Stealth and Compressed SUSY searches with ATLAS and CMS

Giovanni Zevi Della Porta
(University of California, San Diego)

on behalf of the
ATLAS and CMS Collaborations

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compressed and Stealth SUSY

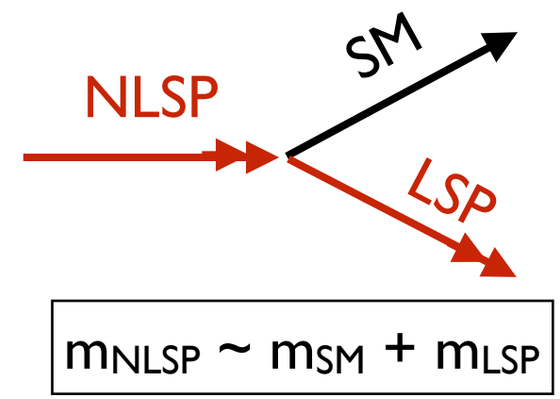
compressed SUSY:

Δm(next-to-LSP, LSP) is close to 0 or to m_{SM} (ex: m_{top})

- EWK-inos can exist in near-degenerate pairs or triplets
- Possible for squarks to have masses close to LSP or to m_{quark}

Kinematics:

- In the NLSP frame, decay products are at rest
- If NLSP is boosted, <u>heavy LSP</u> can inherit boost —> <u>MET</u>



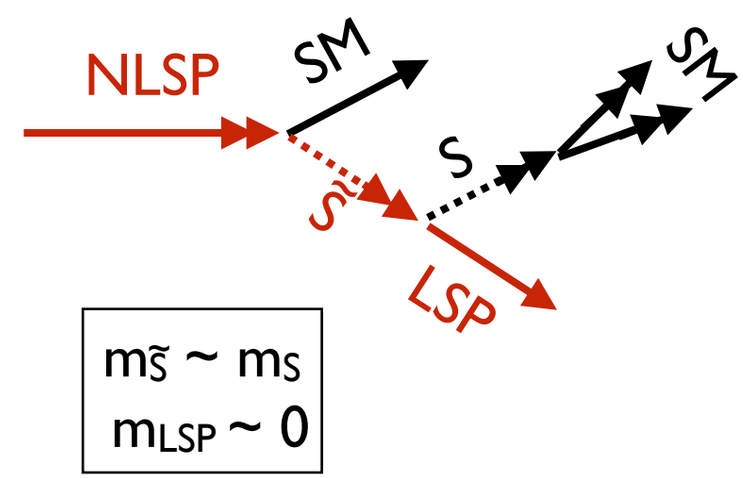
Stealth SUSY (cf. talk by M. Reece)**:**

A new sector with particles (S and $\tilde{S}$) of similar mass

- Almost no SUSY-breaking in "stealth" sector
- LSP (gravitino) is very light

Kinematics:

- All the boost is transferred to SM particles through the massive S
- Light LSP inherits no boost —> <u>no MET</u>

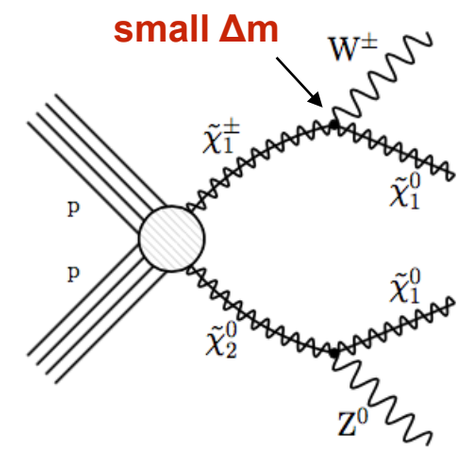


- *Note 1: R-parity is conserved in all these models (all vertices have 2 red one black).*
- *Note 2: Small Δm can limit the decay phase-space, resulting in long-lived particles (not discussed in these slides)*

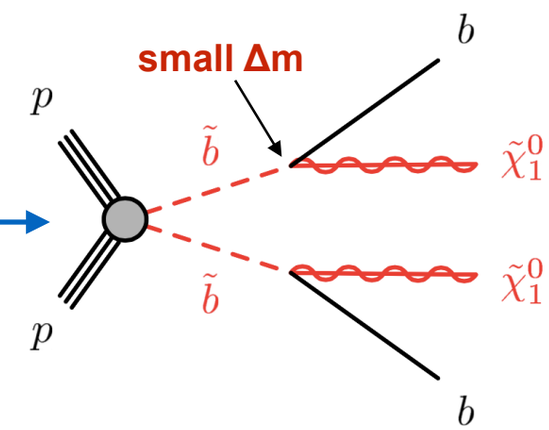
Variety of signals

Signals:

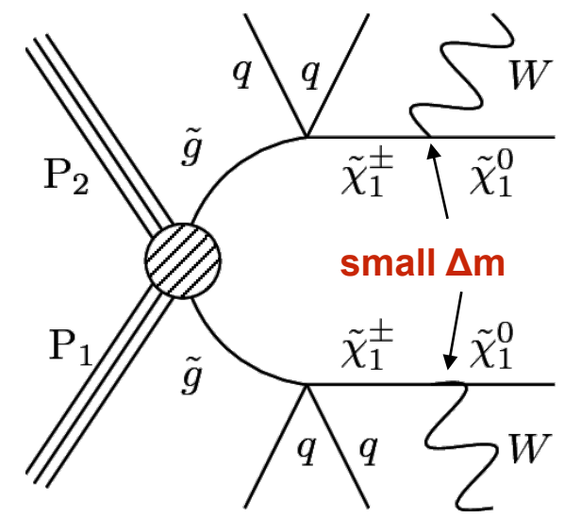
Compressed electroweak SUSY
$\Delta m(\chi, \mathrm{LSP}) \sim 0$



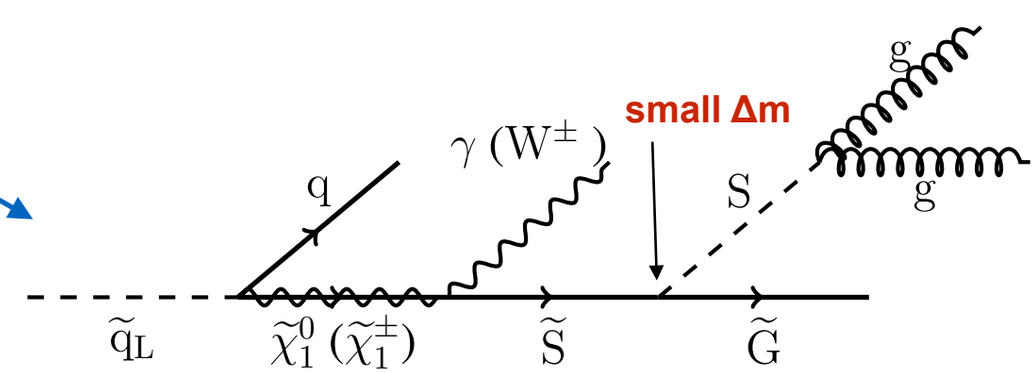
Compressed strong SUSY
$\Delta m(\tilde{q}, \mathrm{LSP}) \sim 0$ or m_{SM}



Strong SUSY with
compressed EWK decay
$\Delta m(\chi, \mathrm{LSP}) \sim 0$



Strong SUSY with Stealth decay
$\Delta m(\tilde{S}, S) \sim 0$



Variety of signals and final states

Signals:

Compressed electroweak SUSY

Compressed strong SUSY

Strong SUSY with compressed EWK decay

Strong SUSY with Stealth decay

Final States:

Soft lepton(s) + MET

VBF jets + MET

Mono-jet + MET (a.k.a. ISR)

jets + MET (+ b-tags)

ttbar-like (spin and σ)

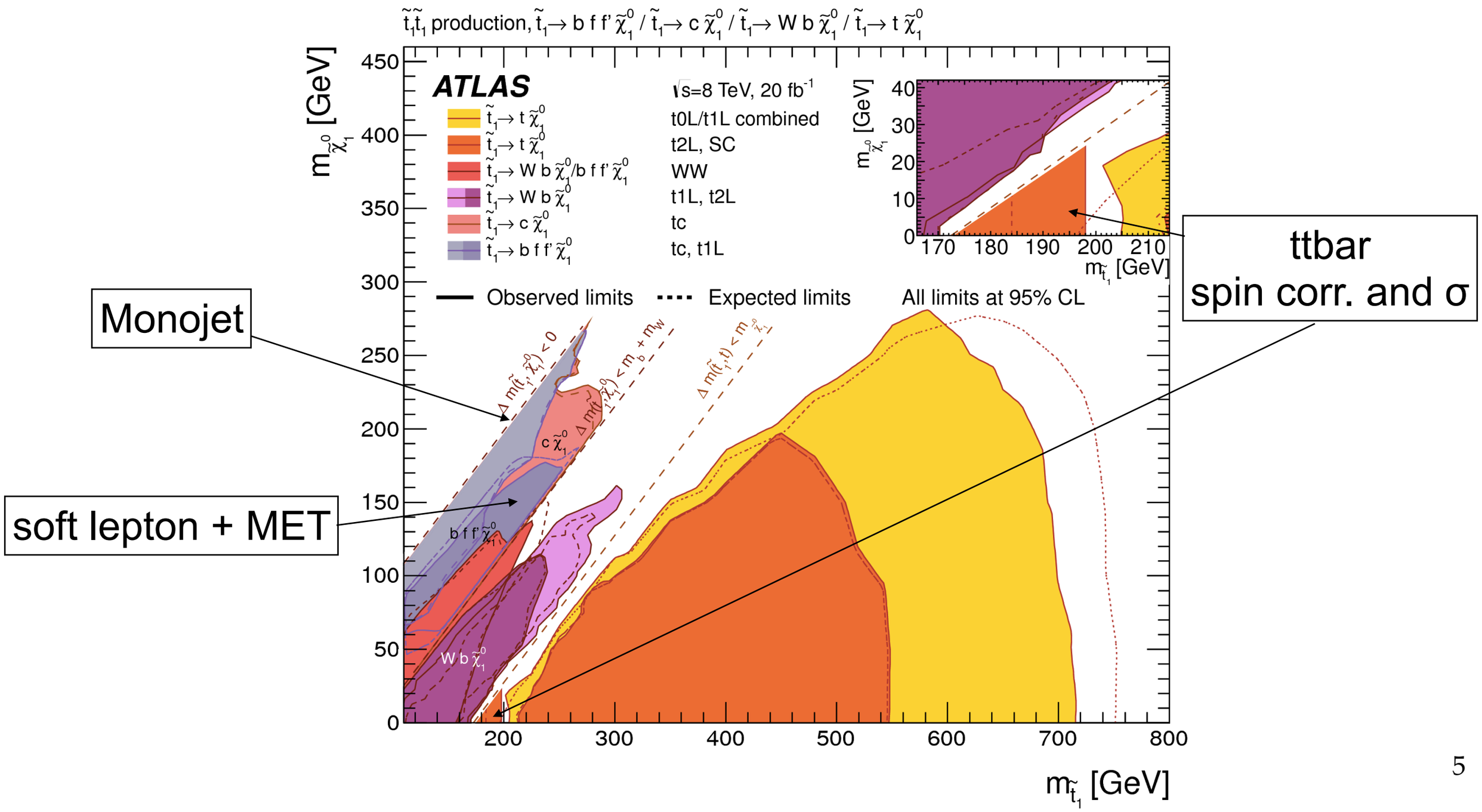
Photons (or leptons) + jets

8 TeV only

New 13 TeV results

State of the art at 8 TeV, 20 fb^{-1}

Natural example: compressed searches for stop



Compressed SUSY searches at 13 TeV

Early 13 TeV searches focus on strong-production

EWK searches require more data to be competitive with 8 TeV

Focus on recent searches with compressed signal regions

	ATLAS	CMS
Monojet	arXiv:1604.07773	CMS-PAS-EXO-16-013 (but no SUSY interpretations)
1 (hard or) soft lepton + MET	arXiv:1605.04285	CMS-PAS-SUS-16-011 LHCP
0 lep, b-tags, MET (sbottom)	ATLAS-CONF-2015-066	CMS-PAS-SUS-16-001
same-sign dileptons	arXiv:1602.09058 (but no compressed SRs)	arXiv:1605.03171

Good agreement observed between data and SM (all searches)

Interpret results using *simplified SUSY models (SMS):*

- ε_{SMS}*A_{SMS} to get cross-section limits as a function of mass
- σ_{SMS} to convert cross-section limits to mass limits

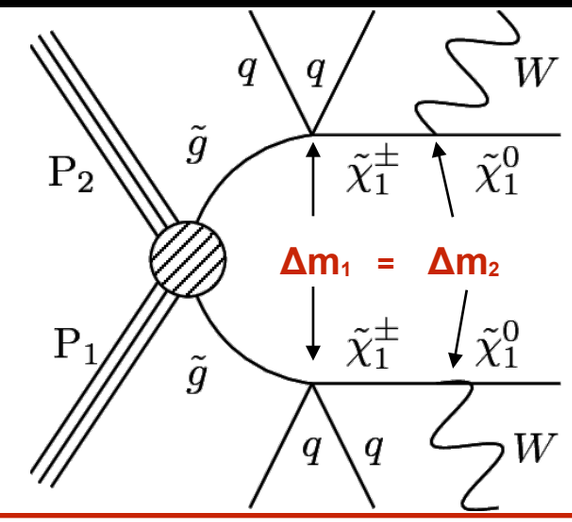
1 lepton + jets + MET (ATLAS)

- 1 lepton: high p_T (>35 GeV) or low p_T (7/6–35 GeV (e/μ))
- 2 "compressed regions" using soft leptons
  - $N_j \geq 2$, ME_T>540 GeV, m_T>100 GeV,
  - $N_j \geq 5$, ME_T>375 GeV, H_T>1.1 TeV, jet aplanarity

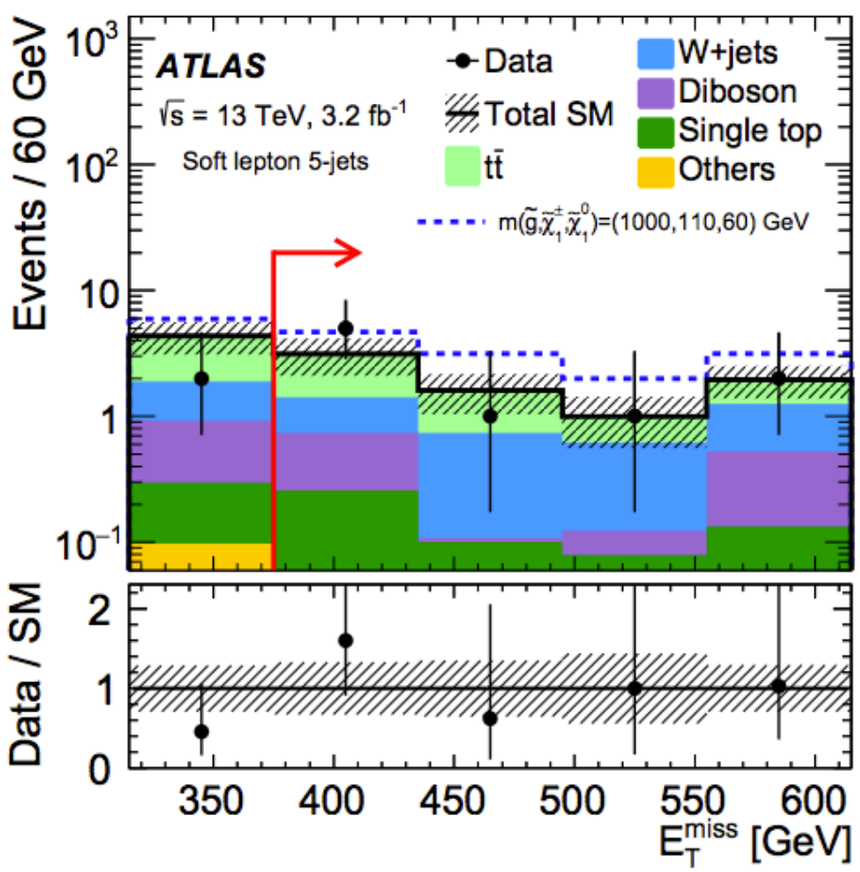
Main backgrounds: ttbar, W+jets

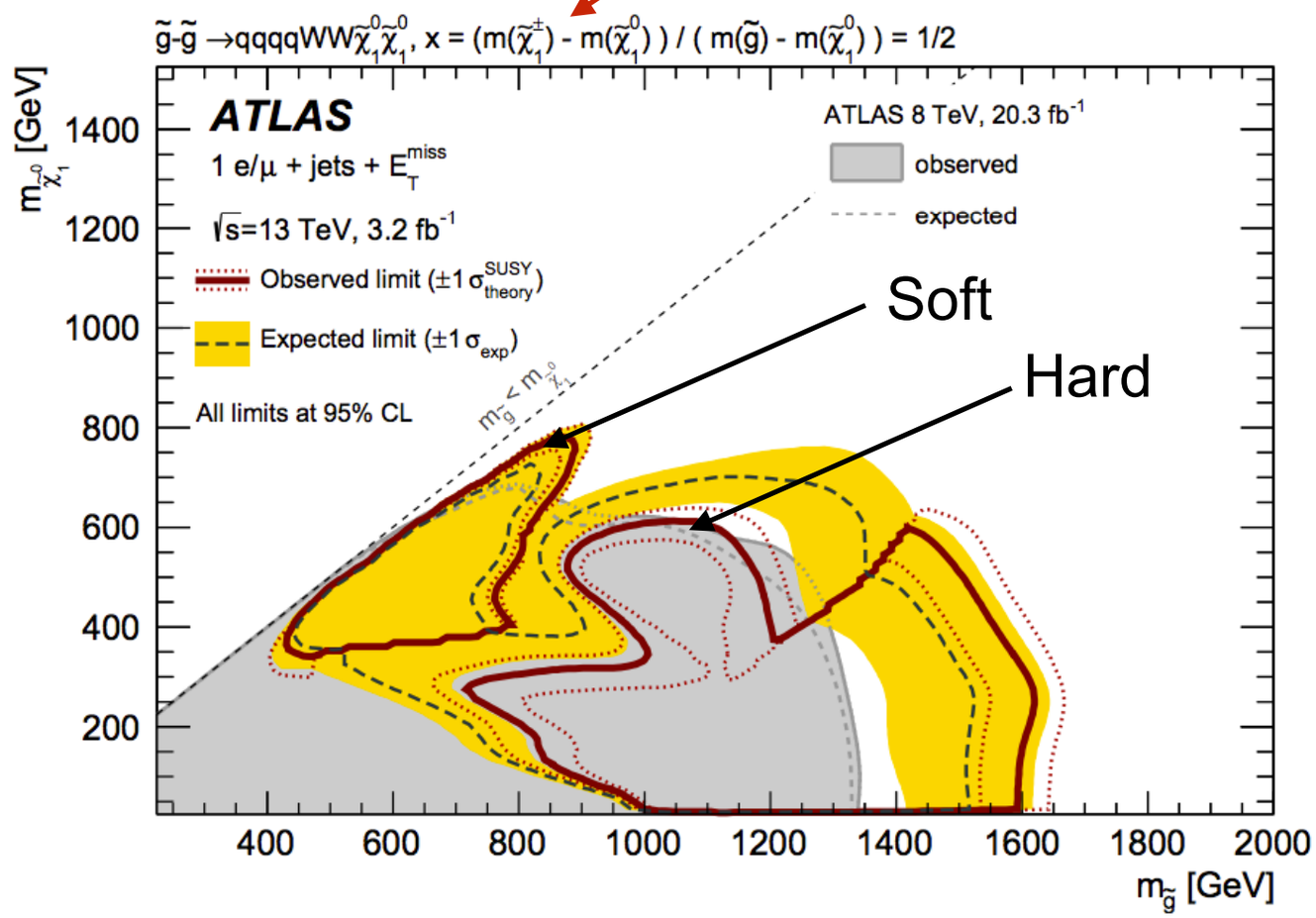
- Normalized in control regions, checked in validation regions

Large region probed by soft lepton



Even mass splitting ($\Delta m_1 = \Delta m_2$): small Δm_2 only near the diagonal





Inclusive 1 soft lepton + MET (CMS)

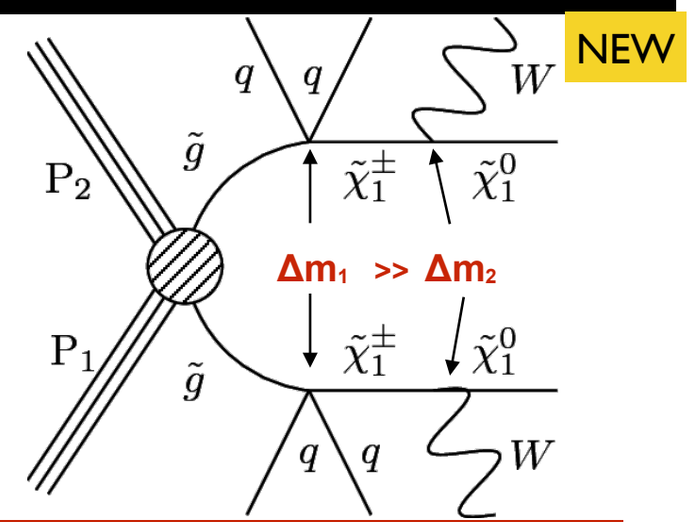
Inclusive: explore all phase space in N_j, N_b, ME_T, m_T

- 1 lepton: only low p_T (5–20 GeV (e/μ))
- MET > 200 GeV (trigger)

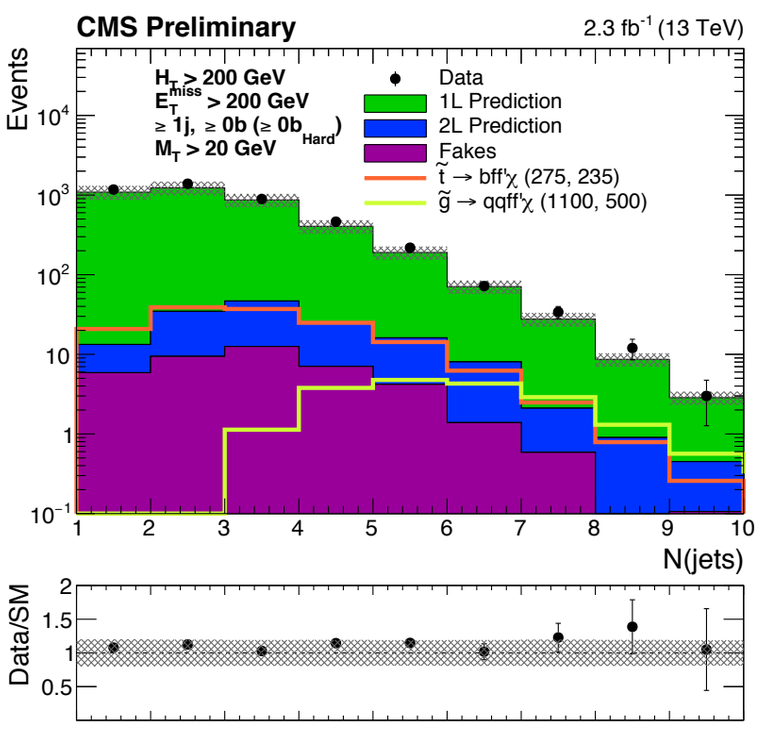
Main backgrounds: 1 lepton (tt, W), 2 lepton (tt)

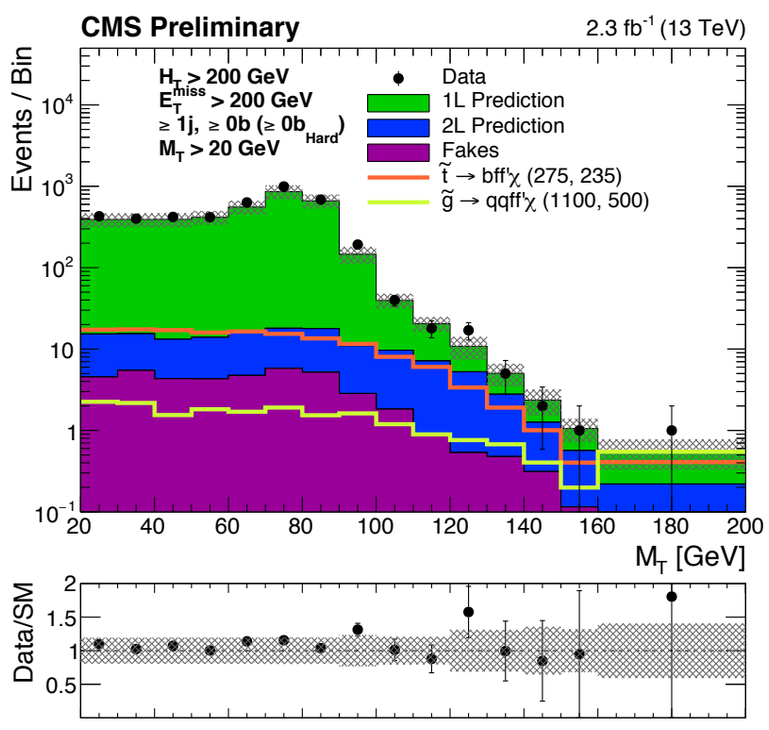
- Estimated in control regions with similar kinematics

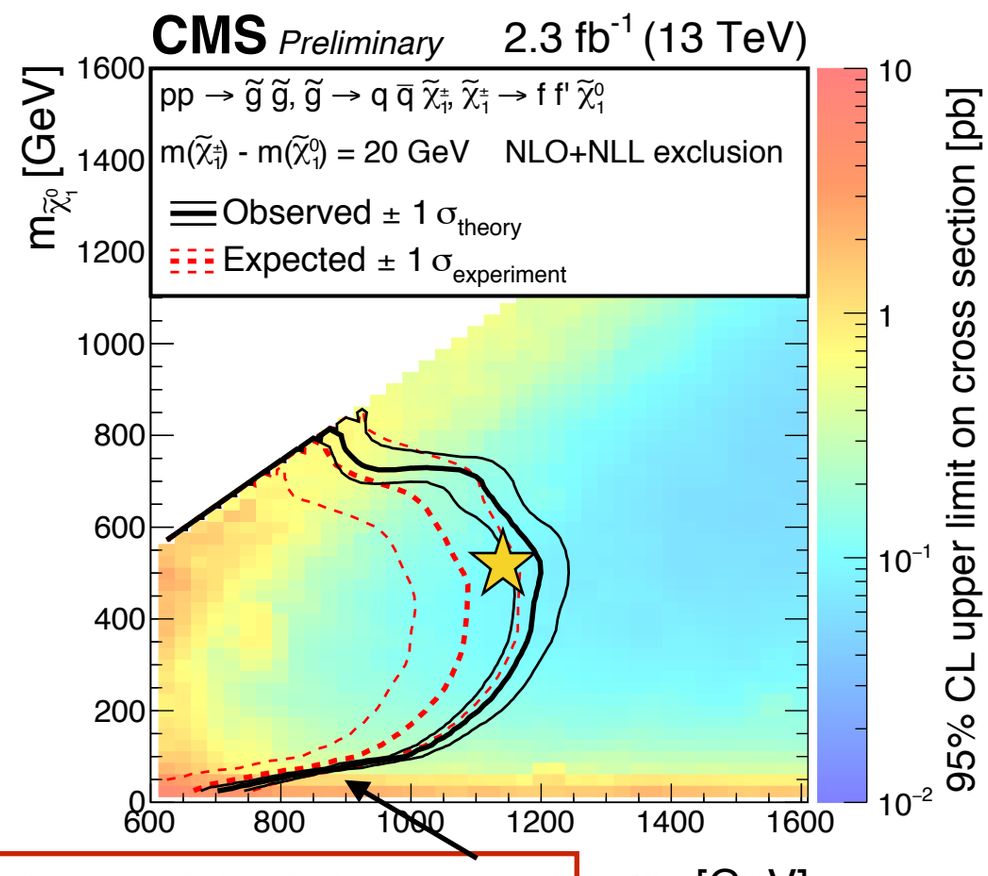
Limit weakens near the diagonal (less MET) and at m_{LSP}~0 (high p_T leptons)



Uneven mass splitting (Δm_2 = 20 GeV): small Δm_2 everywhere







As m_{LSP} ~ 0, leptons inherit the $\chi^\pm$ boost

Inclusive 1 soft lepton + MET (CMS)

NEW

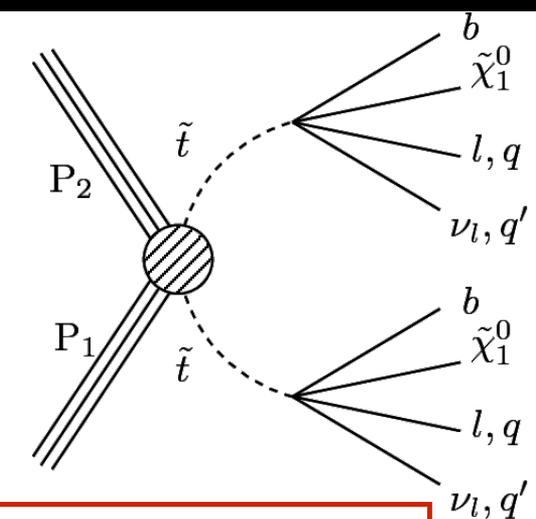
Inclusive: explore all phase space in N_j, N_b, ME_T, m_T

- 1 lepton: only low p_T (5–20 GeV (e/μ))
- MET > 200 GeV (trigger)

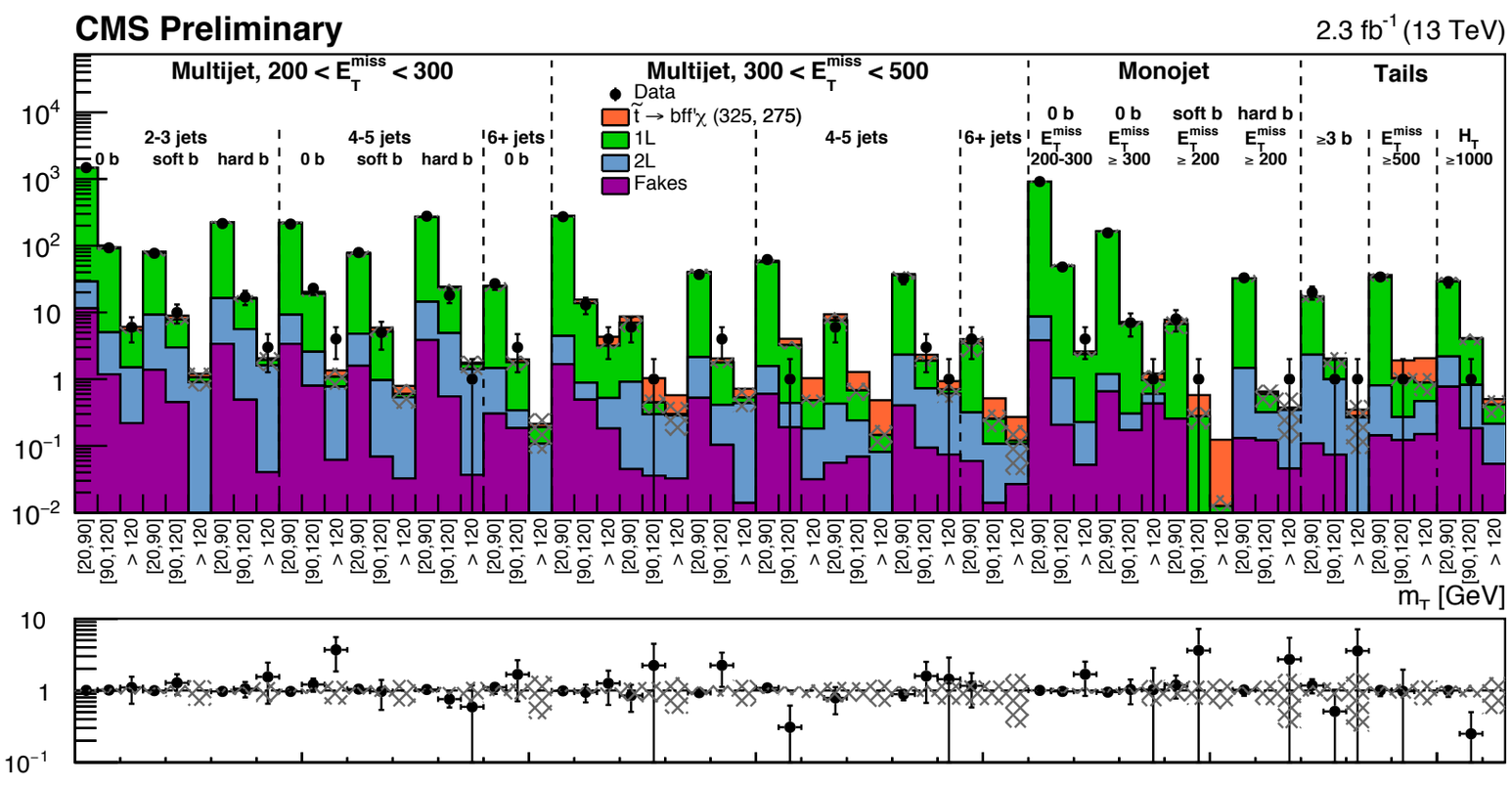
Main backgrounds: 1 lepton (tt, W), 2 lepton (tt)

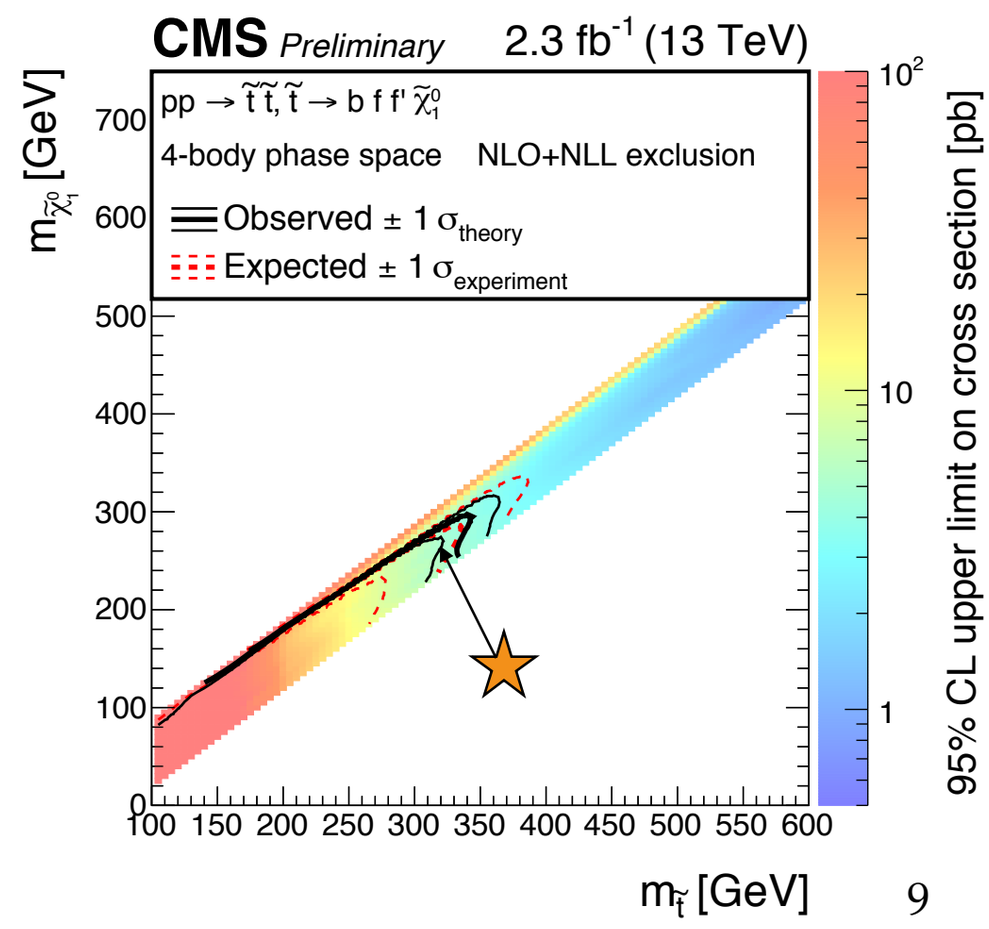
- Estimated in control regions with similar kinematics

Limit weakens near the diagonal (almost no momentum for visible decay products)

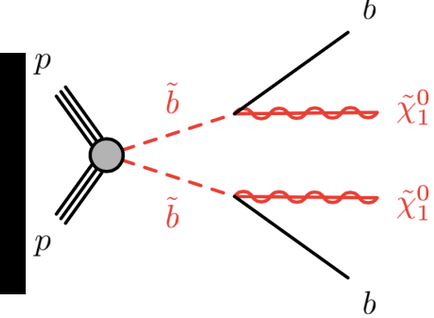


Compressed stop decaying to 4 bodies





sbottom (ATLAS, CMS)



Both sbottom searches have compressed regions with similar selection

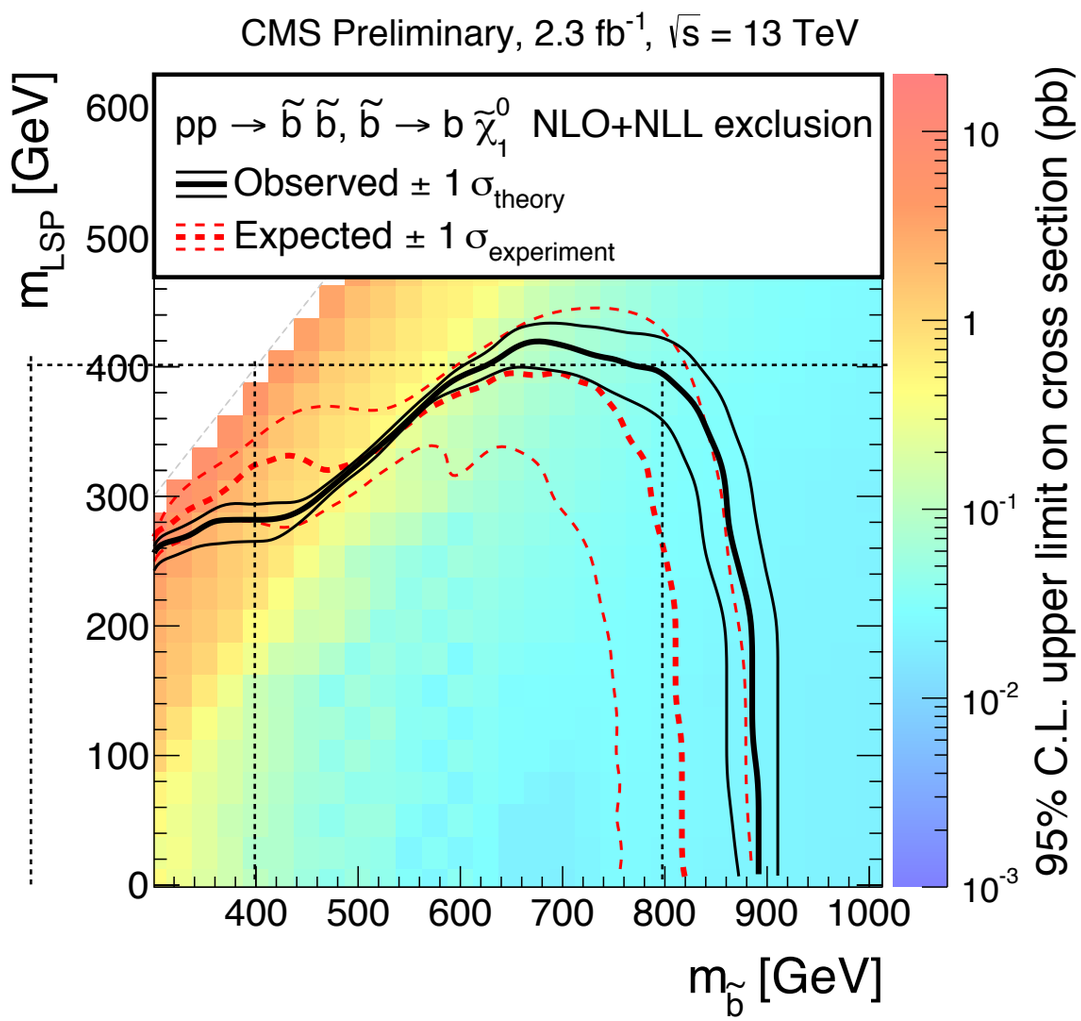
- 0 leptons, 2-3 jets, large MET (binned or >400 GeV)
- ISR jet (non b-tagged, 250-300 GeV), b-tags (1 or 2)

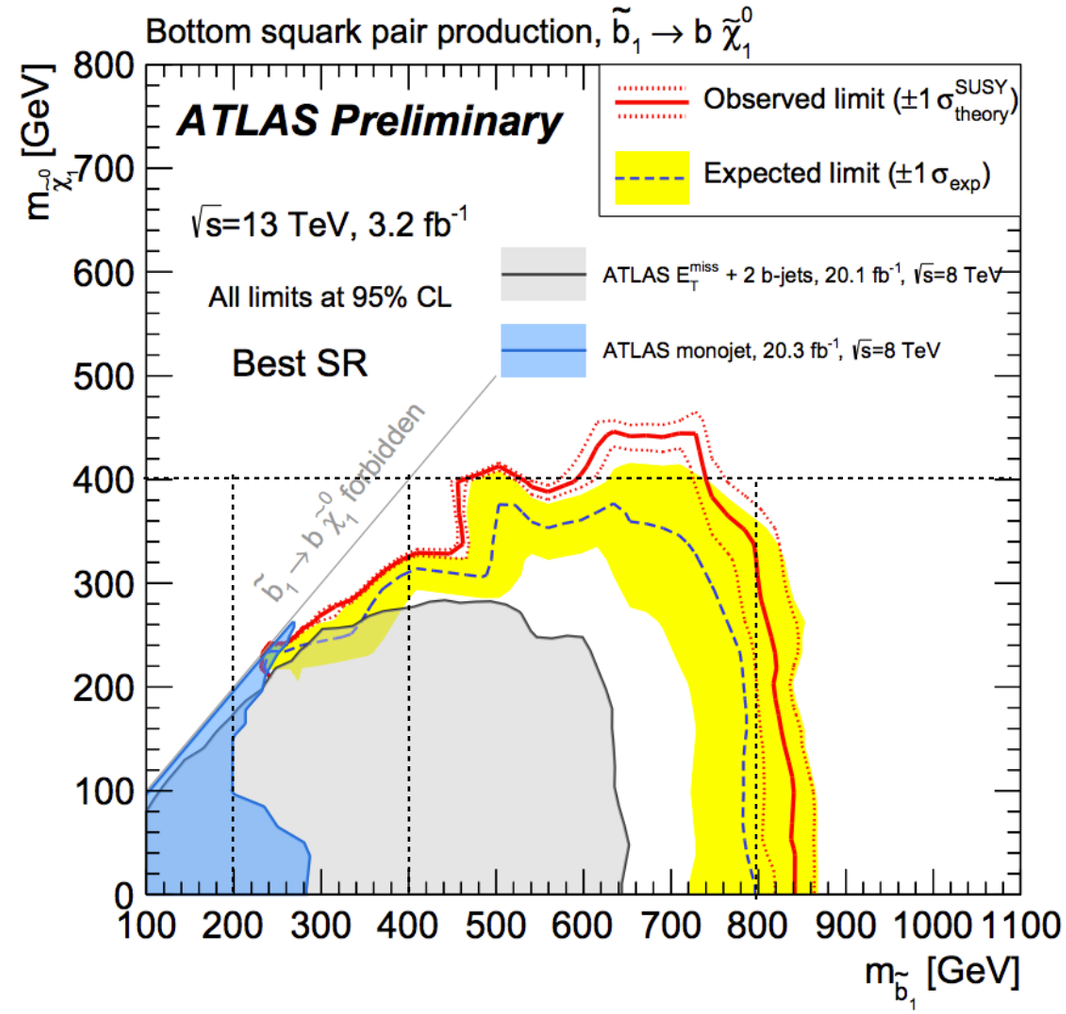
Main backgrounds: ttbar, W(lv) and Z(vv)+heavy-flavor,

- Estimated in control regions with leptons

Limits are comparable: approach diagonal but cannot quite reach it

- b-jets become too soft to be detected





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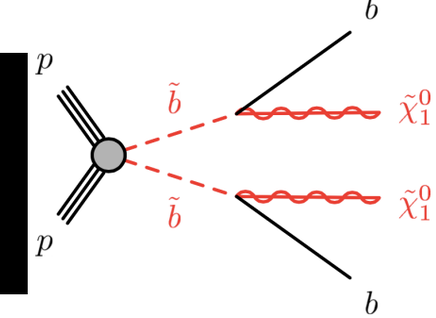

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Main backgrounds: ttbar, W(lv) and Z(vv)+heavy-flavor,

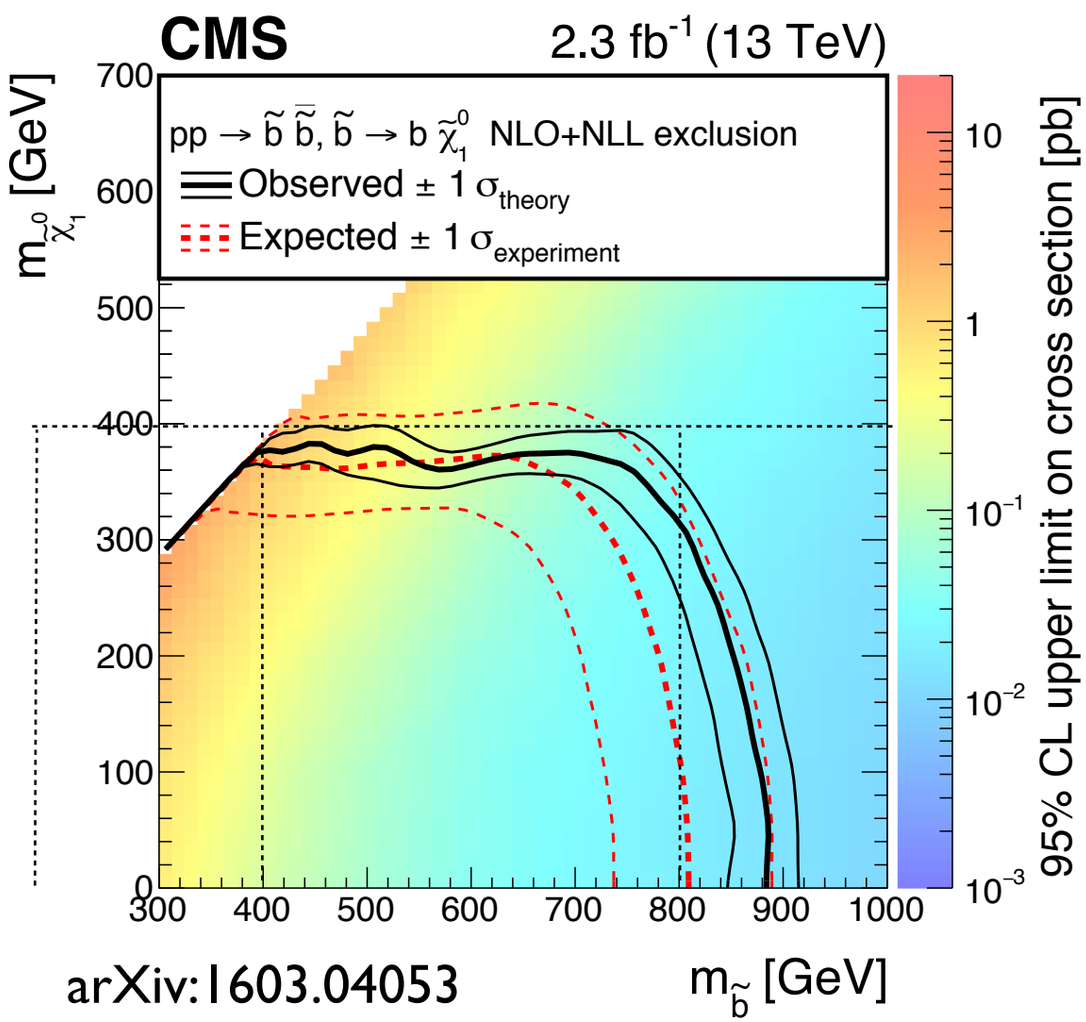
- Estin ... ptons

Limits ... ach diagonal but ca

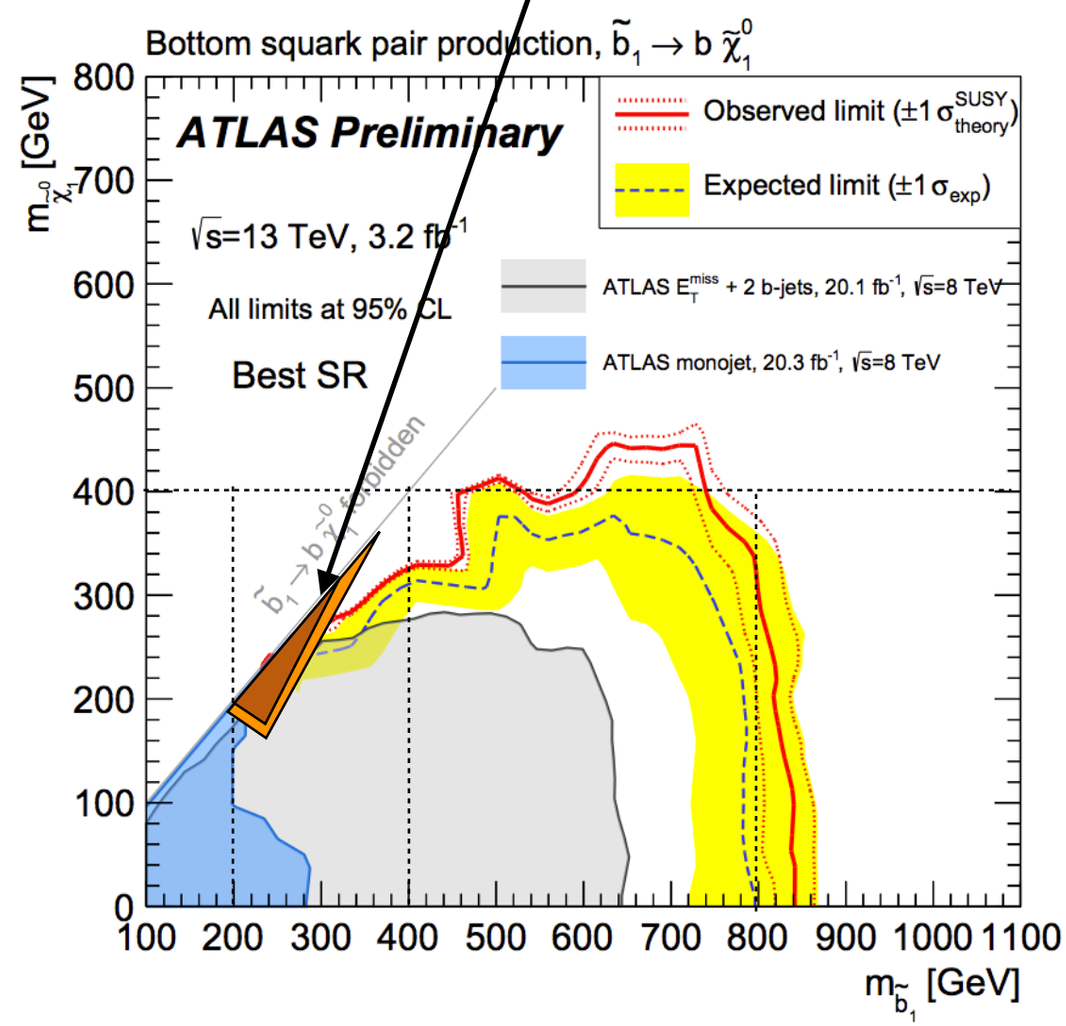
- b-jets ... ed

CMS: Inclusive analysis (including 1j and ≥4) covers the space close to diagonal

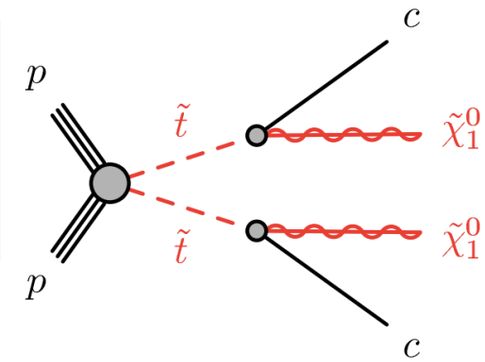
ATLAS: diagonal covered by Monojet search (next)



arXiv:1603.04053



“Monojet” (ATLAS)



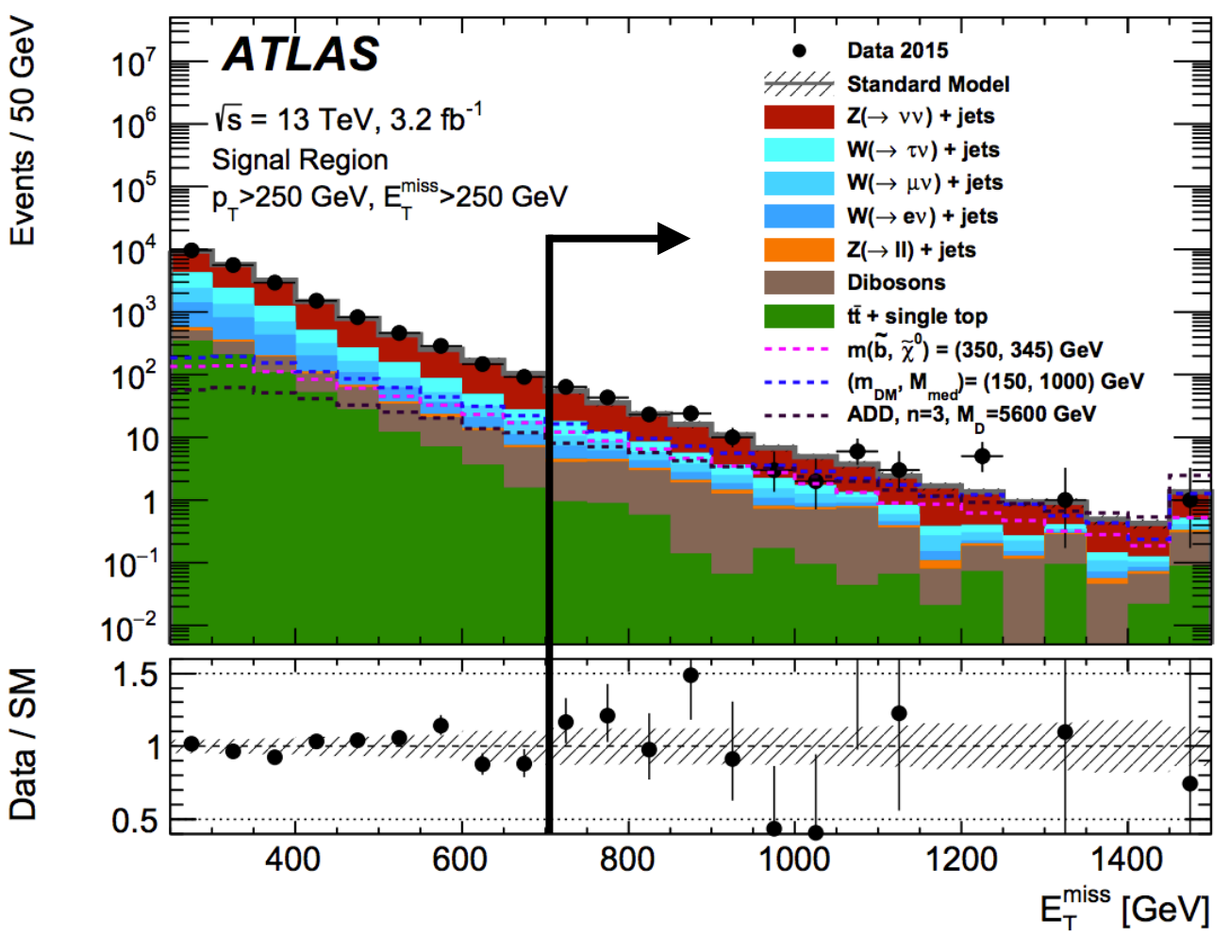
High statistics, high precision

Inclusive final state: 0 lep., p_T^{j1}>250 GeV, $N_{j(pT>30\ GeV)}$<5, $\Delta\varphi(ME_T, j_{1234})$>0.4

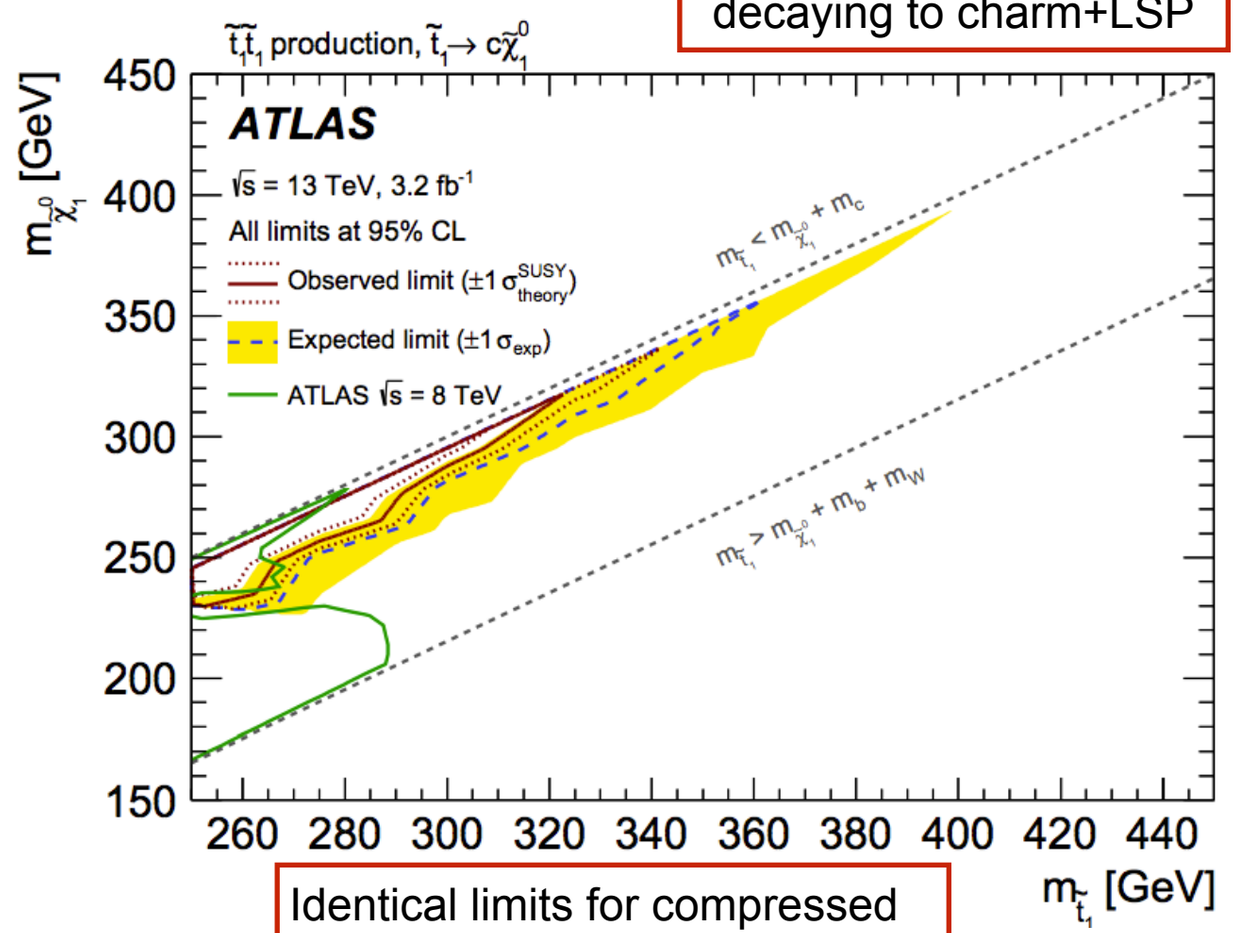
- Backgrounds predicted from control regions: transfer factor systematics < 4%
- Tightest region (MET > 700 GeV): obs. = 185, pred. = 167 ± 20

Limit strongest at diagonal

- *Δm(NLSP, LSP) ~ 0 —> Decay products at rest in NLSP frame —> All boost to heavy LSP’s*
- *For larger Δm, more rich kinematics, lower MET*



Compressed stop decaying to charm+LSP



Identical limits for compressed sbottom to bottom+LSP

same-sign leptons

Rare SM process. Clean. Can trigger without MET

gluinos are neutral: decays can have the same charge

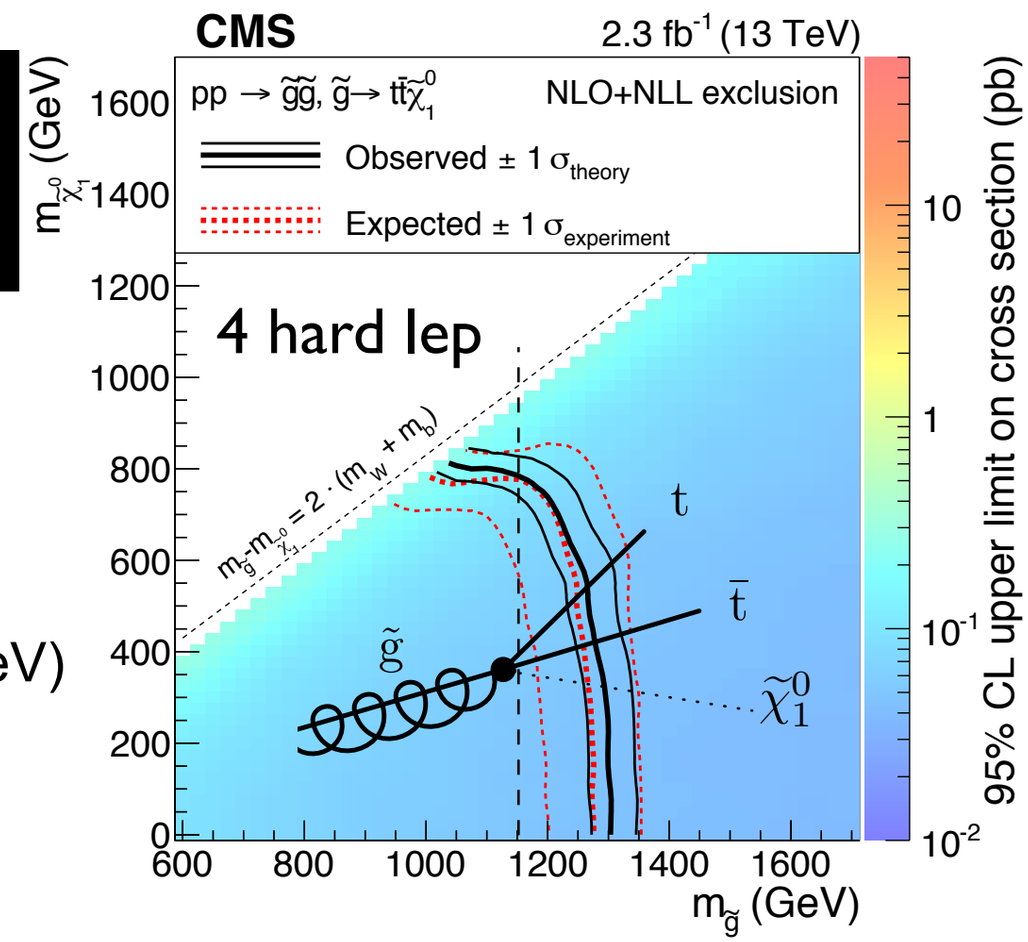
Both ATLAS and CMS searches at high lepton p_T

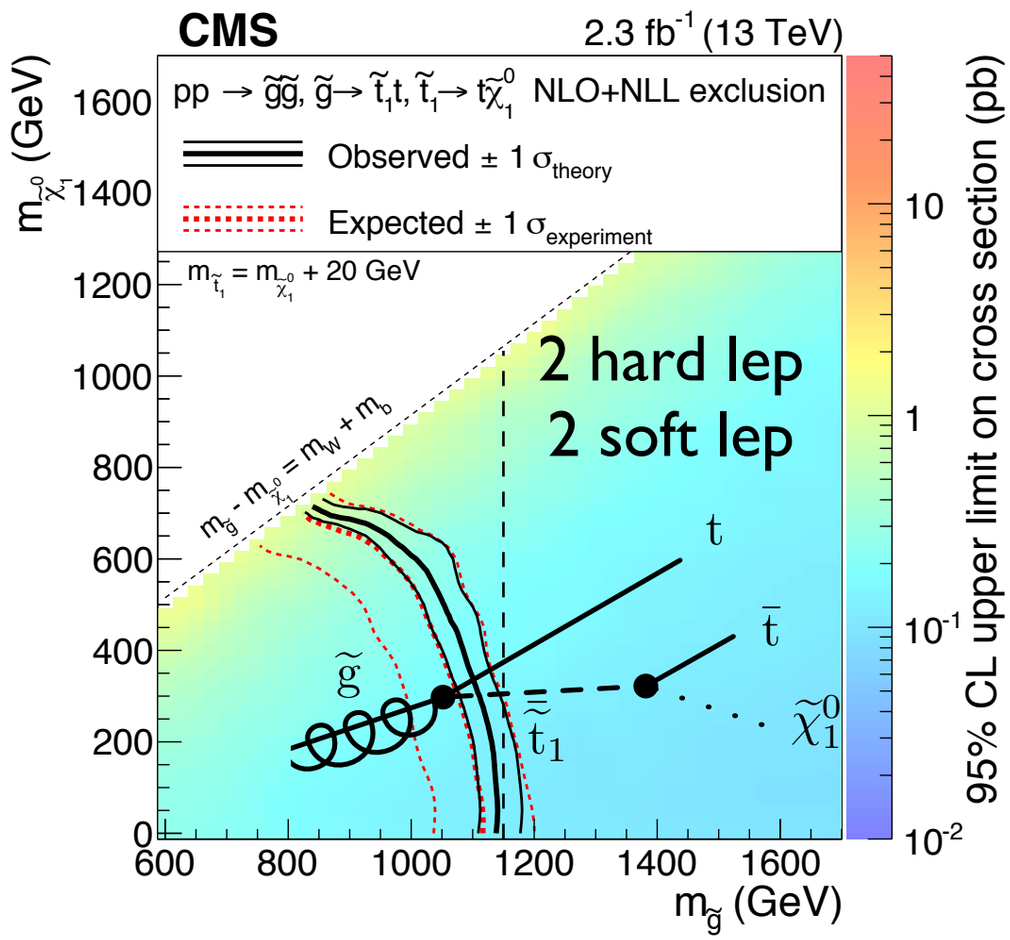
CMS search: extend to softer kinematics

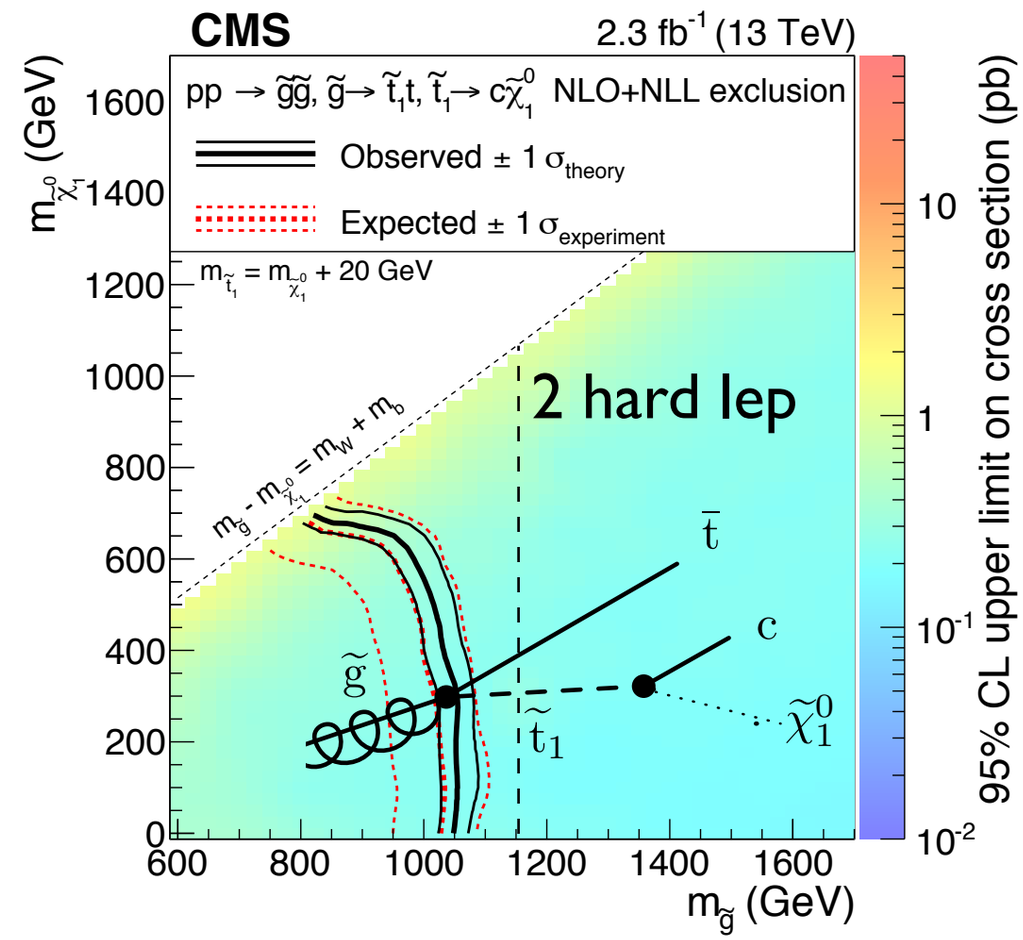
Low MET (>50 GeV), 2 jets, low lepton p_T (10/10, 25/10 GeV)

Study limit in different cases:

- soft leptons recover efficiency in bulk region
- limit at diagonal weakens due to lower MET







Conclusions

Several complementary approaches can be used to probe compressed regions of SUSY phase space

ISR jet, soft leptons, same-sign leptons shown

- Also: VBF, precision measurements (top for stop), etc

Compressed signals can spread over many regions, acceptance in each is small

Inclusive searches often reach best limits by maximizing acceptance

Targeted searches/channels can win in specific topologies

- Super-compressed (monojet), or lepton-rich SUSY (leptonic)

Different channels are necessary to confirm/compare observations

Next steps: 2016/2017 dataset (100 fb^{-1})

Large improvements w.r.t. 8 TeV also for smaller cross-section signals

- searches for compressed (and not) EWK production are picking up

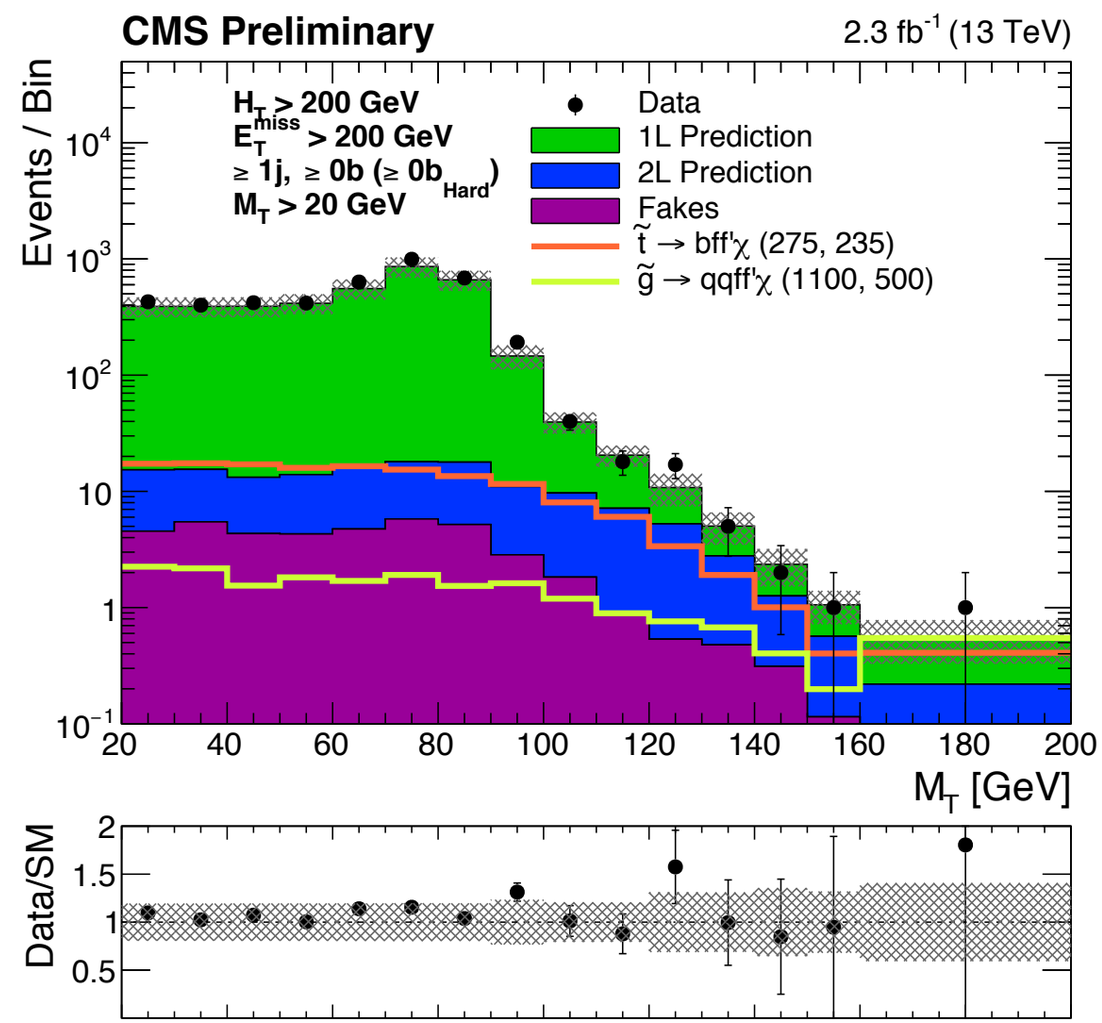
Stealth SUSY: no 13 TeV results yet

Backup

Inclusive 1 soft lepton + MET (CMS): backgrounds

1 lepton backgrounds

- W and Top(1L) with 1 soft lepton and a hard neutrino
- Control Region
  - reverse *W decay kinematics* (hard lep., low MET)
  - maintain similar *event kinematics* (p_T(W))
- Uncertainties: W polarization, W/tt fraction, lep. eff.



2 lepton backgrounds

- Top(2L) with 1 soft lepton, 1 lost lepton, 2 neutrinos
  - 2 or 3 missing objects, producing an m_T tail
- Control Region = SR + 1 extra lepton
- Uncertainties: lepton efficiency, acceptance

Fakes

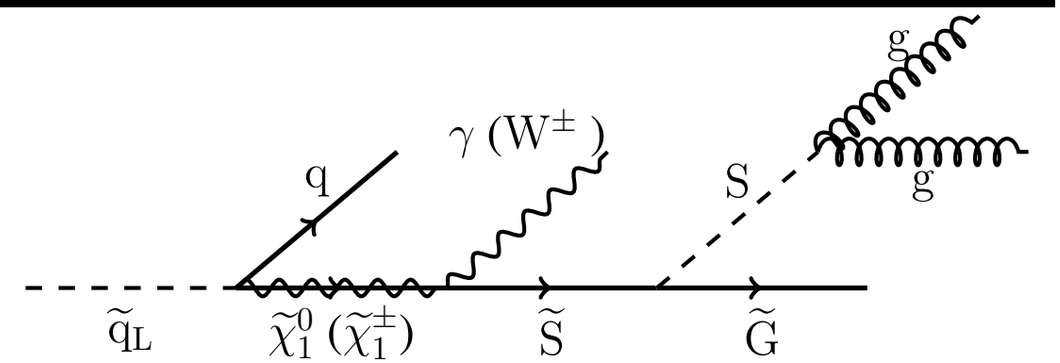
- Small background (very tight ID/ISO requirement)
- Use MC for m_T < 120 GeV (negligible)
- Use Tight/Loose (“fake rate”) method > 120 GeV

arXiv:1411.7255

CMS 8 TeV Stealth Search

2 searches: diphoton and dilepton

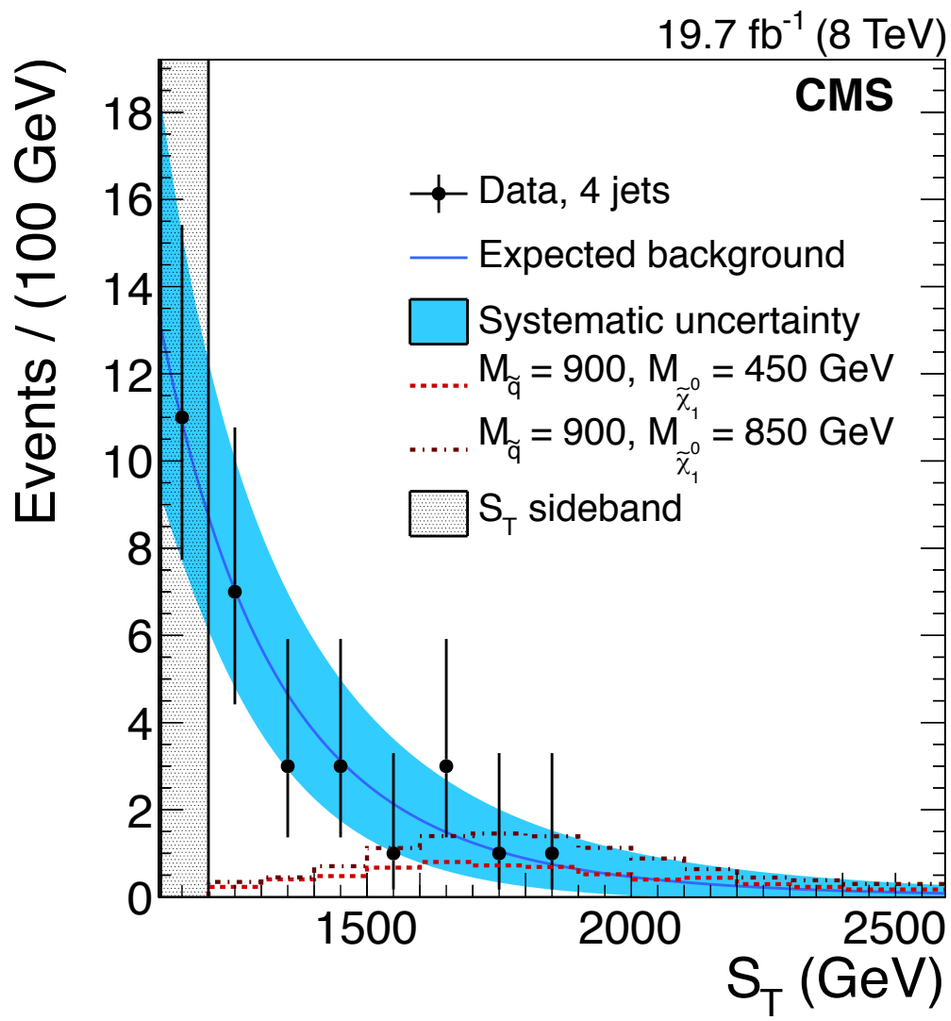
- sensitive to different models

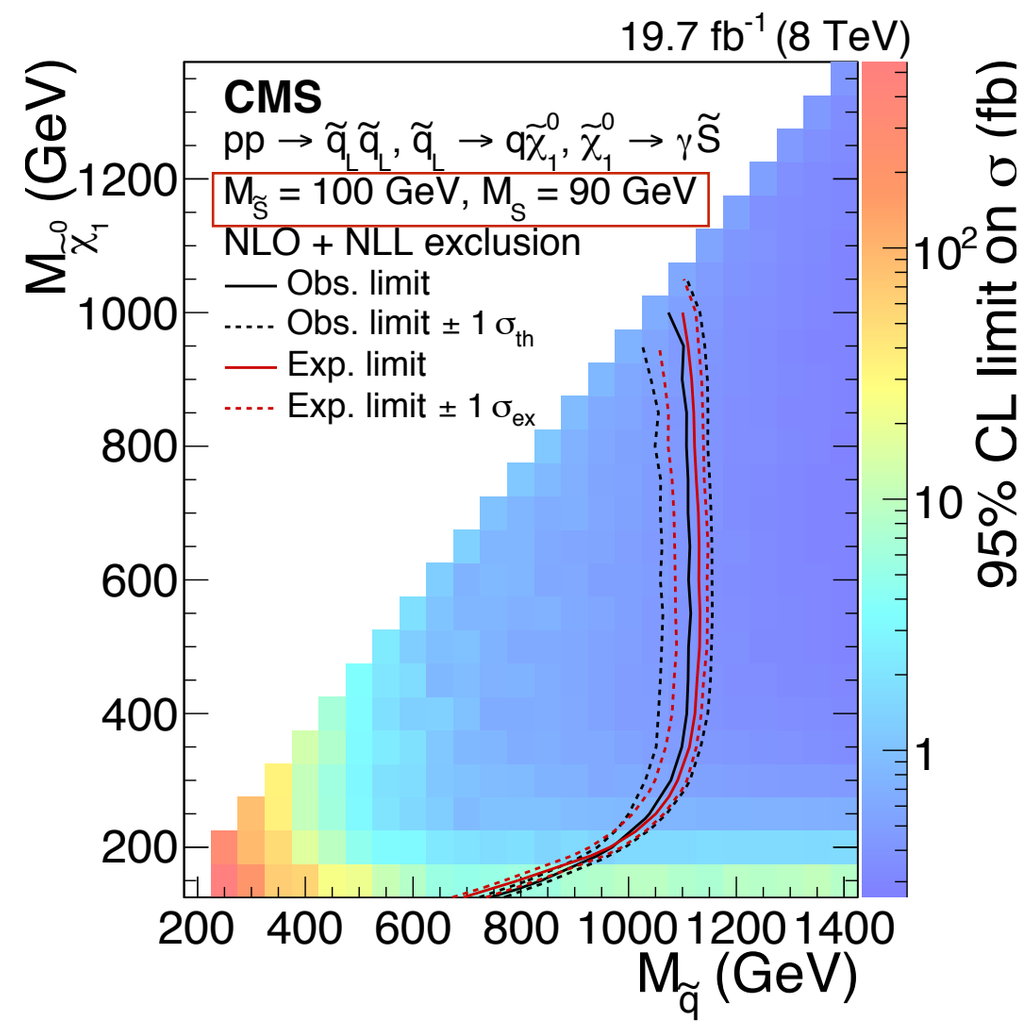


Search variable: S_T

- $S_T = \Sigma (p_T^{jets} + p_T^{photons/leptons} + MET)$
- N(jets) ≥ 4: use lower jet multiplicities to predict S_T shape in the signal region
- S_T > 1200 GeV: normalize the S_T shape at lower S_T values

Results and limits from γγ search





arXiv:1412.4742

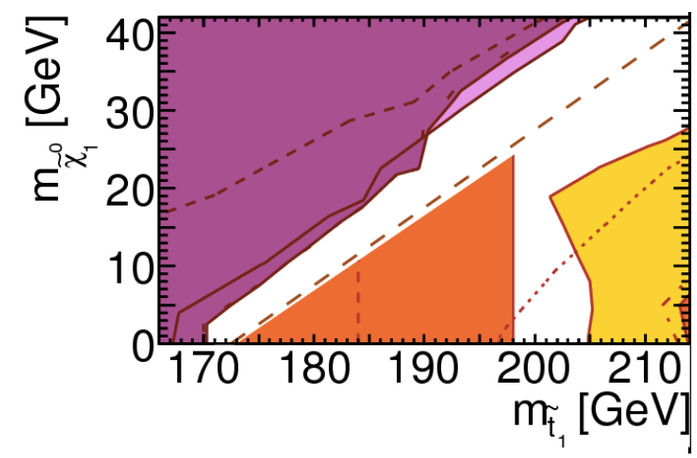
ATLAS 8 TeV tt Spin & Cross Section

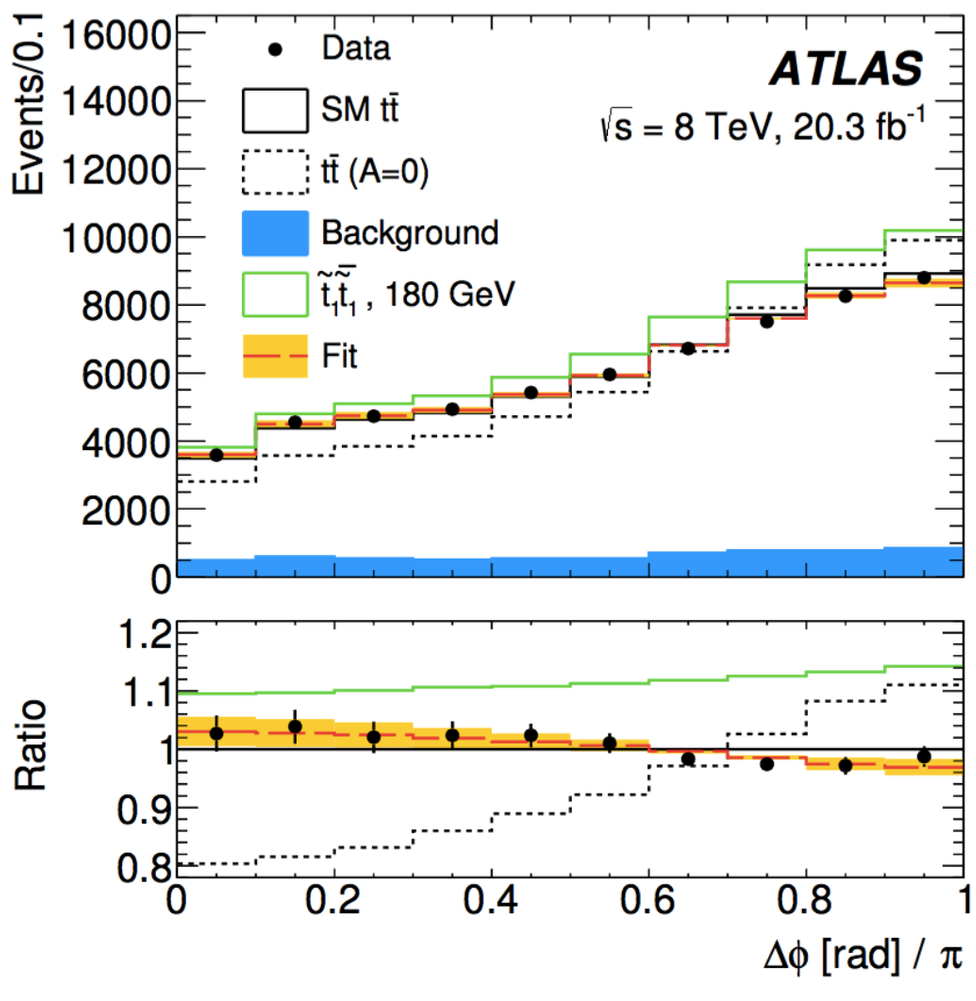
Search for stop with $m_{stop} \sim m_{top}$:

- increase in σ_{tt}
- reduced spin correlation between t and tbar
  - in SM, spin correlation is

$$A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}} = 0.318 \pm 0.005$$

  - stop has spin = 0, so t and tbar spins are uncorrelated (A=0)





Effect of assumptions on limits:

- varying m_{LSP}: few%
- stop —> left-handed top: 10%

  (left/right depends on stop-neutralino mixing)
- don't use σ_{tt}: 30%
- don't use $\Delta\varphi$: 30-40%

1 lepton + jets + MET (ATLAS)

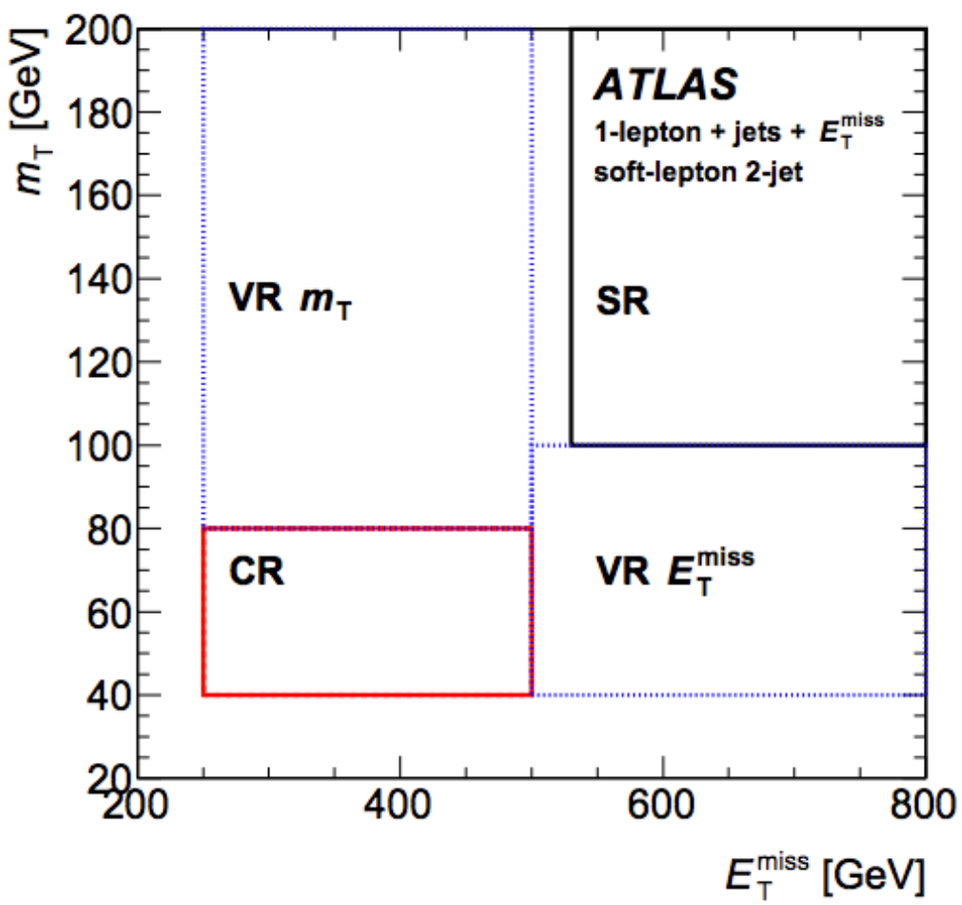
arXiv:1605.04285

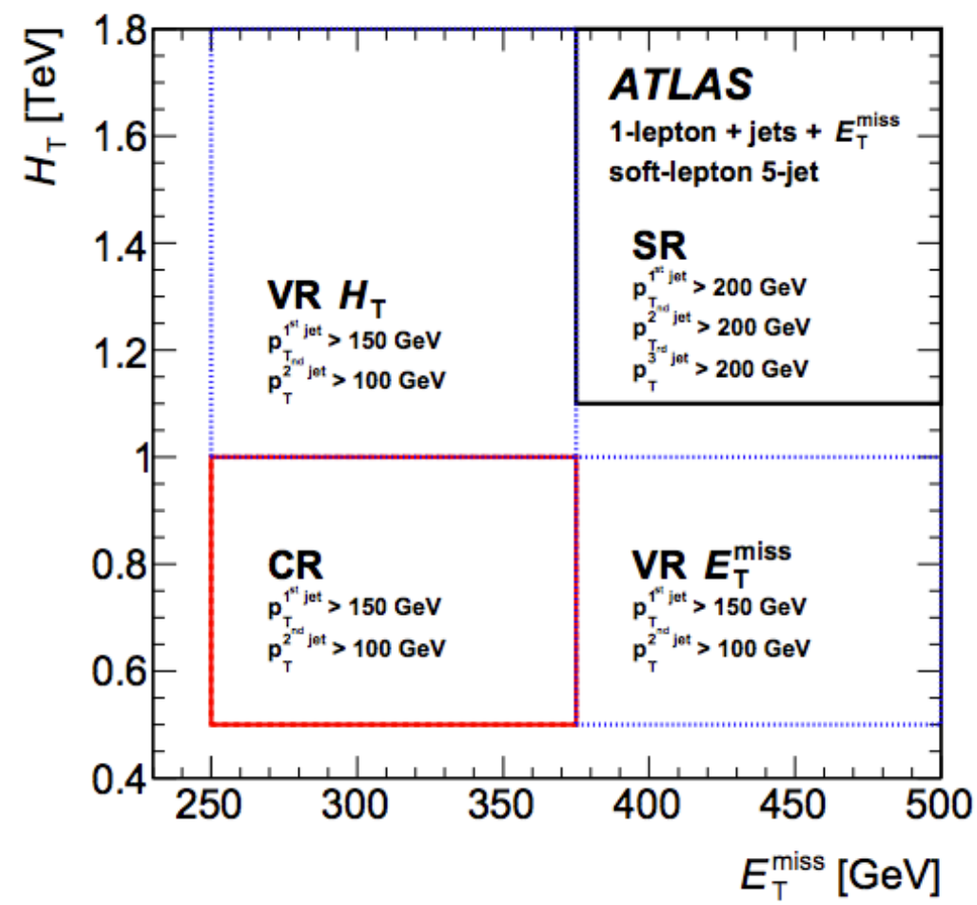
	2-jet soft-lepton SR	5-jet soft-lepton SR
$N_{\text{lep}}(p_{\text{T}}^{\ell=e(\mu)} > 7(6)\text{GeV})$	= 1	= 1
$p_{\text{T}}^{\ell=e(\mu)}$ (GeV)	7(6)–35	7(6)–35
N_{jet}	≥ 2	≥ 5
$p_{\text{T}}^{\text{jet}}$ (GeV)	> 180, 30	> 200, 200, 200, 30, 30
$E_{\text{T}}^{\text{miss}}$ (GeV)	> 530	> 375
m_{T} (GeV)	> 100	-
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$	> 0.38	-
H_{T} (GeV)	-	> 1100
Jet aplanarity	-	> 0.02

	4-jet high-x SR	4-jet low-x SR	5-jet SR	6-jet SR
$N_{\text{lep}}(p_{\text{T}}^{\ell=e(\mu)} > 10\text{GeV})$	= 1	= 1	= 1	= 1
$p_{\text{T}}^{\ell=e(\mu)}$ (GeV)	> 35	> 35	> 35	> 35
N_{jet}	≥ 4	≥ 4	≥ 5	≥ 6
$p_{\text{T}}^{\text{jet}}$ (GeV)	> 325, 30, ..., 30	> 325, 150, ..., 150	> 225, 50, ..., 50	> 125, 30, ..., 30
$E_{\text{T}}^{\text{miss}}$ (GeV)	> 200	> 200	> 250	> 250
m_{T} (GeV)	> 425	> 125	> 275	> 225
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$	> 0.3	-	> 0.1	> 0.2
$m_{\text{eff}}^{\text{inc}}$ (GeV)	> 1800	> 2000	> 1800	> 1000
Jet aplanarity	-	> 0.04	> 0.04	> 0.04

	Hard-lepton				Soft-lepton	
	4-jet low x	4-jet high x	5-jet	6-jet	2-jet	5-jet
Observed events	1	0	0	10	2	9
Fitted background events	1.3 ± 0.5	0.9 ± 0.5	1.3 ± 0.6	4.4 ± 1.0	3.6 ± 0.7	7.7 ± 1.9
$t\bar{t}$	0.40 ± 0.31	0.08 ± 0.07	0.40 ± 0.24	2.5 ± 0.9	0.64 ± 0.33	3.6 ± 1.2
W+jets	0.19 ± 0.12	0.8 ± 0.5	0.16 ± 0.12	0.23 ± 0.16	1.9 ± 0.5	2.5 ± 1.3
Z+jets	0.045 ± 0.023	0.028 ± 0.027	0.073 ± 0.035	0.08 ± 0.08	0.47 ± 0.12	0.09 ± 0.04
Single-top	0.5 ± 0.5	$0.04^{+0.10}_{-0.04}$	$0.21^{+0.22}_{-0.21}$	0.4 ± 0.4	0.16 ± 0.14	0.42 ± 0.33
Diboson	$0.06^{+0.20}_{-0.06}$	$0.002^{+0.014}_{-0.002}$	0.37 ± 0.23	0.9 ± 0.5	0.38 ± 0.16	0.9 ± 0.6
$t\bar{t}$+V	0.048 ± 0.021	0.024 ± 0.012	0.059 ± 0.029	0.23 ± 0.08	0.085 ± 0.028	0.065 ± 0.024

ATLAS 1lepton Control Regions





sbottom (ATLAS)

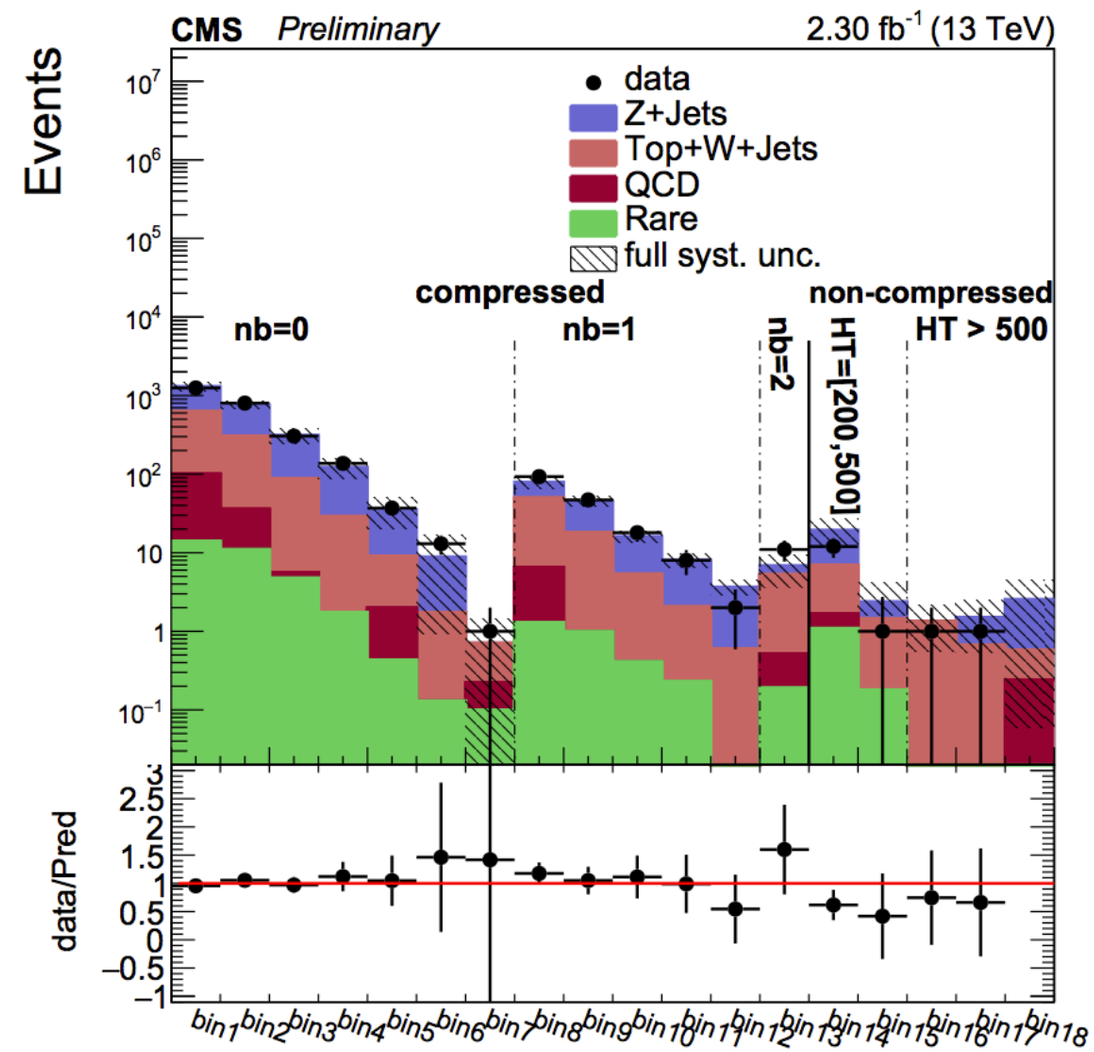
Variable	SRA	SRB
Event cleaning	Common to all SR	
Lepton veto	No e/μ with $p_T > 10$ GeV after overlap removal	
E_T^{miss}	> 250 GeV	> 400 GeV
Leading jet $p_T(j_1)$	> 130 GeV	> 300 GeV
2nd jet $p_T(j_2)$	> 50 GeV	> 50 GeV
Fourth jet $p_T(j_4)$	vetoed if > 50 GeV	
$\Delta\phi^j_{min}$	> 0.4	> 0.4
$\Delta\phi(j_1, E_T^{miss})$	-	> 2.5
b-tagging	j_1 and j_2	j_2 and (j_3 or j_4)
E_T^{miss}/m_{eff}	> 0.25	> 0.25
m_{CT}	> 250, 350, 450 GeV	-
m_{bb}	> 200 GeV	-

Signal region channels	SRA250	SRA350	SRA450	SRB
Observed events	22	6	1	5
Fitted bkg events	40 ± 8	9.5 ± 2.6	2.2 ± 0.6	13.1 ± 3.2
Fitted $t\bar{t}$ events	0.9 ± 0.4	0.37 ± 0.16	0.06 ± 0.03	5.9 ± 2.4
Fitted single top events	2.1 ± 1.3	0.54 ± 0.37	0.15 ± 0.10	1.2 ± 0.8
Fitted W+jets events	6.3 ± 2.4	1.3 ± 0.6	0.41 ± 0.23	1.2 ± 0.6
Fitted Z+jets events	30 ± 7	7.1 ± 2.4	1.5 ± 0.5	3.3 ± 1.4
(Alt. method Z+jets events)	*(33 ± 7)*	*(7.2 ± 1.9)*	*(2.7 ± 0.9)*	
Fitted "Other" events	0.7 ± 0.6	0.1 ± 0.1	0.02 ± 0.02	1.4 ± 0.4
MC exp. SM events	27	6.5	1.5	13
MC exp. $t\bar{t}$ events	1.1	0.45	0.07	6.6
MC exp. single top events	2.7	0.7	0.20	1.2
MC exp. W+jets events	4.7	1.0	0.31	1.2
MC exp. Z+jets events	18	4.2	0.9	2.7
MC exp. "Other" events	0.7	0.1	0.02	1.4

sbottom (CMS)

Selection	non-compressed	compressed
N_{jets}	[2,3]	[2,3]
1st-jet p_T	> 100 GeV	> 250 GeV
2nd-jet p_T	> 75 GeV	> 60 GeV
Veto fourth jet	$p_T > 50$ GeV	$p_T > 50$ GeV
Lepton and isolated track veto	$p_T > 10$ GeV	$p_T > 10$ GeV
b jet	1st and 2nd-jet are b jets	2nd or(and)3rd-jet are b jets
E_T^{miss}	> 250 GeV	> 250 GeV
$\Delta\phi(j_{123}, E_T^{\text{miss}})$	> 0.4	> 0.4
$\Delta\phi(j_1, E_T^{\text{miss}})$	-	> 2.3
$\min M_T(j, E_T^{\text{miss}})$	> 250 GeV	> 200 GeV
H_T	> 200 GeV	-
m_{CT}	> 250 GeV	-

Selection	T2bb ($m_{\tilde{b}}$=325,$m_{\tilde{\chi}_1^0}$=275 GeV)	T2cc ($m_{\tilde{t}}$=250,$m_{\tilde{\chi}_1^0}$=240 GeV)
Preselection ($E_T^{\text{miss}} > 200, p_T(j_1) > 100$ GeV)	1561	4985
$E_T^{\text{miss}} > 250$ GeV	1011	2894
N_{jets} = [2,3], 4^{th}jet veto	643.22	1936
1st-jet $p_T > 250$ GeV	409.25	1046
2nd-jet $p_T > 60$ GeV	311.77	753.65
lepton and isolated track veto	292.55	724.07
$\Delta\phi(j_{123}, E_T^{\text{miss}}) > 0.4$	197.12	613.71
$\min M_T(j, E_T^{\text{miss}}) > 200$ GeV	120.21	522.96
$\Delta\phi(j_1, E_T^{\text{miss}}) > 2.3$	115.23	499.06
1st-jet isn't b	95.17	418.51
$N_{b-\text{tags}} >= 1$	47.71	396.63
$N_{b-\text{tags}} = 0$	47.46	21.88



Sbottom ATLAS vs CMS

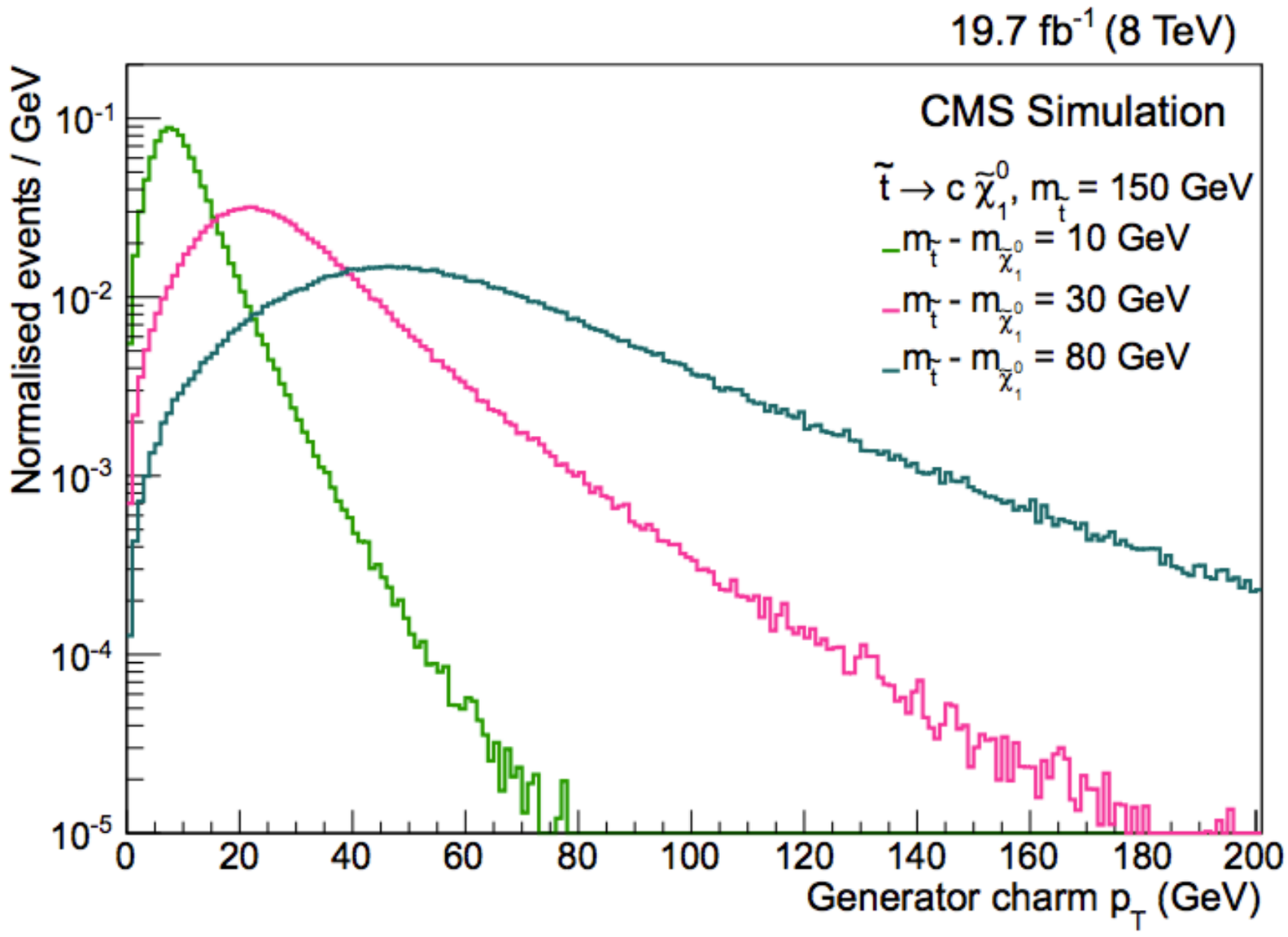
- 0 leptons, ME_T > 250 GeV, MET/(HT+MET) > 0.25, $m_T(j_{1,2}$, MET) > 200 GeV
- 2-3 jets (4th jet veto at 50 GeV), $\Delta\varphi(ME_T, j_{123})>0.4$
- Compressed region:
  - ISR jet: not b-tagged, p_T>250 (300) GeV, $\Delta\varphi(ME_T,j_1)>2.3$ (2.5), p_T^{j2} > 60 (50) GeV
  - b-tags: 2 (including 4th jet if below 50 GeV), bin: [0,1,2]
  - MET: >400 GeV, bin: [250, …, 1000 GeV]

Red: ATLAS
Blue: CMS
Black: both

Charm jet p_T in stop —> c+LSP

Acceptance at larger Δm is sensitive to p_T of jets used for…

- … the veto of 5th jet (Monojet analysis) or 4th jet (sbottom analysis)
- … the list of jets included in Δφ(MET, jet) > 0.4 requirement



from CMS-PAS-SUS-13-009