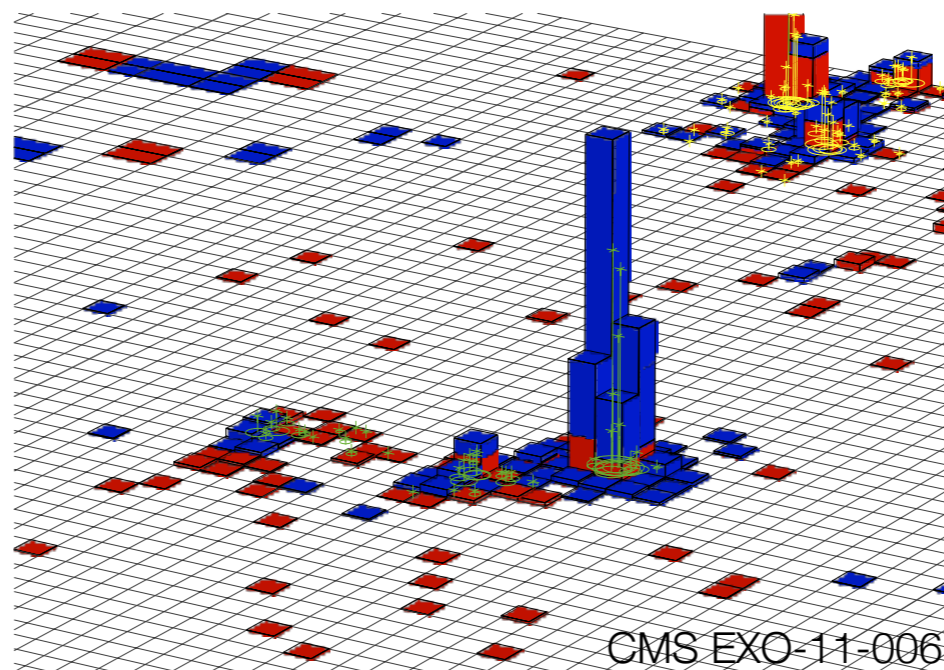


Searches for heavy BSM particles coupling to third generation quarks at CMS



James Dolen
Purdue University Northwest

Phenomenology 2020 Symposium - May 5th, 2020

“Heavy BSM particles coupling to third generation quarks”

Signatures which fall into this category:

Vector-like Quarks

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

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

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

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

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

Resonances

Heavy resonance \rightarrow standard model
(ex. $Z' \rightarrow tt$, $W' \rightarrow tb$)

Heavy resonance \rightarrow vector-like quarks
(ex. $Z' \rightarrow tT$, $Z' \rightarrow TT$, $W' \rightarrow bT$)

Excited quark
(ex. $b^* \rightarrow tW$, $t^* \rightarrow tg$)

Leptoquark
(ex. $LQ \rightarrow t\tau$, $LQ \rightarrow t\mu$)

“Heavy BSM particles coupling to third generation quarks”

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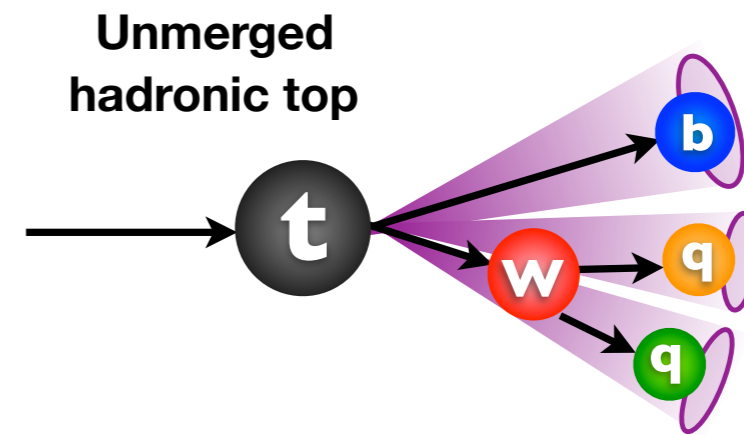
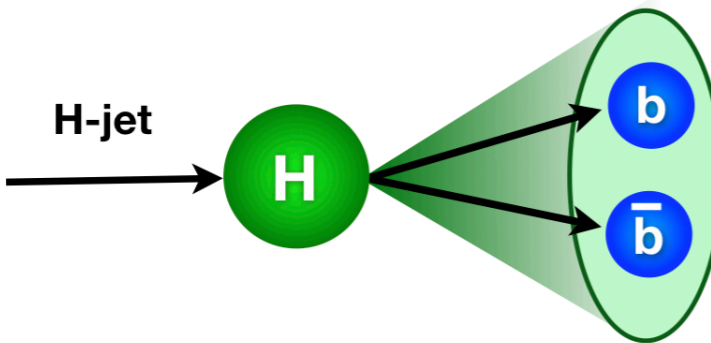
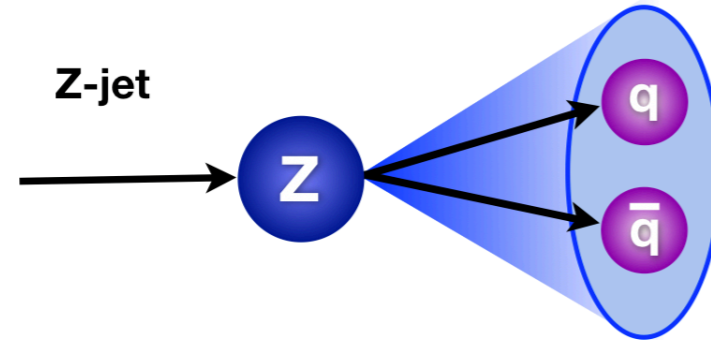
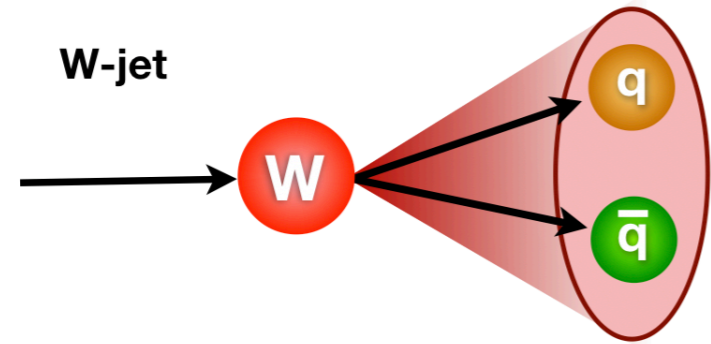
Leptoquark

(ex. $LQ \rightarrow t\tau$, $LQ \rightarrow t\mu$)

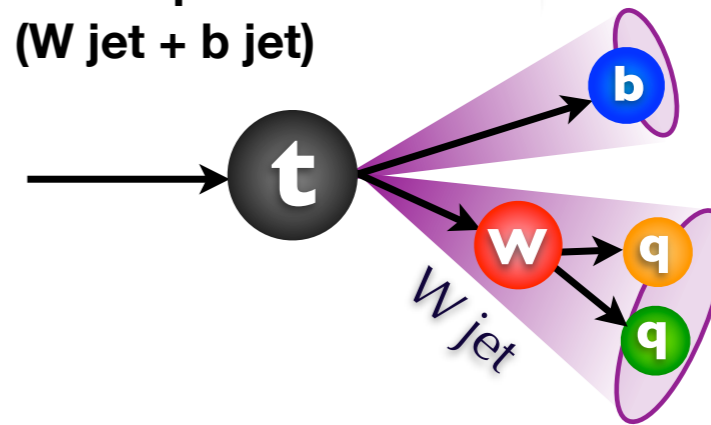
Today: Highlight three of the most recent searches using 2016 CMS data

Jet-tagging Menu

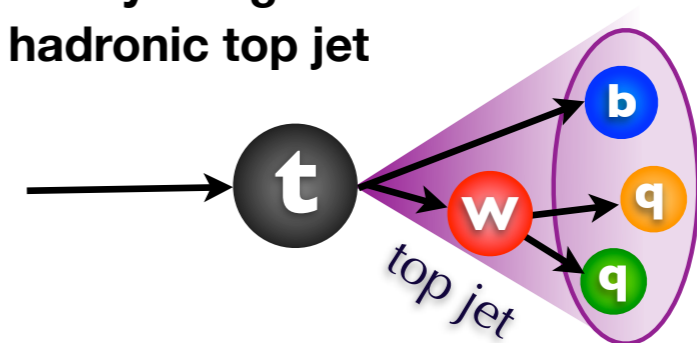
Utilize jet substructure to tag partially or fully merged jets



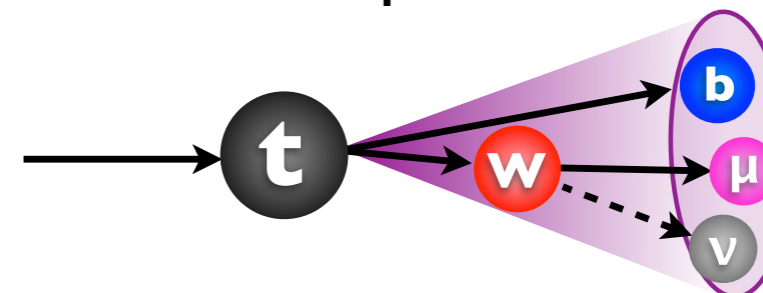
Partially merged hadronic top
(W jet + b jet)



Fully merged hadronic top jet

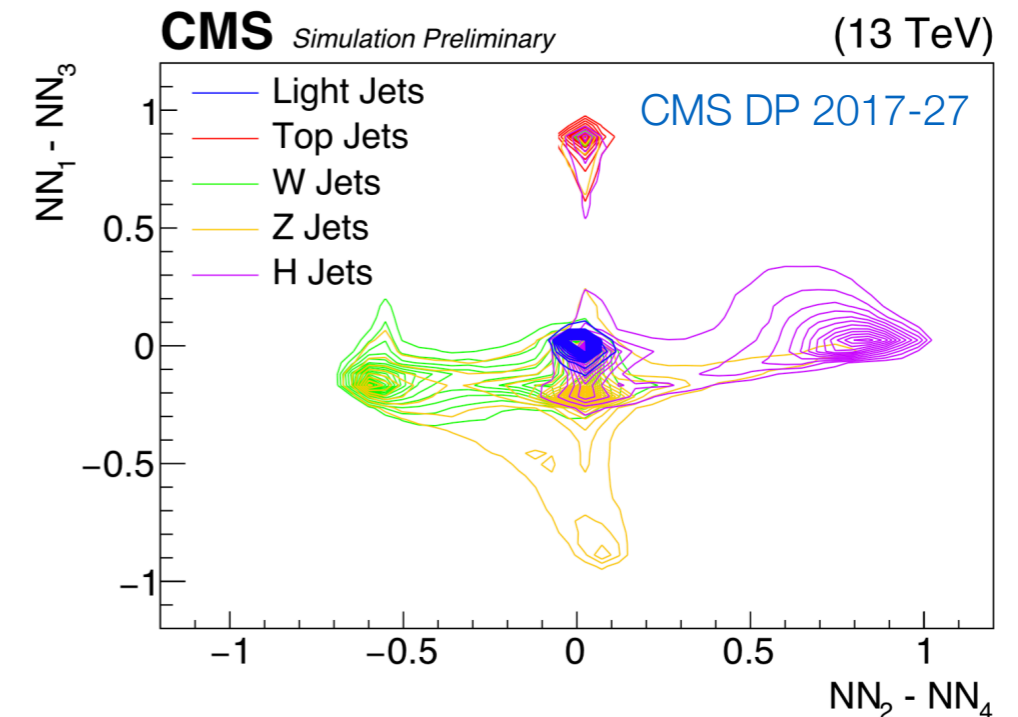
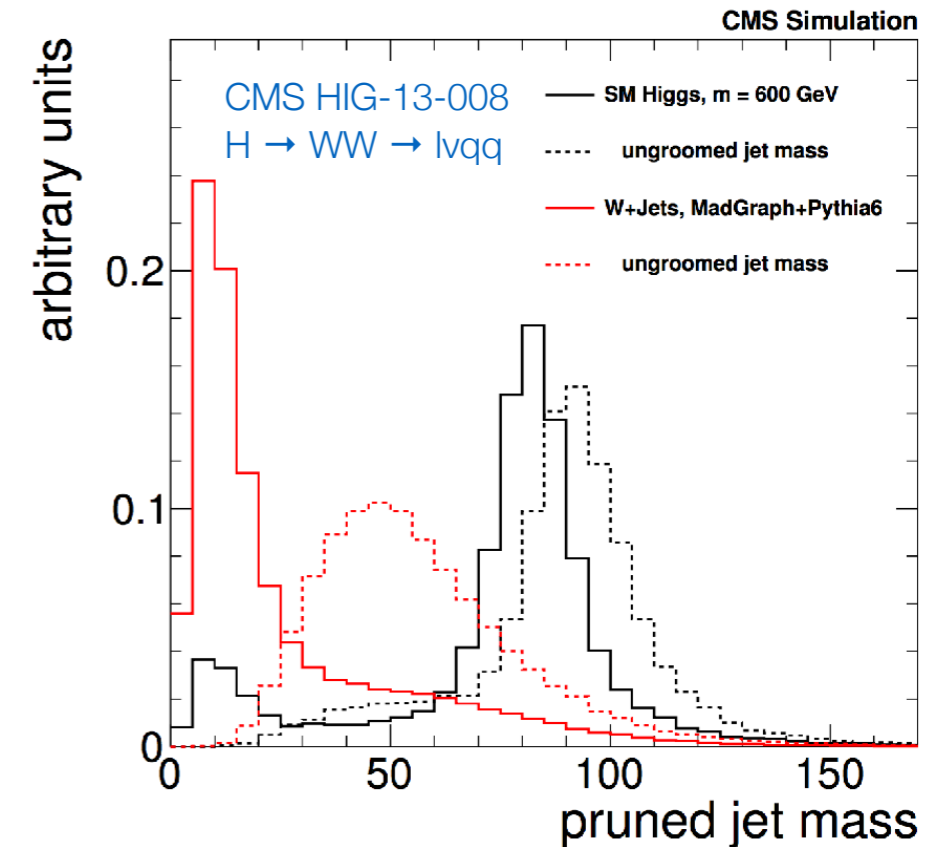
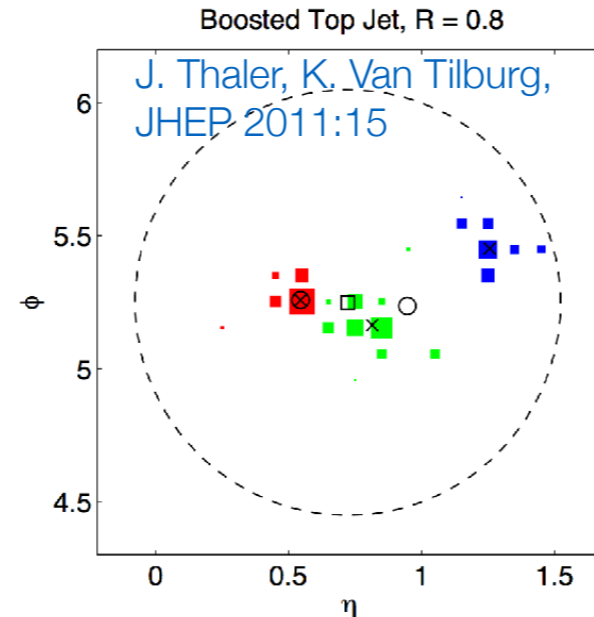


Leptonic top with non-isolated lepton



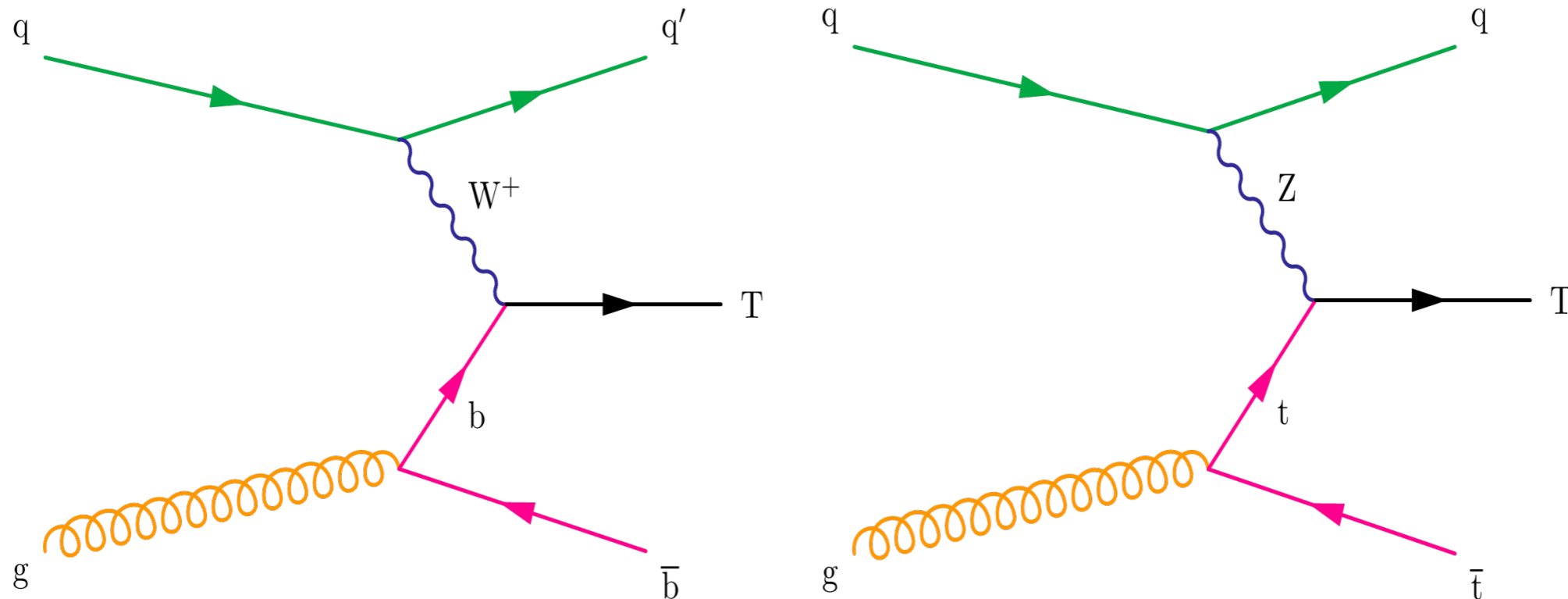
Jet Tagging Tools

- 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. τ_3/τ_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 $2/3$
- Electroweak 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>

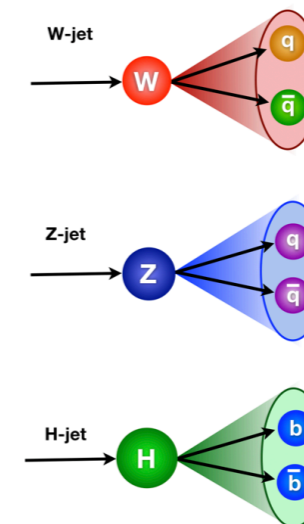
JHEP 01 (2020) 036

Search for vector-like T quark

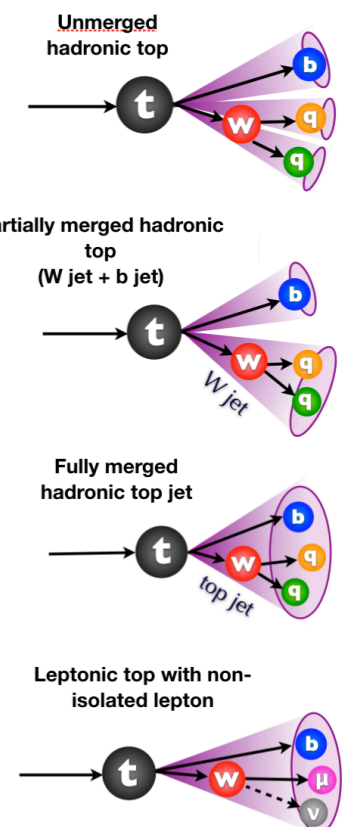
- $T \rightarrow tH$ or $T \rightarrow tZ$
- All-hadronic channel \rightarrow principal backgrounds QCD and $t\bar{t}$
- Low mass search - resolved jets from decays of t, H, Z
 - Five jet final state
 - Chi-squared sorting algorithm used to associate jets with $t/W/Z/H$
 - Further signal discrimination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

Jet-tagging Menu

Utilize jet substructure to tag partially or fully merged jets

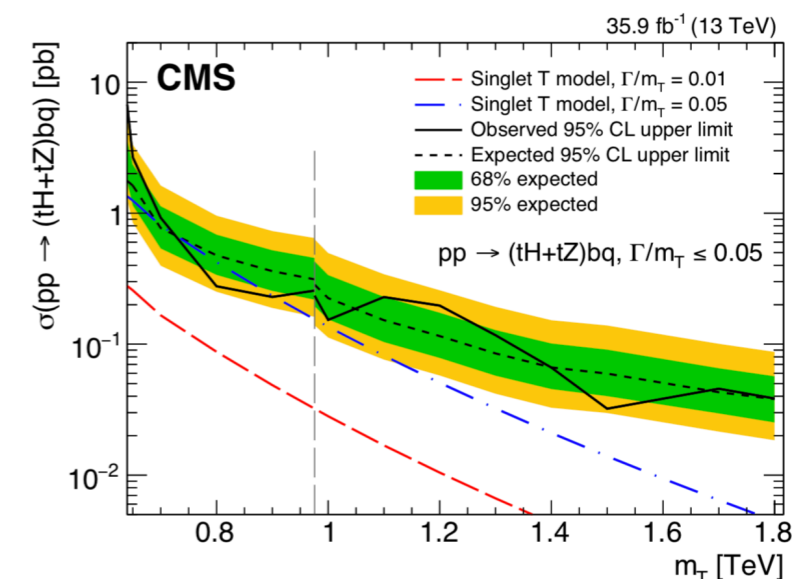
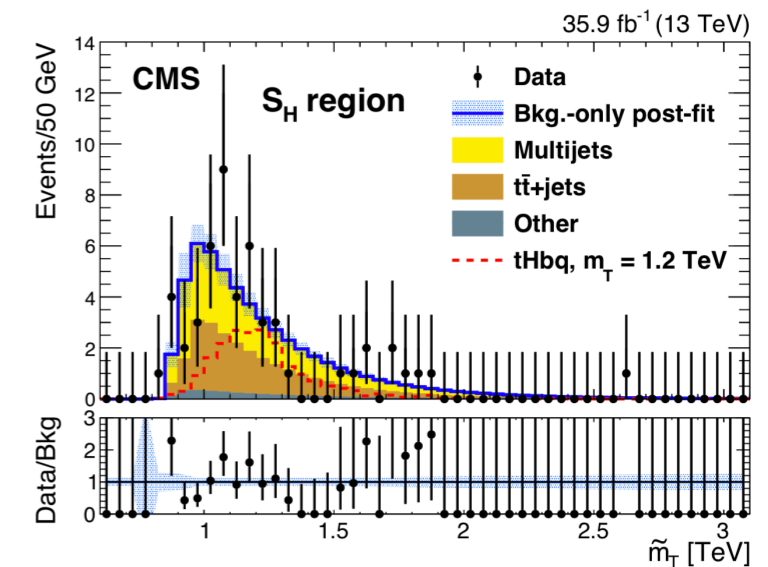
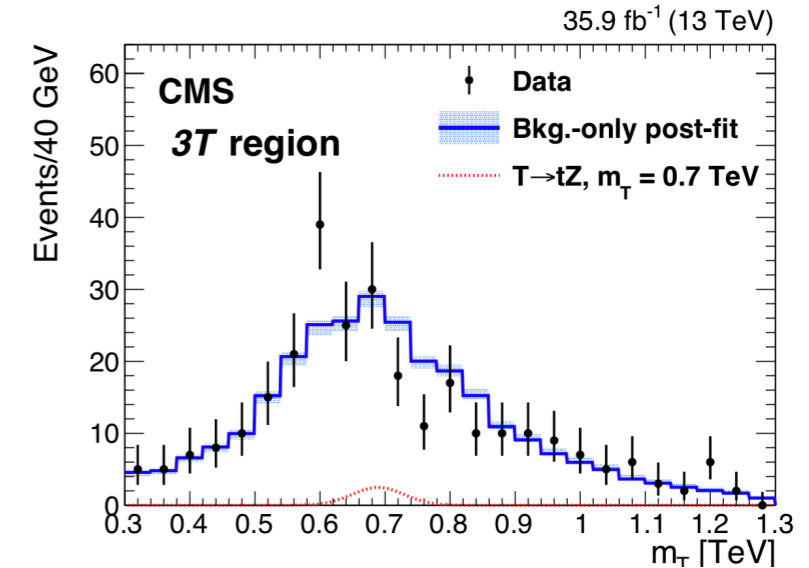


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Search for vector-like T quark

- 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 \rightarrow merged within one jet
- Two analyses

- Cut-Based approach

- targets $T \rightarrow bW$
- 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

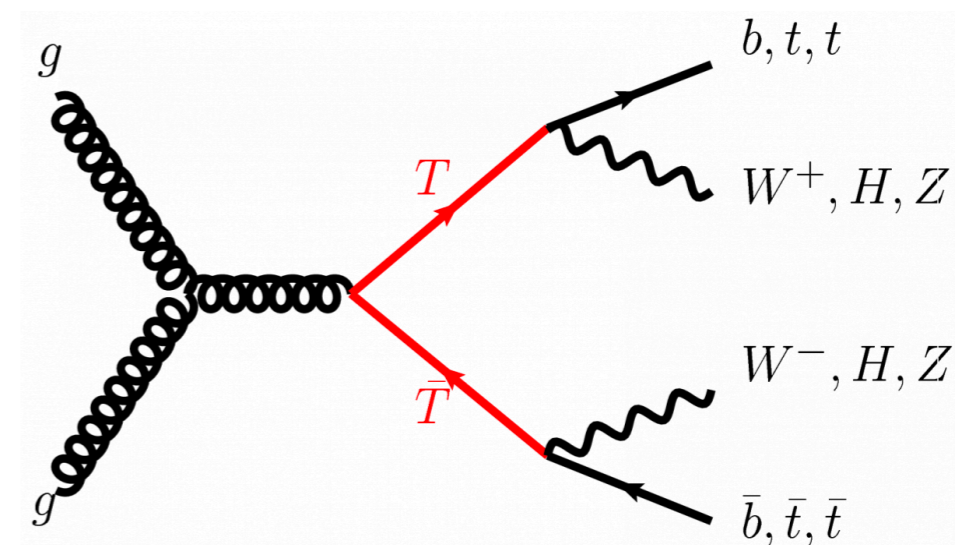


Image credit: ATLAS Collaboration

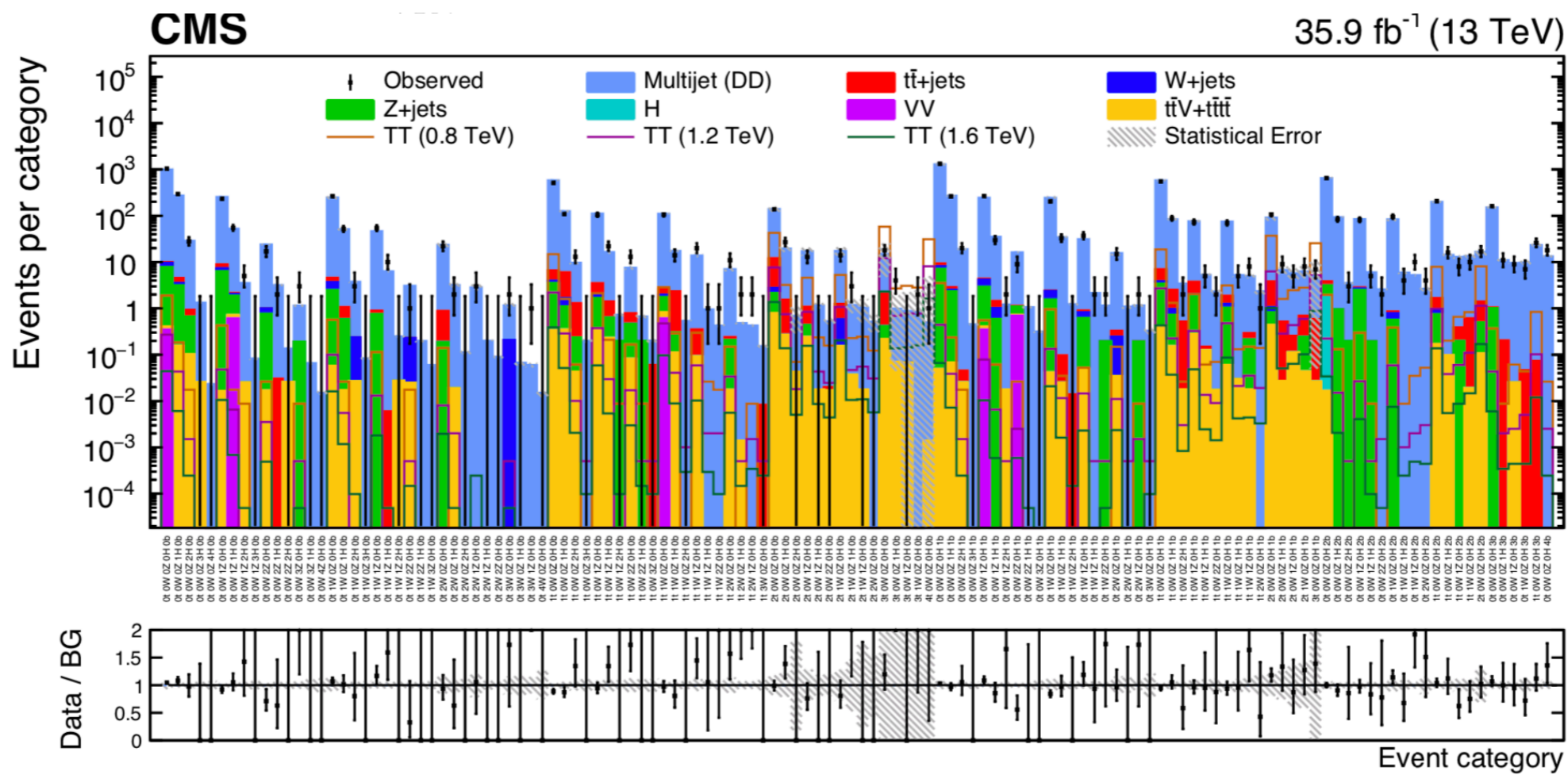
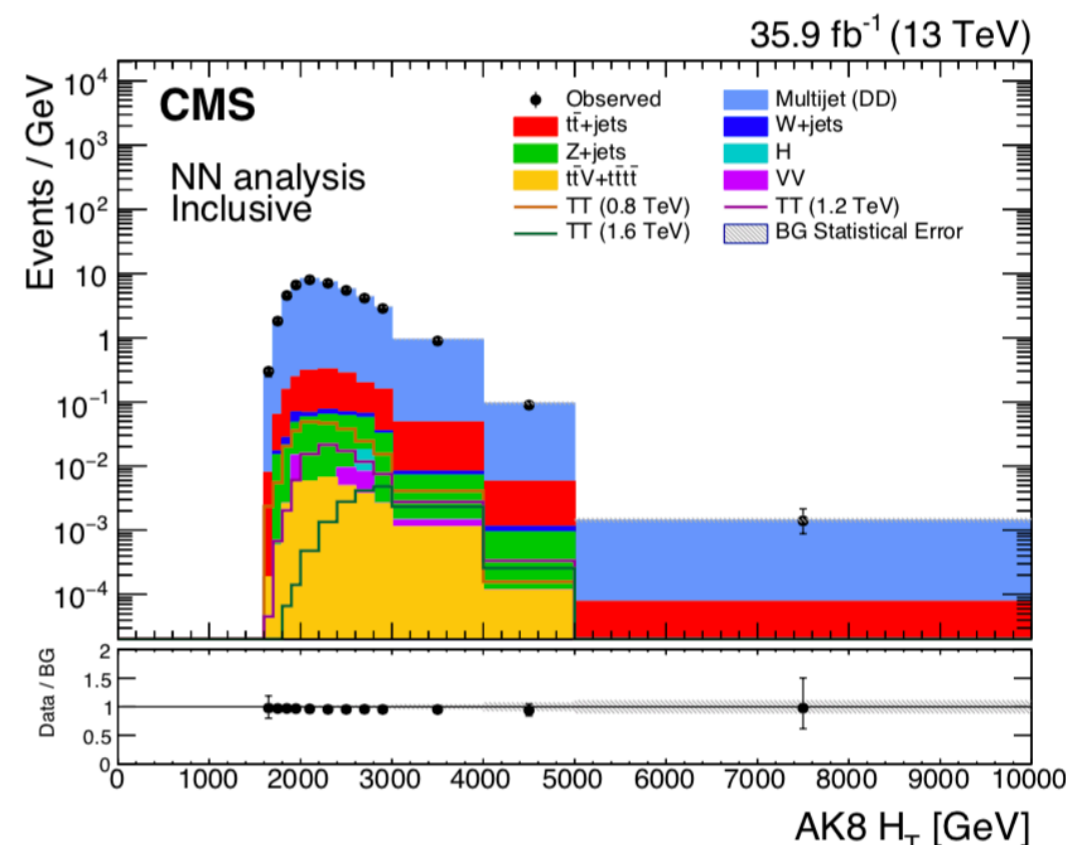
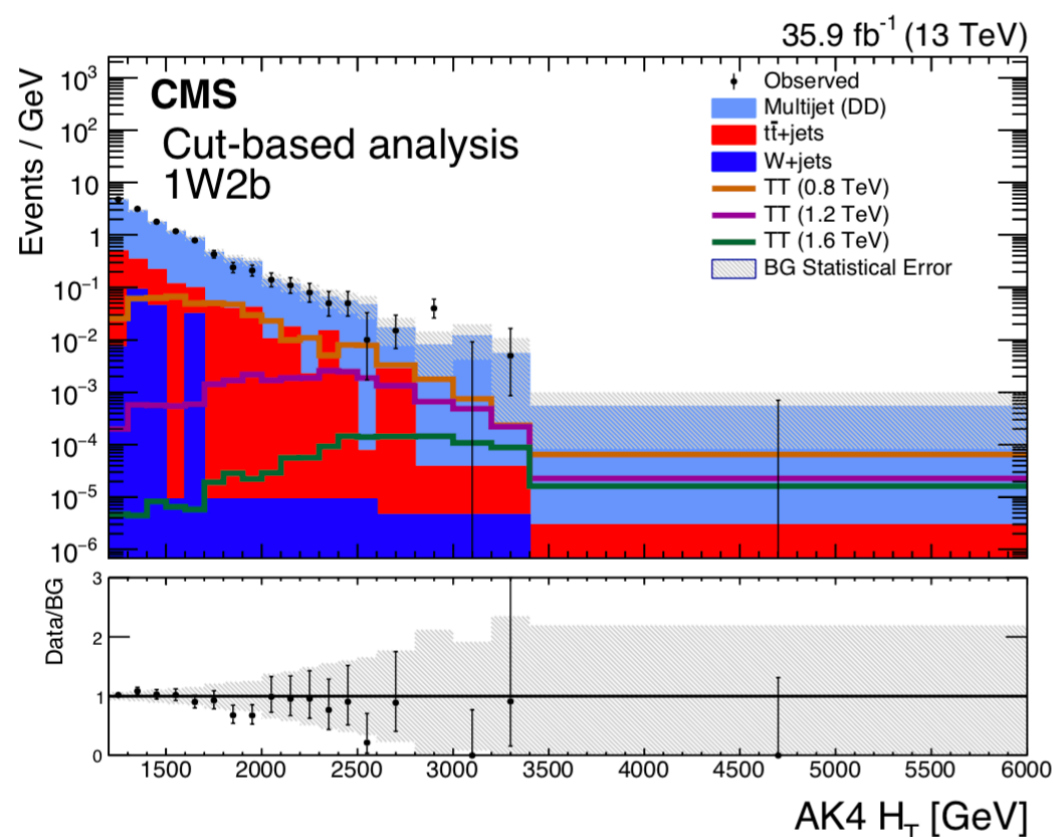
$$\begin{array}{ll} T \rightarrow bW & B \rightarrow tW \\ T \rightarrow tZ & B \rightarrow bZ \\ T \rightarrow tH & B \rightarrow bH \end{array}$$

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

Search for $T\bar{T}$ in the fully hadronic state

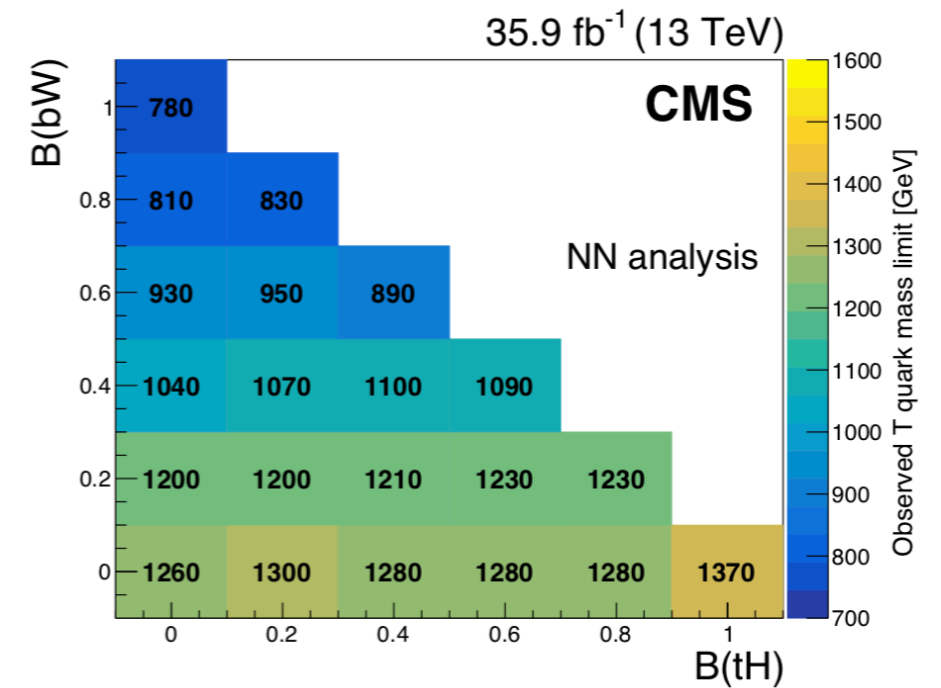
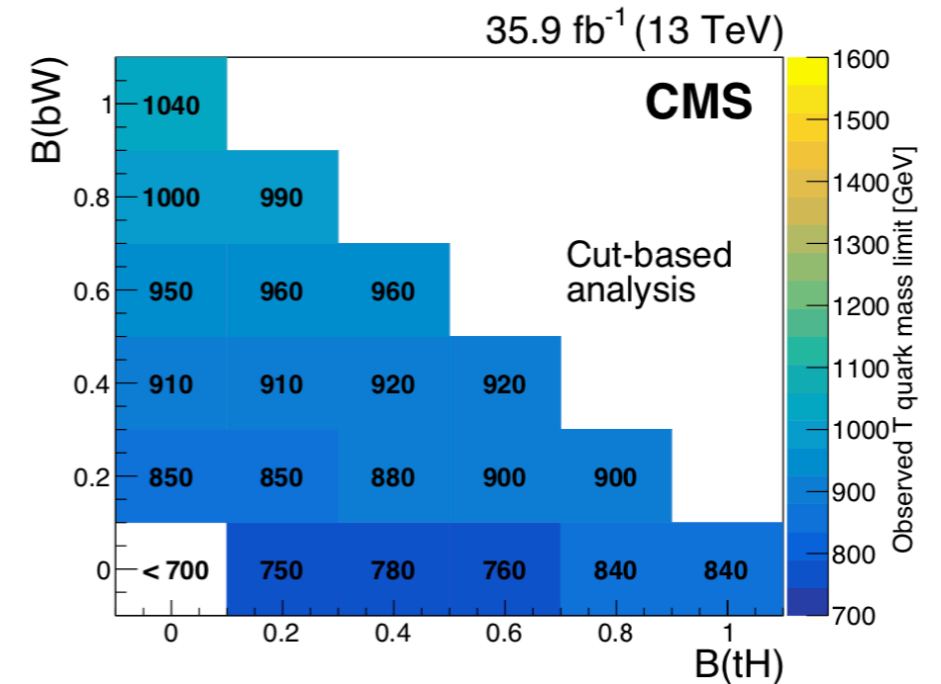
- Cut-based analysis
 - Require two Anti-KT $R=0.8$ jets and two Anti-KT $R=0.4$ jets
 - Two possible combinations of b and W jet. Assignment of jets to T candidate is made such that T candidate mass difference is minimized.
 - Categorize based on the number of W -tags and b -tags - 9 regions
- Neural 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 $T\bar{T}$ in the fully hadronic state

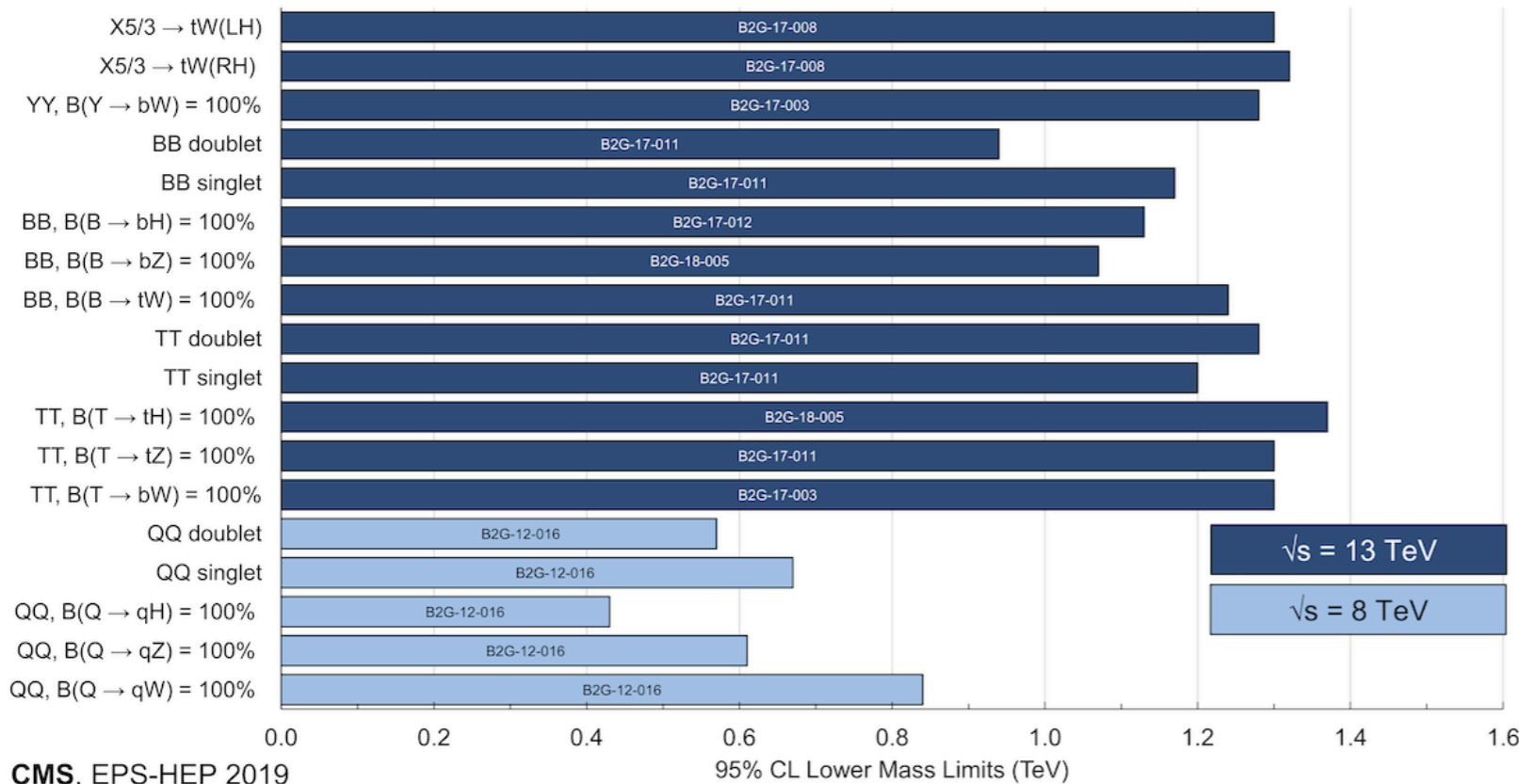


Search for TT in the fully hadronic state

- No significant deviation found
- Limits set
- Result is orthogonal to several other CMS measurements with leptons

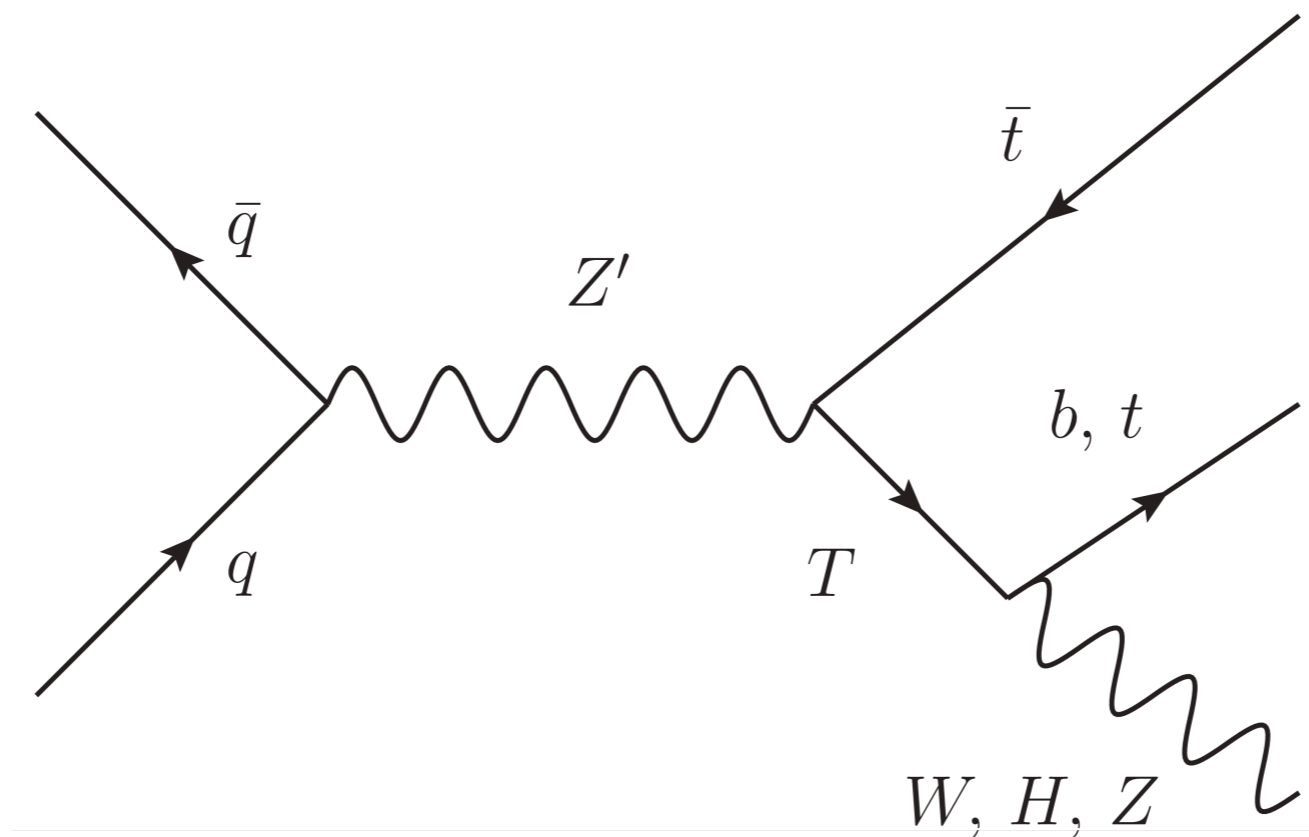


Vector-like quark pair production



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



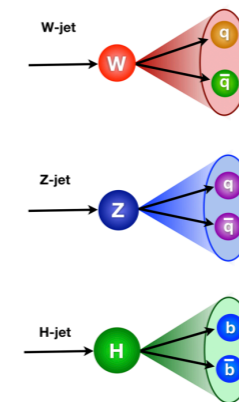
<http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G-17-015/index.html>

Search for resonant tT production

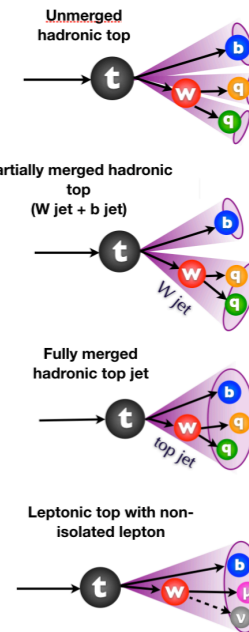
- Optimized for $T \rightarrow tZ$ or $T \rightarrow tH$
- Two principal decay channels:
 - $Z \rightarrow tT \rightarrow tZt$
 - $Z \rightarrow tT \rightarrow tHt$

Jet-tagging Menu

Utilize jet substructure to tag partially or fully merged jets



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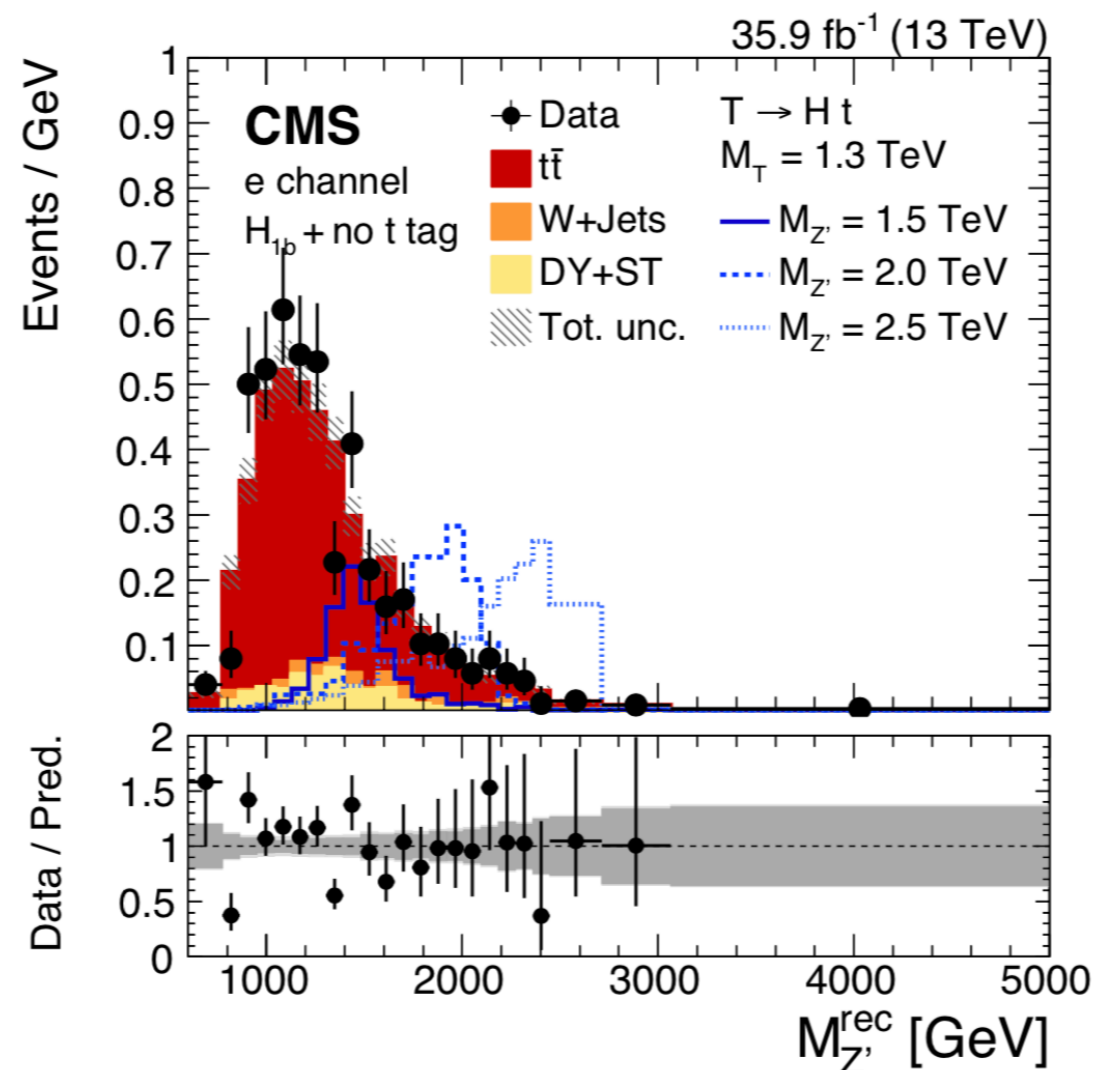


- Require one top to decay leptonically and other top hadronically
 - Search channel: lepton+jets
 - Leptonic top - non-isolated lepton
 - Hadronic top may be merged within a single jet
- H or Z is typically produced with large momentum \rightarrow collimated decay products \rightarrow utilize jet substructure

Search for resonant tT production

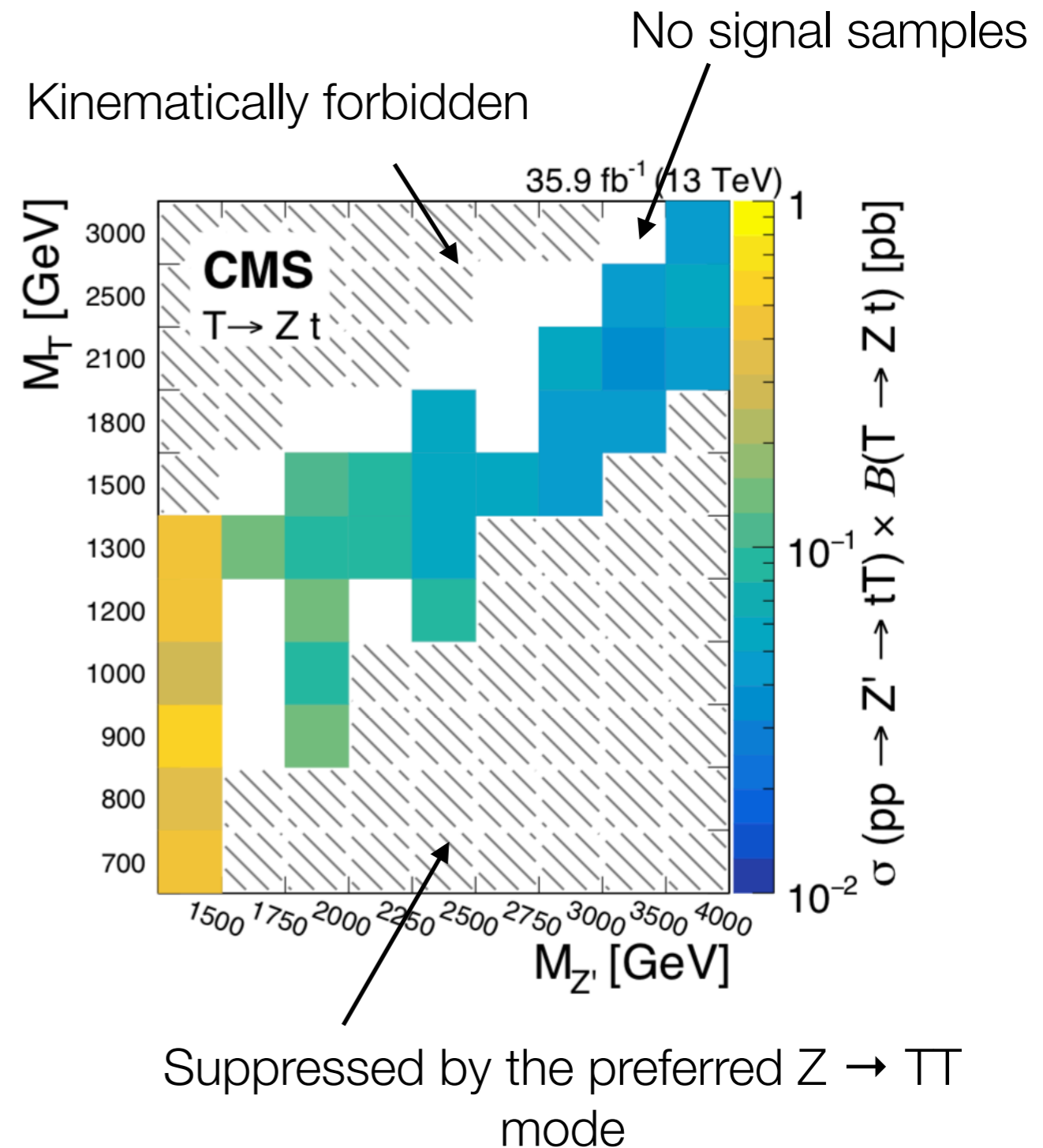
- Categorize events using jet substructure and subjet b-tagging
- Search for an excess in the reconstructed Z mass distribution

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



Conclusion

- Broad search program at CMS for heavy BSM particles decaying to third generation quarks
 - Public results: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
- Motivated models
- No significant excess found in 2016 data
 - Analysis of much more data to come!

Vector-like Quarks

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Excited quark
(ex. $b^* \rightarrow tW$, $t^* \rightarrow t\bar{g}$)

Leptoquark
(ex. $LQ \rightarrow t\bar{\tau}$, $LQ \rightarrow t\bar{\mu}$)

These are not just ideas! Completed analyses for many signal topologies available here:

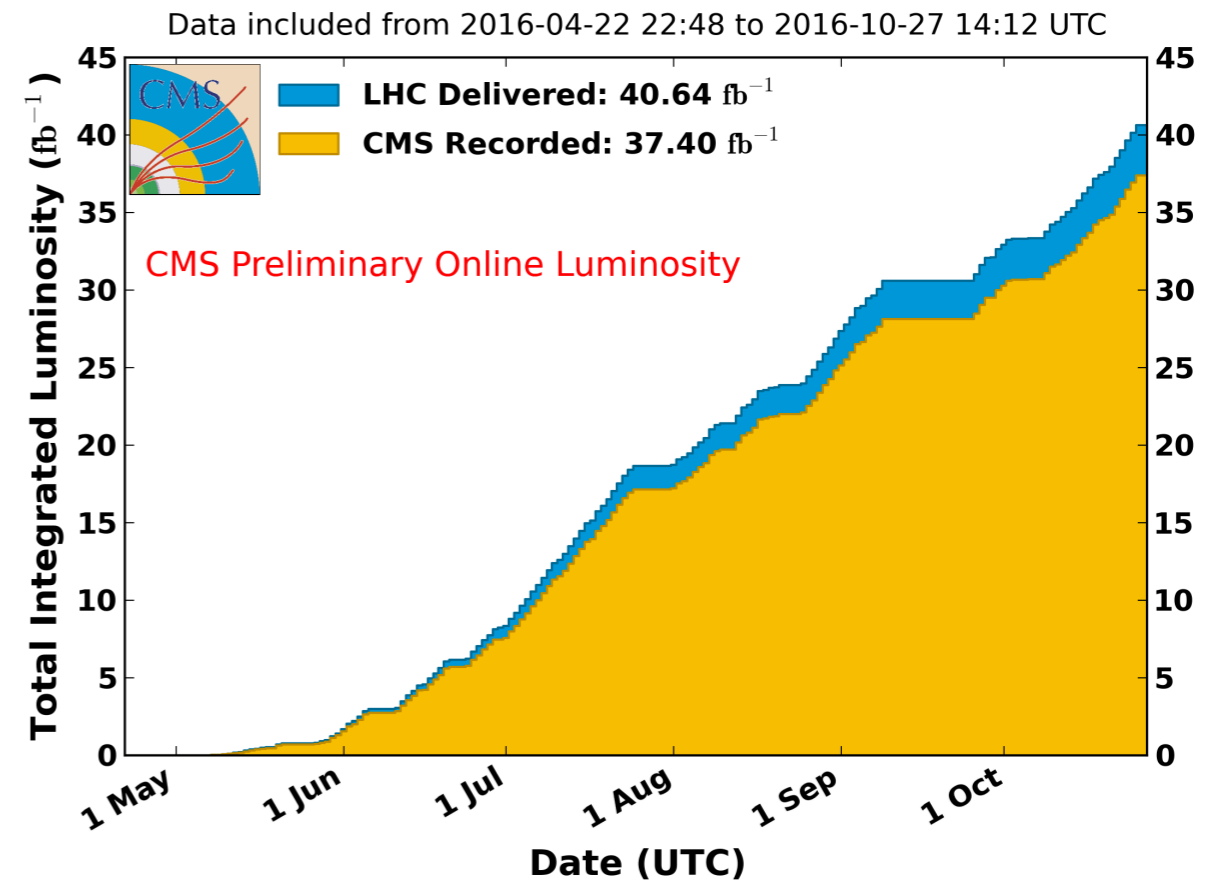
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

Additional Slides

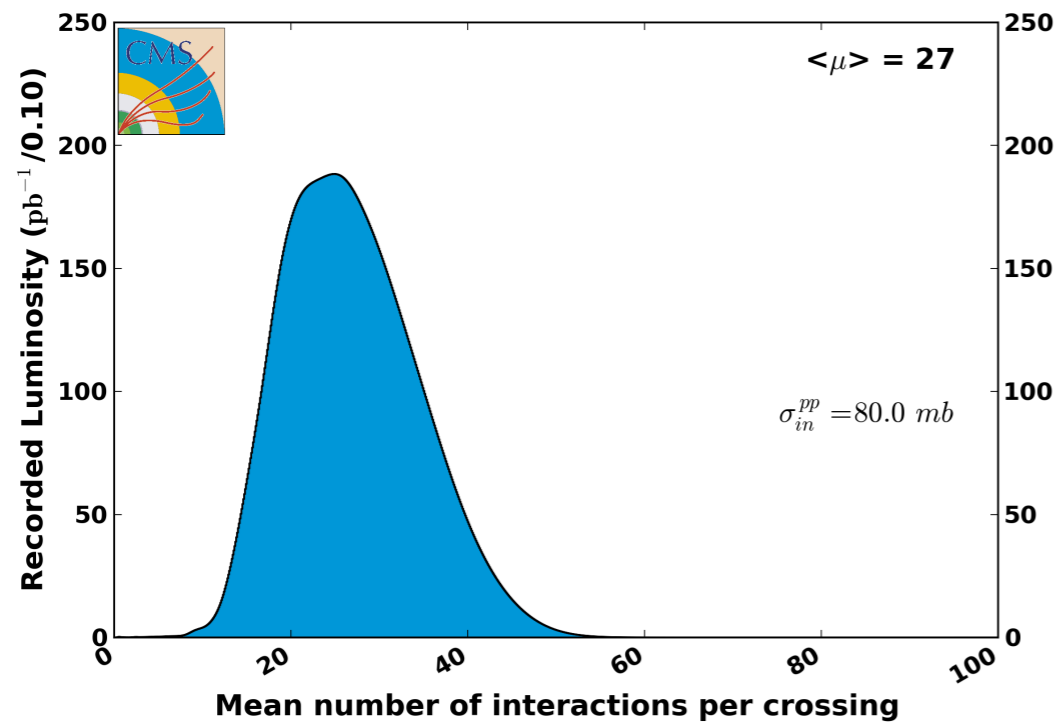
CMS Data 2016

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

CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13$ TeV

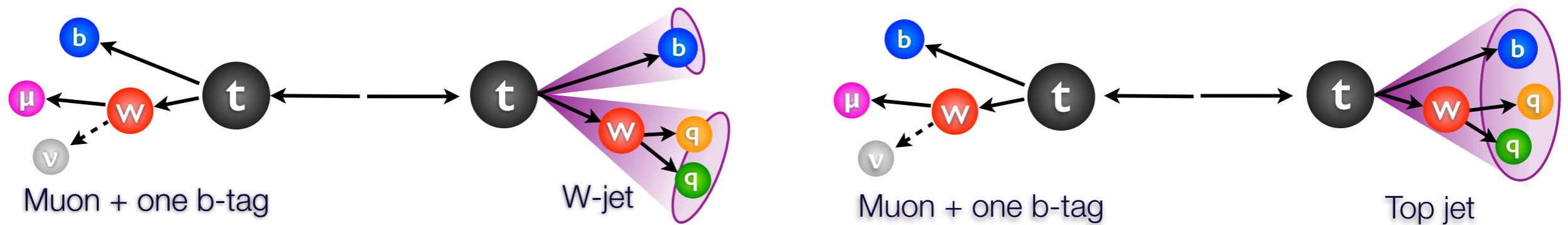


CMS Average Pileup, pp, 2016, $\sqrt{s} = 13$ TeV

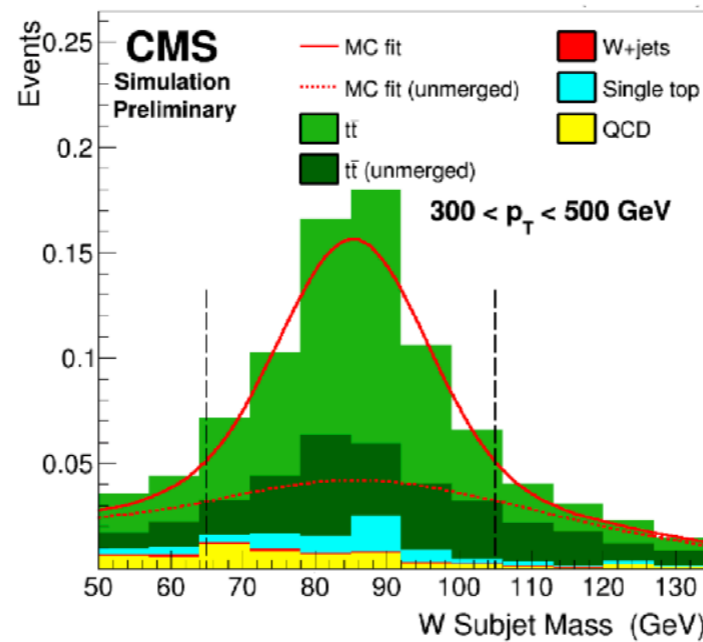
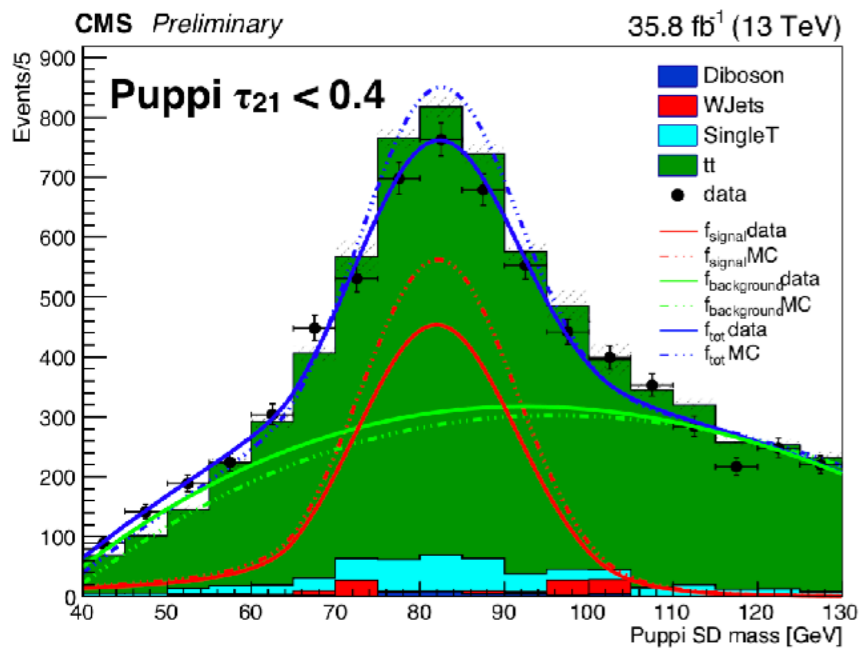


Top and W jet validation in data

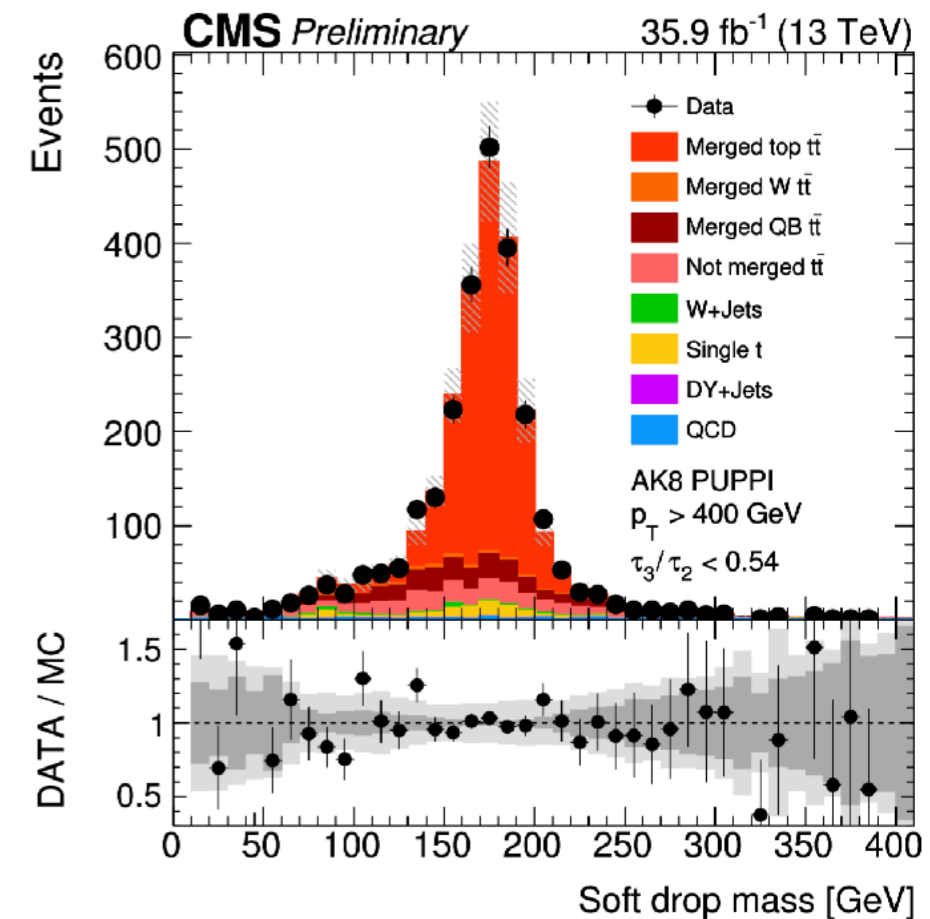
- Semileptonic $t\bar{t}$ selection \rightarrow very pure sample of boosted Ws



- Data-MC scale factors measured

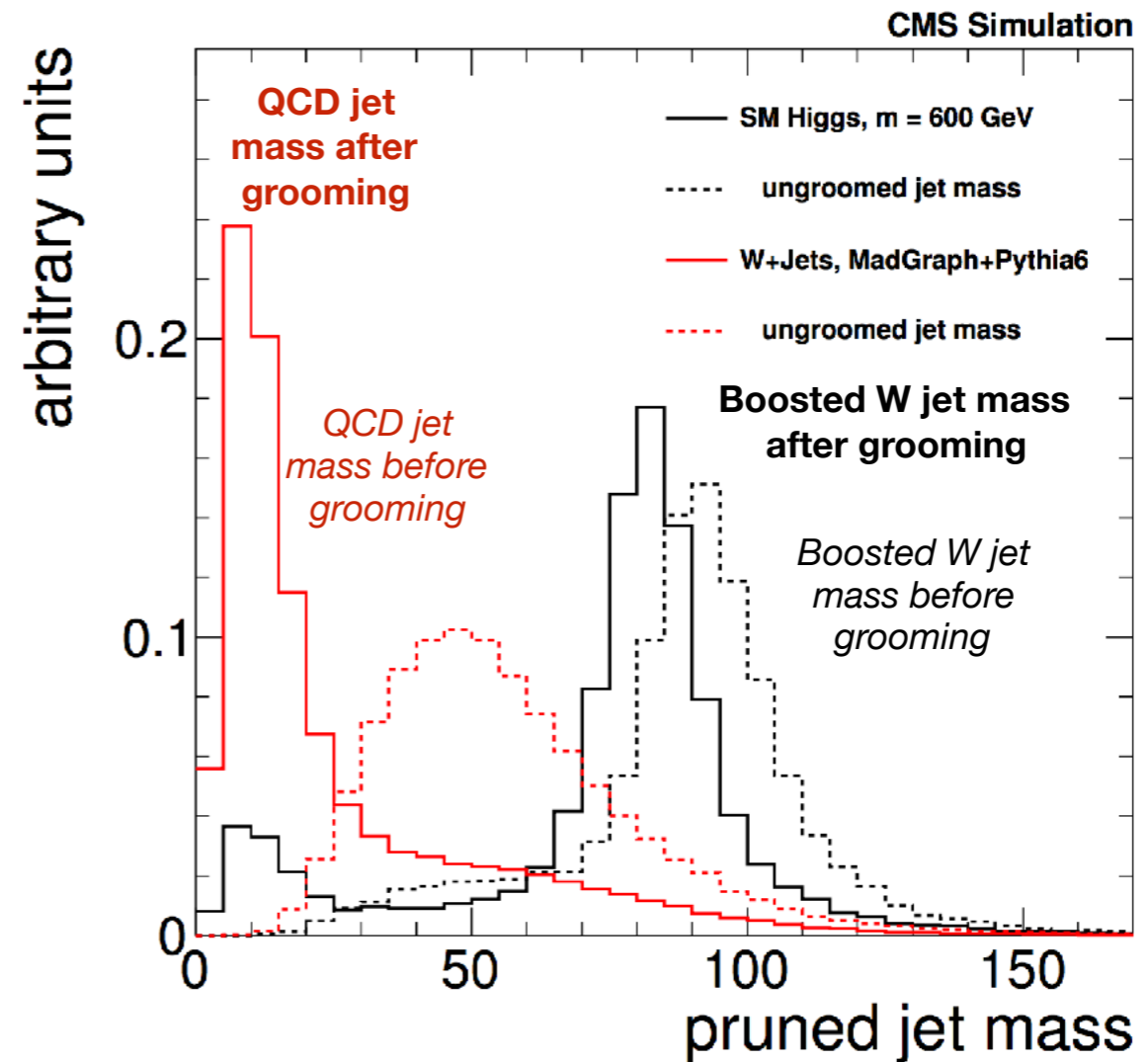
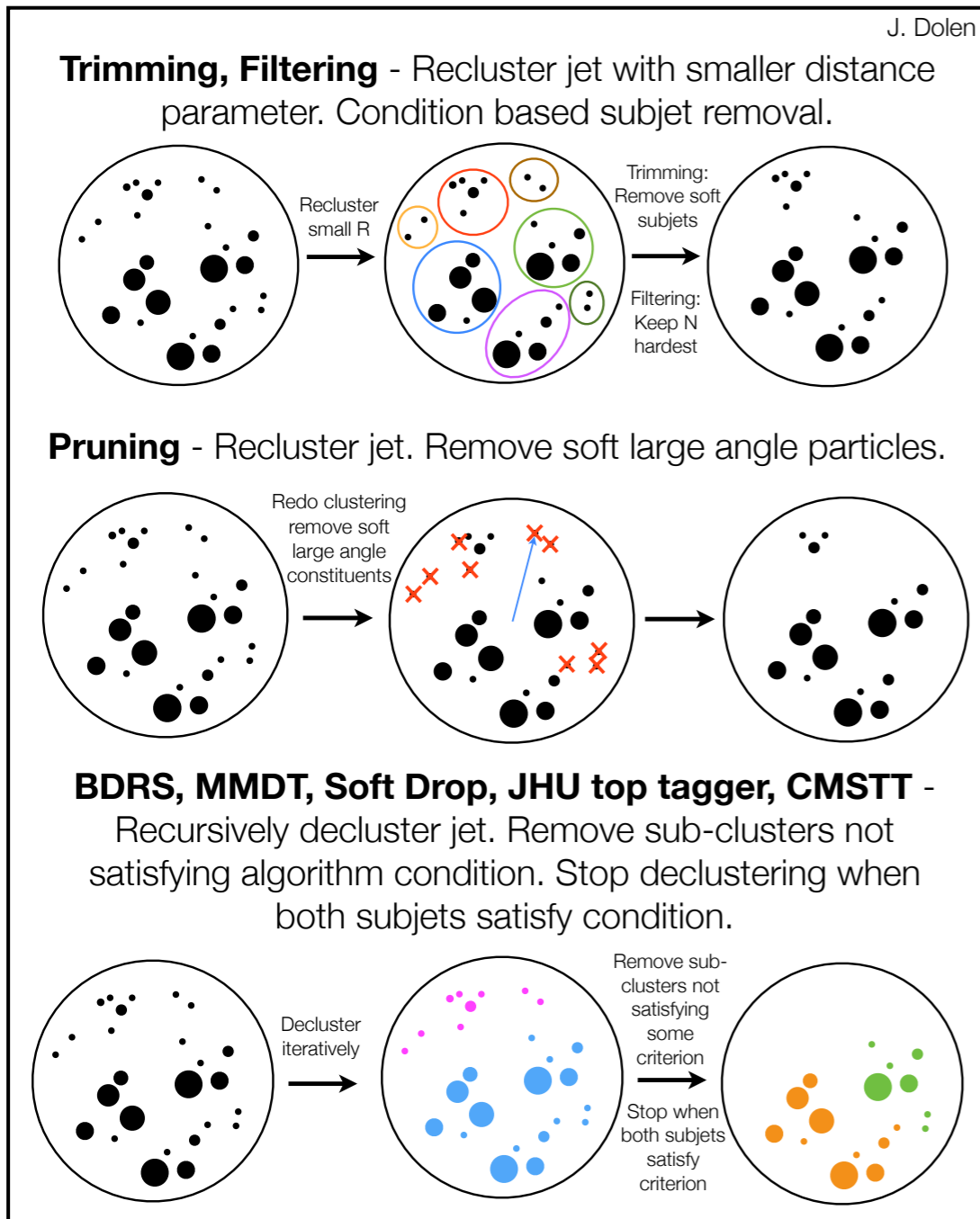


CMS DP 17/026



Jet grooming

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



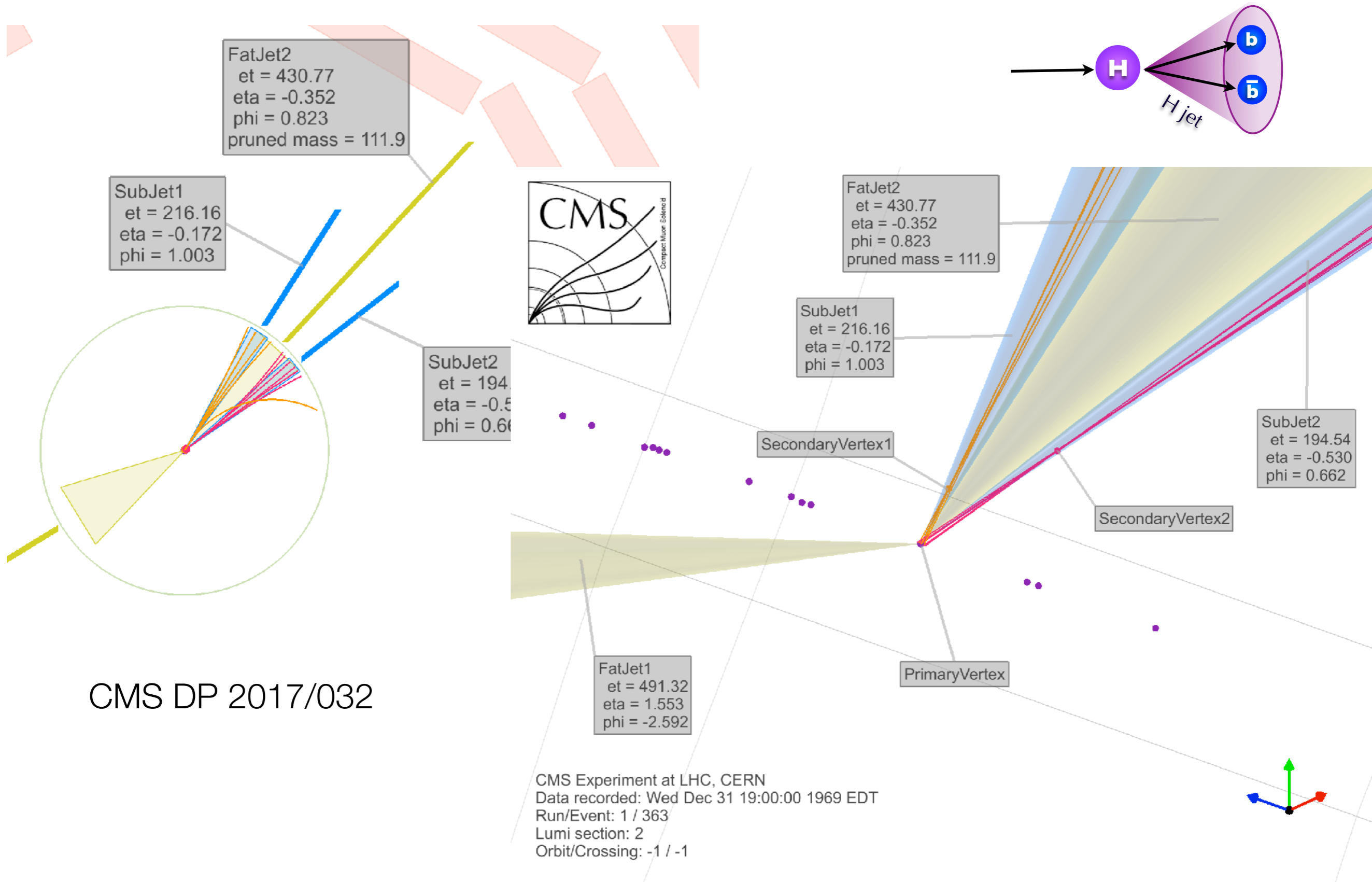
CMS HIG-13-008
H → WW → lvqq

Reduces jet mass dependence on pileup

Reduces measured QCD jet mass (improves discrimination)

Improved jet mass resolution for boosted heavy object

Double b-tagged H-jet



CMS DP 2017/032