# New Physics Searches with Top Quarks at CMS

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*on behalf of the CMS Collaboration*



Boston Jet Physics Workshop
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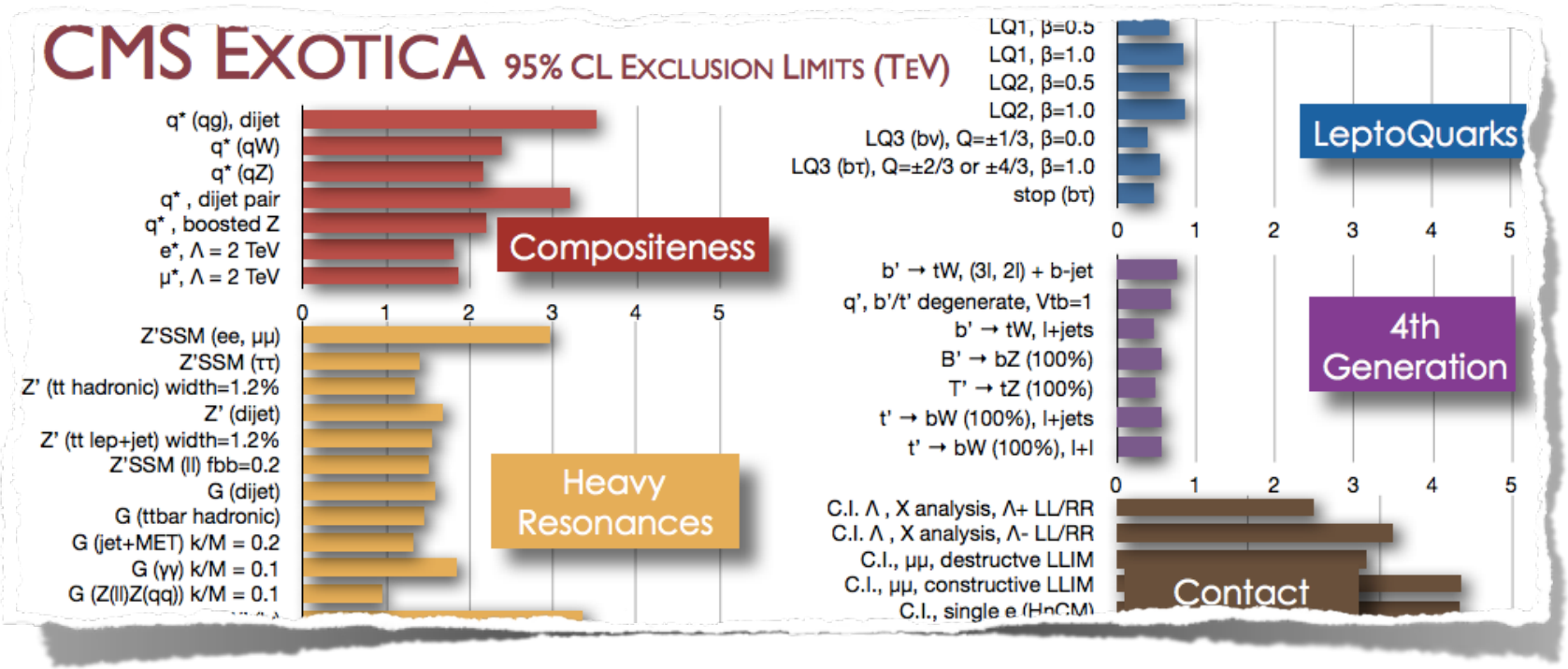
# Introduction

- CMS continues to explore diverse and unique final states in searches for new physics
- Large sample of top quarks produced at the LHC
  - Good testing ground for advanced tools
    - Top quark ID algorithms
    - Jet substructure
    - Event reconstruction
- Focus on non-SUSY signatures here
  - **4th generation partner quarks**
    - Vector-like T', B' decays to SM tops
  - **Top pair resonance searches**
    - Z', RS KK gluon
  - **Excited quarks**
- Will also focus on some of the jet-specific techniques used

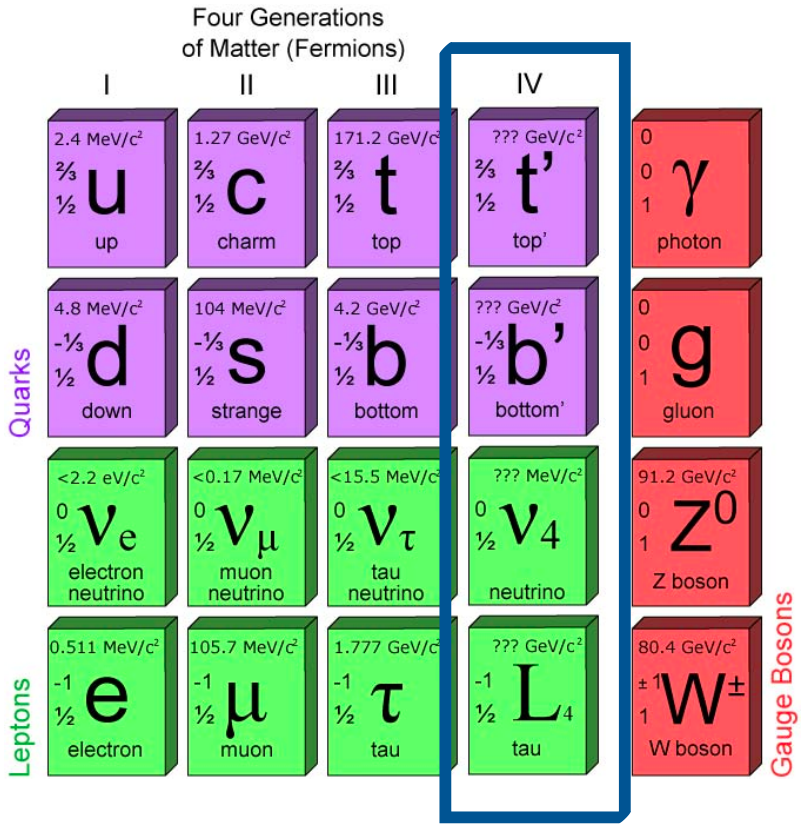


# Fourth Generation Quarks

- Much activity recently in searches for fourth-generation quarks (t', b')

- Higgs discovery and properties strongly constrains or excludes many models
  - Would enhance Higgs cross section by a factor of 5 or more

- Vector-like quark models are still compatible with existing constraints
  - Left- and right-handed components both contribute to CC interaction
  - Do not obtain mass through Yukawa coupling to Higgs



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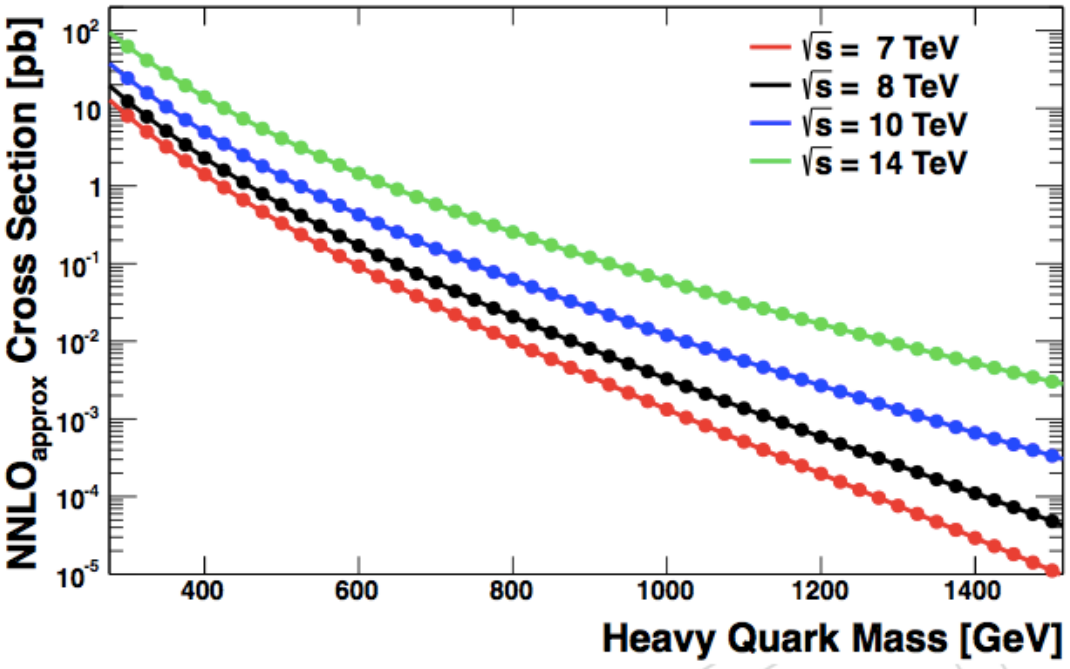
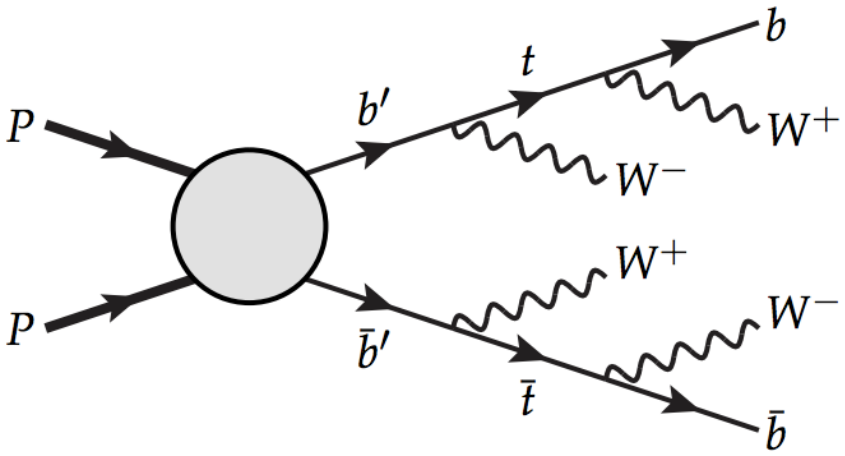
  - Current bounds have $m_Q > \sim 600$ GeV
    - Within reach of LHC experiments!

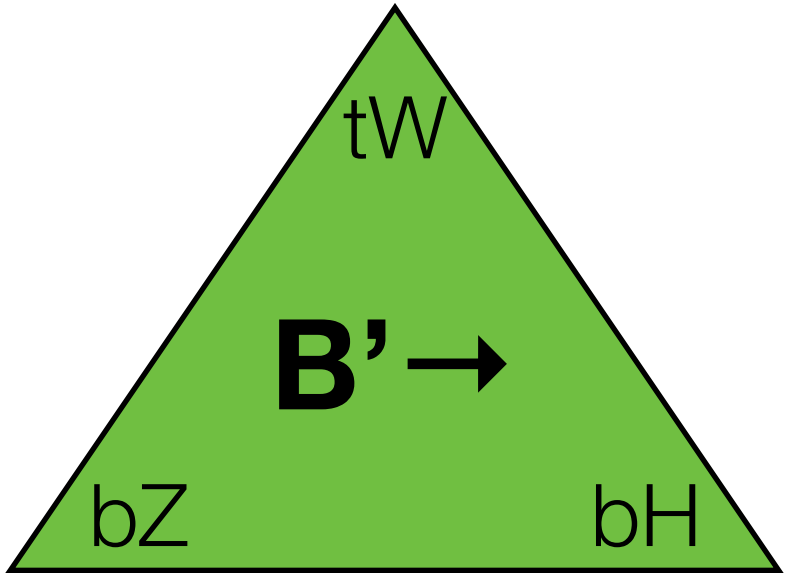


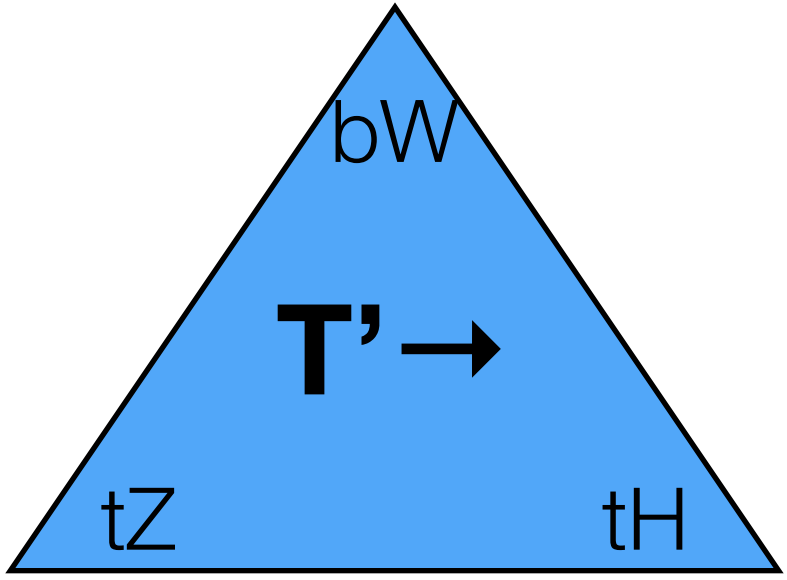
# Fourth Generation Quarks

- Many distinct event topologies to consider!
  - B'→tW, bZ, bH
  - T'→bW, tZ, tH
  - Leptons, b-jets, boosted t/W/Z/H possible in final states




- Common to assume 100% BR to one decay mode
  - Instead want to scan over all possible fractions with same final state

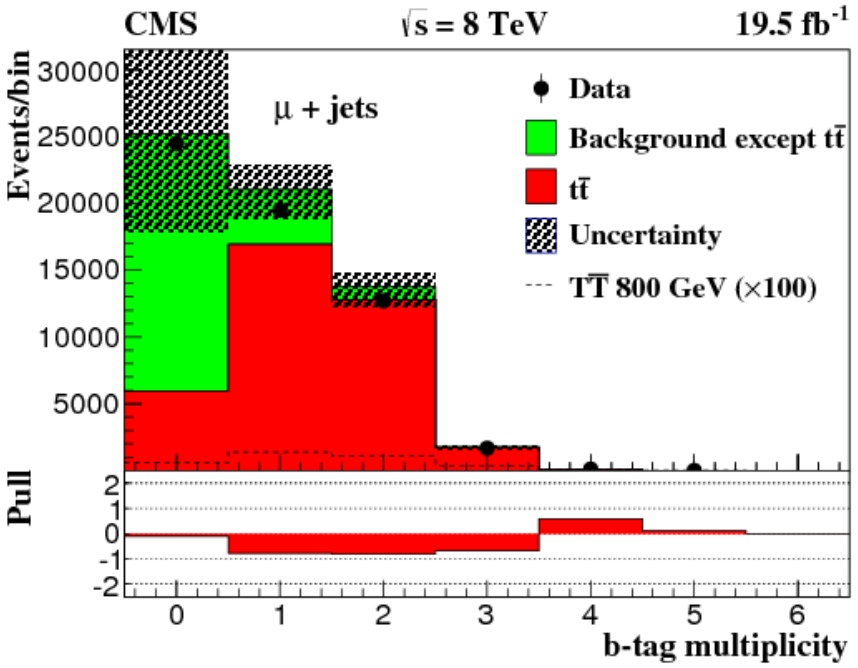


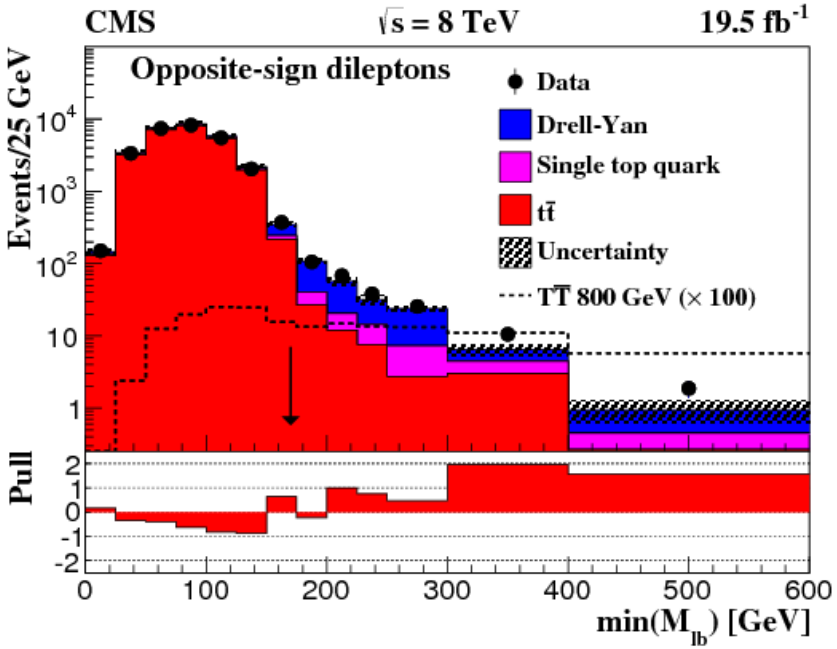



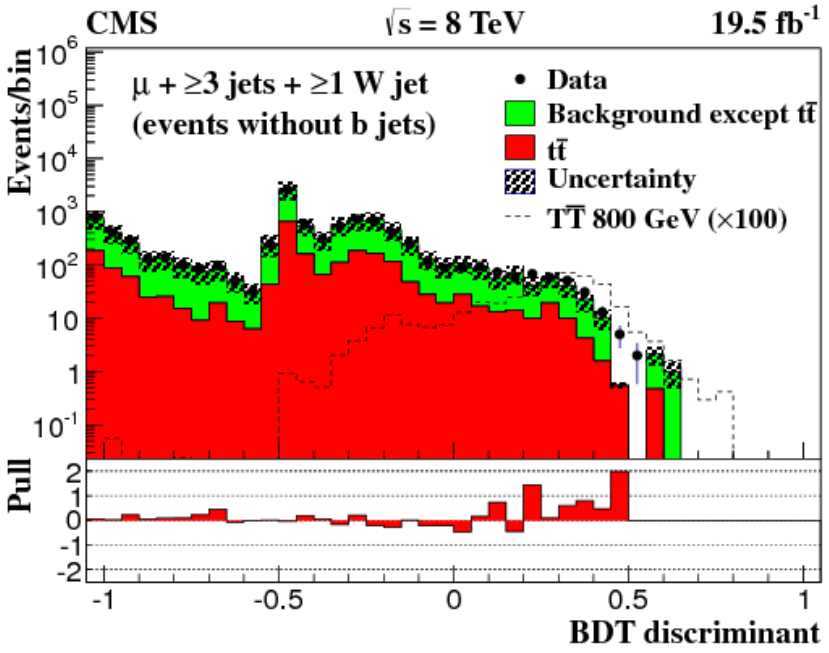
# T' Analyses

CMS-PAS-B2G-12-015
arXiv:1311.7667

- Select final states with 1, 2 (OS and SS), or more leptons
  - Events divided by number of b-tags
- Use large R=0.8 jets to identify merged W or top decay products
  - Mass window required
- BDT used to discriminate signal from dominant SM top pair background
  - OS dilepton channel uses min($m_{lb}$) for discrimination



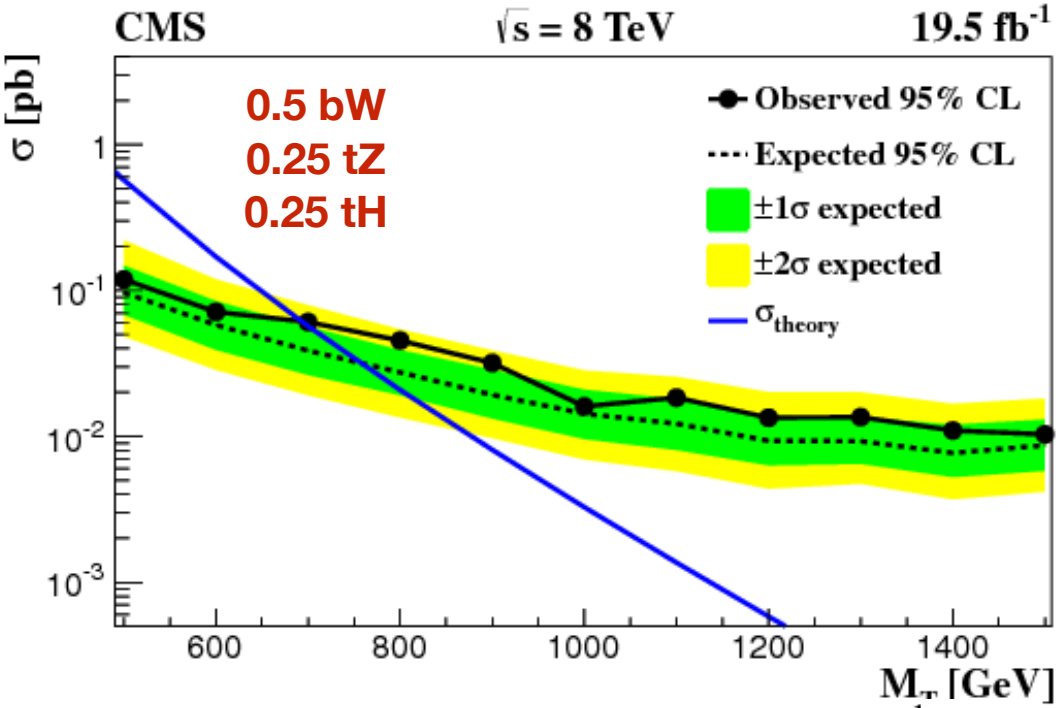



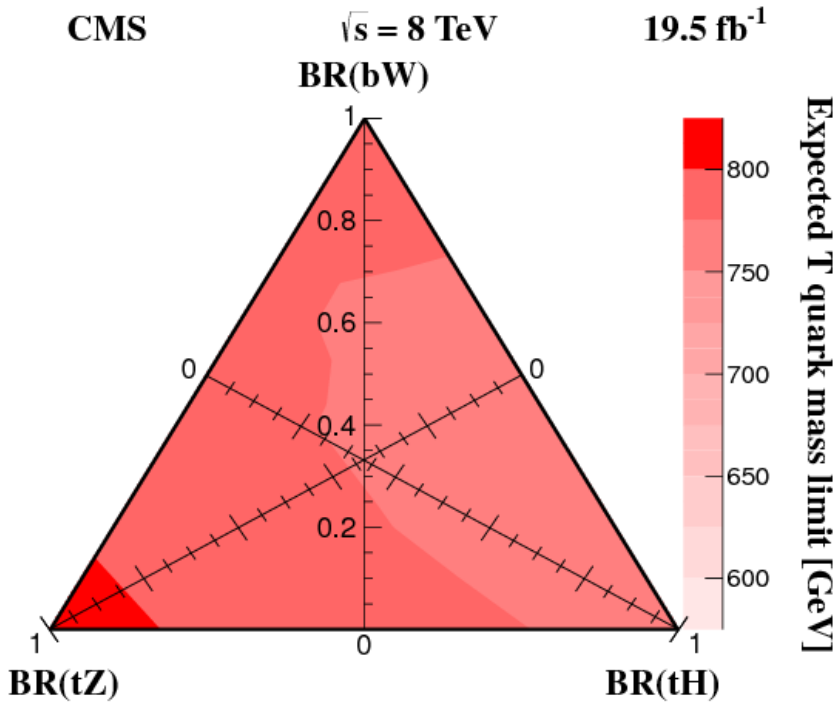



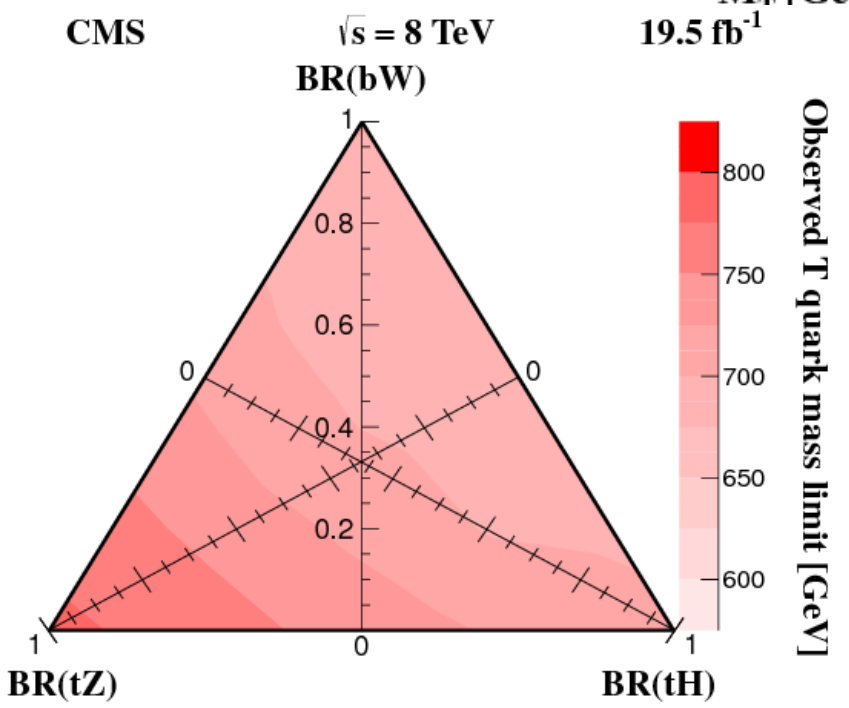
# T' Results

CMS-PAS-B2G-12-015
arXiv:1311.7667

- Combining all channels, limits are produced for various BR combinations
- Observed exclusion limits range from 687 to 782 GeV



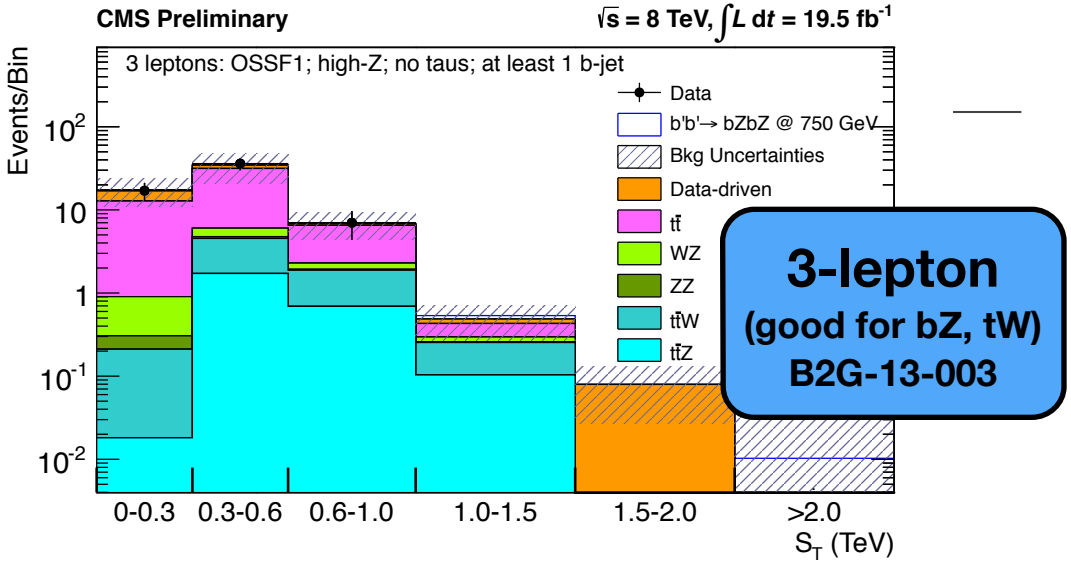



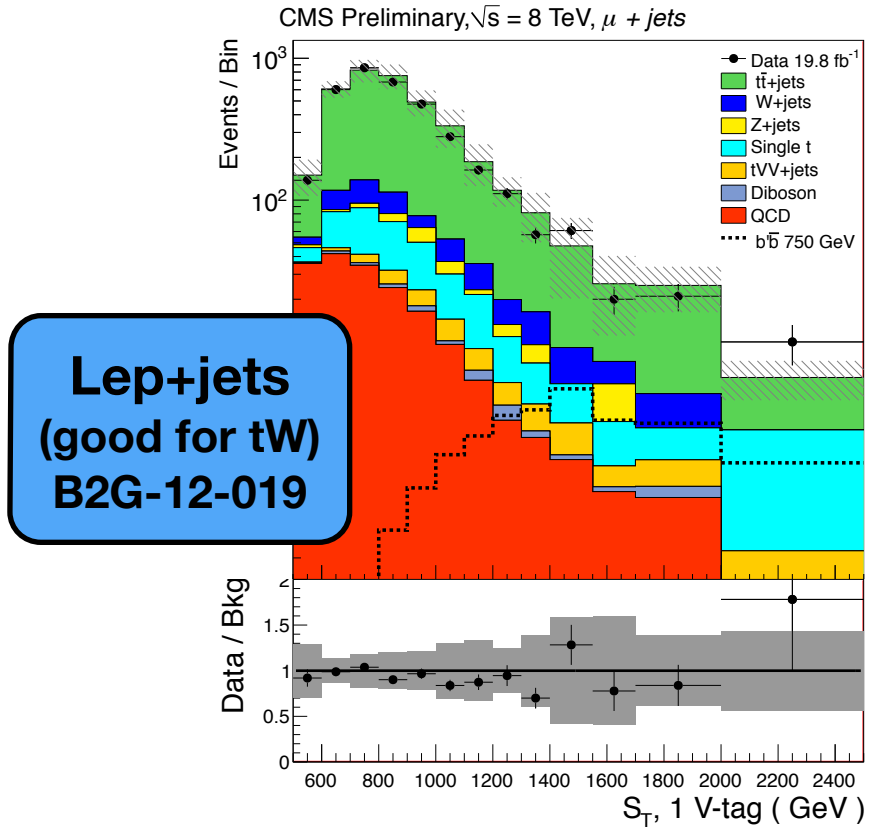
# B' Analyses

- Again, several different final states to probe
  - Single lepton + jets
  - Dilepton OS, SS
  - Multilepton

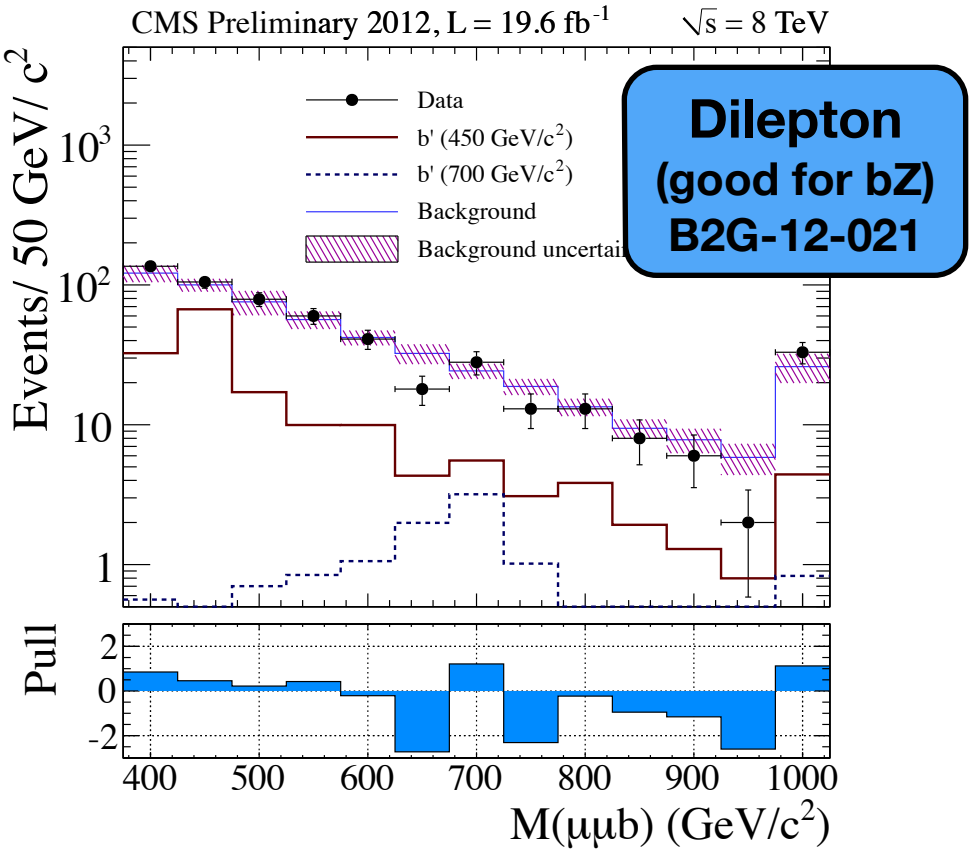
- Mass reconstruction or $S_T$ distribution used to discriminate signal




**3-lepton**
**(good for bZ, tW)**
**B2G-13-003**



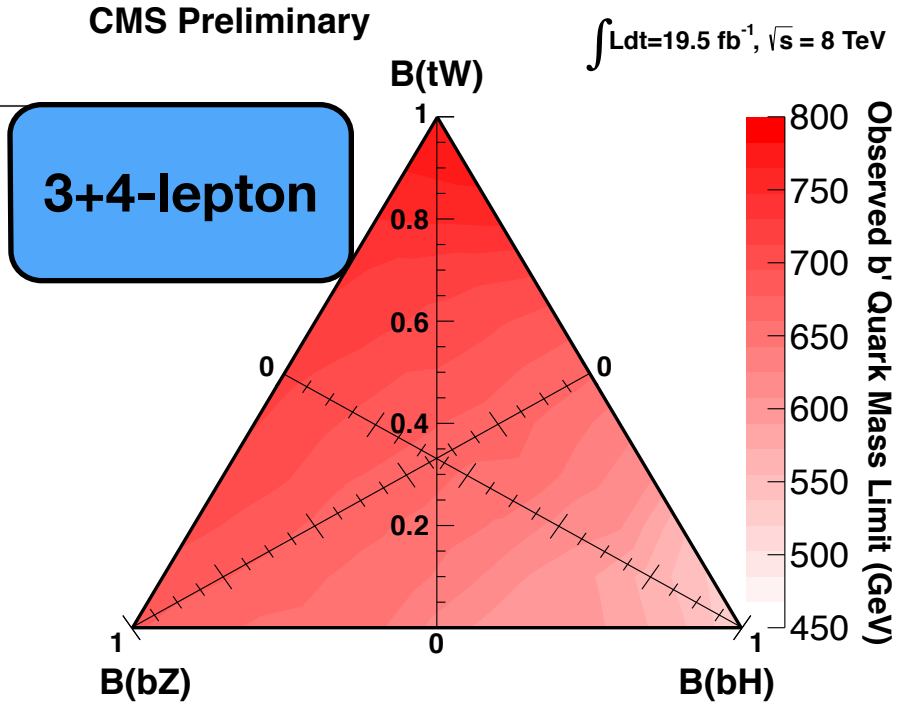

**Lep+jets**
**(good for tW)**
**B2G-12-019**

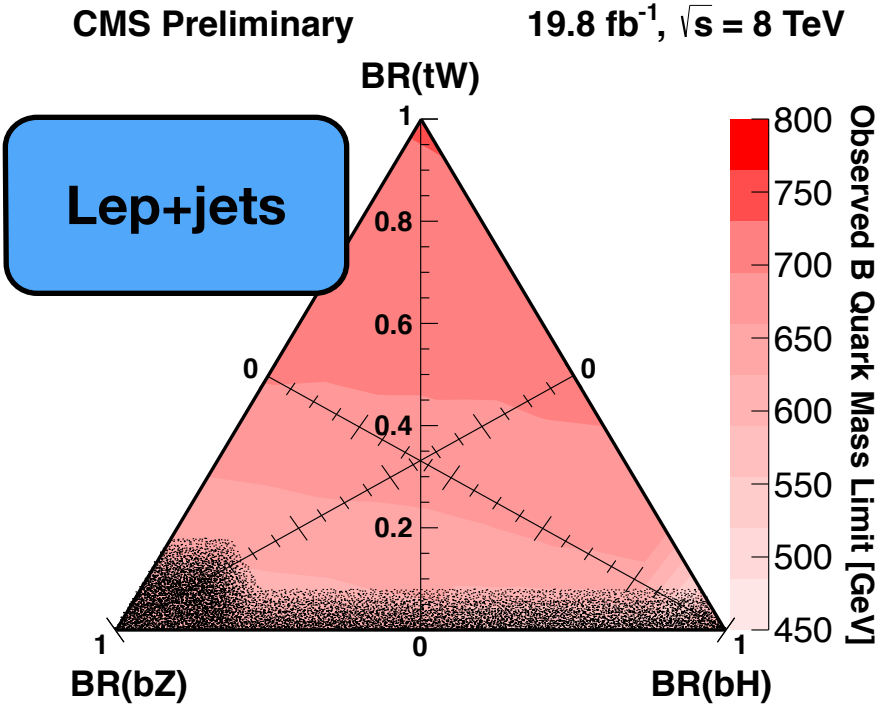


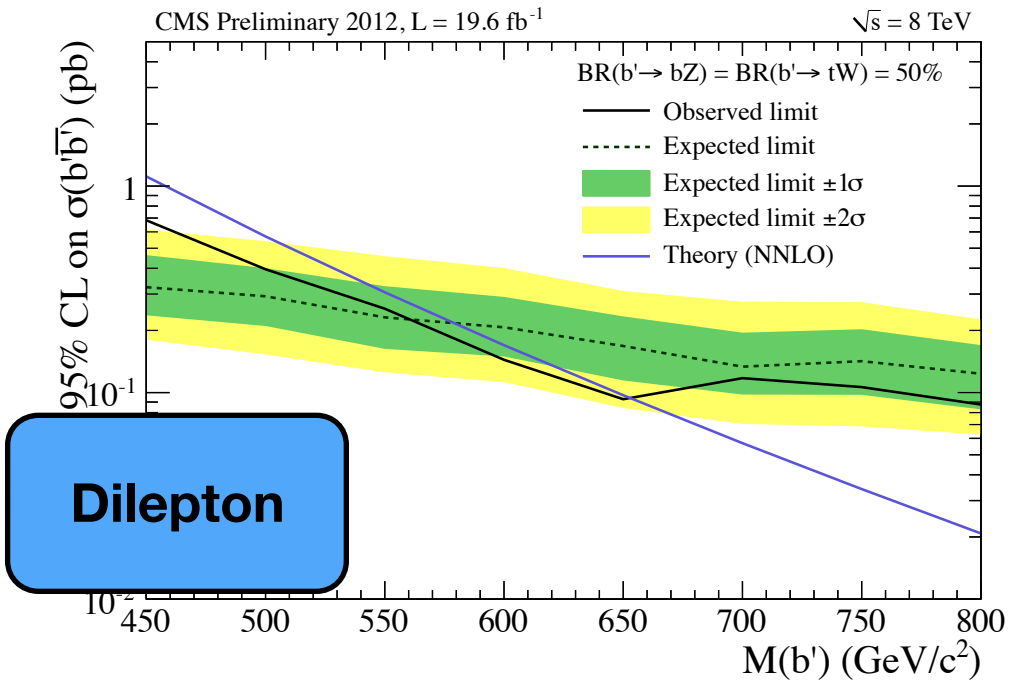

**Dilepton**
**(good for bZ)**
**B2G-12-021**

# B' Results

- Lepton+jets analysis excludes B'→tW for masses < 732 GeV
- Dilepton analysis excludes B'→bZ for masses < 700 GeV
- Multi-lepton analysis excludes B'→tW for masses < 785 GeV



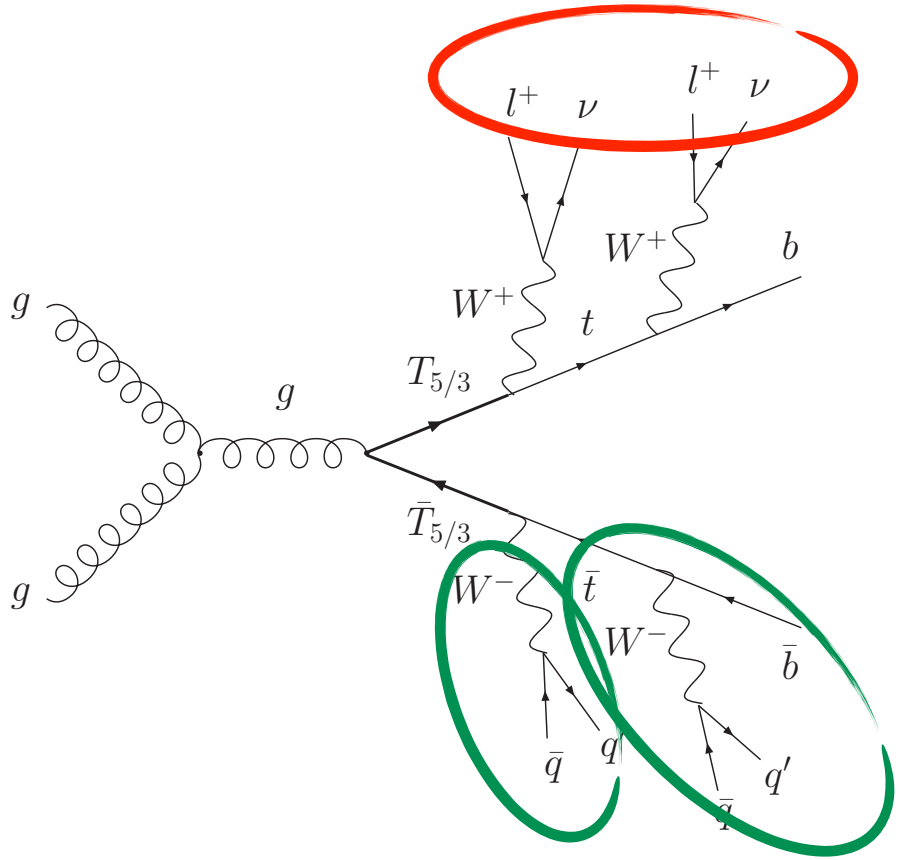



# $T_{5/3}$ Analysis

CMS-PAS-B2G-12-012
arXiv:1312.2391

- CMS search for particles $T_{5/3}$ with exotic charge
  - Solve hierarchy problem and are compatible with observed Higgs mass
  - Found in KK gluon models
- Final state consists of same-sign dileptons
  - Also can identify boosted W or boosted top quarks in the event
    - Use jet substructure!
- Basic event selection:
  - 2 same-sign leptons, $p_T > 30$ GeV
  - 5 or more jets / “constituents”
    - Boosted top = 3
    - Boosted W = 2
  - $H_T > 900$ GeV
  - Quarkonia, Z vetos



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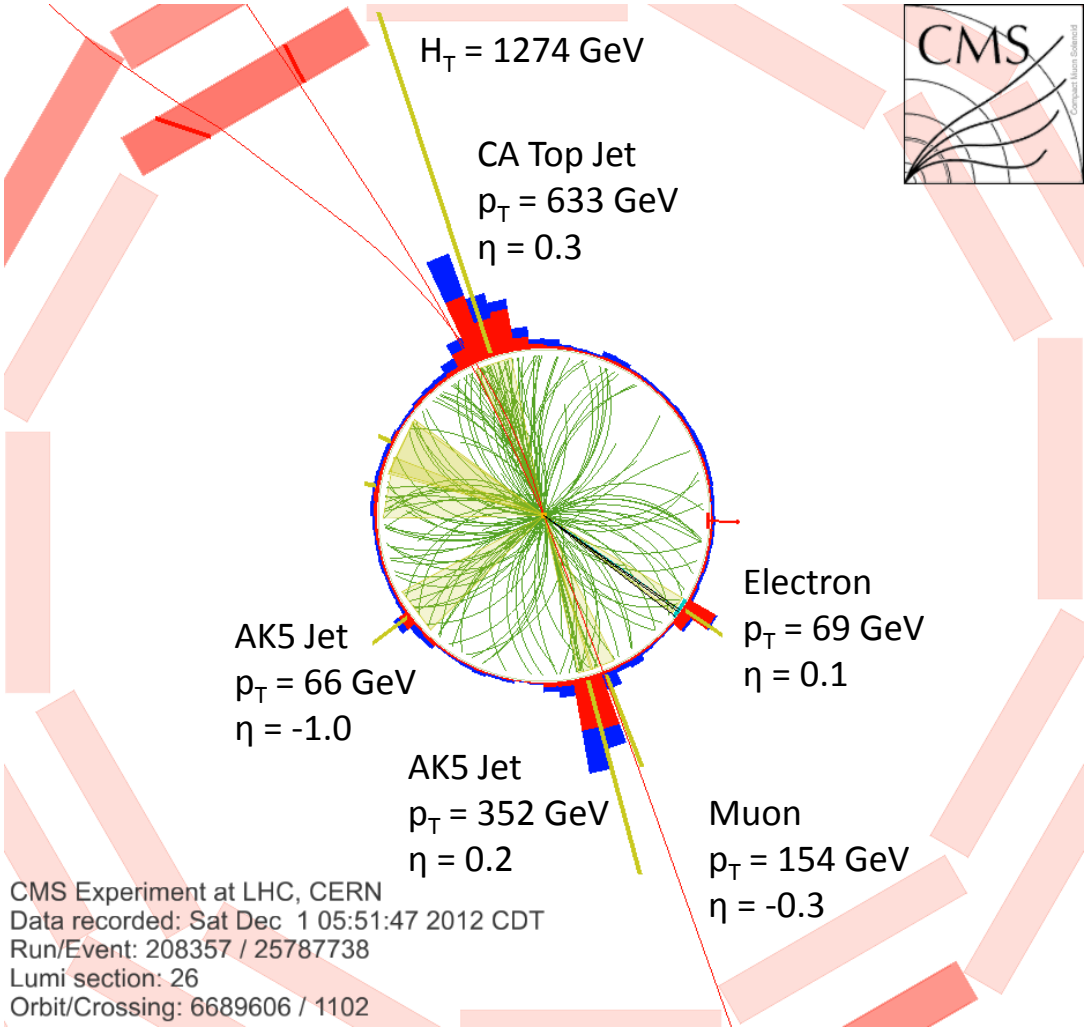

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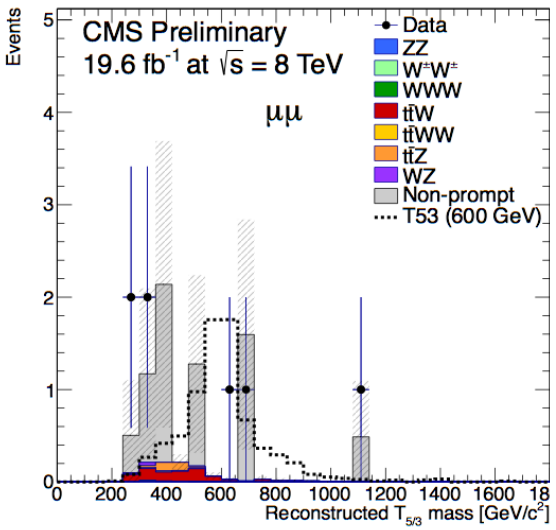
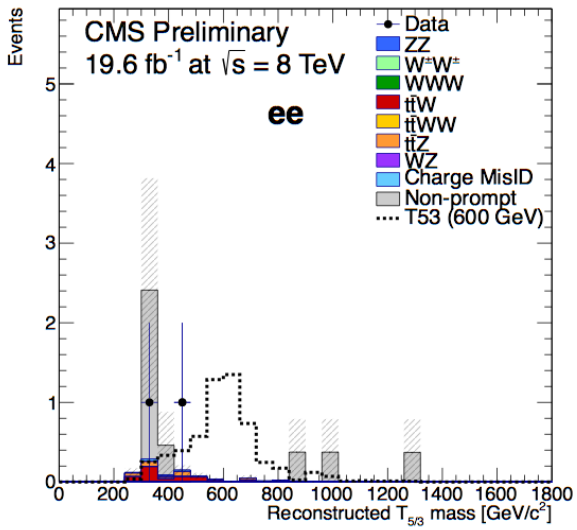
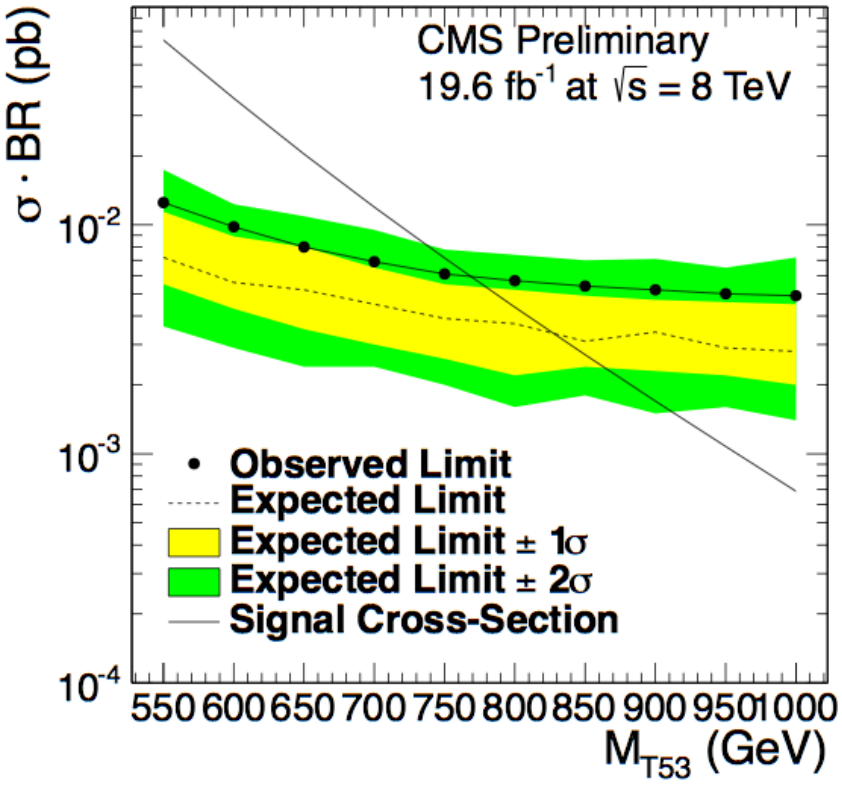
  - Quarkonia, Z vetos
- CMS excludes masses up to 770 GeV

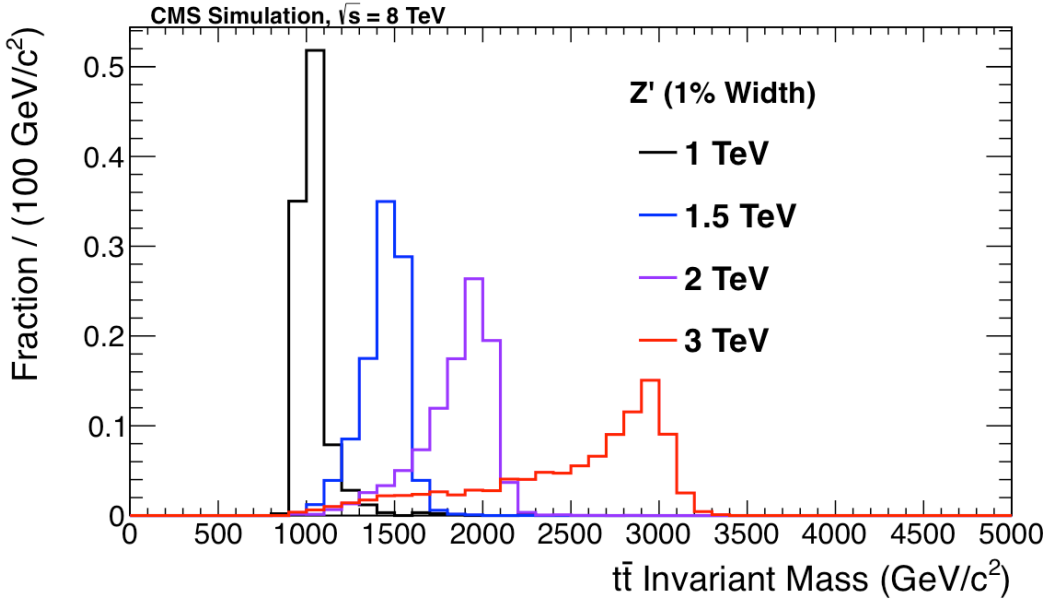


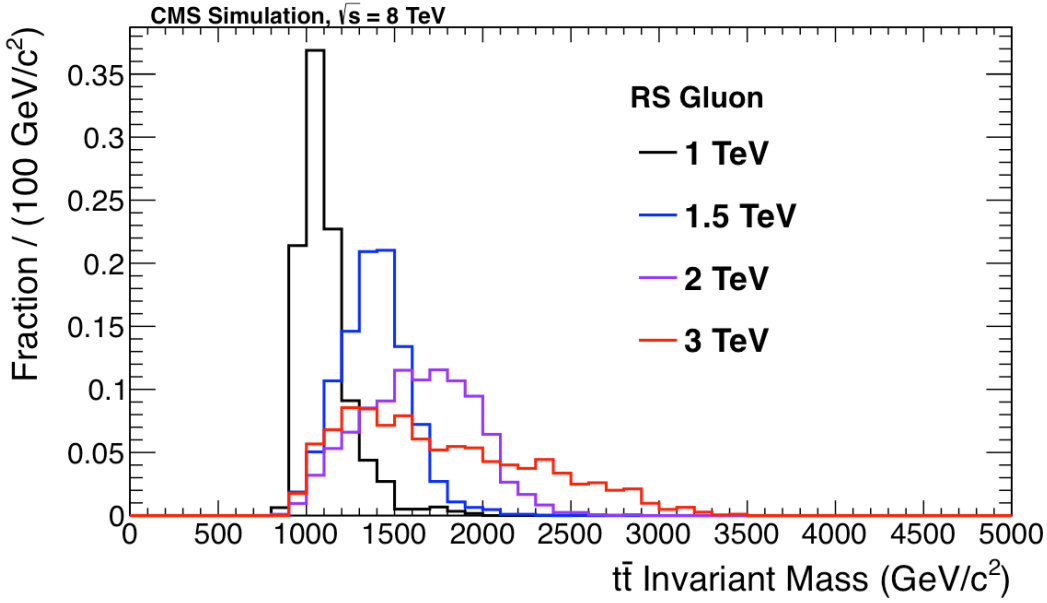



# Top Pair Resonances

- Several searches for new heavy particles with large couplings to top quarks
  - Source of boosted top quarks!
- Mix of techniques used
  - Low mass search : threshold top production, standard reconstruction
  - High mass search : boosted top production, use of top tagging algorithms
- Recent publication of CMS combination of lepton+jets and all-hadronic channels



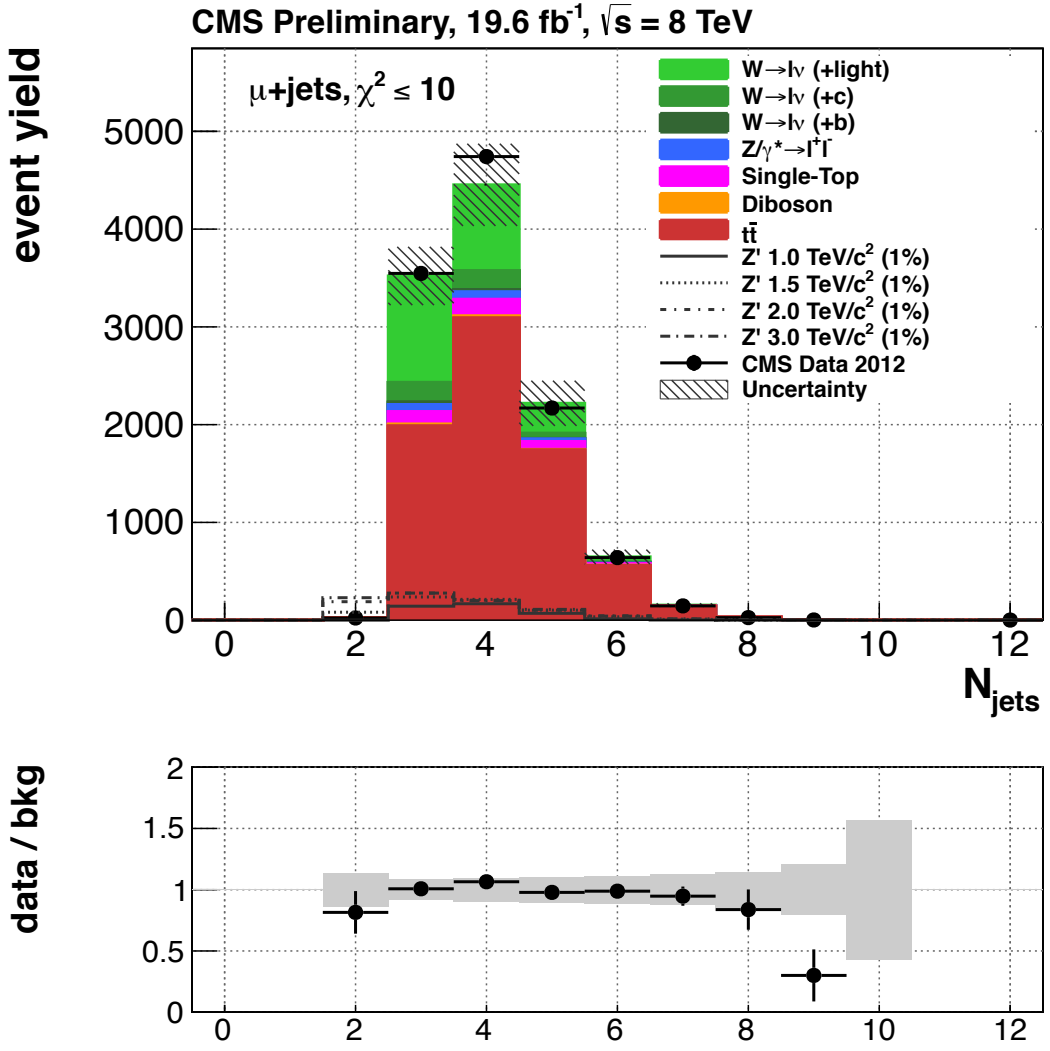
# Lepton+Jets Analysis

CMS-PAS-B2G-12-006

- Two sub-analyses
  - Threshold analysis
  - Boosted analysis

- Choose assignment for each jet
  - Form all combinations, compute $\chi^2$ function
    - Cut to enhance sensitivity

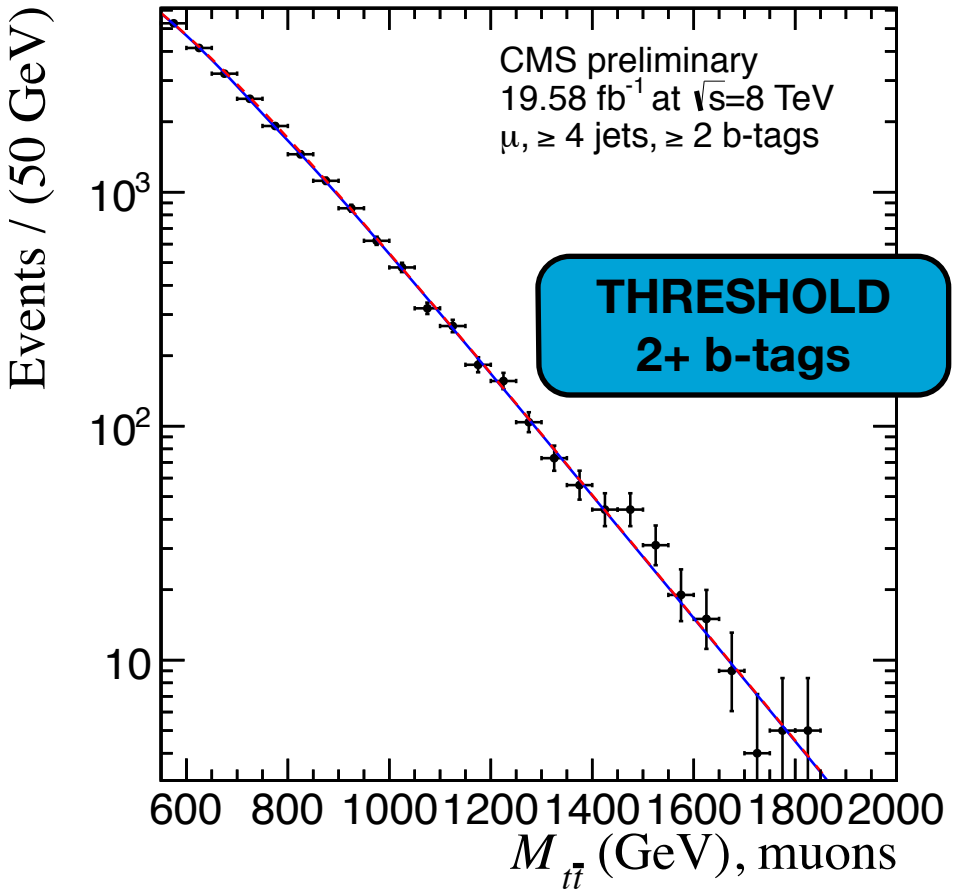
| THRESHOLD | BOOSTED |
|---|---|
| 4+ jets (70/50/30/30 GeV) | 2+ jets (150/50 GeV) |
| Isolated e/μ | Any e/μ |
| MET > 20 GeV | MET > 50 GeV |
| 1+ b-tagged jet | 0+ b-tagged jets |
| | $H_T$ > 150 GeV |

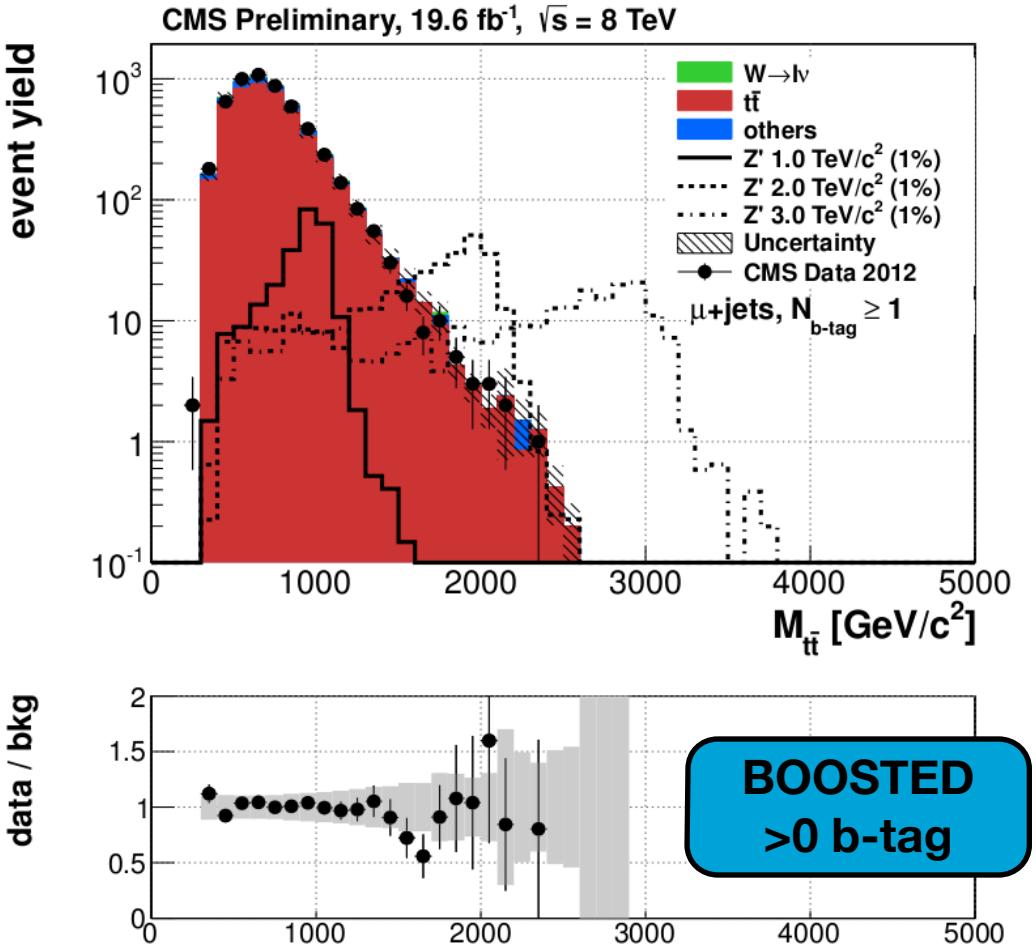


# Lepton+Jets Analysis

CMS-PAS-B2G-12-006

- Threshold analysis uses a fit to data using the $m_{tt}$ spectrum
- Boosted analysis uses MC for background estimation

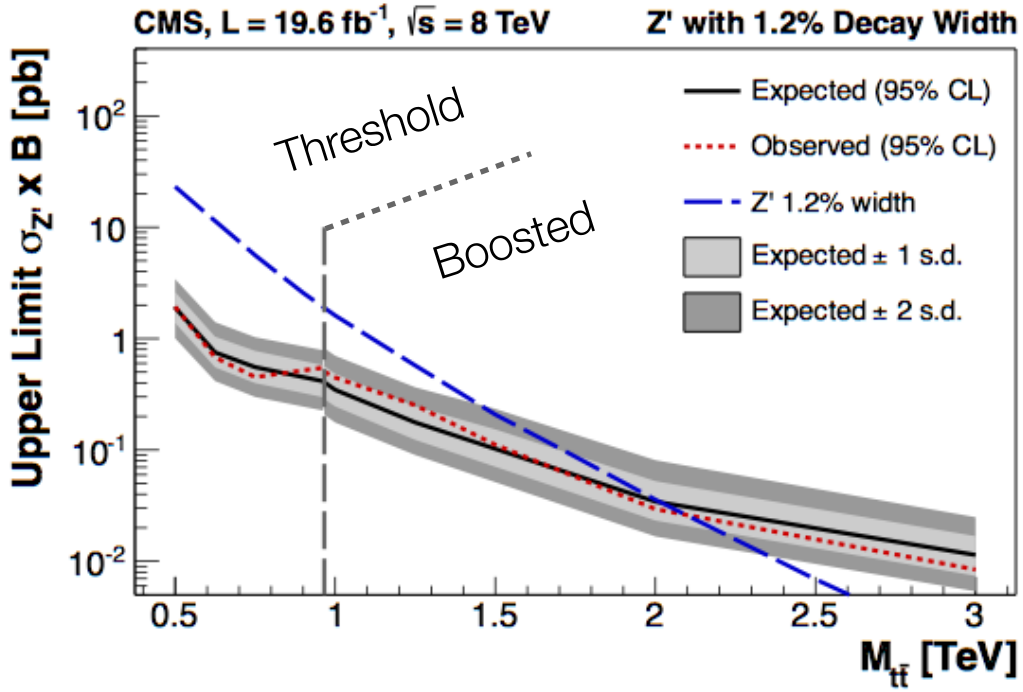


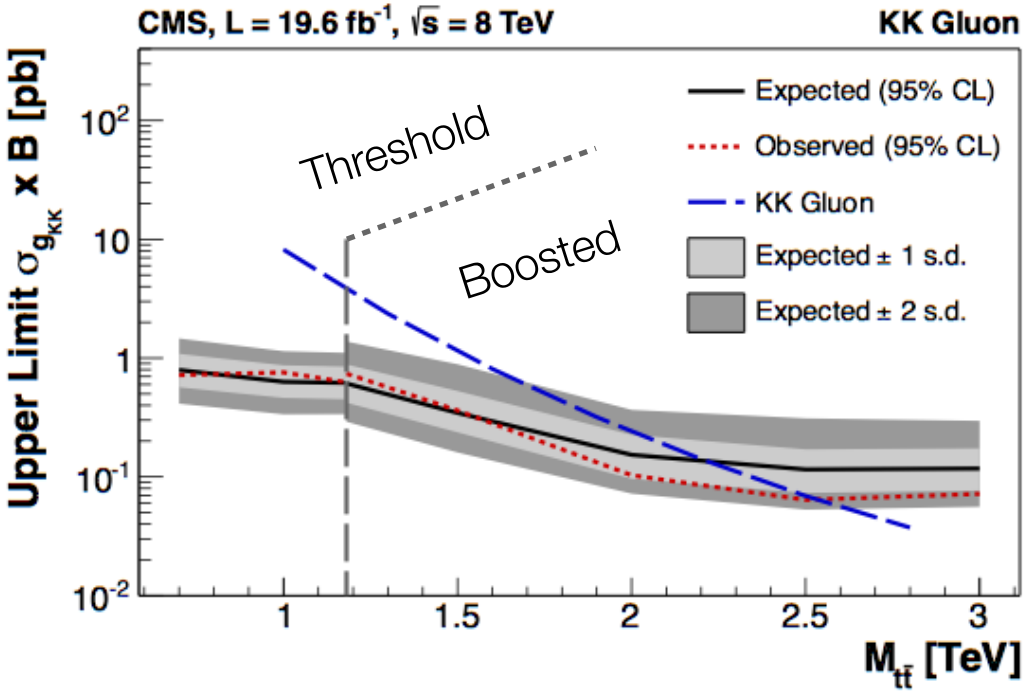



# Lepton+Jets Results

CMS-PAS-B2G-12-006

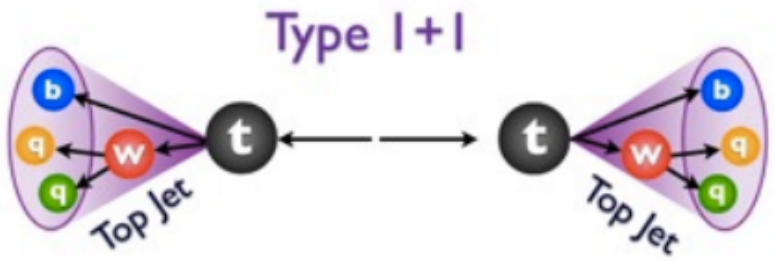
- Vertical line shows transition between threshold and boosted analyses
  - Determined by sensitivity according to expected limits
- 3 signal model hypotheses
  - Narrow (1% width) Z'
  - Wide (10% width) Z'
  - RS KK gluon
- CMS excludes:
  - Narrow Z' up to 2.1 TeV
  - Wide Z' up to 2.68 TeV
  - RS KK gluon up to 2.5 TeV



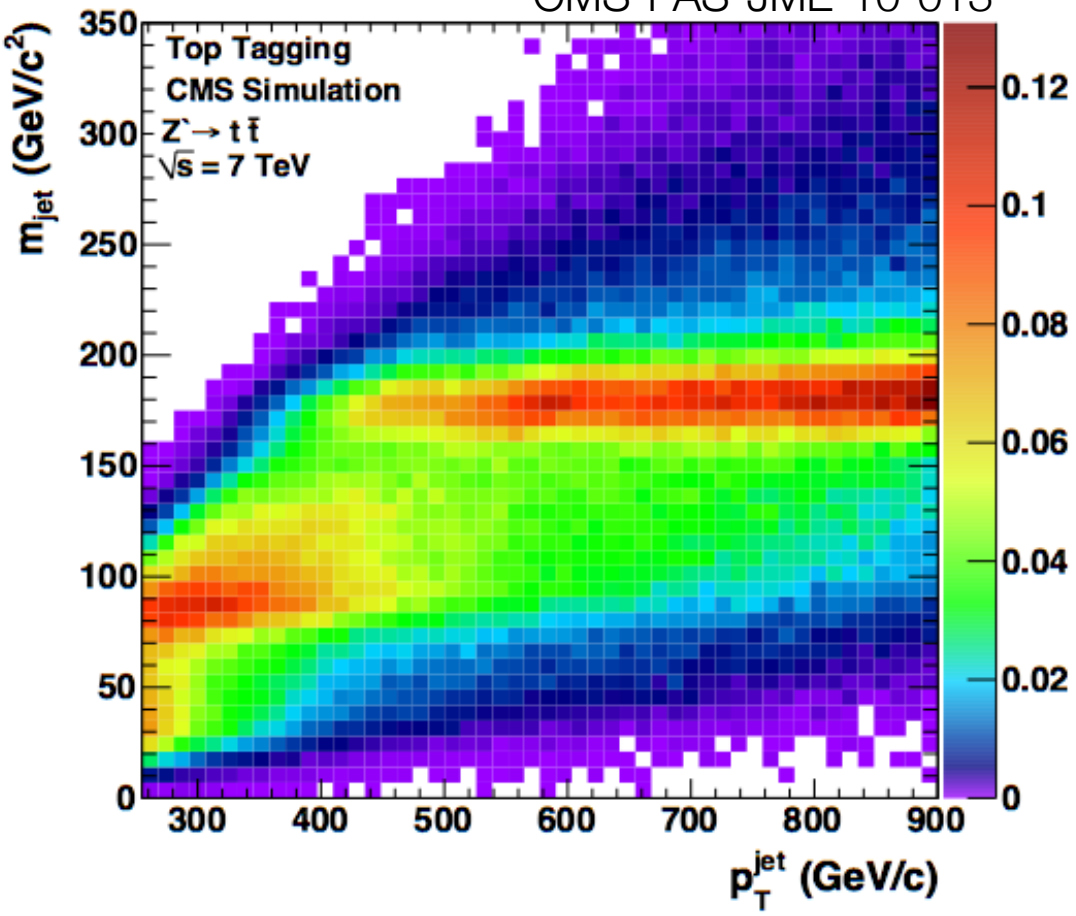
# All-Hadronic Analysis

- Search for dijet events corresponding to two boosted top quarks




- Main background is QCD multijet production
  - Data-derived method to estimate this contribution

CMS-PAS-JME-10-013



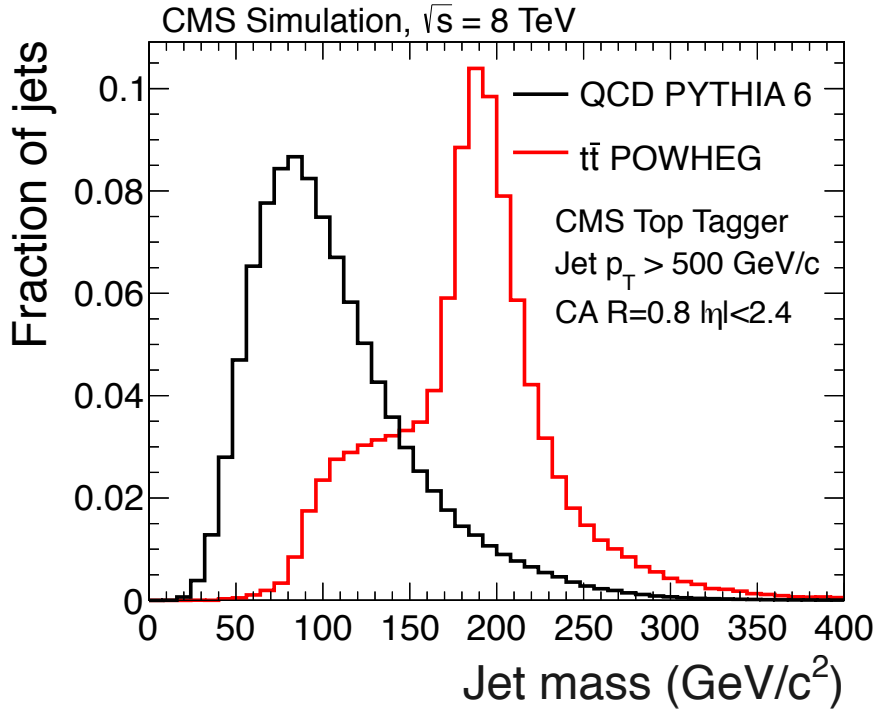

- Event selection consists of:
  - 2 top-tagged jets (R = 0.8, CA) $p_T > 400$
  - Rapidity separation $|\Delta y| < 1.0$
    - Reduces multijet contribution

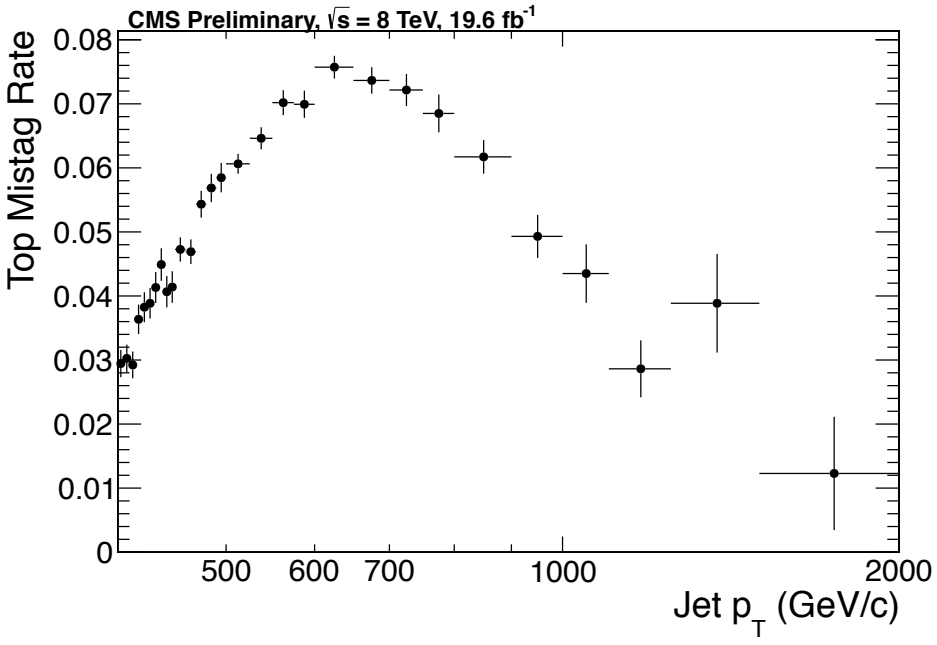
- Use the CMS top-tagger to identify the boosted tops

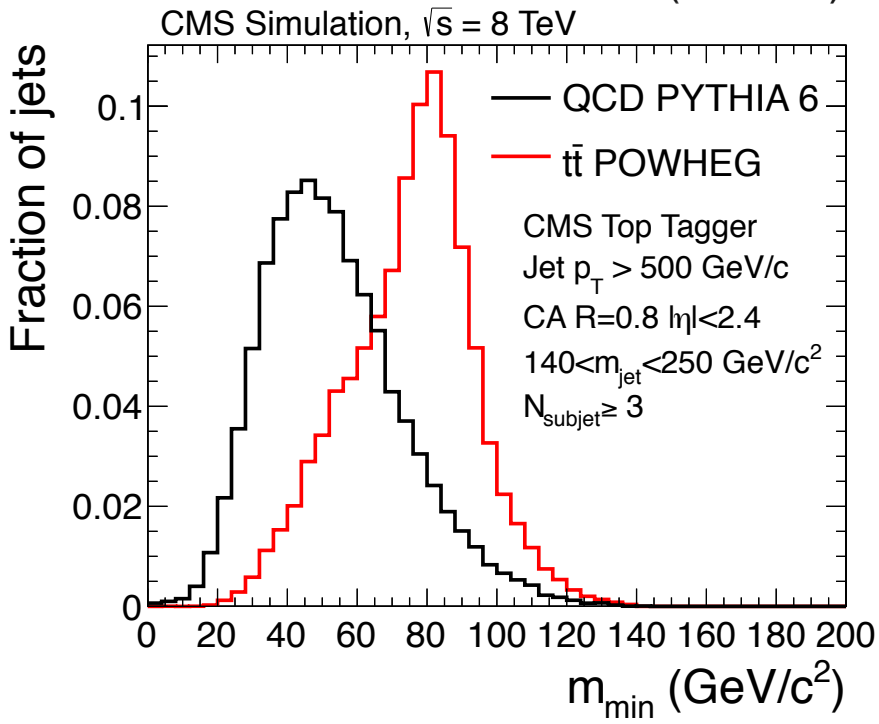
# CMS Top Tagger

CMS-PAS-B2G-12-005,
CMS-PAS-JME-13-006

- Look at substructure quantities to identify top quarks
  - Jet mass in [140, 250] GeV
  - Number of subjets >= 3
  - Minimum pairwise subjet mass > 50 GeV
    - Proxy for *W* within fully-merged jet
- Efficiency ~50% at high $p_T$
- Mistag rate < 10%



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CMS-PAS-JME-13-006

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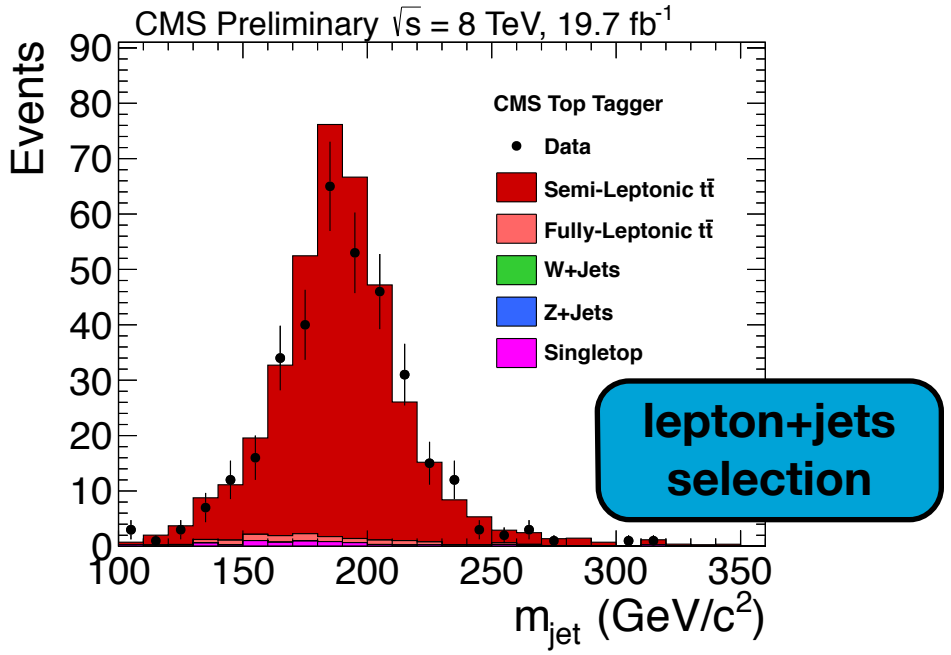
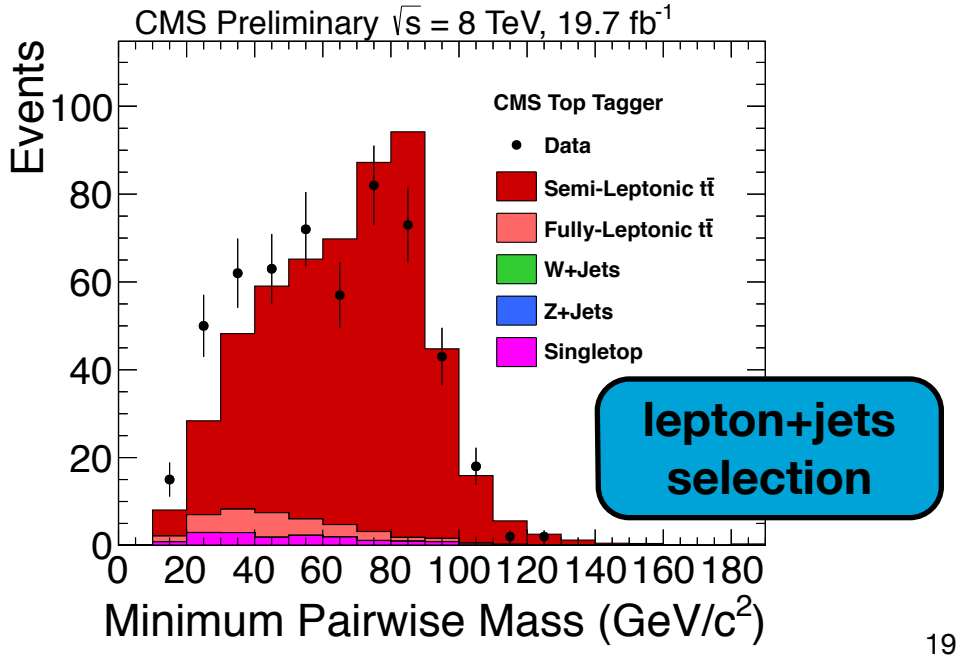
  - Jet mass in [140, 250] GeV
  - Number of subjets >= 3
  - Minimum pairwise subjet mass > 50 GeV
    - Proxy for *W* within fully-merged jet
- Validated in lepton+jets sample enriched in top quarks
- See talk by Jim Dolen later today for much more detail and new updates!

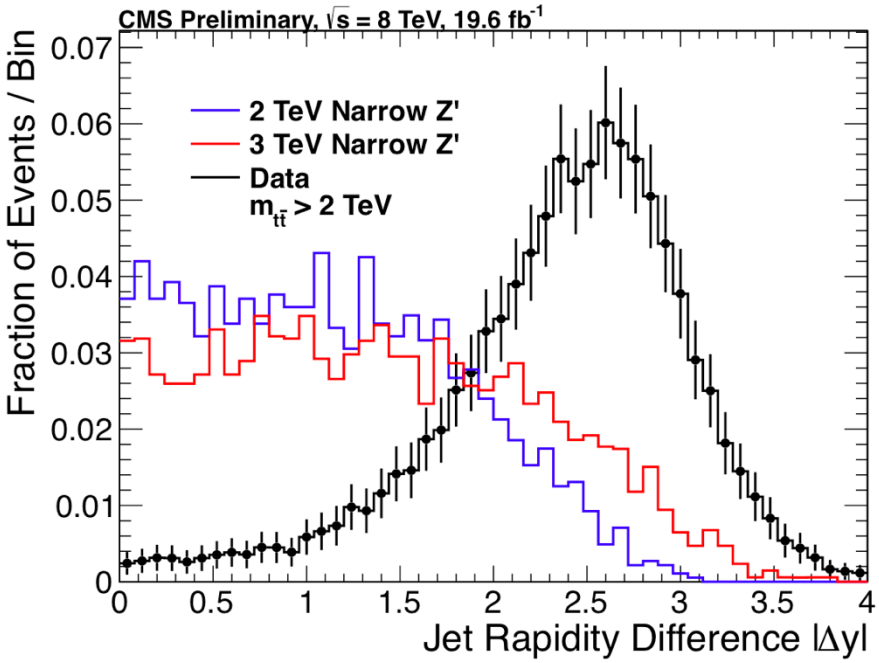


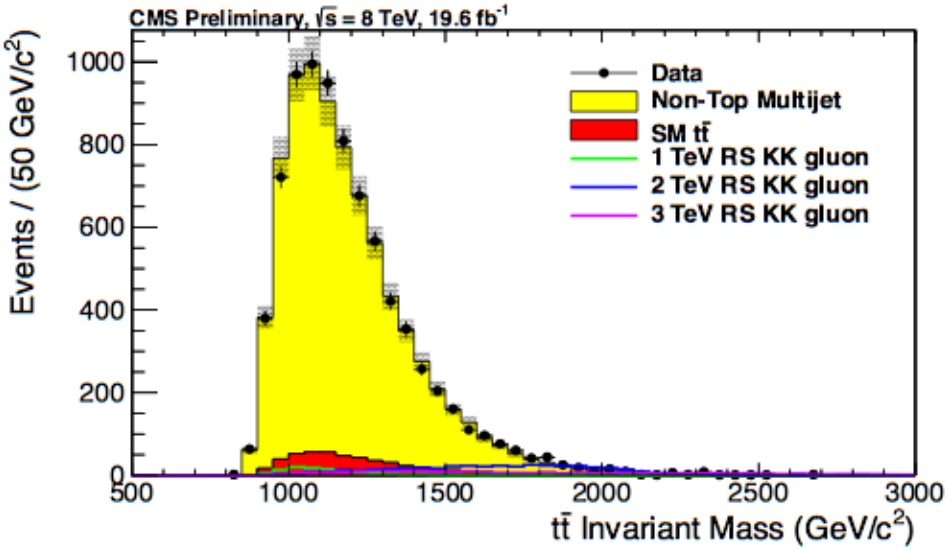



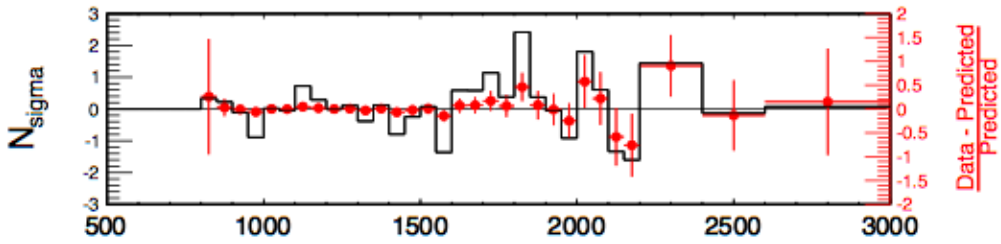
# All-Hadronic Analysis

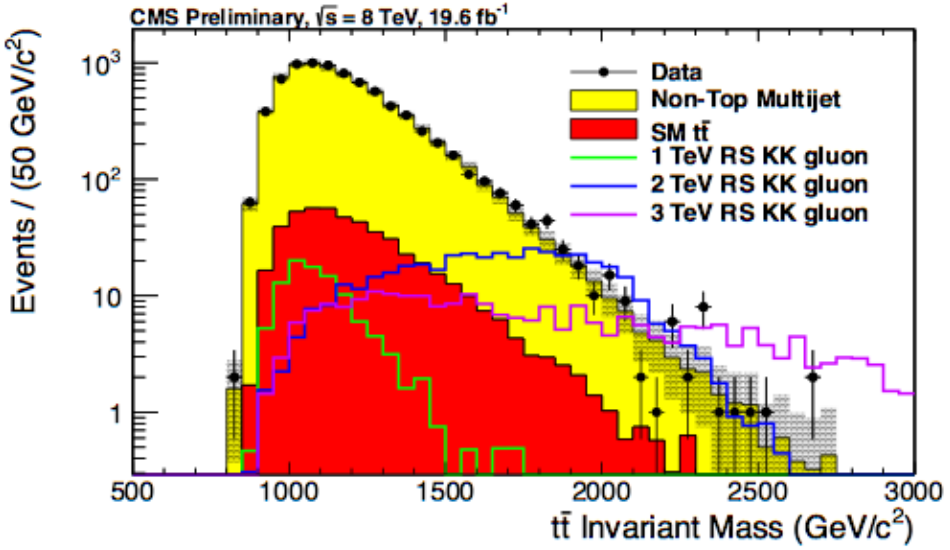
CMS-PAS-B2G-12-005

- Top pair invariant mass formed for signal discrimination
- Jet rapidity separation reduces multijet contribution significantly for high mass candidates



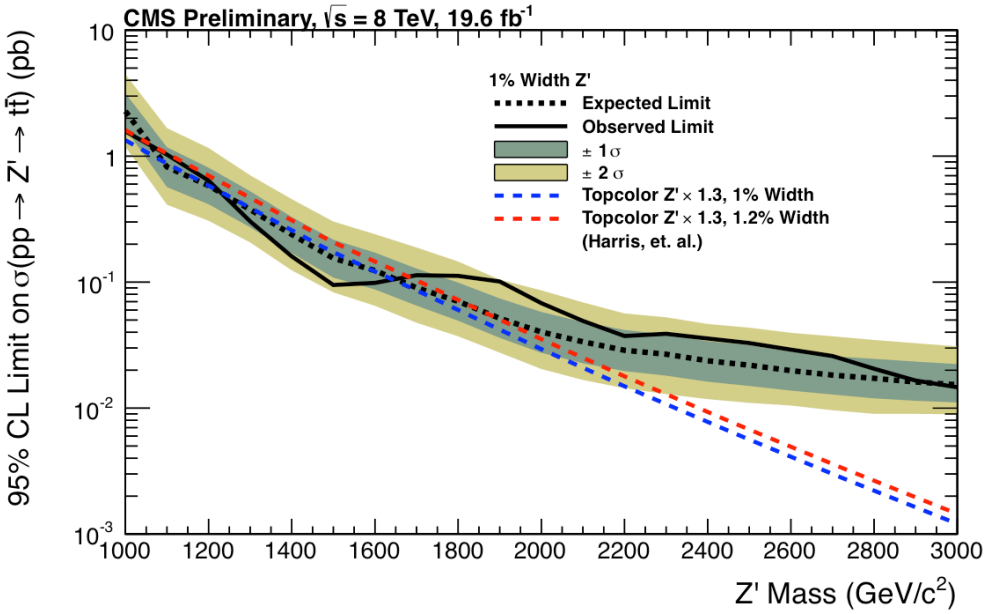



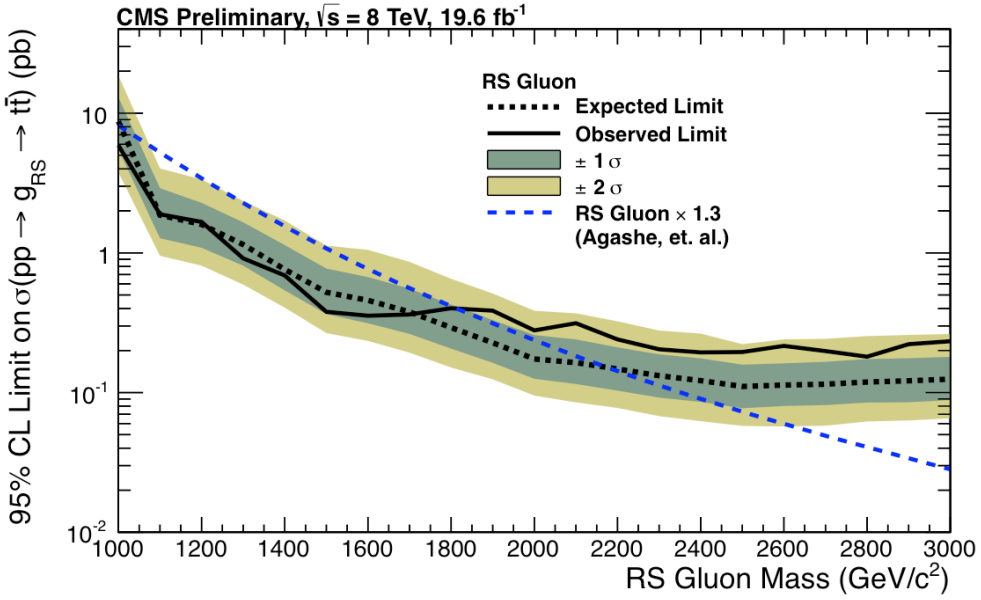



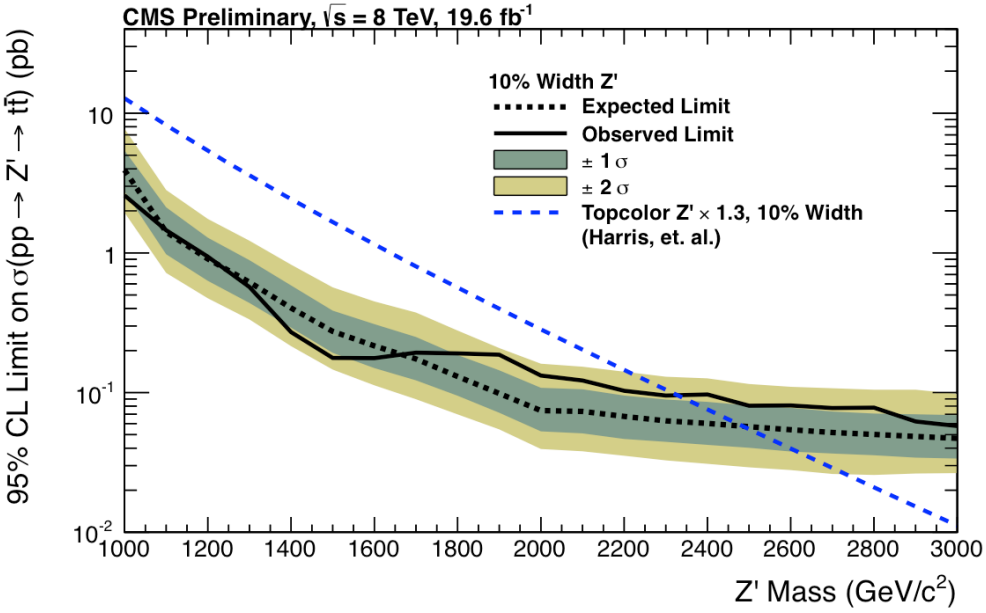
# All-Hadronic Results

CMS-PAS-B2G-12-005

- CMS results with full 8 TeV dataset
- Narrow (1%) Z' exclusion to 1.65 TeV
- Wide (10%) Z' exclusion to 2.35 TeV
- RS KK gluon exclusion to 1.8 TeV
- High mass cross section limits significantly improved due to $|\Delta y|$ criteria



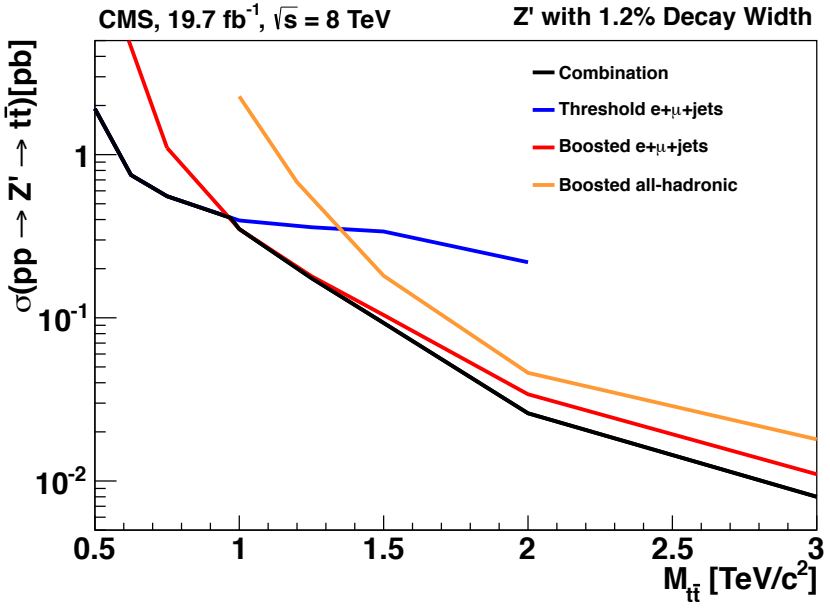
# Combination Results

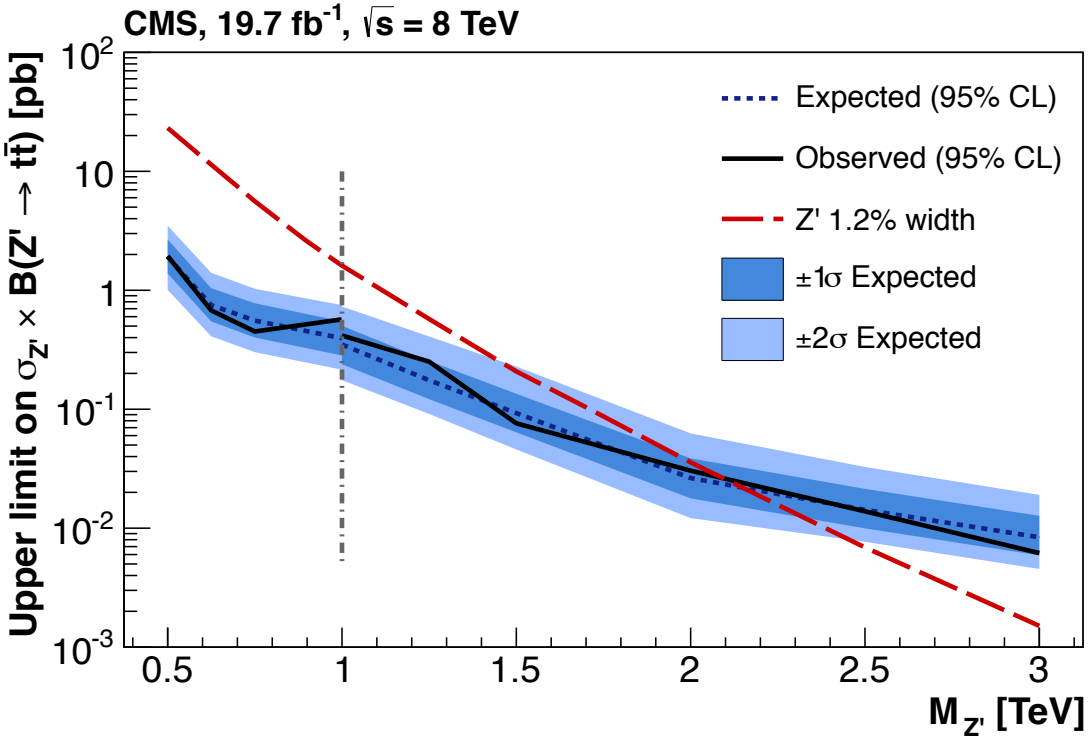
PRL 111, 211804 (2013)

- Statistical combination of 4 channels:
  - Threshold
  - Boosted 0 b-tag
  - Boosted 1 b-tag
  - All-hadronic

| Model | Observed Limit | Expected Limit |
|---|---|---|
| $Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$ | 2.1 TeV | 2.1 TeV |
| $Z', \Gamma_{Z'}/M_{Z'} = 10\%$ | 2.7 TeV | 2.6 TeV |
| RS KK gluon | 2.5 TeV | 2.4 TeV |

- Best limits to date on these physics models
- Recently published in PRL

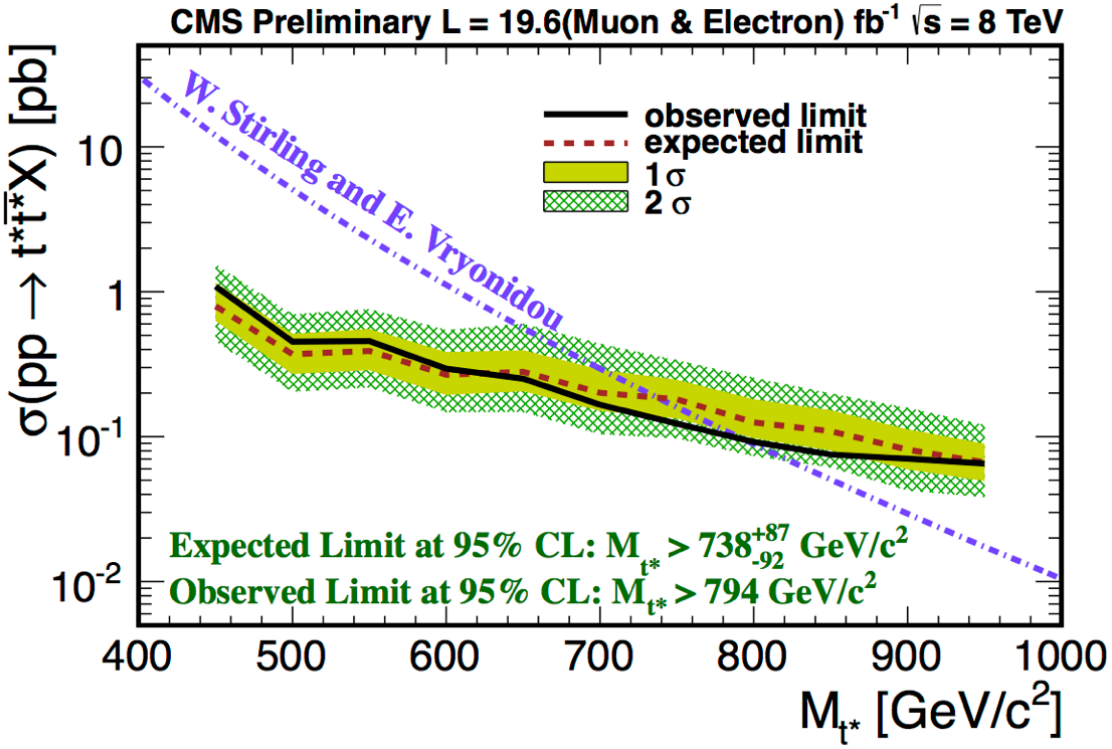


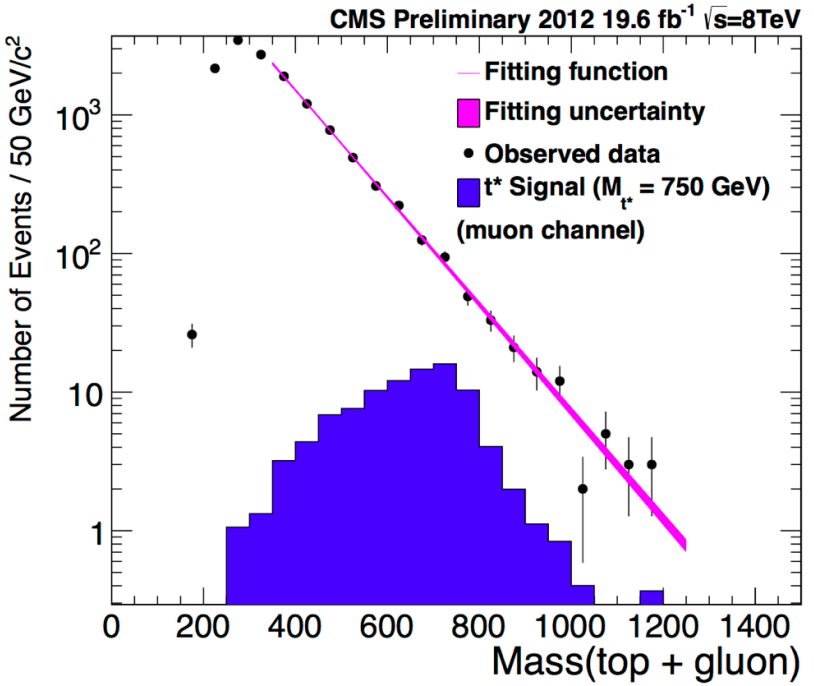



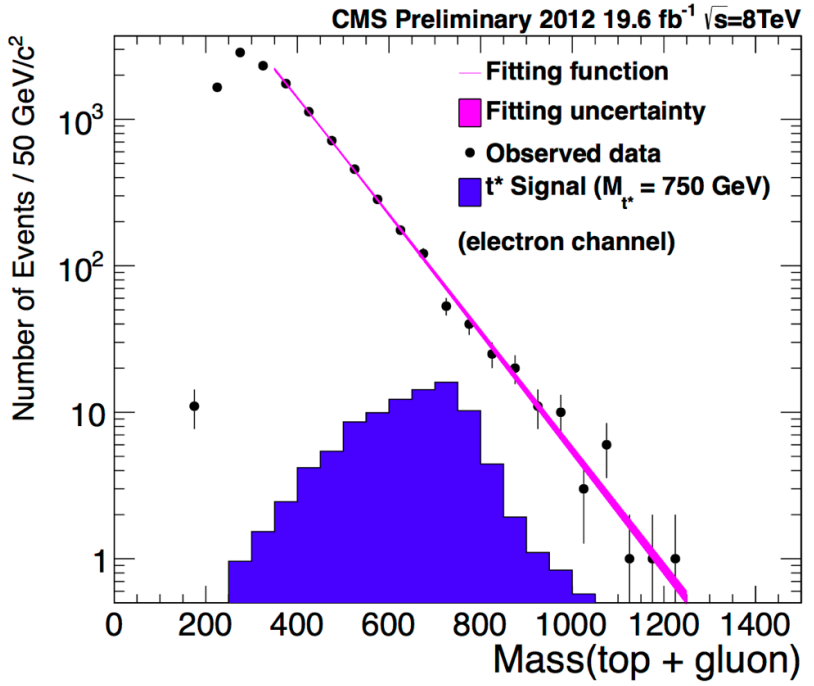
# Excited Top Search

CMS-PAS-B2G-12-014
arXiv:1311.5357

- Search for excited top quark $t^* \rightarrow t+g$
- Electron/muon + missing $E_T$ + ≥6 jets
  - 1 b-tagged jet
- Kinematic constraints to reconstruct candidate t* mass
  - Distribution used in limit setting
- Exclude t* quarks up to 794 GeV



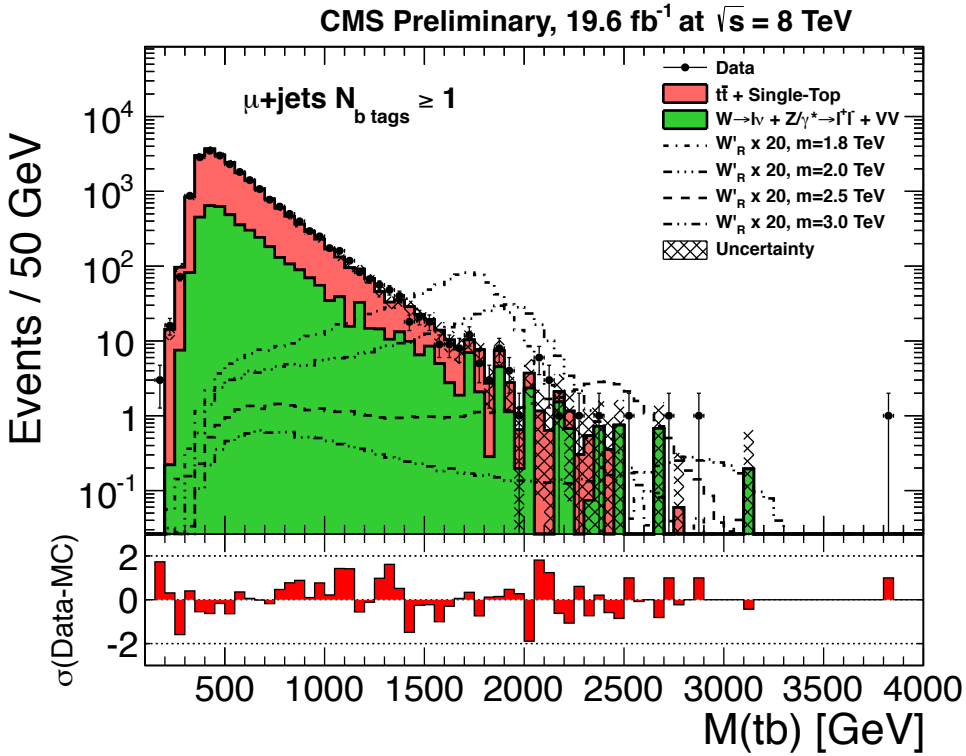



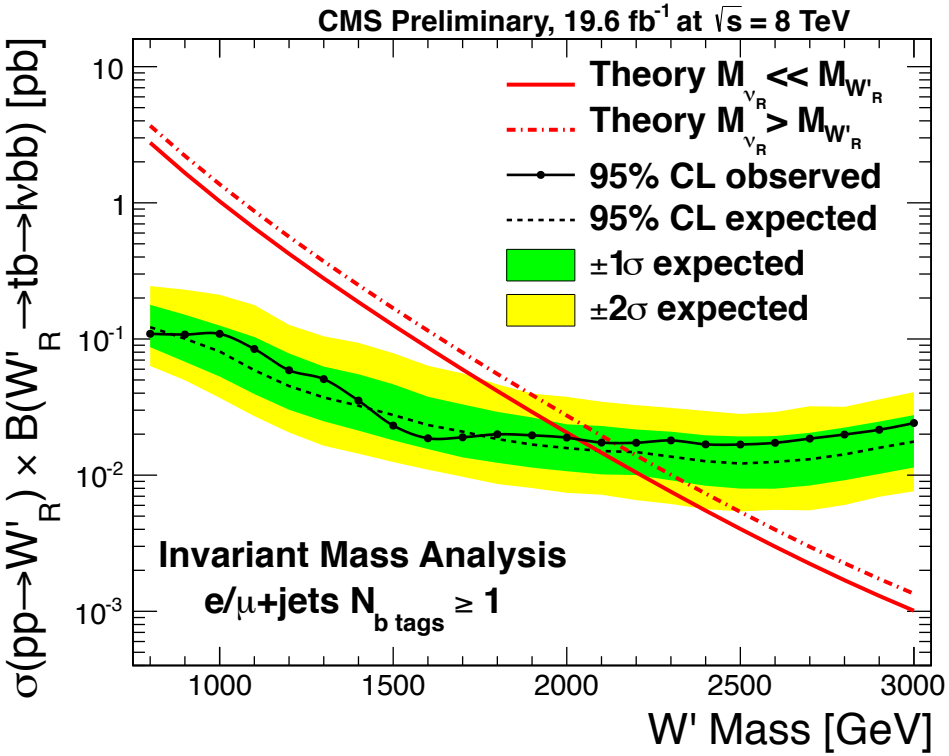



# W'→tb Analysis

CMS-PAS-B2G-12-010

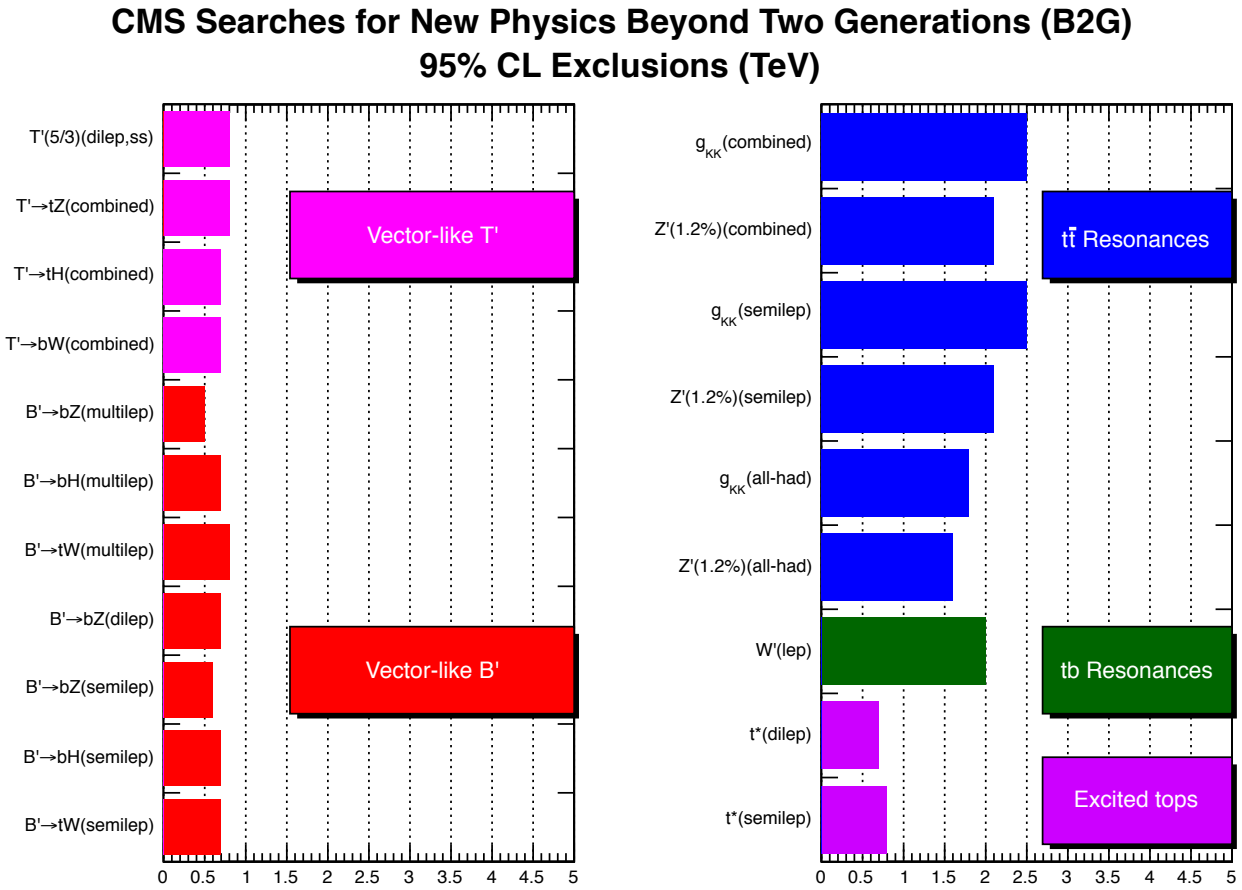
- Search for W' decaying to t+b in the lepton+jets topology
  - 2 b-jets in final state
    - Require 1+ b-tagged jets
- Can reconstruct the event
  - Solve for neutrino 4-vector
  - Invariant t+b mass used for discriminant
- For W' with pure right-handed couplings
  - Masses excluded up to 2.03 TeV
- Also quote results in phase space of right-, left-handed coupling strengths



# Summary

- Many recent CMS results utilizing top quarks reconstructed in the final state
  - New reconstruction techniques becoming prevalent and necessary to maintain sensitivity
    - Jet algorithms
    - Boosted object reconstruction
- Critical to study analysis performance as we work toward 14 TeV collisions
  - Algorithm performance will be critical
- Stay tuned for updates and improvements on many of the analyses presented here today!

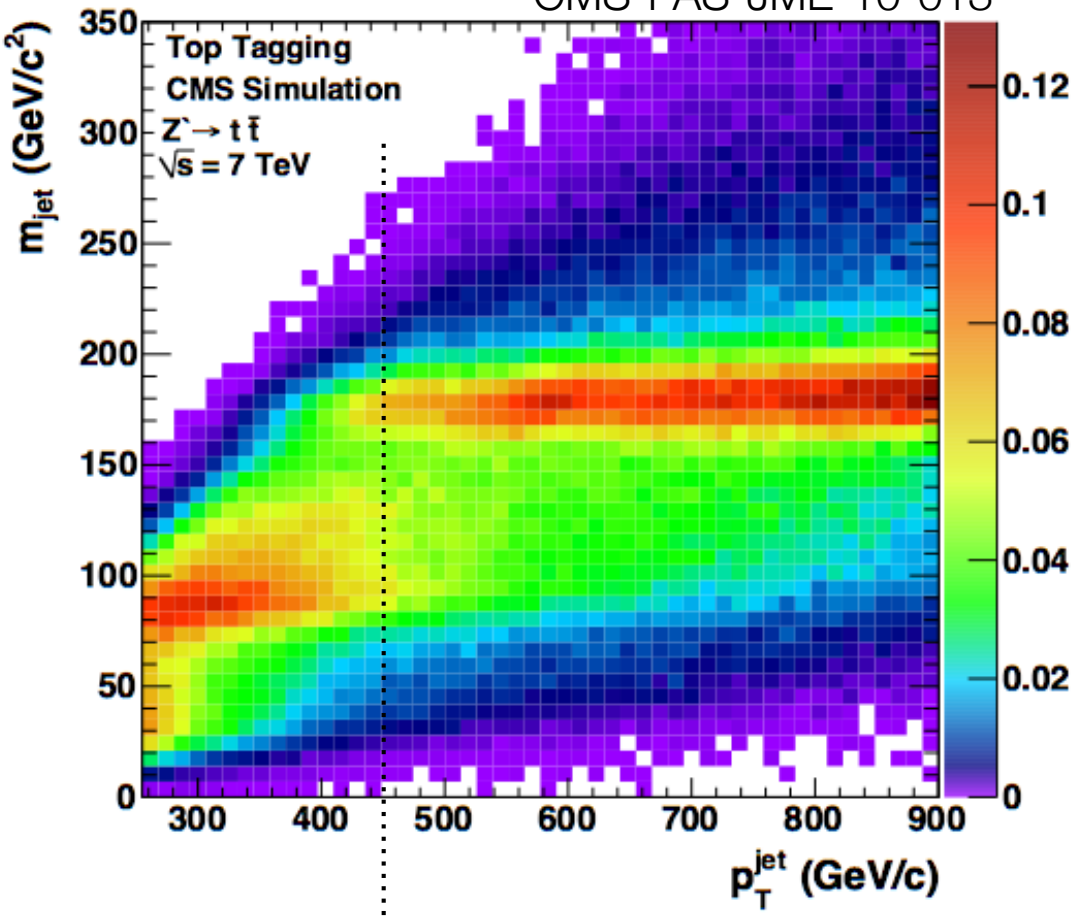


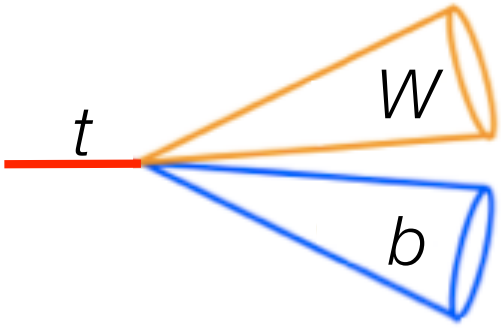
# Backup Material

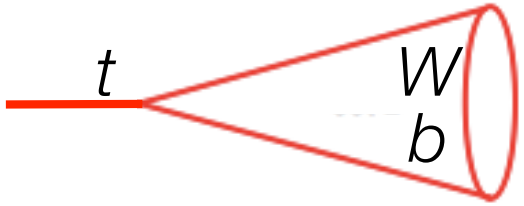
# Kinematic Regimes

- Searches covering different mass ranges call for different strategies
  - $X \rightarrow t\bar{t}$ for example
- Low-mass searches ( < ~1 TeV)
  - Decay products well-separated
  - Standard top quark methods used
- High-mass searches ( > ~2 TeV)
  - Top quarks become boosted
  - Decay products collimated
  - Special reconstruction algorithms required
    - Jet substructure
- Intermediate mass range
  - Partially merged decay products
    - Mix of techniques

CMS-PAS-JME-10-013



# Identifying Boosted Top

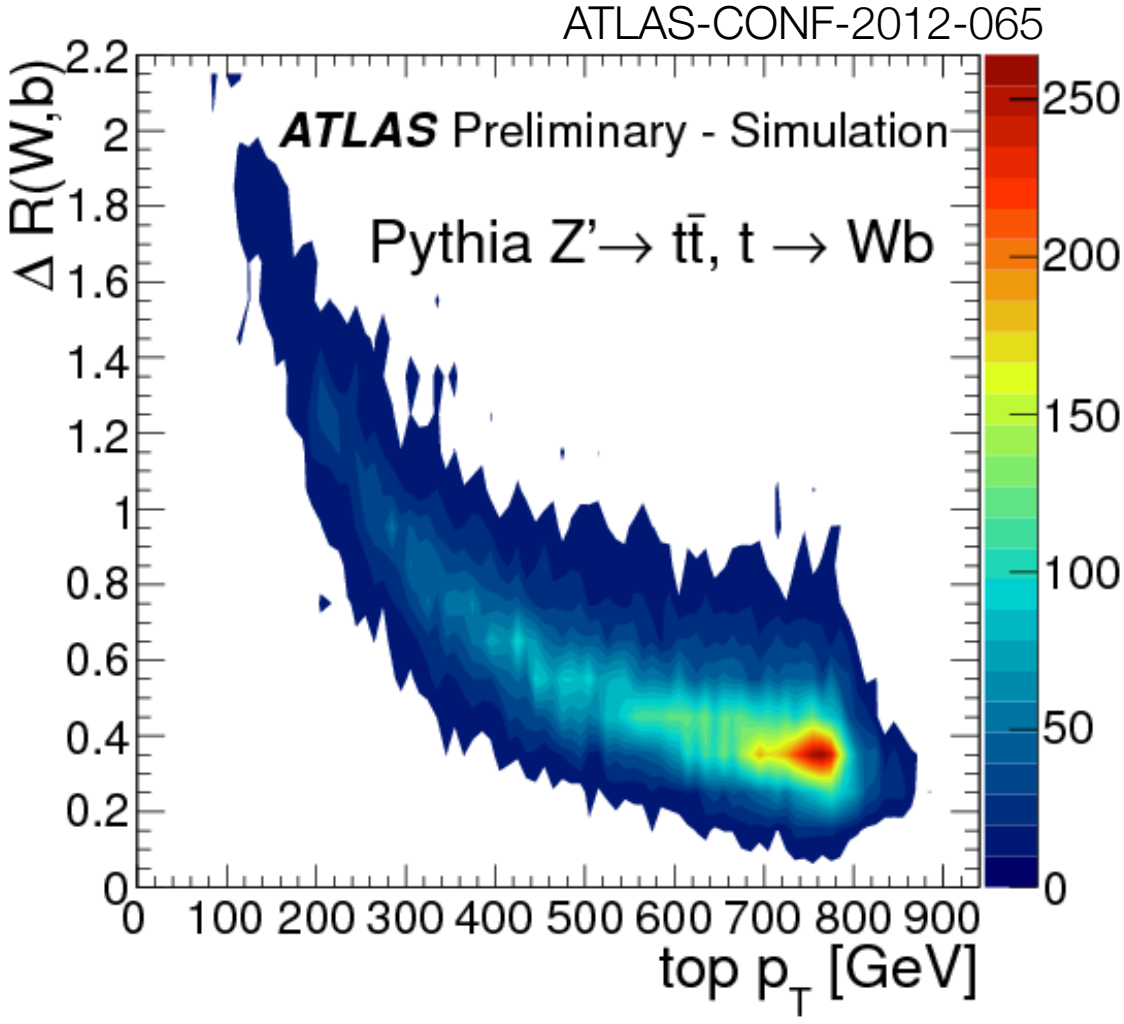
- Angular separation between decay products

$$\Delta R \sim \frac{2m}{p_T}$$

- Choose a large jet cone size for reconstruction to ‘catch’ all decay products

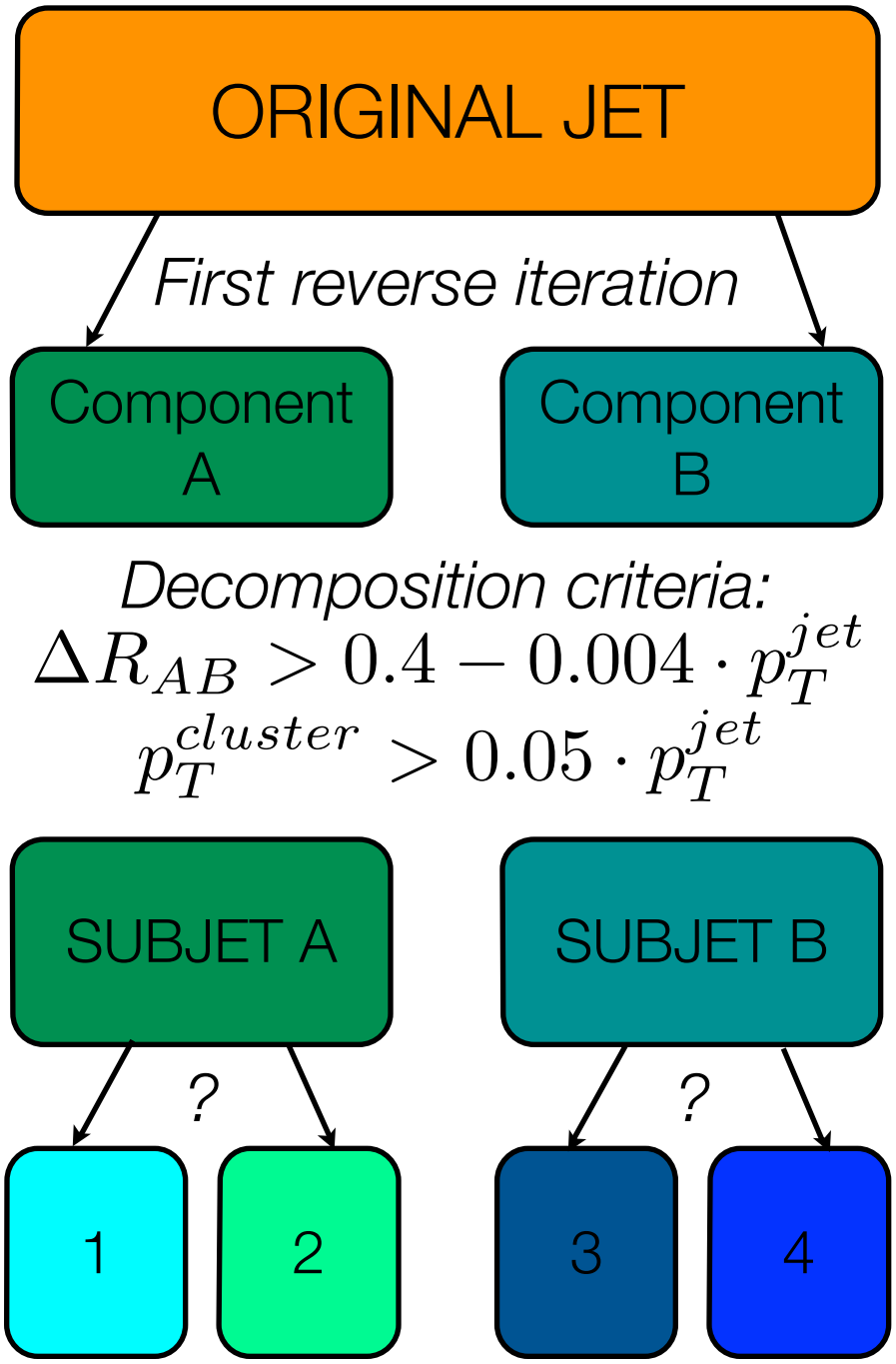
- ATLAS has studied R = 1.0, 1.2, 1.5
- CMS has studied R = 0.8, 1.5

- Use specific algorithms to identify the collimated decay products within this large-R jet



# CMS Top Tagger

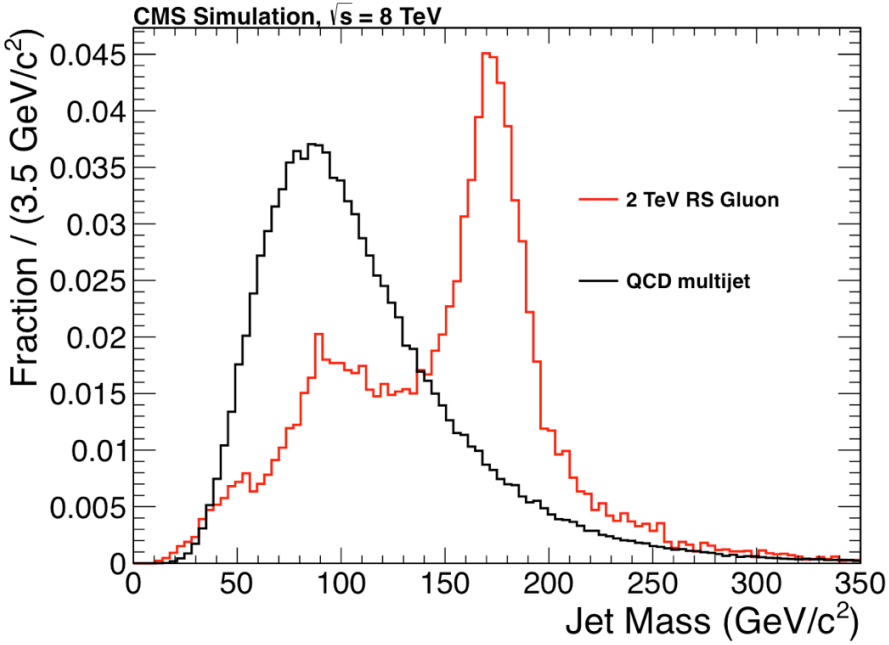
- CMS uses an algorithm based on JHU top tagger
  - Kaplan, Rehermann, Schwartz, Tweedie, PRL 101/142001 (2008)
- The algorithm uses jets with distance parameter $R = 0.8$, clustered with Cambridge-Aachen
- Uses cuts based on jet substructure information
  - Acquired by reversing the jet clustering algorithm
  - Step back in the pairwise sequence to find substructure
  - Can find a maximum of 4 subjets if all decomposition criteria are met
    - Optimized in simulation

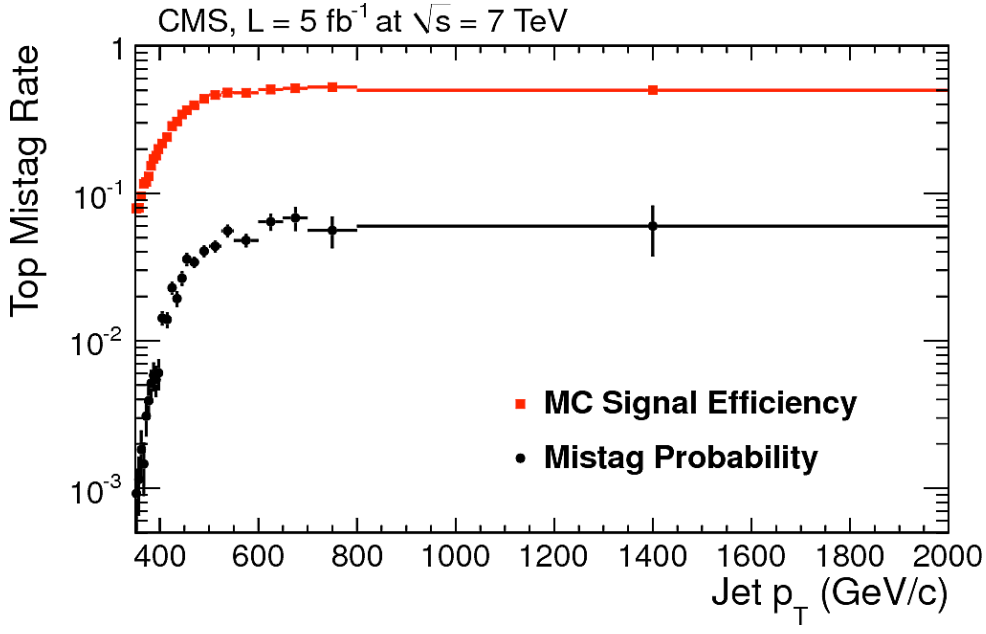


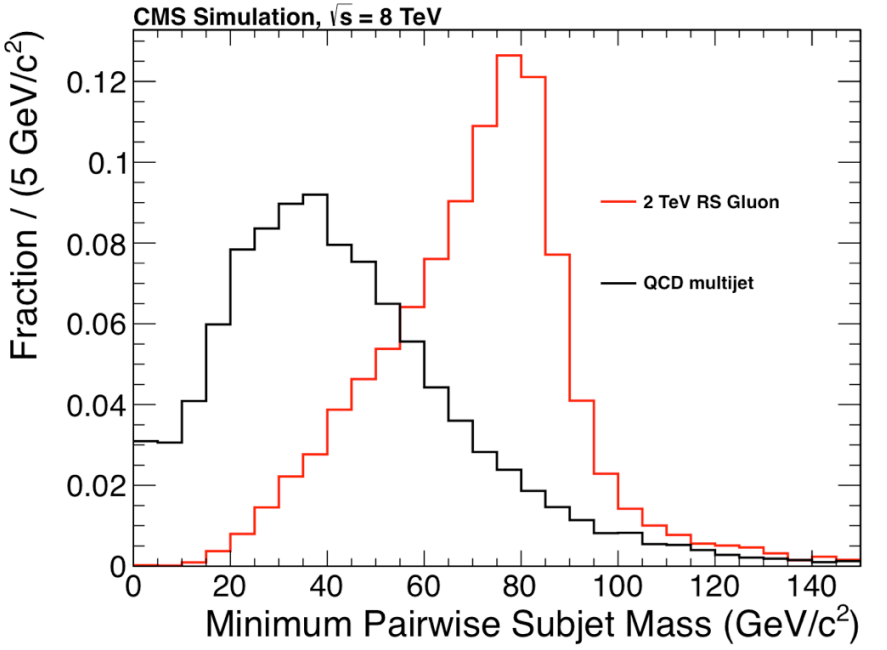
# CMS Top Tagger

CMS-PAS-B2G-12-005,
CMS-PAS-EXO-11-006

- Look at substructure quantities to identify top quarks
  - Jet mass in [140, 250] GeV
  - Number of subjets >= 3
  - Minimum pairwise subjet mass > 50 GeV
    - Proxy for *W* within fully-merged jet
- Efficiency ~50% at high $p_T$
- Mistag rate < 10%



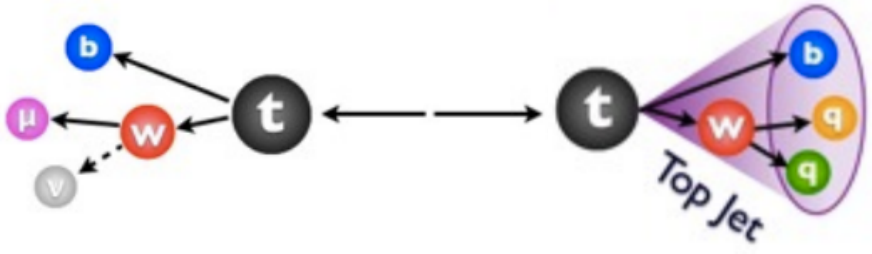



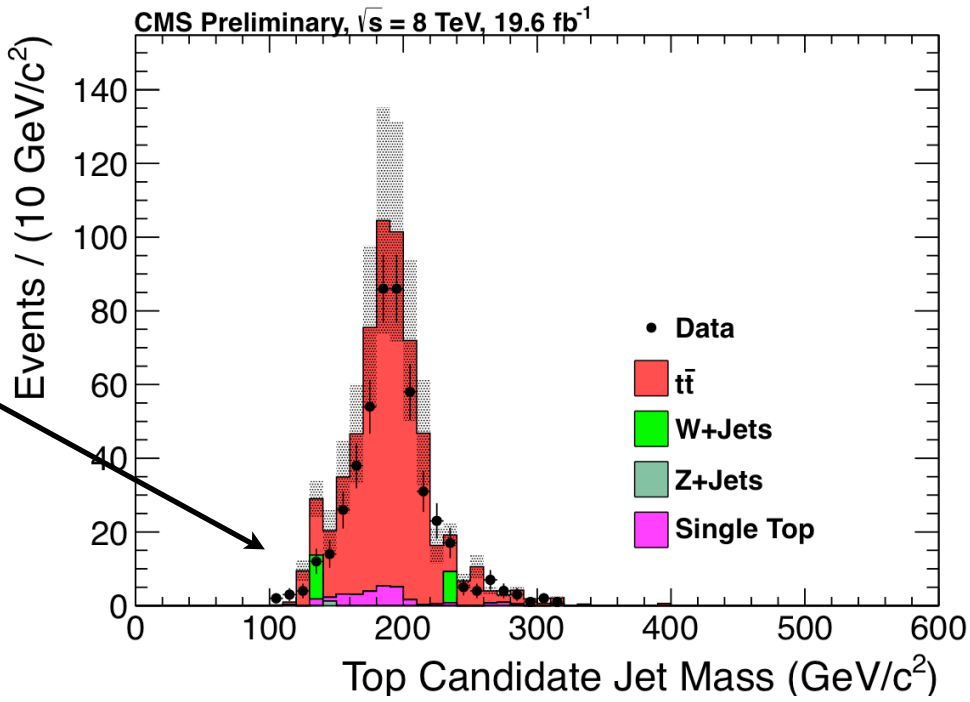



# CMS Top Tagger

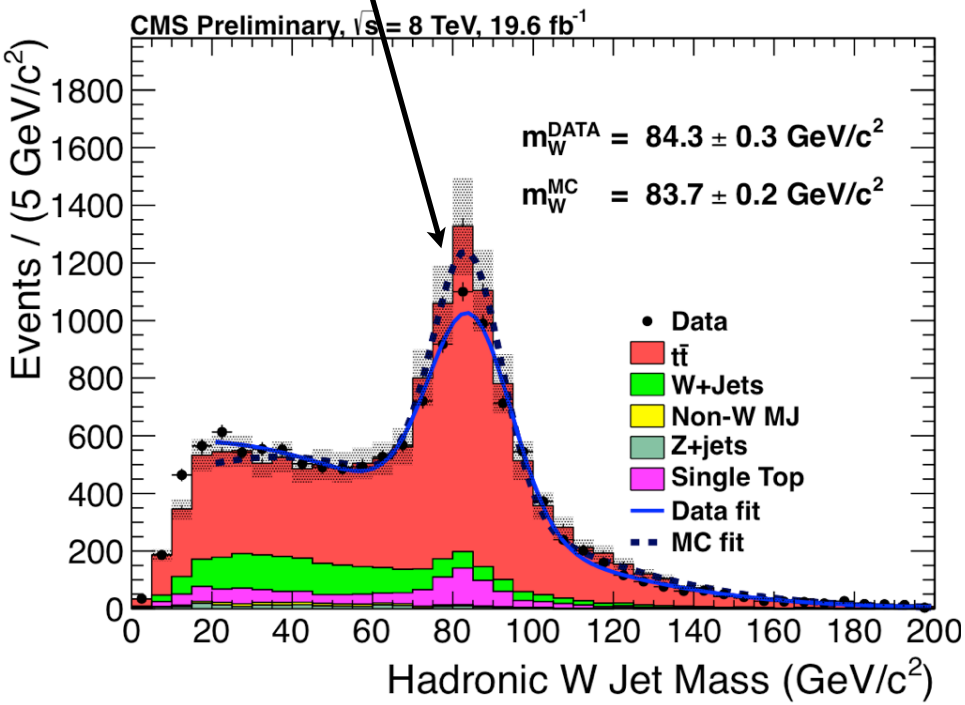
CMS-PAS-B2G-12-005

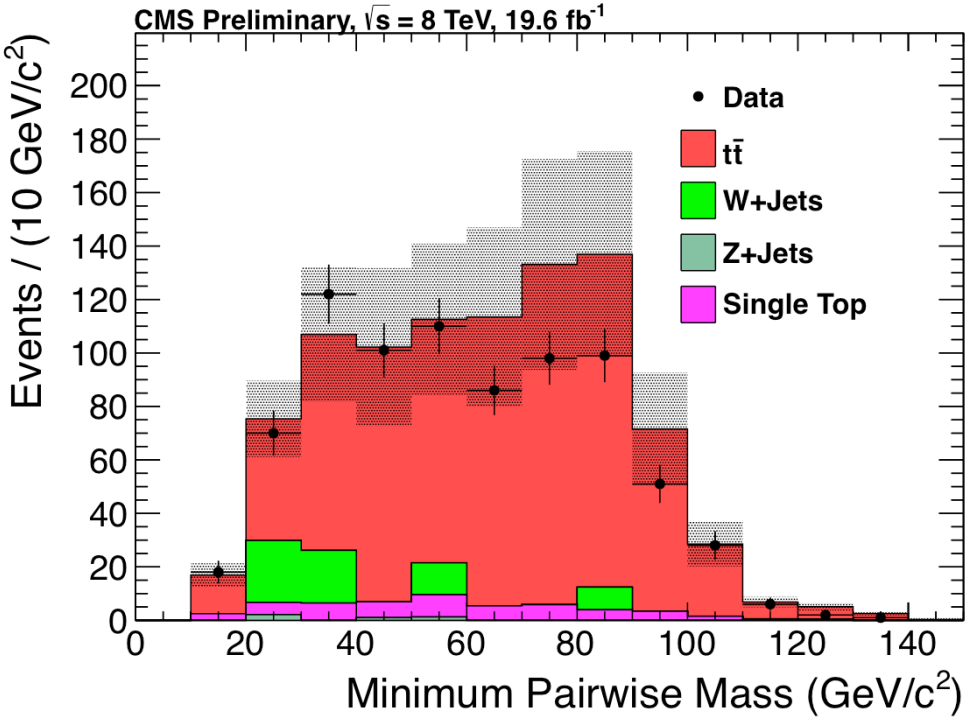
- Validated in a lepton+jets selection
  - Pure sample of $t\bar{t}$ events




- W mass peak serves as a calibration of the subjet energy scale

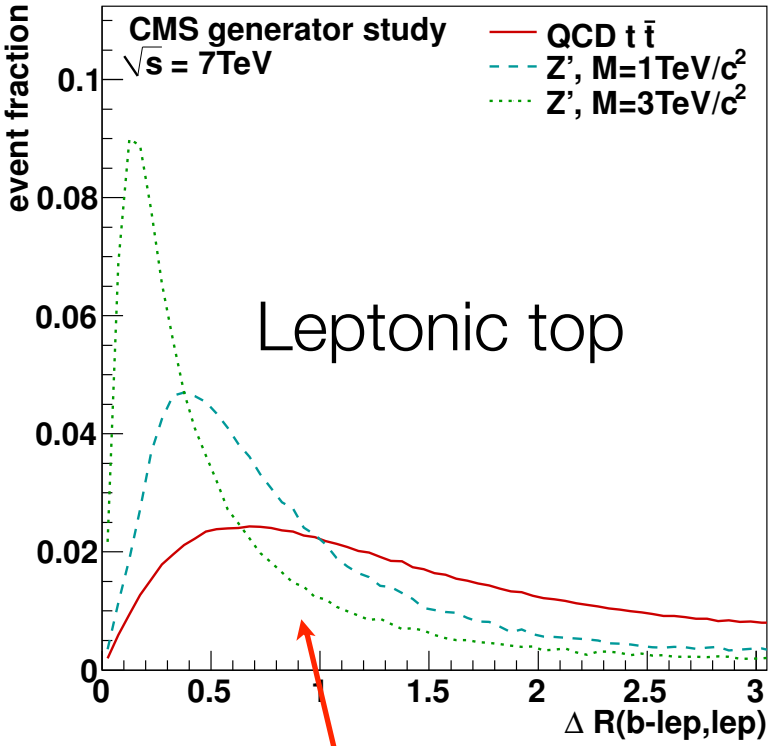


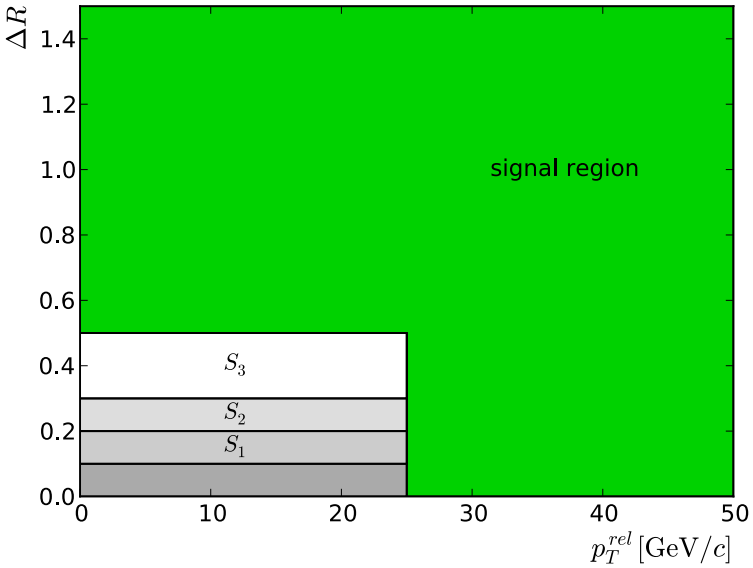



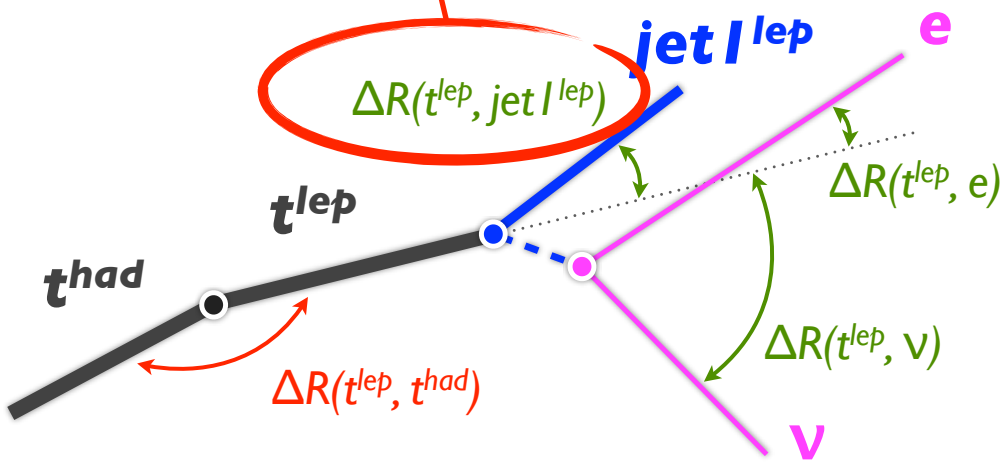
# Leptonic Top Decays

CMS-PAS-EXO-11-092/093

- Specific algorithms needed for leptonic decays as well
  - Avoid veto on good events!
- Special isolation requirements to select events where lepton is inside of jet
  - If lepton within the jet cone, must have 25 GeV of momentum orthogonal to jet axis
  - Reject QCD with special cuts



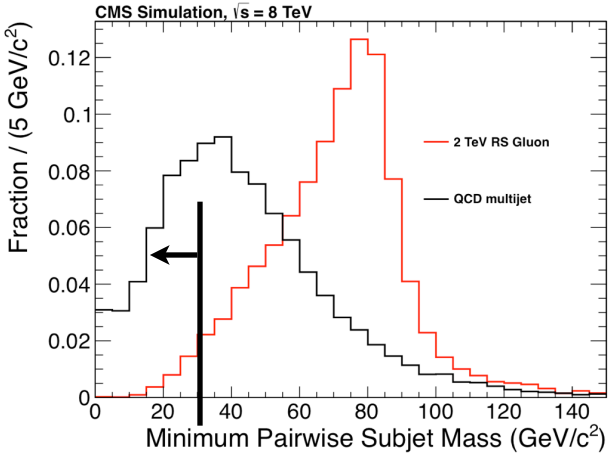



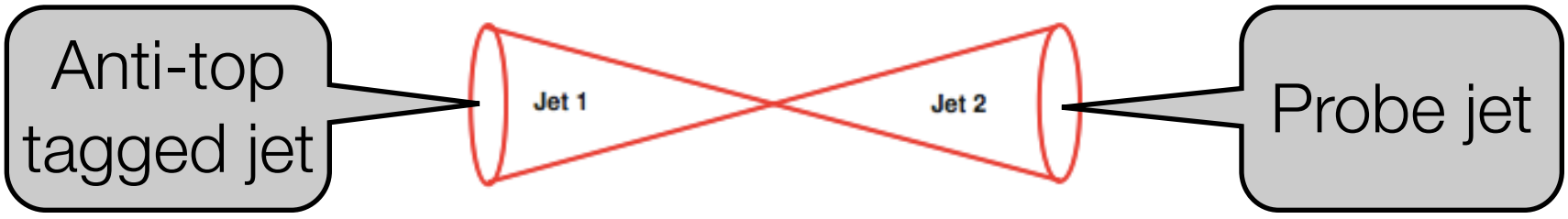
# Background Composition

- Two background processes in this analysis
  - SM top pair production
  - QCD multijet
- QCD multijet contribution determined from a data-derived method
- The mistag rate is measured using Type 1+1 events
  - Similar kinematics to signal region

- Require the 1+1 event selection
  - Jet $p_T > 400$, 400 GeV
  - $|\Delta y| < 1.0$
- Form a sideband region
  - Enriched in QCD dijet events
  - Invert pairwise mass cut on one jet




**Type 1 + Type 1**



# Background Composition

- Two background processes in this analysis
  - SM top pair production
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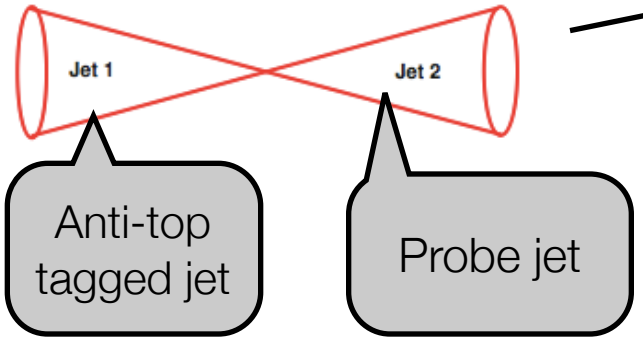
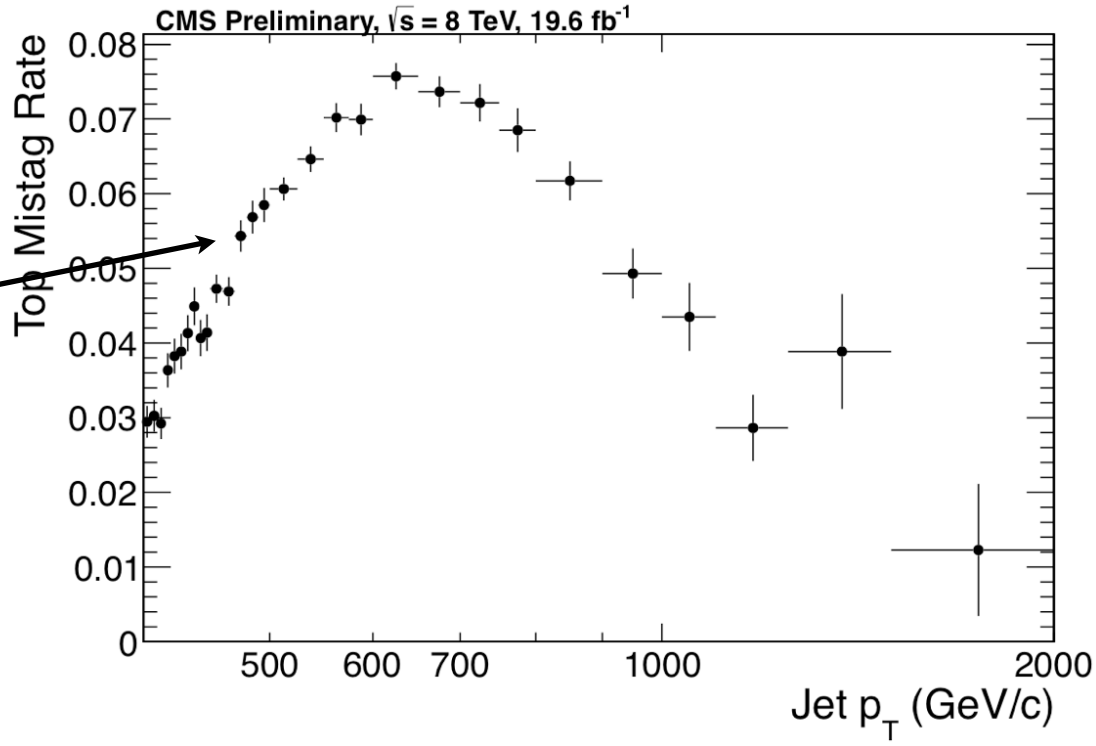
- QCD multijet contribution determined from a data-derived method
- The mistag rate is measured using Type 1+1 events

- Require the 1+1 event selection
  - Jet $p_T > 400$, 400 GeV
  - $|\Delta y| < 1.0$
- Form a sideband region
  - Enriched in QCD dijet events
  - Invert pairwise mass cut on one jet
- Measure tag rate of second jet
  - Subtract ttbar contribution



# Forming the QCD Estimate

- Select events of type 1+X
  - Apply the mistag rate to the 'X' jet to model type 1+1 events
- Mass of the weighted jet not representative of the signal selection
  - Biases shape of $m_{tt}$ distribution
- Jet mass of weighted jet set 'by hand' to follow correct distribution
  - "Mass-modified" procedure