Searches for Massive Top and Bottom Quark Partners at CMS

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On behalf of the CMS Collaboration

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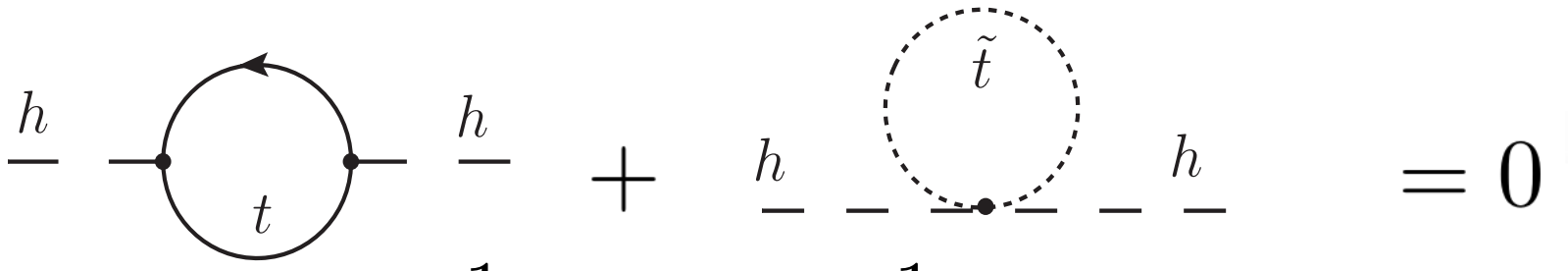
Massive Partners of Top and Bottom Quarks
Supersymmetry

- In supersymmetry the hierarchy problem is solved via contributions from superpartners:



$$\Delta m_h^2 = -\frac{1}{8\pi^2}\lambda_t^2\Lambda^2 + \frac{1}{8\pi^2}\lambda_t^2\Lambda^2 = 0$$

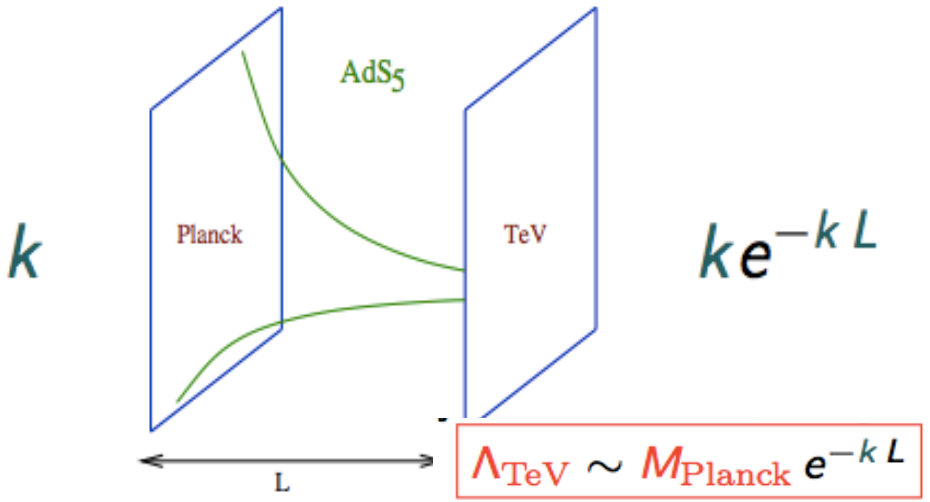
$$\Delta m_h^2 = \frac{1}{8\pi^2}\lambda_t^2(m_{\tilde{t}}^2 - m_t^2)\ln(\frac{\Lambda}{m_h}) \approx 0$$

- Stop is a bosonic partner of the top quark

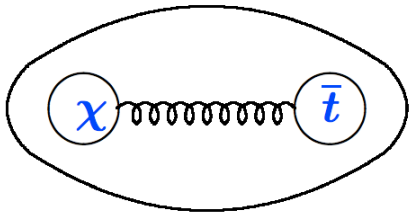
Alternative Solutions to Hierarchy Problem

- Fermionic partners of top quark cancel the top corrections to the Higgs fermions
- New fermions are vector-like

Extra Dimensions



Composite Higgs



Higgs is NOT elementary, composite particle like a pion

Alternative Solutions to Hierarchy Problem

- Fermionic partners of top quark cancel the top corrections to the Higgs fermions
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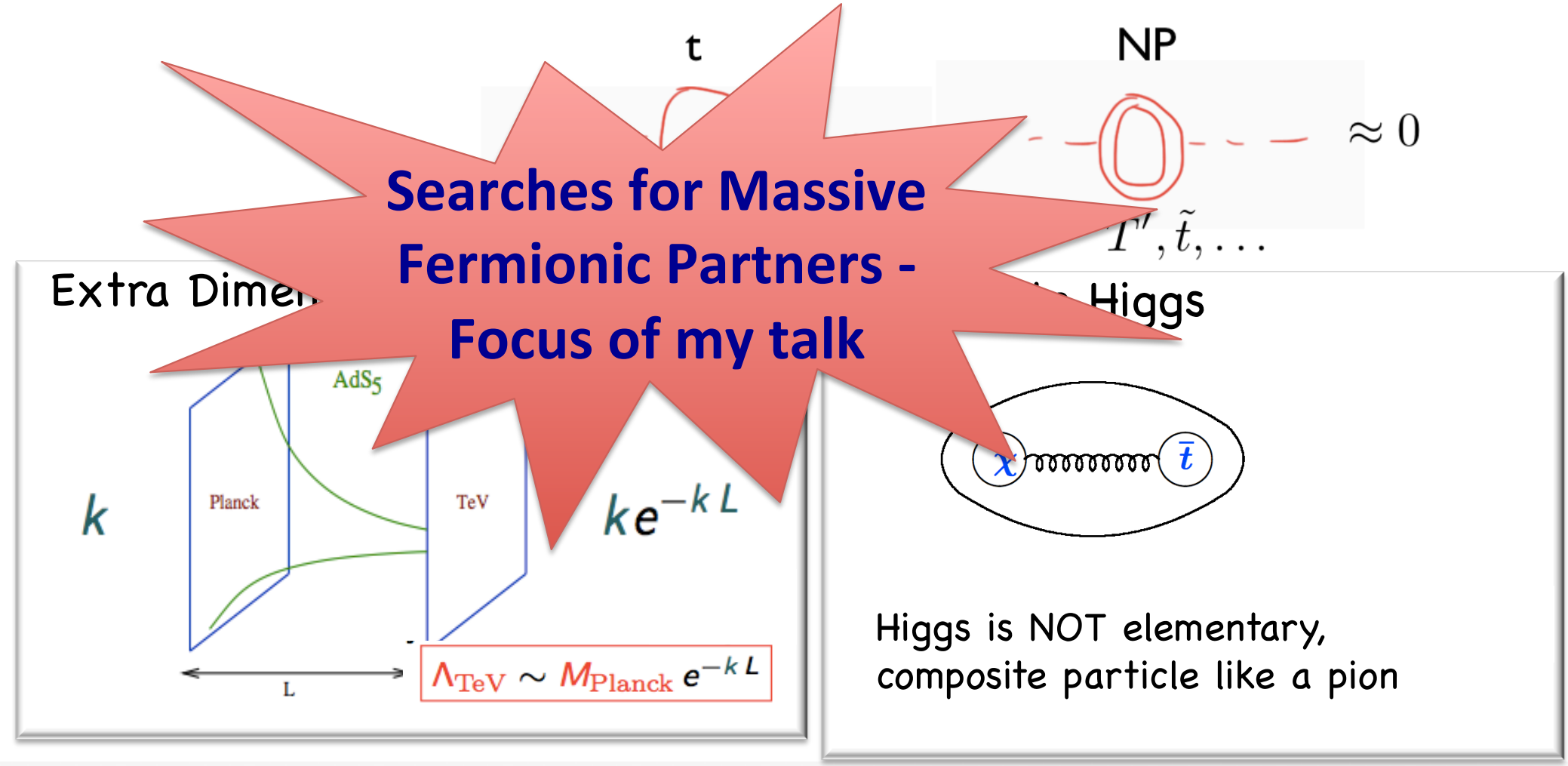
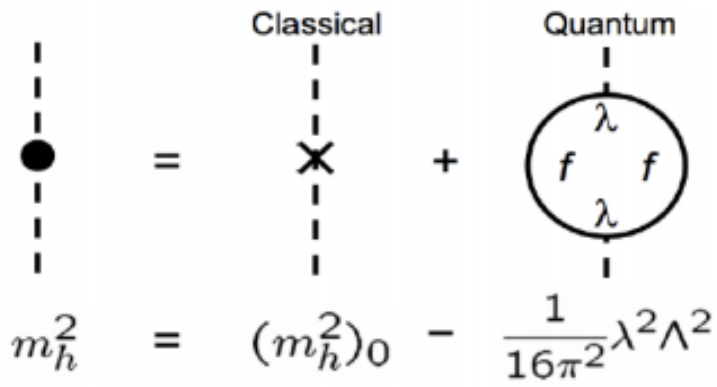


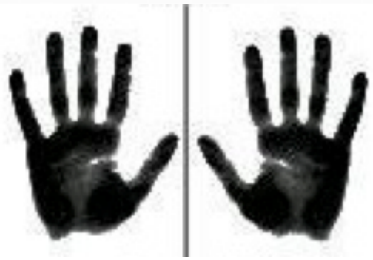
Vector-Like Fermions

- Vector-like quarks are 4th generation quarks with quantum numbers different from Standard Model quarks
- Couplings to W,Z are symmetric or "vector-like"
- Both chiralities have the same representation under the electroweak group $SU(2)_L \times U(1)_Y$
- Vector-like quarks appear in
  - GUT, Composite top, Composite Higgs, Little Higgs
  - Warped extra dimensions
  - Non-minimal super-symmetric extensions
- Cancel quadratic divergences in the Higgs mass induced by radiative corrections in top quark



Chiral vs Vector-like Matter

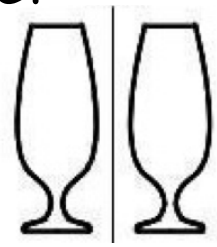
- Chiral Matter

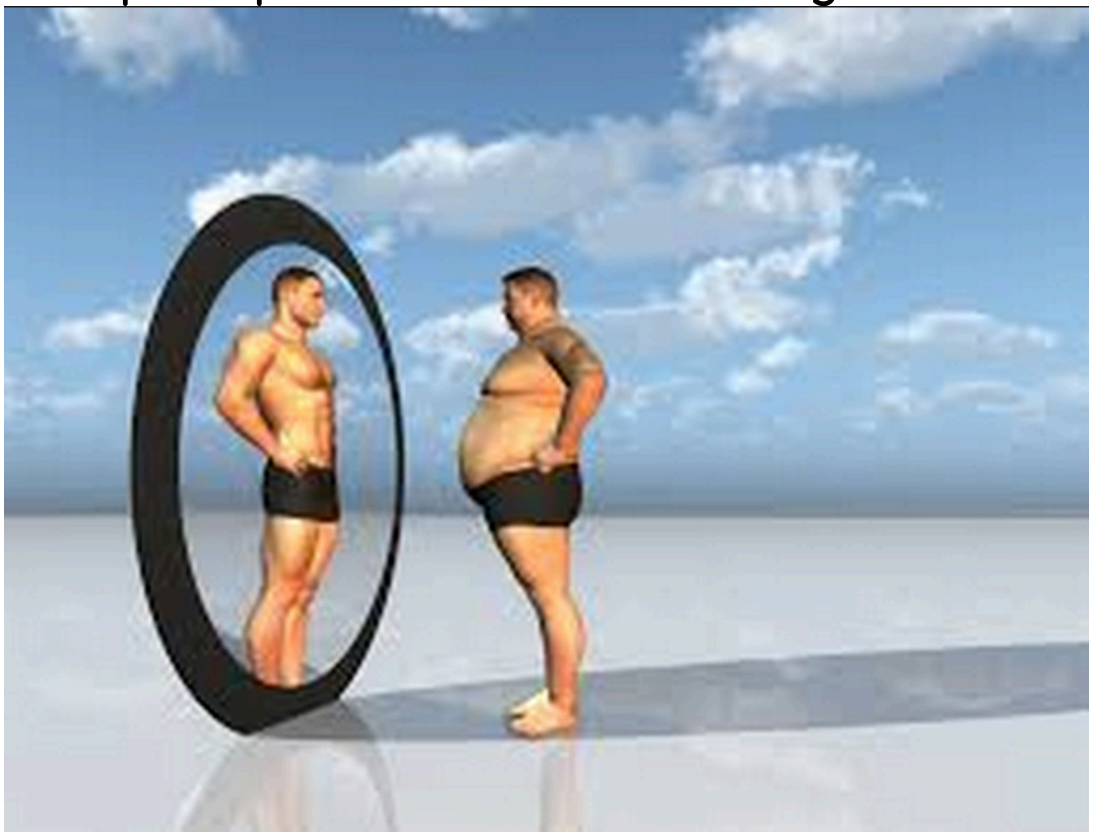


An object that cannot be superimposed on its mirror image

- Vector-Like Matter

Superimposable mirror images





Vector-Like Quarks

	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	(t')	(b')	$\begin{pmatrix} X \\ t' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \end{pmatrix}$	$\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	1/6	7/6	-5/6	2/3	-1/3

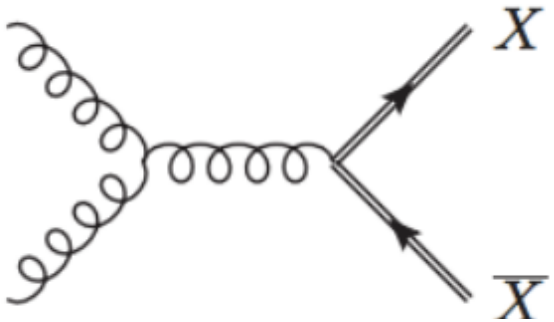
Minimal model: $SO(5) \times U(1)/SO(4) \times U(1)$

$$\mathbf{5}_{SO(5)} \to \mathbf{4}_{SO(4)} \oplus \mathbf{1}_{SO(4)} = (\mathbf{2}_{SU(2)_L}, \mathbf{2}_{SU(2)_R}) \oplus (\mathbf{1}, \mathbf{1})$$

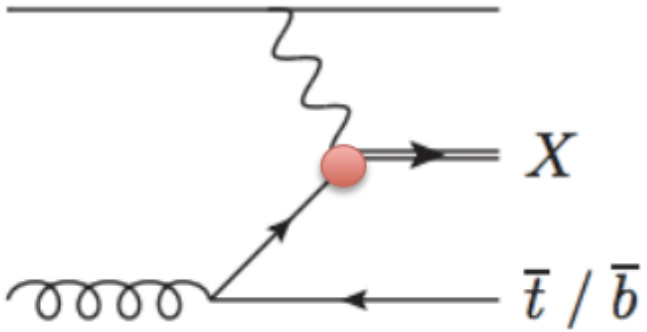
From A. Deandrea presentation at this conference

Production Mechanism

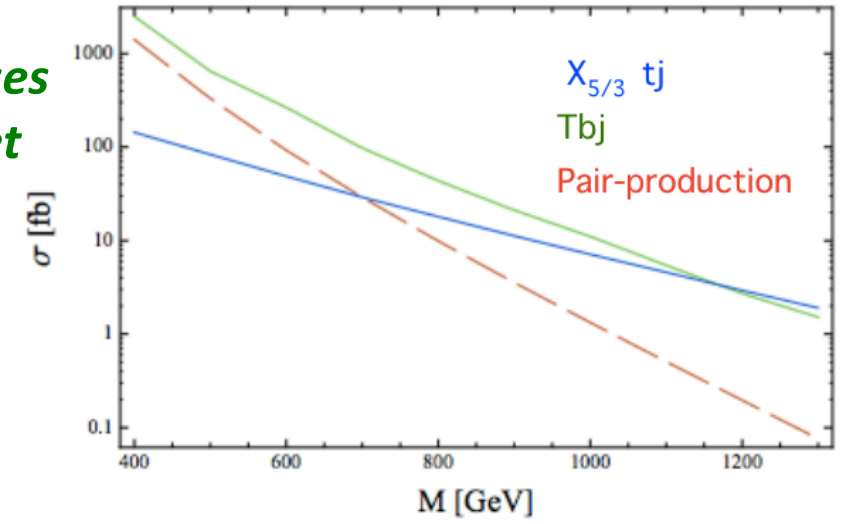
- Pair-production, --model-independent cross section,
- Dominant process at lower vector-like quark masses



- Single production, --model-dependent cross section
- Dominant process at higher vector-like quark masses



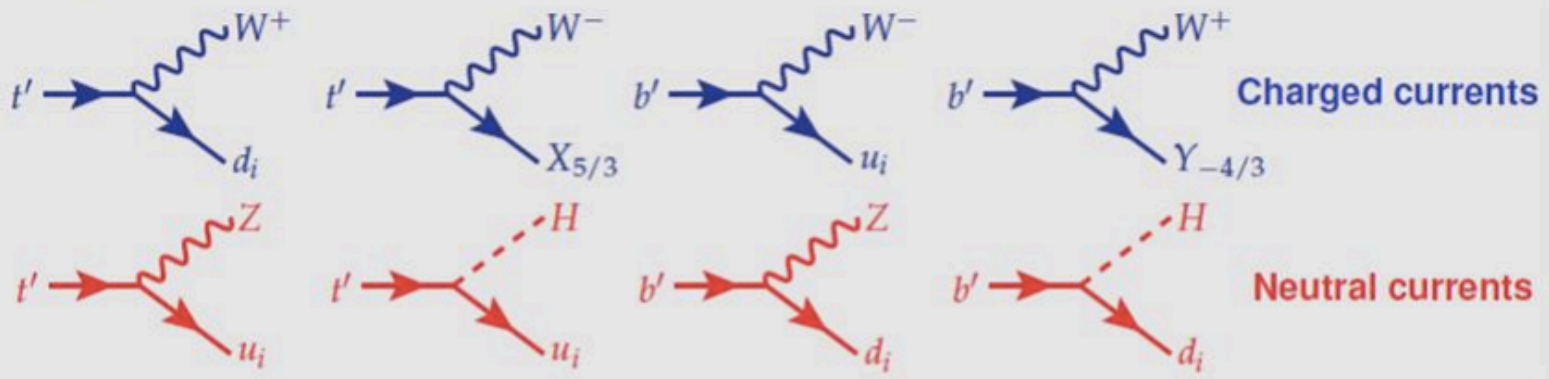
Extensive list of analyses based on Run 1 dataset = This Talk



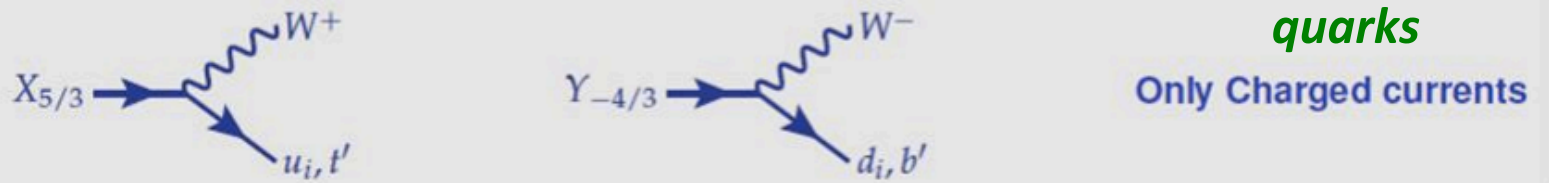
New analyses are in progress in preparation for Run 2 of LHC

Decays

M partners

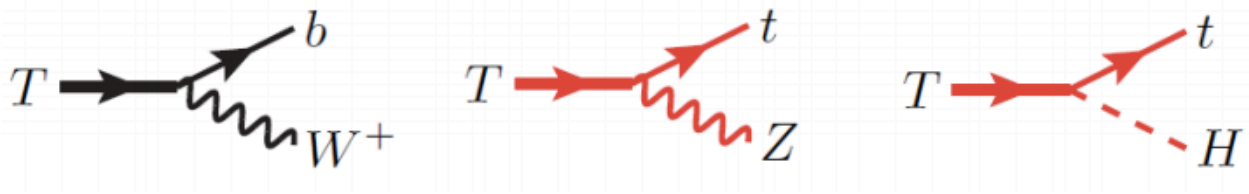


Exotics

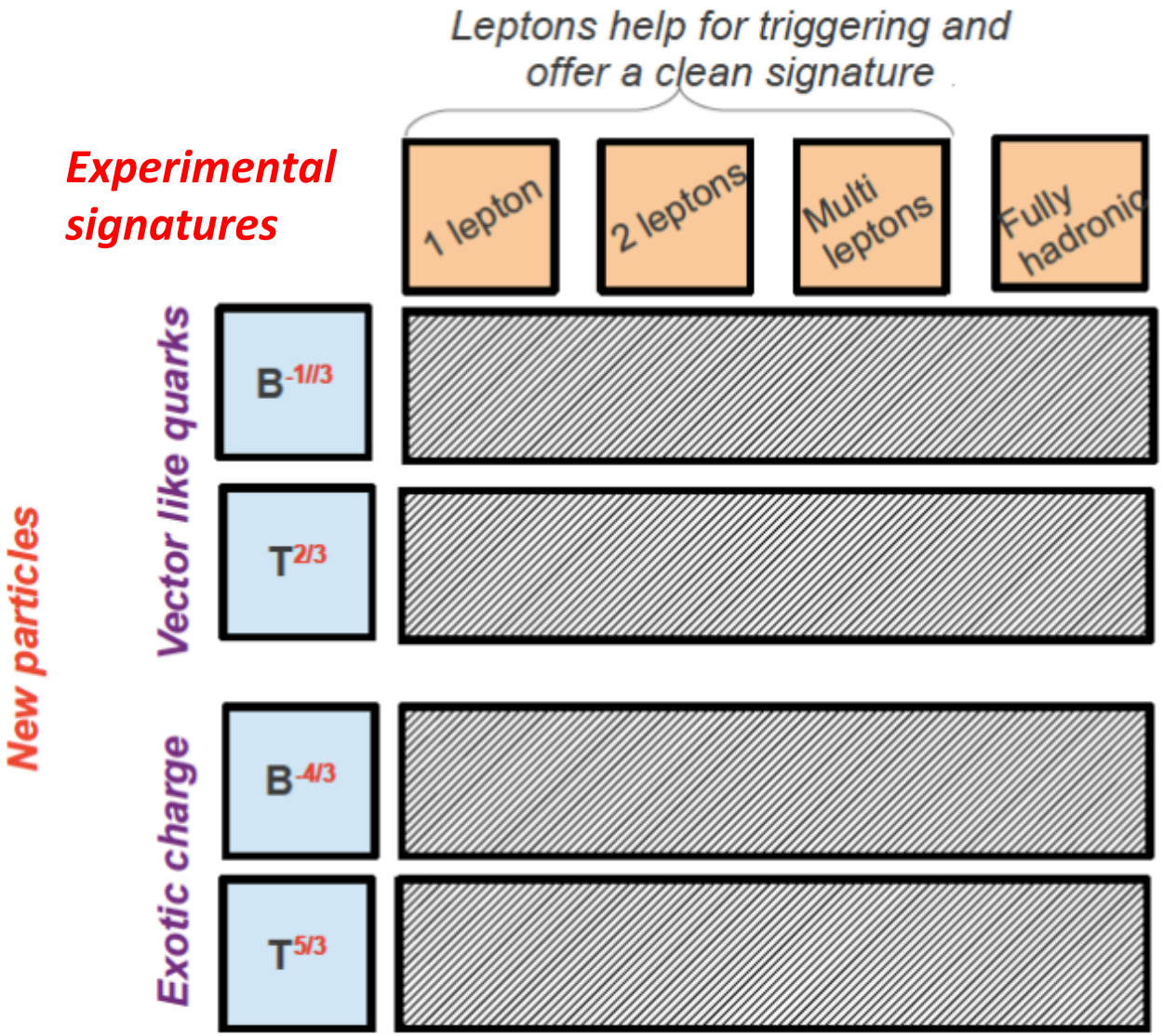


We focus primarily on decays into 3rd gen SM quarks

t'	Wb	Zt	ht
Single, Triplet Y=2/3	50%	25%	25%
Doublets, Triplet Y=-1/3	~ 0%	50%	50%



Searches at CMS



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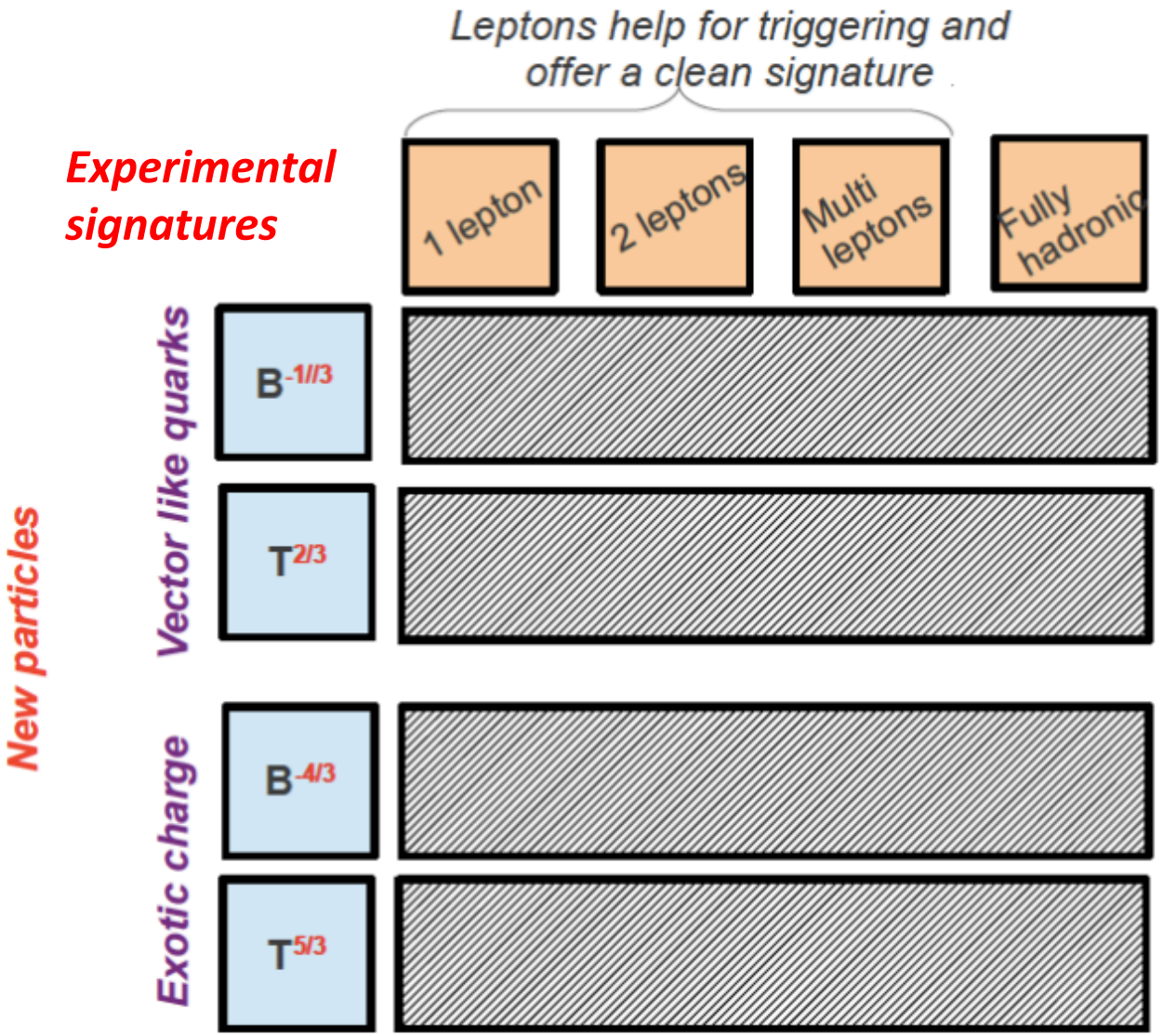


Analyses typically target specific decays

Decays

➔ tW, bZ, bH

Scan over all BRs

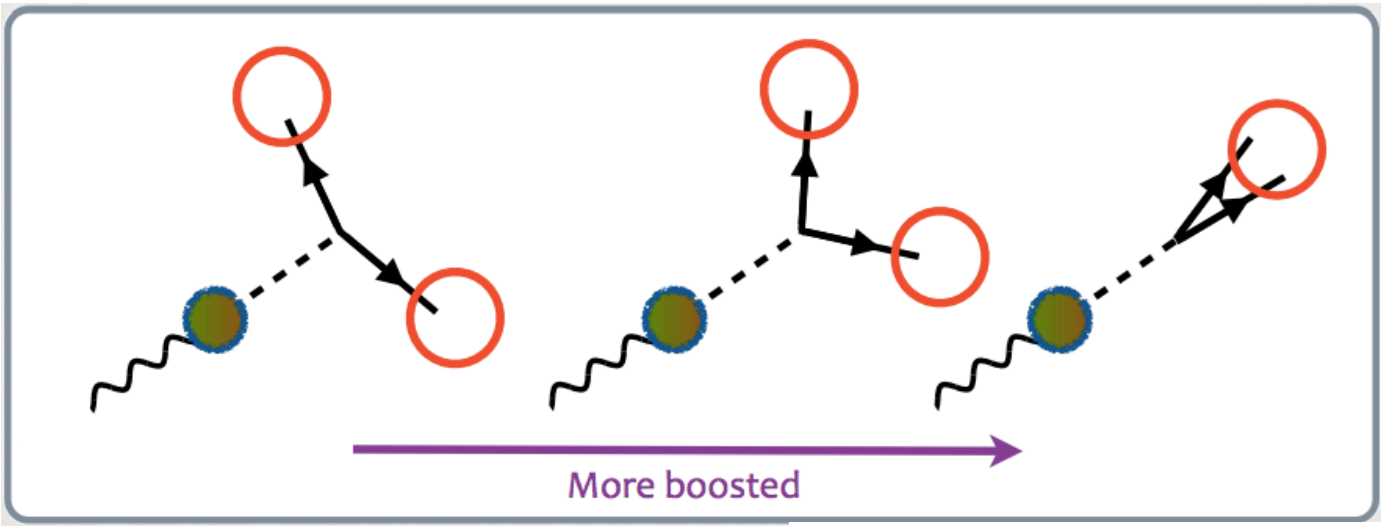
➔ Wb, tH, tZ

➔ Wb (100%)

➔ tW (100%)

Boosted Objects

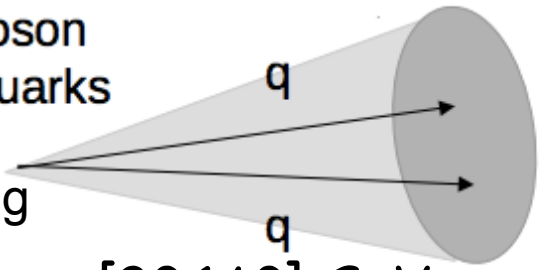
- At higher energies and heavier new particles produce boosted decay products
- We develop and employ new techniques based on the jet substructure using "fat" jets, reconstructed with Cambridge-Aachen algorithm



M_W = [60,130] GeV

R = 0.8

Boosted W boson decaying to quarks

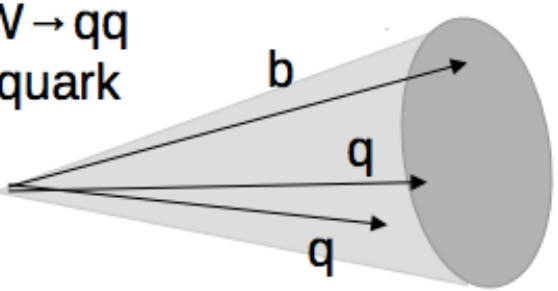


Subjet b-tagging to tag Higgs

M_H = [90,140] GeV

Boosted top quark decaying to W→qq boson and b quark

R = 0.8, 1.5



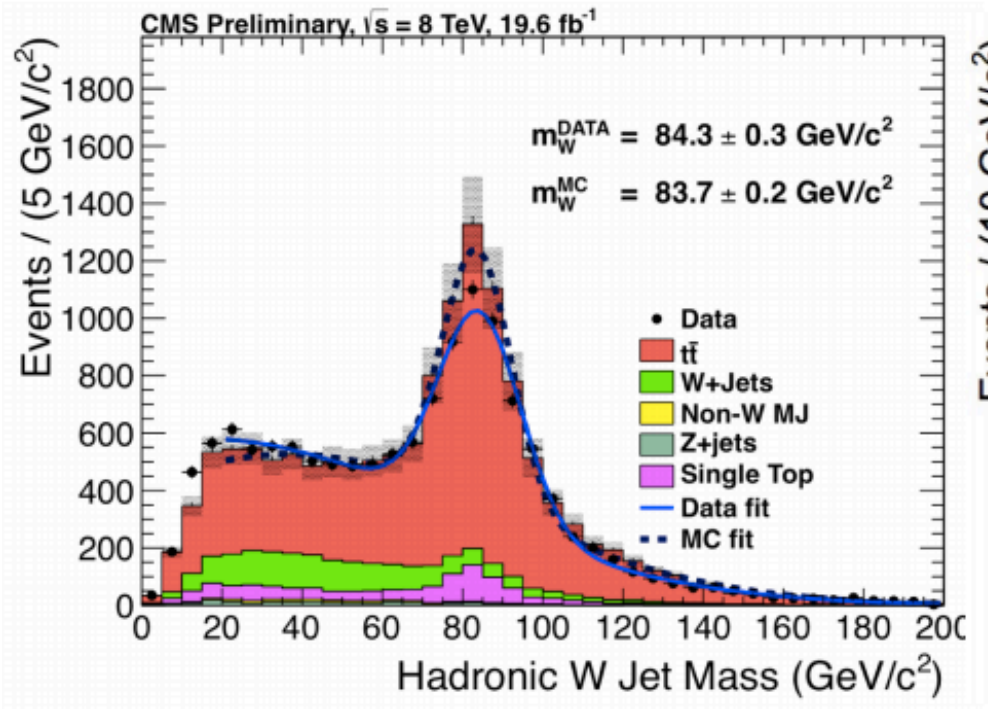
M_t = [140,250] GeV

min M_{12} > 50 GeV

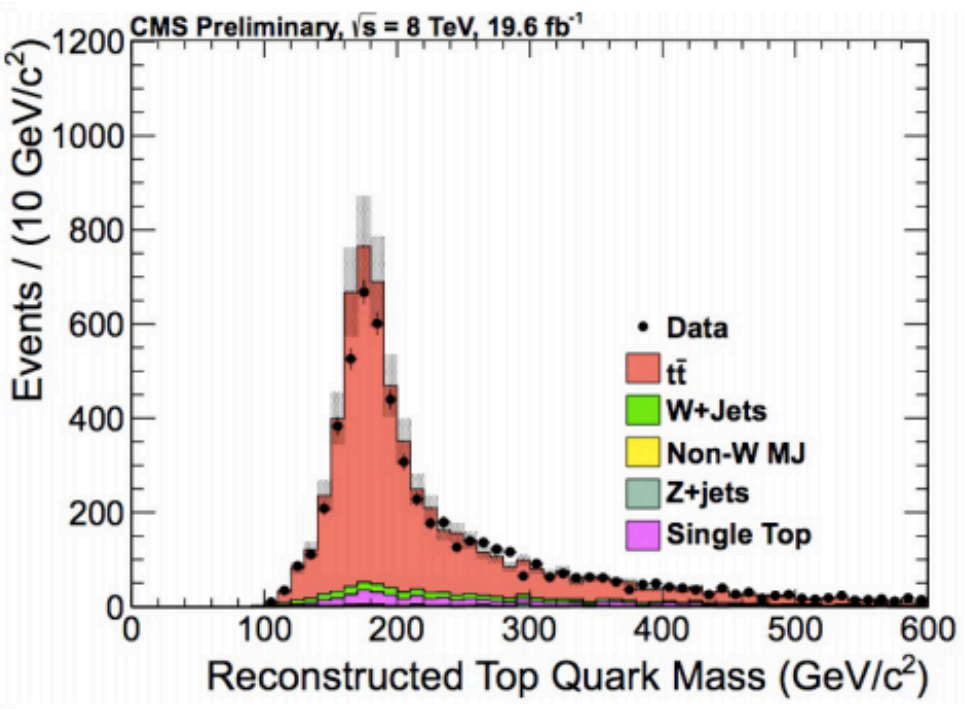
Boosted Objects

CMS-PAS-JME-13-006/007, CMS-PAS-BTV-13-001

Subjet energies are calibrated using W-peak



Validation using semileptonic tt events



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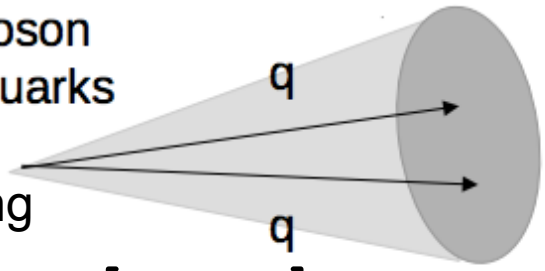

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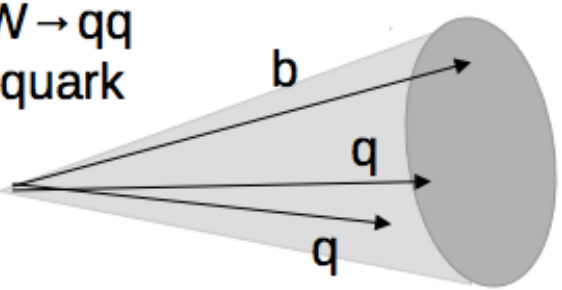


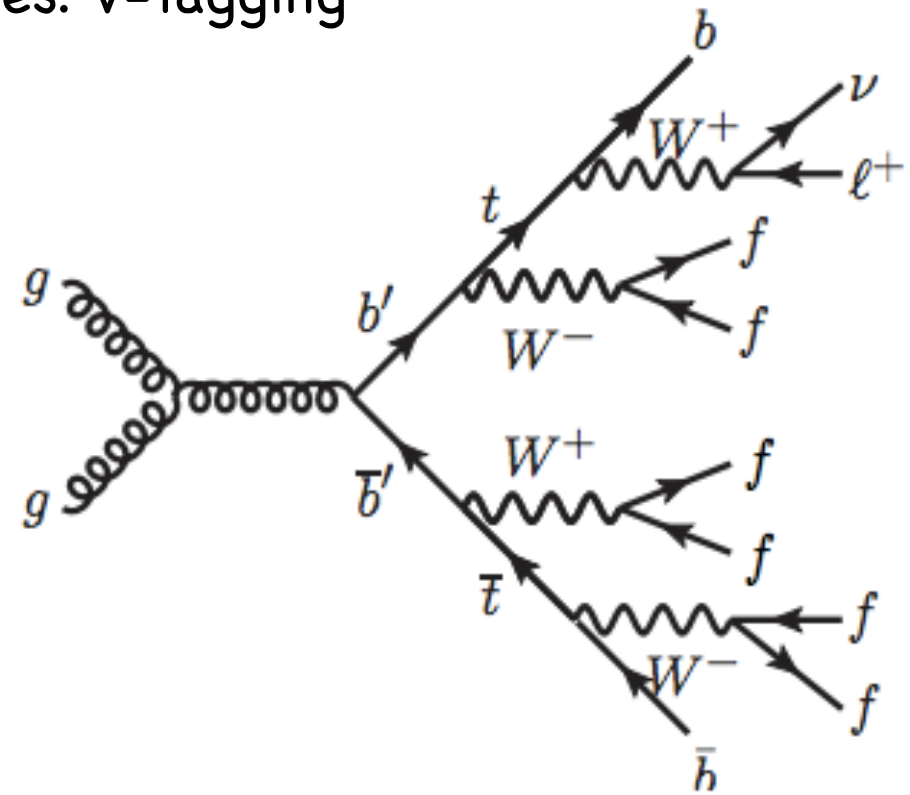
M_t = [140,250] GeV

min M_{12} > 50 GeV

Search for $B^{1/3}$ -> tW in ℓ + jets

CMS-PAS-B2G-12-019

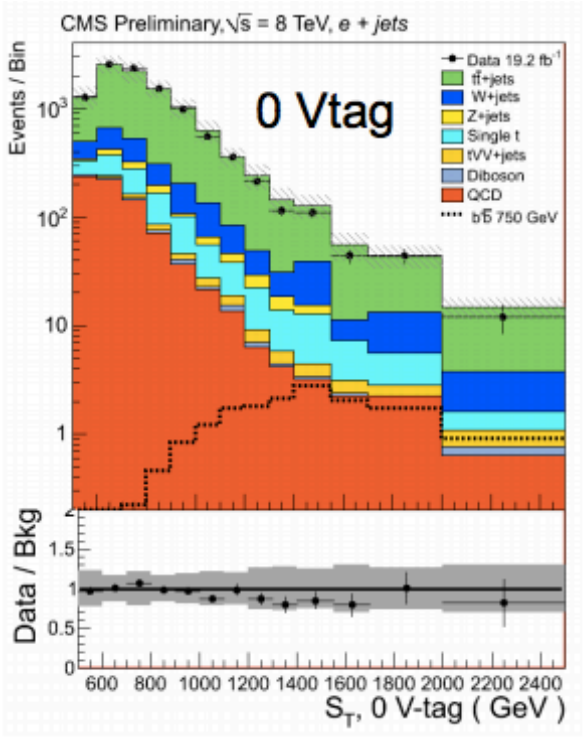
- Signature: lepton + >= 4 jets + 1 btag + MET
- Highly boosted W/Z/Higgs bosons may merge into single jets
- Use jet substructure techniques: V-tagging

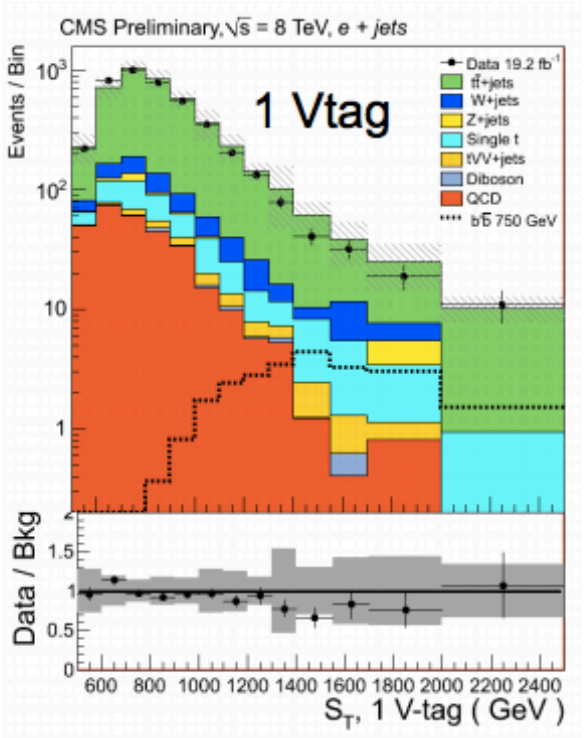


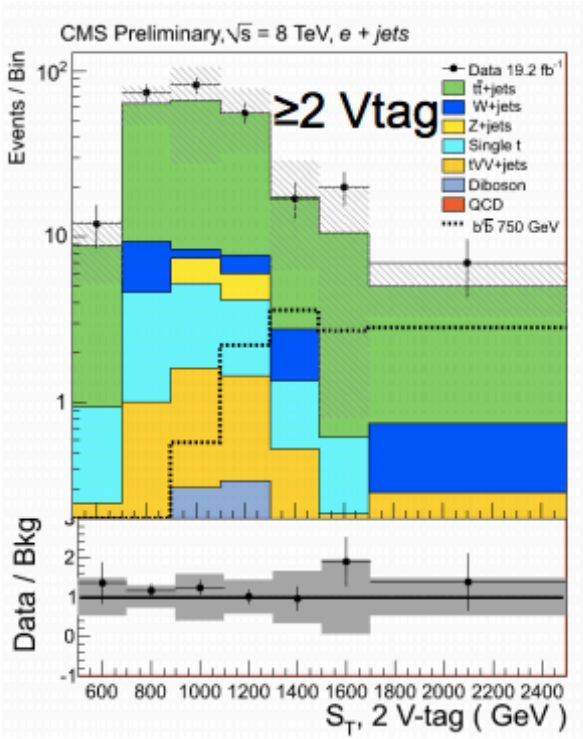
Search for $B^{1/3}$ -> tW in ℓ + jets

CMS-PAS-B2G-12-019

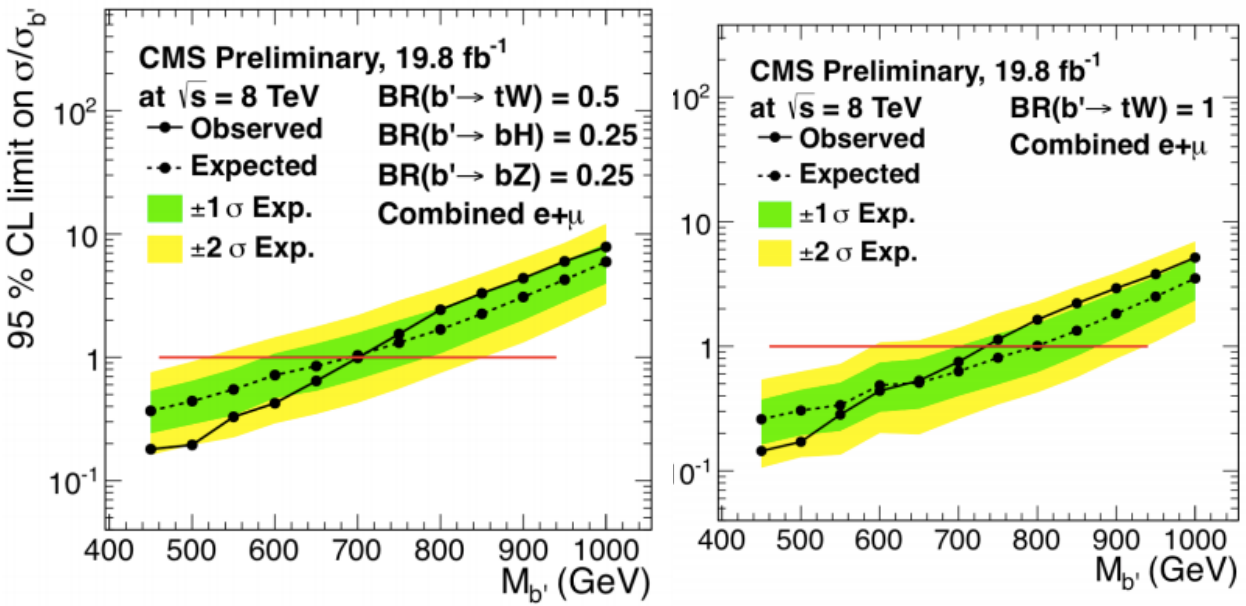
- Signature: lepton + >= 4 jets + 1 btag + MET
- Categorize events based on the number of V-tags
- Perform a fit to S_T distributions as a function of V-tag multiplicity
- Main Background is tt+jets





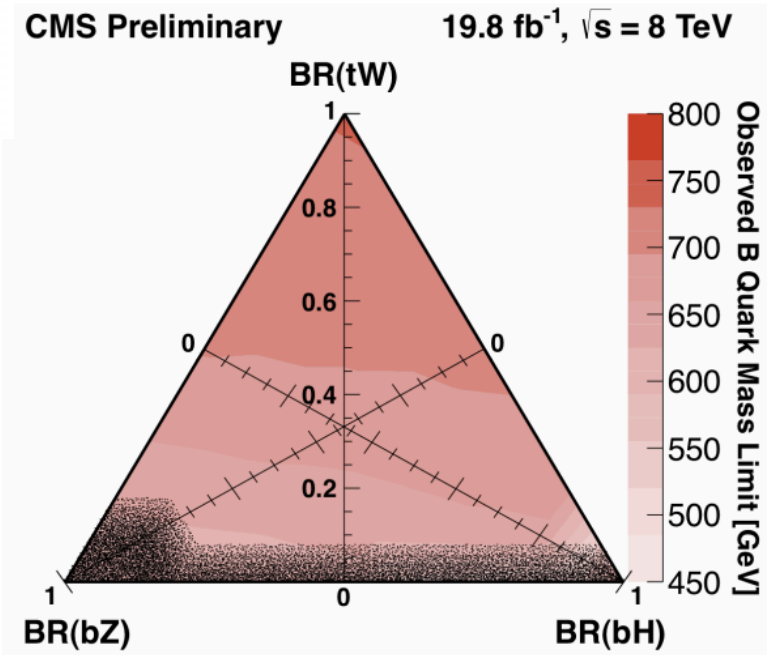


Search for $B^{1/3}$ -> tW in in ℓ + jets



CMS-PAS-B2G-12-019

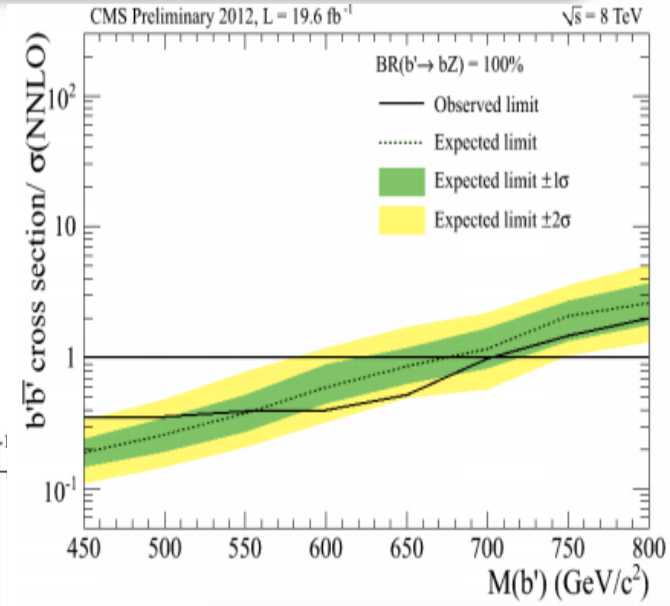
$M_B > 732$ GeV @ 95 % C.L.
BR (B→tW) = 100%

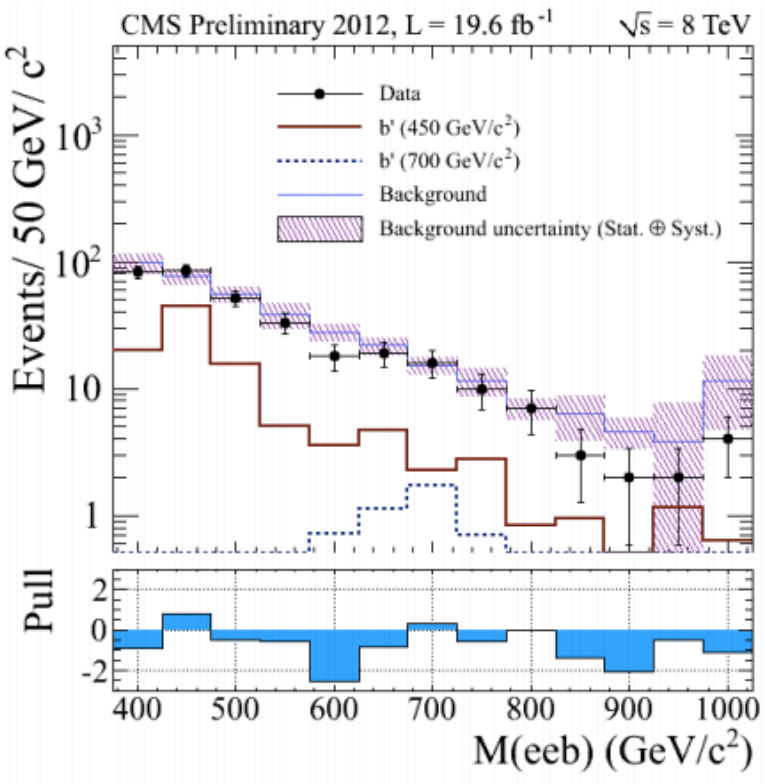


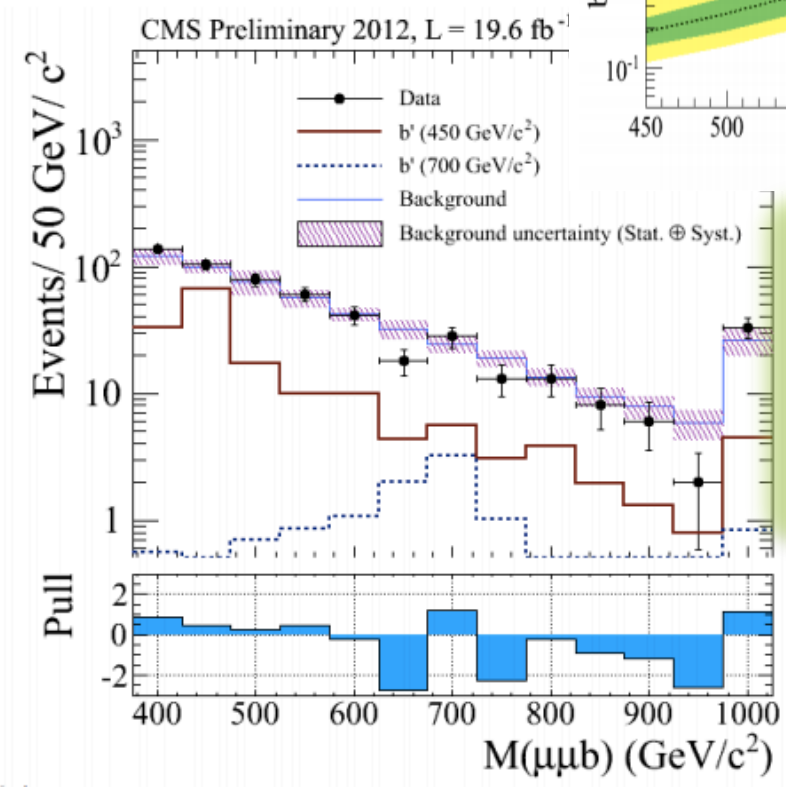
Search for $B^{1/3}$ ->bZ in Di-leptons

CMS-PAS-B2G-12-021

- Target: at least one B->bZ, Z-> ll
- Signature: 2 oppositely charged leptons, consistent with Z-mass + 1b-tag
- Search for resonance in the bZ invariant mass distribution







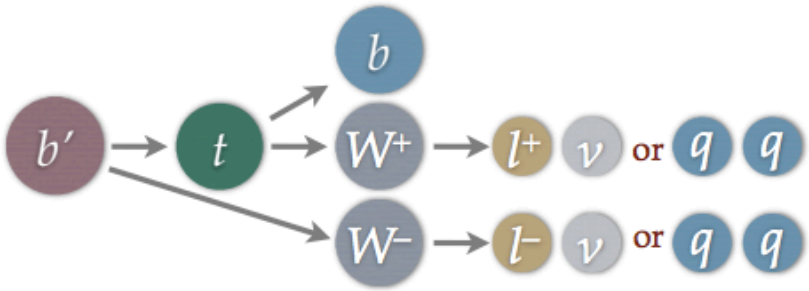
M_B > 700 GeV @ 95 % C.L.
BR (B→bZ) = 100%

Search for $B^{1/3}$ in SS Di-leptons

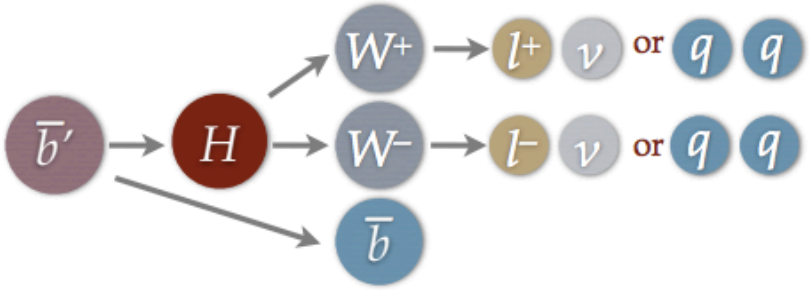
CMS-PAS-B2G-12-020

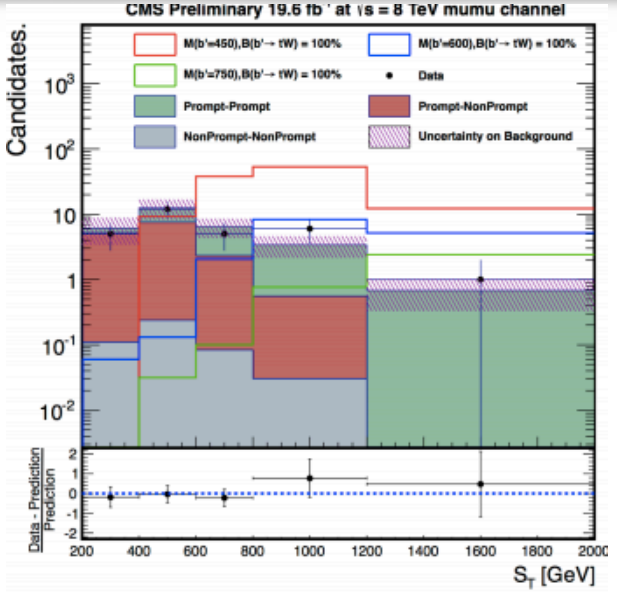
- Signature: 2 SS charged leptons, >= 4 jets, >= 1b-tagged jet
- Background fit to S_T distribution, 5 exclusive bins

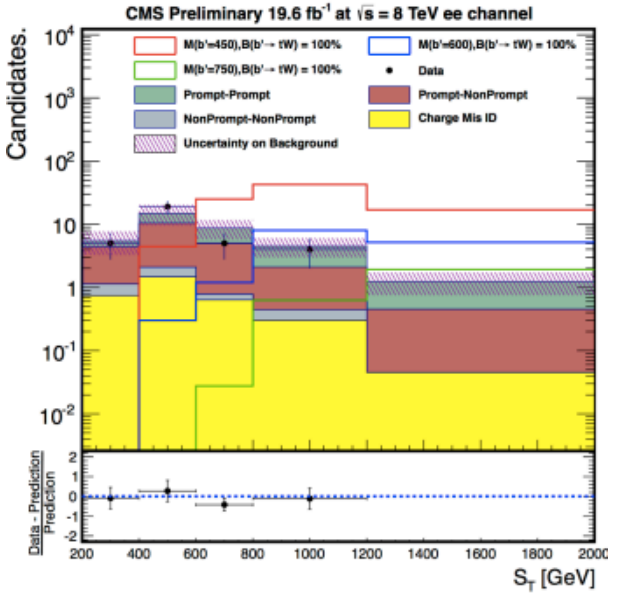
b'→ tW :



b' → bH :



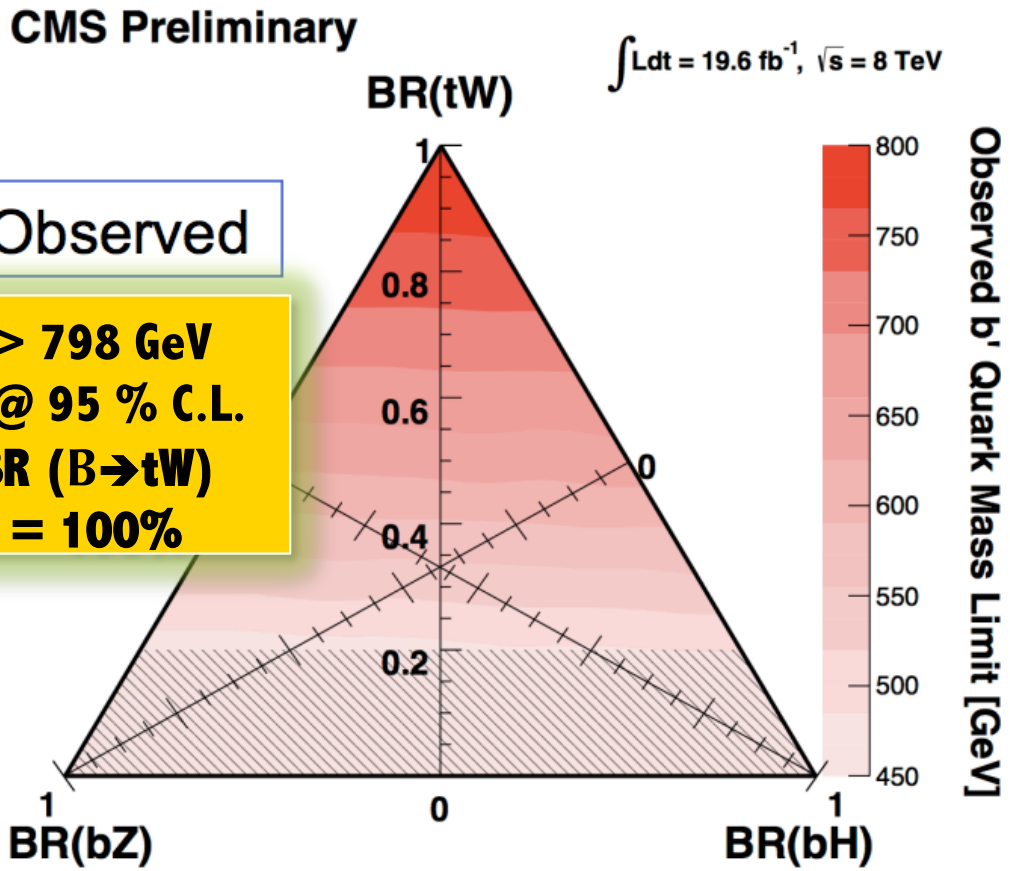




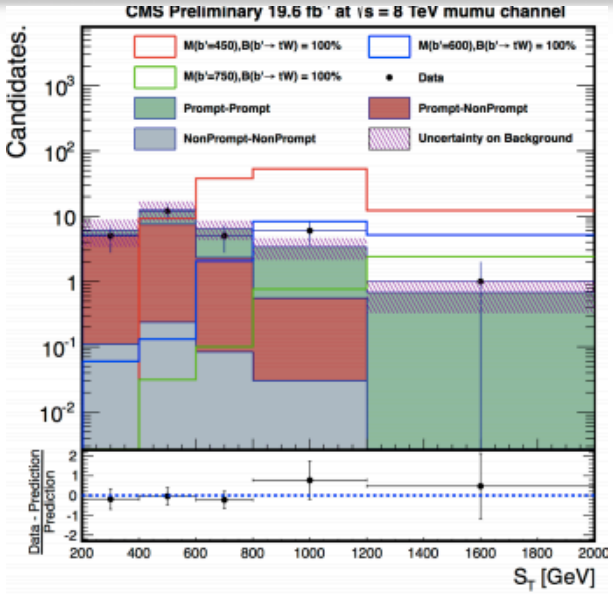
Search for $B^{1/3}$ in SS Di-leptons

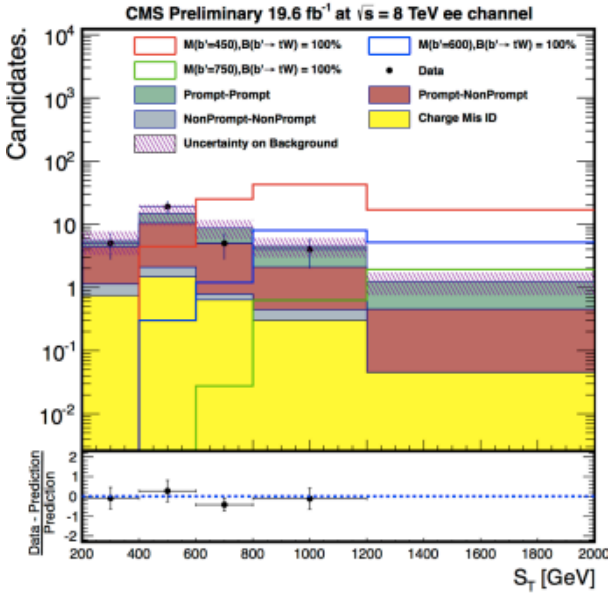
CMS-PAS-B2G-12-020

- Signature: 2 oppositely charged leptons >= 4 jets, 1b-tagged jet
- Background fit to S_T distribution, 5 exclusive bins



M_B > 798 GeV @ 95 % C.L. BR (B→tW) = 100%

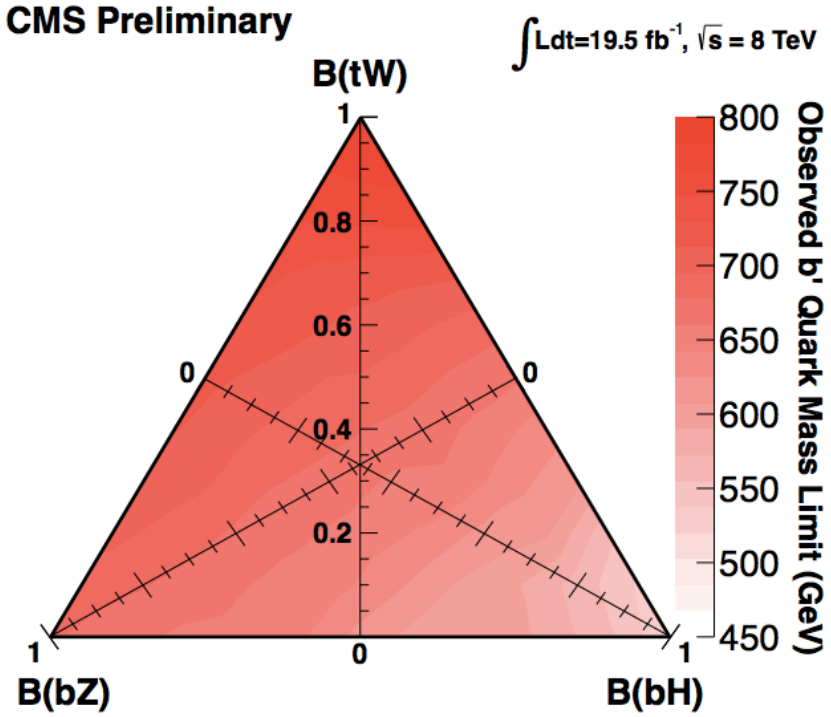


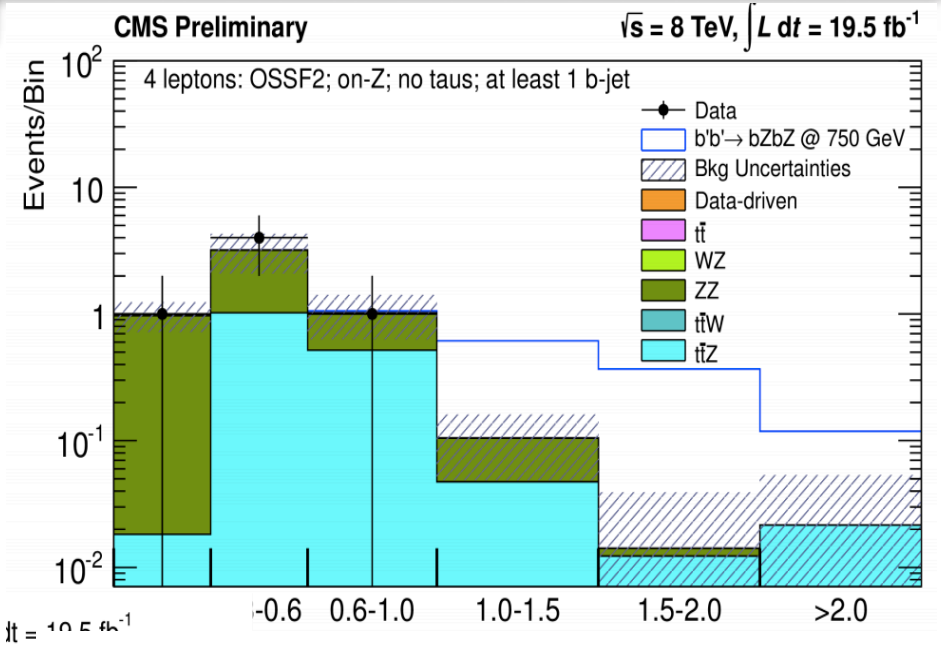


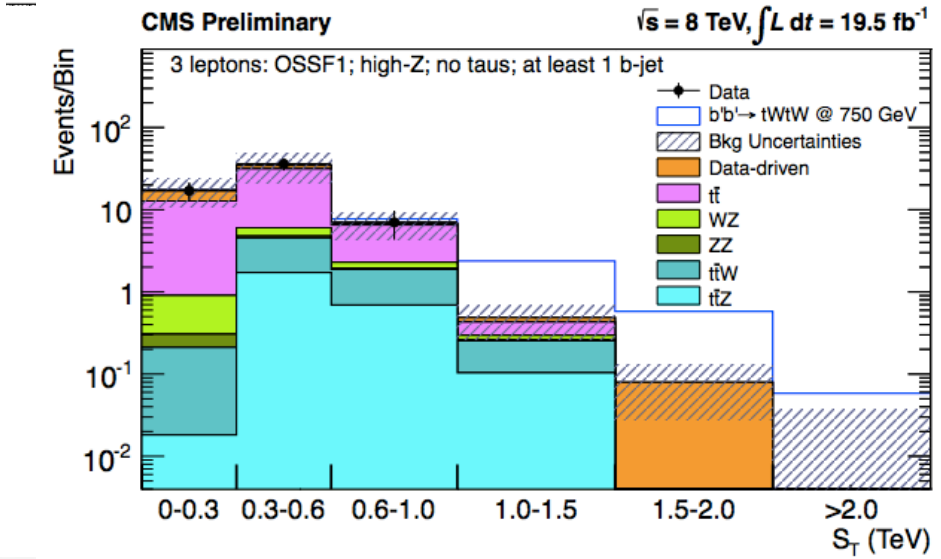
Search for $B^{1/3}$ in Multi-leptons

CMS-PAS-B2G-12-021

- Signature: >=3 leptons (electrons, muons or hadronically decaying taus),
- >= 1 b-tag
- Events classified based on the # of leptons, lepton and jet flavor, H_T and S_T



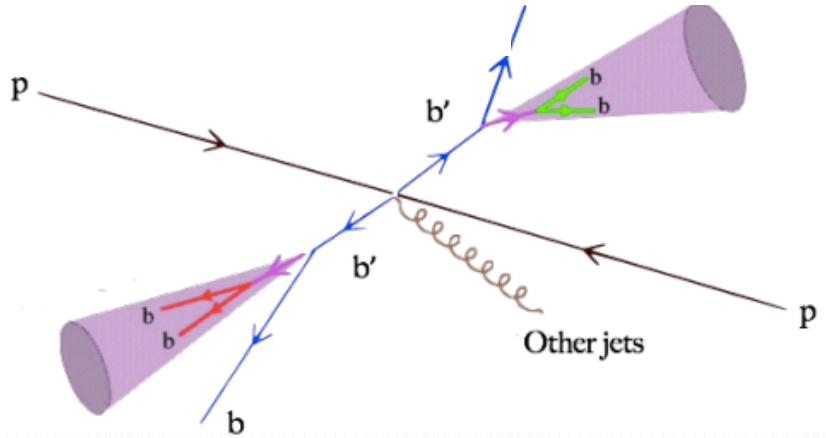


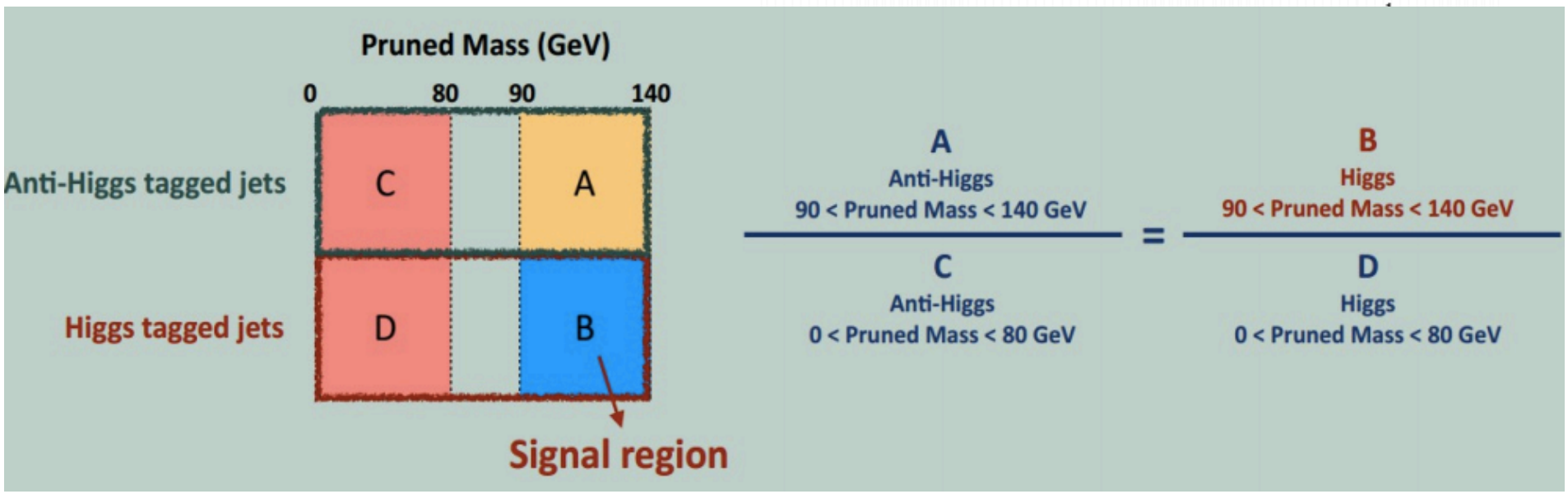


Search for $B^{1/3}$ -> bH, H->bb

CMS-PAS-B2G-14-001

- All-hadronic channel
- Employ Higgs-tagging using jet substructure
- Subjet b-tagging
- Control region from inverted subjet b-tag requirements



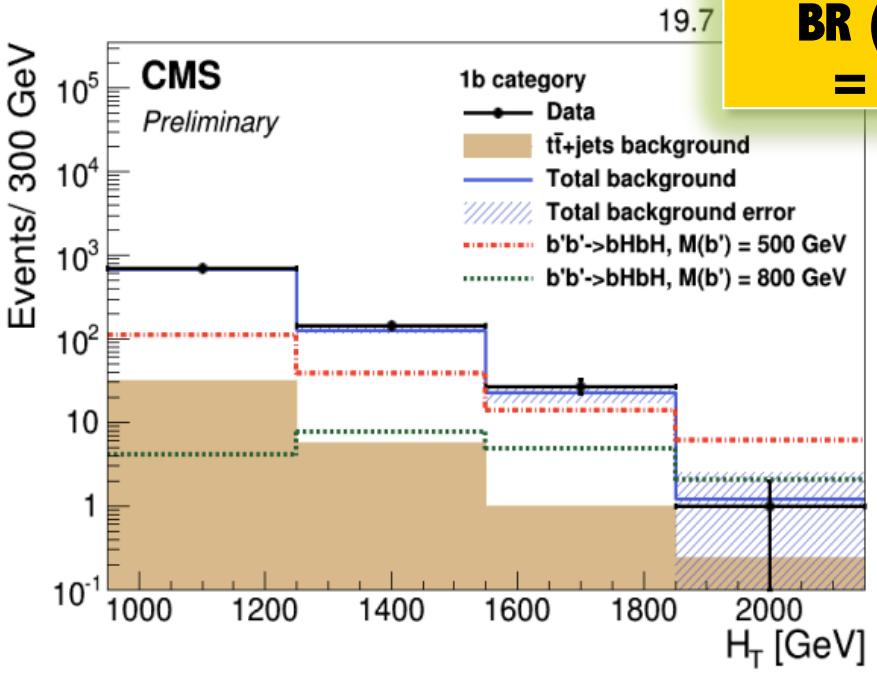


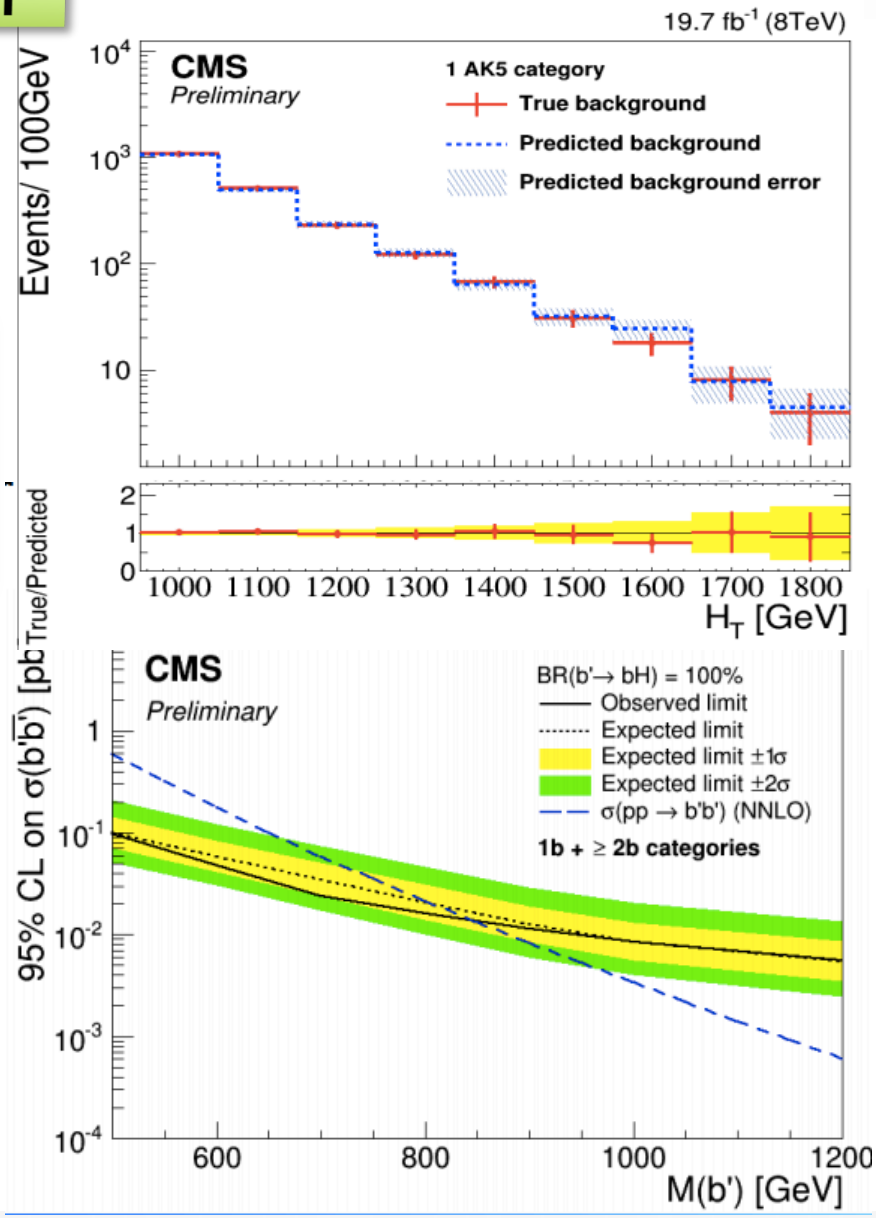
Search for $B^{1/3}$ -> bH, H->bb

CMS-PAS-B2G-14-001

- Closure test in the b-vetoed region
- == 1b, >=2 b categories of events
- Fit to H_T

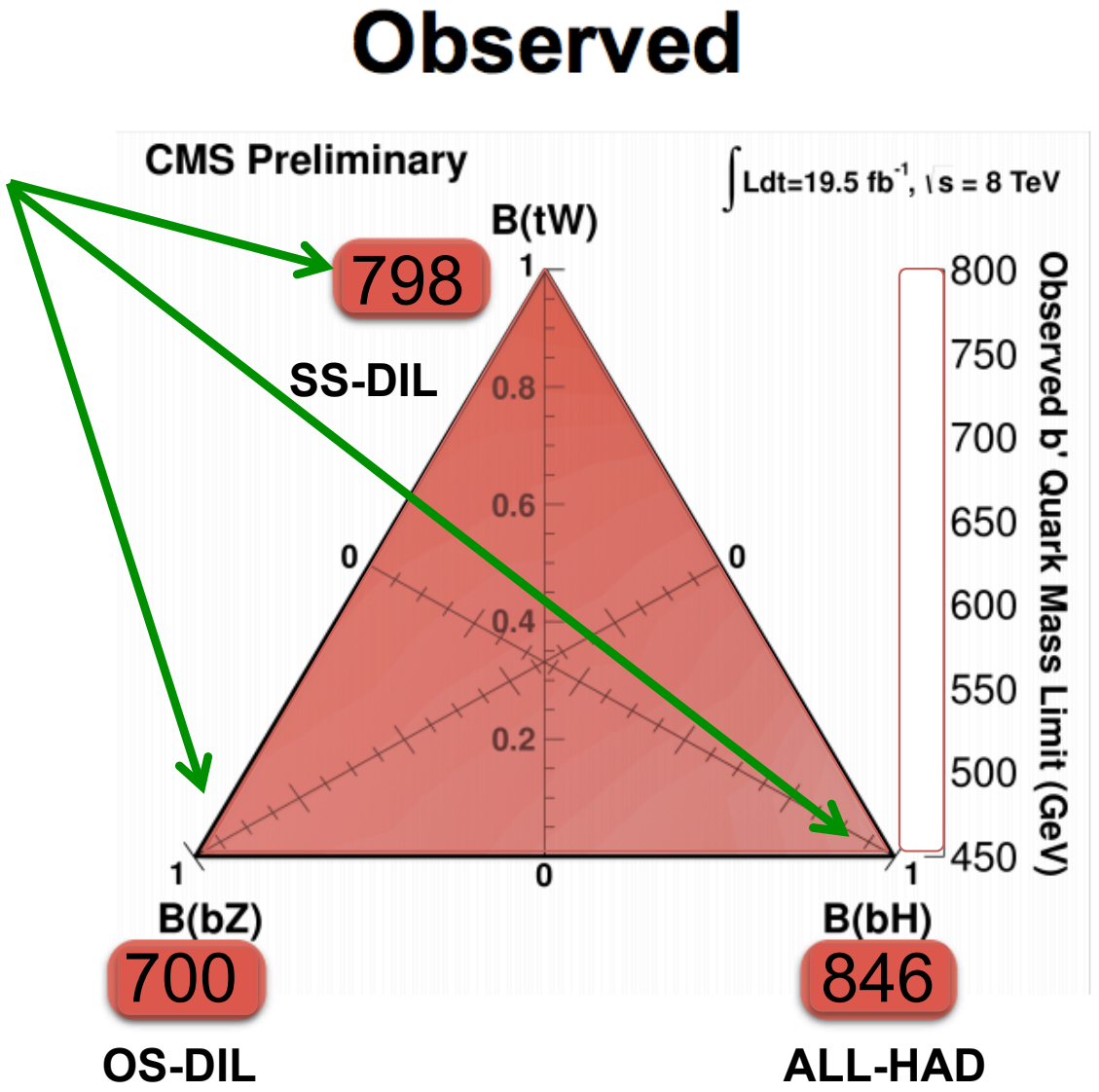
M_B > 846 GeV @ 95 % C.L.
BR (B→bH) = 100%





$B^{1/3}$ Summary

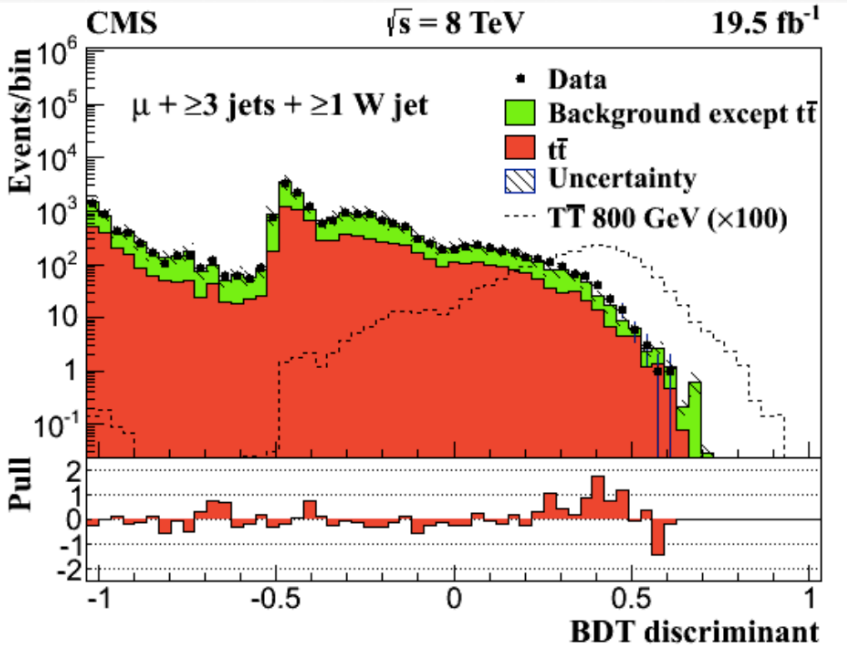
- Best observed limits from individual analyses
- Grand combination will be available very shortly
- Pushes limits up to ~900 GeV

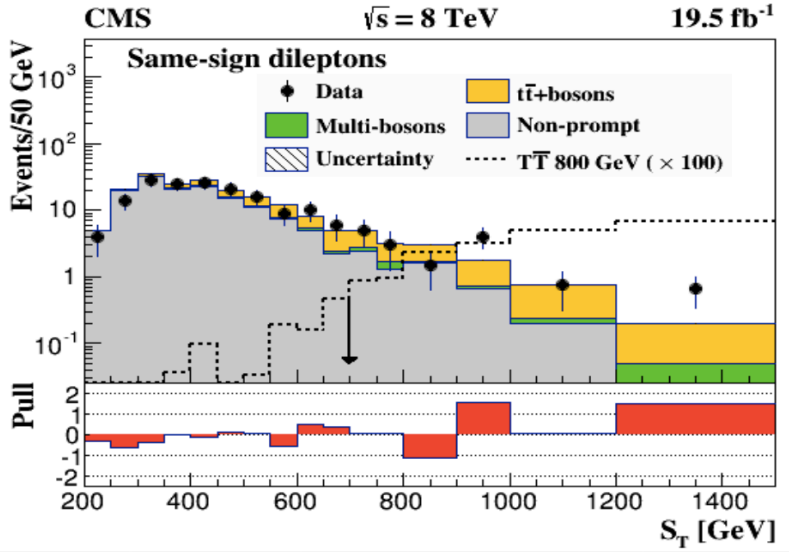


Search for $T^{2/3}$ in Leptonic States

PLB 729 (2014) 149

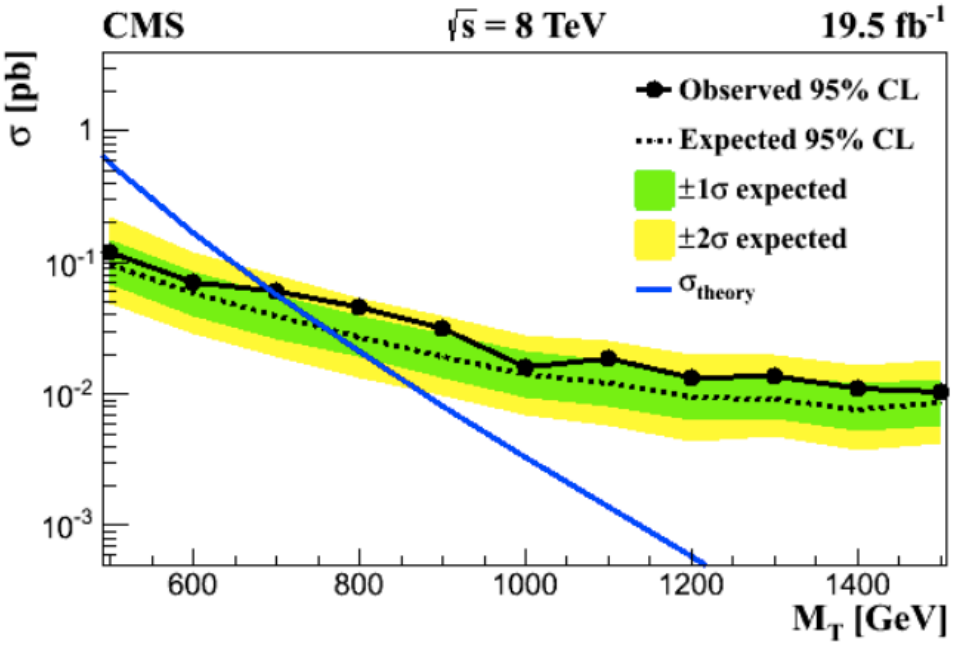
- Combination of l+jets + di-/multi-lepton searches
- Lepton+jets: 1 isolated lepton + >=3 jets, either
  - 4^{th} jet
  - Or W-tagged jet
- Boosted Decision Tree and multiple signal regions to maximize sensitivity
  - With and without W boson tags
  - With and without b-quark tags
- Multi-lepton analysis:
  - 12 categories, cut-and-count
  - SS DIL, OS DIL, + 3^{rd} lepton

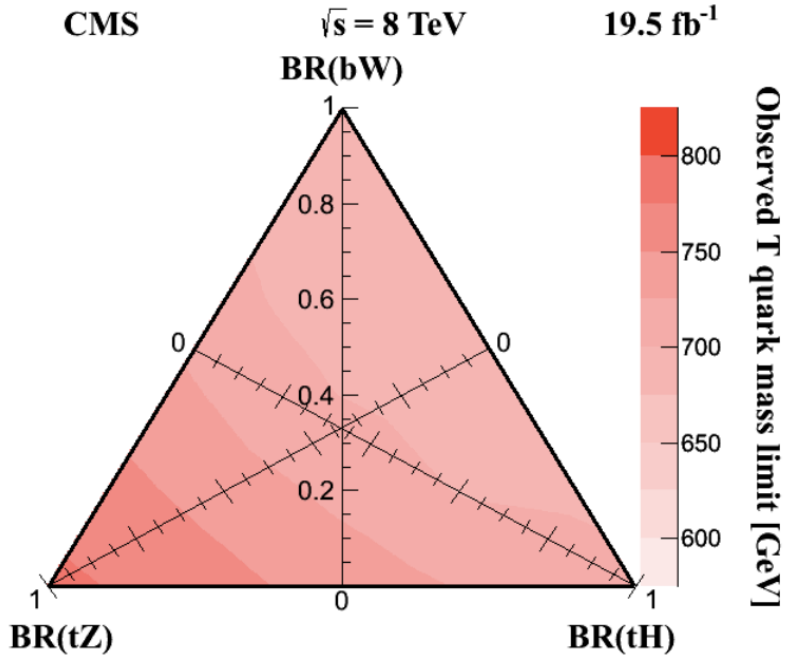




Search for $T^{2/3}$ in Leptonic States

PLB 729 (2014) 149



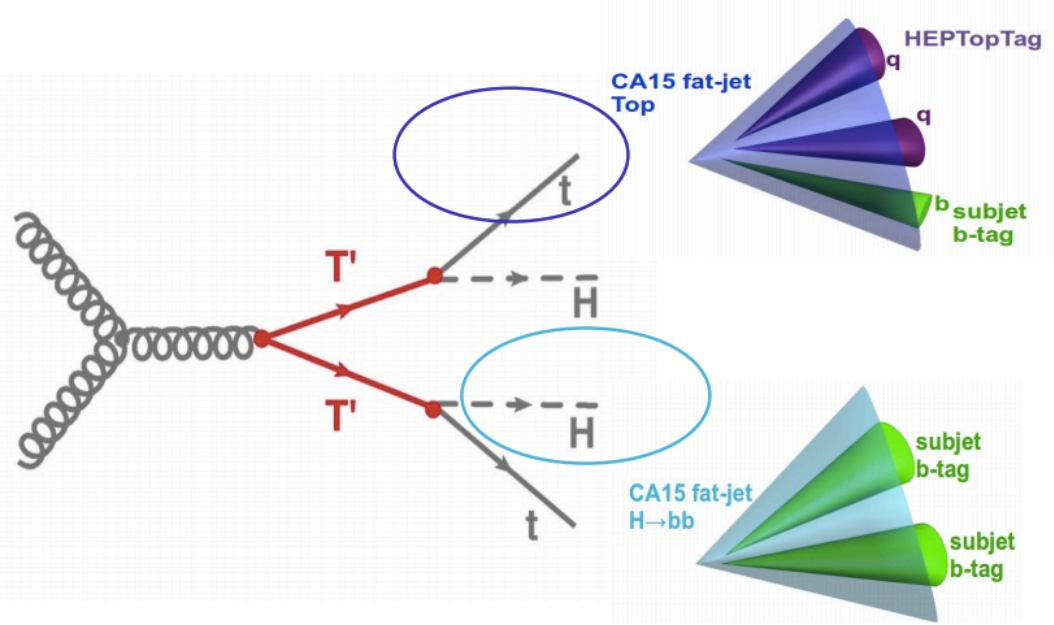


M_T > 696 GeV @ 95 % C.L.
BR (T→Wb) = 50%
BR (T→tH) = 25%
BR (T→tZ) = 25%

Search for $T^{2/3}$ in All-Hadronic State

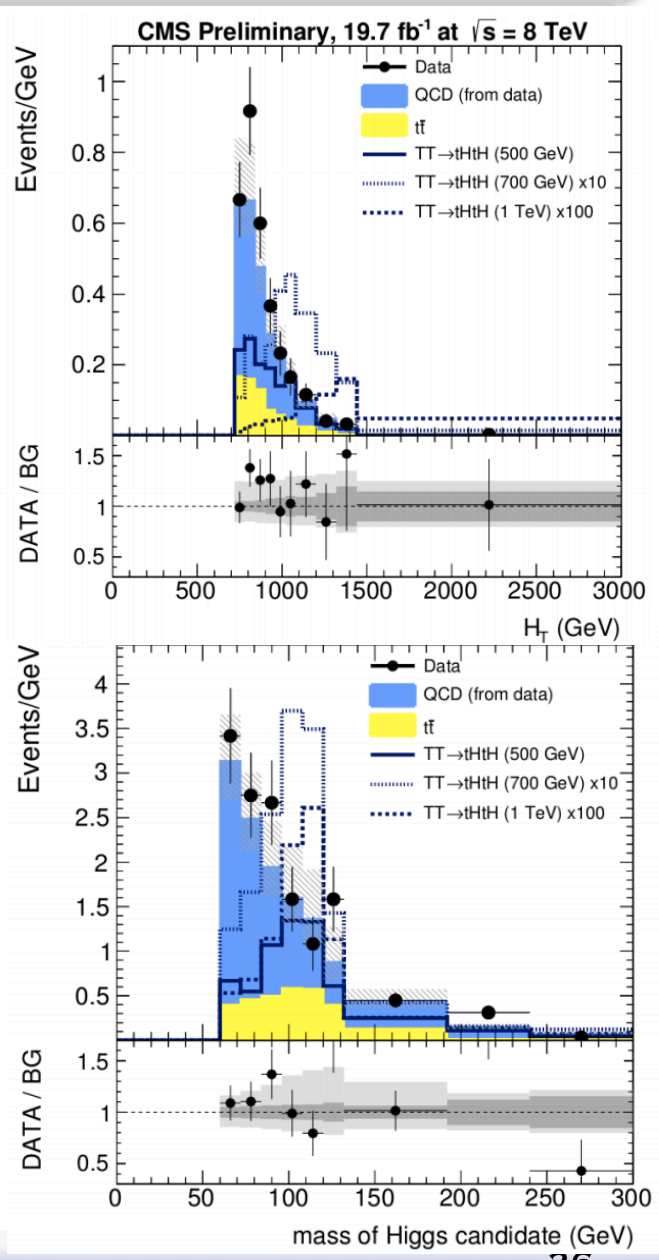
CMS PAS B2G-14-002

- Optimized for T->tH
- Make use of the jet substructure techniques:
  - Top tagging
  - Higgs tagging via subjet b-tagging
- 1 Top-tagged, 1- and 2-Higgs tagged bins



top-tag:
HEPTopTagger
subjet b-tagging

Higgs-tag, H→bb:
2xsubjet b-tagging
jet-mass > 60 GeV



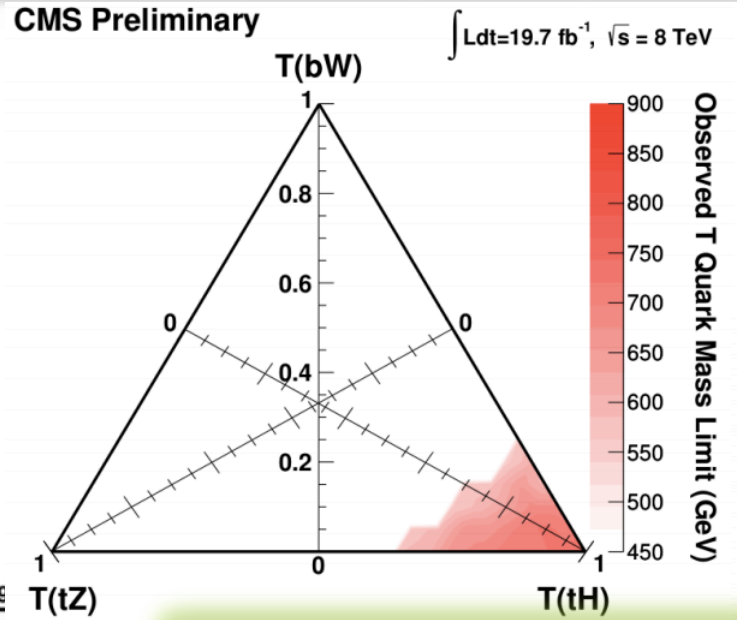
Search for $T^{2/3}$ in All-Hadronic State

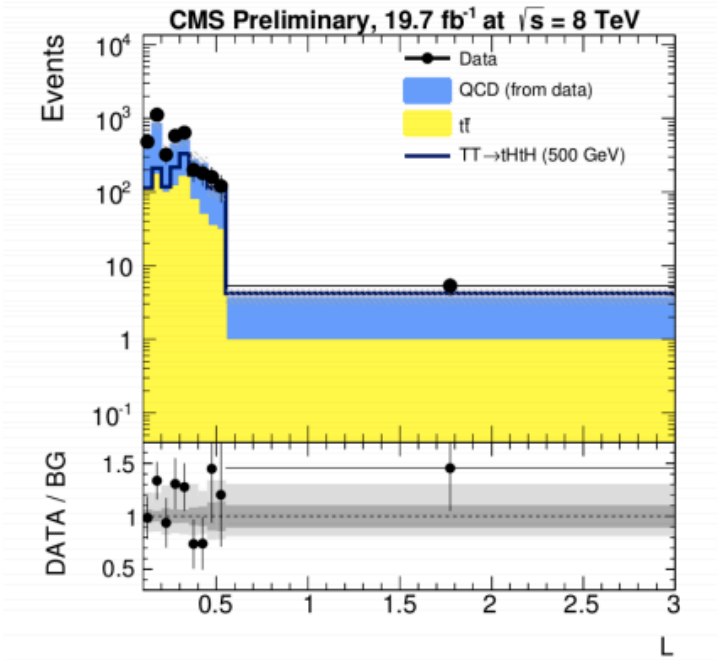
CMS PAS B2G-14-002

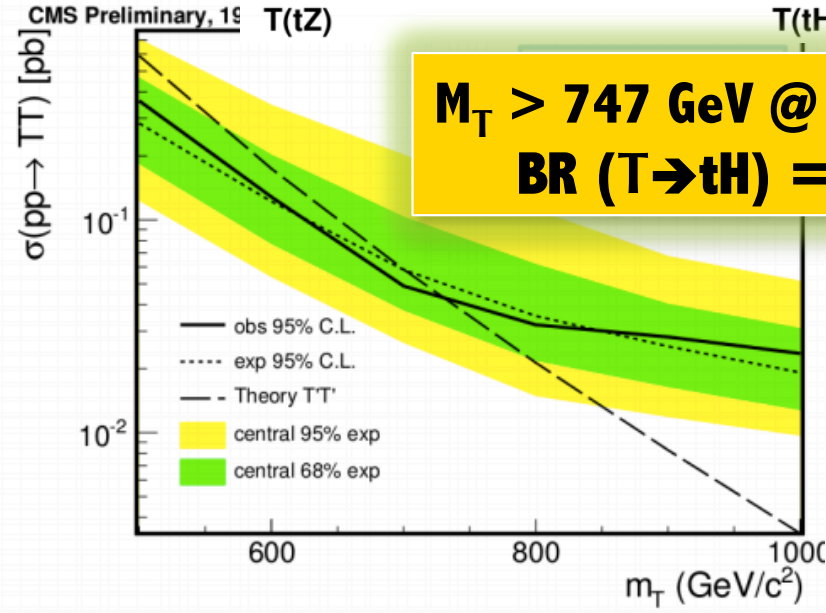
- Background fit based on the likelihood discriminant using two observables

$$L = \ln\left(1 + \frac{P_{\text{signal}}(H_T)}{P_{\text{background}}(H_T)} \frac{P_{\text{signal}}(m_H)}{P_{\text{background}}(m_H)}\right)$$

- With jet substructure the QCD background is reduced to the level of tt





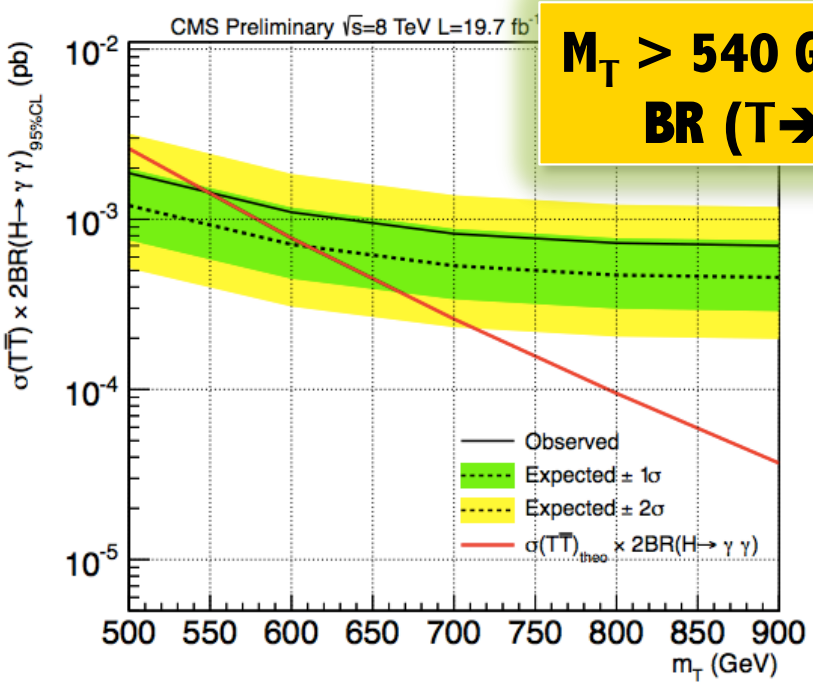


M_T > 747 GeV @ 95 % C.L.
BR (T➔tH) = 100%

Search for $T^{2/3}$ -> tH, H->γγ

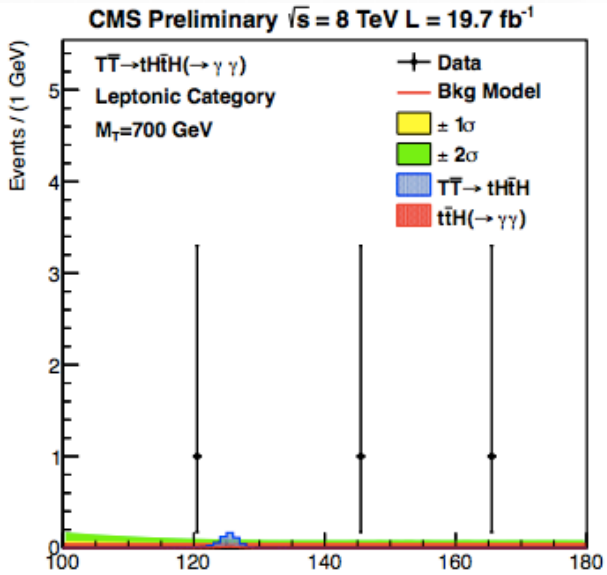
CMS PAS B2G-14-003

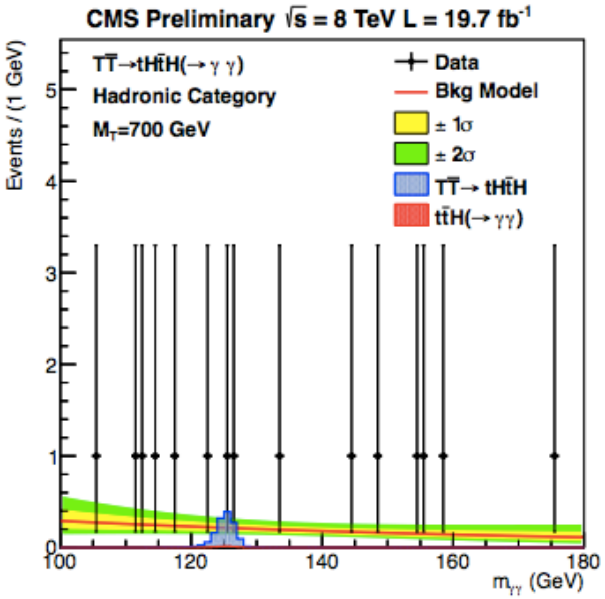
Variable	Hadronic channel	Leptonic channel
$p_T^{lead\ photon}$	$> \frac{3}{4} m_{\gamma\gamma}$ GeV	$> \frac{1}{2} m_{\gamma\gamma}$ GeV
$p_T^{sublead\ photon}$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-



M_T > 540 GeV @ 95 % C.L.
BR (T➔tH) = 100%

- Strategy: fit for the narrow H-> γγ mass peak

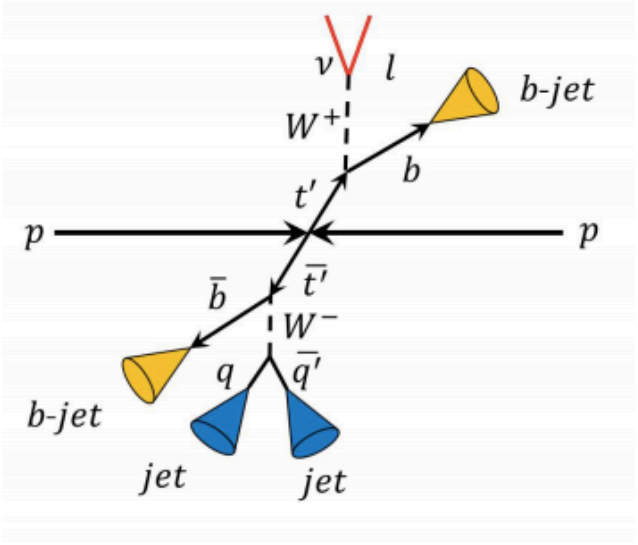


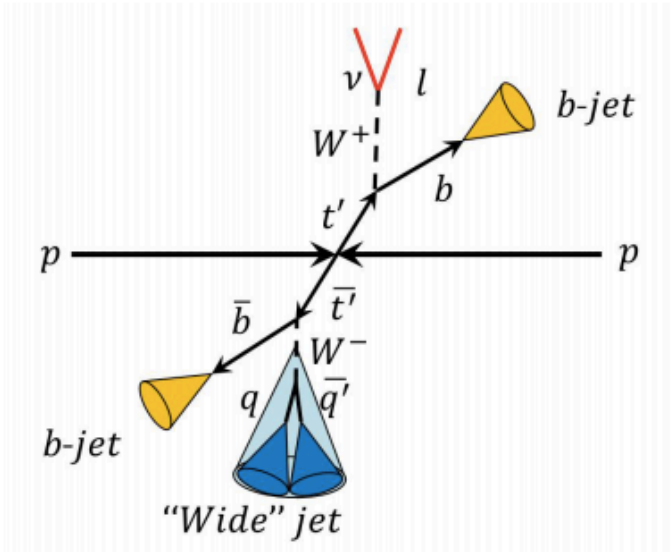


Search for $T^{2/3}$ in ℓ + jets

CMS PAS B2G-12-017

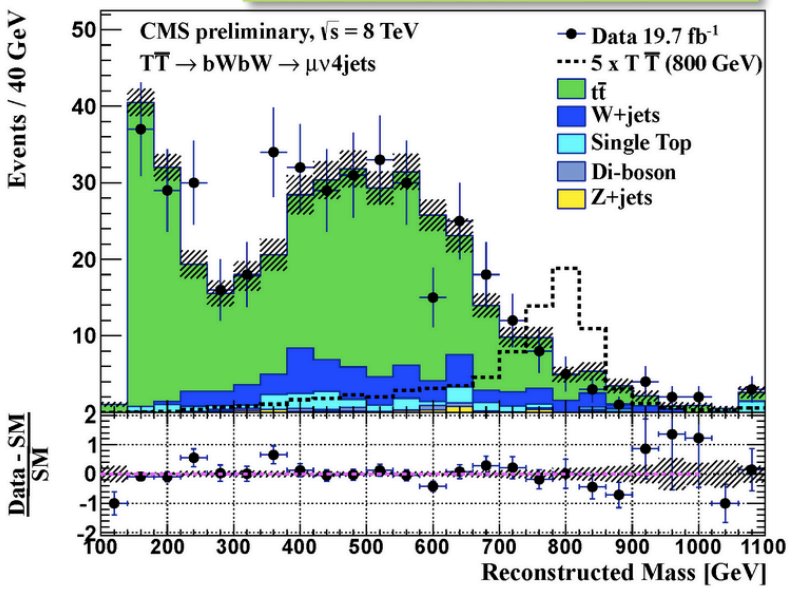
- Signature: lepton + >= 4 jets + 1 btag + MET
- Perform a full kinematic event reconstruction and reconstruct mass of the T quark
- Highly boosted W bosons may merge into single jets
- Make use of == 0 W-tag and == 1 W-tag events

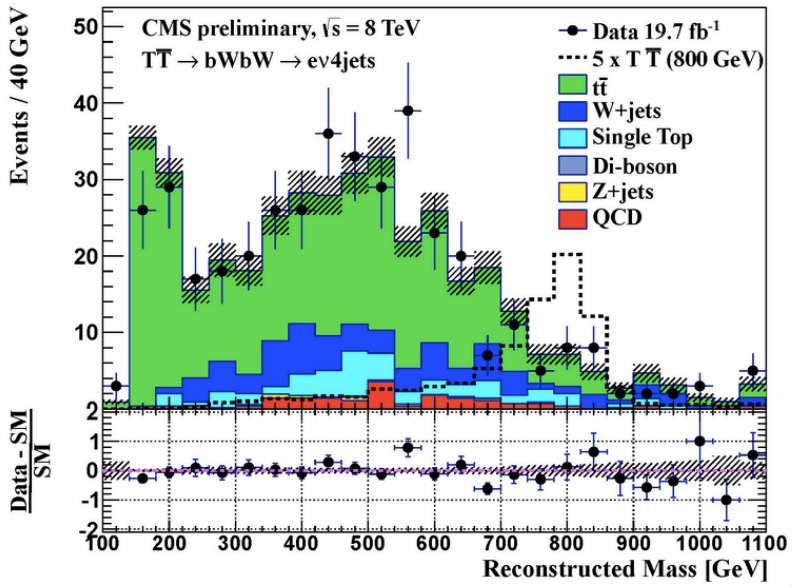




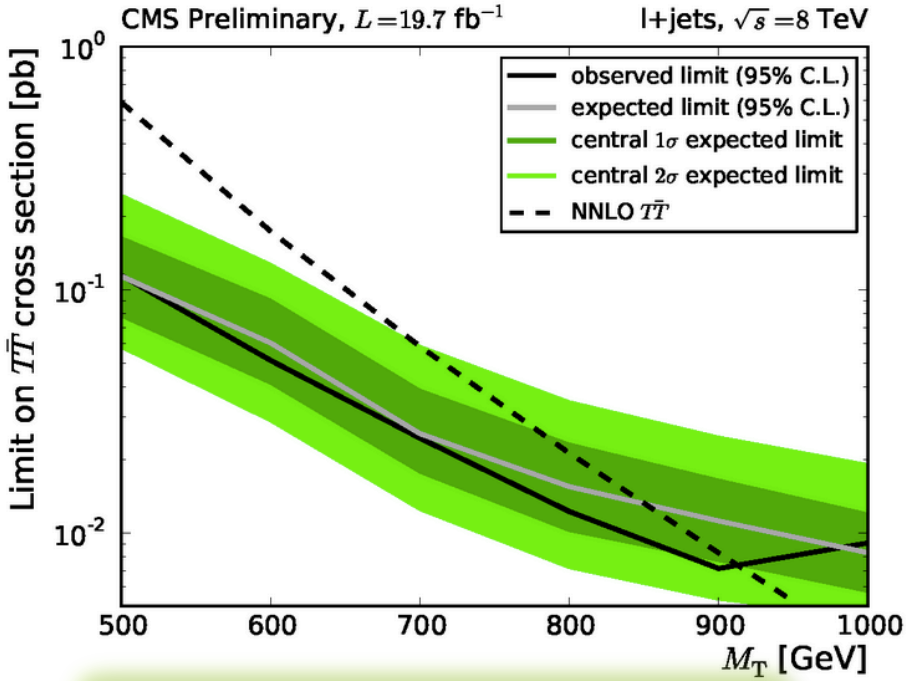
Search for $T^{2/3}$ in ℓ + jets

CMS PAS B2G-12-017





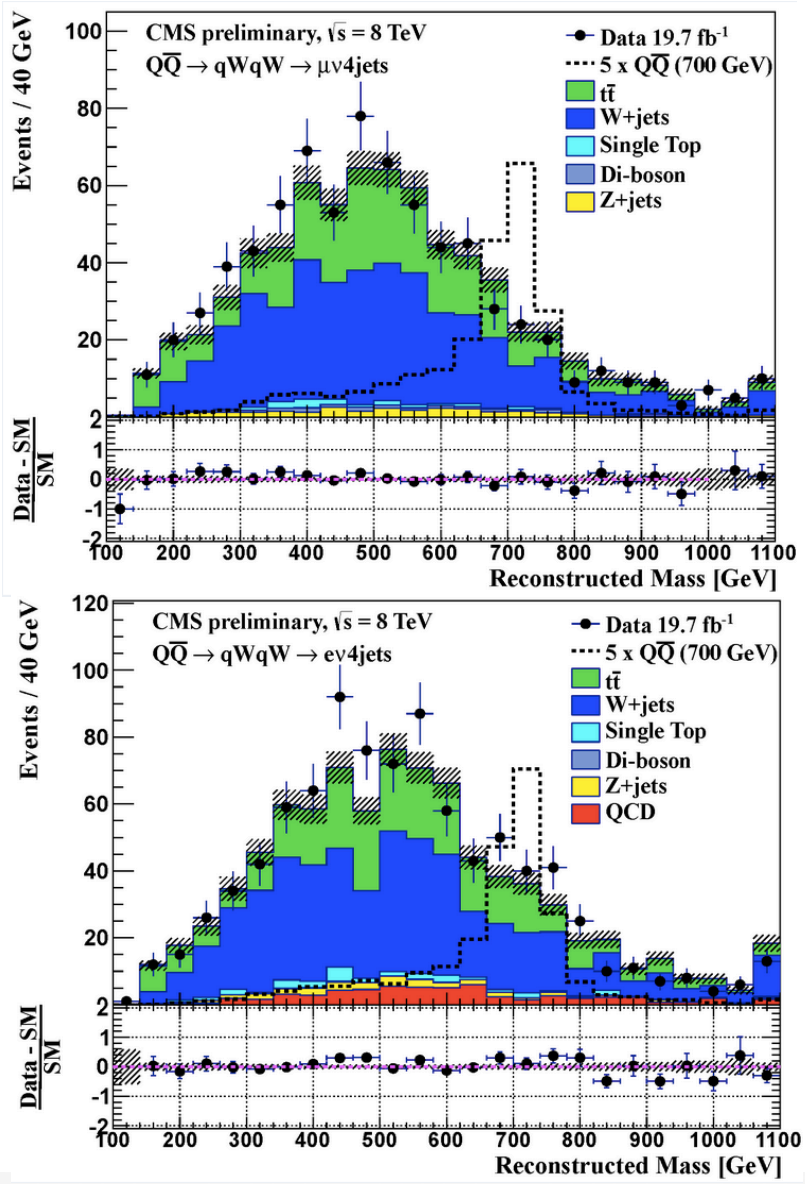
- Perform a fit to the reconstructed mass
- S_T > 1240 GeV - cut optimized for the best sensitivity



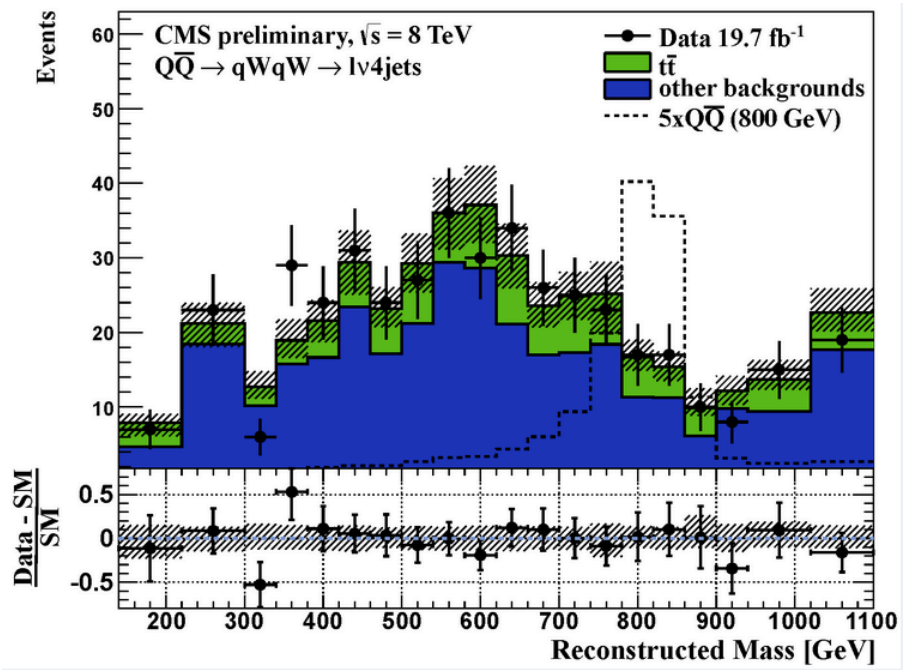
M_T > 912 GeV @ 95 % C.L.
BR (T→Wb) = 100%

Search for Q->Wq in ℓ + jets

CMS PAS B2G-12-017



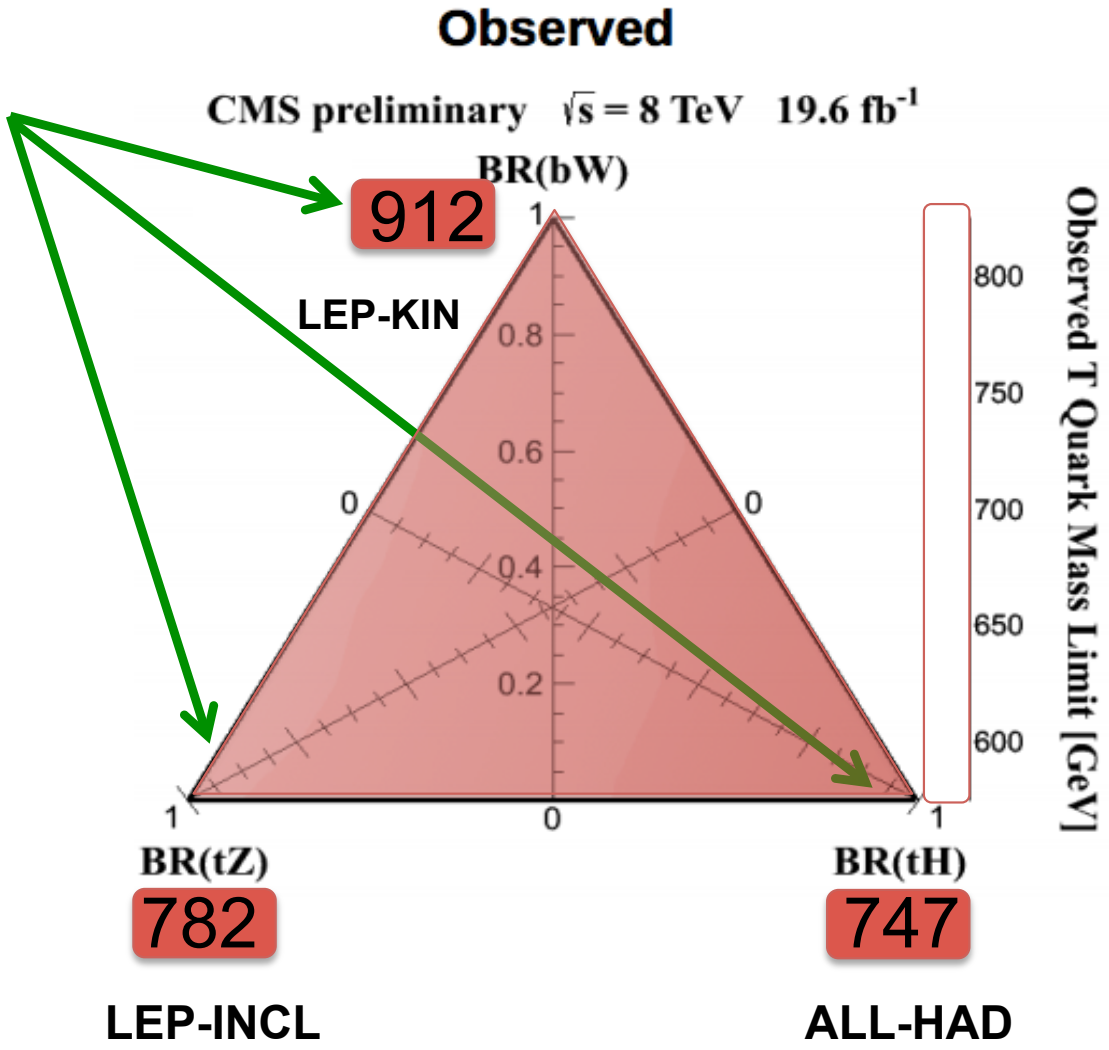
- Similar search in 0-b-tag region
- Search for partners of the light-flavor SM quarks



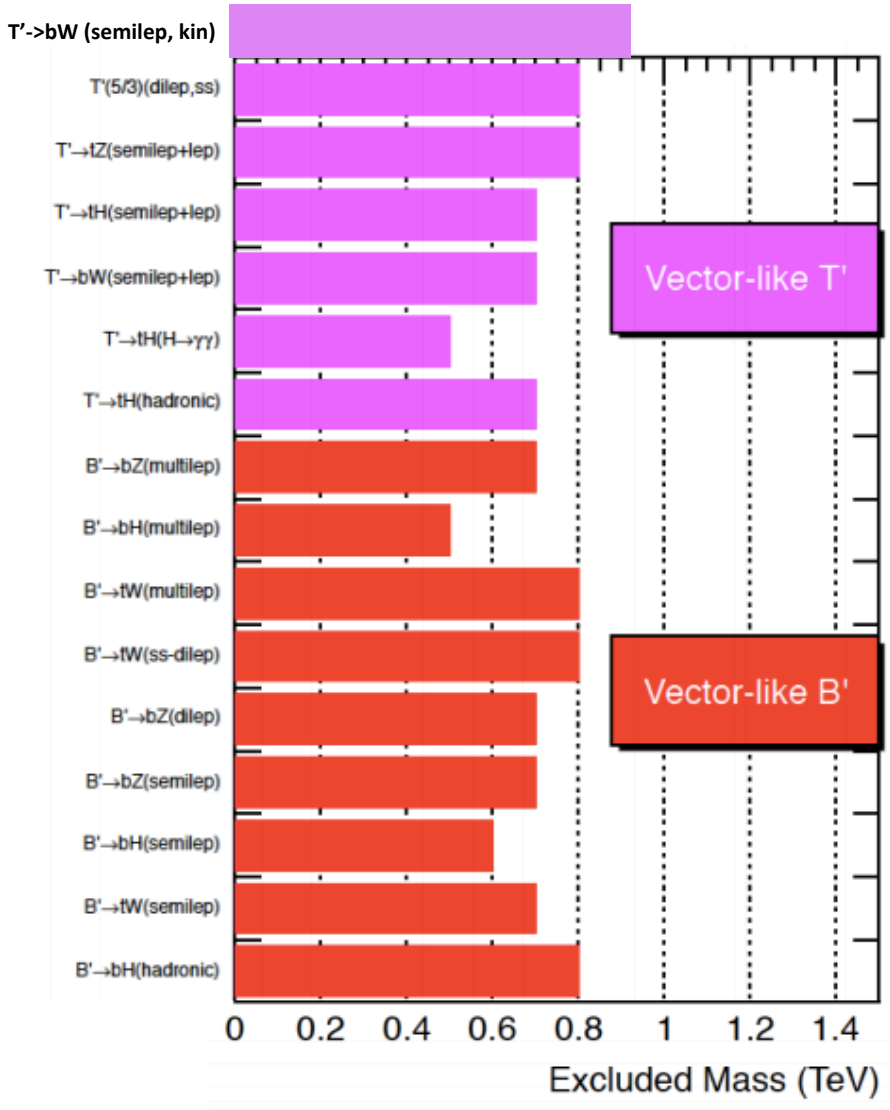
M_T > 788 GeV @ 95 % C.L.
BR (Q→Wq) = 100%

$T^{2/3}$ Summary

- Best observed limits from individual analyses
- Grand combination will be available very shortly
- Pushes limits above ~900 GeV



Summary Table



Conclusions

- Vector-like quarks provide a possible solution to the mass hierarchy problem and can stabilize the Higgs mass at the electroweak scale
- CMS has a rich physics program on searches for very heavy exotic quarks in a multiple number of final states
- Presented analyses based on 8 TeV dataset of 20 fb^{-1} exclude vector-like quarks up to masses of 800 GeV
- Preparation for LHC Run 2 is underway, where single production of these quarks is equally important
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G


Thank you!