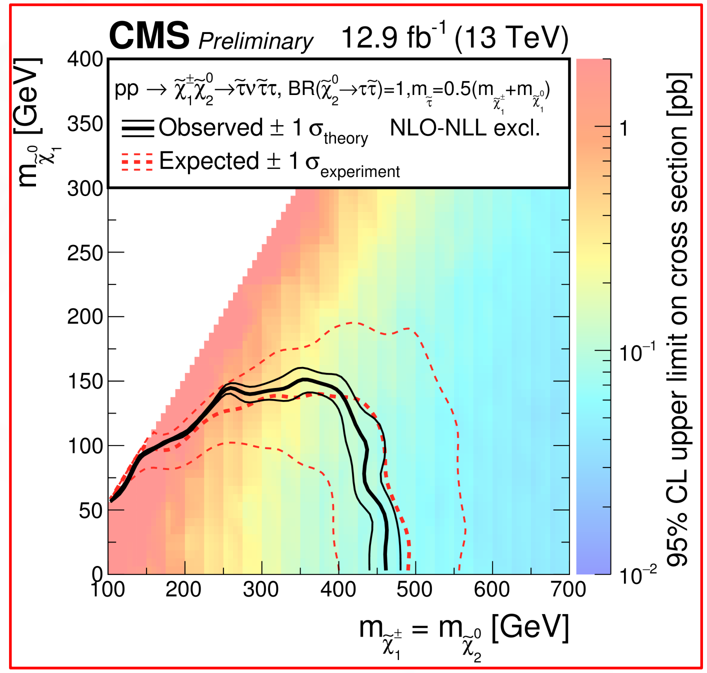
- 2 same-sign leptons and ≥3 leptons include hadronically decaying taus
- SRs defined using lepton flavour and charge, E_T^{miss} and m(ll)/p_T(ll)



CMS-SUS-16-024

Other results in EW prod

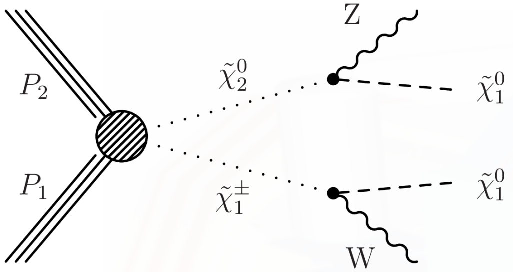
CMS-SUS-16-021
CMS-SUS-16-025
CMS-SUS-16-026



Chargino masses excluded up to ~1 TeV

Chargino masses excluded up to 450 GeV

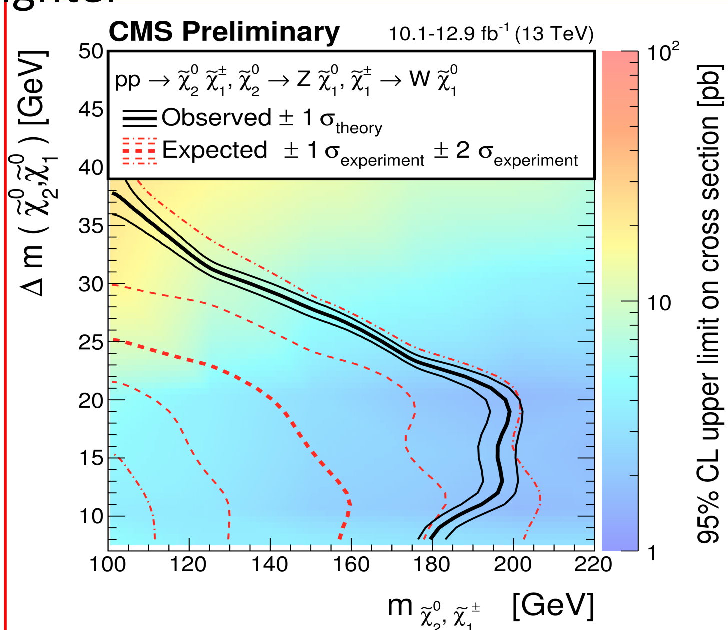
Chargino/neutralino production



CMS-SUS-16-025

Strong motivation for small mass splittings in natural SUSY

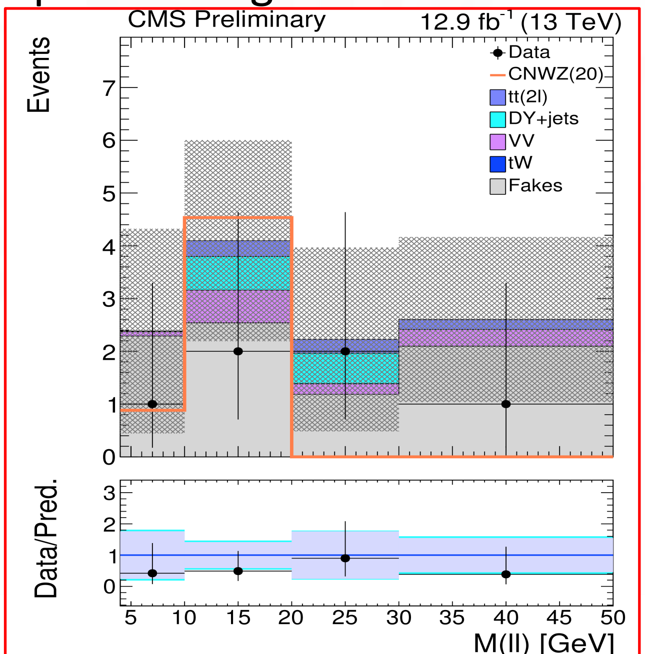
- C~2 and X~1 degenerate, X~1 only slightly lighter



Second-lightest neutralino masses excluded up to 195 GeV

Soft dilepton search

- need very low lepton p_T (≥3.5-5GeV) combination of pure MET & specific 2μ+MET triggers
- other selections: MET, H_T, b-jet veto
- 2 same-sign leptons and ≥3 leptons (include hadronically decaying taus)
- Soft di-lepton search in the more compressed region



CMS Public Results on SUSY

All CMS SUSY results and results presented here can be found at the following URLs

- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html

- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-014/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-015/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-016/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-019/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-020/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-021/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-024/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-025/index.html
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- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-029/index.html
- http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS-16-030/index.html

Conclusions

Excellent LHC performance allowed for considerable increase in sensitivity with partial 2016 data set

- Experiments performed a large set of analyses almost synchronously with data taking

Searches now extended to more challenging scenarios

- Electroweak production, compressed mass spectra, …
- Can expect many more after end of 2016 data taking

No convincing excess is observed and exclusion limits are derived using simplified models

- Mass limits (in simplified model spectra!) pushed to about 1.8TeV (gluinos) and 900GeV (top squarks), 1 TeV/400 GeV (Chargino/neutralino)

More data in Run-2 means

- More challenges: systematics becoming dominating
- More opportunities: electroweak production, compressed spectra
- We don't give up and we hope to see soon deviations from SM predictions

THANKS !! to SILAFE2016 organizers for this talk opportunity and wonderful hospitality