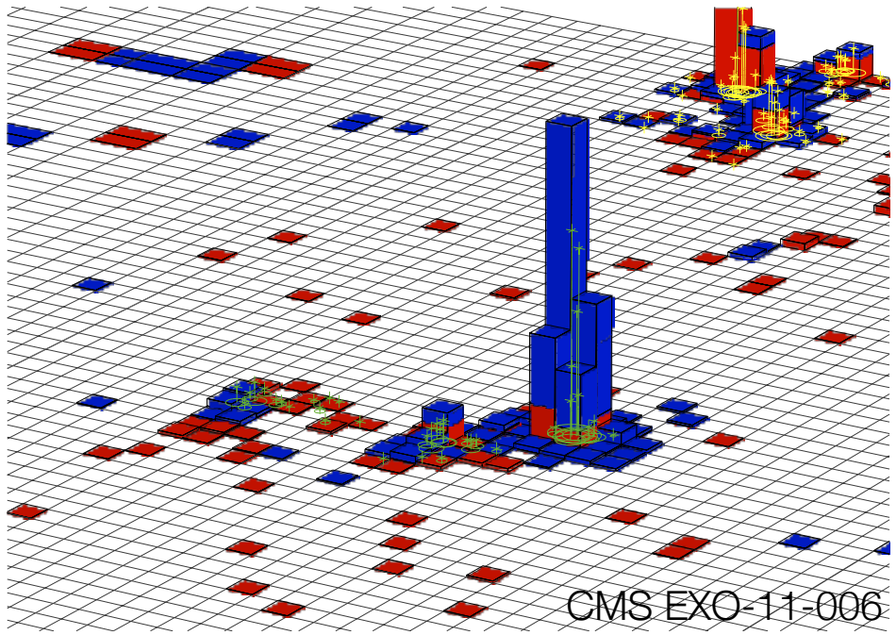
# Searches for heavy BSM particles coupling to third generation quarks at CMS




**James Dolen**

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*Phenomenology 2020 Symposium - May 5th, 2020*

# “Heavy BSM particles coupling to third generation quarks”

## Signatures which fall into this category:

### Vector-like Quarks

$T \rightarrow bW$ $B \rightarrow tW$

$T \rightarrow tZ$ $B \rightarrow bZ$

$T \rightarrow tH$ $B \rightarrow bH$

Single production
(ex. T in association with t and b)

Pair production
(ex. TT, BB, etc.)

### Resonances

Heavy resonance → standard model
(ex. Z` → tt, W` → tb)

Heavy resonance → vector-like quarks
(ex. Z` → tT, Z` → TT, W` → bT)

Excited quark
(ex. b* → tW, t* → tg)

Leptoquark
(ex. LQ → tτ, LQ → tμ)

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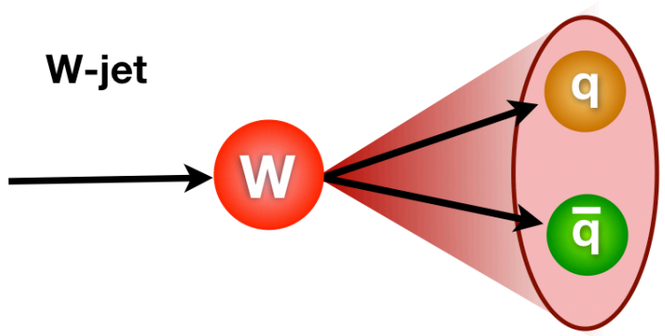
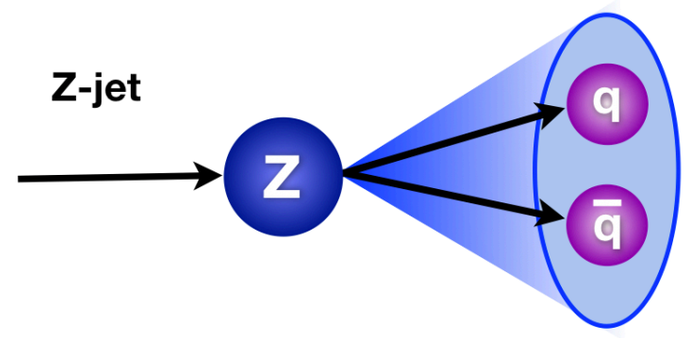
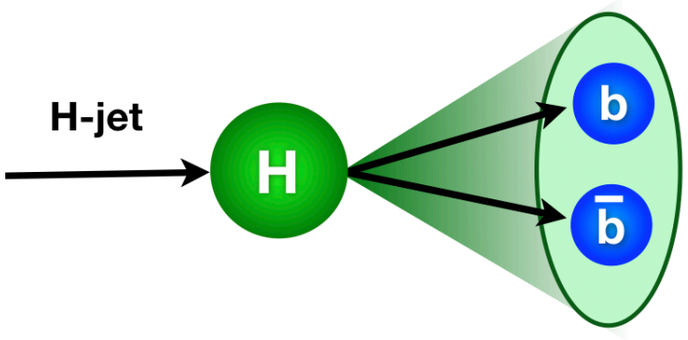
**Today: Highlight three of the most recent searches using 2016 CMS data**

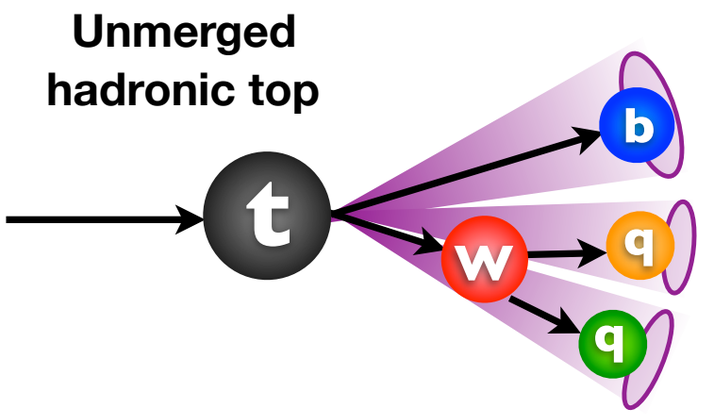
# Jet-tagging Menu

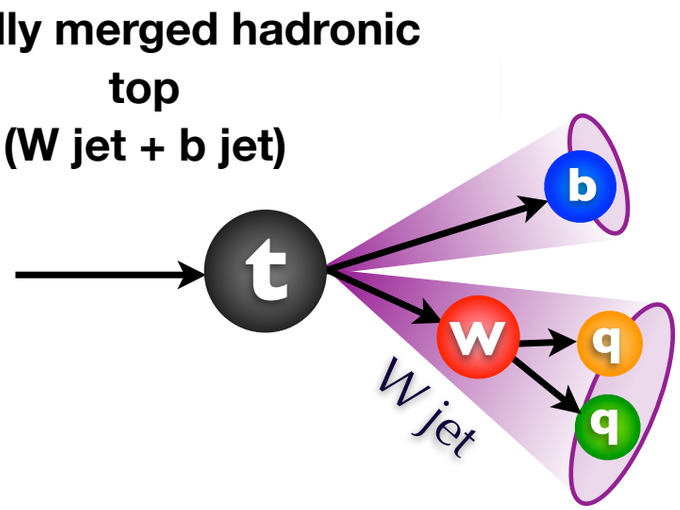
Utilize jet substructure to tag partially or fully merged jets

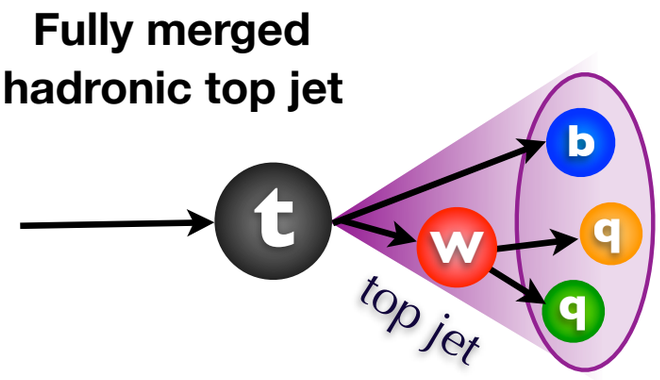


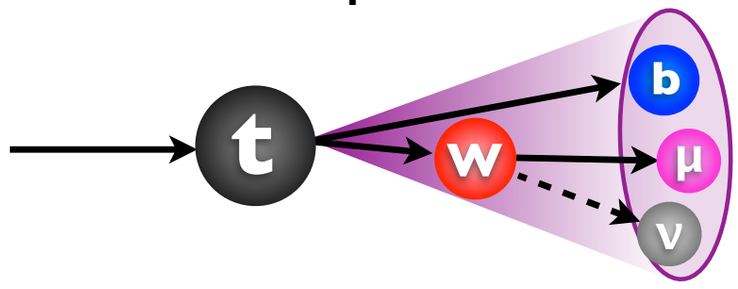



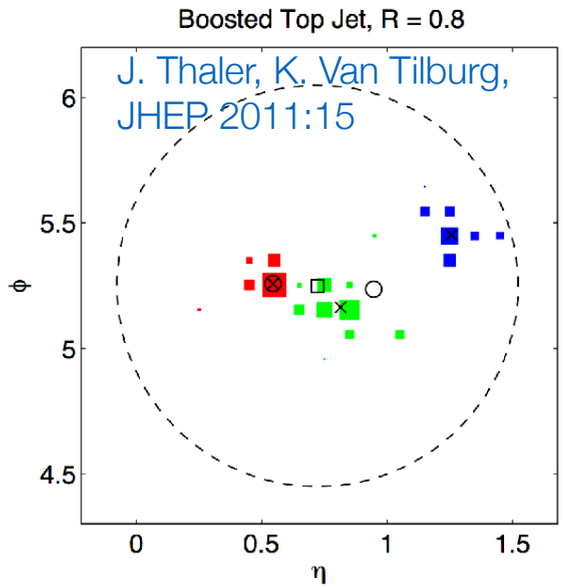



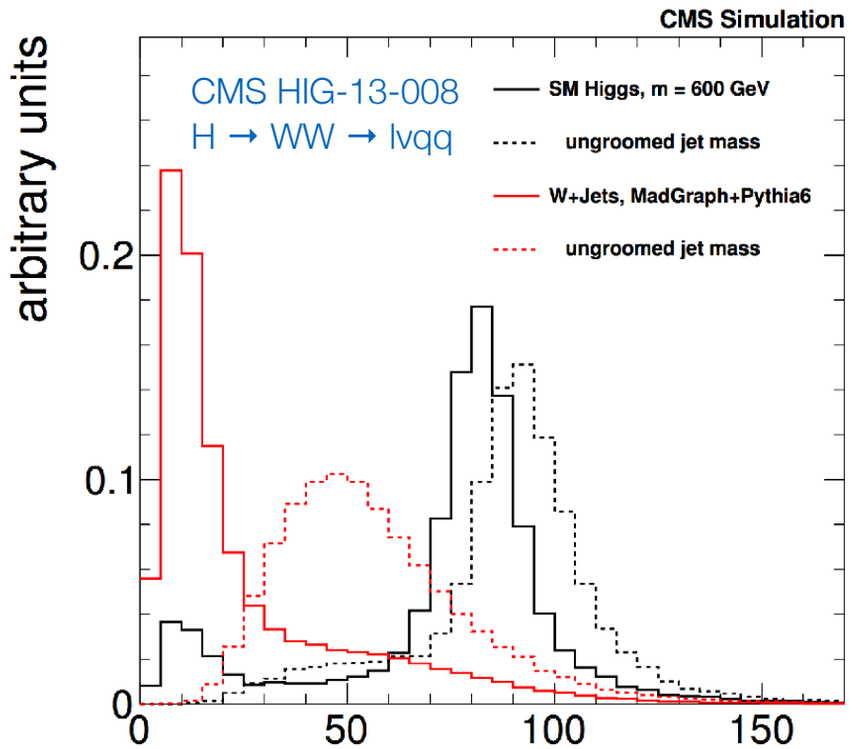



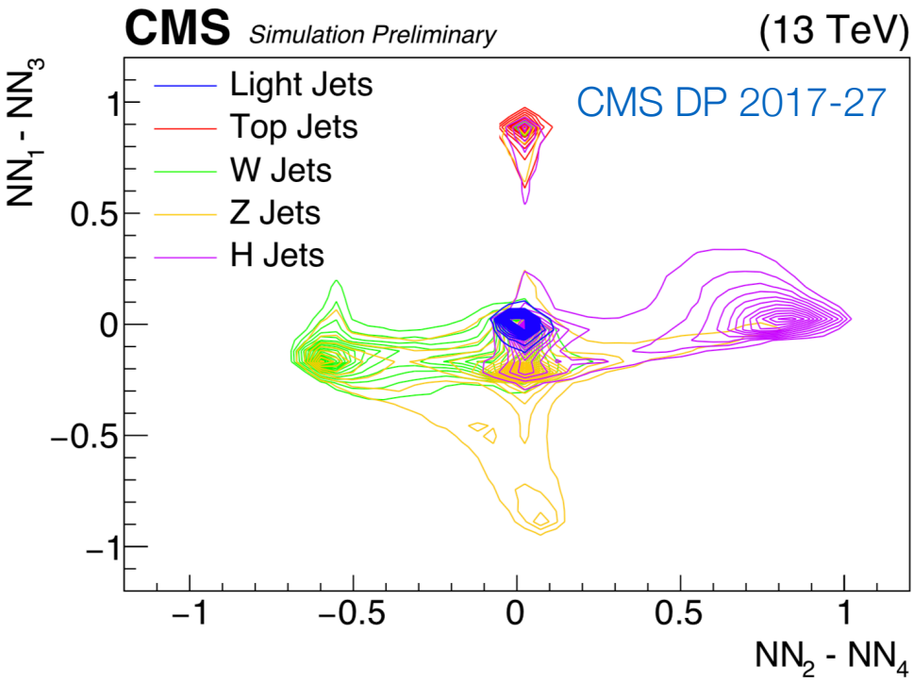
# Jet Tagging Tools

- Jet grooming
  - Pruning, soft drop
- N-subjettiness
  - Determines how consistent a jet is with having N or fewer subjets
  - Better discrimination by using ratios (ex. $\tau_3/\tau_2$)



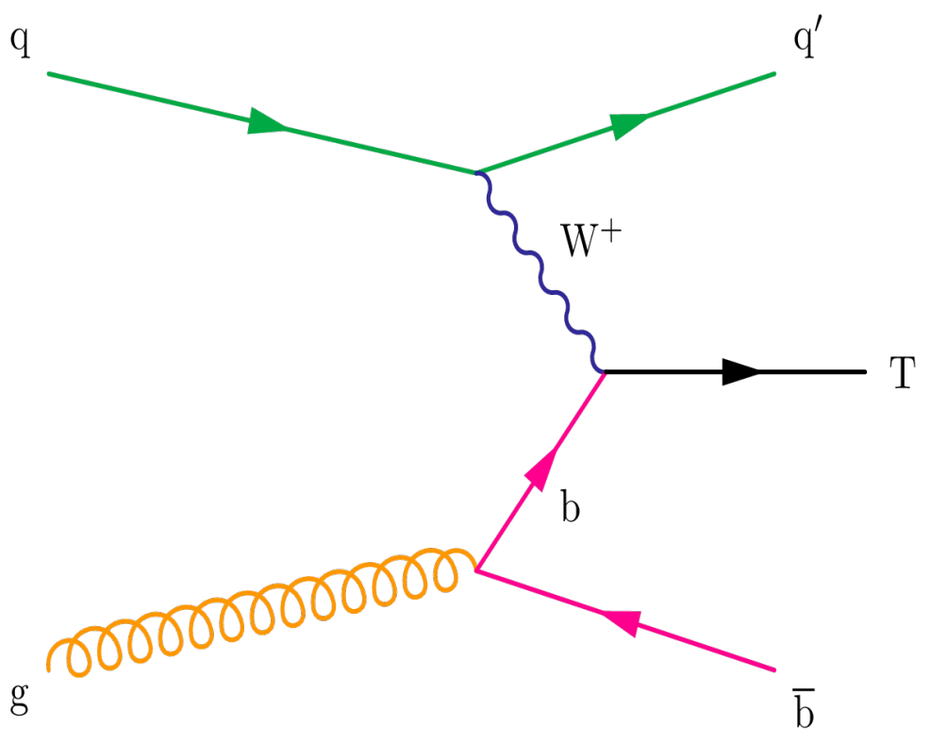



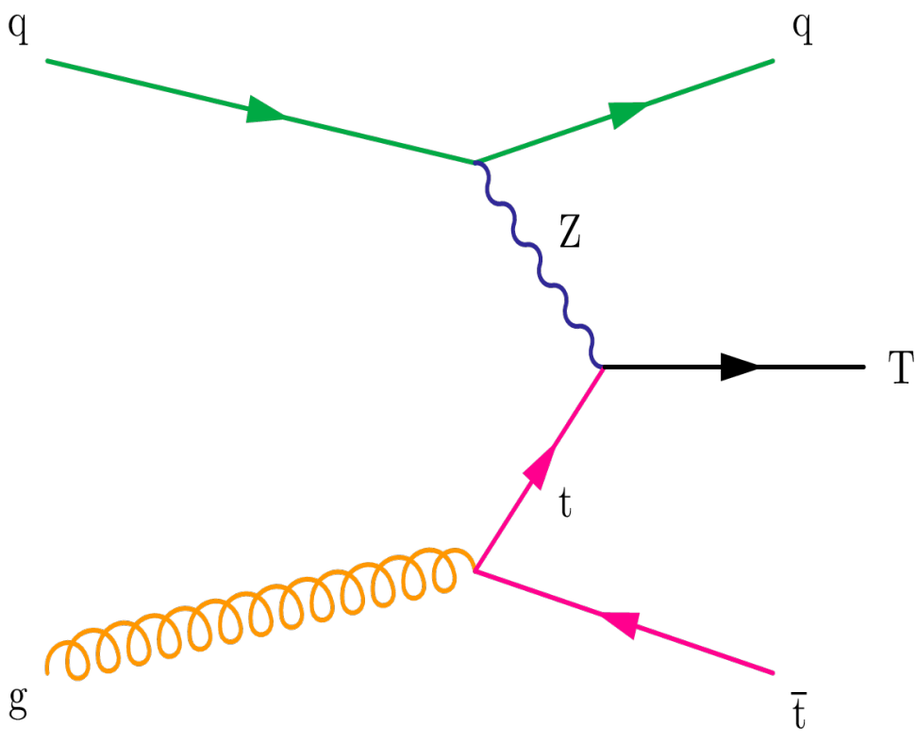

- Subjet b-tagging
- Boosted Event Shape Tagger (BEST)
  - Neural network approach: When boosting to 'correct' reference frame, jet constituents should be isotropic and show the N-prong structure



# *Search for vector-like T quark*

- Vector-like top quark partner T with charge 2/3
- Electroweek production (either charged current or neutral current)
- Hadronic final states




http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-18-003/index.html

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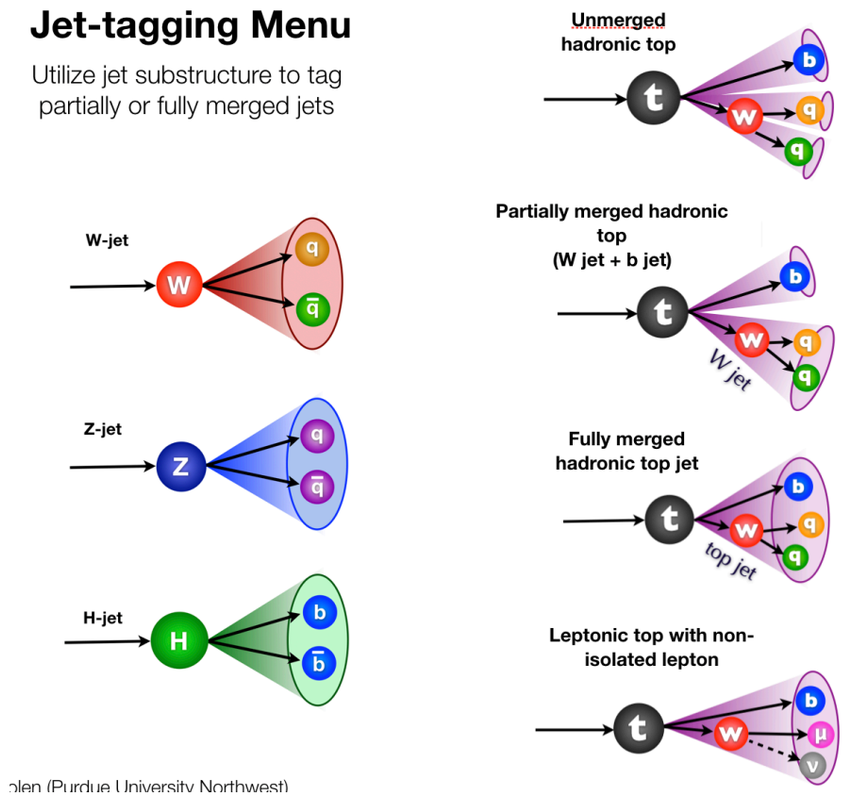
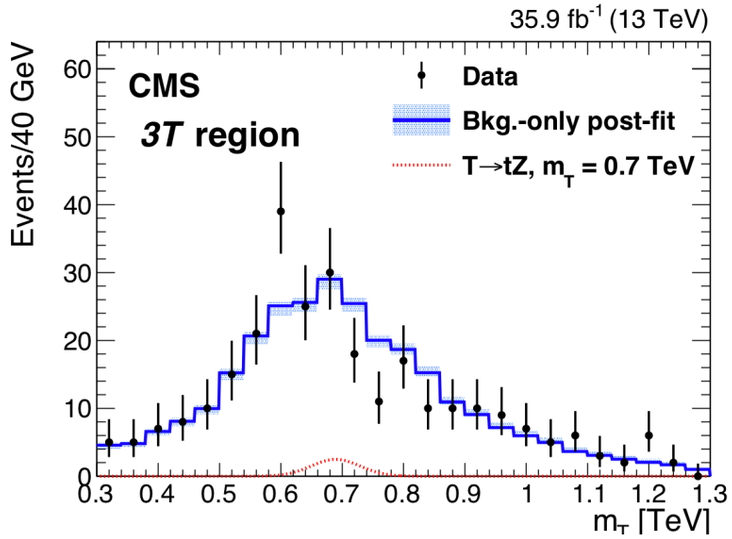
# *Search for vector-like T quark*

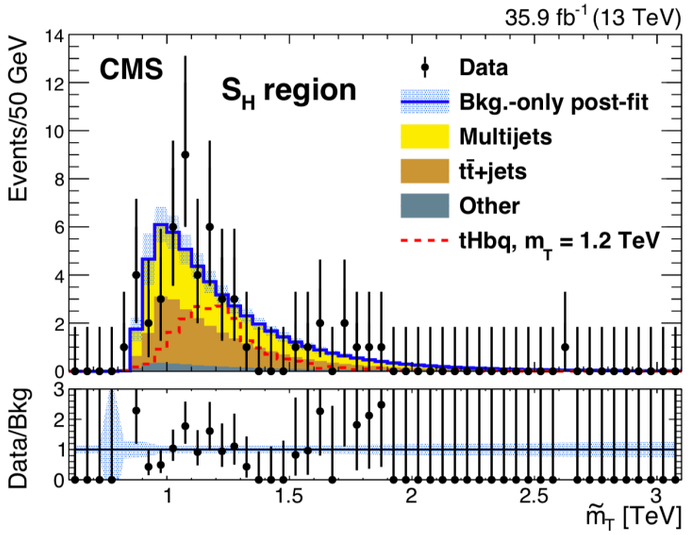
- T → tH or T → tZ
- All-hadronic channel → principal backgrounds QCD and ttbar
- <u>Low mass search</u> - resolved jets from decays of t,H,Z
  - Five jet final state
  - Chi-squared sorting algorithm used to associate jets with t/W/Z/H
  - Further signal discrimination using relative HT (majority of transverse momentum in the event should originate from t and H/Z candidates) and angular variables
- <u>High mass search</u> - merged jets from decays of t,H,Z
  - At least 1 t-tag and 1 H/Z tag

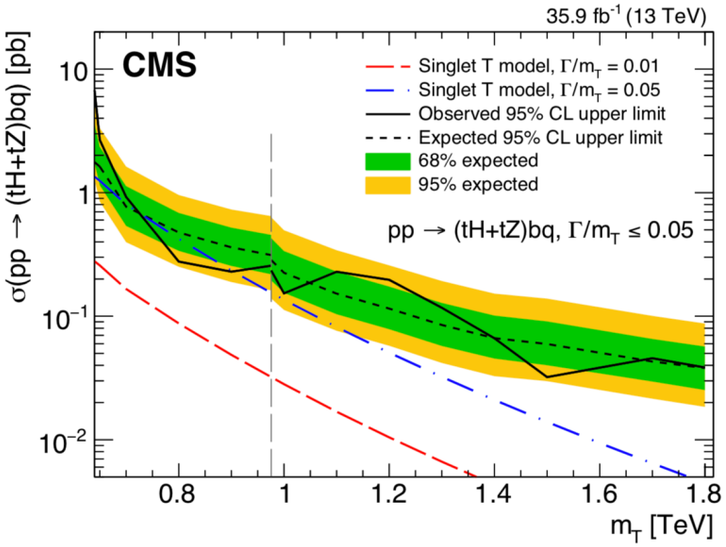


# *Search for vector-like T quark*

- Low mass search
  - Three signal regions based on b-tagging
    - 3 tight working point b-tagged jets, 3 medium working point b-tagged jets, 2 medium 1 loose working point b-tagged jets
- High mass search
  - Six mutually exclusive control regions used to predict the shape of the QCD background
- No significant excess above the SM found
  - Limits set for T-singlet model
  - Four fractional widths considered



# Search for TT in the fully hadronic state

- Search for pair produced vector-like quarks (optimized for TT but BB also so considered)
- Decay products of T are highly boosted → merged within one jet
- Two analyses
  - Cut-Based approach
    - targets T → bW
    - Utilize W-tagging and b-tagging
  - Neural Net Multiclassification approach
    - Broad search for TT or BB
    - Utilize Boosted Event Shape Tagger (BEST) to identify t, W, H, Z

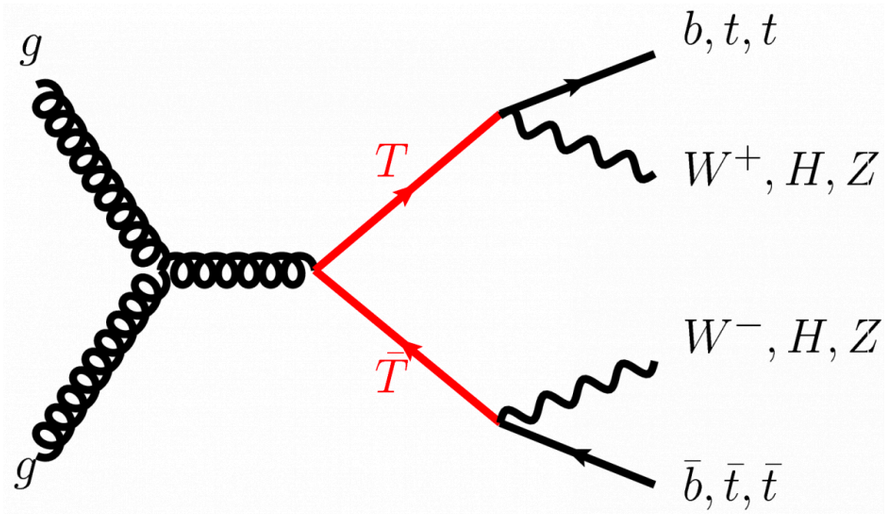



Image credit: ATLAS Collaboration

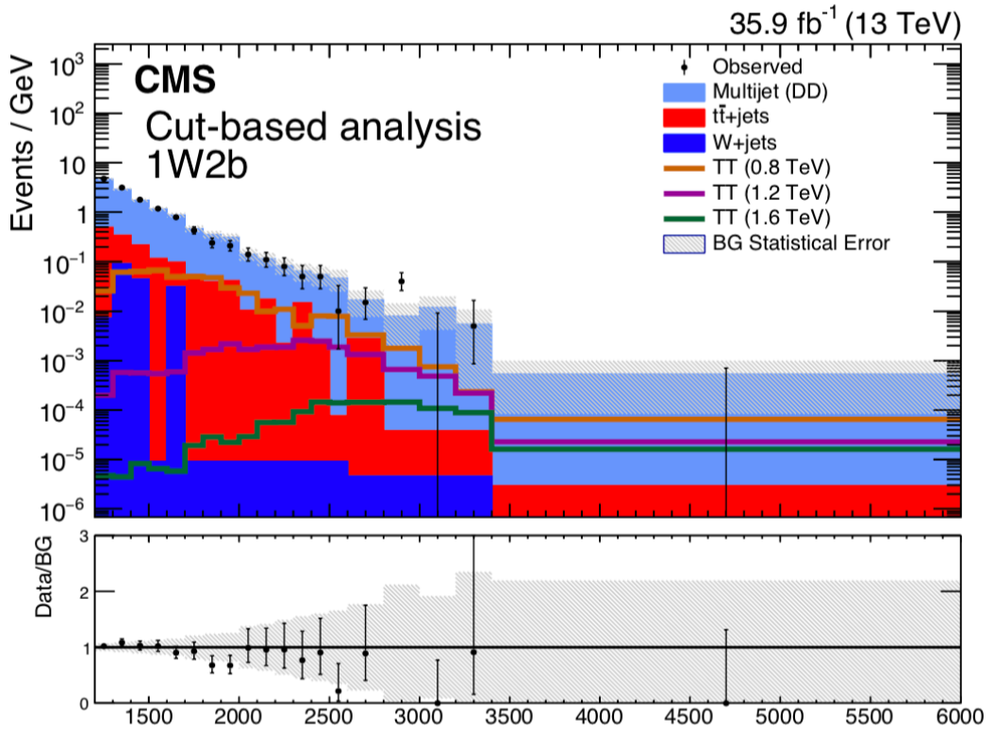
$T \to bW$ $B \to tW$
$T \to tZ$ $B \to bZ$
$T \to tH$ $B \to bH$

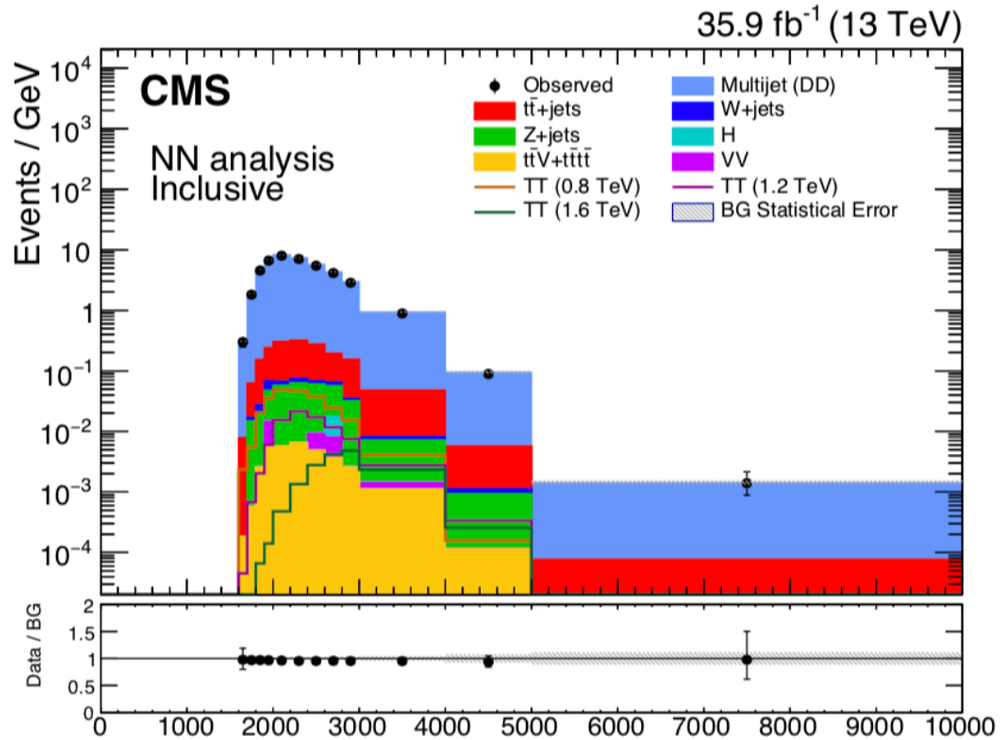
http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-18-005/index.html

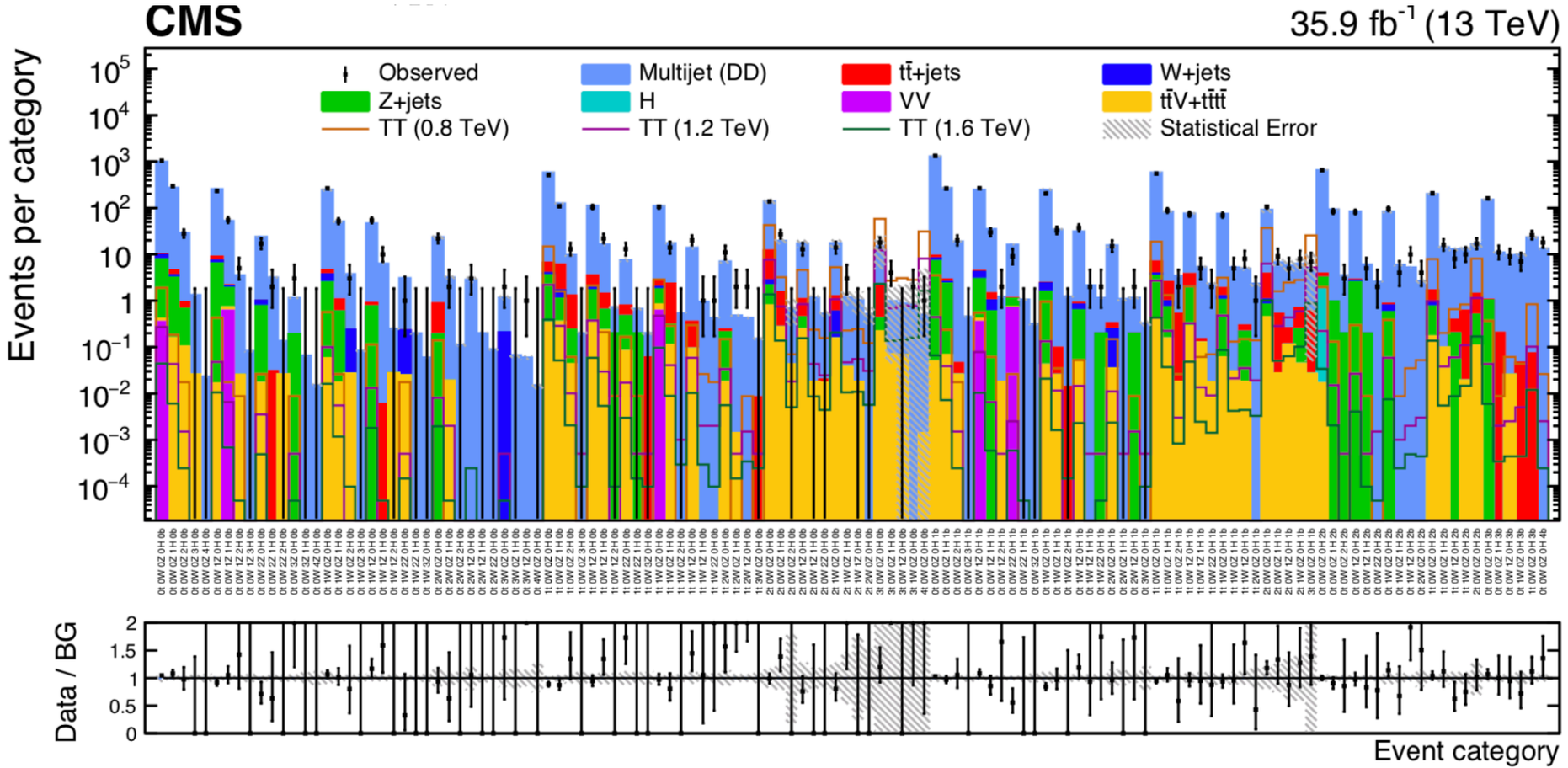
# *Search for TT in the fully hadronic state*

- Cut-based analysis
  - Require two Anti-KT R=0.8 jets and two Anti-KT R=04 jets
  - Two possible combinations of b and W jet. Assignment of jets to T candidate is made such that  T candidate mass difference is minimized.
  - Categorize based on the number of W-tags and b-tags - 9 regions
- Neural Net analysis
  - BEST algorithm used to classify jets into 6 categories: t, b, W, Z, H, light
  - Require exactly 4 jets
  - Categorize based on number of classified jets: 126 independent signal regions

# Search for TT in the fully hadronic state

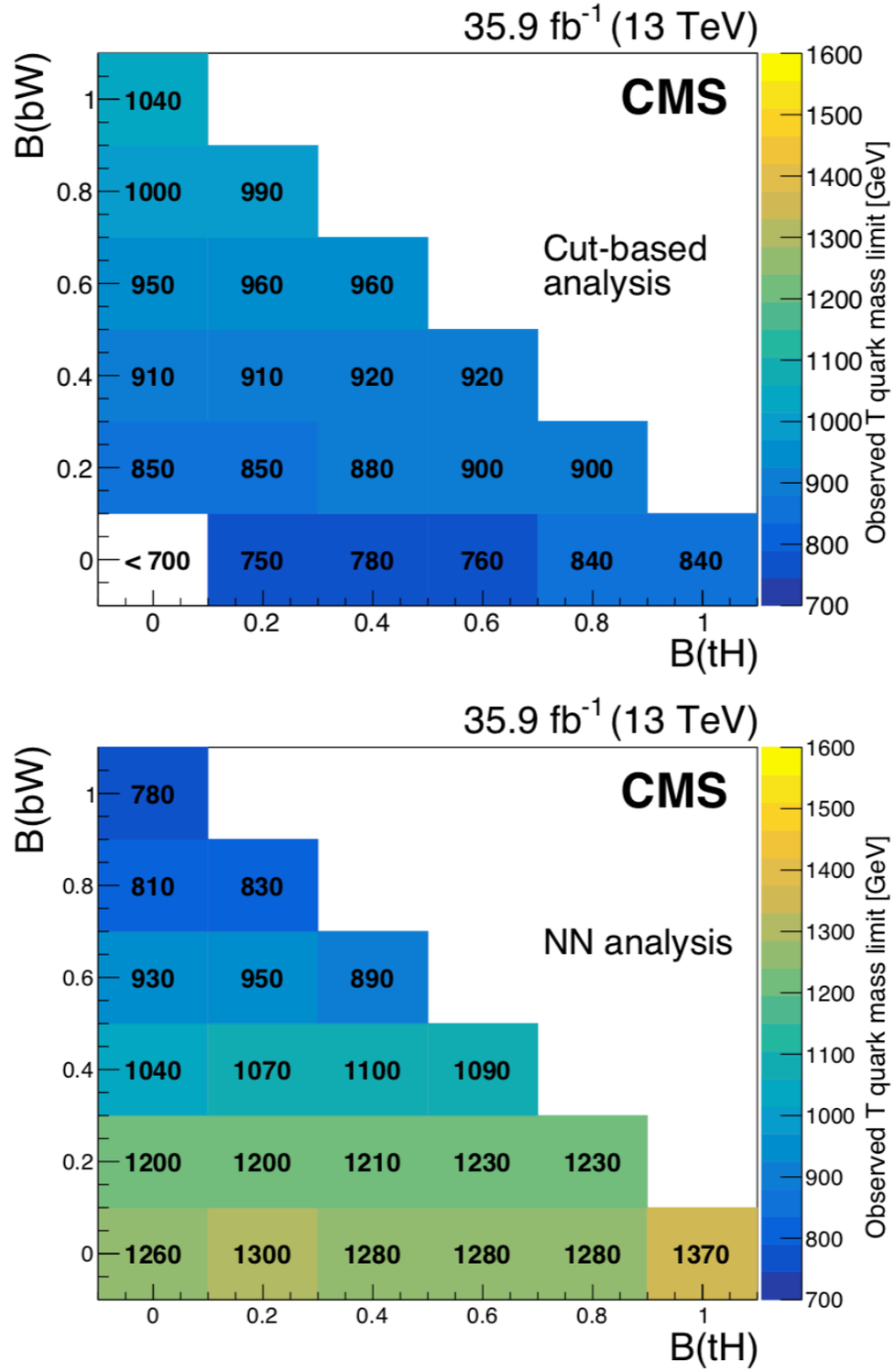


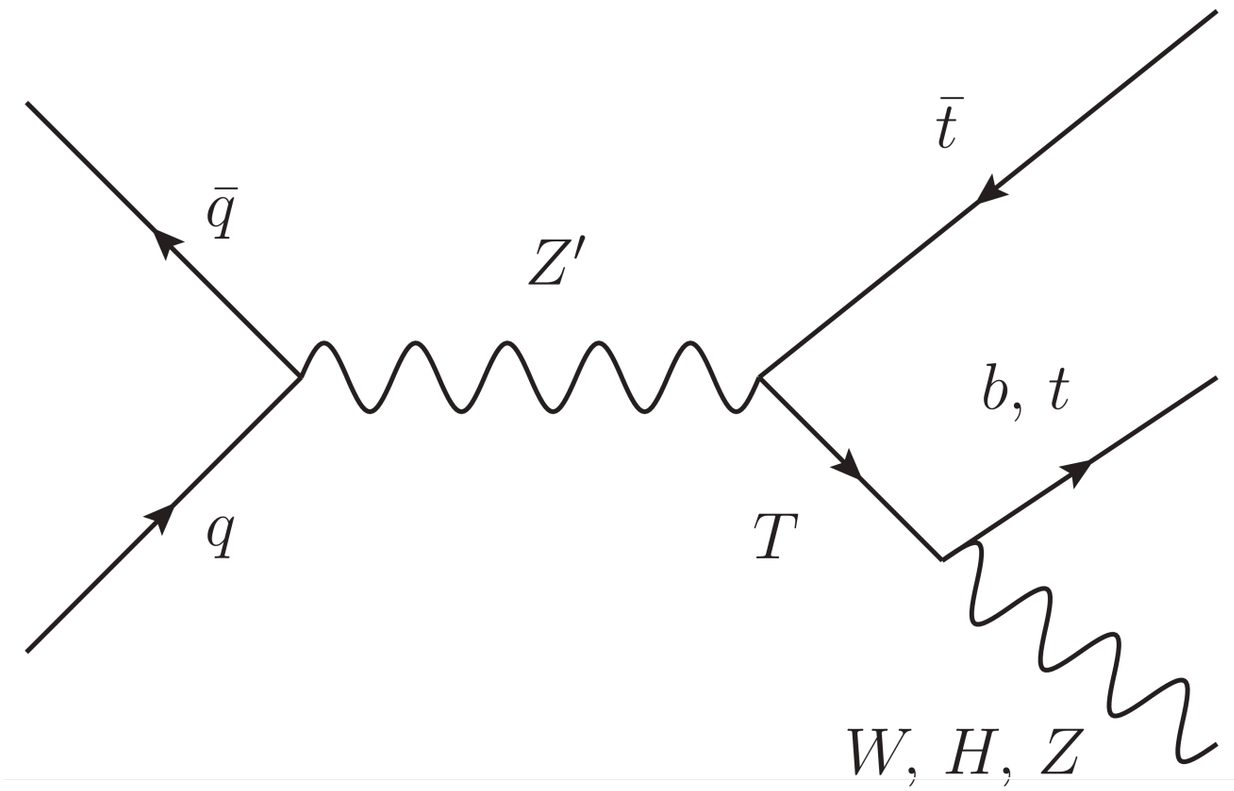
# *Search for TT in the fully hadronic state*

- No significant deviation found
- Limits set



# Search for resonant tT production

- Heavy spin-1 resonance Z'
- Decaying to a top quark and a vector-like top quark partner T
- Benchmark model - Kaluza-Klein Gluon

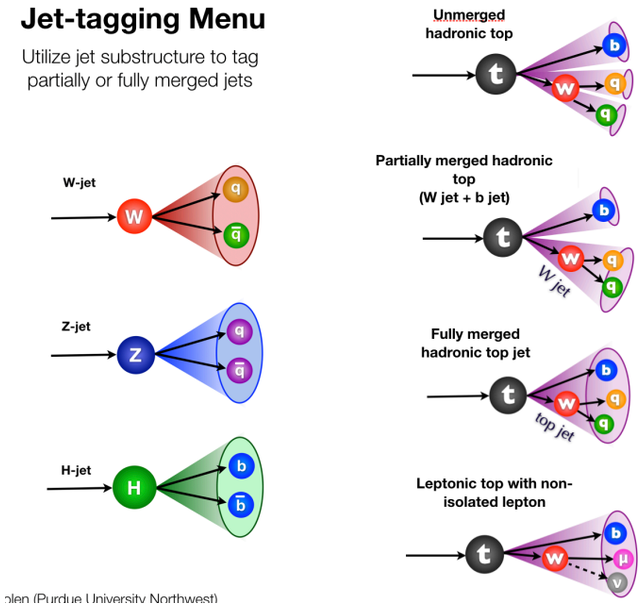



http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-17-015/index.html

Eur. Phys. J. C 79 (2019) 208

# Search for resonant tT production

- Optimized for T → tZ or T → tH
- Two principal decay channels:
  - Z` → tT → tZt
  - Z` → tT → tHt




- Require one top to decay leptonically and other top hadronically
  - Search channel: lepton+jets
  - Leptonic top - non-isolated lepton
  - Hadronic top may be merged within a single jet
- H or Z is typically produced with large momentum → collimated decay products → utilize jet substructure

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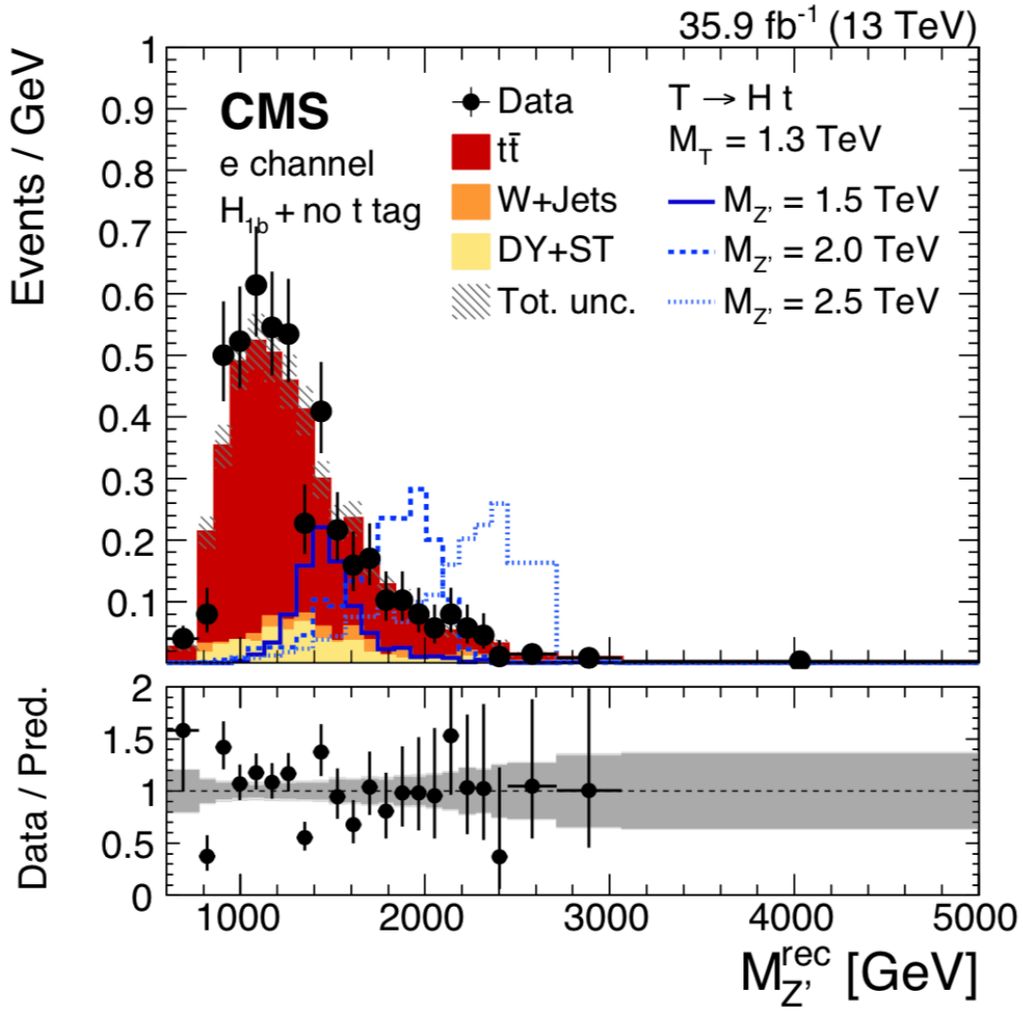
# Search for resonant tT production

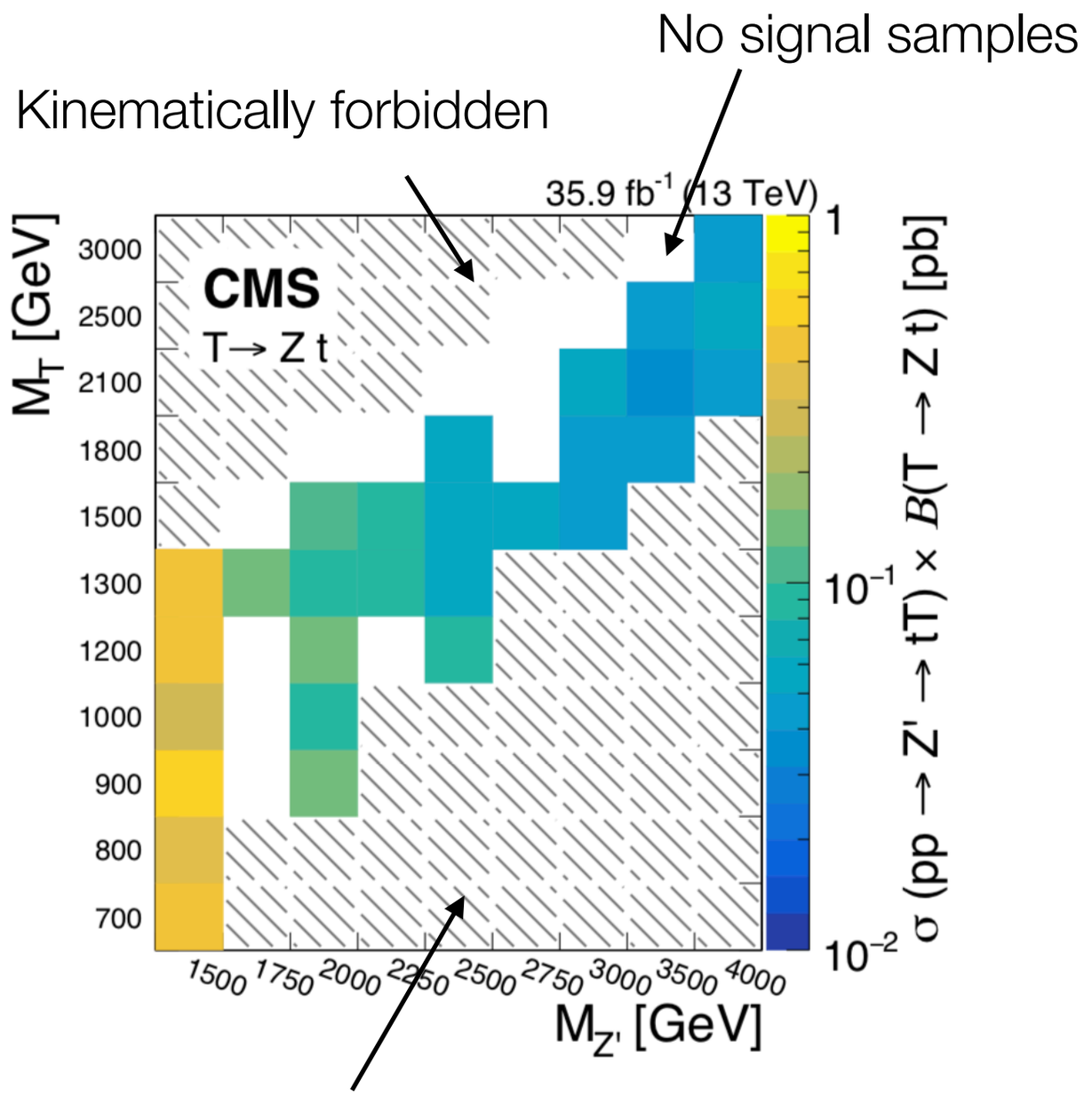
- Categorize events using jet substructure and subjet b-tagging
- Search for an excess in the reconstructed Z` mass distribution

$H_{2b}$ tag + t tag
$H_{2b}$ tag + no t tag
$H_{1b}$ tag + t tag
$H_{1b}$ tag + no t tag
Z/W tag + t tag
Z/W tag + no t tag



# Search for resonant tT production

- No significant excess observed
- Observed limits depends on mass of Z', mass of T, and branching ratio




Suppressed by the preferred Z → TT mode

# Conclusion

- Broad search program at CMS for heavy BSM particles decaying to third generation quarks
- Motivated models
- No significant excess found in 2016 data
  - Analysis of much more data to come!

**Vector-like Quarks**

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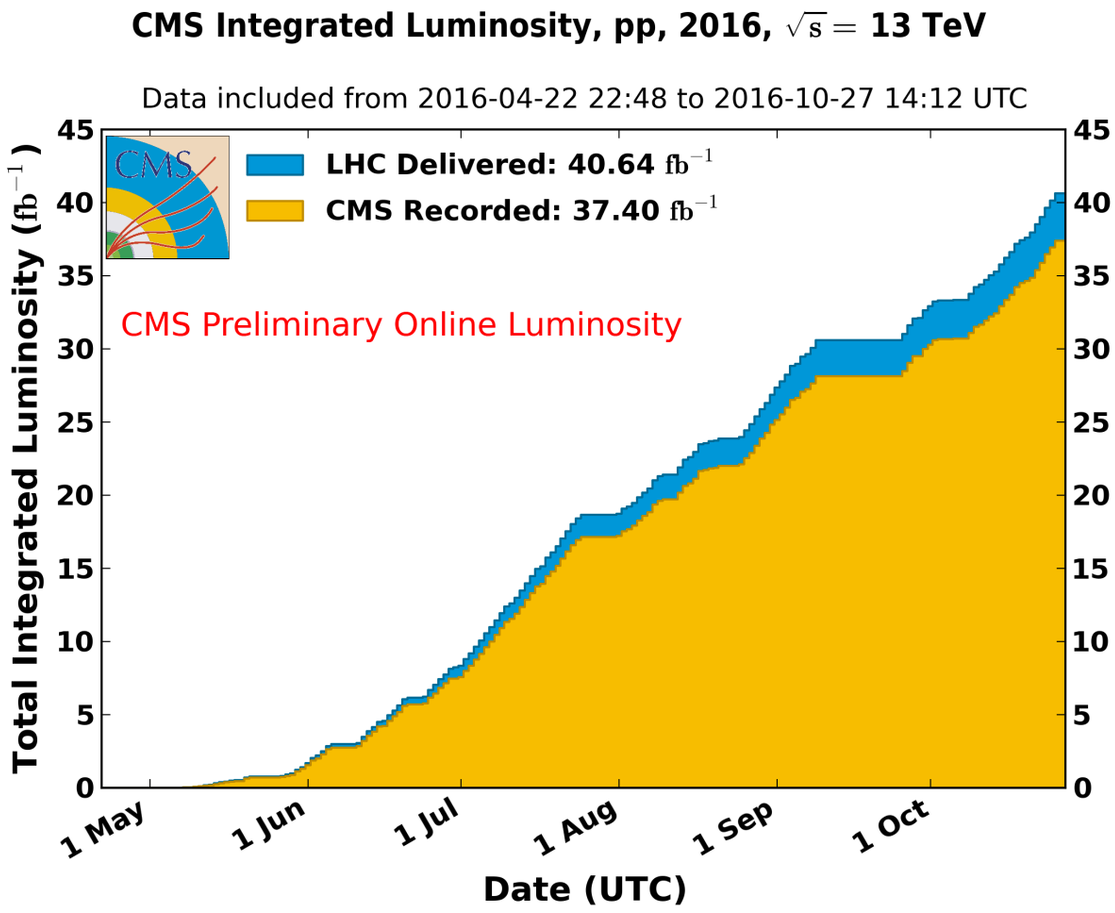
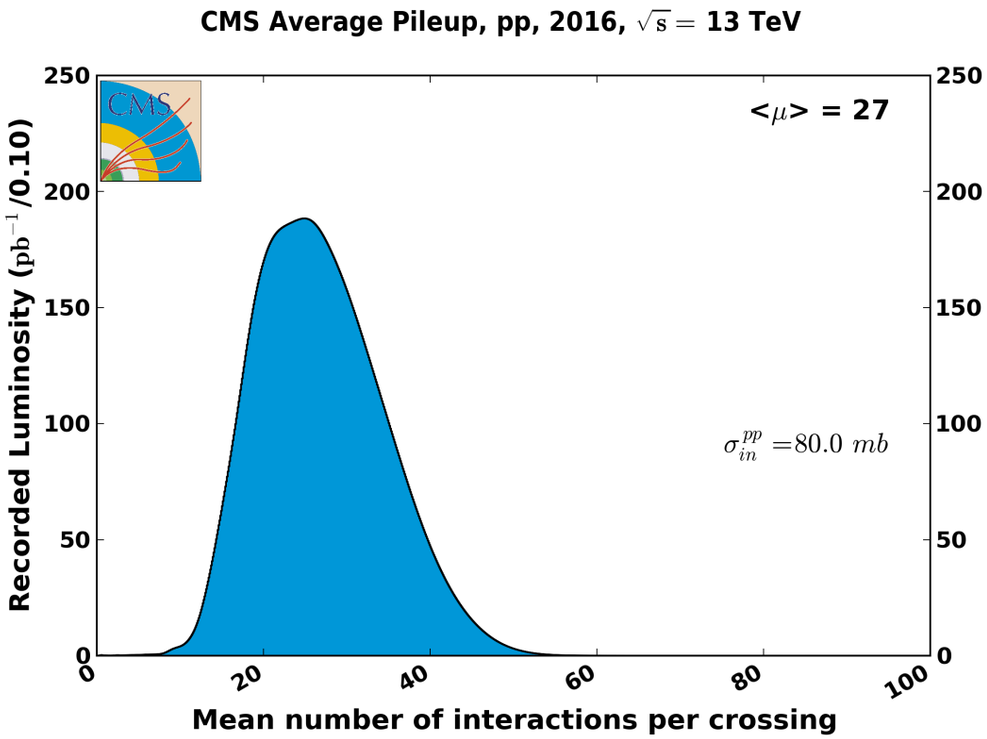
# *Additional Slides*

# CMS Data 2016

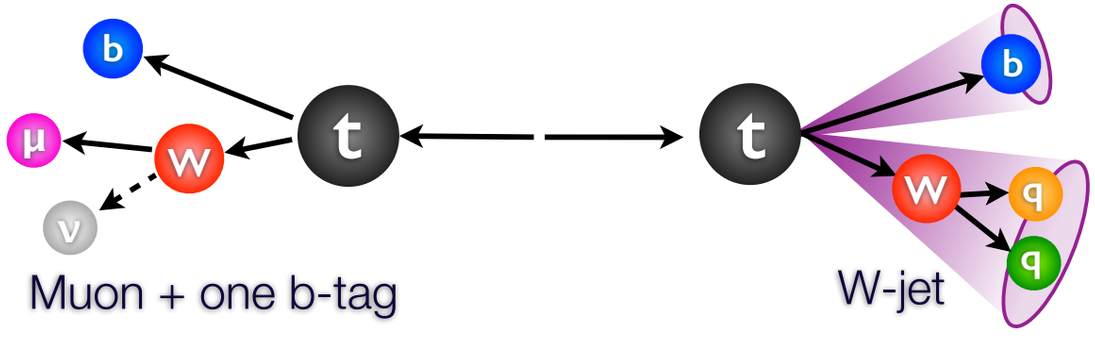
- $\sqrt{s}$ = 13 TeV
- 35.9 fb$^{-1}$
- Average pileup = 27

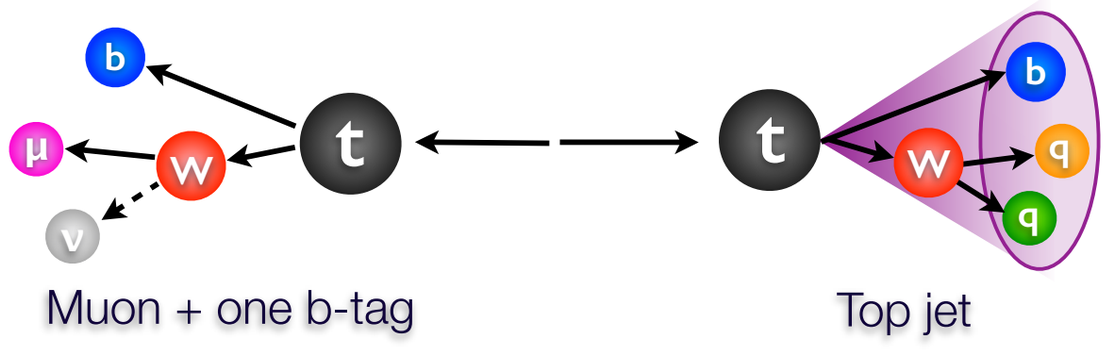


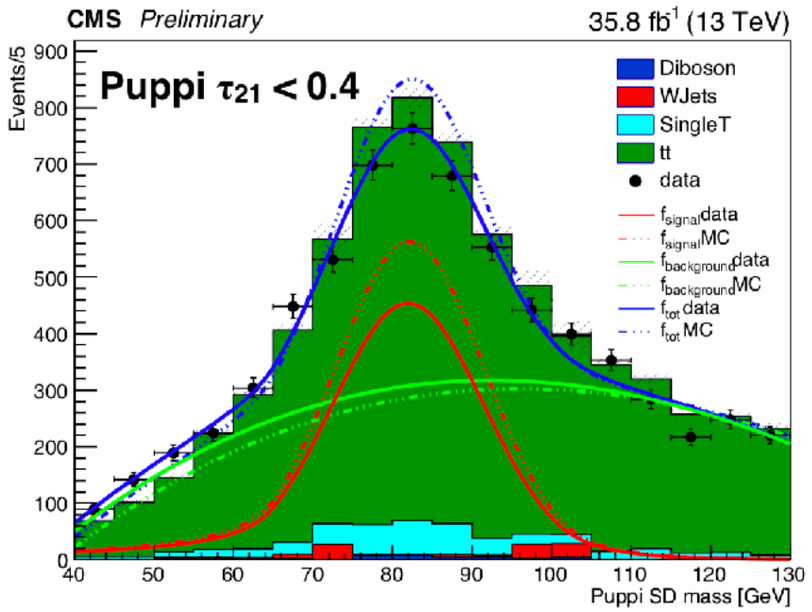
# Top and W jet validation in data

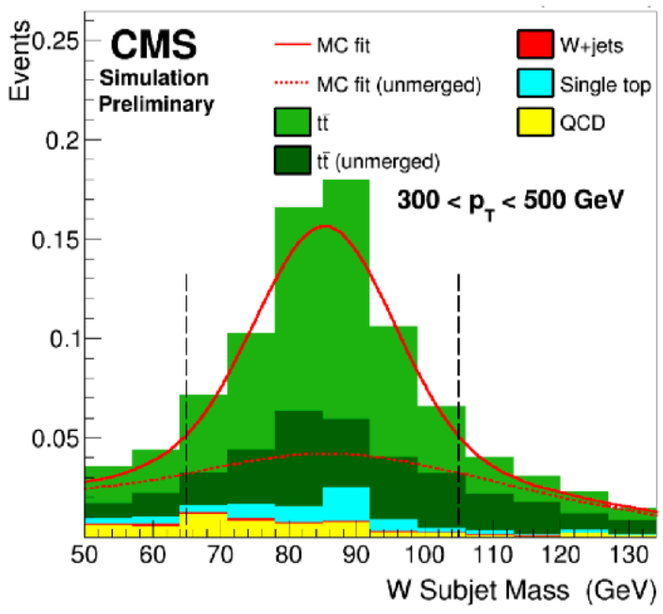
- Semileptonic ttbar selection → very pure sample of boosted Ws

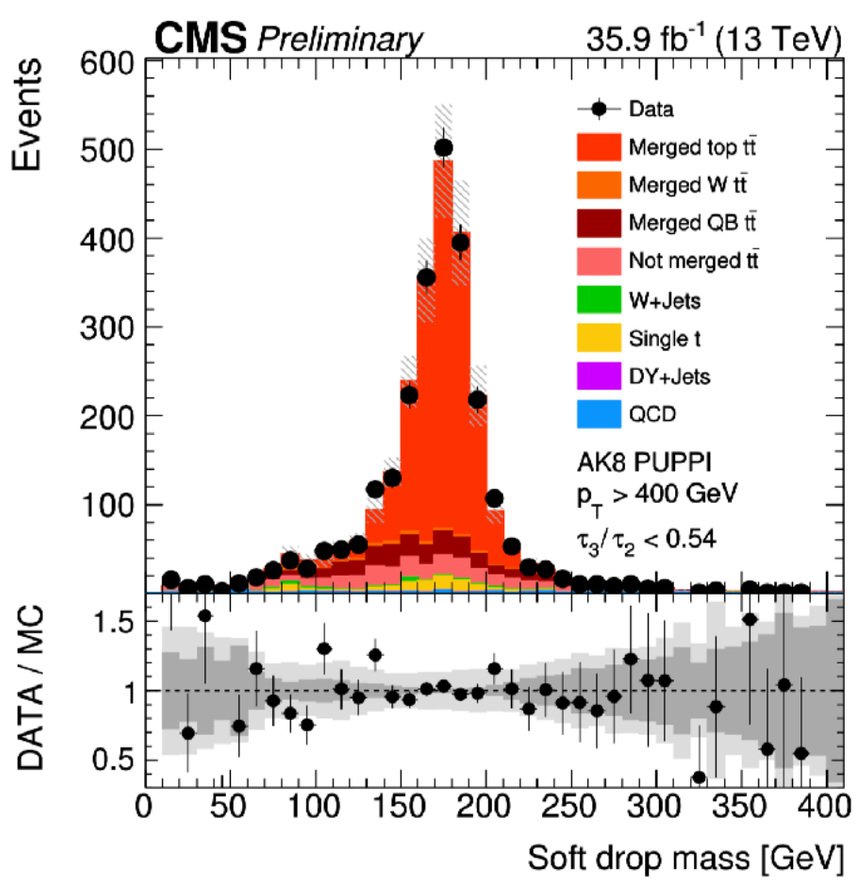



- Data-MC scale factors measured

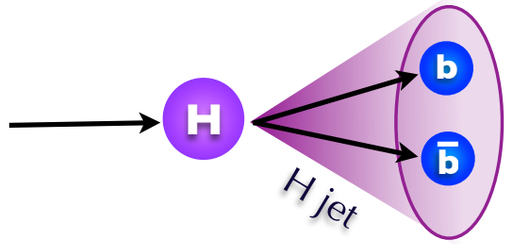



CMS DP 17/026

# Double b-tagged H-jet



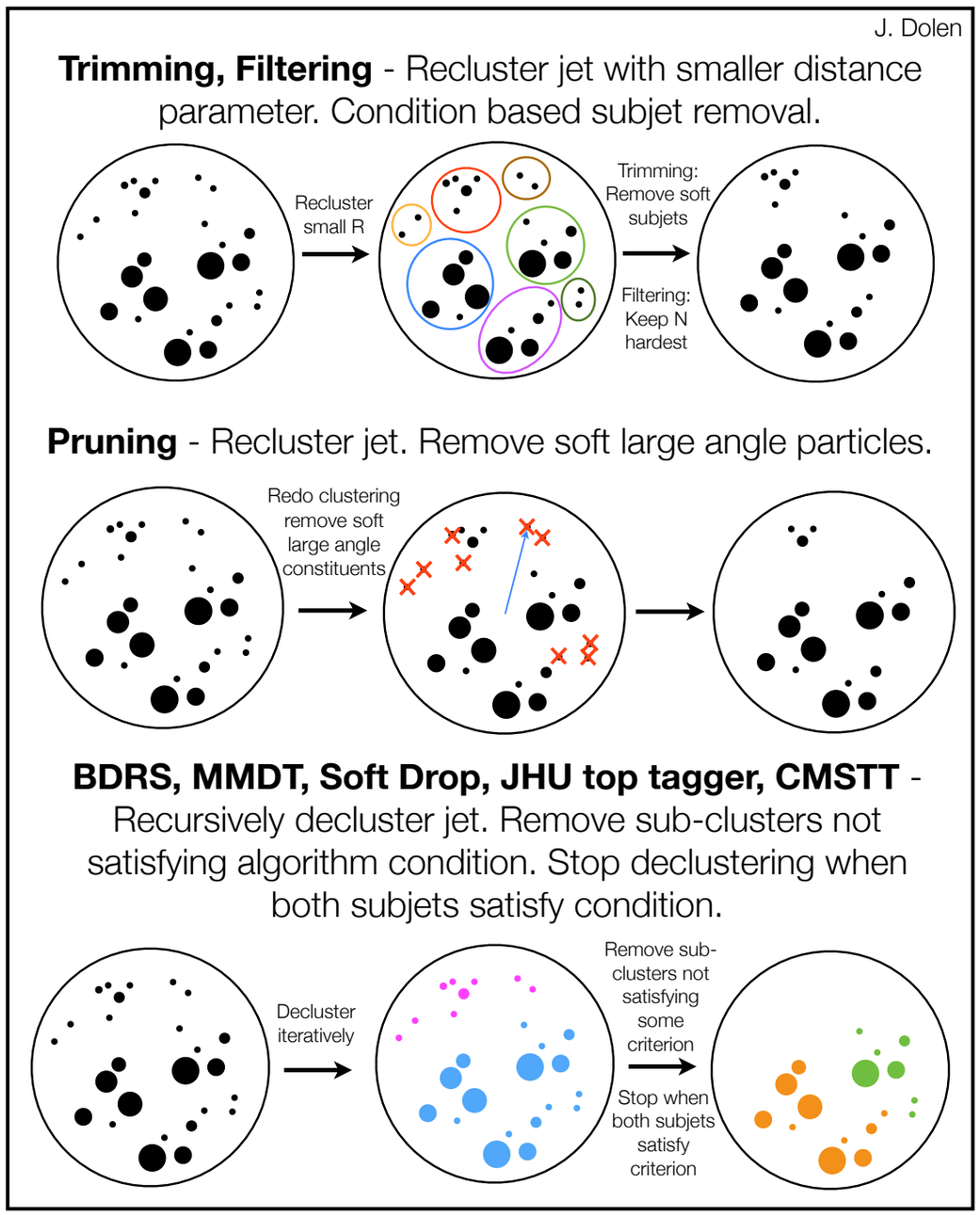


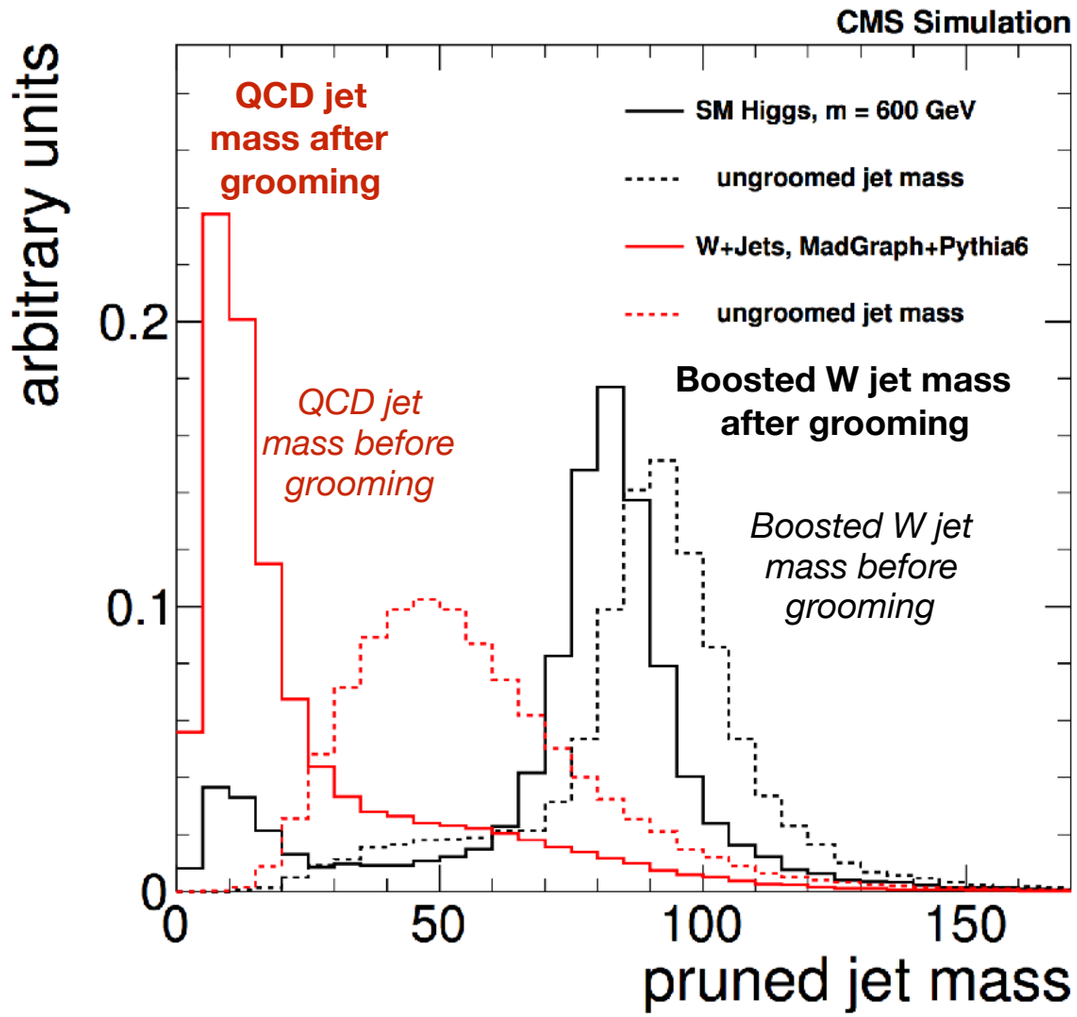


CMS DP 2017/032

# Jet grooming

## Algorithmic jet substructure techniques designed to remove isolated soft radiation in jets (contamination from ISR, UE, pileup)




CMS HIG-13-008
H → WW → lvqq

Reduces jet mass dependence on pileup

Reduces measured QCD jet mass (improves discrimination)

Improved jet mass resolution for boosted heavy object