SUSY searches at 13 TeV with the CMS Experiment

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for the CMS Collaboration

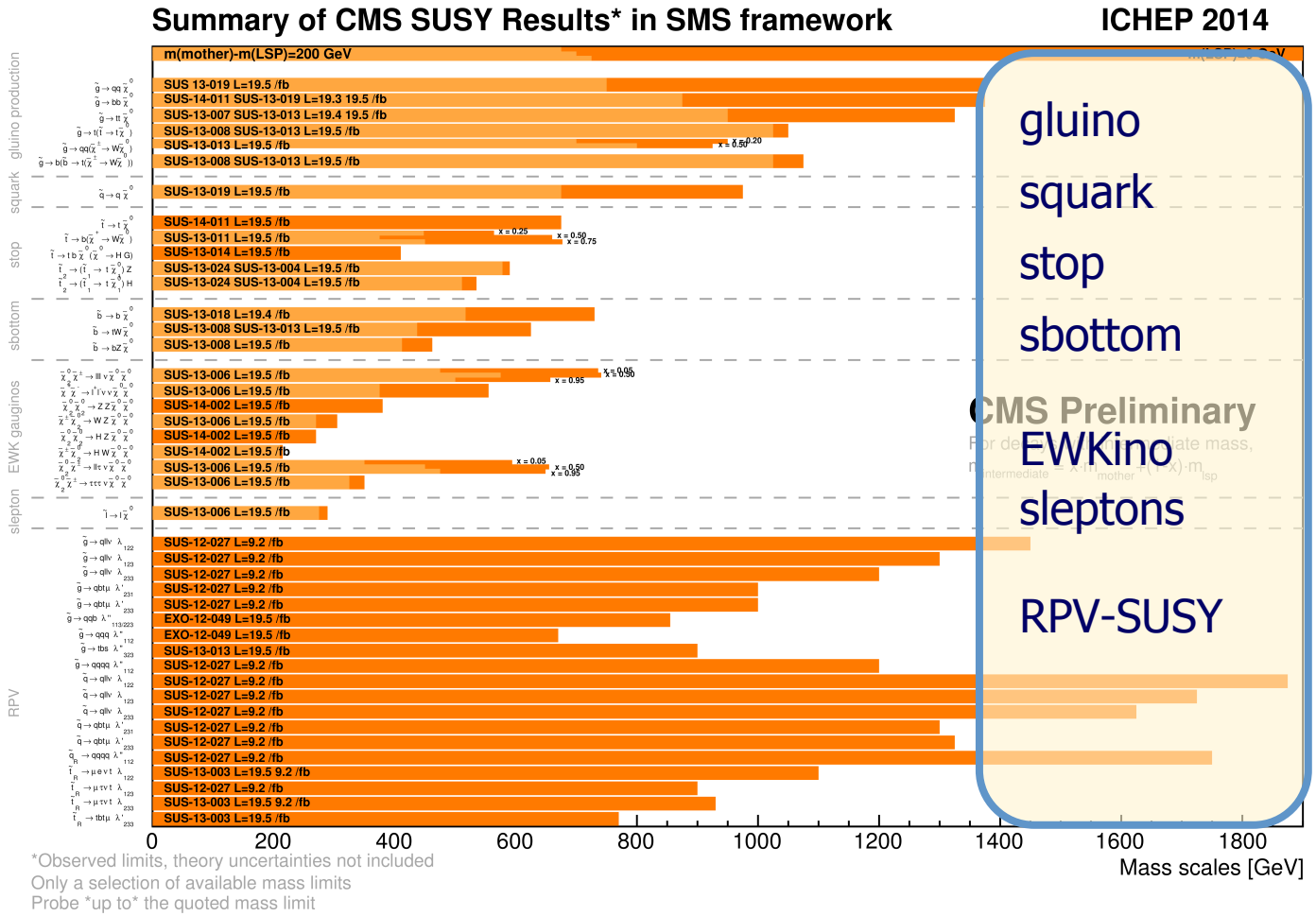
Outline

Introduction

- Searches
  - Gluino-pair production
  - Squark-pair production
- Summary

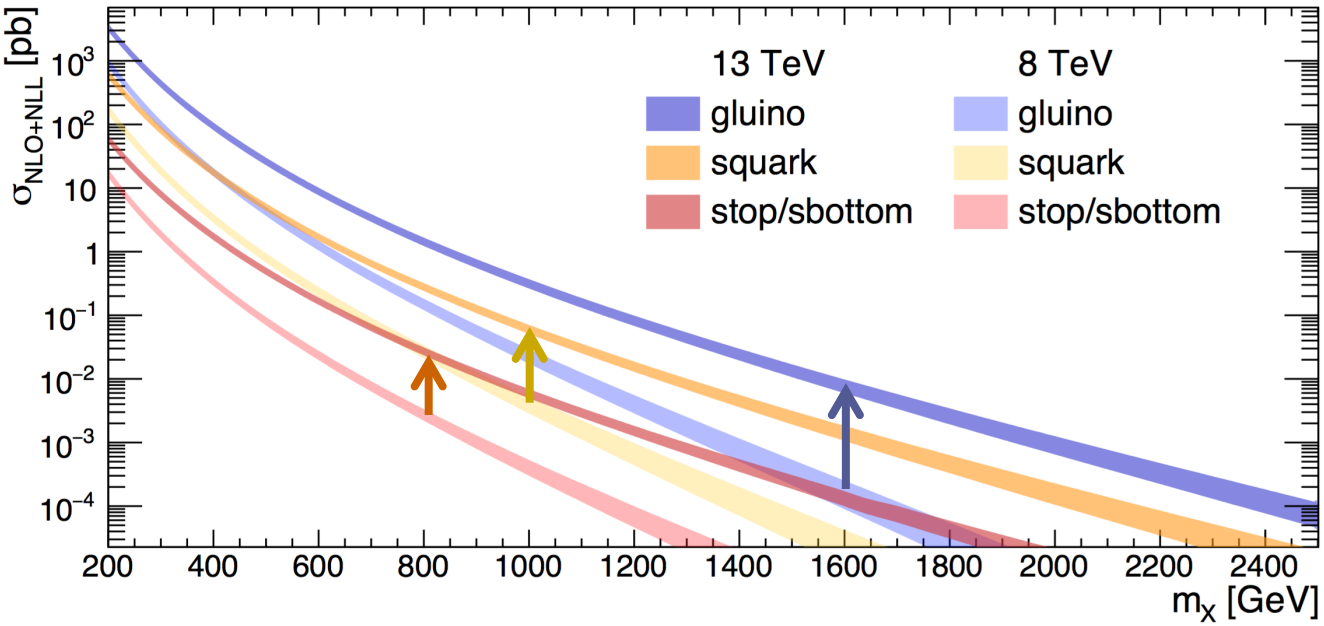
Introduction

Status of SUSY searches with 8 TeV



Introduction

Cross section comparison (13 TeV/8 TeV)

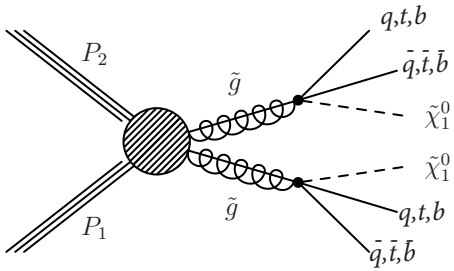


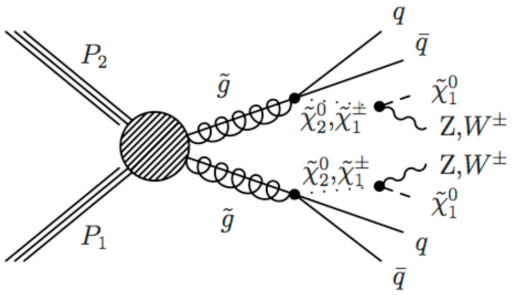
$\tilde{t}/\tilde{b}$ @ 800 GeV → x10
$\tilde{q}$ @ 1 TeV → x15
$\tilde{g}$ @ 1.6 TeV → **x45**

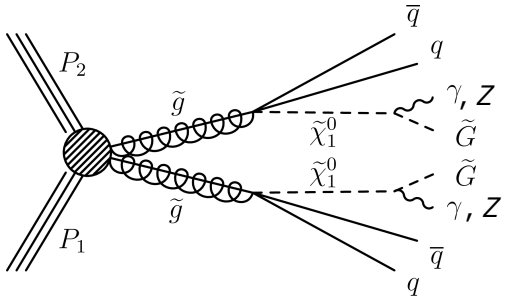
- **Gluinos with so far highest excluded mass (in RPV SUSY) first to search for!**
- **Squarks still enhanced by factor 10-15, starting to reach new territory with 2.3 fb^{-1}**

Introduction

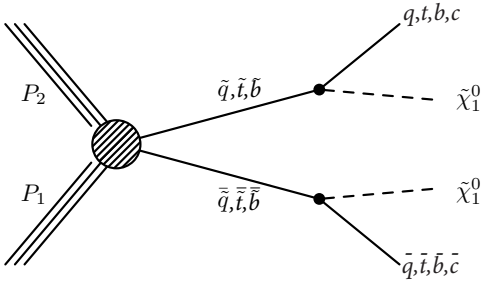
Simplified models for gluino-pair production

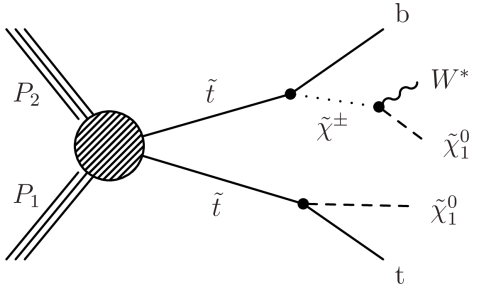


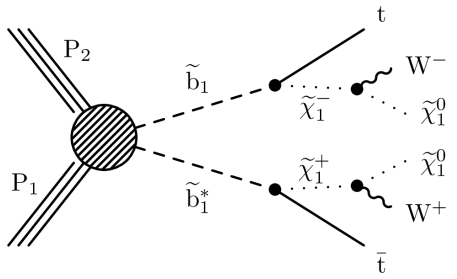




Simplified models for squark-pair production







Where we are...

- Introduction
- **Searches**
  - **Gluino-pair production**
    - all-hadronic final states
    - leptonic final states
  - **Squark-pair production**
    - all-hadronic final states
    - leptonic final states
- Summary

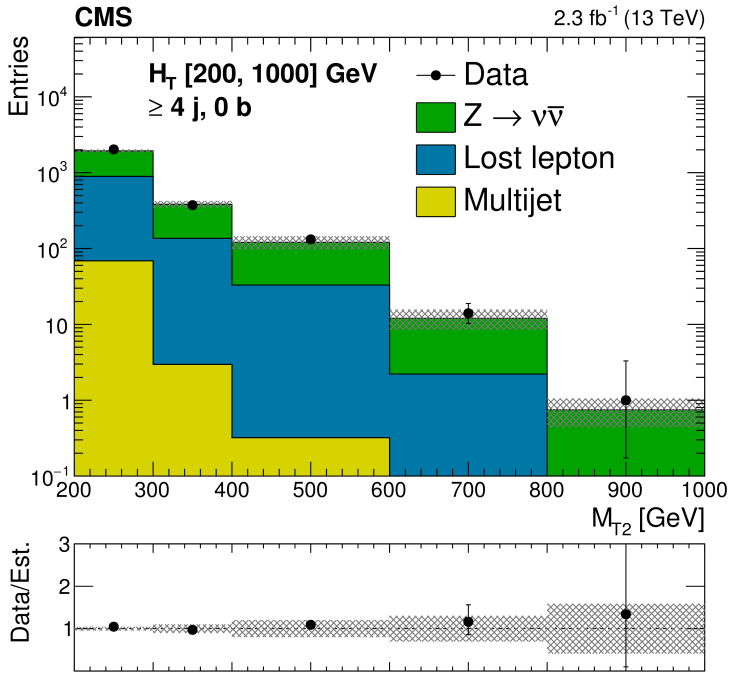
All-hadronic searches

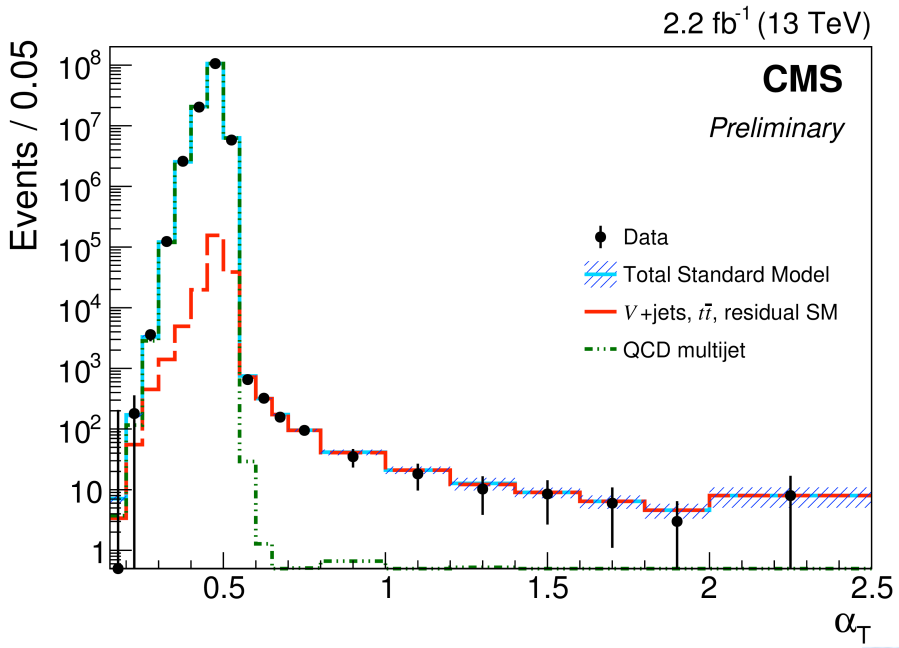
1602.06581, 1603.04053
SUS-15-005

Most all-hadronic searches cover a large model range; typical variables:

- $H_T = \Sigma\, p_T$ (jets), $MH_T = |-\Sigma\, \vec{p}_T$ (jets)|, $ME_T = |-\Sigma\, \vec{p}_T$ (all objects)|
- $M_{T2} = \min_{\vec{p}_T^{\,miss\,X(1)} + \vec{p}_T^{\,miss\,X(2)} = \vec{p}_T^{\,miss}} \left[\max\left(M_T^{(1)}, M_T^{(2)} \right) \right]$

$\alpha_T = p_T^{j2} / M_T$(dijet-system)





All-hadronic searches

1602.06581, 1603.04053
SUS-15-005

Main backgrounds in all-hadronic searches:

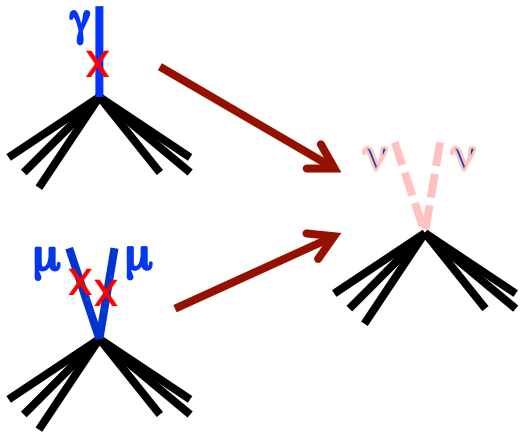
- W+jets and ttbar (with leptonic W decay, but lepton is 'lost')
- QCD multijets (misreconstructed jets might lead to large ME_T)
- $Z \rightarrow \nu\nu$+jets (mimics signal)

All backgrounds determined from data:

- Define control regions (CR) orthogonal but kinematically similar to signal regions (SR)
- Use (partly simulation-based) transfer factors to translate CR yields into SR predictions

Example: $Z \rightarrow \nu\nu$+jets prediction with γ+jets and $Z \rightarrow \mu\mu$

- Declare photon or muons invisible
- Re-calculate MH_T for this event
- Correct for the photon reconstruction efficiency, neutrino branching ratio, cross section ratio, $R_{Z/\gamma}$ and residual differences btw. data and MC

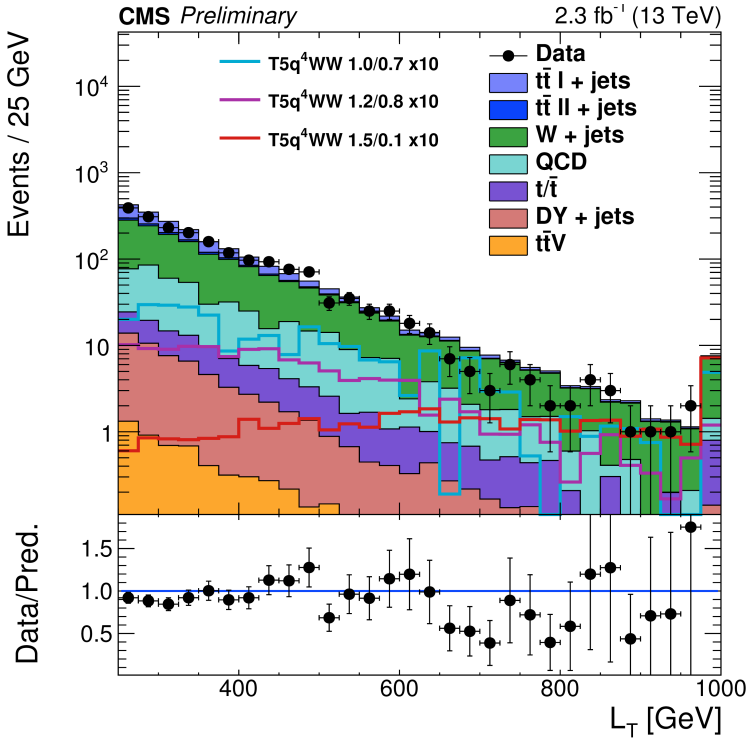


Single-lepton inclusive searches

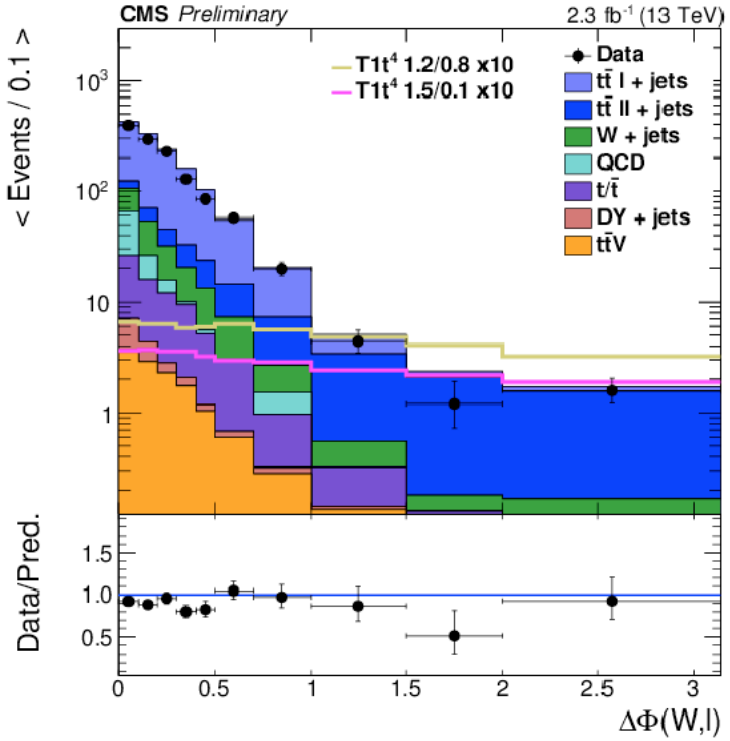
SUS-15-006
1605.04608

Mostly also quite inclusive, and less QCD multijet background; typical variables:

- $L_T = \Sigma\, p_T$ (lepton)+ME_T



$\Delta\Phi$(W,lepton)

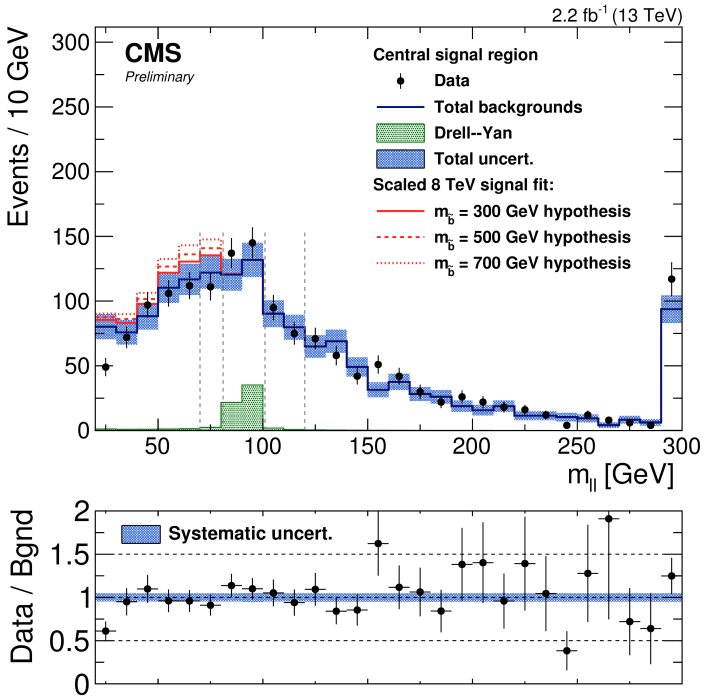


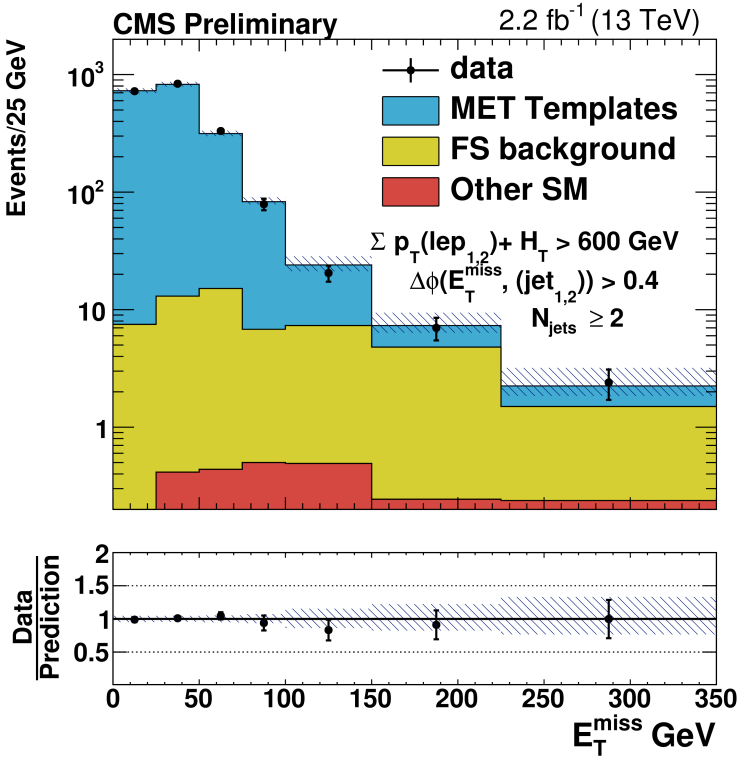
Di-lepton searches

SUS-15-011

Opposite-sign dileptons:

- Mass edge could be visible for some SUSY decays
- Largest deviation from SM prediction with 8 TeV data (ATLAS:on-Z; CMS: off-Z)





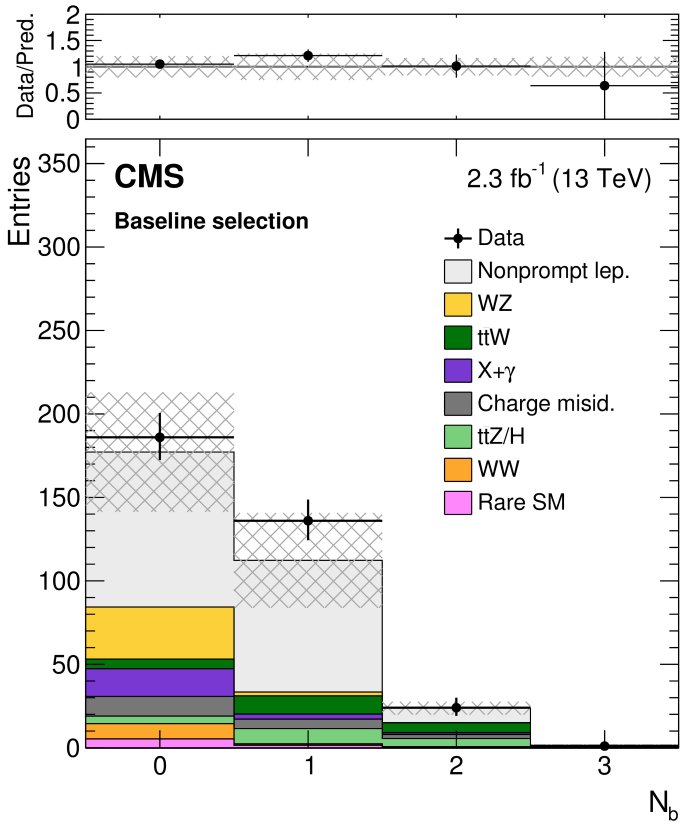
No signal with 13 TeV data

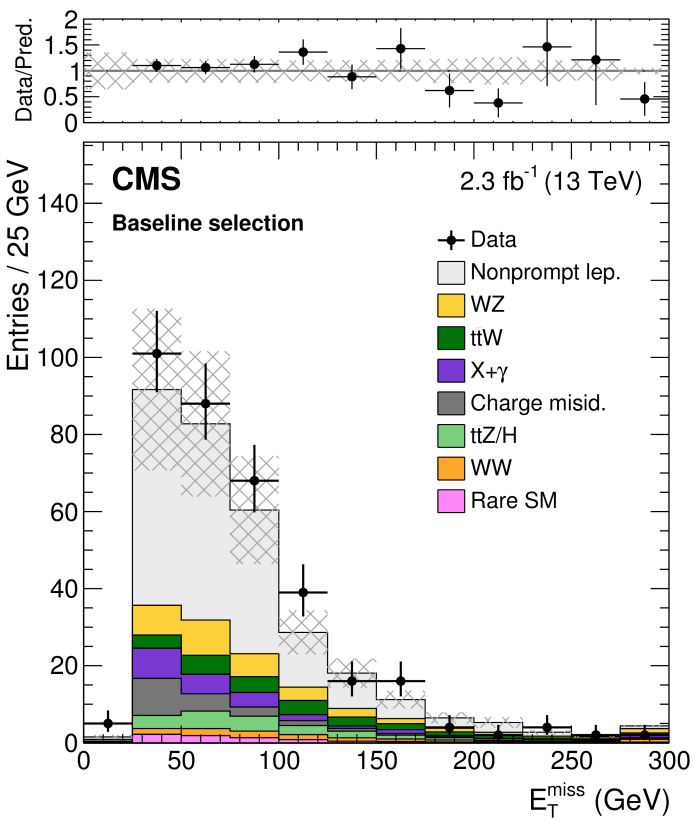
Di-lepton searches

1605.03171

Same-sign dileptons: very clean signature, SM background very low

- Main backgrounds:
  - Non-prompt leptons (HF decays, hadrons, μ from meson decays, γ-conversions,...)
  - SM processes with SS dileptons (WZ, ttV)
  - Charge misidentification



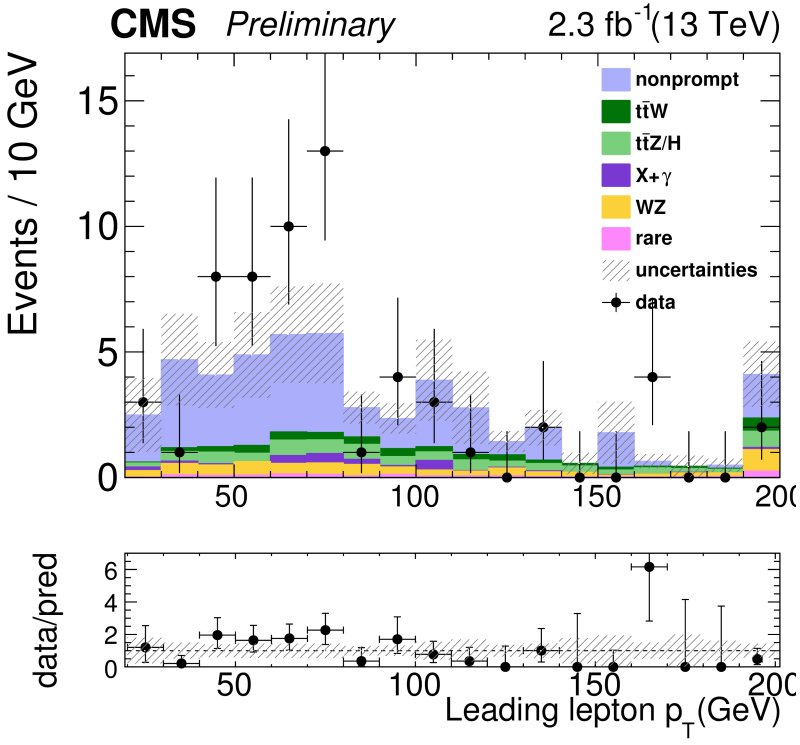


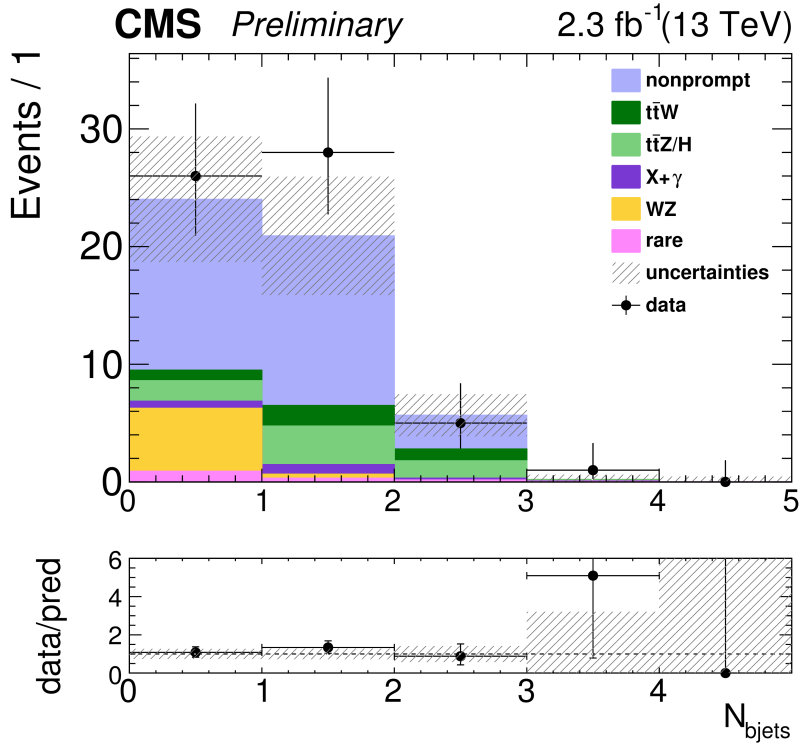
Multilepton searches

SUS-16-003

Multilepton final states expected for many BSM models

- Main backgrounds:
  - Nonprompt leptons (HF decays, hadrons, μ from meson decays, γ-conversions,...)
  - Diboson production (WZ,ZZ), ttV



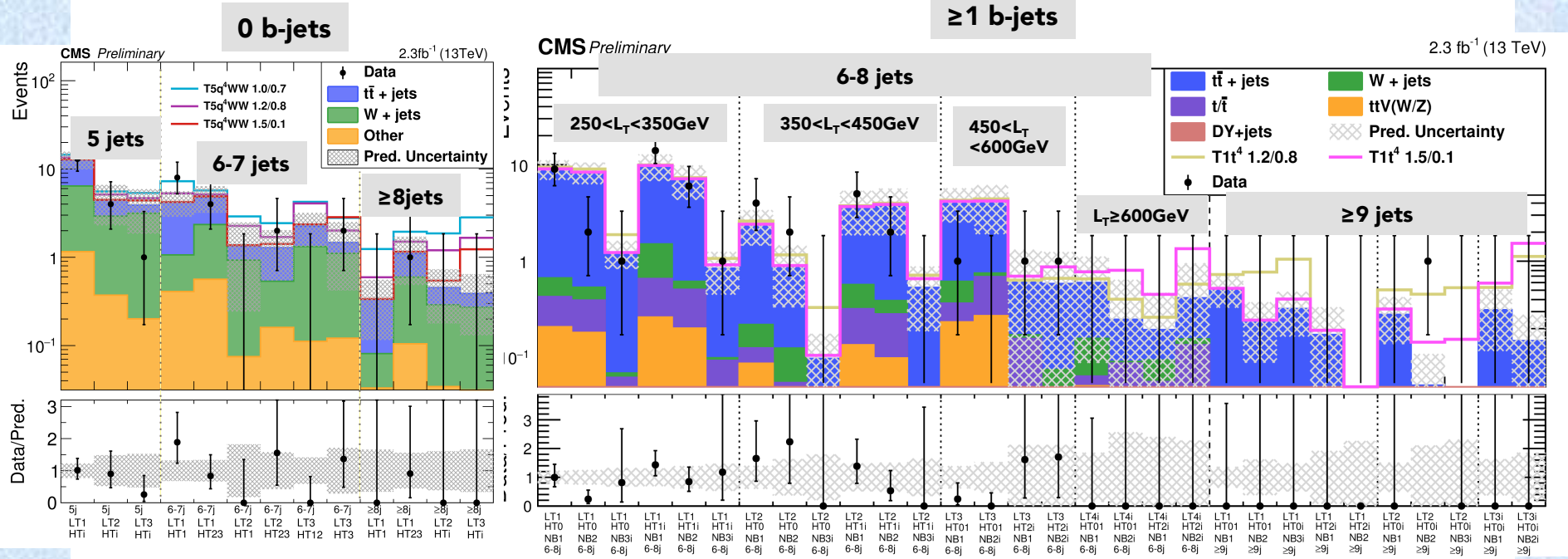


Signal regions

Most analysis define **exclusive signal regions in bins of several variables**:

Example: single-lepton search, binned in:

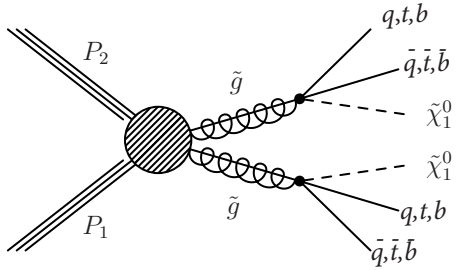
- Number of b-tagged jets
- Number of jets
- L_T
- H_T

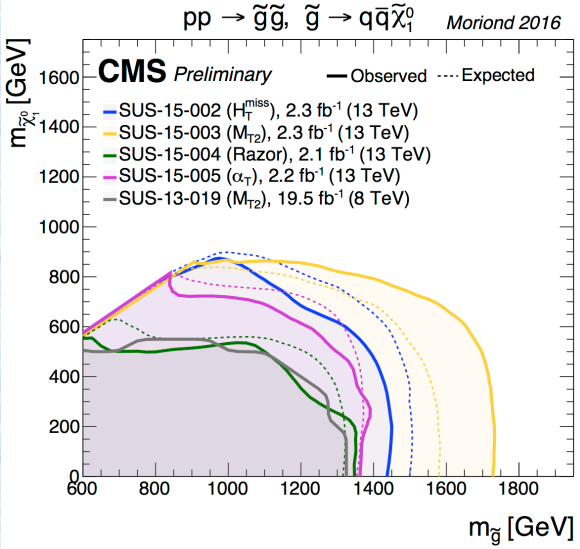


No signal observed

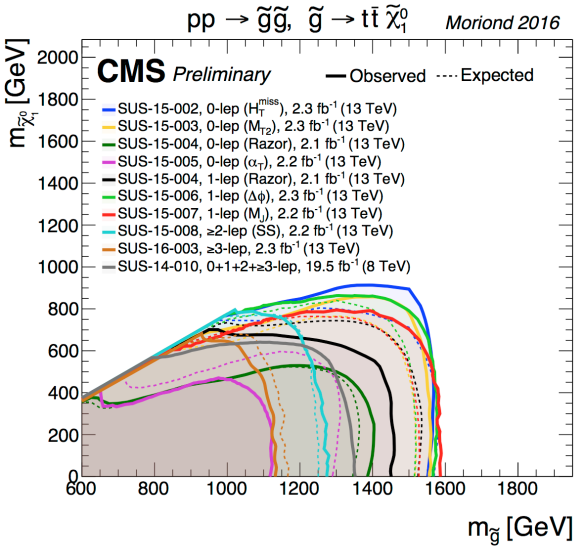
Exclusion limits: gluino production

No signal observed in any search → set limits on neutralino vs gluino mass

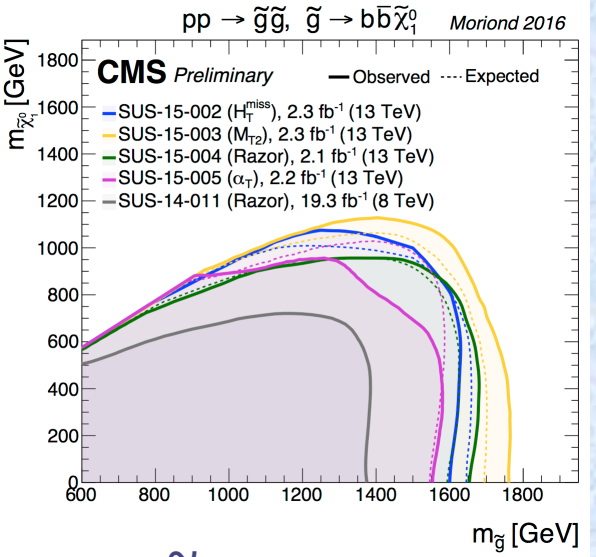




$m(\tilde{g})$ < 1.72 TeV
$m(\tilde{\chi}^0)$ < 850 GeV



$m(\tilde{g})$ < 1.6 TeV
$m(\tilde{\chi}^0)$ < 900 GeV



$m(\tilde{g})$ < 1.75 TeV
$m(\tilde{\chi}^0)$ < 1.1 TeV

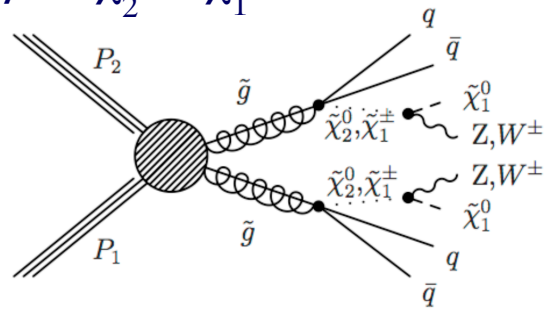
8 TeV limits superseded by more than 200 GeV

Exclusion limits: gluino production

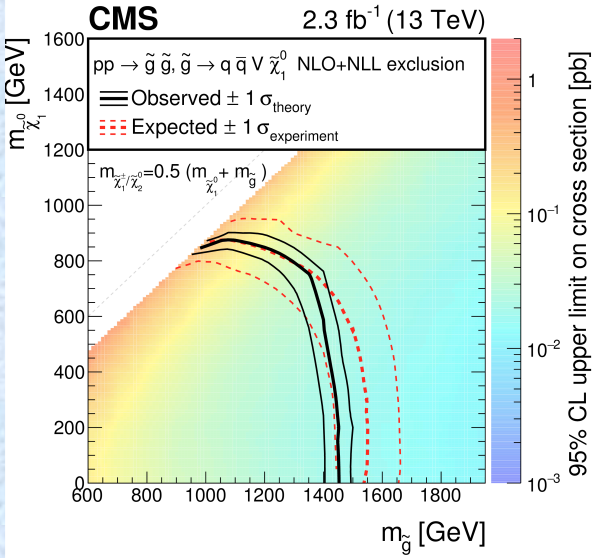
No signal observed in any search → set limits on neutralino vs gluino mass

Exclude decays to light quarks with intermediate decay to $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm$

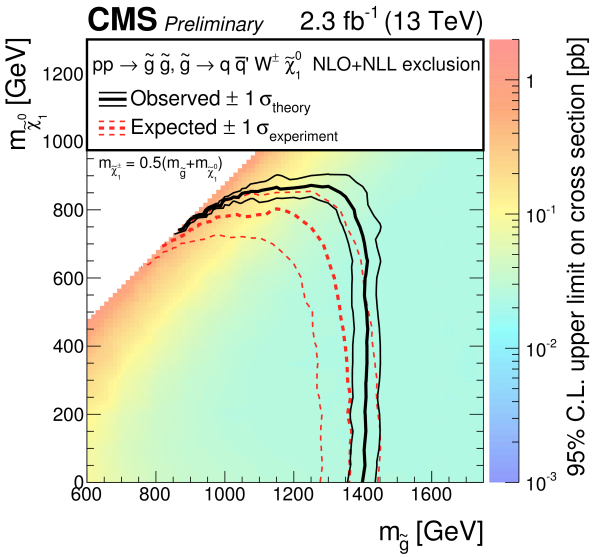
- all-hadronic and single-lepton search have similar sensitivity
- multi-lepton search stronger in searches for EWKinos



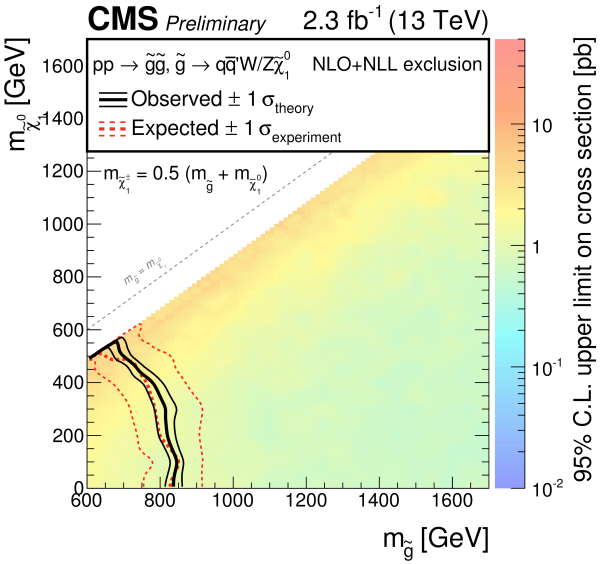
all-hadronic
1602.06581



single-lepton
SUS-15-006



multi-lepton
SUS-16-003

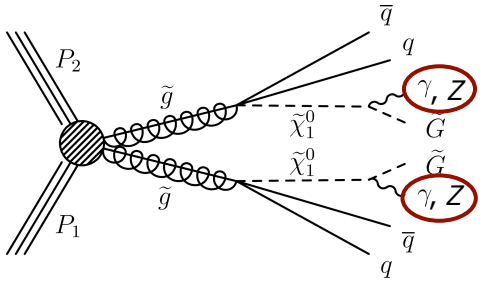


Gluino production in GMSB models

SUS-15-011
SUS-15-012

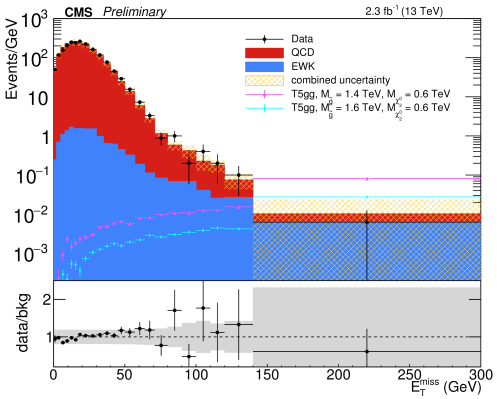
SUSY models with gauge mediation often predict:

- Photons, W or Z bosons
- Gravitino LSP
- Neutralino NLSP

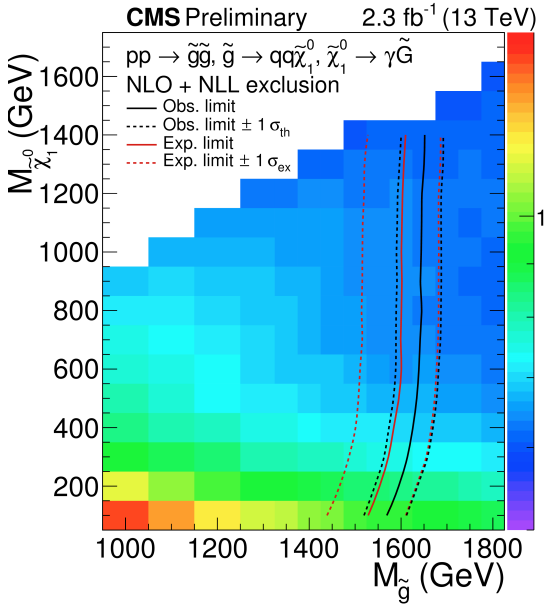


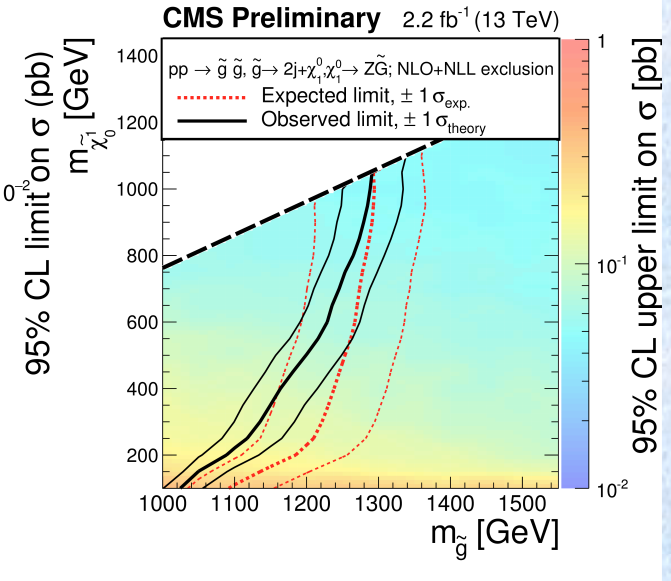
Main backgrounds in searches with photons:

- QCD multijets with mismeasured jets leading to ME_T
- EWK background with intrinsic ME_T and misidentified γ



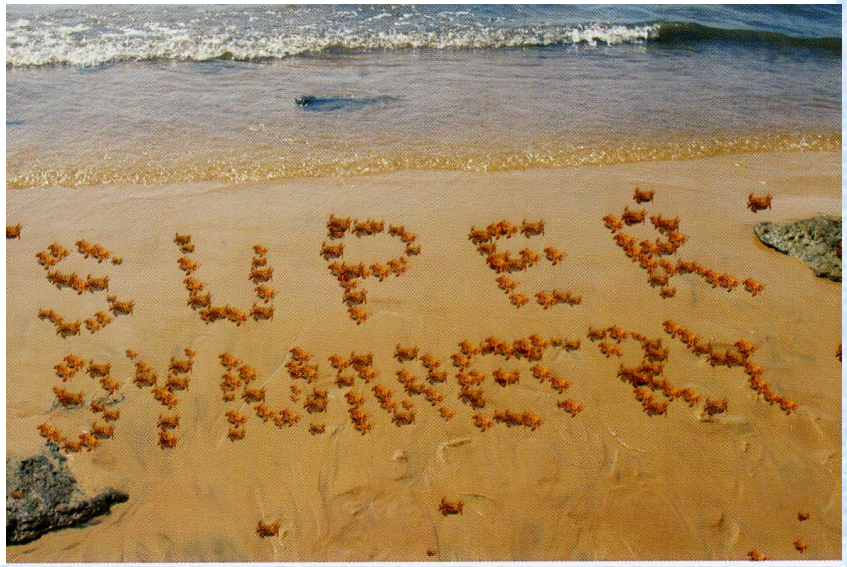
No signal observed





Where we are...

- Introduction
- **Searches**
  - **Gluino-pair production**
    - all-hadronic final states
    - leptonic final states
  - ⇨ **Squark-pair production** ⇦
    - all-hadronic final states
    - leptonic final states
- Summary



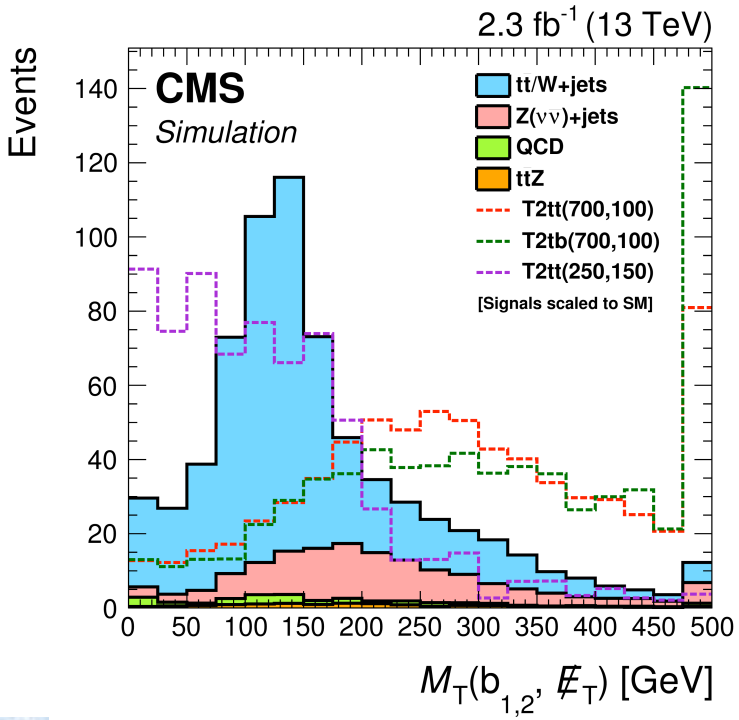
All-hadronic searches

SUS-16-001, SUS-16-007

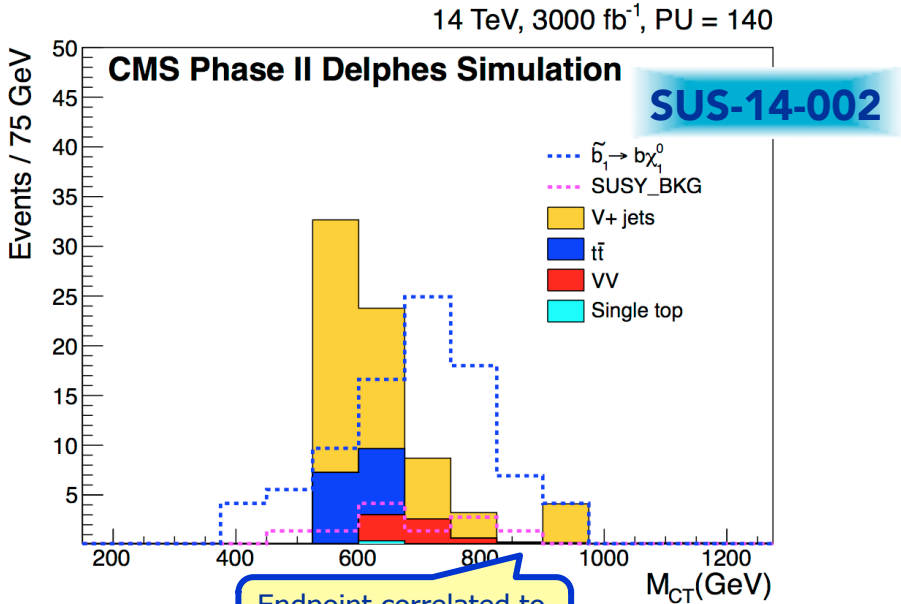
All-hadronic searches are usually sensitive to pair production of light squarks in search regions with lower jet multiplicity

Specialized searches for sbottom and stop pair production; typical variables:

- M_T ($b_{1,2}$, MET)= min(M_T(bjet1,MET),M_T(bjet2,MET))

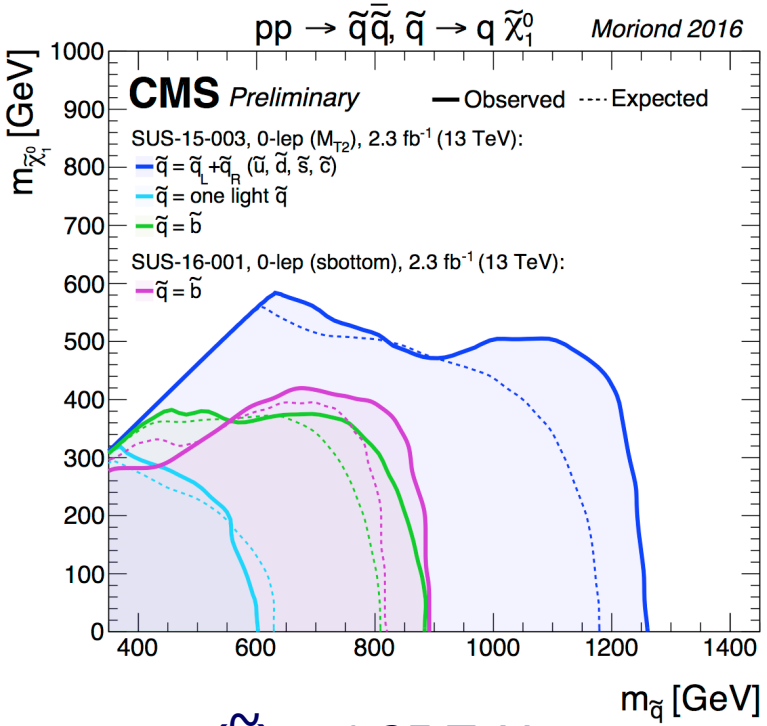


- $M_{CT} \approx \sqrt{2p_T^{j1}p_T^{j2}(1+\cos\Delta\Phi^{j1,j2})}$



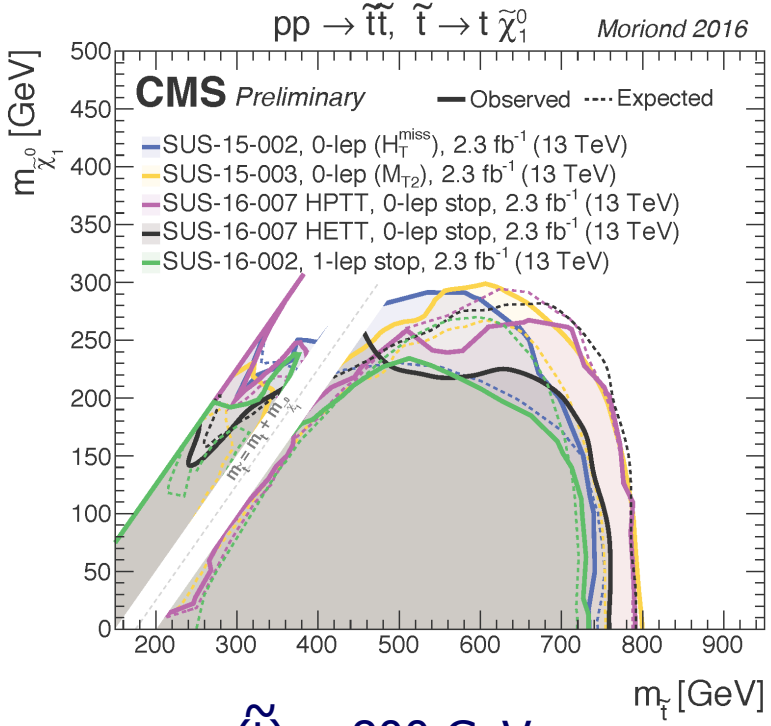
Exclusion limits: squark production

No signal observed in any search → set limits on neutralino vs squark mass



$m(\tilde{q}) < 1.25$ TeV
$m(\tilde{\chi}^0) < 500$ GeV

$m(\tilde{b}) < 900$ GeV
$m(\tilde{\chi}^0) < 400$ GeV



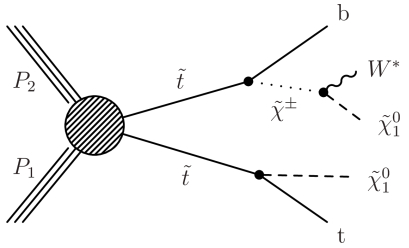
$m(\tilde{t}) < 800$ GeV
$m(\tilde{\chi}^0) < 300$ GeV

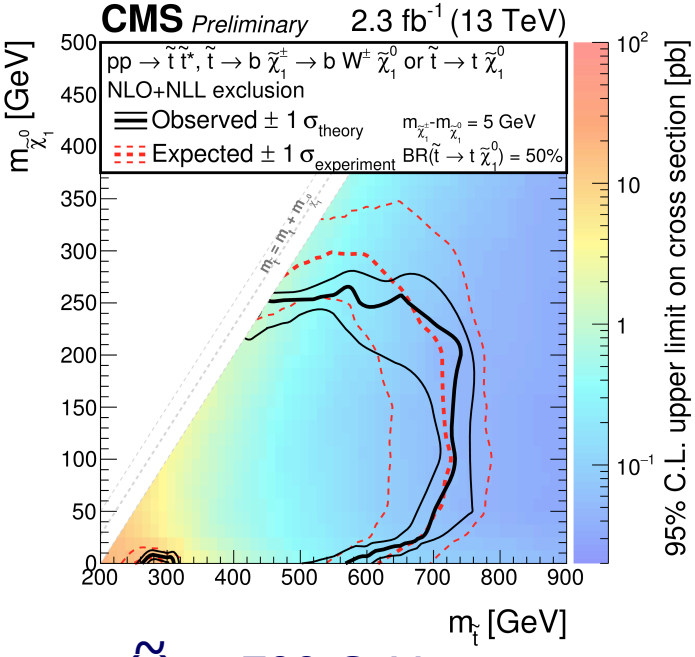
Corridor around $m(\tilde{t}) = m(t) + m(\tilde{\chi}^0)$:
→ difficult due to similarity with top pair production

Exclusion limits: squark production

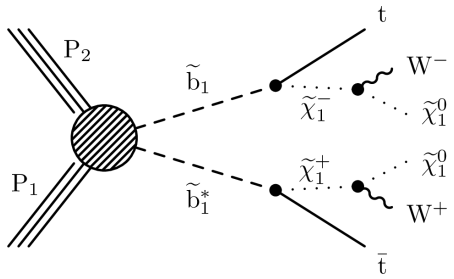
SUS-16-002
SUS-16-004
SUS-16-007

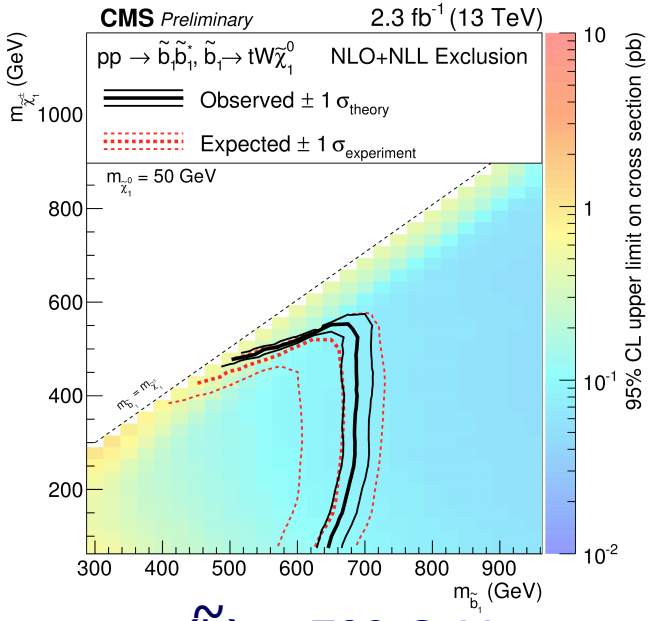
No signal observed in any search → set limits on neutralino vs squark mass





m($\tilde{t}$) < 700 GeV
m($\tilde{\chi}^0$) < 250 GeV





m($\tilde{b}$) < 700 GeV
m($\tilde{\chi}^0$) < 500 GeV

Where we are...

- Introduction
- Searches
  - gluino-pair production
  - squark-pair production

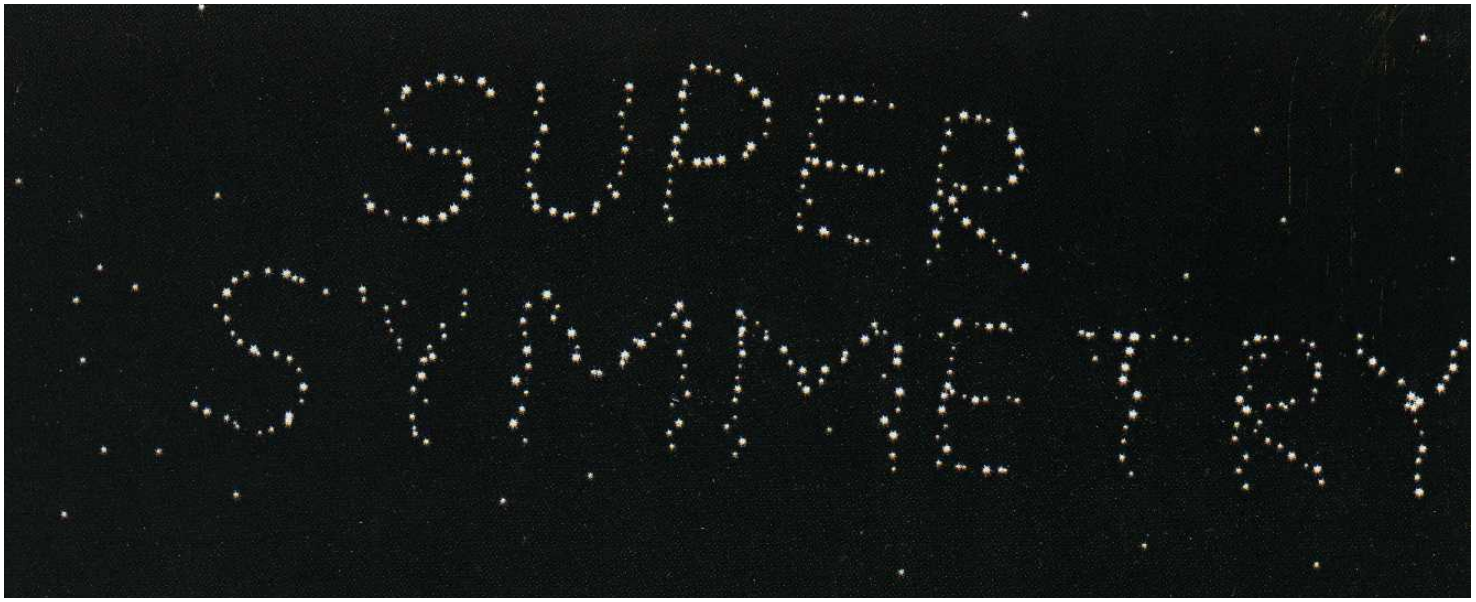
Summary

Summary and Outlook

First results on SUSY searches with 2.3 fb^{-1} of 13 TeV data have been presented

- No signal observed
- Exclusion limits on gluino-pair and squark-pair production exceed already the 8 TeV results by more than 200 GeV
- With data from the 2016 run, sensitivity to electroweak production will open up

  → searches for neutralinos, charginos and sleptons will become sensitive



BACKUP

All-hadronic searches

1602.06581, 1603.04053
SUS-15-005

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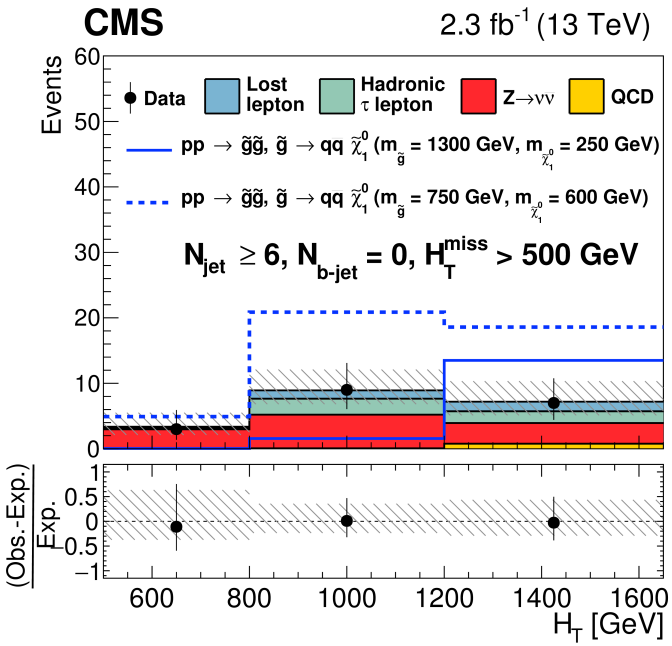
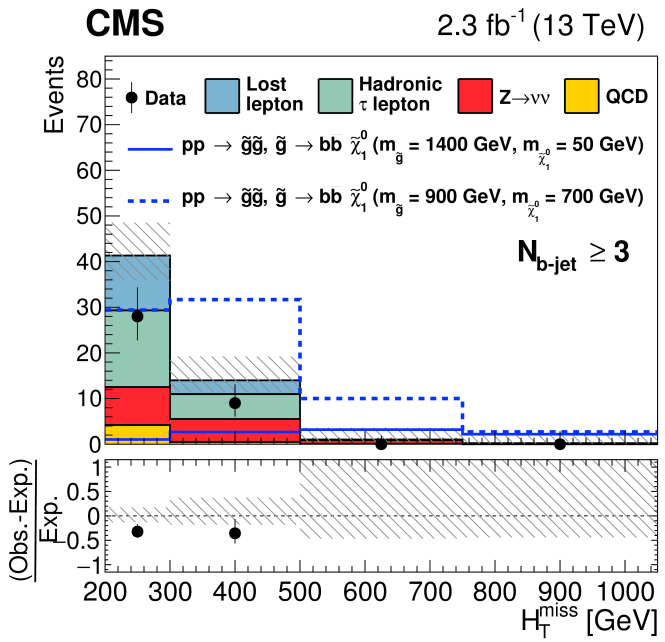
$MH_T = |\, -\Sigma\, \vec{p}_T$(jets)$|$





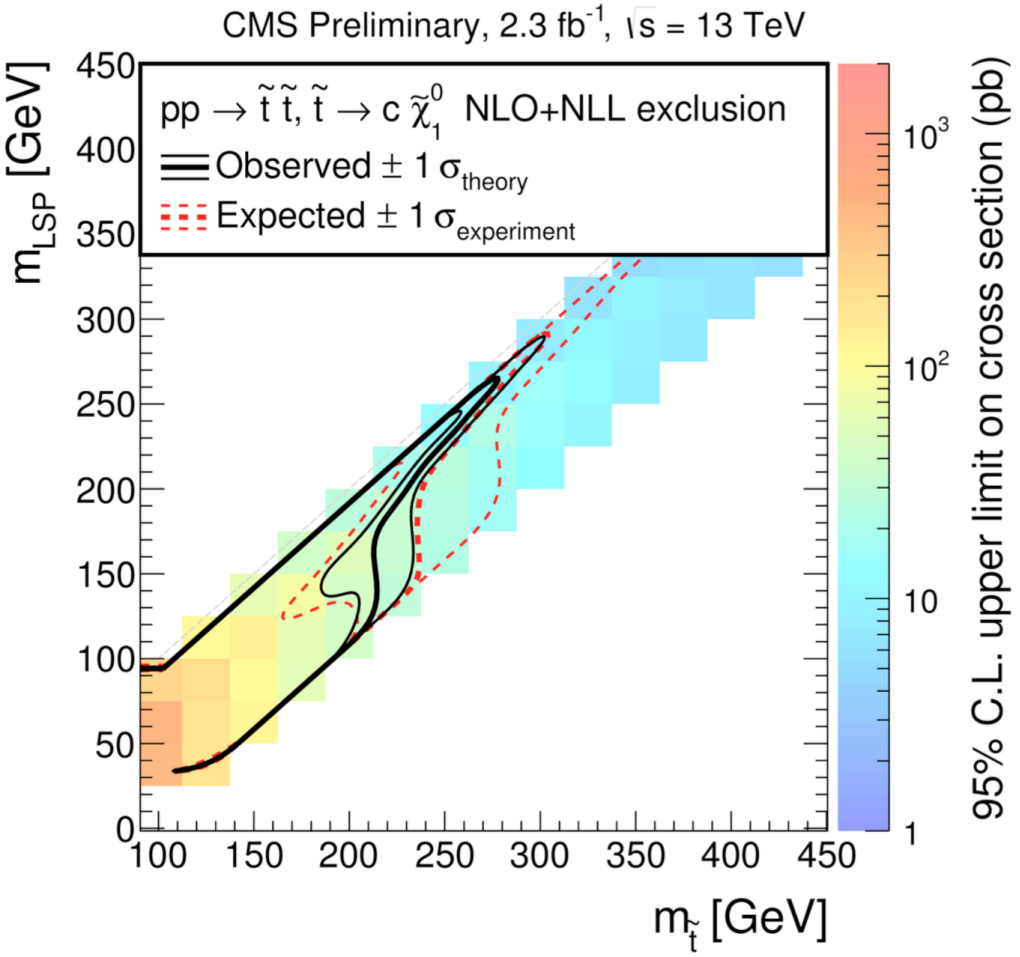
Di-lepton search – signal regions

Comparison ATLAS - CMS

N_{jets} / H_T	$N_{b\text{-jets}}$	E_T^{miss} (GeV)	Predicted	Observed
SRA	0	100-150	$29.1\ ^{+5.3}_{-4.7}$	**28**
		150-225	$9.1\ ^{+3.2}_{-1.9}$	**7**
		225-300	$3.4\ ^{+2.5}_{-1.0}$	**6**
2–3 jets		> 300	$2.1\ ^{+1.4}_{-0.7}$	**6**
	≥ 1	100-150	$14.3\ ^{+4.4}_{-3.2}$	**21**
		150-225	$6.9\ ^{+3.6}_{-2.3}$	**6**
and $H_T > 400$ GeV		225-300	$6.1\ ^{+3.6}_{-2.3}$	**1**
		> 300	$1.5\ ^{+2.4}_{-0.9}$	**3**
SRB	0	100-150	$23.6\ ^{+4.9}_{-3.7}$	**20**
		150-225	$8.2\ ^{+3.4}_{-2.1}$	**10**
		225-300	$0.8\ ^{+1.2}_{-0.2}$	**2**
		> 300	$1.5\ ^{+2.4}_{-0.9}$	**0**
≥ 4 jets	≥ 1	100-150	$44.7\ ^{+7.7}_{-6.6}$	**45**
		150-225	$16.8\ ^{+5.1}_{-3.9}$	**23**
		225-300	$0.6\ ^{+1.2}_{-0.3}$	**4**
		> 300	$1.5\ ^{+2.4}_{-0.9}$	**3**
ATLAS - SR:				
$H_T + p_T^{l_1} + p_T^{l_2} > 600$ GeV	$E_T^{miss} > 225$ GeV	$\Delta\phi_{E_T^{miss},j_1,j_2} > 0.4$	$12.3\ ^{+4.0}_{-2.8}$	**14**

Limit for t→cx

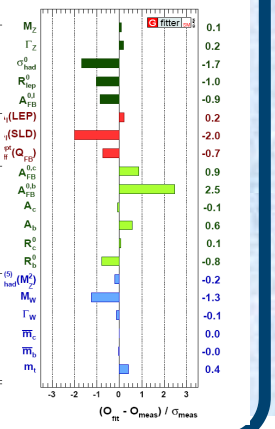
$m(\tilde{t}) < m(b) + m(W) + m(\tilde{\chi}^0)$



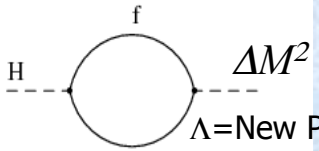
The Standard Model

Finally complete!
Predictive!
Good agreement with data!

Parameter	Input value	Fit value
M_Z [GeV]	91.1875 ± 0.0021	91.1876 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023	2.4956 ± 0.0015
σ^0_{had}	41.540 ± 0.037	41.478 ± 0.014
R^0_l	20.767 ± 0.025	20.741 ± 0.018
$A^{0,l}_{FB}$	0.0171 ± 0.0010	0.01624 ± 0.0002
A_l (LEP)	0.1465 ± 0.0033	0.1473 ± 0.0009
A_l (SLD)	0.1513 ± 0.0021	$0.1465^{+0.0007}_{-0.0010}$
$\sin^2\theta^l_{eff}(Q_{FB})$	0.2324 ± 0.0012	$0.23151^{+0.00010}_{-0.00012}$
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0737 ± 0.0005
$A^{0,b}_{FB}$	0.0992 ± 0.0016	$0.1032^{+0.0007}_{-0.0006}$
A_c	0.670 ± 0.027	$0.6679^{+0.00042}_{-0.00026}$
A_b	0.923 ± 0.020	$0.93463^{+0.00007}_{-0.00008}$
R^0_c	0.1721 ± 0.0030	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	0.21577 ± 0.00005
$\Delta\alpha^{(5)}_{had}(M_Z^2)$	2768 ± 22	2764^{+22}_{-21}
M_W [GeV]	80.399 ± 0.023	$80.371^{+0.008}_{-0.011}$
Γ_W [GeV]	2.098 ± 0.048	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	1.25 ± 0.09
$\overline{m}_b$ [GeV]	4.20 ± 0.07	4.20 ± 0.07
m_t [GeV]	173.1 ± 1.3	173.6 ± 1.2



Radiative corrections to Higgs mass:

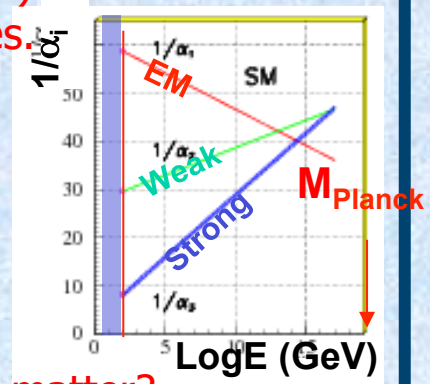


$$\Delta M^2 = \kappa \Lambda^2_{NP}$$

Λ=New Physics Scale

Neutrinos are massive.
Fermion masses stretch over 13 orders of magnitude (from neutrino to top quark).

(Non-)unification of the forces.

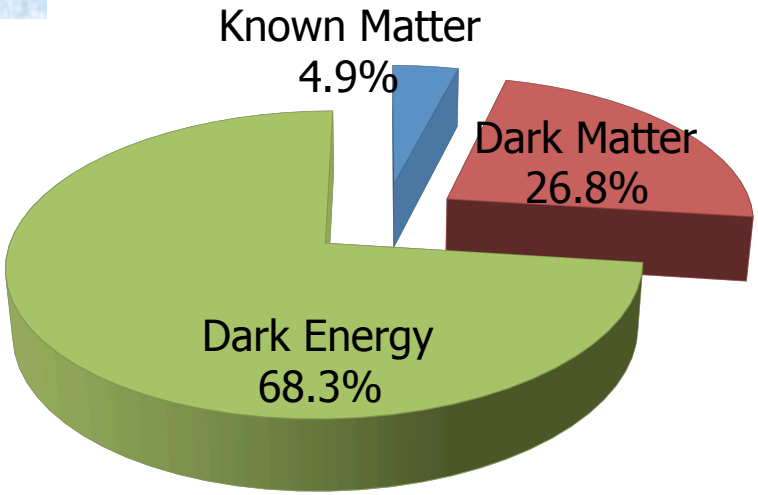


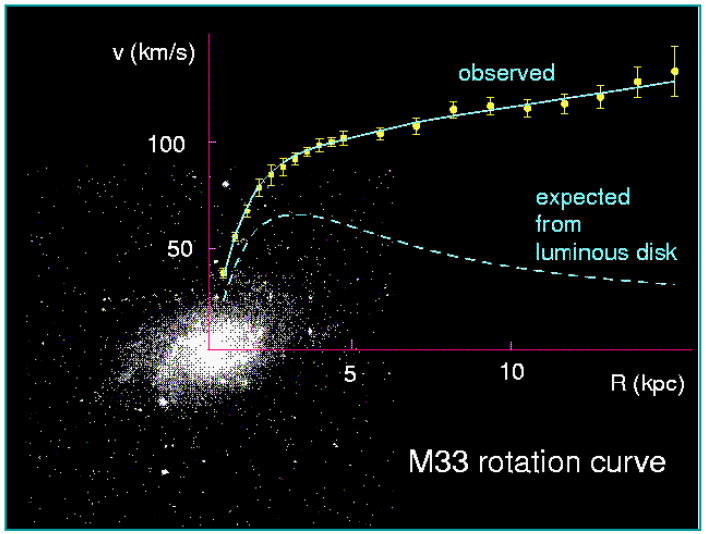
Dark matter?
Where is the anti-matter?
How to include gravity?

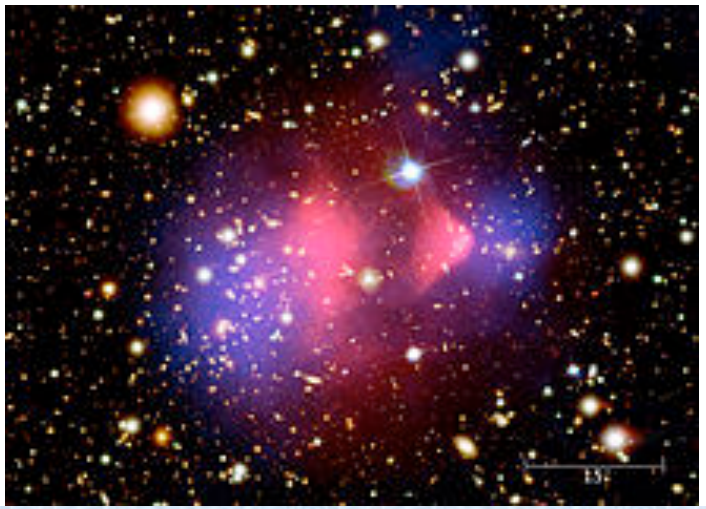
Dark Matter

We don't know much about the largest part of the universe!

Galaxy rotation curves







Bullet cluster(1E 0657-558),
two colliding clusters of galaxies:

- Light-emitting matter
- Dark matter

Introduction to Supersymmetry

SUSY: a beautiful and straight-forward extension of the SM…

- Only possible extension of the Poincare group
- Solves most SM questions (Includes gravity, Dark Matter, unification of the forces
- Predicts a light Higgs
- Perturbative → predictive

- Predicts many new scalar particles
- We don't know their masses
- Hard to find (at least up to now…)
- Adds new quantum number to prevent p decay, but otherwise not theoretically motivated…

- Escaped 30 years of searches!
- SUSY breaking not understood (soft breaking in hidden sector?)
- We are flowed by 105 new parameters…

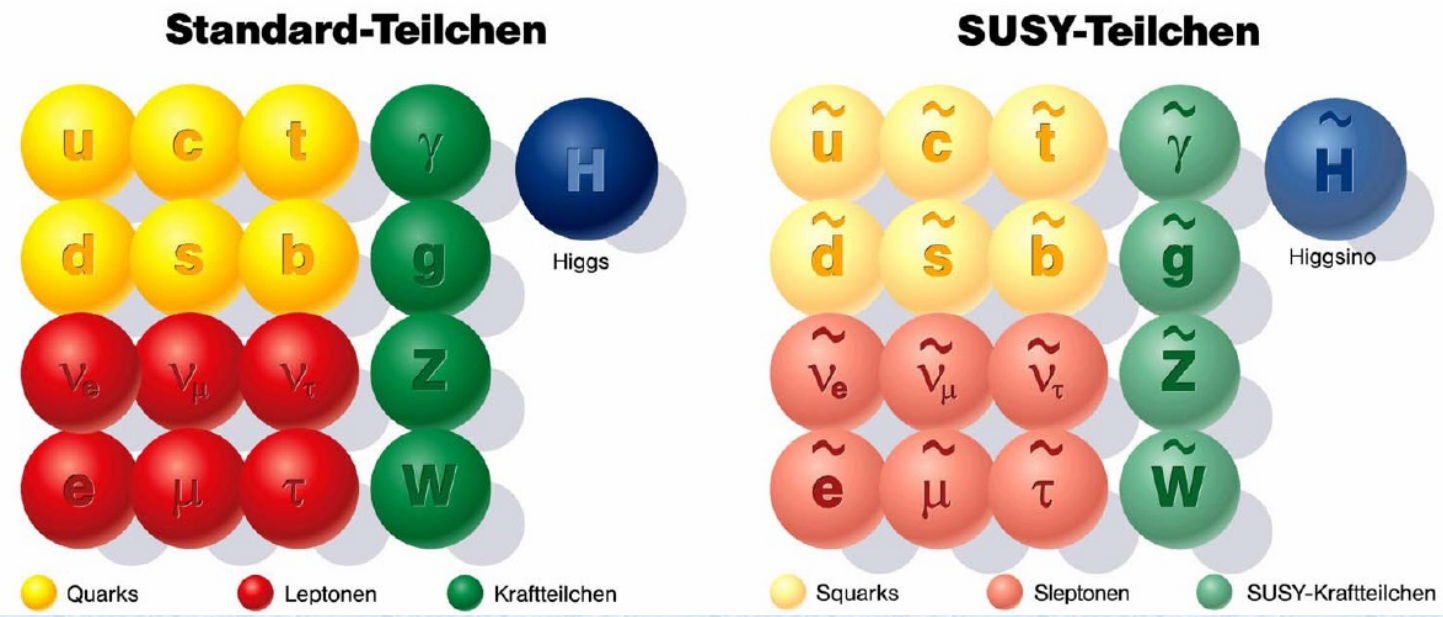
Supersymmetry

Each SM particle gets assigned a SUSY partner particle with spin differing by ½
SUSY transformation:

- Q |fermion> = |boson>
- Q |boson> = |fermion>

Name convention:

- Fermion ←→ S-fermion
- Boson ←→ bos(on)-ino



SUSY Particles

Overview of Particles

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$ $\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$ $\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	(same) (same) $\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$ $\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$ $\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

5 physical Higgs bosons

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

$\chi_1^{+/-}\ \chi_2^{+/-}$

SUSY Models

MSSM → 105 free parameters (masses, couplings, phases)

pMSSM → 19 free parameters (first two sfermion generations degenerate, and with negligible Yukawa couplings)

- 10 sfermion masses
- 3 gaugino masses
- 3 tri-linear couplings (A_b,A_t,$A\tau$)
- μ, M_A, tanβ

CMSSM → 4 free parameters
+ 1 phase

- tanβ, A_0, M_1, $M_{1/2}$, sign(μ)

NMSSM → contains one extra singlet chiral superfield
→ solves μ problem (μ at EW and not Planck scale)

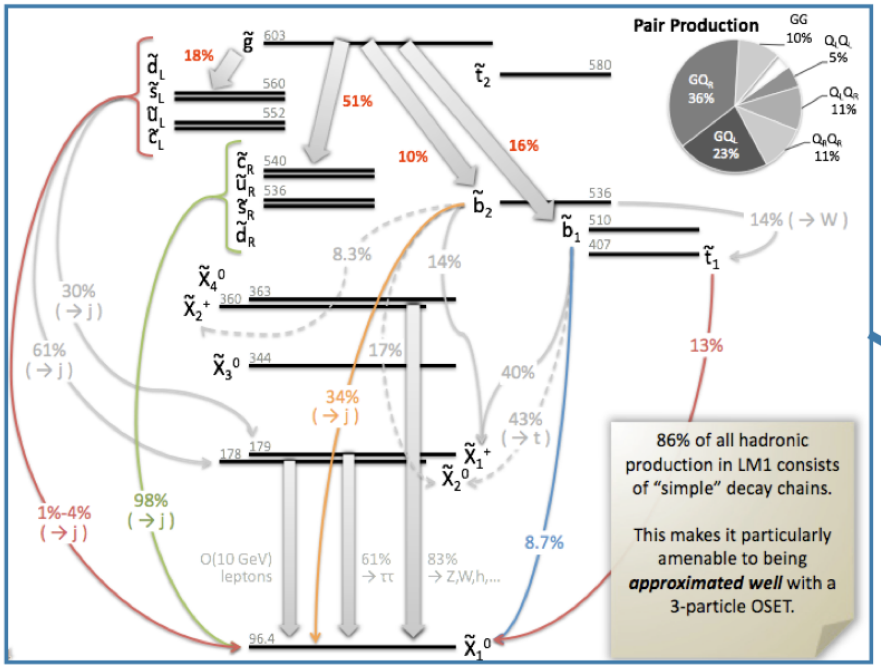
MSSM

Full vs. simplified Model

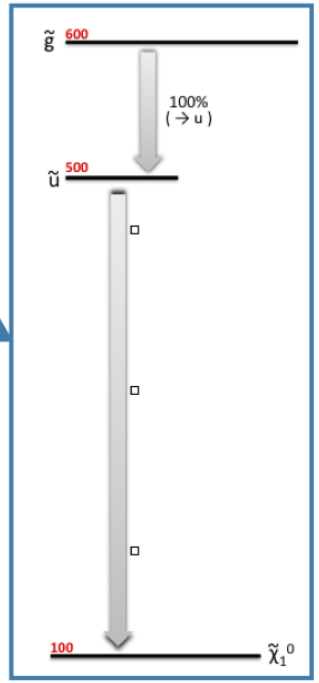
Past: interpretation in CMSSM

Present: try to make it more easier for theorists to compare their model to our result → use simplified model!

CMSSM



What we put in: much simpler…



Simplified Model Spectrum (SMS) with 3 particles, 2 decay modes

Future: ???