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On behalf of the ATLAS and CMS collaborations

University of Zürich
TOP2014 – Cannes, France

# Experimental Results on Top Exotic (non SUSY) from the LHC

Prepared with help from
James Ferrando from ATLAS

# Top quarks in BSM theories

- *"Largest quantum correction to the Higgs boson mass involves a top quark loop, it is natural to suppose that BSM mechanisms involve top quarks"*

- ATLAS:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsTopResults
- CMS:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

# Outline

- Resonances
- Dark matter
- Vector like quarks

# Resonances
# decaying to 1 or 2 top quarks

# Resonances with top quarks

- Extended gauge sector a feature of many BSM theories
  - SM-like W' and Z' appear for e.g. in Little Higgs models
  - Randall-Sundrum Kaluza-Klein excitations in extra dimension models
  - Technicolour, GUT, etc.
- Classic searches using top quarks:
  - W′ and Z′ (and gKK)

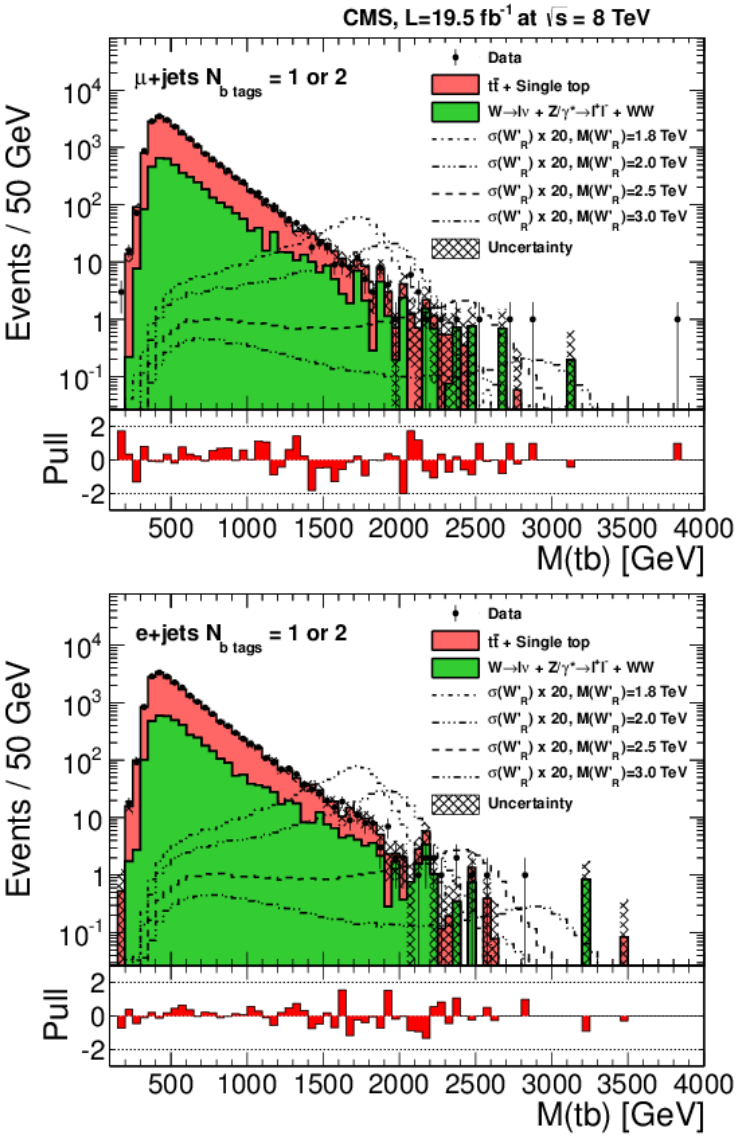
# Search for W′ boson decaying to top

- W′ heavy partner of the SM W boson
- Constrains on W′→lν (currently $M_{W'} > 3.4$ TeV) do not apply to W′ with purely right-handed couplings if the mass of the hyphothetical right-handed neutrino is larger than a few GeV
  - A search for W′→tb makes no assumptions on the mass of the right-handed neutrino
- Some models couple more strongly to fermions of the third generation than other generations
- W′ signal
  - $W'_L$ bosons couple like the SM W, *we consider interference between s-channel tb production via a W boson and via* $W'_L$ *boson*
  - $W'_R$ can only decay leptonically if there is a right-handed neutrino $\nu_R$ such that $M(\nu_R)+M(l)<M(W'_R)$, *we assume* $M(\nu_R)>M(W'_R)$

# Search for W′ Boson (single lepton)

- Fit M(tb) after selecting one high $p_T$ lepton, at least 2 jets, at least one b-tagged jet and to reduce backgrounds $p_{Ttop}$>85 GeV, $p_T^{jet1,jet2}$>140 GeV, 130<$M_{top}$<210 GeV

- Limits on coupling strengths provided for different M(W′) hypothesis

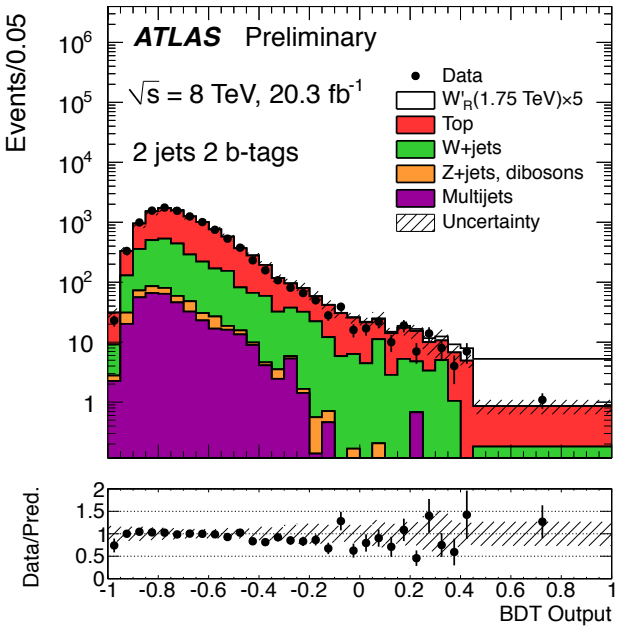


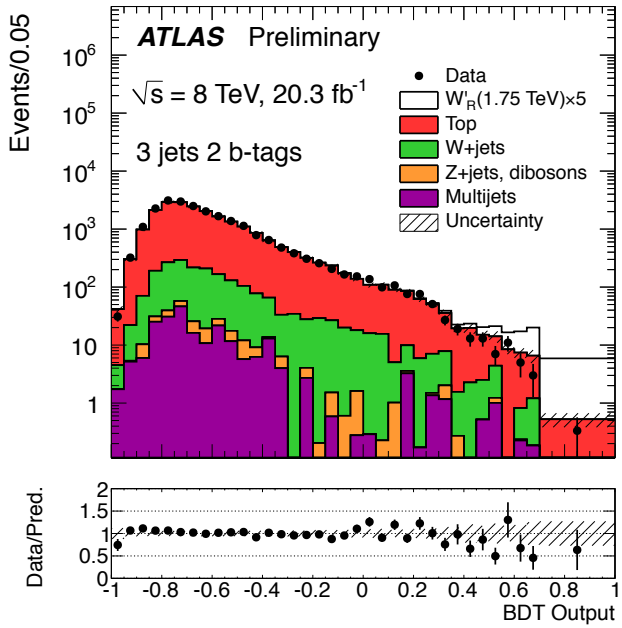

**[JHEP 05 (2014) 108]**

| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| $W'_L$ no int. | 2.05 TeV | 2.02 TeV |
| $W'_L$ | 1.84 TeV | 1.84 TeV |
| $W'_R$ | 2.13 TeV | 2.12 TeV |

# Search for W' Boson (single lepton)

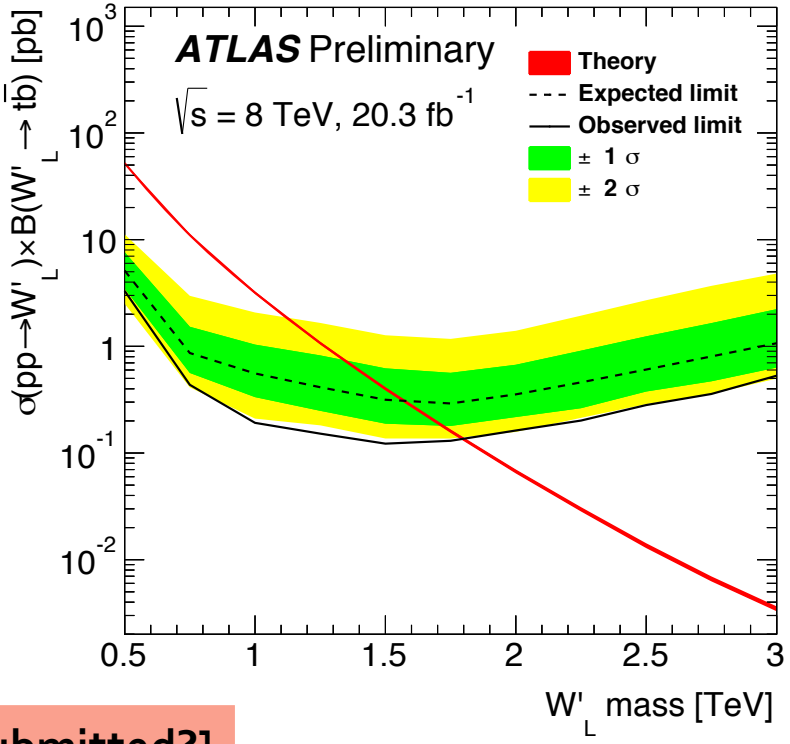
- Select one lepton and 2 or 3 jets with 2 b-tags
- Boosted Decision Tree trained with $W'_R$ and $W'_L$ (with and without interference) hypothesis
- About 10 variables used as input with M(tb) and $p_{Ttop}$ producing the best signal and background separation

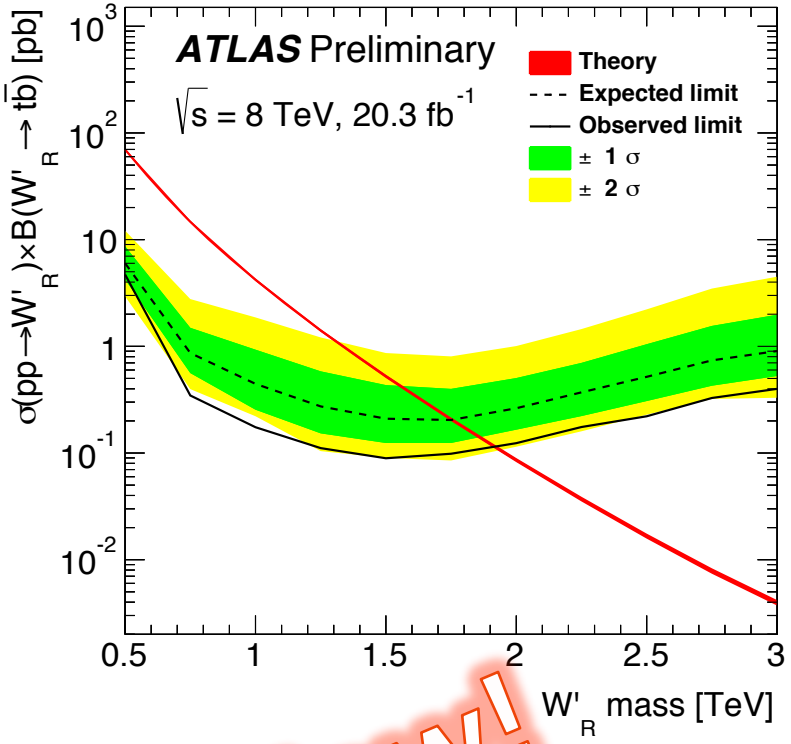



New!

# Search for W′ Boson (single lepton)




**[Submitted?]**

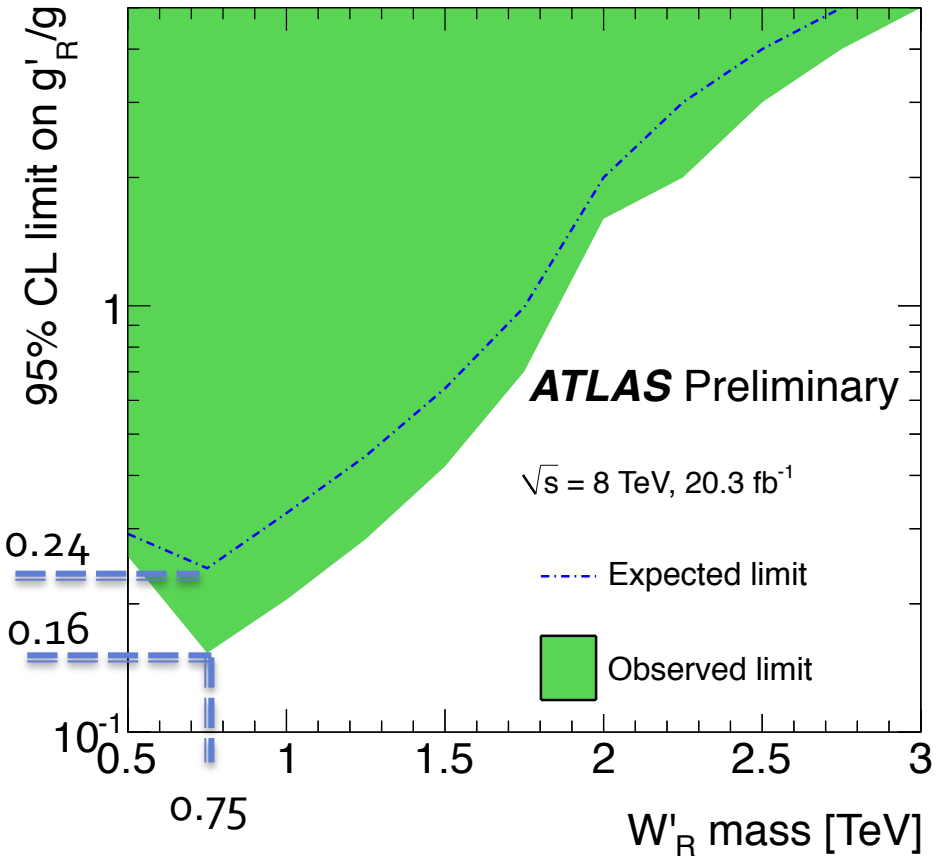
| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| $W'_L$ no int. | 1.80 TeV | 1.57 TeV |
| $W'_L$ | 1.70TeV | 1.54 TeV |
| $W'_R$ | 1.92 TeV | 1.75 TeV |

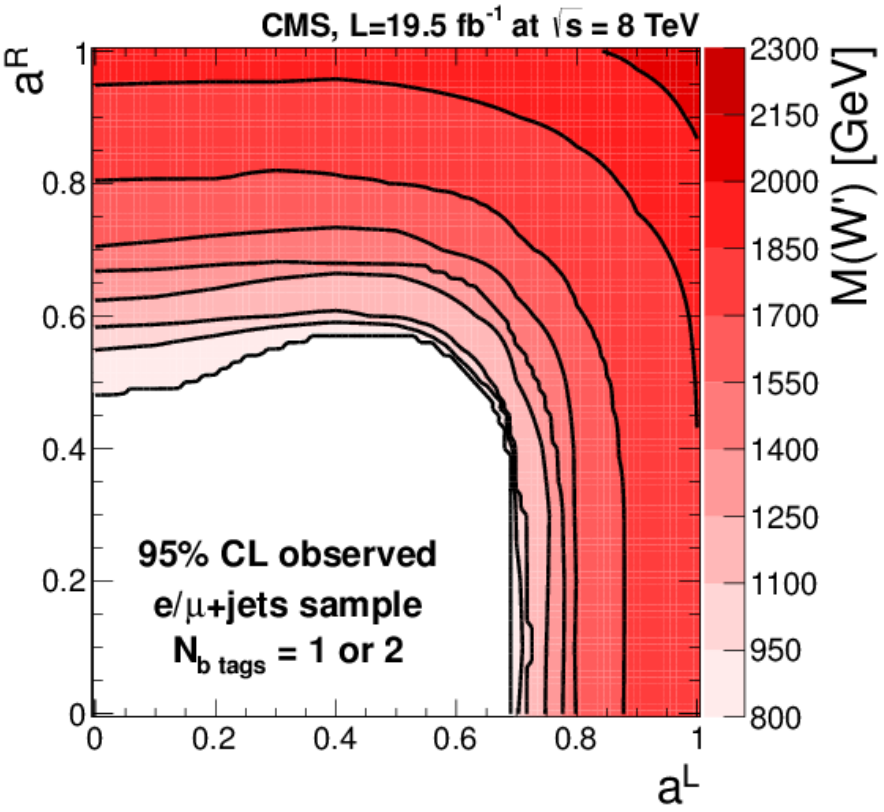
New!

- Observed limits lower explained by deficit in of data in the high BDT region

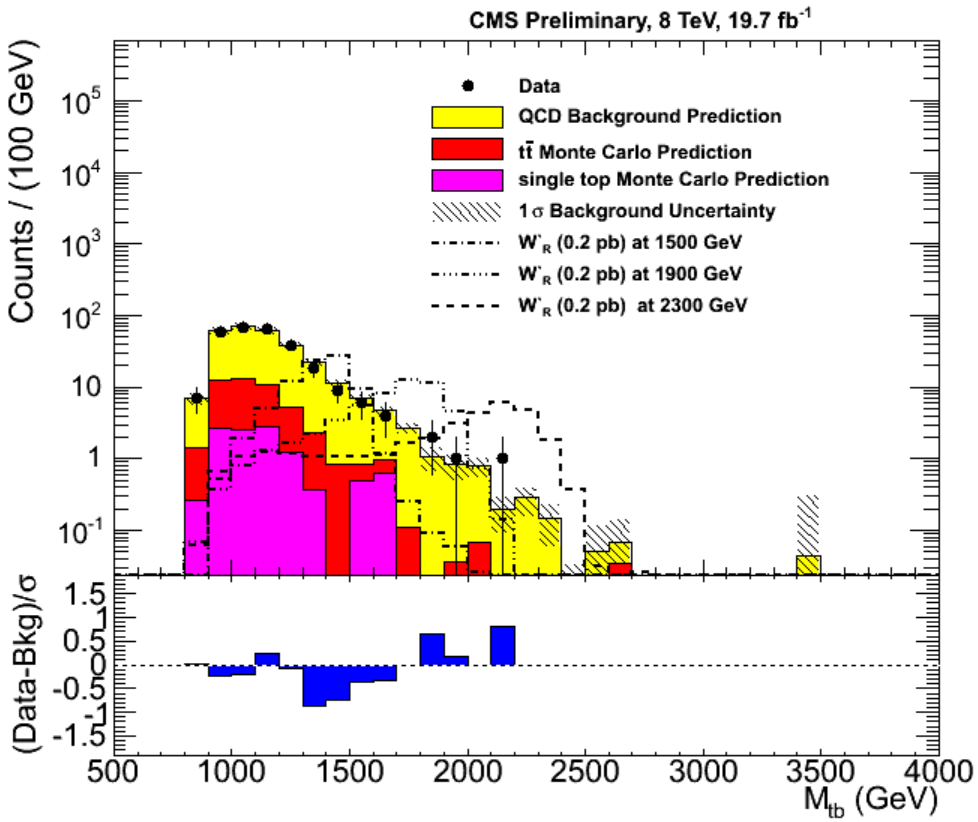
# Search for W′ Boson (single lepton)

- Limits on couplings for different W′ masses derived from W′ cross section



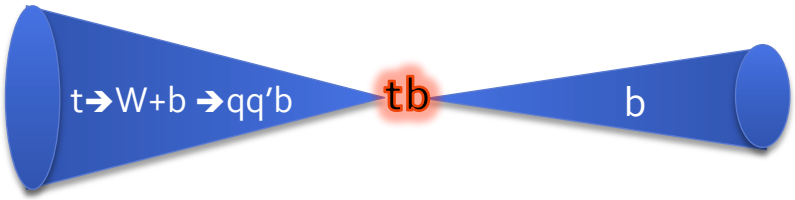
# Search for W′ Boson (all jets)




CMS PAS B2G-12-009

| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| $W'_L$ | 1.94TeV | ? TeV |
| $W'_R$ | 2.02 TeV | 1.99 TeV |

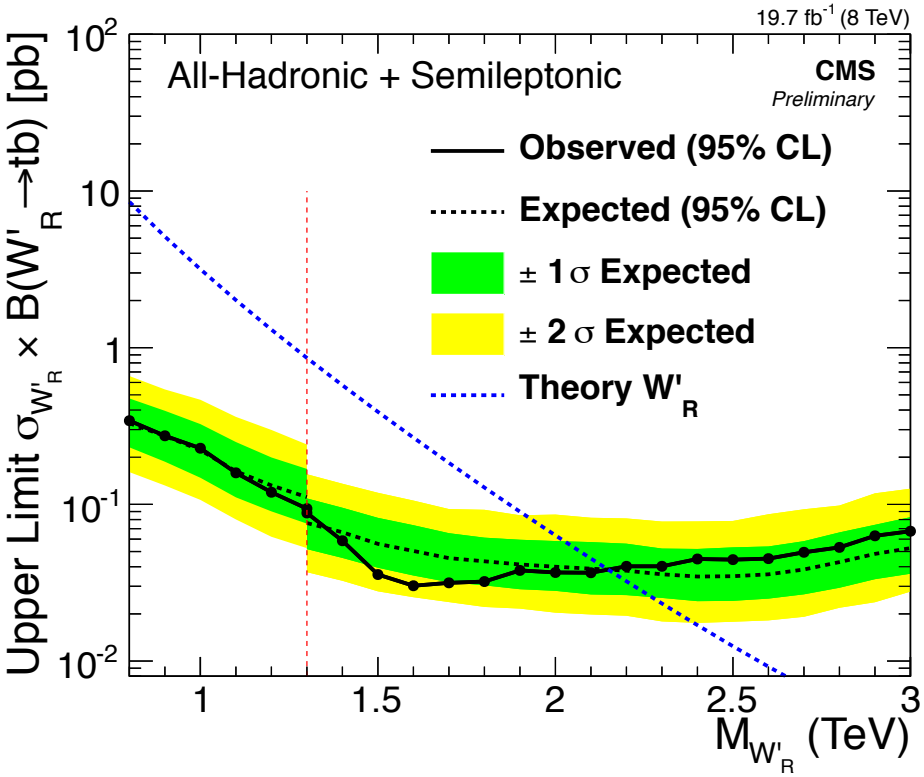
- Uses boosted techniques
  - **Top candidate jet:** $p_T$>450 GeV with CMS top-tagging algorithm
  - **B-candidate jet:** $p_T$>370 GeV using b-tagging and m<70 GeV




- Data derived multijet background estimate
- Reconstruction of M(tb) using these objects

# Search for W′ Boson (combination)

- Combination of single lepton and all hadronic channels
- Single lepton quoted up to 1.3 TeV, combined between 1.3 and 3.1 TeV
- Provides the current most stringent limits for $W'_R$




CMS PAS B2G-12-009

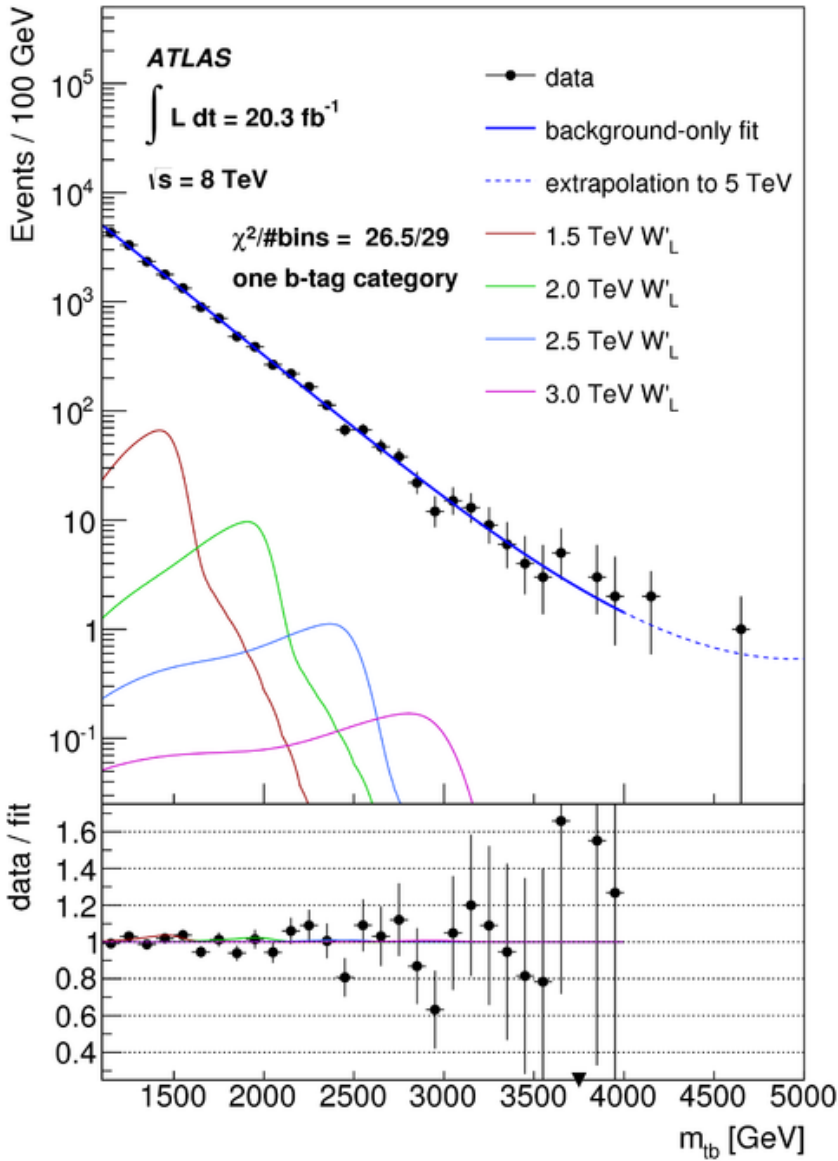
| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| $W'_R$ | 2.15 TeV | 2.15 TeV |

# Search for W′ Boson (all jets)

- Selection uses boosted techniques
  - Single anti-$k_T$ R=1.0 trimmed jet with $p_T$ >350 GeV (**W′ Top Tagger)**
  - Small anti-$k_T$ R =0.4 b-tagged jet with $p_T$>35 GeV
  - Divided in 1 and 2 b-tags
- Background estimate fully from data
- $W'_L$ no interference since 1% contamination from single top estimated

[arXiv:1408.0886]

| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| $W'_L$ no int. | 1.68 TeV | 1.63 TeV |
| $W'_L$ | NA TeV | NA TeV |
| $W'_R$ | 1.76 TeV | 1.85 TeV |



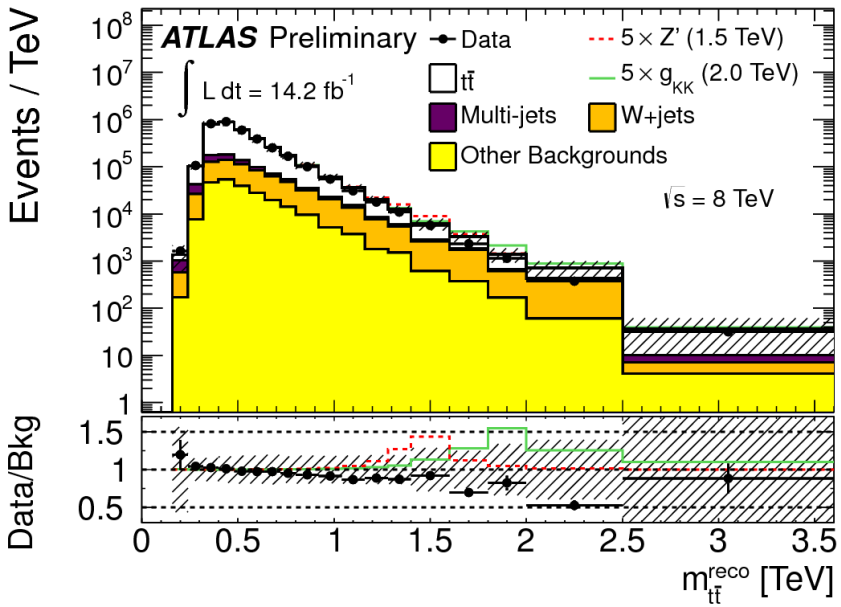
# Search for ttbar resonances

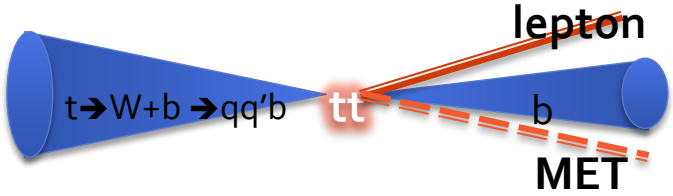
- Mainly introduced to alleviate the *hierarchy problem*
- Two theoretical benchmarks:
  - Narrow resonance(*) (topcolor, leptophobic (Z'))
    - $\Gamma_{Z'}/m_{Z'}$=1.2% (or 1%) with K factor 1.3 [EPJ C72 (2012) 2072 ]
  - Broad resonance(*) (Kaluza-Klein (KK) gluons from RS models with ED)
    - $\Gamma_{ggKK}/m_{gKK}$=15.3% (10-15%) with no K factor
    - [ but also $\Gamma_{Z'}/m_{Z'}$=10%  for CMS]
- Search for enhancement in the invariant mass ttbar spectrum

(*) compare with detector resolution for mtt ~10%

# Search for ttbar resonances (lepton + jets)

- Combine four channels electron, muon with resolved, boosted:
  - **Resolved:** Reconstruct tt with l+MET+4 small radius jets (R=0.4); Choose kinematically best combinatorics
  - **Boosted:**
    - Leptonic top = l +MET + nearby small radius jet (R=0.4)
    - Hadronic top = large radius jet (R=1.0) with high mass, hard substructure
  - Events that fail the boosted selection are examined using the resolved selection



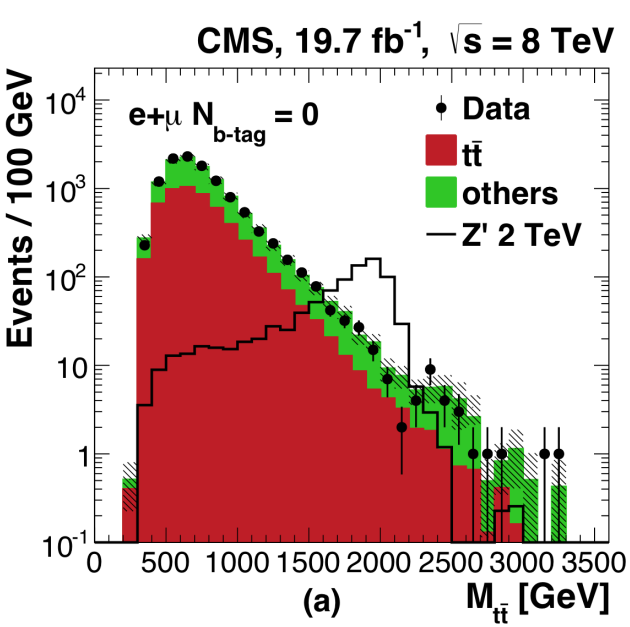



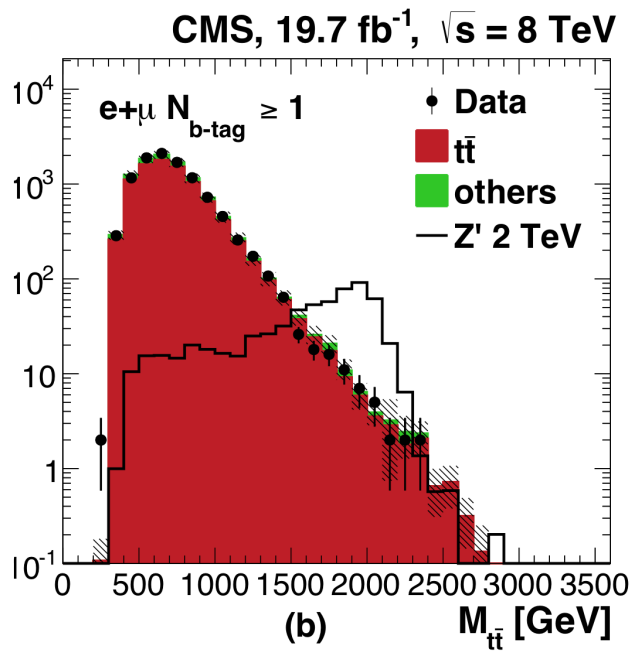

ATLAS-CONF-2013-052

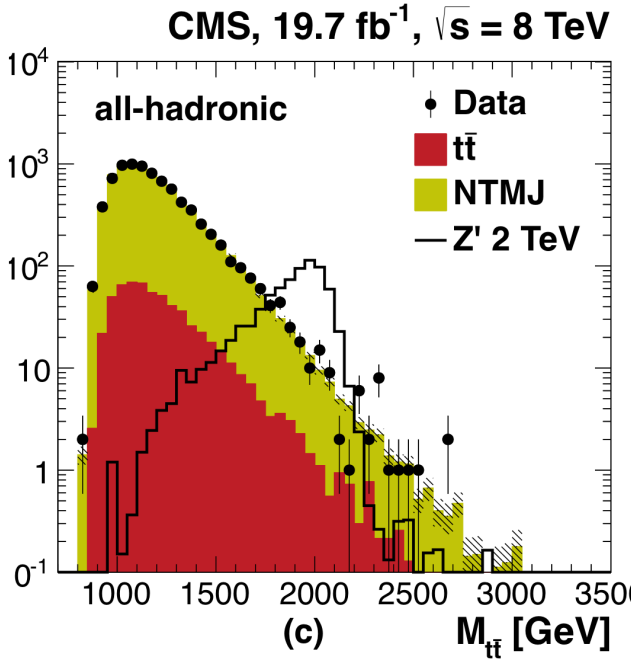
| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| Z' | 1.8 TeV | 1.9 TeV |
| gKK | 2.0 TeV | 2.1 TeV |

# Search for ttbar resonances (l + jets, all-had)

- Lepton+jets:
  - **Resolved ($M_{tt}$<1 TeV)**: Reconstruct tt with l, MET, at least 4 jets. Events separated in e, mu, single and doble-b-tag. Reconstruct $M_{tt}$ chosing the best combinatorics
  - **Boosted ($M_{tt}$>1 TeV):** Higher $p_T$ lepton trigger plus higher leading jet $p_T$ requirement. Reconstruct $M_{tt}$ with one jet assigned to the leptonic side and at least one jet to the hadronic side
  - Not exclusive, limits are combined at 1TeV, found to be best point
- All-hadronic ($M_{tt}$> 1TeV):
  - **Boosted:** Top tagging and CA0.8 jets with pruning to identify substructure (3 or 4 jets)

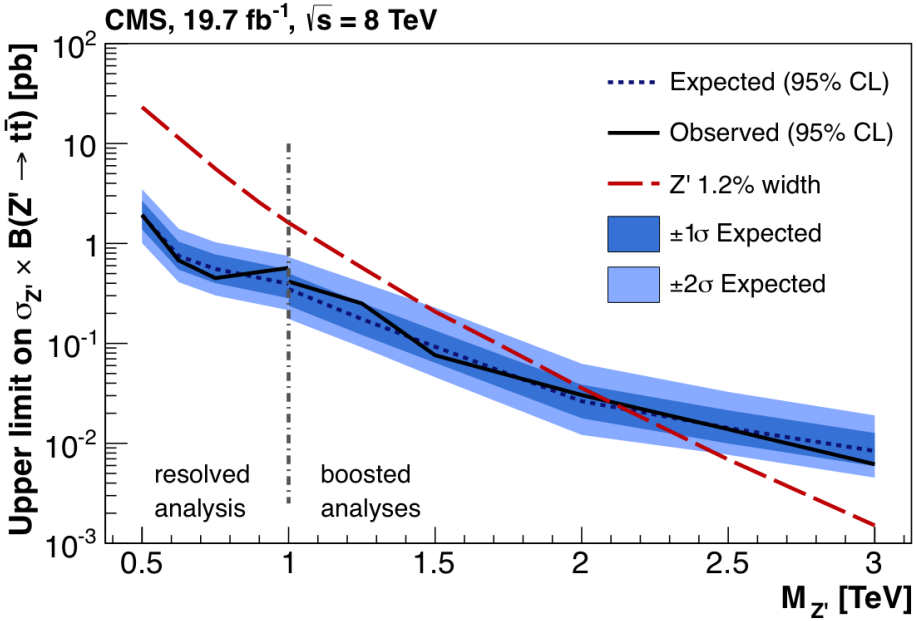


# Search for ttbar resonances (l + jets, all-had)

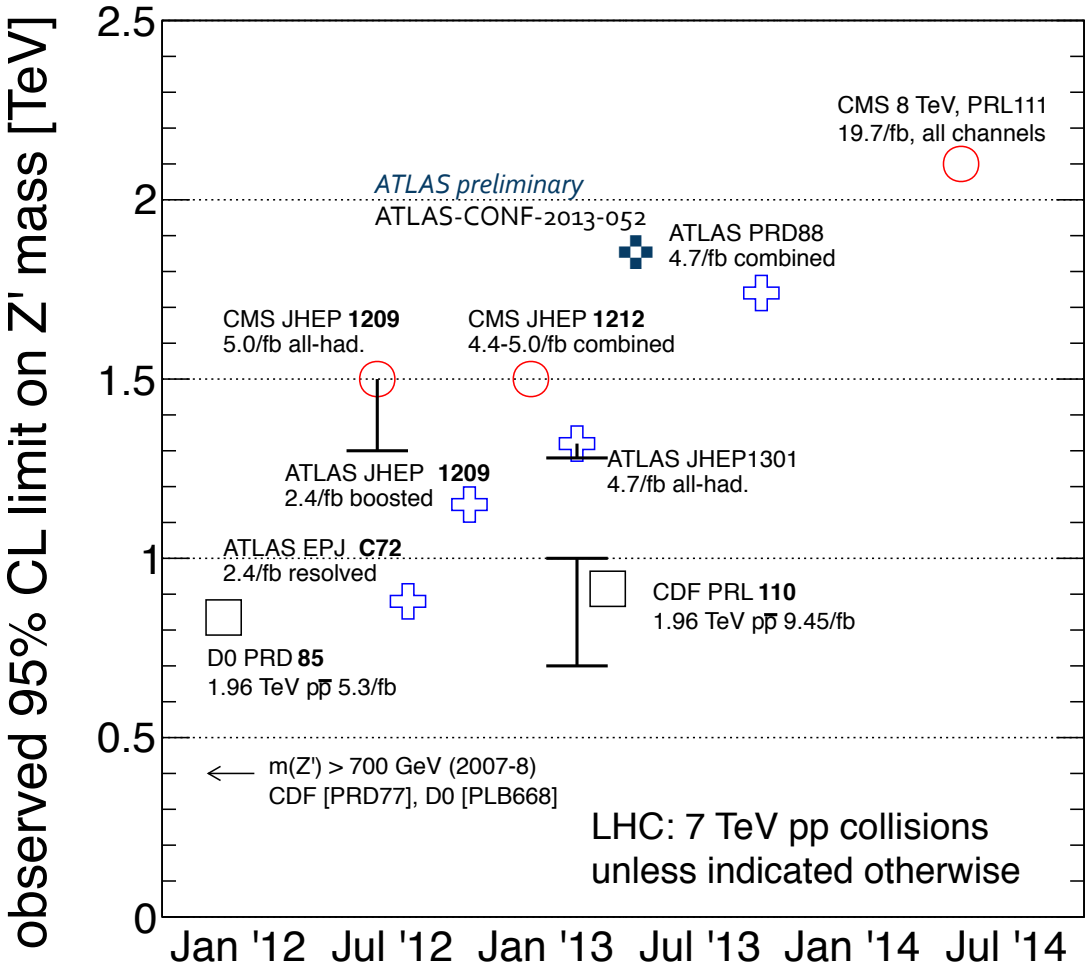
- Combine with resolved and boosted in l+jets channel with boosted hadronic channels for optimal sensitivity over $M_{tt}$ range
- Combination of l+jets and all-hadronic channels improves the expected cross section limits at 2TeV by 25%




PRL 111, 211804 (2013)

| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| Z' 1.2% | 2.1 TeV | 2.1 TeV |
| gKK | 2.5 TeV | 2.4 TeV |
| Z' 10% | 2.7 TeV | 2.6 TeV |

# Search for ttbar resonances (summary)

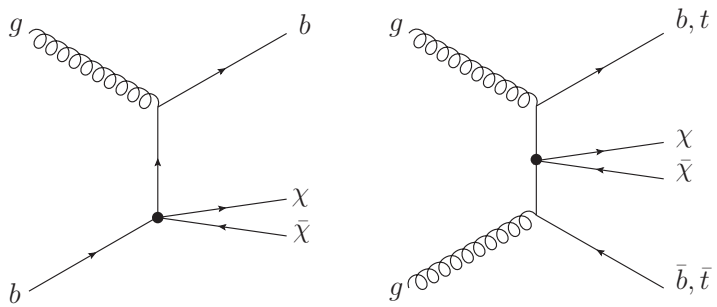


# Dark Matter
# or MET plus one or two top quarks

# Dark matter with *heavy* quarks

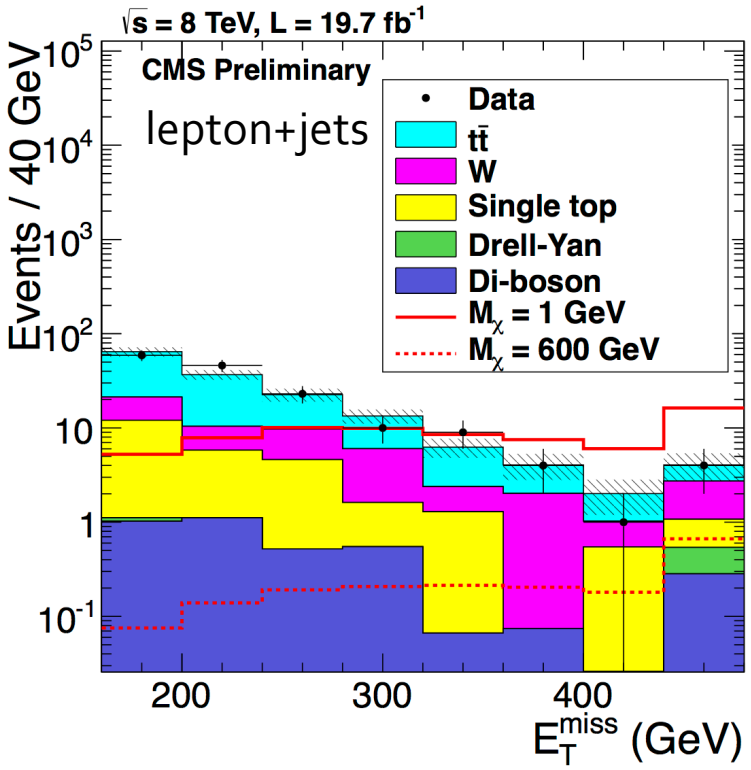
- At LHC low DM masses ($m_\chi$<10 GeV) most sensitive, complementarity to direct searches
- If particles that mediate the interaction between dark matter and SM particles ($M^*$) are too heavy to be produced, interactions can be described as contact operators in EFT with operators expressed in terms of $M^*$
  - (D1) proportional to mass, better constraints from events where DM couples to *heavy quarks*
  - (C1) complex scalar (also proportional to $m_q$)
  - (D9) tensor couplings between WIMPS and quarks

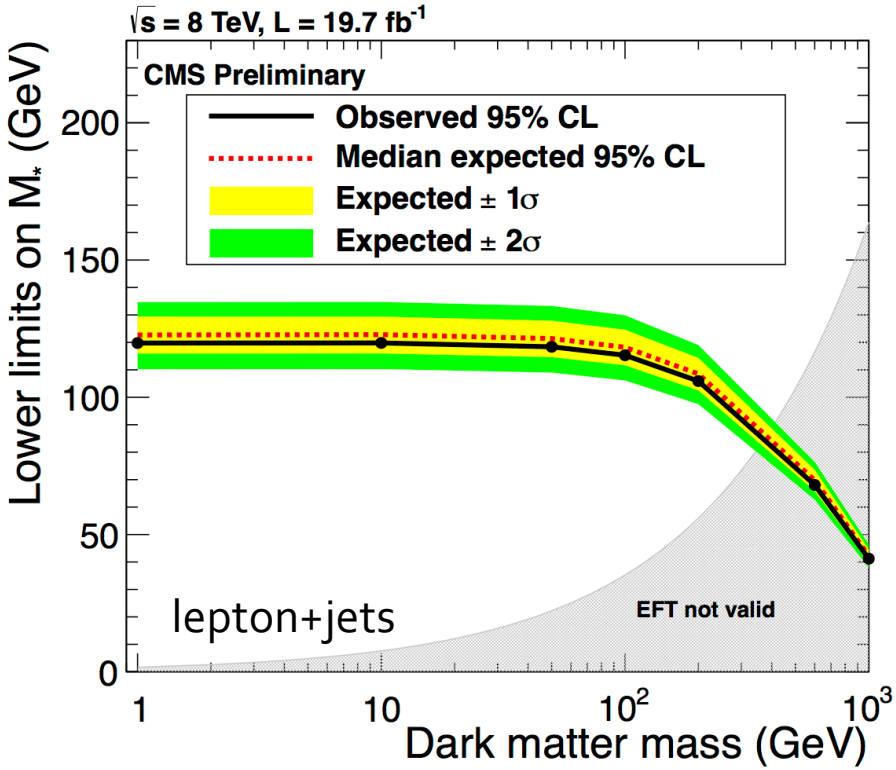
| Name | Initial state | Type | Operator |
|---|---|---|---|
| D1 | $qq$ | scalar | $\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$ |
| D5 | $qq$ | vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ |
| D8 | $qq$ | axial-vector | $\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ |
| D9 | $qq$ | tensor | $\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ |
| D11 | $gg$ | scalar | $\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$ |



# Dark matter with top quark pairs

- Performed on single lepton and dilepton channels
  - Selections on scalar sums of leptons and jets, jet and MET opening angle, $M_T$ and $M_{T2W}$
  - Set lower limits on the interaction scale $M_*$ assuming D1 coupling
  - Lower bound on the validity of the EFT considered

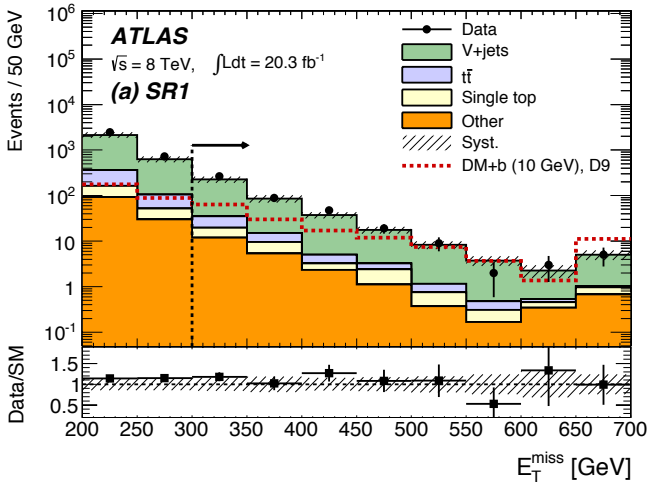


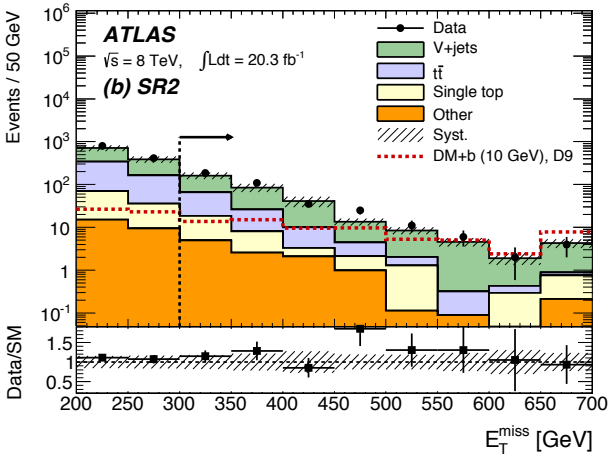



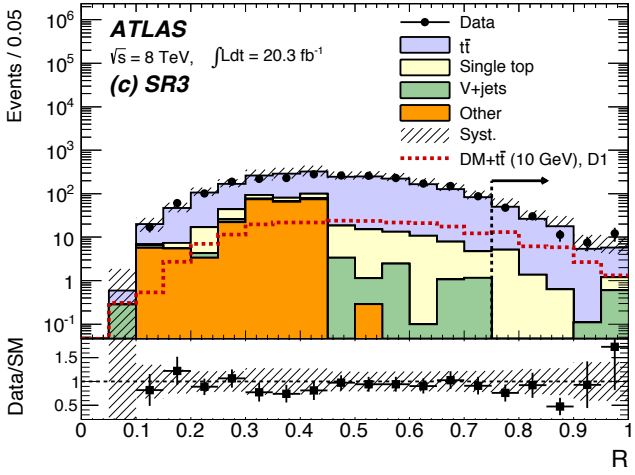
# Dark matter with top quark pairs

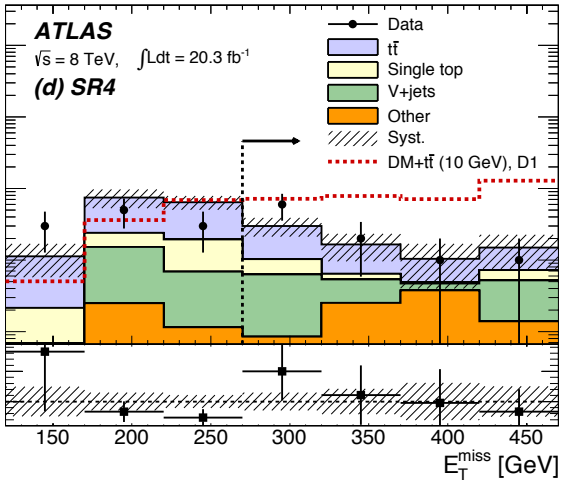
- Select at least one jet $p_T$> 100 GeV, MET > 100 GeV
- Divide sample in 4 regions:
  - SR1 and SR2 regions DM with 1 or 2 b-quarks
  - SR3 tt with all hadronic decay (>5 jets)
  - SR4 tt with semi leptonic decay (stop results are used)
- Use variables like 'Razor' variables (favors decay products of heavy particles), topness, asymetric transverse mass $am_{T2}$

New!



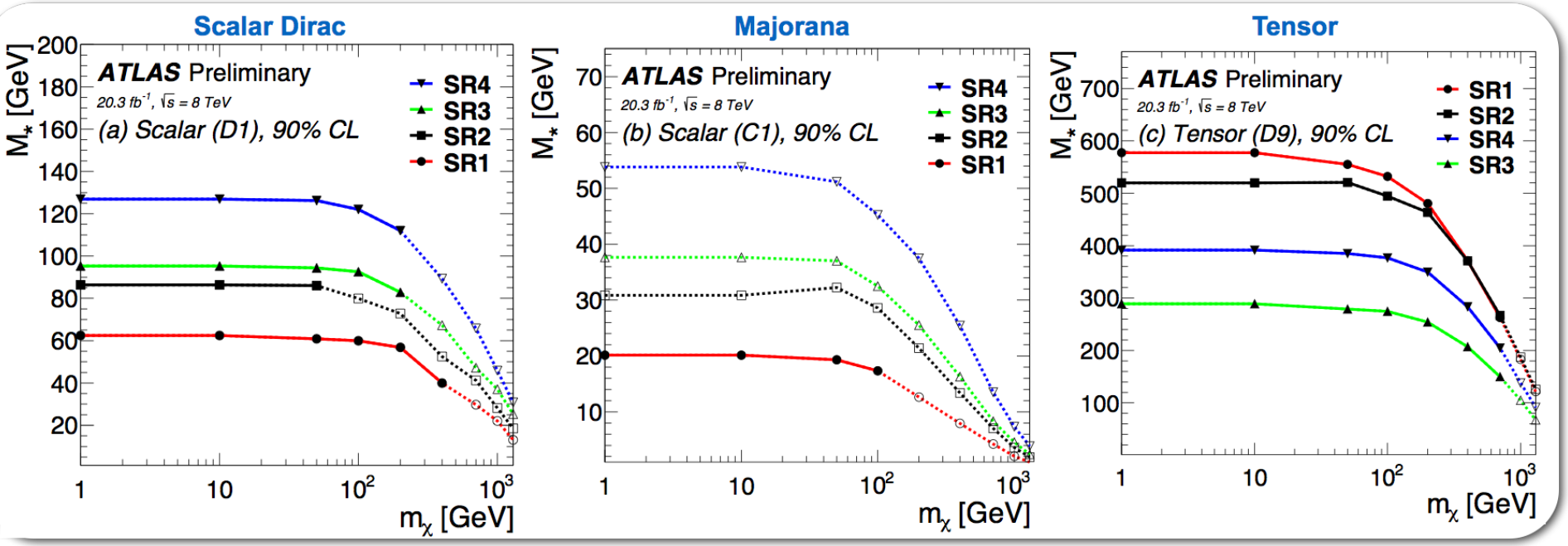
# Dark matter with top quark pairs

- Presenting limits on effective mass scale M* for each operator and signal region

New!

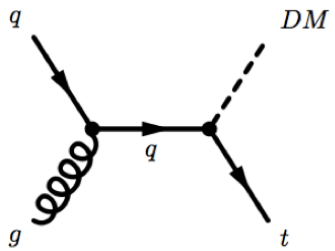
- Solid curves where where $m_{\chi\chi} < Q_{TR}$(momentum transferred), e.g.

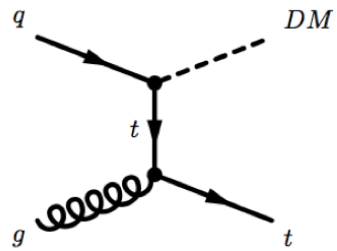
$$Q_{\mathrm{TR}} < \sqrt{\frac{4\pi M_*^3}{m_q}}$$

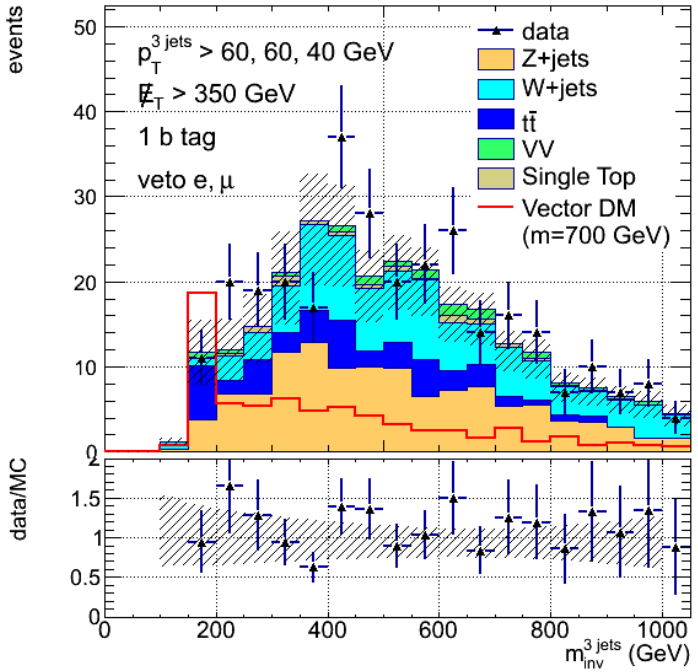


# Dark matter with single top quarks

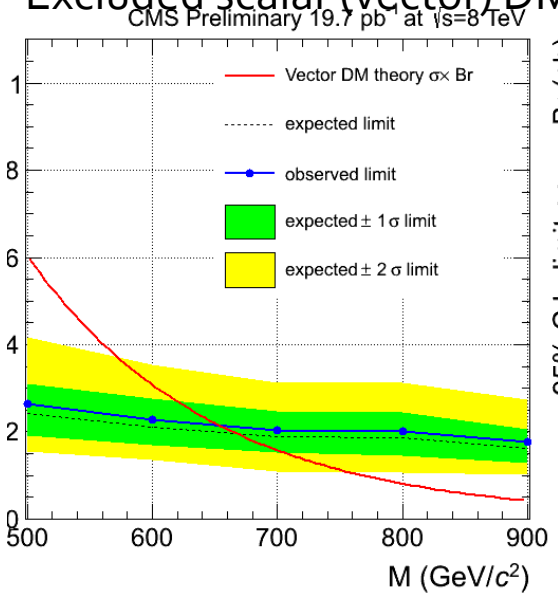
- Monotop: select large MET plus a top quark decaying in all-jets
  - MET>350 GeV, 3 jets (anti-$k_T$ R=0.5) of which 1 b-tagged
    $p_T(j_1)$, $p_T(j_2)$ > 60 GeV and $p_T(j_3)$ > 40 GeV
    veto additional jets with $p_T(j)$ > 35 GeV
    $m_{inv}^{3\,jets}$ < 250 GeV, veto isolated leptons
- Interpreted within EFT where the DM are scalar or vector bosons

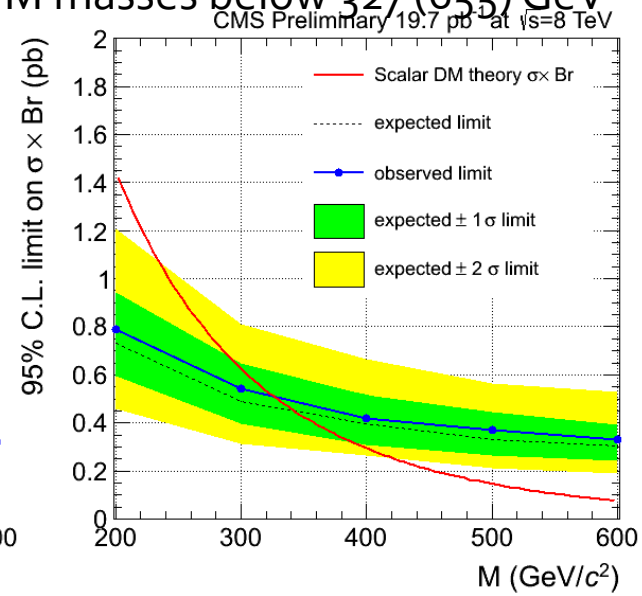



Excluded scalar (vector) DM masses below 327 (655) GeV

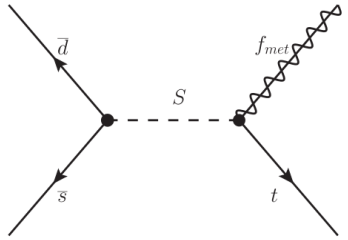


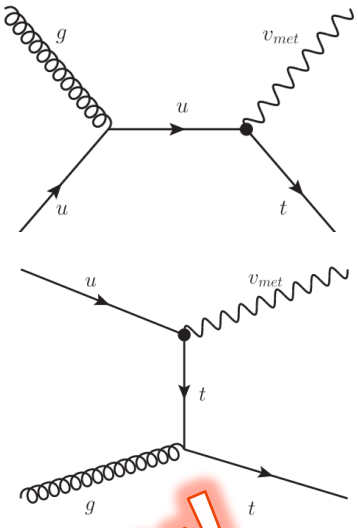
# Dark matter with single top quarks

- Monotop: select one lepton, one b-tagged jet and large MET
- Search interpreted as
  - Resonant production of a +2/3 charged spin-0 boson, S, decaying into a right-handed top quark and a neutral spin-1/2 fermion, $\mathbf{f_{met}}$
  - Non-resonant production of a neutral spin-1 boson, $\mathbf{v_{met}}$, in association with a right-handed top quark
- Divide in two signal regions
  - SRI (resonant model) $m_T(l,MET) > 210$ GeV and $|\Delta\phi(l,b)|<1.2$
  - SRII (non-resonant) $m_T(l,MET) > 250$ GeV and and $|\Delta\phi(l,b)|<1.4$

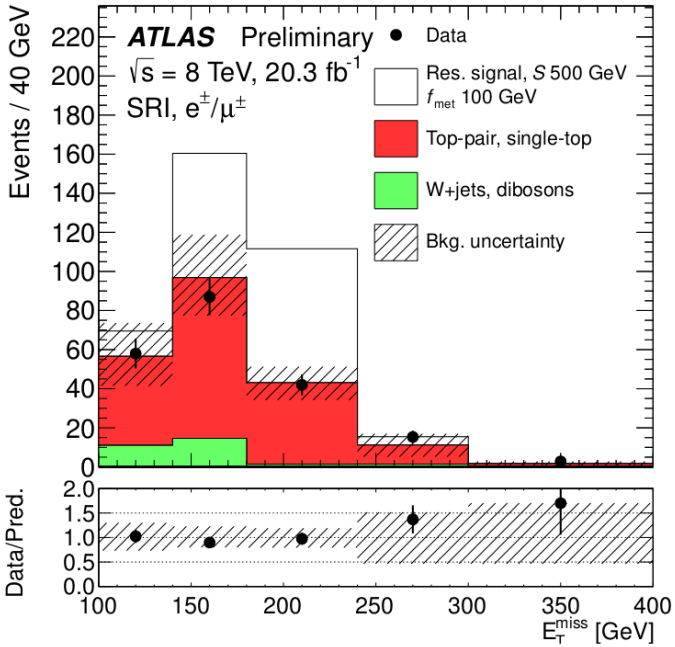
Resonant production

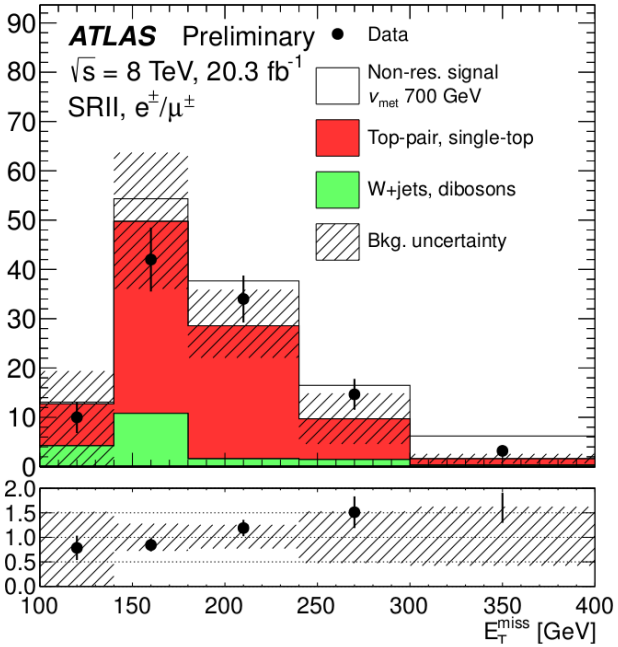



Non-Resonant production

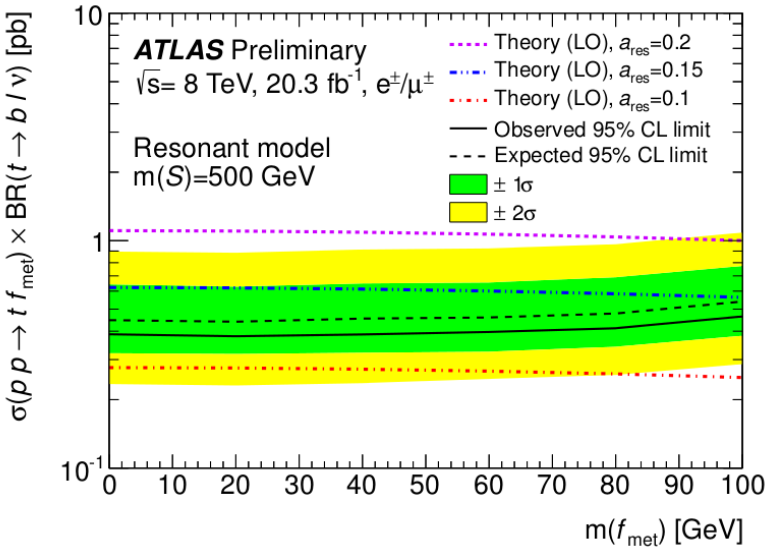


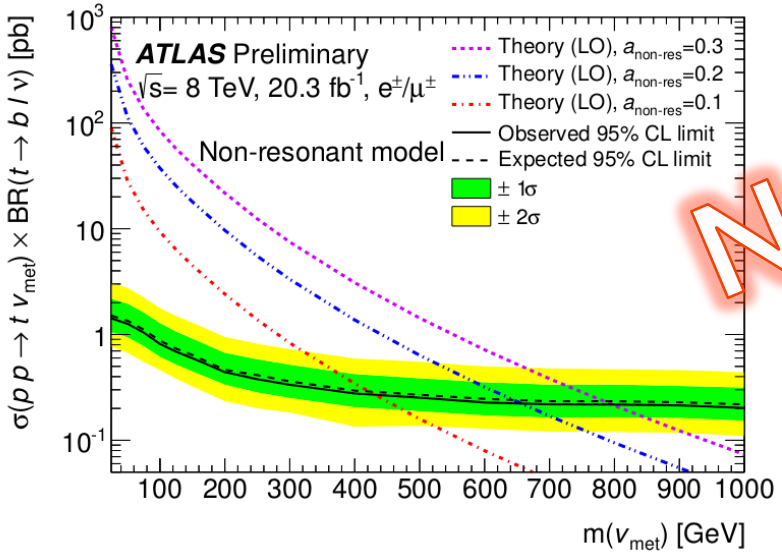

New!



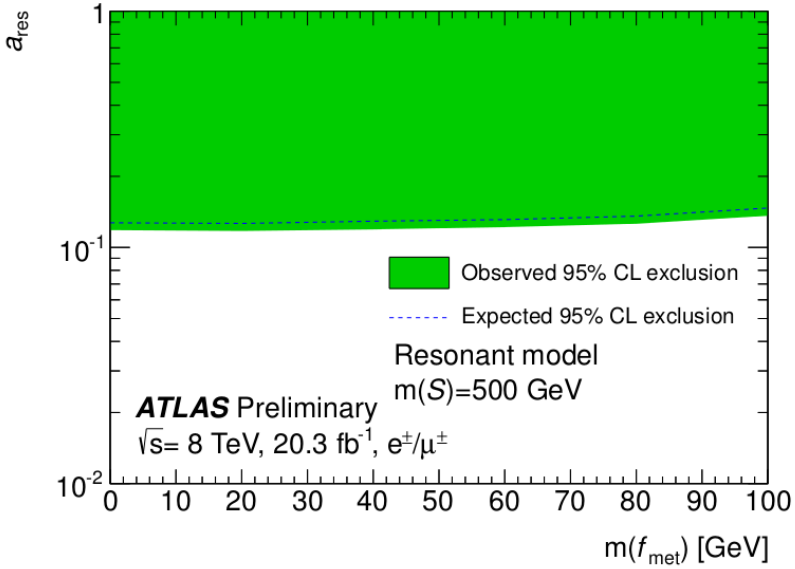



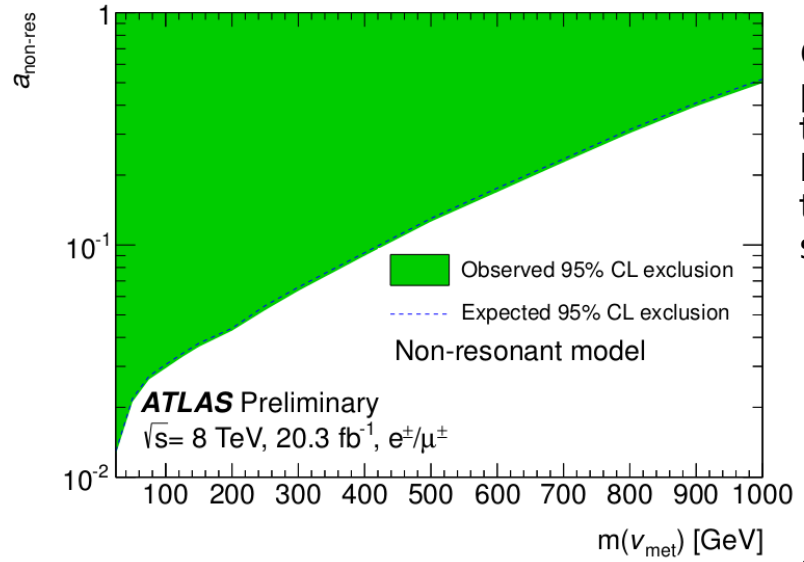
# Dark matter with single top quarks




New!




Cross section proppportional to $a^2$, extract limits on a for the invisible states

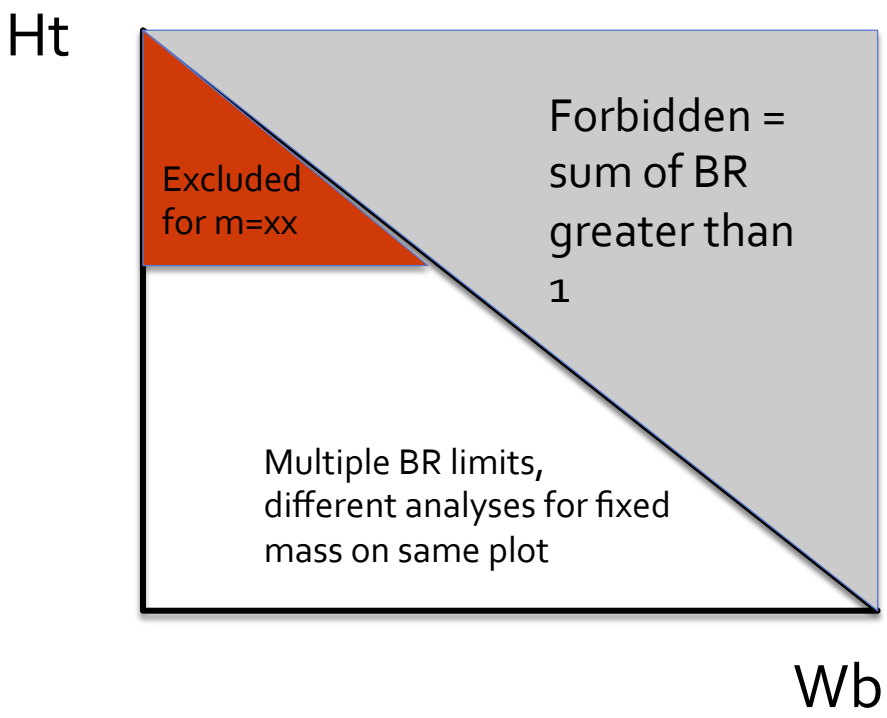
# Vector like quarks

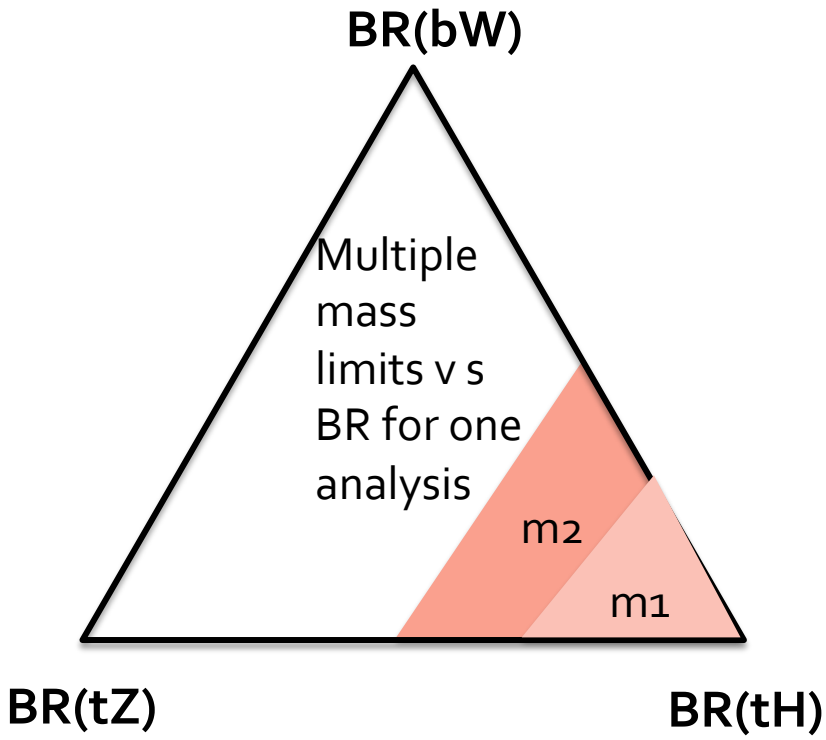
# Vector Like Quarks

- Proposed in extensions of SM to address the naturalness problems
  - Little Higgs, Composite Higgs, etc. *natural models*
- VLQ means left and right handed components transform identically under $(SU2)_L$
- Predominantly VLQ decay to third generation
- Both charged and neutral decays can occur
  - Plenty signatures for searches: single or pair production of B' ➔Wt, Zb, Hb and/or T' ➔Wb,Zt,Ht

# ATLAS and CMS style limit plot

- ATLAS 2-BR plane for a given VLQ mass for many analyses
- CMS 3-BR plane for a given analysis for many VLQ masses



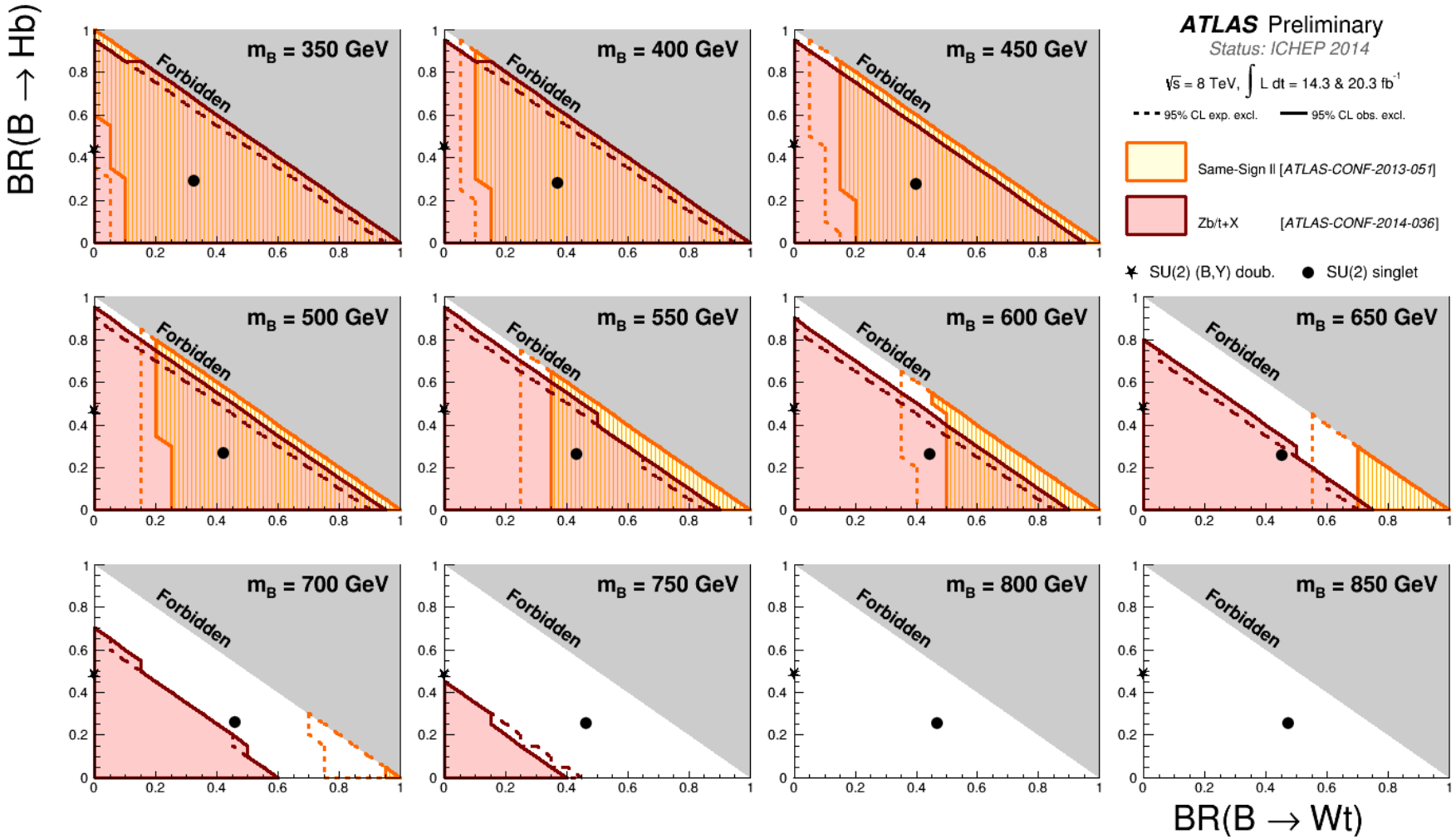



# Search for B′ and T′

- ATLAS-CONF-2013-051:
  - Search for pair prod of B′ ➔Wt, Zb, Hb and T′ ➔Wb,Zt,Ht
  - Same-sign dilepton, 2 or more jets, at least one b-tag, large MET and $H_T$
- ATLAS-CONF-2014-036 (now arXiv:1409.5500):
  - Search for pair and single prod of B′ ➔Zb and T′ ➔Zt
  - Opposite-sign dilepton, no extra lepton, 2 or more central jets, 2 or more b-tagged jets. Discriminant m(Zb)
  - Opposite-sign dilepton, at least 1 extra lepton, 2 or more central jets, 1 or more b-tagged jets. Discriminant $H_T$(jets +leptons)

# VLQ B′ limits

- Coverage for all B′ decay modes
- B′ ruled out for any decay up to 350 GeV

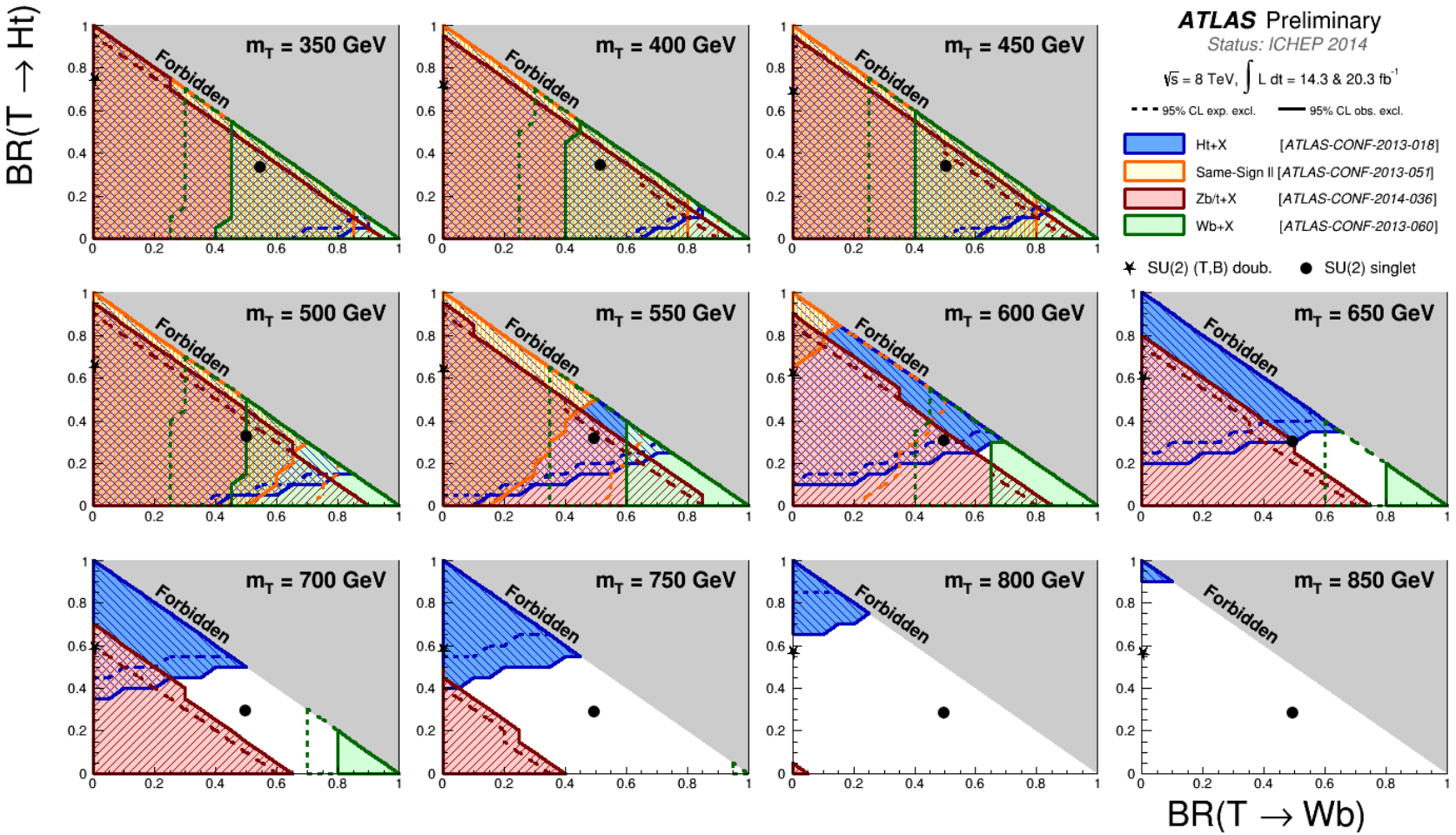


# Search for B' and T'

- ATLAS-CONF-2013-018:
  - Search for T'T'➔HtHt,HtZt,WbHt with H➔bb
  - One lepton, at least 6 jets, at least 2 b-tag, large MET. Discriminant $H_T$
- ATLAS-CONF-2013-060:
  - Search for pair prod of T' ➔Wb,Zt,Ht
  - One lepton, at least 4 jets, at least one b-tag, large MET. Discriminant m(reco)
  - (Veto greater than 6 jets to avoid overlap with ATLAS-CONF-2013-018)

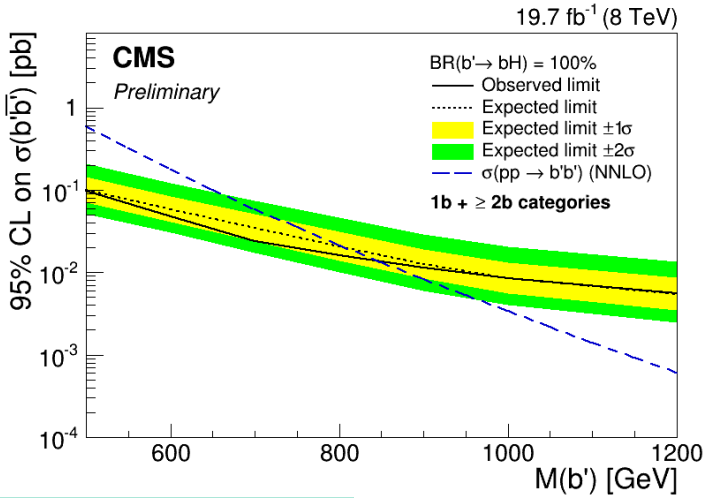
# VLQ T' limits

- Limit set for all allowed decay modes of the T quark
- T quark ruled out for any decay mode up to 550 GeV



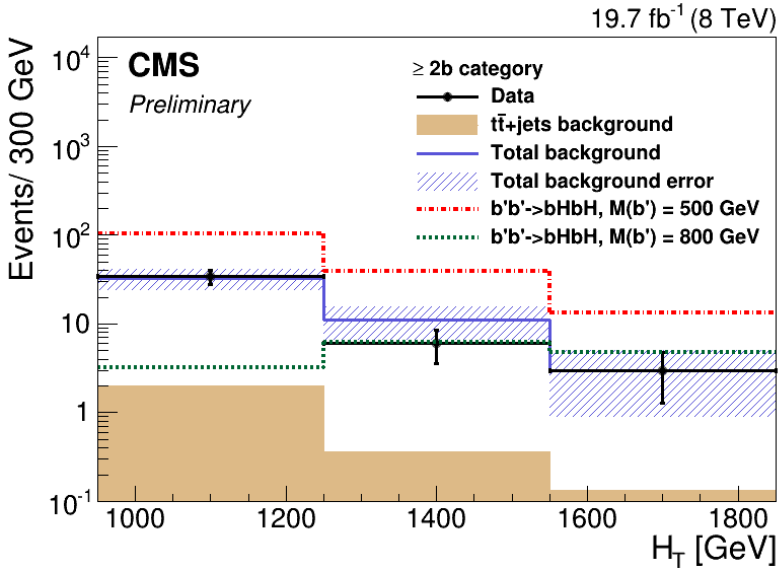
# Search for B′ pairs (B′→bH)

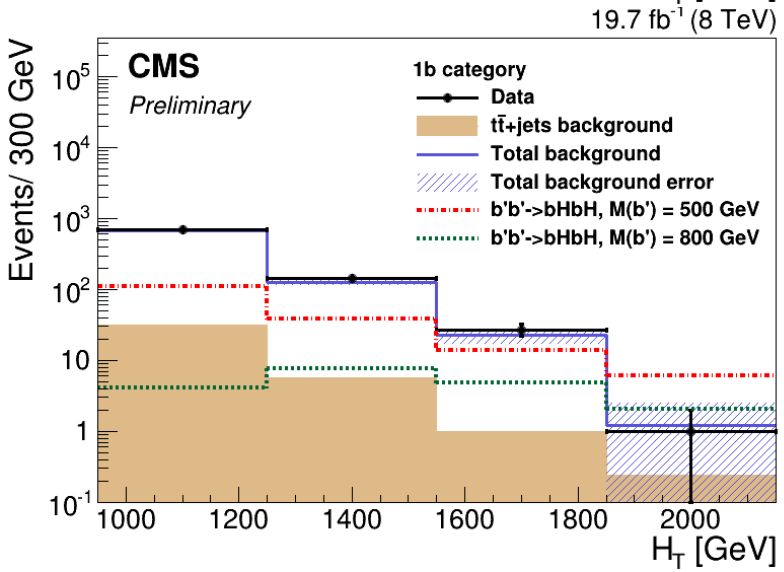
- Consider decays with H→bb
- Only feasible because boosted techniques help reduce multi-jet background
- Rely on both "Higgs-Tagging" and b-tagging




CMS PAS B2G-14-001

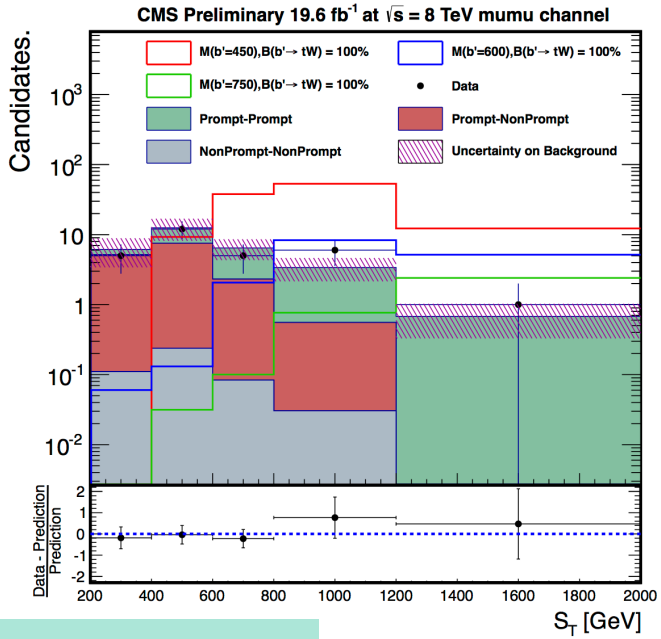
| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| B′ | 846 GeV | 811 GeV |



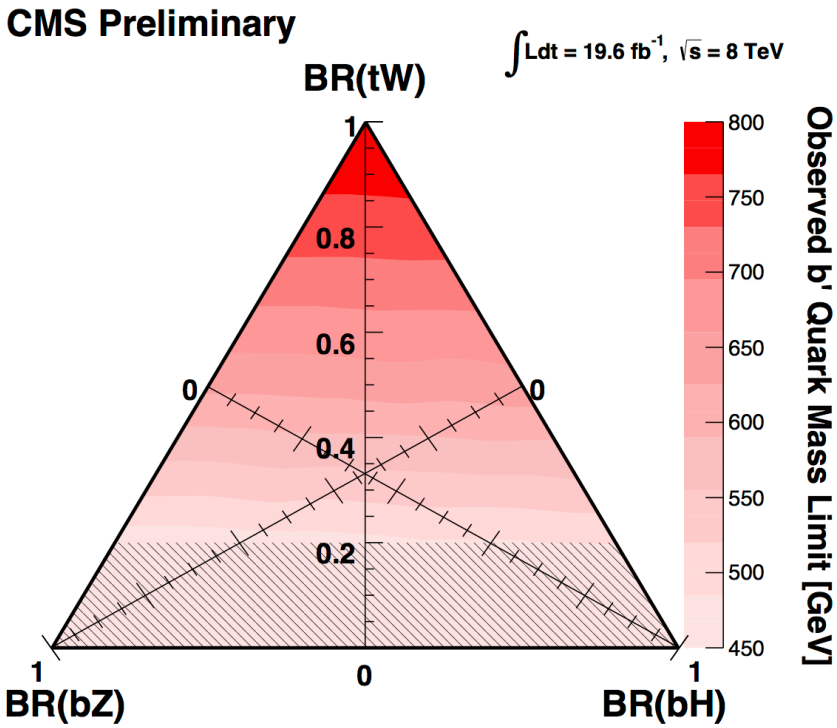
# Search for B′ pairs (B′→tW)

- Also considers bZ (FCNC) and bH
- Select same sign dileptons and at least 4 jets; divide in categories of lepton flavor and $S_T$
  - $S_T$ (sum $p_T$ of jets, leptons and MET) > 200 GeV




CMS PAS B2G-14-020

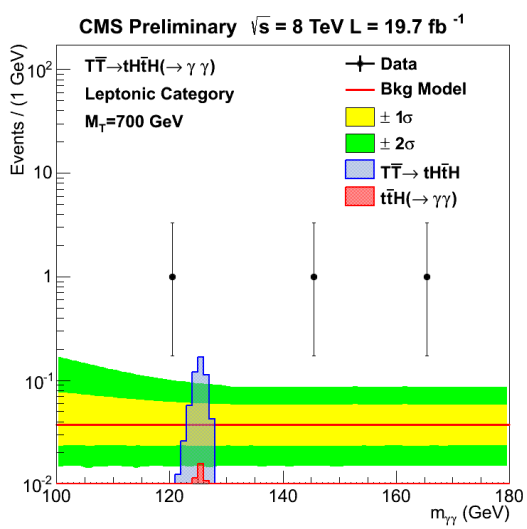
| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| B′ | 798 GeV | 800 GeV |

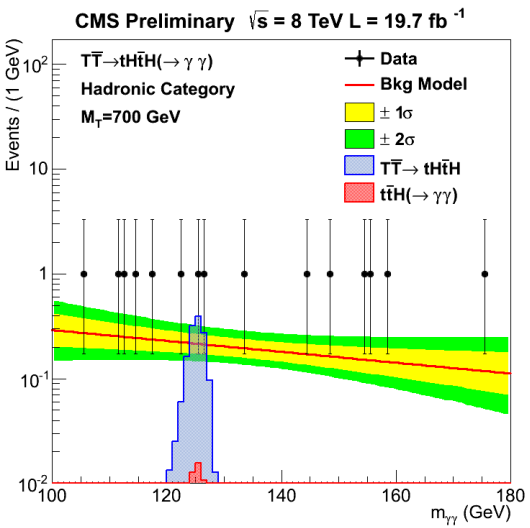



[CMS PAS B2G-14-020]

# Search for T′ pairs (T′→tH, H→γγ)

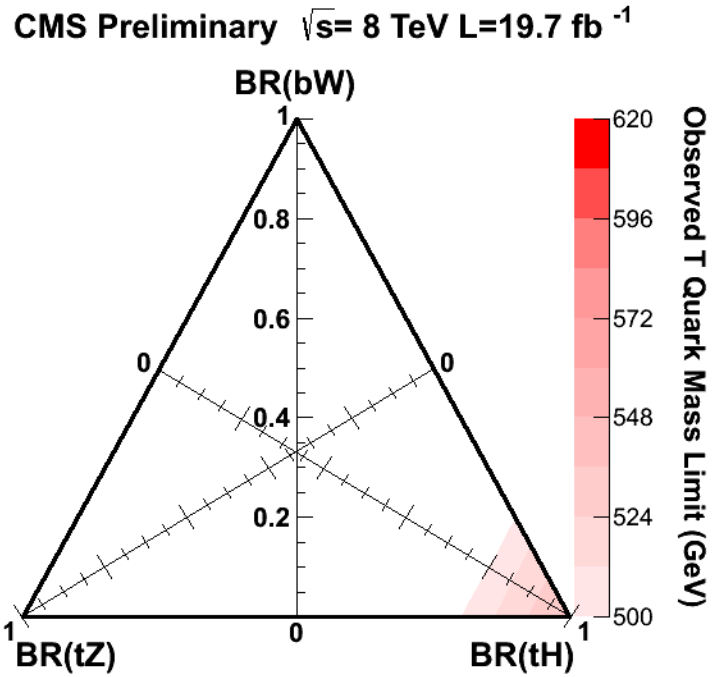
- Exploit the **narrow resonance** of H→γγ, by fitting the peak in Mγγ distribution and $S_T$ > 1 TeV
- Analysis in hadronic and semileptonic channel
- Search is limited by statistics, yet a very powerful analysis for Run 2




CMS PAS B2G-14-003

| Model | Obs. exclusion | Exp. exclusion |
|---|---|---|
| T′ | 540 GeV | 607 GeV |



# Conclusions

- Top quark plays an important role in searches for physics BSM
- An exhaustive list of searches has been done using 8 TeV LHC dataset by ATLAS and CMS
- All channels have been used, many of them were already combined to achieve better precision
- Many reconstruction techniques have been developed or improved for these searches
- Looking forward to Run 2!