Some Issues in RPV SUSY

Matt Strassler

- Special thanks to Jared Evans, Yevgeny Kats
- Work done with Evans, Kats and David Shih
- Work done by them

CMS-LPC SUSY 2013

Main Message (my personal view)

- Optimization for Reach vs. Optimization for Coverage

For Coverage, Systematic Approach to Searches Pays Off

- Done
  - The jets + MET search (increasing multiplicity with decreasing MET)
  - The multi-lepton search (in MET and S_T binning)

- Needed
  - 1 lepton + jets
  - 2 leptons (OS, SS, OSSF) + jets
  - 2 tau (OS, SS) + jets
  - 8 TeV multilepton optimized for 4 tau?

- Within these, search for jj, jjj, ℓj, ℓjj resonances
  - [possibly with boost/substructure methods]

CMS
Jets + MET

N_{jets}	Selection H_T	$\not{H}_T$	$Z \to \nu\bar{\nu}$ from γ+jets	$t\bar{t}/W \to e,\mu$+X	$t\bar{t}/W \to \tau_h$+X	QCD	Total background	Obs. data
3-5	500-800	200-300	1821.3±326.5	2210.7±447.8	1683.7±171.4	307.4±219.4	6023.1±620.2	6159
3-5	500-800	300-450	993.6±177.9	660.1±133.3	591.9± 62.5	34.5± 23.8	2280.0±232.1	2305
3-5	500-800	450-600	273.2± 51.1	77.3± 17.9	67.6± 9.5	1.3± 1.5	419.5± 55.0	454
3-5	500-800	> 600	42.0± 8.7	9.5± 4.0	6.0± 1.9	0.1± 0.3	57.6± 9.7	62
3-5	800-1000	200-300	215.8± 40.0	277.5± 62.4	191.6± 23.2	91.7± 65.5	776.7±101.6	808
3-5	800-1000	300-450	124.1± 23.7	112.8± 26.9	83.3± 11.2	9.9± 7.4	330.1± 38.3	305
3-5	800-1000	450-600	46.9± 9.8	36.1± 9.9	23.6± 3.9	0.8± 1.3	107.5± 14.5	124
3-5	800-1000	> 600	35.3± 7.5	9.0± 3.7	11.4± 3.2	0.1± 0.4	55.8± 9.0	52
3-5	1000-1250	200-300	76.3± 14.8	103.5± 25.9	66.8± 10.0	59.0± 24.7	305.6± 40.1	335
3-5	1000-1250	300-450	39.3± 8.2	52.4± 13.6	35.7± 6.2	5.1± 2.7	132.6± 17.3	129
3-5	1000-1250	450-600	18.1± 4.4	6.9± 3.2	6.6± 2.1	0.5± 0.7	32.1± 5.9	34
3-5	1000-1250	> 600	17.8± 4.3	2.4± 1.8	2.5± 1.0	0.1± 0.3	22.8± 4.7	32
3-5	1250-1500	200-300	25.3± 5.5	31.0± 9.5	22.2± 3.9	31.2± 13.1	109.7± 17.5	98
3-5	1250-1500	300-450	16.7± 4.0	10.1± 4.4	11.1± 3.6	2.3± 1.6	40.2± 7.1	38
3-5	1250-1500	> 450	12.3± 3.2	2.3± 1.7	2.8± 1.5	0.2± 0.5	17.6± 4.0	23
3-5	>1500	200-300	10.5± 2.8	16.7± 6.2	15.2± 3.4	35.1± 14.1	77.6± 16.1	94
3-5	>1500	> 300	10.9± 2.9	9.7± 4.3	6.5± 2.0	2.4± 2.0	29.6± 5.8	39
6-7	500-800	200-300	22.7± 6.1	132.5± 58.6	127.1± 21.5	18.2± 9.2	300.5± 63.4	266
6-7	500-800	300-450	9.9± 3.1	22.0± 10.8	18.6± 4.3	1.9± 1.7	52.3± 12.1	62
6-7	500-800	> 450	0.7± 0.6	0.0± 1.6	0.1± 0.3	0.0± 0.1	0.8± 1.7	9
6-7	800-1000	200-300	9.1± 2.8	55.8± 25.4	44.6± 8.2	13.1± 6.6	122.6± 27.7	111
6-7	800-1000	300-450	4.2± 1.6	10.4± 5.5	12.8± 3.1	1.9± 1.4	29.3± 6.6	35
6-7	800-1000	> 450	1.8± 1.0	2.9± 2.5	1.3± 0.5	0.1± 0.4	6.1± 2.7	4
6-7	1000-1250	200-300	4.4± 1.6	24.1± 12.0	24.0± 5.5	11.9± 6.0	64.4± 14.6	67
6-7	1000-1250	300-450	3.5± 1.4	8.0± 4.7	9.6± 2.5	1.5± 1.5	22.6± 5.7	20
6-7	1000-1250	> 450	1.4± 0.8	0.0± 1.8	0.8± 0.5	0.1± 0.3	2.3± 2.1	4
6-7	1250-1500	200-300	3.3± 1.3	11.5± 6.5	6.1± 2.5	6.8± 3.9	27.7± 8.1	24
6-7	1250-1500	300-450	1.4± 0.8	3.5± 2.6	2.9± 1.5	0.9± 1.3	8.8± 3.4	5
6-7	1250-1500	> 450	0.4± 0.4	0.0± 1.2	0.1± 0.2	0.1± 0.3	0.5± 1.3	2
6-7	>1500	200-300	1.3± 0.8	10.0± 6.9	2.3± 1.3	7.8± 4.0	21.5± 8.1	18
6-7	>1500	> 300	1.1± 0.7	3.2± 2.8	2.9± 1.2	0.8± 1.1	8.0± 3.3	3
≥8	500-800	> 200	0.0± 0.6	1.9± 1.5	2.8± 1.3	0.1± 0.4	4.8± 2.1	8
≥8	800-1000	> 200	0.6± 0.5	4.8± 2.9	2.7± 1.1	0.5± 0.9	8.7± 3.3	9
≥8	1000-1250	> 200	0.6± 0.5	1.4± 1.5	3.1± 1.2	0.7± 0.9	5.8± 2.2	8
≥8	1250-1500	> 200	0.0± 0.7	5.1± 3.5	1.3± 0.8	0.5± 0.9	6.9± 3.7	5
≥8	1500-	> 200	0.0± 0.6	0.0± 2.1	1.5± 1.0	0.9± 1.3	2.4± 2.8	2

Why (and Why Not) R-parity

- R-parity: a symmetry sufficient to forbid proton decay, but not quite necessary
  - But proton decay requires both B and L violation
  - R-parity violation in B-violating OR L-violating operators is allowed
  - Or both must be very small
- R-parity is however flavor-violating, so there are constraints on the couplings
  - Strongest for lighter generations, naturally

$$W = \tfrac{1}{2}\lambda_{ijk}\, L_i L_j E^c_k + \lambda'_{ijk}\, L_i Q_j D^c_k + \tfrac{1}{2}\lambda''_{ijk}\, U^c_i D^c_j D^c_k + \mu_i L_i H_u$$

i, j, k = generation indices

- $|\lambda'_{ijk}\lambda''_{i'j'k'}| < 10^{-9} \Leftarrow$ Proton decay
- $|\lambda^*_{i12}\lambda'_{i11}| < 2 \times 10^{-8} m^2_{\tilde{\nu}} \Leftarrow \mu \to e$ (Ti)
- $|\lambda^*_{i21}\lambda'_{i31}| < 2 \times 10^{-5} m^2_{\tilde{\nu}} \Leftarrow B^0_d \to e^\pm \mu^\mp$
- $|\lambda'^*_{i31}\lambda'_{i13}| < 3 \times 10^{-8} m^2_{\tilde{\nu}} \Leftarrow B\bar{B}$ mixing
- $|\lambda''^*_{i23}\lambda''_{i12}| < 6 \times 10^{-5} m^2_{\tilde{u}_{iR}} \Leftarrow B^+ \to \phi\pi^-$
- and many, many, many more. . .

- $|\lambda_{13k}| < 3 \times 10^{-2} \Leftarrow \mathrm{BR}(\tau^- \to \nu\nu e^- / \nu\nu\mu^-)$
- $|\lambda'_{111}| < 3.3 \times 10^{-4} \Leftarrow \nu$-less $\beta\beta$ decay
- $|\lambda'_{22k}| < 10^{-1} \Leftarrow \mathrm{BR}(D^0 \to K^-\mu^+\nu / K^-e^+\nu)$
- $|\lambda''_{312}| < 2.1 \times 10^{-3} \Leftarrow n\bar{n}$ oscillation
- $|\lambda''_{223}| < 1.25 \Leftarrow$ RG evolution
- and many more. . .

Worst features of R-parity violation

- Abandon Dark Matter Candidate
  - But – dark matter could be axions, primordial black holes, some other hidden particle, some weird clumps of something or other…
  - Even with R-parity violation, there could be a non-MSSM particle stabilized by some other global symmetry

- Need to carefully avoid either large L or large B violation – taste?
  - Not so crazy if L and B violation inherit SM generation structure
  - But requires some detailed model of flavor to do this…
    - e.g. strong dynamics suppressing all interactions of lighter generations

Thus these features aren't so bad really... [well, we're drunk on data…]

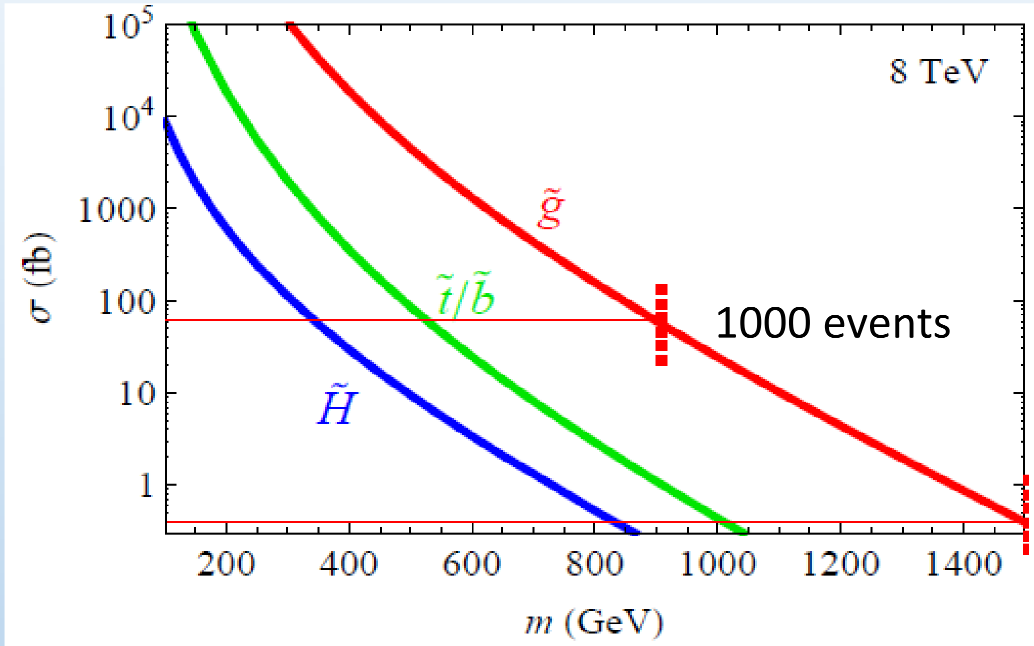
Best features of R-parity violation

- Possible links with flavor, neutrino masses, baryo/lepto-genesis, …

- Forces us to think more broadly about low-MET high-multiplicity signals
  - There may be no MET at all, >> 4 objects in most SUSY events
  - Resonances in object pairs and triplets
  - Can mix leptons and quarks in ways our simplest models don't
  - Can violate flavor dramatically if couplings sufficiently small
  - Standard Model LSP need not be neutral,
    - also true in R-parity preserving models such as GMSB, HV, etc.
  - Common to have metastable LSP that decays in flight or post detector

- Searches for R-parity violation cover other models with zero or very low MET
  - GMSB models without photons
  - SUSY Hidden Valleys [MJS 06], especially Stealth SUSY [Fan et al. 11]
  - Non-SUSY models of various types

The Natural Sparticles
(though not the only ones to think about)



Typically squeezed, realistically yielding either:

Invisible Transitions:

$\tilde{H}_2^0 \to \tilde{H}_1^0 + Z^* \quad \sim \tilde{H}_1^0$

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

$\tilde{H}_1^0 \to \{\text{3-body RPV}\}$

Direct decays:

$\tilde{H}_2^0 \to \{\text{3-body RPV}\}$

$\tilde{H}^\pm \to \{\text{3-body RPV}\}$

$\tilde{H}_1^0 \to \{\text{3-body RPV}\}$

$\text{BR}(\tilde{H}_i^0 \to \ell^+) = \text{BR}(\tilde{H}_i^0 \to \ell^-) \Rightarrow \text{SS}\ell$ signatures common

What Do We Really Know About Natural SUSY?

Evans, Kats, Shih & MJS

Will we ever be able to say , **with almost no assumptions,**

"All natural SUSY models are ruled out" ?

- Not necessarily assuming R-parity conservation
- Not assuming mSUGRA or CMSSM-like relations
- Not assuming GMSB, AMSB, or any other particular SUSY-breaking scenario
- Not assuming a minimal (i.e. MSSM) spectrum of particles

- Not exactly; **but how close can we get to this statement**?

- DEFINE NATURAL:
  - We will pick a definition and give you a methodology to answer the question
  - If you want to pick a different definition, you can use our methods and draw your own conclusion

Are **All** Accessible Natural SUSY Models Excluded?

- Consider all natural SUSY models that have an accessible gluino
  - Below 8 TeV kinematic limit – Up to 1.4 TeV
- Take naturalness to mean
  - Higgsino below 400 GeV (to avoid fine-tuning Higgs at tree level)
  - No other obvious assumptions

Then **gluino pair production** is generally (but not quite always) enough to generate

1. MET, and/or
2. Tops, and/or
3. High multiplicity

any one of which would have been observed in existing ATLAS and/or CMS searches.

- Conservatively:
  - Study gluino pair production in these models in context of ATLAS/CMS searches
  - Not considered: tightly squeezed regions

Conservative Focus on Jets

- To obtain conservative limits we study the least spectacular signals
  - We assume signals are mostly all-jets + possibly MET
  - + possibly a lepton or photon or 2
    - Signals with >2 leptons and/or photons are easily observed over backgrounds
    - Limits on these cases are (or could be made) stronger than those presented below
- Our First Goal: Show that for gluino mass up to TeV and beyond
  - Any model with even a fraction of usual MET is
  - Any model with even a moderate number of top quarks is ruled out
- Our Second Goal : Consider models with almost no MET and very few top quarks
    - Which of these classes might still survive?
    - How can they be effectively sought or killed off?

Searches – (no searches with MVA, BDT, Neural Net or jet substructure)

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
3ℓ	8	19.5	PAS-SUS-13-008
4ℓ	8	19.5	PAS-SUS-13-010
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	8	19.5	PAS-SUS-13-013
t' (SS DIL)	8	19.6	PAS-B2G-13-015
SS DIL	7	4.98	arXiv:1205.6615
SS DIL w/b	7	4.98	arXiv:1205.3933
SSSF DIL	7	4.98	arXiv:[illegible]
SSSF DIL	7	[illegible]	arXiv:1201.[illegible]
SS DIL	7	4.7	arXiv:1210.4538
SS DIL+jets+MET	7	2.05	arXiv:1203.[illegible]
SS DIL+MET	7	1.04	arXiv:1110.6189
b' (SS DIL)	7	[illegible]	CONF-2012-[illegible]
b' (SS DIL)	7	4.9	arXiv:1204.1088

Final State	$\sqrt{s}$	$\mathcal{L}$	Reference
t' (OS DIL)	8	19.6	PAS-B2G-13-015
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
ℓ+jets+MET	8	5.8	CONF-2012-104
ℓ+3b+jets+MET	8	20.1	CONF-2013-061
ℓ+b+6j+MET	8	19.4	PAS-SUS-13-007
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.[illegible]
τ+ℓ+jets+MET	7	4.7	arXiv:1210.1314
[illegible] (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
[illegible] 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	$\sim$ 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
jets+MET	8	19.5	PAS-SUS-13-012
b+jets+MET	8	19.4	arXiv:1305.2390
3b+jets+MET (old)	8	12.8	CONF-2012-145
3b+jets+MET	8	20.1	CONF-2013-061
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
[illegible]+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
6-7 jets (no MET)	8	20.3	CONF-2013-091
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

Over 70 separate searches implemented by Yevgeny Kats and Jared Evans
Validated by comparing our results to experimental search limits where available
Not considered: certain complex searches (BDTs, MVAs, Razor, etc.)
Limitations: bins, searches not combined

The Ones That Matter For Us

Search	Data (fb^{-1})	Reference
ATLAS 2-6 jets + large $\not{E}_T$	20.3	[16]
ATLAS 7-10 jets + low $\not{E}_T$	20.3	[18]
CMS jets + $\not{E}_T$	19.5	[17]
ATLAS 6-7 high-p_T jets	20.3	[20]
CMS black holes (BH)	12.1	our re-analysis of [21] (see section 3.2)
LSST lepton + many jets w/b	20 (expected)	our implementation of [19] (see section 3.3)

Table 1: Searches most important to our study. All use the 8 TeV LHC data.

Recast

Reinterpreted

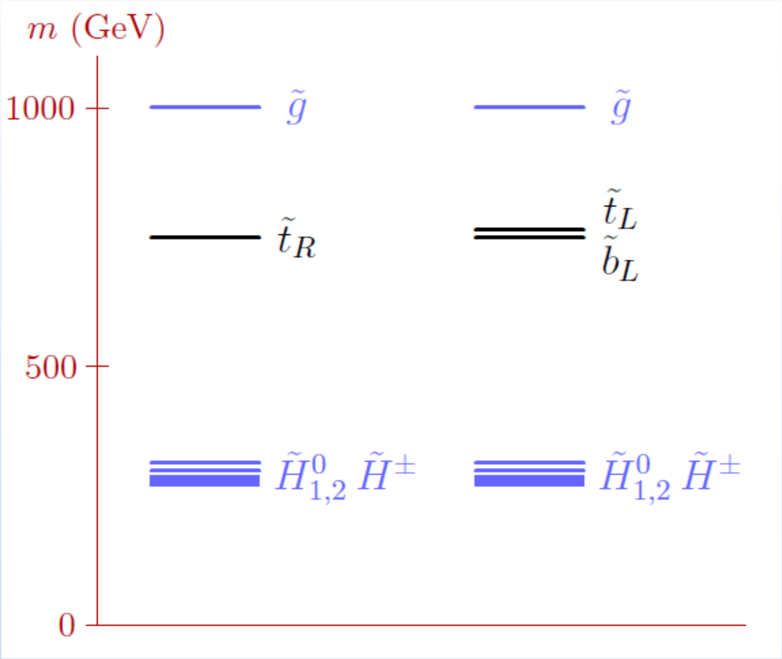
Proposed in 2011

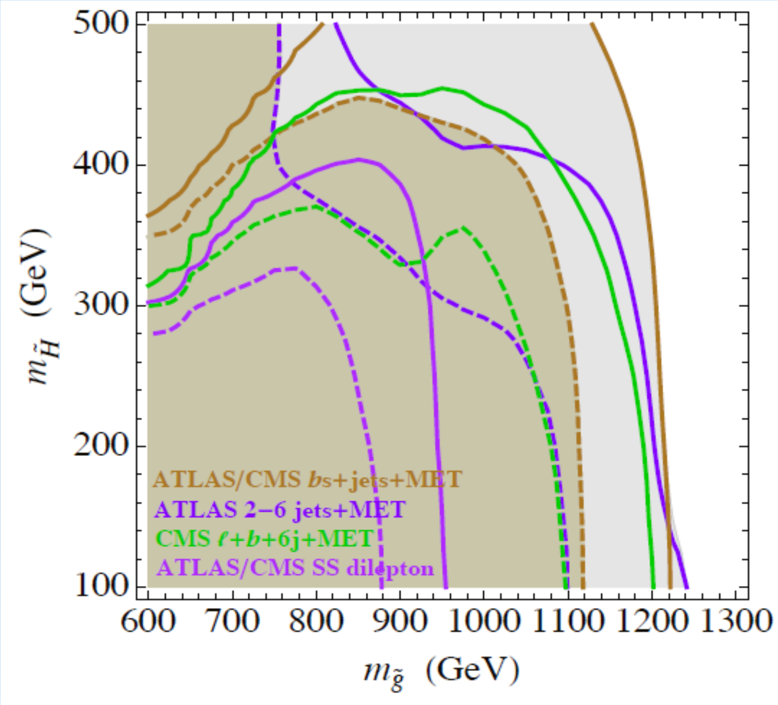
Also crucial by assumption but not used/needed in our study:

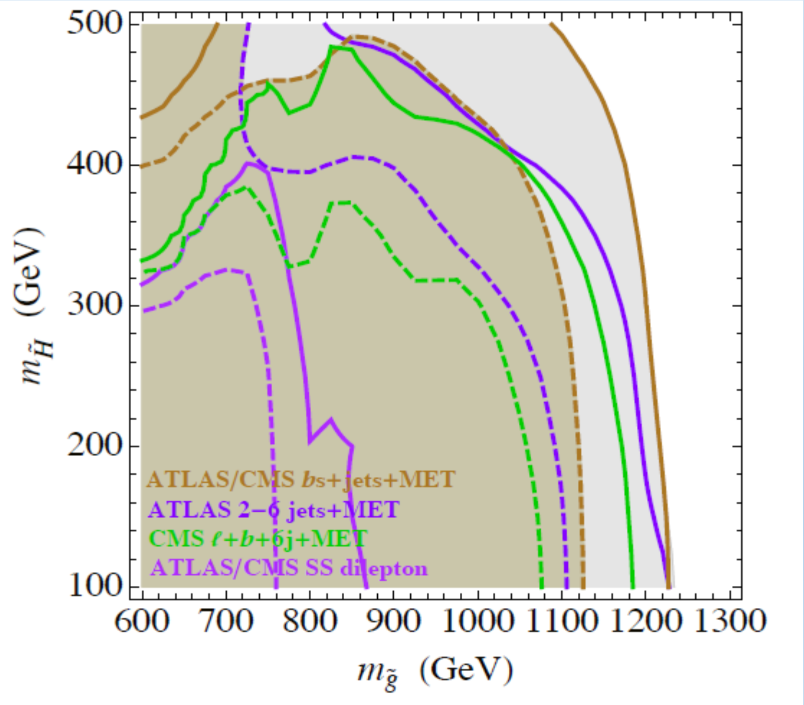
- GMSB-type searches for 2 photons + MET
- Multi-lepton searches
- Searches for many b quarks + X

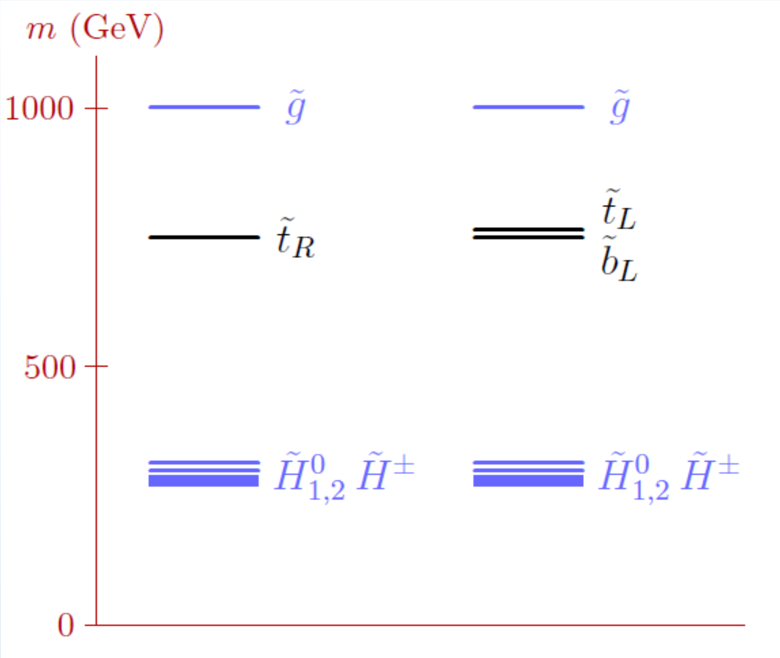
Unfairly penalized by our limited methods:

- CMS alpha-T and Razor

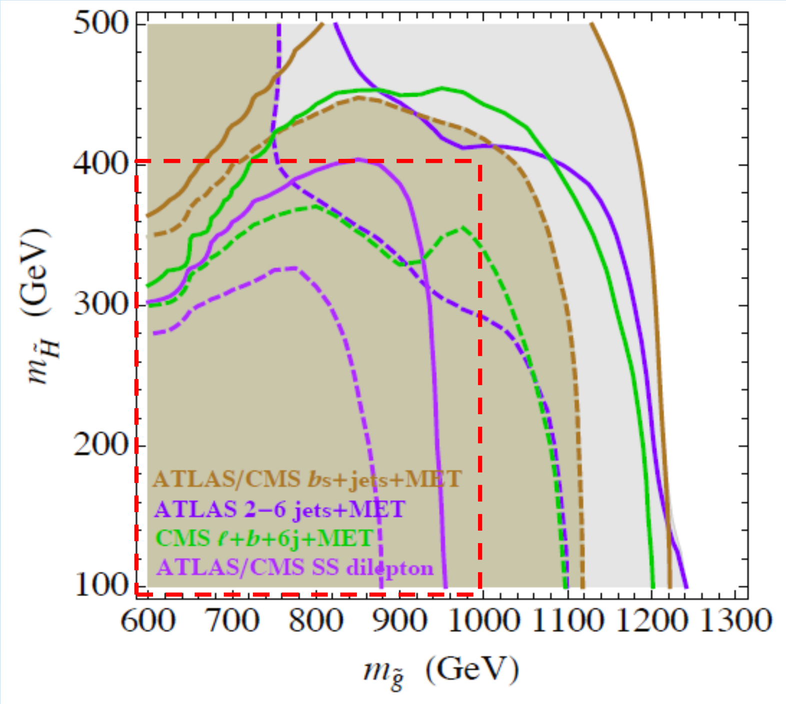

m (GeV)
1000
500
0
g̃
t̃_R
t̃_L
b̃_L
H̃⁰_{1,2} H̃^±


ATLAS/CMS bs+jets+MET
ATLAS 2−6 jets+MET
CMS ℓ+b+6j+MET
ATLAS/CMS SS dilepton
m_H̃ (GeV)
m_g̃ (GeV)

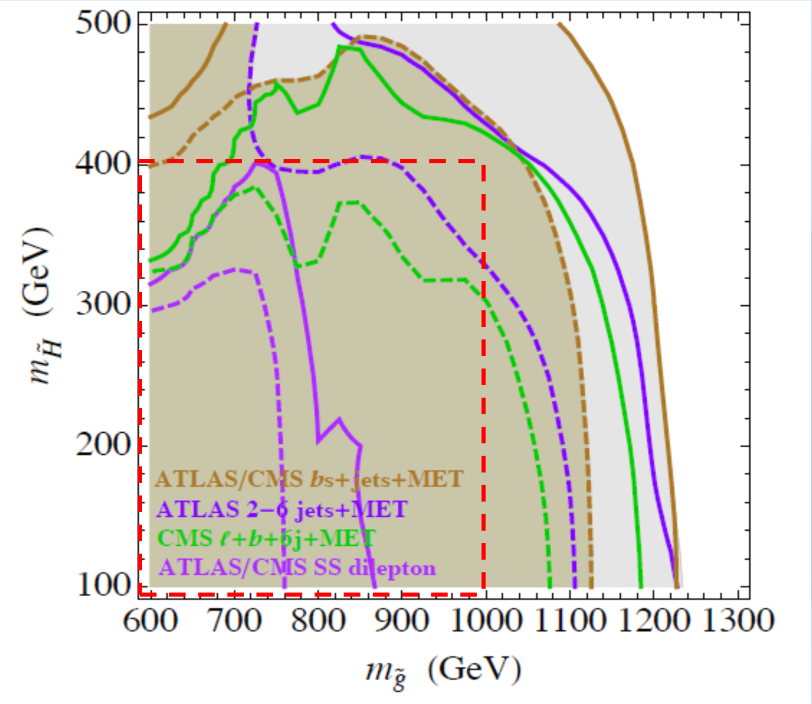

ATLAS/CMS bs+jets+MET
ATLAS 2−6 jets+MET
CMS ℓ+b+6j+MET
ATLAS/CMS SS dilepton
m_H̃ (GeV)
m_g̃ (GeV)



m (GeV)
1000
500
0
$\tilde{g}$
$\tilde{g}$
$\tilde{t}_R$
$\tilde{t}_L$
$\tilde{b}_L$
$\tilde{H}^0_{1,2}\ \tilde{H}^\pm$
$\tilde{H}^0_{1,2}\ \tilde{H}^\pm$



$m_{\tilde{H}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
ATLAS/CMS bs+jets+MET
ATLAS 2−6 jets+MET
CMS ℓ+b+6j+MET
ATLAS/CMS SS dilepton

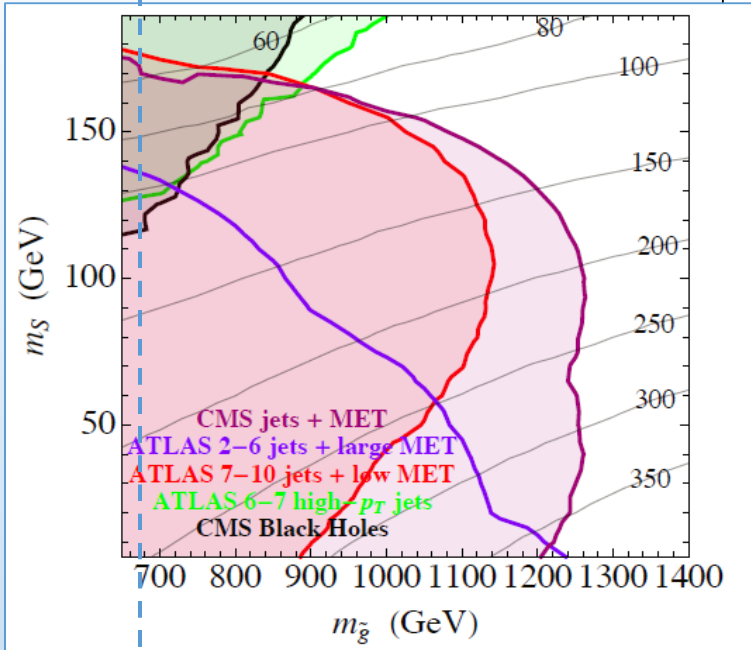


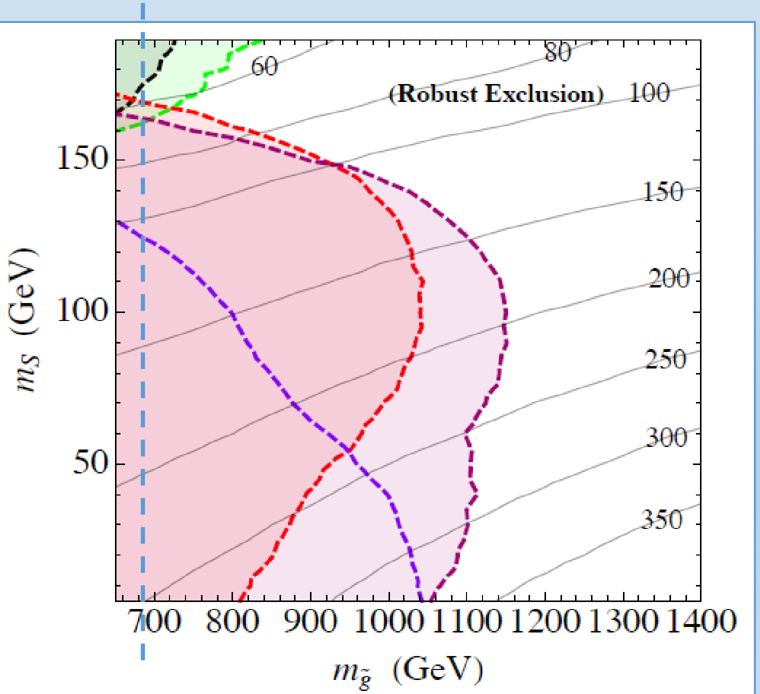
$m_{\tilde{H}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
ATLAS/CMS bs+jets+MET
ATLAS 2−6 jets+MET
CMS ℓ+b+6j+MET
ATLAS/CMS SS dilepton

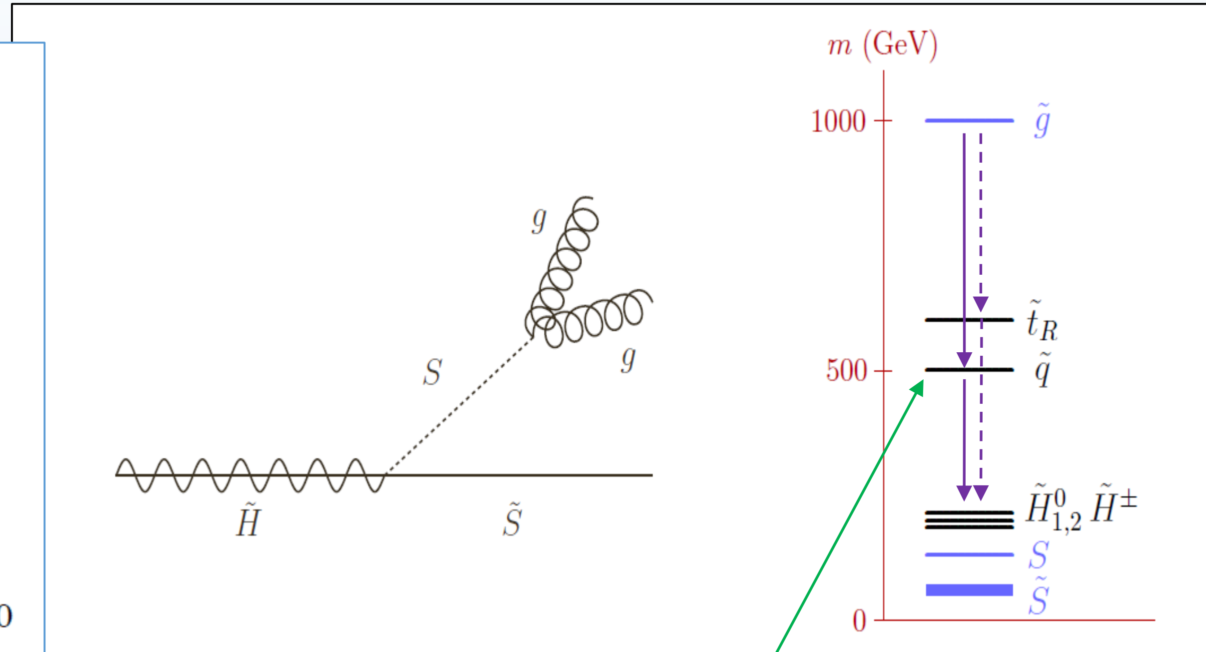
Accessible SUSY with MET and jjjjjets: Excluded

- Hidden Valley Models can interpolate (holding S_T roughly fixed) between
  - mSUGRA-like limit (few high-pT jets+ large MET)
  - RPV-like (Stealthy) limit (high-multiplicity of jets, no MET)

- Simple Example:
  - Gluino (e.g. 600 GeV)
  - RH top squark (e.g. 500 GeV)
  - Higgsino χ (e.g. 200 GeV)
    - $\tilde{g} \rightarrow t\, b\, \chi^+$; $\chi^+ \rightarrow \chi^0$ + soft – so large MET signal with b's + often leptons
  - More conservative signal: e.g. add charm squark at e.g. 500 GeV
    - [See Mahbubani et al. 2012 for justification]
    - $\tilde{g} \rightarrow \tilde{c}\, c$ dominates ; $\tilde{c} \rightarrow c + \chi^0$; so large MET signal with no b's, leptons
  - Now change the MET by adding effects of a small Hidden Valley sector







2nd Generation

See Mahbubani, Papucci, Perez, Ruderman, Weiler 2012

Accessible SUSY with top quarks: Excluded

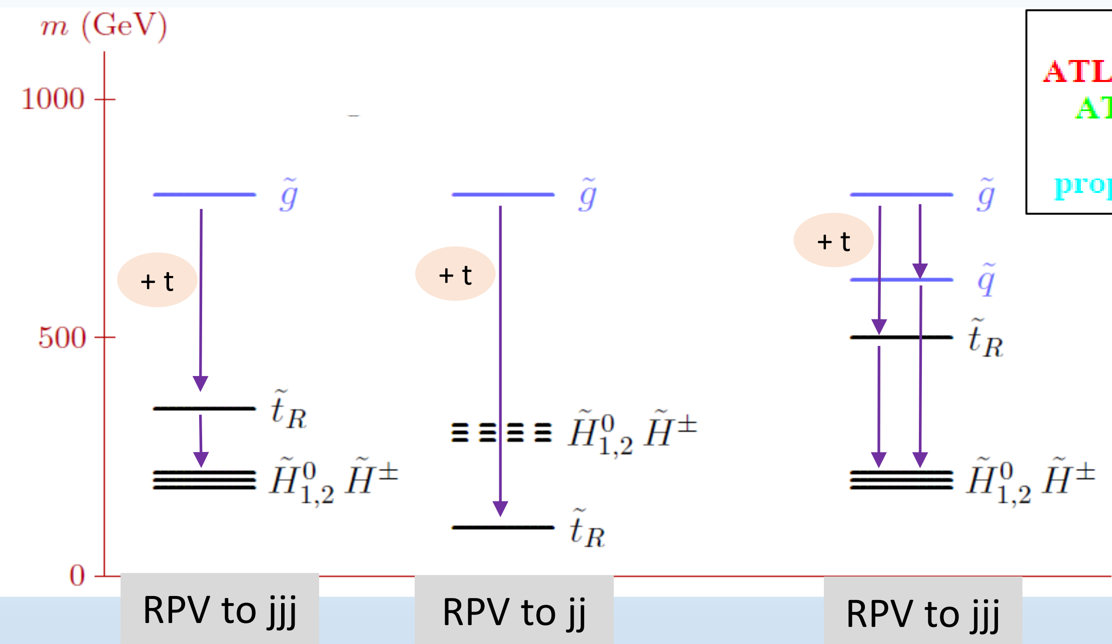
Consider

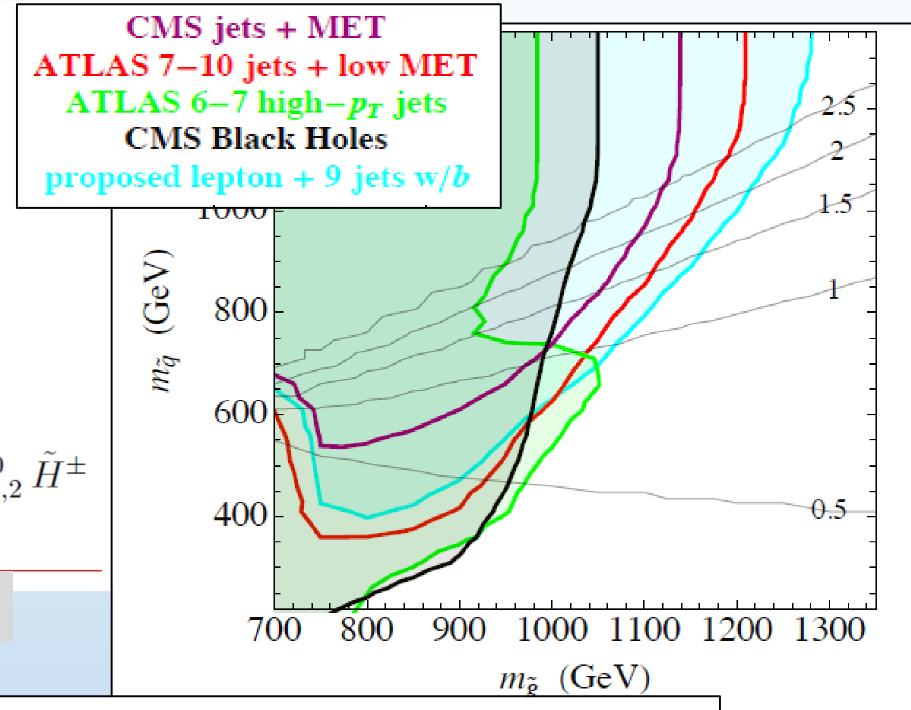
- Gluino production ➔ top quarks unless special effort
  - Either Gluino → top stop
  - Or LSP → t X X by R-parity violation
- Gluinos that don't produce MET w/out compression produce more jets (conservatively!)

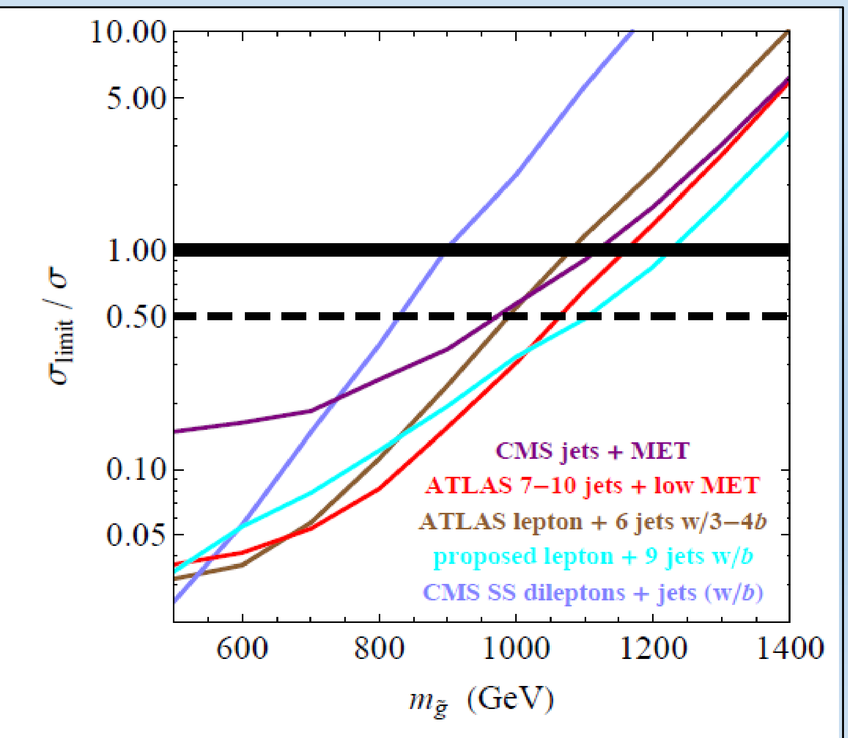
- So search for top produced with many jets at a gluino rate

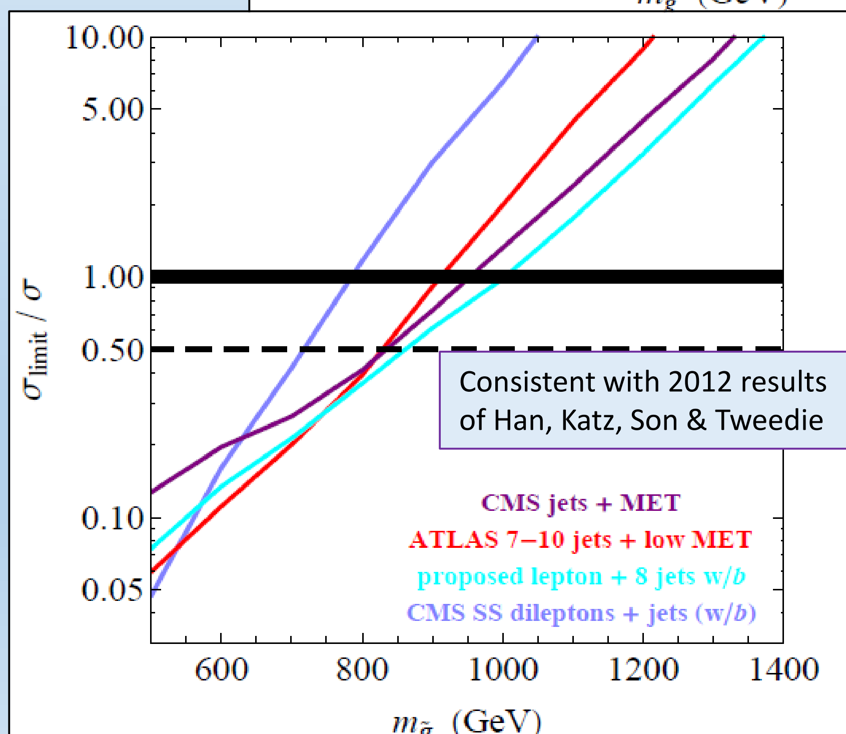
- Lepton + many jets including 1 b tag (and a minimal M_T cut to remove fake leptons)
  - As suggested by Lisanti, Schuster, MJS & Toro (7/2011)
- Main background is top; signals comparable to or larger than background at large S_T
- Never implemented by ATLAS/CMS but many related searches with one lepton
  - With lower S_T ; 3 b's ; fewer jets ; higher MET

- Alternative: a veto on "lepton" still keeps leptons!
  - Hadronic tau
  - Lost electron or muon in multijet environment
- CMS, ATLAS searches for many jets + low MET









Consistent with 2012 results of Han, Katz, Son & Tweedie

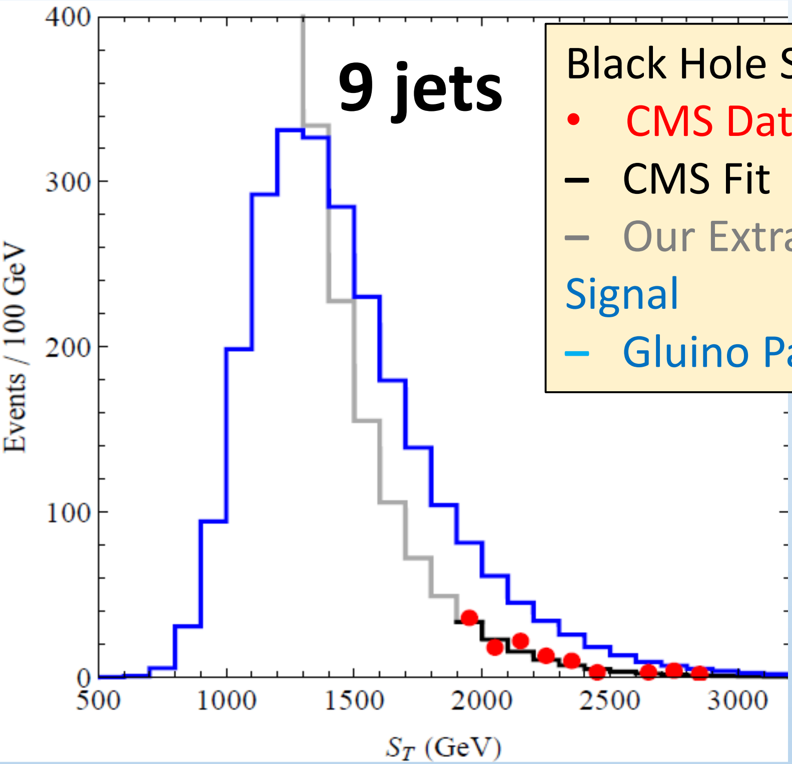
All-Hadronic Final States?

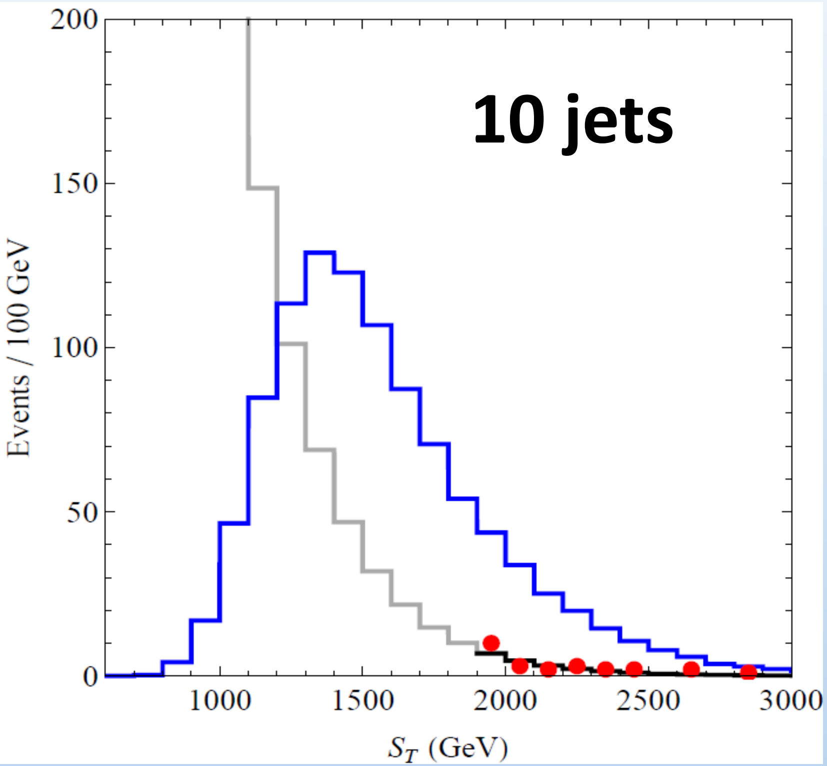
What if the gluino decays predominantly to all-jet final states?

- Or other high-color and/or high-spin particle?

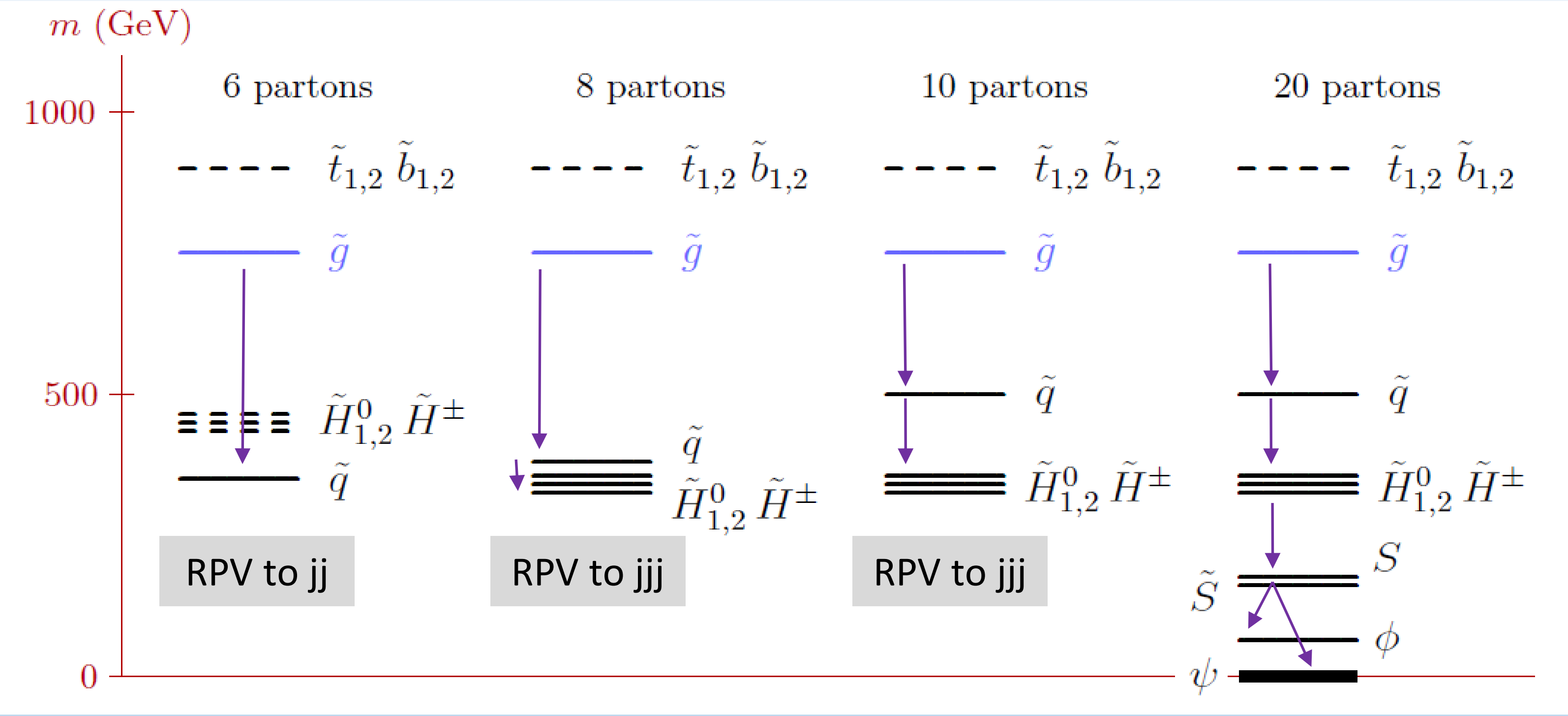
- What if it decays to 2 jets? [pair-of-dijet-resonances]
- What if it decays to 3 jets? [trijet resonance or 6-jet counting or ??]
- What if it decays to 4 jets? [borderline case]
- What if it decays to 5 jets? [then it apparently exceeds QCD backgrounds]

Gluino Can Exceed QCD



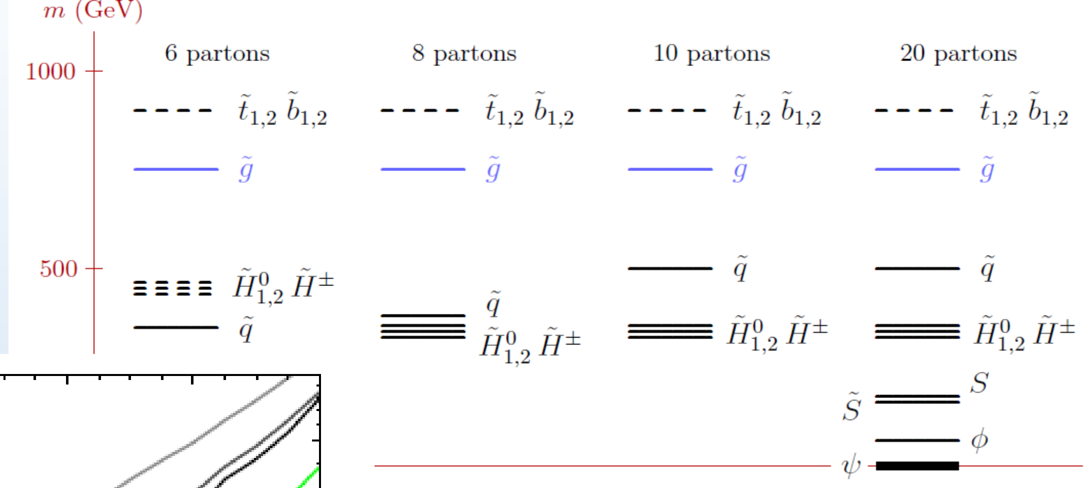


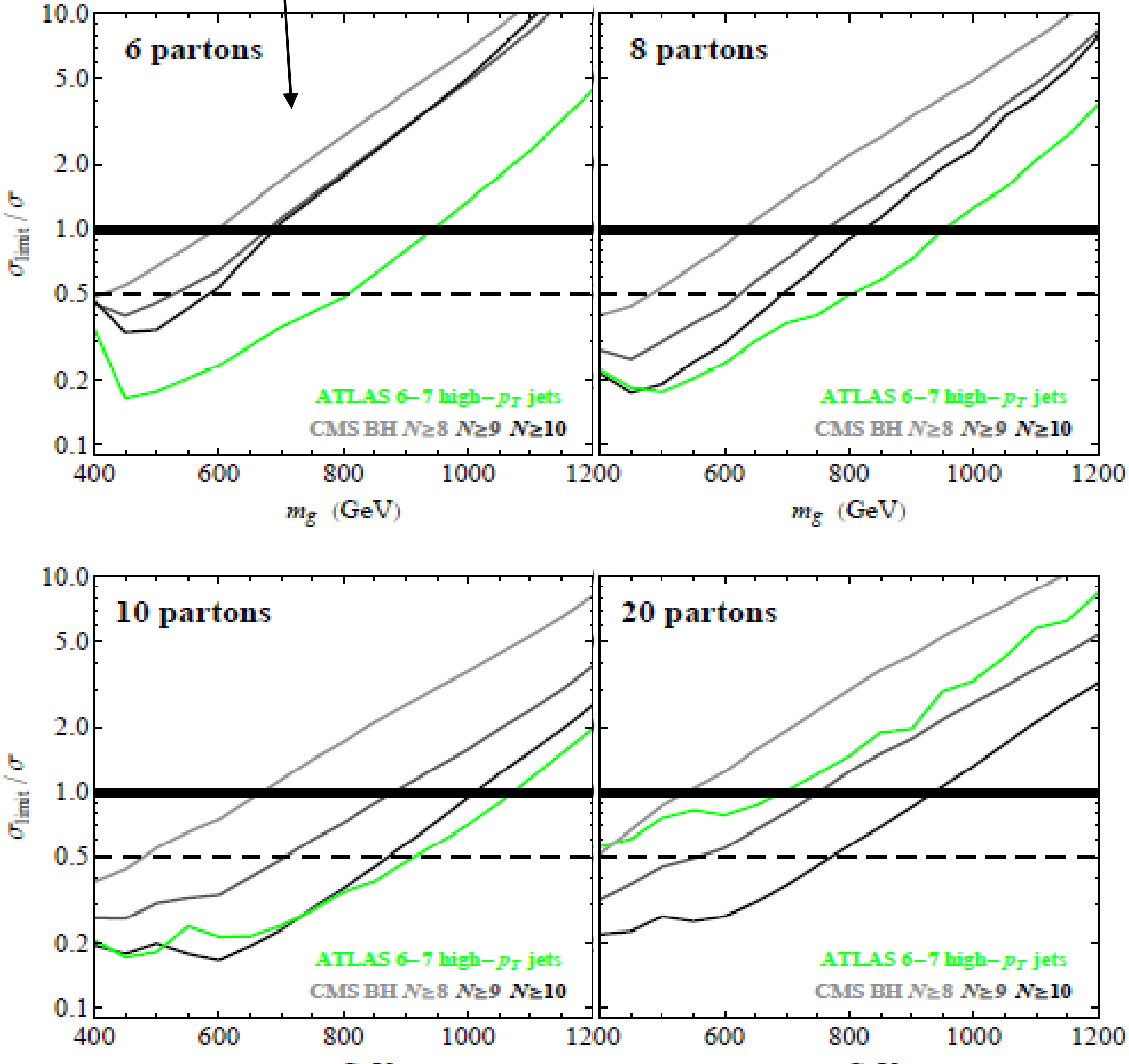
- Gluino (650 GeV)
- RH top squark (500 GeV), charm squark at 550 GeV
    - g → c c dominates ; c → c + χ^0 ;
- Higgsino χ (250 GeV) → j j j via RPV



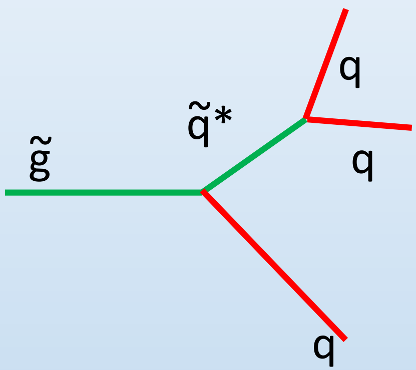
m (GeV)
1000
500
0
6 partons
8 partons
10 partons
20 partons
$\tilde{t}_{1,2}\ \tilde{b}_{1,2}$
$\tilde{g}$
$\tilde{H}^0_{1,2}\ \tilde{H}^\pm$
$\tilde{q}$
RPV to jj
RPV to jjj
RPV to jjj
S
$\tilde{S}$
ϕ
ψ

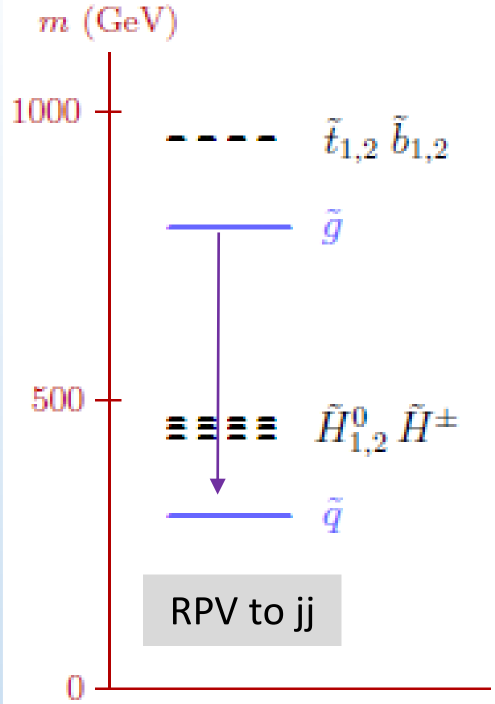
CMS 3-jet resonance search not included! We cannot reliably reproduce the fitting strategy used in that search.

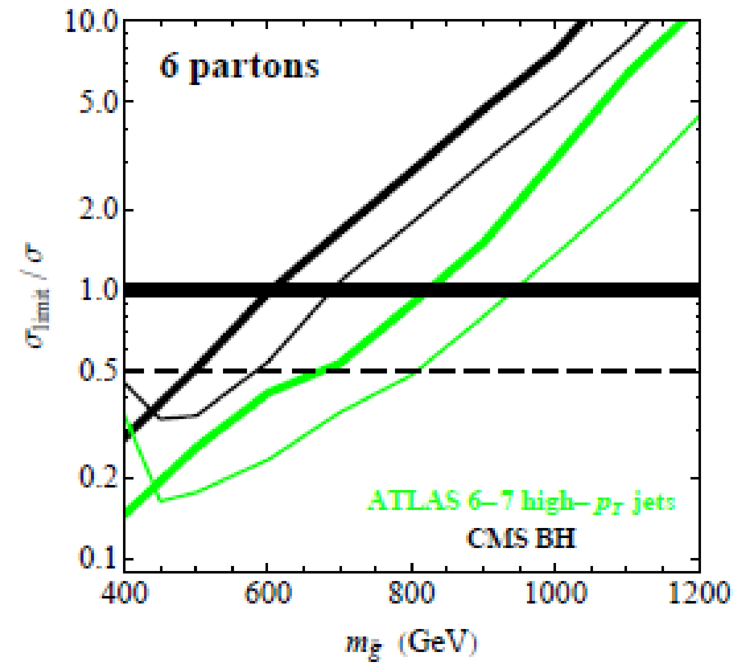




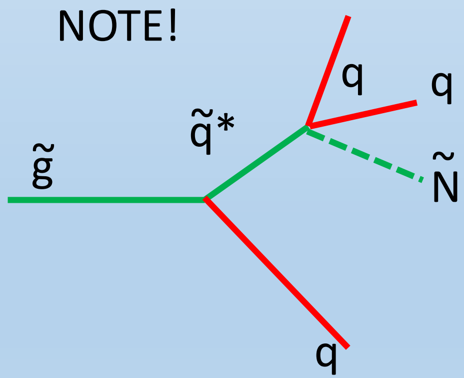
We Find:
Modified Black Hole Search Conservatively Rules Out High Multiplicity RPV For Gluinos up to 900 GeV or More



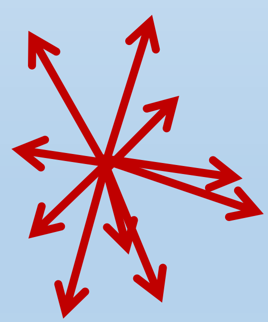




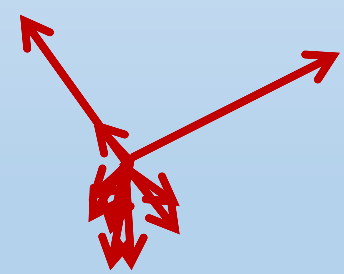
NOTE!



Challenge for CMS resonance search



Easy Case: Not Like QCD



Hard Case: pT distributed like C
What about Angles, Event Shap

What else remains?

- Biggest loophole is likely to be models with multiple signatures that require combining searches
  - Should these searches be combinable in the 14 TeV run?
- There are a few mostly minor loopholes that we know about
  - Biggest known issue: lepton gap
    - Lepton vetoes in zero-lepton searches vs. lepton selection in leptonic searches
  - Some searches need to be updated for full data set
    - Lepton + photon + MET
    - Two photons + MET
- Gluino cascade produces exotic objects that cause events to be discarded, mislabeled or misinterpreted
- Other loopoles that we missed (audience invited to find them!)

Top Squarks, Higgsinos (if no gluinos)

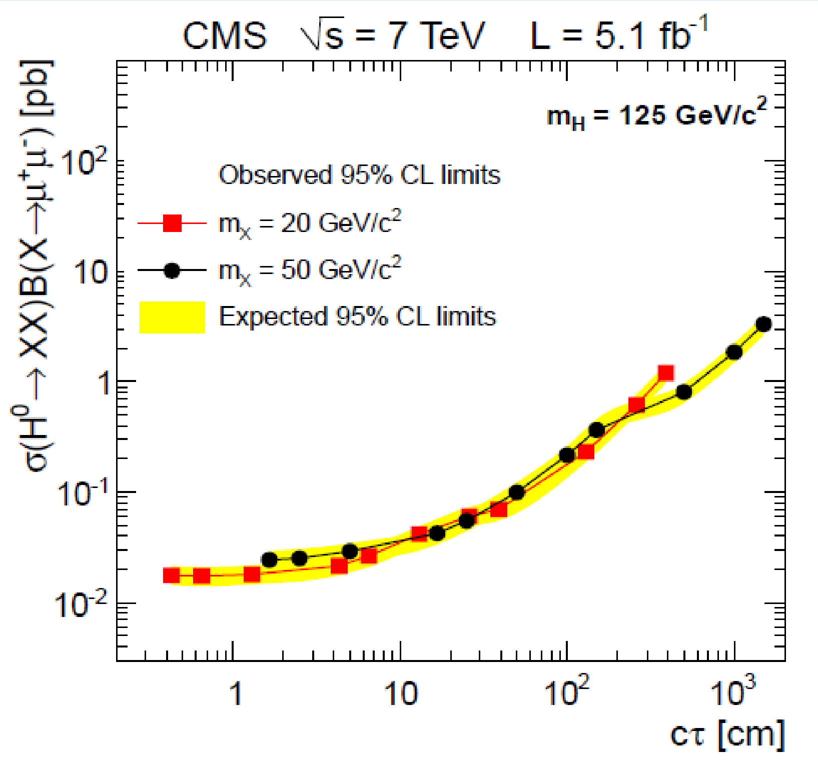
- Extensive studies of all final states by Evans and Kats
- Results: Many cases are not well covered, but often unnecessarily
  - Single lepton cases often require the same Lisanti et al. leptons + jets search
  - Most powerful dilepton search is the lepto-quark search!
    - Muons + jets with kinematics above top quark background
    - Could be much more powerful if binned in # jets, # b's, OS vs SS
      - Even more important for tau pair + jets
  - Search for all-jets with many b-tags well-motivated
    - *For many reasons!!*
  - 4 tau + MET final states – optimize?
- Within these searches, resonances in 1-lepton+1-jet, 1-lepton+2-jet, 2-jet, 3-jet

Long-Lived Particles in RPV context

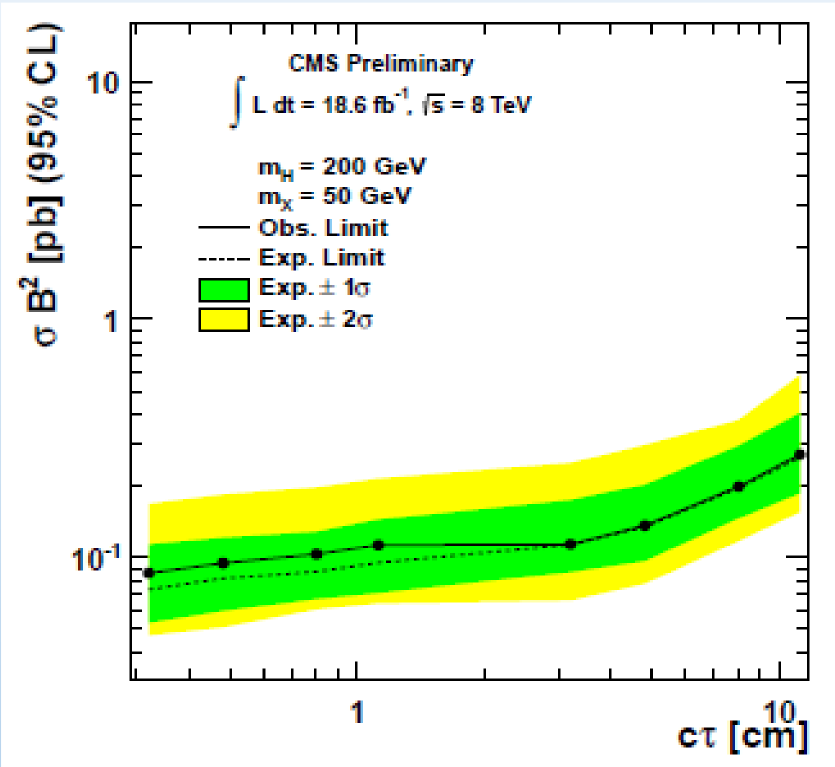
- **Stable** Charged or Colored particles well-studied in 2011-2012 data
- **Stopped** particles well-studied, though are there any biases that could be relaxed?
- Particles **decaying in flight** across the detector are a still problematic frontier
  - Studies so far:
    - ATLAS
      - Track stubs from decaying charged particle (requires MET, clean stub)
      - Displaced vertices in muon system (requires 2 vertices)
      - Displaced very light muon pairs (m_{ll} = 0.4 GeV only, 2 vertices)
      - Multi-track vertices in pixels (requires p_T>50 muon in vertex) ←
      - Non-pointing photons with MET > 75 GeV
    - CMS
      - Late photons + MET (requires p_T>100 GeV, 3 jets, MET~100)
      - Displaced light to medium lepton pairs ←
      - Displaced medium jet pairs ←

Recent CMS Advances

Displaced lepton pair + X



Displaced jet pair + X

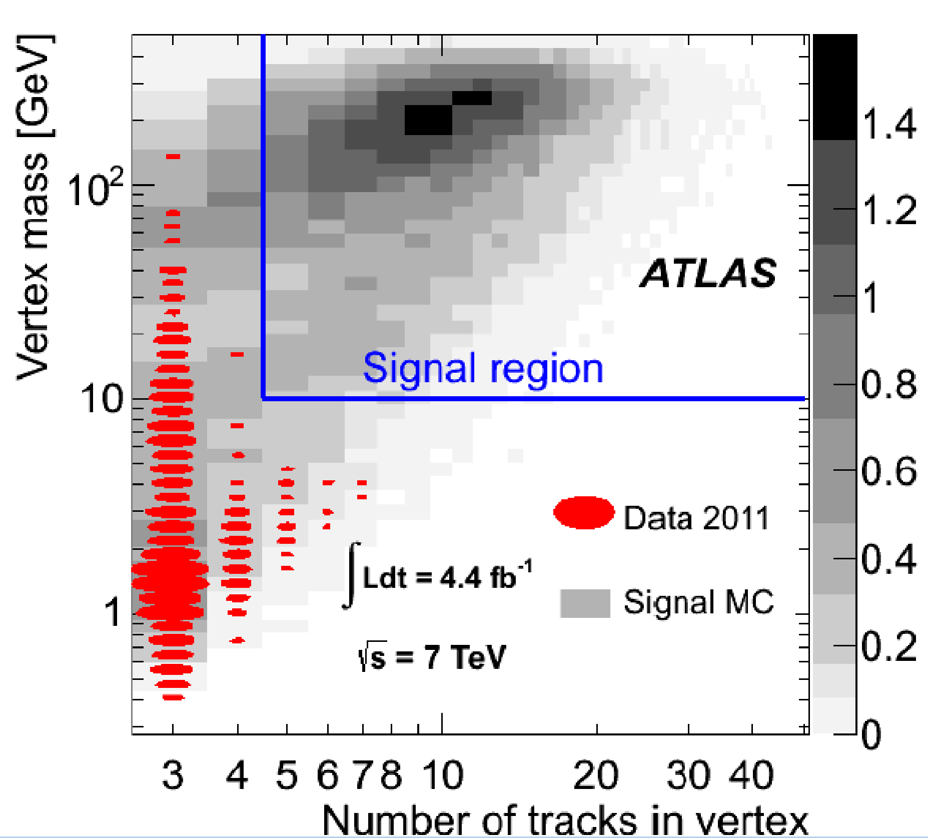


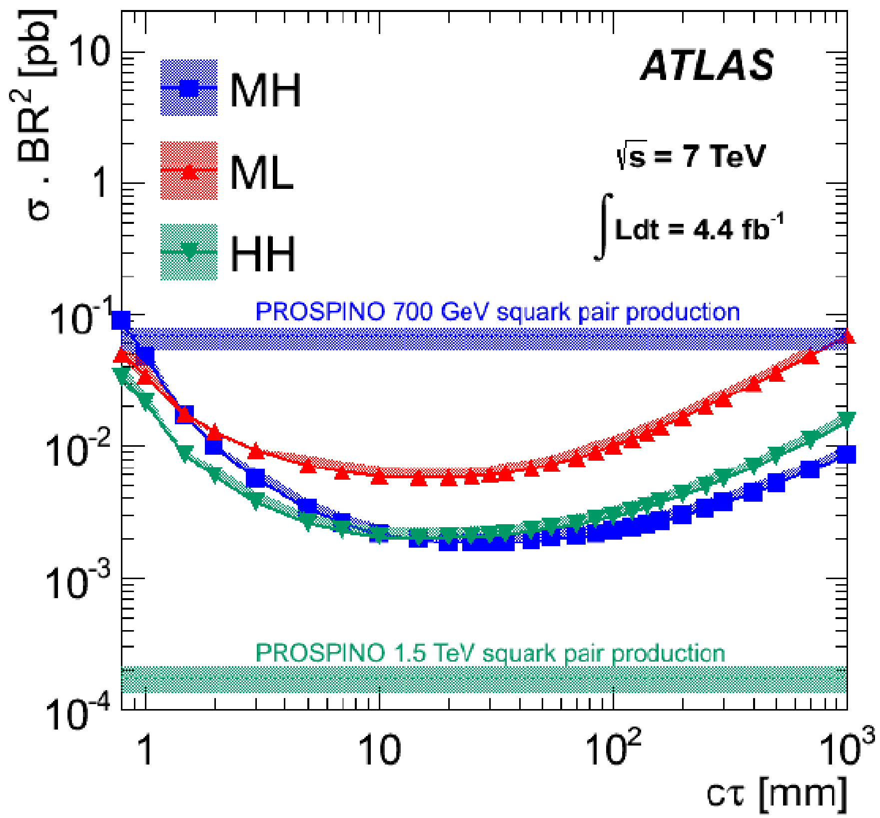
For the electron channel, these data are collected with a trigger that requires two clustered energy deposits in the ECAL, each with transverse energy $E_T > 38$ GeV. For the muon channel, the trigger requires two muons, each reconstructed without using any primary vertex constraint and having $p_T > 30$ GeV/c. The tracker information is not used in either trigger.

that requires the transverse energy sum of all the jets in the event, H_T, to be above 300 GeV and further demands the presence of at least 2 jets, each passing the following criteria:

- $p_T > 60$ GeV and $|\eta| < 2$;
- not more than two associated tracks that have impact parameters smaller than 300 μm;
- not more than 15% of the total jet energy to be carried by associated tracks that have transverse impact parameters smaller than 500 μm.

Search for long-lived, heavy particles in final states with a muon and multi-track displaced vertex in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector





It is required that the trigger identifies a muon candidate with transverse momentum $p_T > 40$ GeV and $|\eta| < 1.05$,

To ensure that the muon candidate is associated with the reconstructed DV, the distance of closest approach of the muon with respect to the DV is required to be less than 0.5 mm. This requirement ensures that the vertex that we reconstruct gave rise to the muon that triggered the event,

We Need to Push Harder

- With some efficiency, most LLE, LQD, UUD cases all covered for medium lifetime
  - Vertex pointing requirement should be relaxed
  - Squark → quark + electron
  - Slepton → lepton + neutrino challenging

- Long Lifetime
  - Particle with ~ 100 ns lifetime or greater usually escapes detector
    - Even if produced in pairs, usually get MET, at most get one vtx in detector
    - MUST be rare or we'd have seen a MET signal
    - So must search for single vertex + MET in outer portions of detector
      - [ATLAS ideal]
    - Or a muon coming from nowhere?
      - [CMS opportunity?]
- Short Lifetime
  - Particle with ~ps lifetime confusable with b's
  - Must look for high-mass displaced vertex and distinguish from overlapping b's

Summary

- Gluinos in RPV appear to be almost fully covered over 1 TeV
  - Cases with tops or intrinsic MET are mostly covered robustly
- All/Mostly-Hadronic Final States –
  - Often gluinos exceed QCD backgrounds and observed data
  - Specific kinematic regimes challenge the existing strategies
  - Need QCD theorists and experimentalists to discuss systematics
- Searches with systematic coverage
  - Within them: searches for resonances
- Long-Lived Particles –
  - Searches finally becoming mature; need to keep raising the bar
  - Missing cases, reinterpretations, longer/shorter lifetimes
- Other topics not covered
  - Boosted techniques