MITP Program: Probing the TeV scale and beyond
JGU Mainz, July 2014

# Toward Full LHC Coverage of Natural Supersymmetry

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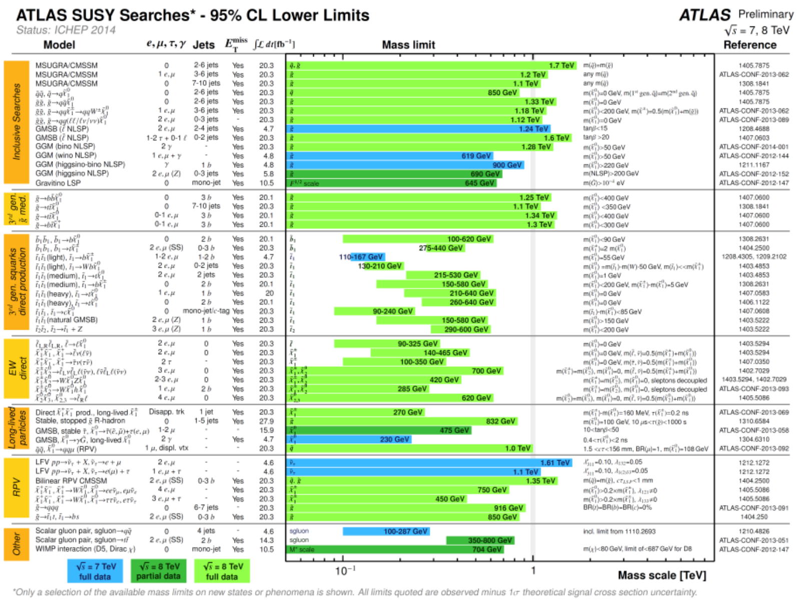
*Weizmann Institute*

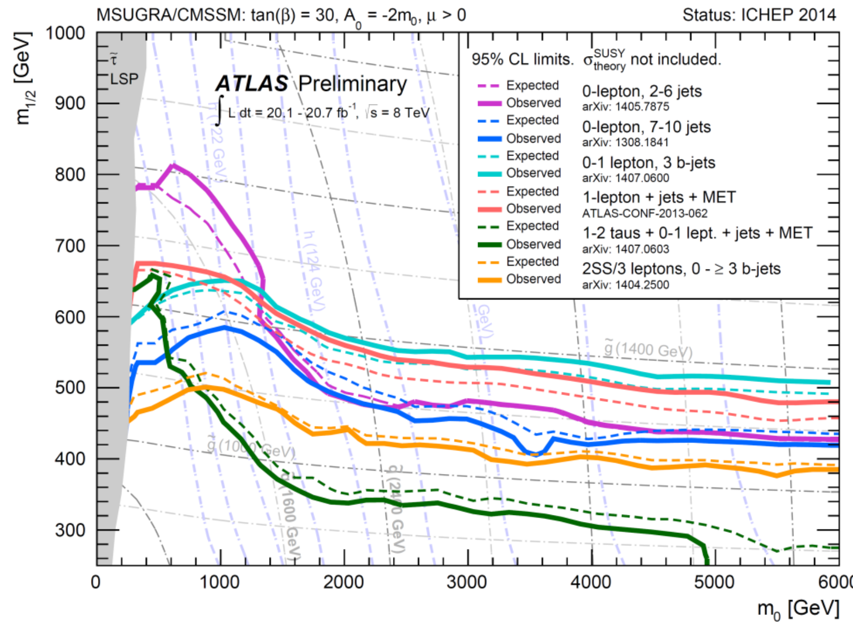
Work with Jared Evans, David Shih, Matt Strassler

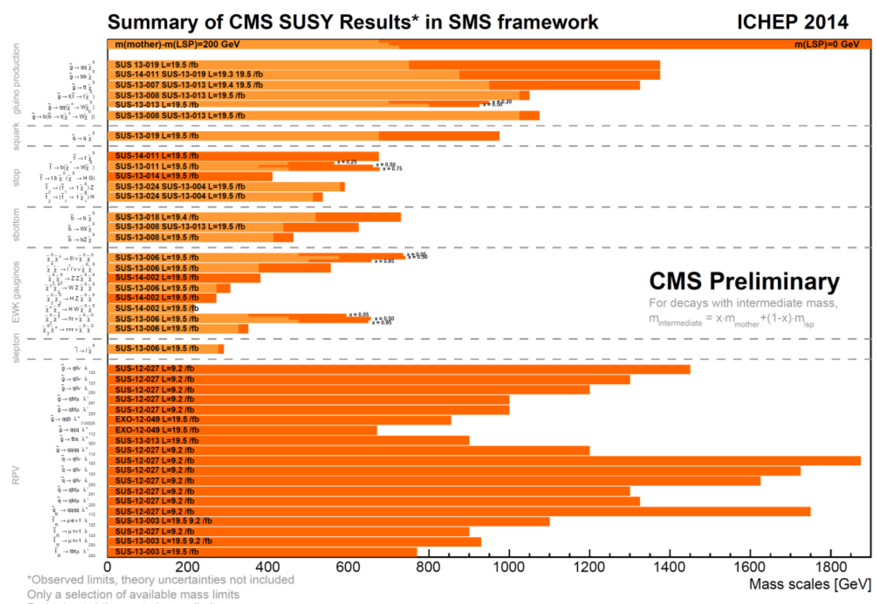
**arXiv:1310.5758**

# Motivation

LHC has excluded many “motivated” and simplified models of SUSY.



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But…

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… there are many possible superpartner spectra

ways to violate $R$-parity

ways to extend the MSSM

**To what extent has the LHC excluded SUSY *in general* ?**

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Main motivation for SUSY at LHC

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125 GeV | SUSY | soft

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$m_H^2$: 125 GeV; $|\mu|^2$: SUSY; $m_{H_u}^2$: soft

Stops (and gluinos) contribute to $m_{H_u}^2$ at 1 loop (2 loops).

**Has the LHC *done all it could* to discover/exclude *natural* SUSY?**

If holes exist, can new search strategies help?

# Scope of our work

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**Any (motivated / not yet motivated) extension of the MSSM, any spectrum (in particular, any LSP), any RPV, etc.**

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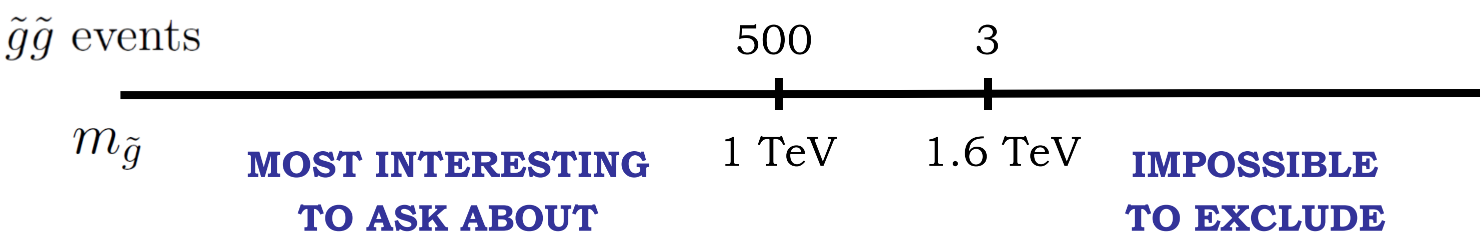


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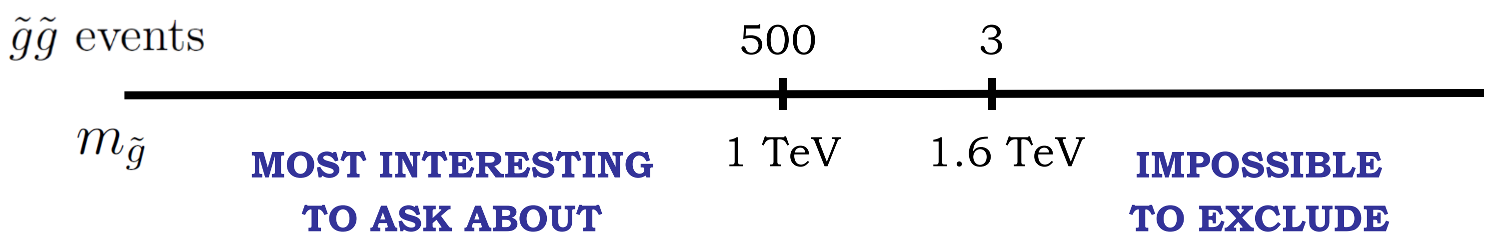



**Has the LHC *done all it could* to discover/exclude *natural* SUSY?**

- **All decays are prompt** (otherwise experimental subtleties may play a role)

# Line of reasoning

- Gluino events (almost) always contain **at least one** of 3 signatures:
  (1) **Missing energy (MET)** (e.g., stable LSP)
  (2) **Top quarks** (e.g., decays via stops)
  (3) **High object multiplicity** (6 or more)

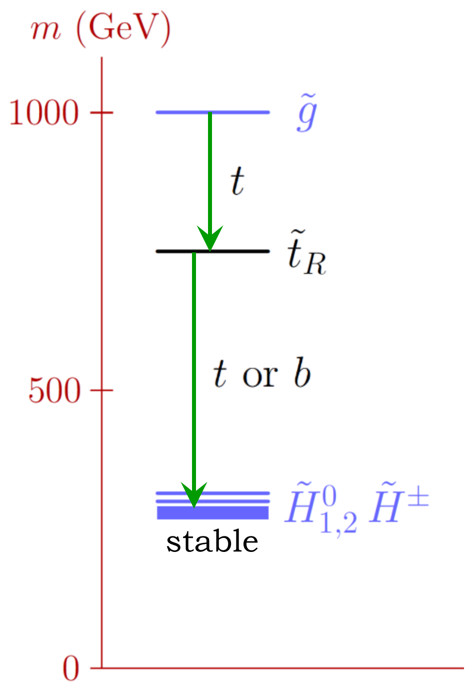
  *Gluino*

- There exist **model-independent searches** sensitive to **each** of these signatures.

- These searches exclude gluinos up to ~ 1 TeV even in **very conservative scenarios**.

# Setting the stage

Example: "minimal" natural SUSY scenario




$pp \to \tilde{g}\tilde{g}$

Large MET

Tops

Multiple jets

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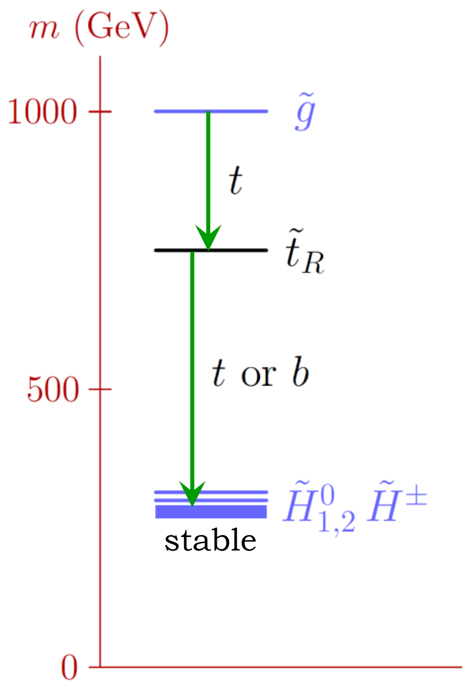


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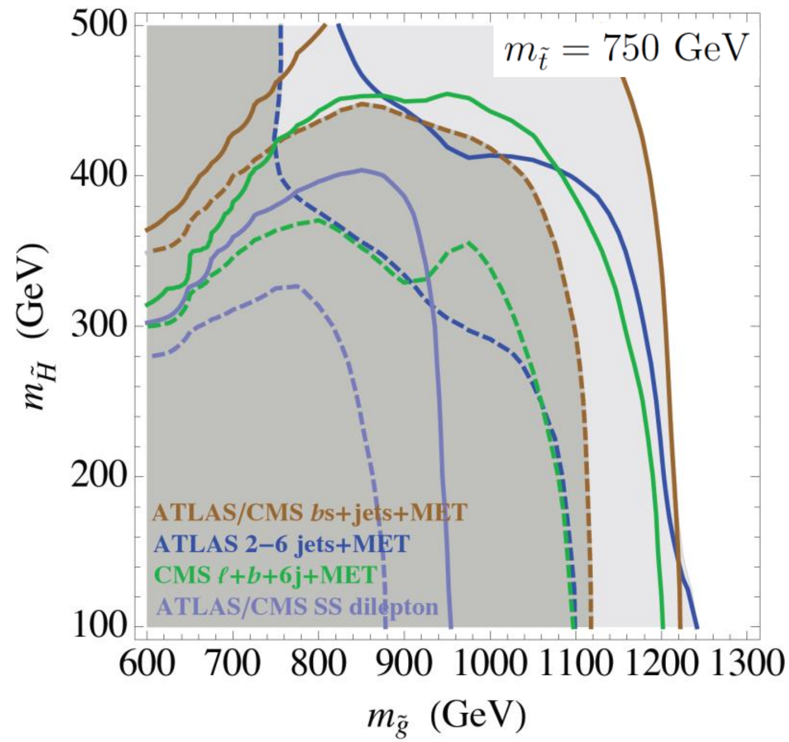

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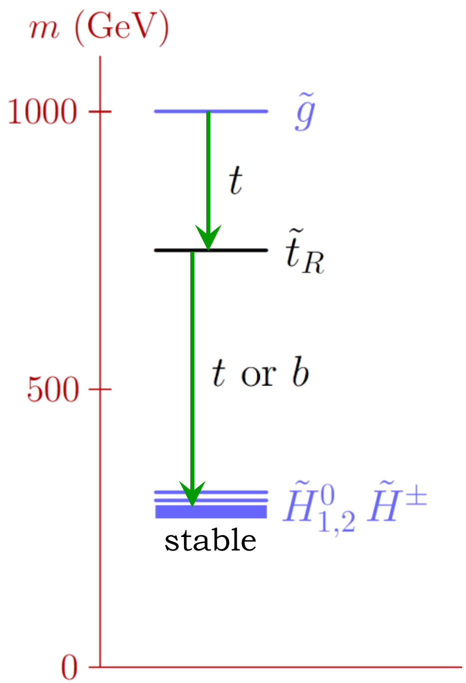


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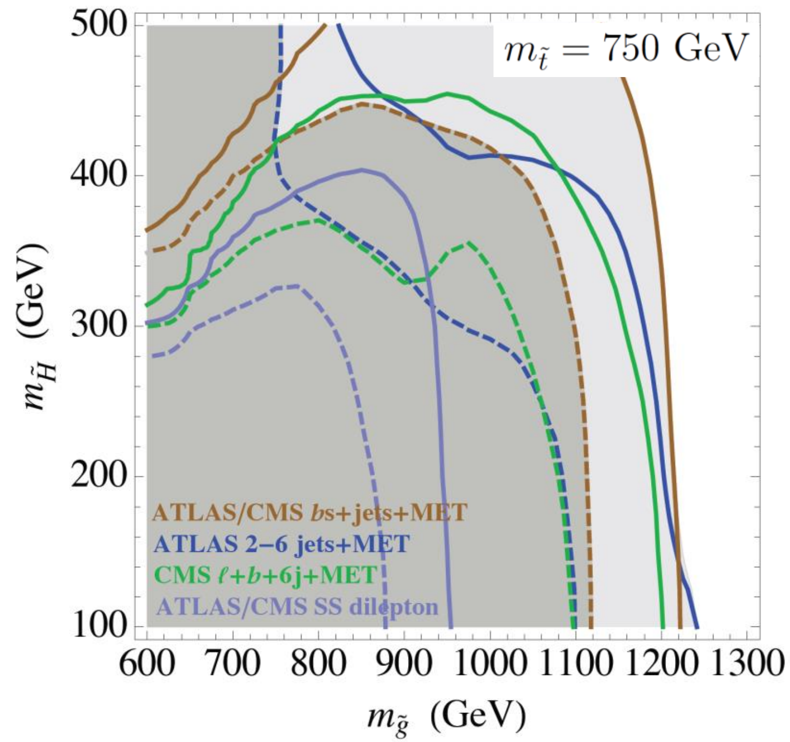



**Next steps:** examine scenarios with...

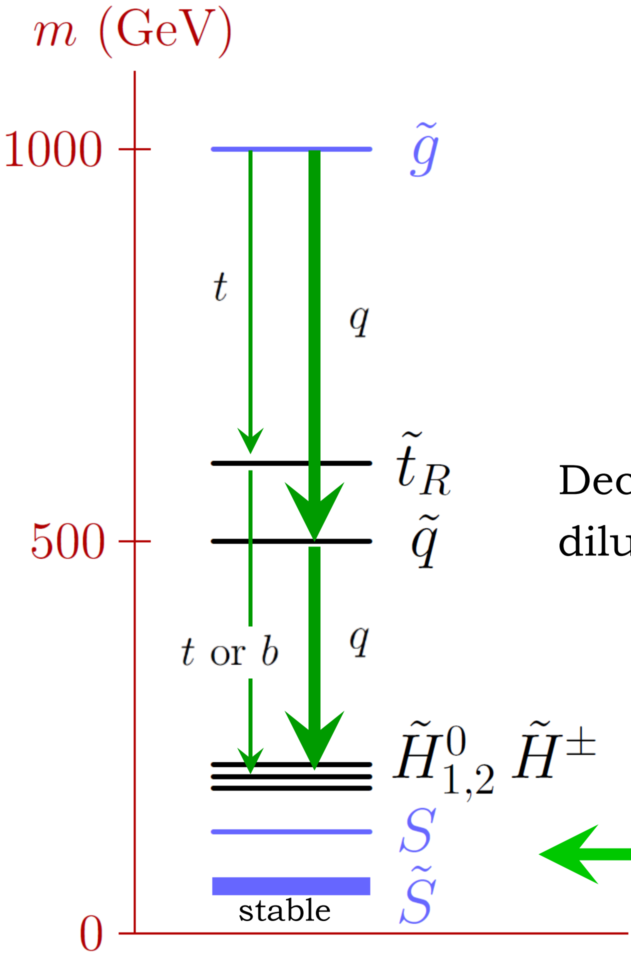
- Varying **MET**. (Almost) no tops
- **Tops.** No MET from the LSP
- No MET. No tops. Varying jet **multiplicity**

and no other helpful objects (leptons/photons/$b$-jets)

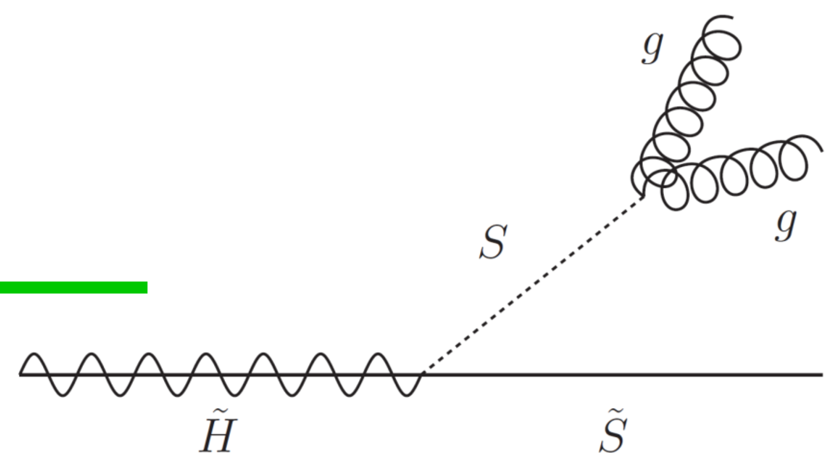
# Most important searches

| | | ATLAS EXPERIMENT | CMS |
|---|---|---|---|
| MET | **large MET + several jets** | CONF-2013-047 | PAS-SUS-13-012 |
| MET / tops | **low MET + many jets** | arXiv:1308.1841 | |
| tops | **lepton + *b* + many jets** | theoretical proposal arXiv:1107.5055 | |
| jet multiplicity | **6-7 high-$p_T$ jets** | CONF-2013-091 | |
| jet multiplicity | **high object multiplicity ("black hole")** | | arXiv:1303.5338 special interpretation |

# Varying MET, (almost) no tops



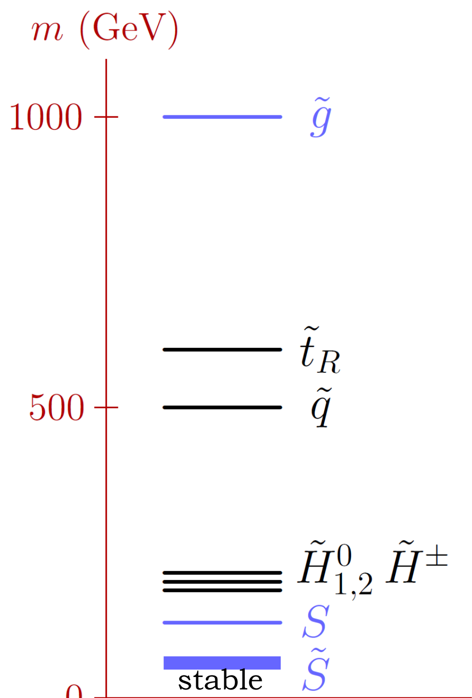

Decays via 2nd-gen. squarks
dilute/eliminate decays with tops



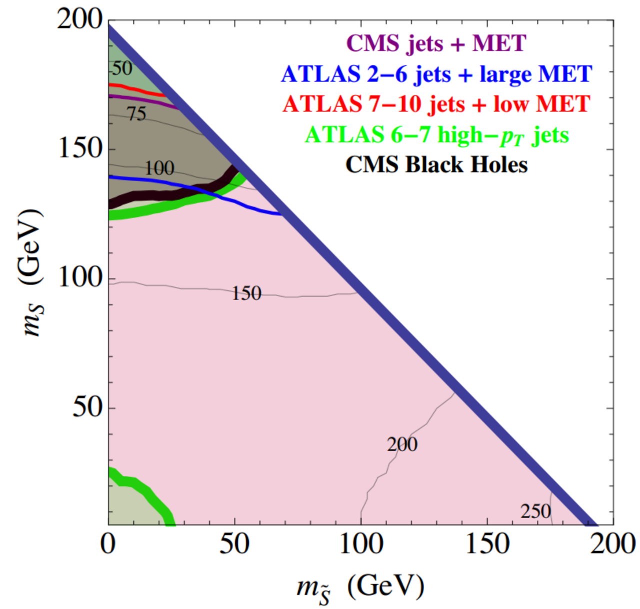

MET determined by masses of "hidden valley" particles $S$, $\tilde{S}$

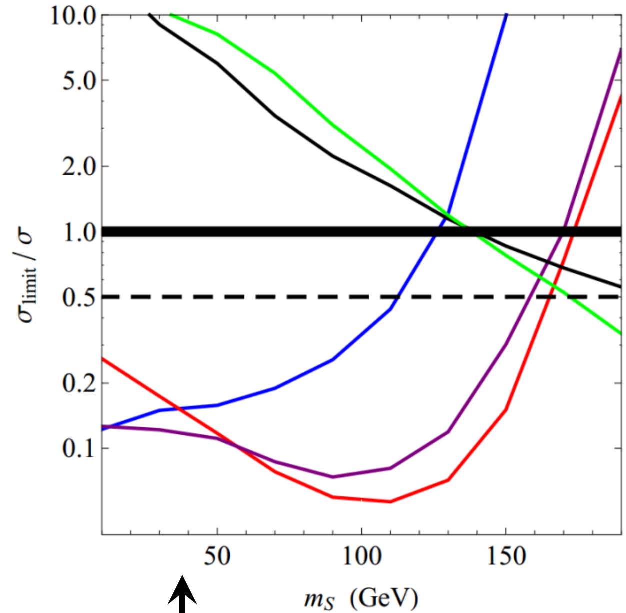
**MET** $\rightarrow$ **2 jets** (per gluino)

# Varying MET, (almost) no tops

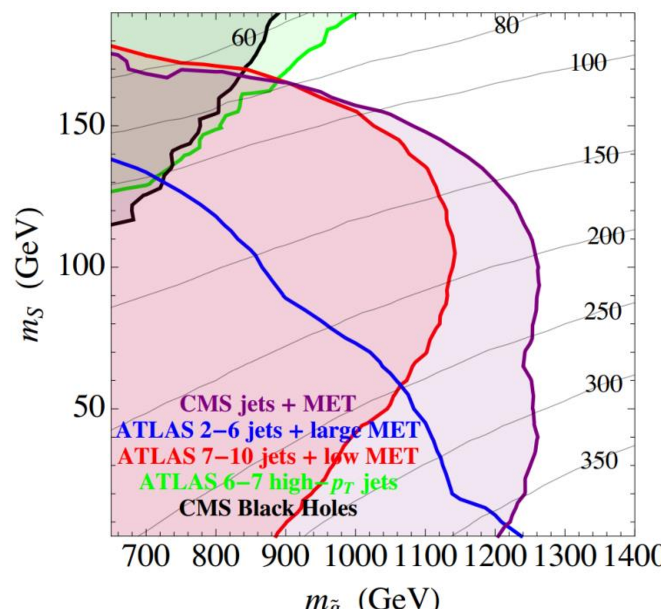



$m_{\tilde{g}} = 750$ GeV, $m_{\tilde{t}} = 600$ GeV, $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{H}} = 200$ GeV



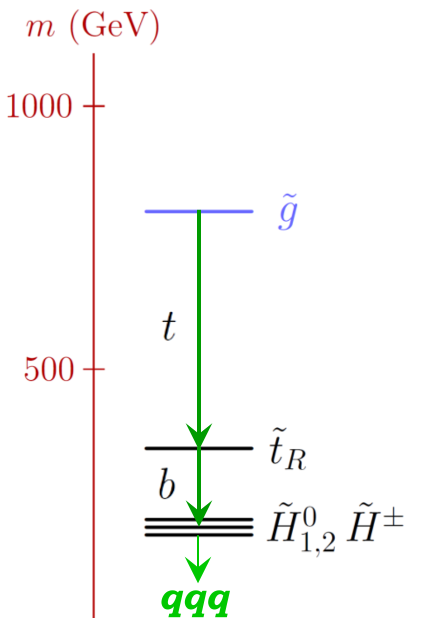

$m_S + m_{\tilde{S}} = 190$ GeV

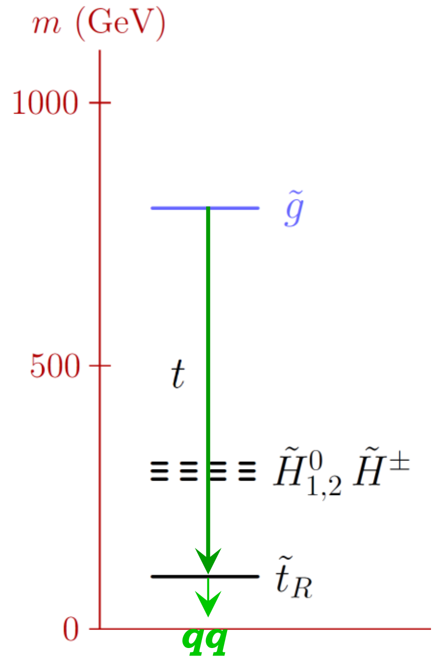



**The gluino can't hide**

You have either enough MET or sufficiently large jet multiplicity.

# Tops, no MET from LSP



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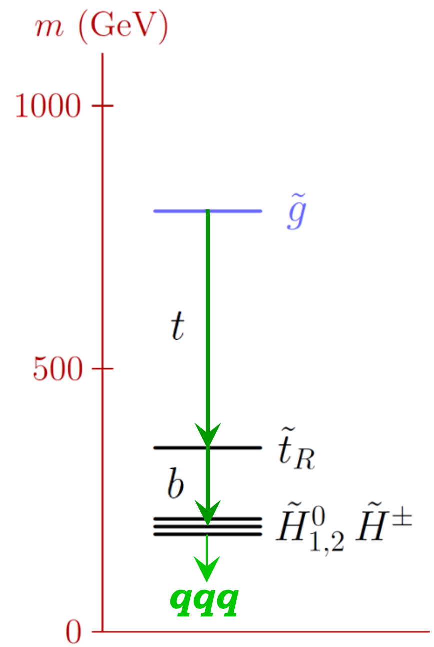
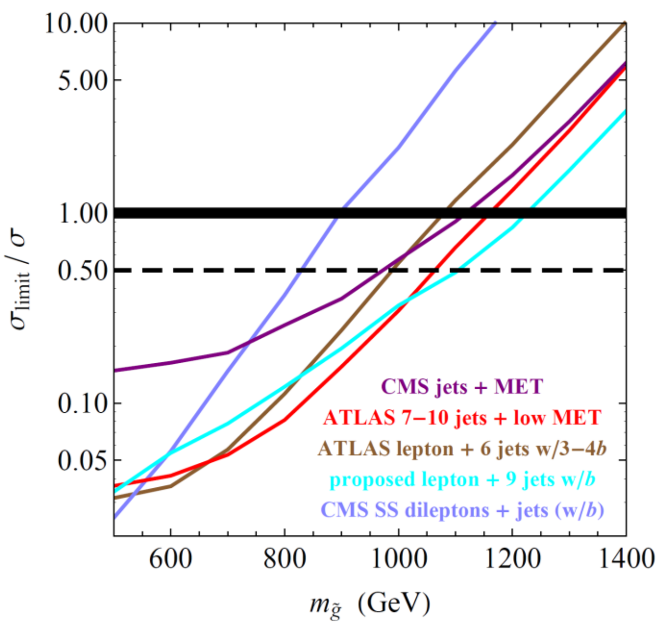
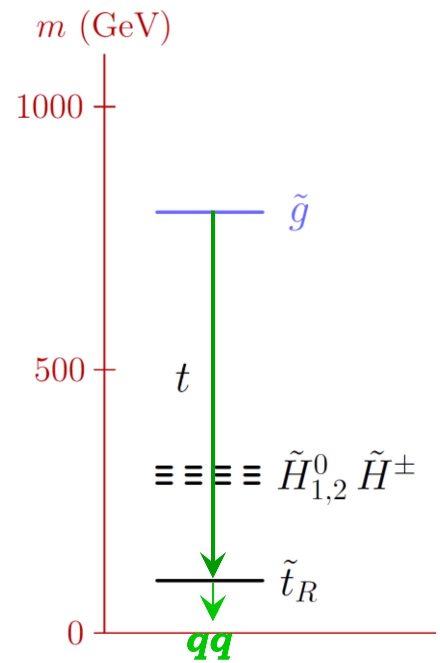
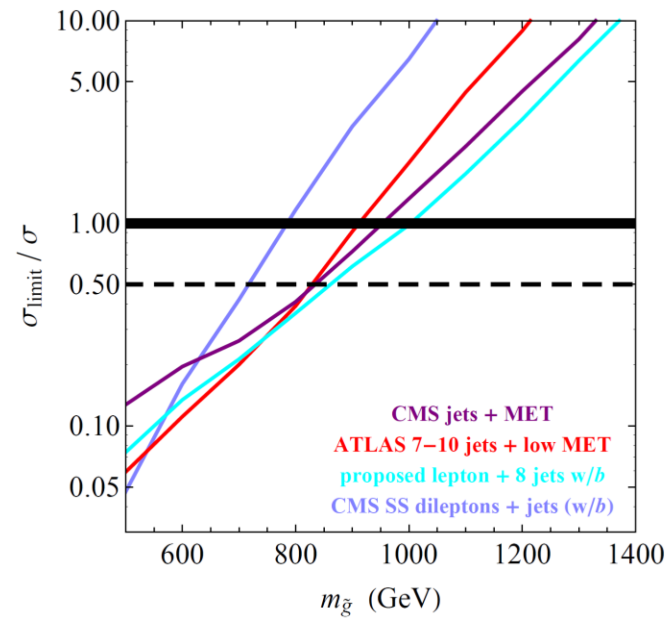


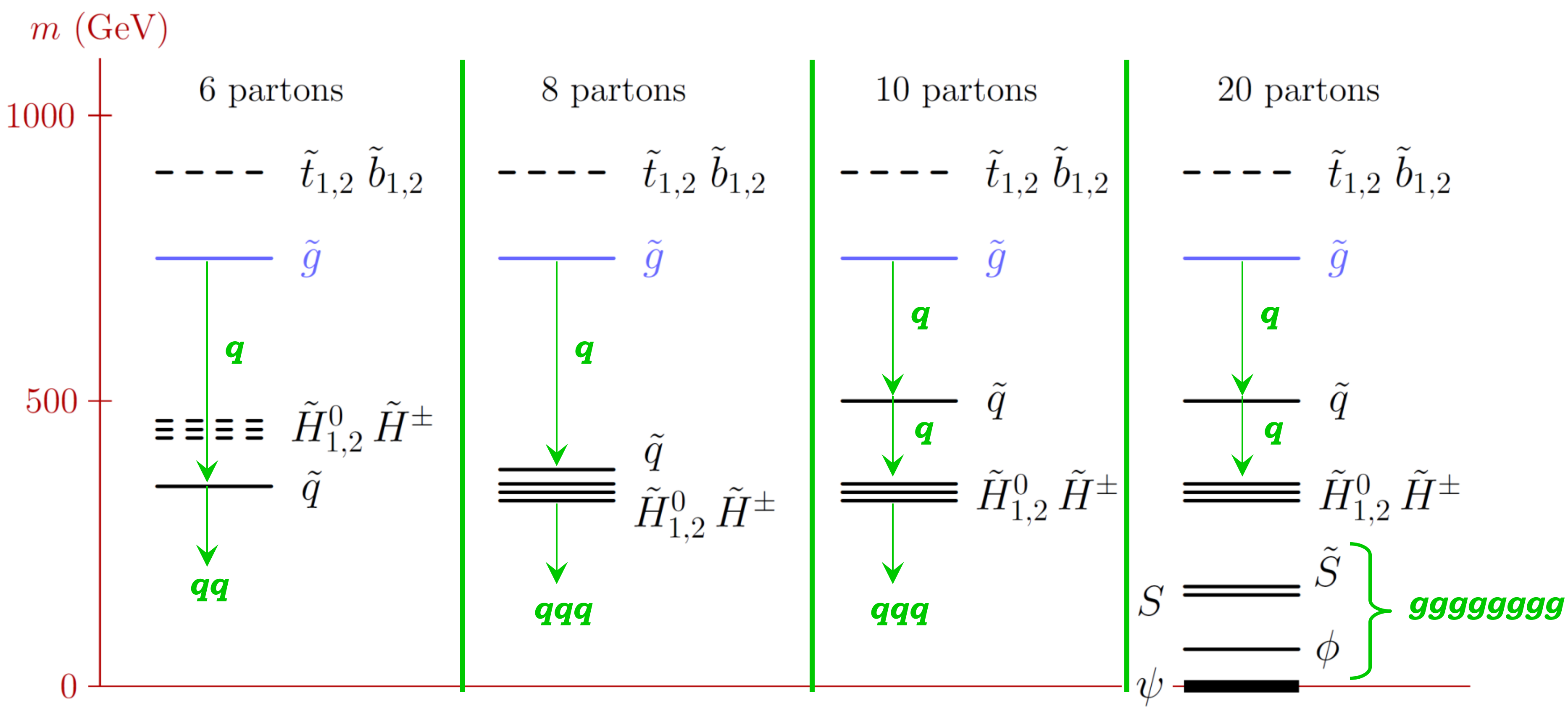

**Low MET + many jets searches**

- Neutrinos from tops provide enough MET
- Neutrino always appears with a lepton, but lepton veto is evaded by $\tau_h$ / lost $e$, $\mu$

**Proposed lepton + many jets search**

Strongest (or comparable) limits expected

# All-hadronic final states (no MET, no tops)



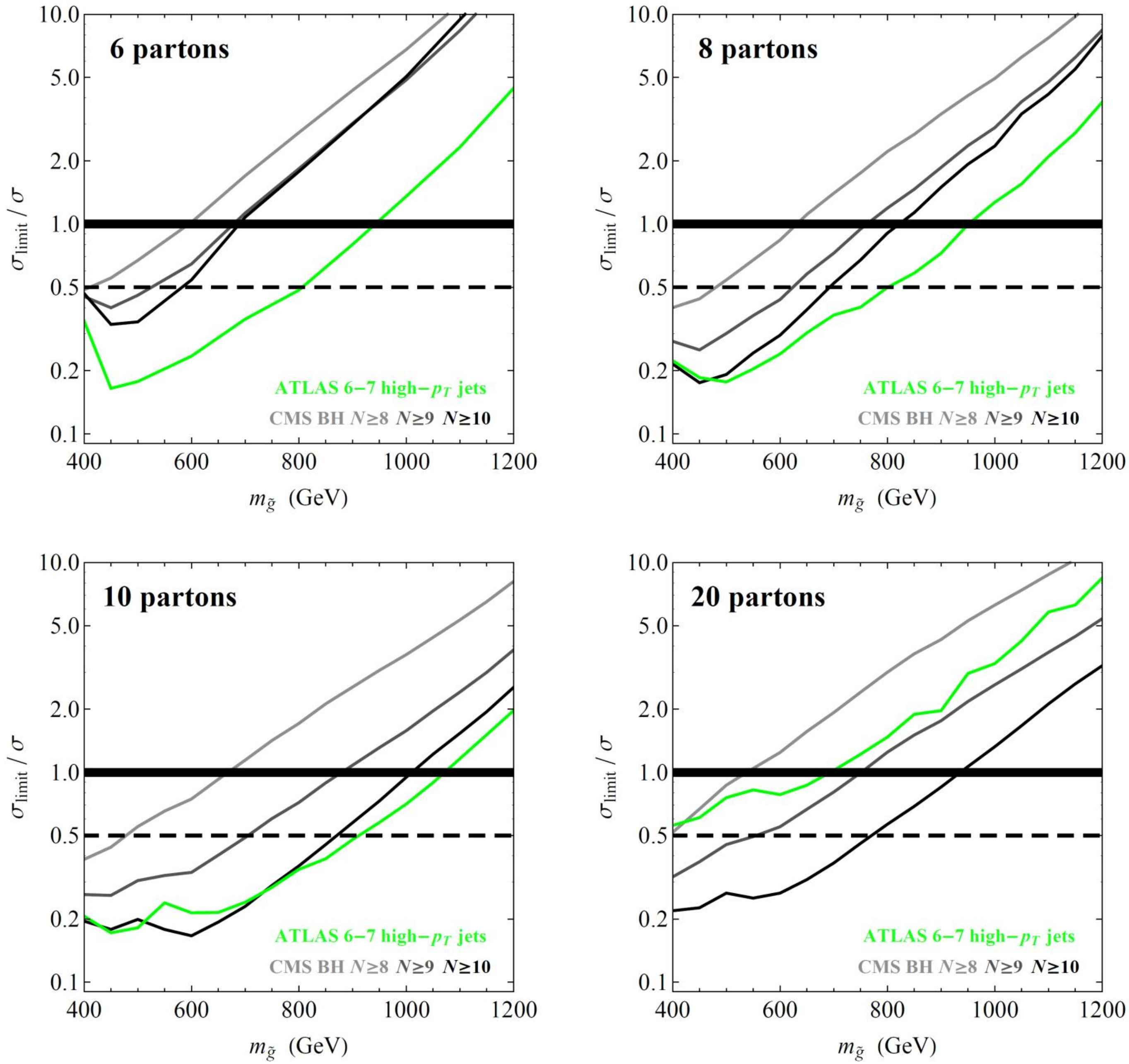

$$\tilde{H}^0_1 \to S\tilde{S}$$

$$\tilde{S} \to S\psi$$

$$S \to \phi\phi$$

$$\phi \to gg$$

# All-hadronic final states (no MET, no tops)

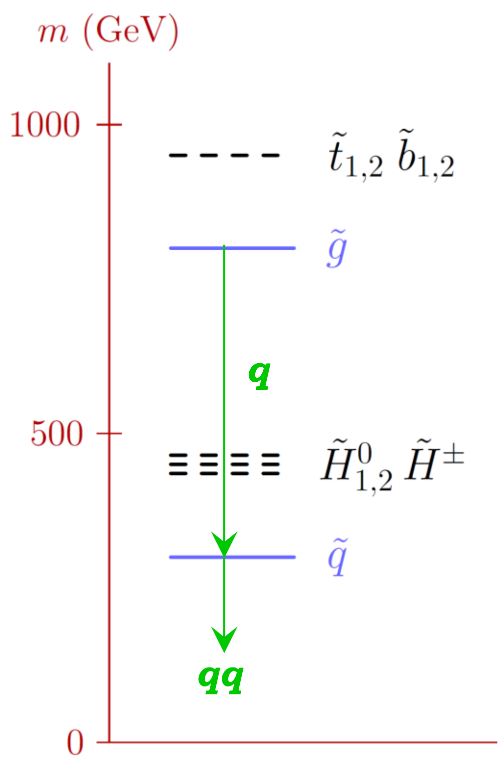


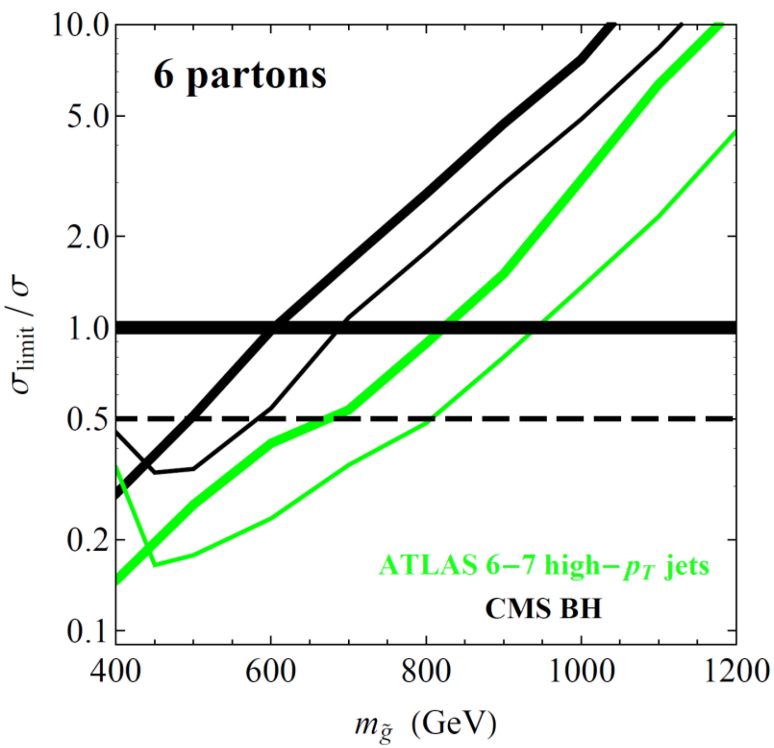
# Non-generic all-hadronic scenarios

Searches not sufficiently diverse.

- $S_T$ range of CMS BH search is **too high** for gluinos
- Both searches: unsophisticated object selection:
  # objects above a **uniform** $p_T$ threshold
- No search considers jet **substructure**

Indeed, some cases (usually containing **hierarchies**) have weaker limits:




Thin

$m_{\tilde{q}} = 350$ GeV

**Thick**

$m_{\tilde{q}} = 150$ GeV

A more comprehensive set of all-hadronic searches is motivated!

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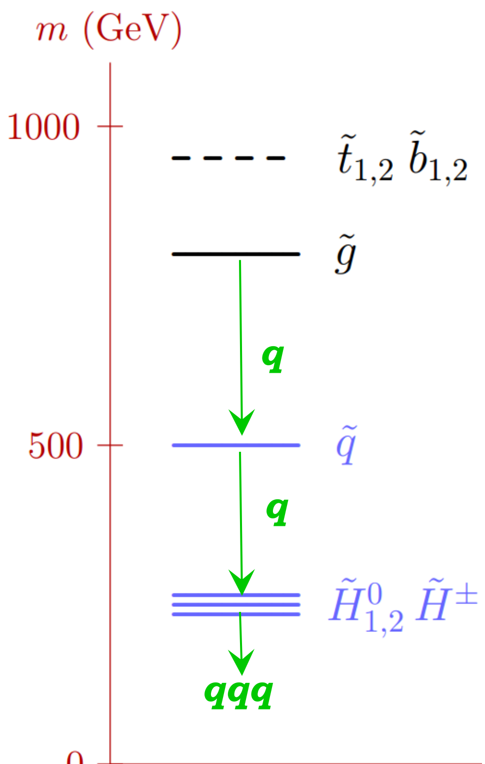


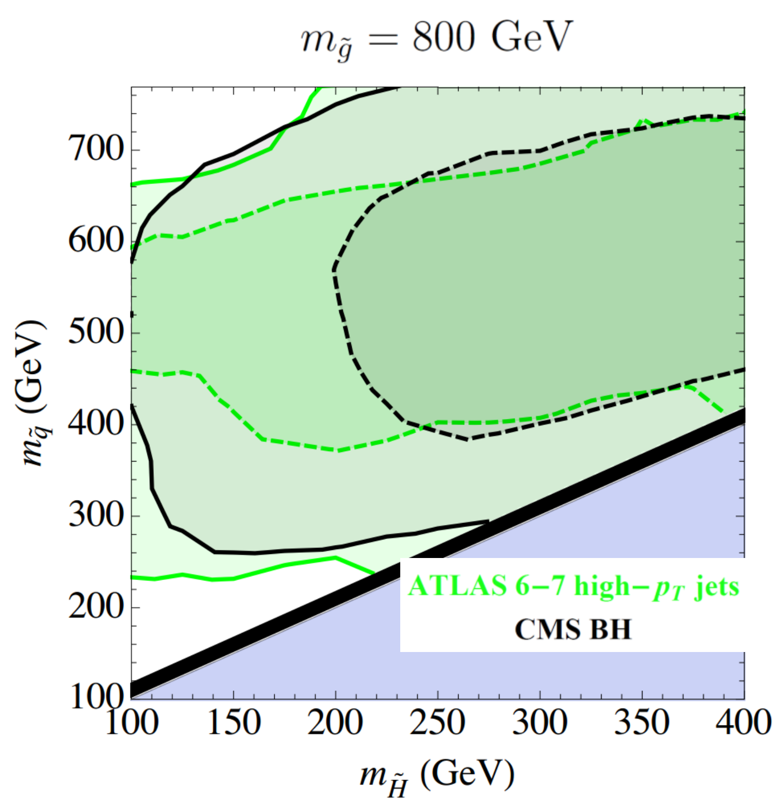


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# Summary

- Gluino events (almost) always contain **at least one** of 3 signatures:
  (1) **Missing energy (MET)** (e.g., stable LSP)
  (2) **Top quarks** (e.g., decays via stops)
  (3) **High object multiplicity** (6 or more)
- There exist **model-independent searches** sensitive to **each** of these signatures.
- These searches exclude gluinos up to ~ 1 TeV even in **very conservative scenarios**.

## Motivated additional searches

For scenarios with **tops** and **no MET** from LSP:

- Lepton + $b$ + many jets

For **all-hadronic** scenarios:

- "CMS BH"-like search for lower $S_T$
- Staggered $p_T$ cuts (will likely require use of additional kinematic properties for background reduction)
- Jet substructure

# Additional Material

# Simulation and limit setting

- Process generation and showering in Pythia
- Detector simulation (incl. FastJet), with:
  - Lepton ID eff. (per search)
  - Lepton isolation (per search)
  - Jet energy resolution
  - *b*-tagging (per search)
  - and more…
- Event selection as used in each search
- Validation on examples from ATLAS/CMS papers: typically agree within ~30% (sometimes a factor of ~2)
- Signal efficiency threshold ~ $10^{-4}$ (instead of including systematic uncertainty for signal tails)
- Limits based on ATLAS/CMS's background estimates for each search region. Search region giving the best limit is used.

# MET-based searches

**Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum and 20.3 fb$^{-1}$ of $\sqrt{s}$ = 8 TeV proton-proton collision data**

**ATLAS CONF-2013-047**

| Requirement | Channel | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A (2-jets) | | B (3-jets) | | C (4-jets) | | D (5-jets) | E (6-jets) | | |
| | L | M | M | T | M | T | – | L | M | T |
| $E_T^{miss}$[GeV] > | 160 | | | | | | | | | |
| $p_T(j_1)$ [GeV] > | 130 | | | | | | | | | |
| $p_T(j_2)$ [GeV] > | 60 | | | | | | | | | |
| $p_T(j_3)$ [GeV] > | – | | 60 | | 60 | | 60 | 60 | | |
| $p_T(j_4)$ [GeV] > | – | | – | | 60 | | 60 | 60 | | |
| $p_T(j_5)$ [GeV] > | – | | – | | – | | 60 | 60 | | |
| $p_T(j_6)$ [GeV] > | – | | – | | – | | – | 60 | | |
| $\Delta\phi(\text{jet}_i, \mathbf{E}_T^{miss})_{min}$ > | 0.4 ($i$ = {1, 2, (3 if $p_T(j_3)$ > 40 GeV)}) | | | | 0.4 ($i$ = {1, 2, 3}), 0.2 ($p_T$ > 40 GeV jets) | | | | | |
| $E_T^{miss}/m_{eff}(Nj)$ > | 0.2 | –[a] | 0.3 | 0.4 | 0.25 | 0.25 | 0.2 | 0.15 | 0.2 | 0.25 |
| $m_{eff}$(incl.) [GeV] > | 1000 | 1600 | 1800 | 2200 | 1200 | 2200 | 1600 | 1000 | 1200 | 1500 |

(a) For SR A-medium the cut on $E_T^{miss}/m_{eff}(Nj)$ is replaced by a requirement $E_T^{miss}/\sqrt{H_T}$ > 15 GeV$^{1/2}$.

**Search for new phenomena in final states with large jet multiplicities and missing transverse momentum at $\sqrt{s}$ = 8 TeV proton-proton collisions using the ATLAS experiment**

**ATLAS arXiv:1308.1841**

| | Multi-jet + flavour stream | | | | | Multi-jet + $M_J^\Sigma$ stream | | |
|---|---|---|---|---|---|---|---|---|
| Identifier | 8j50 | 9j50 | ≥ 10j50 | 7j80 | ≥ 8j80 | ≥ 8j50 | ≥ 9j50 | ≥ 10j50 |
| Jet $\|\eta\|$ | < 2.0 | | | < 2.0 | | < 2.8 | | |
| Jet $p_T$ | > 50 GeV | | | > 80 GeV | | > 50 GeV | | |
| Jet count | = 8 | = 9 | ≥ 10 | = 7 | ≥ 8 | ≥ 8 | ≥ 9 | ≥ 10 |
| $b$-jets ($p_T$ > 40 GeV, $\|\eta\|$ < 2.5) | 0 \| 1 \| ≥ 2 | 0 \| 1 \| ≥ 2 | — | 0 \| 1 \| ≥ 2 | 0 \| 1 \| ≥ 2 | — | | |
| $M_J^\Sigma$ [GeV] | — | | | — | | > 340 and > 420 for each case | | |
| $E_T^{miss}/\sqrt{H_T}$ | > 4 GeV$^{1/2}$ | | | > 4 GeV$^{1/2}$ | | > 4 GeV$^{1/2}$ | | |

**large MET + several jets**

**low MET + many jets**

**CMS-PAS-SUS-13-012**

Search for New Physics in the Multijets and Missing Momentum Final State in Proton-Proton Collisions at $\sqrt{s}$ = 8 TeV

| $N_{jets}$ | $H_T$ | $\not{H}_T$ |
|---|---|---|
| 3-5 | 500-800 | 200-300 |
| 3-5 | 500-800 | 300-450 |
| 3-5 | 500-800 | 450-600 |
| 3-5 | 500-800 | > 600 |
| 3-5 | 800-1000 | 200-300 |
| 3-5 | 800-1000 | 300-450 |
| 3-5 | 800-1000 | 450-600 |
| 3-5 | 800-1000 | > 600 |
| 3-5 | 1000-1250 | 200-300 |
| 3-5 | 1000-1250 | 300-450 |
| 3-5 | 1000-1250 | 450-600 |
| 3-5 | 1000-1250 | > 600 |
| 3-5 | 1250-1500 | 200-300 |
| 3-5 | 1250-1500 | 300-450 |
| 3-5 | 1250-1500 | > 450 |
| 3-5 | >1500 | 200-300 |
| 3-5 | >1500 | > 300 |
| 6-7 | 500-800 | 200-300 |
| 6-7 | 500-800 | 300-450 |
| 6-7 | 500-800 | > 450 |
| 6-7 | 800-1000 | 200-300 |
| 6-7 | 800-1000 | 300-450 |
| 6-7 | 800-1000 | > 450 |
| 6-7 | 1000-1250 | 200-300 |
| 6-7 | 1000-1250 | 300-450 |
| 6-7 | 1000-1250 | > 450 |
| 6-7 | 1250-1500 | 200-300 |
| 6-7 | 1250-1500 | 300-450 |
| 6-7 | 1250-1500 | > 450 |
| 6-7 | >1500 | 200-300 |
| 6-7 | >1500 | > 300 |
| ≥8 | 500-800 | > 200 |
| ≥8 | 800-1000 | > 200 |
| ≥8 | 1000-1250 | > 200 |
| ≥8 | 1250-1500 | > 200 |
| ≥8 | 1500- | > 200 |

# Top-based searches
## Proposed $\ell$ + $b$ + many jets

**Study of LHC Searches for a Lepton and Many Jets**

Lisanti, Schuster, Strassler, Toro
JHEP 1211 (2012) 081 [arXiv:1107.5055]

**Basic idea:** can use high jet multiplicity instead of MET

**Event selection:** lepton + $b$ + many jets (+ very low MET)

**Dominant background:** $t\bar{t}$ + jets

**Look for signal on the tail of $S_T$ distribution**

**Some *b'*, *t'* searches are similar, but not sufficiently general:**

- Jet multiplicity not sufficiently high
- $b$-tag multiplicity too high
- Too model-specific (e.g., use BDT)

# $\ell$ + $b$ + many jets

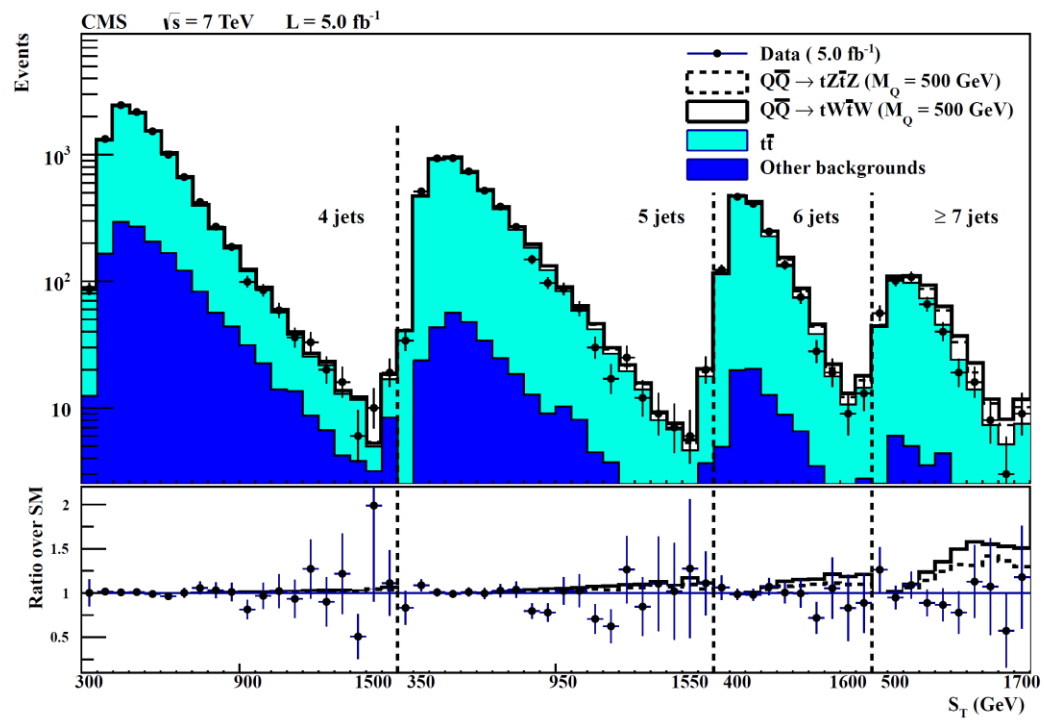
CMS-PAS-B2G-12-004, arXiv:1210.7471 (5/fb at 7 TeV)

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
- MET > 20 GeV
- 1+ $b$-tags
- $N_{\text{jets}} = 4, 5, 6, 7+$ (with $p_T > 35$ GeV)
- $S_T$ distributions (incl. lepton, jets, MET)



# Proposed $\ell$ + $b$ + many jets

## Expected limits for 20/fb at 8 TeV

**Selection**

Same as in 7 TeV CMS search:

- Leptons, jets, MET, $b$-tagging

Different from CMS search:

- $N_{\text{jets}}$ = 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 5 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**

Hard for us to estimate. Assume 50% (probably conservative).

| $S_T$ cut (GeV) | Background events | | | Limit on $\sigma \times \epsilon$ (fb) | | |
|---|---|---|---|---|---|---|
| | $n \geq 7$ | $n \geq 8$ | $n \geq 9$ | $n \geq 7$ | $n \geq 8$ | $n \geq 9$ |
| 800 | 1740 | 480 | 119 | 73 | 20 | 5.1 |
| 1000 | 830 | 280 | 86 | 35 | 11.8 | 3.7 |
| 1200 | 370 | 141 | 52 | 15.5 | 6.0 | 2.3 |
| 1400 | 164 | 64 | 27 | 7.0 | 2.8 | 1.24 |
| 1600 | 74 | 30 | 13.2 | 3.2 | 1.41 | 0.71 |
| 1800 | 32 | 15.5 | 7.7 | 1.49 | 0.79 | 0.46 |
| 2000 | 14.4 | 6.8 | 2.8 | 0.75 | 0.42 | 0.25 |
| 2200 | 8.1 | 3.7 | 1.54 | 0.50 | 0.29 | 0.2 |
| 2400 | 4.7 | 1.94 | 0.70 | 0.33 | 0.2 | 0.15 |
| 2600 | 2.1 | 1.06 | 0.32 | 0.25 | 0.2 | 0.15 |
| 2800 | 1.20 | 0.42 | 0.13 | 0.2 | 0.15 | 0.15 |
| 3000 | 0.32 | 0 | 0 | 0.15 | 0.15 | 0.15 |

# 6-7 high-$p_T$ jets (no MET)

ATLAS-CONF-2013-091 (20.3/fb at 8 TeV)

a.k.a. **Search for massive particles decaying into multiple quarks with the ATLAS detector in $\sqrt{s}$ = 8 TeV *pp* collisions**

**Search regions**

| $N_{\text{jets}} \geq$ | 6 | 7 | | | | |
|---|---|---|---|---|---|---|
| $p_T >$ (GeV) | 180 | 80 | 100 | 120 | 140 | 180 |

+ similar regions with *b* tagging

# High object multiplicity ("black hole")

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 $N = 3, 4, \ldots, 10$
- $S_T$ distributions

**Background estimation (for each $N$)**

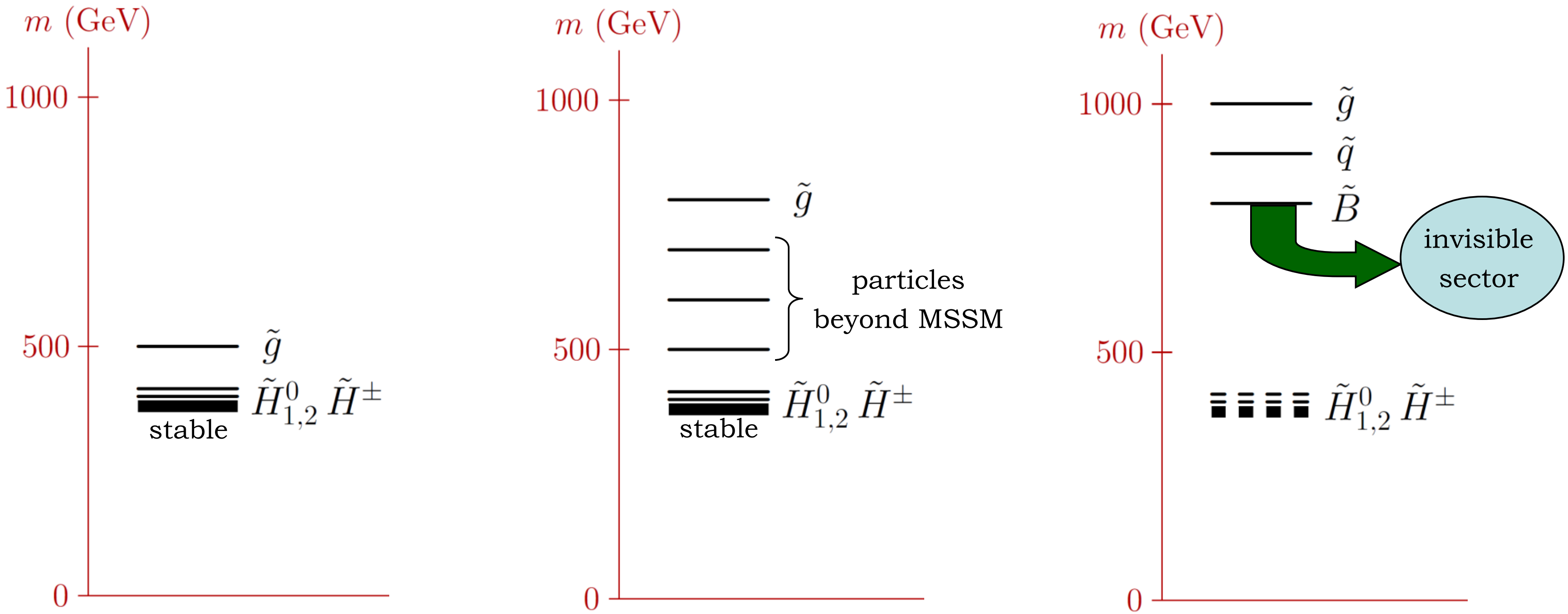
- Shape from $N = 2$ data
- Normalization from control region 1.9 TeV < $S_T$ < 2.3 TeV

**~1 TeV gluinos have $S_T$ ~ 2 TeV**
**Signal contaminates control regions!**

Reinterpret the data **conservatively:**
Set expected background to 0.
Works because **signal is larger than QCD.**

| Search region | | Events | Limit on |
|---|---|---|---|
| $N \geq$ | $S_T$ (GeV) $>$ | in data | $\sigma \times \epsilon$ (fb) |
| 8 | 1900 | 425 | 38 |
| | 2200 | 122 | 11.7 |
| 9 | 1900 | 111 | 10.7 |
| | 2200 | 35 | 3.8 |
| 10 | 1900 | 25 | 2.9 |
| | 2200 | 10 | 1.4 |

# Compressed spectra




In gluino frame: LSP approximately at rest

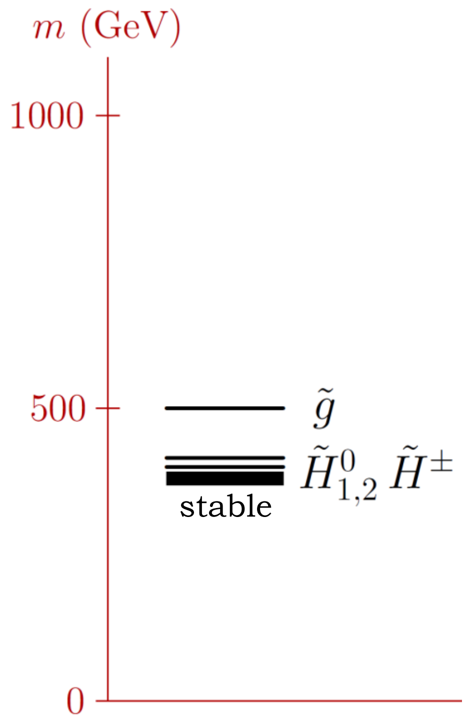
↓

In collision frame: LSPs back-to-back

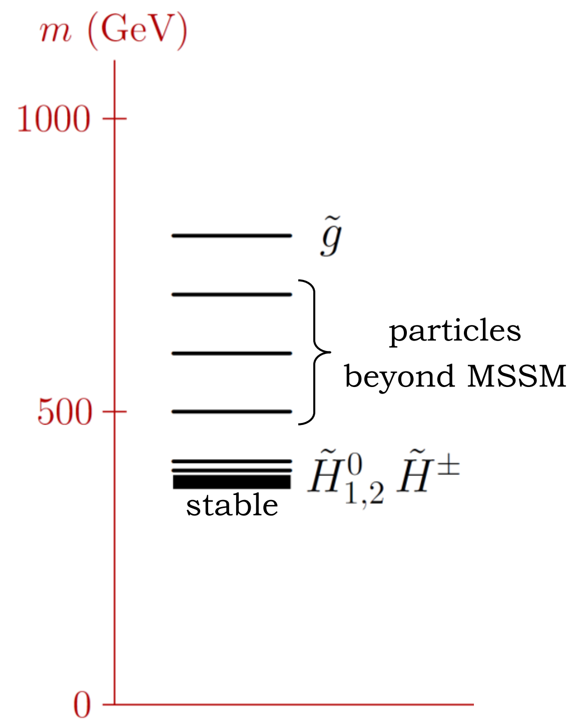
↓

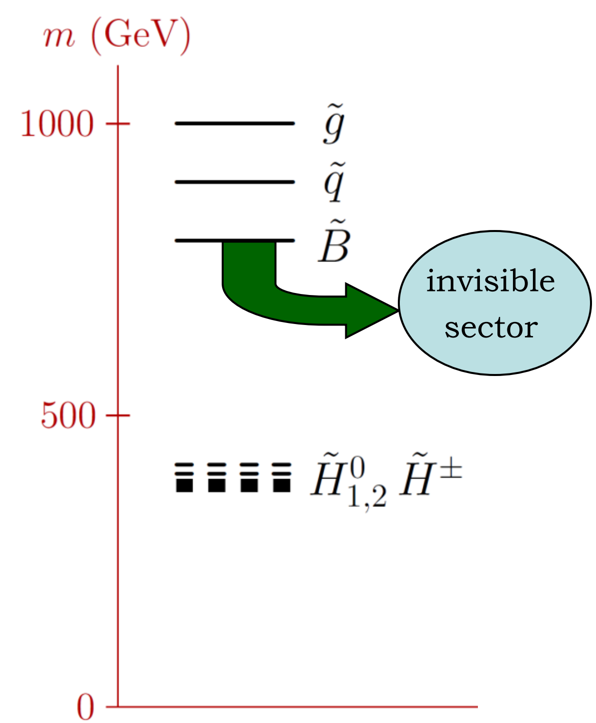
MET is very low
(and no hard jets)

# Compressed spectra

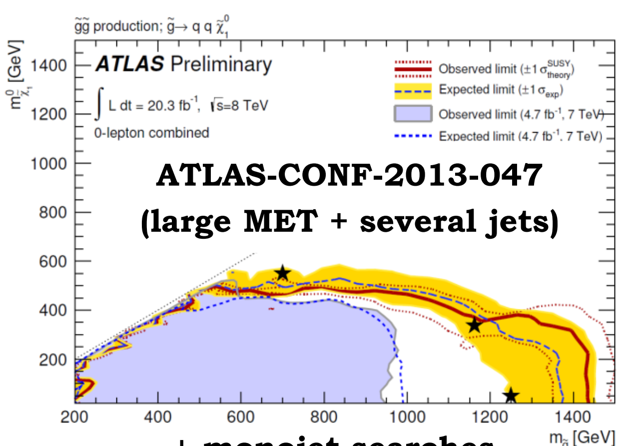



ISR eliminates
this loophole




Possibly loopholes
but very contrived




**+ monojet searches**