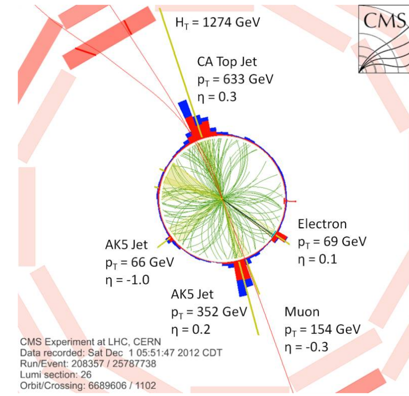
# Search for vector-like quark top and bottom partners

**Eric Chabert** (UDS/CNRS)
On behalf the **CMS collaboration**




*Same sign dilepton event with boosted jets*

# Physics motivation

Many extensions of physics beyond the standard model suggest the existence of **fermionic** partners of bottom/top quarks

**Electroweak symmetry breaking mechanism**:

Cancel loop contributions from the top quark to the Higgs boson mass

- Such particles might help to solve the fine tuning problem
- Mass should be at or below the TeV scale

# Physics motivation

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**Constraints from the discovery of the Higgs boson (?):**

- ~~4th generation~~: disfavored (should enhance $H \to \tau\tau$ and suppress $H \to \gamma\gamma$)

- **Vector-like quarks (VLQ)**:
  - left and right-handed chiralities transformed in the same fashion under $SU(2) \otimes U(1)$
  - Mass independent from the Higgs boson coupling
  - No constraint from Higgs discovery

- Quarks with exotic charges **5/3**, -4/3:
  - do not contribute significantly to the Higgs cross section
  - almost no constraints from Higgs discovery

**Viable alternatives to solve the hierarchy problem !**

# Physics motivation

## Models involving vector-like quarks:

- Composite-Higgs models
- Little-Higgs models
- Top-condensate models
- Models with extra-dimensions
- Non-minimal supersymmetric extensions

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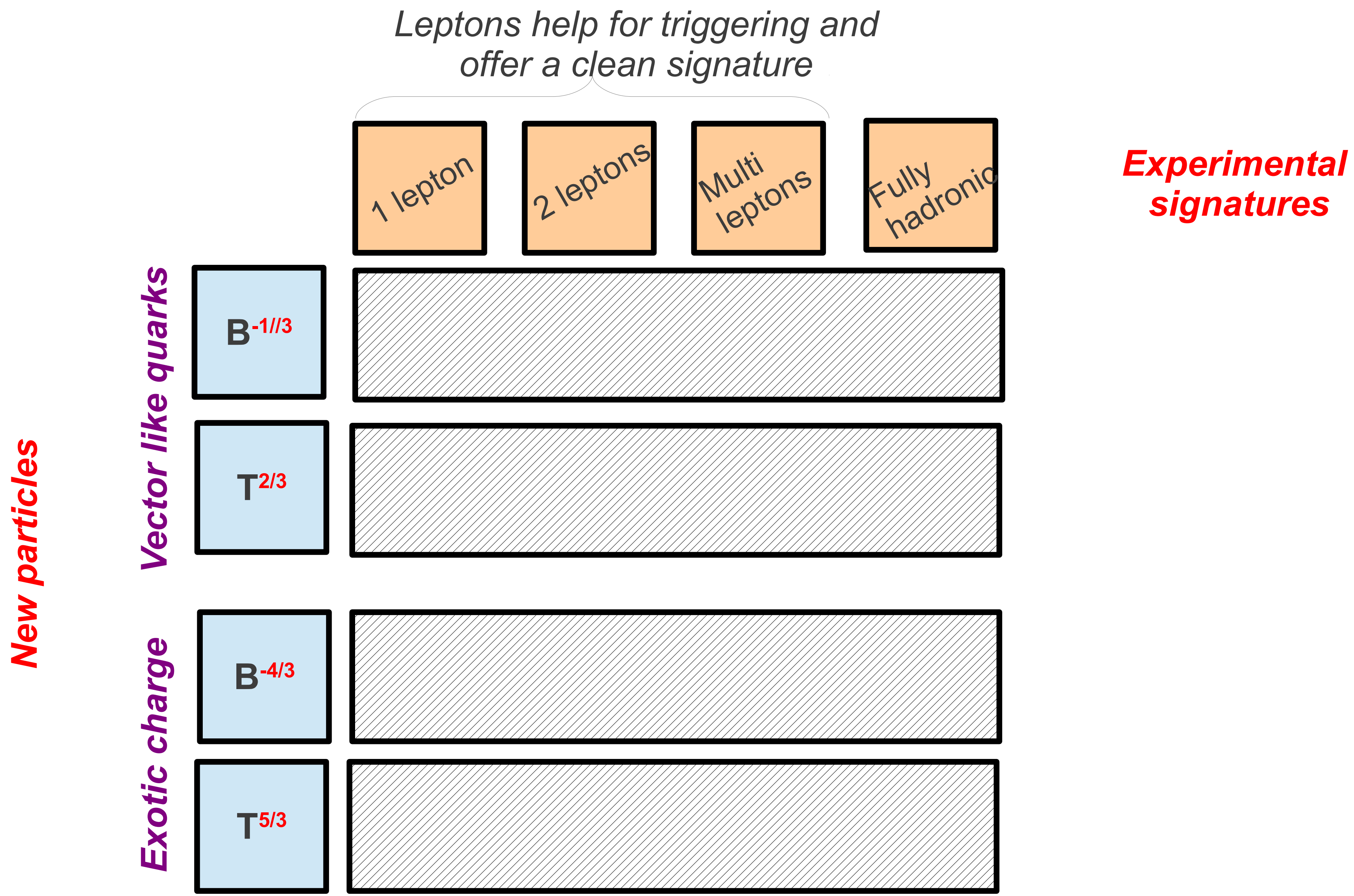
## vector-like quarks & FCNC:

- Unlike for chiral quarks, FCNC are not suppressed
- VLQ can decay into different final states and branching ratios are considered as free parameters in the experimental searches
  - Ex: $t' \rightarrow tZ$ or $t' \rightarrow tH$
- The Higgs boson is used as a probe for new physics

# Searched signals & channels

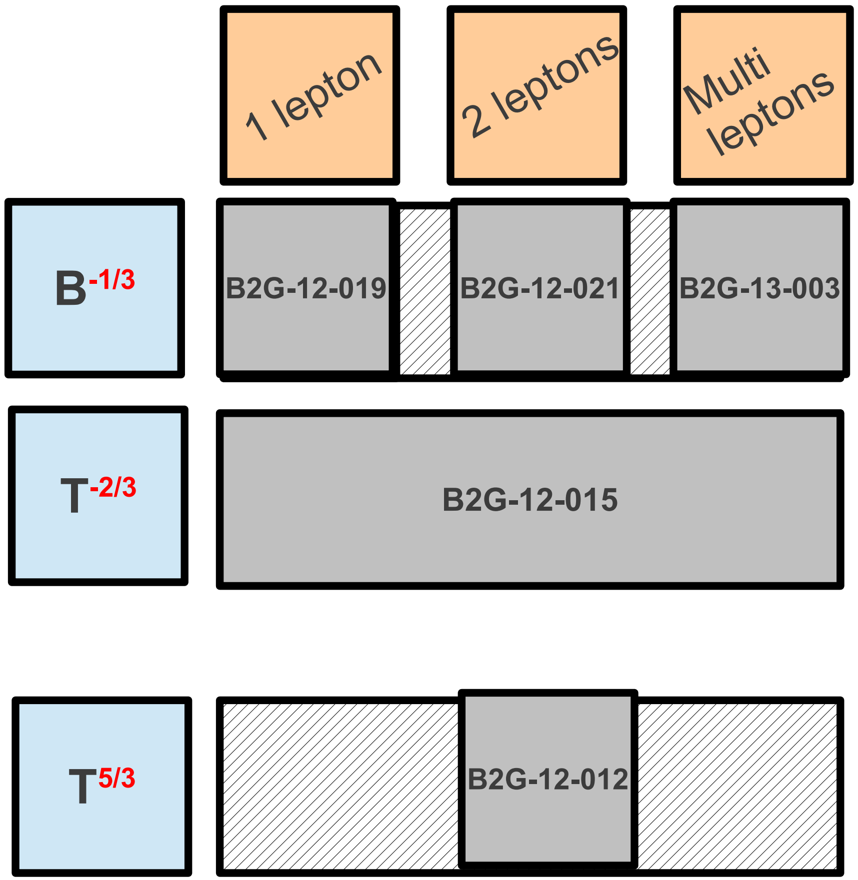
Looking for **pair-produced** 3rd generation partners



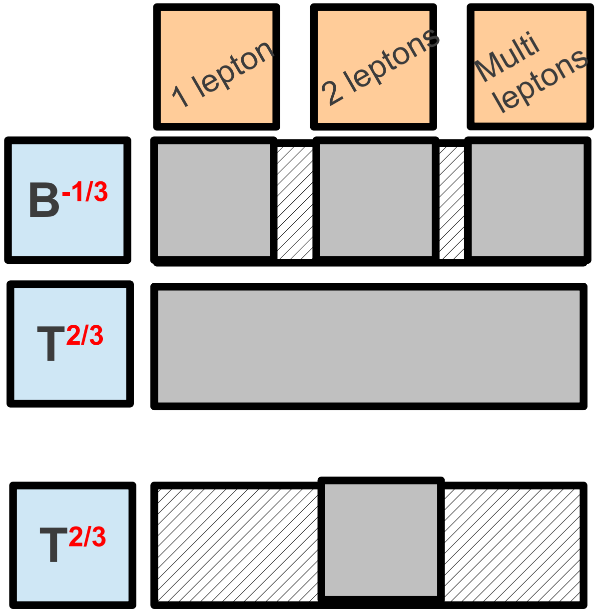
# Public results

Public results @ 8 TeV
$\int L dt \approx 19\ fb^{-1}$

*Previous results @ 7 TeV*
*Not discussed here*



# Decay chains




B→tW FCNC: B→bZ  B→bH

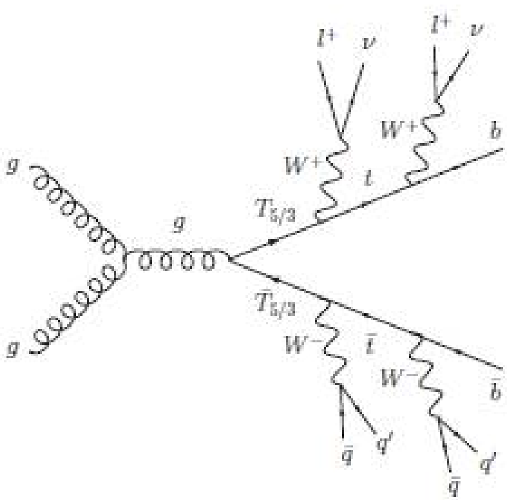
BB→tWtW
BB→tWbZ
BB→tWbH
BB→bZbZ
BB→bZbH
BB→bHbH

t→bW

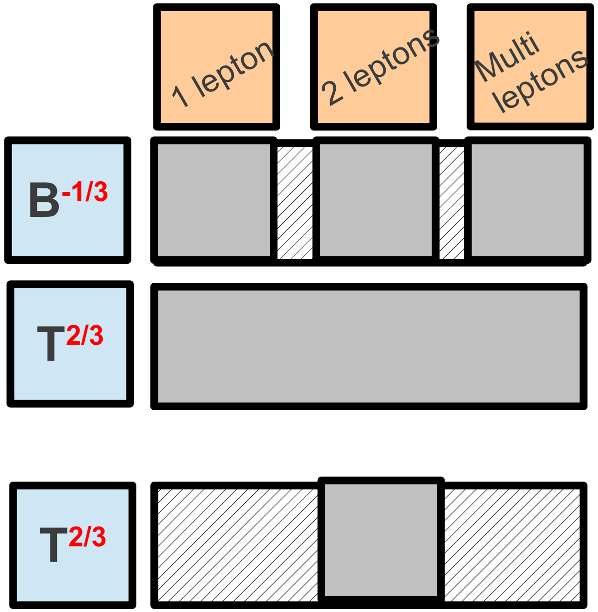
T→bW FCNC: T→tZ  T→tH

TT→bWbW
TT→bWtZ
TT→bWtH
TT→tZtZ
TT→tZtH
TT→tHtH

$T^{5/3}$→tW (100%)



# Decay chains




B→tW FCNC: B→bZ B→bH

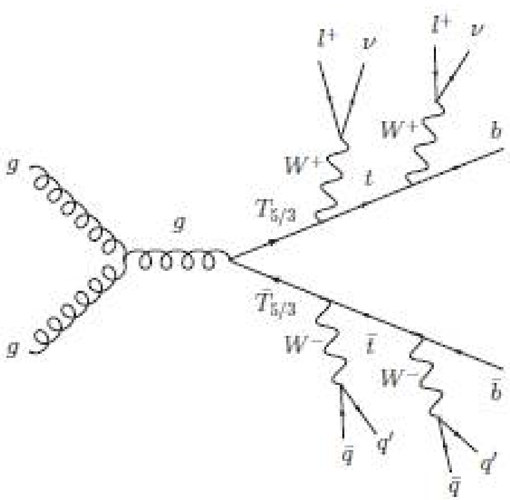
T→bW FCNC: T→tZ T→tH

$T^{5/3}$→tW (100%)

BB→tWtW
BB→tWbZ
BB→tWbH
BB→bZbZ
BB→bZbH
BB→bHbH

TT→bWbW
TT→bWtZ
TT→bWtH
TT→tZtZ
TT→tZtH
TT→tHtH

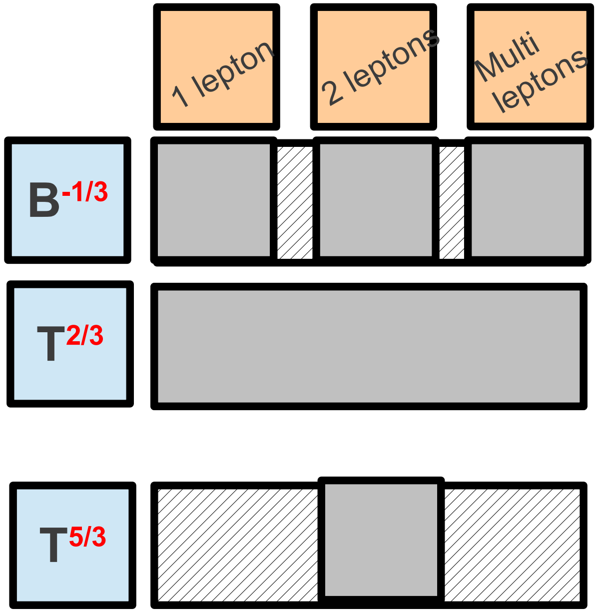
t→bW




**Complex and busy final states:**

- Multiple b quarks
- Many bosons (V/W/H)
- New discovered Higgs boson used as a probe to BSM
- Many possible channels (0 to ≥4 leptons)
- Branching ratios are free parameters

# Analysis tools



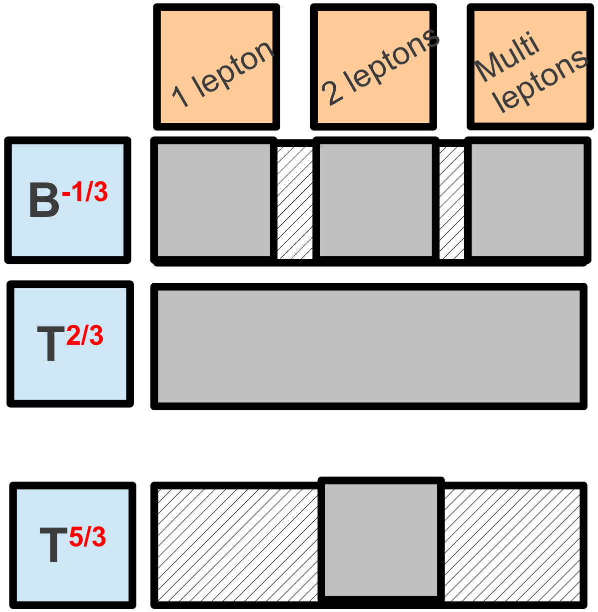

**B-tagging:**

- Combined Secondary Vertex algorithm:

Likelihood Ratio using impact parameter, significance of tracks and secondary vertices

- Performances: $\varepsilon_b \approx 70\%$ - $\varepsilon_{light} \approx 1\%$

# Analysis tools

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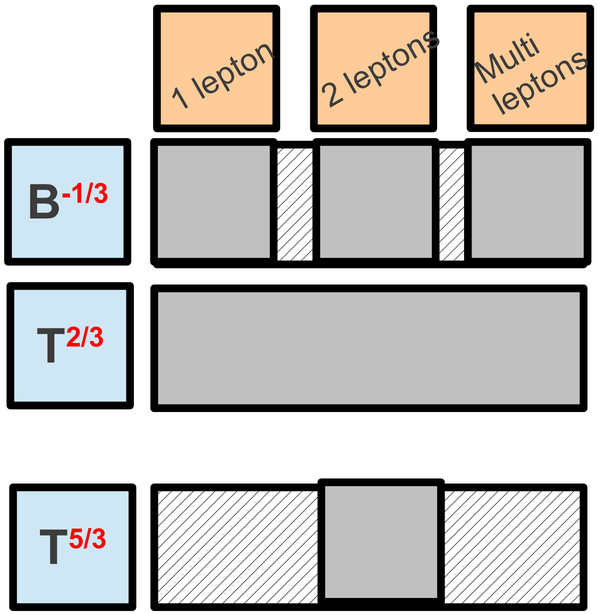
**Boosted regime:**

With **high mass** of partners, bosons (top) produced in the decay chain tend to have a high $p_T$ and consequently their decay products start to merge and look like one jet.

Advanced techniques of jet reconstruction are used.

# Analysis tools

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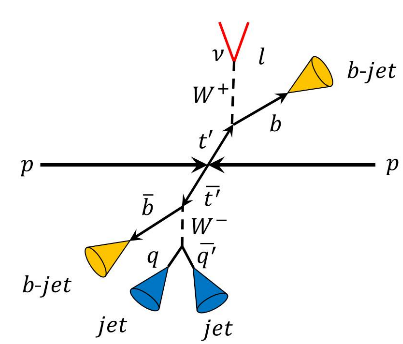
Advanced techniques of jet reconstruction are used.

**V-tagging :**

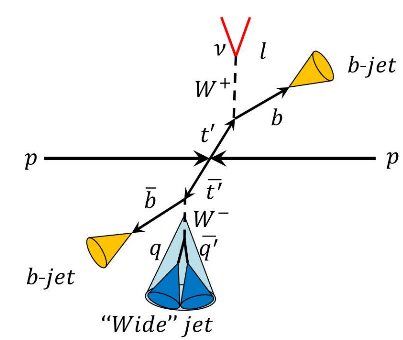
- V can be either **W – Z or H** boson
- Cambridge Algorithm - R = 0.8
- Use pruning technique
- Require 2 subjets
- Mass window:

  [50-120] GeV if it includes W/Z

  [50-150] GeV if it also includes H
- $p_T$(V-jet)>200 GeV

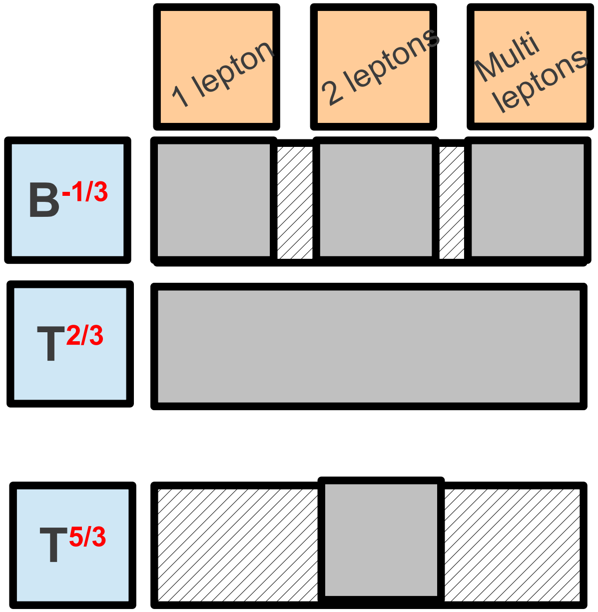



"Narrow" jets – AK5 (anti-kt R=0.5)




"wide" jets – CA8

# Analysis tools

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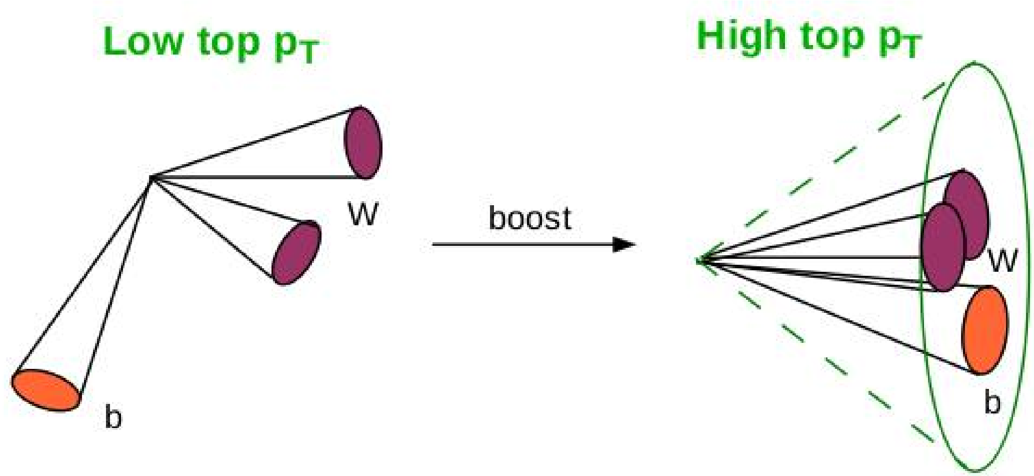
With **high mass** of partners, bosons (top) produced in the decay chain tend to have a high $p_T$ and consequently their decay products start to merge and look like one jet.
Advanced techniques of jet reconstruction are used.

**top-tagging:**

- Cambridge Algorithm - R = 1.2
- Use pruning technique
- Require ≥ 3 subjets
- $M_{min(pair\text{-}wise\ subjets)}$>50 GeV
- Mass window: [150-250] GeV
- $p_T$(V-jet)>200 GeV



# VLQ $B^{1/3}$ : lepton +jets channel

$B^{-1/3}$

$T^{2/3}$

$T^{5/3}$

**Selection:**

- Trigger: Single lepton
- 1 isolated lepton (e,μ)
- ≥ 4 AK5 jets ($P_T$>200,60,40,30 GeV)
- ≥ 1 b-tagged jet
- $E_T$>20 GeV
- Centrality = $\Sigma_{jets}P_T/\Sigma_{jets}E_T$ >0.4

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**Data-driven components:**

Trigger/lepton efficiency

V-tagging efficiency

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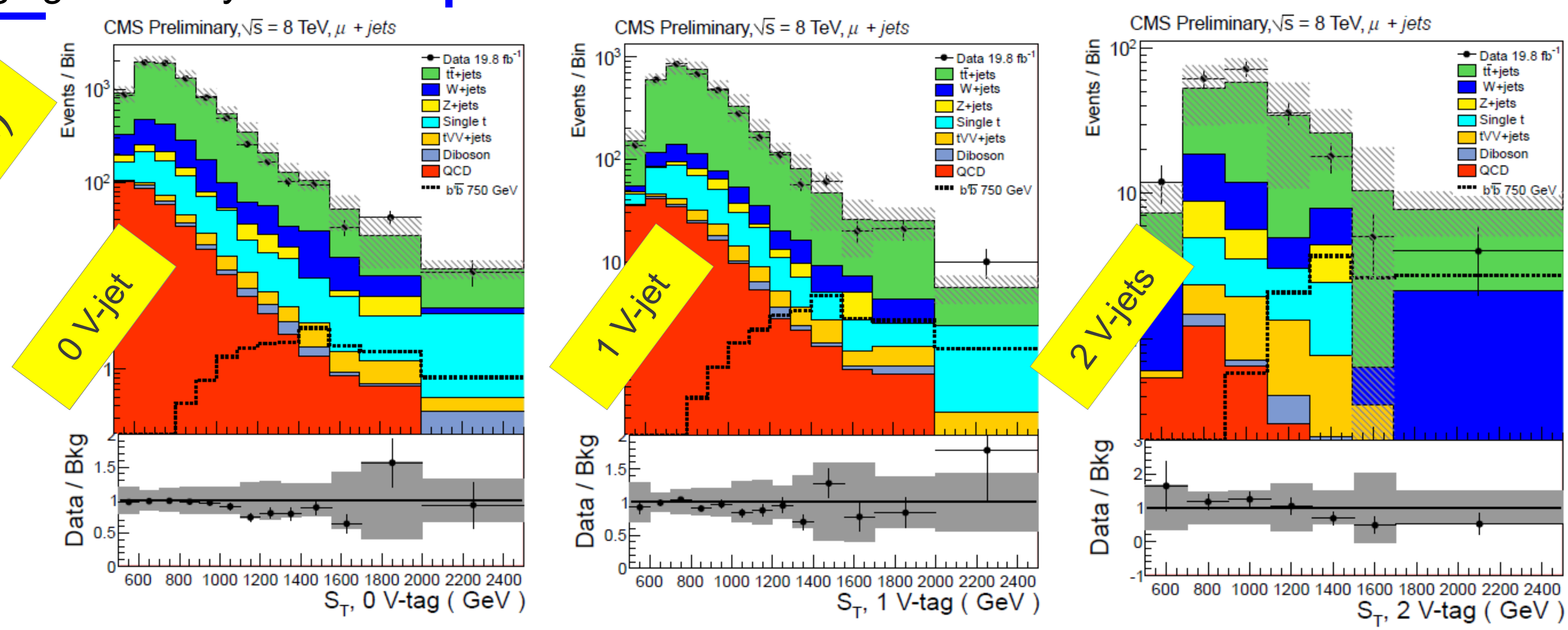
**Data-driven components:**

Trigger/lepton efficiency
V-tagging efficiency

**Search signal regions:**

Channels: e & μ channels
Categorization:
0, 1 , ≥2 V-tagged jets
V-tagging: mass consistent with W/Z or H
$50<m_{V\text{-}jet}<150$
Discriminating variable:
$S_T = \Sigma_{l,jets,MET} P_T$
Fit: simultaneous likelihood fit of $S_T$ distributions
Treatment of systematics (normalisation & shape)

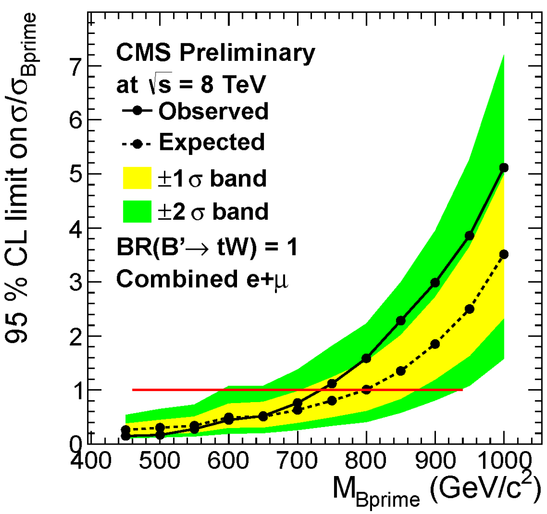
$S_T$ distribution (μ channel)



# VLQ $B^{1/3}$ : lepton +jets channel

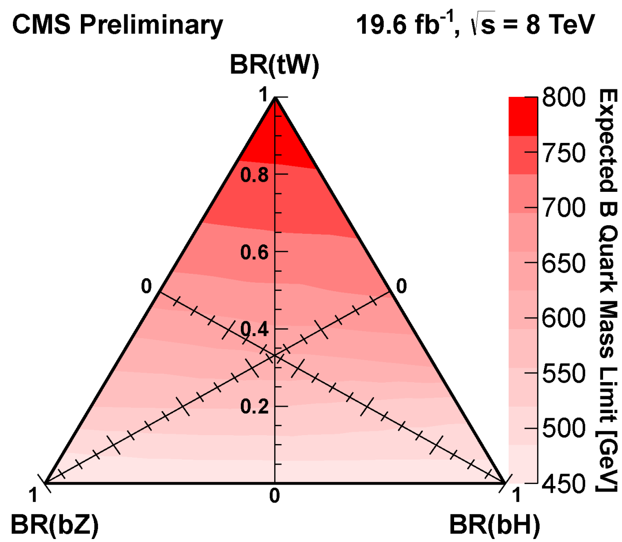
$S_T$ distributions for 0, 1 and ≥2 V-tag categories are fit simultaneously in both e and μ channels to test for presence of signal.

For BR(B→tW)=100%:

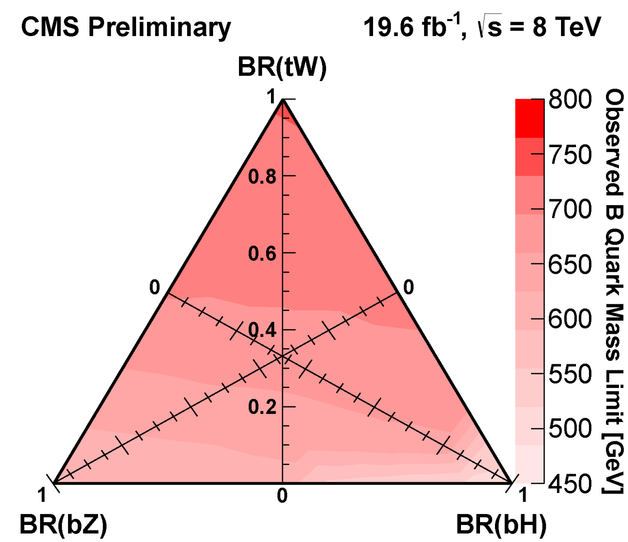



**Observed limit**: 732 GeV

A scan was done with BR to tW, bZ, bH varying with step of 0.1:




Expected limits




Observed limits

Masses below **582-732 GeV** are excluded on 95% CL depending on combination of branching fractions.

# VLQ $B^{1/3}$ : opposite sign dilepton

$B^{-1/3}$

$T^{2/3}$

$T^{5/3}$

B pair production, $B \rightarrow bZ$ with $Z \rightarrow l^+l^-$, $B \rightarrow tW$ decays are allowed. $BR(B \rightarrow bH)=0$

**Selection:**

- Trigger: dilepton
- 2 Opposite Sign isolated lepton (e or μ)
- $60<M(ll)<120$ GeV
- $P_T(ll)>150$ GeV
- $\geq$ 1 b-tagged jet ($P_T>80$ GeV)

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## Search signal regions:

Channels: $e^+e^-$ & $\mu^+\mu^-$ channels

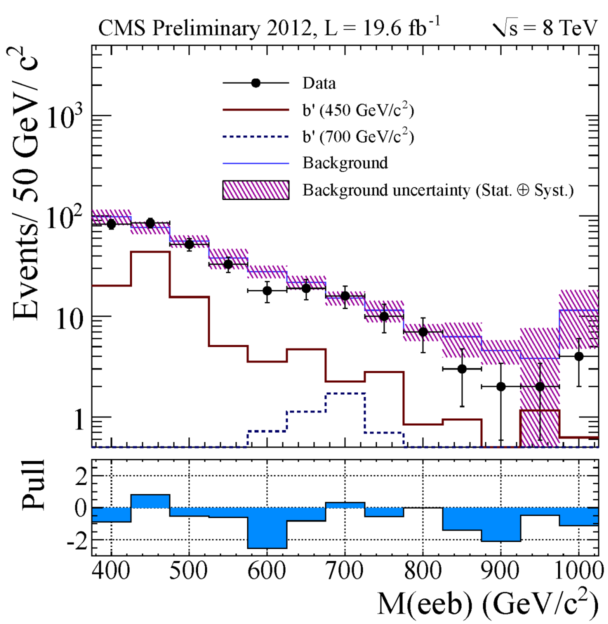
Discriminating variable:

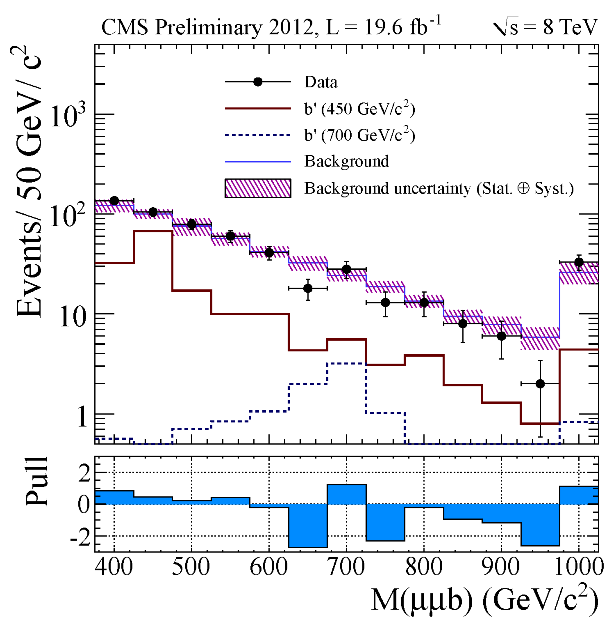
**Mass(llb)** : peak to the mass of B for signal

Fit: likelihood fit of **Mass(llb)** distributions

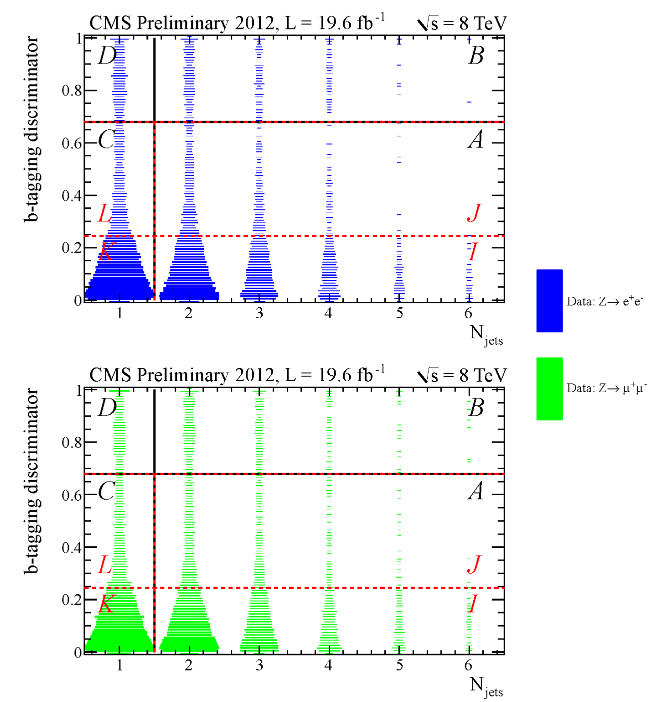
Treatment of systematics (normalisation & shape)

### Mass(llb) distributions




**Modelisation of the distributions with data-driven method:**

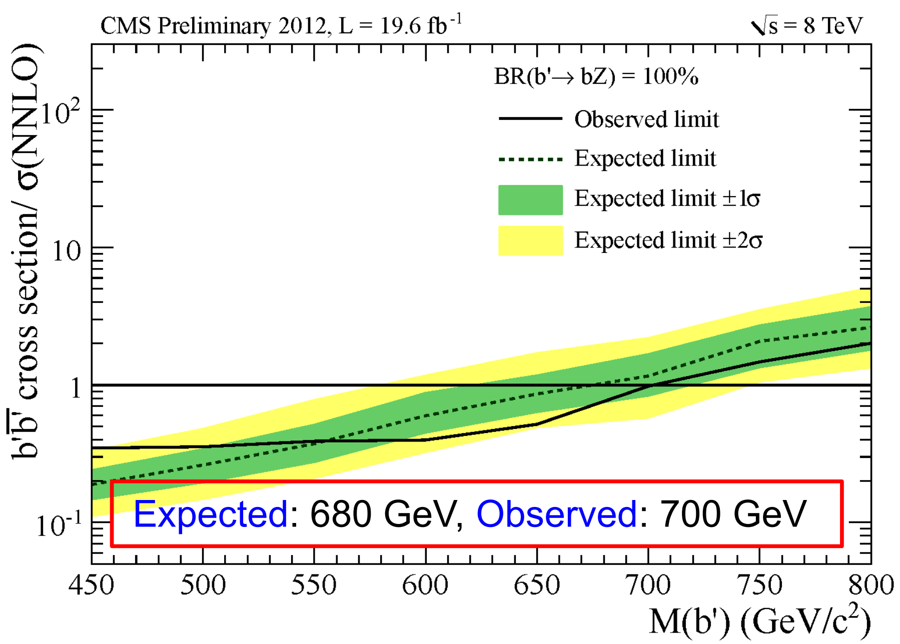


# VLQ $B^{1/3}$ : opposite sign dilepton

The limits are calculated using a combined fit of the signal and background shapes to the mass distribution of B candidates obtained in data.

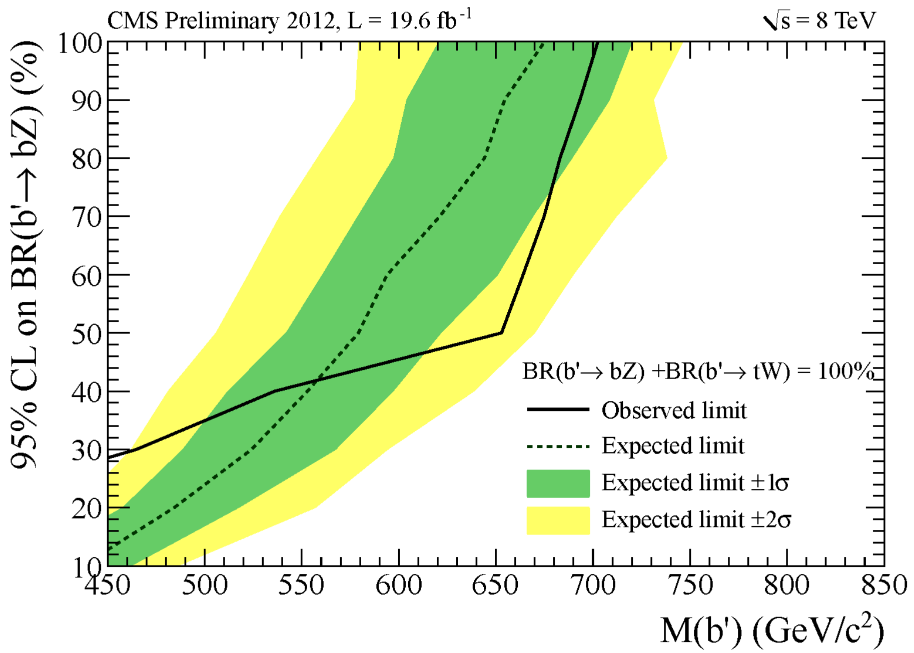
Assumption: BR(B → bZ) + BR(B → tW) = 100%.

For BR(B→bZ)=100%:




Expected: 680 GeV, Observed: 700 GeV

BR(B → bZ) & M(B) dependence:



# VLQ $B^{1/3}$ : multilepton channel

$B^{-1/3}$

$T^{2/3}$

$T^{5/3}$

**Selection:**

- Trigger: dilepton
- ≥ 3 isolated leptons (e,μ or τ)
- M(ll)>12 GeV: quarkonia veto
- Reject lepton from conversion: |M(lll)-MZ|<15 GeV
- ≥ 1 b-tagged jet ($P_T$>80 GeV)

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## Data-driven components:

**Reductible background**

Background with non-prompt leptons
Ttbar background (dilepton CR)
Asymmetric internal photon conversion

**Irreductible background**

Modeling of MET (WZ and rare process)

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## Search signal regions:

**Categorization:**

Number of leptons (3 or 4), taus (0,1), b-jets (1,≥1)

$N^{ossf}$ (0,1,2), Z On/off shell

**=> Many independent signal regions !**

Discriminating variable:

$S_T$ : 6 bins

Fit: likelihood fit of $S_T$ distributions

Treatment of systematics (normalisation & shape)

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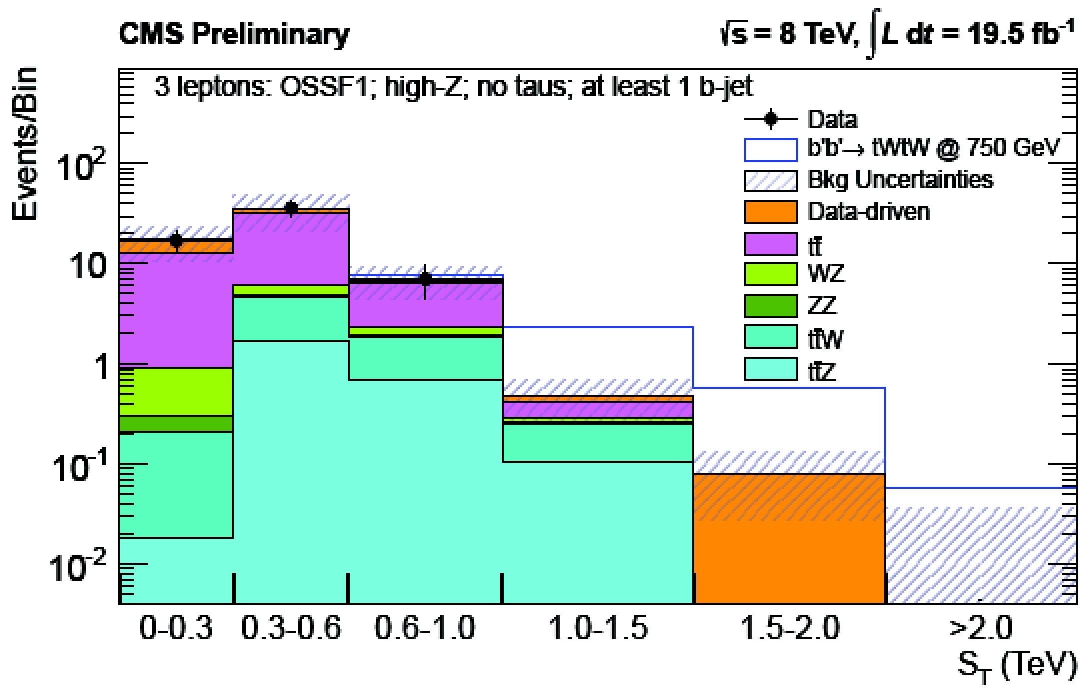
Ttbar background (dilepton CR)

Asymmetric internal photon conversion

**Irreductible background**

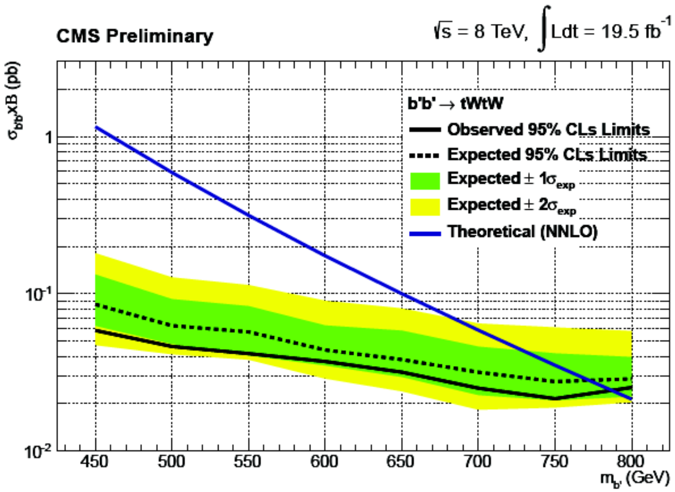
Modeling of MET (WZ and rare process)



# VLQ $B^{1/3}$ : multilepton channel

$S_T$ distributions for all categories are fitted to test for presence of signal.

For BR(B→tW)=100%:




**Observed limit**: 785 GeV

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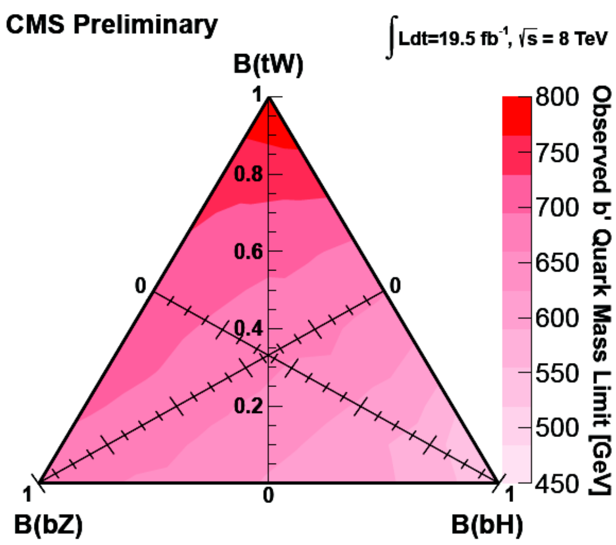


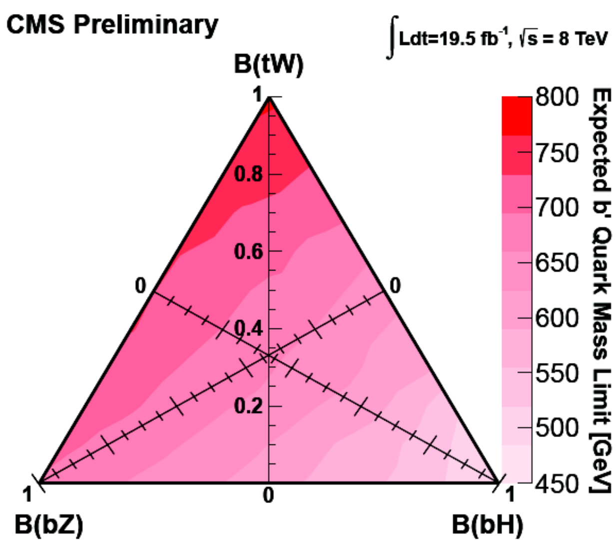


Observed limits

Expected limits

Masses below 520-785 GeV are excluded on 95% CL depending on combination of branching fractions.

# VLQ $T^{2/3}$ : lepton+jets channel

$B^{-1/3}$

$T^{2/3}$

$T^{5/3}$

**Selection:**

- Trigger: single lepton
- 1 isolated lepton (e or μ)
- ≥ 3 jets (120,90,50 GeV)
- 1 W-jets or a 4[th] jet $p_T$>35 GeV)
- ≥ 1 b-tagged jet
- MET > 20 GeV

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**Data driven components:**

- W+light-jets background
- W+heavy-flavor-jets background

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- MET > 20 GeV

## Search signal regions:

Channels: e & μ channels

Discriminating variable: **BDT discriminant**

**Input variables:**

- Nof jets, Nof b-jets, Nof w-jets, Nof top-jets
- $P_l^{lepton}$, $P_T^{3rd\ jet}$, $P_T^{4th\ jet}$, $P_T^{w\text{-}jet}$
- $H_T$, MET

Fit: likelihood fit of **BDT** distributions

Treatment of systematics (normalisation & shape)

## Data driven components:

- W+light-jets background
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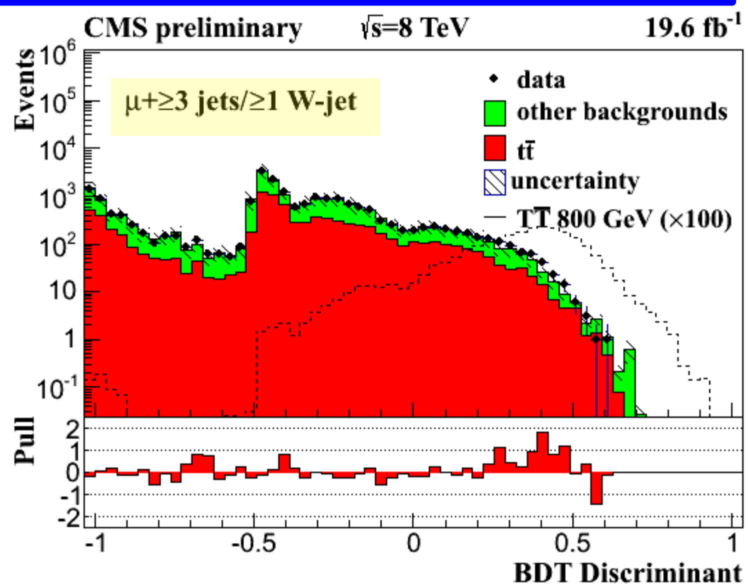


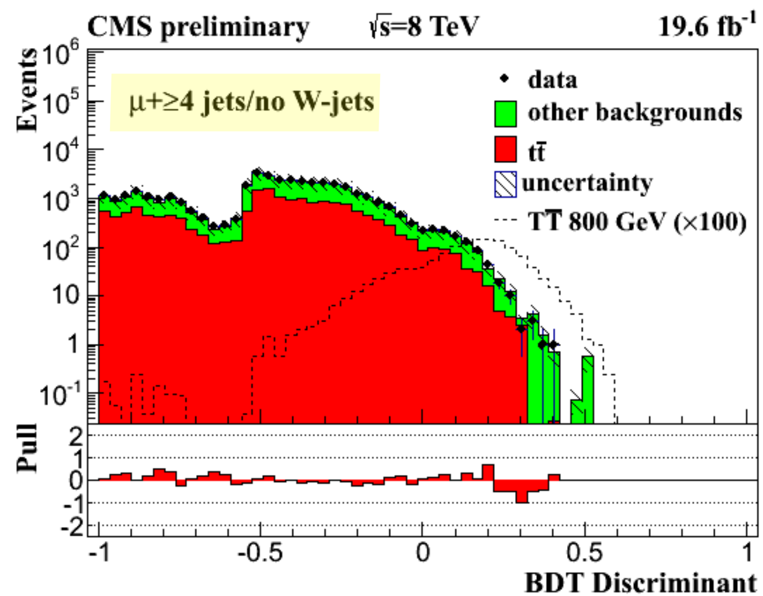


*Same distribution with 0 b-jet showed a good data/MC agreement*

# VLQ $T^{2/3}$ : multilepton channel

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$T^{5/3}$

**Selection:**

- Trigger: dilepton
- $\geq 2$ isolated lepton (e or μ)
- M(ll)>20 GeV: quarkonia veto
- $\geq$ 1 b-tagged jet
- MET > 30 GeV

**Signal regions selection:**

- Jets multiplicity
- $H_T$
- $S_T$
- M(lb)

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- Jets multiplicity
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- $S_T$
- M(lb)

**Search signal regions:**

Channels: 12 independent channels
Depending on the number of leptons, their sign and their flavor

Counting experiment

Fit: likelihood fit based on the number of events in each category
Treatment of systematics (normalisation & shape)

**Opposite Sign Dilepton**

**Off-Z peak**: sensitive to TT→tWtW
**Z-peak**: sensitive to T→tZ & T→tH

**Same Sign Dilepton**

sensitive to T→tZ & T→tH

**Trilepton**

sensitive to T→tZ & T→tH

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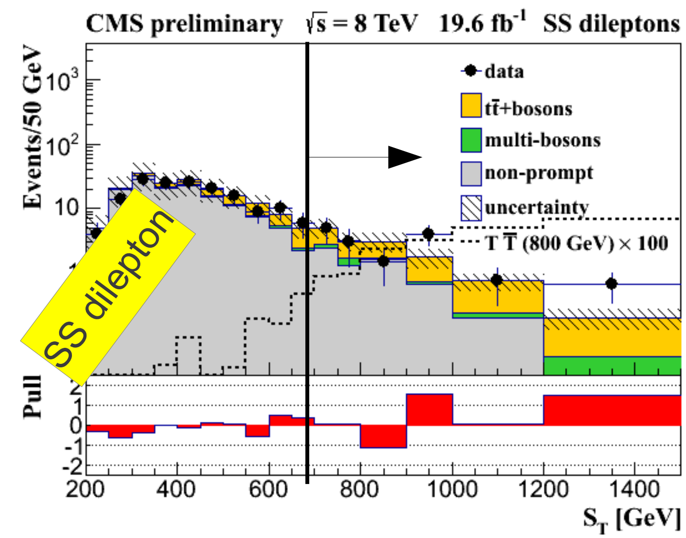


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**Z-peak**: sensitive to T→tZ & T→tH

## Same Sign Dilepton

sensitive to T→tZ & T→tH

## Trilepton

sensitive to T→tZ & T→tH

## Data driven components:

- Fake rate
- Electron charge misreconstruction

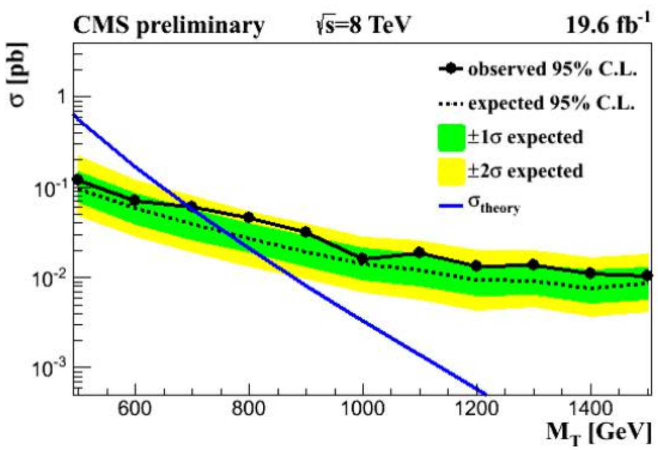
# VLQ $T^{2/3}$ : all channels

The limits are calculated with a likelihood fit

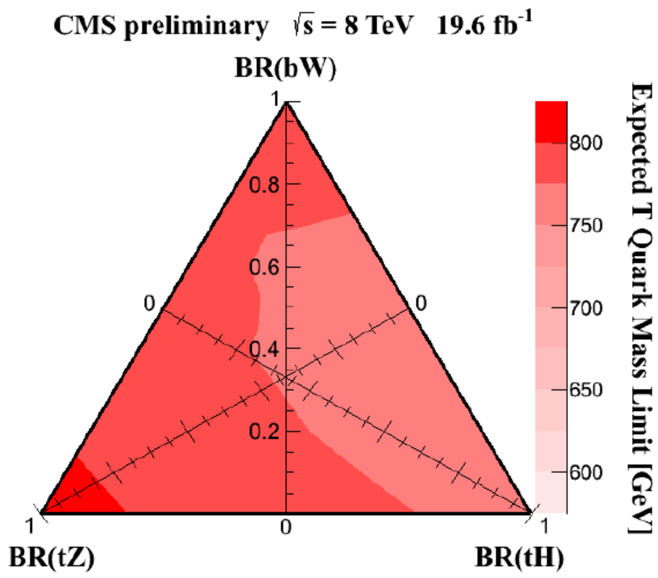
- based on the number expected and observed for the multilepton channels
- based on the BDT discribution for the lepton+jets channels

A scan was done with BR to tW, bZ, bH varying with step of 0.1:

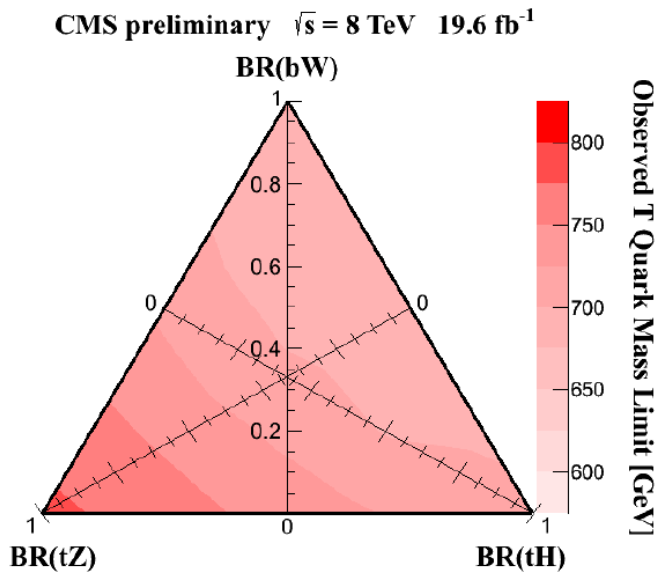
For BR(B→tW)=50%
BR(B→tZ)=25%
BR(B→tH)=25%




**Observed limit**: 696 GeV




Expected limits




Observed limits

Masses below 687-782 GeV are excluded on 95% CL depending on combination of branching fractions.

# Search for $T^{5/3}$ – same sign dilepton

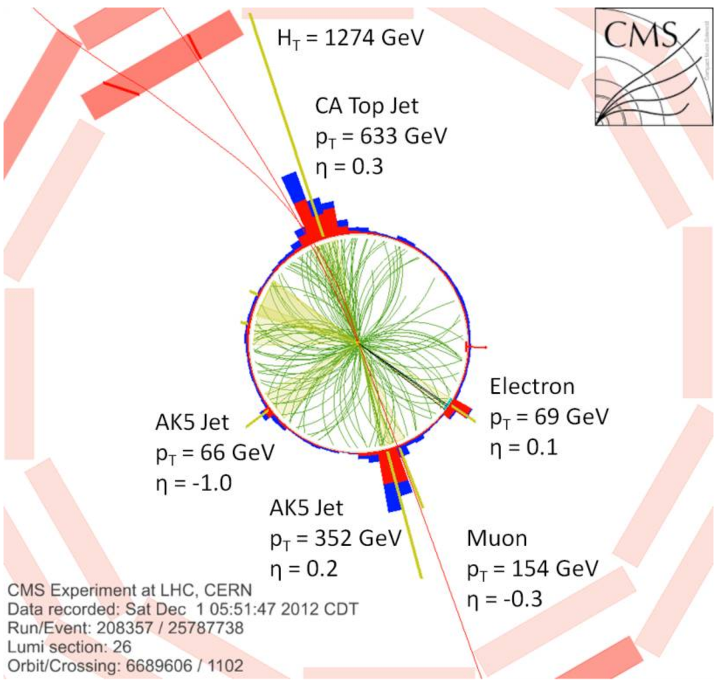
$B^{-1/3}$

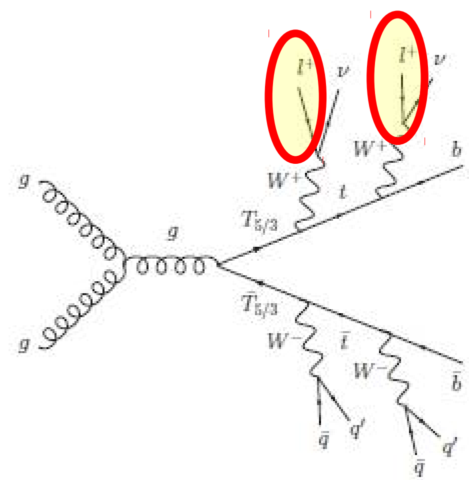
$T^{2/3}$

$T^{5/3}$

**Selection:**

- Trigger: double lepton
- 2 isolated lepton SS (e or μ)
- M(ll) > 20 GeV : quarkonia veto
- Z-veto: 76-106 GeV
- Nof constituents $\geq 5$
  - ✯ jet = 1 constituent
  - ✯ W-tagged jet = 2 constituents
  - ✯ Top-tagged jet = 3 constituents
- $H_T$>900 GeV



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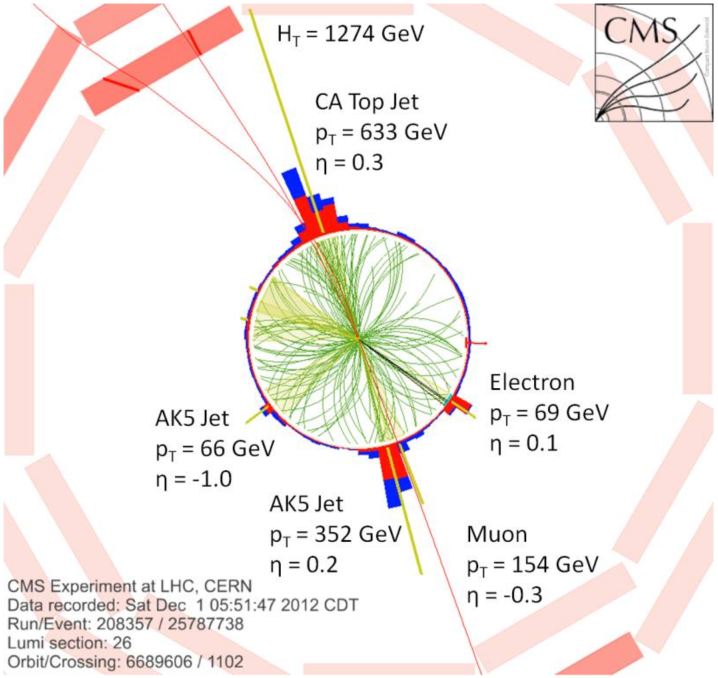
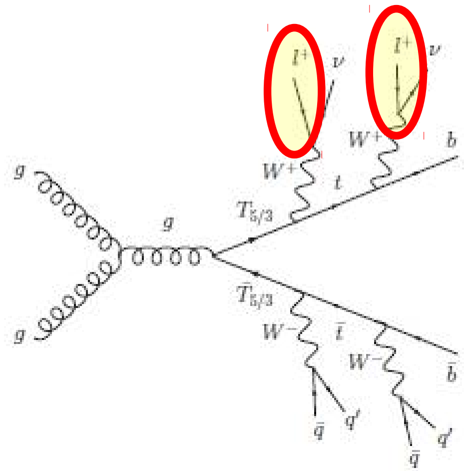
## Backgrounds

SS prompt leptons (VV,VVV,ttV,ttVV):
taken from theory

OS prompt leptons:
charge misreconstruction estimation from data

Background with non-prompt leptons:
data driven method based on fake rate estimation



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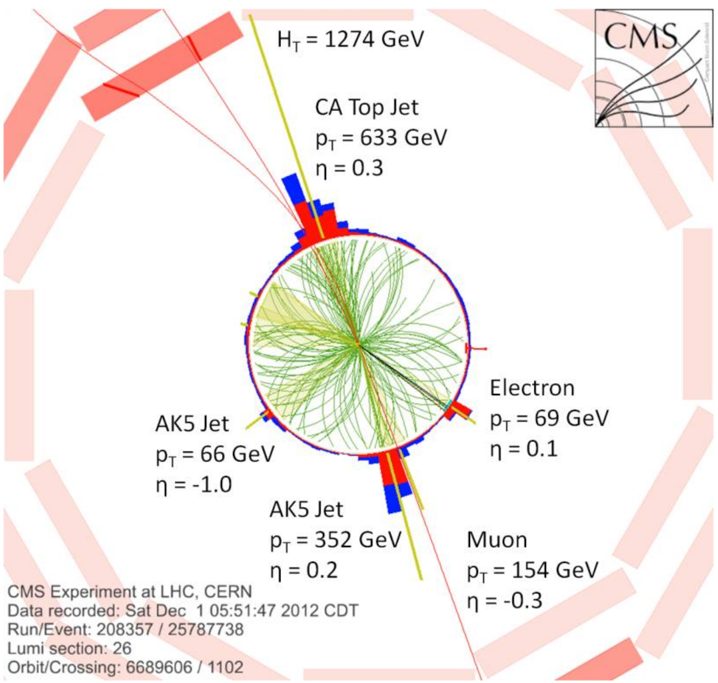
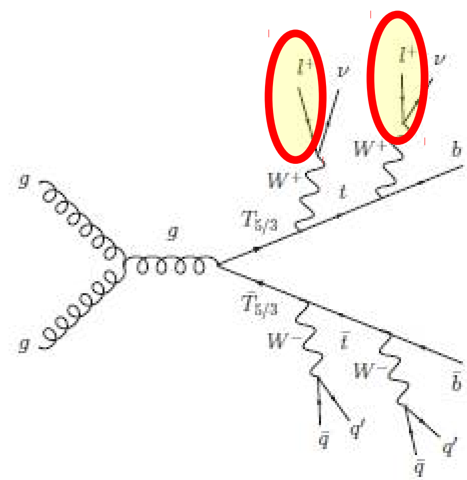
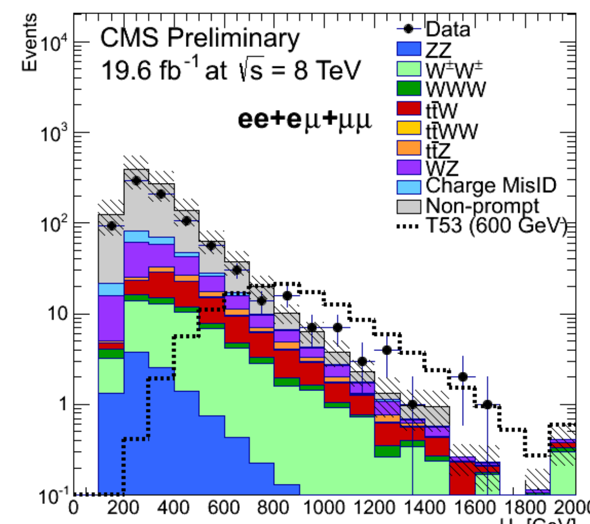
## Search signal regions:

Channels: ee - eμ - μμ channels

Counting experiment after selection



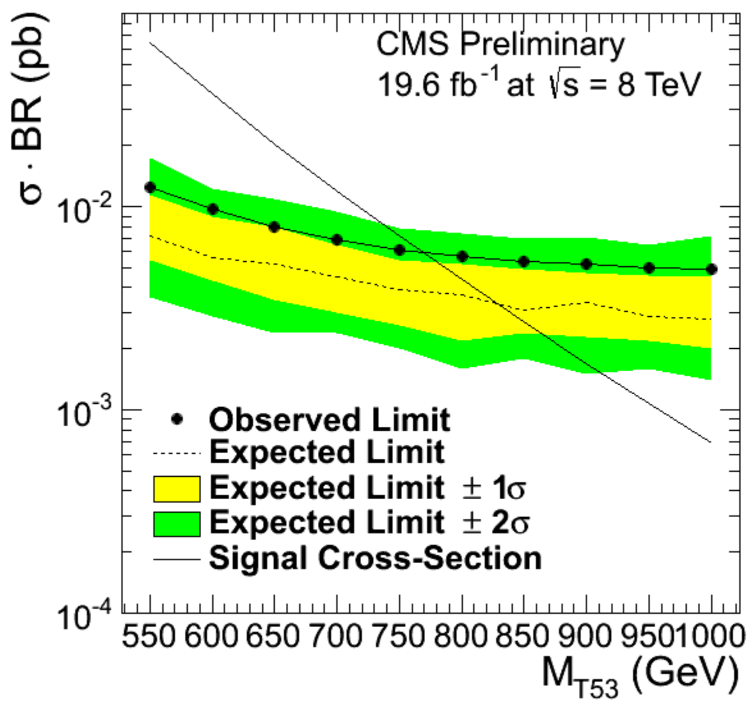


# Search for $T^{5/3}$ – same sign dilepton

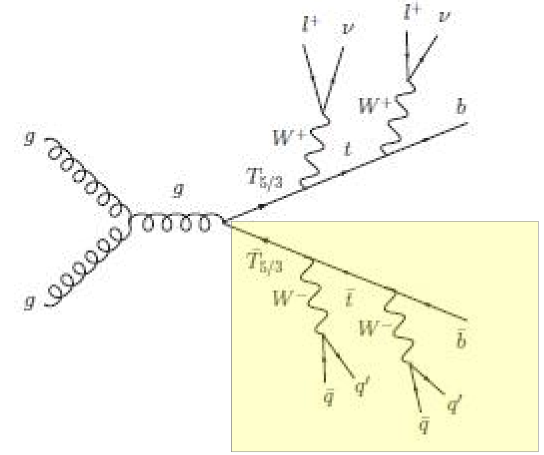
**Hypothesis:**
- $m(B^{1/3}) > m(T^{5/3})$
- $T^{5/3} \rightarrow tW$

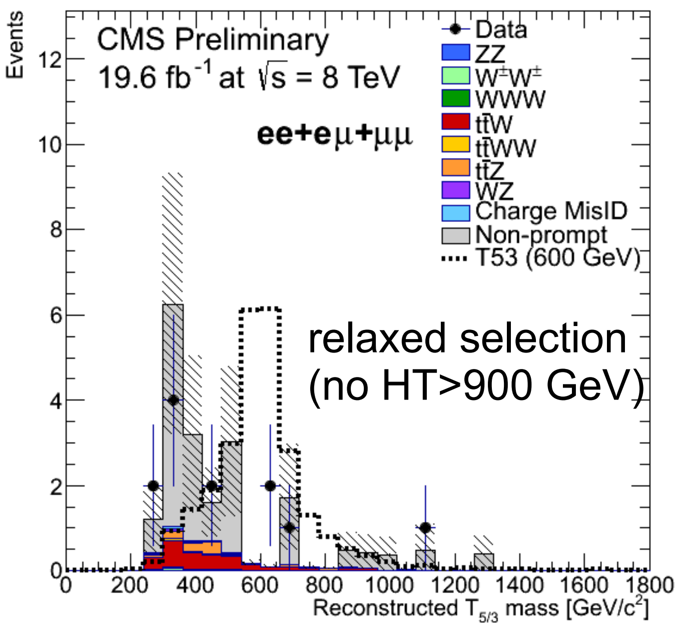
Expected events: 6.6±2.0. Observed events: 11.

**Expected mass limit: 830 GeV Observed: 770 GeV.**




**Mass reconstruction:**
Mass is composed of hadronic objects (jets, W-jet, CA-jet) following a certain procedure

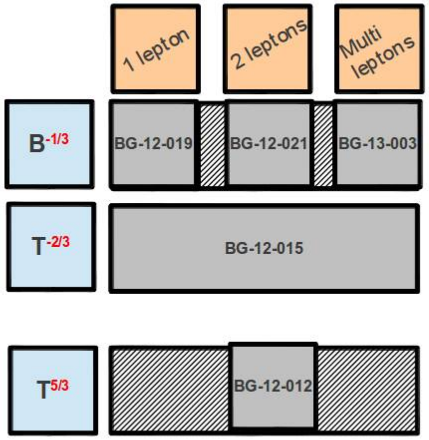





relaxed selection (no HT>900 GeV)

# Conclusion

- CMS analysis with 8 TeV data cover well the **searches of fermionic bottom/top quark partners**
- Such partners appear in many BSM models helping to solve the **hierarchy problem** without almost no constraint from the Higgs boson discovery
- **FCNC** are considered as possible decay of those heavy quarks
- **Higgs boson** is even used to probe new physics (final state)



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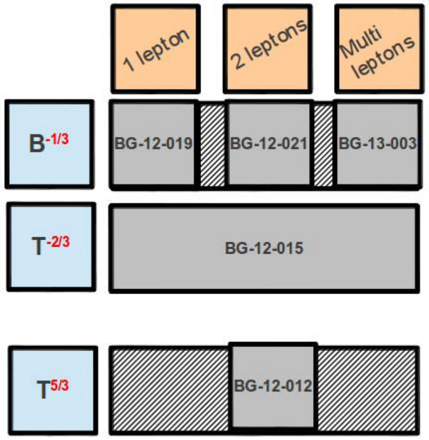


- Some analysis used **W-tagging and top-tagging** tools as they are sensitive to boosted regime: gain in sensitivity
- All the analysis use **data-driven methods** to estimate the key components (bkg, shape modeling) of their strategy
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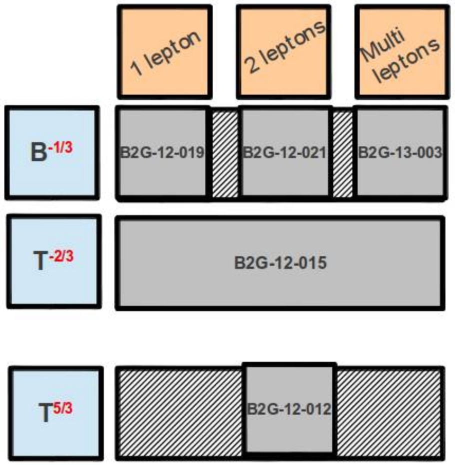


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- No excess has yet been found
- Limits have been set with a order of 500-800 GeV depending on the partners and its BR
- **The TeV scale has not been reached … so stay tuned !**