Physics Beyond Higgs: Searches for Vector-like quarks at CMS

Sadia Khalil

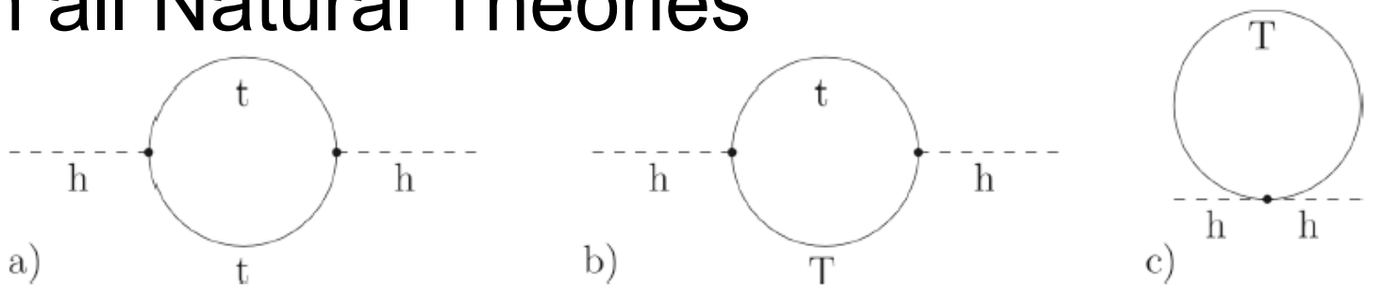
US LUA Meeting

Nov 12-14, 2014

Argonne National Lab, IL, USA

Top Partners

- Top Partners are what cancels the top loop divergence in m_H and are light in all Natural Theories



  - **Light Higgs** plus **Low Tuning** need **light Partners**

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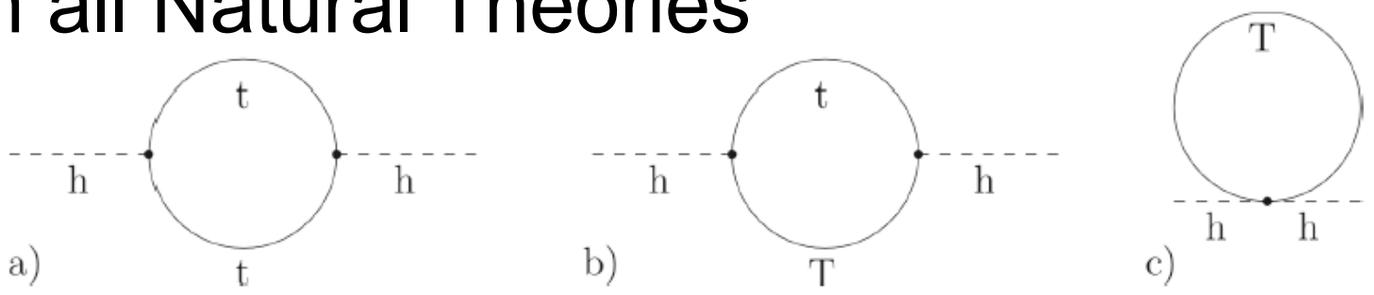

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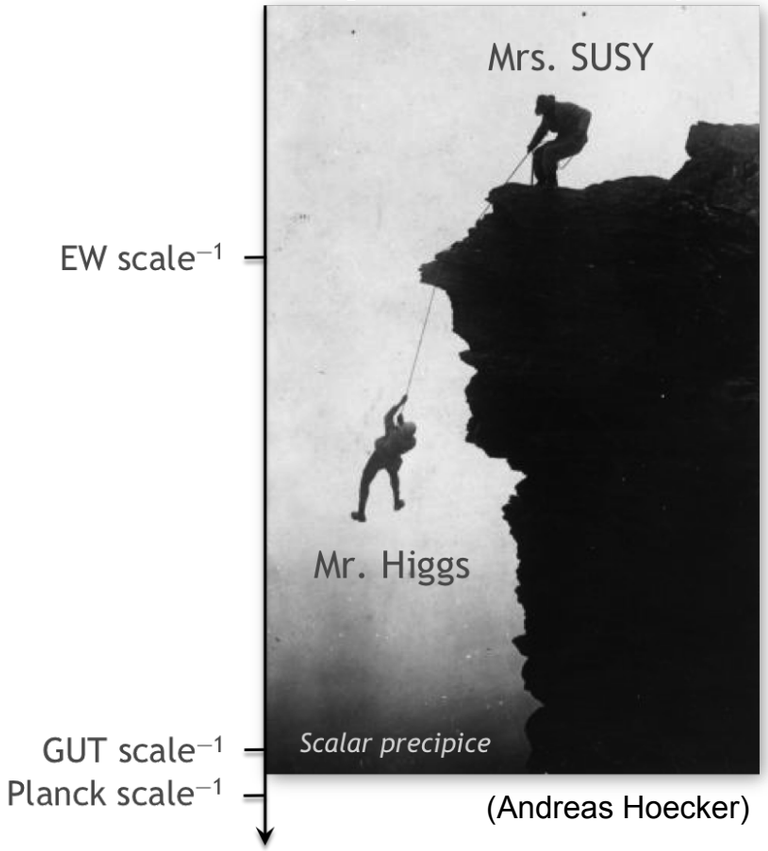
SUSY

bosonic partners(stops)



(Andreas Hoecker)

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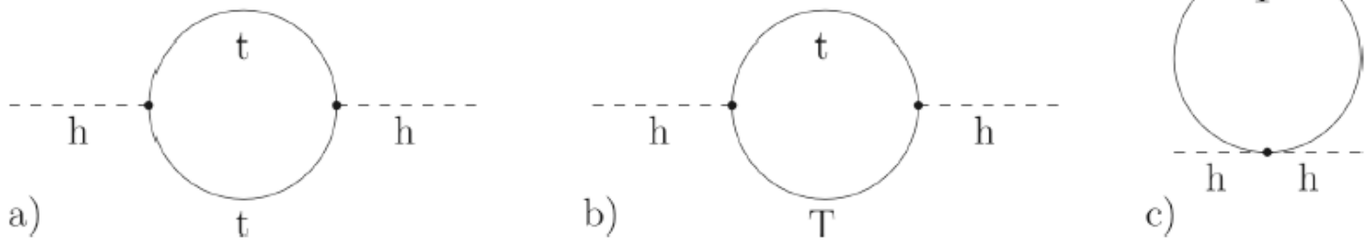

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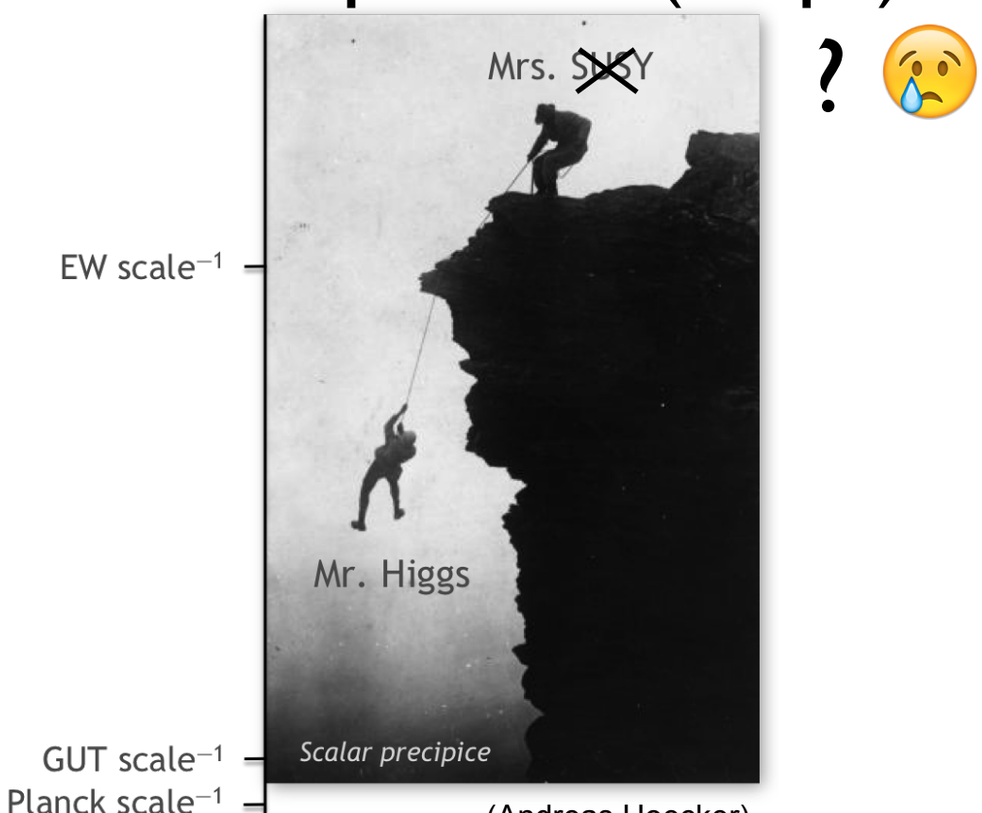

?

(Andreas Hoecker)

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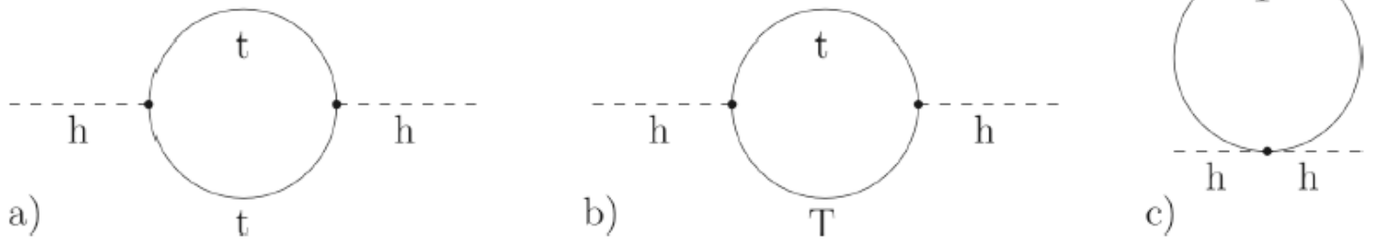

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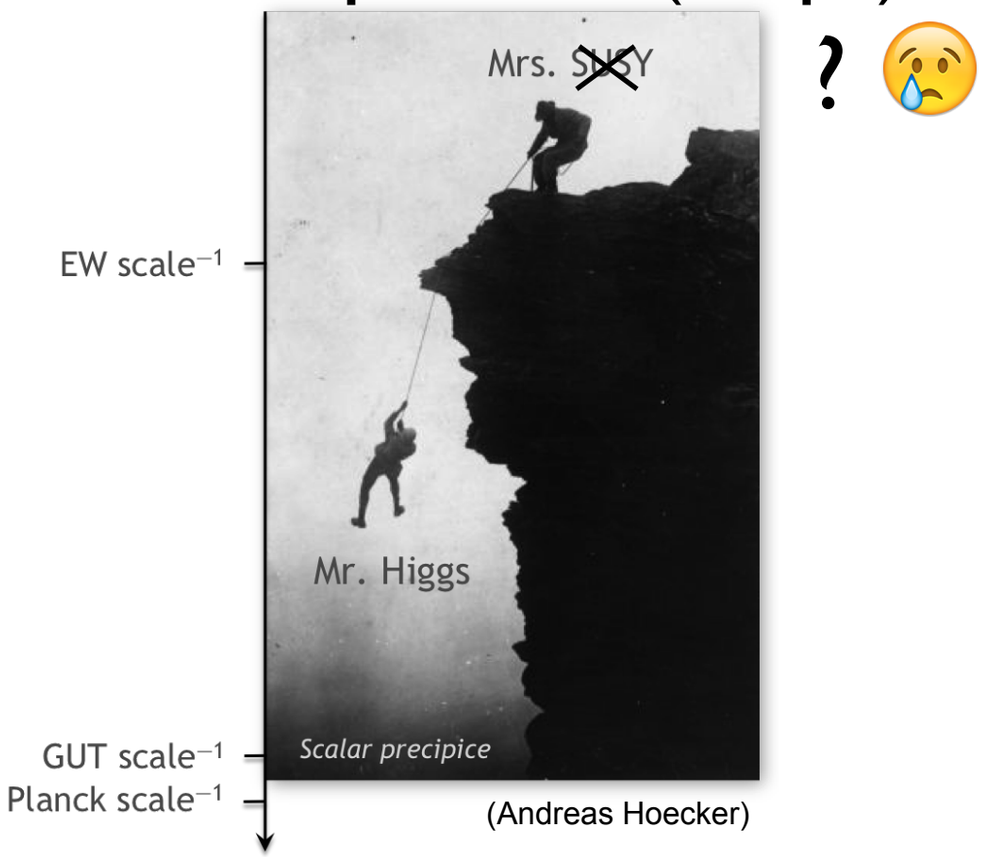
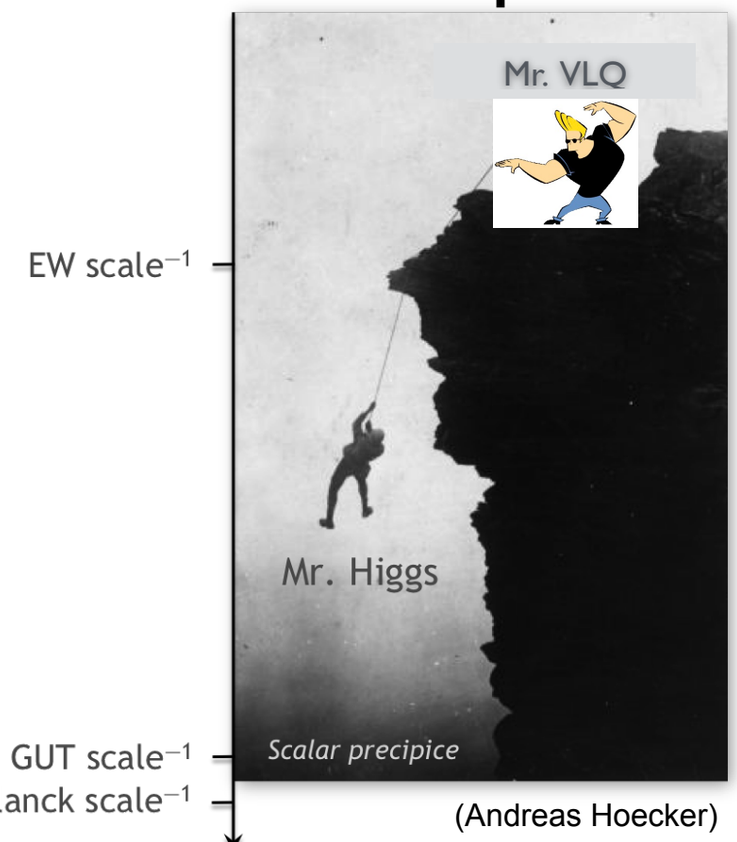


?

(Andreas Hoecker)

X-dim, Little Higgs, Composite Higgs…

fermionic partners



(Andreas Hoecker)

Let's not miss the possibility

http://arxiv.org/abs/1205.0013
http://arxiv.org/abs/1211.5663

Introduction

- *All Standard Model fermions are <u>chiral</u>: their masses are not gauge invariant, and arise from the Higgs coupling.* $J^{\mu+} = J_L^{\mu+} = \bar{u}\gamma^\mu(1-\gamma^5)d = V - A$
- **Vectorlike** (i.e.**non-chiral) fermions** – a new form of matter.
  - **Masses allowed by $SU(3)_c \times SU(2)_W \times U(1)_Y$ gauge symmetry, ⇒ naturally heavier than the t quark.** $J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} = \bar{u}\gamma^\mu d = V$
  - Produced as

Singlets	Doublets	Triplets
$\mathbf{1}_{2/3} = T$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	
$\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$

Notation

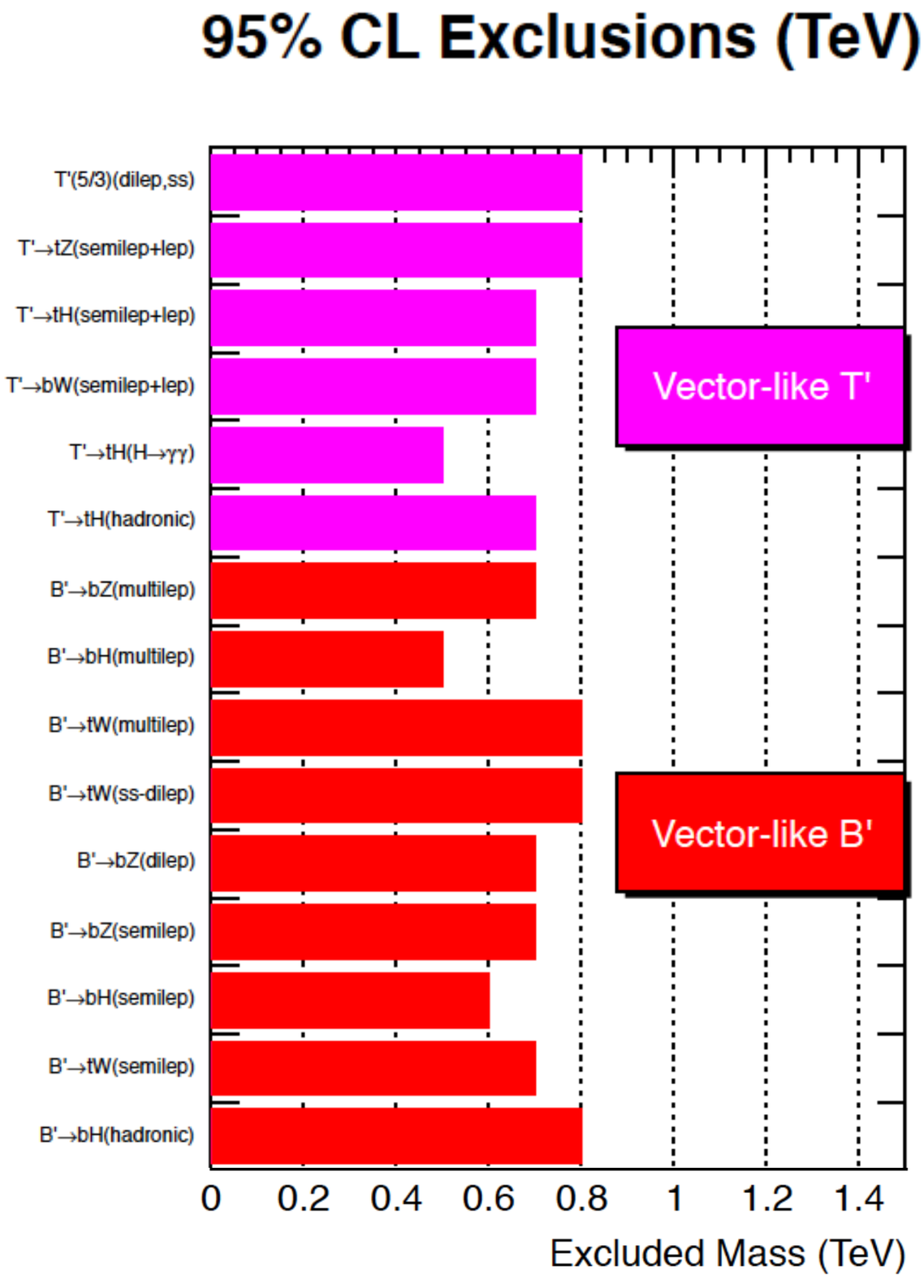
$\mathbf{Isospin}_{\text{Hypercharge}}$

$T \to +2/3$
$B \to -1/3$
$X \to +5/3$
$Y \to -4/3$

} Electric charge

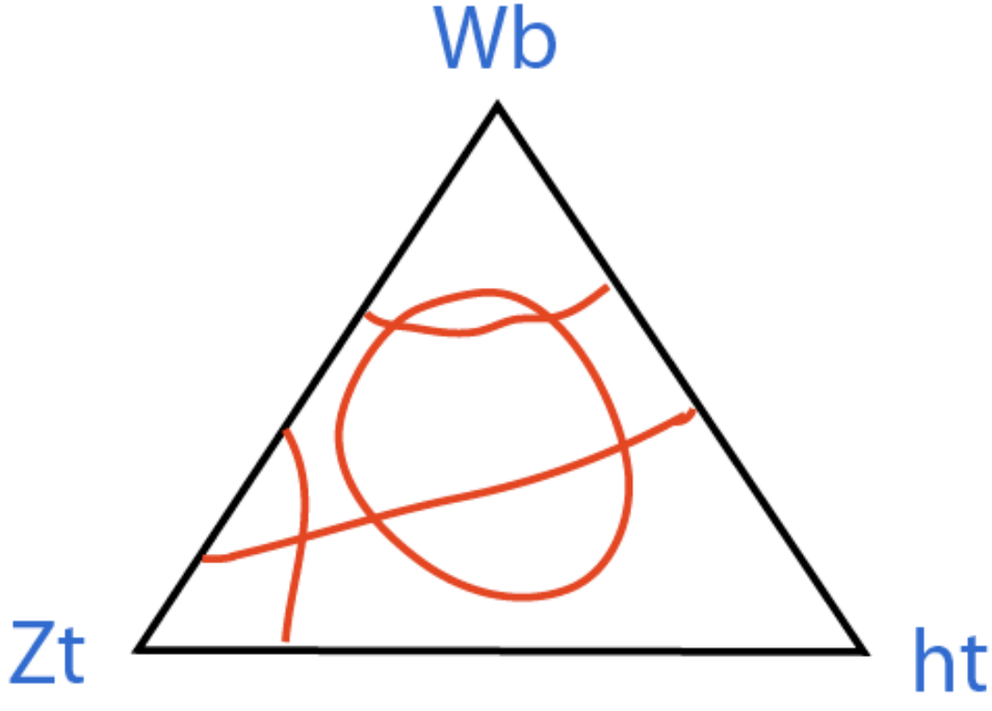
G Cacciapaglia, A. Deandrea (arXiv:1007.2933)

Run1 Searches



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

- LHC Run1 focused on pair production of VLQ, with typical constraints of $m_Q \sim$ 750 GeV
- Searches have been performed in all the full phase space of a triangle with all possible combinations of B.R



Michael Peskin's representation

Common procedures

- **Strategy:**
  - Look for excesses over a known background in high S_T(sum p_T of final decay products) and reconstructed mass tails

B2G-14-002

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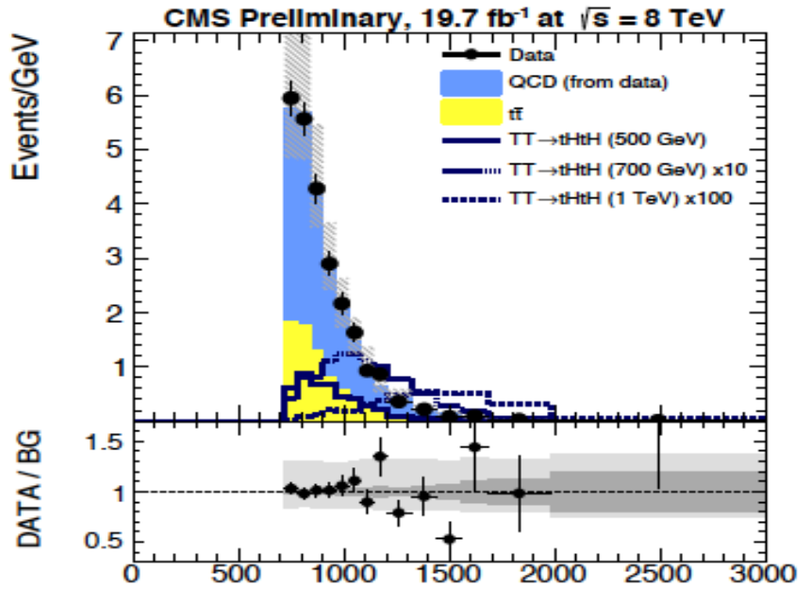
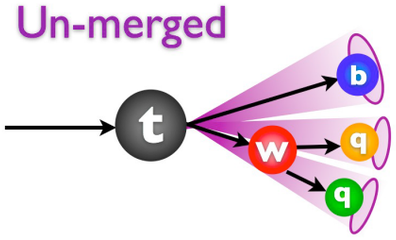
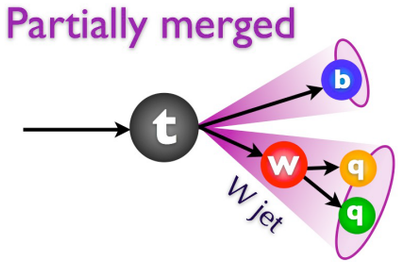
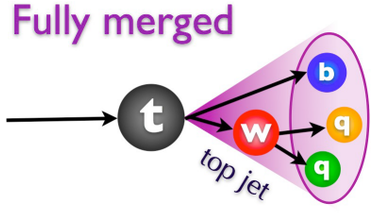
- **Jet Substructure tagging tools:**
  - The New Physics searches often imply to look for massive objects
    - boosted decay products => merged jets
    - tag tops, W/Z and Higgs

B2G-14-002

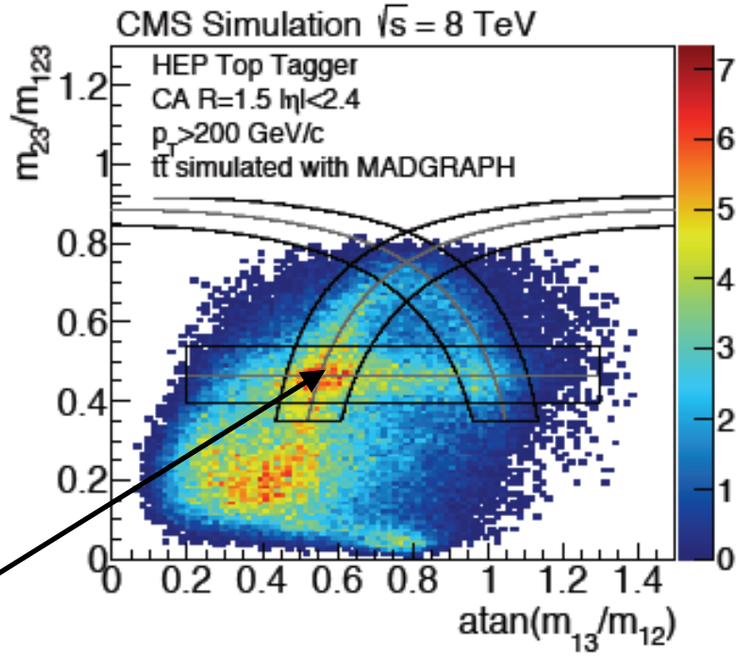








Example: t′ →tH



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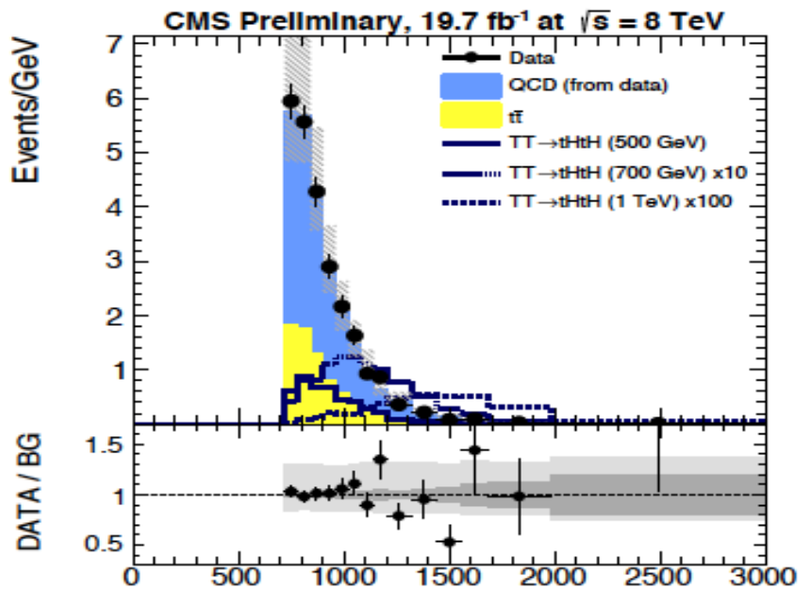

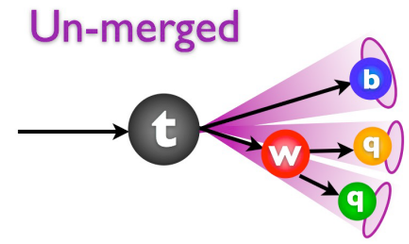

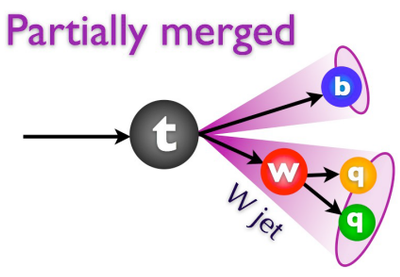

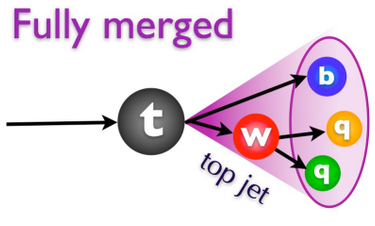

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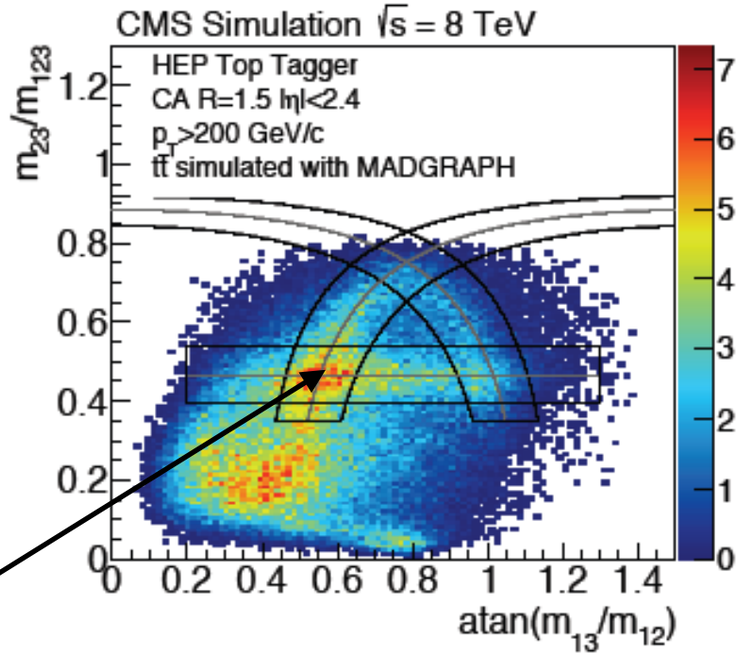

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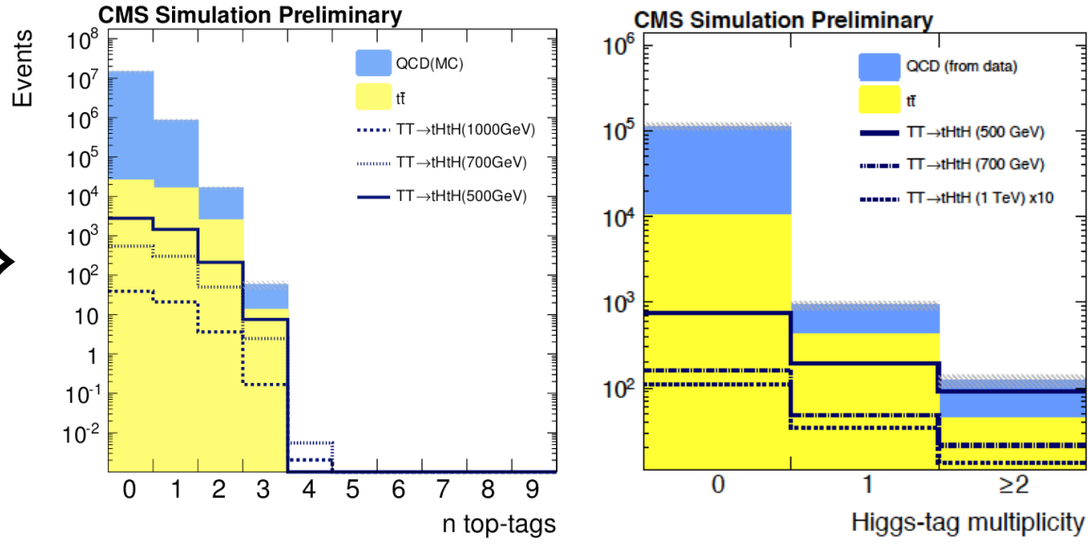
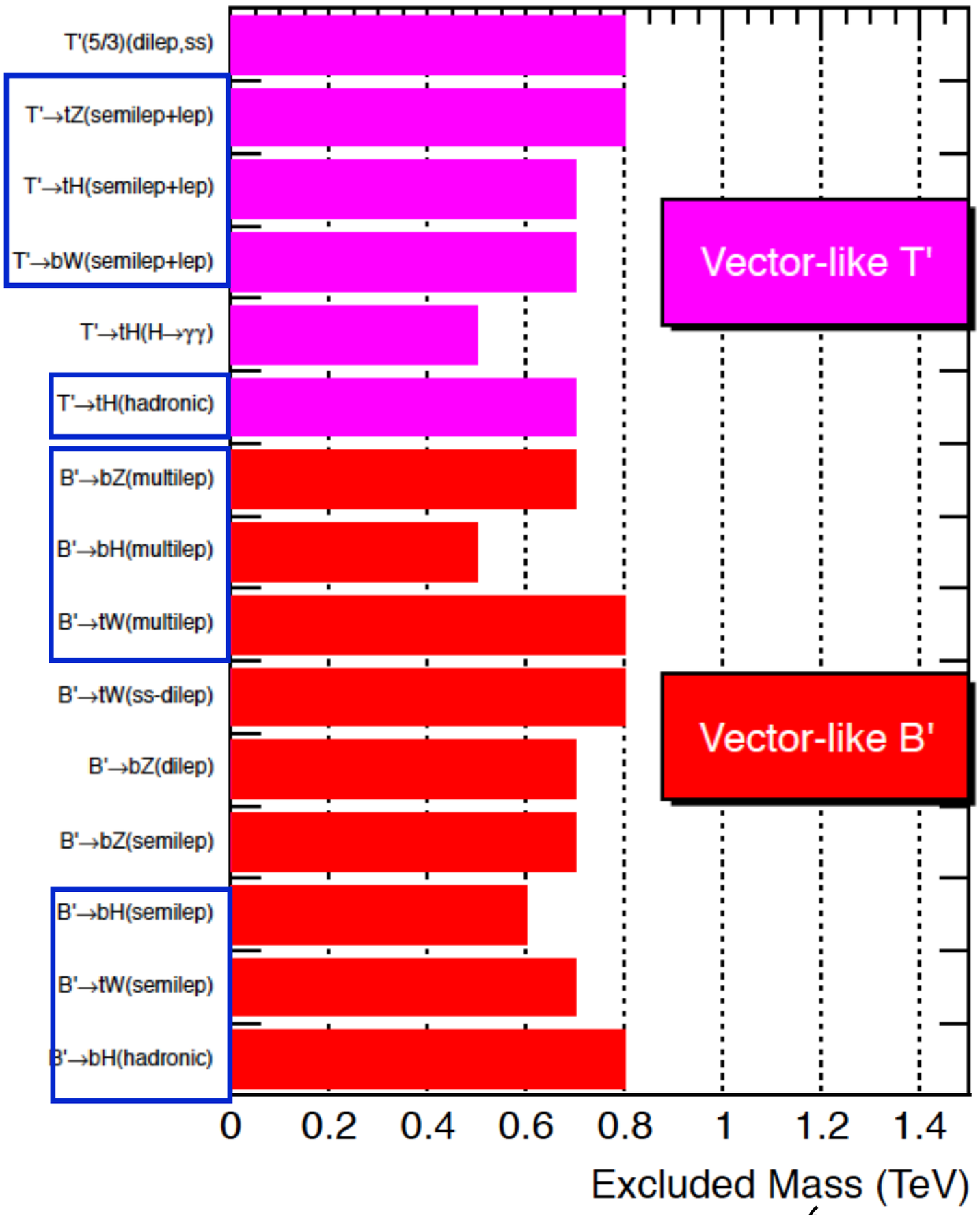




Selected analyses

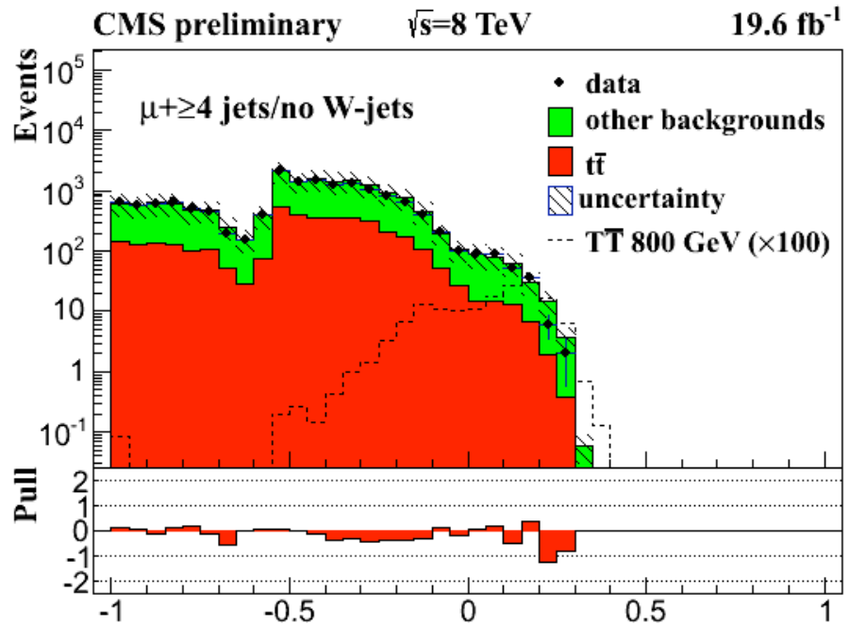
$T_{2/3}$ quark, leptons+jets

Physics Letters B 729 (2014) 149

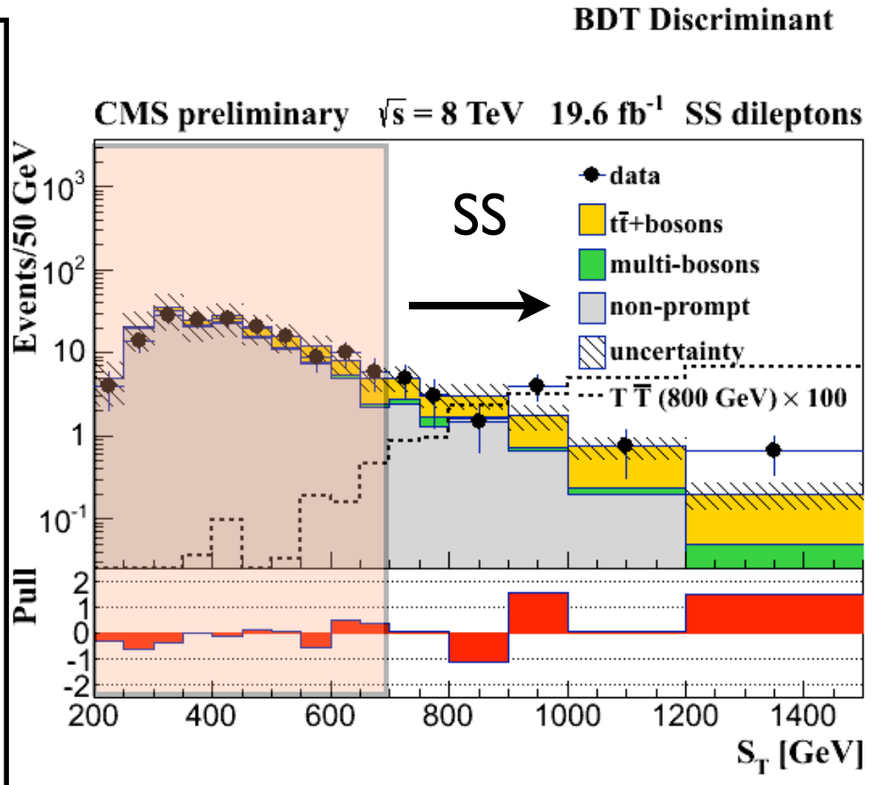
CMS-PAS-B2G-12-015

T→bW, tZ, tH

- **<u>Single lepton</u>**: 1 isolated lepton (e/mu)
- Hadronic W-tag and top-tagging
- Strategy: BDT
- **0 W:** N_{jets}, N_{btags}, H_T, MET, lepton p_T, $p_{T,j3}$ and $p_{T,j4}$
- **≥ 1 W:** 0 W variables + N_{Wjet}, $p_{T,WJet}$, $N_{topJets}$



- **<u>Multileptons:</u>** Categorized into four mutually exclusive channels optimized using S_T, H_T, min(m_{lb}), $N_{Jets,\ bjets}$ ..
- OS dilepton offZ (dominant signal = T→bW)
- OS dilepton onZ (dominant signal = T→tZ)
- SS dilepton (dominant signal = T→tZ, tH)
- Trileptons (dominant signal = T→tZ, tH)
- Strategy: Binned Likelihood fit for 12 different channels
- OS onZ, OS offZ, SS x ee, eμ, μμ = 9
- Trileptons = eee, μμμ+eeμ, μμμ = 3



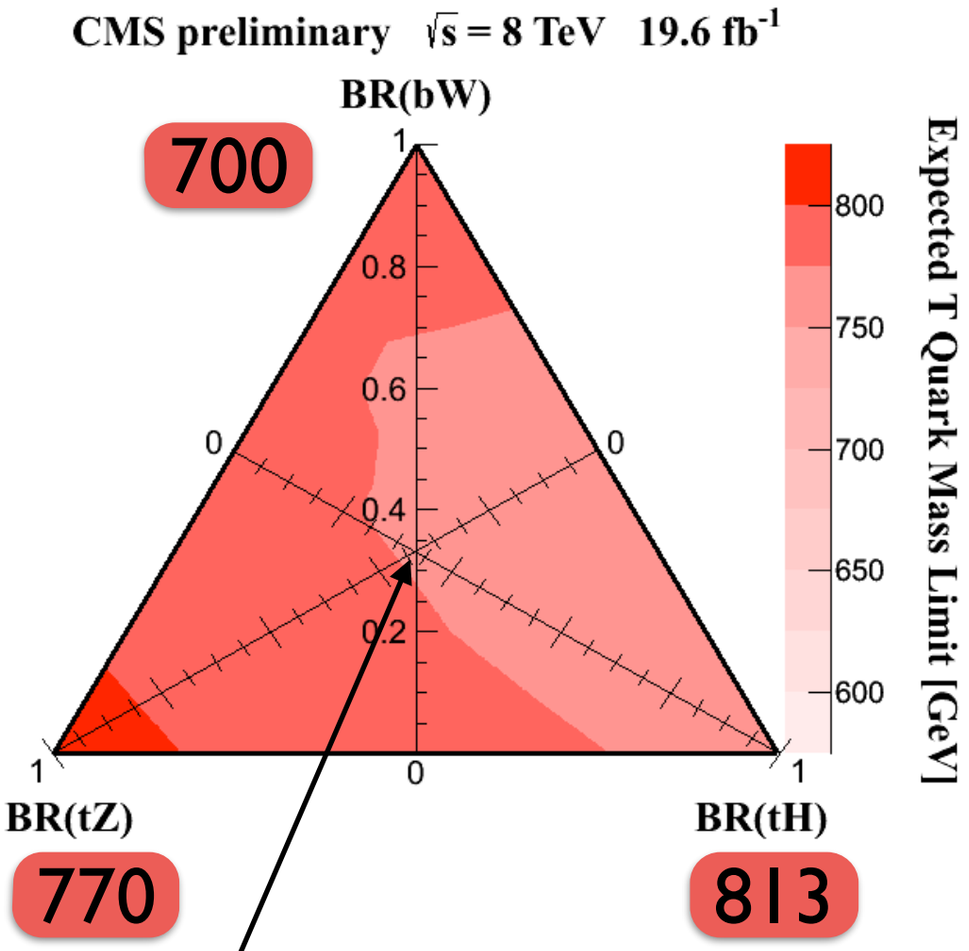
$T_{2/3}$ quark, inclusive search

Physics Letters B 729 (2014) 149

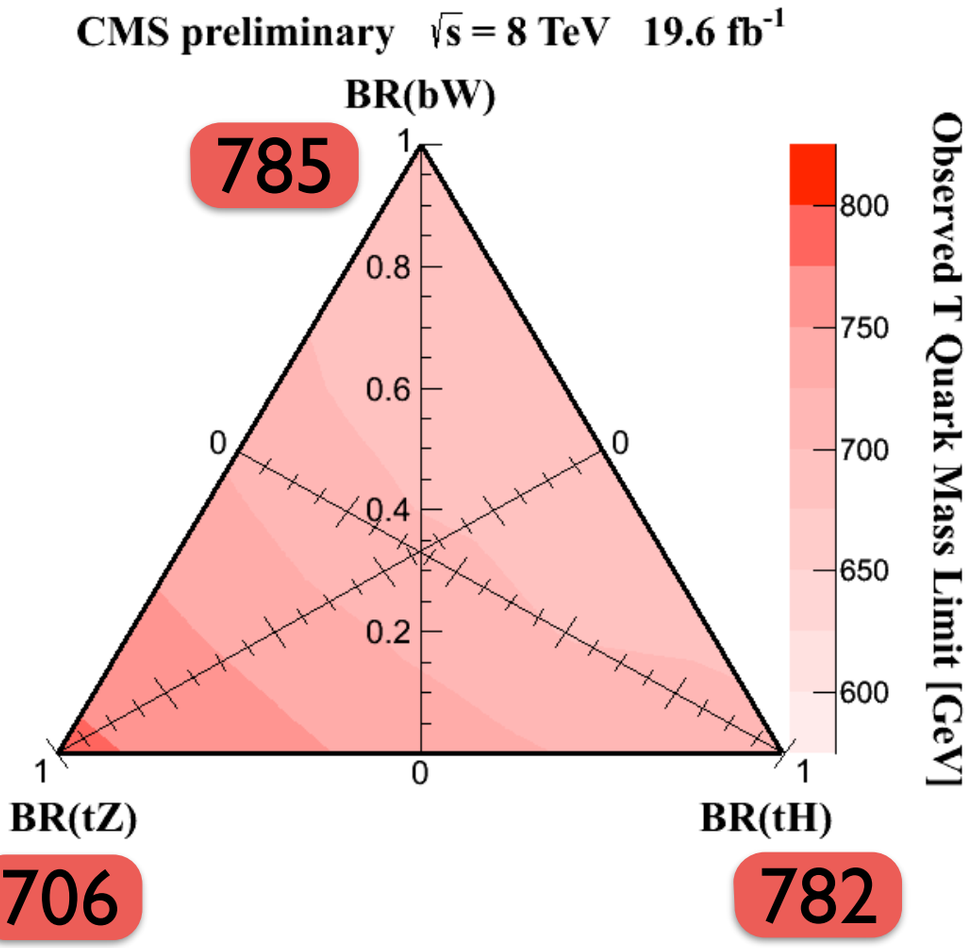
CMS-PAS-B2G-12-015

Combine limits: A mass bound of **[687, 782] GeV** is set at 95% CL for all possible BR.

Expected



Observed



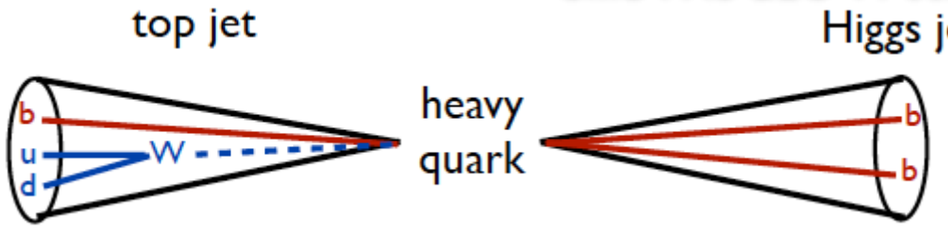
Benchmark point, tW:bZ:bH=0.50:0.25:0.25 : 696(Obs), 773(Exp)

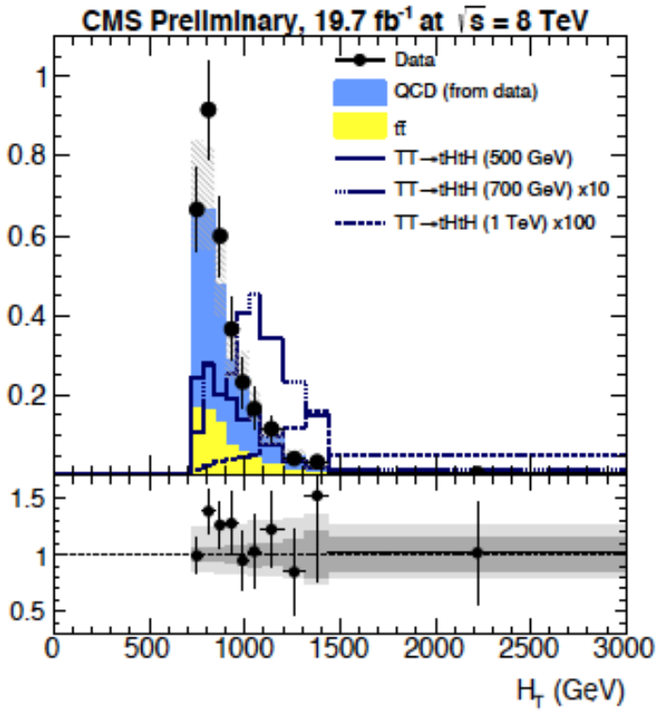
$T_{2/3}$ quark, all hadronic

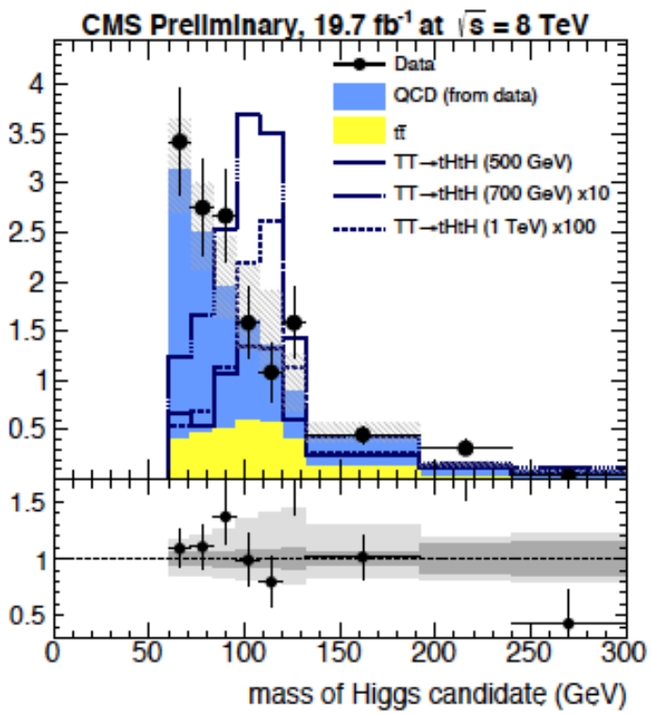
T→tH, H→bb

- Special substructure analysis using subject b-tagging
  - Tag tops and Higgs using HEP top-tagger (cone size = 1.5)
  - H_T>720 GeV, sub-jets in H_T have p_T>150 GeV
  - In addition to double b-tagging, require m_H>60 GeV

CMS-PAS-B2G-14-002







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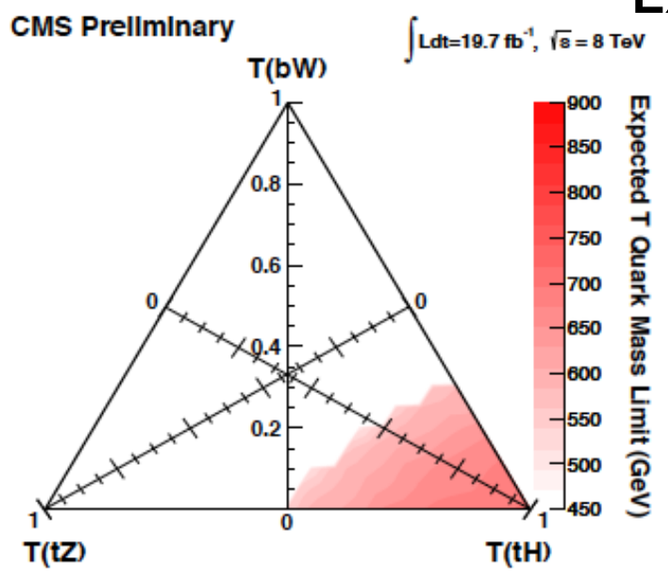
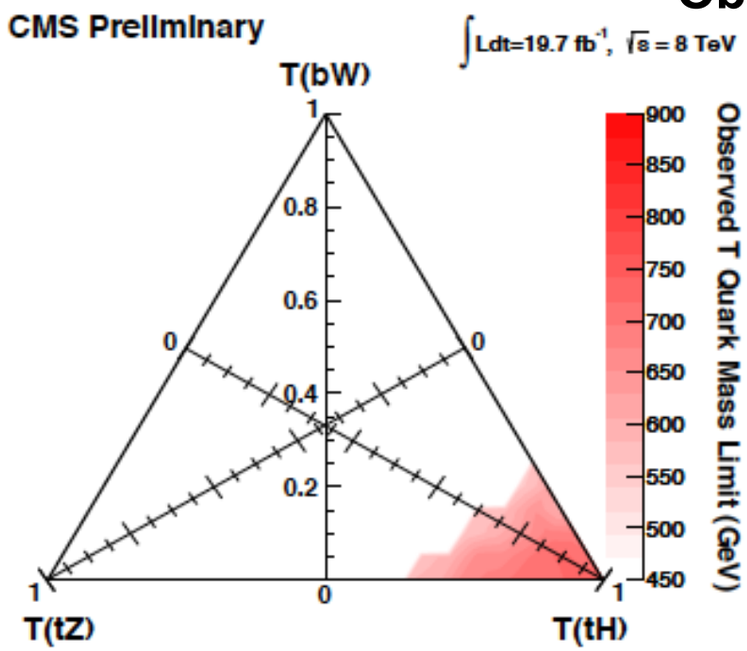


701

Observed



747

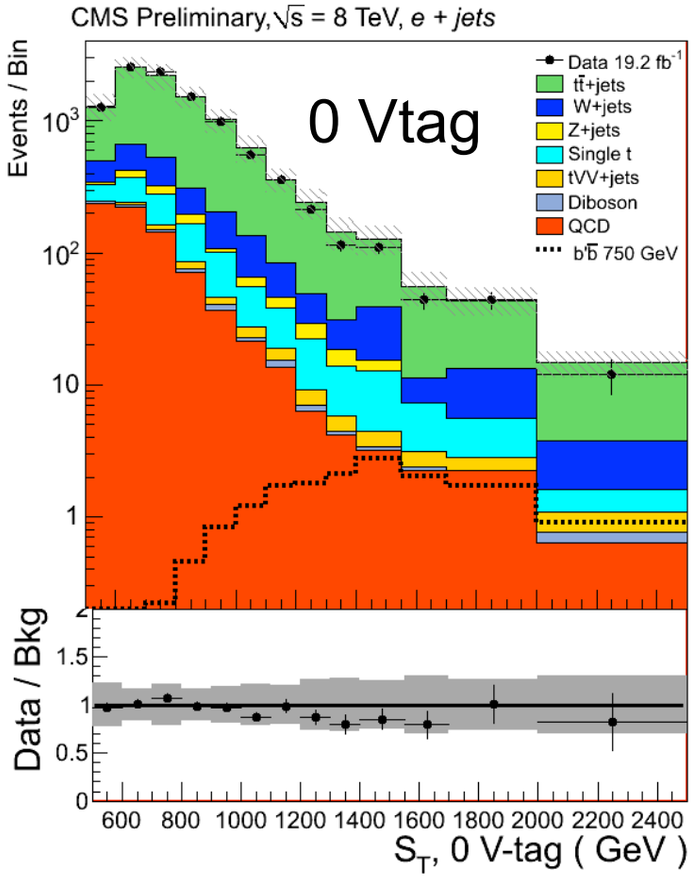
$B_{-1/3}$ quark, l+jets

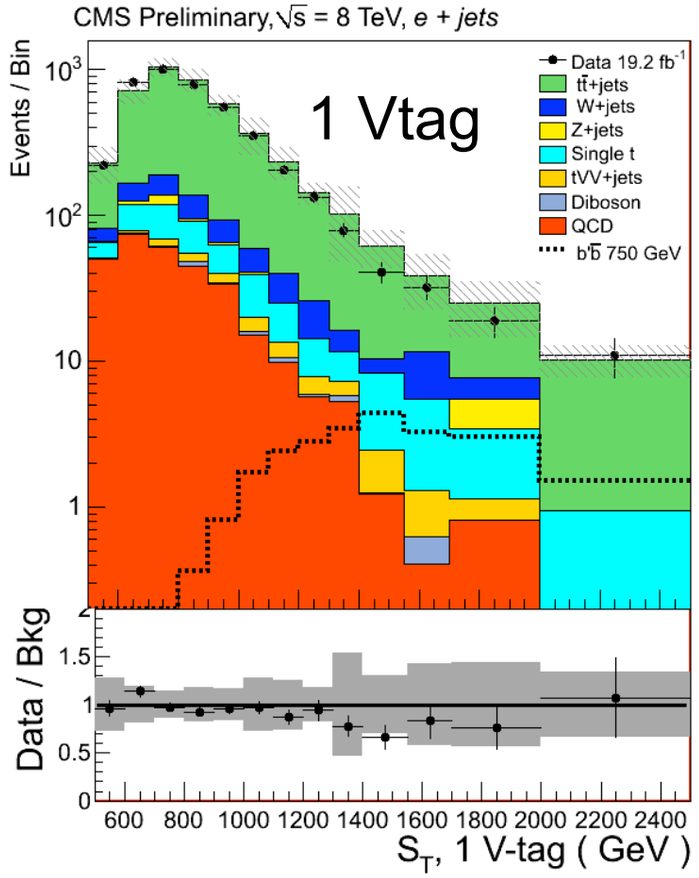
CMS-PAS-B2G-12-019

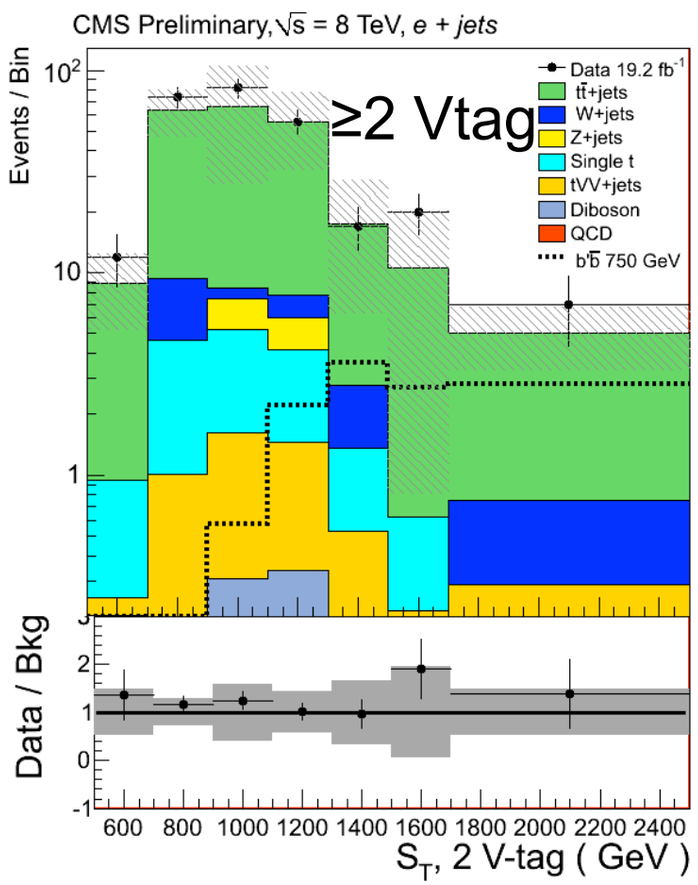
B→tW, bZ, bH

- Selection
  - One isolated lepton (muon or electron)
  - ≥ 4 high p_T jets, ≥ 1 b-jet, MET > 20 GeV
  - Boosted jets consistent with W, Z, H jets:
    - p_T>200 GeV, 50 < M_{jet} < 150 GeV
- Strategy
  - Events are categorized by number of V-tagged jets (0, 1 and ≥2 V-tag categories) in S_T bins.

$$S_T = p_T^l + \Sigma p_T^{jet} + E_T^{miss}$$







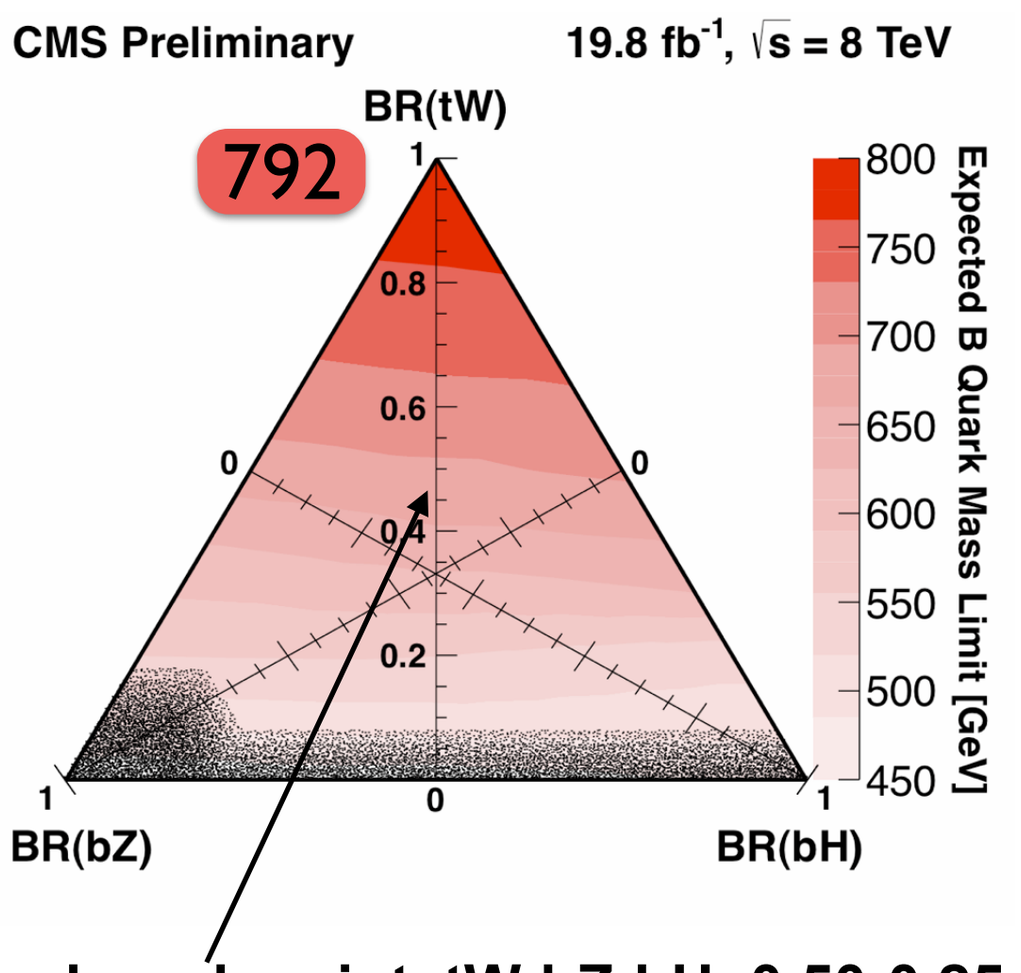
Similar bins for muon channel

$B_{-1/3}$ quark, l+jets

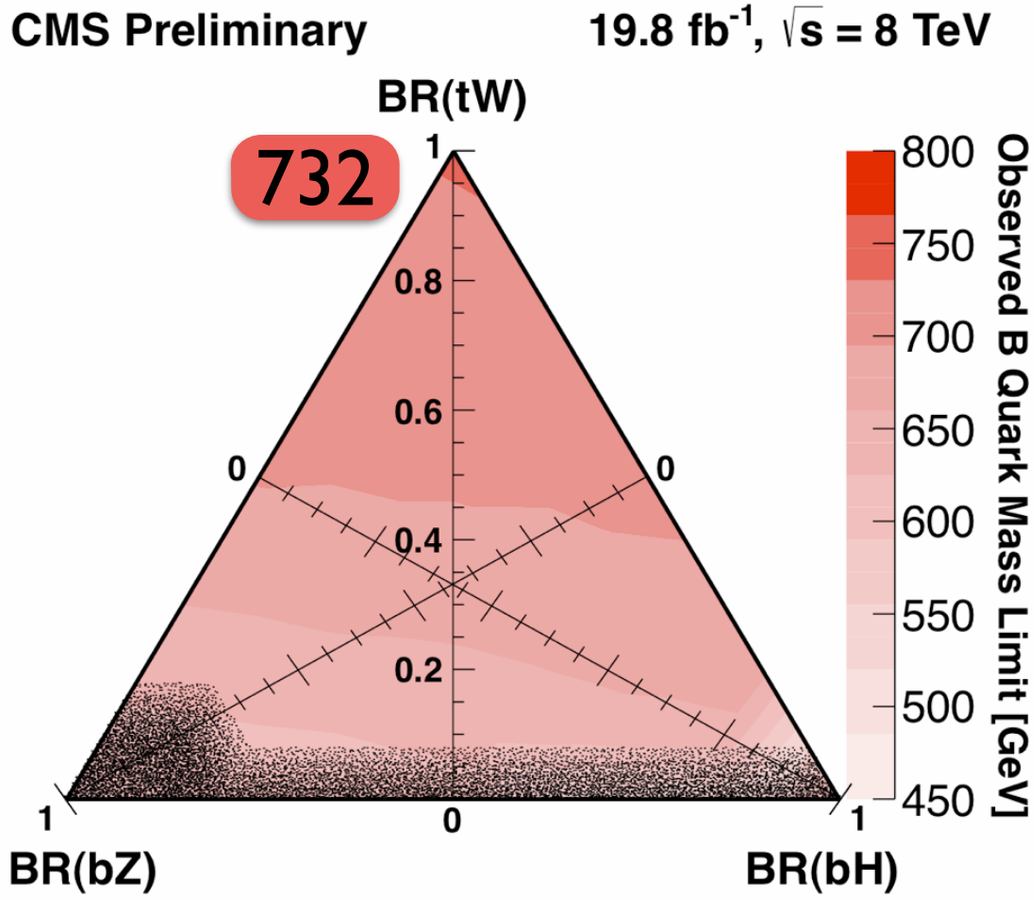
CMS-PAS-B2G-12-019

Combine e+μ limits: A mass bound of **[582, 732] GeV** is set at 95% CL for all possible BR.

Expected



Observed



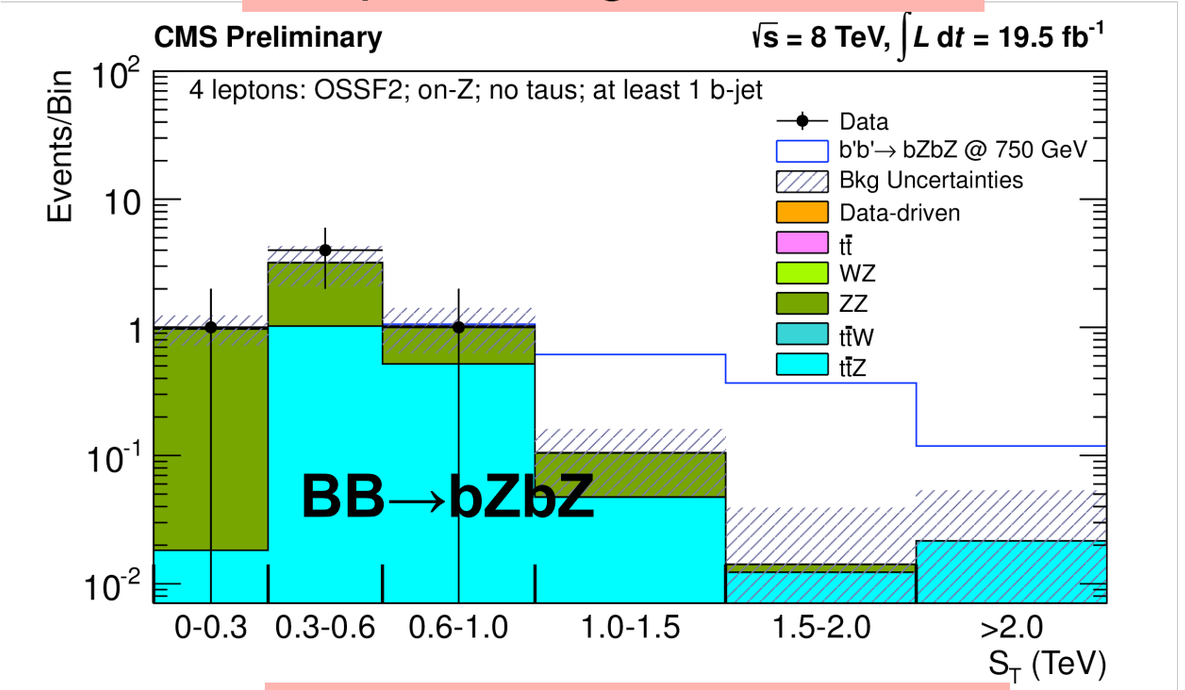
Benchmark point, tW:bZ:bH=0.50:0.25:0.25 : 700(Obs), 689(Exp)

$B_{-1/3}$ quark, multileptons

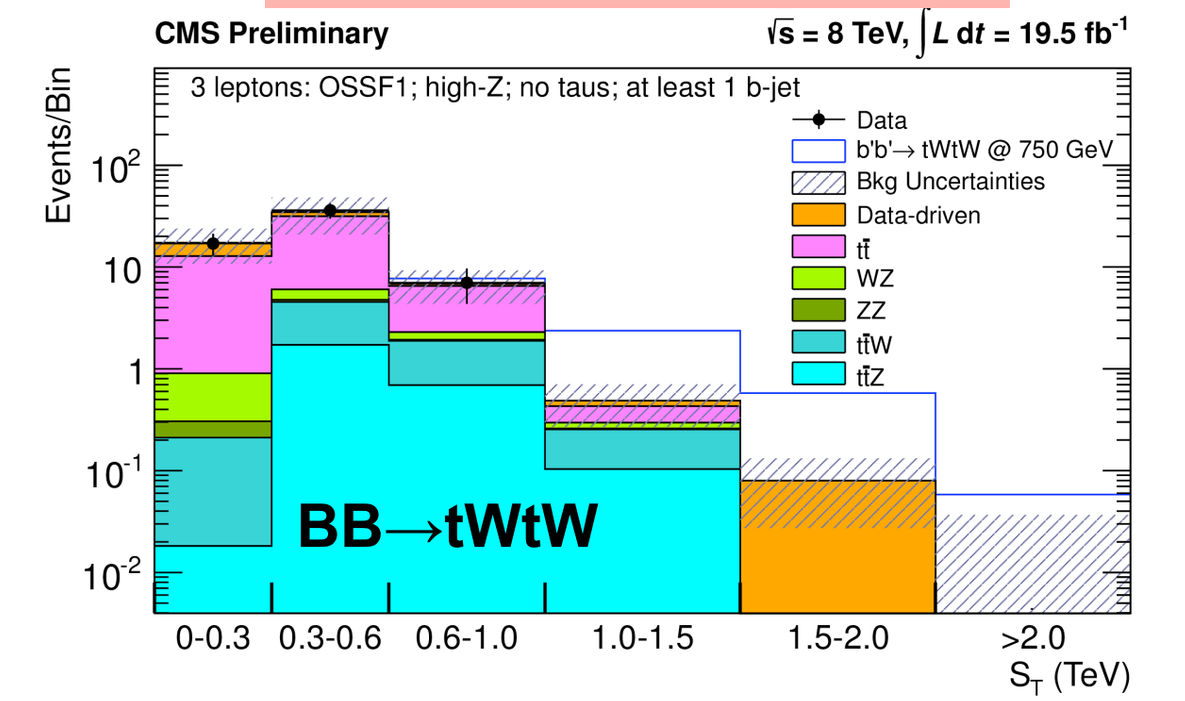
- Event selection:
  - ≥ 3 isolated leptons (τ_l = e or μ, ≤1τ_h)
- Classification:
  - number of leptons, taus, b-jets
  - # of opposite-sign same flavor (OSSF)
    - OSSF0 = $\mu^+\mu^+e^-$
    - OSSF1 = $\mu^+\mu^-\mu^-$ and $\mu^+\mu^-e^-$
    - OSSF2 = $\mu^+\mu^-e^-e^+$
  - on/off Z: OSSF in Z window (75–105 GeV)?
- Use S_T in multiple exclusive channels

CMS-PAS-B2G-13-003

4 lep, ≥1b-tag, OSSF on Z



3 lep, ≥1b-tag, OSSF off Z

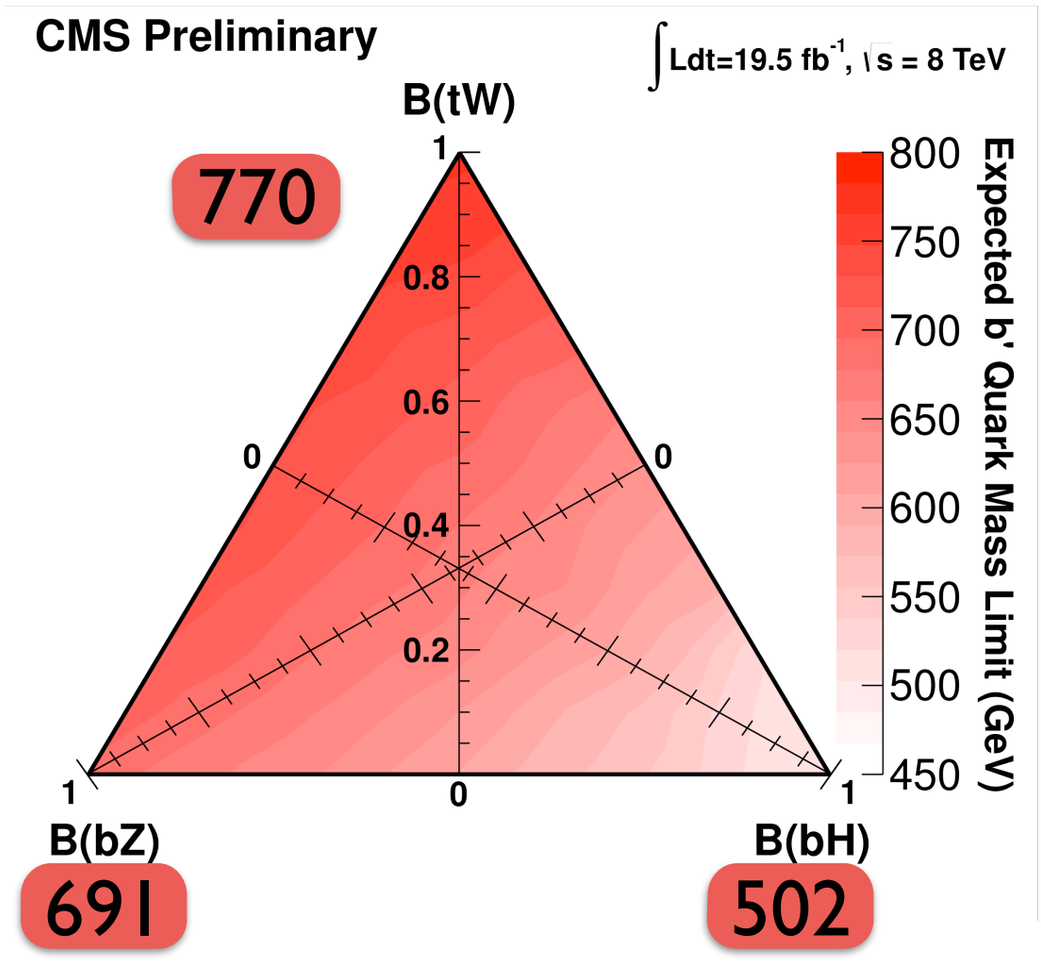


$B_{-1/3}$ quark, multileptons

CMS-PAS-B2G-13-003

B→tW, bZ, bH

Expected



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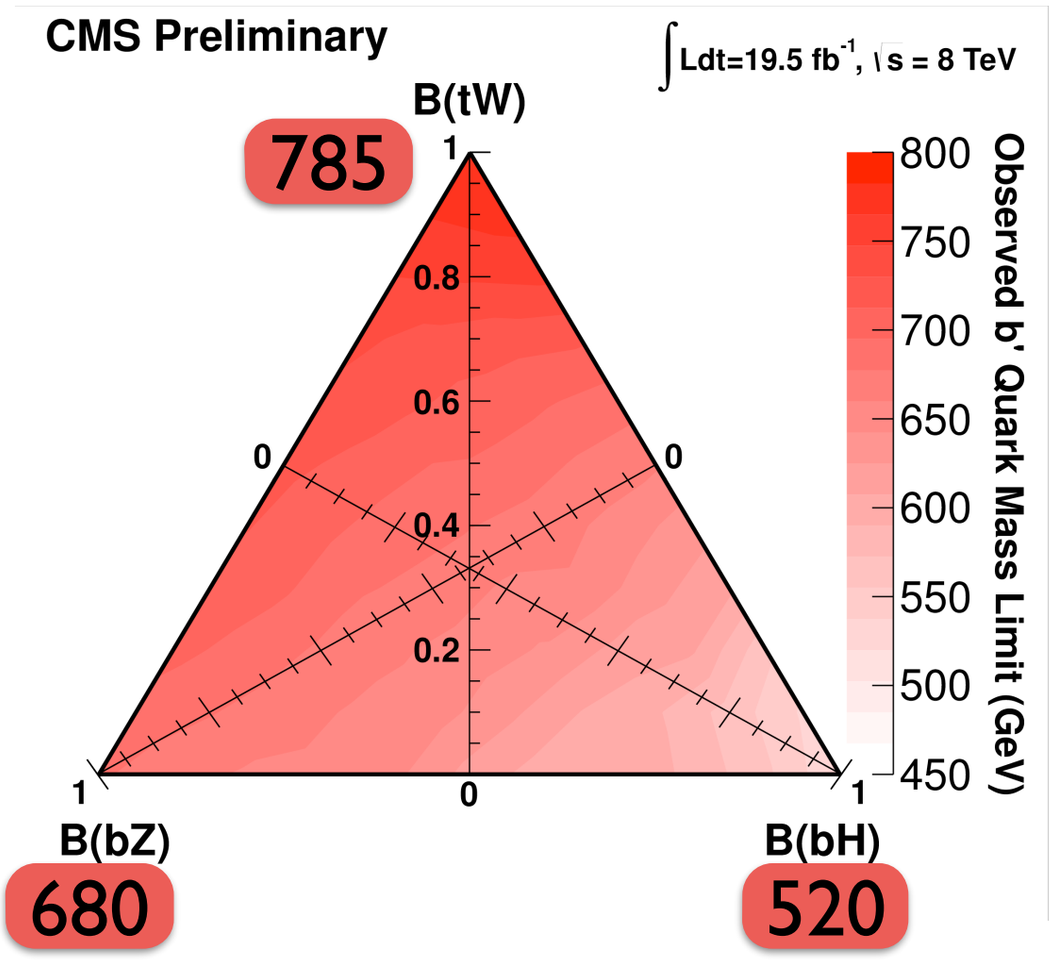
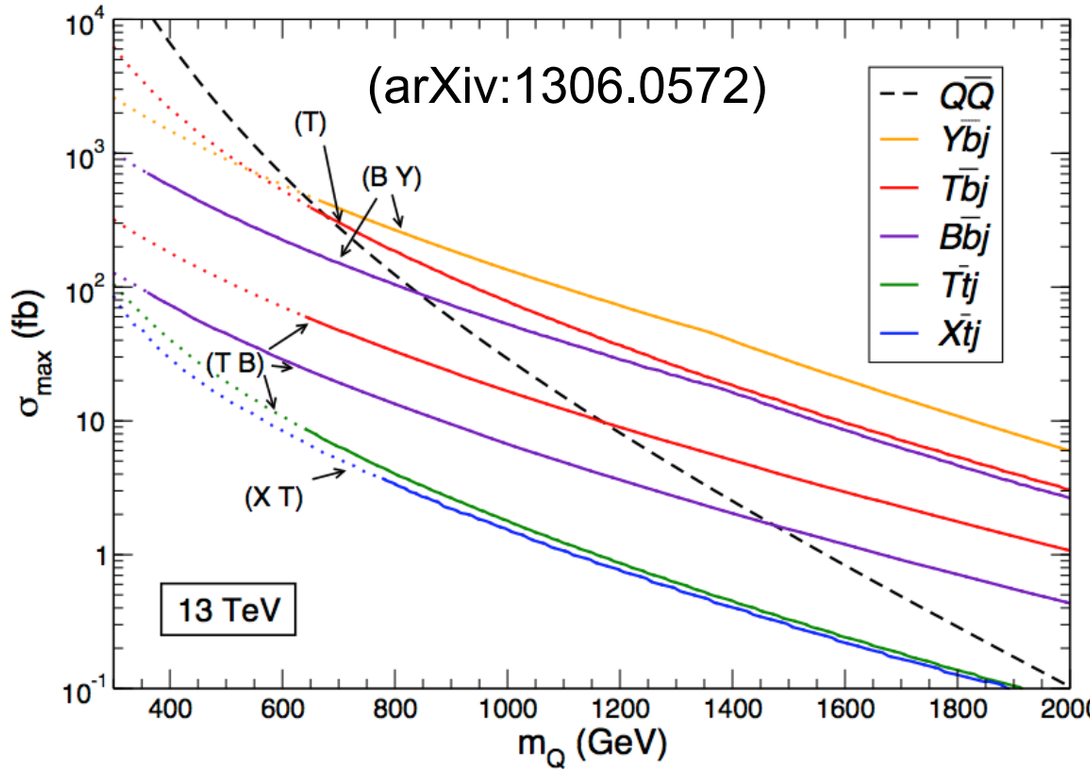


A mass bound of **[520, 785] GeV** is set at 95% CL for all possible BR.

Run 2 Preparation

- Single production is extremely important to target higher masses due to its relatively high x-section
  - e.g, Doublet (Y,B) production which can explain the deviation in Z->bb forward-backward asymmetry, if b-quarks couples to (Y,B)



- Pair Production

T pair production $\longrightarrow$ 6 possible decays: W^+j W^+b Zj Zt Hj Ht

(only) 36 possible combinations of decays into SM particles!

each one with its peculiar kinematics

B pair production $\longrightarrow$ 6 possible decays: W^-j W^-t Zj Zb Hj Hb

36 possible combinations of decays into SM particles

X pair production $\longrightarrow$ W^+j W^+t

4 combinations

Y pair production $\longrightarrow$ W^-j W^-b

4 combinations

VLQ Workshop 2014, Hamburg

Luca Panizzi

light generations not the focus at startup

Conclusion

- CMS is very actively pursuing the search program for VLQ
- Many interesting analyses with more and more stringent limits
- Extensive use of jet substructure techniques
- Legacy results for the Run 1 combinations to come, stay tuned :

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

- Getting ready for data at higher energy !

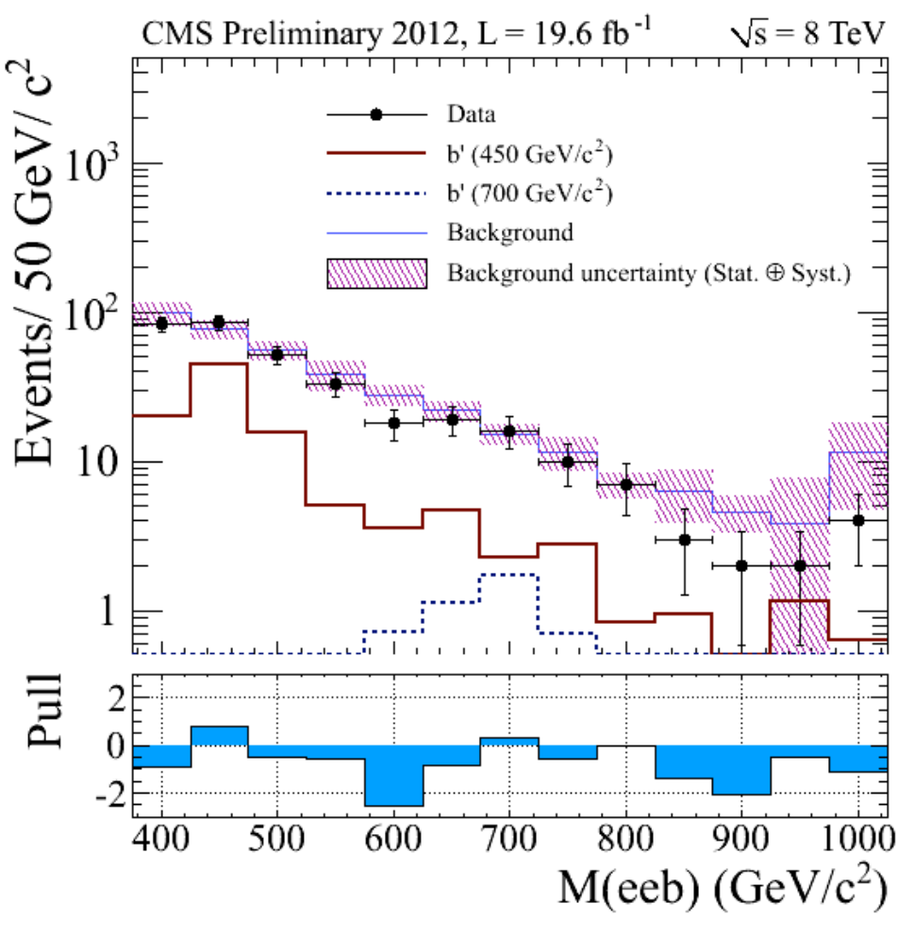
Backup

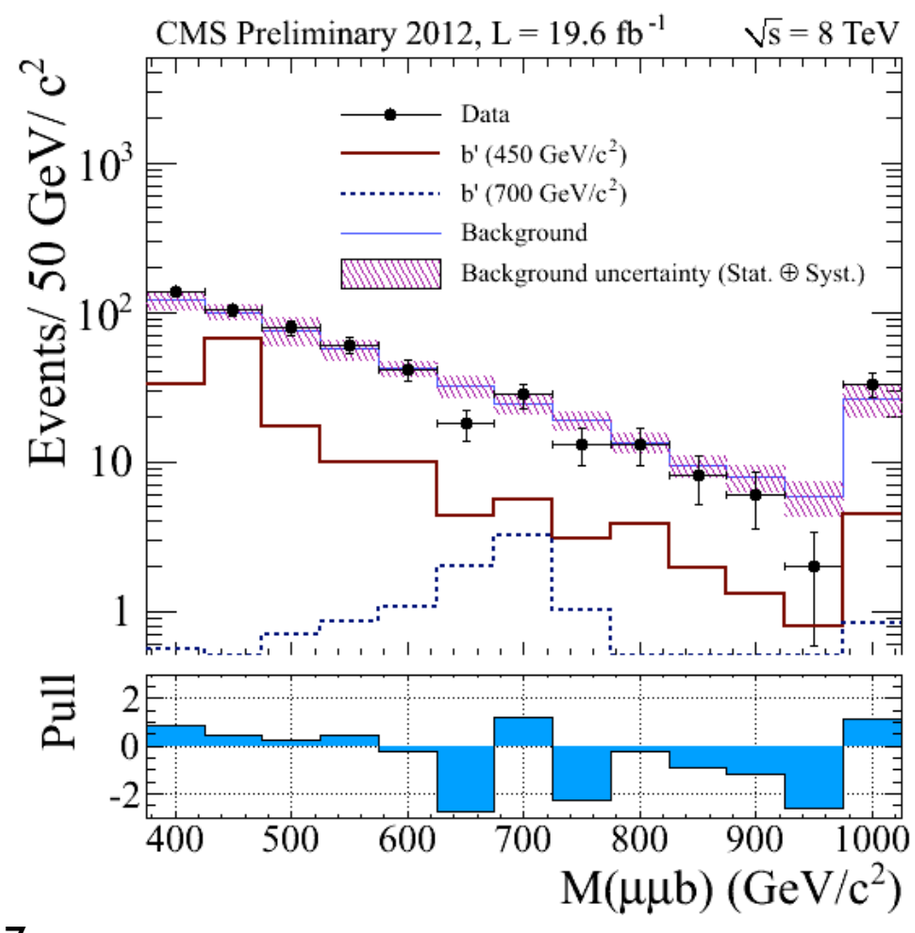
$B_{-1/3}$ quark, OS dilepton

CMS-PAS-B2G-12-021

B→tW, bZ

- **Selection**
  - Two OS isolated leptons (muon or electron), 60<M(ll)<120 GeV, p_T(ll)>150 GeV
  - ≥ 1 b-jet with p_T > 20 GeV
  - Background estimate with data driven method
- **Strategy**
  - Reconstruct invariant mass of B candidate in both e and μ
  - Fit simultaneously in both channels to test for presence of signal.





$B_{-1/3}$ quark, OS dilepton

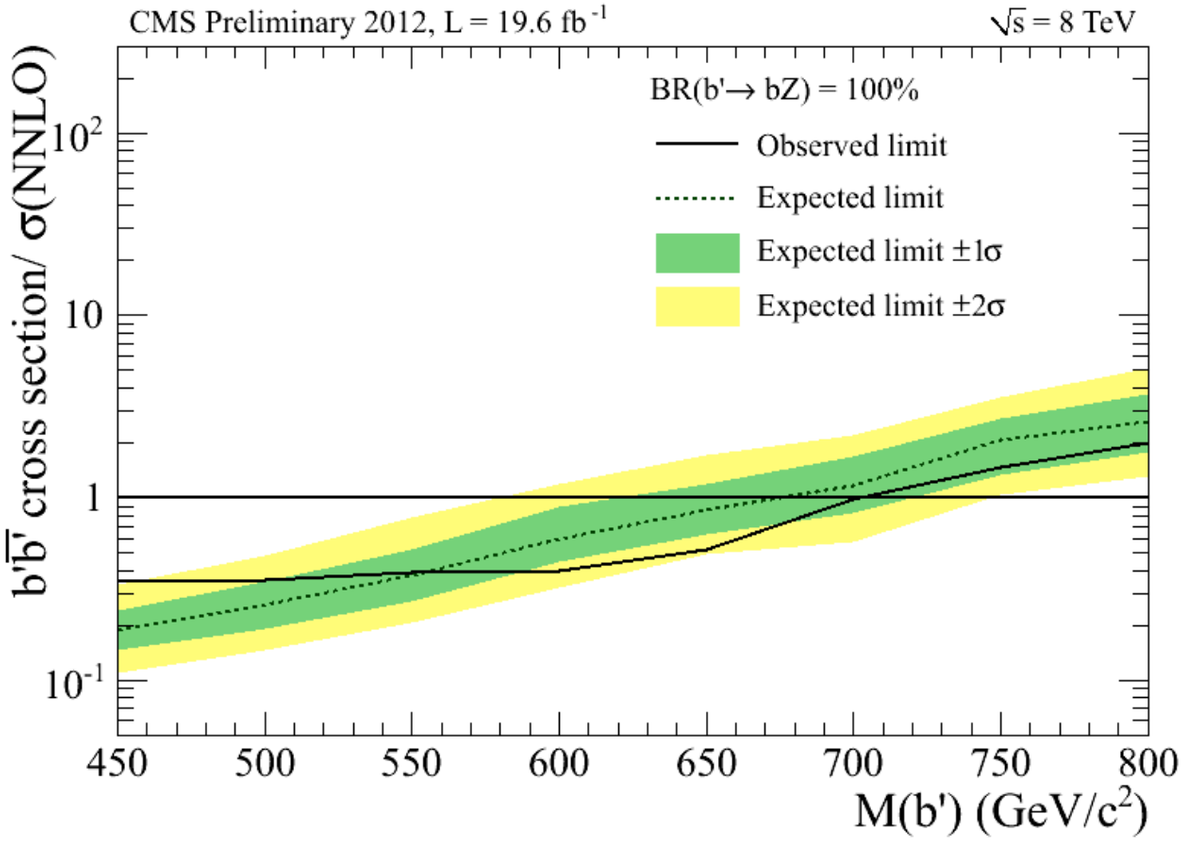
CMS-PAS-B2G-12-021

B→tW, bZ (OS dilepton channel)

- Signal templates of M(B) mass distribution are prepared with different admixtures of the B → bZ and B → tW final states, assuming

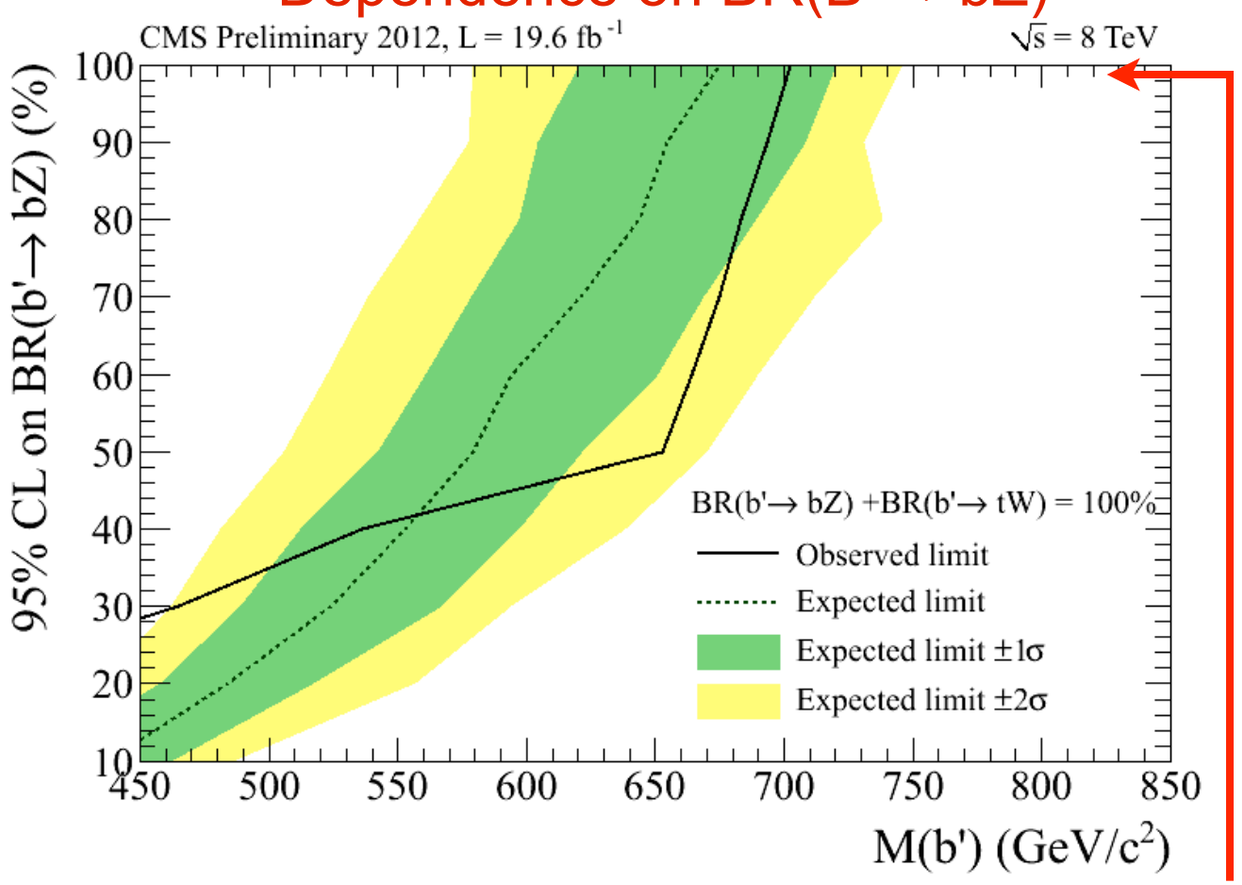
$$BR(B \rightarrow bZ) + BR(B \rightarrow tW) = 100\%.$$

B → bZ, with 100% BR



700(Obs), 680(Exp)

Dependence on BR(B → bZ)



dilepton channel is sensitive, unlike l+jets

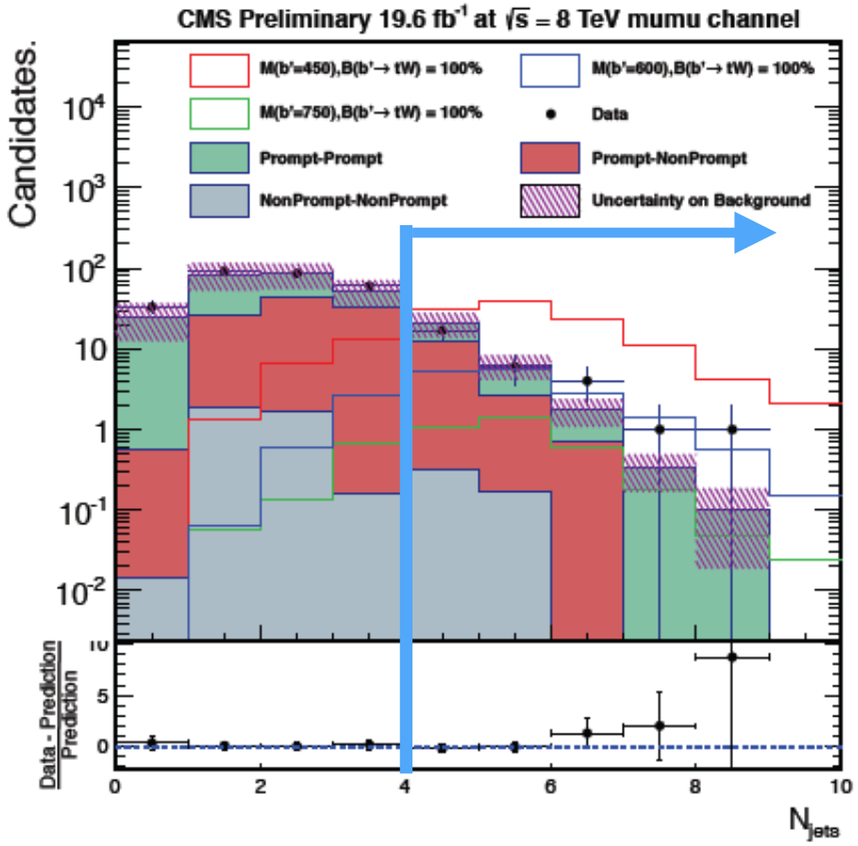
$B_{-1/3}$ quark, SS dilepton

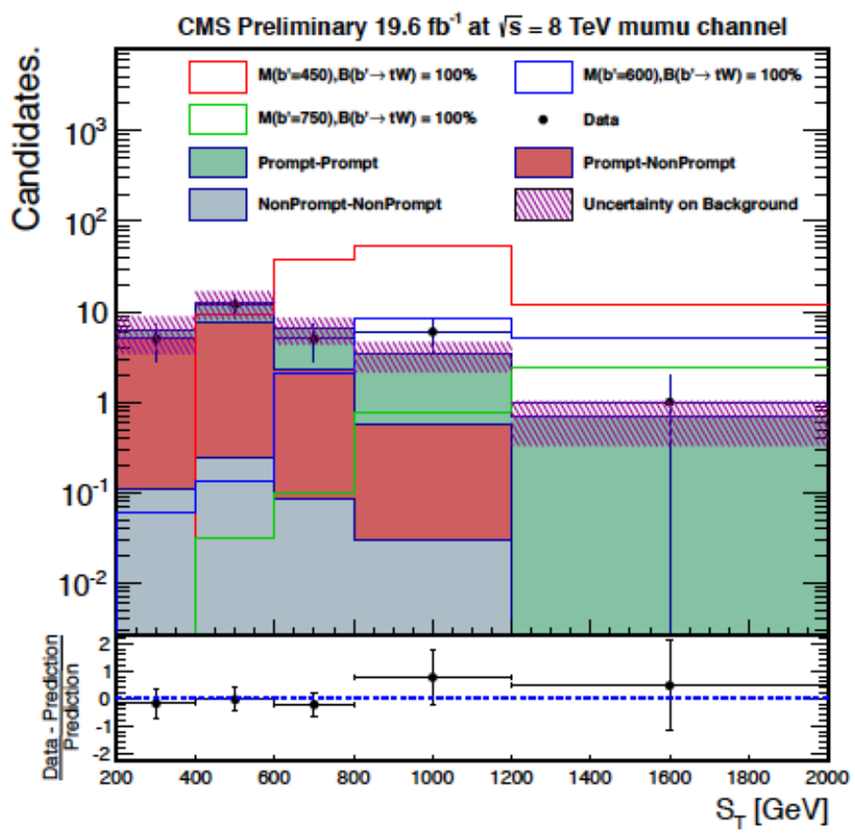
CMS-PAS-B2G-12-020

B→tW, bZ, bH

- **Final state**
  - In BB→tW+tW-, tW+bH, bHbH→bW+W-bW+W-
    - Two W bosons decaying hadronically and other two leptonically => same-sign lepton pair + 6jets
  - ≥ 4 jets, MET >30 GeV

- **Strategy**
  - Search in all three channel: ee, eμ, μμ
  - Binned ST into five bins
  - [200,400], [400,600],[600,800], [800,1200],[≥1200] GeV



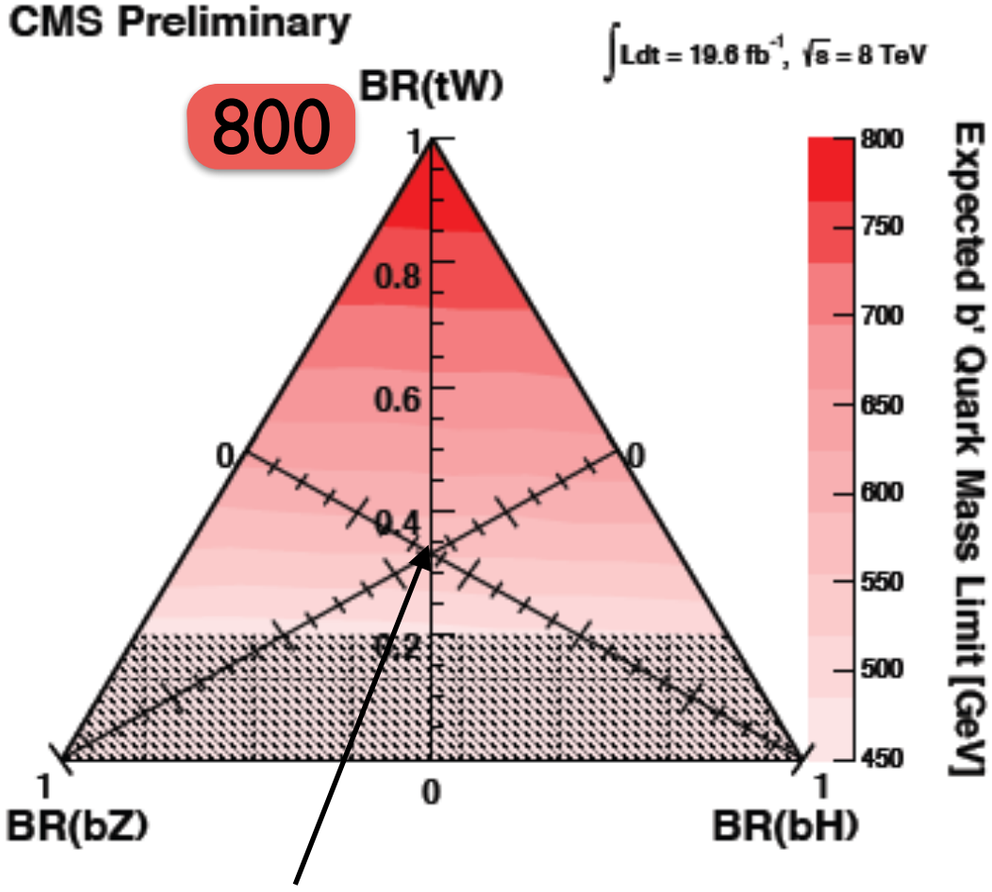


$B_{-1/3}$ quark, SS dilepton

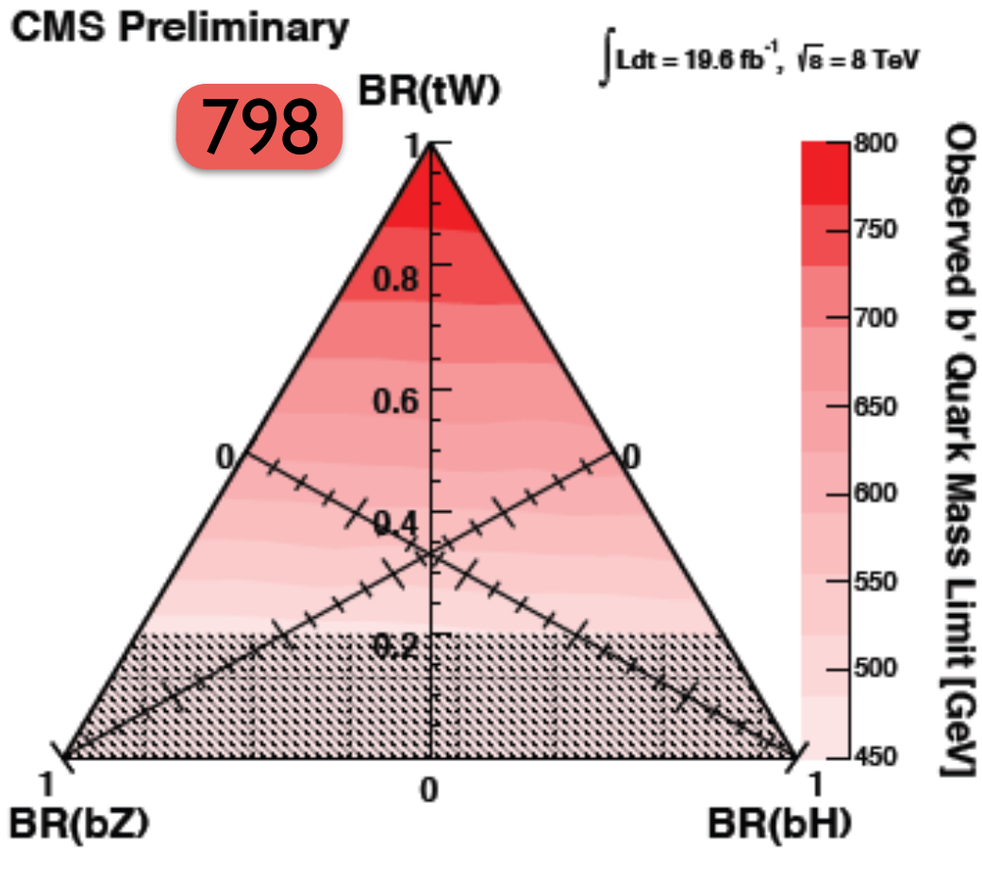
CMS-PAS-B2G-12-020

B→tW, bZ, bH

Expected



Observed



Benchmark point, tW:bZ:bH=0.50:0.25:0.25 : 641(Obs), 646(Exp)

$T_{2/3}$ quark, hadronic/leptonic

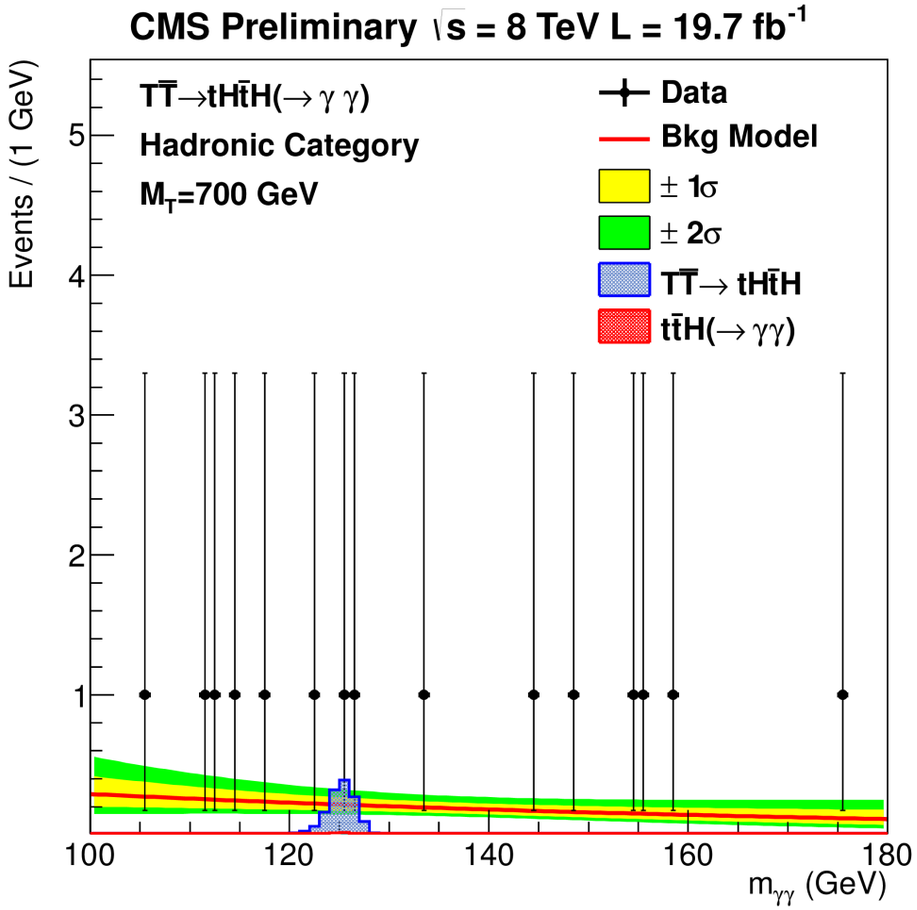
CMS-PAS-B2G-14-003

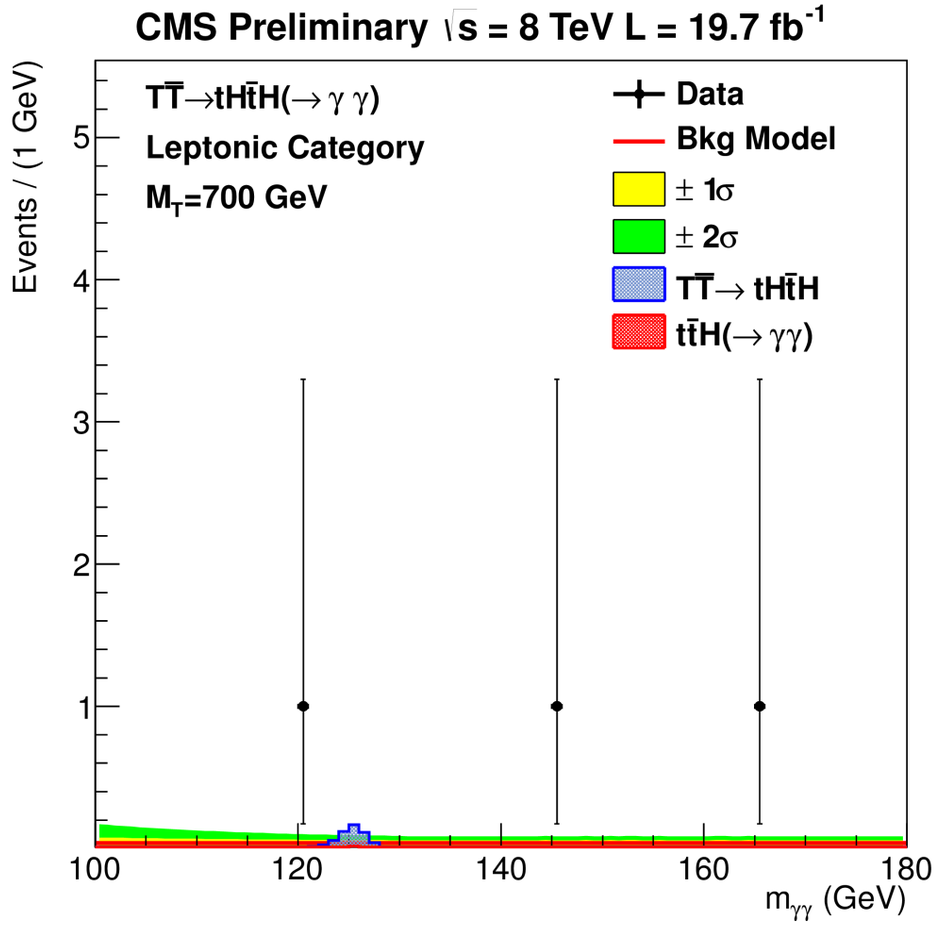
T→tH(→γγ)

- **Event Selection**

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	-

- **Strategy**
  - Exploit the **narrow resonance** of H→γγ, by fitting the peak in Mγγ distribution
  - S_T > 1000 GeV

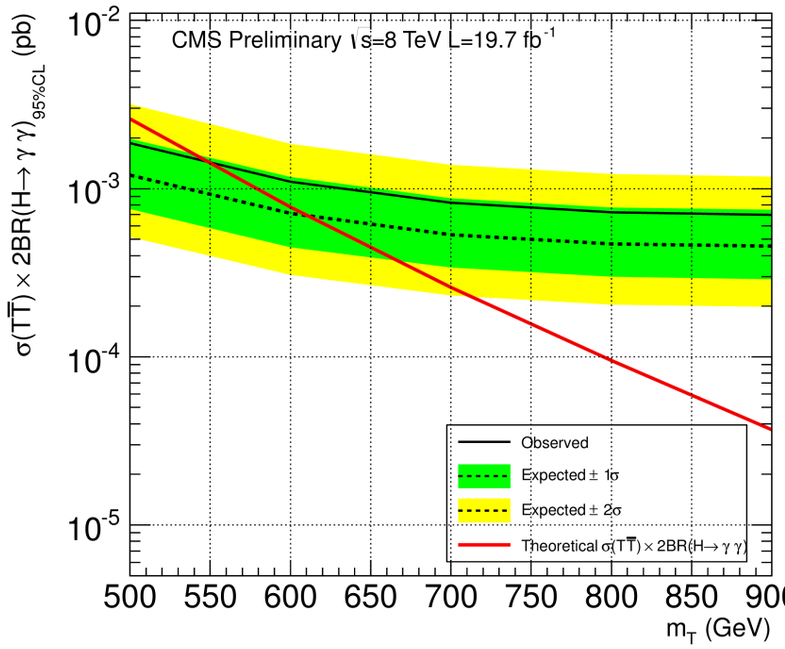




$T_{2/3}$ quark, hadronic/leptonic

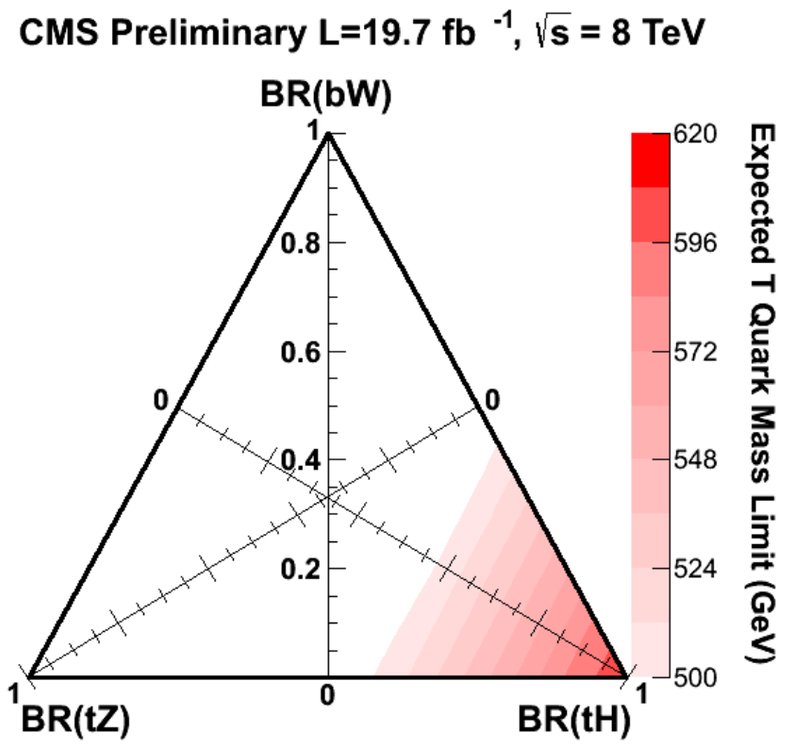
CMS-PAS-B2G-14-003

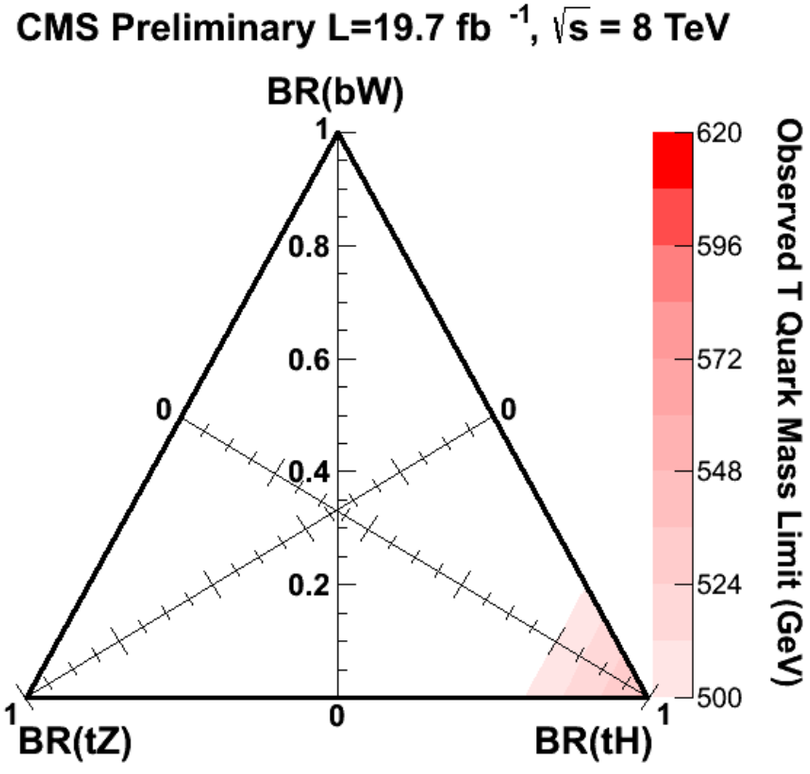
T→tH(→γγ)



exp. limit = 607 GeV
obs. limit = 540 GeV

- Search is limited by statistics, yet a very powerful analysis for Run 2





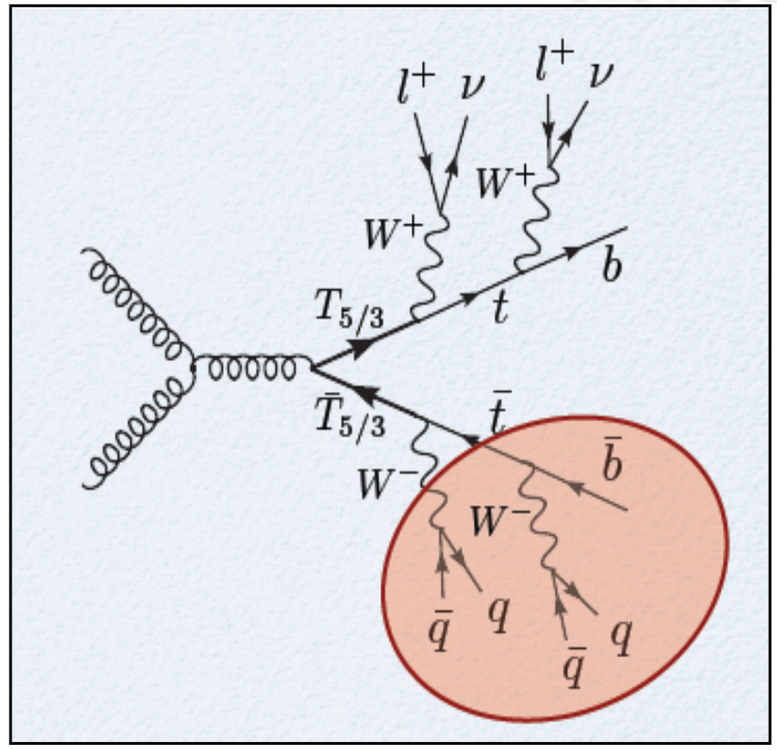
$T_{5/3}$ Top Partners

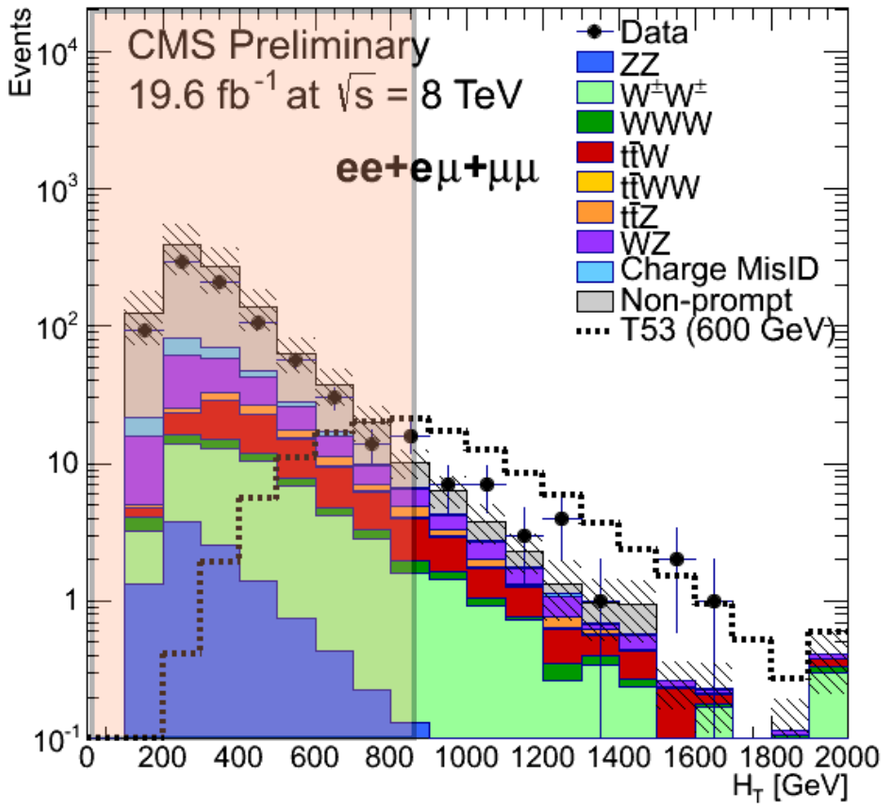
- Pair production of charge 5/3 top partner with 100% decay to tW→bW
  W^+W^+
- Striking signature: same-sign dileptons, where hadronically decaying $T_{5/3}$ can be reconstructed

$$l^{\pm}l^{\pm} + 2b + 2\mathrm{W}$$

- **Selection:**
  - Two same-sign leptons (e or μ) outside Z window
  - 5 or more "constituents" in addition to the two SS leptons
  - constituent=lepton, jet, W-tagged jet (2), or top-tagged jet (3)
    - Use W-tagger and HEP top-tagger with CA8 jets (CMS-PAS-JME-10-013)
  - H_T > 900 GeV (jets+leptons)

CMS-PAS-B2G-12-012





SS DIL + ≥ 2 jets

$T_{5/3}$ Top Partners

- **Strategy:** Mass reconstruction
- Backgrounds
  - Same-sign prompt leptons (WZ, ZZ, ttV, ttWW, $W^{\pm}$ $W^{\pm}$)
  - Opposite sign prompt leptons with charge misidentification
  - Same sign non-prompt leptons (from heavy flavor or conversions)
- Counting experiment
  - 6.6 ± 2.0 expected vs. 11 observed
  - Exclude the $T_{5/3}$ up to masses of 770 GeV

CMS-PAS-B2G-12-012