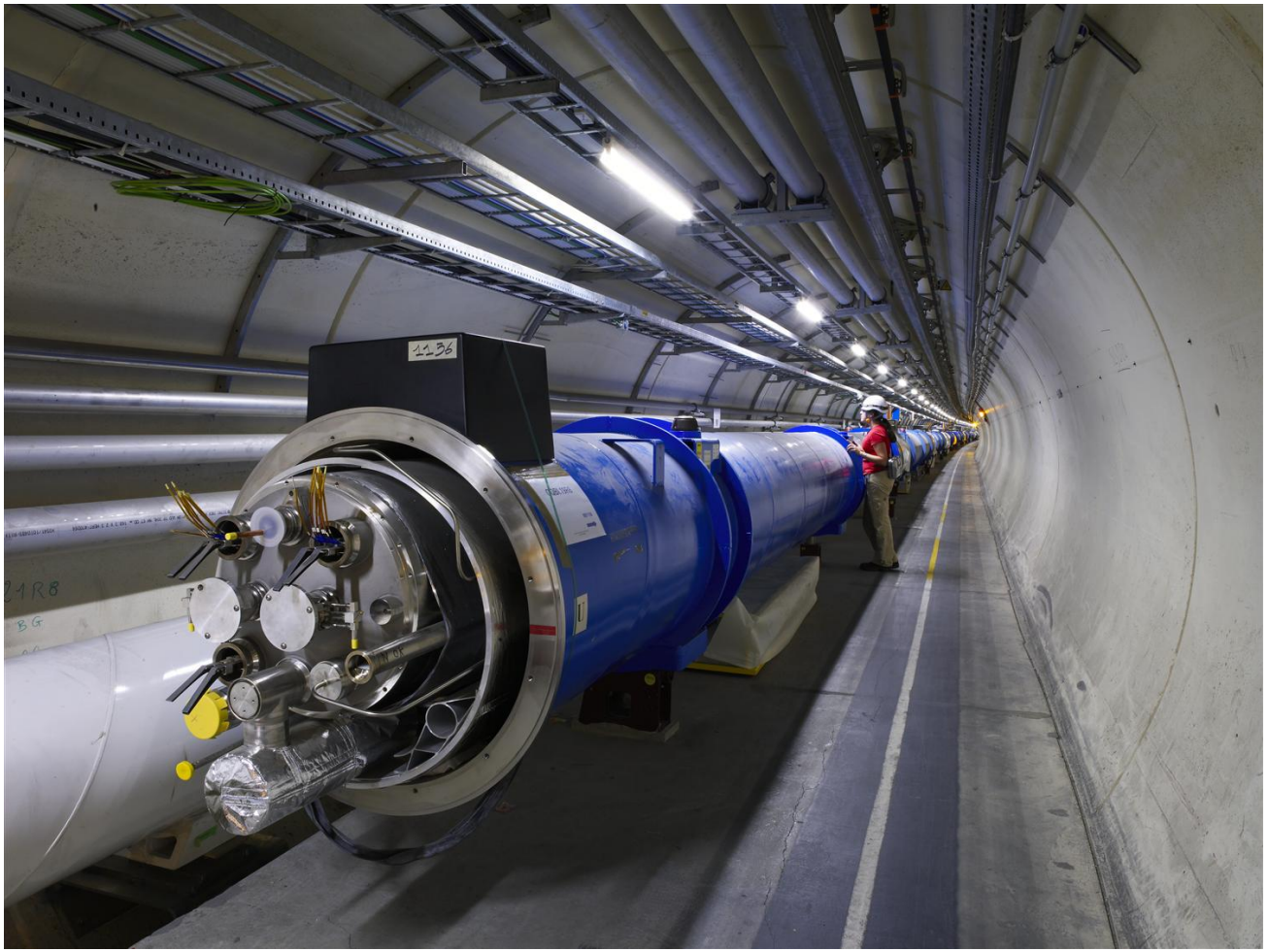
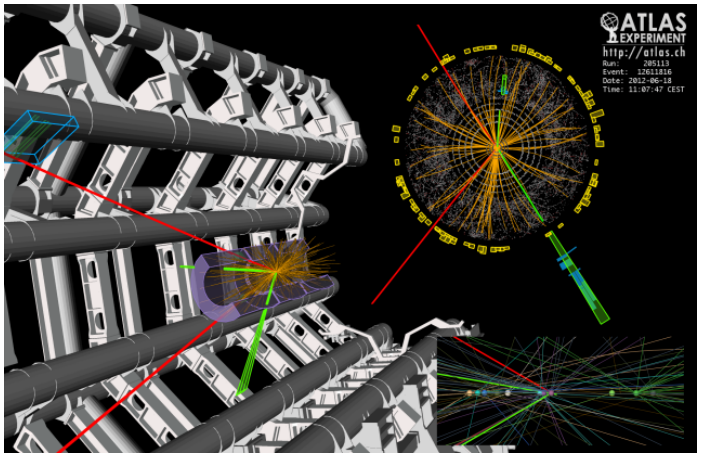
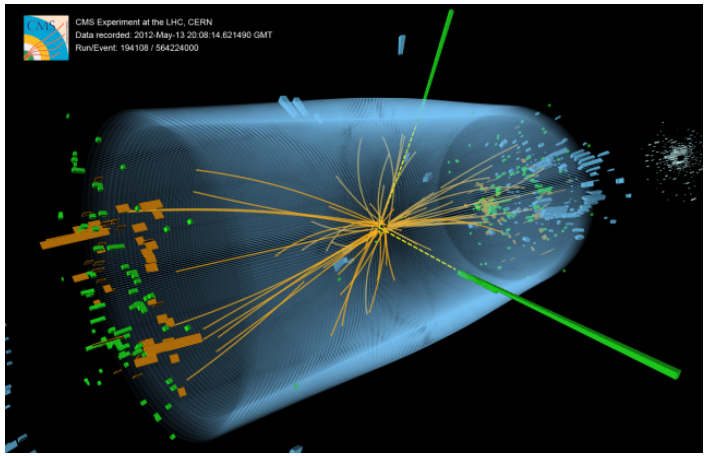






SUSY and BSM Highlights from the LHC

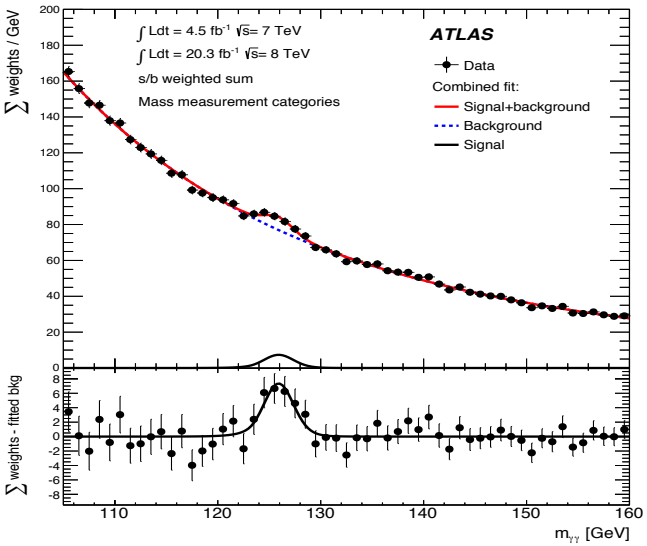
J. Pilcher – August 25, 2014

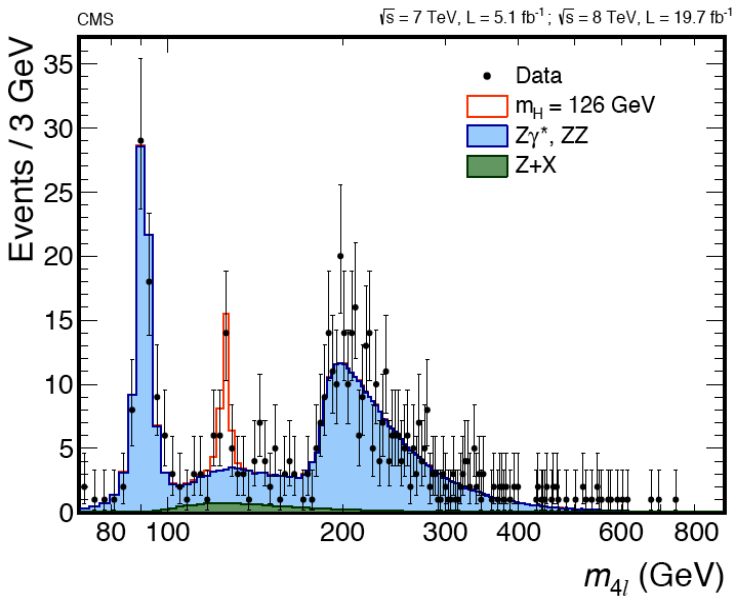
Introduction

- Theme this week is advancing the energy frontier
- Driving argument for a new facility is likely to be discovery through higher energy
- LHC results will be critical to the argument
  - current energy frontier
  - BSM discoveries at the LHC could be just the tip of the iceberg
- Do we expect BSM physics or are we shooting in the dark?

Where's the problem?

- The Higgs boson exists and has couplings close to SM values



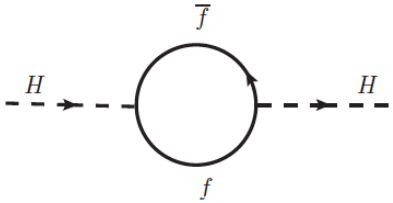


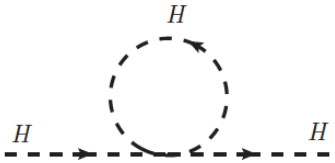
$M_H = 125.15 \pm 0.24$ GeV

- Important input to BSM issues
  - coupling measurements limit new physics (Jeff's talk)
  - mass itself provides important input
- Consider effect of Higgs self-energy corrections (for a fundamental scalar)

$$m_h^2 = m_{h0}^2 + \Delta m^2$$

Physical mass — Bare mass — Correction



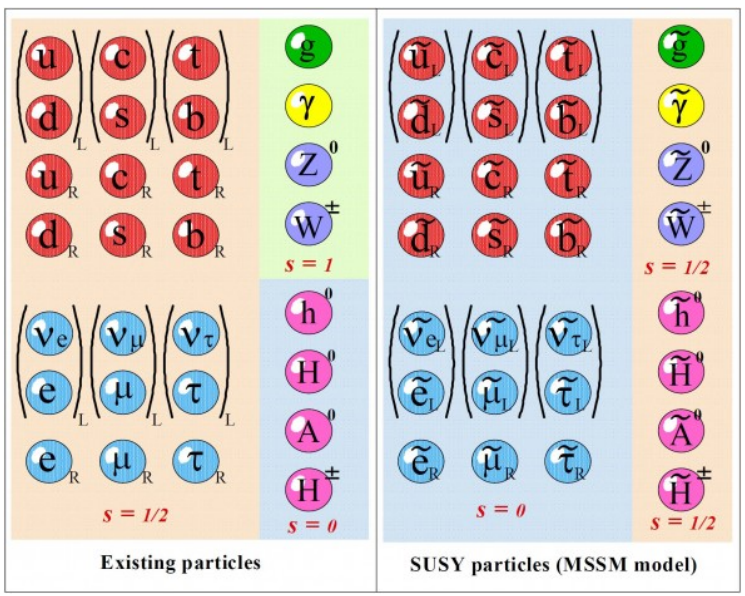


Naturalness Problem

$$\Delta m^2 \sim \frac{\Lambda^2}{16\pi^2}$$

Λ is energy scale of new physics or Planck mass

- The "correction" can be far larger than the mass itself
  - for $\Lambda \sim M_{Pl}$, $\Delta m^2 / m_h^2 \sim 10^{30}$
- supersymmetry is one answer
  - bosons enter the loop terms with the opposite sign to fermions and the divergence is cancelled
  - the price is a doubling of the mass spectrum and > 100 new parameters



- but many positive features
  - enables hierarch between EW and Planck scales
  - generates EW symmetry breaking
  - allows gauge coupling unification at ~10^{16} GeV
  - has candidate for dark matter
  - allows EW baryogenesis
  - important in string theories
  - simplest form (MSSM) predicts a light Higgs with

$$m_h < 135 \text{ GeV}$$

Expected properties of MSSM

- SUSY is broken so masses of new states differ from their partners
  - may be much more massive

Natural SUSY if $M_{SUSY} \sim M_{Weak}$

- in MSSM Higgs sector is expanded to (h, H^0, A^0, $H^{\pm}$), with h being the lightest

$$m_h^2 = m_Z^2 \cos^2 2\beta + \Delta M^2 (m_{\tilde{t}_1}, m_{\tilde{t}_2}, \ldots)$$

  - for $m_h = 125\ \mathrm{GeV}$ and no stop mixing $m_{\tilde{t}} \leq 4\ \mathrm{TeV}$ (smaller with mixing)

Feng, 3-loop calculation - arXiv:1306.2318

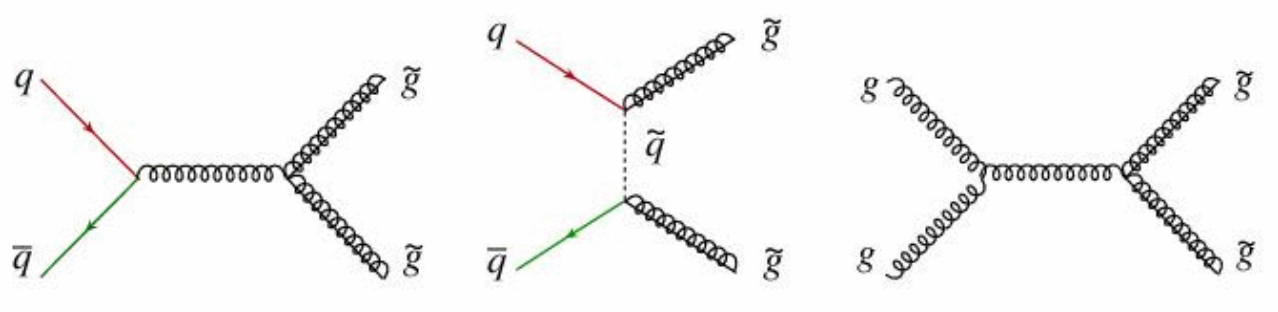
- $M_A >> M_Z$ is a "decoupling limit"
  - h couplings go to SM values
  - M_A, M_{H0}, $M_{H\pm}$ are all large
  - high precision EW relations are preserved

- lightest supersymmetric state may be stable (R-parity conservation)
  - weakly interacting, uncharged
  - missing energy in detected final states
  - candidate for dark matter

R=1 for SM particles
R=-1 for SUSY particles

Observables of the MSSM

- gluinos and squarks carry color charge
  - strongly produced
  - cross sections depend primarily on gluino and squark masses



- Higgsino-gaugino mass eigenstates (spin ½)
  - neutral states $\tilde{h}, \tilde{H}, \tilde{Z}^0, \tilde{\gamma}$ mix to form the neutralino mass eigenstates $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$ with $M_{\chi_1} < M_{\chi_2} < \ldots$

    χ_1^0 could be LSP and dark matter

    expected to be "light" compared to gluinos
  - charged states $\tilde{H}^{\pm}, \tilde{W}^{\pm}$ mix to form the chargino mass eigenstates $\chi_1^{\pm}, \chi_2^{\pm}$
  - electroweak production

Disclaimers

- Additional constraints on SUSY parameter space from
  - lepton number conservation, suppression of FCNC, CP violation, EDM limits
- Supersymmetry is a broad framework with many variants
  - split-SUSY
    - charginos and neutralinos at TeV scale but squarks and sleptons heavy
    - gives up naturalness but preserves DM candidate and gauge coupling unification
  - focus point SUSY
  - high scale SUSY
  - gravity mediated
  - gauge mediated
  - anomaly mediated
  - mSUGRA (4 parameters plus a sign)
    - a.k.a. constrained MSSM (CMSSM)
  - phenomenological MSSM (19 parameters)
  - next-to-minimal SUSY (NMSSM)
  - R-parity violating (RPV) SUSY
- Experimental input is critical to narrow the options

Comment on negative searches

- Many negative searches to follow
  - simplified models assumed

- Significance not limited to the simplified models reported
  - most searches involve a specific event topology or signature

    eg. missing energy, number of jets, b-tagged jets, …

  - a set of signal regions is established
  - observed event rates in signal regions usually agree with SM background expectations
  - results constrain observable cross section in these channels for any non-SM effects

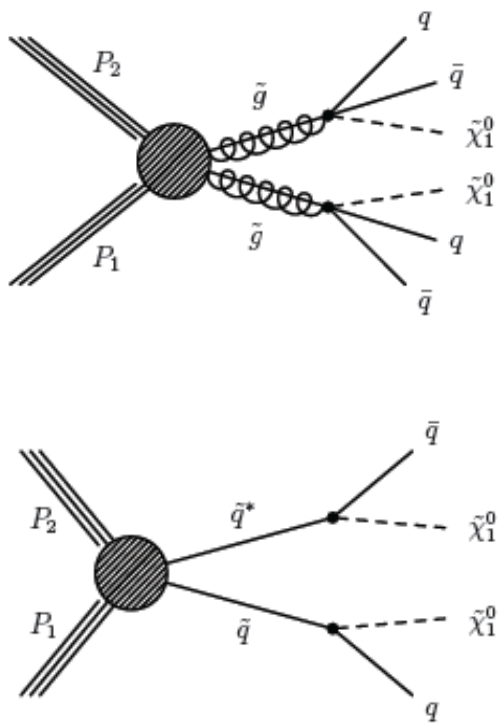
    most papers quote these observable cross section limits

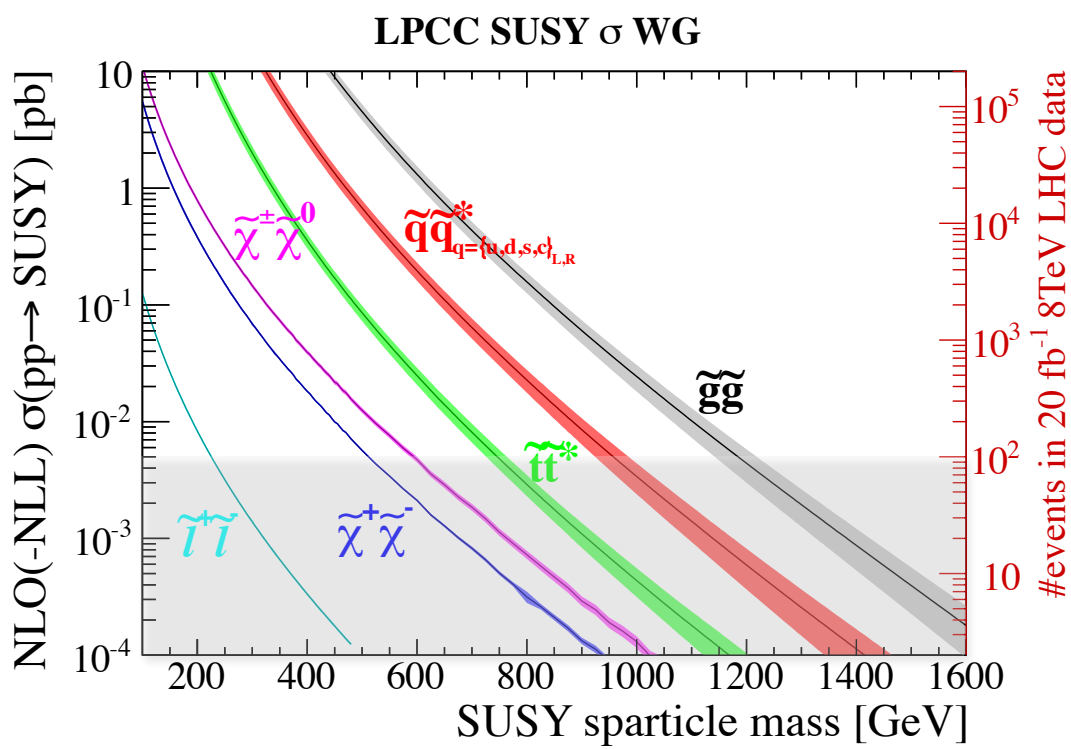
    observable cross sections uncorrected for detector acceptance (model dependent)
- simplified models only serve as specific examples
  - more general use of cross section limits in pMSSM model

arXiv:1307.8444

Strong production of SUSY

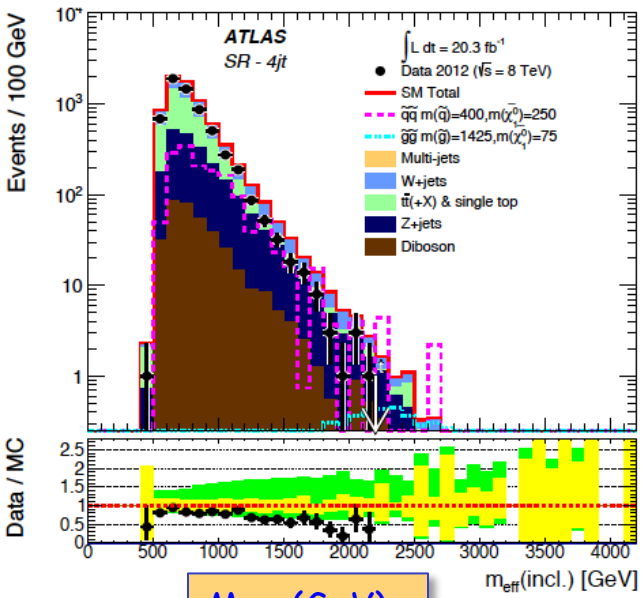
- states produced in pairs if R-parity conserved
  $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}^*$
- followed by cascade decays to lighter states, SM states, and LSP
- colored states often heavier than uncolored
  - mass splitting of light-flavored squark generations usually small
- principal unknown parameter in production cross section is the mass of the gluinos and squarks





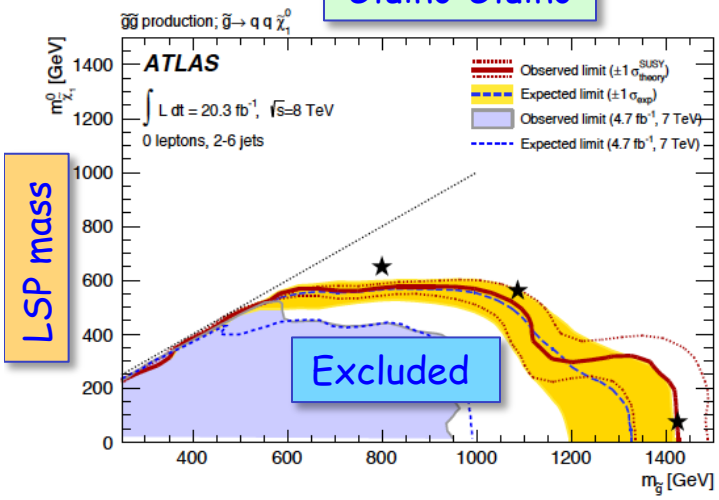
Gluinos and light-flavored squarks

- searches require 2 to 6 jets plus E_T^{miss}
- multiple search regions defined and SM backgrounds estimated
  - no excess seen

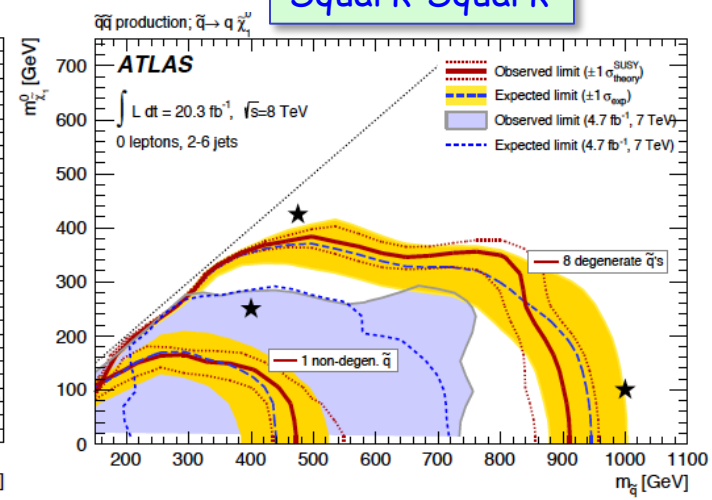


M_{eff} (GeV)

Gluino-Gluino

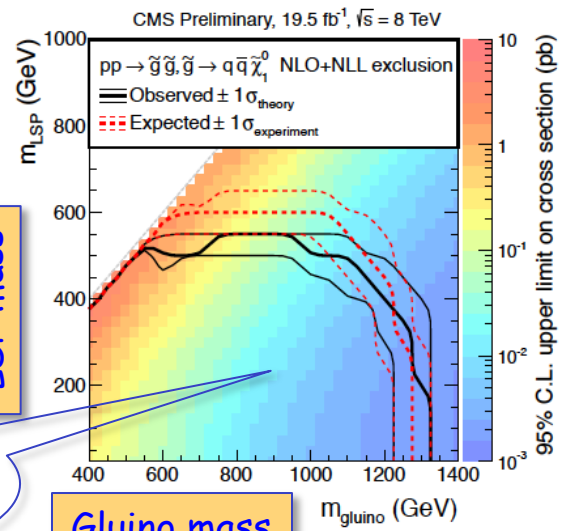


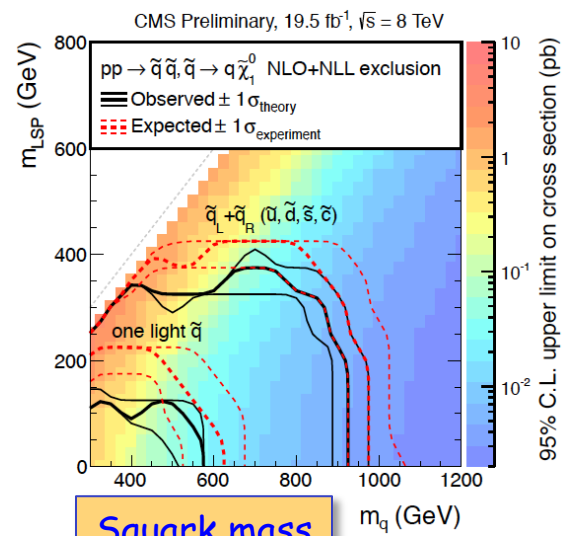
Squark-Squark



Very similar results from both expts.

$M_{\tilde{g}}$ > 1300 GeV (if M_{LSP} < 200 GeV)
$M_{\tilde{q}}$ > 875 GeV (if M_{LSP} < 200 GeV)
(degenerate light-flavor squarks)





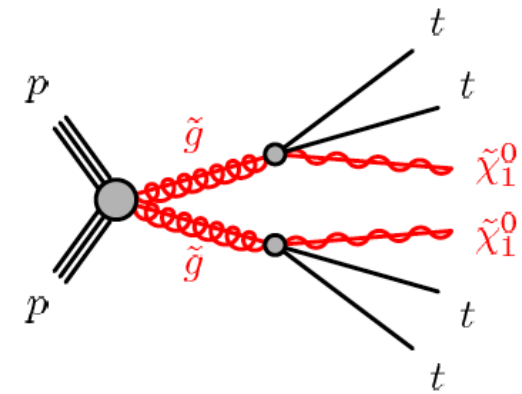
Note cross section limits

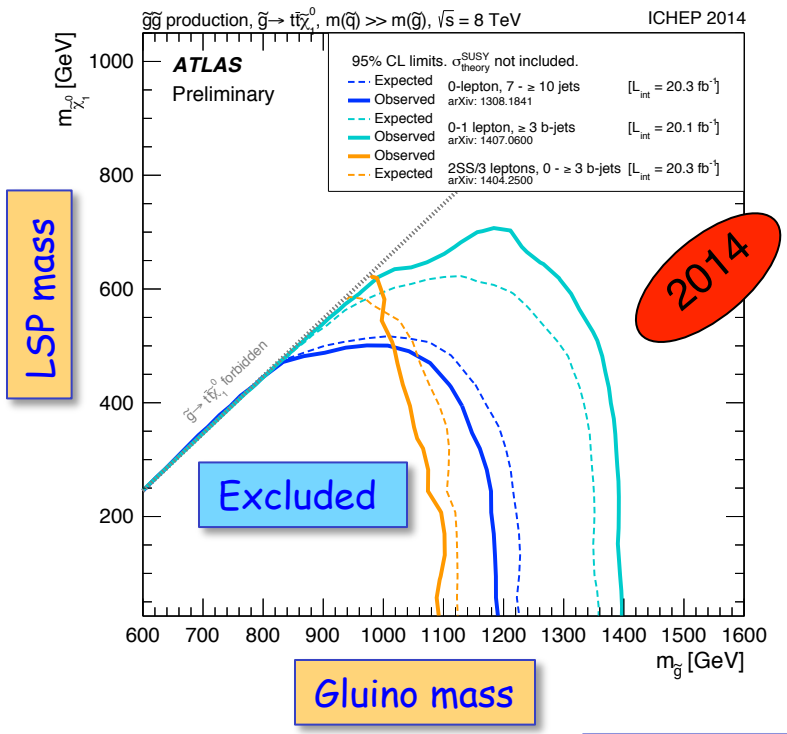
Gluino production with off-shell stops

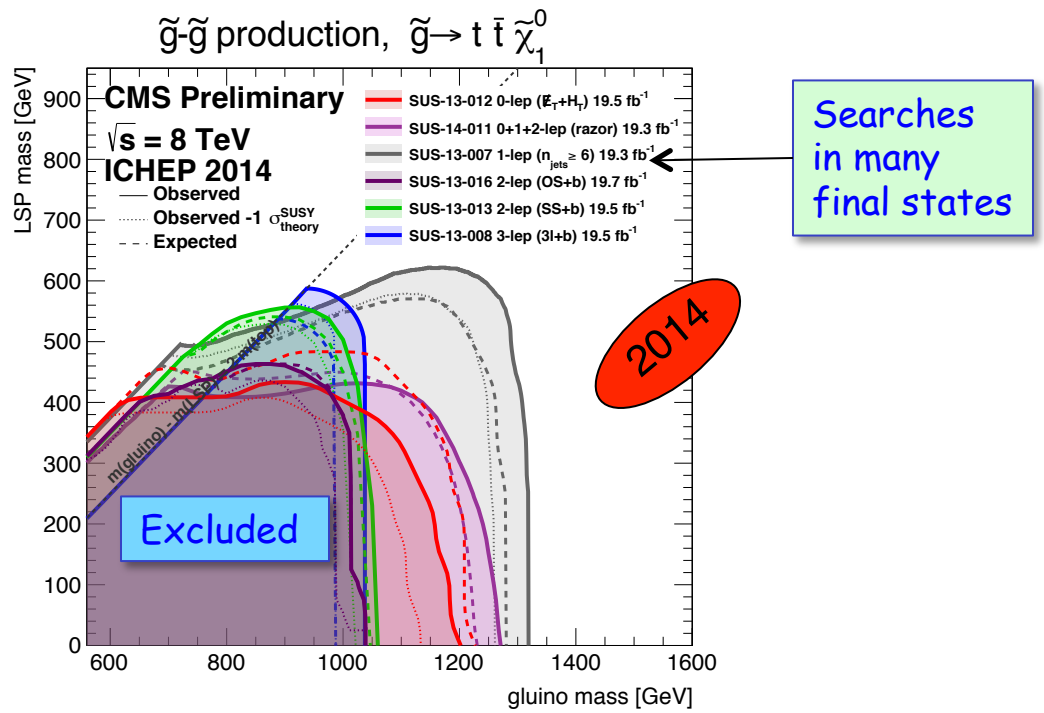
- gluinos can decays via virtual stop if $m_{\tilde{t}} > m_{\tilde{g}}$

$$\tilde{g} \rightarrow tt\tilde{\chi}_1^0$$

  - final states with 4 top quarks and 2 neutralinos
  - leads to exclusion in gluino-neutralino mass plane
- final states with multiple jets, E_T^{miss}, b-jets, 0-1 leptons
  - no excesses seen in any of several final states





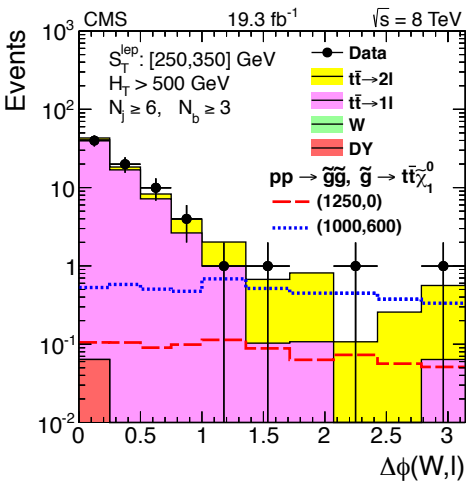


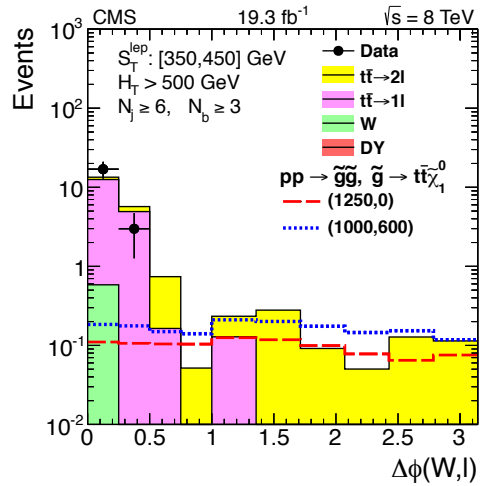
$M_{\tilde{g}}$ > 1340 GeV (for M_{LSP} < 200 GeV)

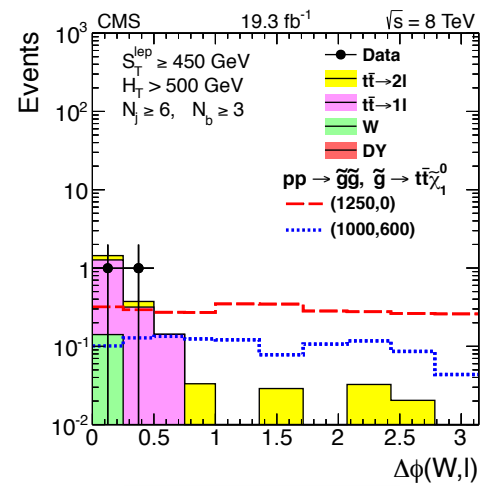
Gluino production with off-shell stops

- Look at a few event distributions for most powerful channels from the two experiments

CMS







arXiv:1311.4937

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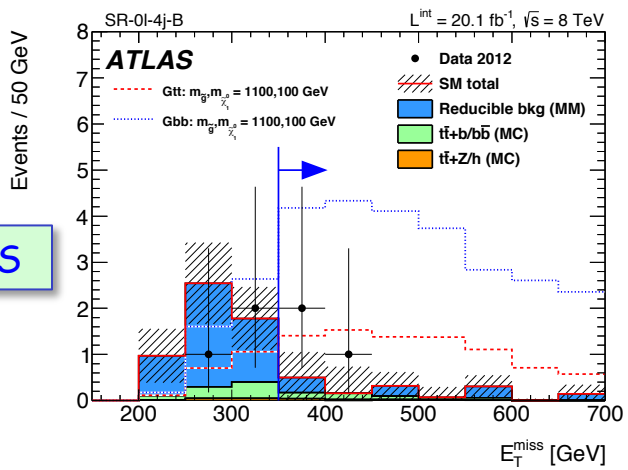
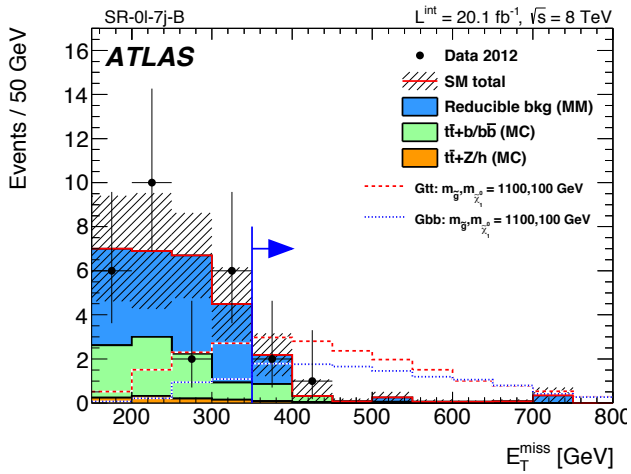
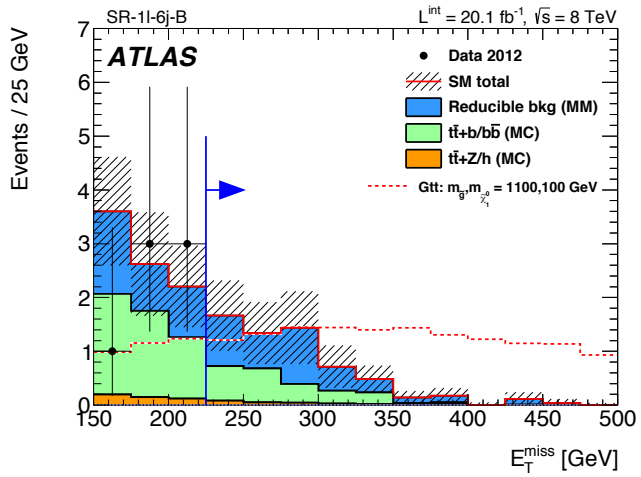


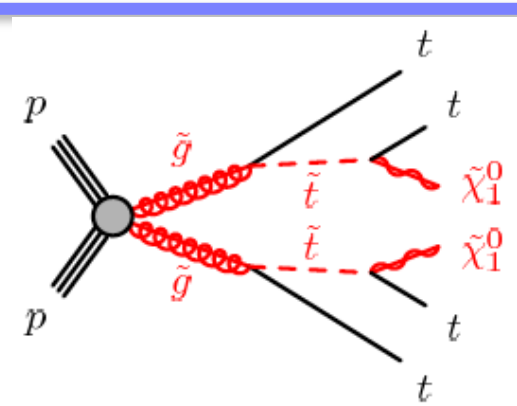




arXiv:1407.0600

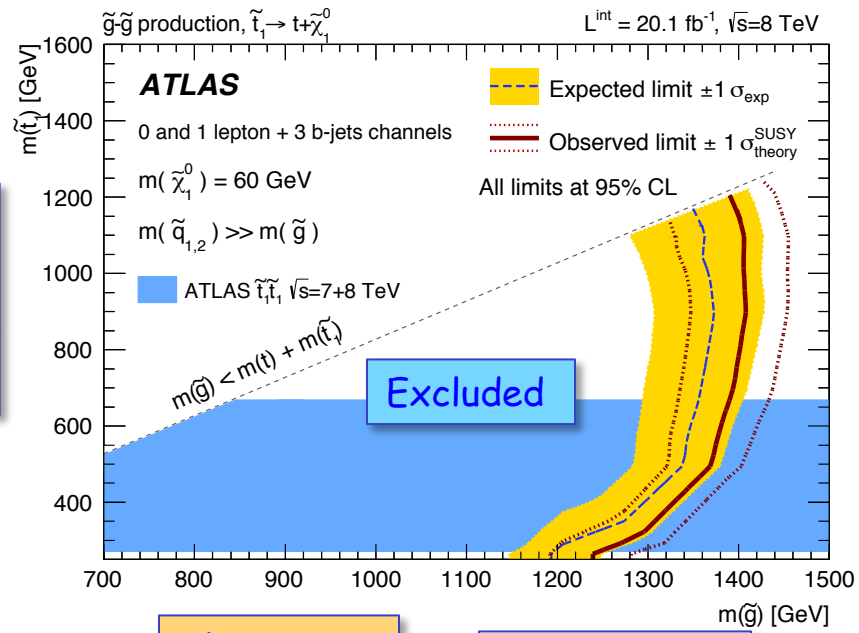
Gluino production with on-shell stops

- Effective if gluinos not too much heavier than stops
- Same search channels as above jets, b's, E_T^{miss}
- no excess signal above backgrounds
- simplified models exclude
  - $M_{\tilde{t}} < M_{\tilde{g}} - M_t$ for $M_{\tilde{g}} < 1340\ GeV$
- plots below show limits for $\tilde{g} \rightarrow \tilde{t}_1 t,\ \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$
- also limits for $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm},\ \tilde{\chi}_1^{\pm} \rightarrow W^{\pm}\tilde{\chi}_1^0$



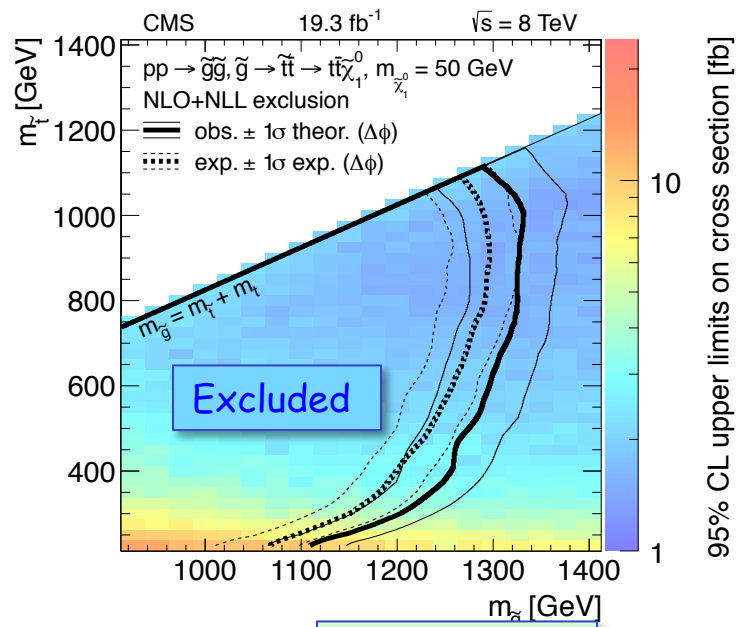
Assume $\tilde{t}_1$ is lightest squark and 100% BR for $\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

Stop mass



Gluino mass

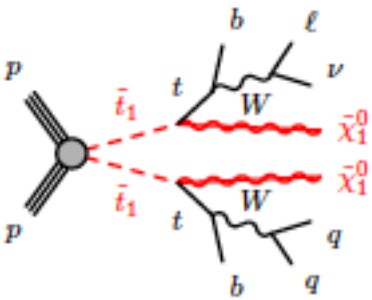
arXiv:1407.0600



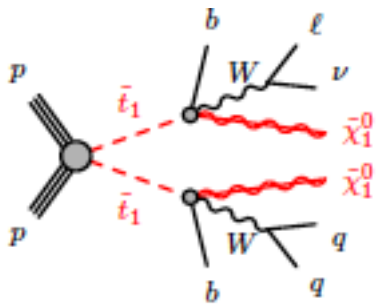
arXiv:1311.4937

Direct stop pair production

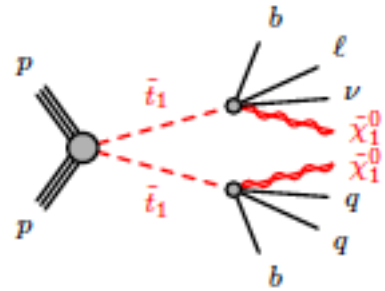
- several possible decay modes
  - depend on relative masses of $\tilde{t}_1, t, W, \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$



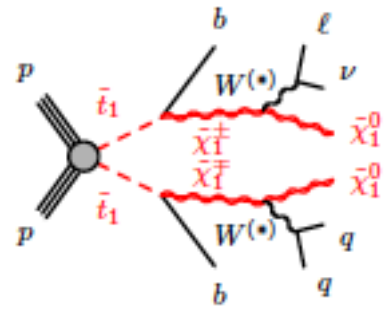
Decay to real top plus neutralino



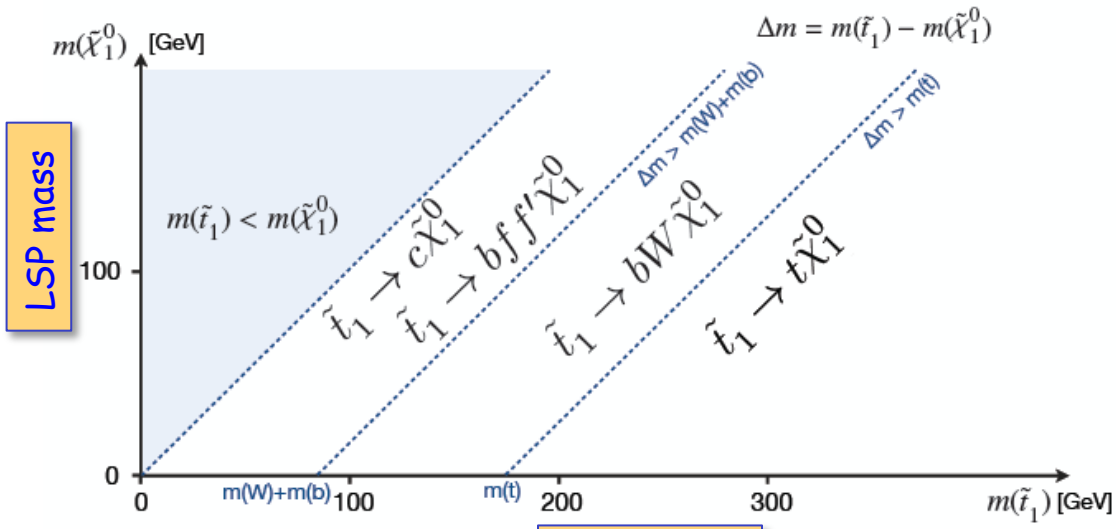
Decay to real b, W, plus, neutralino



Decay to virtual top plus neutralino



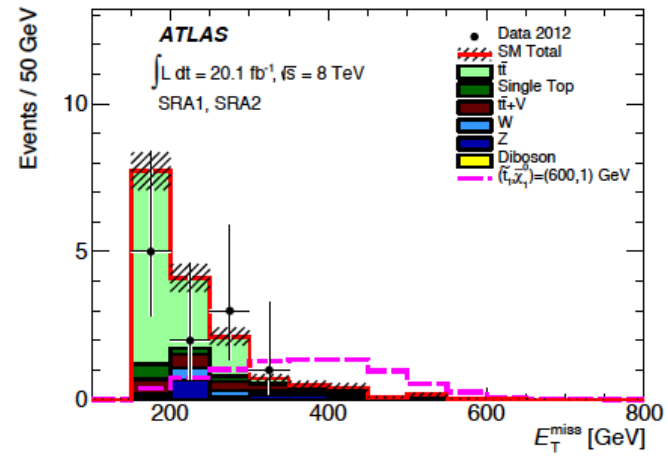
Decay to real b, virtual W, neutralino

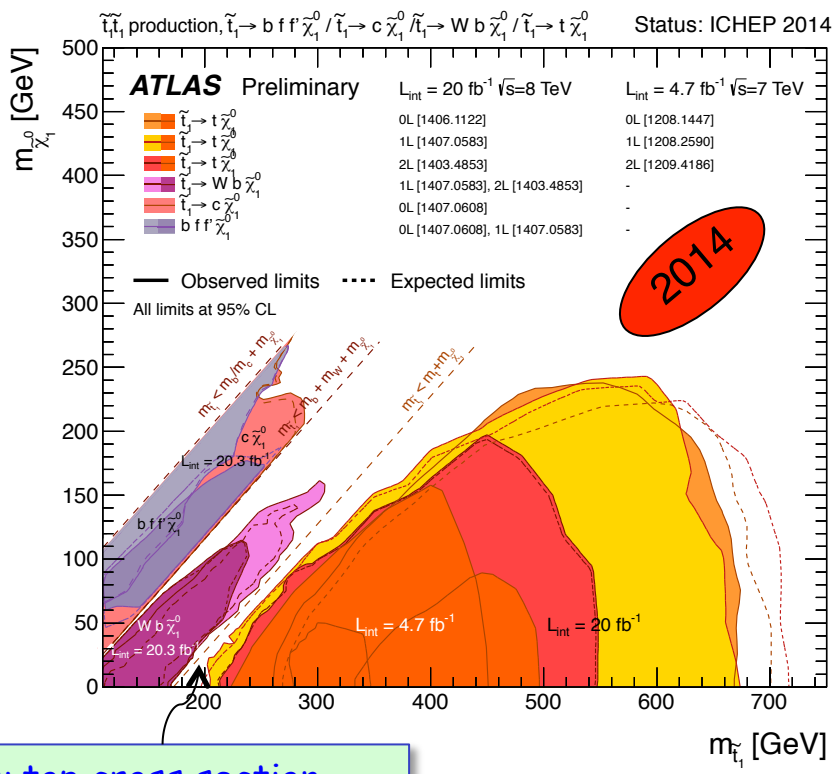


Direct stop pair production

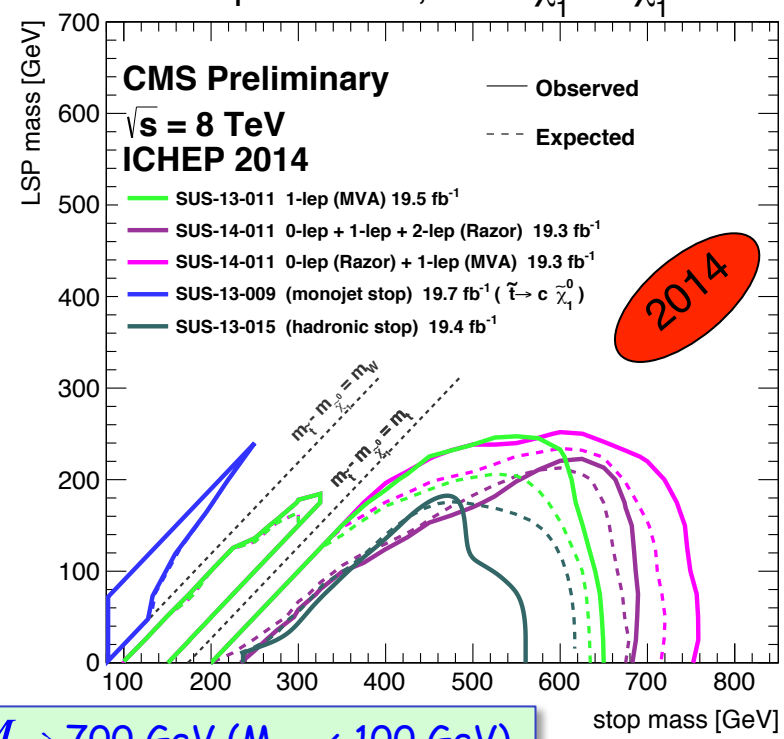
- searches in many final states by both experiments
  - 0, 1 or 2 leptons, jets, E_T^{miss}
  - all negative

Example of data and expected signal for one search region ($M_{\tilde{t}}$ = 600 GeV)





$\tilde{t}$-$\tilde{t}$ production, $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$ / $c\,\tilde{\chi}_1^0$

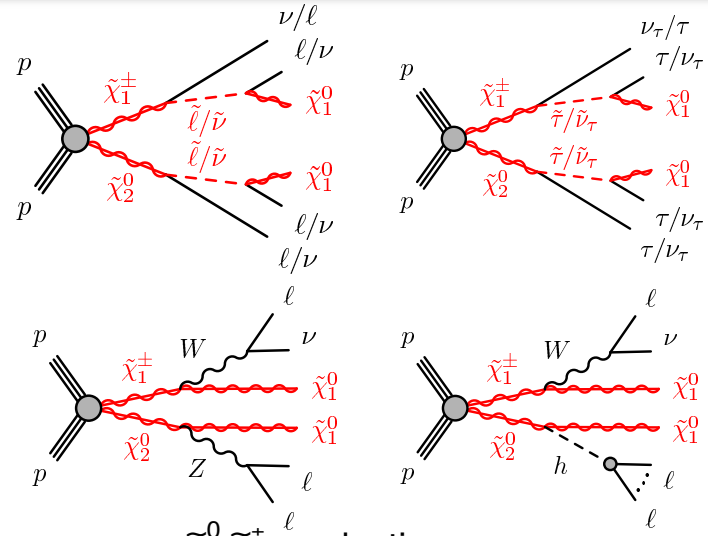


New top cross section measurement shrinks this gap (arXiv: 1406.5375)

$M_{\tilde{t}}$ > 700 GeV (M_{LSP} < 100 GeV) (except for a few gaps)

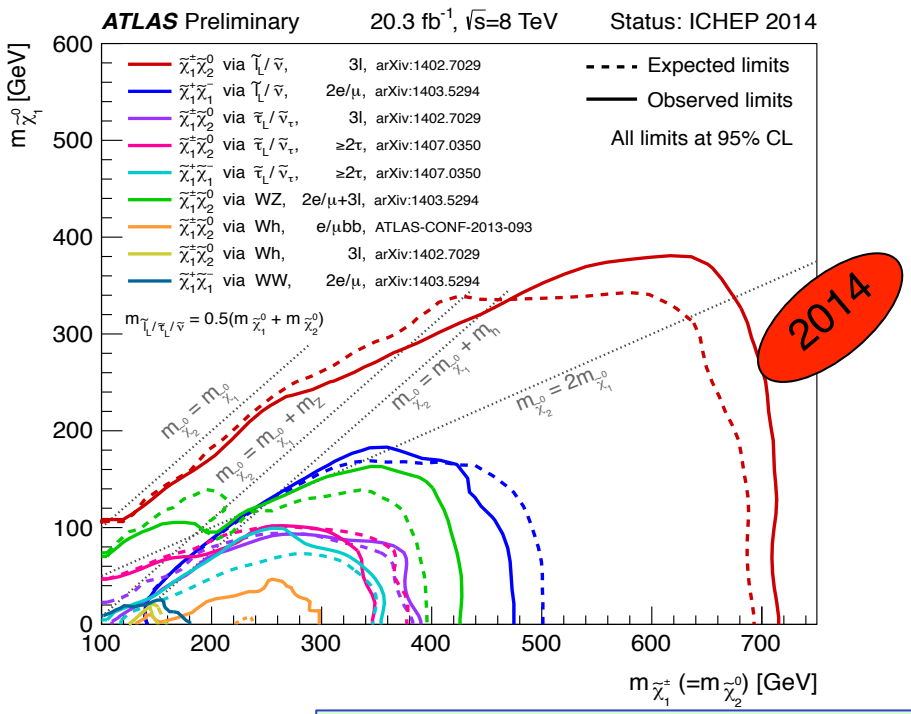
EW production of SUSY

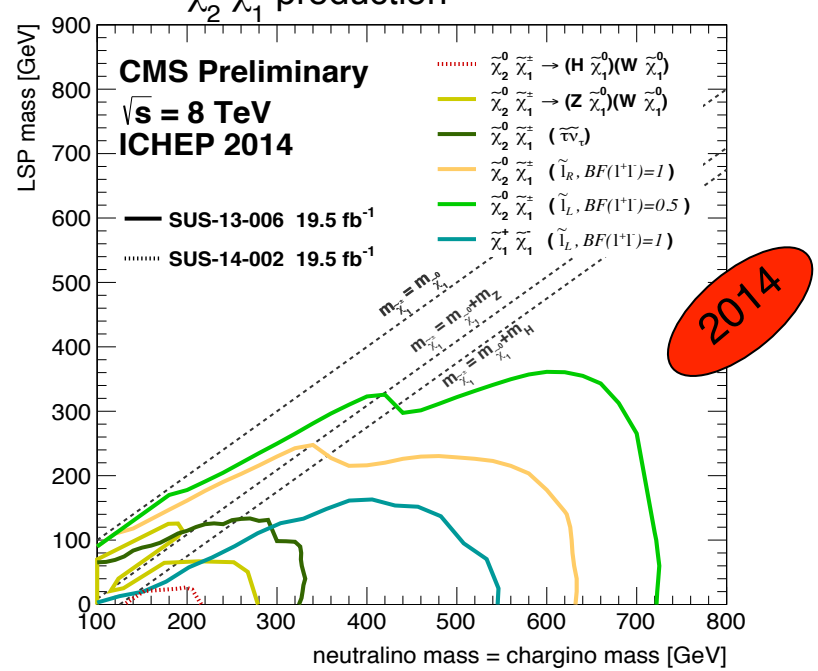
- EW production
  $\chi^0\chi^\pm, \chi^+\chi^-, \tilde{\ell}^+\tilde{\ell}^-$
  - insensitive to squark and gluino masses
    expected to be lighter
  - smaller cross sections
  - Wino state ($\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$ degenerate) with bino $\tilde{\chi}_1^0$
- search channels include leptons, E_T^{miss}
  - some target WZ or W-h final states



$\tilde{\chi}_2^0$-$\tilde{\chi}_1^\pm$ production

Limits on $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production





$M_{\tilde{\chi}_2^0}$ > 700 GeV for M_{LSP} < 100 GeV and light sleptons

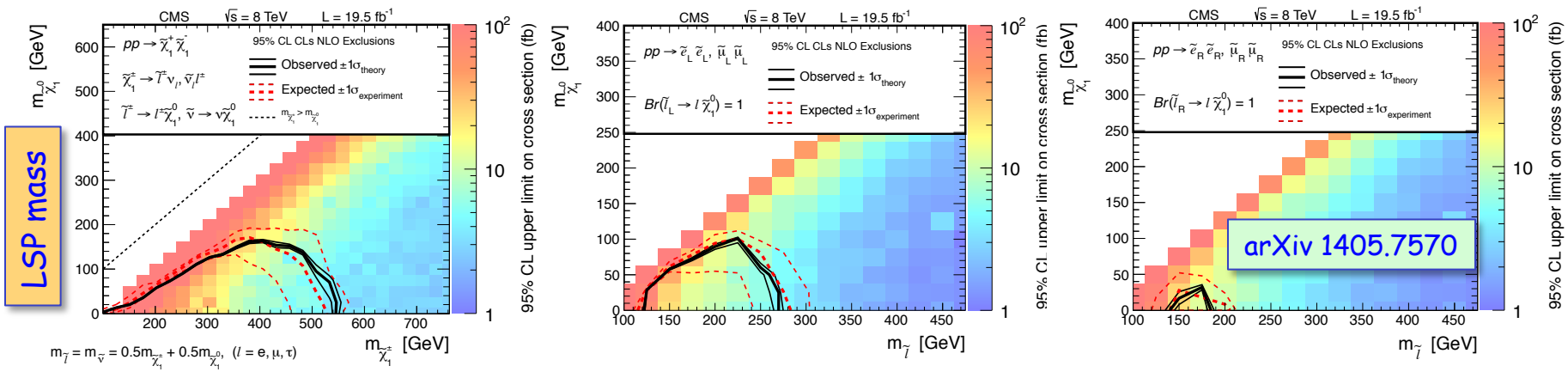
EW production of SUSY

- The same final states give exclusions on production of $\chi_1^+\chi_1^-$ and $\tilde{\ell}^+\tilde{\ell}^-$
  - good agreement between experiments
  - no significant signals seen (results below from 2-lepton final states)

$\chi_1^+\chi_1^-$ | $\tilde{e}_L\tilde{e}_L, \tilde{\mu}_L\tilde{\mu}_L$ | $\tilde{e}_R\tilde{e}_R, \tilde{\mu}_R\tilde{\mu}_R$

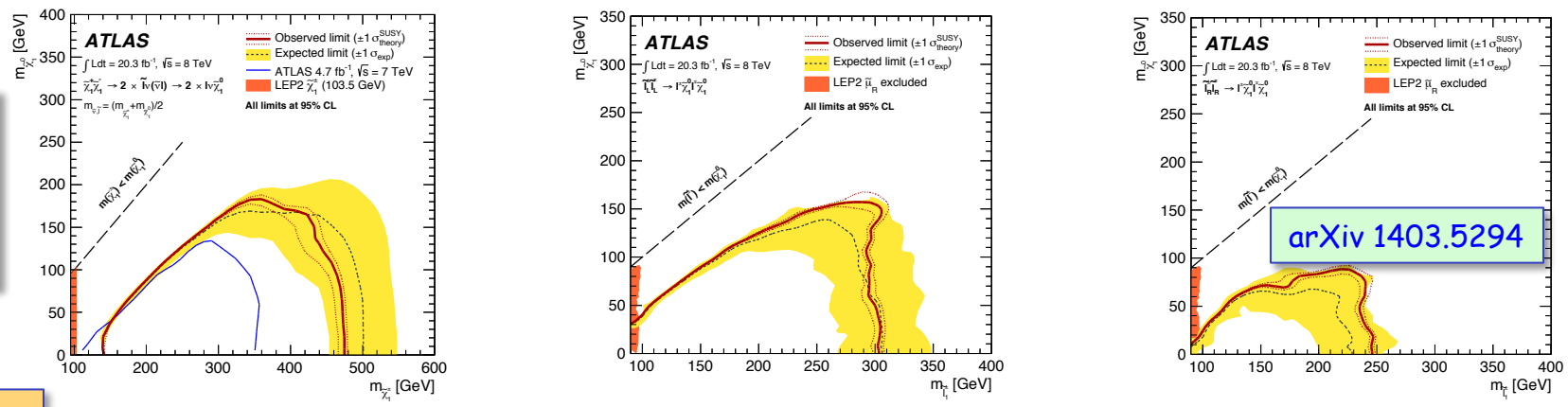
CMS

LSP mass



ATLAS

LSP mass



Limits for $m_{\tilde{\chi}_1^0} \leq 50$ GeV

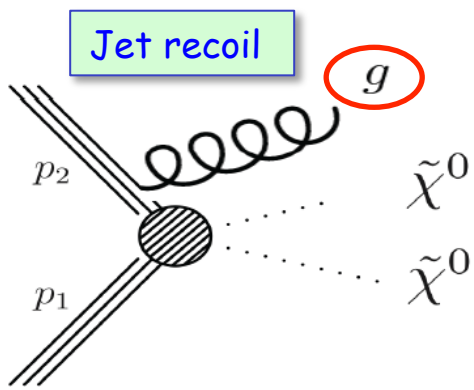
180 < $m_{\tilde{\chi}^\pm}$ < 520 GeV excl.

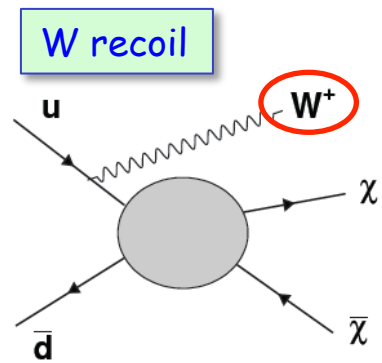
110 < $m_{\tilde{\ell}_L}$ < 290 GeV excl.

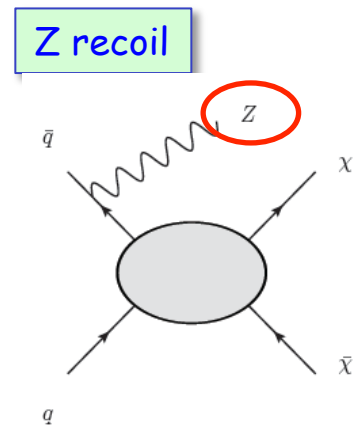
130 < $m_{\tilde{\ell}_R}$ < 230 GeV excl.

Direct production of dark matter

- detected through initial state radiation
  - "mono-jets", "mono-W", "mono-Z", "mono-photon"

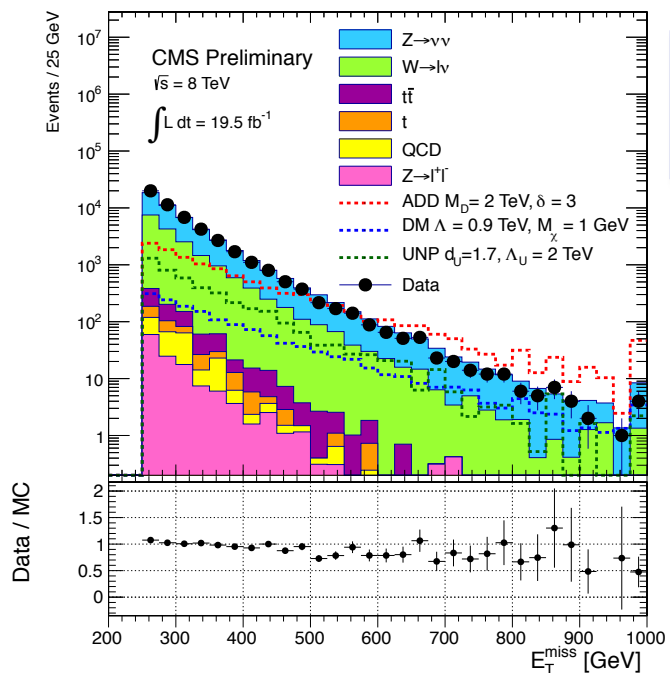






Select final states with recoil of interest and large E_T^{miss}

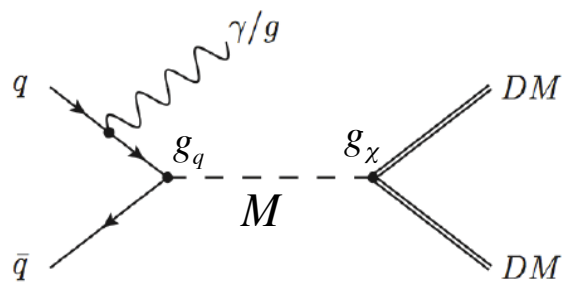
- backgrounds from $Z^0 \to \nu\bar{\nu}$ and $W^\pm \to \ell^\pm\nu$ with missed $\ell^\pm$
- measure backgrounds from similar final states with identified $Z^0 \to \mu^+\mu^-$ and $W^\pm \to \ell^\pm\nu$
- diboson backgrounds larger in W/Z recoil

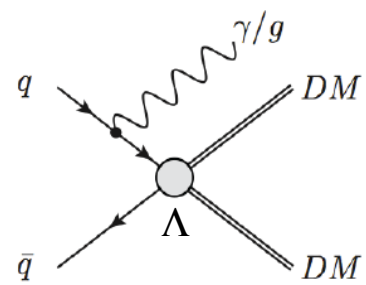


CMS monojet search arXiv:1408.3583

Implications for direct detection

- agreement between data and bkgd. constrains size of possible BSM cross section
- characterize cross section limit using effective field theory
  - can compare with direct detection experiments for $\chi + N \rightarrow \chi + N$



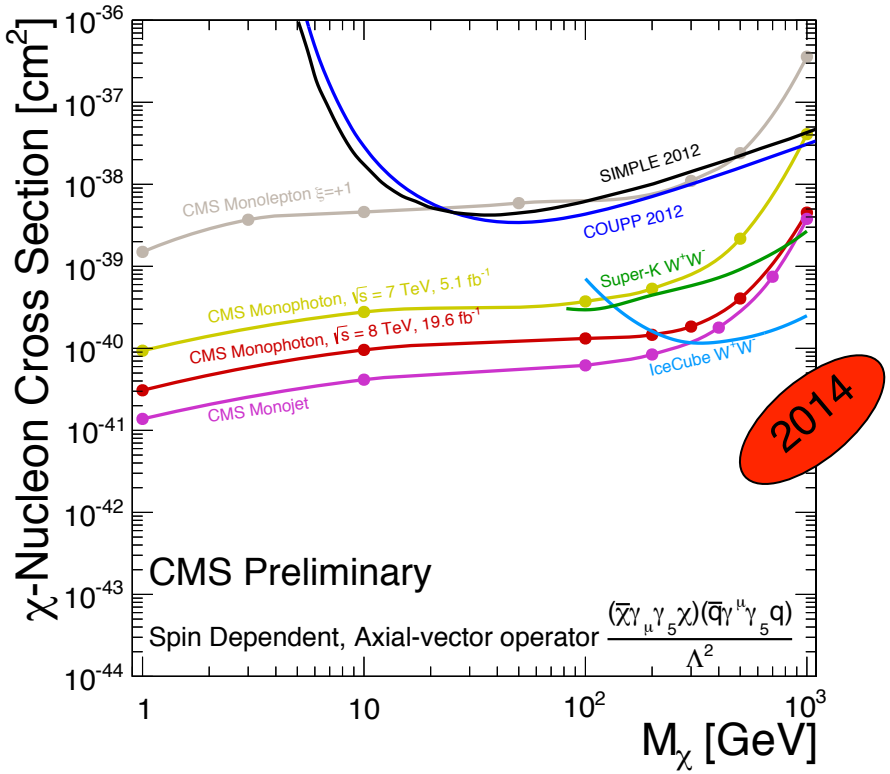


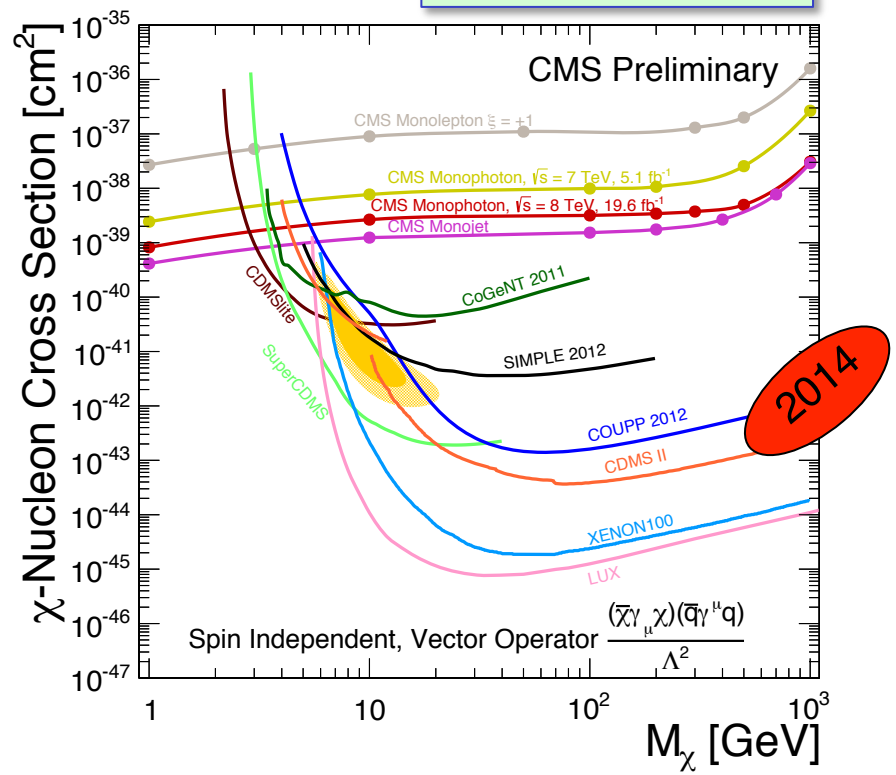
$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

- details depend on quark-DM coupling
  - spin-independent DM scattering for vector and scalar interaction
  - spin-dependent DM scattering for axial vector interaction
  - for picture to hold, characteristic energy transfers should be small wrt. L i.e. $m_{DM} < 2\pi\Lambda$
- collider cross section gives upper limit on $\sigma(m_{DM}, \Lambda)$
  - for given m_{DM}, extract lower limit on Λ
  - gives upper limit on cross section for direct detection

Implications for direct detection

CMS PAS EXO-12-047

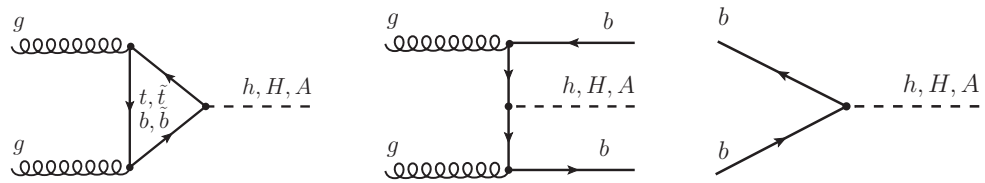




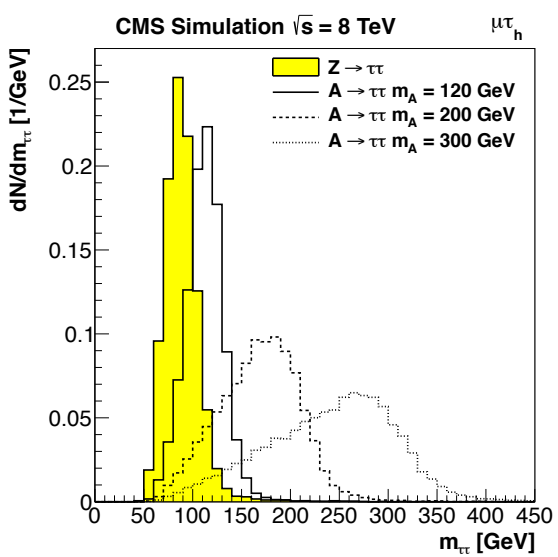
- for spin dependent case LHC provides best limit for $m_{DM} < 300$ GeV (monojet case)
  - effective field theory requirement is very well respected
- for spin independent case LHC provides best limit for $m_{DM} < 3$ GeV (monojet case)
- very similar results from ATLAS

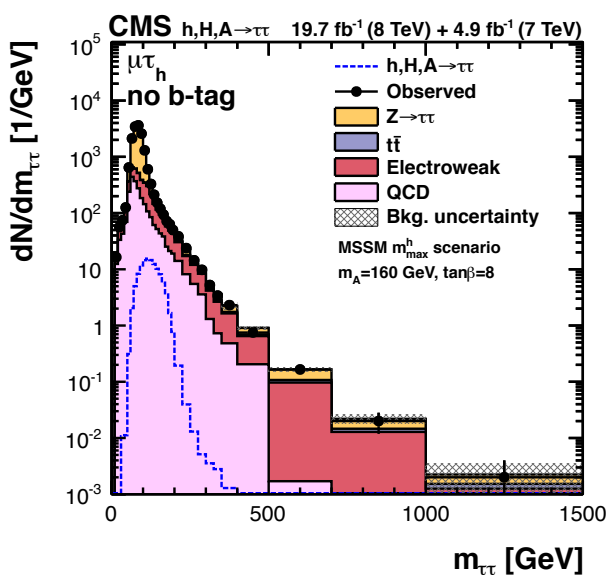
MSSM Higgs sector

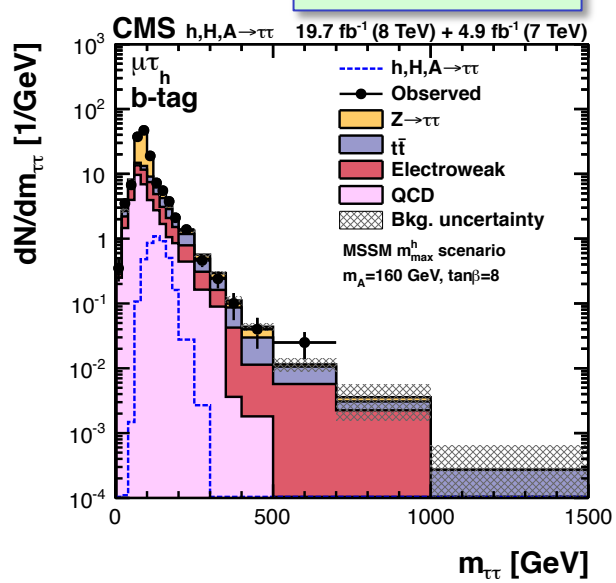
- if the 125 GeV Higgs is the MSSM state h we also expect additional Higgs states H^0, A^0, $H^\pm$
  - characterized to leading order by M_A and $\tan\beta = v_u/v_d$ ratio of VEVs for two Higgs doublets
- measurements have shown that couplings of h are similar to SM expectations
  - suggests decoupling limit where $M_A \gtrsim 2\, M_Z$
  - H^0, A^0, $H^\pm$ are heavy and almost degenerate
  - coupling of A^0 to $\tau^\pm$ and $b \sim m \tan\beta$
- search for h, H^0, $A^0 \to \tau^+\tau^-$
  - especially with b-tagged jet



arXiv:1408.3316

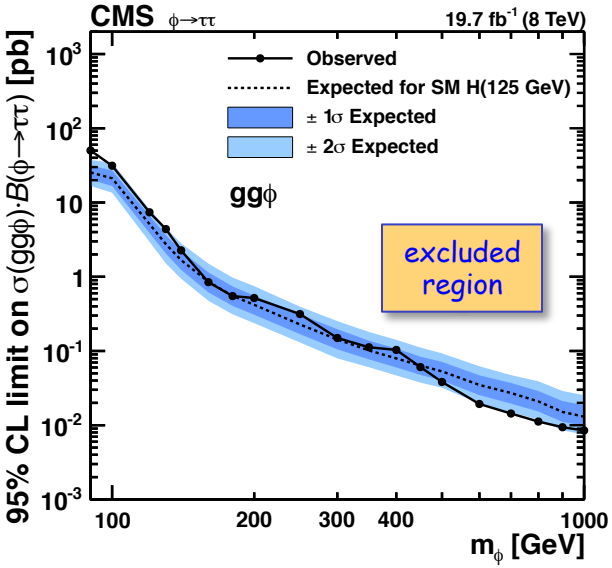


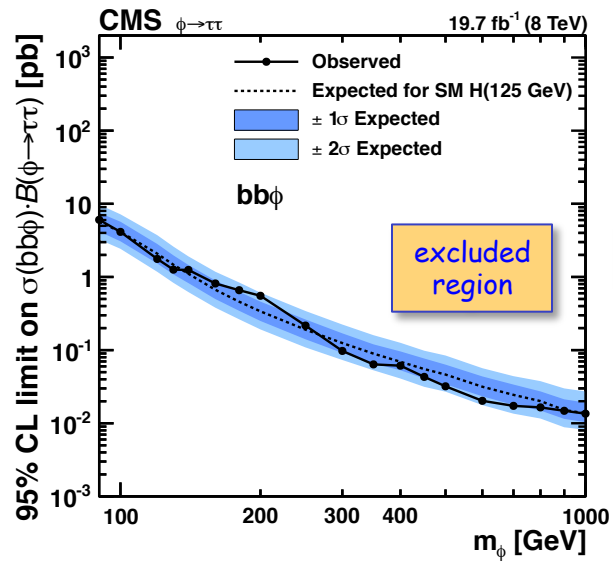




MSSM Higgs sector

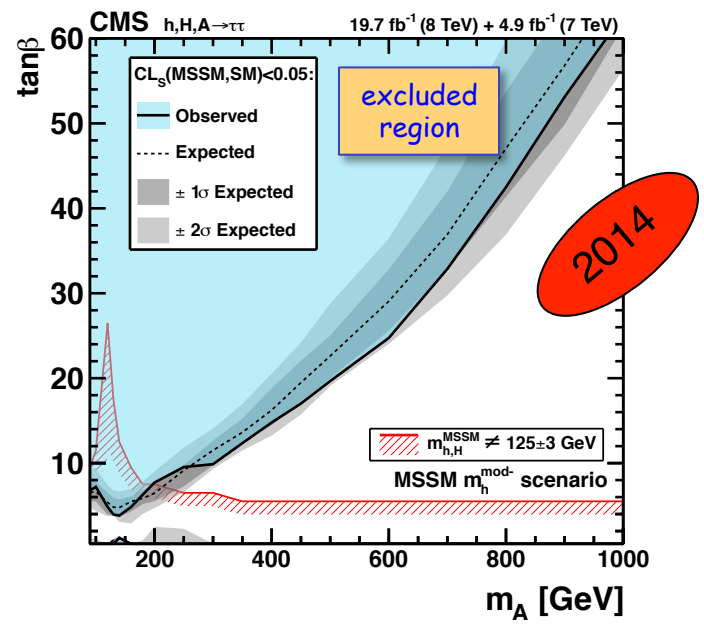
- Limits on cross section time branching ratio for a single resonance ϕ





arXiv:1408.3316

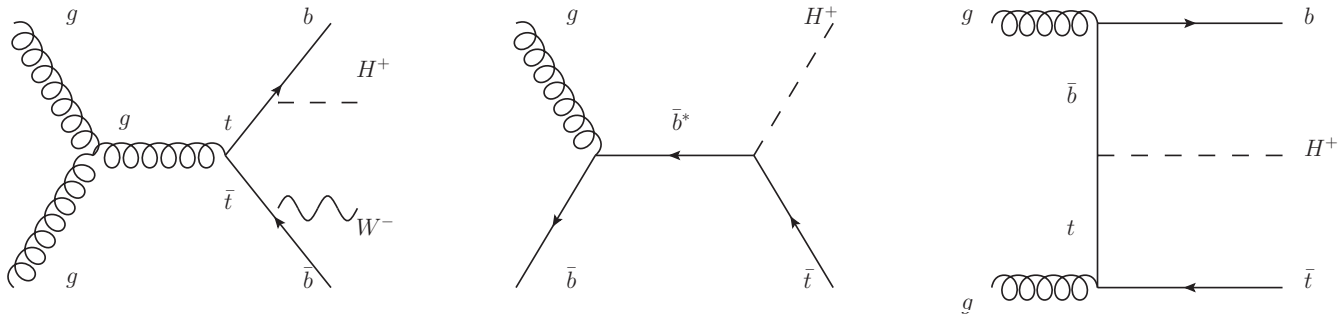
- Limits in m_A-tanβ plane from negative search for the 3 MSSM states h, H^0, A^0

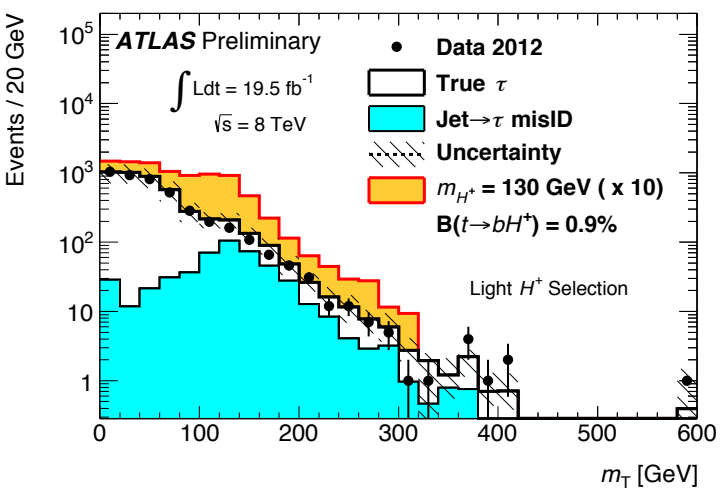


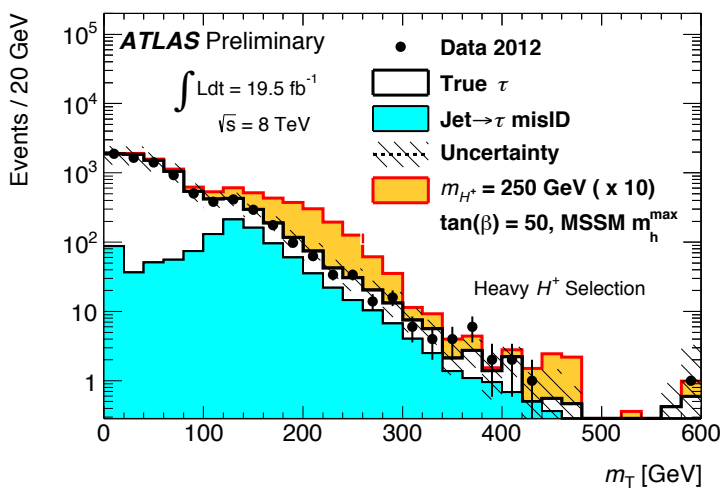
Very similar limits from ATLAS

MSSM Higgs sector

- search for $H^{\pm}$
  - in direct production at high masses with $H^+ \to \tau^+ \nu$
  - in top quark decays for low mass $t \to b\, H^+ \to b\, \tau^+ \nu$
  - τ detected in hadronic final states



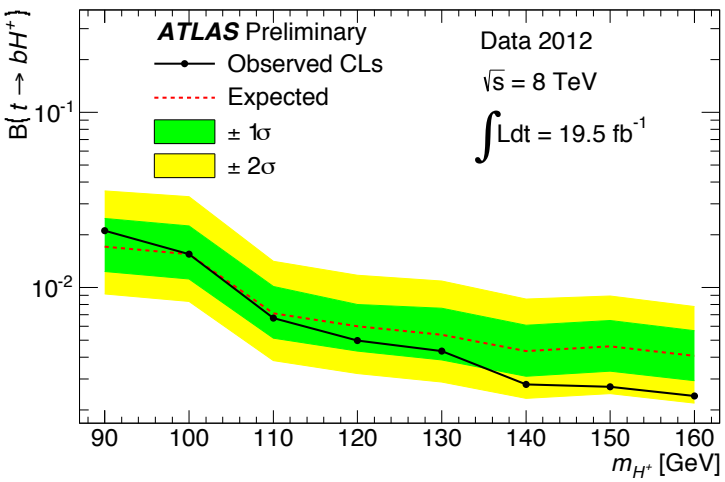


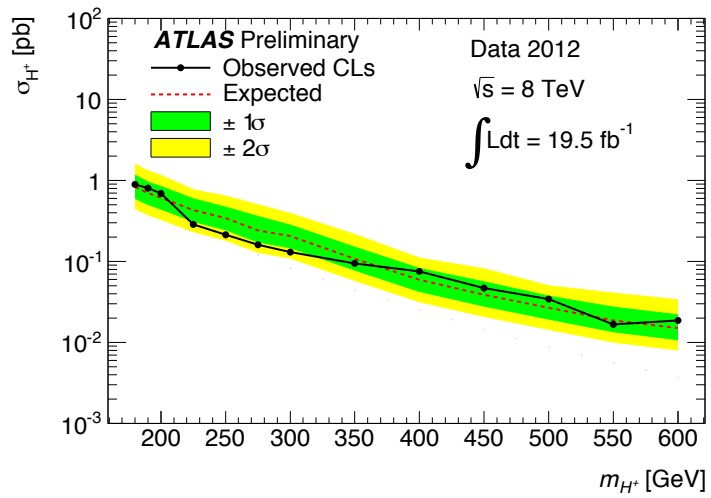


ATLAS-CONF-2013-090

MSSM Higgs sector

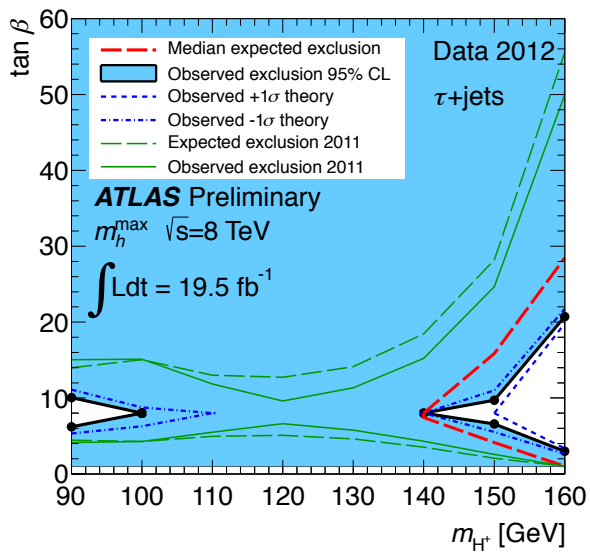
- Limits on top quark branching ratio and cross section for direct production

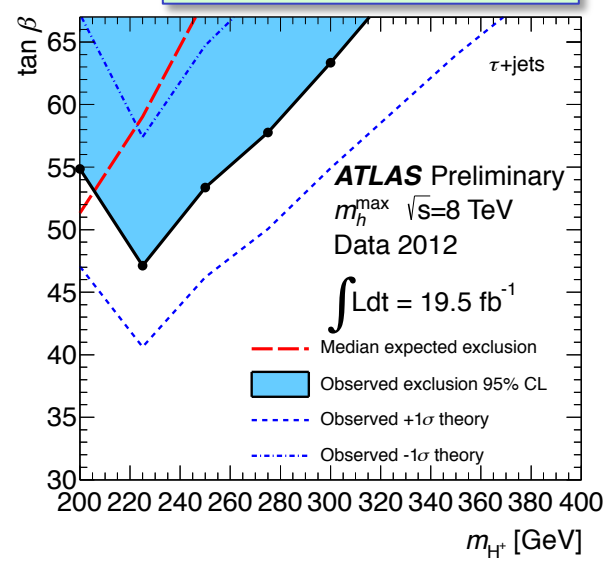




- Limits in m_H - $\tan\beta$ plane

ATLAS-CONF-2013-090





“Other” channels

- Most searches described so far are in traditional SUSY channels
  - SUSY has many variants
- No time for these but see “summary charts” on following pages for references
  - R-parity violating final states
    - little or no missing energy
  - detector activity in empty LHC bunches (stopped gluinos, R-hadrons)
    - predicted in split SUSY theories where scalars have much higher masses and fermions are at TeV scale
    - gluinos may have very long lifetime
  - disappearing charged tracks
    - in anomaly mediated SUSY lightest chargino is nearly degenerate with lightest neutralino
    - chargino could have a detectable lifetime
  - long-lived heavy particle
    - in gauge mediated SUSY breaking stau may have a long lifetime and look like a heavy muon
  - long-lived neutral decaying to photon from displaced vertex
    - in gauge mediated breaking lightest neutralino may be long lived
- All searches negative so far

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})=2\, m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma G$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e, \mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

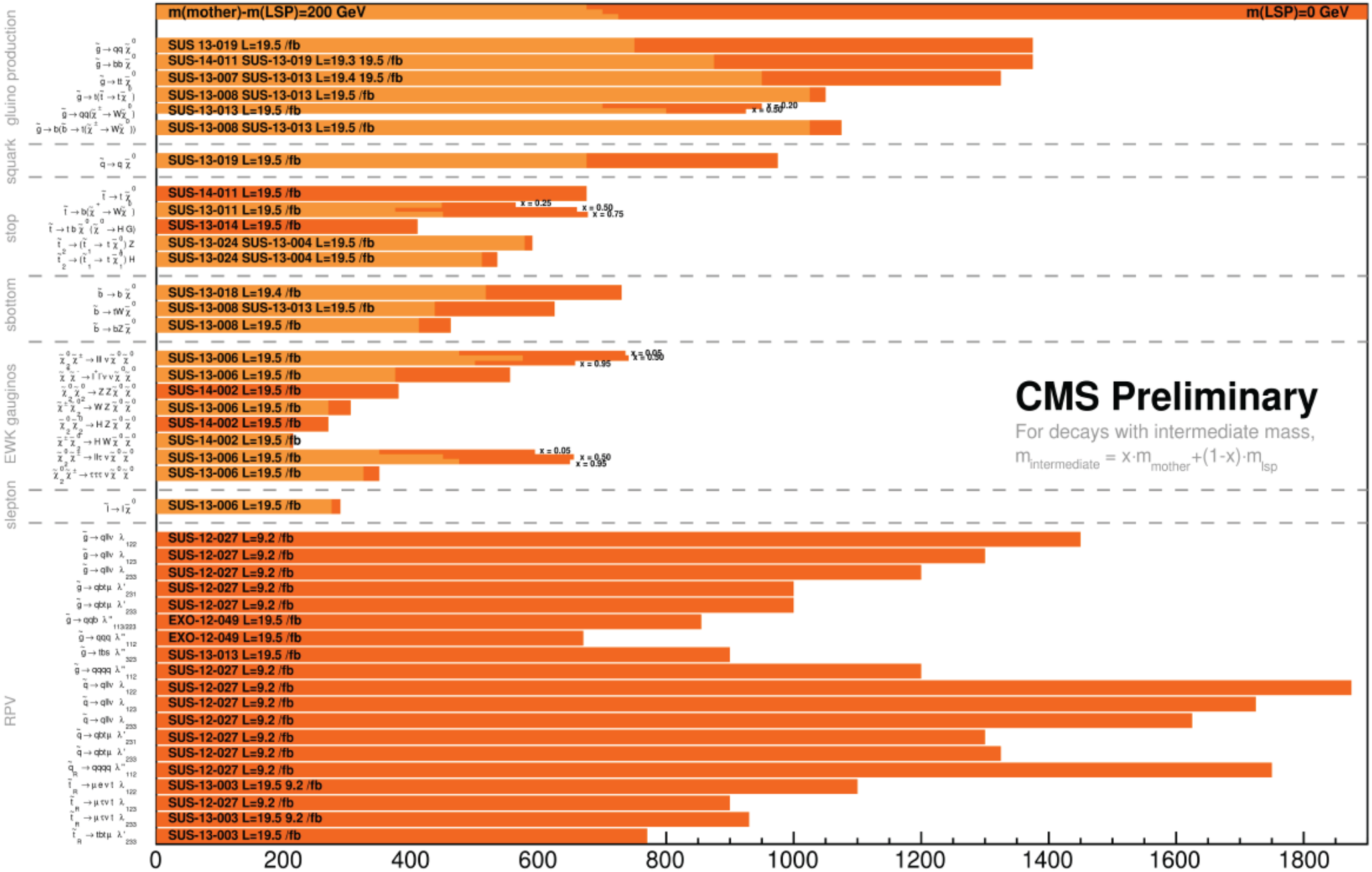
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Conclusions on SUSY

- The observed Higgs mass is suggestive of the MSSM
  - but no hints yet of SUSY states
- Perhaps SUSY has unexpected features and is escaping detection
- Perhaps CM energy is still too low?
  - Run 2 starts at 60% higher energy next spring
- Perhaps SUSY mass scale is well above LHC energies
  - no weak scale SUSY
  - some alternative mechanism is associated with Higgs mass fine tuning

    e.g. Higgs is bound state of particles associated with a new symmetry

    signatures will differ from typical weak SUSY signatures
- Important to look for BSM effects not associated with SUSY

Other BSM topics

- Heavy gauge bosons Z', W'
- Vector-like quarks B, T
- Contact interactions
- Extra dimensions
  - higher dimensional Planck scale is at TeV scale
- Excited electrons or muons
- Leptoquarks
- Excited quarks or gluons
- Microscopic black holes

- There are papers or preliminary reports on all these
  - I will just touch on the first four topics here

Heavy neutral vector bosons

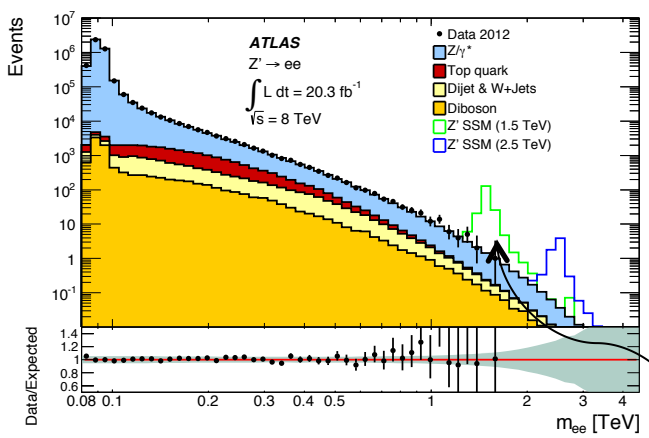
- Search for $Z' \to e^+ e^-$ and $Z' \to \mu^+ \mu^-$
  - could be directly produced at electron or muon collider
  - interpret here in terms of sequential standard model (SSM) with SM couplings

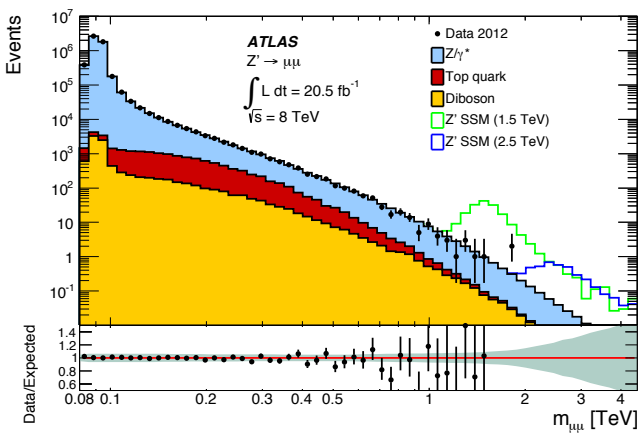
    Also appears in grand unified theories, Minimal Z' model, walking techicolor, graviton excitation in Randall-Sundrum model, quantum black holes

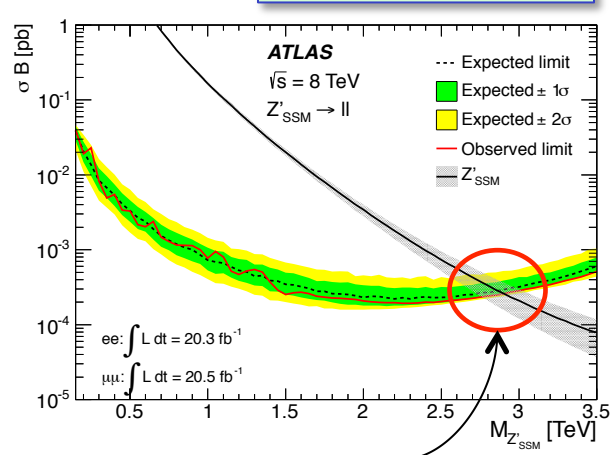
    All with their own parameters and couplings
  - main background is the Drell-Yan process $q\bar{q} \to Z^0 \to \ell^+\ell^-$
  - fit observed mass spectra to signal template + predicted background vs mass

    no significant signal found (p-values 28%, 27%)
  - upper limit on possible size of signal gives exclusion in $B \cdot \sigma$

arXiv:1405.4123







Resolution < 2%

$M_{Z'}$ > 2.90 TeV (2.87 expected)
(similar result from CMS)

Contact interactions in $\ell^+\ell^-$ final state

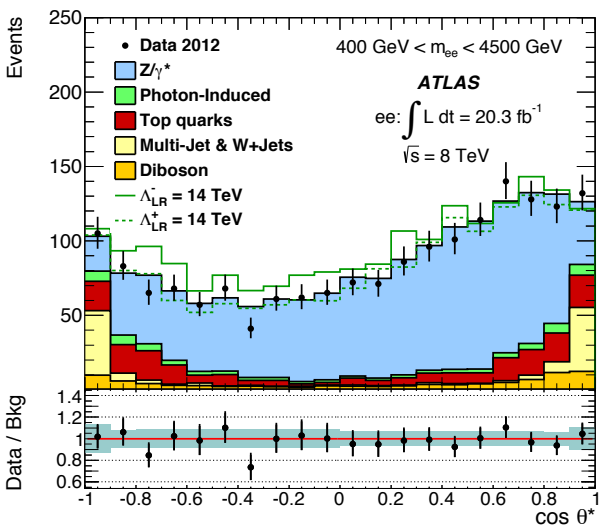
- same $\ell^+\ell^-$ data could show evidence of non-SM interaction between the leptons and quarks
  - departure of mass spectrum SM prediction and change in angular distribution of lepton pair
  - can see evidence of new interaction before direct production of new states (Fermi's four-fermion model of weak interactions)

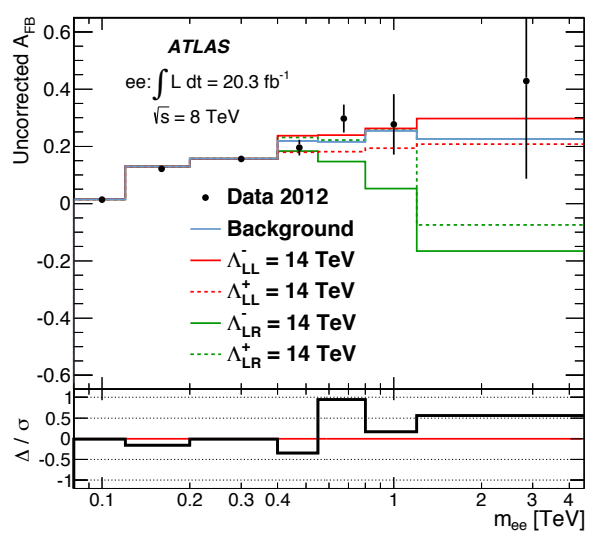
$$\sigma_{tot} = \sigma_{DY} - \eta_{ij}\frac{F_I}{\Lambda^2} + \frac{F_C}{\Lambda^4}$$

$\eta_{ij} \Rightarrow$ chiral structure (±1, 0)
$F_I \Rightarrow$ strength of interference term
$F_C \Rightarrow$ strength of direct term
$\Lambda \Rightarrow$ energy scale of new interaction

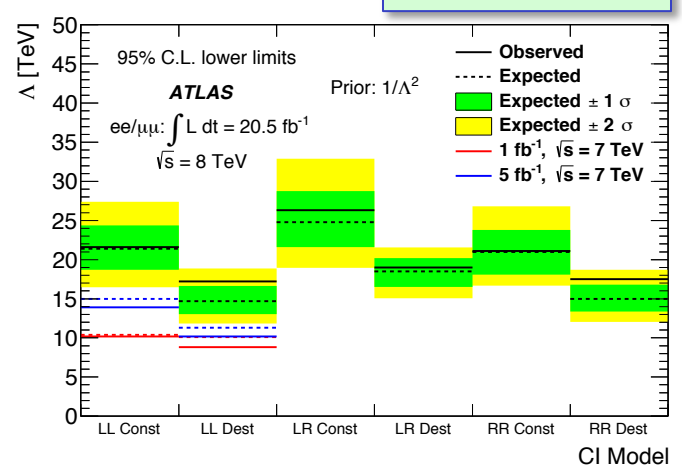
  - decay angle of di-lepton system also carries useful information

$\cos\theta^*$ of ℓ^- in di-lepton rest frame gives $A_{FB} = (N_F - N_B)/(N_F + N_B)$





arXiv:1407.2410



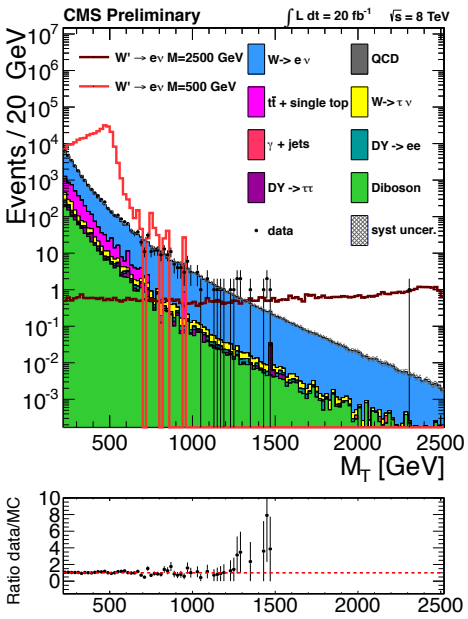
Contact interactions in quark-lepton system limited to Λ > 15 TeV

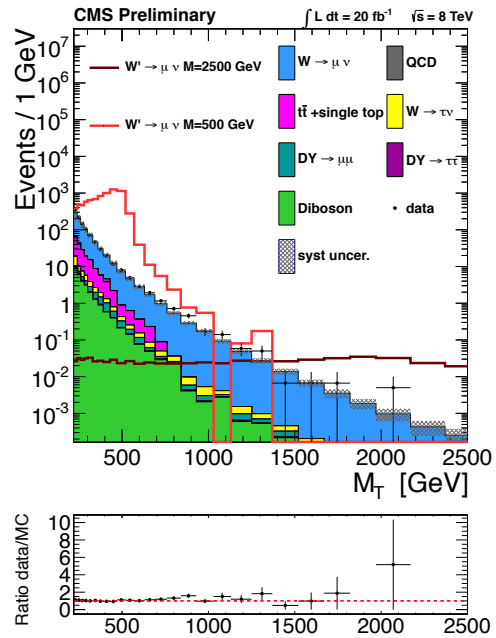
Heavy charged vector boson

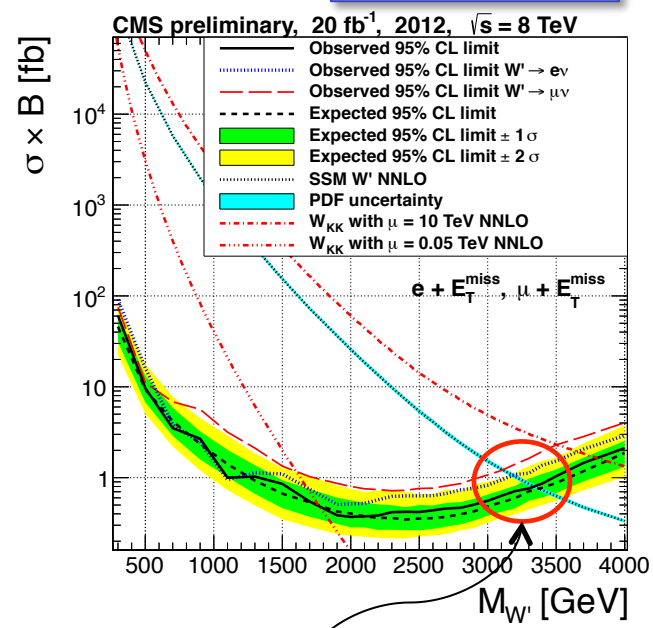
- Search for $W' \to e\nu$, $W' \to \mu\nu$
  - analog of the W in the sequential standard model (SSM)
    also predicted as a Kaluza-Klein excitation in models with universal extra dimensions
  - main background is $q\bar{q}' \to W^{\pm} \to \ell^{\pm}\nu$
  - reconstruct transverse mass of W charged lepton and transverse missing energy

$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$

arXiv:1408.2745







The data also limit quark-lepton contact interaction to $\Lambda > 13$ TeV.

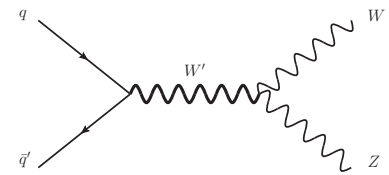
$M_{W'} > 3.35$ TeV
(similar result from ATLAS)

Search for WZ resonances

- Search for $W' \rightarrow W^{\pm}Z^{0} \rightarrow \ell^{\pm}\nu\ \ell^{+}\ell^{-}$
  - interpret in terms of extended gauge model with $W' \rightarrow WZ$

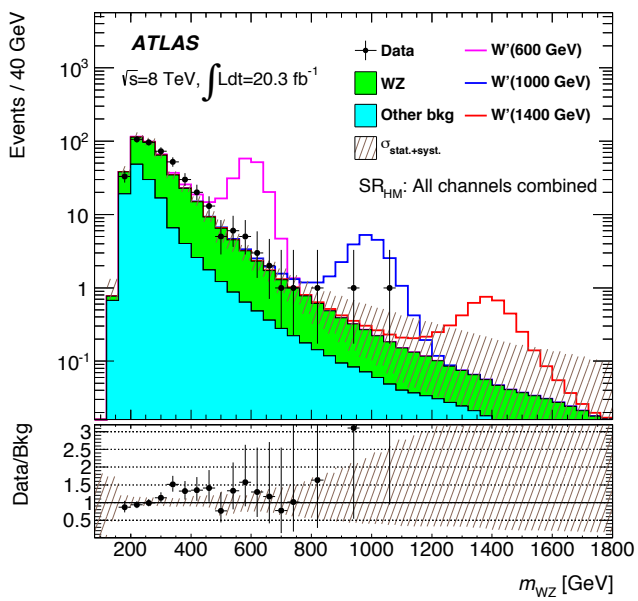
    W' couplings to SM particles same as W, except suppressed WWZ coupling

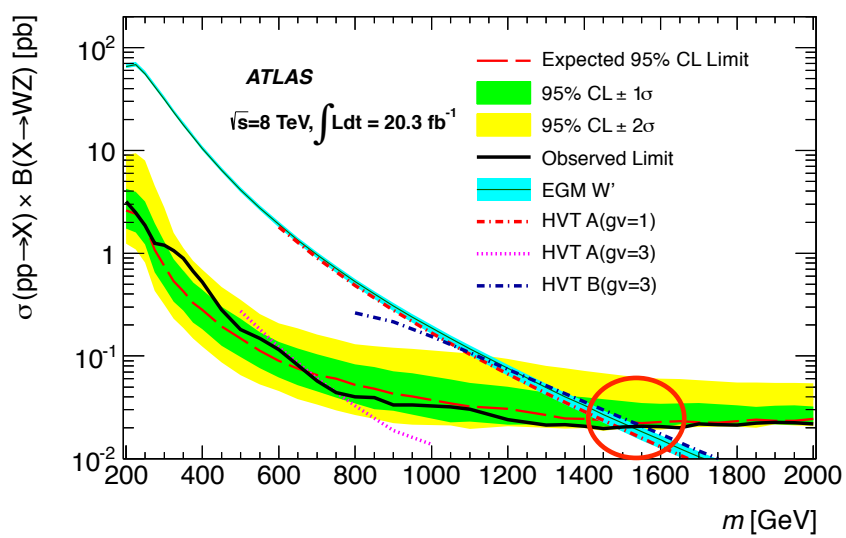
    width of W' is narrow compared to resolution



  - also predicted in GUT theories, little Higgs theories, technicolor, composite Higgs theories
  - reconstruct mass of WZ system

    calculate longitudinal momentum of neutrino using W mass constraint





arXiv:1406.4456

$M_{W'} > 1.52$ TeV
(similar result from CMS)

Search for vector-like quarks

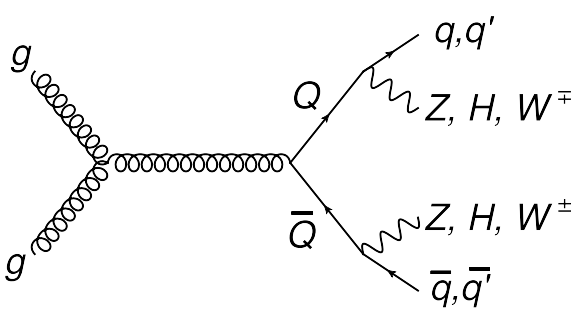
- perhaps the Higgs is a pseudo-Nambu-Goldstone boson from a broken higher symmetry
  - like pions in QCD
  - described in little Higgs theories, composite Higgs theories
  - expect new states associated with this new interaction

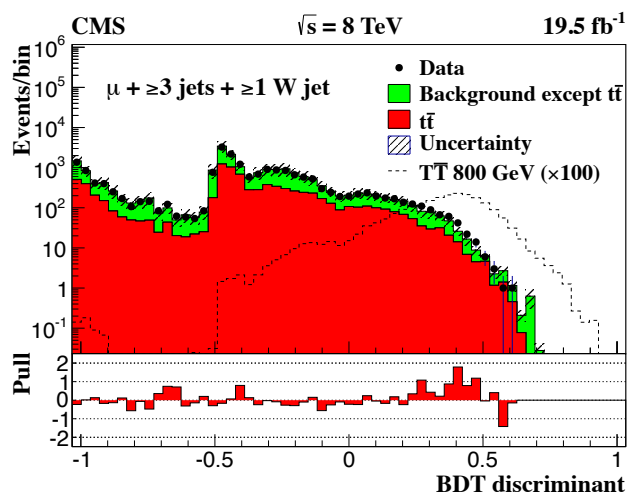
    strongly interacting states which can mix with SM states and cancel the Higgs mass divergence

    vector-like quarks are a common feature of these models

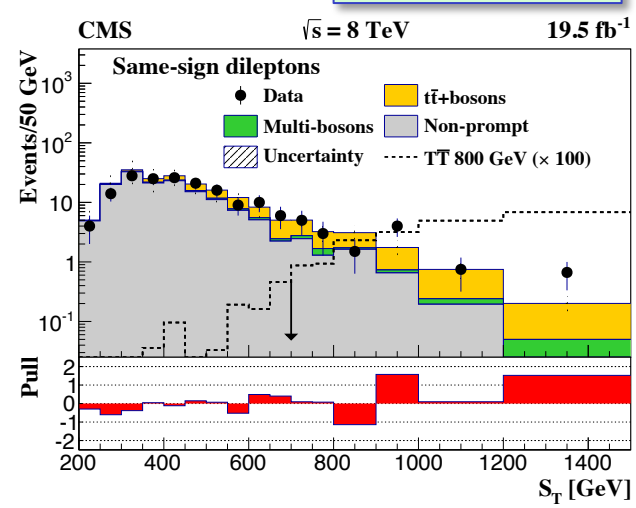
    – L-handed and R-handed components in the same multiplet
- CMS searches for $T\bar{T}$ pair production with $T \to bW, T \to tZ, T \to tH$
  - final states with b quarks and W boson
  - uses 5 categories of final states with leptons, jets, E_T^{miss}, b jets

arXiv: 1311.7667





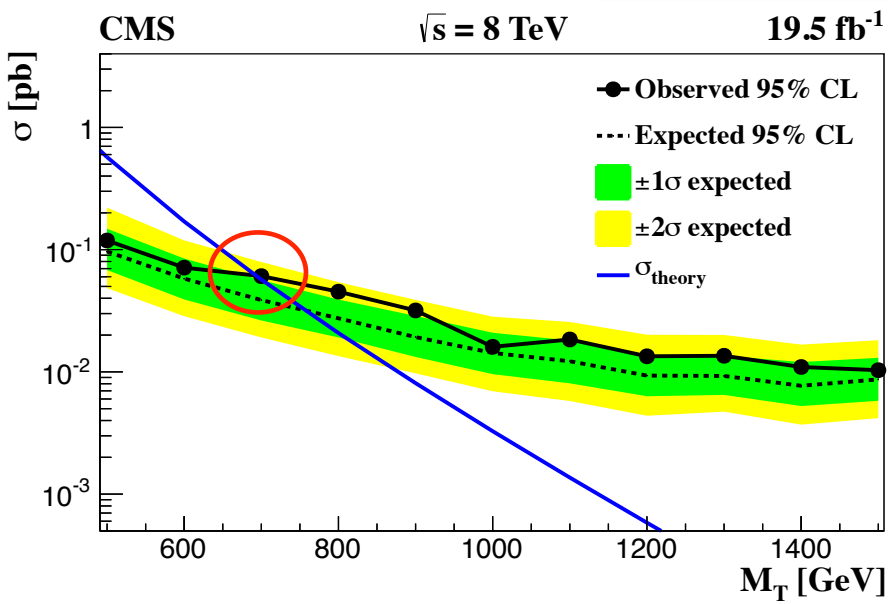
BDT for 1-lepton category



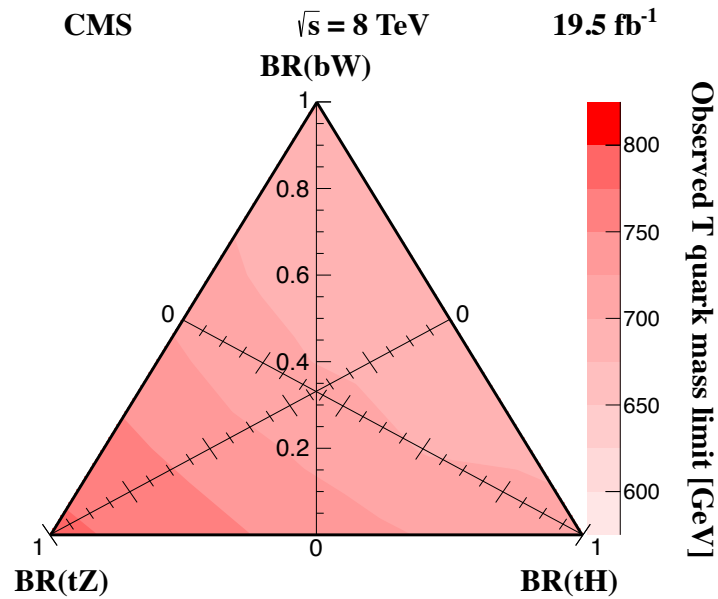
Scalar transverse energy for one multilepton category

Search for vector-like quarks

arXiv: 1311.7667



M_T > 700 GeV for "standard" branching fractions to (bW, tH, tZ) of (0.5, 0.25, 0.25).



Mass limits for arbitrary branching fractions. M_T > 690 – 780 GeV

ATLAS limits, depending on model and branching fractions,

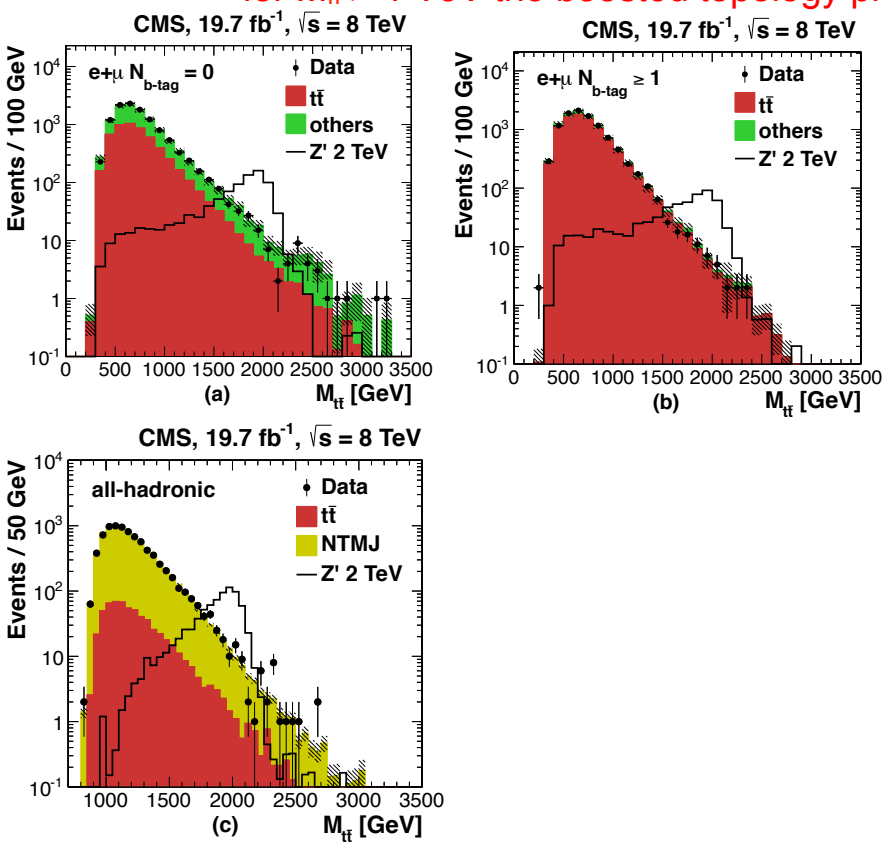
M_T > 660 – 810 GeV

M_B > 690 – 790 GeV

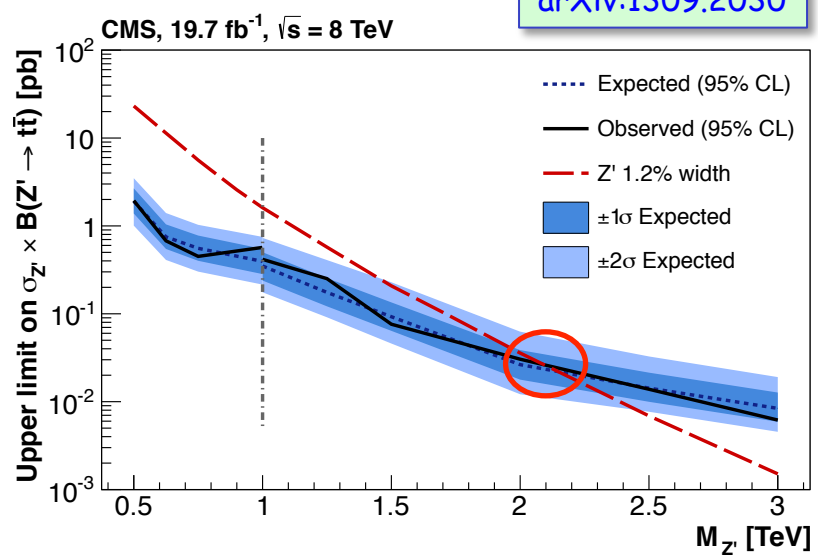
Search for ttbar resonances

- Naturalness problem for Higgs mass may involve BSM effects coupling to t quarks
- Z′ bosons may couple preferentially to t quarks
- Search for anomalies in $t\bar{t}$ mass spectrum
  - consider final states where one top decays to $b\ell^{\pm}\nu$ and other decays to bqq' (semi-leptonic)
  - also final states where both both top quarks decay to bqq' (all-hadronic)
  - final states may involve top quarks with all decay products resolved or a single "fat" jet (boosted topology)

for M_{tt} > 1 TeV the boosted topology predominates



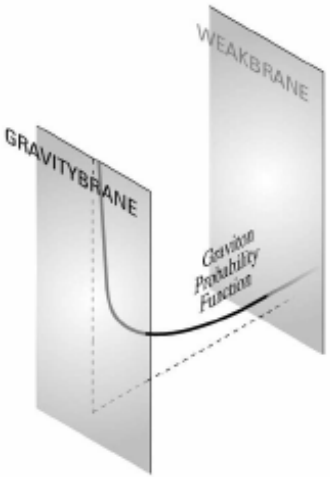
arXiv:1309.2030

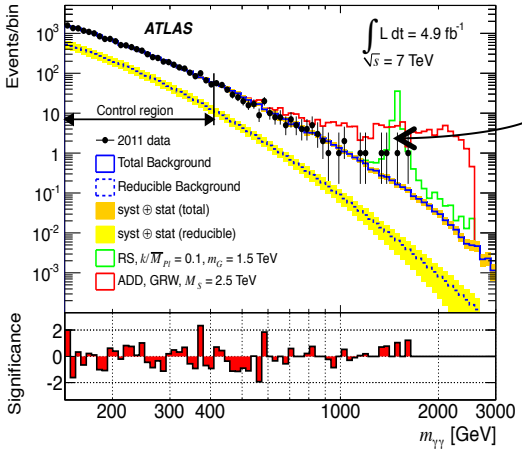


Model	Observed Limit	Expected Limit
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV

Search for extra dimensions

- aim is to resolve disparity between EW scale of 100 GeV and Planck scale of 10^{19} GeV
  - Randall-Sundrum (RS) model, leading to a narrow graviton resonance
    - * two 4-dimensional branes in 5 dimensional space
    - * SM on one brane, gravity on the other, gravitons propagate between them
    - * extra dimension compactified leading to Kaluza-Klein tower of graviton excitations
    - * characterized by curvature of extra dimension k and reduced Planck mass $\bar{M}_{Pl} = M_{Pl} / \sqrt{8\pi}$
    - * width of lightest KK state is 0.014% for $k / \bar{M}_{Pl} = 0.01$ (narrower than detector resolution)
    - * narrow enhancement in $\gamma\gamma$ or $\ell^+\ell^-$ mass spectrum or missing energy in mono-jet search
  - Arkani-Hamed, Dimopoulos, Dvali (ADD) model, leading to a broad $\gamma\gamma$ or $\ell^+\ell^-$ mass enhancement
    - * gravity propagates in n large extra spatial dimensions, compactified to scale R while SM is in 3+1 dimensions $\bar{M}_{Pl}^2 = M_D^{n+2} R^2$
    - * leads to an apparent Planck scale which is large relative to the fundamental Planck scale M_D which is at TeV scale
    - * spacing of KK graviton states ~1/R so continuum is nearly continuous





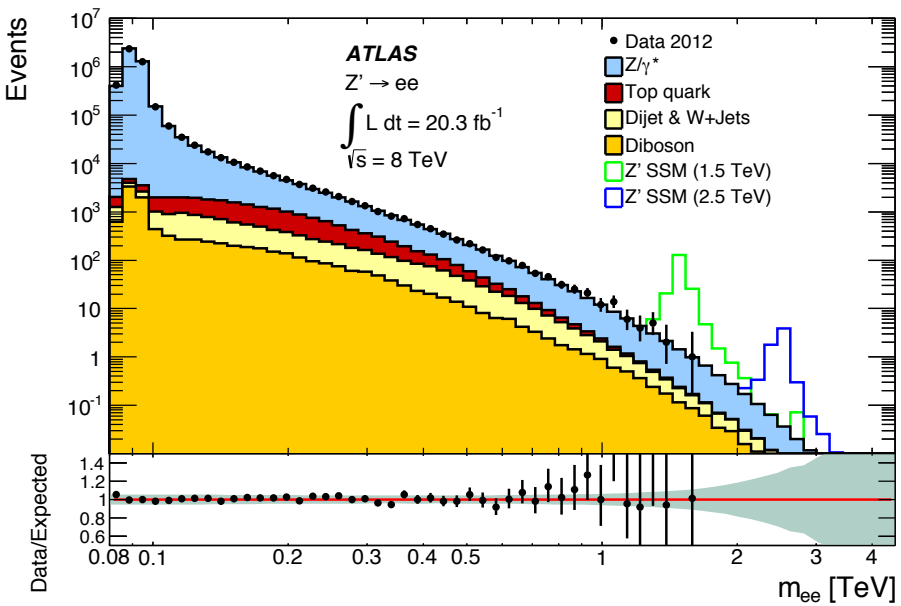
Examples of signals for extra dimension from RS and ADD models.

arXiv:1210.8389

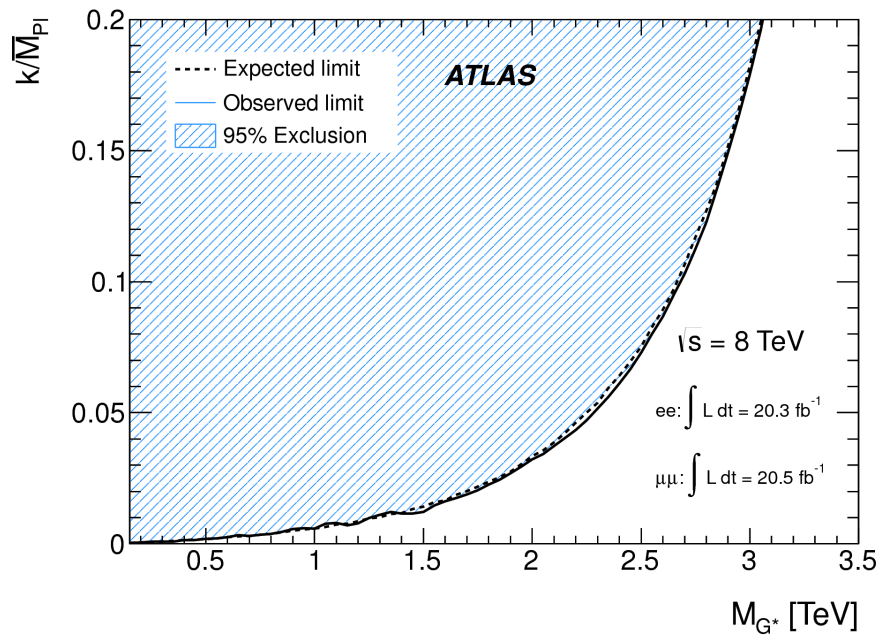
Search for extra dimensions

- Most stringent limits from $\ell^+\ell^-$ mass spectrum
  - also limits from $\gamma\gamma$ mass spectrum, mono-jet search, black hole search

Limits on RS model with narrow G*
(arXiv:1405.4123)



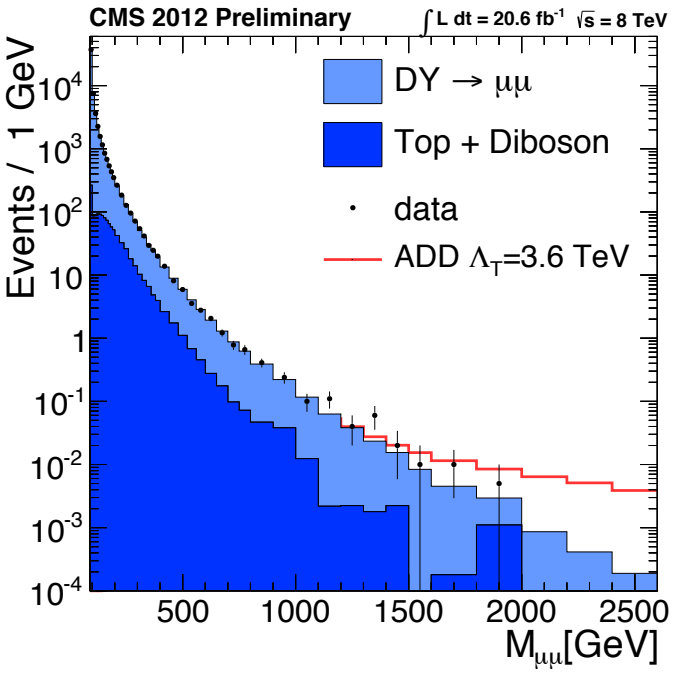
Observed ee mass spectrum



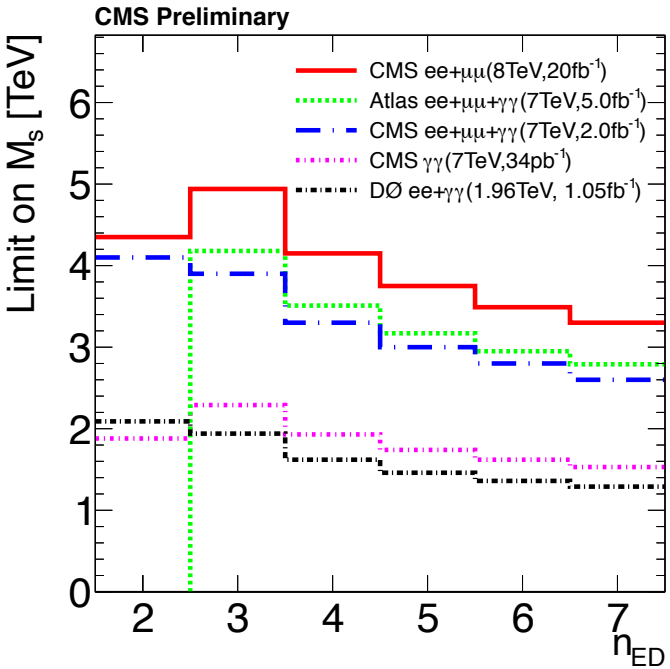
Excluded lowest G* mass

Search for extra dimensions

Limits on ADD model with broad mass enhancement (CMS PAS EXO-12-027)



Observed μμ mass spectrum



Excluded string scale mass vs number of extra dimensions eg. M_s > 3.5 TeV for n=6

Additional topics

- see ATLAS and CMS summary charts and cited references

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

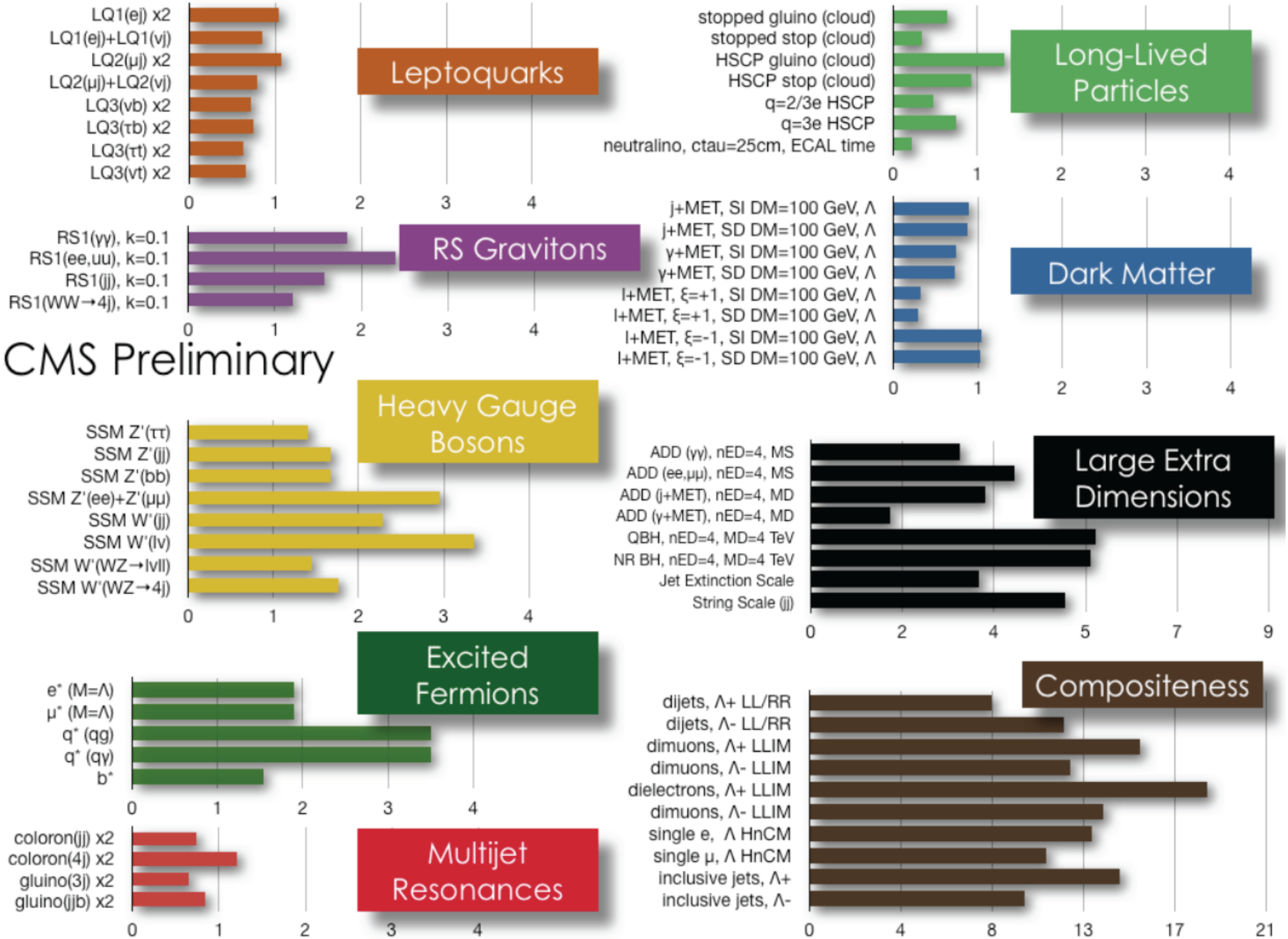
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D	4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S	5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th}	5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th}	5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th}	6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass	1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass	730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass	590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass	2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$	4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1}	1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass	2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass	1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass	3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass	1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass	1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass	1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass	1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ	7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ	21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ	3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_*	731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_*	2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass	660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass	685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass	534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass	790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass	670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	T mass	735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass	755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass	720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass	3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass	4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2 j or 1 j	Yes	4.7	b^* mass	870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass	2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass	960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass	1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^\pm$ mass	245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass	409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass	490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass	862 GeV	DY production, $\lvert g \rvert = 1g_D$	1207.6411

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

10^{-1} 1 10 Mass scale [TeV]

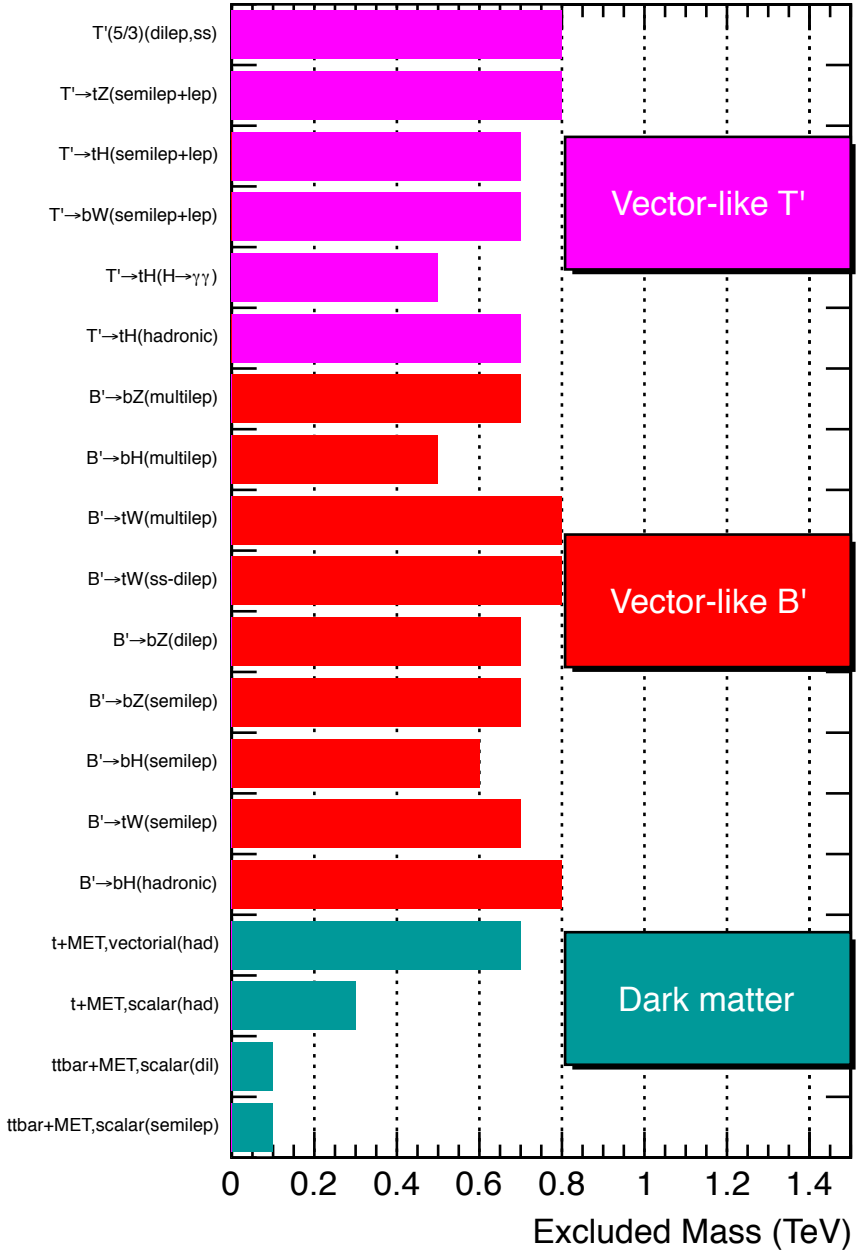
*Only a selection of the available mass limits on new states or phenomena is shown.

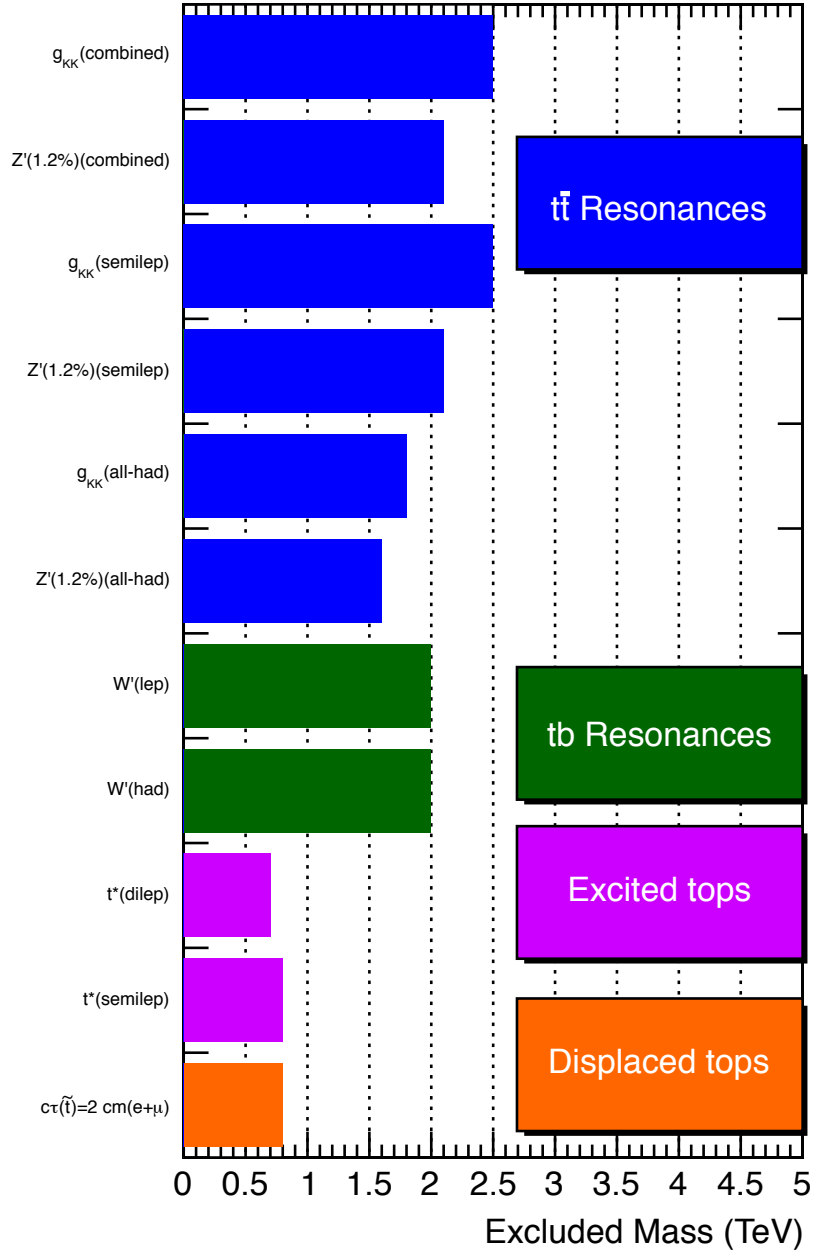


CMS Exotica Physics Group Summary – ICHEP, 2014

CMS Searches for New Physics Beyond Two Generations (B2G)

95% CL Exclusions (TeV)





Conclusions

- no BSM discoveries yet
- Many channels examined
  - simple models used to place mass limits
  - also searches for many unconventional channels
- Both high p_T experiments are clearly capable of seeing new physics
  - detectors and collider have performed very well (~25 fb^{-1} of data from Run 1)
  - active analysis teams with powerful software tools

    over 150 papers from each experiment on new particle searches
  - current limits and results are very comparable from the two
  - each team would like to make the first discovery
- The work will be reenergized next year at 60% higher energy and increased luminosity
  - more on the potential of these runs in talks this afternoon