LHC Searches Examined via the RPV MSSM

Part II: Stops and Gluinos

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Stops (w/Jared Evans)

arXiv:1209.0764 [JHEP 1304 (2013) 028] updated with 8 TeV searches

Gluinos (w/Jared Evans, David Shih, Matt Strassler)

work in progress

Outline

- Motivation
- Simplified models
- Relevant existing searches
- Gaps in coverage
- New search opportunitues
- Conclusions

- Stop production
- Gluino production

Motivation

Theory-motivated question

SUSY can stabilize the electroweak (EW) scale. Expect:

- Higgsinos near EW scale
- Certain colored partners (stops & sbottoms, gluinos) not much heavier

Are models with natural superpartner spectra still allowed?

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Cover all classes of final states, regardless of theory motivation.

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How can they be addressed?

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Why RPV?

- RPC SUSY already well-covered. RPV may still contain surprises!
- Freedom in RPV couplings $\rightarrow$ Many interesting benchmark models

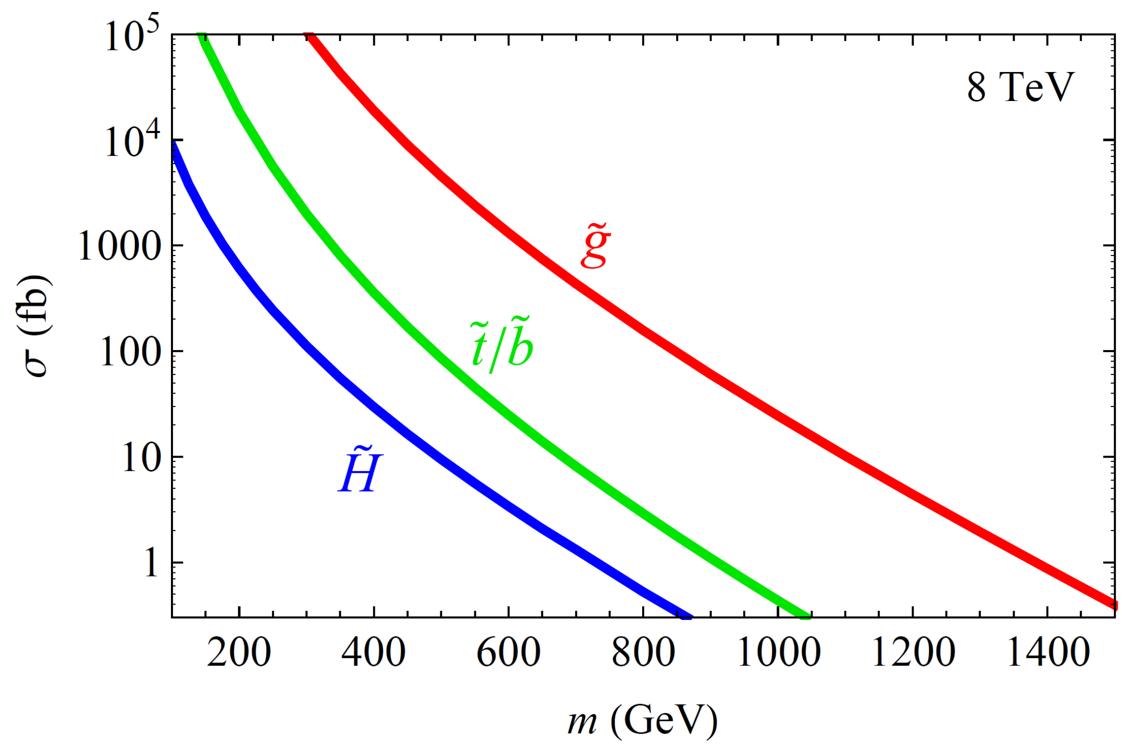
Superpartner spectrum

EW scale without fine-tuning:

- Higgsinos: below ~ 200 GeV
- RH & LH stops, LH sbottom: below ~ 500 GeV
- Gluino: below ~ 1000 GeV (unless it's a Dirac gluino, beyond MSSM)

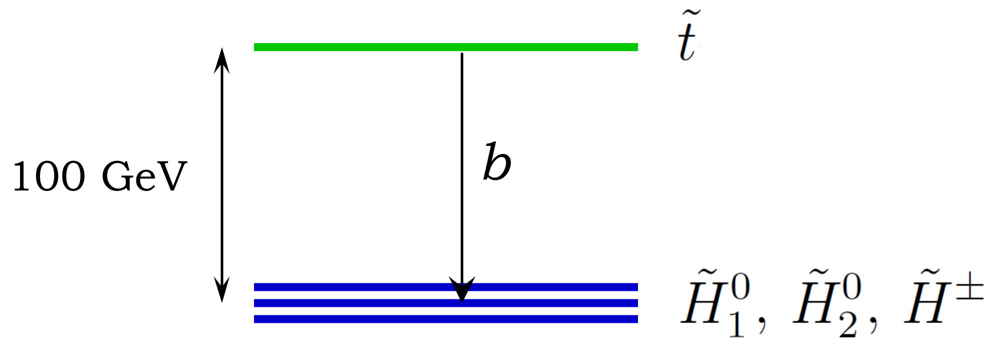
Dominant production process depends on the spectrum

- Higgsino – yesterday
- **Stop – today**
- Sbottom – similar to stop
- **Gluino – today**



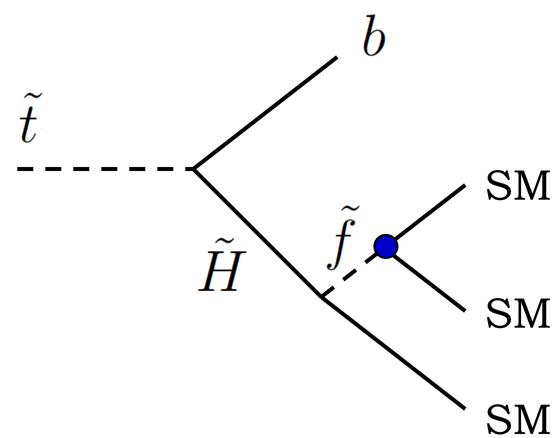
Other superpartners will also be around and mediate decays.

Simplified models with stops



Production (model-independent): $pp \rightarrow \tilde{t}\,\tilde{t}^*$

Decay to a higgsino (chargino): $\tilde{t} \rightarrow b\,\tilde{H}^+$



Higgsino decay:

Case 1: $\tilde{H}^+ \rightarrow W^{+*}\,\tilde{H}^0_1\,, \quad \tilde{H}^0_1 \rightarrow \mathrm{RPV}$

$W^{+*} \rightarrow$ soft particles (unobservable)

Case 2: $\tilde{H}^+ \rightarrow \mathrm{RPV}$

For simplicity, the sfermion mediator $\tilde{f}$ assumed off-shell.

Simplified models with stops

Scenario			Final state (for each stop)	
● Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq$, νbbq	$etbq$, νtbq
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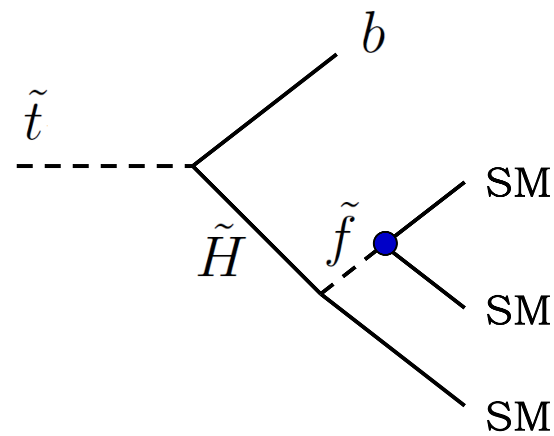

Case 1

$$\tilde{H}^+ \to W^{+*}\,\tilde{H}_1^0$$

$$\tilde{H}_1^0 \to \text{RPV}$$

Stop and antistop can give same-sign leptons

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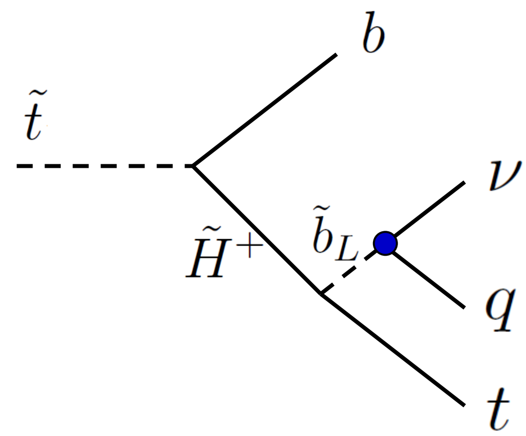
EXAMPLE



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Searches

ATLAS CMS

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
3ℓ+jets+MET	8	13.0	CONF-2012-151
3ℓ+MET (old)	8	13.0	CONF-2012-154
3ℓ+MET	8	20.7	CONF-2013-035
4ℓ (old)	8	13.0	CONF-2012-153
4ℓ+MET	8	20.7	CONF-2013-036
3-4ℓ	8	19.5	PAS-SUS-13-003
b' (3ℓ)	7	4.9	arXiv:1204.1088
3ℓ	7	1.02	CONF-2011-158
4ℓ	7	1.02	CONF-2011-144
3ℓ+MET	7	2.06	arXiv:1204.5638
3ℓ+MET	7	4.7	arXiv:1208.3144
4ℓ+MET	7	2.06	CONF-2012-001
3-4ℓ	7	4.98	arXiv:1204.5341
SS DIL+MET	8	5.8	CONF-2012-105
SS DIL w/b (SUSY)	8	20.7	CONF-2013-007
SS DIL w/b (Exo.)	8	14.3	CONF-2013-051
SS DIL w/b	8	10.5	arXiv:1212.6194
SS DIL	7	4.98	arXiv:1205.6615
SS DIL w/b	7	4.98	arXiv:1205.3933
SSSF DIL	7	4.98	arXiv:1207.6079
SSSF DIL	7	1.6	arXiv:1201.1091
SS DIL	7	4.7	arXiv:1210.4538
SS DIL+jets+MET	7	2.05	arXiv:1203.5763
SS DIL+MET	7	1.04	arXiv:1110.6189
b' (SS DIL)	7	4.7	CONF-2012-130
b' (SS DIL)	7	4.9	arXiv:1204.1088
OS DIL+MET	7	1.04	arXiv:1110.6189
OS DIL+jets+MET	7	4.7	arXiv:1208.4688
OS DIL+MET	7	4.98	arXiv:1206.3949
leptonic m_{T2}	7	4.7	arXiv:1209.4186
Z+jets+MET	7	4.98	arXiv:1204.3774
Z+jets+MET	7	2.05	arXiv:1204.6736

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ℓ+jets+MET	8	5.8	CONF-2012-104
ℓ+b+$6j$+MET	8	19.4	PAS-SUS-13-007
$(\mu j)(\nu j)$	8	19.6	PAS-EXO-12-042
ℓ+$7j$+MET	7	4.7	CONF-2012-140
ℓ+jets+MET	7	4.7	PAS-SUS-12-010
ℓ+jets+MET	7	4.7	CONF-2012-041
ℓ+b+jets+MET	7	2.05	arXiv:1203.6193
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-027
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-028
$1/2\tau$+jets+MET	8	20.7	CONF-2013-026
4ℓ+MET w/τ	8	20.7	CONF-2013-036
3-4ℓ w/τ	8	19.5	PAS-SUS-13-003
$1/2\tau$+jets+MET	7	4.7	arXiv:1210.1314
τ+ℓ+jets+MET	7	4.7	arXiv:1210.1314
τ+jets+MET (old)	7	2.05	CONF-2012-005
2τ+jets+MET (old)	7	2.05	arXiv:1203.6580
OS DIL+MET w/τ	7	4.98	arXiv:1206.3949
SS DIL w/τ	7	4.98	arXiv:1205.6615
3-4ℓ w/1τ	7	4.98	arXiv:1204.5341
3-4ℓ w/2τ	7	4.98	arXiv:1204.5341
$t\bar{t}$ xsec (DIL)	8	2.4	PAS-TOP-12-007
$t\bar{t}$ xsec (DIL)	7	0.70	arXiv:1202.4892
$t\bar{t}$ xsec (DIL)	7	2.3	arXiv:1208.2671
$t\bar{t}$ xsec (DIL w/τ)	7	~ 2	arXiv:1203.6810
$t\bar{t}$+jet (LJ)	7	5.0	PAS-EXO-11-056
$t\bar{t}$+m_T (LJ)	7	1.04	arXiv:1109.4725

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
2-6 jets+MET	8	20.3	CONF-2013-047
2-6 jets+MET (old)	8	5.8	CONF-2012-109
7-10 jets+MET w/b	8	20.3	CONF-2013-054
7-10 jets+MET w/M_J^Σ	8	20.3	CONF-2013-054
6-9 jets+MET	8	5.8	CONF-2012-103
b+jets+MET	8	19.4	arXiv:1305.2390
$3b$+jets+MET	8	12.8	CONF-2012-145
jets w/α_T w/b	8	11.7	arXiv:1303.2985
monojet+MET	8	19.5	PAS-EXO-12-048
monojet+MET	8	10.5	CONF-2012-147
2-6 jets+MET	7	4.7	CONF-2012-033
6-9 jets+MET	7	4.7	CONF-2012-037
jets+MET	7	4.98	arXiv:1207.1898
jets+MET (old)	7	1.1	PAS-SUS-11-004
b+jets+MET	7	2.05	arXiv:1203.6193
b+jets+MET	7	4.98	arXiv:1208.4859
b+jets+MET (old)	7	1.1	PAS-SUS-11-006
$3b$+jets+MET	7	4.7	CONF-2012-058
jets w/α_T w/b	7	4.98	PAS-SUS-11-022
jets w/α_T (old)	7	1.14	arXiv:1109.2352
ℓ+b+jets (low MET)*	7	5.0	arXiv:1210.7471
ℓ+$3b$+jets (low MET)	8	14.3	CONF-2013-018
6 jets (no MET)	7	4.6	arXiv:1210.4813
up to 10 objects ("BH")	8	12.1	arXiv:1303.5338
$(\mu j)(\mu j)$	8	19.6	PAS-EXO-12-042
$(\tau b)(\tau b)$	7	4.8	PAS-EXO-12-002

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SS DIL+MET	8	5.8	CONF-2012-105
SS DIL w/b (SUSY)	8	20.7	CONF-2013-007
SS DIL w/b (Exo.)	8	14.3	CONF-2013-051
SS DIL w/b	8	10.5	arXiv:1212.6194
SS DIL	7	4.98	arXiv:1205.6615
SS DIL w/b	7	4.98	arXiv:1205.3933
SSSF DIL	7	4.98	arXiv:1207.6079
SSSF DIL	7	1.6	arXiv:1201.1091
SS DIL	7	4.7	arXiv:1210.4538
SS DIL+jets+MET	7	2.05	arXiv:1203.5763
SS DIL+MET	7	1.04	arXiv:1110.6189
b' (SS DIL)	7	4.7	CONF-2012-130
b' (SS DIL)	7	4.9	arXiv:1204.1088
OS DIL+MET	7	1.04	arXiv:1110.6189
OS DIL+jets+MET	7	4.7	arXiv:1208.4688
OS DIL+MET	7	4.98	arXiv:1206.3949
leptonic m_{T2}	7	4.7	arXiv:1209.4186
Z+jets+MET	7	4.98	arXiv:1204.3774
Z+jets+MET	7	2.05	arXiv:1204.6736

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
ℓ+jets+MET	8	5.8	CONF-2012-104
ℓ+b+$6j$+MET	8	19.4	PAS-SUS-13-007
$(\mu j)(\nu j)$	8	19.6	PAS-EXO-12-042
ℓ+$7j$+MET	7	4.7	CONF-2012-140
ℓ+jets+MET	7	4.7	PAS-SUS-12-010
ℓ+jets+MET	7	4.7	CONF-2012-041
ℓ+b+jets+MET	7	2.05	arXiv:1203.6193
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-027
ℓ+b+jets+MET	7	4.98	PAS-SUS-11-028
$1/2\tau$+jets+MET	8	20.7	CONF-2013-026
4ℓ+MET w/τ	8	20.7	CONF-2013-036
3-4ℓ w/τ	8	19.5	PAS-SUS-13-003
$1/2\tau$+jets+MET	7	4.7	arXiv:1210.1314
τ+ℓ+jets+MET	7	4.7	arXiv:1210.1314
τ+jets+MET (old)	7	2.05	CONF-2012-005
2τ+jets+MET (old)	7	2.05	arXiv:1203.6580
OS DIL+MET w/τ	7	4.98	arXiv:1206.3949
SS DIL w/τ	7	4.98	arXiv:1205.6615
3-4ℓ w/1τ	7	4.98	arXiv:1204.5341
3-4ℓ w/2τ	7	4.98	arXiv:1204.5341
$t\bar{t}$ xsec (DIL)	8	2.4	PAS-TOP-12-007
$t\bar{t}$ xsec (DIL)	7	0.70	arXiv:1202.4892
$t\bar{t}$ xsec (DIL)	7	2.3	arXiv:1208.2671
$t\bar{t}$ xsec (DIL w/τ)	7	~ 2	arXiv:1203.6810
$t\bar{t}$+jet (LJ)	7	5.0	PAS-EXO-11-056
$t\bar{t}$+m_T (LJ)	7	1.04	arXiv:1109.4725

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
2-6 jets+MET	8	20.3	CONF-2013-047
2-6 jets+MET (old)	8	5.8	CONF-2012-109
7-10 jets+MET w/b	8	20.3	CONF-2013-054
7-10 jets+MET w/M_J^Σ	8	20.3	CONF-2013-054
6-9 jets+MET	8	5.8	CONF-2012-103
b+jets+MET	8	19.4	arXiv:1305.2390
$3b$+jets+MET	8	12.8	CONF-2012-145
jets w/α_T w/b	8	11.7	arXiv:1303.2985
monojet+MET	8	19.5	PAS-EXO-12-048
monojet+MET	8	10.5	CONF-2012-147
2-6 jets+MET	7	4.7	CONF-2012-033
6-9 jets+MET	7	4.7	CONF-2012-037
jets+MET	7	4.98	arXiv:1207.1898
jets+MET (old)	7	1.1	PAS-SUS-11-004
b+jets+MET	7	2.05	arXiv:1203.6193
b+jets+MET	7	4.98	arXiv:1208.4859
b+jets+MET (old)	7	1.1	PAS-SUS-11-006
$3b$+jets+MET	7	4.7	CONF-2012-058
jets w/α_T w/b	7	4.98	PAS-SUS-11-022
jets w/α_T (old)	7	1.14	arXiv:1109.2352
ℓ+b+jets (low MET)*	7	5.0	arXiv:1210.7471
ℓ+$3b$+jets (low MET)	8	14.3	CONF-2013-018
6 jets (no MET)	7	4.6	arXiv:1210.4813
up to 10 objects ("BH")	8	12.1	arXiv:1303.5338
$(\mu j)(\mu j)$	8	19.6	PAS-EXO-12-042
$(\tau b)(\tau b)$	7	4.8	PAS-EXO-12-002

Especially interesting!

ℓ + b + jets (low MET)

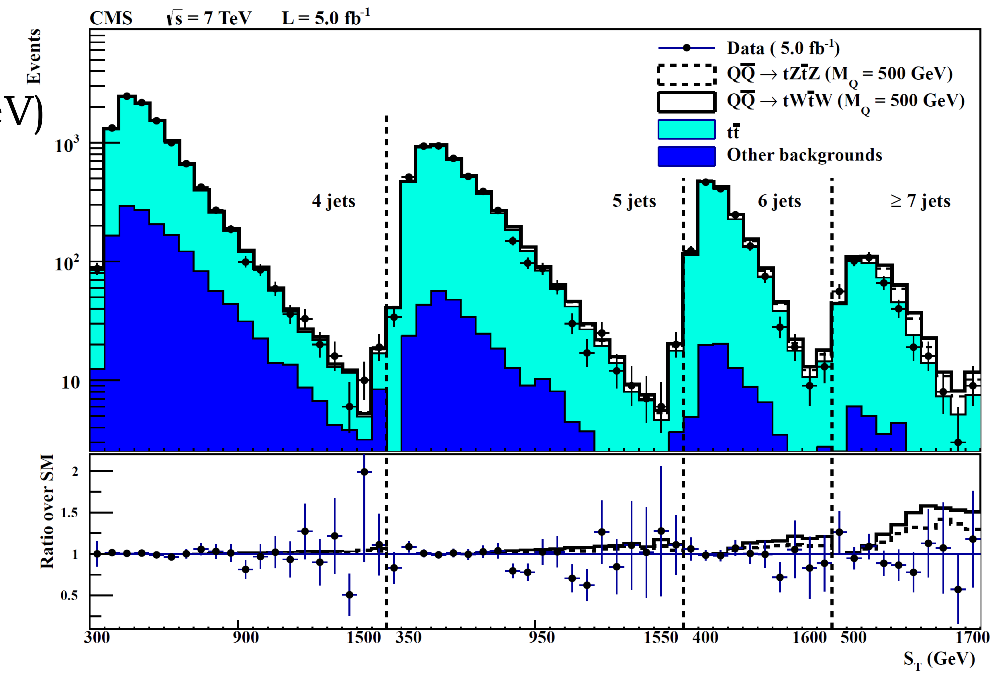
CMS-PAS-B2G-12-004, arXiv:1210.7471 (5/fb at 7 TeV)

a.k.a.

Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at $\sqrt{s} = 7$ TeV

Selection

- Exactly 1 lepton ($p_T^e > 35$ GeV, $p_T^\mu > 42$ GeV)
- Jets with $p_T > 100, 60, 50, 35$ GeV
- $N_{\text{jets}} = 4, 5, 6, 7+$ (with $p_T > 35$ GeV)
- MET > 20 GeV
- 1+ b-tags
- S_T distributions (incl. lepton, jets, MET)



cf. Searches for lepton(s) + many jets
Lisanti, Schuster, Strassler, Toro (arXiv:1107.5055)

Interpretation difficulties / limitations

- **Systematic uncertainties** per S_T bin not provided
- Would like to use **higher S_T** (for gluinos), as high as it goes in the data
- Would like to use **higher N_{jet}** bins (for stops and gluinos)

$\ell + b$ + jets (low MET)

CMS-PAS-B2G-12-004, arXiv:1210.7471 (5/fb at 7 TeV)

a.k.a.

> Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

Selection

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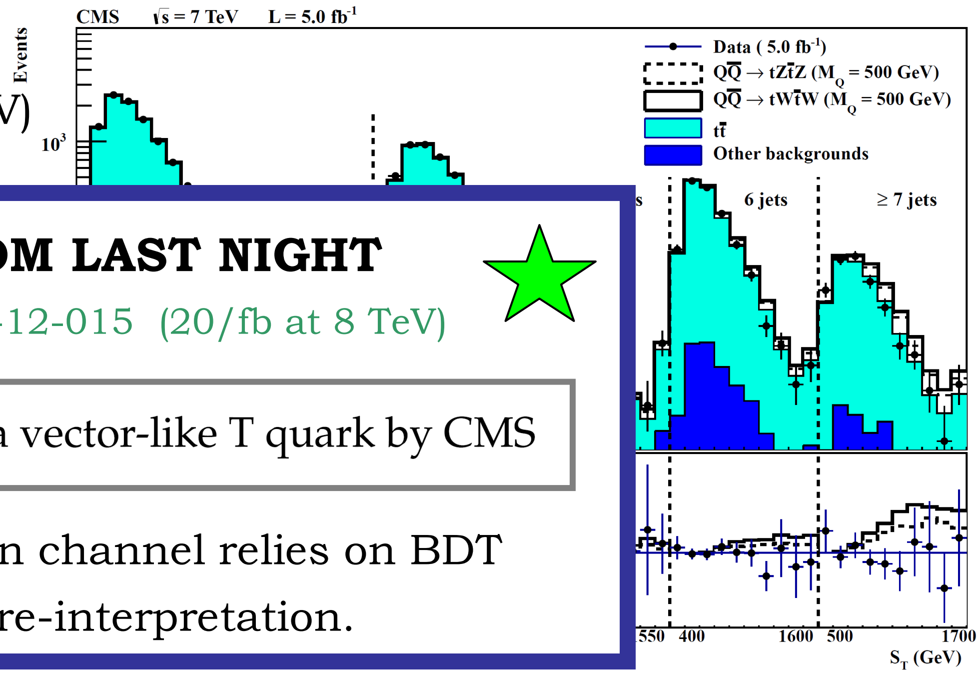
- 1+ b-tags
- S_T distributions (incl. lepton, jets, M



cf. Searches for lepton(

Lisanti, Schuster, Strassler,

NEW FROM LAST NIGHT

CMS-PAS-B2G-12-015 (20/fb at 8 TeV)

> Inclusive search for a vector-like T quark by CMS

However, single-lepton channel relies on BDT so we can't use it for re-interpretation.

Interpretation difficulties / limitations

- **Systematic uncertainties** per S_T bin not provided
- Would like to use **higher S_T** (for gluinos), as high as it goes in the data
- Would like to use **higher N_{jet}** bins (for stops and gluinos)

$\ell + b$ + jets (low MET)

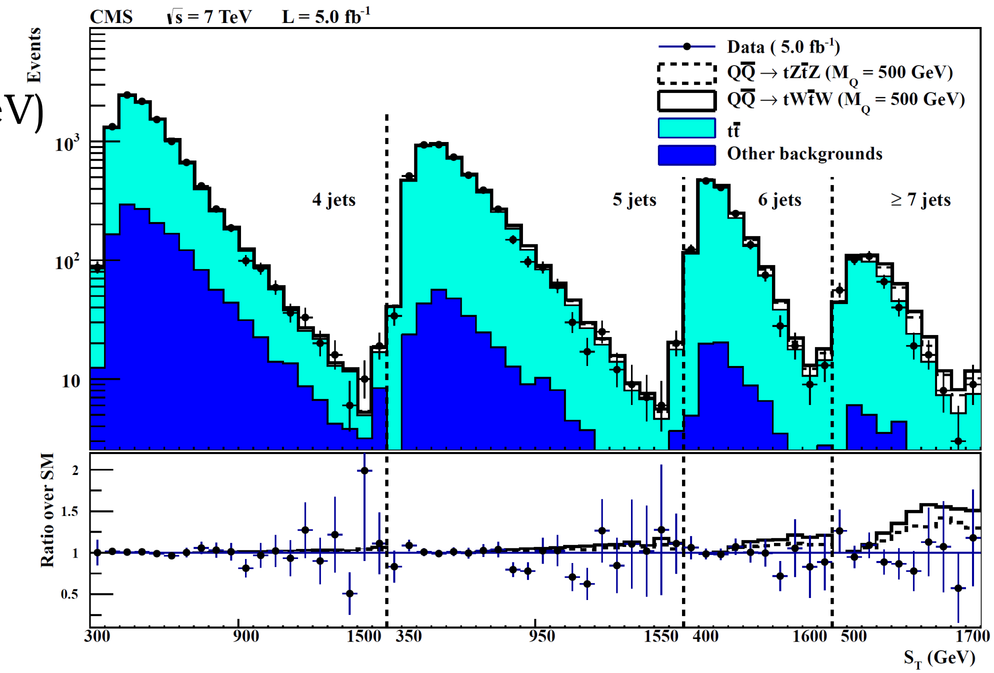
CMS-PAS-B2G-12-004, arXiv:1210.7471 (5/fb at 7 TeV)

a.k.a.

Search for heavy quarks decaying into a top quark and a W or Z boson using lepton + jets events in pp collisions at $\sqrt{s} = 7$ TeV

Selection

- Exactly 1 lepton ($p_T^e > 35$ GeV, $p_T^\mu > 42$ GeV)
- Jets with $p_T > 100, 60, 50, 35$ GeV
- $N_{\text{jets}} = 4, 5, 6, 7+$ (with $p_T > 35$ GeV)
- MET > 20 GeV
- 1+ b-tags
- S_T distributions (incl. lepton, jets, MET)



cf. Searches for lepton(s) + many jets
Lisanti, Schuster, Strassler, Toro (arXiv:1107.5055)

Interpretation difficulties / limitations

- **Systematic uncertainties** per S_T bin not provided
- Would like to use **higher S_T** (for gluinos), as high as it goes in the data
- Would like to use **higher N_{jet}** bins (for stops and gluinos)

ℓ + b + jets (low MET)

Our extension to 20/fb at 8 TeV

Selection

Same as in CMS search:

- Leptons, jets, MET, b-tagging

Different from CMS search:

- N_{jets} = 4+, 5+, 6+, 7+, 8+, 9+
- $S_T > S_T^{\max}$, with $S_T^{\max}$ = 400, 600, 800, …, 3000

Background estimation

$t\bar{t}$ + jets: ALPGEN + Pythia (matched up to 4 extra jets)

S_T distributions for 7 TeV agree with CMS if we normalize by 1.6.
Same factor applied to 8 TeV distributions.

Systematic uncertainties

Tentatively assume 25% (similar to ATLAS search from next slide)

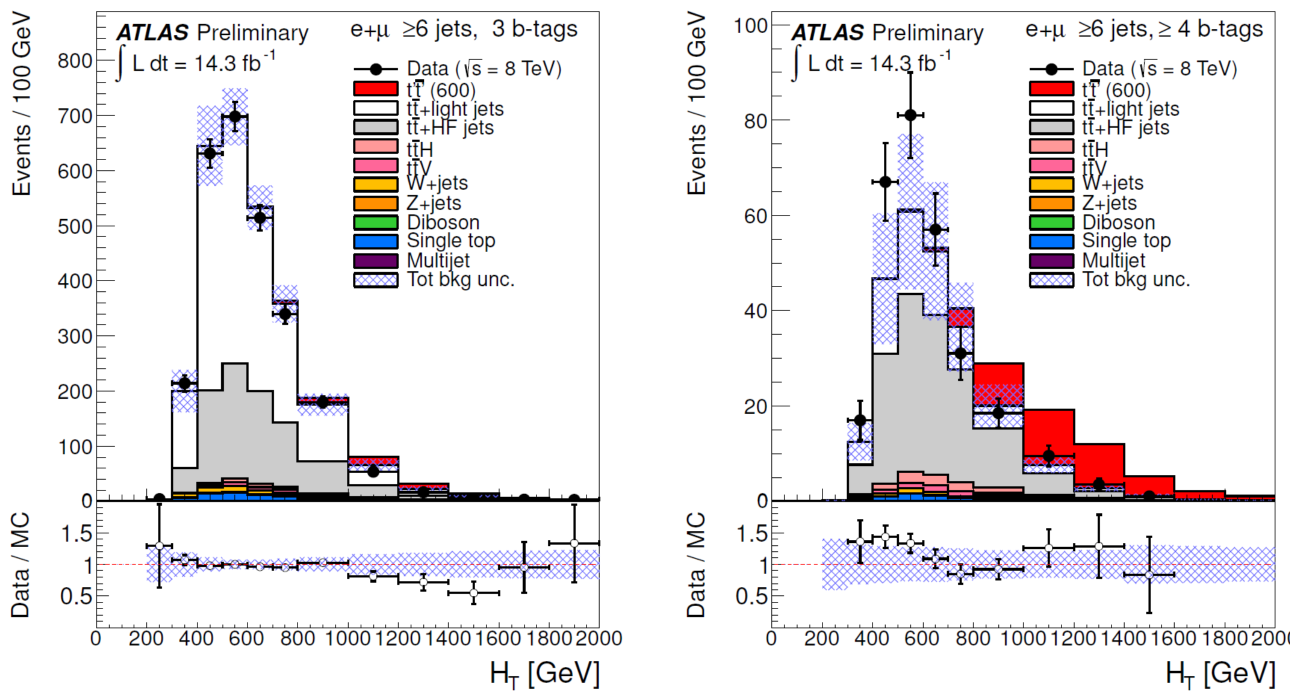
$\ell + 3b$ + jets (low MET)

ATLAS-CONF-2013-018 (14.3/fb at 8 TeV)

a.k.a. **Search for heavy top-like quarks decaying to a Higgs boson and a top quark in the lepton plus jets final state in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector**

Selection

- Exactly 1 lepton with $p_T > 25$ GeV
- 6+ jets with $p_T > 25$ GeV
- MET > 20 GeV
- MET + $m_T > 60$ GeV
- 3 or 4+ b-tags
- H_T distributions (incl. lepton, jets, MET)



We defined search regions as: $H_T > 800, 1000, 1200, 1400, 1600, 1800$ GeV

6 jets (no MET)

ATLAS, arXiv:1210.4813 (4.6/fb at 7 TeV)

a.k.a. **Search for pair production of massive particles decaying into three quarks with the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions at the LHC**

We restrict ourselves to the "Resolved analysis" part of this search.

Selection

- 6+ jets with $p_T > 80$ (or 120, or 160) GeV

In our context

Would be useful to include regions with:

- Higher jets multiplicities
- *b*-tagging

Up to 10 objects ("BH")

CMS, arXiv:1303.5338 (12.1/fb at 8 TeV)

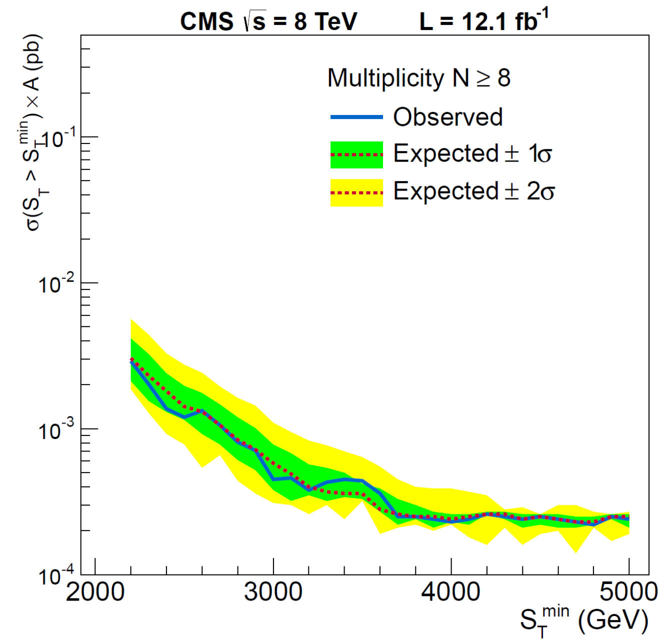
a.k.a. **Search for microscopic black holes in pp collisions at $\sqrt{s} = 8\,\text{TeV}$**

Selection

- At least N objects (jets, leptons, photons) with p_T > 50 GeV where N = 3+, 4+, …, 10+
- S_T distributions (incl. those objects + MET, if > 50 GeV)

Background estimation

- Shape taken from N = 2
- Normalization (for each N) fixed by the control region 1.9 TeV < S_T < 2.3 TeV



In our context

Unfortunately, not applicable for masses below ~1 TeV due to control region contamination, tail uncertainty

$(\mu j)(\mu j)$

CMS-PAS-EXO-12-042 (19.6/fb at 8 TeV)

a.k.a. **Search for pair production of second-generation scalar leptoquarks in pp collisions at $\sqrt{s} = 8$ TeV with the CMS Detector**

Selection

- 2 muons
- Two leading jets $p_T > 125, 45$ GeV
- Cuts on S_T (2 muons + 2 jets), $M_{\mu\mu}$, $M_{\min}(\mu, \text{jet})$
  with different thresholds for each leptoquark (LQ) mass:

M_{LQ} (GeV)	300	350	400	450	500	550	600	650	700	750	800	850	900	950	$\geq$1000
$S_T >$ (GeV)	380	460	540	615	685	755	820	880	935	990	1040	1090	1135	1175	1210
$M_{\mu\mu} >$ (GeV)	100	115	125	140	150	165	175	185	195	205	215	220	230	235	245
$M_{min}(\mu, \text{jet}) >$ (GeV)	115	115	120	135	155	180	210	250	295	345	400	465	535	610	690

In our context

- Relevant to 2 muons + *many* jets scenarios, e.g., $\tilde{t} \to \mu bbq$
  Will use each LQ mass as a search region (for stops of any mass).
- Accounting for higher jet multiplicity and/or using b-tagging, could be beneficial.
  Same for 1$^{\text{st}}$ and 3$^{\text{rd}}$ generation LQ searches (not yet public with 8 TeV)

Simulation and limit setting

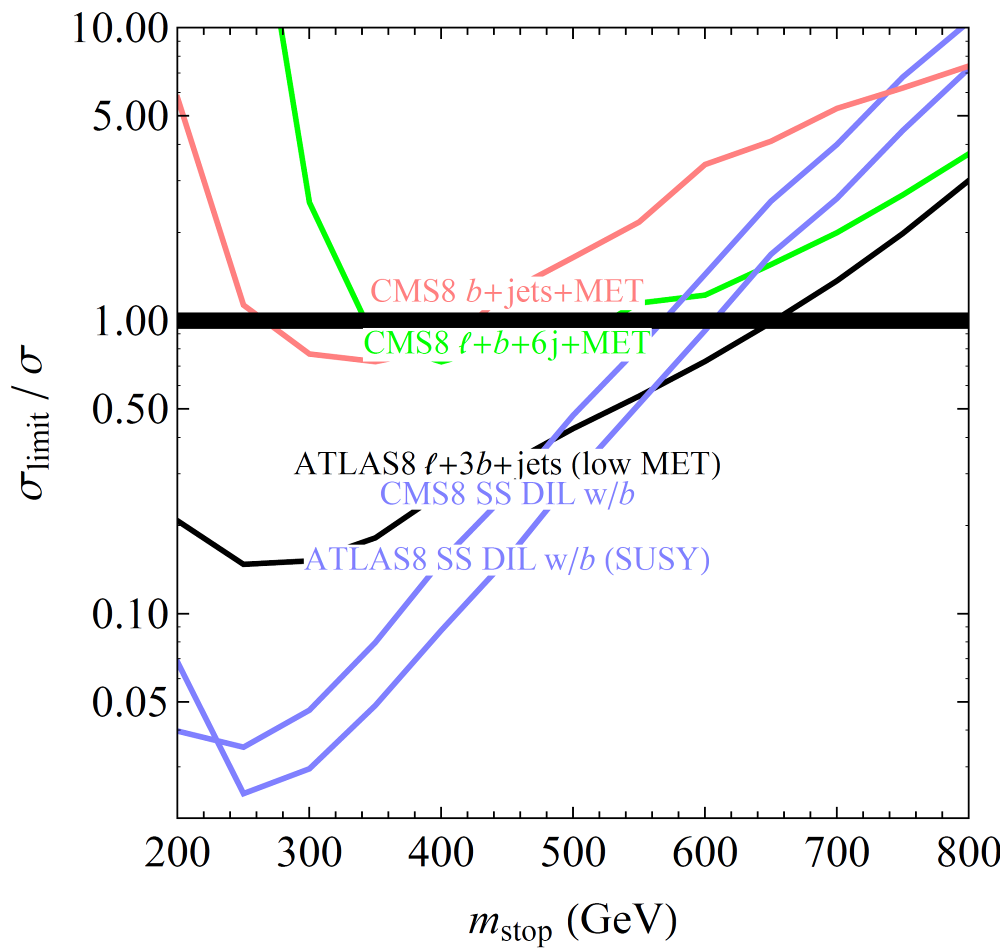
- Detector simulation (incl. FastJet), with:
  - Lepton ID eff. (per search)
  - Lepton isolation (per search)
  - Jet energy resolution
  - *b*-tagging (per search)
  - and more…
- Cuts of ATLAS and CMS searches from the table
- Validation on examples from ATLAS and CMS papers: typically agree within ~30% (sometimes a factor of ~2)
- Efficiency threshold ~ 10^{-3} (instead of including systematic uncertainty for the signal tails)

  Typically has an effect for very low masses.
- Use backgrounds (and uncertainties) from the collaborations to derive limits. Search region with the best limit is used.

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq,\ \nu bbq$	$etbq,\ \nu tbq$
	321	$(\tilde{\nu}_\tau,\ \tilde{\tau})_L$	τbqq	τbqq
	323	$\tilde{b}_R$	$\tau bbq,\ \nu bbq$	$\tau tbq,\ \nu tbq$
		$(\tilde{\nu}_\tau,\ \tilde{\tau})_L$	τbbq	τbbq
	232	$\tilde{t}_L$	μtbq	μbbq
		$\tilde{b}_L$	νbbq	νtbq
	233	$\tilde{t}_L$	μtbb	μbbb
		$\tilde{b}_L$	νbbb	νtbb
	332	$\tilde{t}_L$	τtbq	τbbq
		$\tilde{b}_L$	νbbq	νtbq
	333	$\tilde{t}_L$	τtbb	τbbb
		$\tilde{b}_L$	νbbb	νtbb
UDD	213	$\tilde{b}_R$	$bbqq$	$tbqq$
	312	$\tilde{t}_R$	$tbqq$	$bbqq$
	323	$\tilde{t}_R$	$tbbq$	$bbbq$

Now let's look at some results!

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq,\ \nu bbq$	$etbq,\ \nu tbq$
	321	$(\tilde{\nu}_\tau,\ \tilde{\tau})_L$	τbqq	τbqq
	323	$\tilde{b}_R$	$\tau bbq,\ \nu bbq$	$\tau tbq,\ \nu tbq$
		$(\tilde{\nu}_\tau,\ \tilde{\tau})_L$	τbbq	τbbq
	232	$\tilde{t}_L$	μtbq	μbbq
		$\tilde{b}_L$	νbbq	νtbq
	233	$\tilde{t}_L$	μtbb	μbbb
		$\tilde{b}_L$	νbbb	νtbb
	332	$\tilde{t}_L$	τtbq	τbbq
		$\tilde{b}_L$	νbbq	νtbq
	333	$\tilde{t}_L$	τtbb	τbbb
		$\tilde{b}_L$	νbbb	νtbb
UDD	213	$\tilde{b}_R$	$bbqq$	$tbqq$
	312	$\tilde{t}_R$	$tbqq$	$bbqq$
	323	$\tilde{t}_R$	$tbbq$	$bbbq$



Even though MET and SS dileptons are available, the lepton + many jets search (essentially without a MET requirement) sets the best limit at high masses.

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq$, νbbq	$etbq$, νtbq
	321	$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbqq	τbqq
	323	$\tilde{b}_R$	τbbq, νbbq	τtbq, νtbq
		$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbbq	τbbq
	232	$\tilde{t}_L$	μtbq	μbbq
		$\tilde{b}_L$	νbbq	νtbq
	233	$\tilde{t}_L$	μtbb	μbbb
		$\tilde{b}_L$	νbbb	νtbb
	332	$\tilde{t}_L$	τtbq	τbbq
		$\tilde{b}_L$	νbbq	νtbq
	333	$\tilde{t}_L$	τtbb	τbbb
		$\tilde{b}_L$	νbbb	νtbb
UDD	213	$\tilde{b}_R$	$bbqq$	$tbqq$
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Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq$, νbbq	$etbq$, νtbq
	321	$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbqq	τbqq
	323	$\tilde{b}_R$	τbbq, νbbq	τtbq, νtbq
		$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbbq	τbbq
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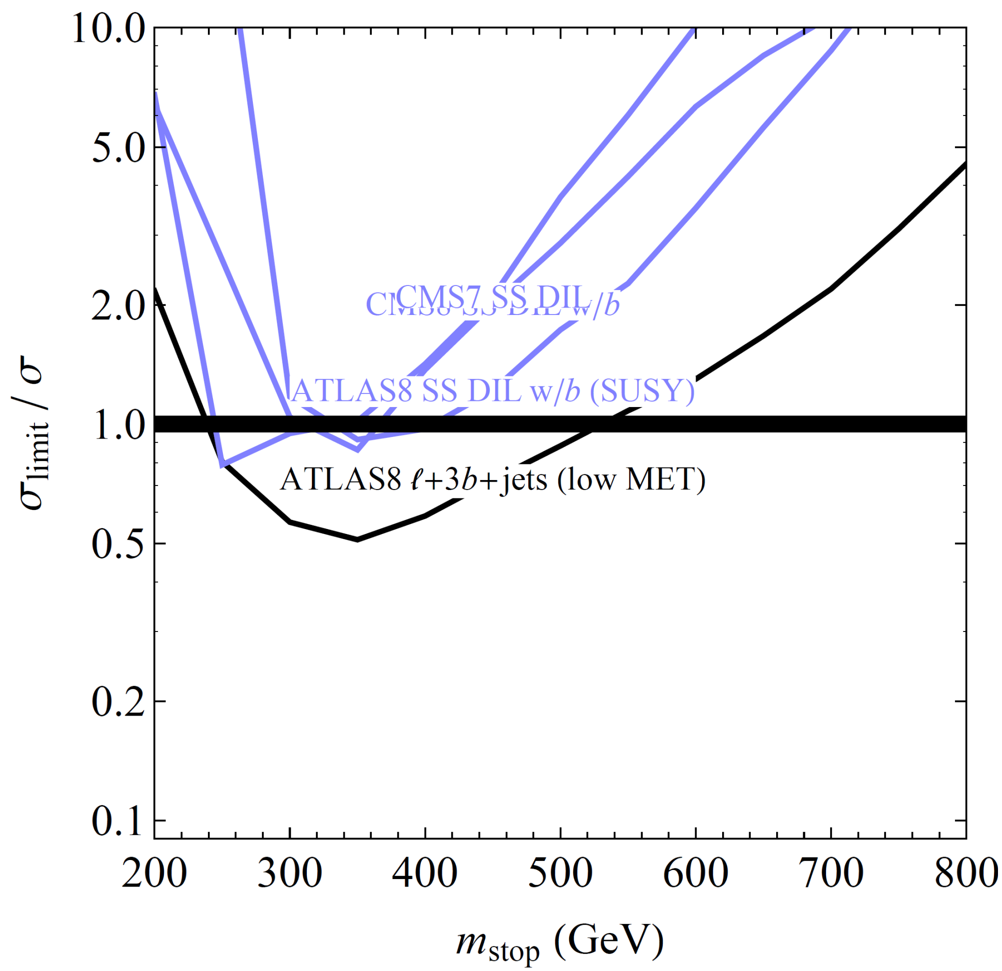
	323	$\tilde{t}_R$	$tbbq$	$bbbq$



The lepton + many jets search is good also at utilizing leptons from tau decays.

Can it be optimized for lower masses?

<table>
<tr><th colspan="3">Scenario</th><th colspan="2">Final state (for each stop)</th></tr>
<tr><th colspan="2">Coupling</th><th>Mediator $\tilde{f}$</th><th>Case 1</th><th>Case 2</th></tr>
<tr><td rowspan="9">LQD</td><td>123</td><td>$\tilde{b}_R$</td><td>$ebbq$, νbbq</td><td>$etbq$, νtbq</td></tr>
<tr><td>321</td><td>$(\tilde{\nu}_\tau, \tilde{\tau})_L$</td><td>$\tau bqq$</td><td>$\tau bqq$</td></tr>
<tr><td>323</td><td>$\tilde{b}_R$
$(\tilde{\nu}_\tau, \tilde{\tau})_L$</td><td>$\tau bbq$, νbbq
τbbq</td><td>τtbq, νtbq
τbbq</td></tr>
<tr><td>232</td><td>$\tilde{t}_L$
$\tilde{b}_L$</td><td>μtbq
νbbq</td><td>μbbq
νtbq</td></tr>
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$\tilde{b}_L$</td><td>μtbb
νbbb</td><td>μbbb
νtbb</td></tr>
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$\tilde{b}_L$</td><td>τtbq
νbbq</td><td>τbbq
νtbq</td></tr>
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$\tilde{b}_L$</td><td>τtbb
νbbb</td><td>τbbb
νtbb</td></tr>
<tr><td rowspan="3">UDD</td><td>213</td><td>$\tilde{b}_R$</td><td>$bbqq$</td><td>$tbqq$</td></tr>
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</table>

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
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	321	$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbqq	τbqq
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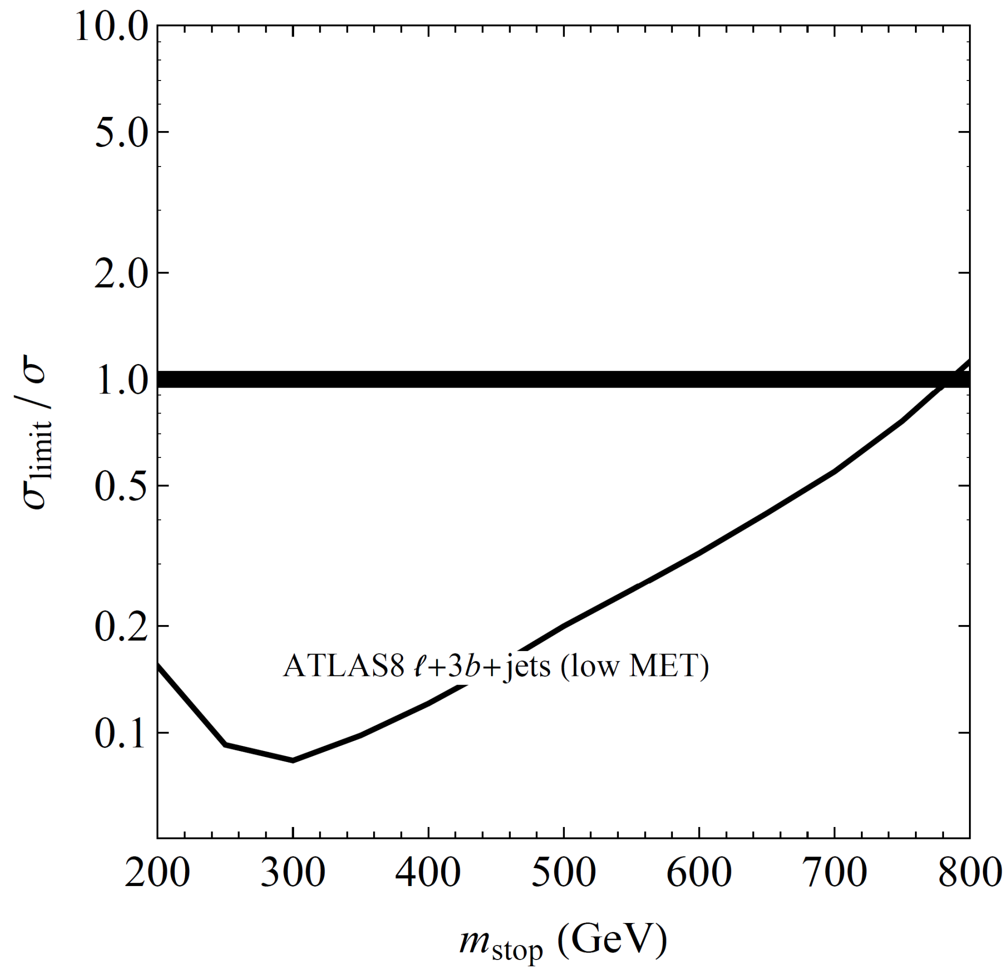

The search becomes even more powerful when more b's are present.

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq$, νbbq	$etbq$, νtbq
	321	$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbqq	τbqq
	323	$\tilde{b}_R$	τbbq, νbbq	τtbq, νtbq
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Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
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	323	$\tilde{b}_R$ $(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbbq, νbbq τbbq	τtbq, νtbq τbbq
	232	$\tilde{t}_L$ $\tilde{b}_L$	μtbq νbbq	μbbq νtbq
	233	$\tilde{t}_L$ $\tilde{b}_L$	μtbb νbbb	μbbb νtbb
	332	$\tilde{t}_L$ $\tilde{b}_L$	τtbq νbbq	τbbq νtbq
	333	$\tilde{t}_L$ $\tilde{b}_L$	τtbb νbbb	τbbb νtbb
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	312	$\tilde{t}_R$	$tbqq$	$bbqq$
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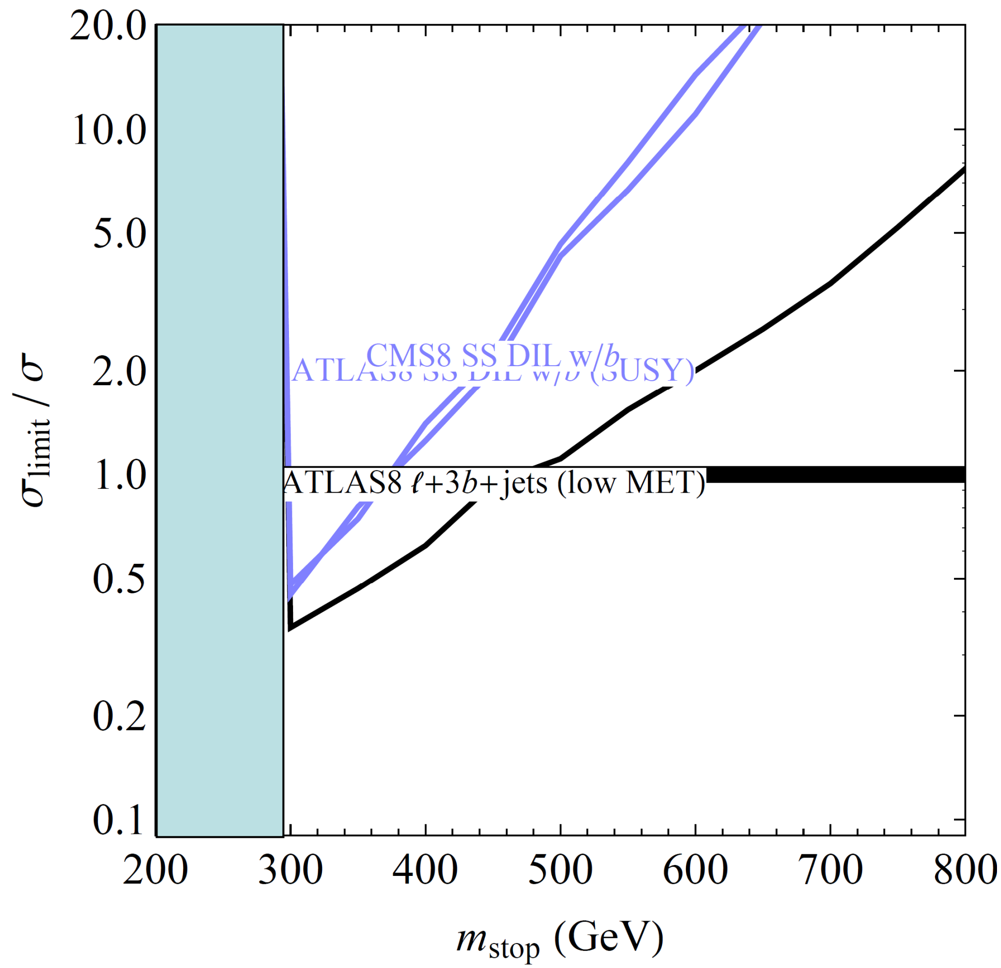

Powerful also when leptons are coming from tops.

Could be strengthened by bins with more than 6 jets (the events contain 10 parton-level jets).

Scenario			Final state (for each stop)	
Coupling		Mediator $\tilde{f}$	Case 1	Case 2
LQD	123	$\tilde{b}_R$	$ebbq$, νbbq	$etbq$, νtbq
	321	$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbqq	τbqq
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		$(\tilde{\nu}_\tau, \tilde{\tau})_L$	τbbq	τbbq
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		$\tilde{b}_L$	νbbq	νtbq
	233	$\tilde{t}_L$	μtbb	μbbb
		$\tilde{b}_L$	νbbb	νtbb
	332	$\tilde{t}_L$	τtbq	τbbq
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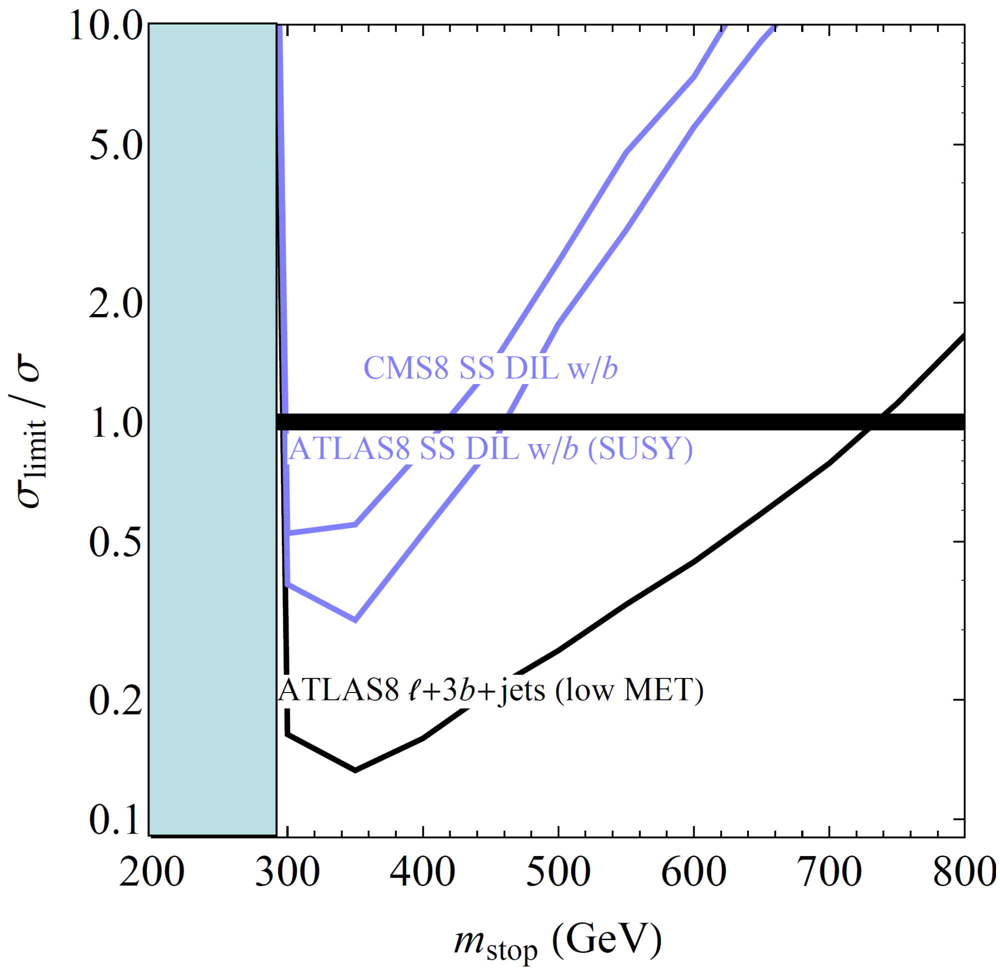

Again, even stronger limit in a more b-rich scenario.

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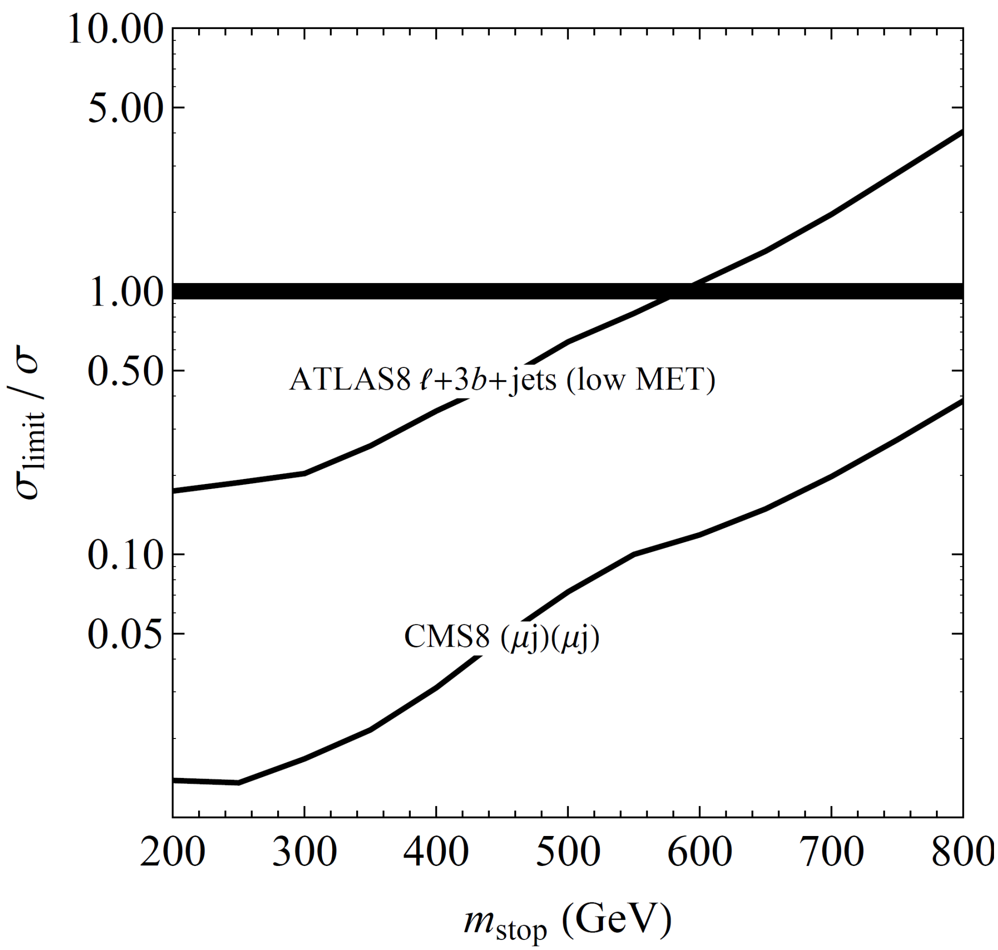

- The lepton + many jets search is effective despite needing to lose the 2nd muon
- An analogous "OS dilepton + many jets" search would be extremely powerful
- Even the LQ search sets very strong limits, despite its 2-body motivations and not using the high *b* multiplicity

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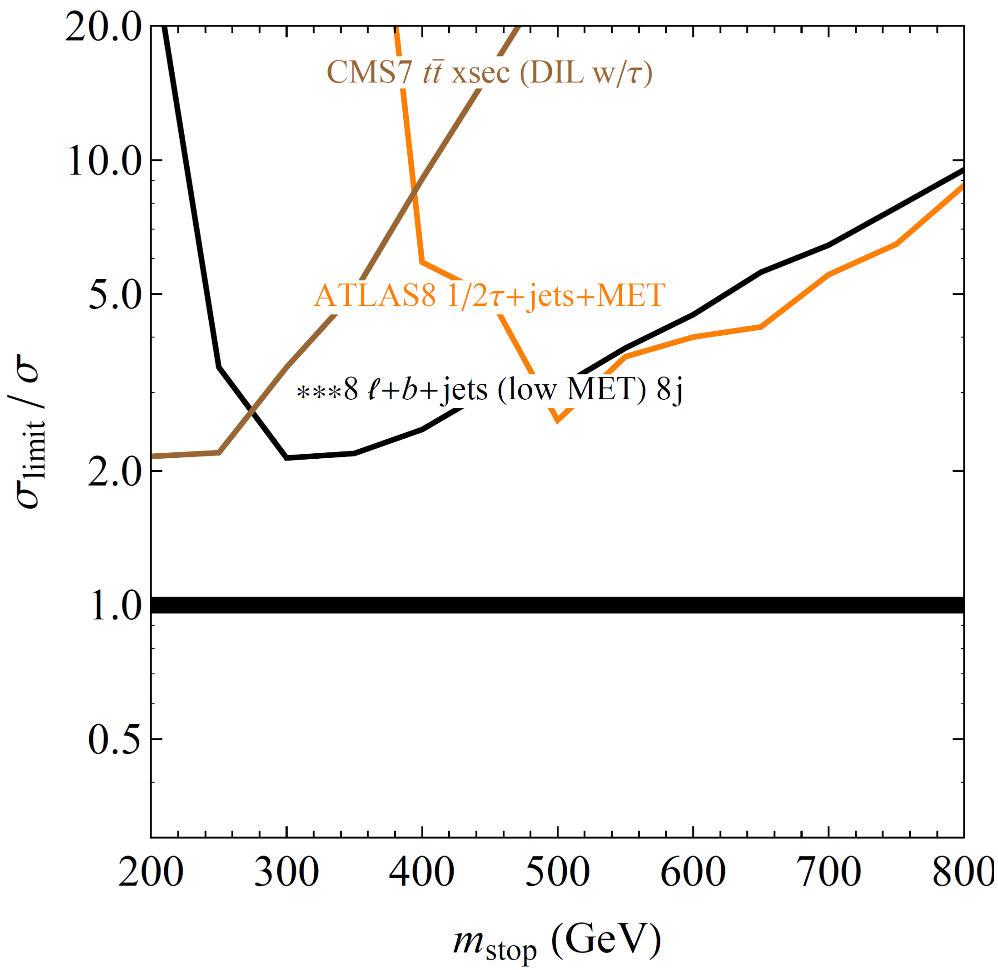

- Our 8 TeV extension of CMS lepton + many jets is not sufficiently strong here. Ideas for a better search:
  - "lepton + τ_h + many jets" analogous to "lepton + many jets"
  - τ_h (+ τ_h/ℓ) + jets + MET, but with b-tagging and lower MET cuts
  - Generalization of LQ3 search, $(\tau b)(\tau b)$
- Low masses: $t\bar{t}$ xsec w/ $\ell + \tau_h$ (with only 2/fb at 7 TeV) better than all searches! Construct search based on $t\bar{t}$ xsec measurement (use high jet multiplicity)

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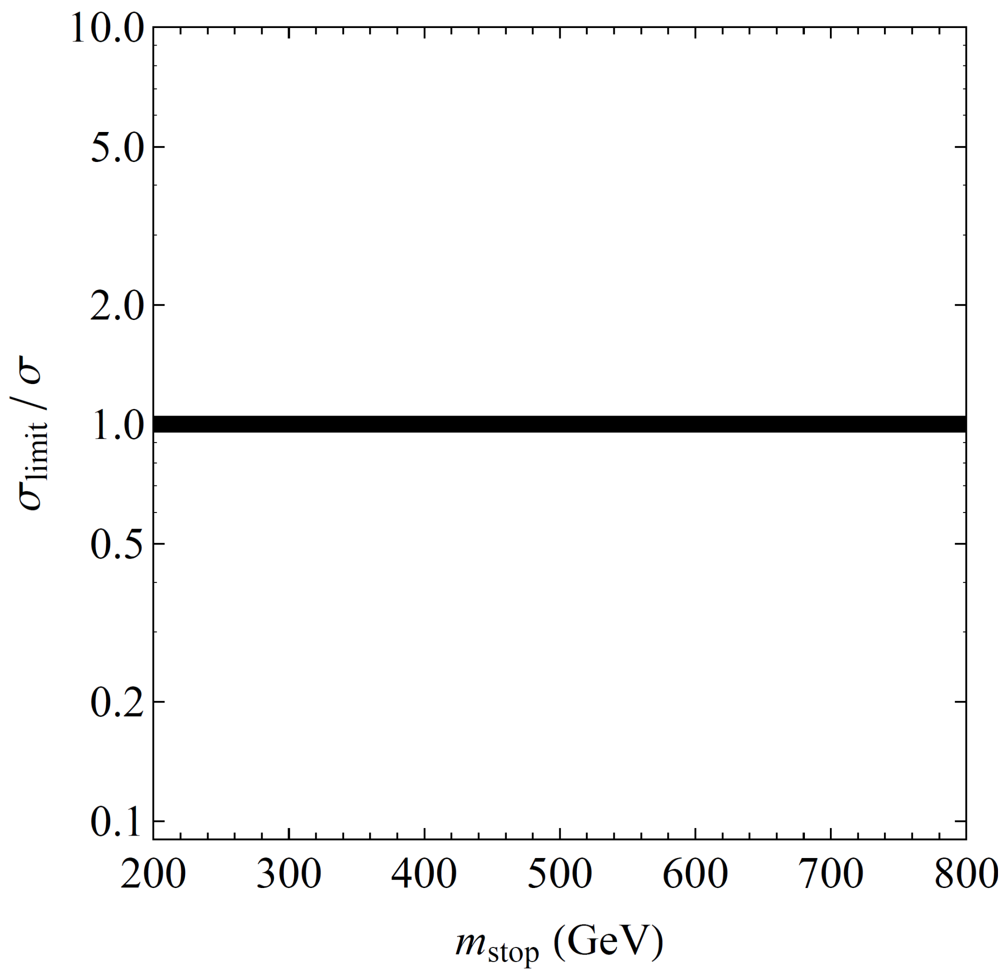


- No limits from existing searches
- Events with 6 b-jets!
- Resonant structures are present

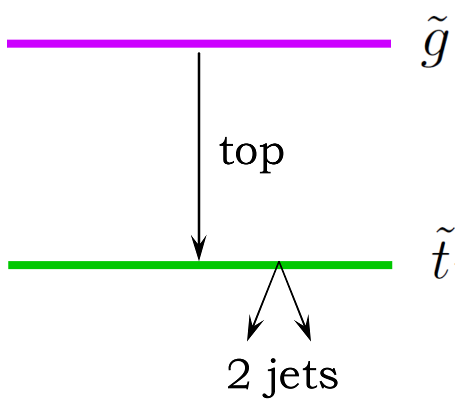
Models with gluino production

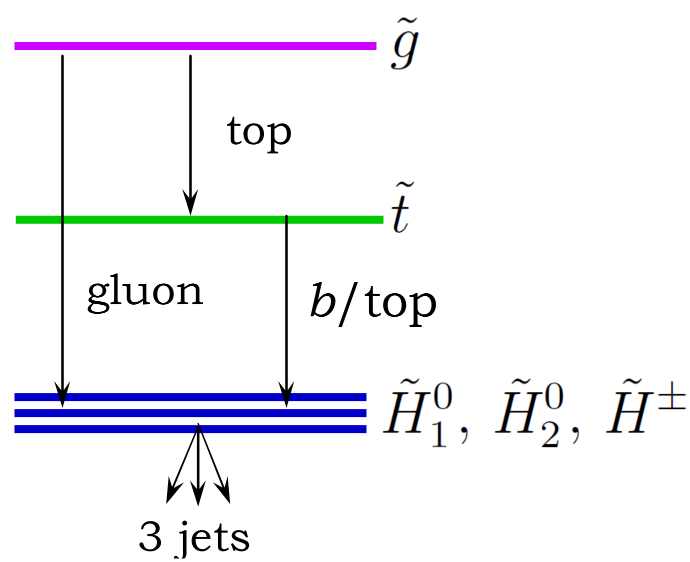
- Gluinos are hard to miss:
  – Large cross sections
  – Multi-object cascade decays

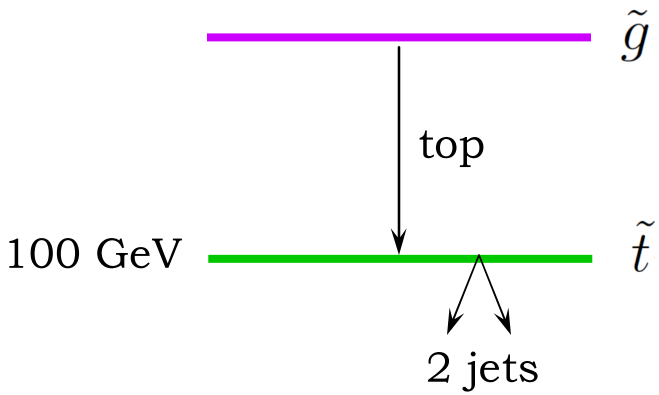
- If higgsinos are light, the LSP (higgsino or another particle) is light
  ⇨ Gluino mass limits ~1 TeV in RPC models studied by ATLAS + CMS
  ⇨ Difficult to imagine *any* RPC scenario with much weaker limits
  Evans, Kats, Shih, Strassler (work in progress)

- RPV couplings with leptons can't hide gluinos.
  Remaining possibility: UDD

- Two examples of simplified models with UDD





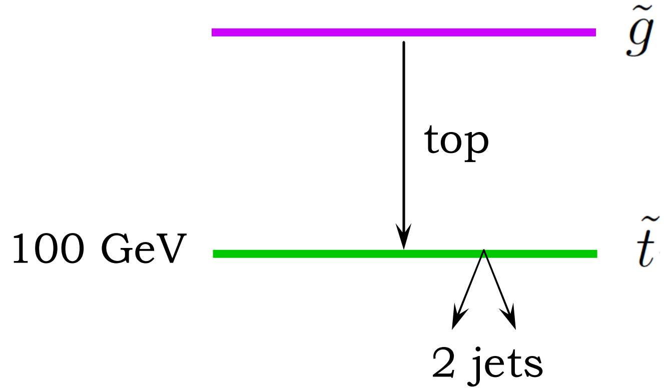


Production: $pp \rightarrow \tilde{g}\tilde{g}$

Decays: $\tilde{g} \rightarrow \tilde{t}\,\overline{t}$ or $\tilde{t}^{*}t$

$\tilde{t} \rightarrow \overline{d}\,\overline{s}$ (via UDD312)

Final state: 2 tops + 4 jets



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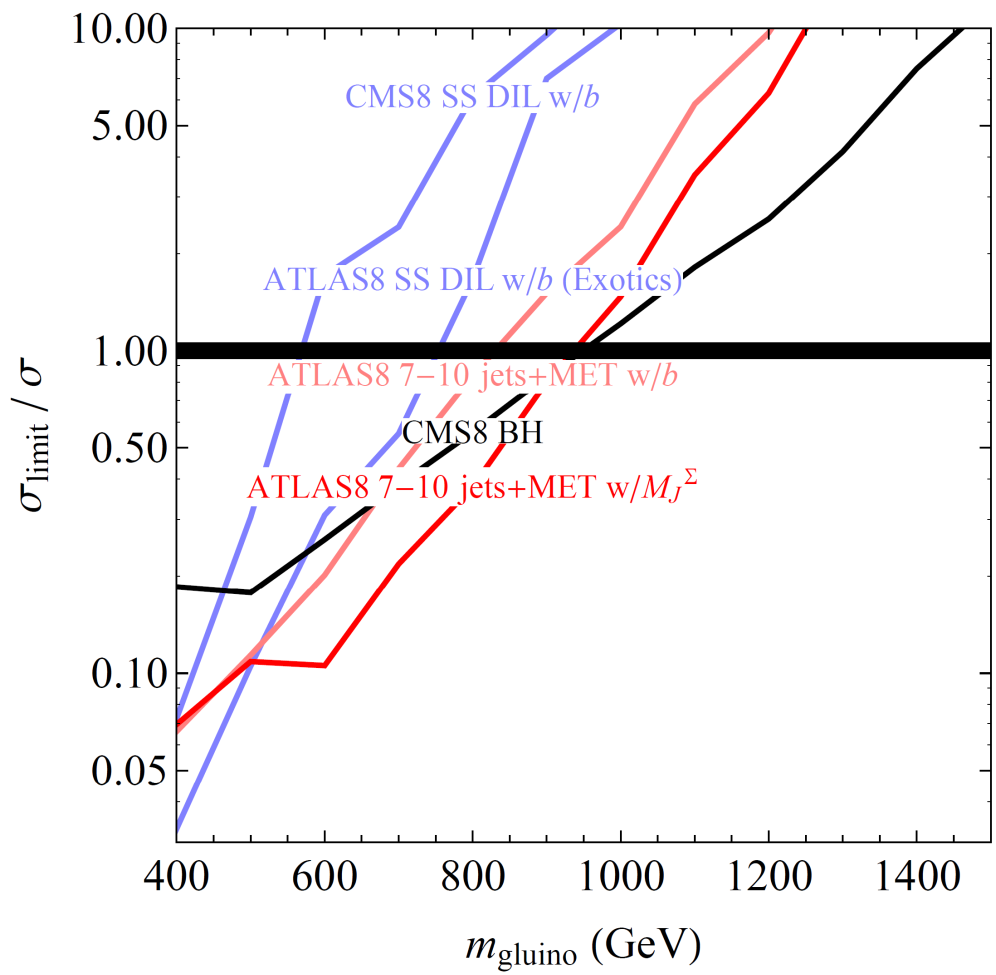
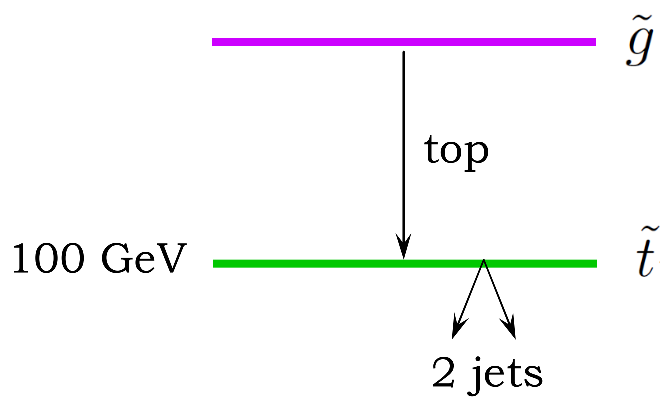


Naively, some searches set limits. But their interpretation is problematic!



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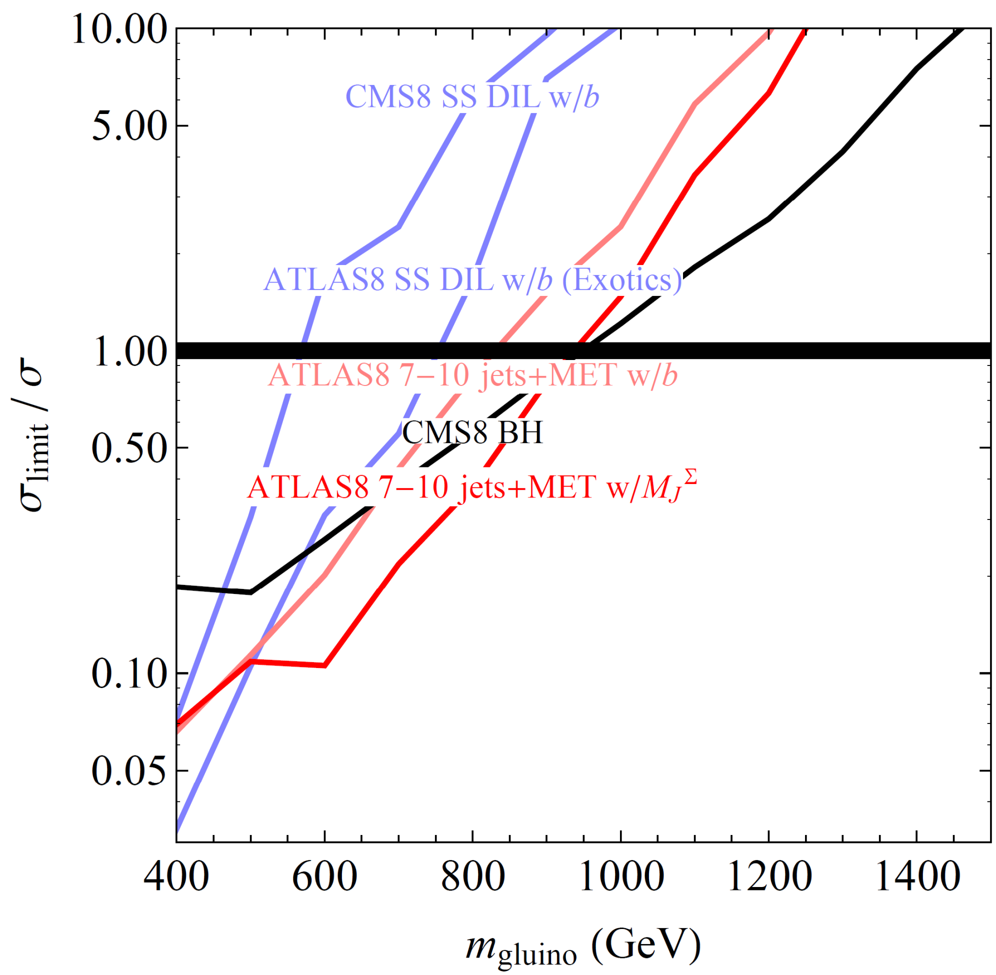
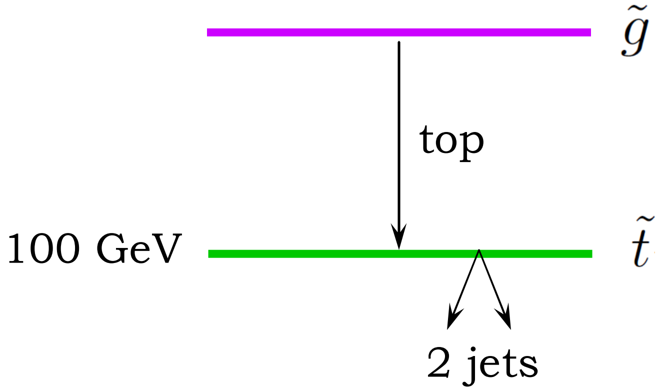


Naively, some searches set limits. But their interpretation is problematic:

- Neutrinos (MET) appear together with leptons. So limits from 7-10 jets+MET rely on evading the lepton veto (hadronic tau or isolation/ID efficiency/...). Subtle!
- Black holes search cannot be used below ~1 TeV due to control region contamination.
- SS dilepton limits are weak, and would not apply at all for SUSY with Dirac gluinos.



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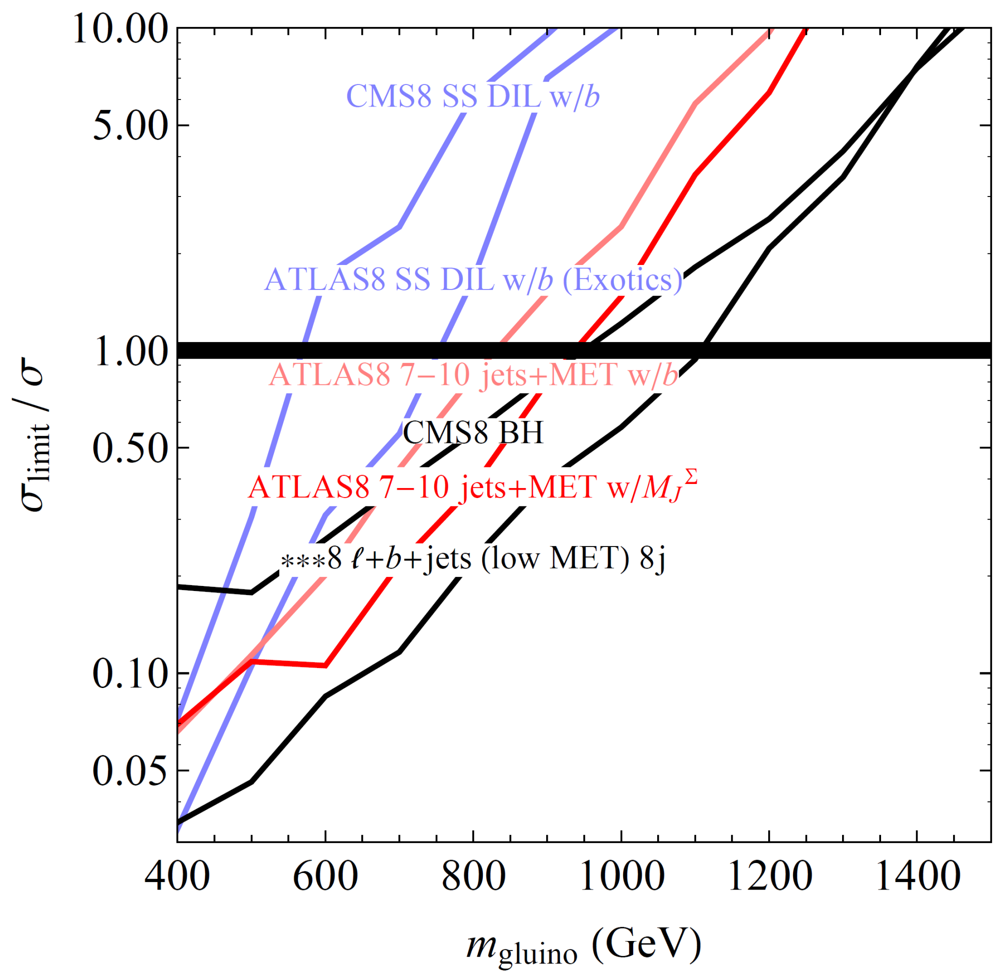

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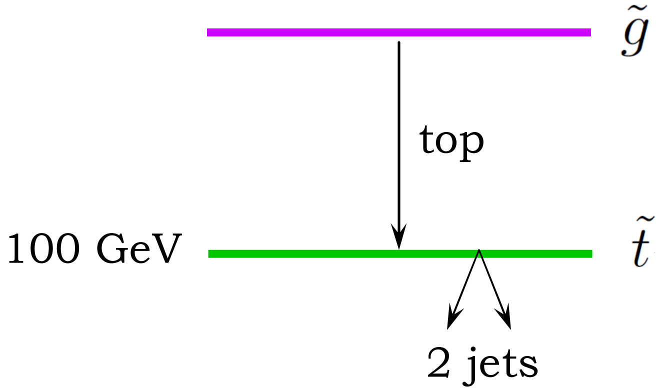
On the other hand, a search for lepton + many jets (low MET) is very promising!



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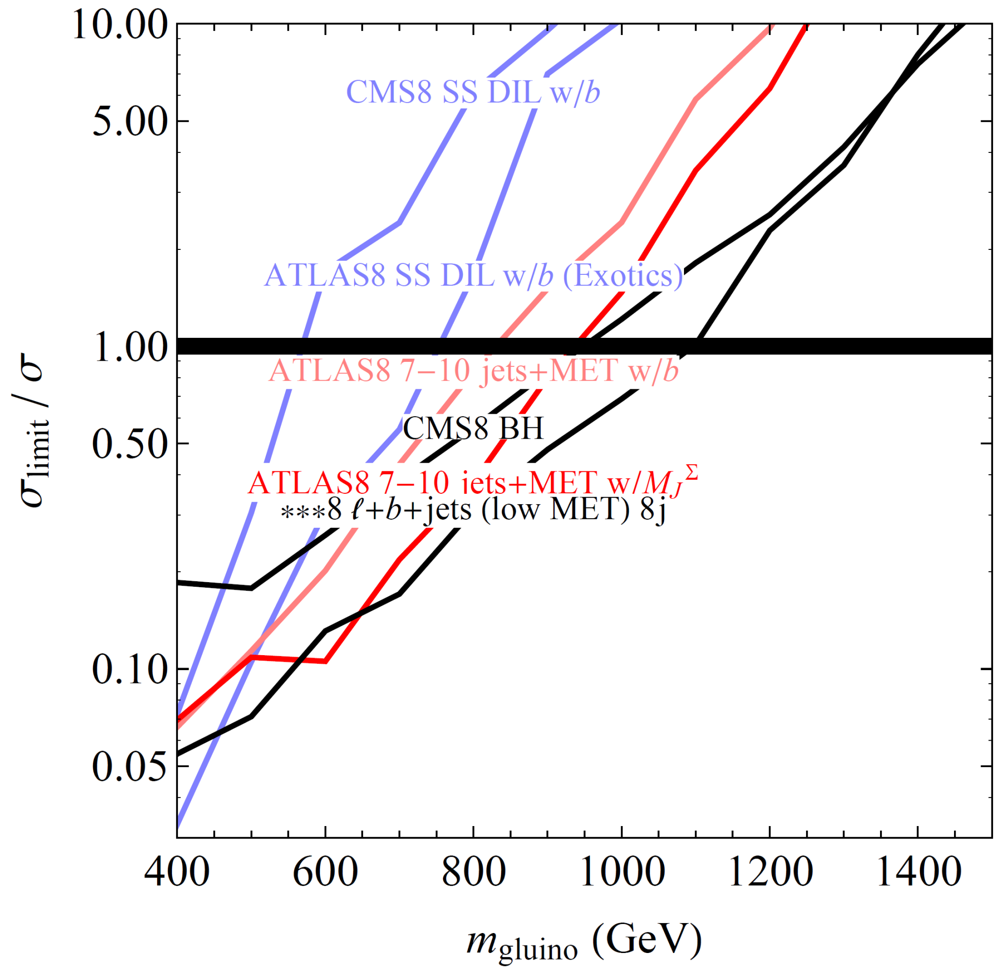

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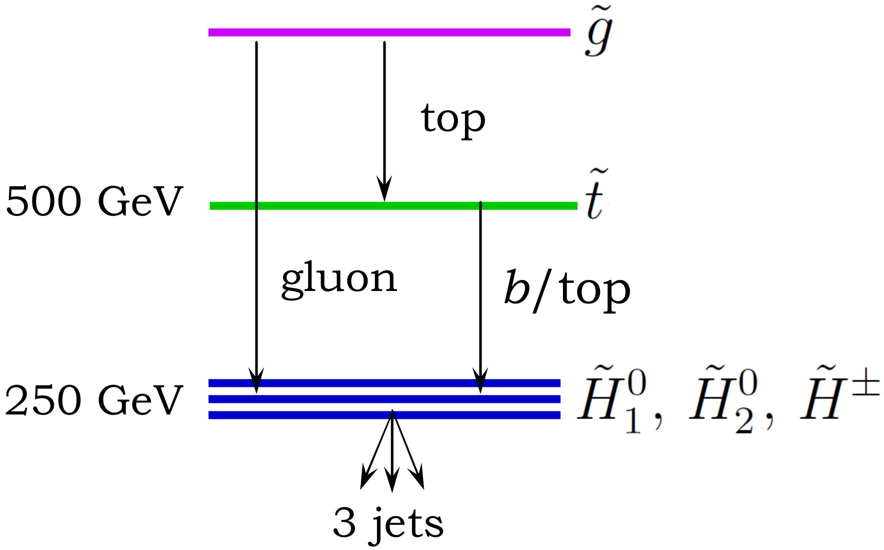
…even if we change our systematic uncertainty guess from 25% to 50%.



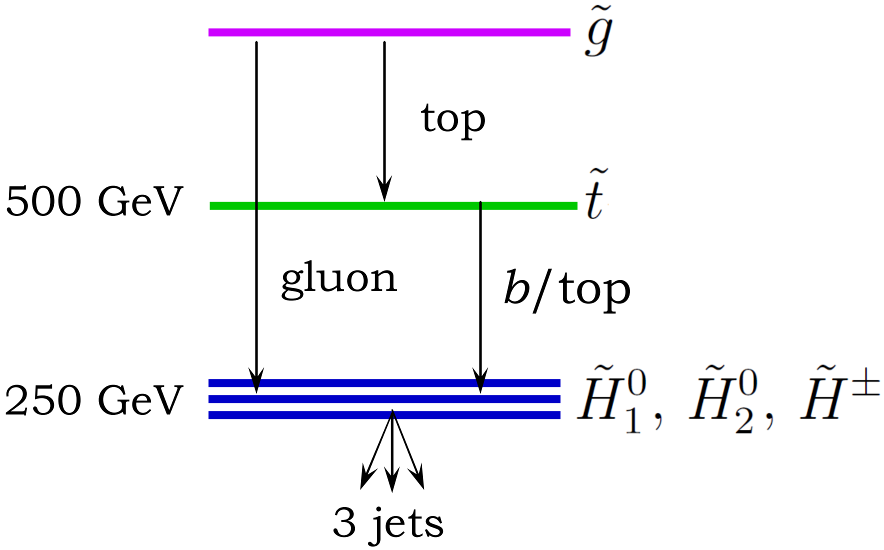
Production: $pp \rightarrow \tilde{g}\tilde{g}$

Heavy gluino	**Light gluino**
$\tilde{g} \rightarrow \tilde{t}\,\bar{t}$ or $\tilde{t}^*t$ $\tilde{t} \rightarrow b\,\tilde{H}^+,\ t\,\tilde{H}^0$	$\tilde{g} \rightarrow g\,\tilde{H}^0$

$\tilde{H}^0 \rightarrow bqq$ (via UDD213)

FINAL STATES:

4 tops + 6 jets 3 tops + 7 jets 2 tops + 8 jets (incl. 6 b-jets)	8 jets (incl. 2 b-jets)



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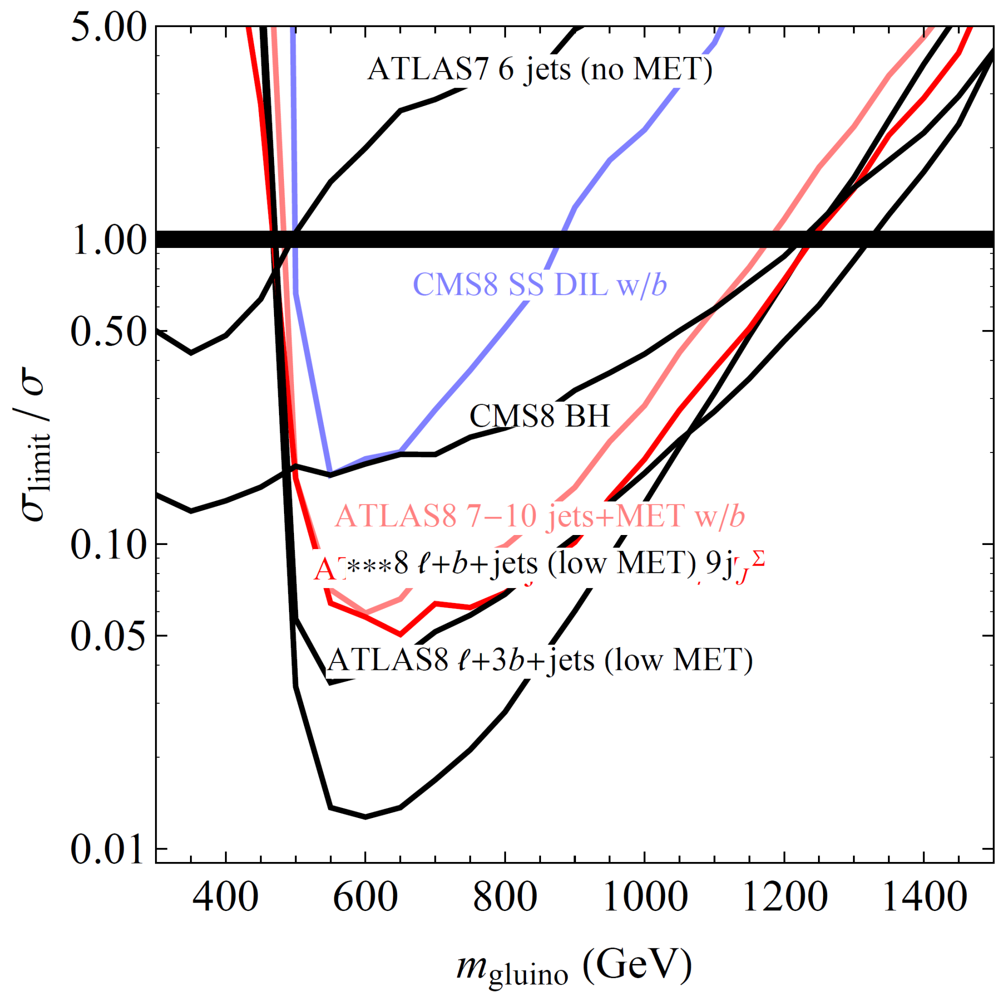
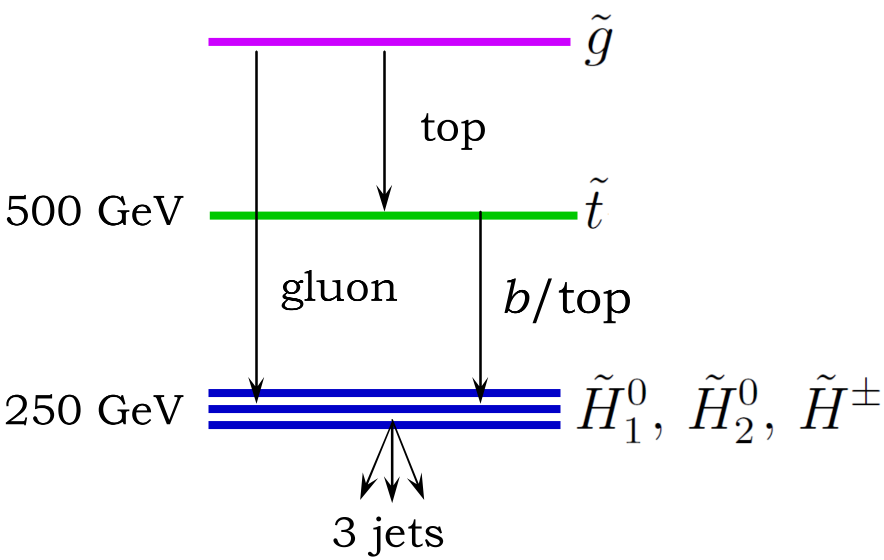


High masses – similar to previous example:

- 7-10 jets+MET and BH are problematic
- Lepton + many jets (low MET) very useful

Low masses:

- 6 jets (no MET) limit within our uncertainty
- Could use higher jet multiplicity, b-jets



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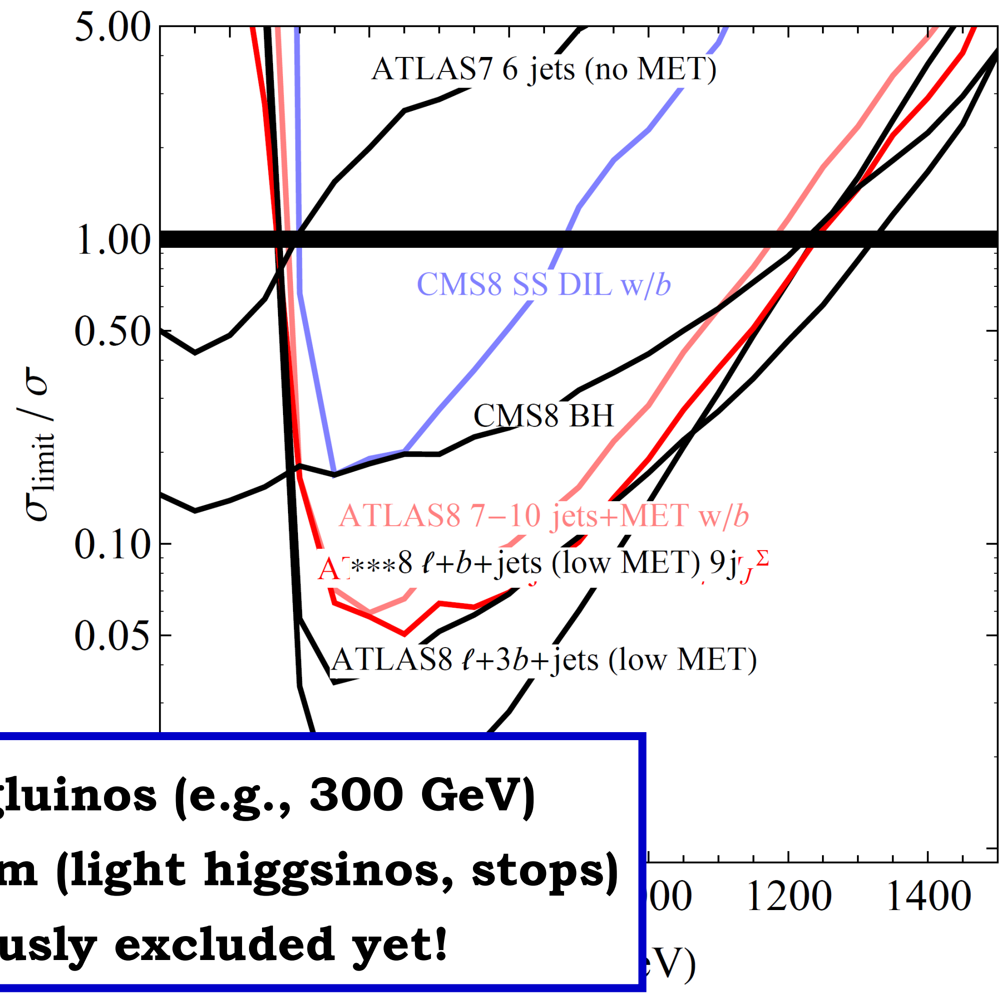

Even very light gluinos (e.g., 300 GeV)
in a natural spectrum (light higgsinos, stops)
are not obviously excluded yet!

Heavy gluino

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Searches in multijet final states

Very few searches exist

- ATLAS 6-jet (resolved + boosted) arXiv:1210.4813 (7 TeV, 4.6/fb)
- CMS 3-jet resonances arXiv:1208.2931 (7 TeV, 5/fb)
- CMS black holes arXiv:1303.5338 (8 TeV, 12.1/fb)
- CMS 8-jet (ANN for a specific decay) CMS-PAS-EXO-11-075 (7 TeV, 5/fb)

More features of the signals can be utilized

- Higher jet multiplicities
- Multiple b-jets (sometimes as many as 6)
- Additional resonant structures
- Signals much larger than the data (for sufficiently high jet / b-jet multiplicity). For such scenarios, searches should be possible even for low S_T.

Multijet searches – not just for multijet-only scenarios

Even in scenarios with tops (but no other sources of MET or leptons), multijet searches might sometimes do better than lepton + many jets searches.

Conclusions

Lepton(s) + many jets (low MET) – relevant to a large, diverse set of scenarios

Promising searches:

- Lepton + many jets
- OS dileptons + many jets (~ generalization of LQ searches)
- Lepton + hadronic tau + many jets

- Jet multiplicities up to ~10
- Low and high b-jet multiplicities
- S_T: from as low as possible to as high as the data goes

See also *Lisanti, Schuster, Strassler, Toro* (arXiv:1107.5055)

Multijet searches

- Even very light gluinos (e.g., 300 GeV), in a natural spectrum (light higgsinos, stops), are not obviously excluded yet.
- Scenarios addressed by lepton + many jets might get even stronger limits from appropriate multijet searches.
- Can use higher multiplicities, b-tagging, resonant structures, …

New physics in the $t\bar{t}$ sample – relevant to several low-mass stop scenarios

Useful handles:
- Extra jets
- Extra b-jets
- Violation of lepton flavor universality (e.g., excess in taus only)

For reinterpretations by theorists

Include simple cut-and-count bins with measured event yields, expected background and systematic uncertainty.