Boosted Top Quarks, $t\bar{t}$ Resonances, and Top Partner Searches at the LHC

Justin Pilot, *UC Davis*
on behalf of the ATLAS and CMS Collaborations

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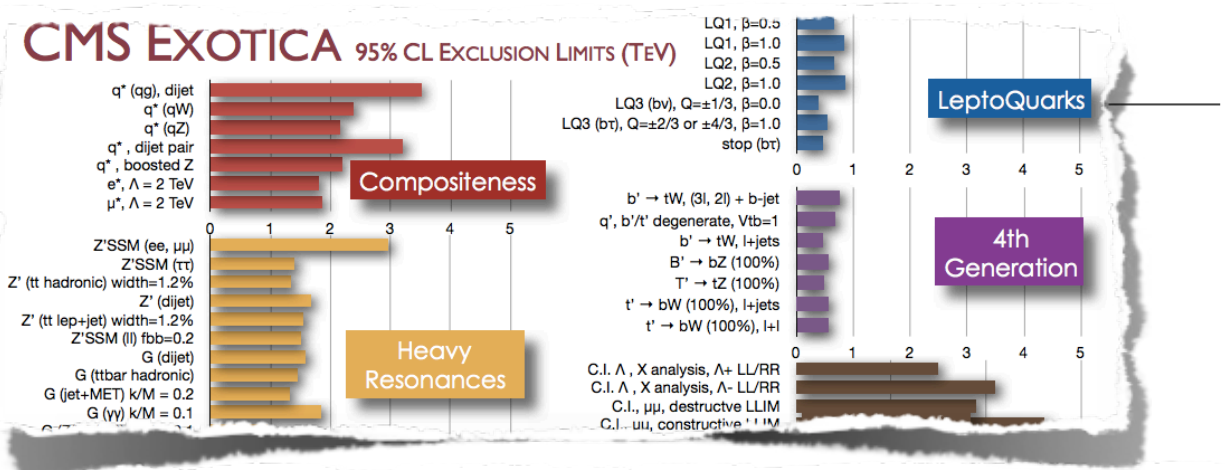
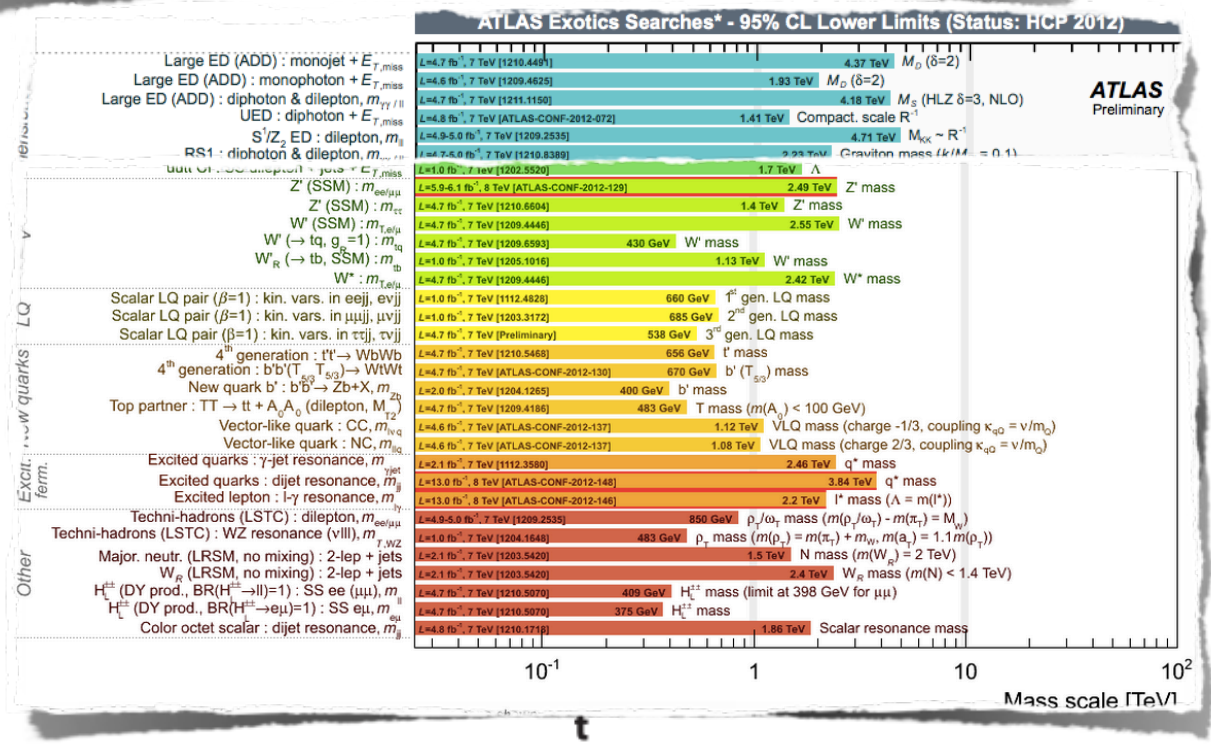
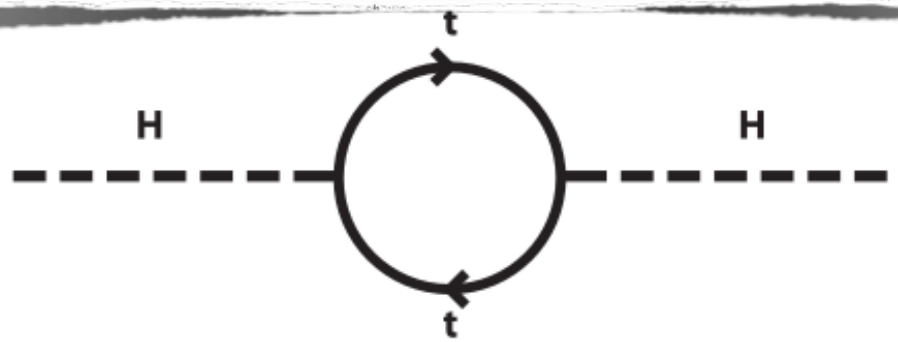
Introduction

- LHC experiments continue to push exclusion limits higher and higher
- The LHC is a top quark factory
  - Large dataset
  - Many decay channels which can be analyzed independently
- A perfect final state to probe new physics!
  - Unique event signatures
  - Can provide solution to the hierarchy problem without SUSY
  - Special techniques for top reconstruction can increase mass reach

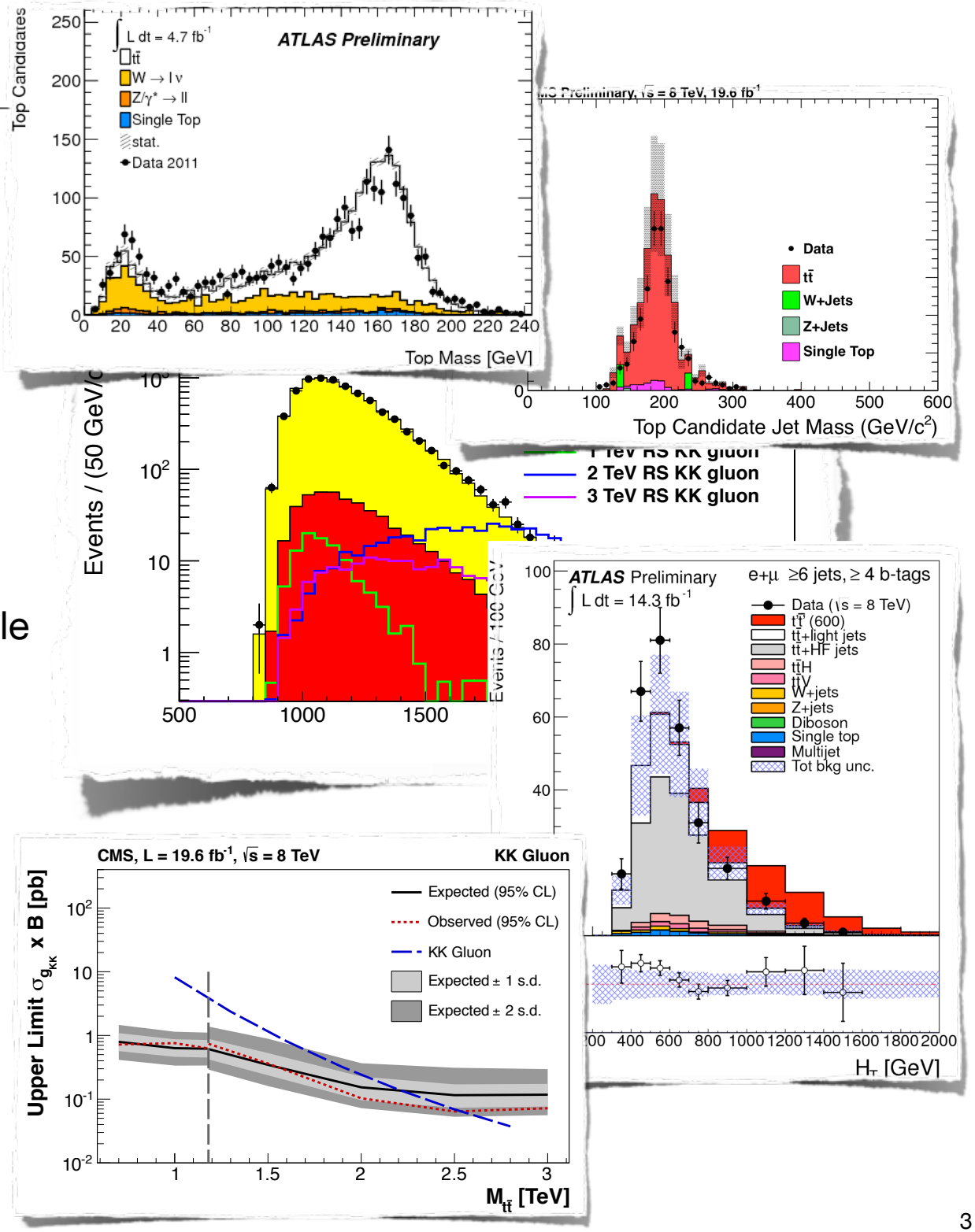






Outline

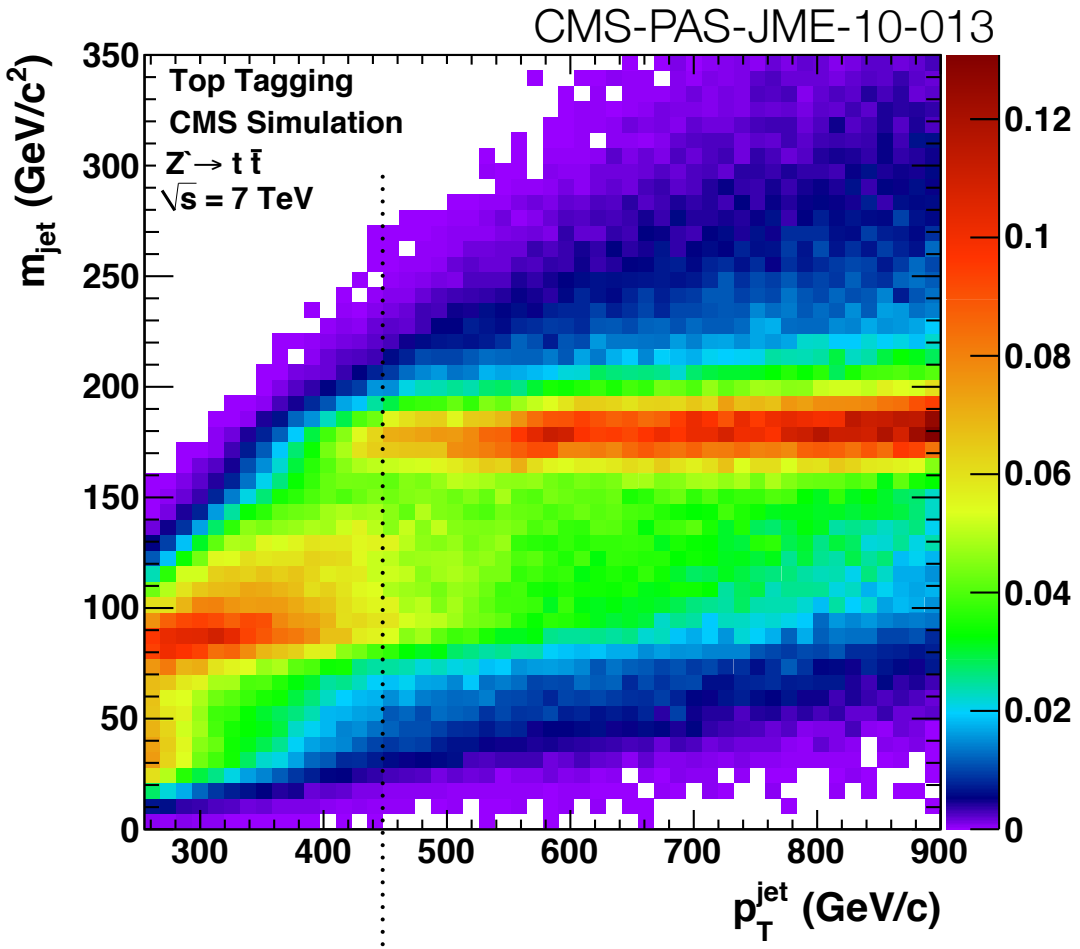
- Top reconstruction techniques
  - Boosted topologies
  - Jet substructure algorithms
  - Performance on data
- Searches for new physics
  - Top pair resonances in multiple final states
    - All-hadronic
    - Lepton + jets
    - Dilepton
  - Top partners
    - Vector-like t' quarks
    - Charge-5/3 quarks
    - Excited t* quarks

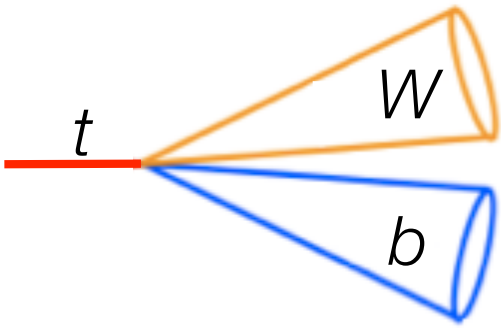


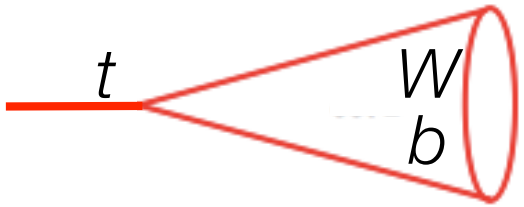
Top Quark Reconstruction

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







Identifying Boosted Top

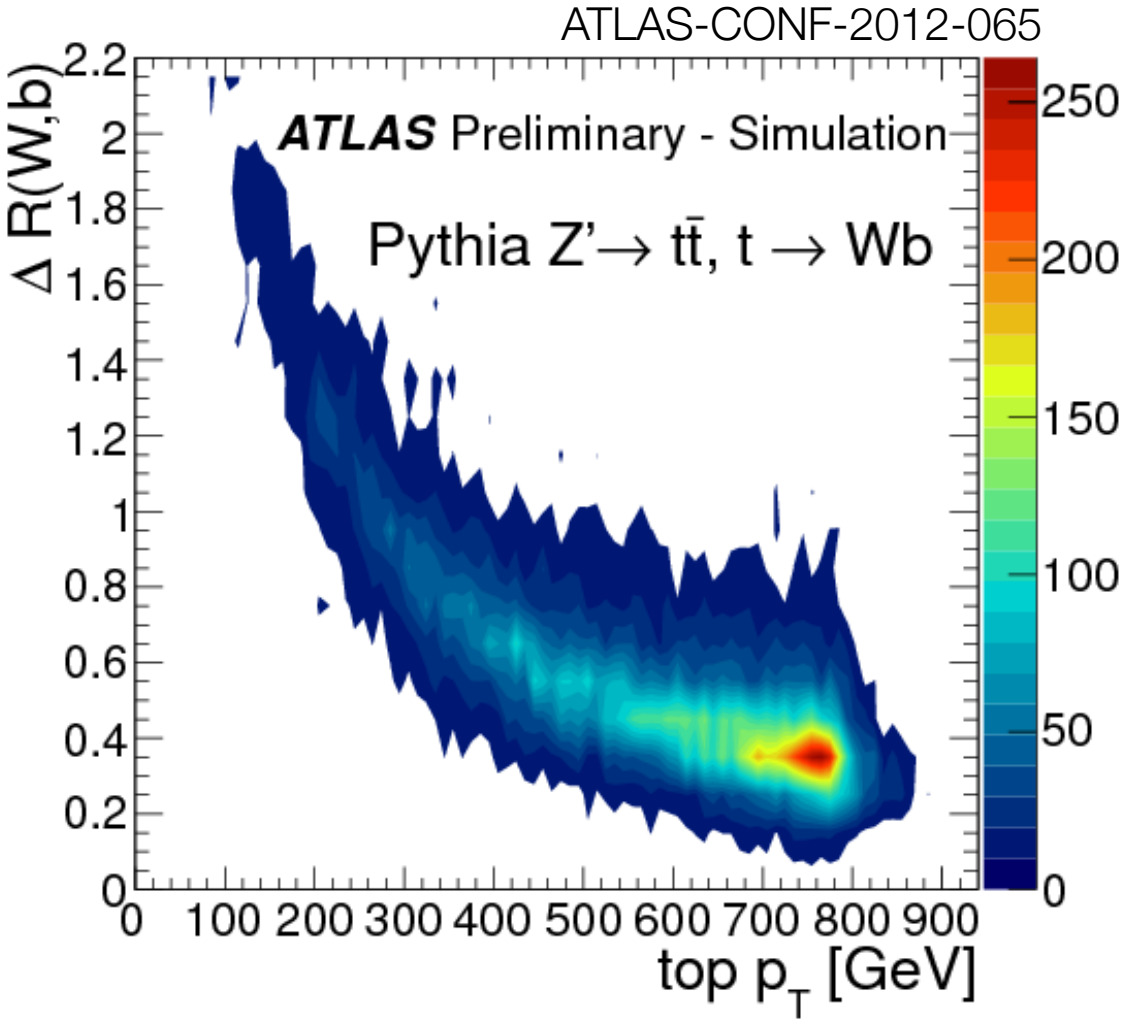
- Angular separation between decay products

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

- 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

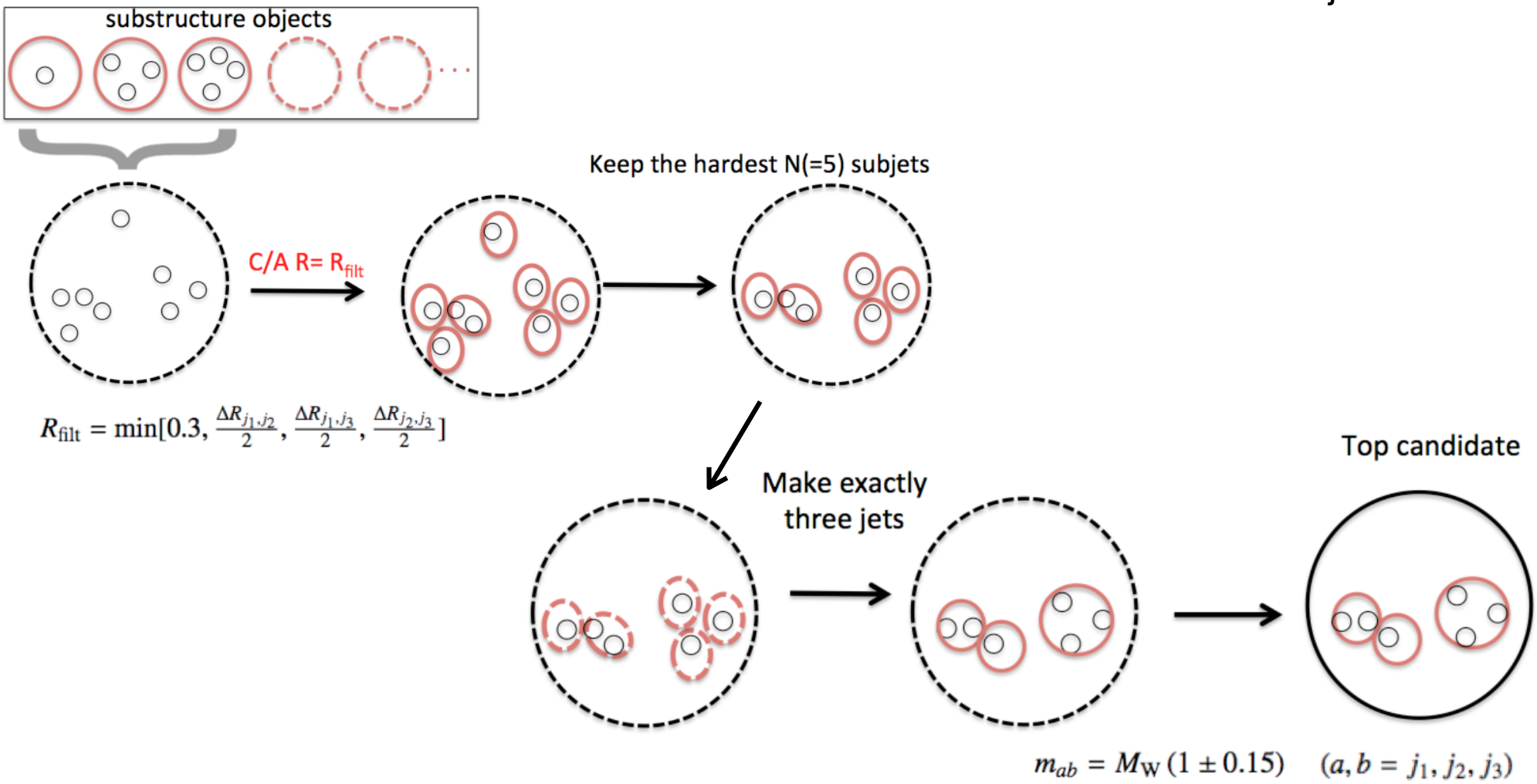
- Use specific algorithms to identify the collimated decay products within this large-R jet



HEP Top Tagger

ATLAS-CONF-2012-065

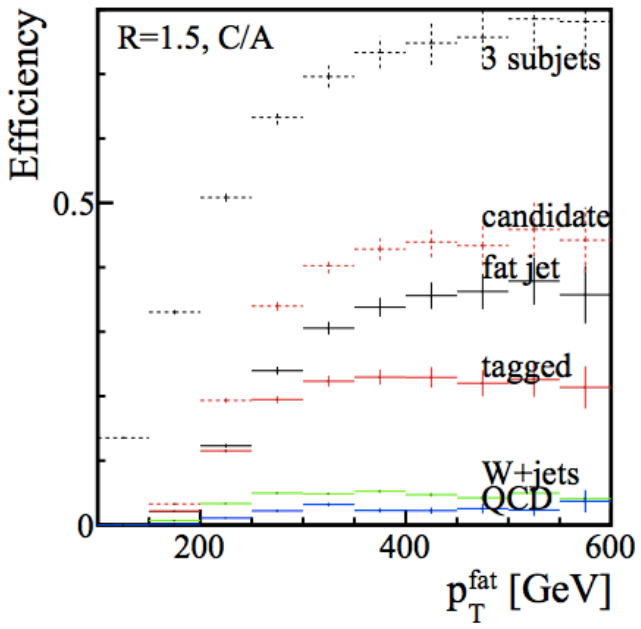
- ATLAS has extensively studied and optimized the HEPTopTagger
  - Plehn, Spannowsky, Takeuchi, arXiv:1111.5034
- HEPTopTagger reclusters the large-R jet using a smaller distance parameter
  - Removes soft, wide-angle radiation
- Left with 3 decay products of top quark reconstructed as subjets

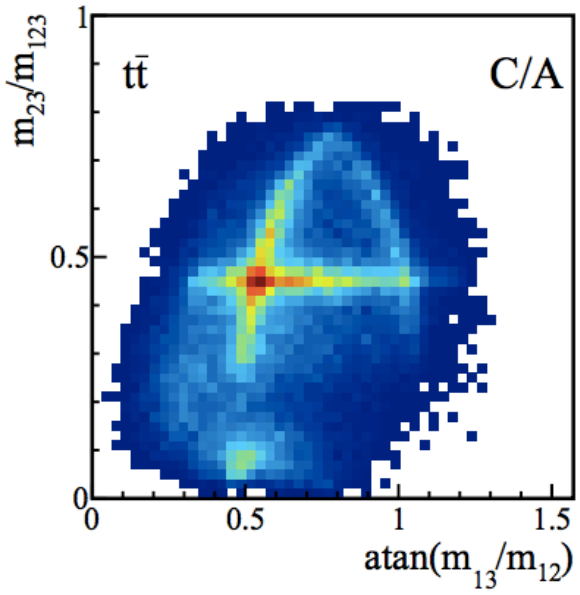


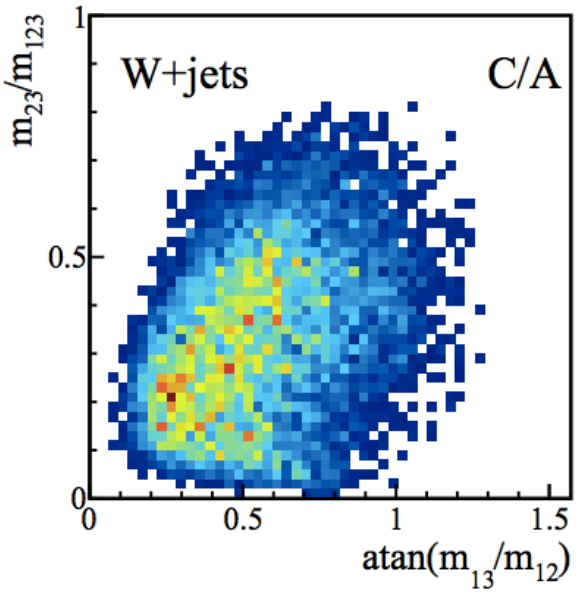
HEP Top Tagger

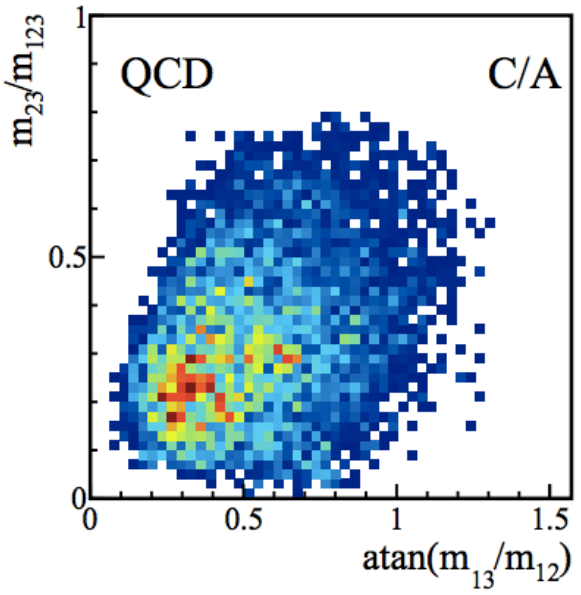
Plehn, Spannowsky, Takeuchi, arXiv:1111.5034

- Can then use the three subjets to impose criteria
- W mass, top quark mass
- Good discriminating power between top pair events and backgrounds





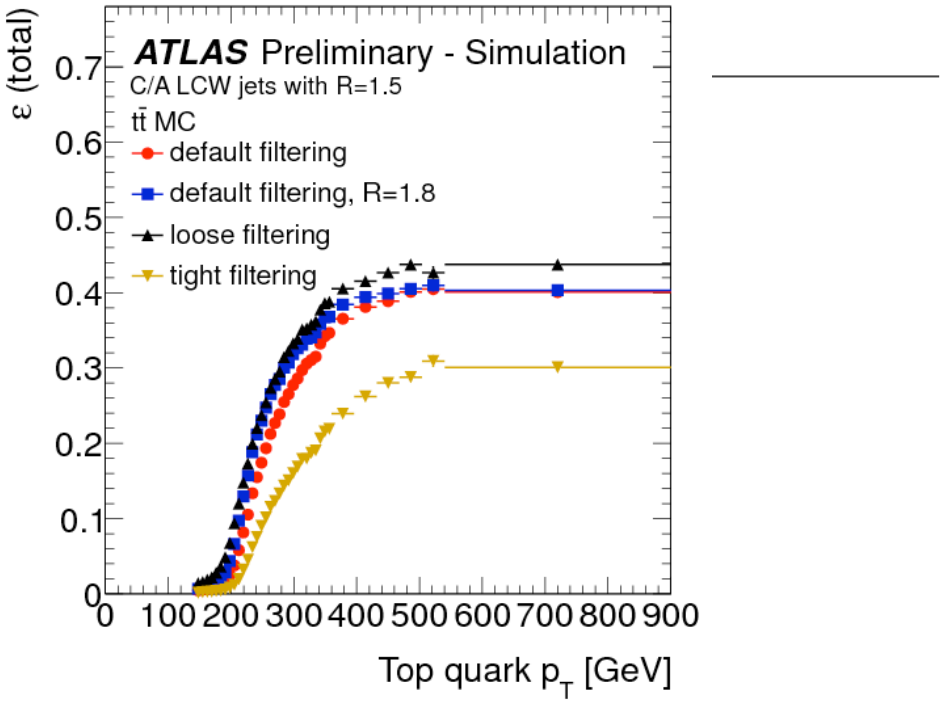


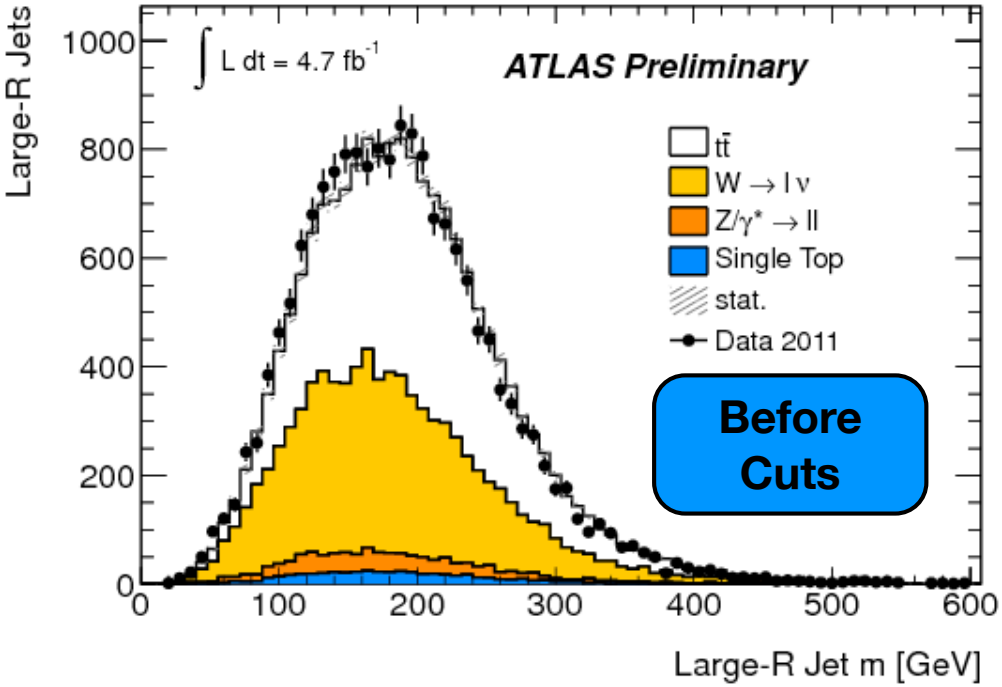


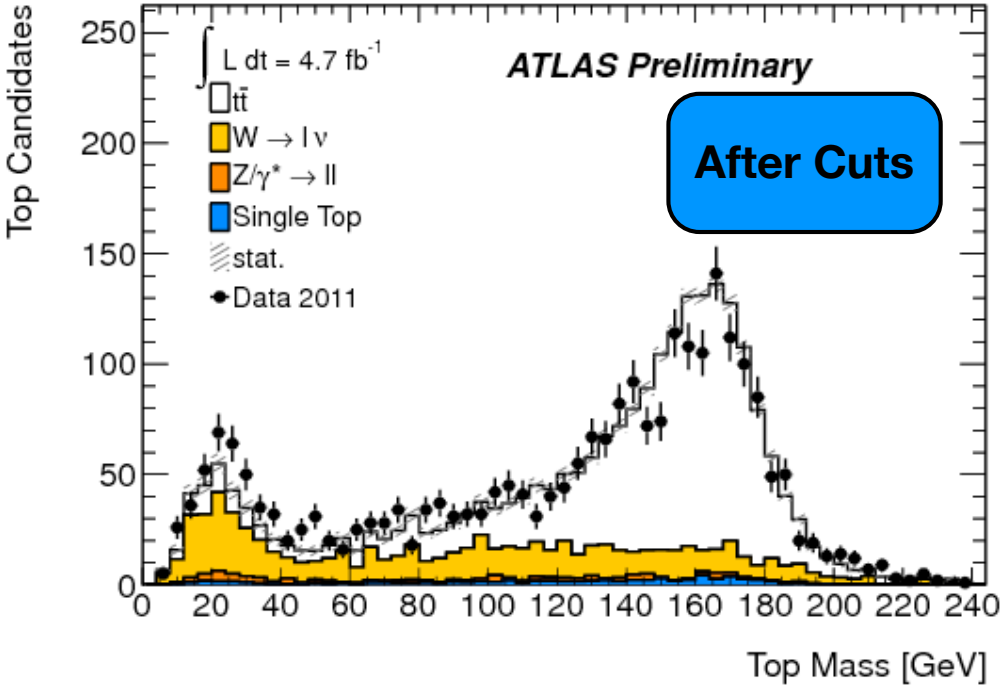
HEP Top Tagger

ATLAS-CONF-2012-065

- Can then use the three subjets to impose criteria
- W mass, top quark mass
- Good discriminating power between top pair events and backgrounds
  - Efficiency ~40% at high-p_T
  - Mistag rate ~few percent

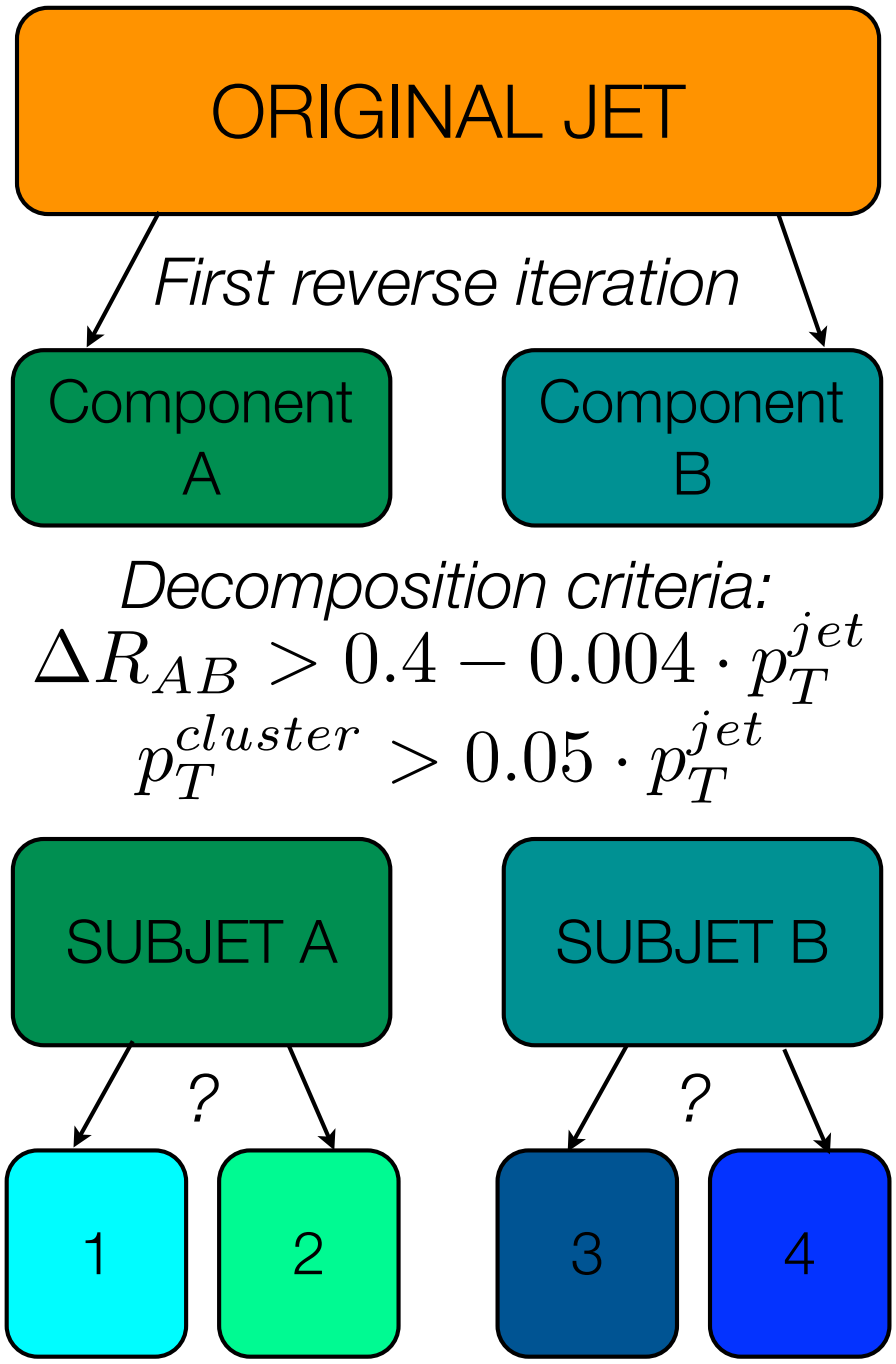






CMS Top Tagger

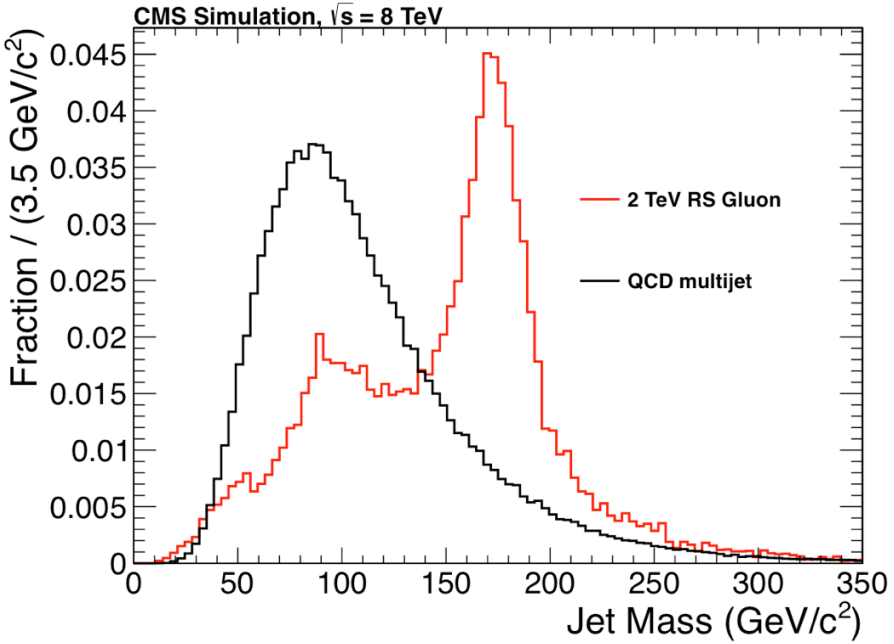
- CMS uses an algorithm based on JHU top tagger
  - Kaplan, Rehermann, Schwartz, Tweedie, PRL 101/142001 (2008)
- The algorithm uses jets with distance parameter $R = 0.8$, clustered with Cambridge-Aachen
- Uses cuts based on jet substructure information
  - Acquired by reversing the jet clustering algorithm
  - 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

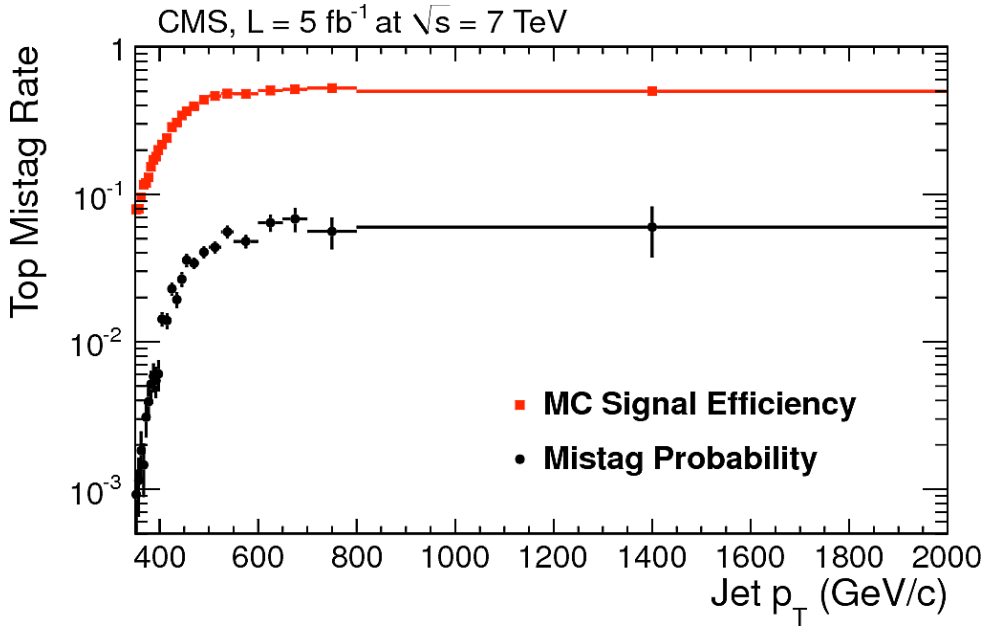


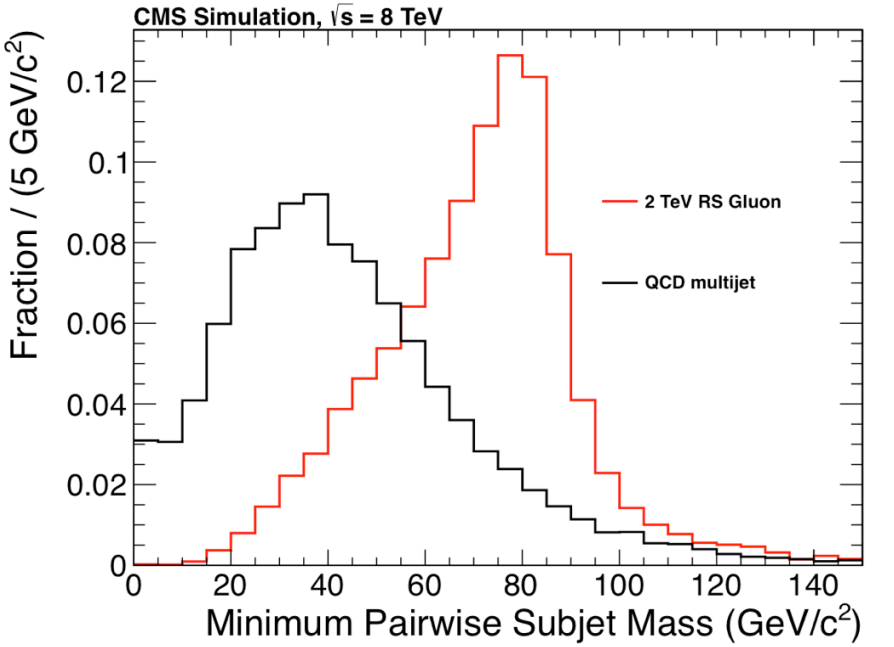
CMS Top Tagger

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%



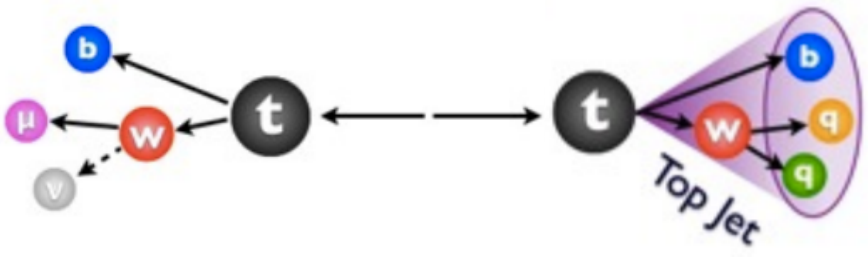


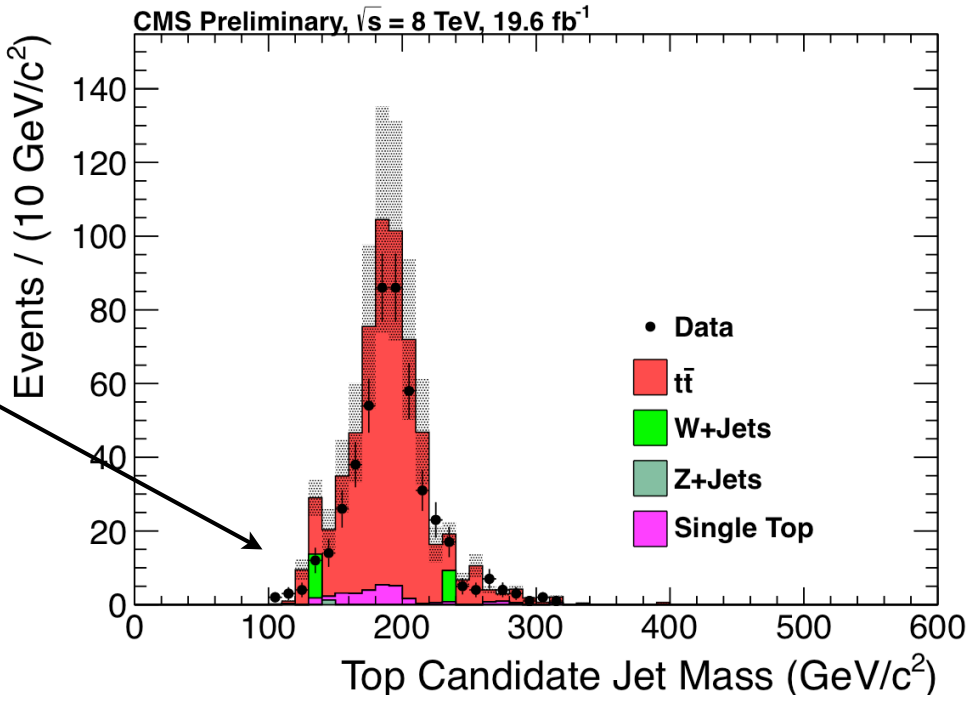


CMS Top Tagger

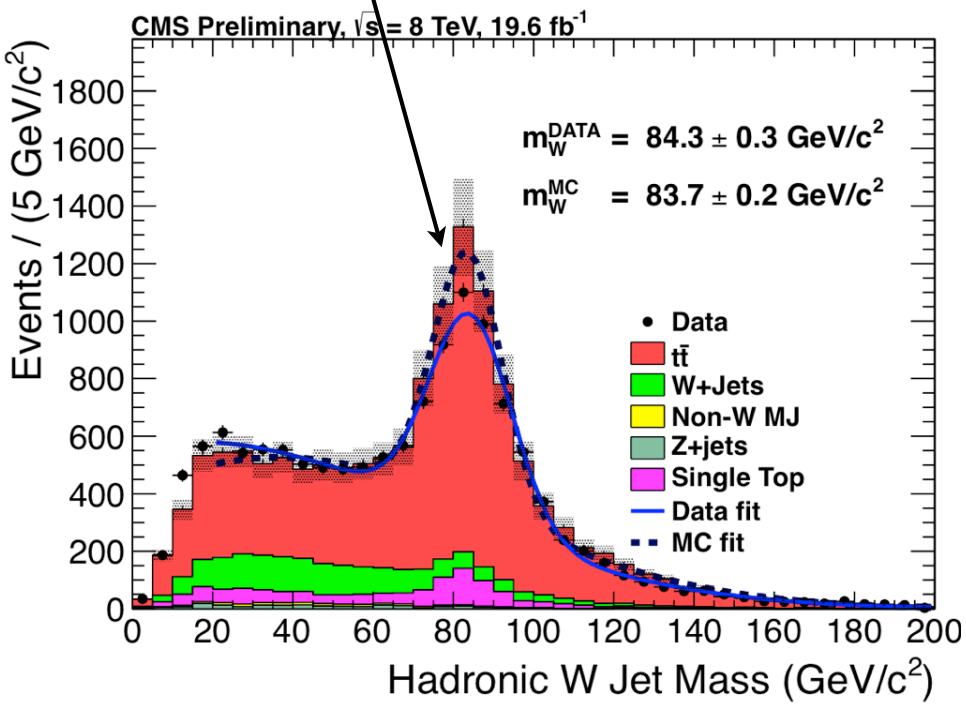
CMS-PAS-B2G-12-005

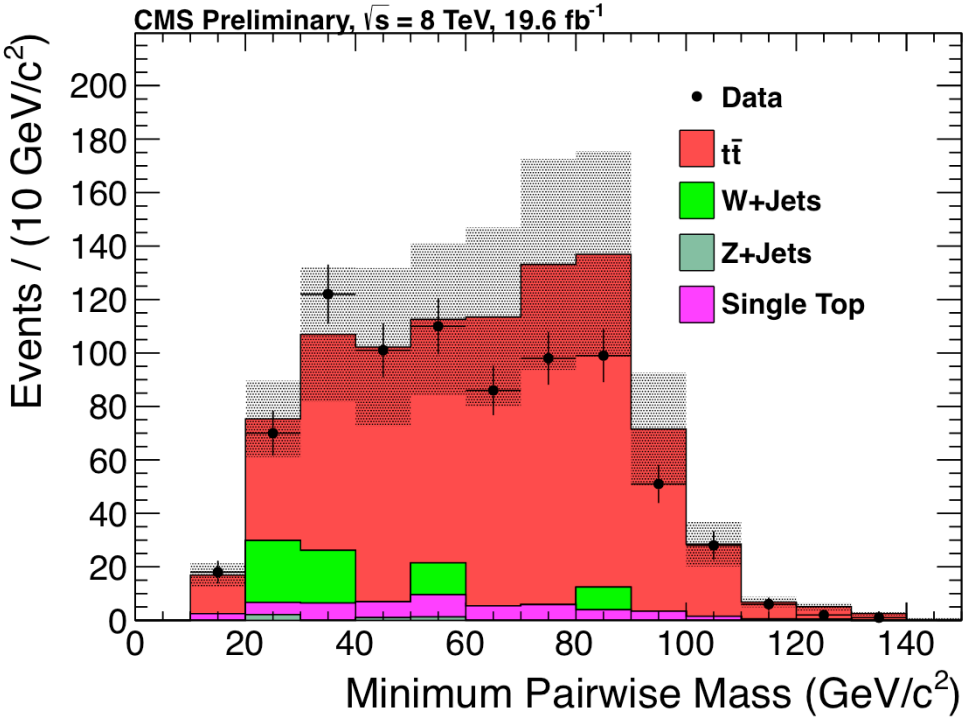
- Validated in a lepton+jets selection
  - Pure sample of $t\bar{t}$ events





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

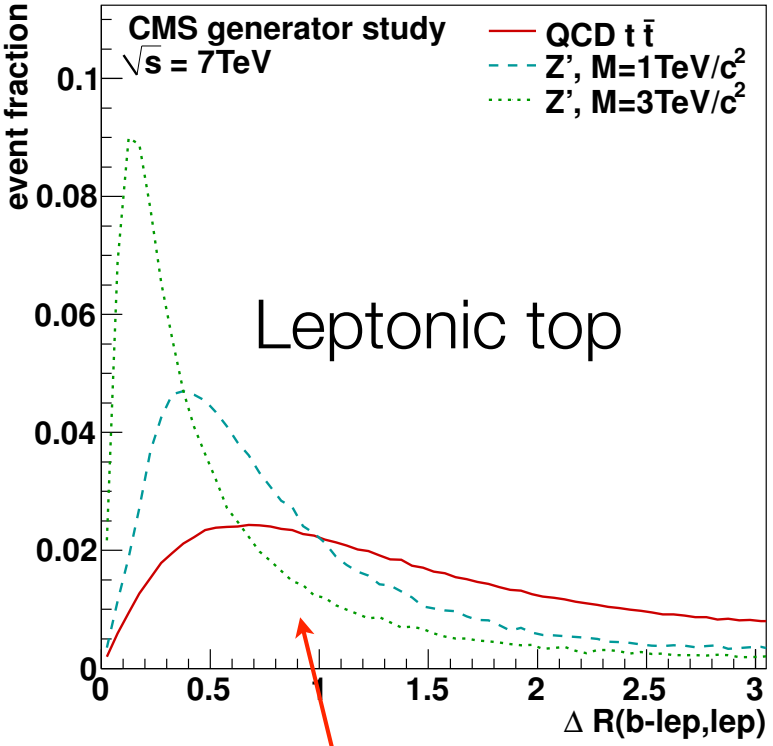


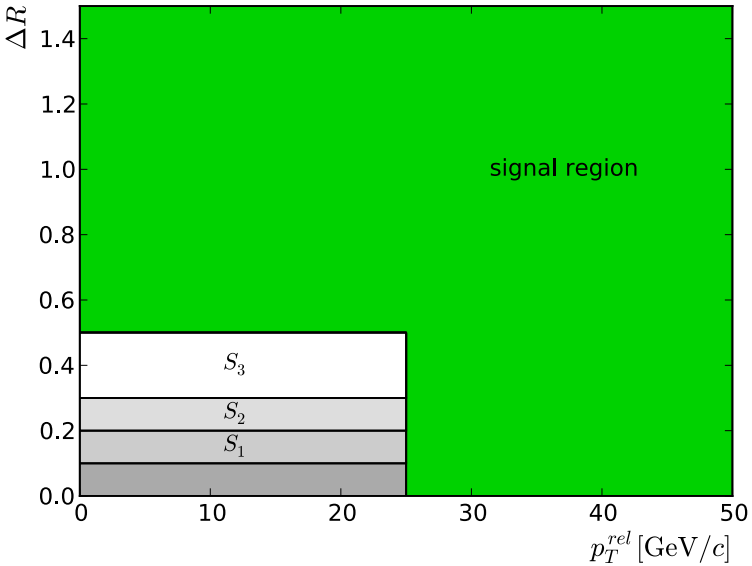


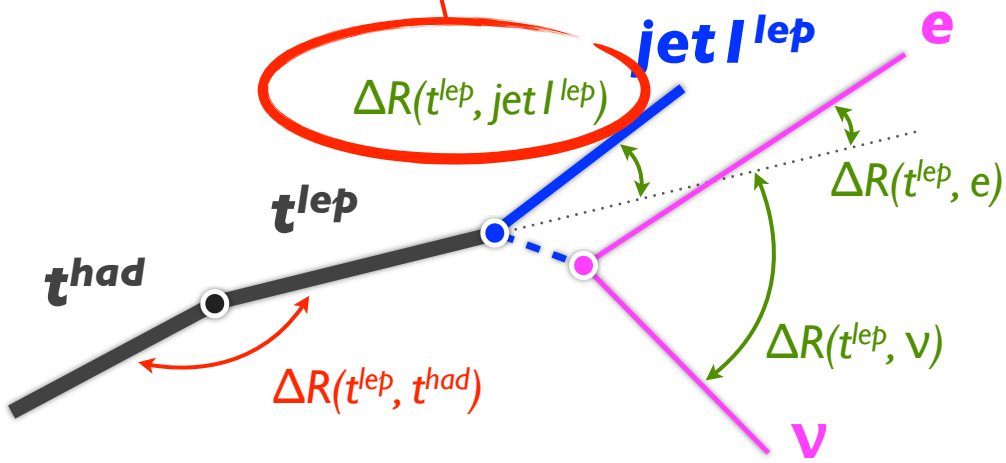
Leptonic Top Decays

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





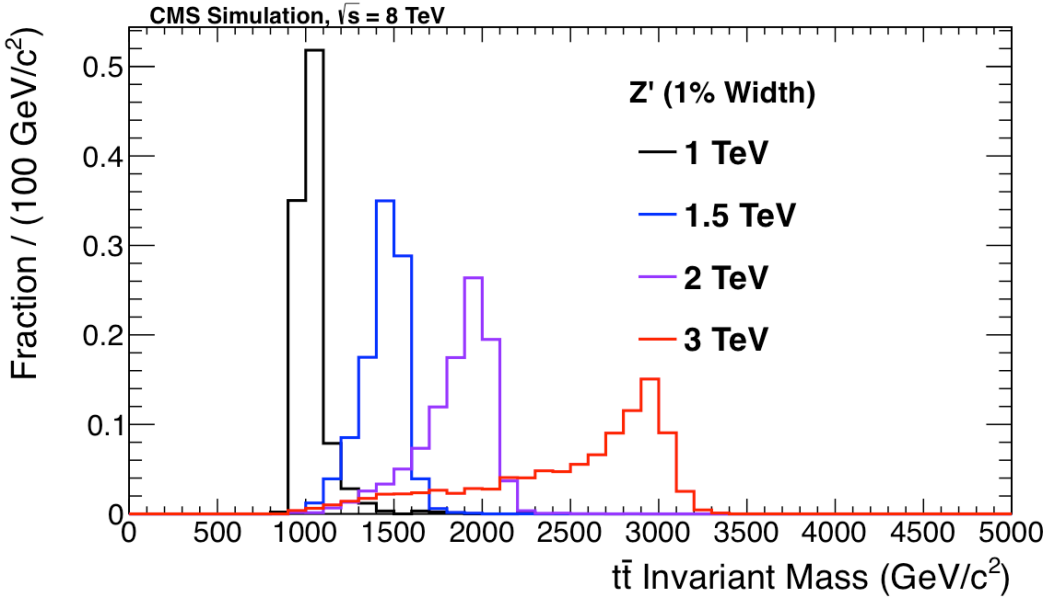


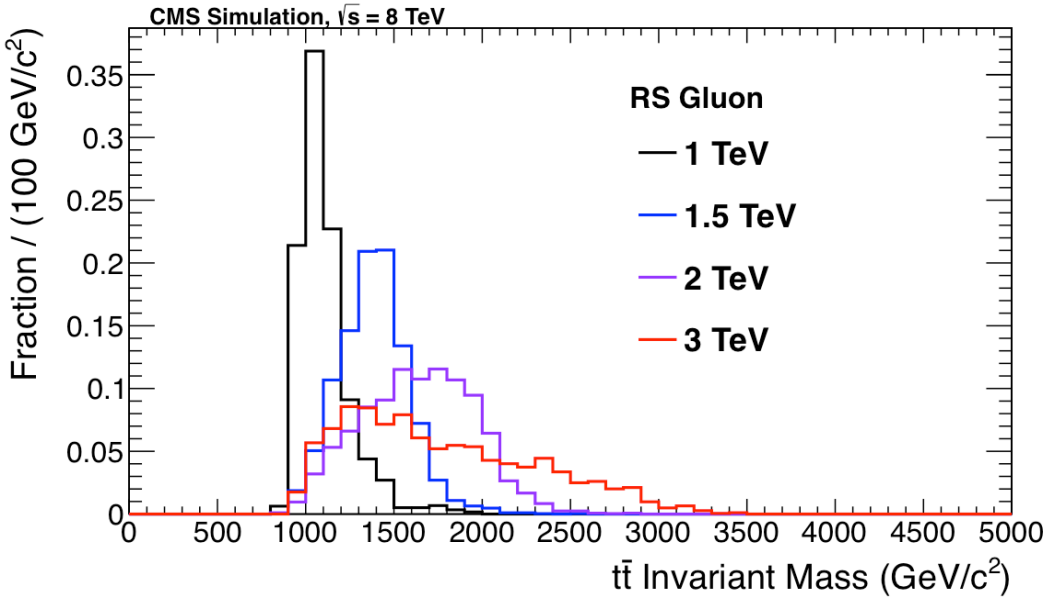
$t\bar{t}$ Resonance Searches

Top Pair Resonances

CMS-PAS-B2G-12-005

- Both ATLAS and CMS search for resonances in the m_{tt} spectrum
  - $Z' \rightarrow t\bar{t}$
    - Widths $\Gamma/m_{Z'} = 1\%, 10\%$
  - RS KK gluon $\rightarrow t\bar{t}$
    - Mass-dependent width
- Searches use a mix of techniques
  - Low mass → threshold analysis, standard jet reconstruction
  - High mass → boosted analysis, jet substructure used
- All channels analyzed
  - All-hadronic
  - Lepton+jets
  - Dilepton



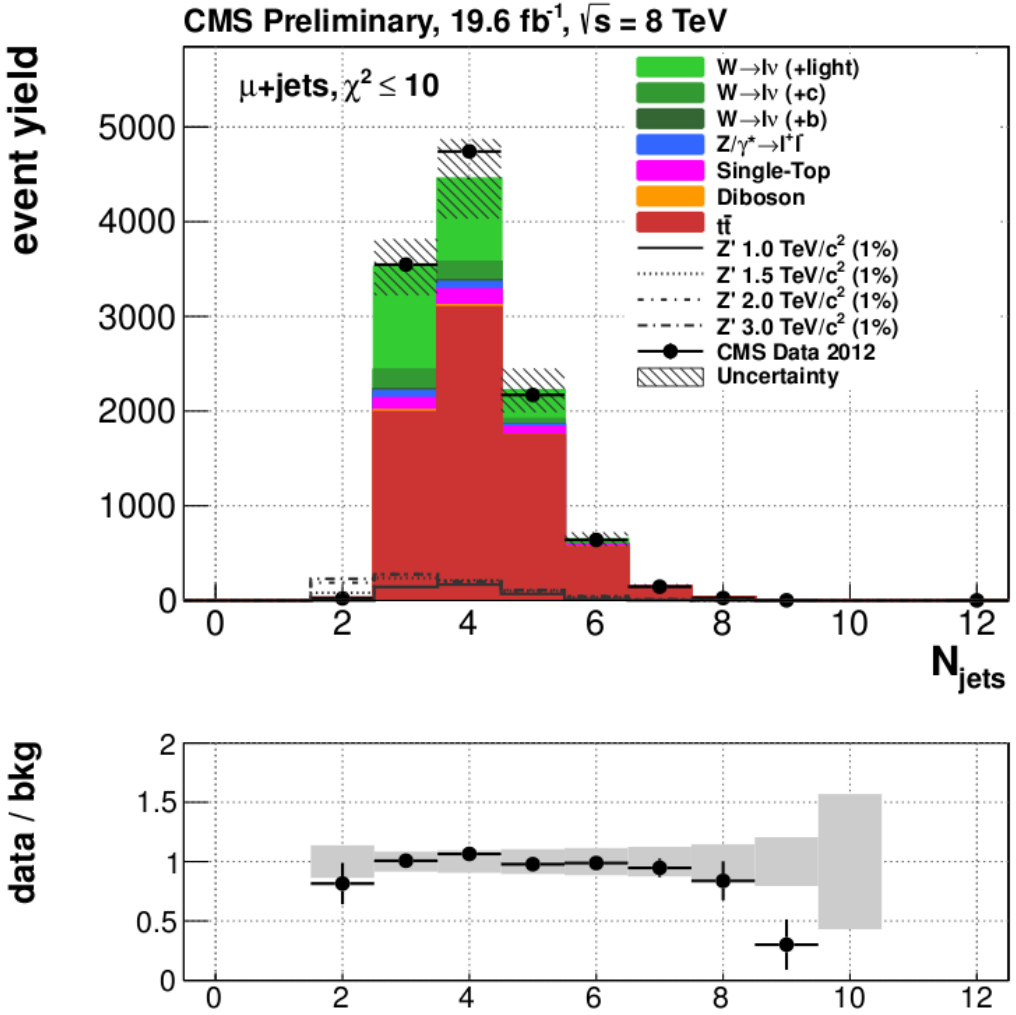


Lepton + Jets Searches

CMS-PAS-B2G-12-006

- Threshold analysis
  - Standard top reconstruction at low pT
  - 4 or more jets, pT > 70, 50, 30, 30 GeV
  - Isolated high pT electron/muon
  - Missing E_T > 20 GeV
  - >= 1 b-tagged jet

- Boosted Analysis
  - Merged top decay products
  - 2 or more jets pT > 150, 50 GeV
  - No isolation requirement on electron/muon
  - 0 or 1 b-tagged jets
  - H_T > 150 GeV
  - Missing E_T > 50 GeV



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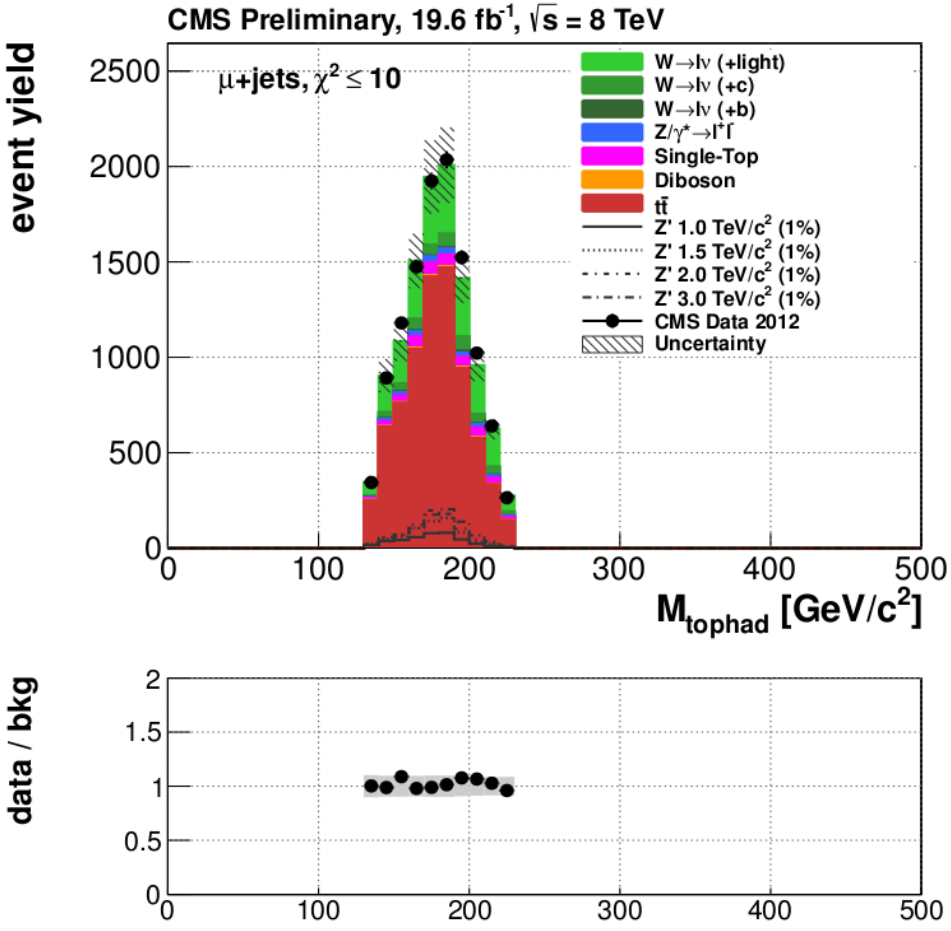
  - 0 or 1 b-tagged jets
  - H_T > 150 GeV
  - Missing E_T > 50 GeV

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

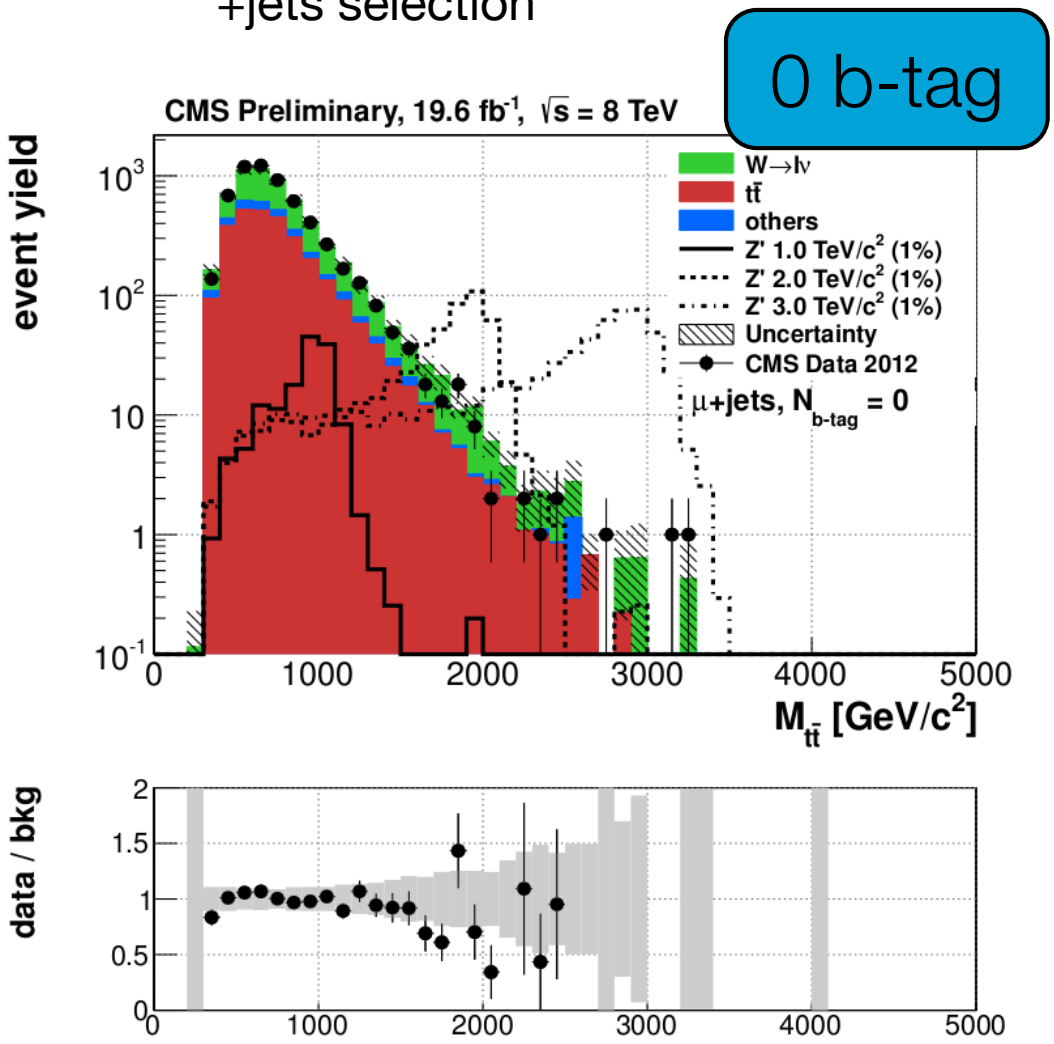
$$\chi^2_x = (x_{meas} - x_{MC})^2 / \sigma^2_{MC},$$

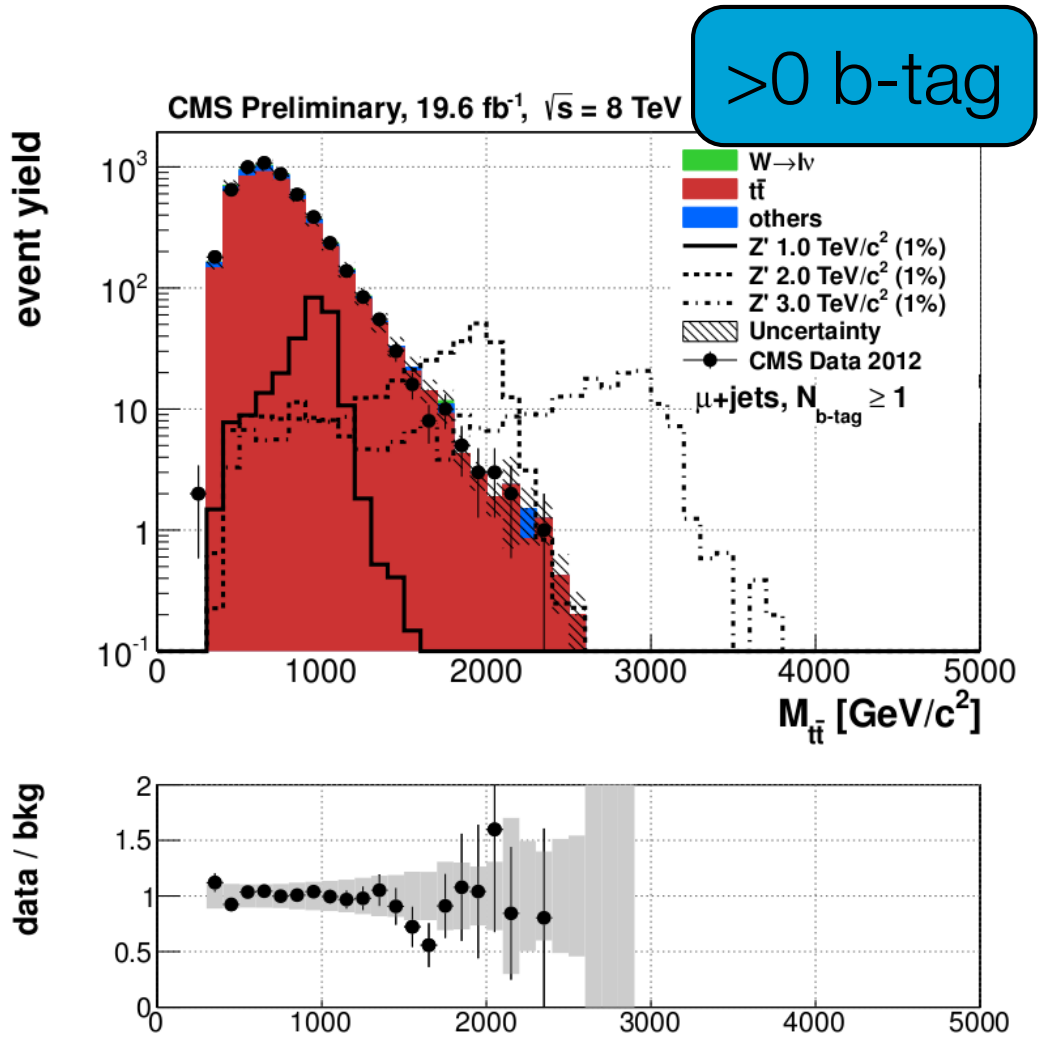


Lepton + Jets Searches

CMS-PAS-B2G-12-006

- Final discriminating distributions used to set limits
  - 0 and ≥1 b-tag channels, muon +jets selection





Lepton + Jets Searches

ATLAS-CONF-2013-052

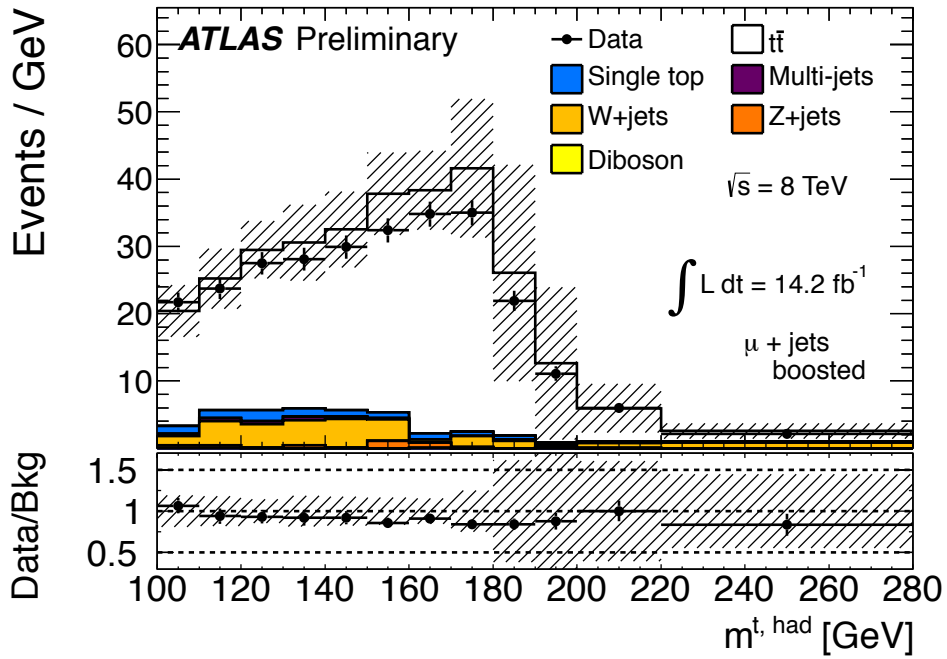
- ATLAS also uses a resolved and boosted selection

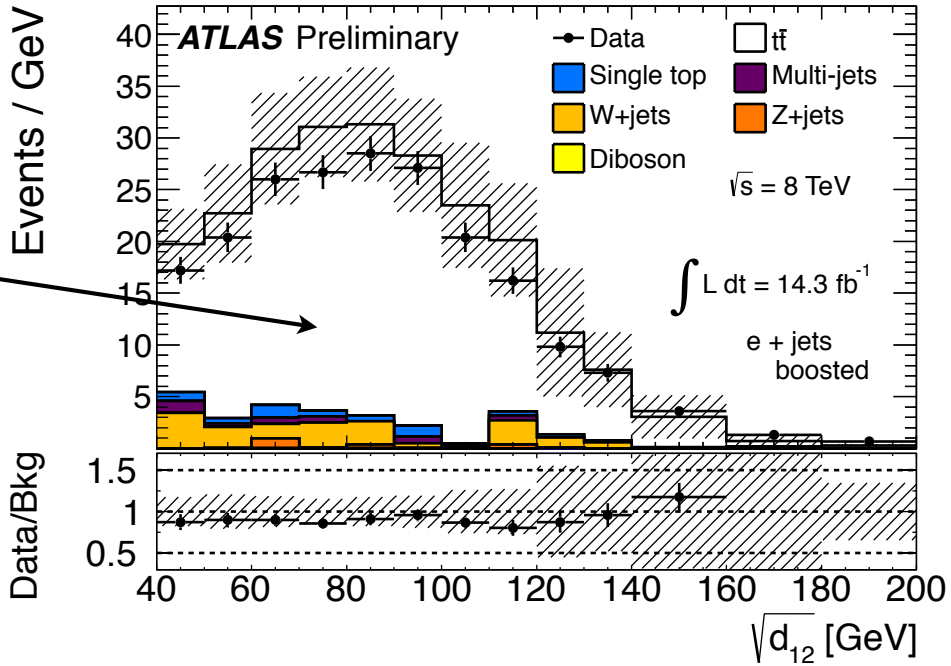
- Isolated muon/electron, $p_T > 25$ GeV
- Missing $E_T > 20/25$ GeV (e/μ)

- Resolved selection:
  - ≥ 3 jets, $p_T > 25$ GeV
    - If one jet mass > 60 GeV
    - Otherwise ≥ 4 jets
  - χ^2 algorithm used for reconstruction

- Boosted selection:
  - Large R = 1.0 jet
    - $p_T > 350$ GeV
    - Mass > 100 GeV
    - k_T splitting scale > 40 GeV

- Require ≥ 1 b-tagged jet
  - Could overlap with the large R jet
  - Could be assigned to leptonic decay

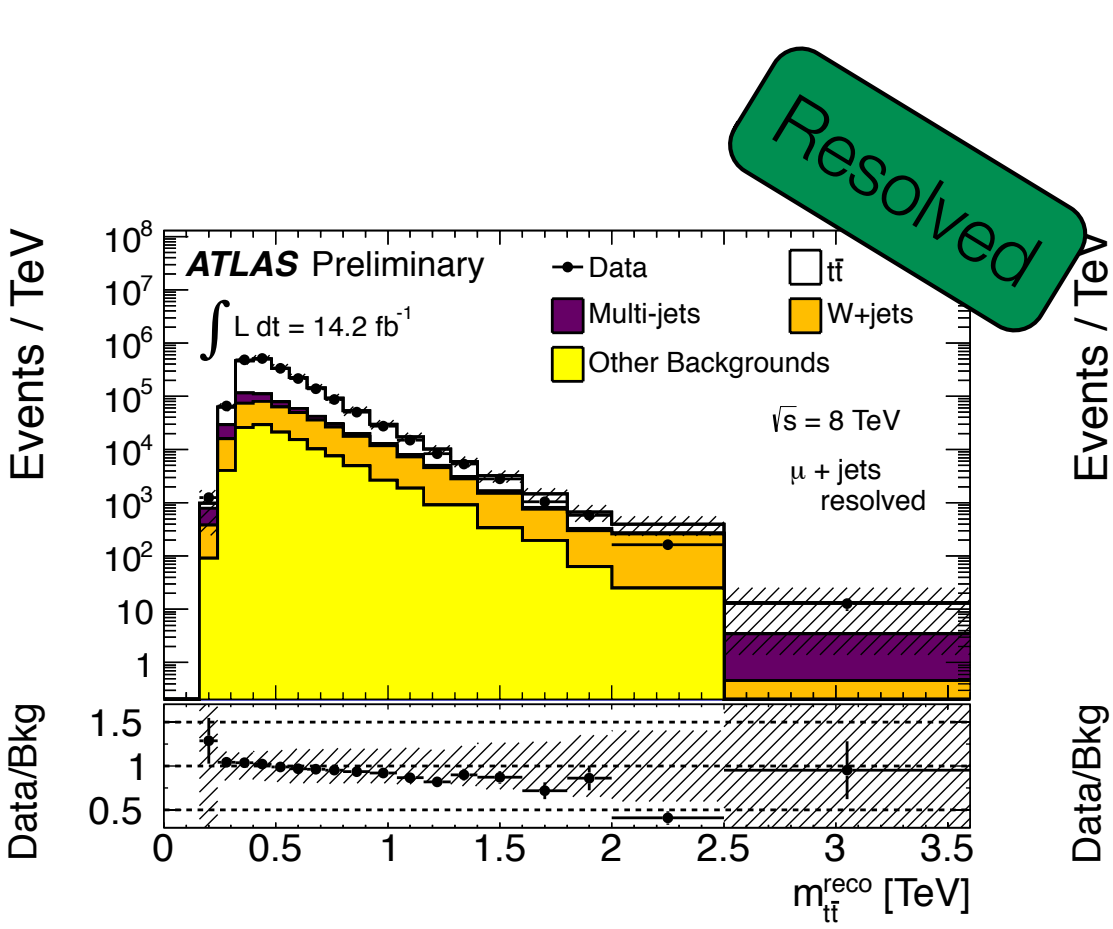


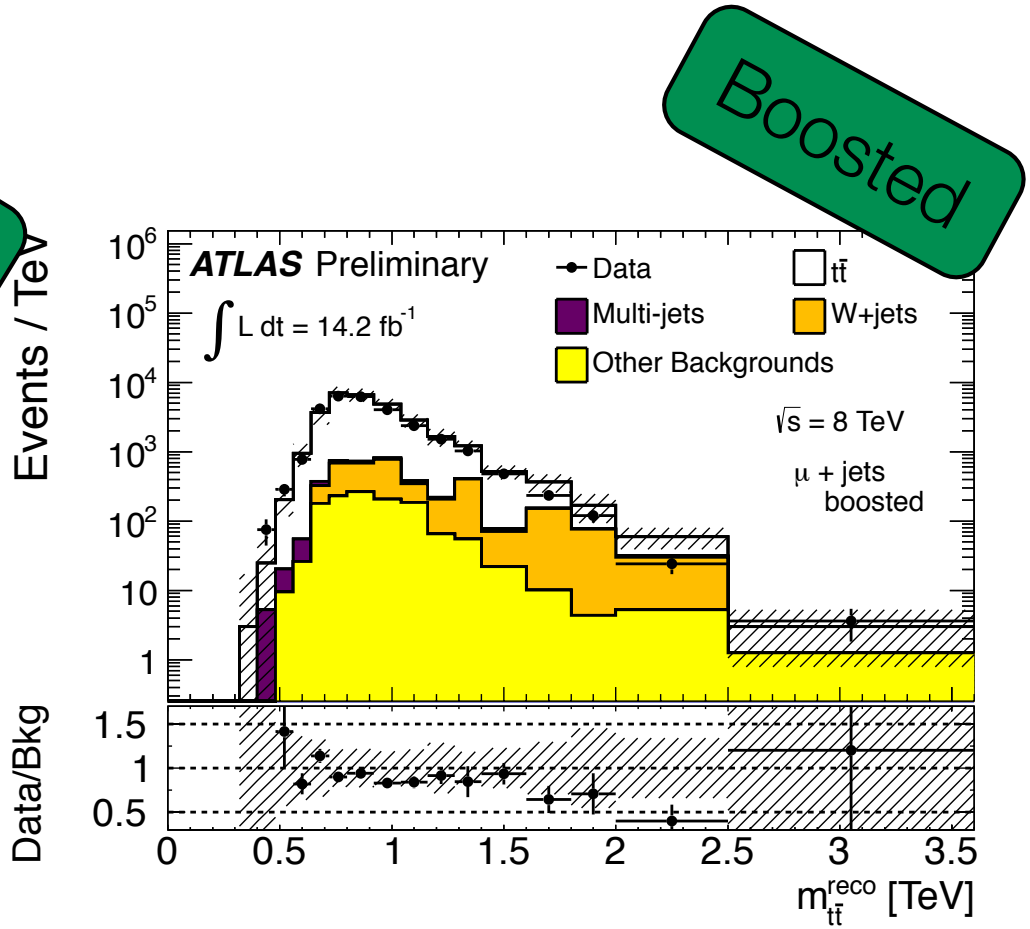


Lepton + Jets Searches

ATLAS-CONF-2013-052

- Resolved and boosted selections combined to produce final result
- Reconstructed $t\bar{t}$ mass distribution used for signal discrimination

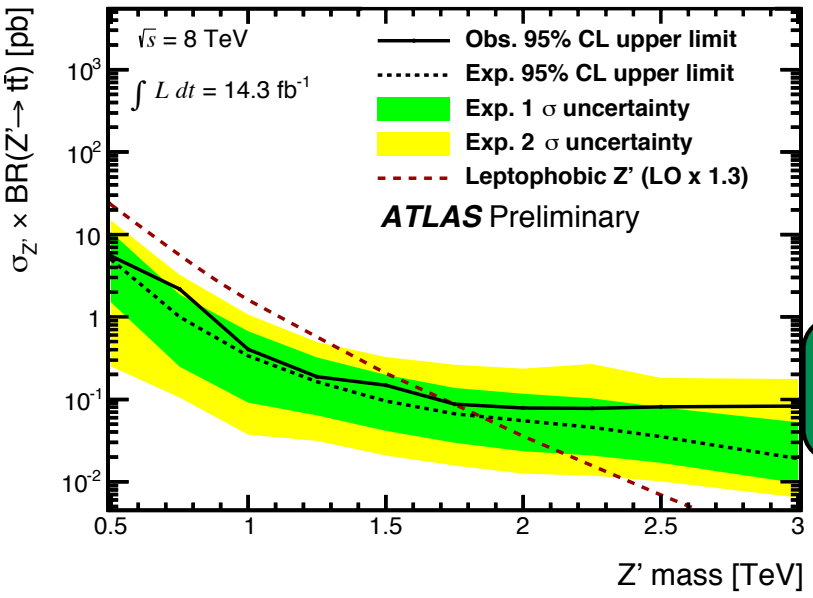




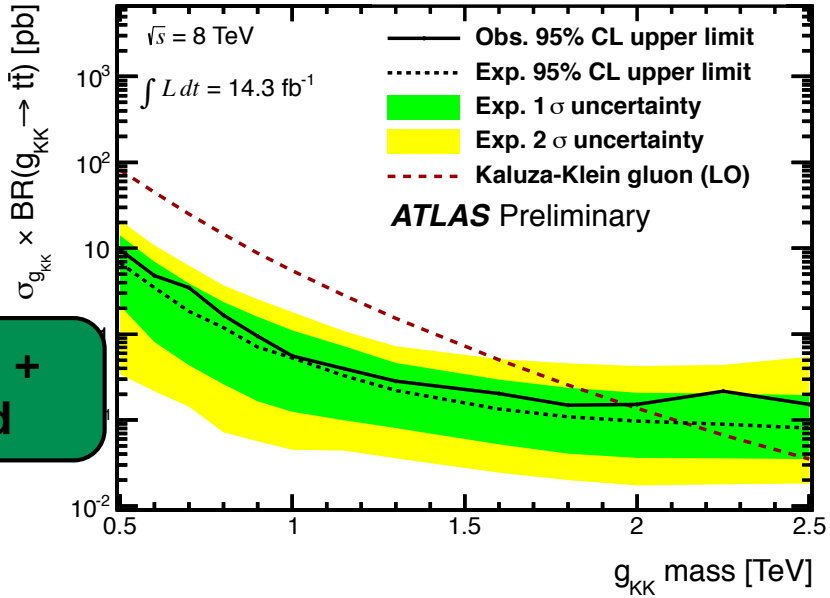
Lepton + Jets Limits

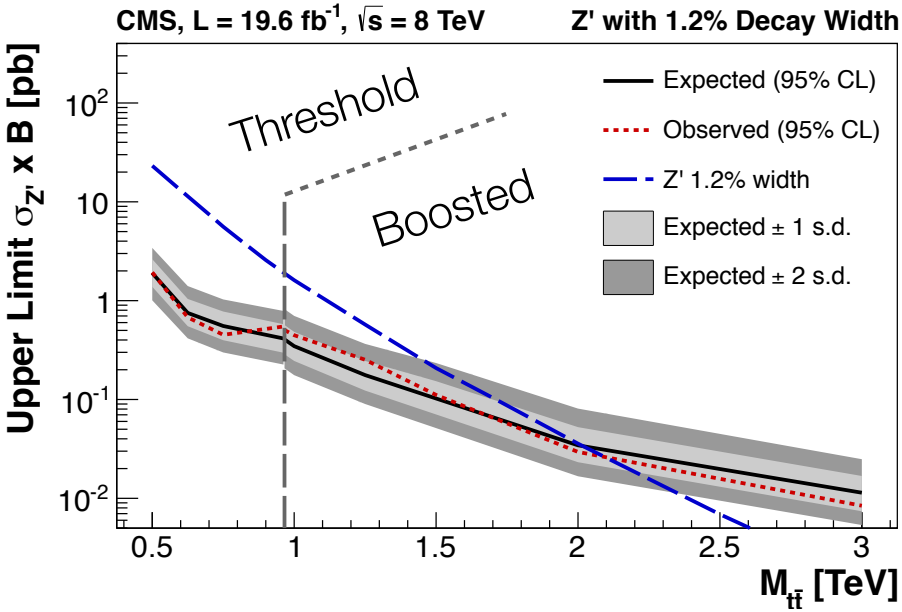
ATLAS-CONF-2013-052,
CMS-PAS-B2G-12-006

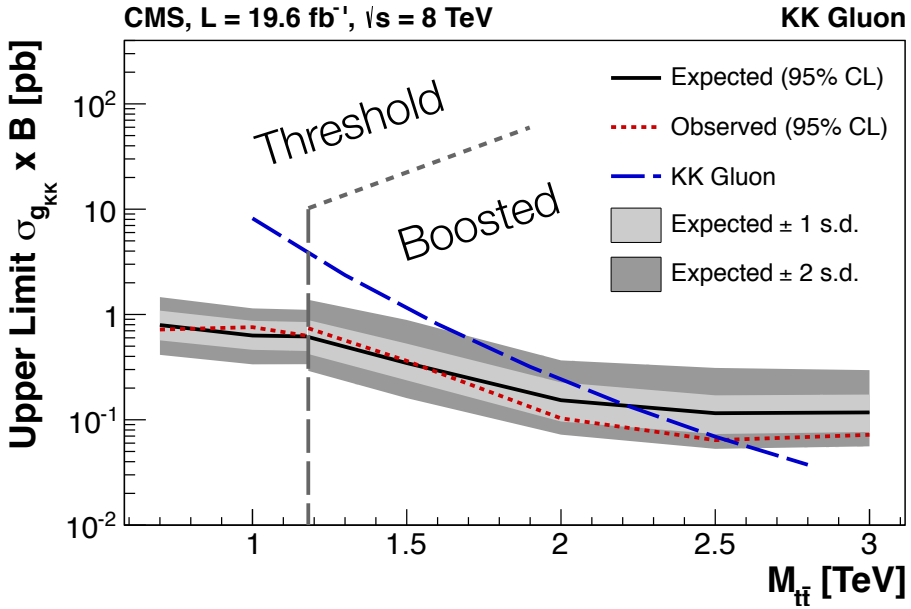
- ATLAS (8 TeV) excludes Z' up to 1.8 TeV, KK gluons to 2.0 TeV
- CMS (8 TeV) excludes Z' up to 2.1 TeV, KK gluons to 2.5 TeV
  - Slightly different KK gluon models



Resolved + Boosted



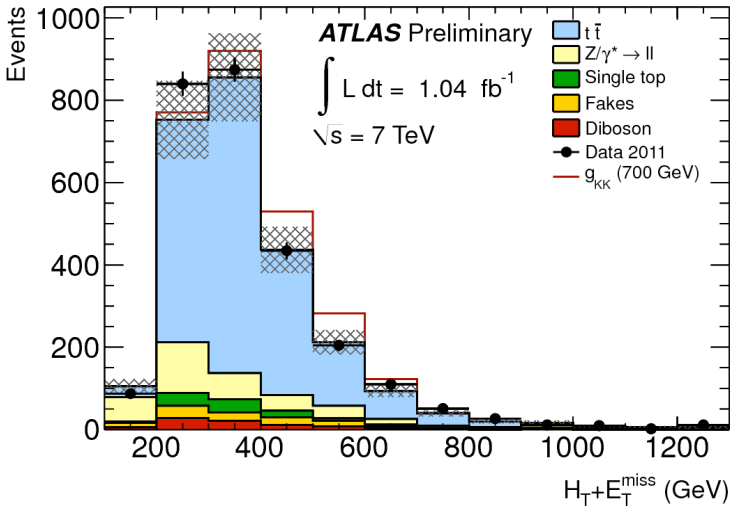


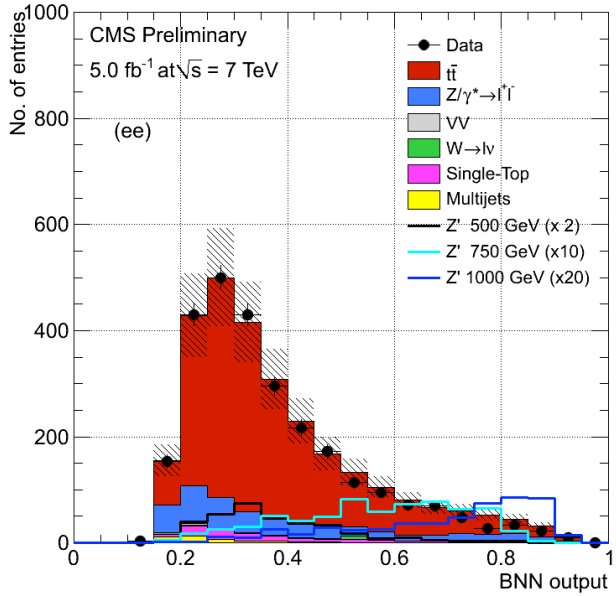


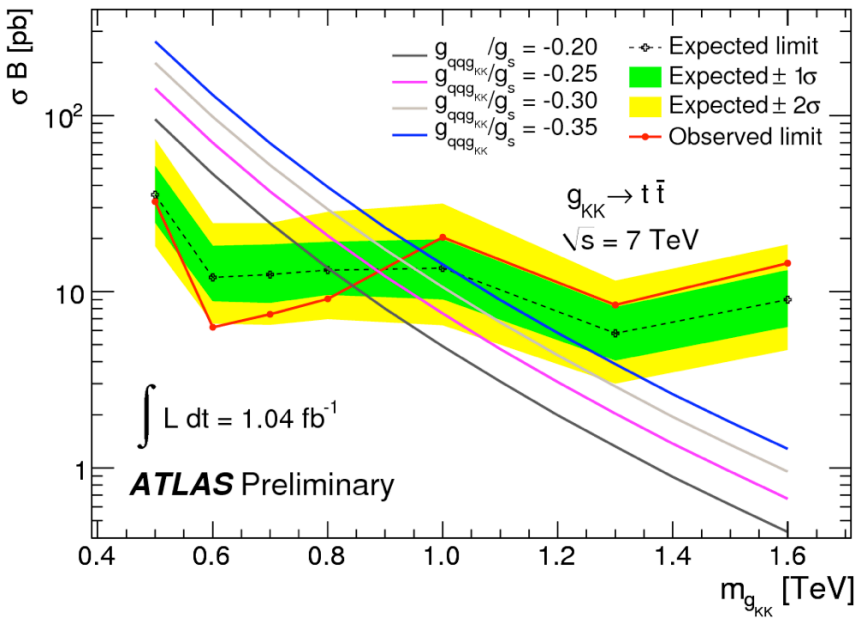
Dilepton Searches

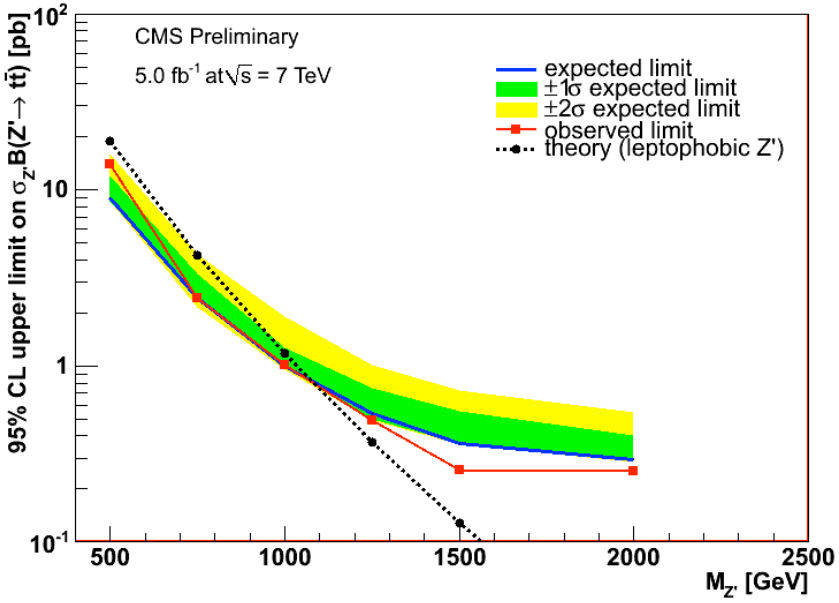
ATLAS-CONF-2011-123,
CMS-PAS-TOP-11-010

- CMS uses NN approach, ATLAS uses H_T+E_T spectrum
- Exclusions up to ~1 TeV, depending on signal model considered





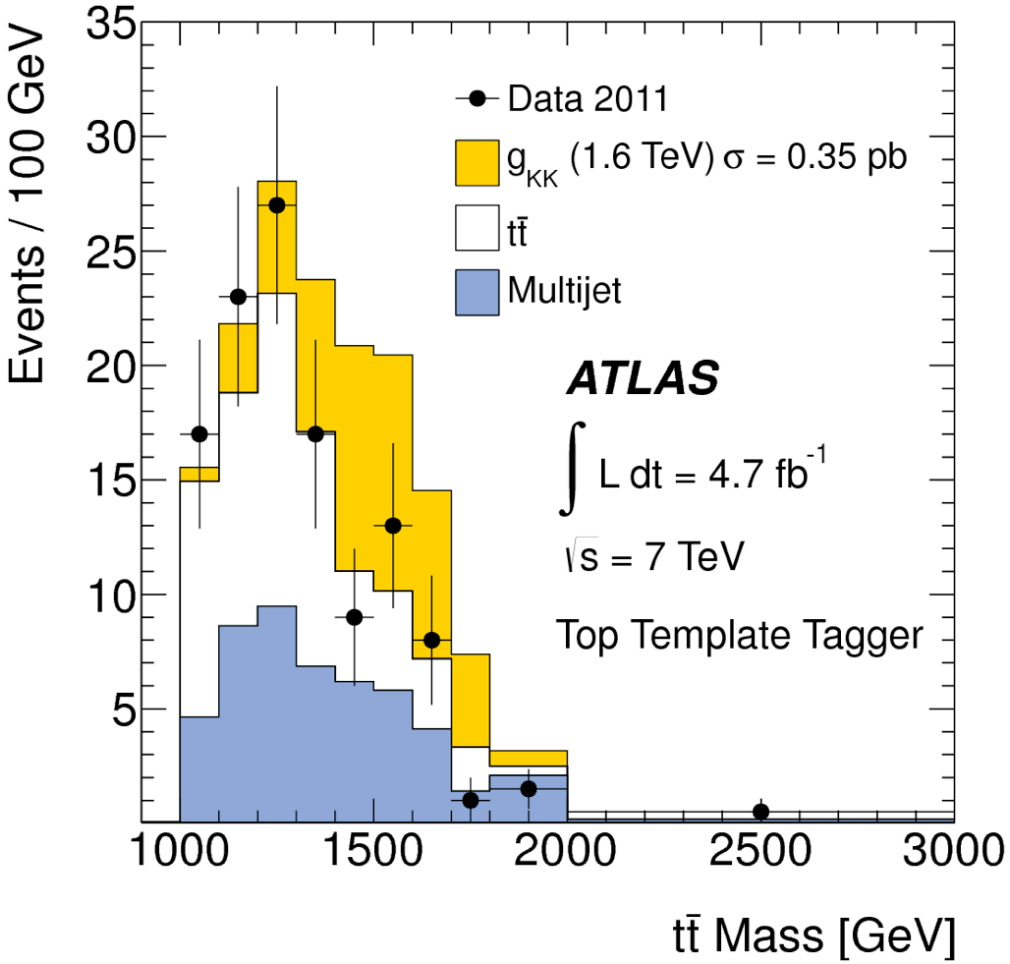


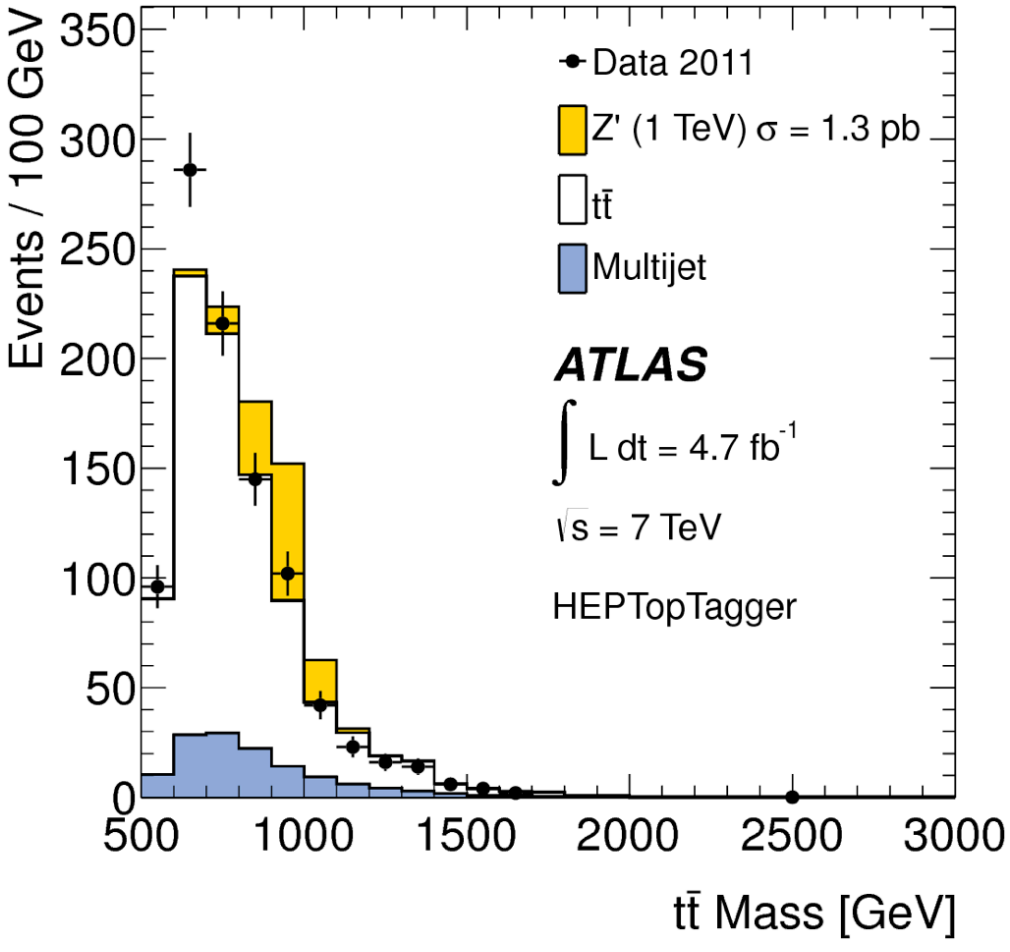


All-Hadronic Searches

ATLAS: JHEP01(2013)116

- ATLAS uses two top taggers
  - HEPTopTagger
  - Template Tagger
- Large *R* jets used to catch decay products
- Require a b-tagged jet close to the identified ‘fat jet’
- m_{tt} distribution used to set limits
  - Z’ narrow, wide resonances
  - RS gluons

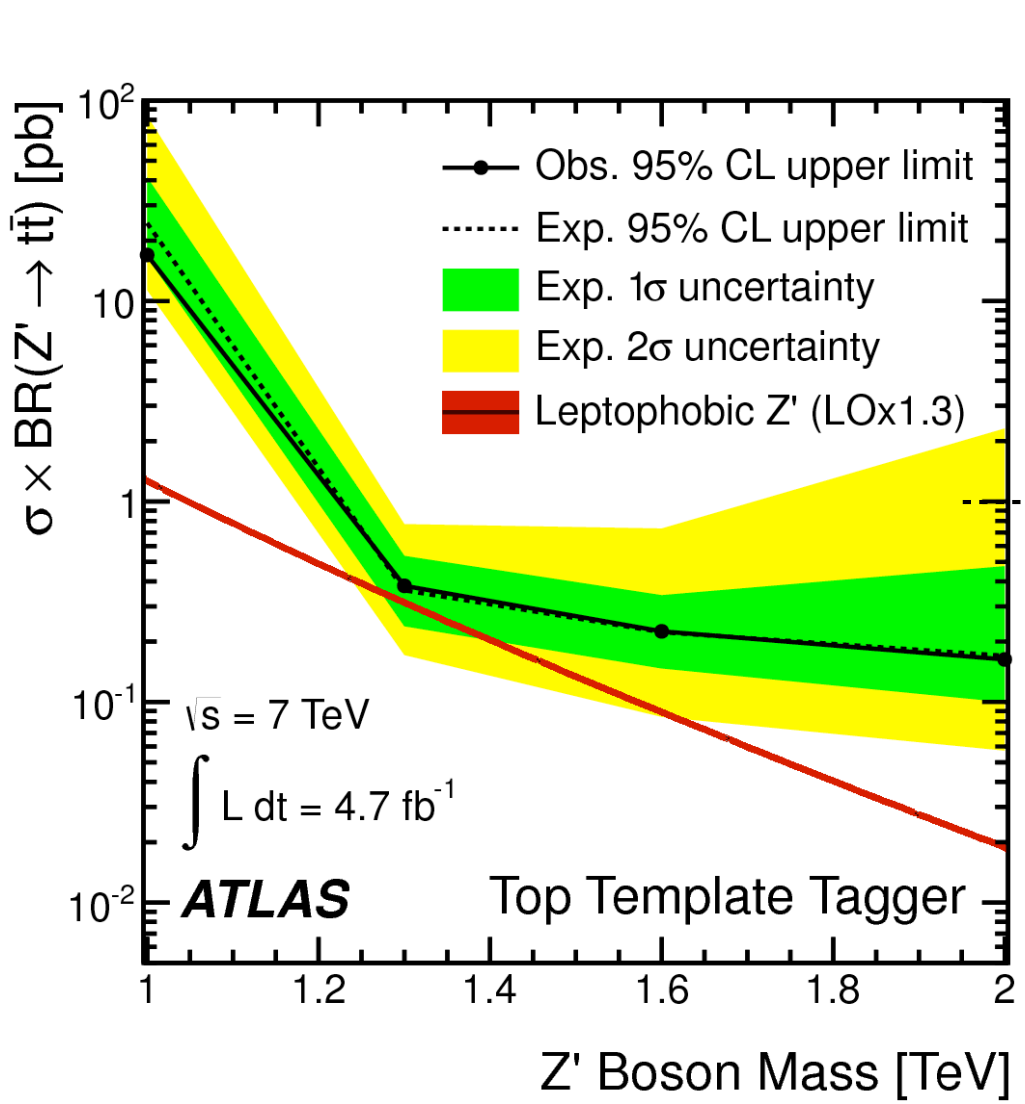


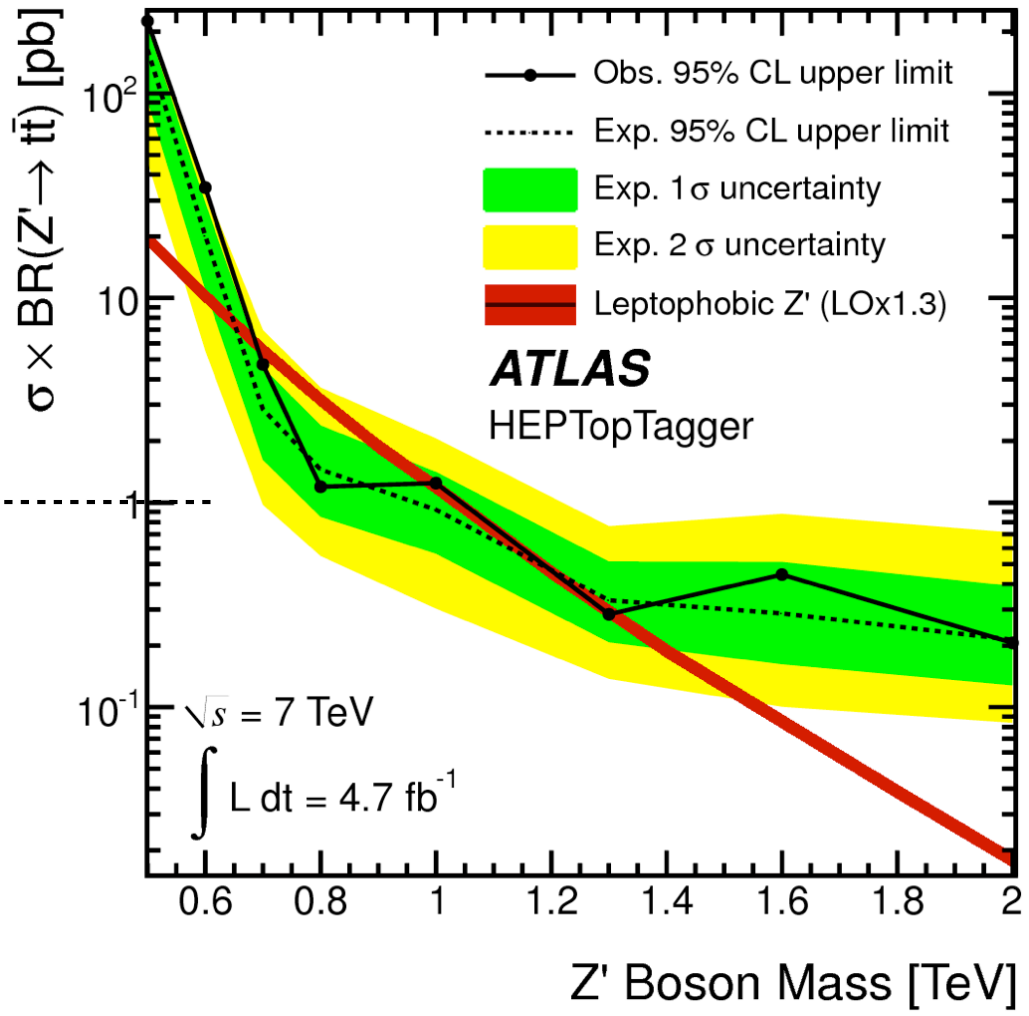


All-Hadronic Searches

ATLAS: JHEP01(2013)116

- Limits from ATLAS with 7 TeV dataset
- KK gluons excluded to 1.62 TeV
- Z' bosons excluded from 1.0 to 1.32 TeV

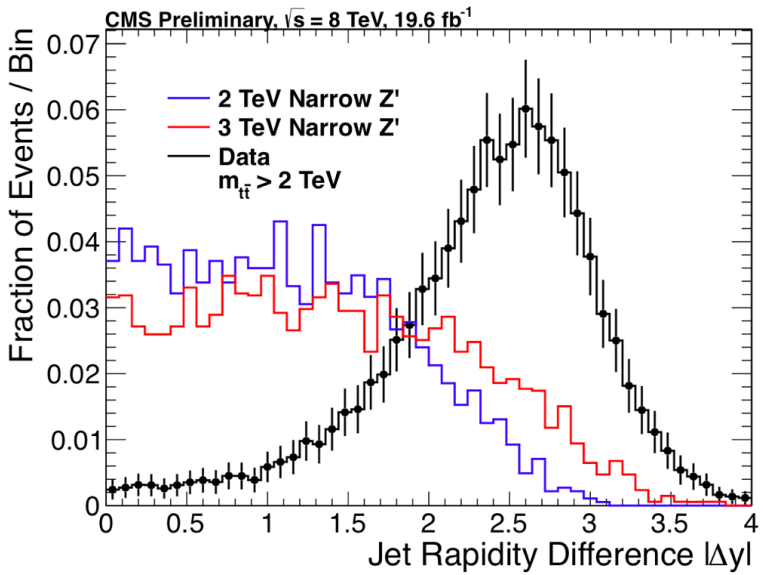




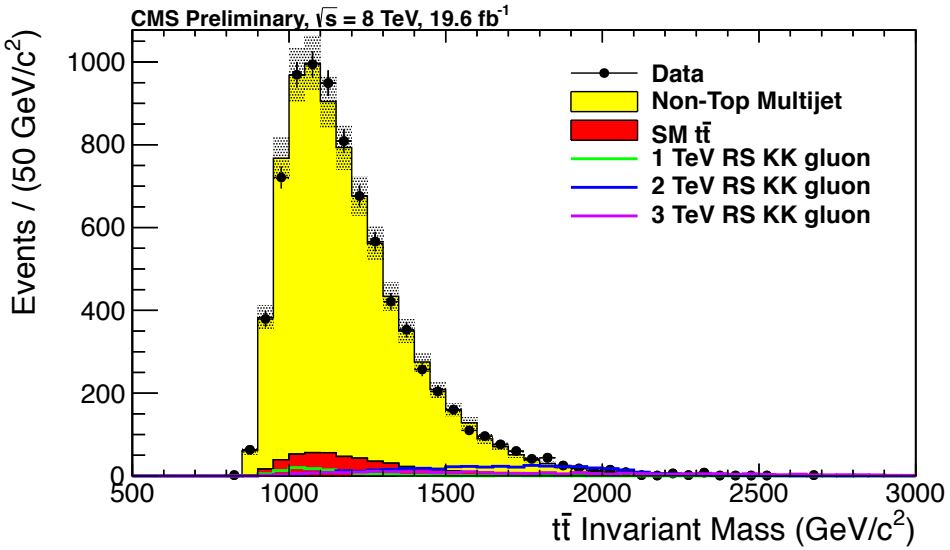
All-Hadronic Searches

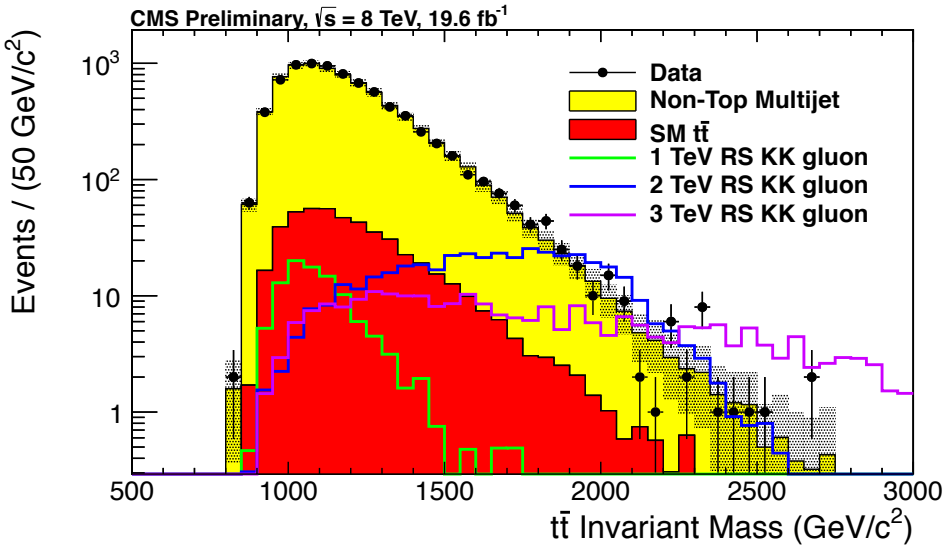
CMS-PAS-B2G-12-005

- CMS uses the JHU-based top tagger
- Dijet event topology
  - 2 jets $p_T > 400$ GeV
  - Rapidity separation $|\Delta y| < 1.0$
    - Enhances sensitivity at high mass



- Main background is multijet events
  - Determined from data using a mistag rate applied to loosened selection

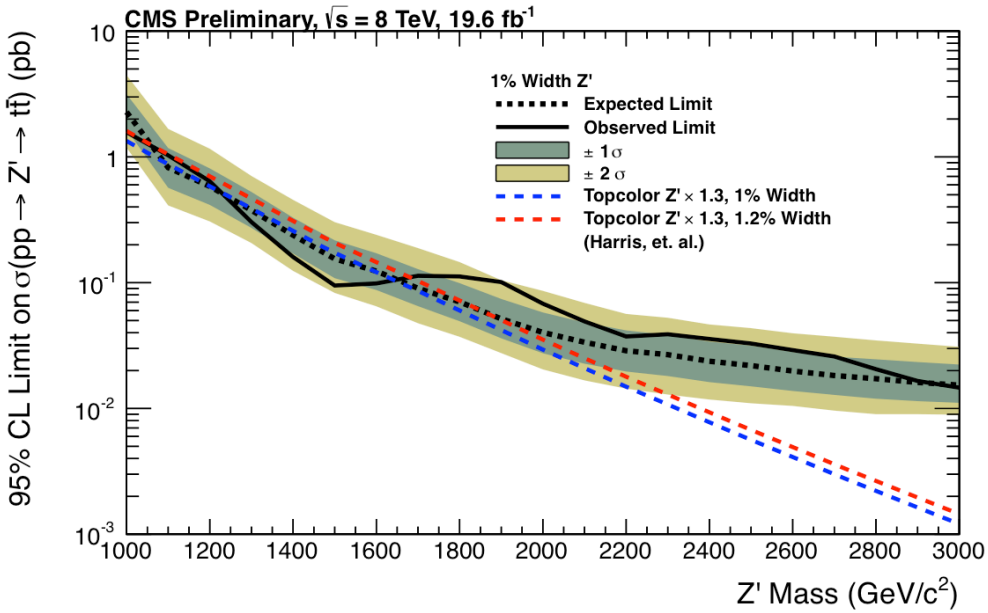


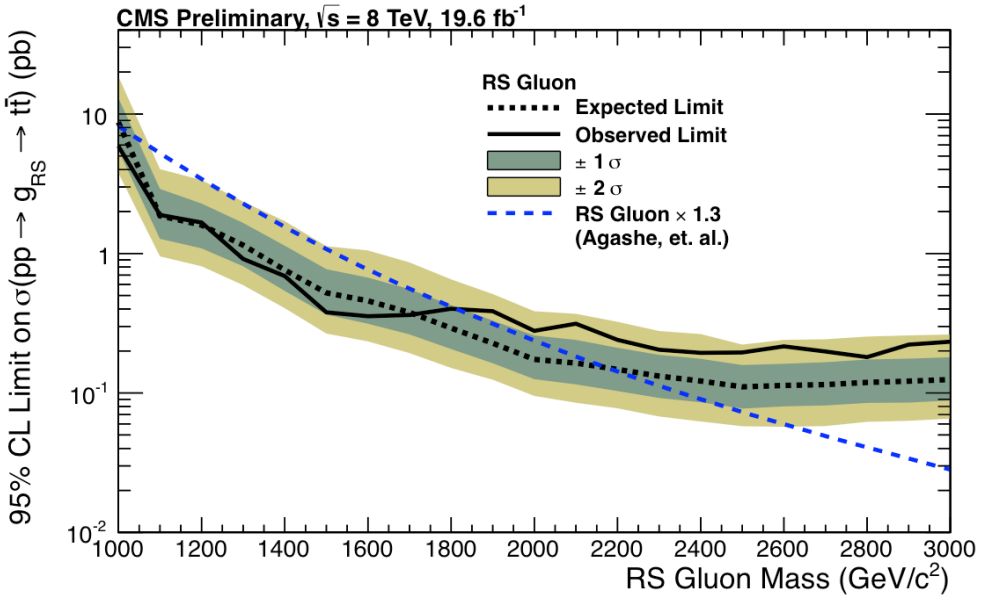


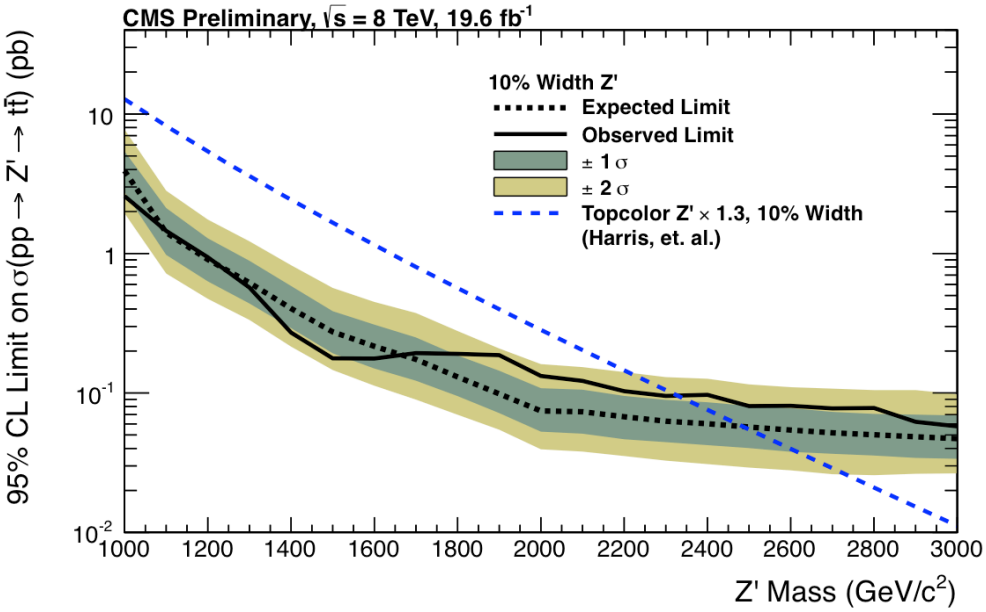
All-Hadronic Searches

CMS-PAS-B2G-12-005

- CMS results with 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







Enhancement Analysis

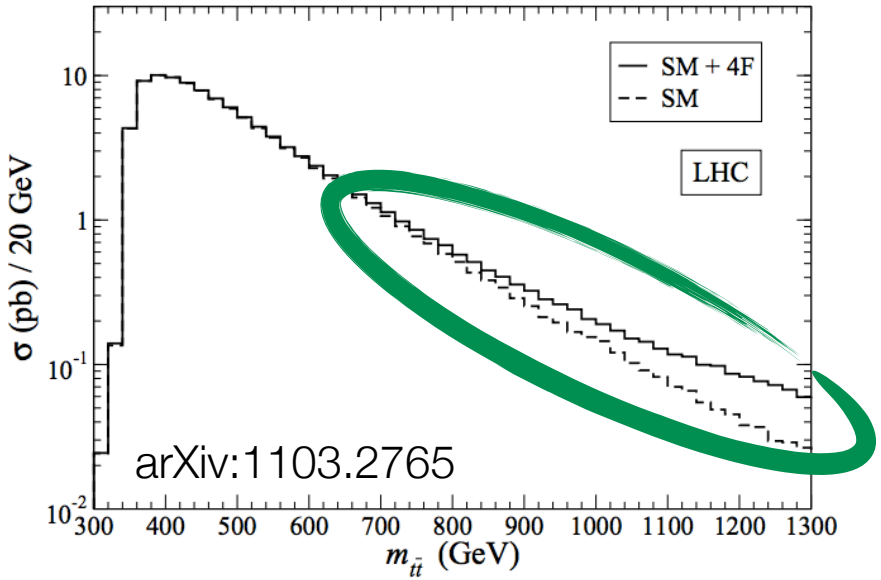
CMS-PAS-B2G-12-005

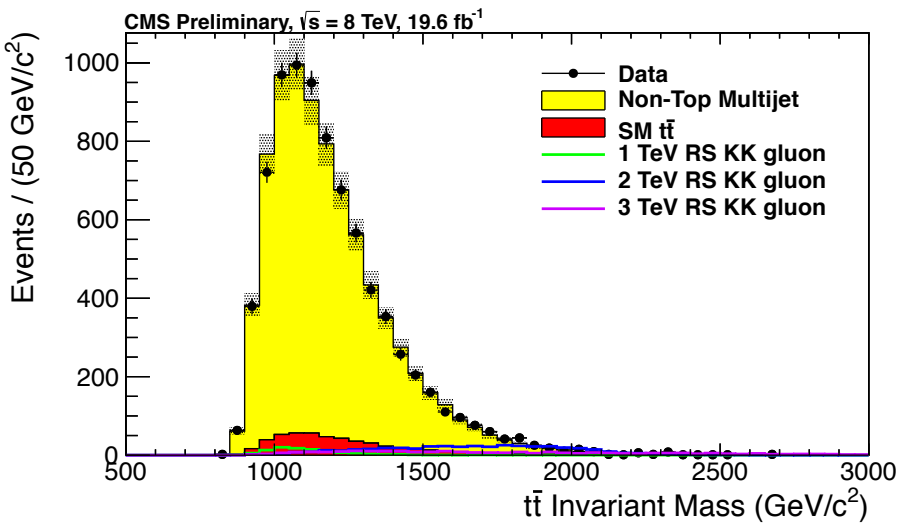
- To produce a limit on this general enhancement we use a simple counting experiment with events having $m_{tt} > 1$ TeV

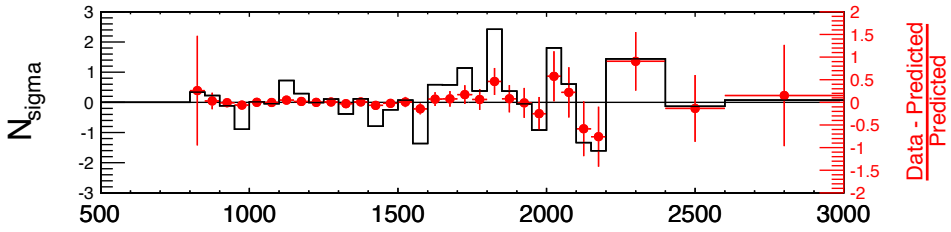
- Result is limit on the enhancement ratio

$$\mathcal{S} = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}}$$

- New result -- set limit of **$S < 1.79$** (expect $S < 2.29$) at 95% CL







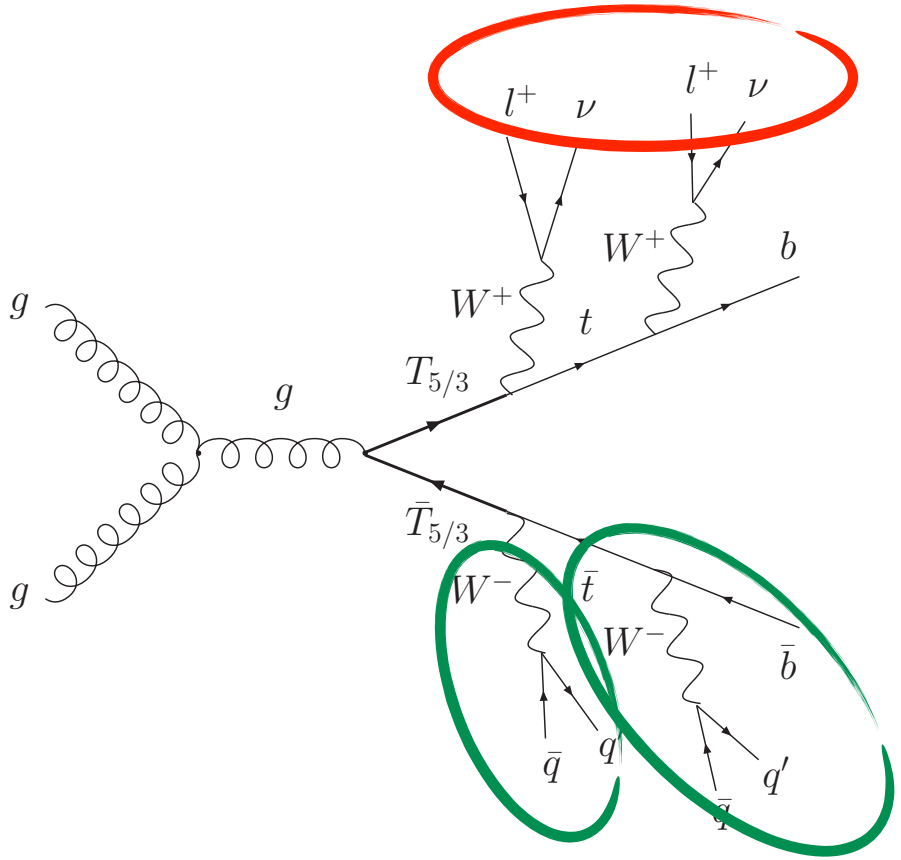
Top Partner Searches

Search for Top Partners

CMS-PAS-B2G-12-012

- 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 “constituents”
    - Boosted top = 3
    - Boosted W = 2
  - $H_T > 900$ GeV
  - Quarkonia, Z vetos

See Y-M. Tzeng, Parallel Talk for more!



Search for Top Partners

CMS-PAS-B2G-12-012

- CMS search for particles $T_{5/3}$ with exotic charge
  - Solve hierarchy problem and are compatible with observed Higgs mass
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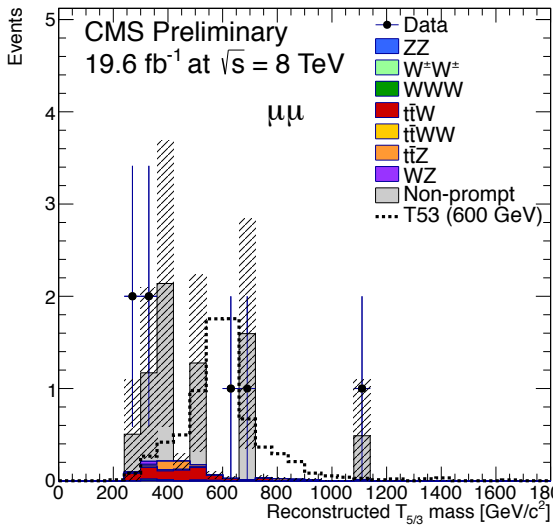
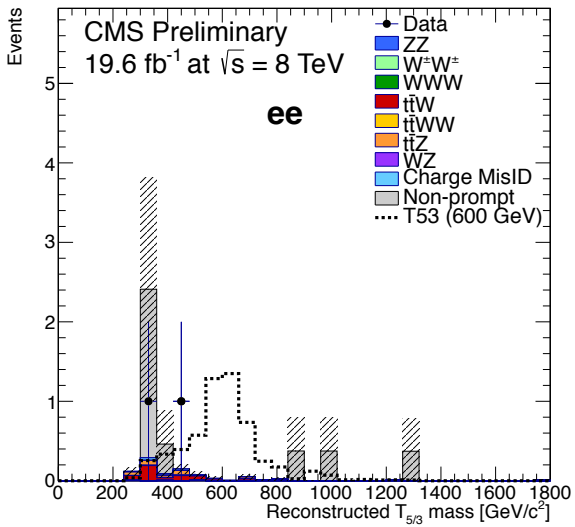
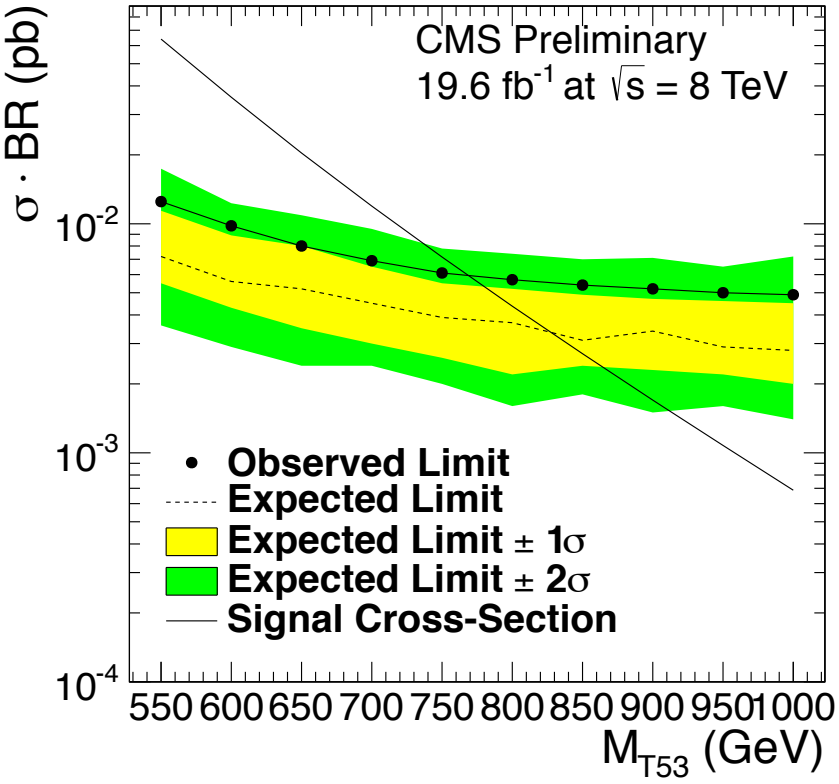
    - Use jet substructure!
- Basic event selection:
  - 2 same-sign leptons, $p_T > 30$ GeV
  - 5 or more "constituents"
    - Boosted top = 3
    - Boosted W = 2
  - $H_T > 900$ GeV
  - Quarkonia, Z vetos
- CMS excludes masses up to 770 GeV







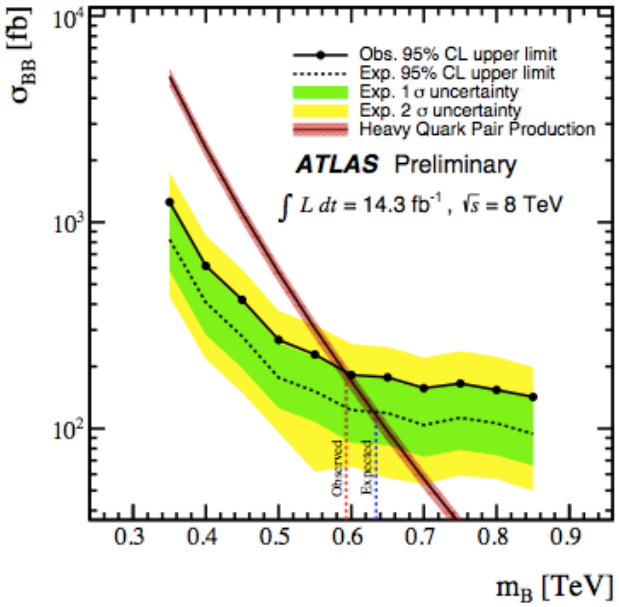
Search for Top Partners

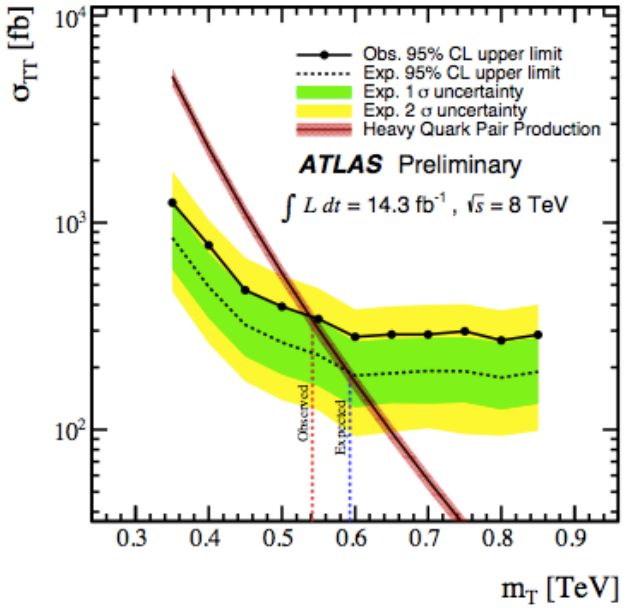
ATLAS-CONF-2013-051

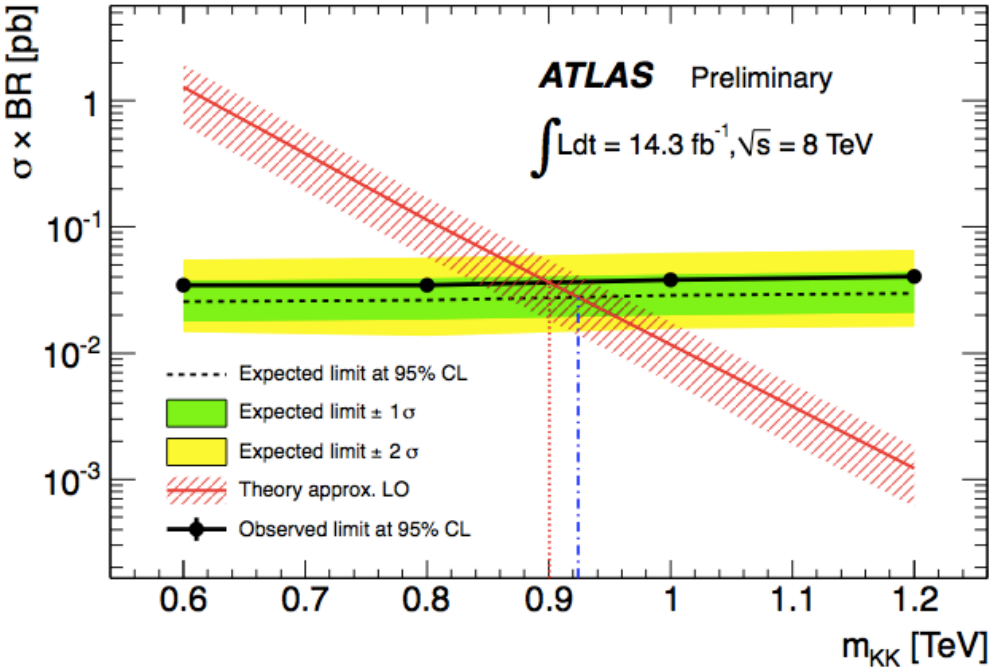
- ATLAS uses a similar final state to probe several physics models
  - 4th gen., vector-like
  - 4 top contact interaction
  - Same-sign top pairs

- Select events containing:
  - 2 same-sign leptons
  - ≥ 2 jets, 1 b-tagged
  - Missing E_T > 40 GeV
  - H_T > 550 GeV
  - Quarkonia, Z vetos

- Vector-like quarks excluded to 590 GeV (B), 540 GeV (T)
- KK gluons excluded to 900 GeV
- Four-top cross-section limits:





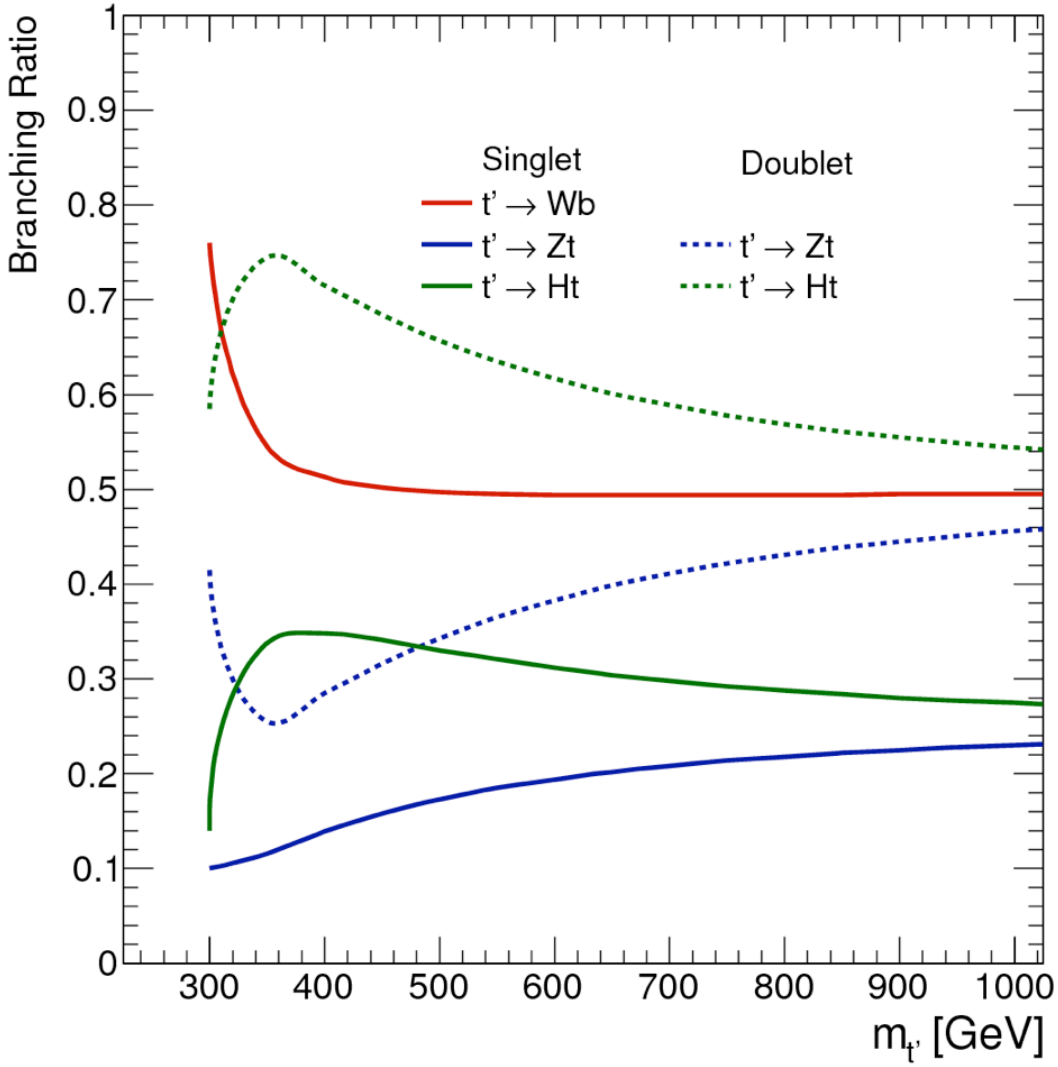


	95% C.L. upper limit		
	$\sigma(pp \to tttt)$ [fb]		$\lvert C\rvert/\Lambda^2$ [TeV^{-2}]
Model	Expected 1σ range	Observed	Observed
Standard Model	43-89	85	—
Contact interaction	29-61	59	15

Vector-Like Quarks

ATLAS-CONF-2013-018

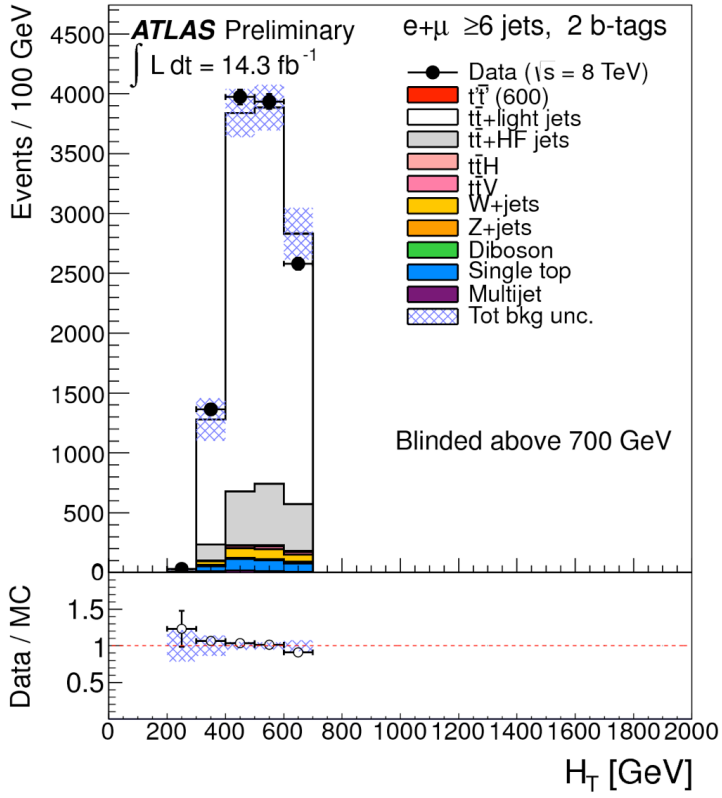
- Vector-like top partners have many possible decay modes
  - t'→bW
  - t'→tZ
  - t'→tH
- Unique final states
  - Rich in b-jets
  - Can give boosted tops, W
- ATLAS released new results with 8 TeV dataset (~14 fb^{-1})
- Scan over branching ratios to probe all decay modes

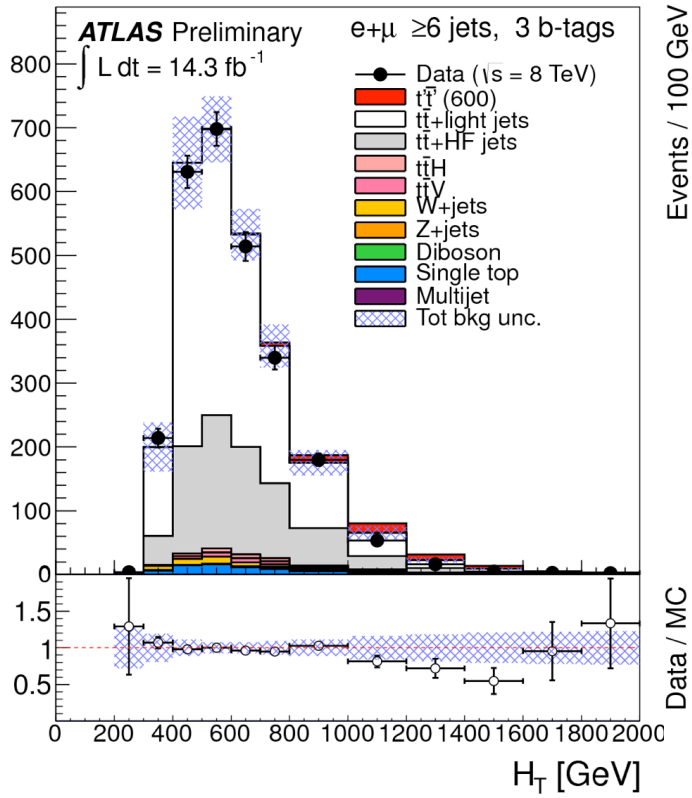


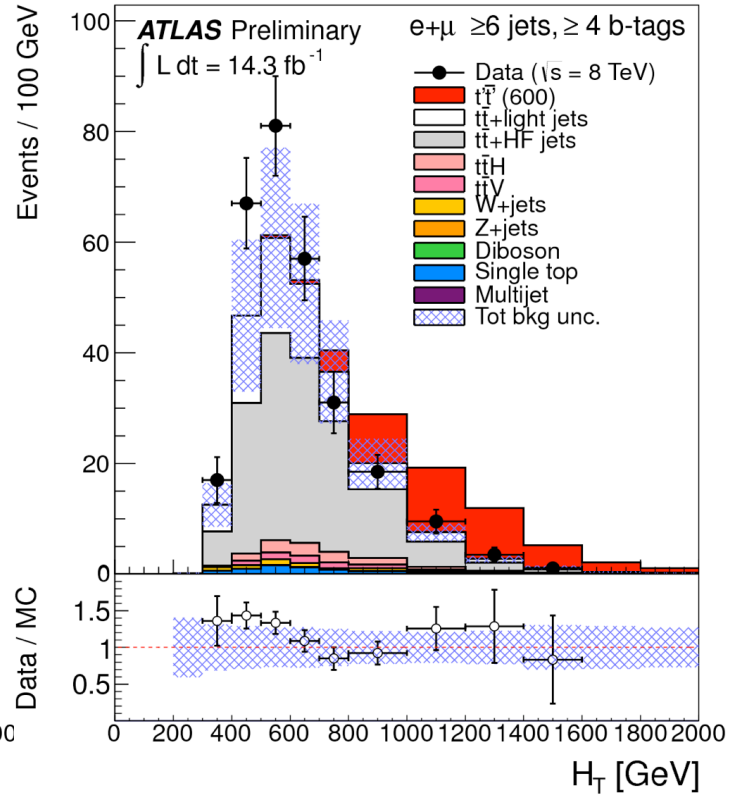
Vector-Like Quarks

ATLAS-CONF-2013-018

- Select events with:
  - 1 good electron/muon
  - 6 or more jets
  - 2, 3 or 4 b-tags
- Main background is top pair events
  - Normalization determined after fit to data
- H_T distribution used to discriminate signal
  - Separated into bins of b-tagged jets





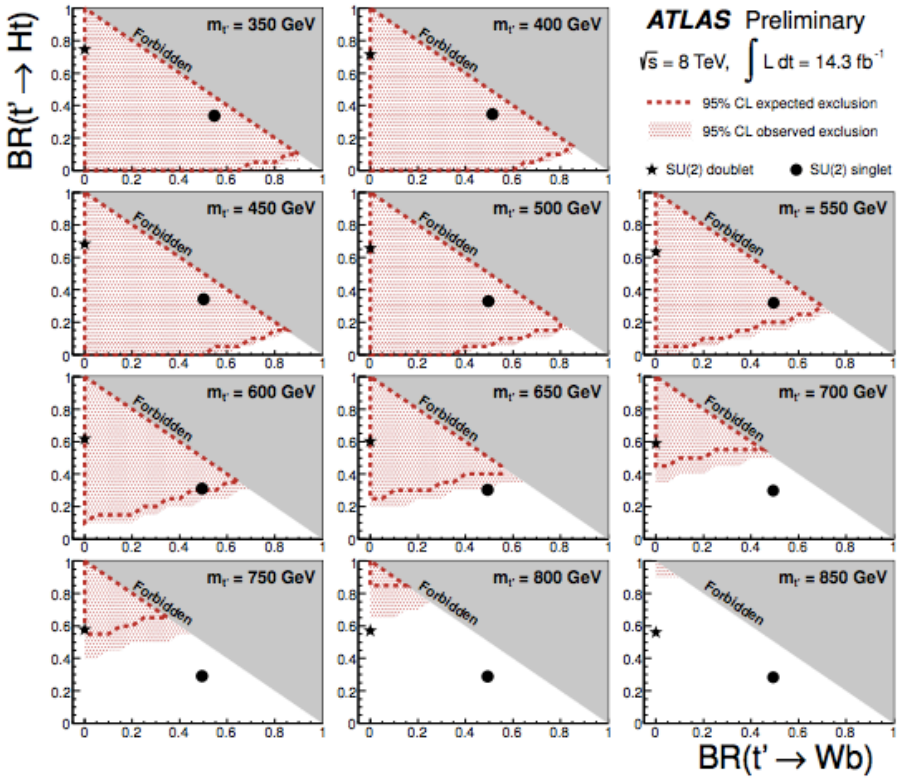


Vector-Like Quarks

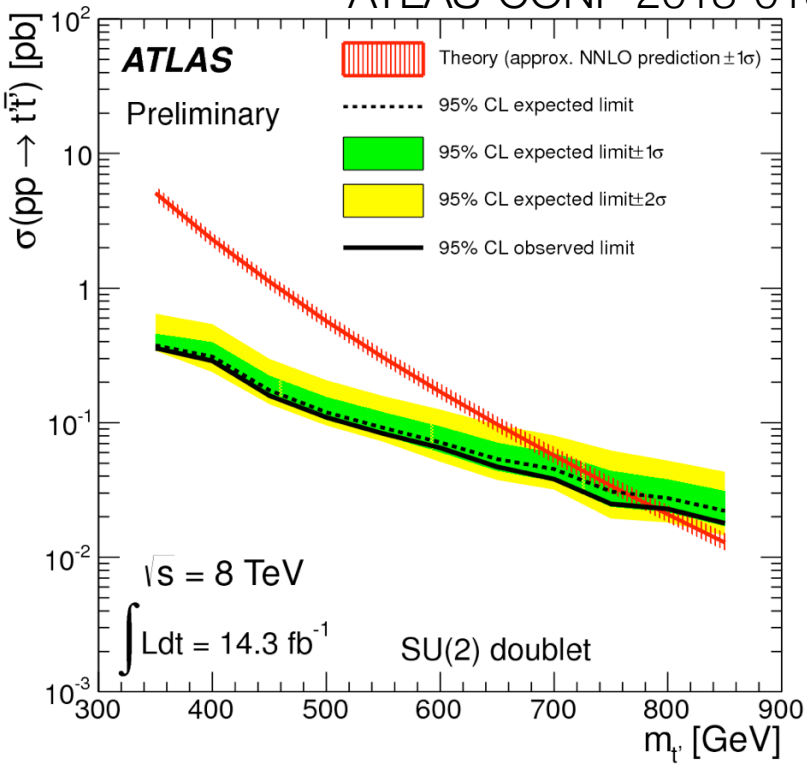
- Exclude t' vector-like quarks up to
  - 790 GeV, for SU(2) doublet model
  - 640 GeV, for SU(2) singlet

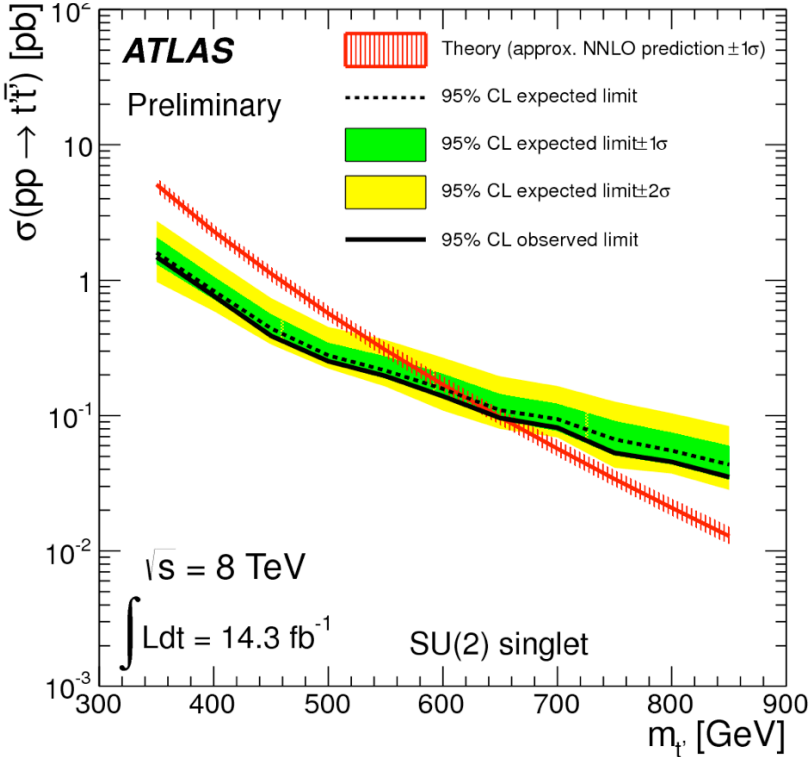
- CMS sets comparable limits of 660-760 GeV, see Y-M. Tzeng, parallel talk

- Also can scan in the plane of B(t'→tH) vs B(t'→bW) :



ATLAS-CONF-2013-018

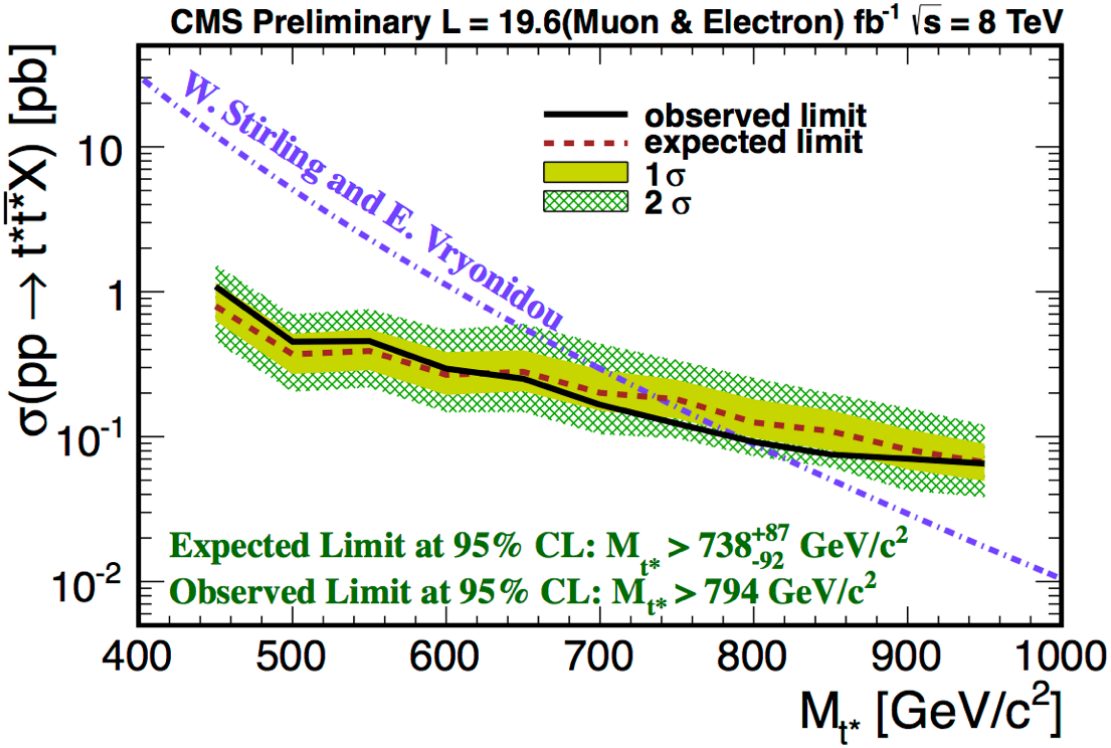


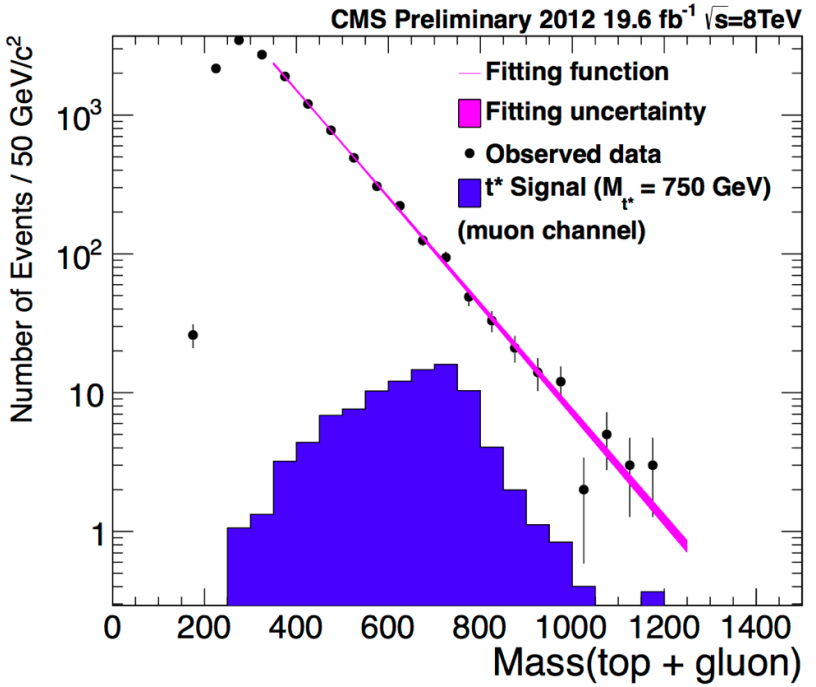


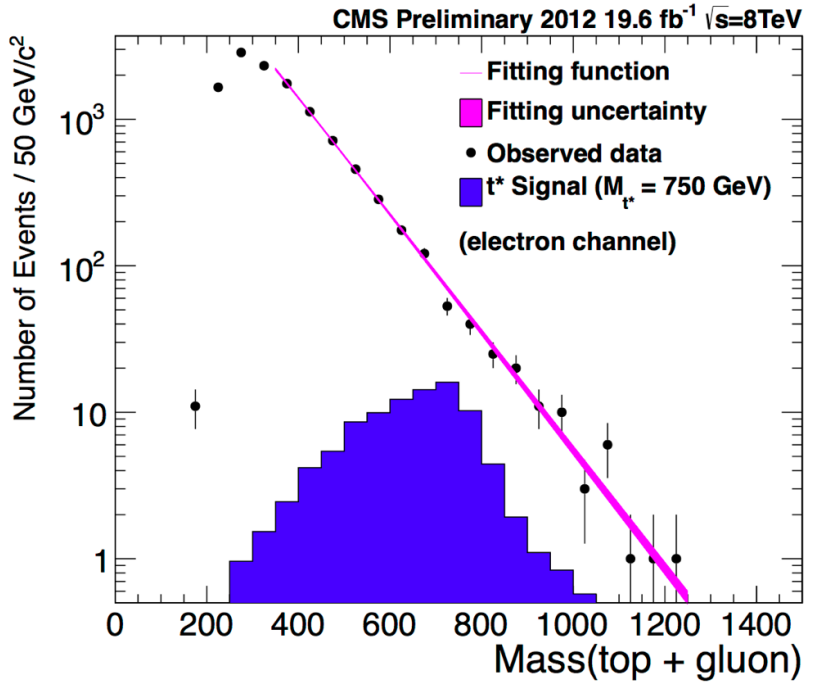
Excited Top Search

CMS-PAS-B2G-12-014

- 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







Summary and Conclusion

- Many new analysis results from both CMS and ATLAS presented
  - Mass reach continues to increase, now setting multi-TeV scale exclusions!
- These analyses benefit greatly from the use of substructure tools
  - Specialized reconstruction techniques to maintain sensitivity in the boosted regime
  - Will become even more critical during the next LHC run at higher energy!
- Please see documentation of individual analyses, parallel talks, and posters for more detail
  - Just a broad overview here
- Thanks for your attention!
  - Comments, questions?