DM searches at LHC with a focus on conventional candidates and techniques (e.g. SUSY)

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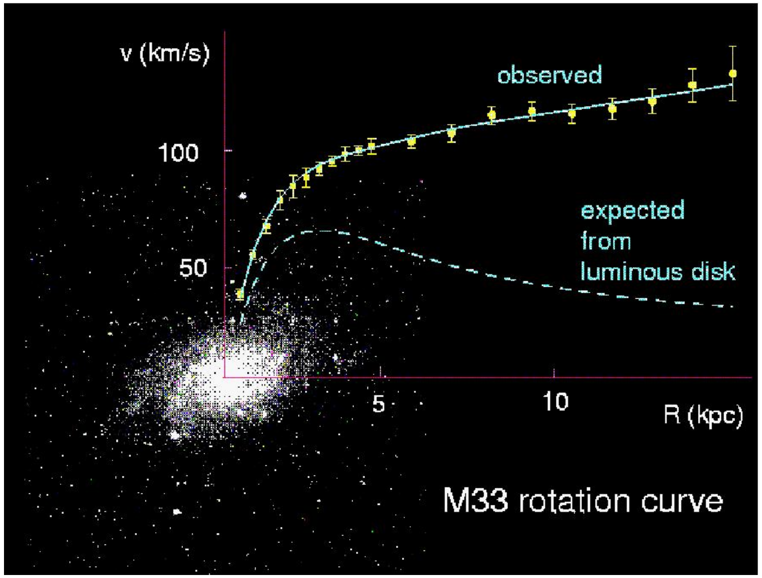
On behalf of ATLAS & CMS Collaborations



中国科学院高能物理研究所
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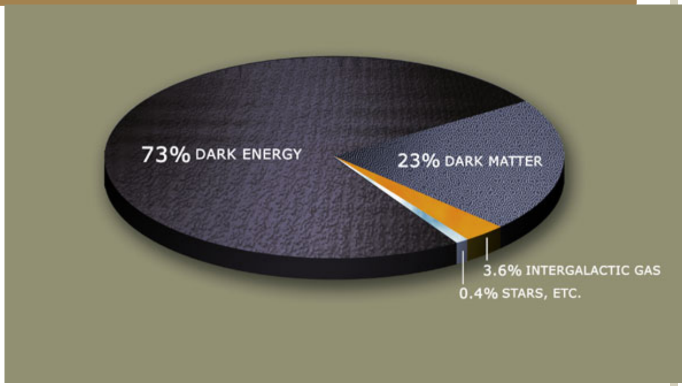
Dark Matter (DM) Particle Candidates

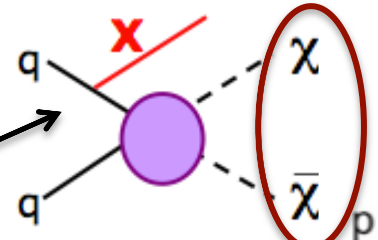
- **Requirements on DM particle candidate:**
  - **Stable**: still present in Universe today, No strong or EM interactions
  - **Massive** enough to be non-relativistic during formation of structure in universe
  - Mass of O(1-1000) GeV predicts correct relic density (consistent with DM seen today)

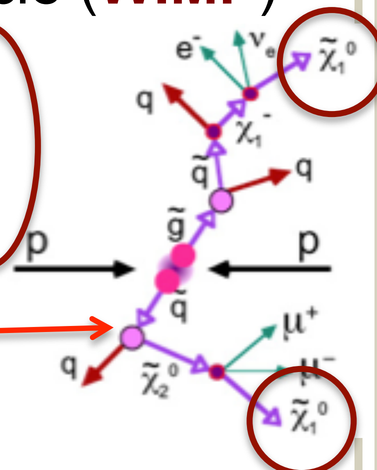


23% of universe consist of cold Dark Matter (Lambda-CDM model)

- **DM candidate**: Weakly Interacting Massive Particle (**WIMP**)

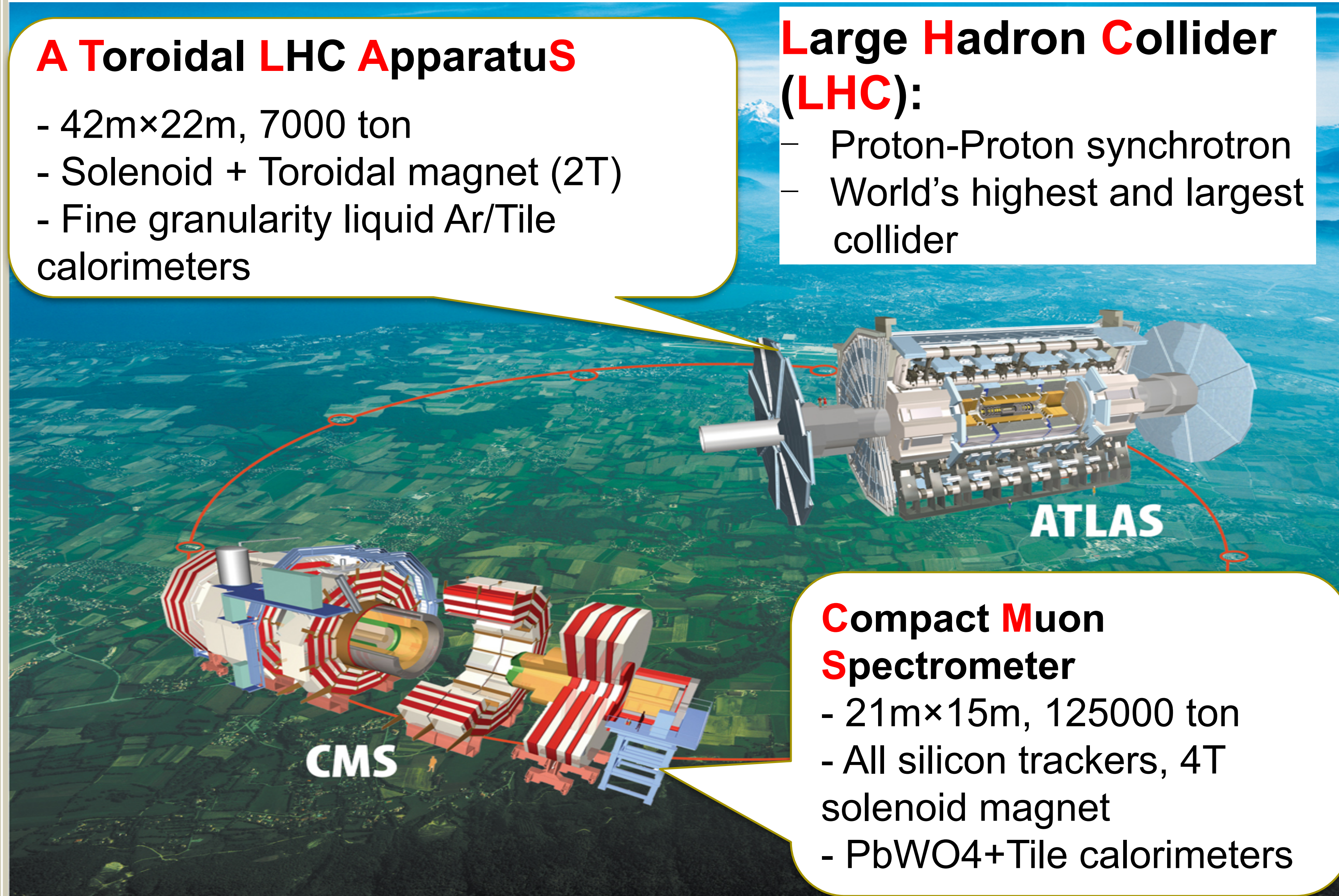
- **DM search @ LHC:**
  - (1) Direct WIMP production: mono-X (James's talk)
  - **(2) Indirect production search: (SUSY) -> this talk**





ATLAS and CMS detectors @ LHC

ATLAS and CMS: two multi-purpose detectors @LHC



A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton
- Solenoid + Toroidal magnet (2T)
- Fine granularity liquid Ar/Tile calorimeters

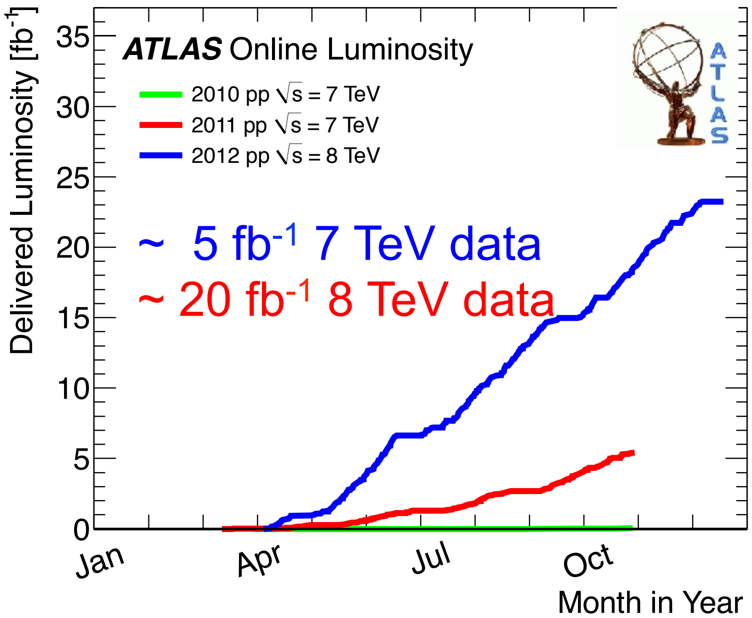
Large Hadron Collider (LHC):

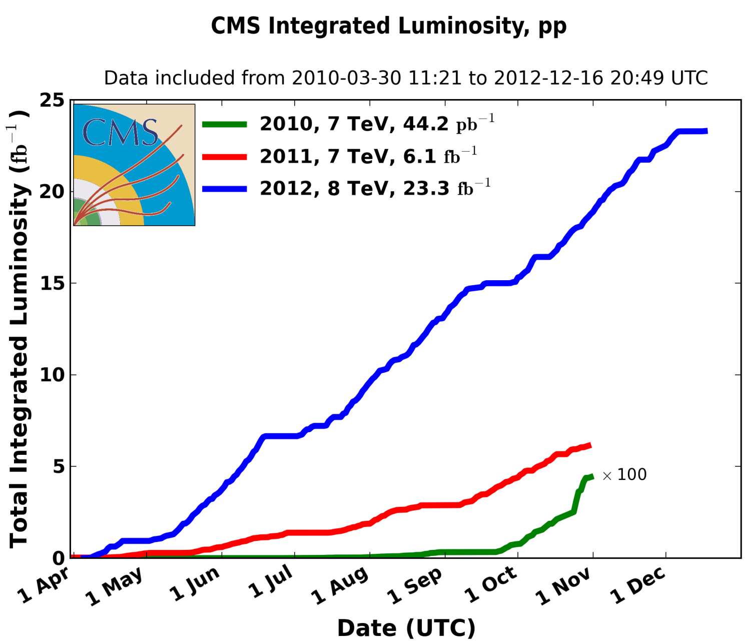
– Proton-Proton synchrotron
– World's highest and largest collider

Compact Muon Spectrometer

- 21m×15m, 125000 ton
- All silicon trackers, 4T solenoid magnet
- PbWO4+Tile calorimeters

LHC run - 1





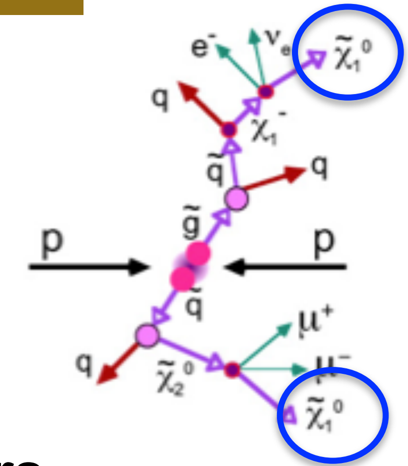
- **Successful LHC run in 2010-2012**
- **Similar for ATLAS & CMS:**
  - ~ 5 fb^{-1} 7 TeV data
  - ~ 20 fb^{-1} 8 TeV data

–> most results shown used full 8 TeV data, few with half 8 TeV data

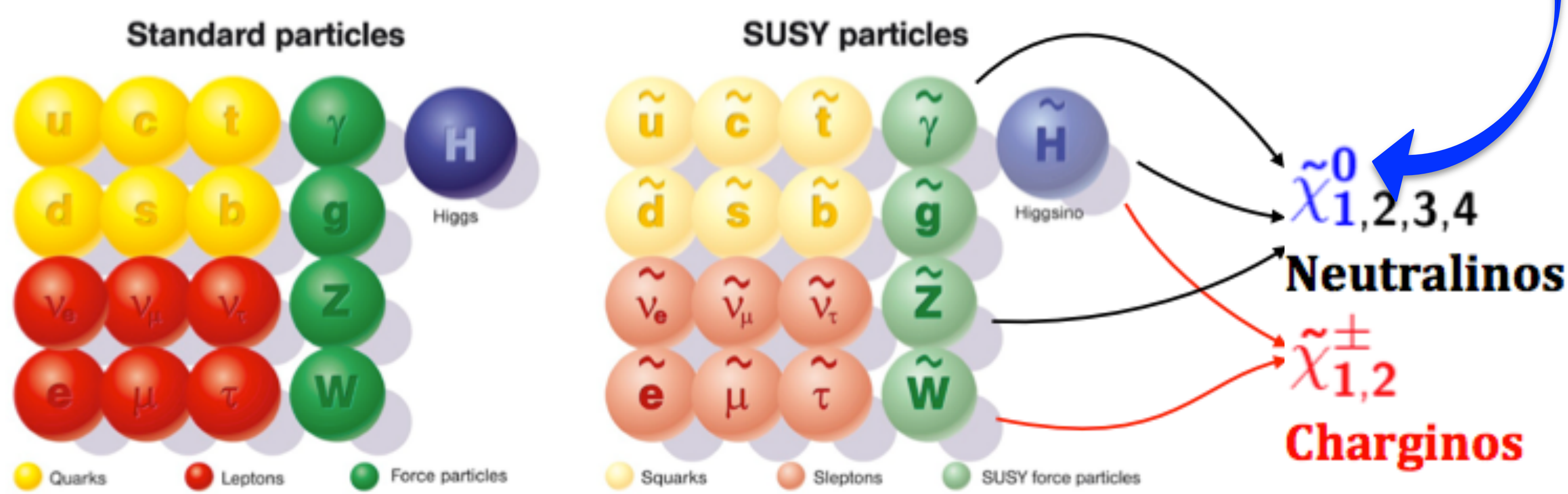
- **Peak luminosity at 2012:**
  - **7.7 * 10 33 cm-2s-1 (~30 pileup events)**
  - **<μ> ~ 21 @ 8TeV**
- **Data quality (2012):**
  - **93.7% ready for physics**

SUSY and DM candidate

- Last possible extension of Poincare group: Fermion <-> Bosons
- Conserved R parity (originally introduced for stability of proton) $R = (-1)^{3(B-L)+2S}$

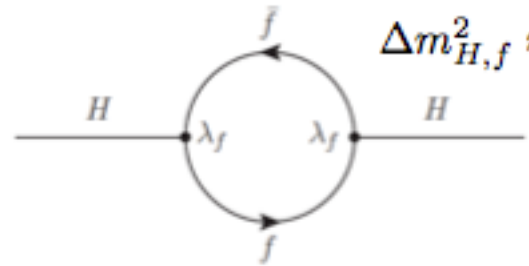


  - SUSY particles produced/annihilated in pairs
  - Lightest SUSY particle (LSP) stable (DM candidate)
  - Typical signature: jets/leptons/photons + **MET**



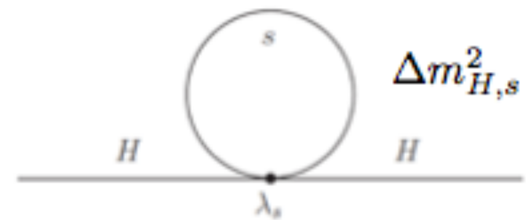
SUSY and DM candidate

- Solve hierarchy problem without "fine tuning"
  - SUSY contributions to Higgs mass cancel SM contributions



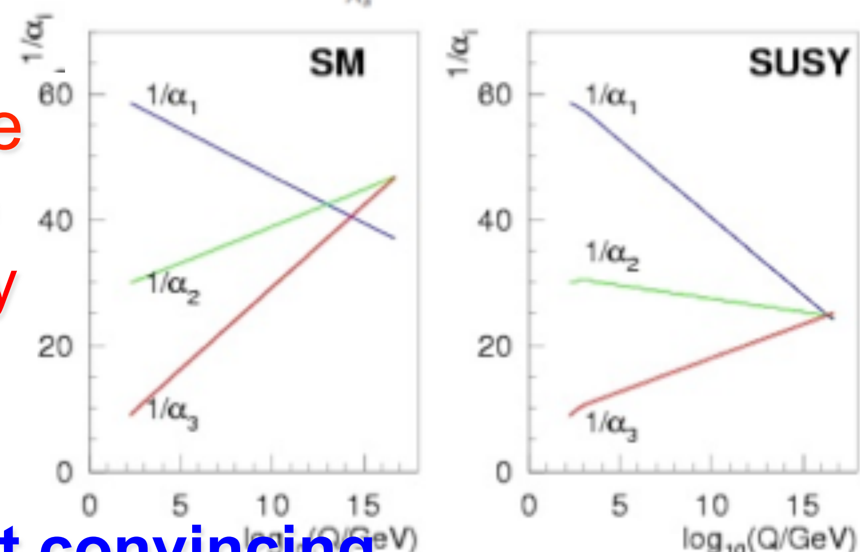
$$\Delta m^2_{H,f} \approx -\frac{\lambda_f^2}{8\pi^2}\Lambda^2_{\rm UV}$$

- Unification of gauge couplings
  - New particle content changes running of couplings



$$\Delta m^2_{H,s} \approx \frac{\lambda_s}{16\pi^2}\Lambda^2_{\rm UV}$$

- Provide Dark Matter candidate
  - Lightest SUSY particle (LSP) can be stable and only weekly interacting
  - **Today's talk !**

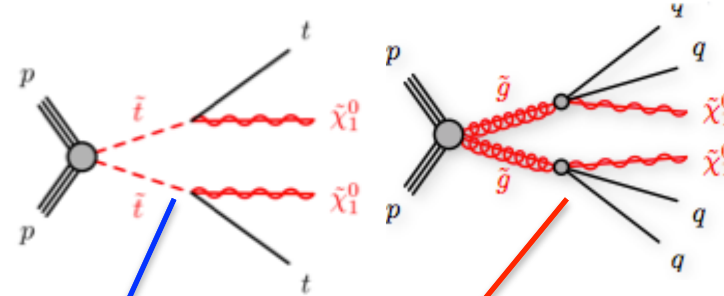


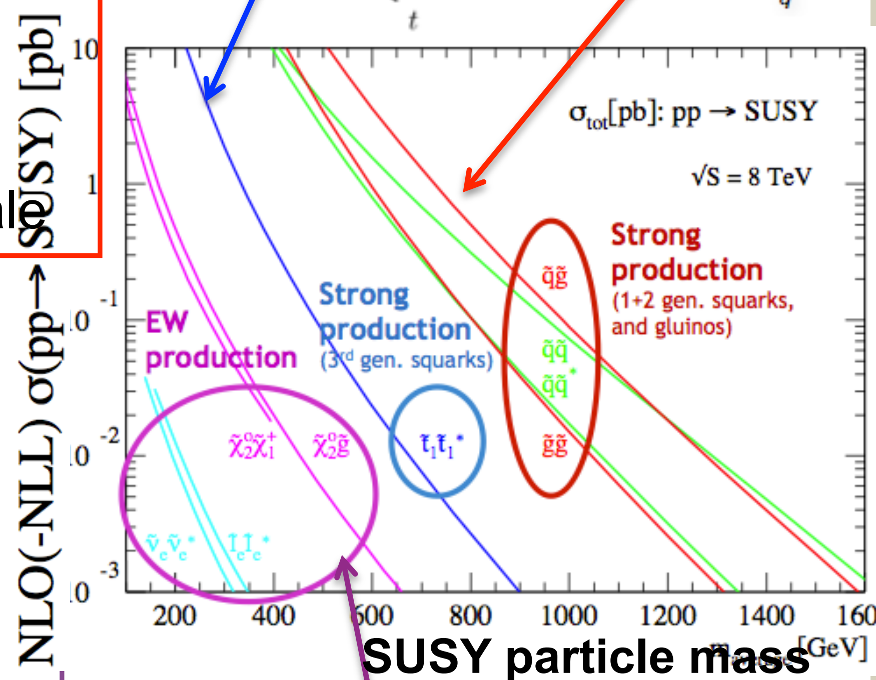
Some of the arguments are most convincing for SUSY particles at ~TeV scale

How Do we Search SUSY @ LHC ?

Strong production: gluino pair, gluino-squark and squark pair (include **3rd generation**) production

1）Generic signatures :
Multi -jets + n_lepton/n_photon(n=0,1, ≥2) + large E_T^{miss}
2）large xs, but heavy SUSY mass scale

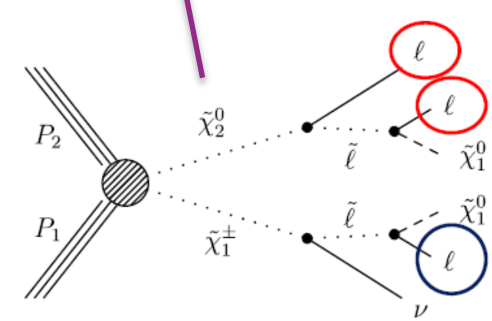




Final states:
n_jets + n_leptons/n_photons + *large E_T^{miss}* (n≥0)

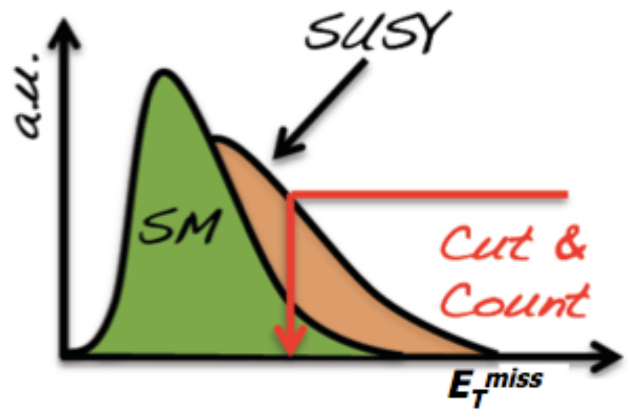
Weak production: direct gaugino/slepton production

1）Generic signatures:
low–jet multiplicity + ≥ 2leptons + large E_T^{miss}
2）low xs, but small SUSY mass scale



How Do we Search SUSY @ LHC ?

- **SUSY search strategy:** search for **deviation from SM**
  - -> rely on the SM understanding and detector understanding
  - -> Try to establish excess of events in some sensitive kinematic distribution

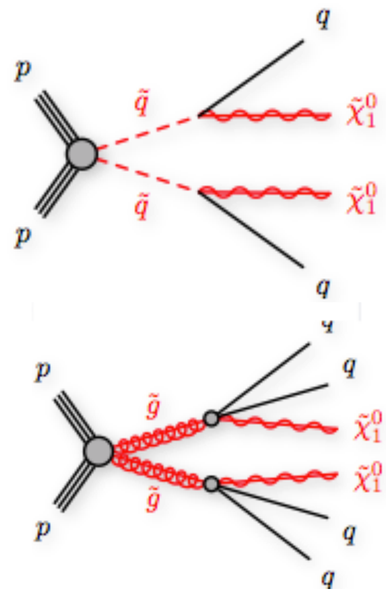


- SM bkgs (top, multijets, V, VV, VVV, Higgs):
  - The **reducible** (ie, fake) backgrounds are always taken from data
  - The **irreducible** bkgs, if dominant, are taken from MC normalized to data in dedicated CRs, while subdominant bkg is fully taken from MC
  - The **validation** region is used to cross check SM prediction with data

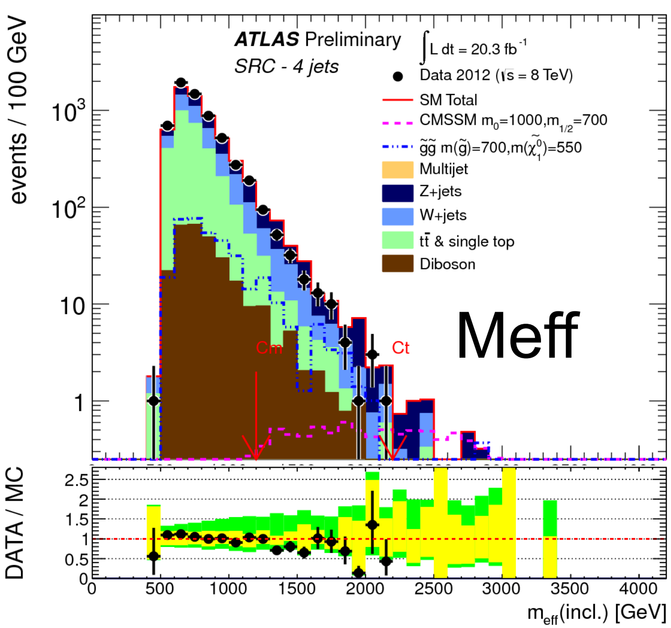
- **SUSY sensitive variables:**
  - Missing transverse energy: E_T^{miss}
  - $H_T = \sum p_T^l + \sum p_T^{jet}$
  - Effective mass: Meff (= H_T + E_T^{miss})

Inclusive SUSY search (Strong Production)
- 0 L + 2-6 jets + MET (ATLAS-CONF-2013-047)

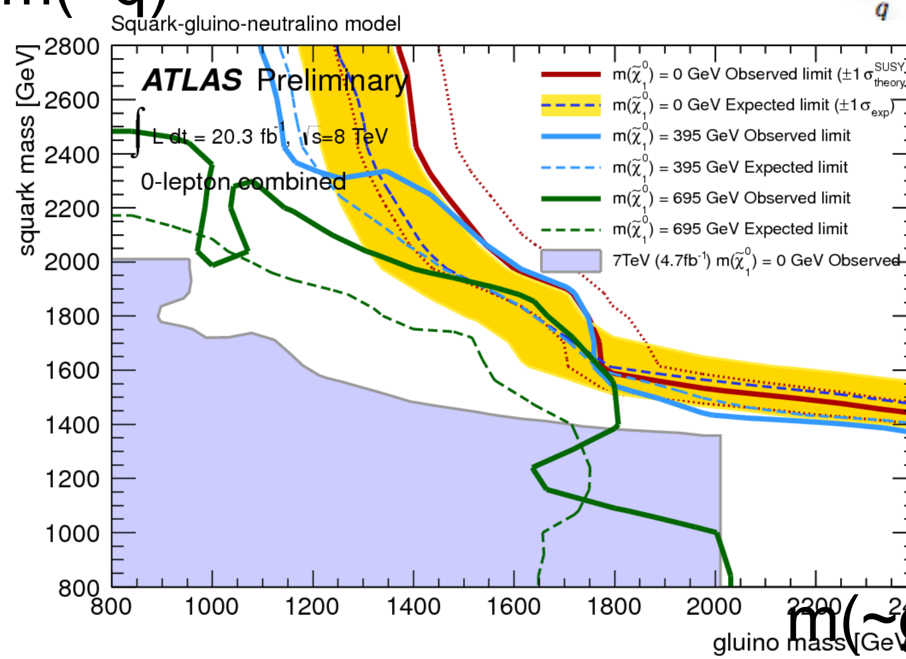
- **Very powerful inclusive search**
- jet + MET trigger
- Main discriminating variable: **Meff**
- Up to 3 SRs for each jet multiplicity
- Backgrounds taken from dedicated data CRs (and validated)



m(~q)



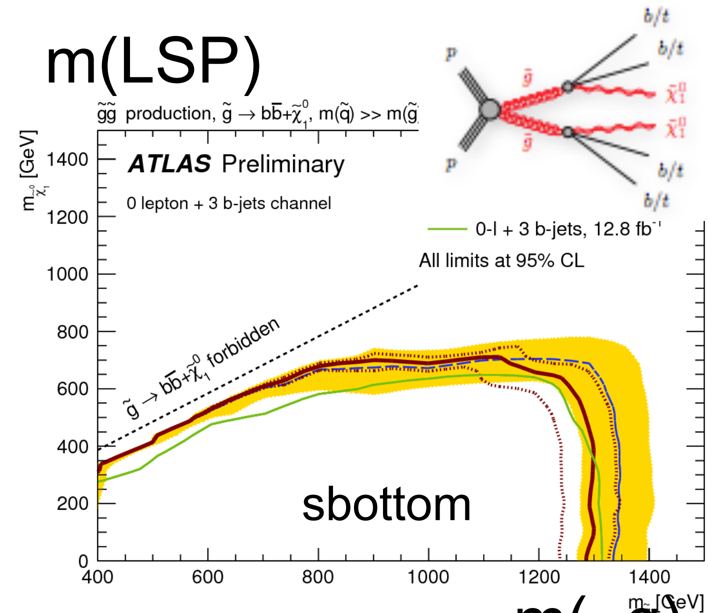
Meff

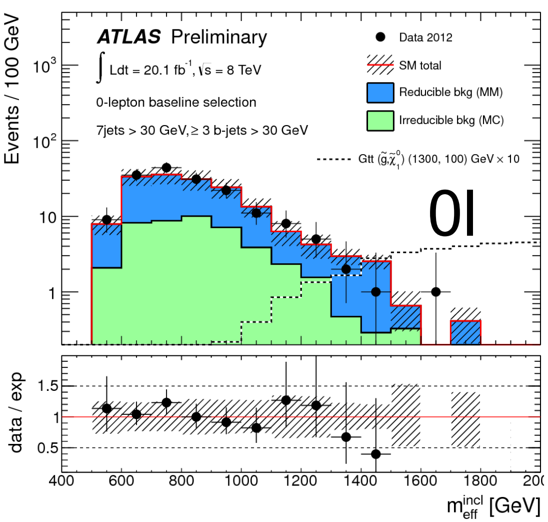


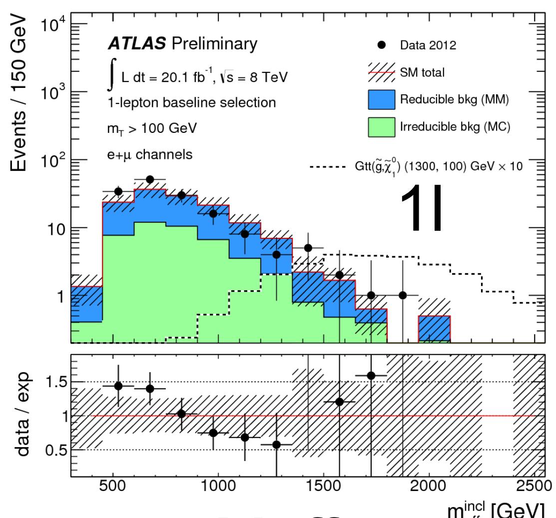
m(~g)

Inclusive SUSY search (Strong Production)
- 0-1 L + ≥ 3 b-jets + MET (ATLAS-CONF-2013-061)

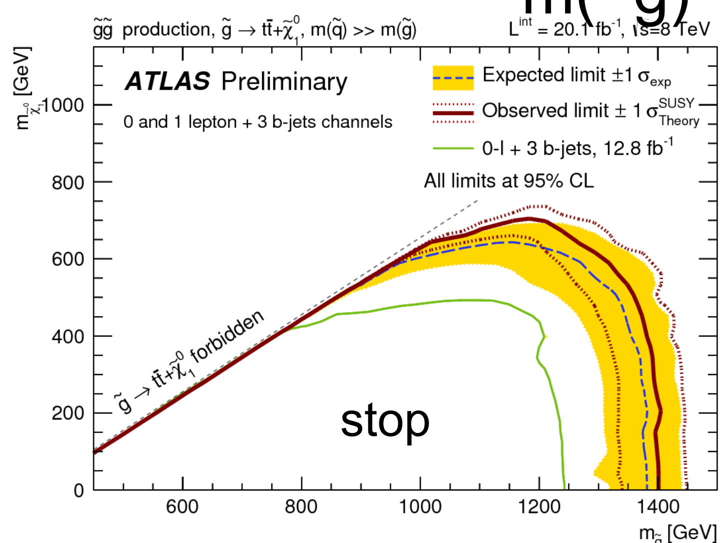
- Gluino-mediated stop/sbottom production (0-1l + 3 b-jet +MET)
- **Most powerful search for high Gluino mass**
- jet + MET trigger
- Discriminating variable: **Meff**
- Reducible bkg (tt+fake b's) from MM
- Irreducible bkg (tt+bb, ttV) from MC





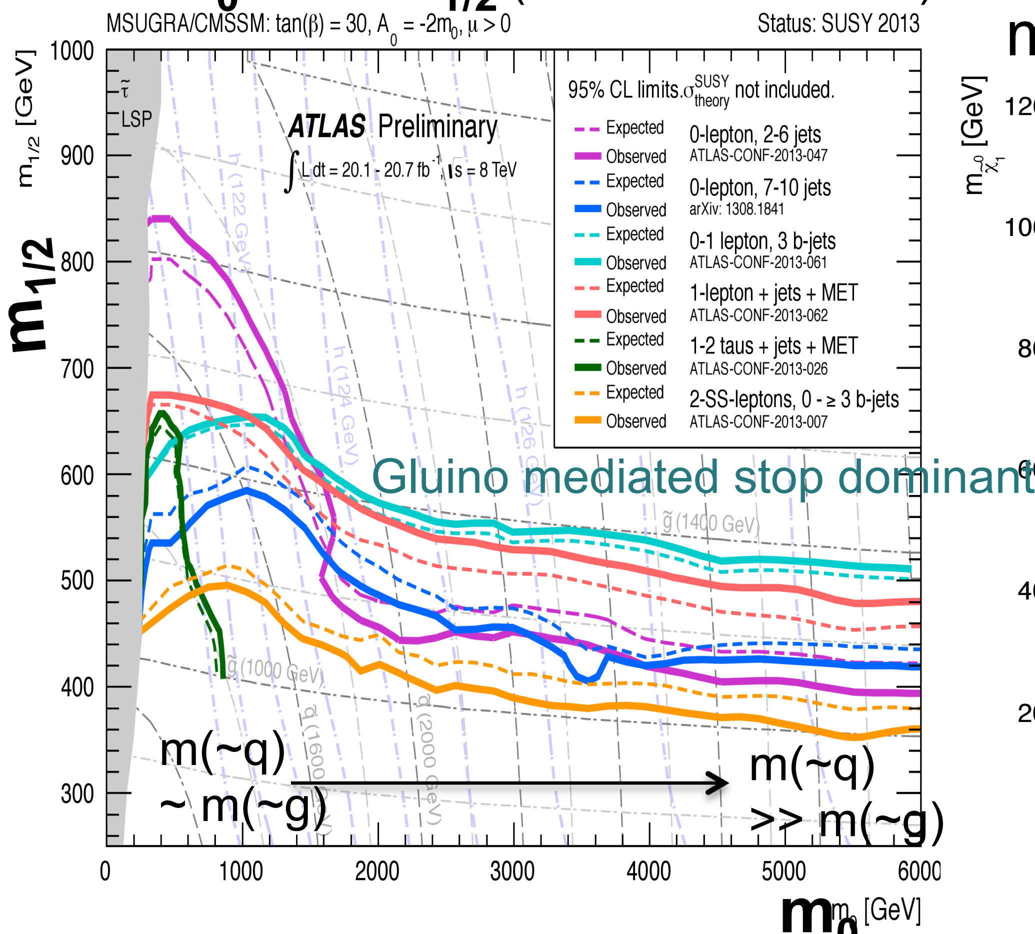


Meff

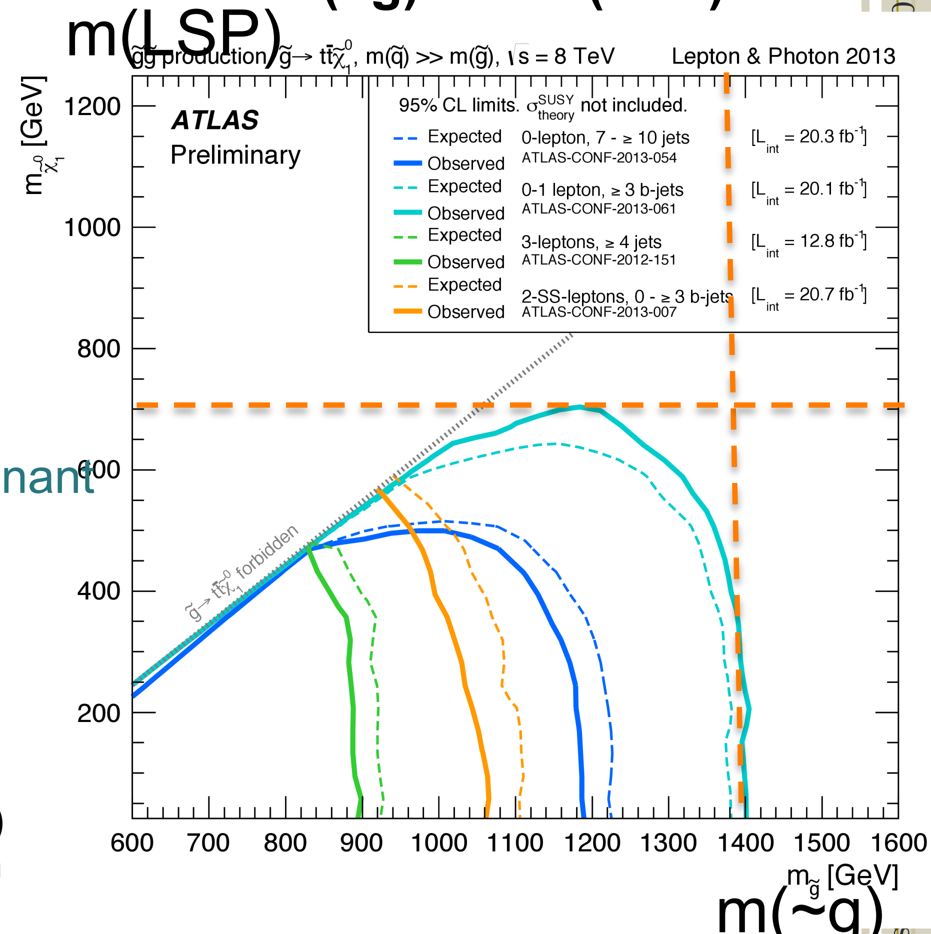


Inclusive search for squark and gluino production

m_0 .vs. $m_{1/2}$ (mSUGRA/cMSSM)



M(~g) .vs. m(LSP)



- m(~q) ~m(~g): m(~g) > 1.7 TeV
- M(~q) >> m(~g): m(~g)>1.35 TeV
- Conditional/indirect limit on LSP: m> 200-300 GeV

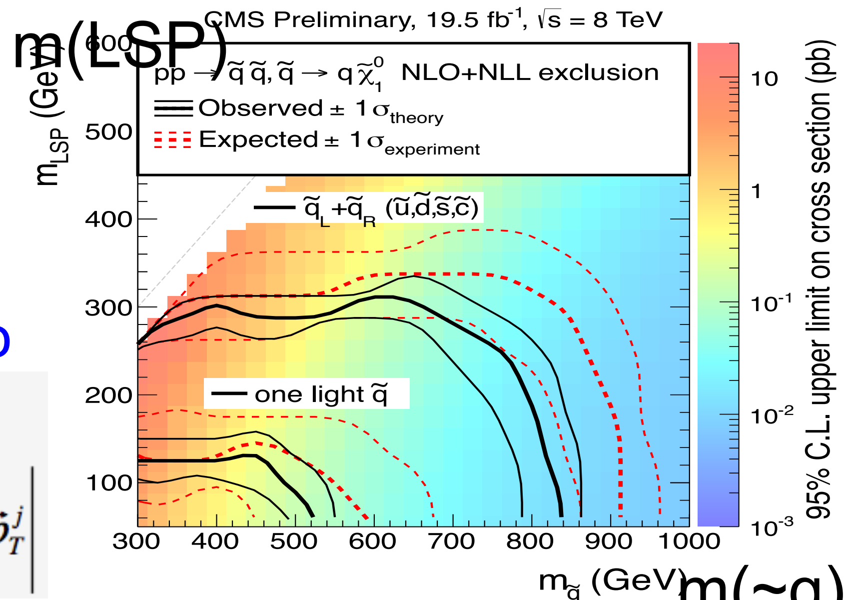
No exclusion for M(LSP) ≥ 700 GeV
Strongest limit: m(~g) ≥ 1400 GeV

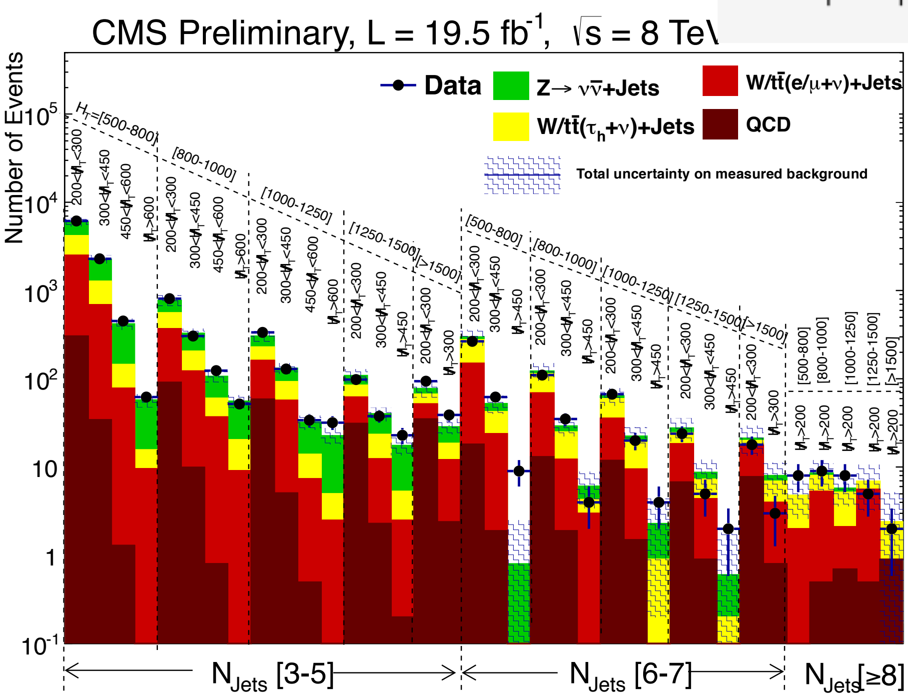
All-hadronic SUSY search using MHT (CMS-SUS-12-012)
– For more result using α_T, refer: CMS-SUS-12-028; 1303.2985

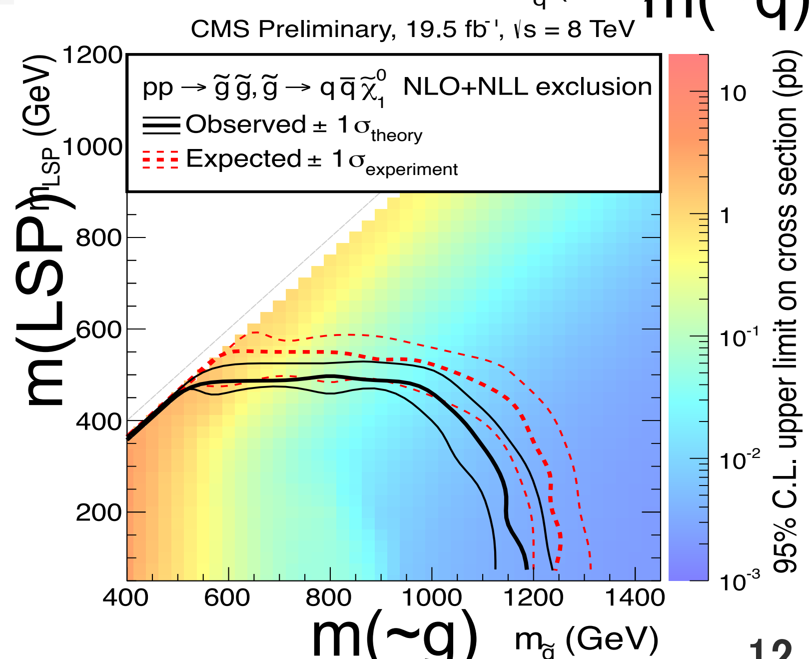
- Signature: (multi-jets (≥3j) +MHT)
- Classify events based on **jet multiplicity**, **HT, MHT** (36 excl. bins)
- Most bkg estimated from data
- squark mass up to 0.8 TeV and gluino mass up to 1.15 TeV excluded for light LSP

$$H_T = \sum_{j=jets} |\vec{p}_T^{\,j}|$$

$$\not{H}_T = |\vec{\not{H}}_T| = \left| -\sum_{j=jets} \vec{p}_T^{\,j} \right|$$





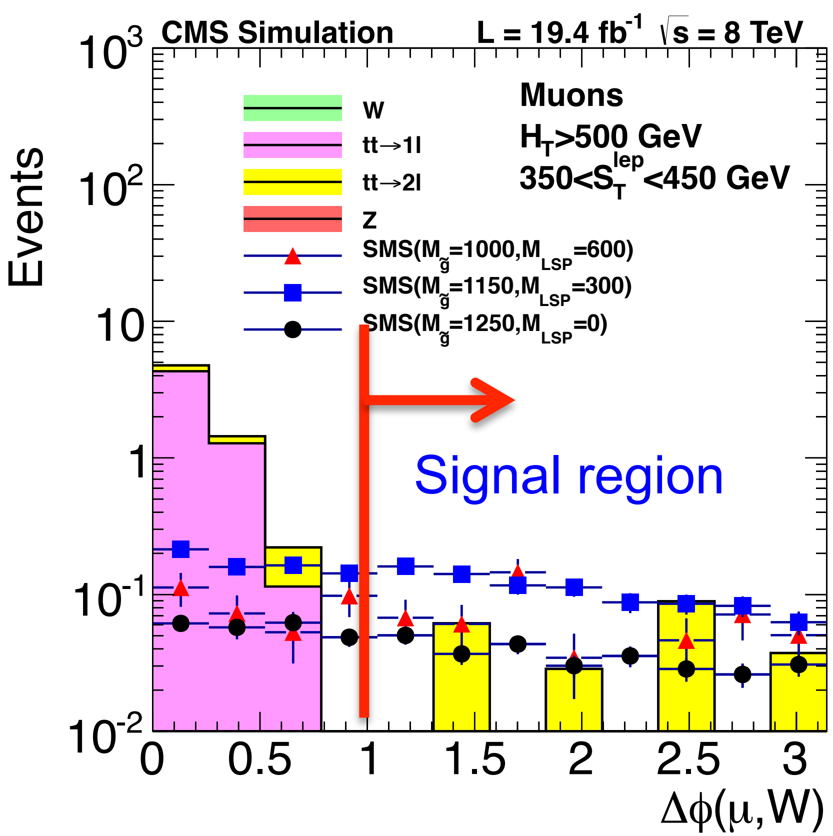


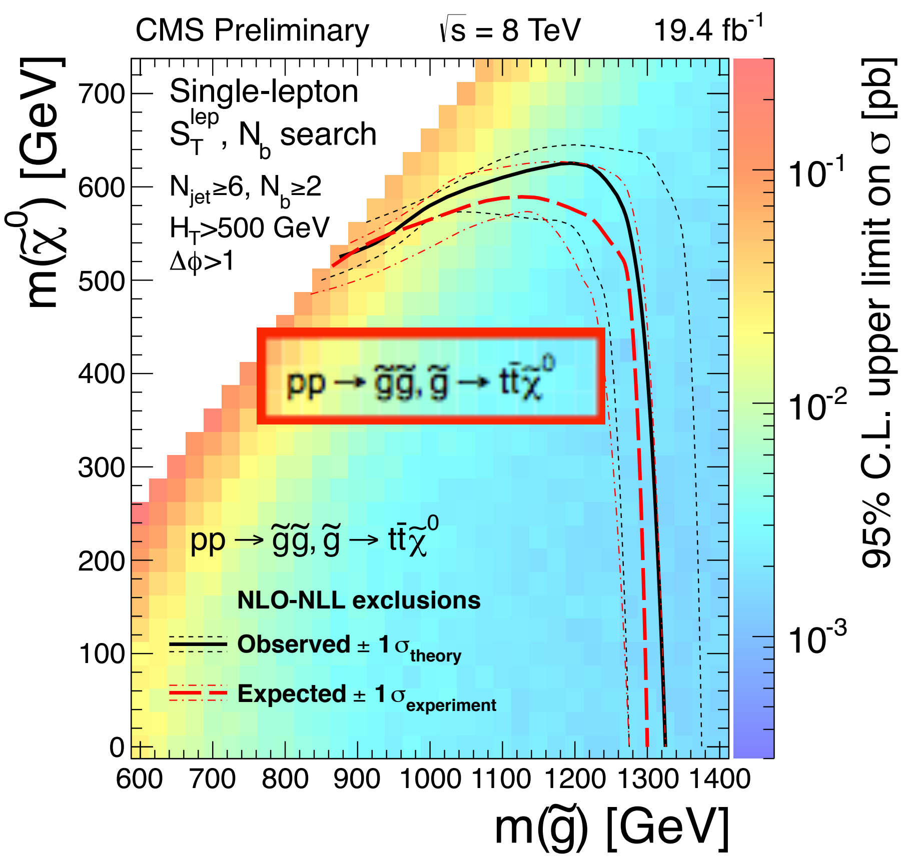
Inclusive SUSY search (Strong Production)

- 1 L + 6jets(2b) + MET (CMS-SUS-13-007)

- Gluino-mediated stop/sbottom production (1l + 6jets (2b) +MET)
- **Very powerful search for high Gluino mass**

- ΔΦ(l, W) method: strong suppression of 1-lep bkg (similar to MT)
- Also use ST=p_T(lep) + MET

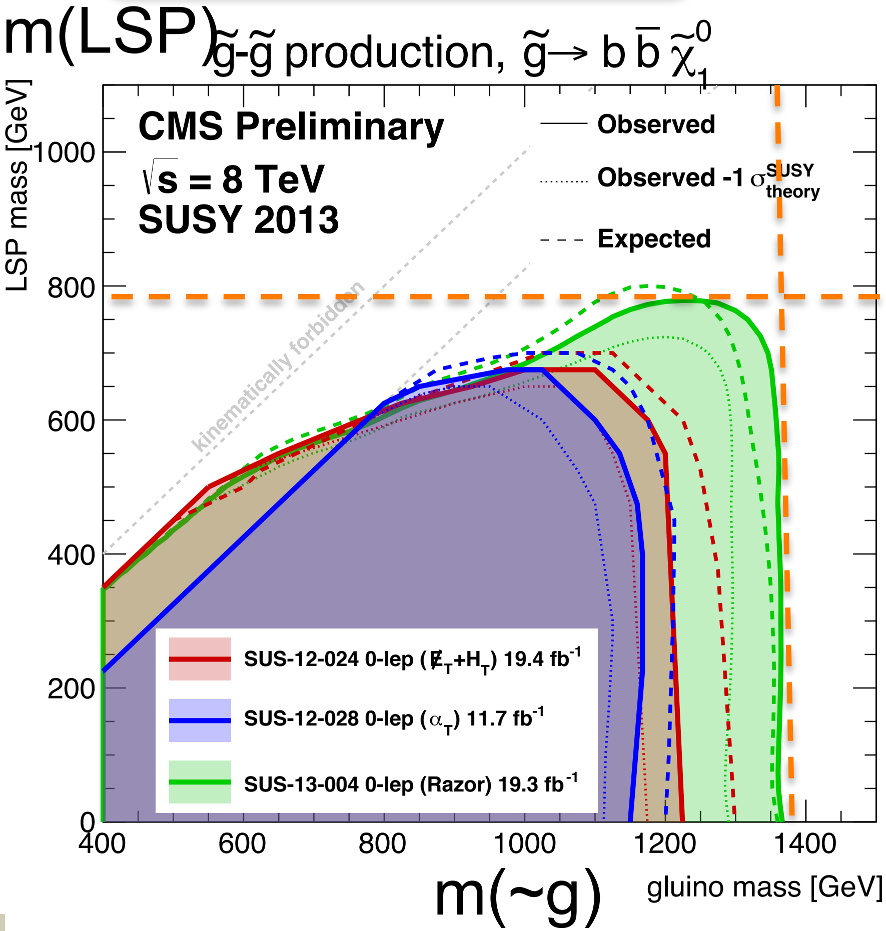


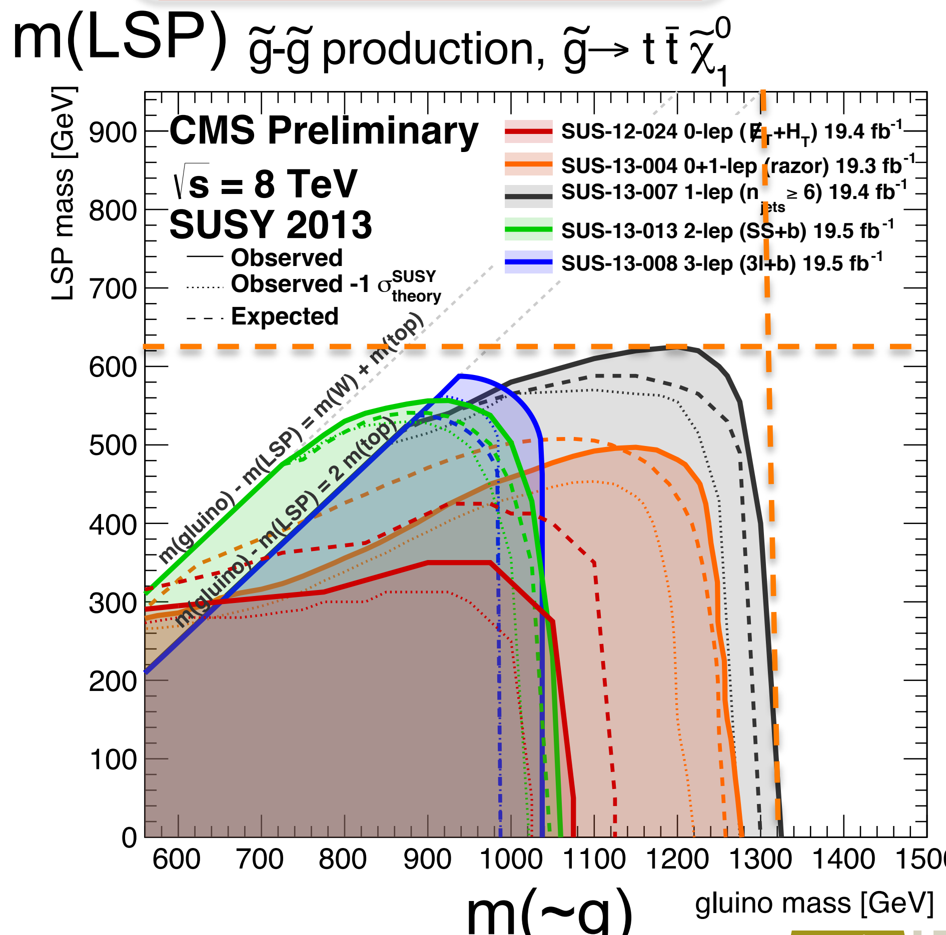


Summary of gluino-mediated stop/sbottom production

4b + MET final state: Hadronic searches most sensitive

4t + MET final state: Single lepton searches most sensitive





No exclusion for M(LSP) ≥ 750 GeV
Strongest limit: m(~g) ≥ 1375 GeV

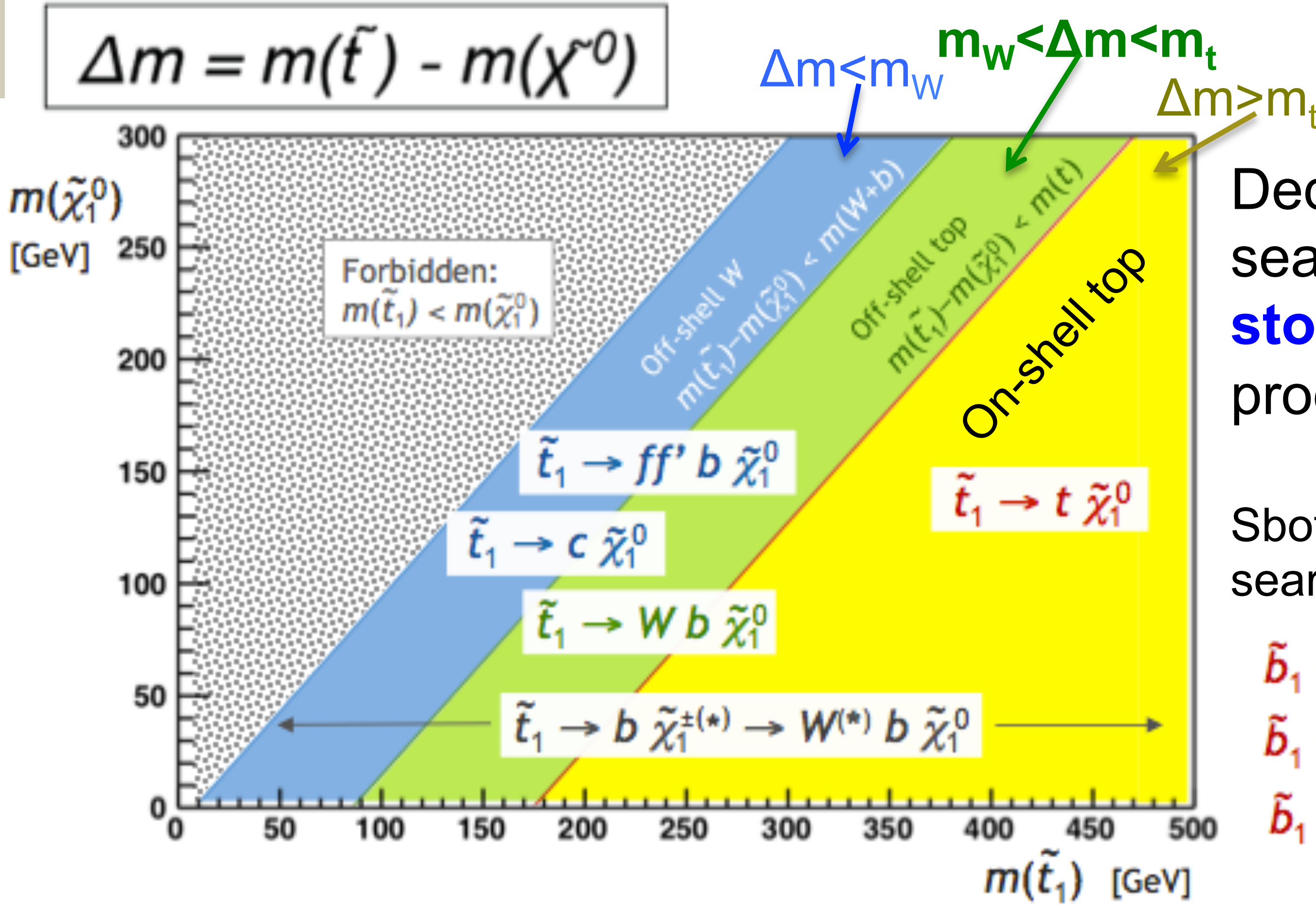
No exclusion for M(LSP) ≥ 600 GeV
Strongest limit: m(~g) ≥ 1320 GeV

16-21.09.2013

Direct stop/sbottom pair production

- Large spectrum of possible stop/sbottom decays
- Effort concentrated on simplified models with 100% BRs to chosen final state

$$\Delta m = m(\tilde{t}) - m(\tilde{\chi}^0)$$



Dedicated effort to search for **direct stop/sbottom pair** production

Sbottom decays searched for:

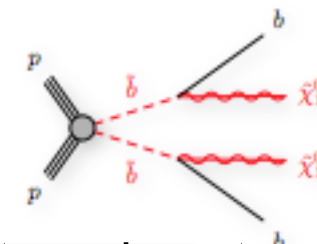
$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_1^0$

$\tilde{b}_1 \rightarrow t\,\tilde{\chi}_1^\pm$

$\tilde{b}_1 \rightarrow b\,\tilde{\chi}_2^0 \rightarrow b\,h(Z)\,\tilde{\chi}_1^0$

Direct sbottom pair production

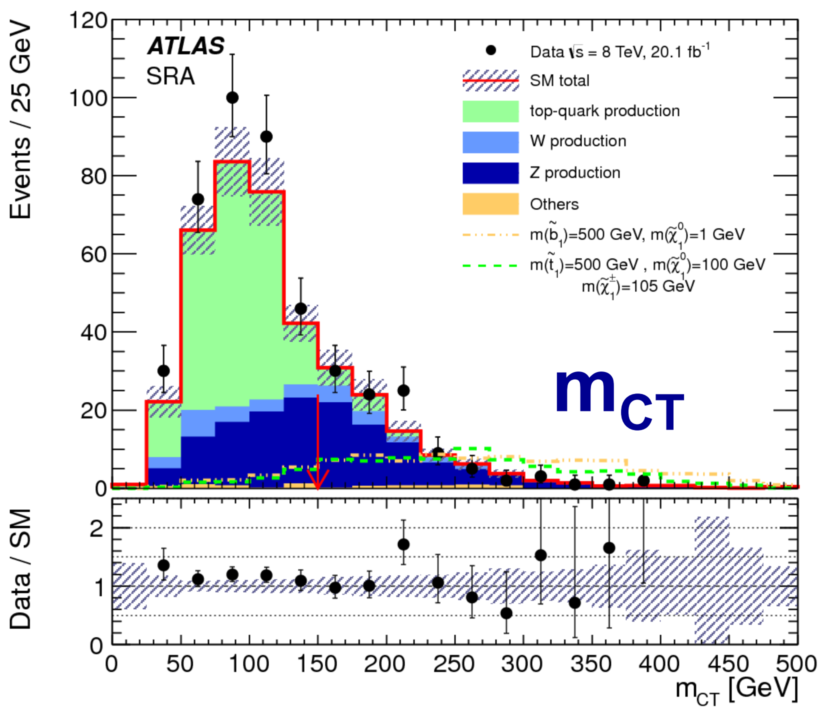
- bb + MET (1308.2631)

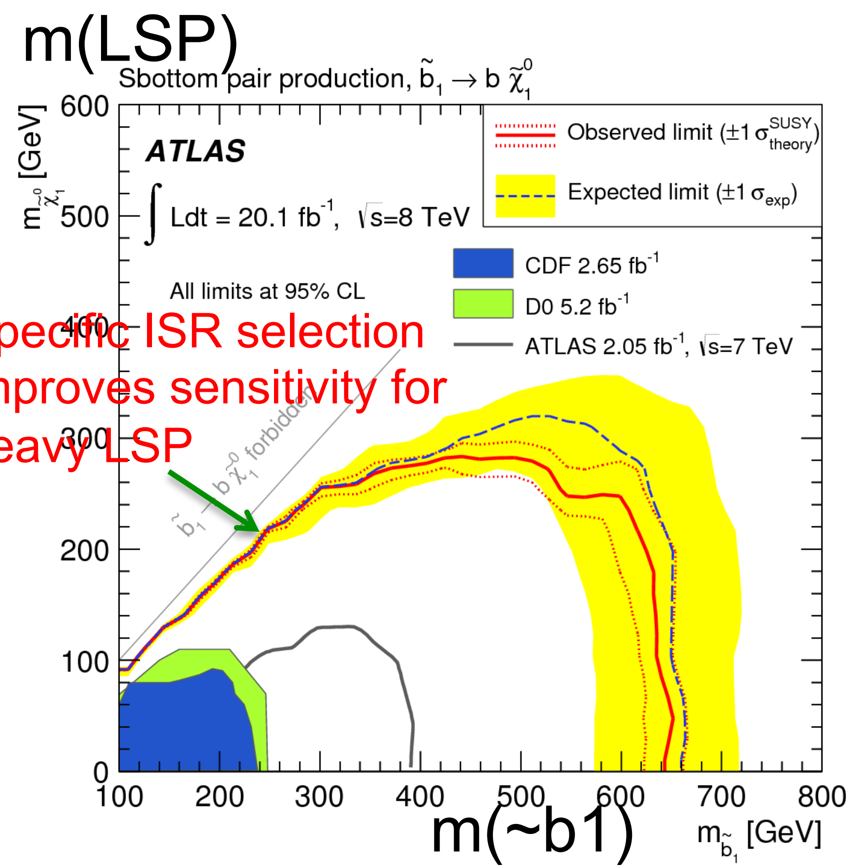


- Final state: 2b + MET
- **Sensitive to direct sbottom production**
- Discriminating variable: **m_{CT}**

$$m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [\mathbf{p}_T(v_1) - \mathbf{p}_T(v_2)]^2$$

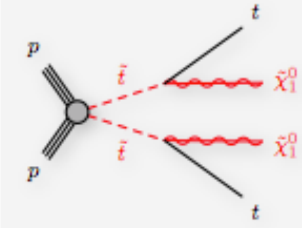
- use m_{CT} variable to reduce top bkg
- Remaining bkg dominated by Z(vv) +bb
- SR with ISR jet to help with compressed scenario





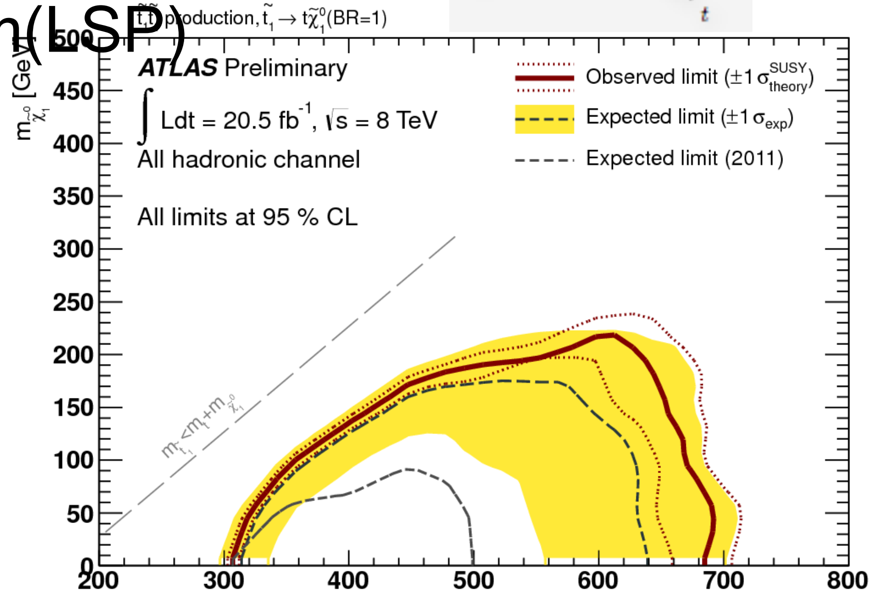
Direct stop pair production

- ttbar + MET (ATLAS-CONF-2013-024)

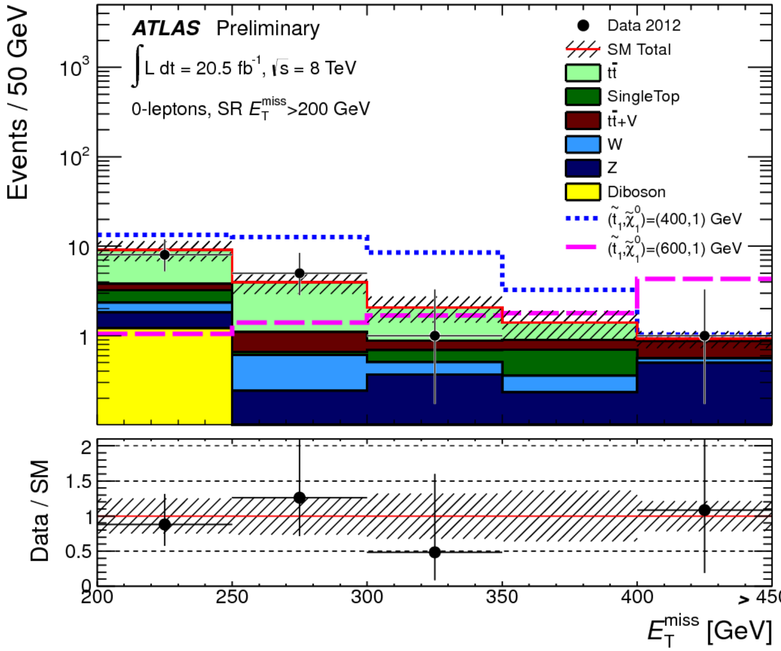


- Final state: 0l + 6j (2b) + MET
- Discriminating variable: **MET**
- 3 SRs (different MET cut) targeting medium and heavy stops
- Largest bkg from semi-leptonic top, further suppressed by m_T(b,MET) cut

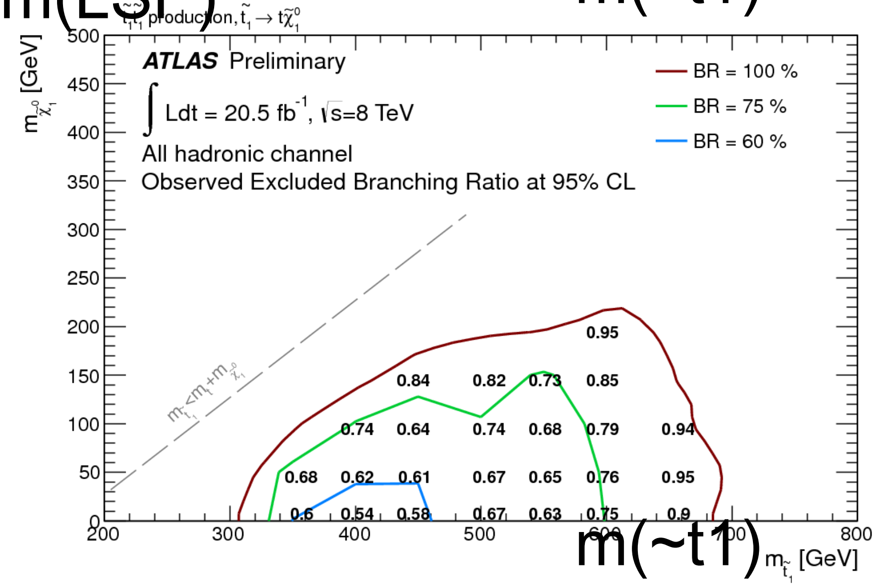
m(LSP)



m(~t1)



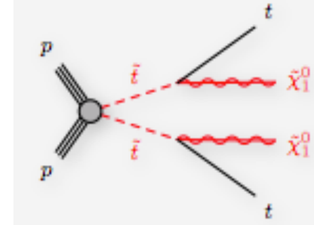
m(LSP)



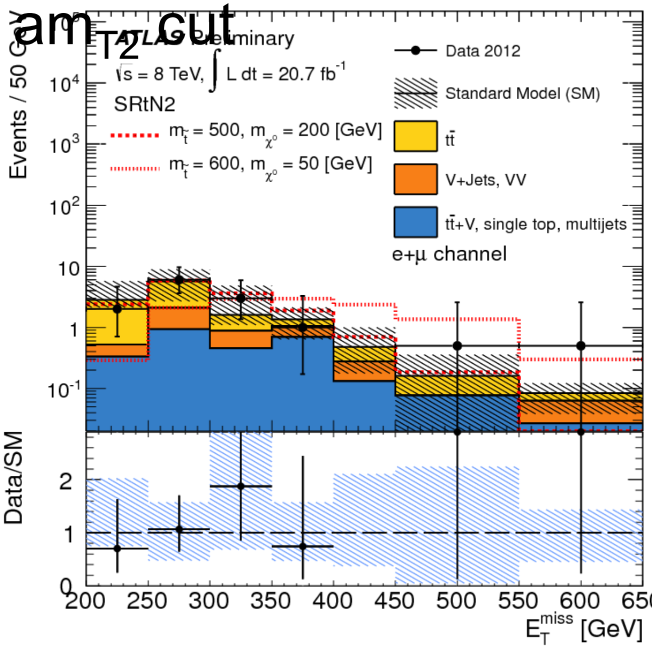
m(~t1)

Direct stop pair production

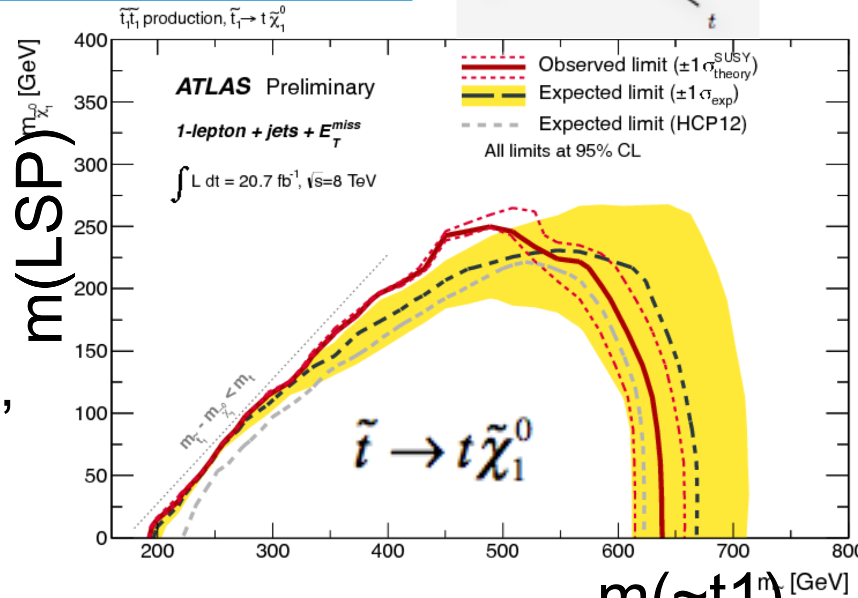
- ttbar + MET (ATLAS-CONF-2013-037)

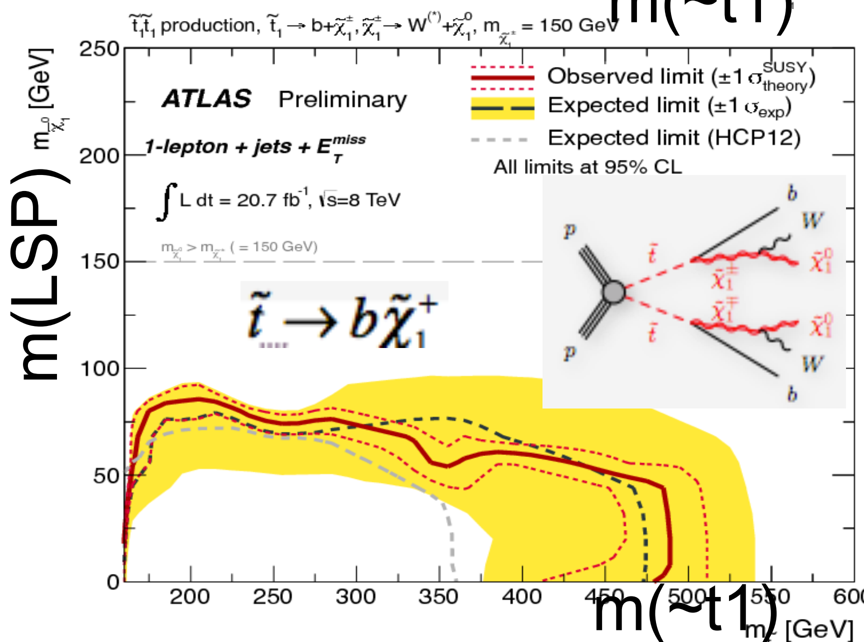


- Final state: 1l + 4j (2b) + MET
- Discriminating variable: **MET**
- 6 SRs targeting different parts of the simplified model plane (~t–>tN1/~t–>bC1)
- Dominant bkg from di-leptonic top, further suppressed by m_{T2} and am$_{T2}$ cut

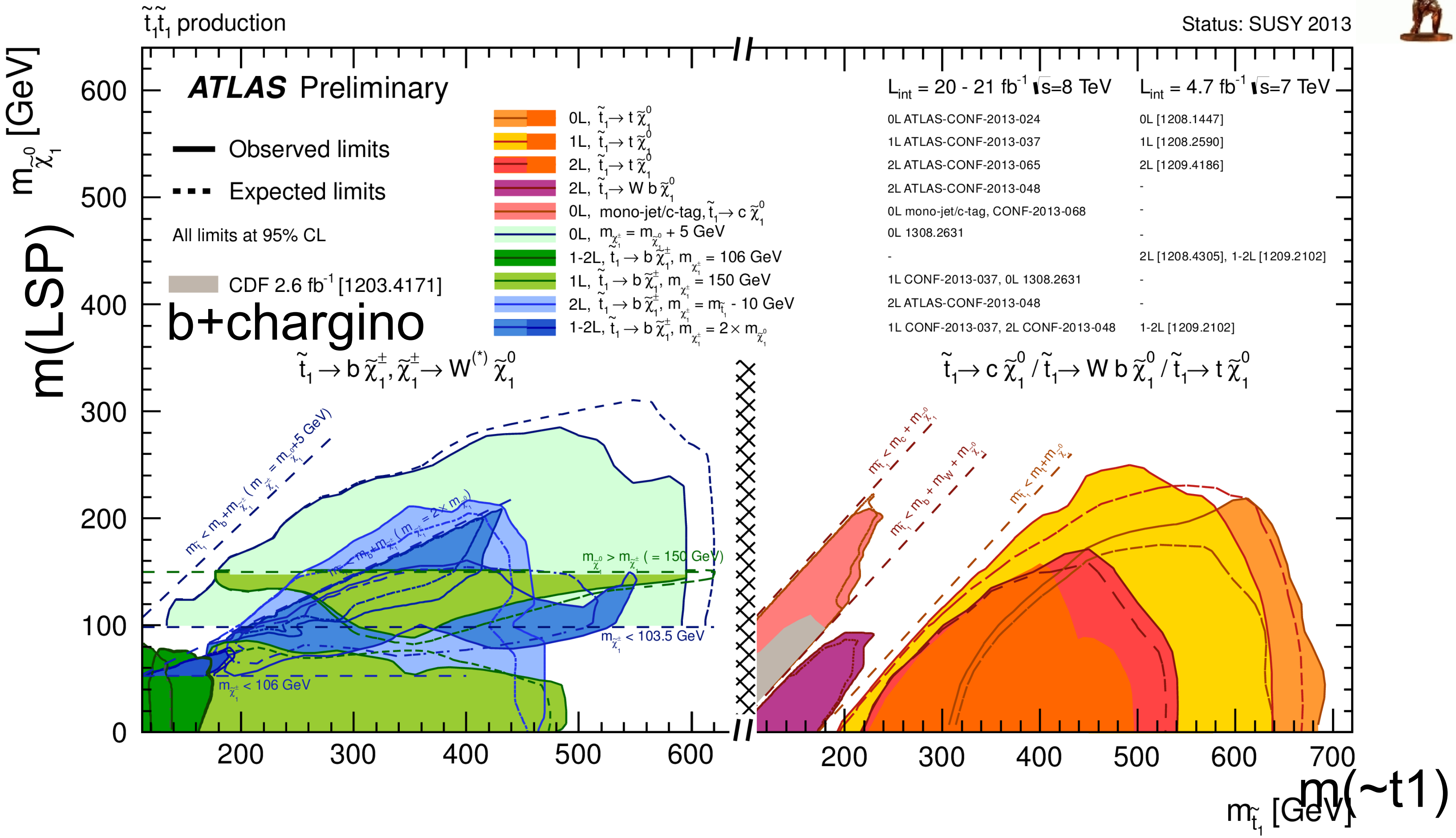


$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T)\right)\right]$$





Direct stop pair production (summary)



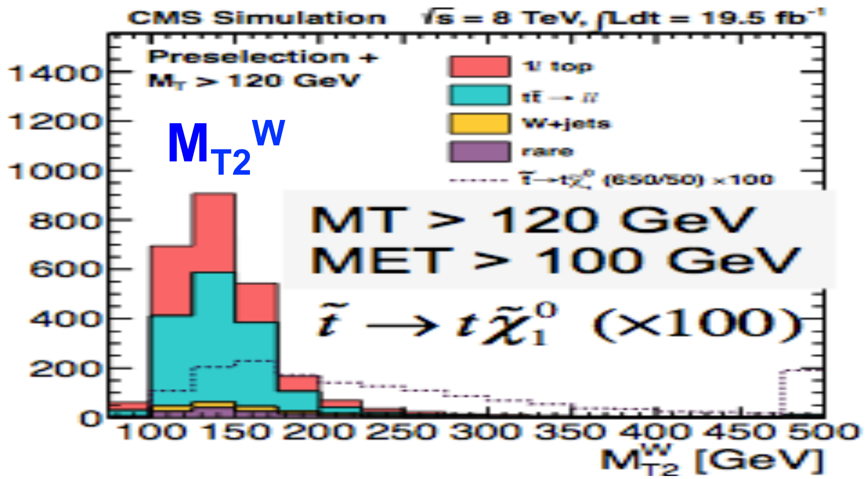
– **Exclusion for m(~t1) < ~660GeV for massless LSP**
– **Exclusion up to m(LSP) ~250 GeV**

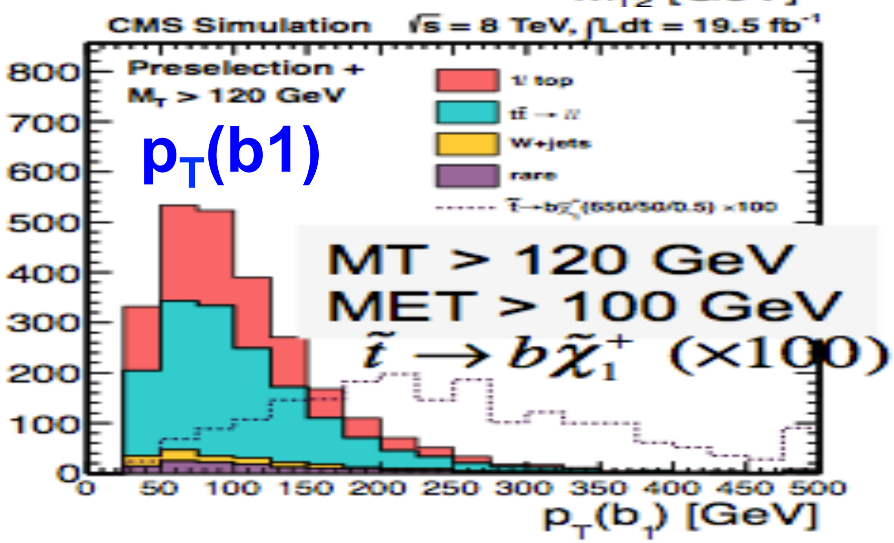
These plots overlay contours belonging to different stop decay channels, different sparticle mass hierarchies, and simplified decay scenarios

Direct stop pair production

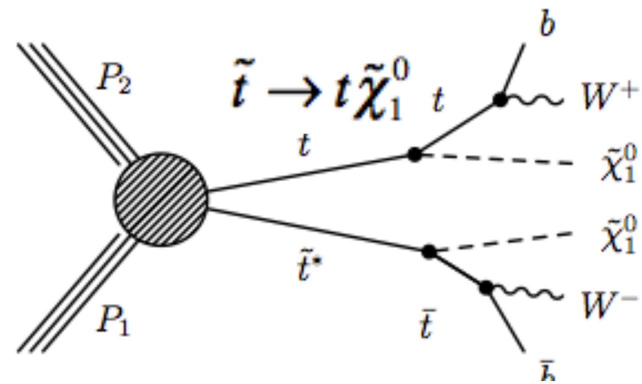
- ttbar + MET (CMS-SUS-13-011; 1308.1586)

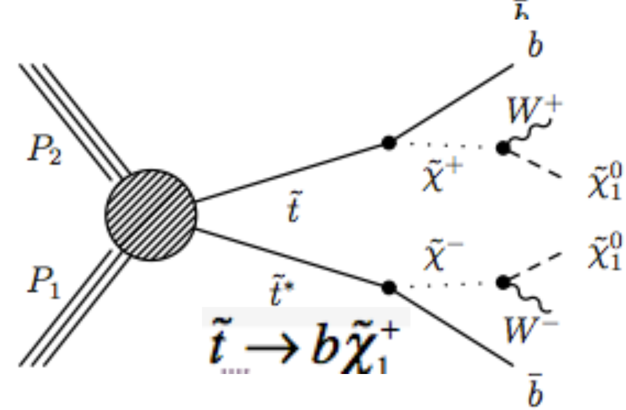
- Final state: 1l + 4j (2b) + MET
- targeting 2 decay modes:
  ~t -> tN1 and ~t -> bC1





- Use TMVA technics
- M_{T2}^{W} used to suppress ttbar
- input: M_{T2}^{W}, p_T(b1),MET, dphi(j,MET), dR(lb) …
- **BDTs** for separate modes and regions

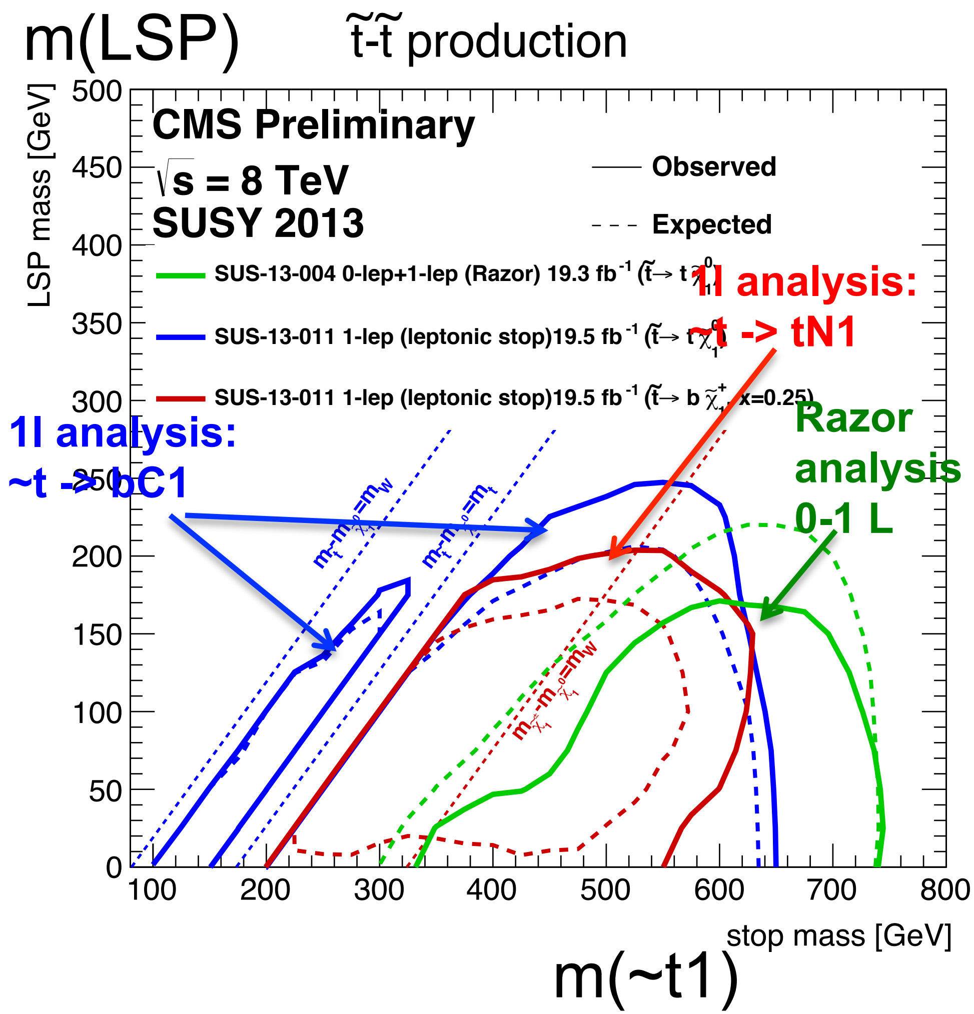




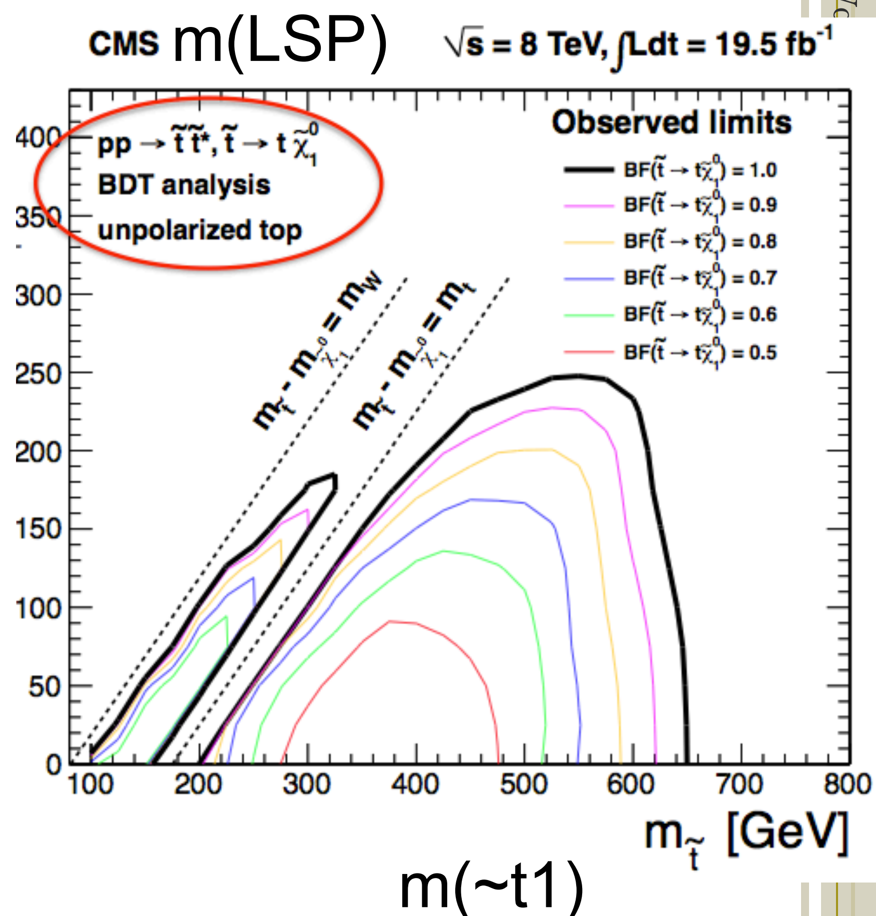
Direct stop pair production

- ttbar + MET (CMS-SUS-13-011; CMS-SUS-13-004)

100% BF for each decay channel



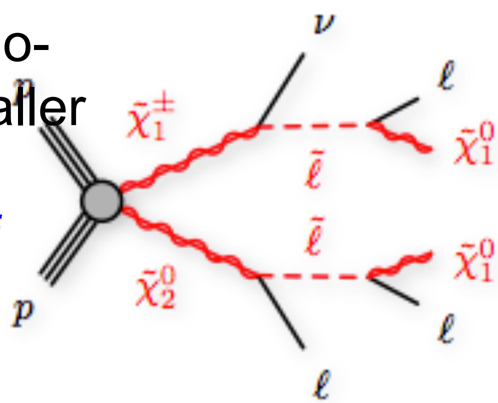
Dependence on BF

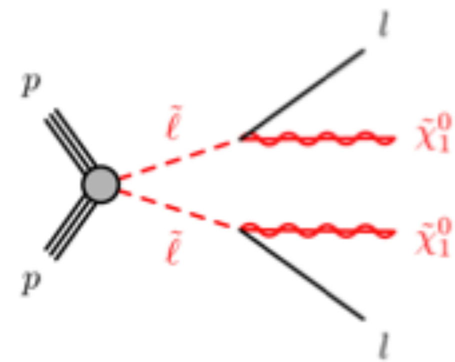


ElectroWeak production
(direct chargino/neutralino and slepton production)

- Search strategy depends on slepton mass and gauge mixture
- Final state: 2/3/4 leptons + MET

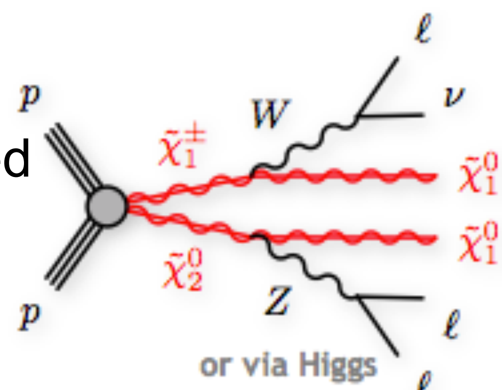
- Largest cross section for wino-like C/Ns. Smaller if higgsino
  3l + MET FS if light sleptons

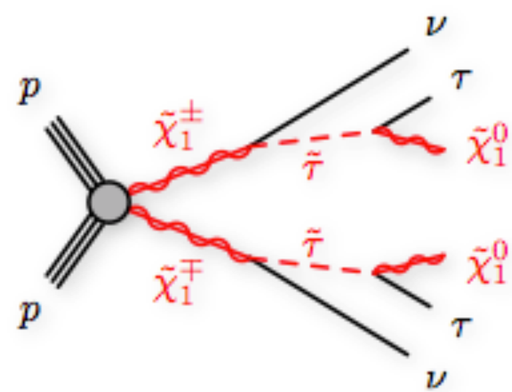




- Large cross section for slepton-left
  - 2l + MET (l = e/μ/τ)

- If sleptons heavy, reduced BR to leptons (WZ+MET)
  Equivalent picture for C1C1 production (WW+MET)

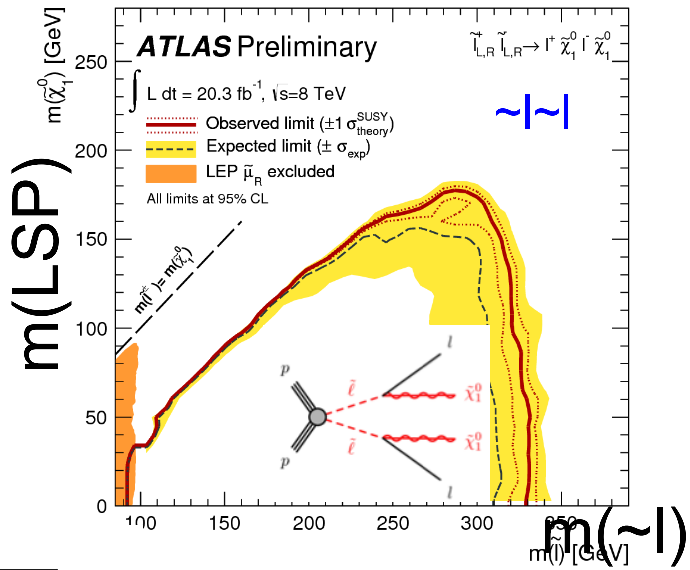


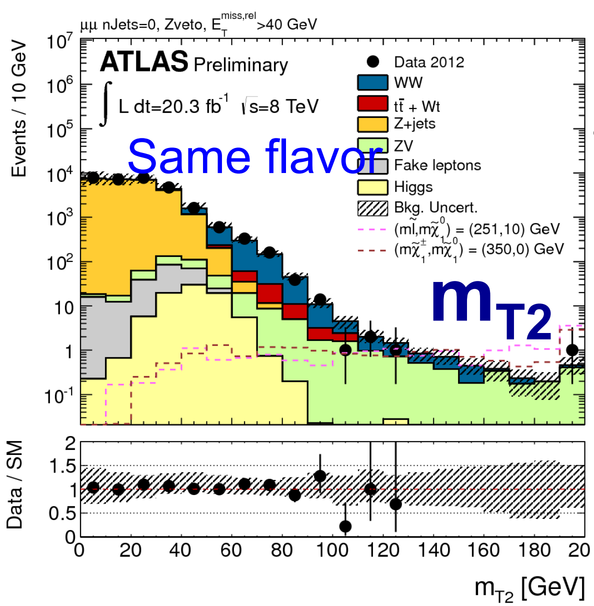


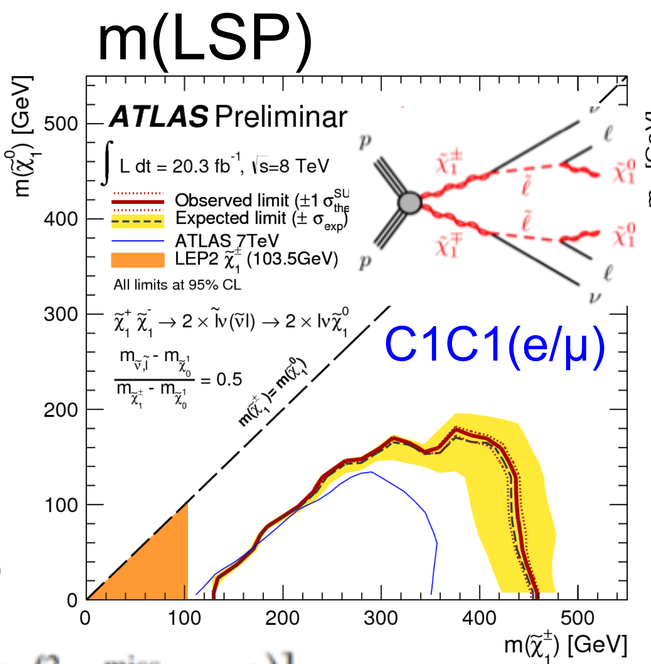
- Plausible possibility for light stau if other sleptons are heavy
  - 2l + MET (l = e/μ/τ)

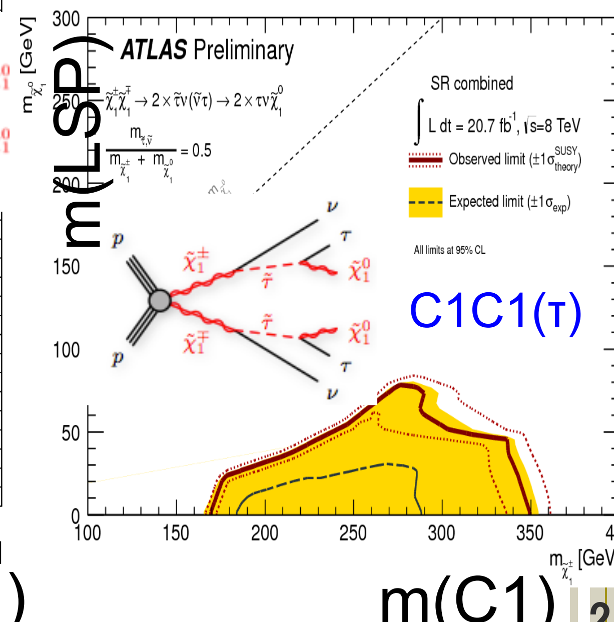
Electroweak production -(direct C1/ slepton production) (ATLAS-CONF-2013-049; ATLAS-CONF-2013-028)

- Direct chargino/slepton production
- Final state: **2l + MET (l=e/μ/τ)**
- Discriminating variable: **m_{T2}** and **MET**
- jet veto to reduce top bkg
- dominant bkg is di-boson events
- Exclusion limits for direct slepton and direct C1 separately





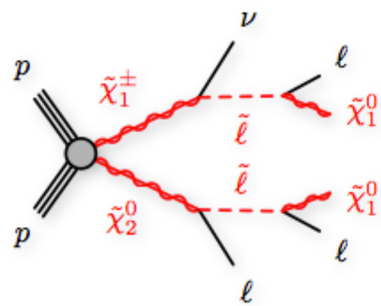




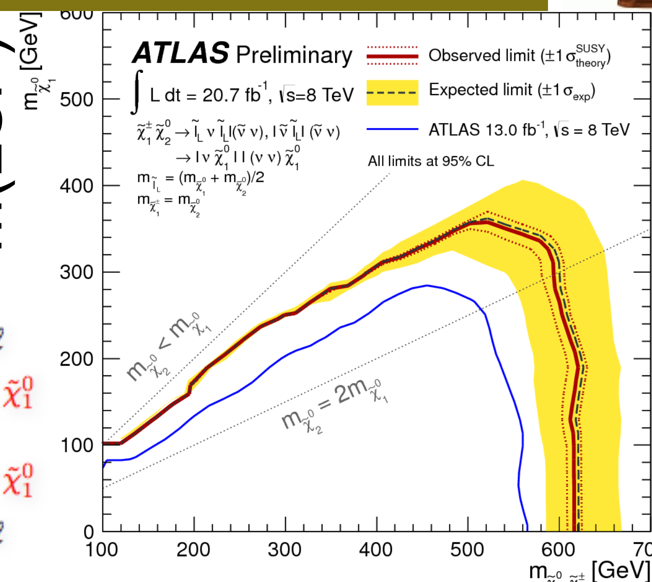
$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{miss} - \mathbf{q}_T)\right)\right]$$

ElectroWeak production
- (direct C1N2 production) (ATLAS-CONF-2013-035)

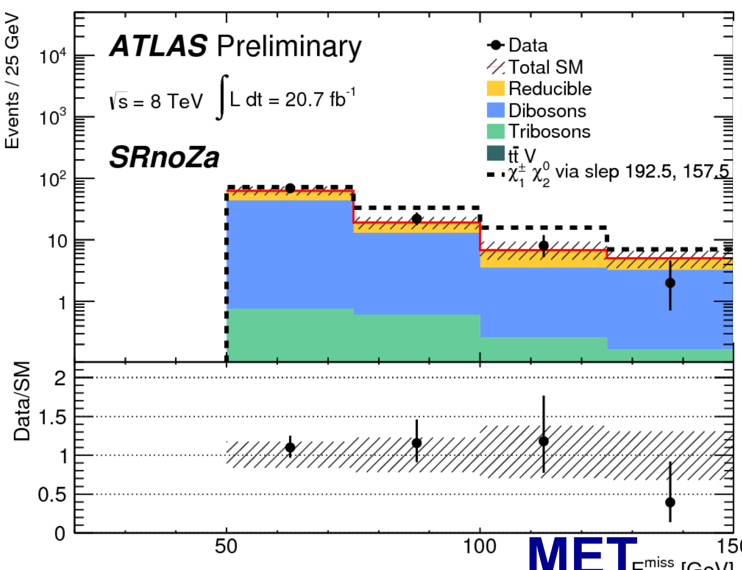
- Direct C1N2 production
- Final state: **3l + MET (l=e/μ/τ)**
- Discriminating variable: **MET**
- 6 SRs targeting C1N2 production
- Dominant bkg: WZ (top reduced by b-jet veto)



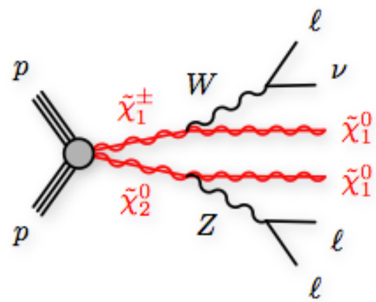
m(LSP)

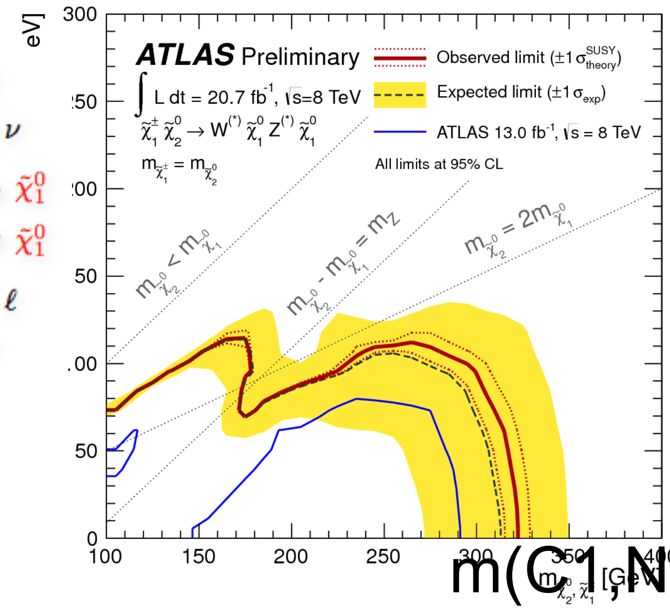


m(LSP) m(C1,N2)



MET

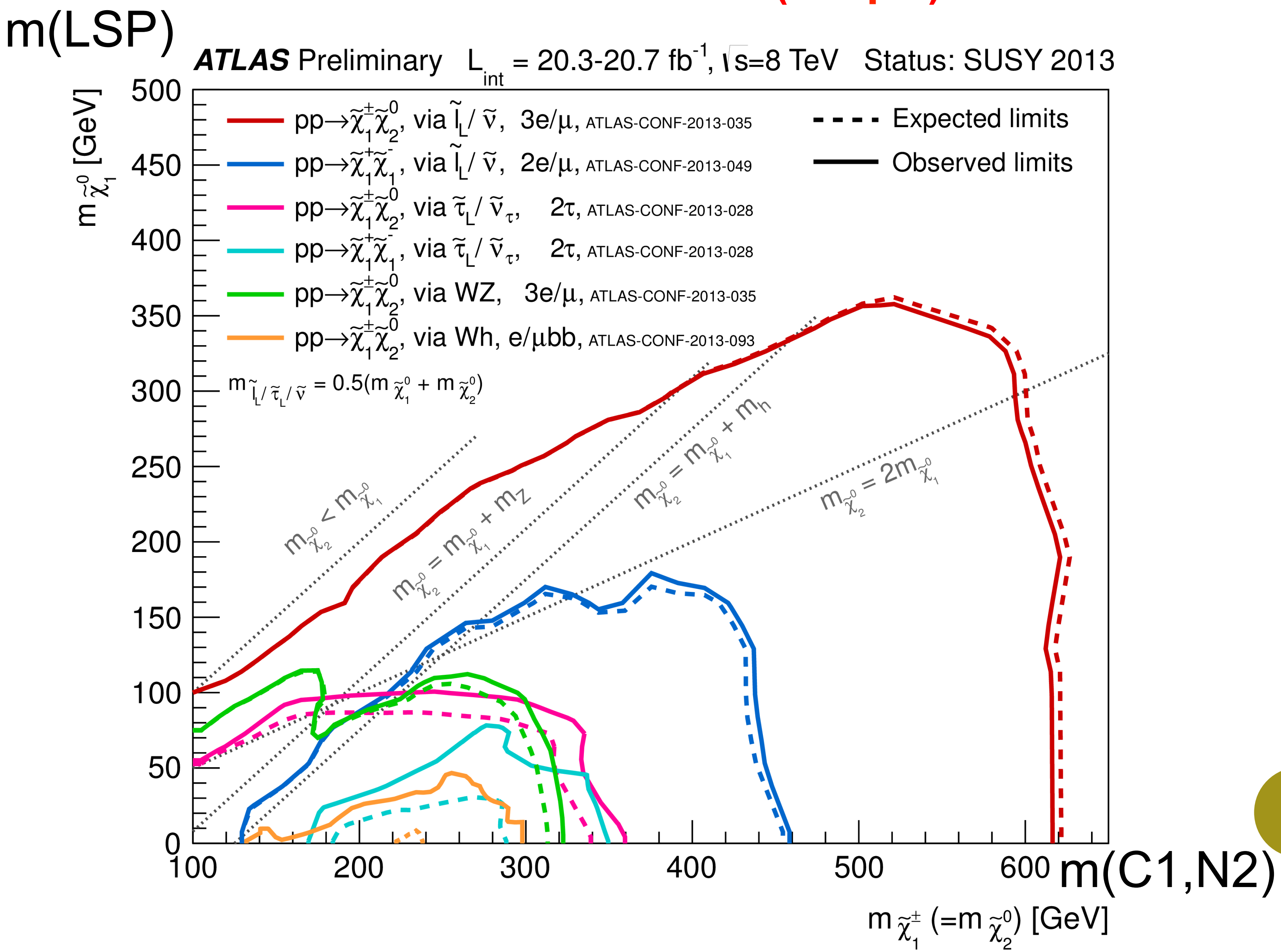




m(C1,N2)

ElectroWeak Production Summary

– Final state: **2-4l + MET (l=e/μ/τ)**



ElectroWeak production

- (direct C1N2 production) (SUS-13-006; SUS-13-017)

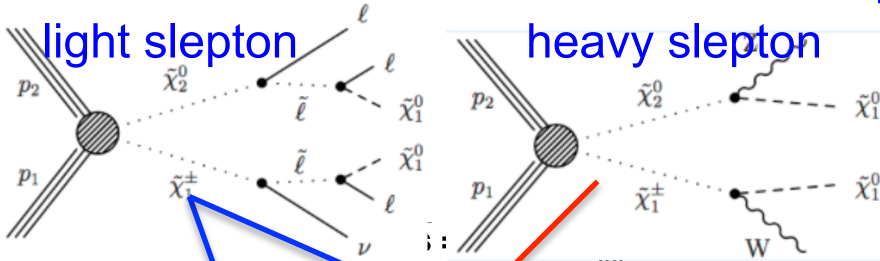
- Final state: **3l + MET (l=e/μ/τ)**
- b-veto to reject top bkg
- MET>50GeV to suppress Z
- Classify events based on lepton flavors, M_{ll}, M_T(l, MET), MET

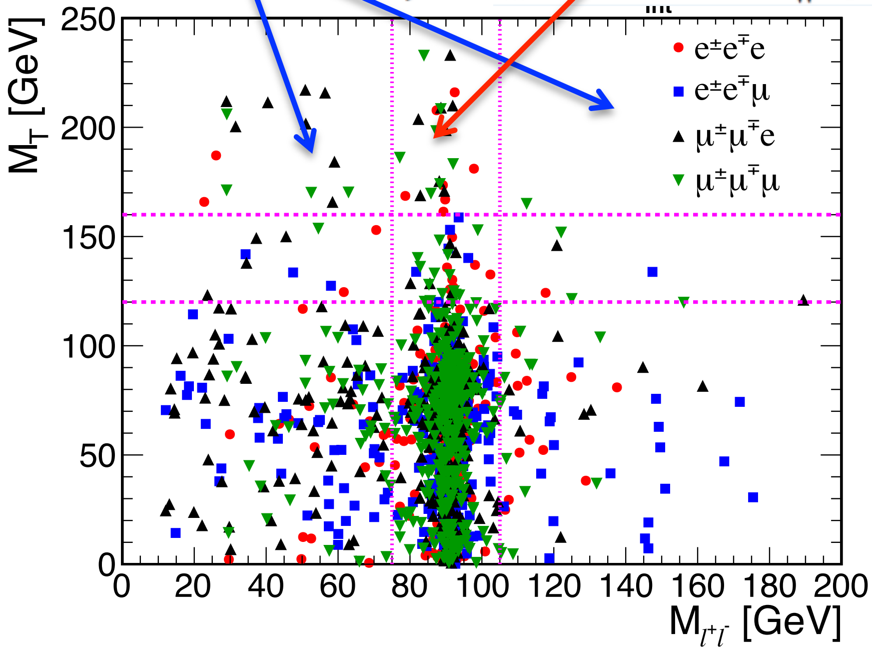
Dominant bkg: WZ, tt+fake

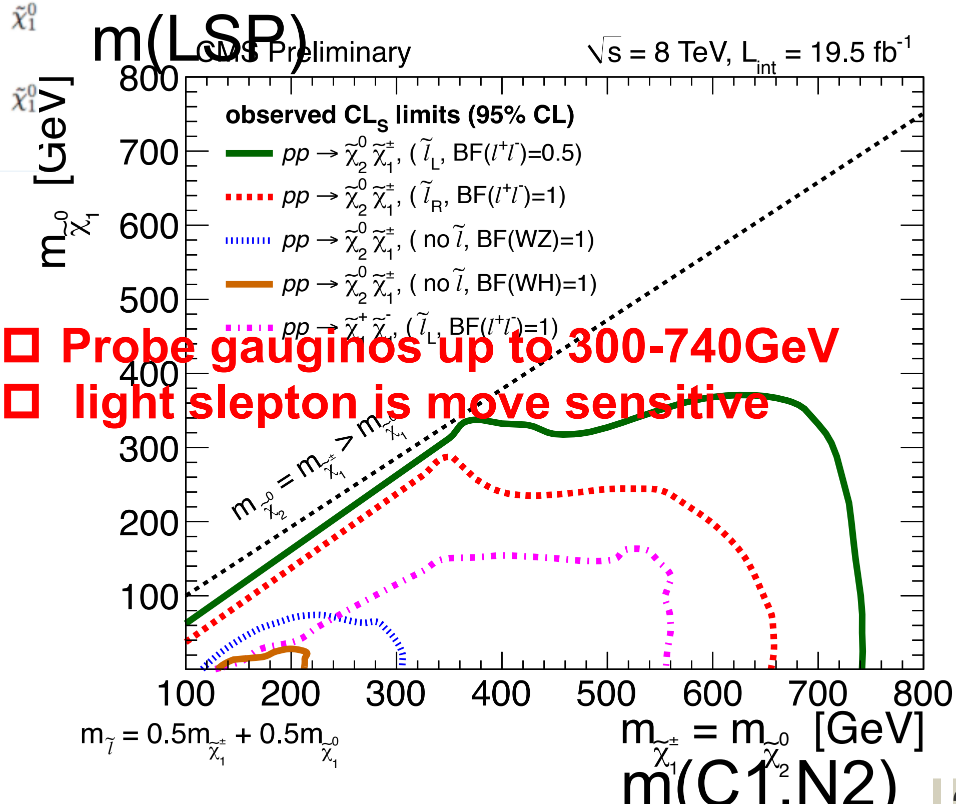
- WZ: MC with data-driven MET corrections
- tt+fake: data-driven fake rate method

Associated C1N2 production benefits from combined 2/3l leptons including tau

light slepton — heavy slepton







- ☐ **Probe gauginos up to 300-740GeV**
- ☐ **light slepton is move sensitive**

Summary & Outlook

- ATLAS and CMS are carrying out a detailed and thorough search for DM candidate (SUSY) in the LHC run-1 dataset
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

  - No evidence for dark matter so far
  - The overall behavior of SM backgrounds are well understood

95% CL exclusions for (best
massless LSP scenarios:

$m(\tilde{g}) < 1300$ GeV
$m(\tilde{q}) < 1400$ GeV
$m(\tilde{b}) < 650$ GeV
$m(\tilde{t}) < 680$ GeV
$m(\tilde{\ell}_L) < 300$ GeV
$m(\chi^{\pm} = \chi^{0})_{\text{light }\tilde{\ell}} < 650$ GeV
$m(\chi^{\pm} = \chi^{0})_{\text{heavy }\tilde{\ell}} < 340$ GeV

- High energy running in 2015 will significantly increase our sensitivity to many SUSY scenarios, especially cover difficult SUSY regions

  ➔ If SUSY particles can be observed, we could access information on DM identity !

Looking forward to the next exciting years!


Thanks !!!

SUSY Models

- Constrained MSSM:
  - Only 5 free parameters -> strongly correlated masses
  - LHC@7/8 TeV -> largest part of interesting parameter space excluded
- Simplified Models:
  - Not really a model (Br~100%, most masses fixed at high scales)
  - Important tool for interpretation
- Phenomenological MSSM:
  - 19 free parameters
    - ✓ M1,M2,M3
    - ✓ tan β, μ and m_A
    - ✓ 10 sfermion mass parameters
    - ✓ A_t, A_b and A_τ
  - pMSSM captures "most" of phenomenologic features of R-parity conserving MSSM
  - Comprehensive and computationally realistic approximation of the MSSM with neutralino LSP

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

ATL[illegible]**ary**

$\int \mathcal{L} dt = (4.6 - 22.9)$ fb^{-1}

[illegible]eV

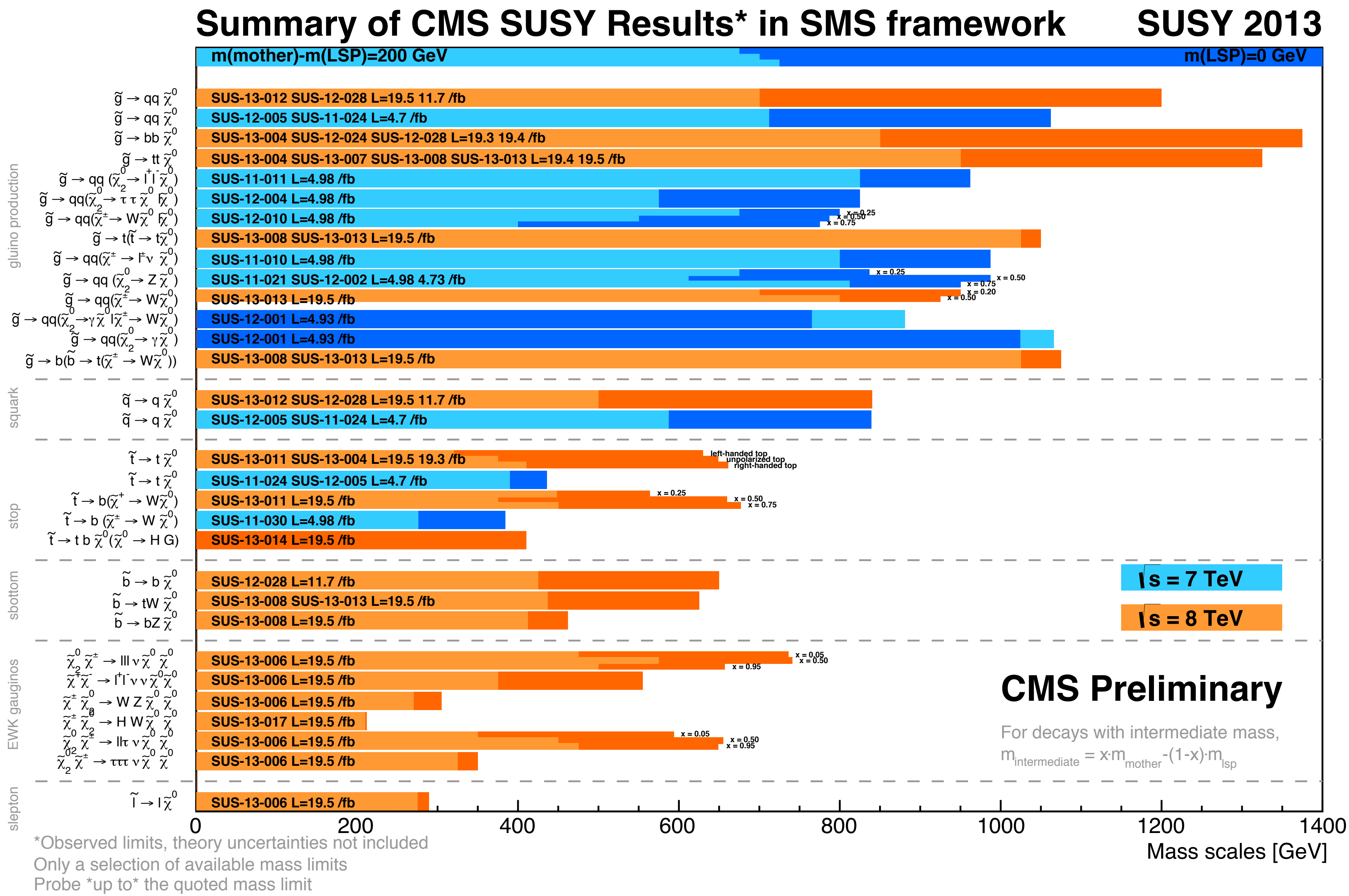
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt[fb^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$m(\tilde{q})$=$m(\tilde{g})$	[illegible]047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	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	$\tilde{q}$	740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	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	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	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	$m(\tilde{H})$>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
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	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	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3^{rd} 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	20.7	$\tilde{b}_1$	275-430 GeV	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(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	$\tilde{t}_1$	130-220 GeV	$m(\tilde{\chi}_1^0)$ =$m(\tilde{t}_1)$-$m(W)$-50 GeV, $m(\tilde{t}_1)$<<$m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(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	20.7	$\tilde{t}_1$	200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	$m(\tilde{t}_1)$=$m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
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	$\tilde{\ell}$	85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell}, \tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	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
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	22.9	$\tilde{g}$	832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	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<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, 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	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	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	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
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)	1 b	Yes	14.3	sgluon	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

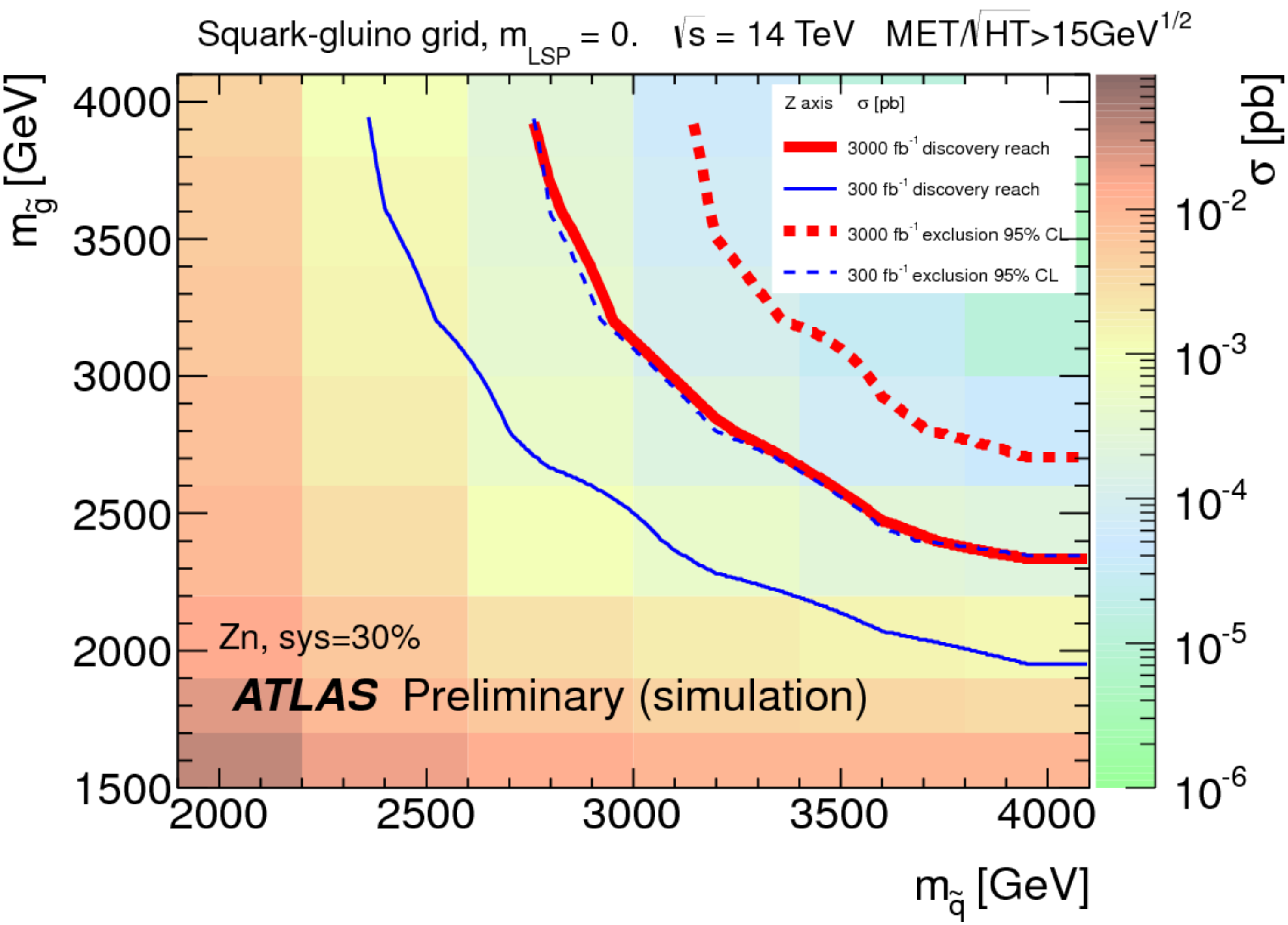
10^{-1} — 1 — **Mass scale [TeV]**

*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.

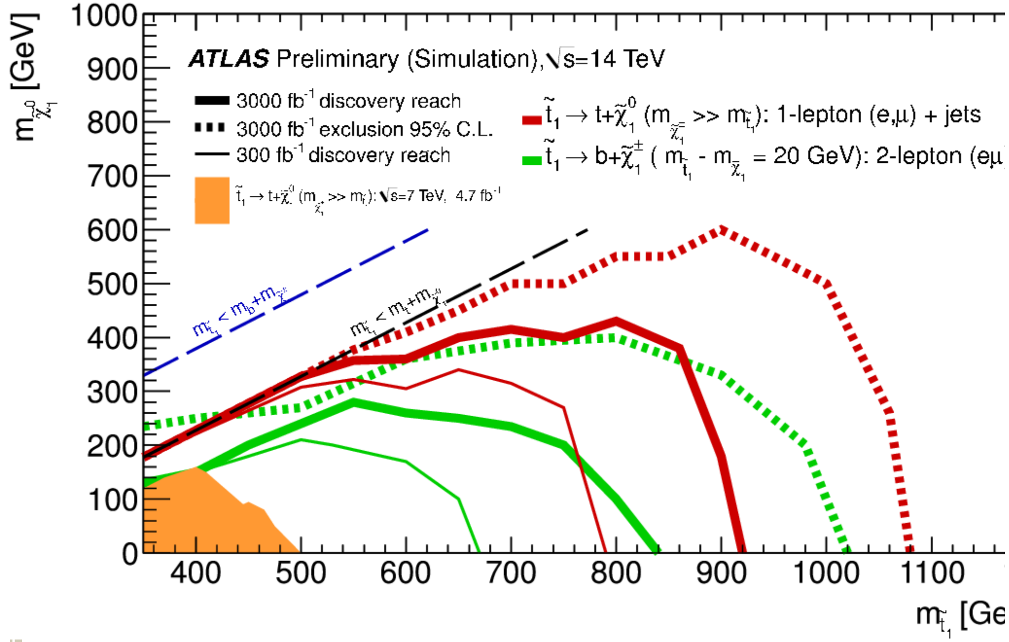
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

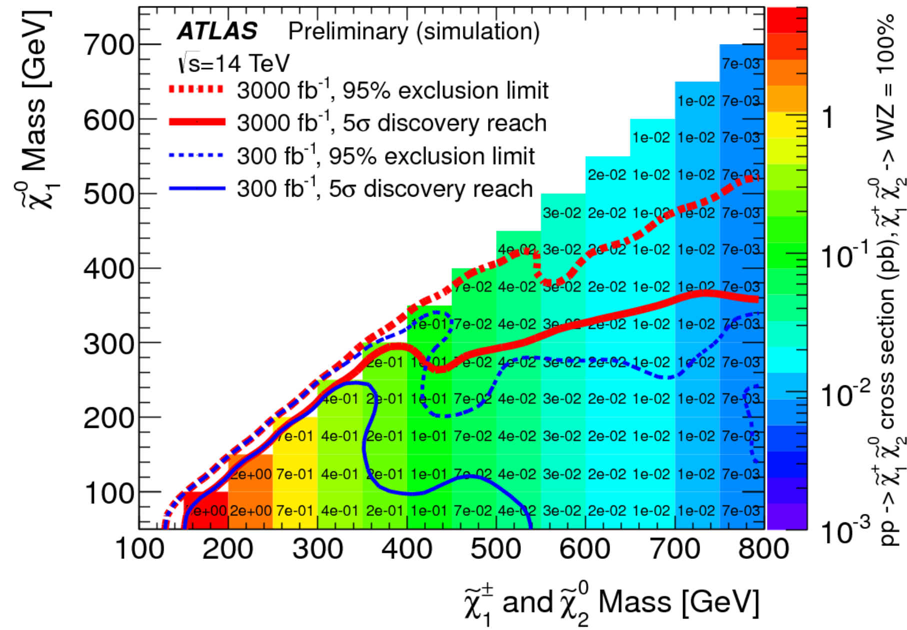


2015-2017: 100 fb^{-1}, ~ 1* 10^{34} cm^{-1}s^{-1} (LS1)
2020-2022: 300 fb^{-1}, ~ 2* 10^{34} cm^{-1}s^{-1} (LS2)
2022-2030: 3000 fb^{-1}, ~ 5* 10^{34} cm^{-1}s^{-1} (LS3)



32





The sensitivity to heavy SUSY particles will be increased significantly when the centre of mass-energy of the LHC reaches a value close to the design one, i.e $\sqrt{s}$ = 14 TeV. An increase of integrated luminosity from 300 fb^{-1} to 3000 fb^{-1} improves the sensitivity to gluinos and first/second generation squarks by approximately 400-500 GeV reaching masses above 3 TeV and to stops by more than 100-150 GeV reaching masses of 1 TeV. The discovery potential for charginos and heavy neutralinos extends by almost 500 GeV in chargino mass reaching masses above 1 TeV, i.e. it doubles with the increased dataset.

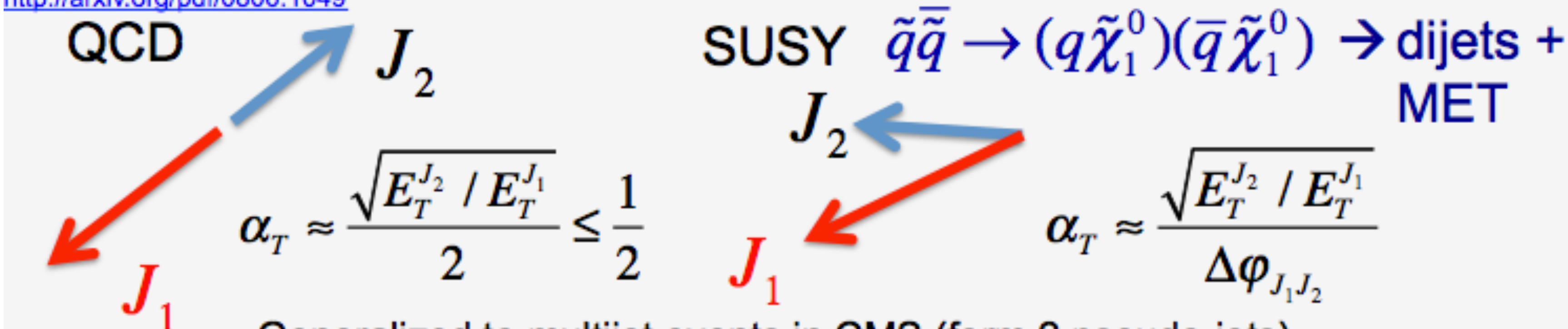
All-hadronic SUSY search using α_T

(CMS-SUS-12-028; 1303.2985)

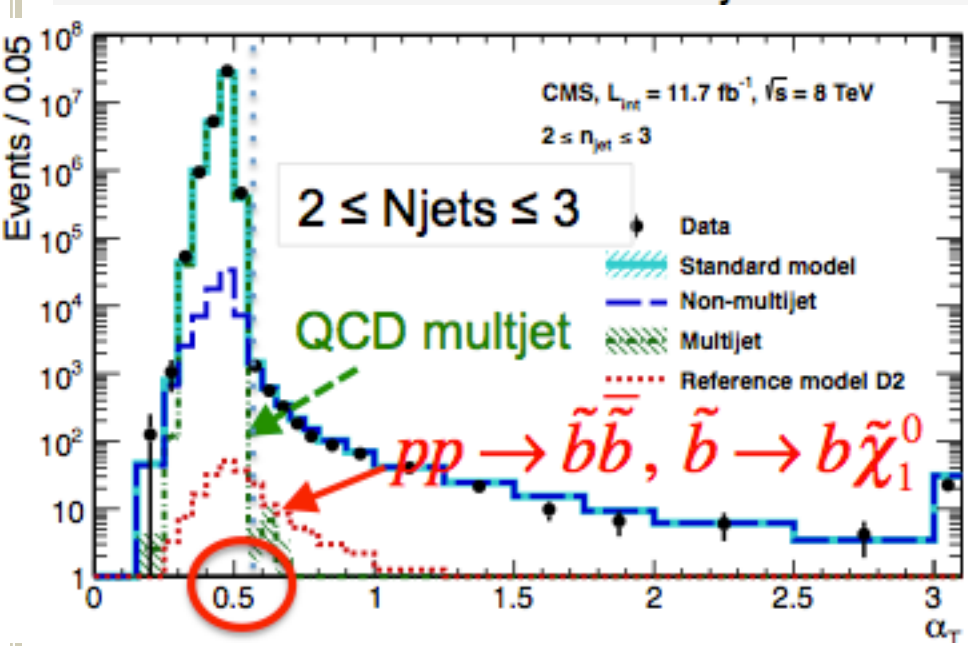
$$\alpha_T \equiv E_T^{J_2} / M_T(J_1 J_2) = \frac{\sqrt{E_T^{J_2} / E_T^{J_1}}}{\sqrt{2(1-\cos\Delta\varphi_{J_1 J_2})}}$$

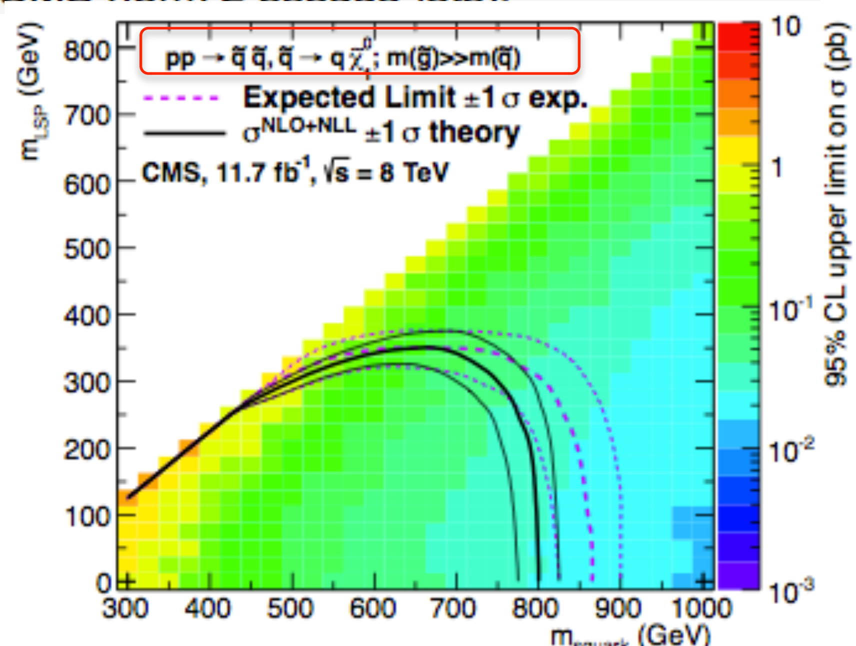
More: All-hadronic SUSY search using MH_T (CMS-SUS-13-012);

http://arxiv.org/pdf/0806.1049



Generalized to multijet events in CMS (form 2 pseudo-jets).

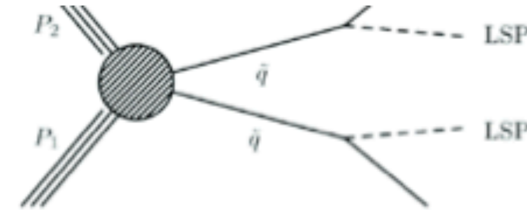




Razor – Definition

C. Rogan, arXiv:1006.2727

Example: direct squark production with $\tilde{q} \rightarrow \tilde{\chi}_1^0 + q$



Define

$$M_R = \sqrt{(|\vec{p}_{q1}| + |\vec{p}_{q2}|)^2 - (p_{z,q1} + p_{z,q2})^2}$$

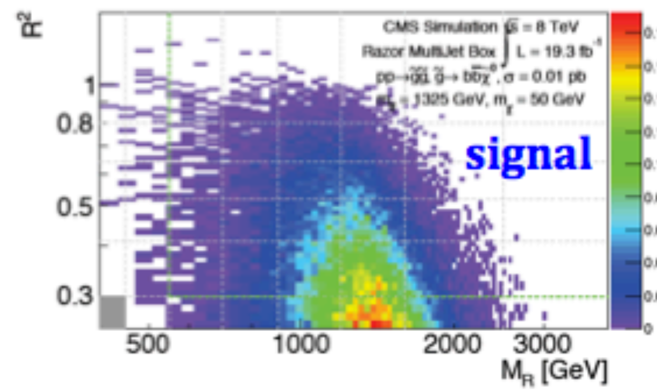
and

$$M_T^R = \sqrt{\frac{E_{\mathrm{T}}^{\mathrm{miss}}(p_{\mathrm{T}}^{q1} + p_{\mathrm{T}}^{q2}) - \vec{E}_{\mathrm{T}}^{\mathrm{miss}}(\vec{p}_{\mathrm{t}}^{\,q1} + \vec{p}_T^{\,q2})}{2}}$$

Cluster more than two jets to two "Mega-Jets"

Define **the "Razor"**:

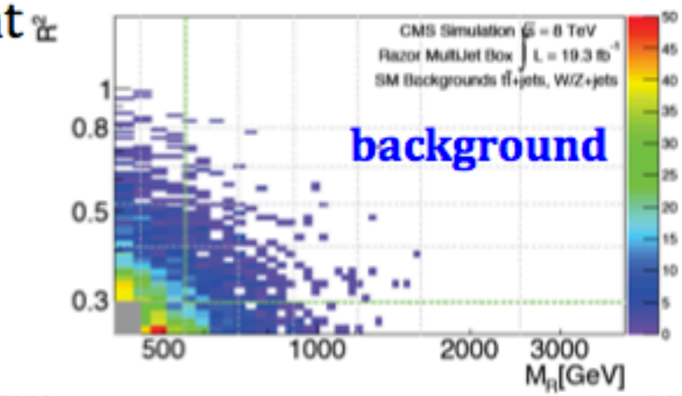
$$R = \frac{M_T^R}{M_R}$$



- For signal: M_R has peak and $M_T{}^R$ has endpoint at

$$M_\Delta = \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}_1^0}^2}{M_{\tilde{q}}}$$

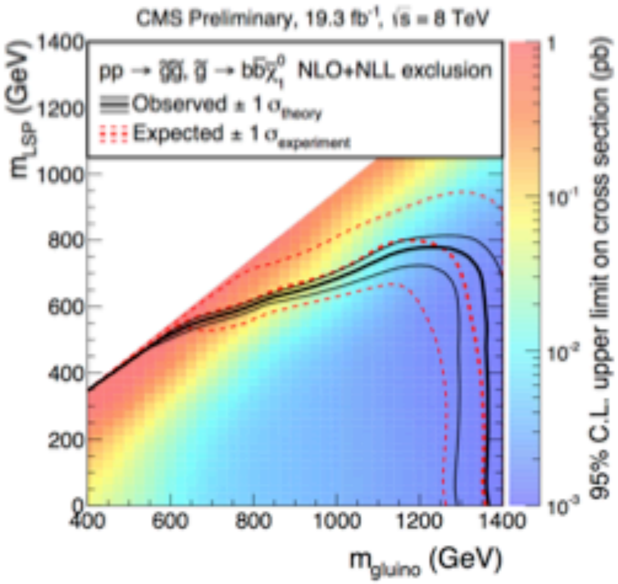
- For bg: exponentially falling at relevant scales

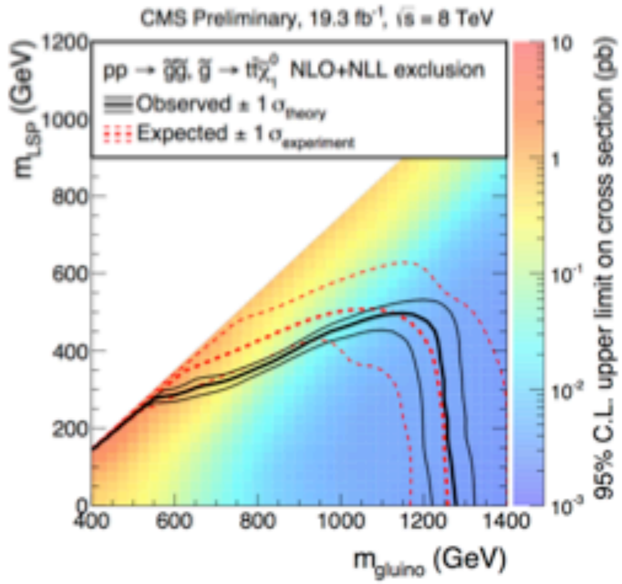


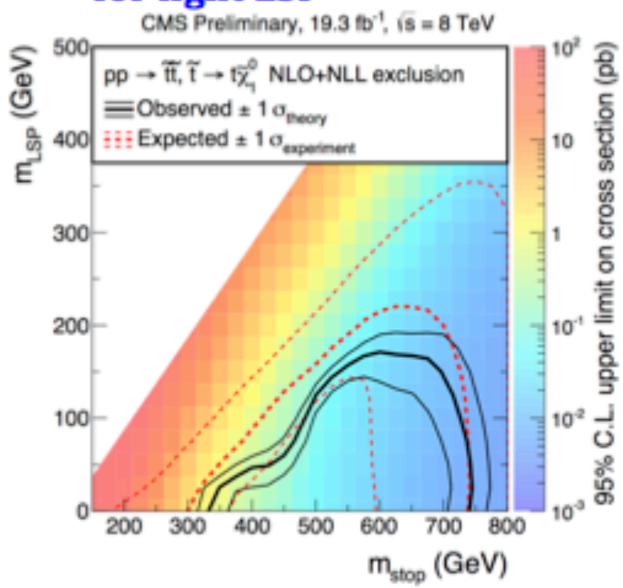
Razor – Interpretation

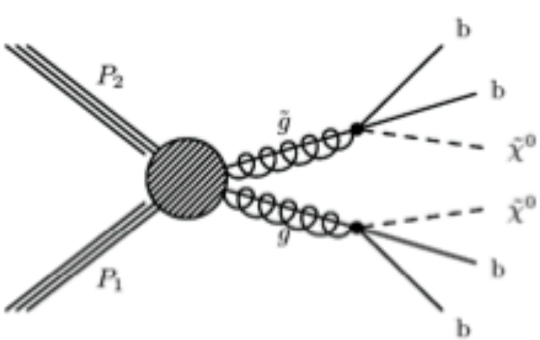
- Sensitive limits in various Simplified Models of scenarios which involve third generation squarks

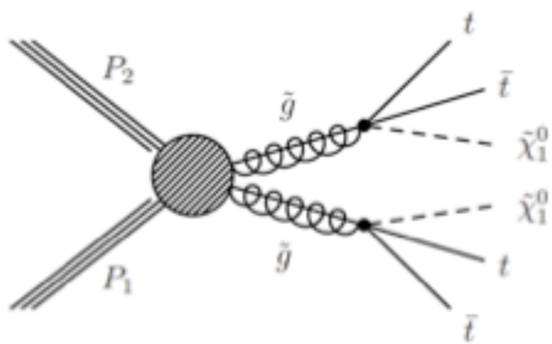
probe $m_{\tilde{t}}$ up to 0.7 TeV for light LSP

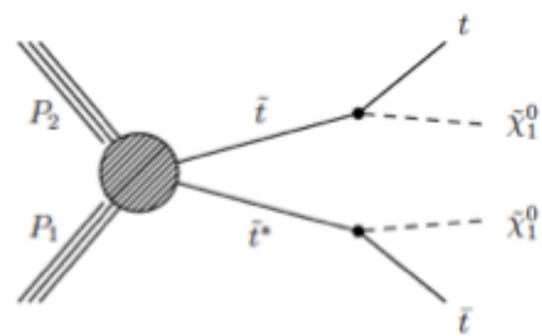








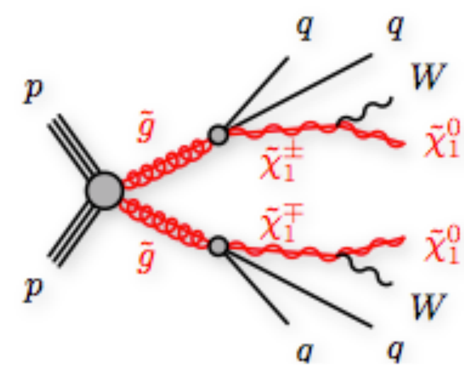




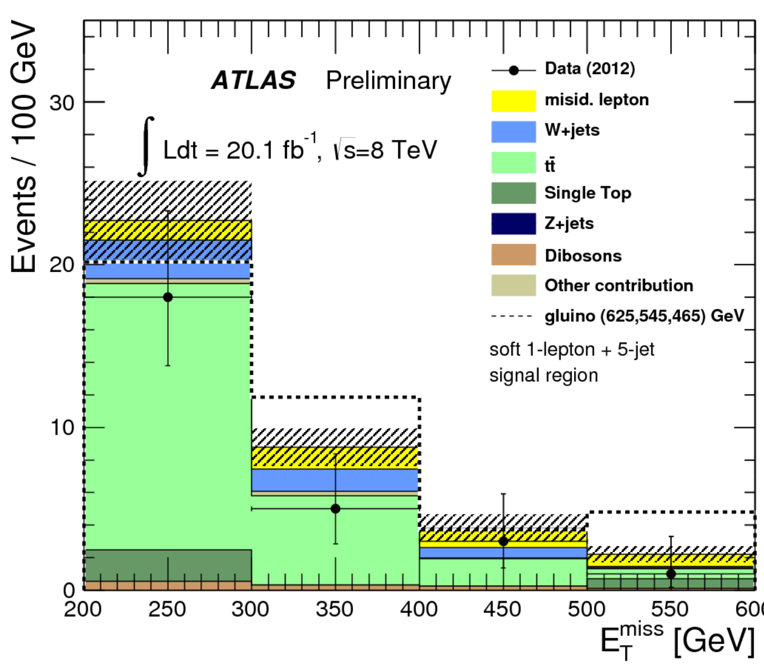
Inclusive SUSY search (Strong Production)

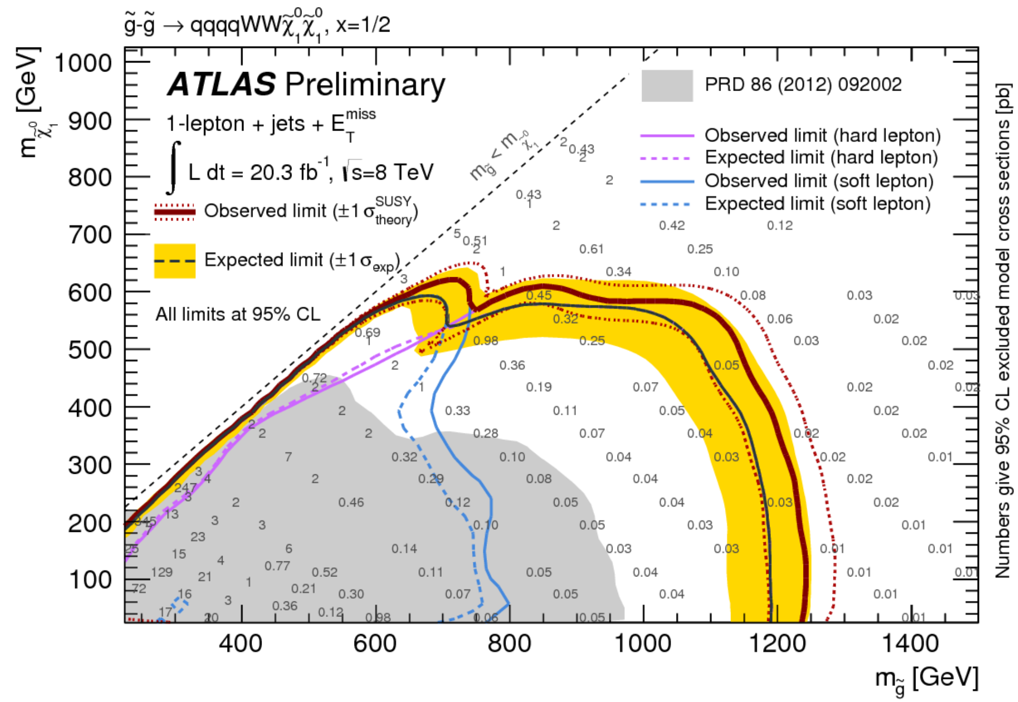
- 1-2 L + jets + MET (ATLAS-CONF-2013-062)

- single lepton or MET trigger
- Discriminating variable: **MET, Meff**
- M_T used to reduce the W+jets and top bkg
- Hard lepton analysis (p_T>25GeV) complemented with soft-lepton (p_T>10[e], 6 [μ]GeV) for compressed spectra
- SRs with 3-6 jets and various MET, M_{eff} cut



$$m_T = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos(\Delta\phi(\vec{\ell}, \vec{p}_T^{miss})))}$$





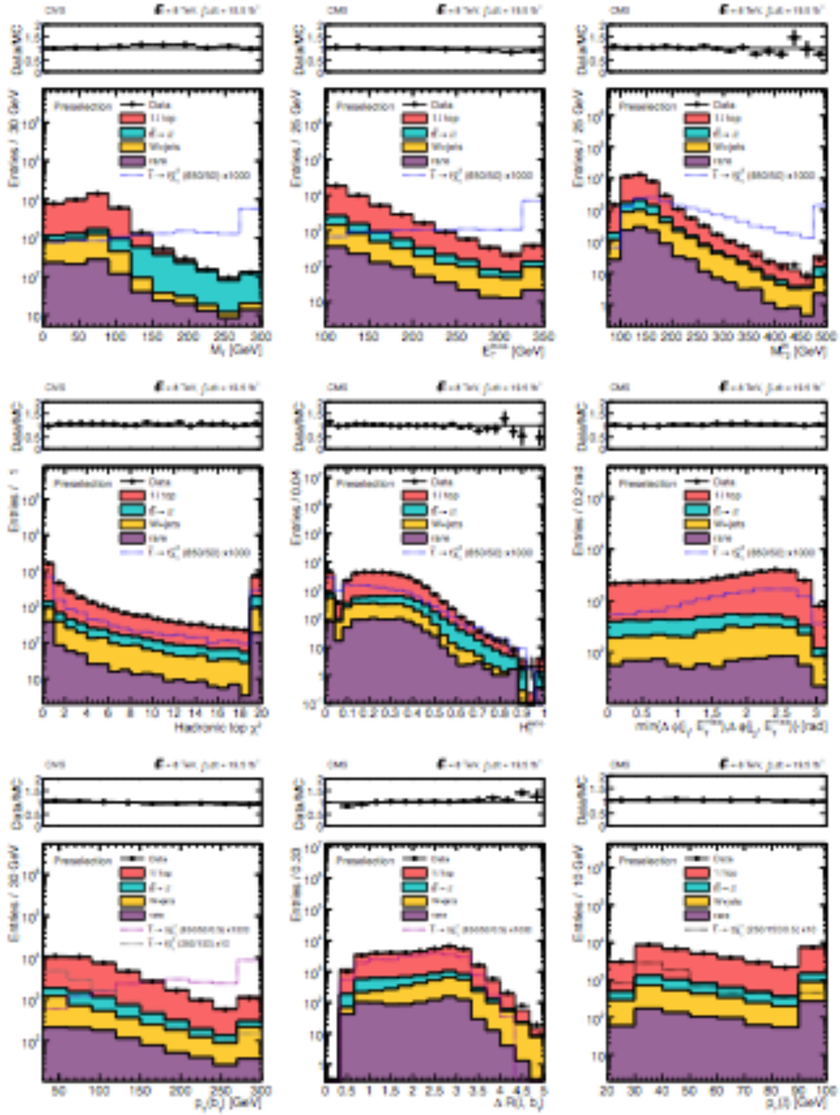


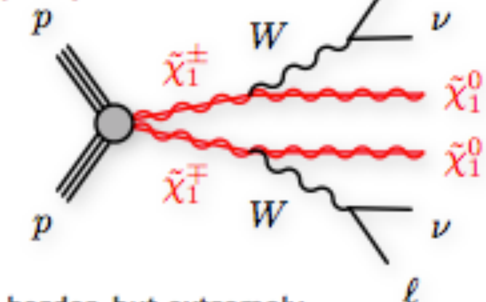
Figure 2: Comparison of data with MC simulation for the distributions of M_T, E_T^{miss}, M_{T2}^W, hadronic top χ^2, H_T^{ratio}, minimum $\Delta\phi$ between the E_T^{miss} vector and the two leading jets, p_T of the leading b-tagged jet, ΔR between the leading b-tagged jet and the lepton, and lepton p_T, after the preselection. For the top six plots, distributions for the $\tilde{t} \to t\tilde{\chi}_1^0$ model with $m_{\tilde{t}} = 650\,\mathrm{GeV}$ and $m_{\tilde{\chi}_1^0} = 50\,\mathrm{GeV}$, scaled by a factor of 1000, are overlayed. In the last row, we also show distributions of $\tilde{t} \to t\tilde{\chi}_1^0$ with $m_{\tilde{t}} = 250\,\mathrm{GeV}$ and $m_{\tilde{\chi}_1^0} = 100\,\mathrm{GeV}$ (bottom left, scaled by 10), and of $\tilde{t} \to b\tilde{\chi}^+$ with $m_{\tilde{t}} = 650\,\mathrm{GeV}$, $m_{\tilde{\chi}_1^0} = 50\,\mathrm{GeV}$, and $x = 0.5$ (two bottom left plots, scaled by 1000), as well as of $m_{\tilde{t}} = 250\,\mathrm{GeV}$, $m_{\tilde{\chi}_1^0} = 150\,\mathrm{GeV}$, and $x = 0.5$ (bottom right, scaled by 10). For all distributions, the last bin contains the overflow.

ElectroWeak production

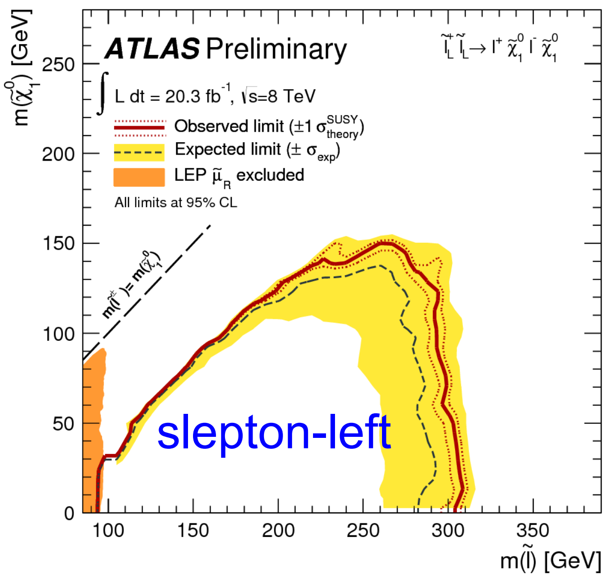
(ATLAS-CONF-2013-049; ATLAS-CONF-2013-028)

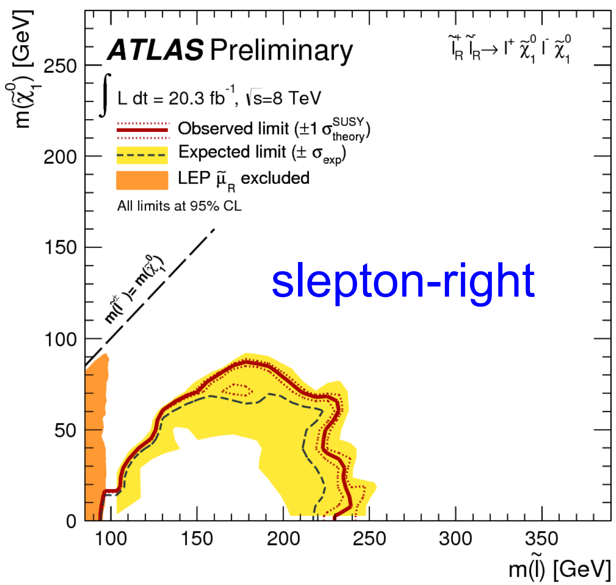
- ~2.5 times smaller xsec on slepton-right
- First limits on slepton-right production-only from LHC

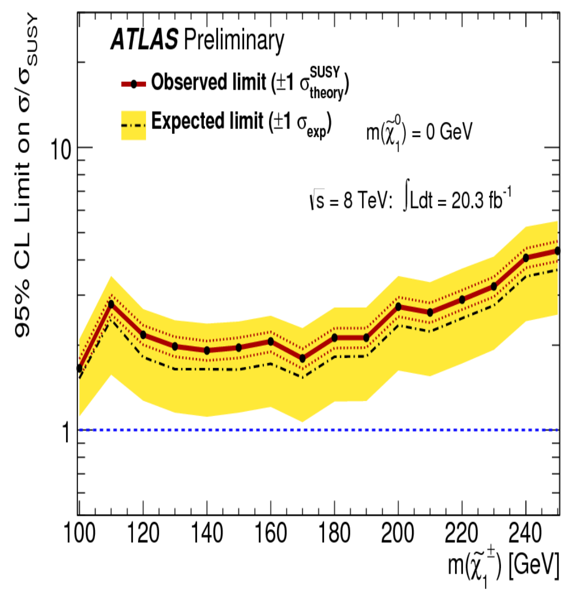
Chargino production with heavy sleptons?



Much harder, but extremely interesting scenario - barely sensitive



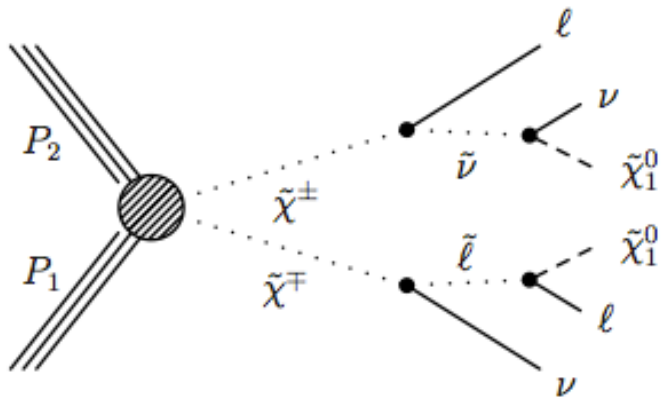


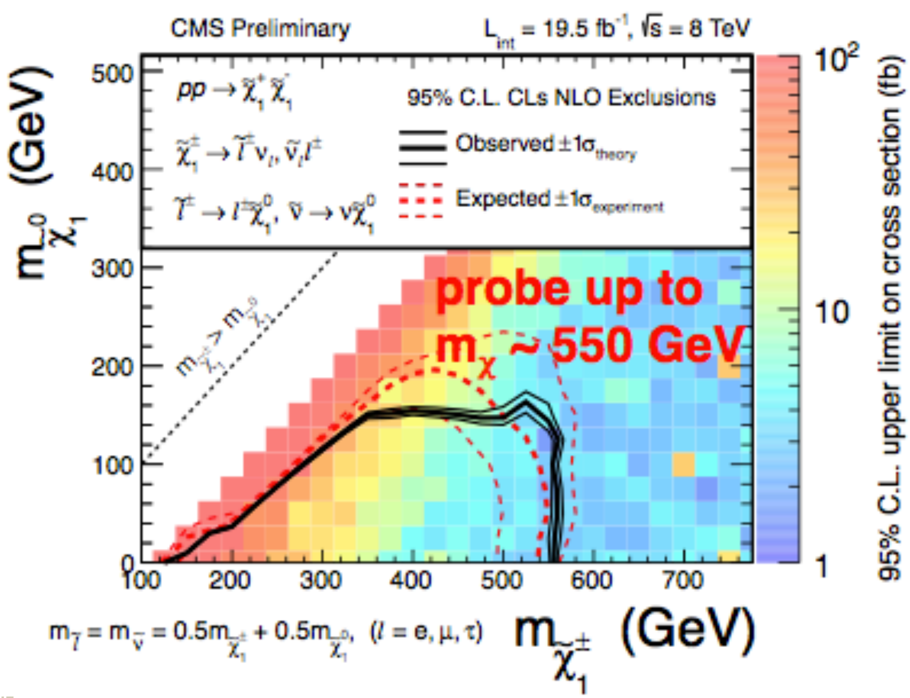


ElectroWeak production

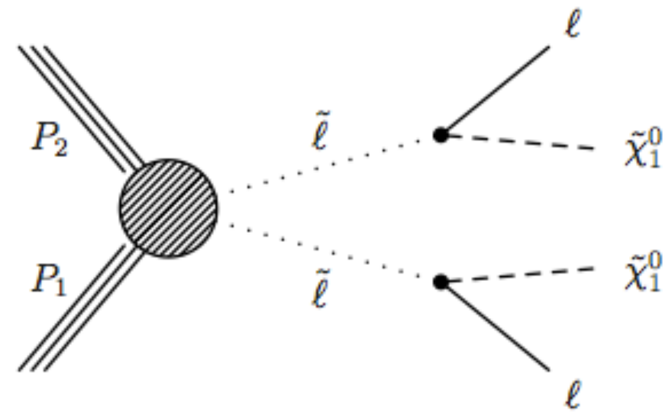
(SUS-13-006; SUS-13-017)

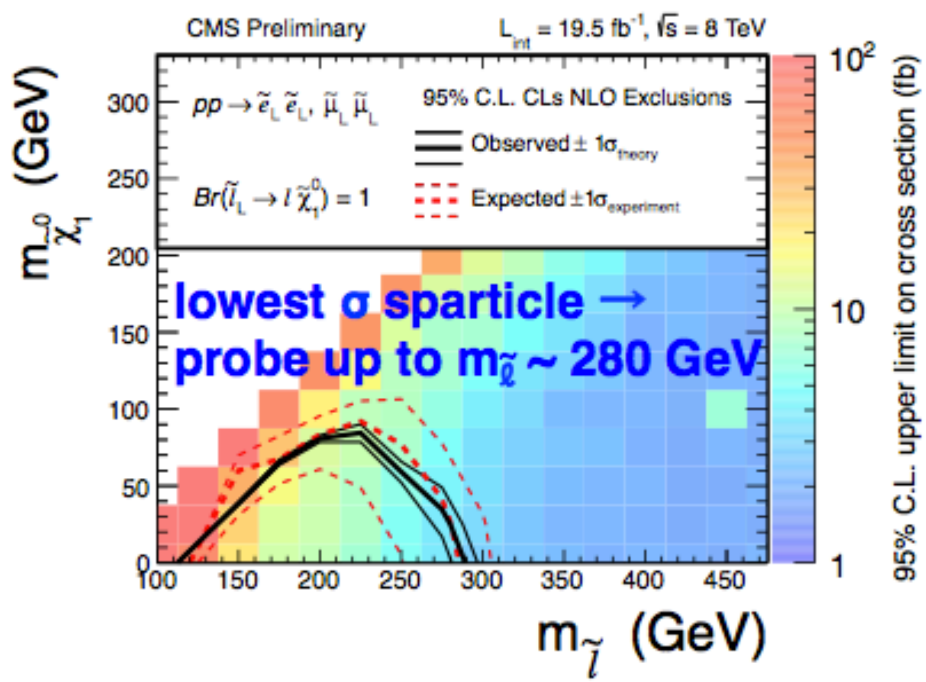
Use ee+μμ and eμ lepton pairs





Use ee+μμ lepton pairs only





WH – Interpretation

SUS-13-017

Combination of 1ℓ + 2 b-tags, 2ℓ (SS) and 3ℓ

→ Search is getting sensitive to this process (probing neutralino/chargino masses up to 210 GeV)

→ Very promising for 13/14 TeV

***H* decay modes:**

- $H \to b\bar{b}$: **1ℓ + 2 b-tags**
- $H \to W(\to l\nu)W(\to q\bar{q})$: **2ℓ (SS)**
- $H \to W^+W^-/\tau^+\tau^-/ZZ$: **3ℓ (reinterpretation of SUS-13-002)**

$W^{\pm}$