Lake Louise Winter Institute 2016

Search for vector like quarks at CMS

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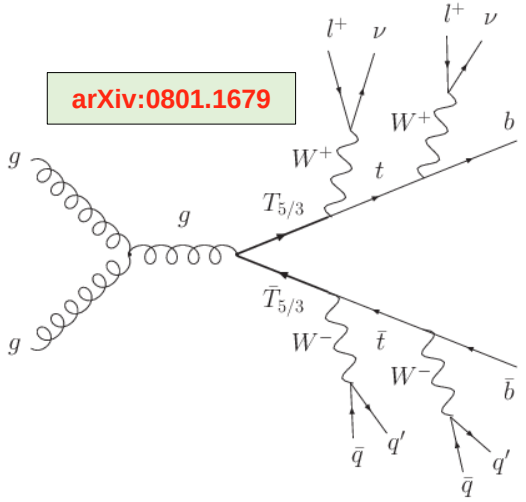
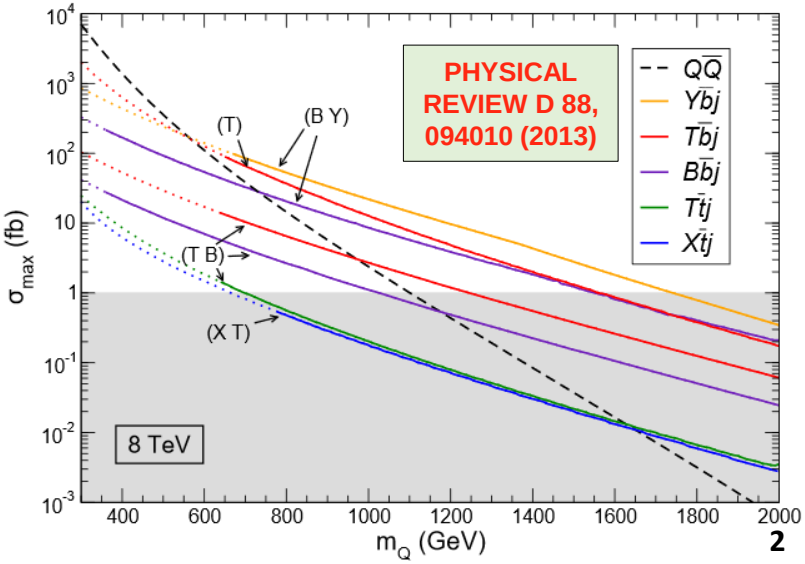
Theoretical Motivation

- Discovery of Higgs boson motivates **search for new physics**
- Possible explanations given by: little Higgs models, extra dimensions models, composite Higgs models
- These theories **predict existence of heavy vector-like quarks (VLQ)**
- Vector-like quarks are hypothetical new spin-1/2 particles: left- and right-handed chiralities transform in the same way under the standard model symmetry group
- In this talk, **VLQ pair production searches** at CMS will be shown

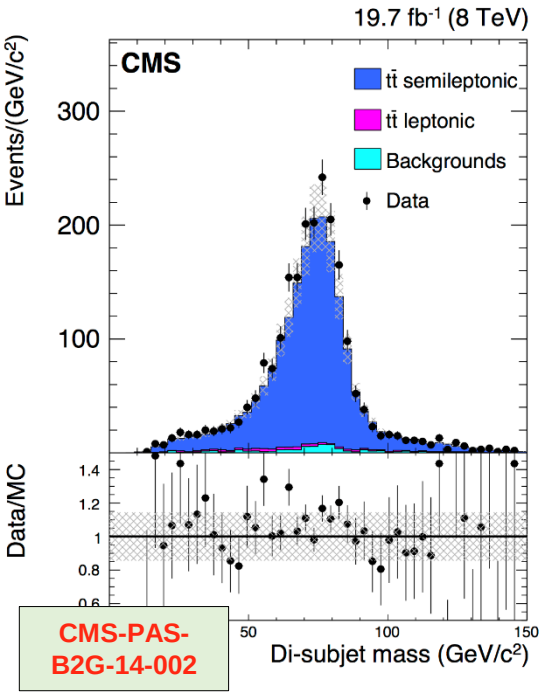


$$T \to W^+ b, \quad T \to Zt, \quad T \to Ht,$$
$$B \to W^- t, \quad B \to Zb, \quad B \to Hb,$$
$$X \to W^+ t,$$
$$Y \to W^- b,$$

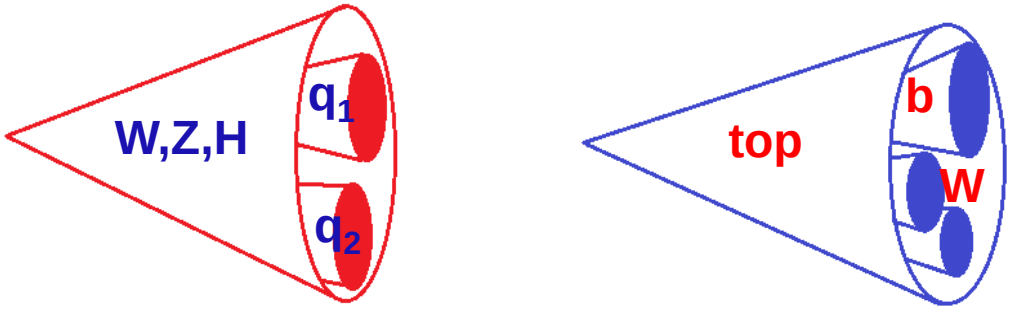


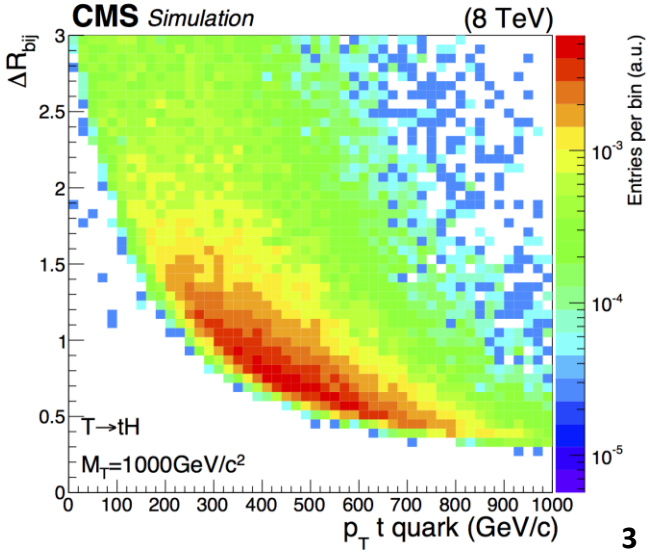
Experimental techniques

- **Boosted topologies**: resonance with high mass (~TeV) → decay products are produced close to each other
- Proper techniques have been developed
- Jet grooming techniques allow to distinguish signal/background: **pruning/filtering/trimming**
- Definition of **useful variables**: mass of the jet/subjets, N-subjetness, mass drop, subjet b-tagging



W, Z, H, top tagging





VLQ searches @ CMS

$T_{5/3}$ search (8 TeV and 13 TeV)	
VLQ production	$pp \rightarrow T_{5/3}T_{5/3}$
VLQ decay	tWtW

$T_{2/3}$ search (8 TeV)						
VLQ production	$pp \rightarrow T_{2/3}T_{2/3}$					
VLQ decay	bWbW	tZtZ	tHtH	bWtH	bWtZ	tZtH

$B_{-1/3}$ search (8 TeV)						
VLQ production	$pp \rightarrow B_{-1/3}B_{-1/3}$					
VLQ decay	tWtW	bZbZ	bHbH	tWbH	tWbZ	bZbH

Search for pair production of VLQ T' with charge 2/3

$T_{2/3}$ search (8 TeV)						
VLQ production	$pp \rightarrow T_{2/3}T_{2/3}$					
VLQ decay	bWbW	tZtZ	tHtH	bWtH	bWtZ	tZtH

$T_{2/3}T_{2/3} \rightarrow$ Inclusive

CMS-PAS-B2G-12-015: *Inclusive search for a vector-like T quark by CMS*

Single lepton

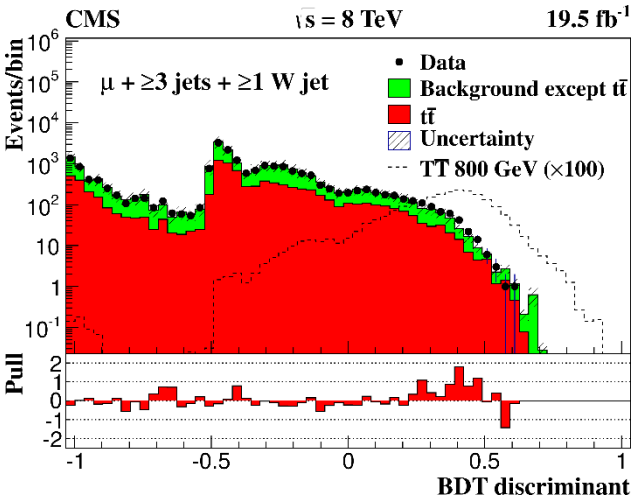
- One isolated electron or muon
- Count additional jets, W-jets and top-jets
- BDT: jet/b-jet multiplicities, H_T, E_T^{miss}, lepton p_T, p_T of the third and fourth jets. For events with a W-jet: number and p_T of W jets and the number of top-jets

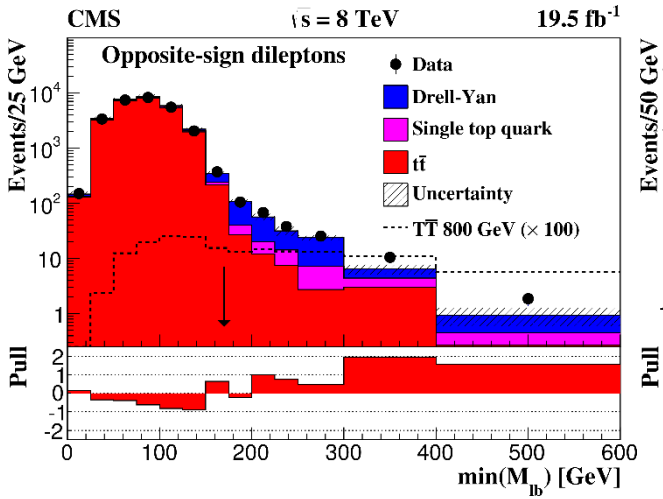
Multilepton

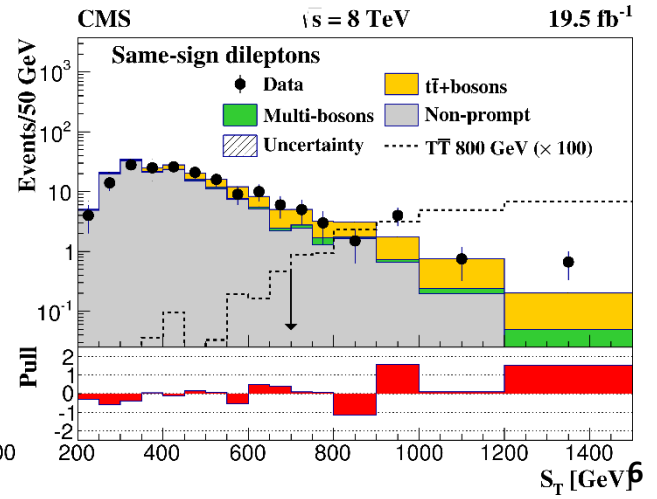
- Opposite sign dilepton from or not a Z boson (6 categories)
- Same sign dilepton (3 categories)
- Three leptons (3 categories)

Results

- Limits for for $T_{2/3}$ mass between 687 and 782 GeV





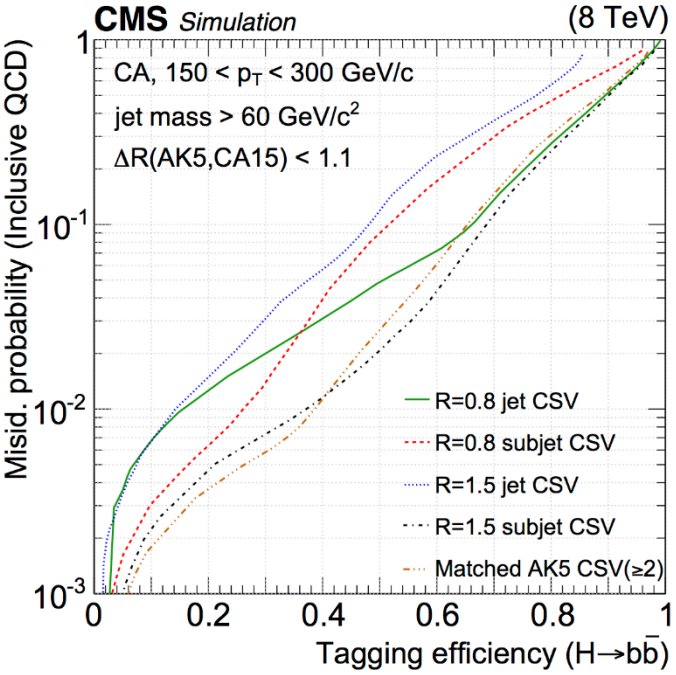


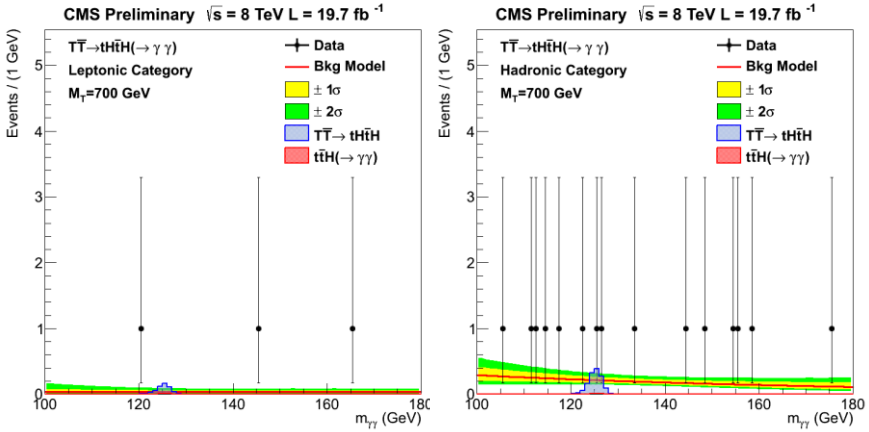
$T_{2/3}T_{2/3} \rightarrow tH$ + inclusive

- **CMS-PAS-B2G-14-002**: *Search for top-Higgs resonances in all-hadronic final states using jet substructure methods*
- **CMS-PAS-B2G-14-003**: *Search for vector-like top quark partners produced in association with Higgs bosons in the diphoton final state*

tH fully hadronic

- One top-jet, from HEPTopTagger algorithm, with M(jet) in [140,250] GeV and subjet b-tagging
- One or two H-jet with two subjet b-tagged and with $M_{inv} > 60$ GeV
- Likelihood ratio obtained starting from H_T and m_{bb} distributions



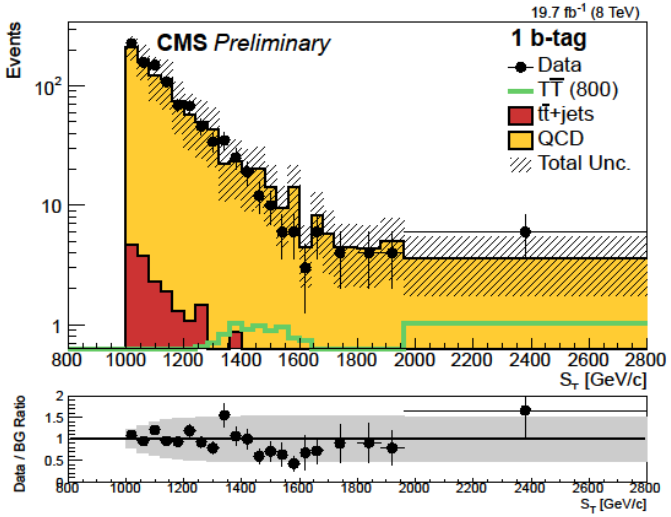


tH in diphoton

- Higgs boson to photons to allow for full mass reconstruction
- Two search channels: leptonic and hadronic categories

$T_{2/3}T_{2/3} \rightarrow bWbW$

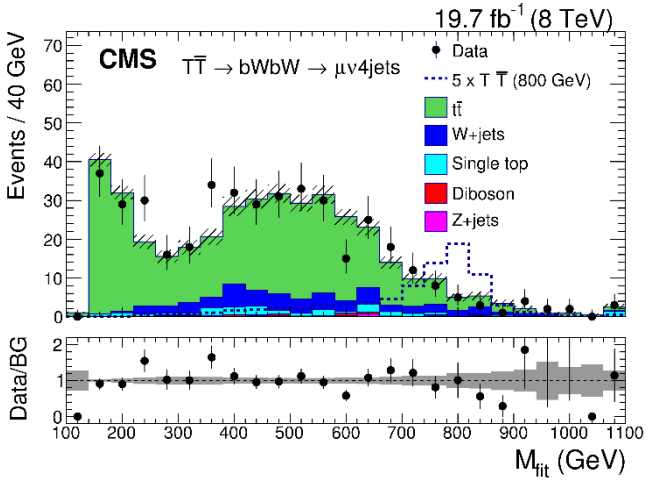
CMS-PAS-B2G-12-013: *Search for pair-produced vector-like top quark partners decaying to bW in the fully hadronic channel using jet substructure at 8 TeV*



- Fully hadronic final state: 2 W-jets and 2 jets (at least one is b-tagged)
- tt background from simulation, QCD from data-driven method
- Variable sensitive to signal: S_T, scalar sum of p_T of W-jets and jets

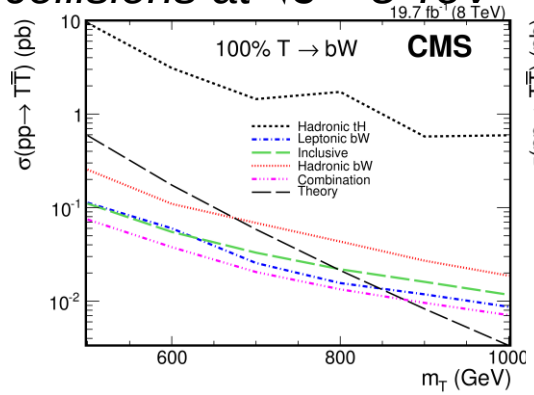
CMS-PAS-B2G-12-017: *Search for vector-like quarks in final states with a single lepton and jets in pp collisions at $\sqrt{s}$=8 TeV*

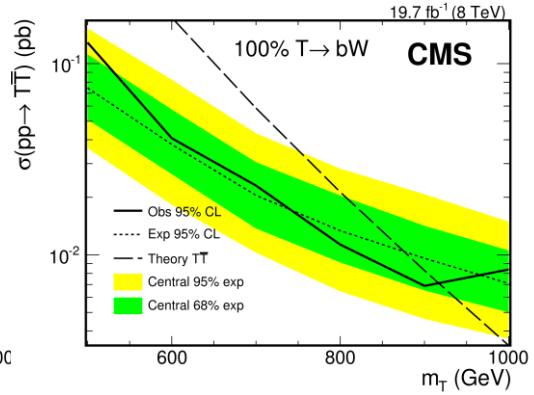
- One isolated electron or muon
- At least 4 jets or 3 jets + 1W-jet
- Kinematic fit for hypothesis TT→bWbW→$\ell\nu$bqqb to find the mass of the resonance

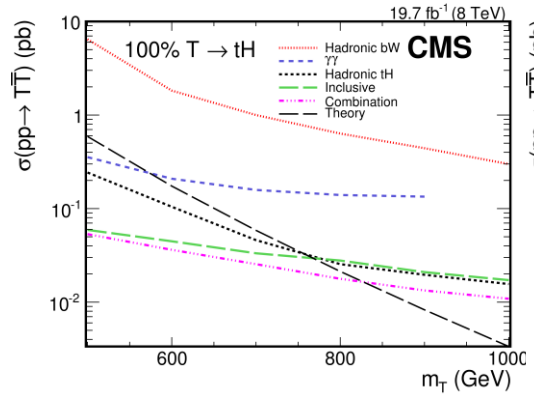


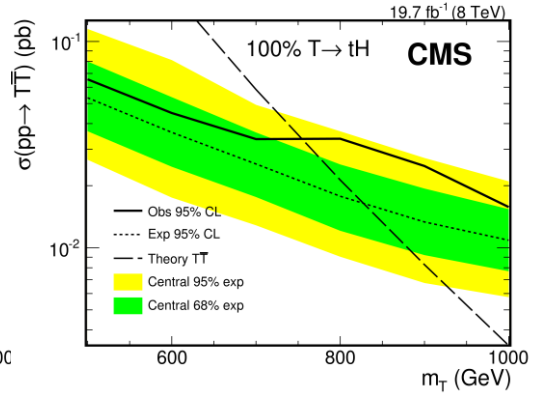
$T_{2/3}T_{2/3}$ - Combination

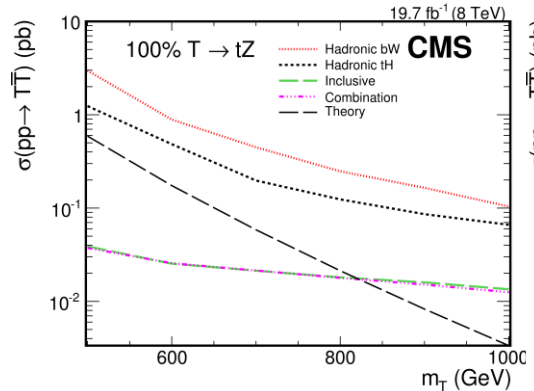
CMS-PAS-B2G-13-005: *Search for vector-like charge 2/3 T quarks in proton-proton collisions at $\sqrt{s}$ = 8 TeV*

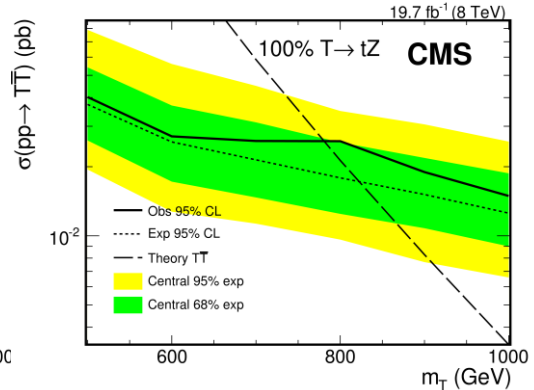




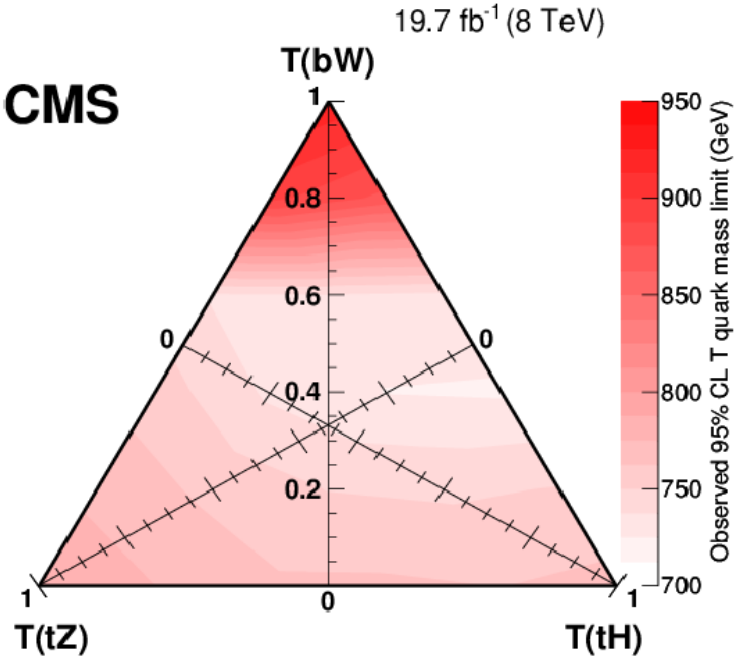








- The 5 searches are combined together
- The 2 single-leptonic analyes are considered exclusively
- Lower mass **limits between 720 and 920 GeV**



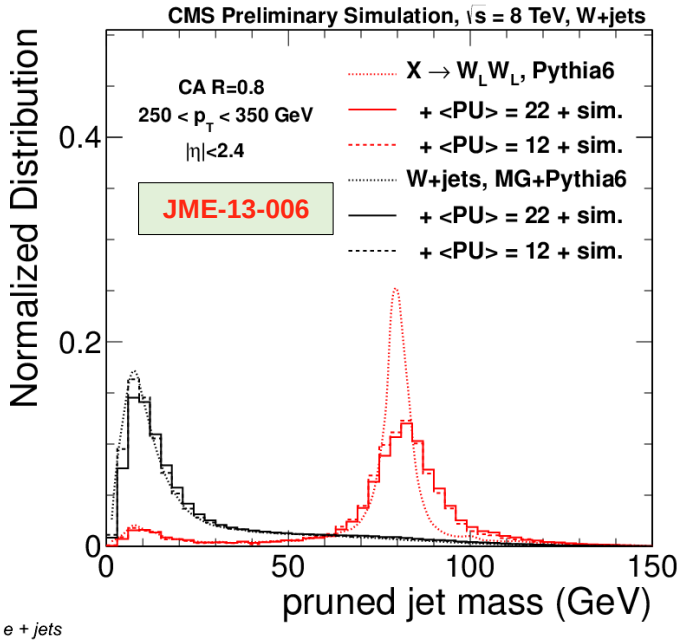
Search for pair production of VLQ B' with charge -1/3

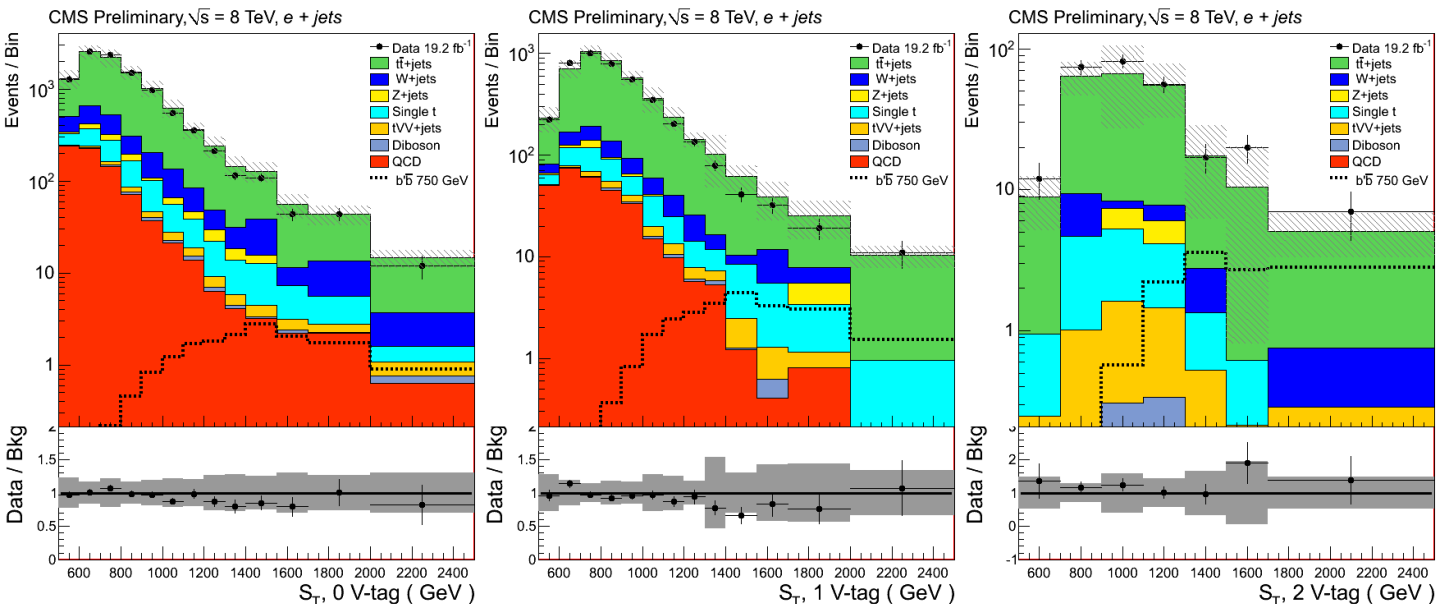
$B_{-1/3}$ search (8 TeV)						
VLQ production	$pp \rightarrow B_{-1/3}B_{-1/3}$					
VLQ decay	tWtW	bZbZ	bHbH	tWbH	tWbZ	bZbH

$B_{-1/3}B_{-1/3} \rightarrow$ Lepton+Jets

CMS-PAS-B2G-12-019: *Search for pair-produced vector-like quarks of charge -1/3 in lepton + jets final state in pp collisions at $\sqrt{s}$ = 8 TeV*

- One isolated lepton and at least four jets (at least one is b-tagged)
- Events divided in 0, 1 and ≥2 V-jets (either W, Z or H boson)
- V-jets identified with **pruning algorithm** and **mass drop**





To discriminate B quark signal from background, S_T (scalar sum of jets, leptons and missing energy pt) is used

$B_{-1/3}B_{-1/3} \rightarrow$ Multilepton

- **CMS-PAS-B2G-12-020**: *Search for pair-produced vector-like quarks of charge -1/3 in same-sign dilepton final state*
- **CMS-PAS-B2G-12-021**: *Search for pair-produced vector-like quarks of charge -1/3 in dilepton+jets final state in pp collisions at $\sqrt{s}$ = 8 TeV*
- **CMS-PAS-B2G-13-003**: *Search for Vector-Like b' Pair Production with Multilepton Final States in pp collisions at $\sqrt{s}$ = 8 TeV*

Same sign dilepton

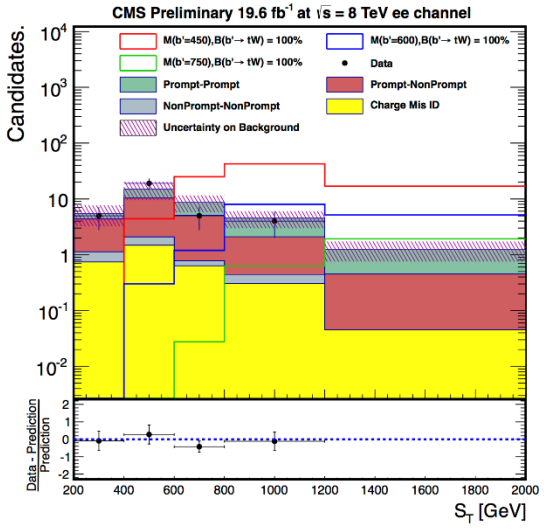
- Two SS leptons and four jets
- S_T distribution

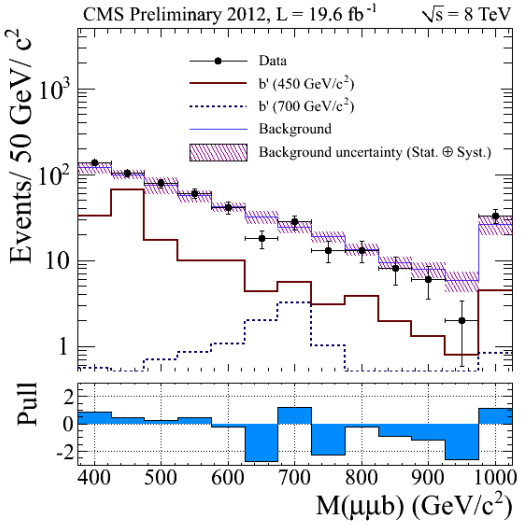
Opposite sign dilepton

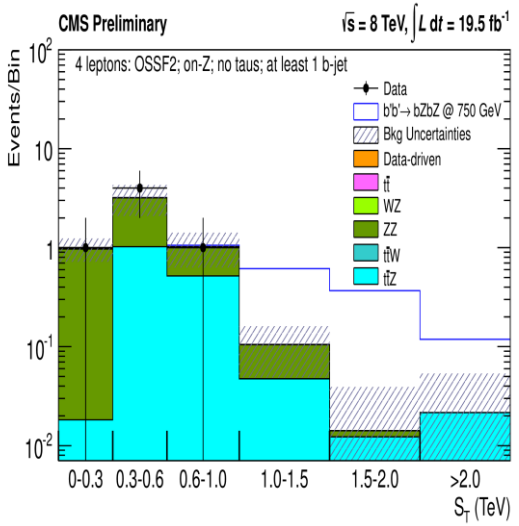
- Two leptons from a Z boson
- At least one b-jet

Multilepton

- At least three leptons
- Number of opposite-sign same flavor



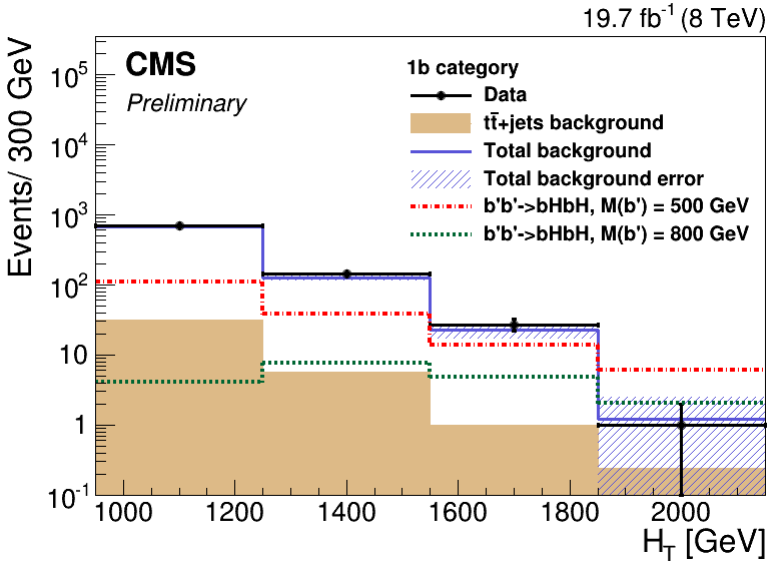


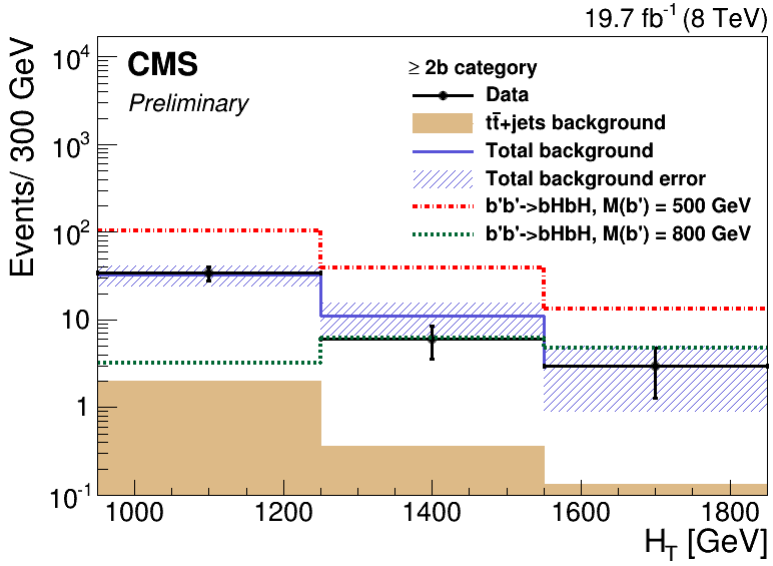


$B_{-1/3}B_{-1/3} \rightarrow bH$ all hadronic

CMS-PAS-B2G-14-001: *Search for pair-produced vector-like quarks of charge -1/3 decaying to bH using boosted Higgs jet-tagging in pp collisions at $\sqrt{s}$ = 8 TeV*

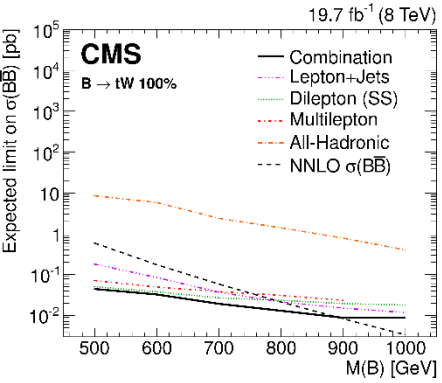
- At least one H-tagged jet: jet mass, N-subjettiness and subjets b-tagging
- At least one additional b-jet (two categories on number of b-jets)
- H_T distribution used to discriminate signal and background
- tt background from simulation, QCD estimated from data-driven method

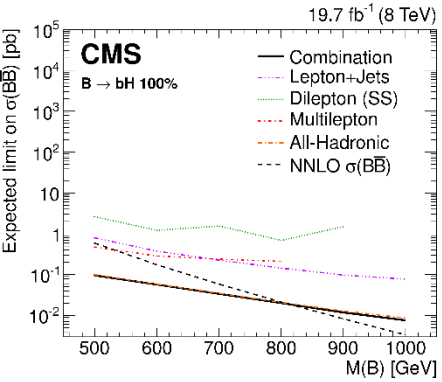


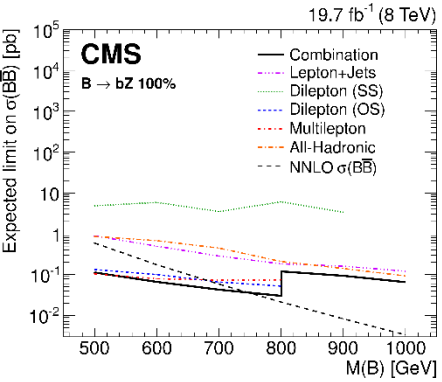


$B_{-1/3}B_{-1/3}$ - Combination

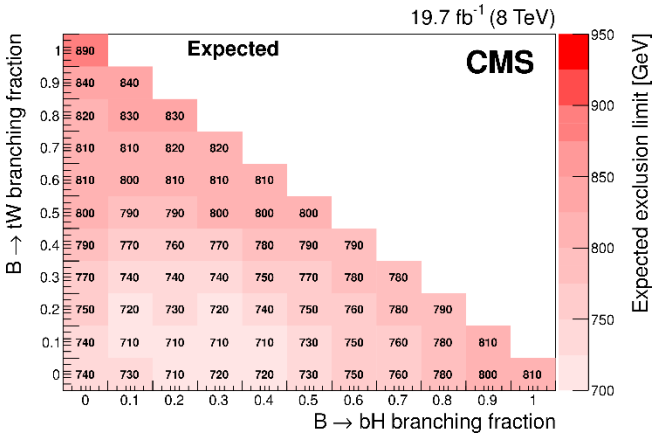
CMS-PAS-B2G-13-006: *Search for pair-produced vector-like B quarks in proton-proton collisions at √s = 8 TeV*

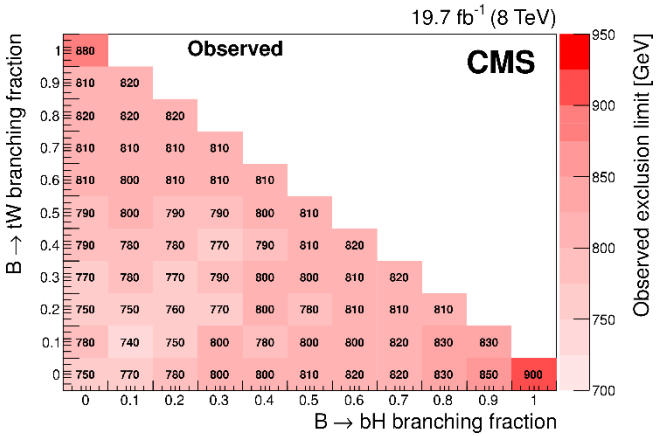






- The 5 searches are combined together
- Observed exclusion limit ranges **between 740 GeV and 900 GeV** for the mass of the $B_{-1/3}$





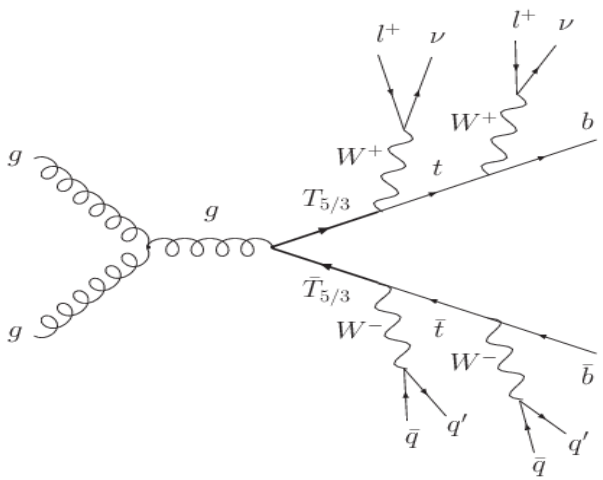
$T_{5/3}$ search (8 TeV and 13 TeV)	
VLQ production	$pp \rightarrow T_{5/3}T_{5/3}$
VLQ decay	tWtW

Search for pair production of VLQ with charge 5/3

$T_{5/3}T_{5/3}$ search

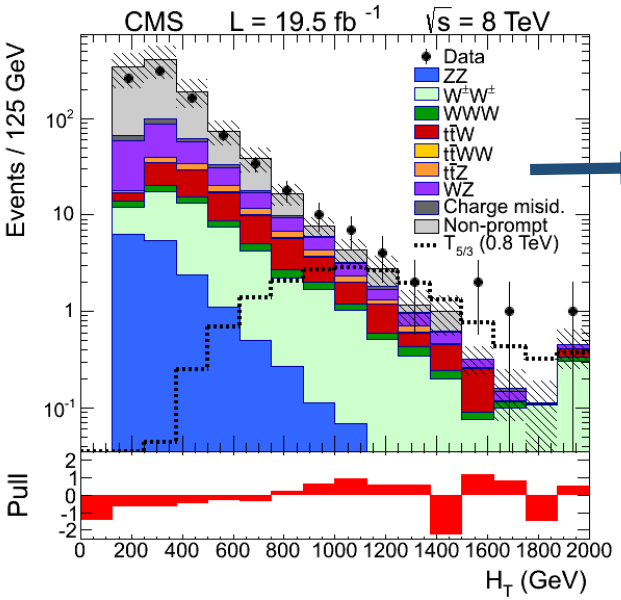
- **Phys. Rev. Lett. 112 (2014) 171801**: *Search for Top-Quark Partners with Charge 5/3 in the Same-Sign Dilepton Final State*

8TeV



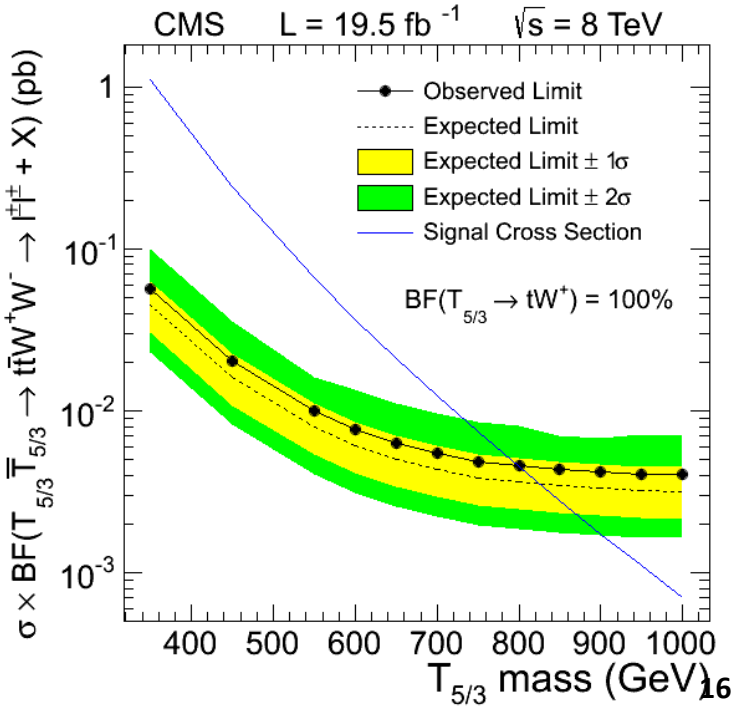
Same-sign dilepton signature:

- two leptons from W decays
- top-jets and W-jets are reconstructed
- minimum number of constituents: leptons, jets, W-jets, top-jets



Background:

1. SM irreducible
2. charge misidentification
3. *Non-prompt* leptons



$T_{5/3}T_{5/3}$ search

- **CMS-PAS-B2G-15-006**: *Search for top quark partners with charge 5/3 at √s=13 TeV*

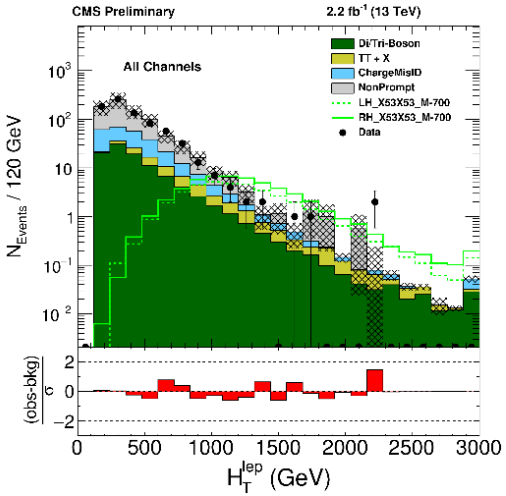
13 TeV

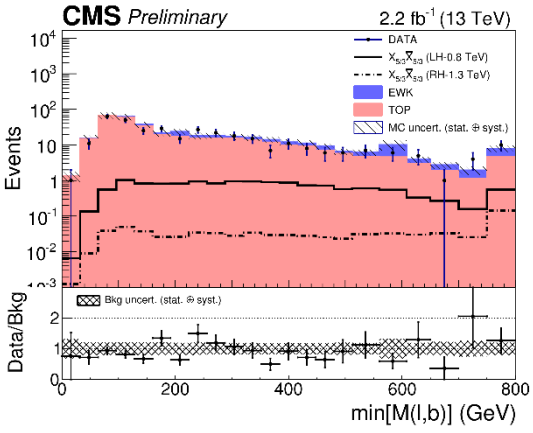
Same-sign dilepton signature:

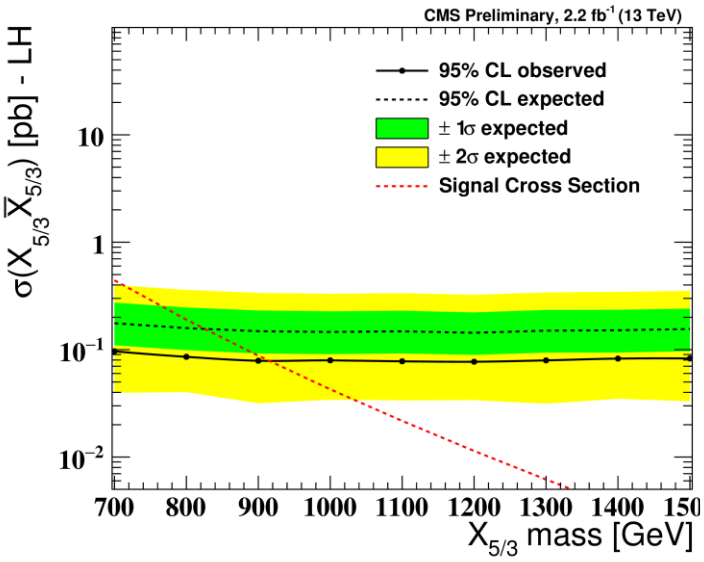
- Similar selection as before
- Re-optimized for 13 TeV data

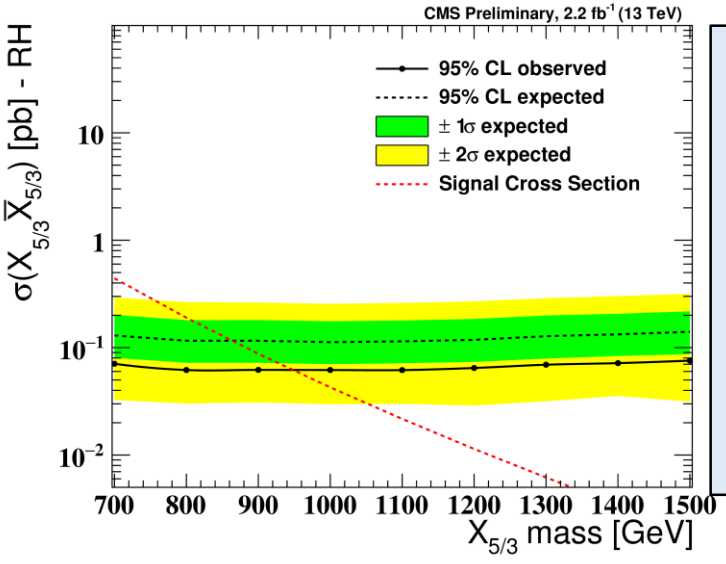
Lepton+jets (only 13 TeV)

- One lepton from W decay
- at least 4 jets, 1 b-jets, categories with 0 or 1+ W-jets





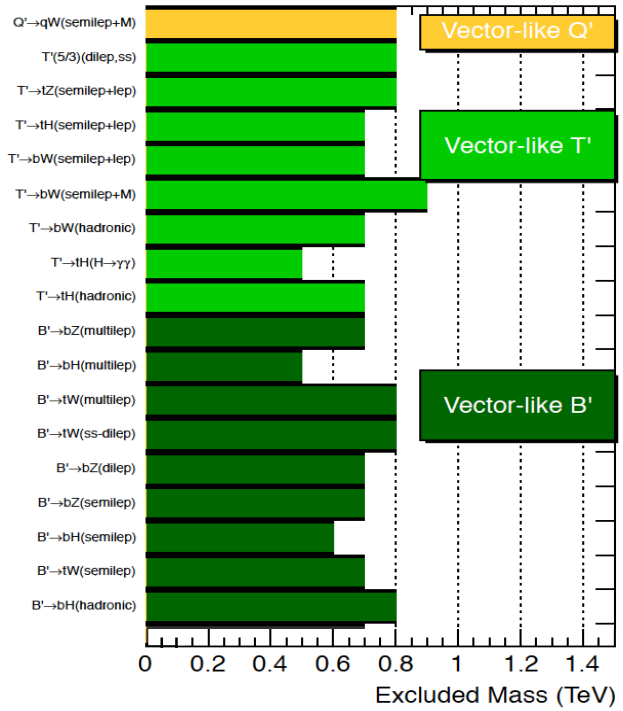




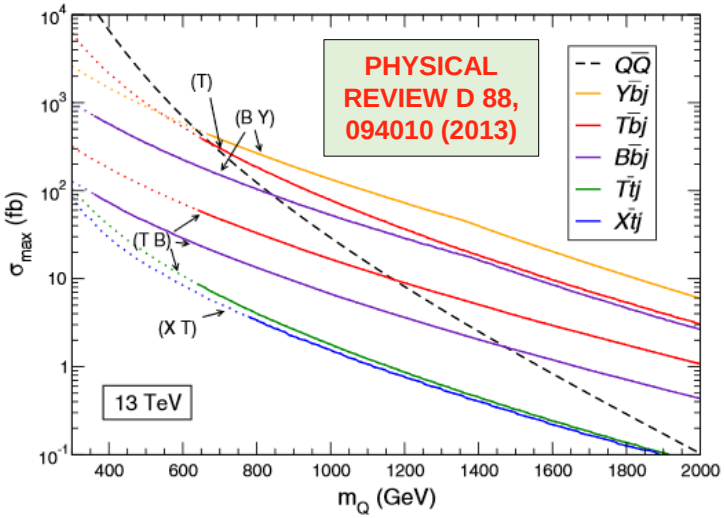
Exclusion observed (expected) limit of 960/940 (900/860) GeV for RH/LH $T_{5/3}$ mass

→ improved with respect to Run1

Conclusions



- CMS has a **robust programme** focused on search for VLQ
- Search for **pair production of VLQ $T_{5/3}$, $T_{2/3}$, $B_{-1/3}$** performed during **Run 1**:
  - limits up to ~850 GeV
- First result for pair production of **$T_{5/3}$** at **Run 2**:
  - extend limits up to ~950 GeV



Run 2 perspective:

- Extend sensitivity of previous analyses
- **Single production** of VLQ become sensitive
- **Boosted techniques** are being improved


Thank you for your attention

BACKUP

Jet grooming techniques

ref. JHEP05 (2013) 090

- Designed to separate between jet from heavy particles and jet from QCD
- **Jet mass highly depends on grooming techniques**
- Understand the dependence for the jet mass with the pileup
- Three algorithms can be used:

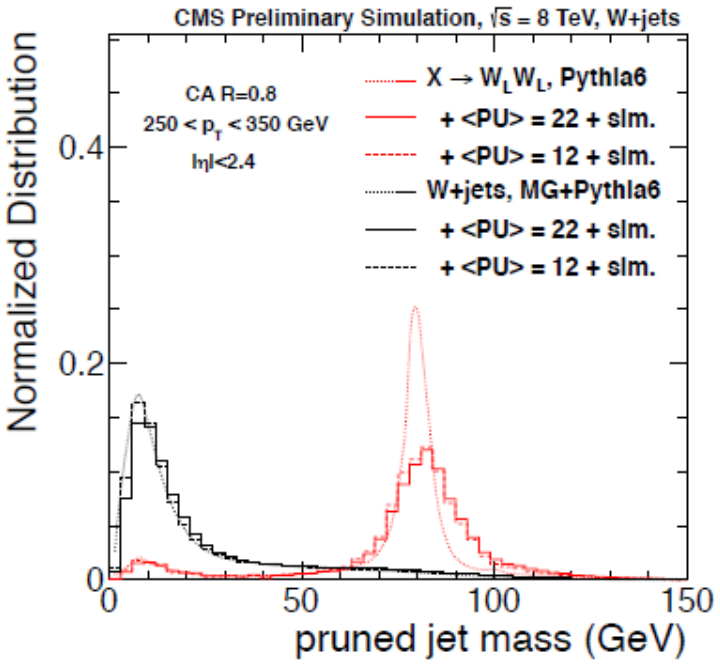
1. ***Filtering algorithm*** → the constituents of the jet are reclustered with CA 0.3 and only the three hardest subjets are considered
2. ***Trimming algorithm*** → the constituents of the jet are reclustered with k_t 0.2 and particles at low p_t are ignored
3. ***Pruning algorithm*** → remove constituents that are at large angles or soft

Pruning algorithm

- Developed by ***S.Ellis et al***: **[Phys. Rev. n D80 (2009)]**
- Main idea → add a set of requirements during the clustering algorithm
  → ***to prune the jet***: remove constituents that are at large angles or soft
- **Starting point**: jets clustered with CA algorithm and distance parameter of 0.8
- Steps of the algorithm:
  1. **rerun** the clustering sequence
  2. **two more requirements** are asked:

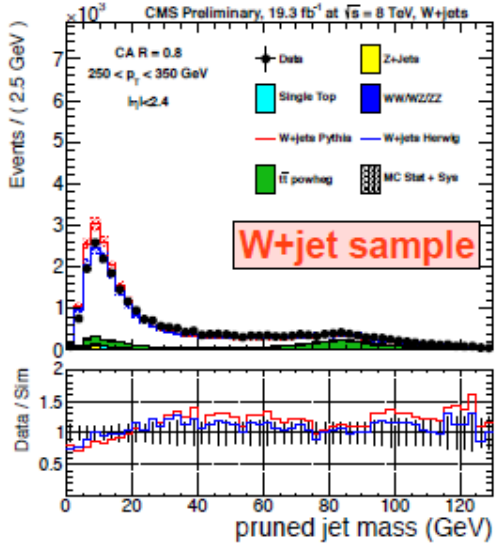
- $z_{ij} \equiv \frac{min(p_T^i, p_T^j)}{p_T^p} > z_{cut}$ → remove **soft** particles
- $\Delta R_{ij} < \alpha \cdot m_{jet}/p_T^{jet}$ → remove **large angle** particles

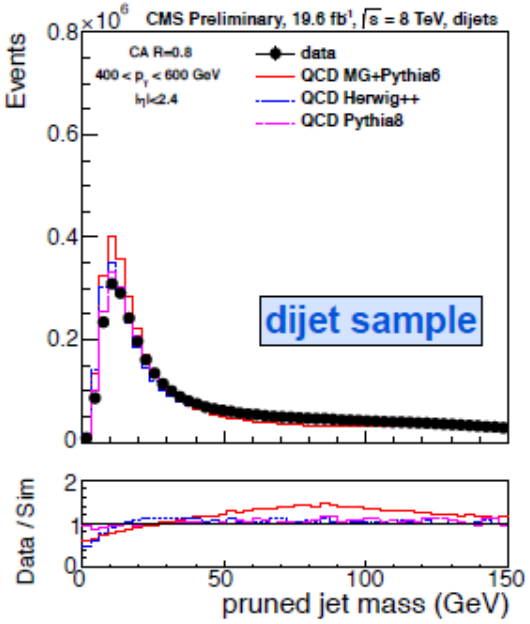
W-tagging algorithm: pruned mass



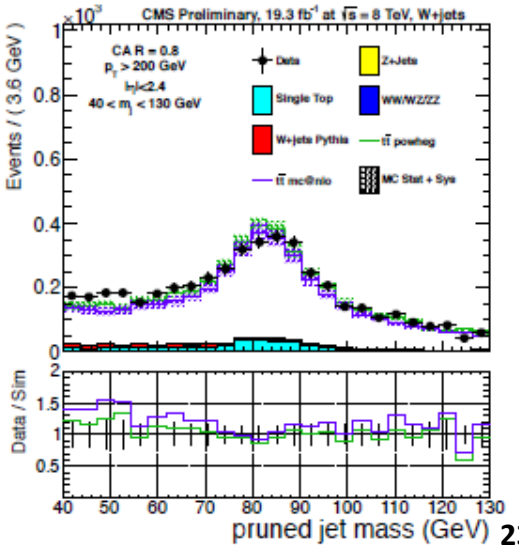
ref. CMS PAS JME-13-006

- **Signal** with real hadronic W peaks at W mass
- **QCD jets** peak at lower value
- **Pileup** and **detector effects** results in broadening the W mass and shift it at higher value
- **Different pileup scenarios** have not effects, due to the pruning
- **data/MC comparison** in three different samples: **W+jets**, **dijet** and **ttbar**

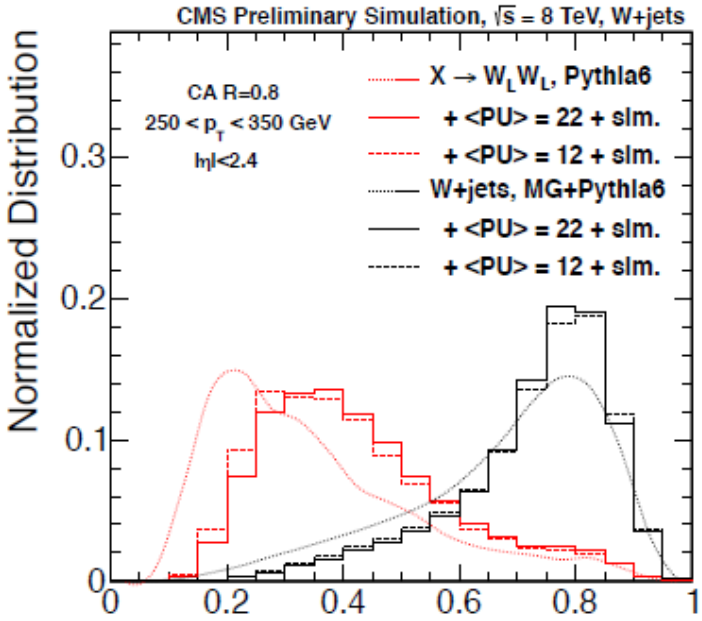




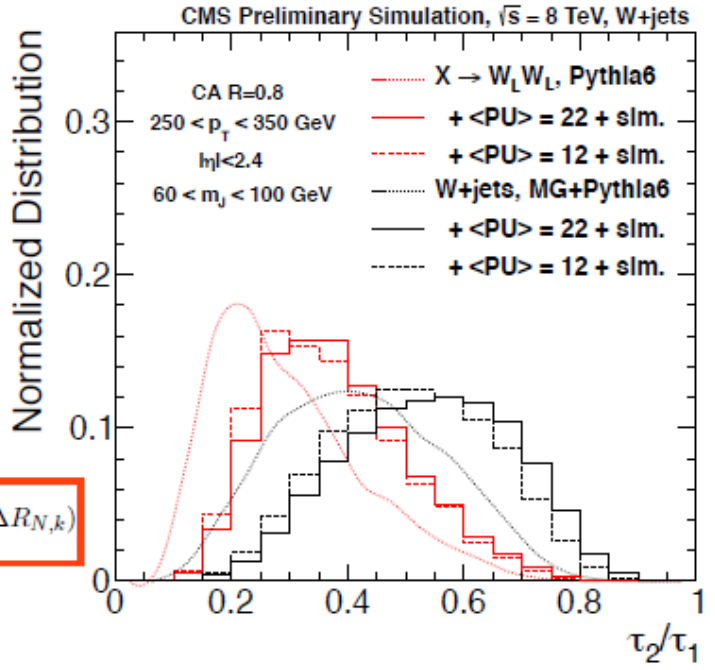
ttbar sample



W-tagging algorithm: N-subjettiness

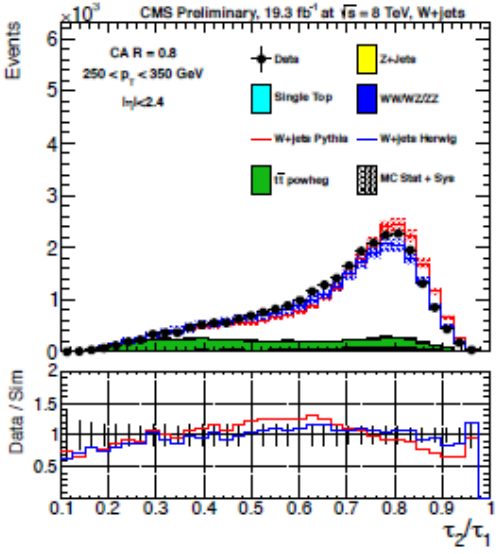


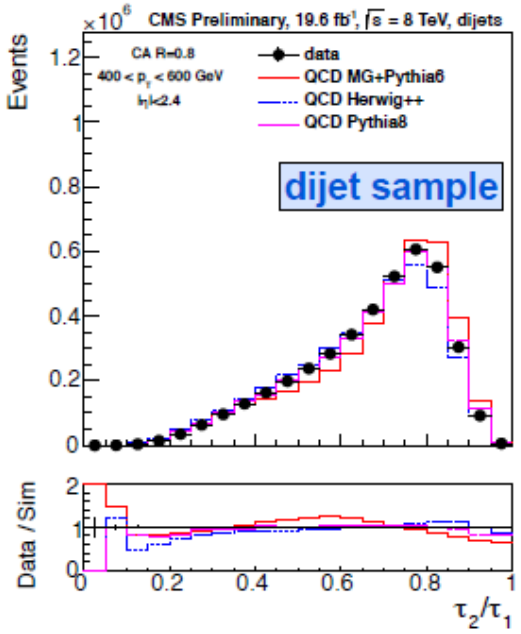
after the pruned mass cut:
60 < m(jet) < 100 GeV



$$\tau_N = \frac{1}{d_0}\sum_k p_{t,k} min(\Delta R_{1,k}, \Delta R_{2,k}, ..., \Delta R_{N,k})$$

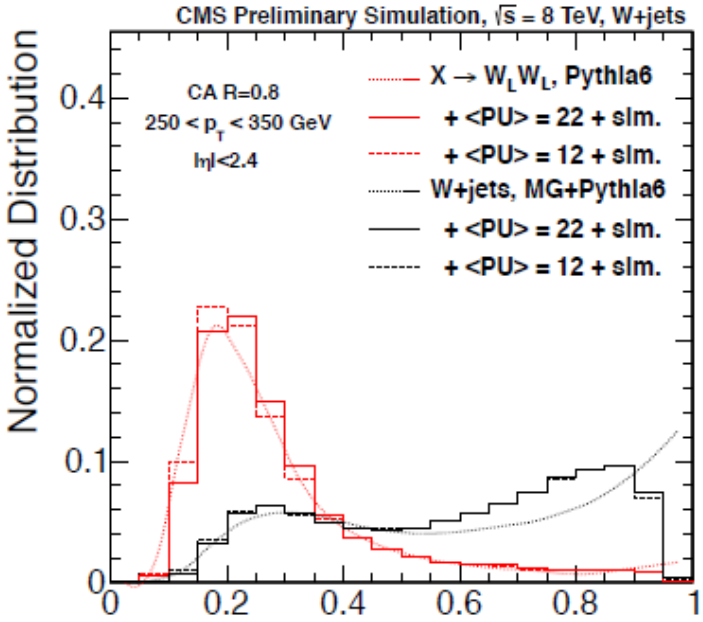
W+jet sample





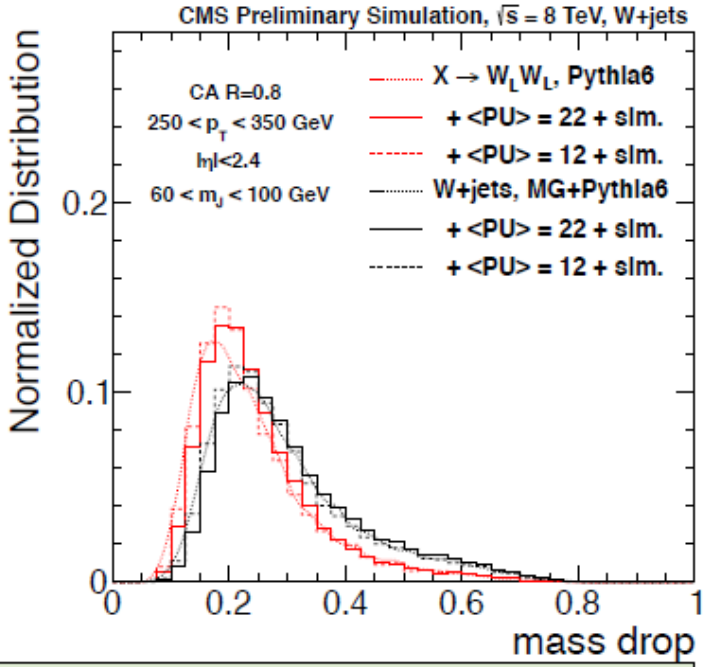
- The **discriminant** variable is the **ratio** between 2- and 1-subjettiness
- High **correlation** between **τ_{21}** and **m(jet)**
- Disagreement between generator and simulation level from **pileup**
- **Data/MC comparison** in two different samples: **W+jets** and **dijet**
- Data/MC disagreements motivate measurement of **SF**

W-tagging algorithm: mass drop

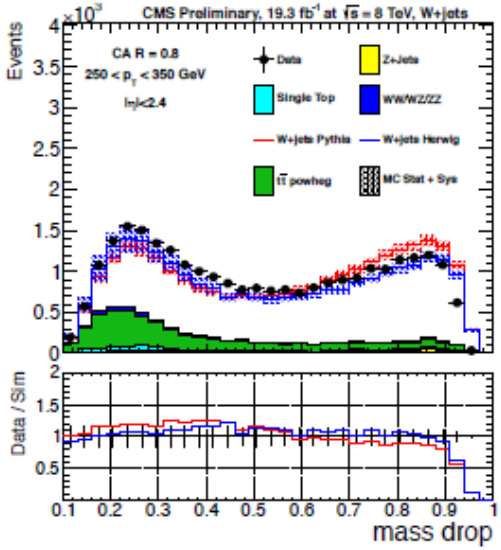


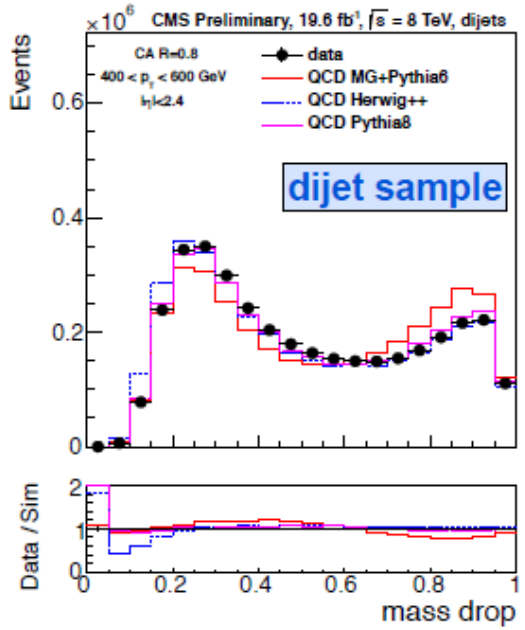
$$\mu = m_1 / m_{jet}$$

after the pruned mass cut:
60 < m(jet) < 100 GeV



W+jet sample





- It peaks at low value for the signal
- High **correlation** between mass drop variable and m(jet)
- **Data/MC comparison** in two different samples: **W+jets** and **dijet**
- Best agreement with herwig++ (W+jets) and pythia8 (dijet)

top-tagging algorithm (I)

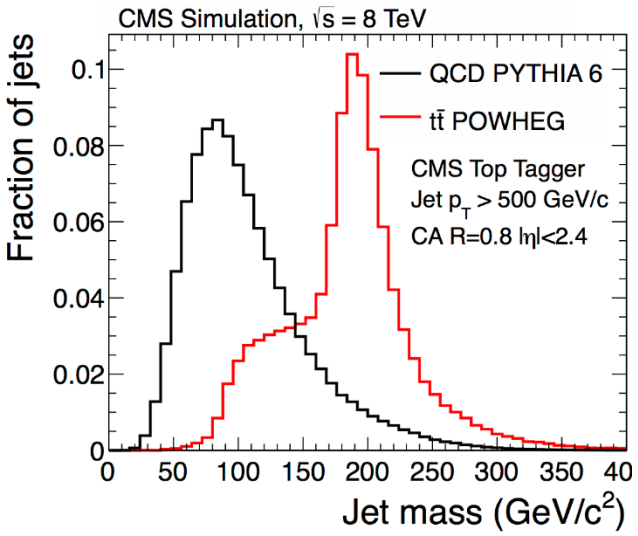
- Developed by ***Kaplan et al***: [Phys. Rev. Lett. 101, 142001 (2008)]
- Main idea: **look for the three partons** that come from the top decaying hadronically
- **Starting point**: jets clustered with CA algorithm and distance parameter of 0.8
- Steps of the algorithm:
  1. the clustering sequence is examined in reverse...
  2. ... till **two subjets satisfy two requirements**
  3. repeat the decomposition on the two subjets

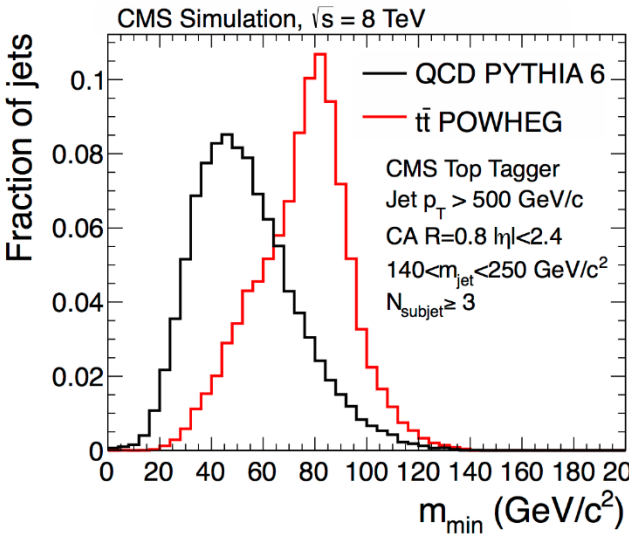
- $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4 - A \cdot p_T^C$
- $p_T^{cluster} > \delta_p \cdot p_T^{hard\ jet}$

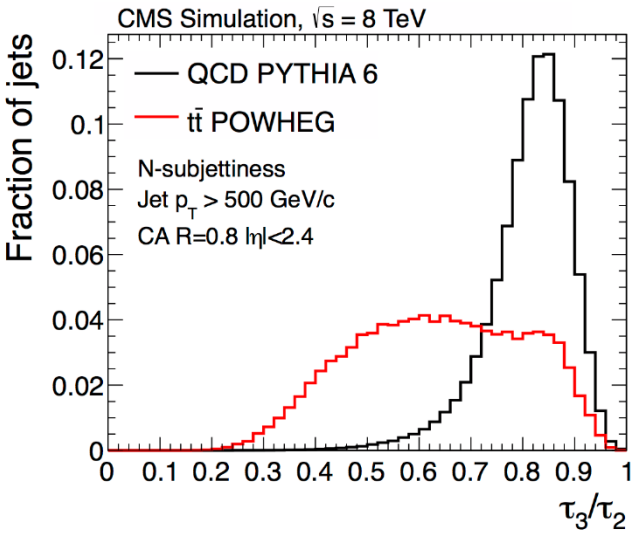
remove **subclusters** that are too **close**

remove **low-pt** subclusters

top-tagging algorithm (II)







Three variables used to tag top-quark:

- Mass of the jet
- N-subjettiness
- Minimum pairwise subjets

mass of the four-vector of all the constituents of the jet

number of subjets found by the algorithm

minimum **invariant mass** between two of the three subjets

ref. CMS PAS JME-13-007