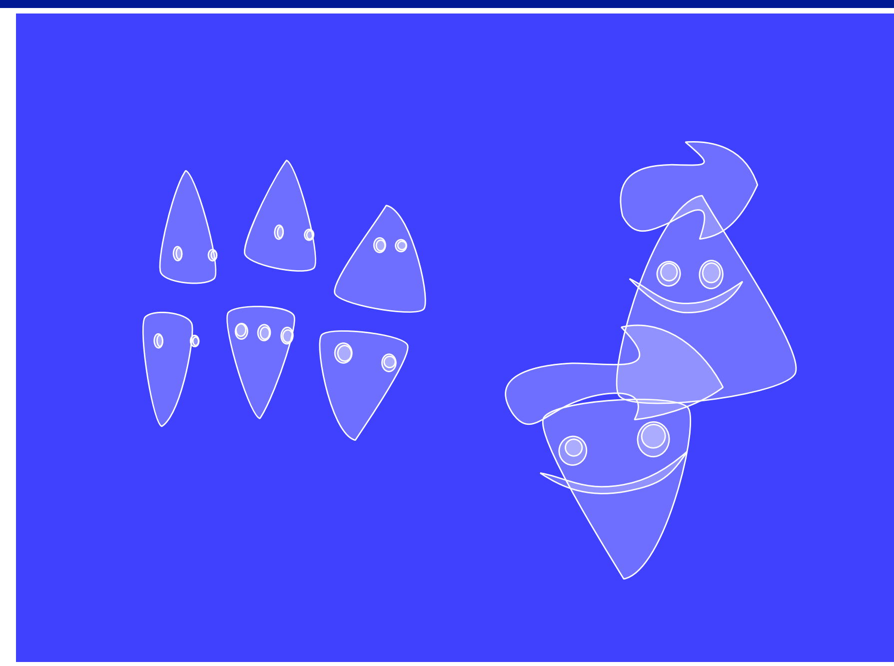
Searches for B Vector-like quarks with leptons at CMS



Sadia Khalil on behalf of CMS Collaboration

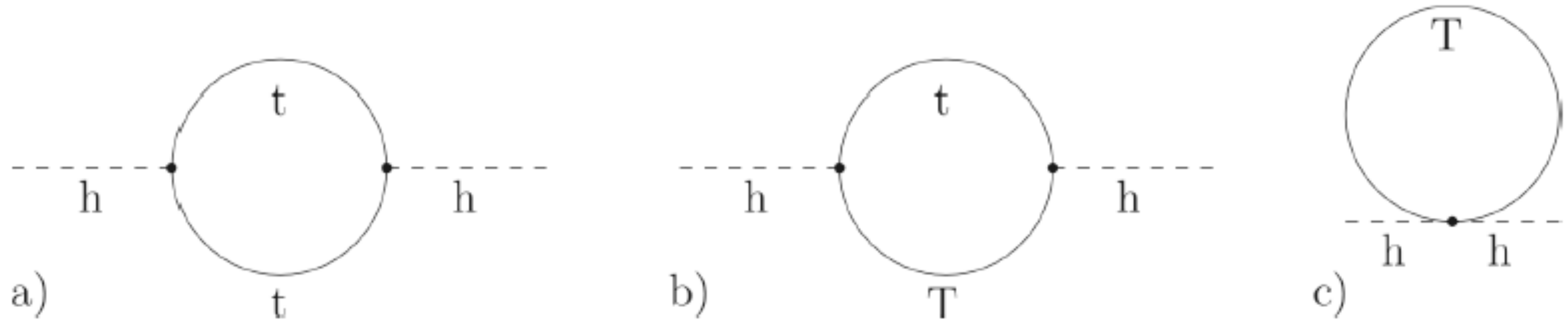
Vector-like quark workshop

Sep 15-16, 2014

DESY, Hamburg, Germany

Motivation

- Top Partners are what cancels the top loop divergence in m_H



- Top Partners are light in all Natural Theories

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\ \text{GeV}}{m_H}\right)^2 \left(\frac{M_P}{400\ \text{GeV}}\right)^2$$

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

SUSY	X-dim, Little Higgs, Composite Higgs…
bosonic partners(stops)	fermionic partners

http://arxiv.org/abs/1205.0013

http://arxiv.org/abs/1211.5663

Introduction

- What are **Vector-like fermions:**
  - Fermions that transforms as *(3,1,+2/3)* under $SU(3)_c \times SU(2)_W \times U(1)_Y$
- Why are called “vector-like”?

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\left(J^{\mu+}W_\mu^+ + J^{\mu-}W_\mu^-\right)$$ Charged current Lagrangian

  - SM chiral quarks: ONLY left-handed charged currents

$$J^\mu = J_L^{\mu+} + J_R^{\mu+} \quad \text{with} \quad \begin{aligned} J_L^{\mu+} &= \bar{u}_L\gamma^\mu d_L = \bar{u}\gamma^\mu(1-\gamma^\mu)d = V - A \\ J_R^{\mu+} &= 0 \end{aligned}$$

  - vector-like quarks: BOTH left-handed and right-handed charged currents

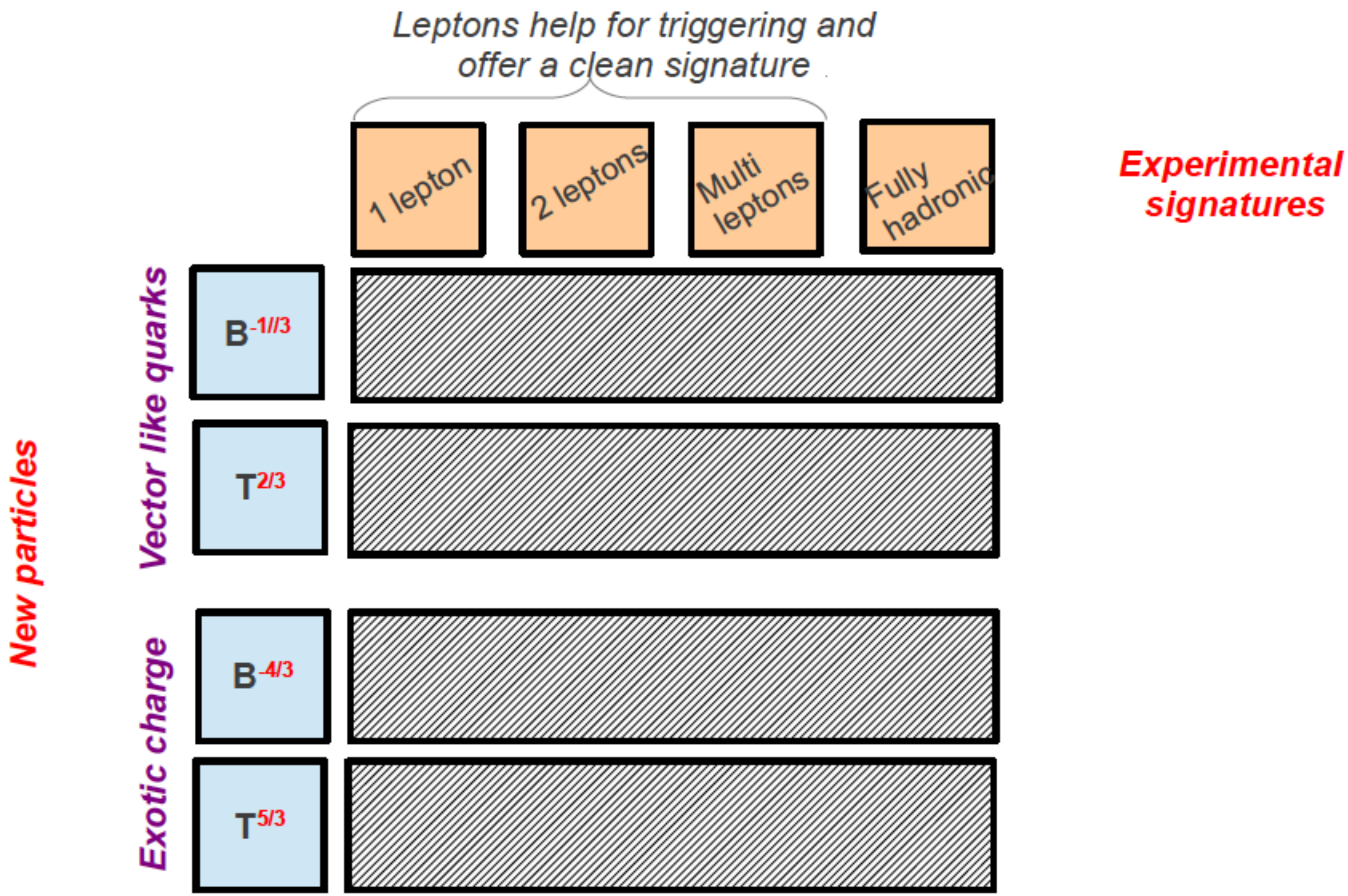
$$J_L^{\mu+} + J_R^{\mu+} = \bar{u}_L\gamma^\mu d_L + \bar{u}_R\gamma^\mu d_R = \bar{u}\gamma^\mu d = V$$

Introduction

- Models involving VLQ:
  - Composite/Little-Higgs, extra-dimensions, non-minimal SUSY extensions, etc.
- Vector-like quarks & FCNC:
  - Unlike for chiral quarks, FCNC are not suppressed
  - VLQ can decay into different final states and BR are considered as free parameters in the experimental searches
  - The W/Z/H bosons are used as a probe for new physics
- VLQ mixing:
  - Mixes maximumly with top quarks and CMS during Run1 has studied it with great emphasis
  - Mixing is not only constrained with the 3rd generation G Cacciapaglia, A. Deandrea (arXiv:1007.2933) , Andrea Wulzer et.el (arXiv:1211.5663)
- VLQ Production:
  - Pair through strong production mechanism (CMS focus in Run1 with typical constraints of m_Q~ 750 GeV
  - Single quarks in association with a b-quark or a top quark (Main focus in Run2)

Searched Signals & Channels

- Pair-produced 3rd generation partners



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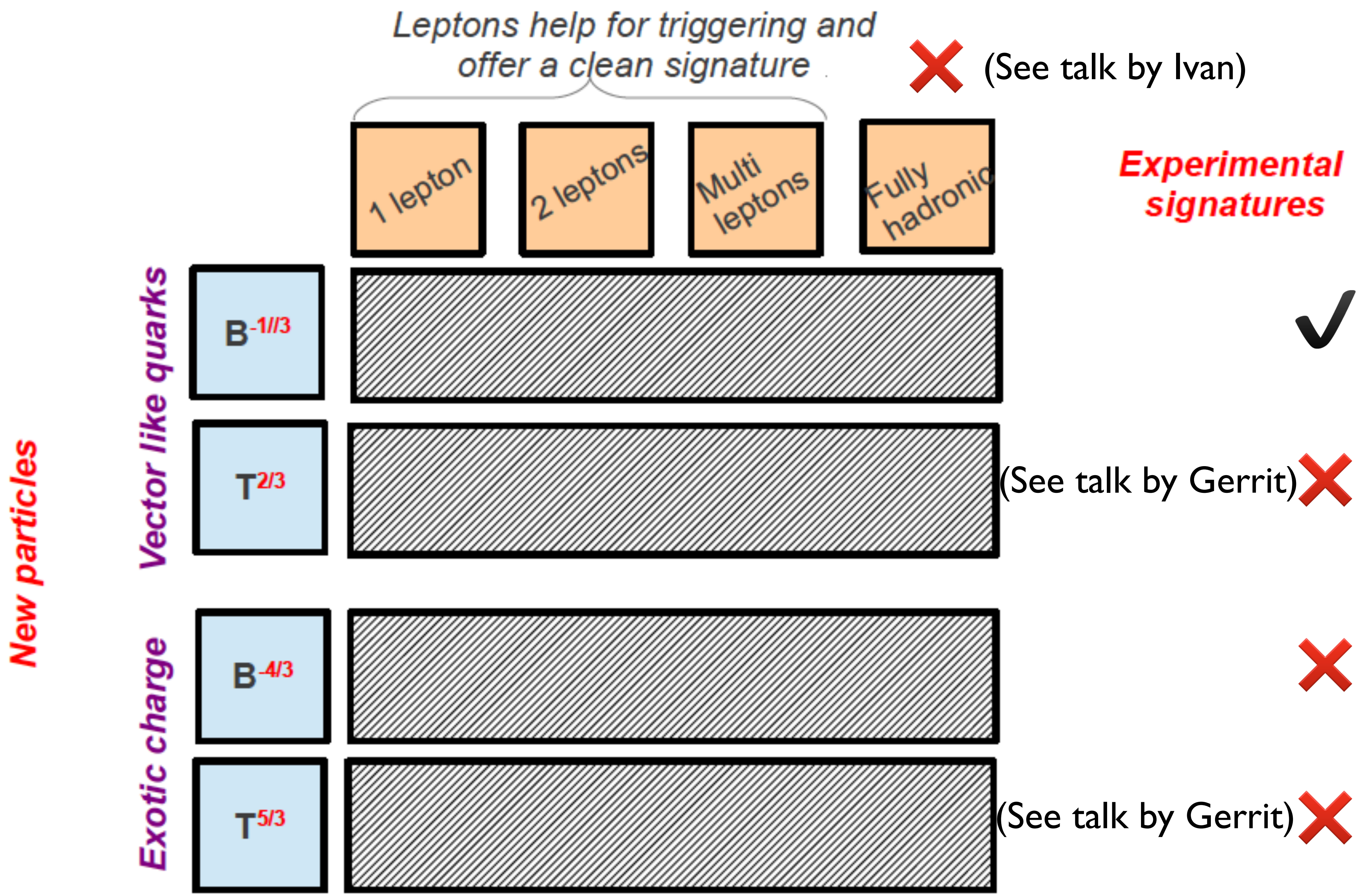
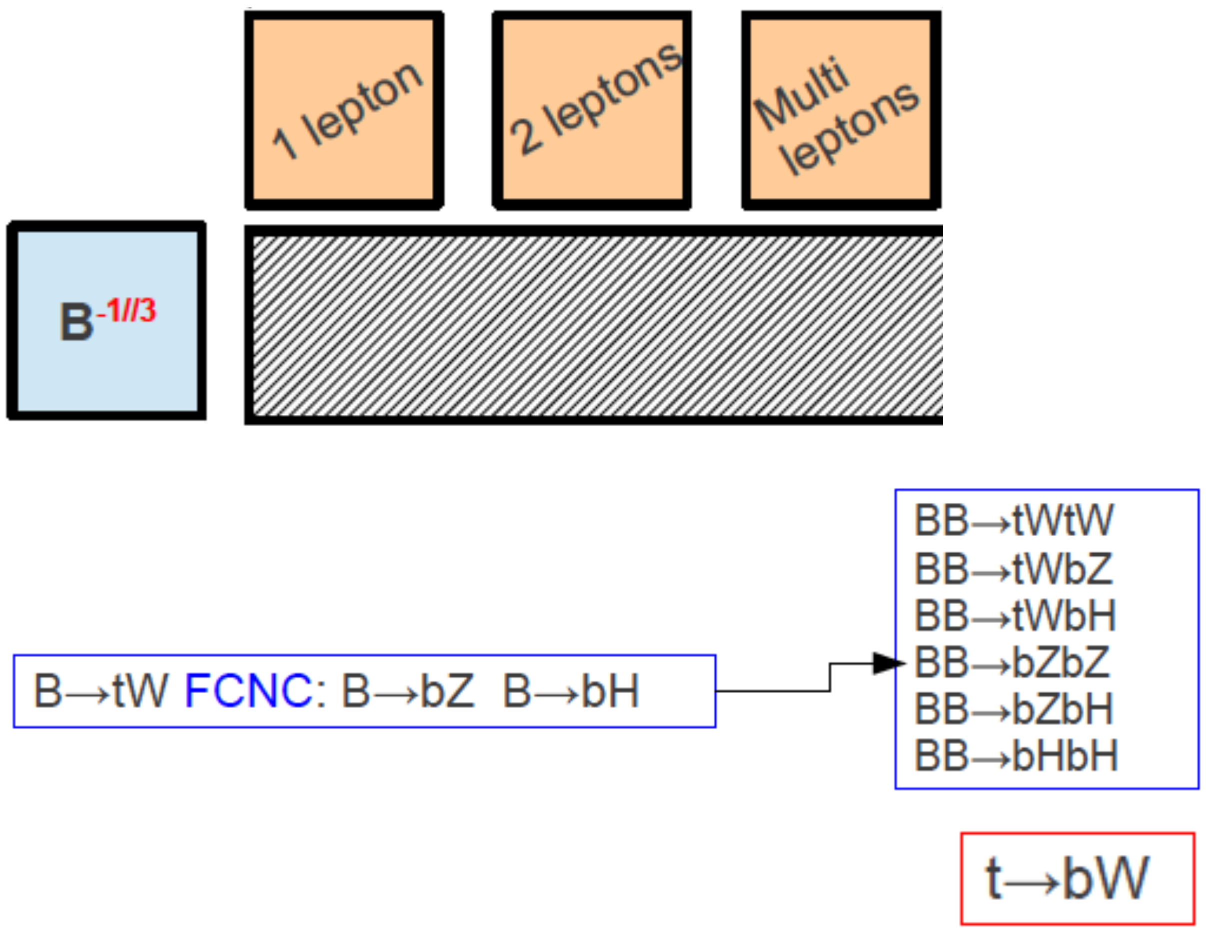


Searched Signals & Channels

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



- Complex and busy final states
  - Multiple b quarks, bosons
  - Many possible channels (0 to ≥4 leptons)
  - B.R are free parameters

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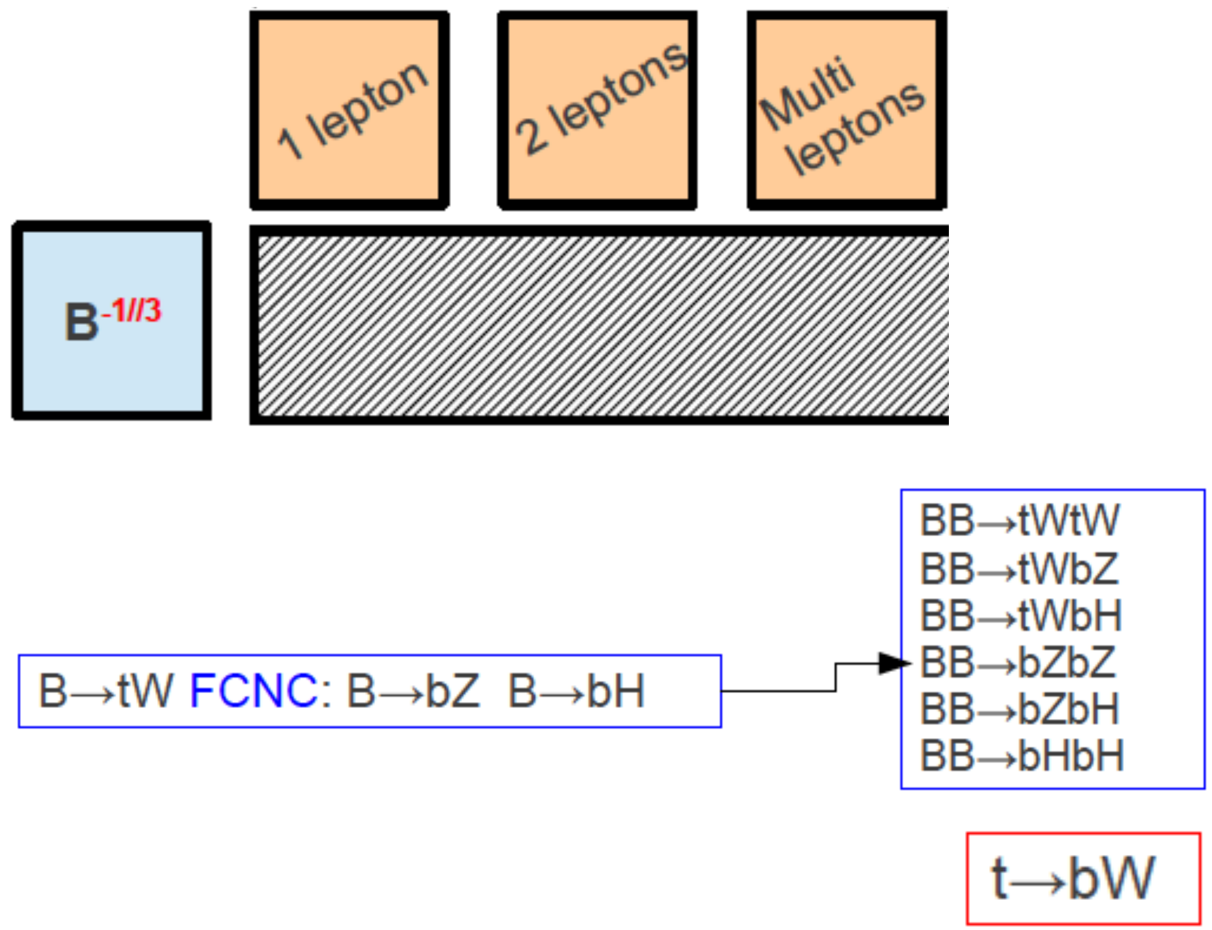

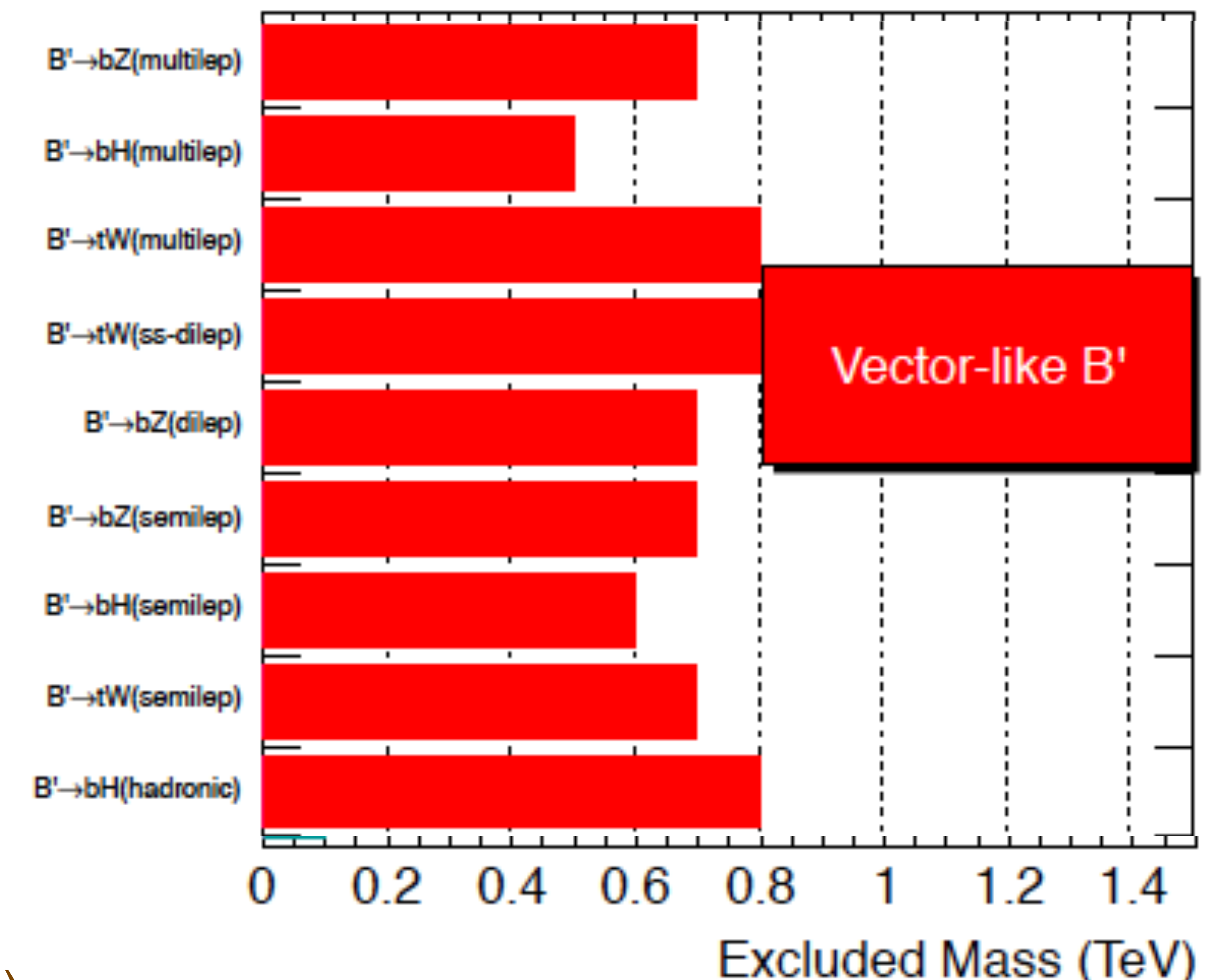

- Complex and busy final states
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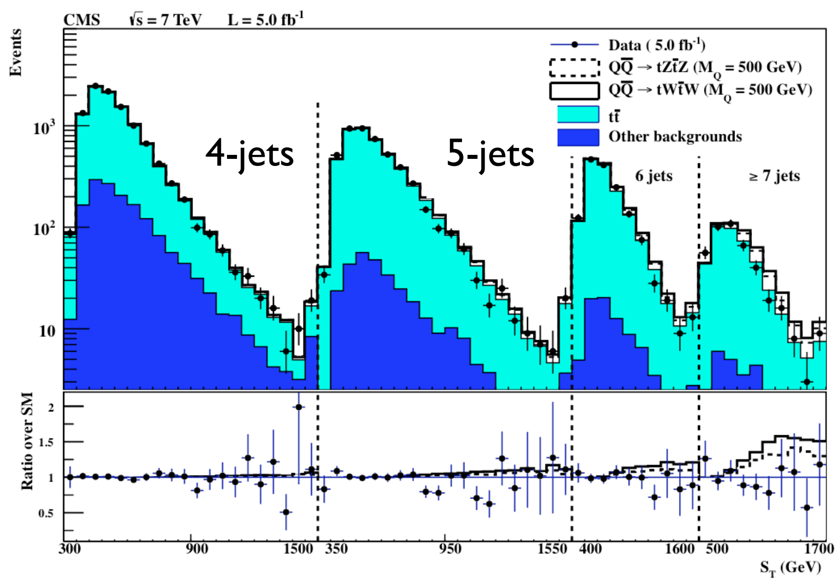
  - Many possible channels (0 to ≥4 leptons)
  - B.R are free parameters

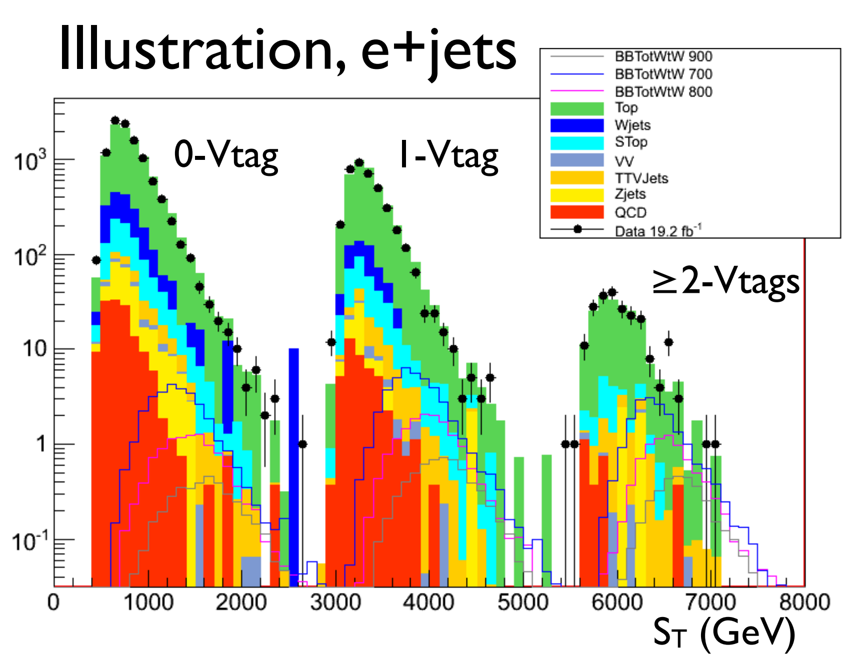
Common Strategies

- Look for excesses over a known background in high S_T(sum p_T of final decay products) tails
- Use N_{jets}, N_{bosons} as additional variable to enhance search sensitivity

B2G-12-004



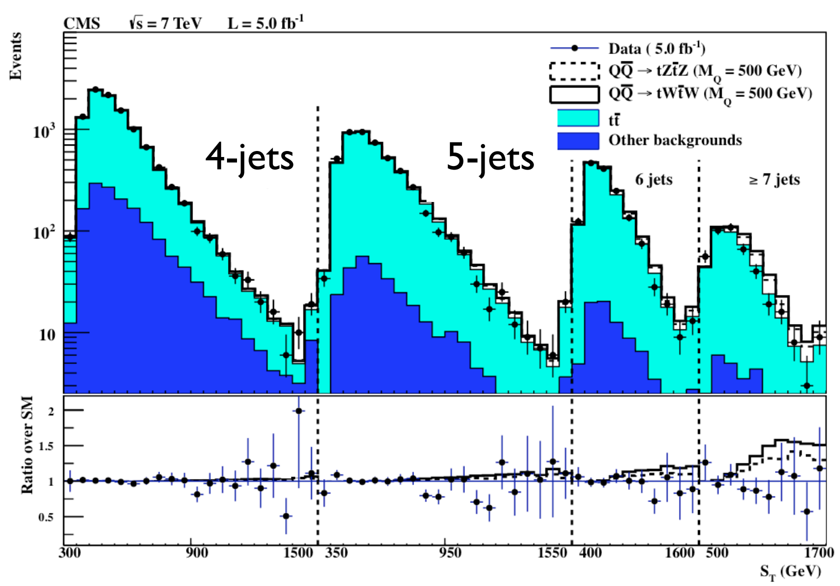
B2G-12-019



Common Strategies

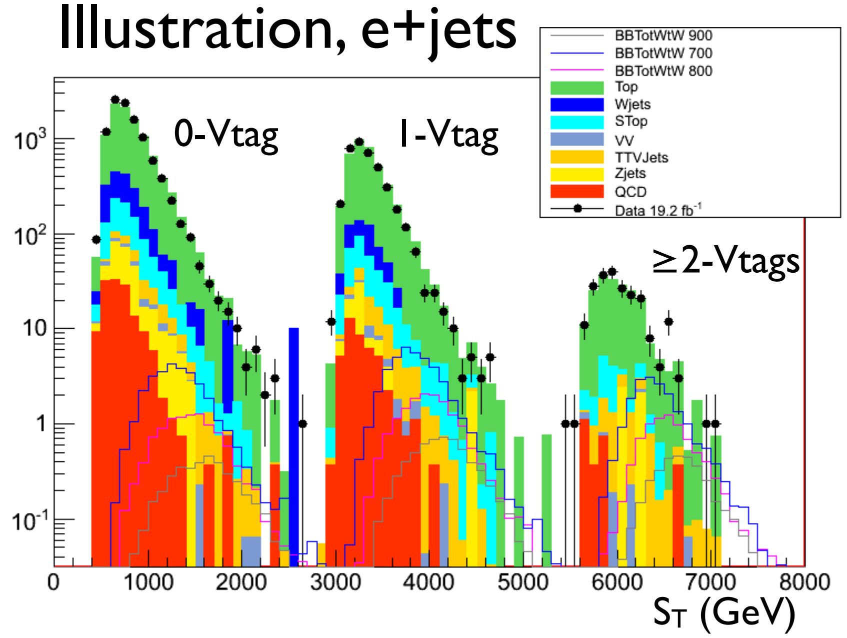
- Look for excesses over a known background in high S_T(sum p_T of final decay products) tails
- Use N_{jets}, N_{bosons} as additional variable to enhance search sensitivity
- Use kinematic properties if applicable; e.g, mass reconstruction

B2G-12-004

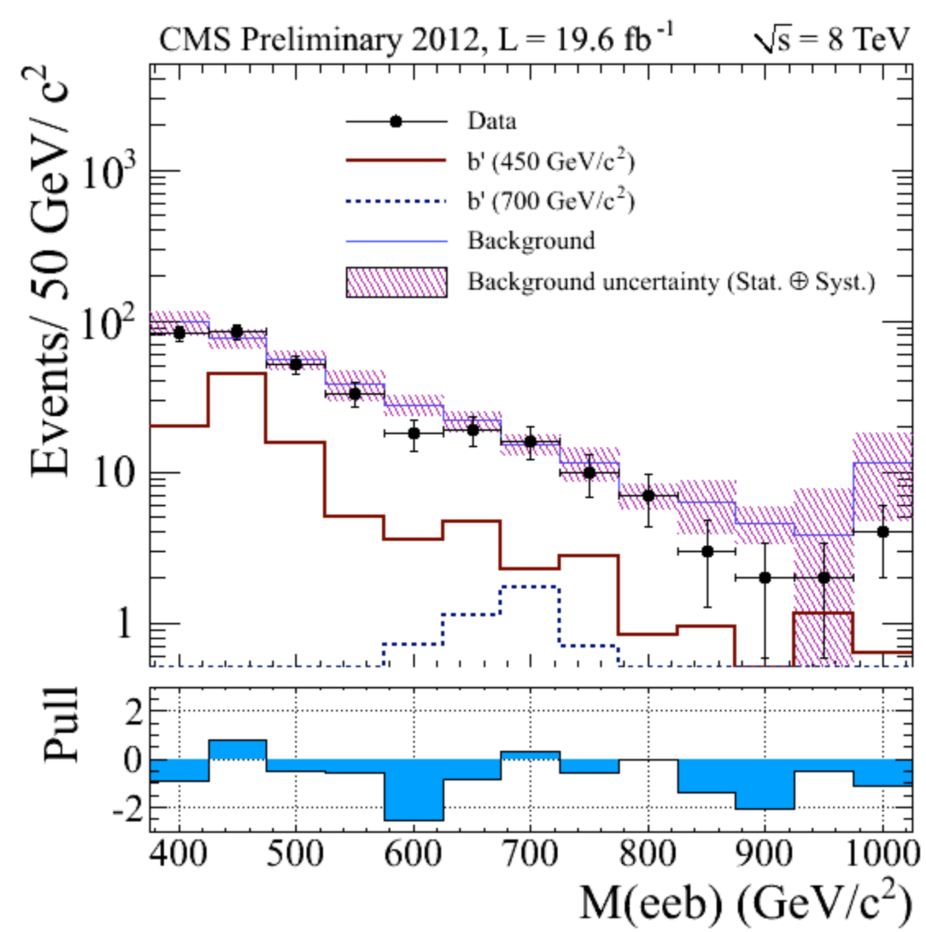


Illustration, e+jets

B2G-12-019

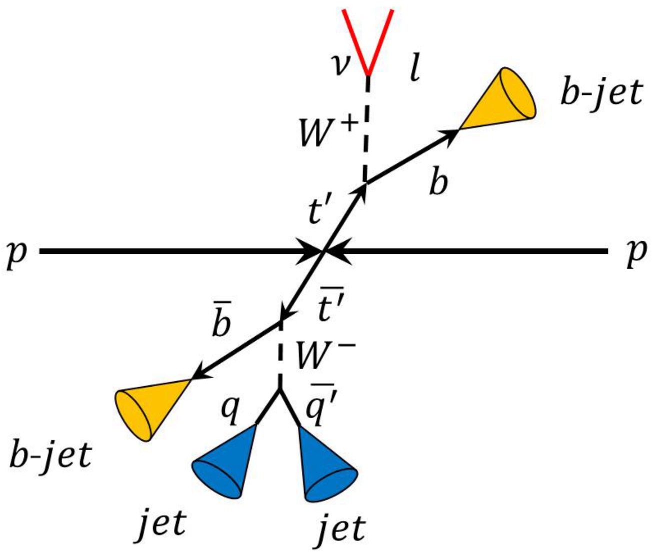


B2G-12-022

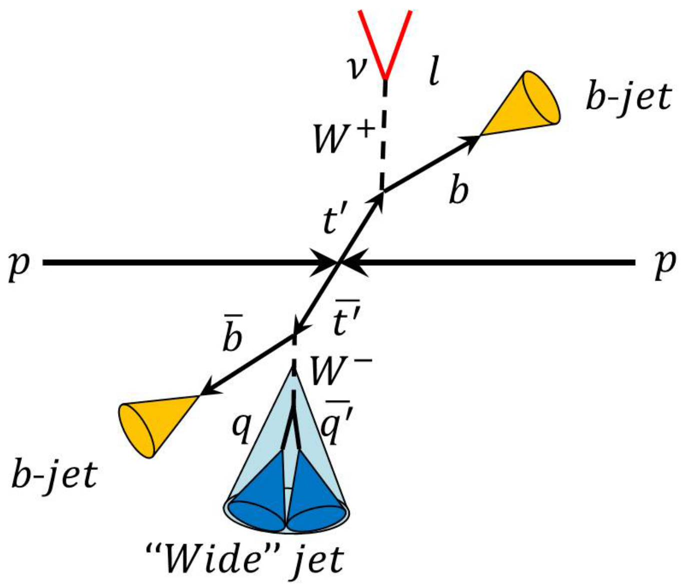


Common tools

- **B-tagging**
  - Combine Secondary Vertex algorithm
    - Likelihood Ratio using impact parameter, significance of tracks and secondary vertices
  - Performances: $\varepsilon_b \approx 70\%$ - $\varepsilon_{light} \approx 1\%$
- **Boosted regime**
  - The New Physics searches often imply to look for massive objects
    - Boosted decay products ⇒ merged jets
    - Require advanced techniques of jet reconstruction and W/Z, top, Higgs tagging



“Standard” jets – AK5
(anti-kt R=0.5)



“wide” jets – CA8/CA15

Common samples & uncertainties

- Generators for background samples
  - Ttbar : MadGraph/POWHEG + PYTHIA 6 (Z2*)
  - Single t : MadGraph/POWHEG +PYTHIA
  - W/Z+jets, ttW, ttZ : MadGraph + PYTHIA
  - WW/WZ/ZZ, ttH : PYTHIA
- Generators for signal samples
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  - All efficiencies studied on MC and data, selection tuned to be on the plateau

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- Systematics:
  - All HLT, reconstruction and selection efficiencies and data/MC differences
  - Luminosity (2.6% (2013ReReco) to 4.4% (2012ReReco))
  - Jet energy scale (~5% eta and p_T dependent), Jet energy resolution (~1%)
  - MC : factorization and renormalisation scale, jet-parton matching scale, dedicated systematic samples
  - Data driven estimation: specific methods, data/MC, closure tests

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

CMS-PAS-B2G-12-019

B→tW, bZ, bH

- Selection
  - One isolated lepton (e,μ)
  - ≥ 4 AK5 jets (p_T >200,60,40,30 GeV), ≥ 1 b-jet,
  - MET > 20 GeV
  - Centrality = $\Sigma_{Jets}\, P_T/\Sigma_{Jets}\, E_T > 0.4$
- Data driven components
  - QCD multijet background
  - Trigger/lepton and V/b-tagging efficiencies

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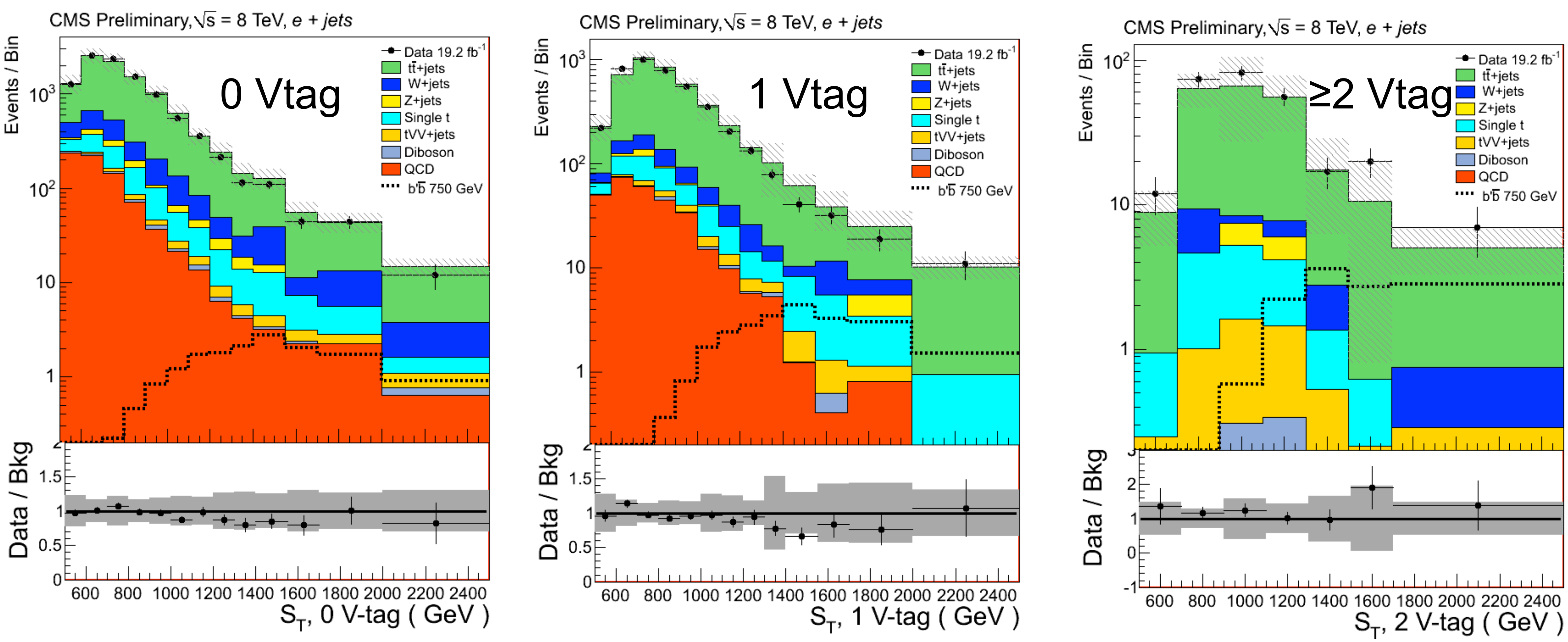
- Search Strategy
  - Discriminating variable:

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

  - Events Categorization:
    - 0, 1 and ≥ 2 V-tag
    - V-tagging: jet mass consistent with W/Z or H
      - p_T>200 GeV, 50 < M_{jet} < 150 GeV



Similar bins for muon channel

Backgrounds

CMS-PAS-B2G-12-019

- QCD multijets
  - Shapes: invert isolation or fail electron ID (e+jets)
    invert isolation (μ+jets)
  - Normalization: Fit the MET distribution constraining EWK(Single top, Z+jets, dibosons, VV+jets) = 5%, TT+jets and W+jets = 10%
- Top, W/Z/ttV+jets, dibosons from simulations

Event Counts

Background process	e+jets events	μ+jets events
$t\bar{t}$+jets	11397 ± 85	9550 ± 79
W+jets	1247 ± 37	1137 ± 37
Multijet	1072 ± 19	505 ± 4
Single top	775 ± 17	683 ± 17
Z+jets	222 ± 22	238 ± 23
$t\bar{t}$+ V+jets	92 ± 1	82 ± 1
Diboson (WW, WZ, ZZ)	43 ± 2	34 ± 2
Total background	14846 ± 99	12229 ± 91
Data	14640	11695

Systematic Uncertainties

CMS-PAS-B2G-12-019

Parameter type	Source	Uncertainty (%)
Distribution	Q^2 scales for $t\bar{t}$+jet	9.1
	Matching partons	6.5
	Jet energy scale	5.5
	b-tagging Scale Factor	2.1
	V-tagging Scale Factor	1.0
	Jet energy resolution	< 1
	Pile-up	< 1
Normalization	Lepton ID/reco/trigger	2.0
	Luminosity	4.4
	$t\bar{t}$ cross section	10
	Other Electroweak Backgrounds	50
	QCD Multijet Background	100

- Shape uncertainty estimates are from change in background acceptance
- Use shape templates due to shape uncertainties in final fit result

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

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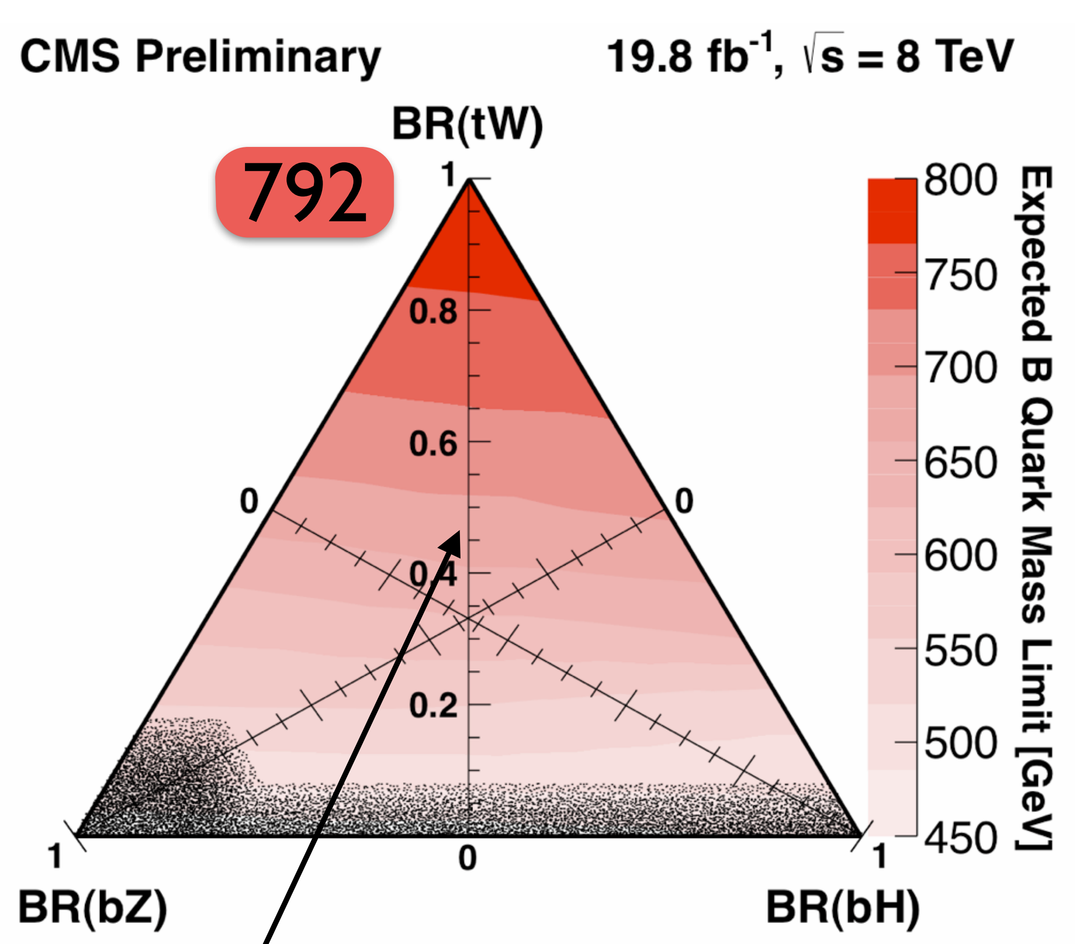
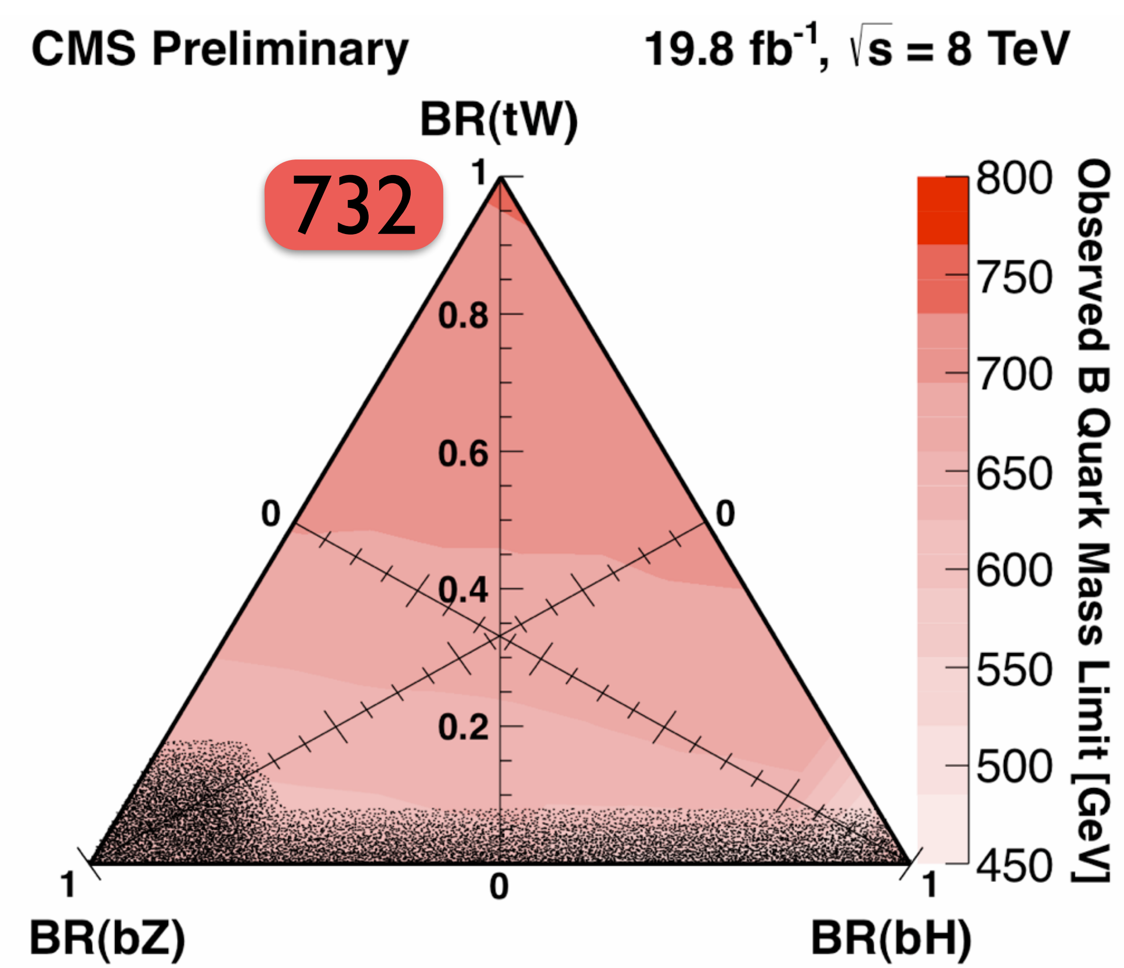
Combine e+μ limits: A mass bound of **[582, 732] GeV** is set at 95% CL for all possible BR.

Expected



Observed



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

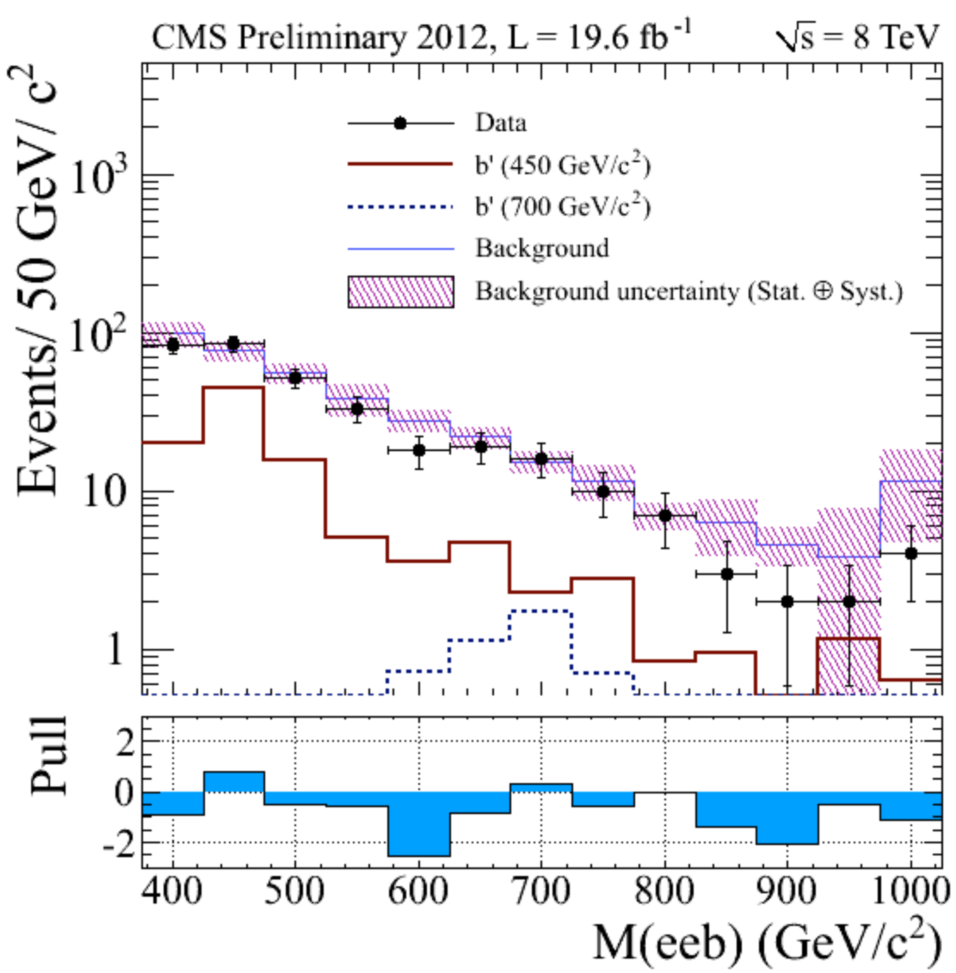
$B_{-1/3}$ quark, OS dilepton

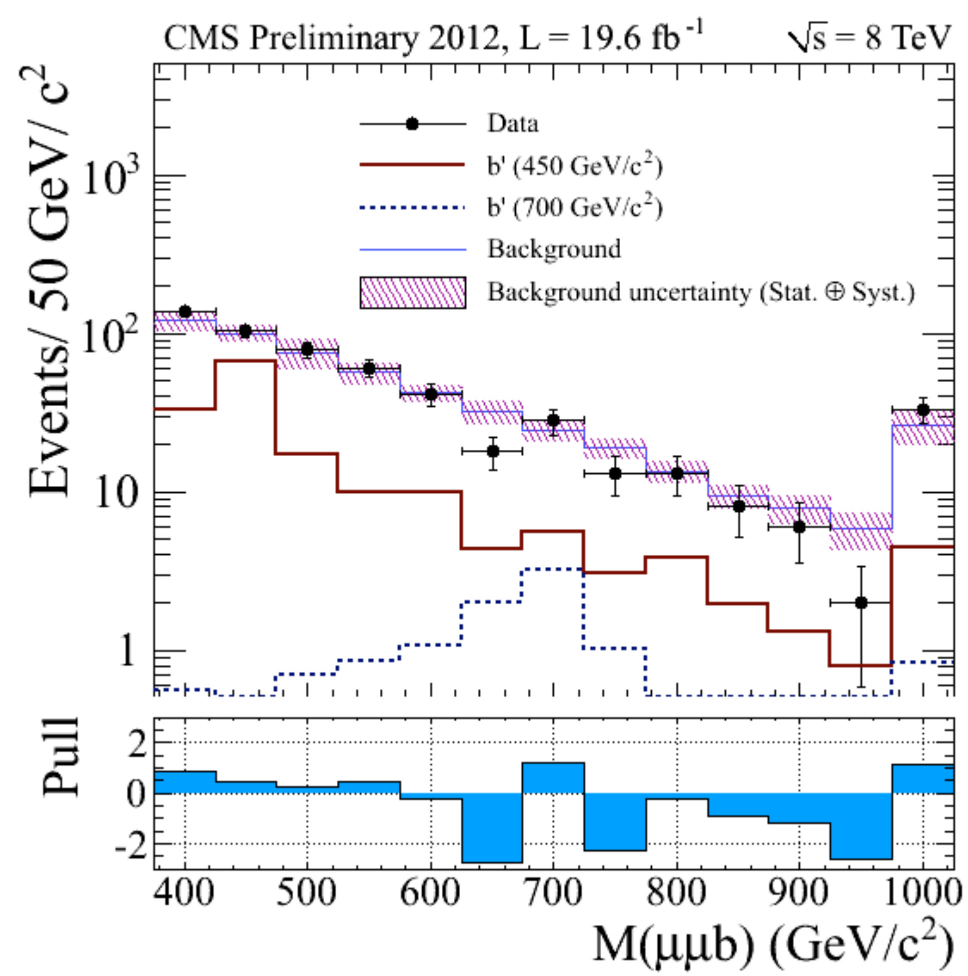
CMS-PAS-B2G-12-021

B→tW, bZ

- **Selection**
  - Two OS isolated leptons (e or μ)
  - 60<M(ll)<120 GeV
  - p_T(ll)>150 GeV
  - ≥ 1 b-jet with p_T > 80 GeV

- **Strategy**
  - Channels: e+e- & μ+μ-
  - Reconstruct invariant mass of B candidate, Mass(llb): peak to the signal mass
  - With Mass(llb) > 375 GeV, fit Mass(llb) simultaneously to test for presence of signal.





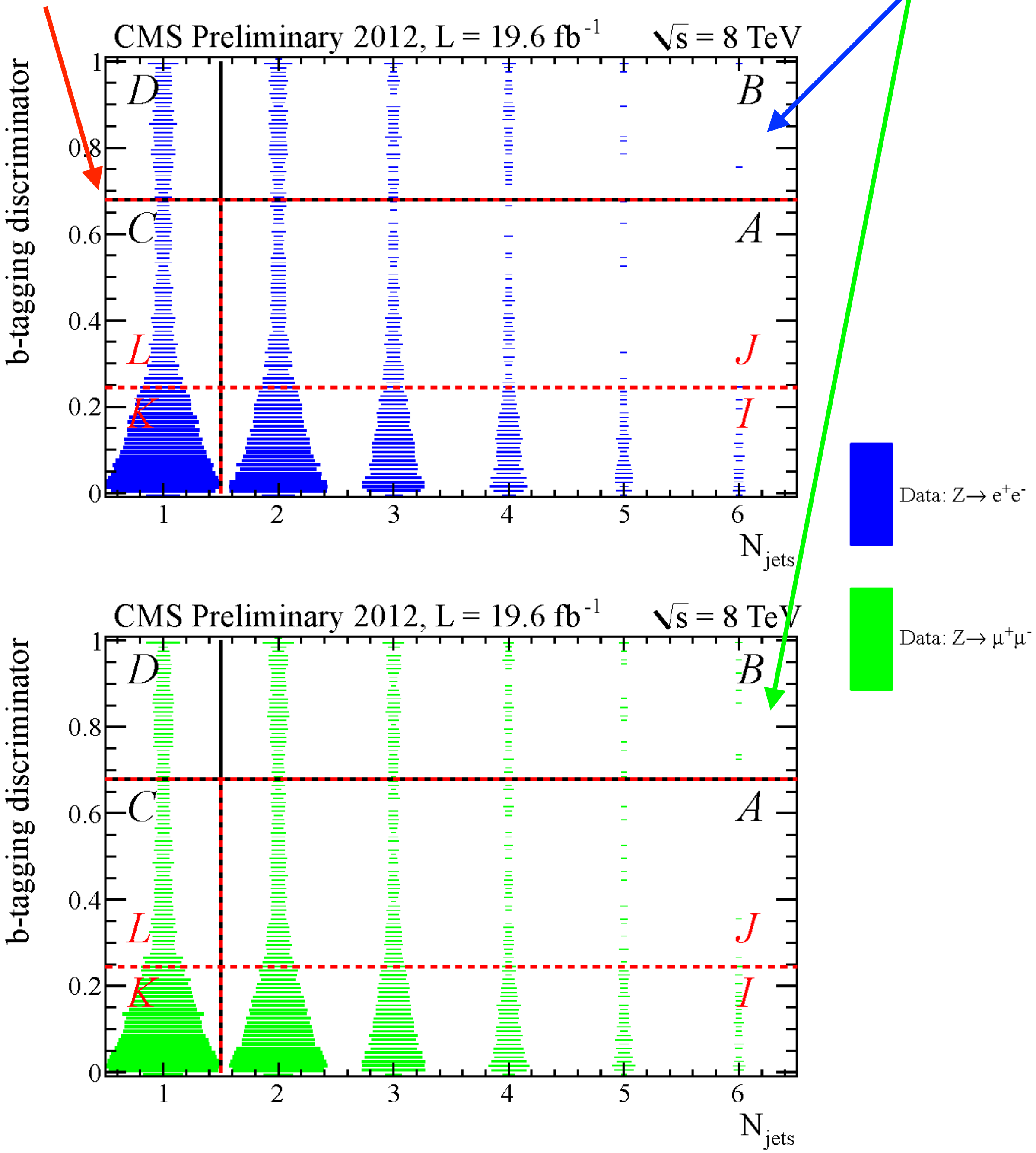
Background

CMS-PAS-B2G-12-021

Modeling of the distributions with data-driven method:

threshold >0.679

B = Signal Region



- Hard to reproduce M(llb) shape using simulation in the presence of high p_T Z
- Use ABCD method of evaluate it from data
  - $N_B = N_A \times N_D/N_C$ assuming no correlation
  - Use region IJKL to find the correlation
    - Apply correction factors to N_B
  - Shape of M(llb) is tested to be same in region A and B

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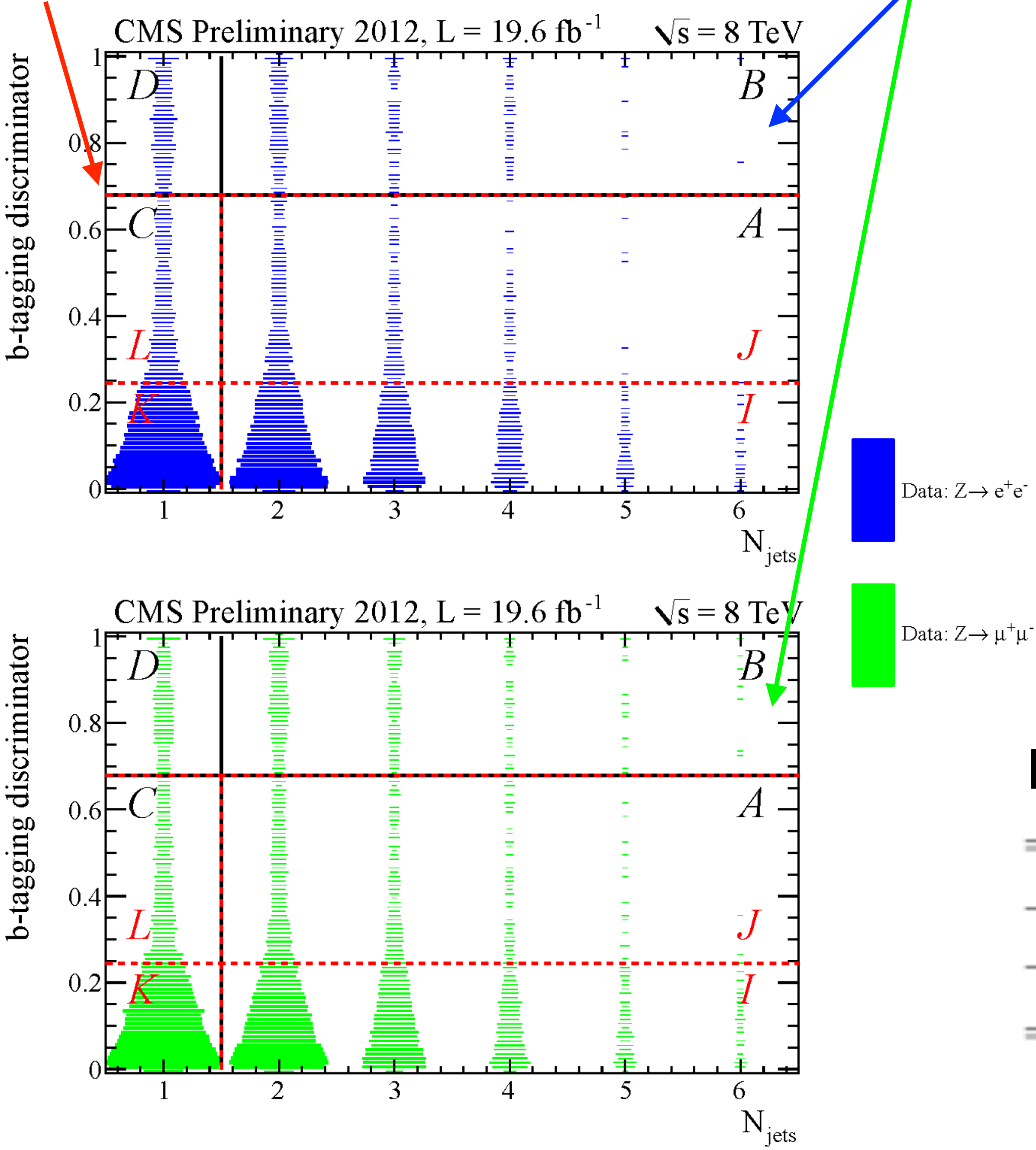

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Expected Events

Channel	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
Expected background in data	379 ± 70	534 ± 79
Observed events	334	542

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

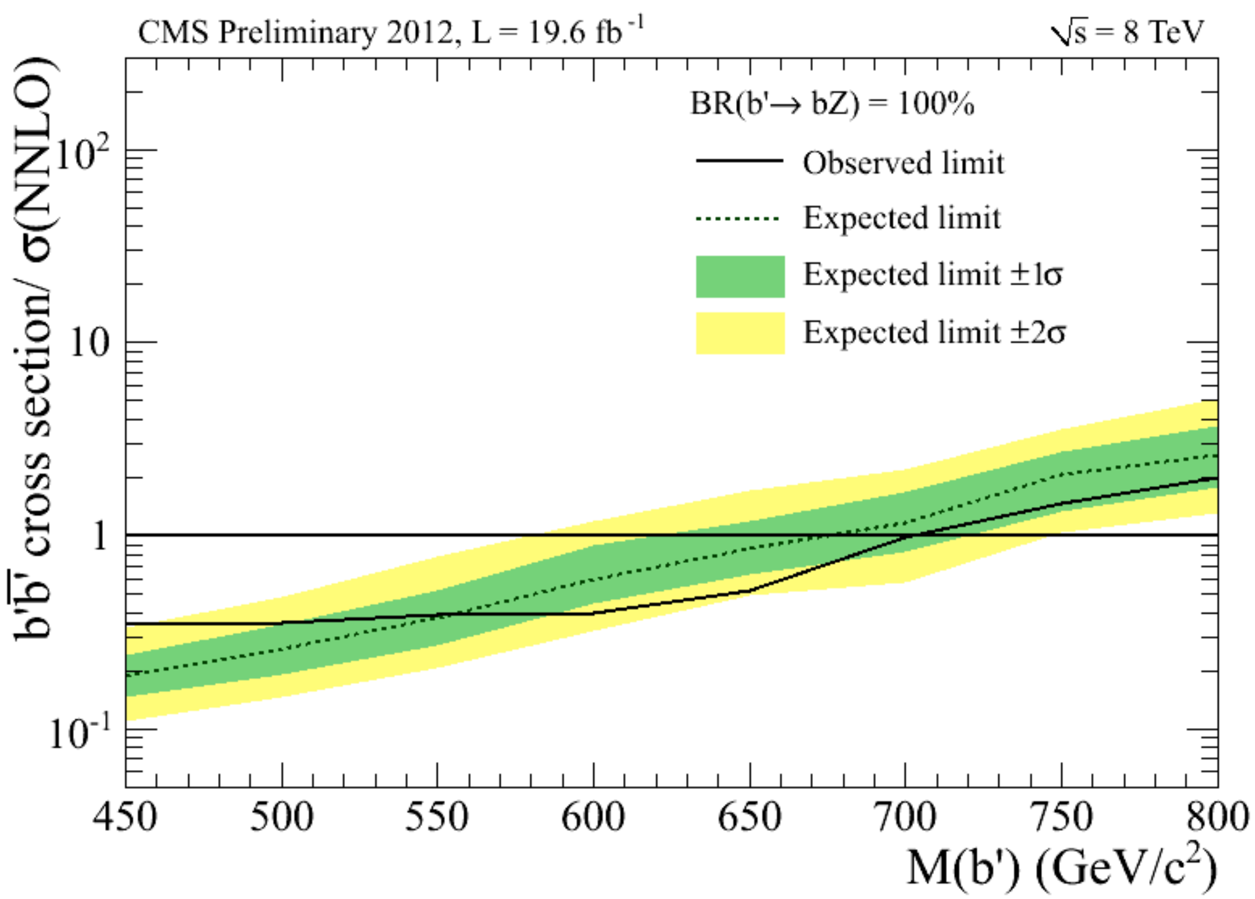
CMS-PAS-B2G-12-021

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

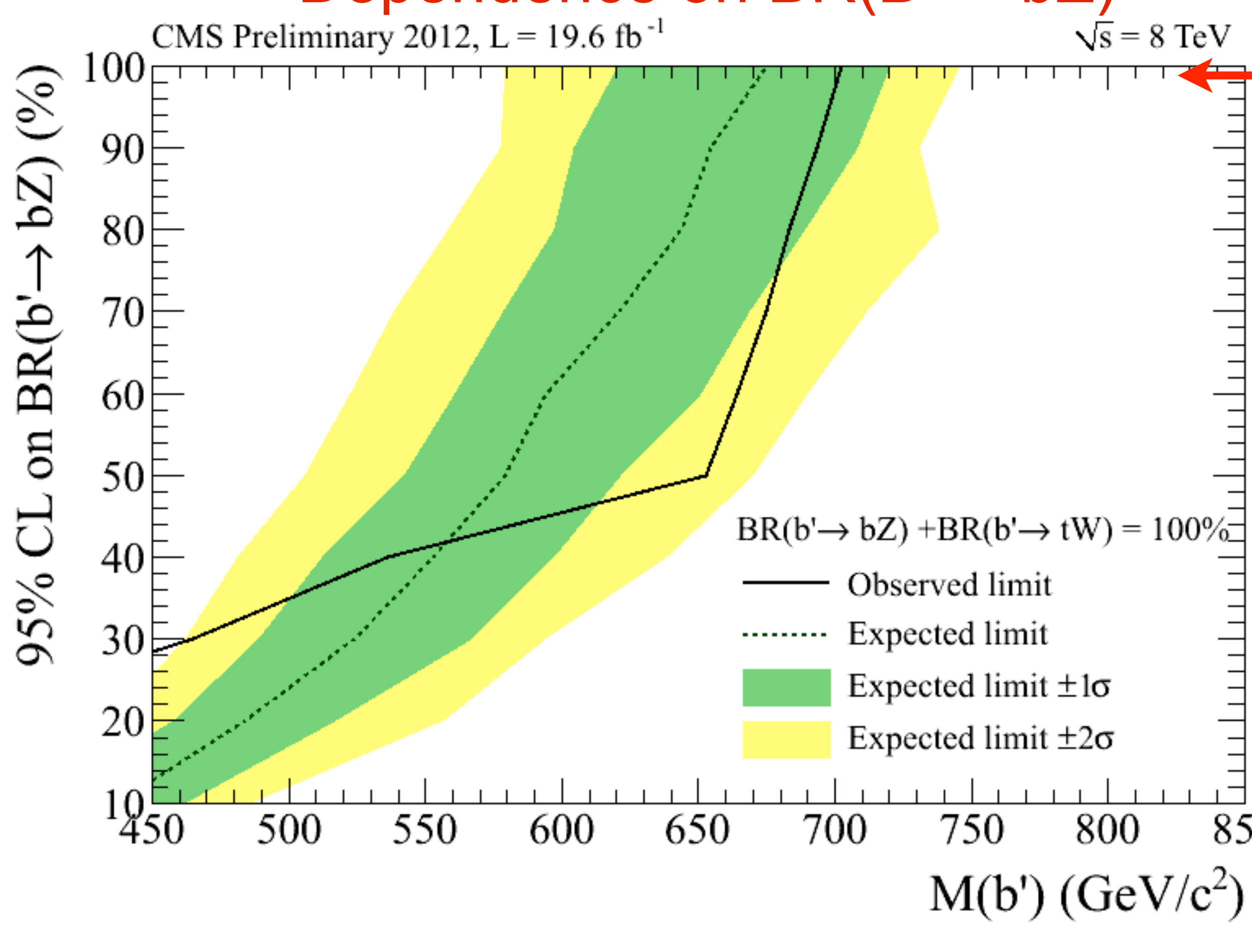
BR(B → bZ) + BR(B → tW) = 100%.

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

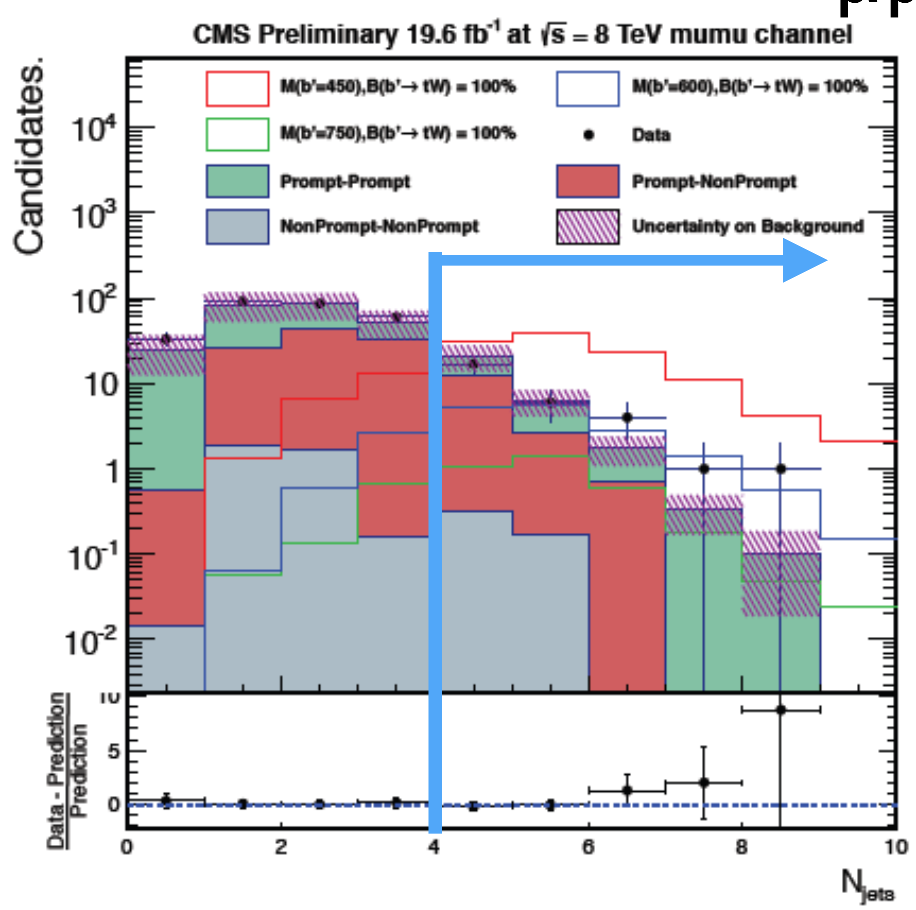
CMS-PAS-B2G-12-020

B→tW, bZ, bH

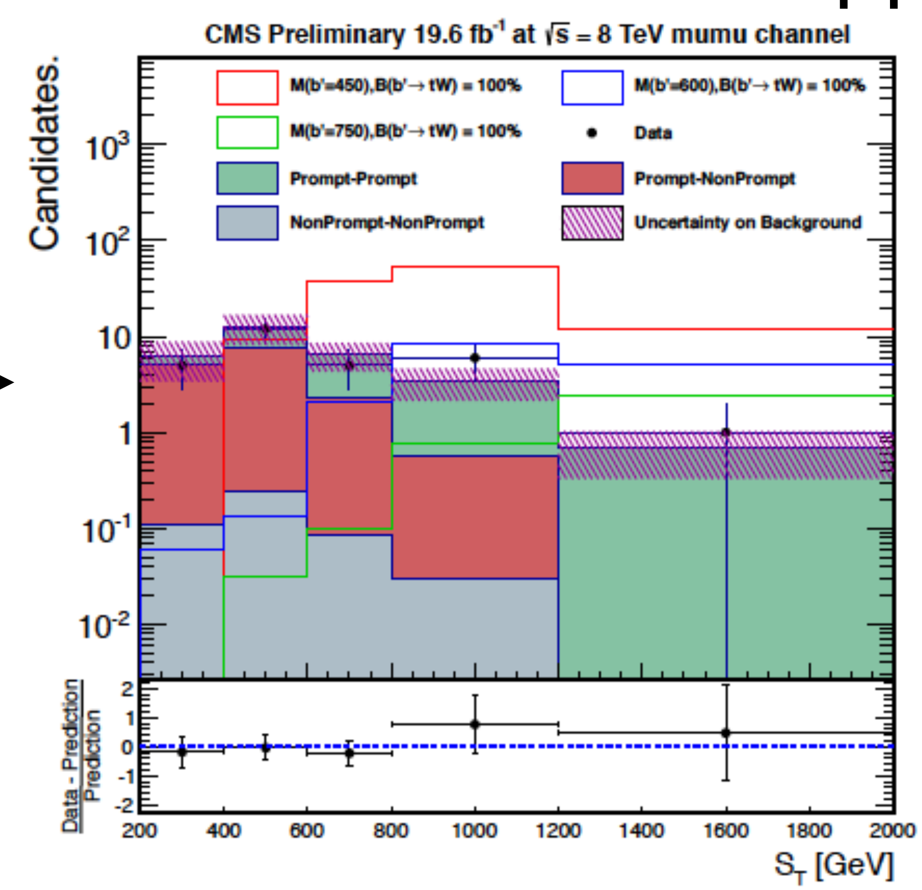
- **Final state**
  - In BB→tW^+tW^-, tW^+bH, bHbH→$bW^+W^-bW^+W^-$
    - Two W bosons decaying hadronically and other two leptonically => same-sign lepton pair + 6jets
  - ≥ 4 jets, MET >30 GeV
  - S_T > 200 GeV

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

μμ



μμ



Backgrounds

CMS-PAS-B2G-12-020

- Four Categories
  - Type I (MC) -- Fake lepton
    - ttW/Z, diboson and tribosons
  - Type II (data driven)-- Charge Misidentification
    - use ratio to SS DL/ OS DL for combine Z+jets and ttbar+jets and multiply the ratio to the prediction in control region
  - Type III (data) -- Prompt and non-prompt dileptons
    - use Tight/Loose method
    - Several control regions: N_{LL}, N_{TL}, $N_{LT,}$ N_{TT}
    - Estimate: N_{pp}, $N_{pf/}N_{fp}$, N_{ff} as 2, 1 and 0 prompt leptons
    - Non-prompt fake rate: f_1 and f_2
    - Prompt leptons rates: p_1 and p_2

$$\begin{pmatrix} N_{pp} \\ N_{pf} \\ N_{fp} \\ N_{ff} \end{pmatrix} = \begin{pmatrix} (1-p_1)(1-p_2) & (1-p_1)(1-f_2) & (1-f_1)(1-p_2) & (1-f_1)(1-f_2) \\ p_1(1-p_2) & p_1(1-f_2) & f_1(1-p_2) & f_1(1-f_2) \\ (1-p_1)p_2 & (1-p_1)f_2 & (1-f_1)p_2 & (1-f_1)f_2 \\ p_1p_2 & p_1f_2 & f_1p_2 & f_1f_2 \end{pmatrix}^{-1} \begin{pmatrix} N_{LL} \\ N_{TL} \\ N_{LT} \\ N_{TT} \end{pmatrix}$$

B-1/3 quark, SS dilepton

Event Yield

CMS-PAS-B2G-12-020

Table 4: The events yield of this analysis in the signal region. Errors are a total quadratic sum of systematic uncertainty and statistical uncertainty.

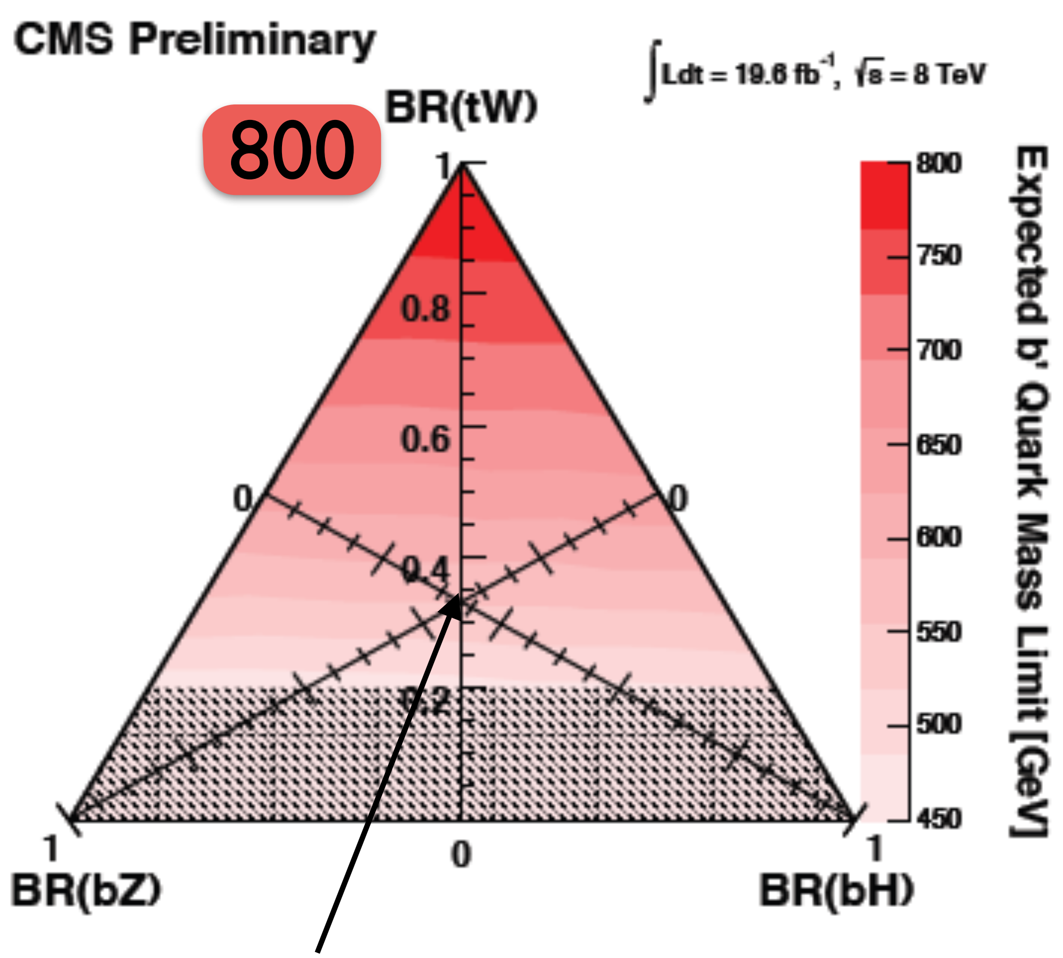
$\mu\mu$	Total Events Yield	$200 \le S_T < 400$	$400 \le S_T < 600$	$600 \le S_T < 800$	$800 \le S_T < 1200$	$S_T \ge 1200$
Data	29	5	12	5	6	1
Background Estimation	29.16 ± 1.59 (stat.) ± 10.37 (sys.)	6.14 ± 0.84 (stat.) ± 2.61 (sys.)	12.50 ± 1.08 (stat.) ± 4.25 (sys.)	6.45 ± 0.67 (stat.) ± 2.03 (sys.)	3.39 ± 0.44 (stat.) ± 1.17 (sys.)	0.68 ± 0.15 (stat.) ± 0.32 (sys.)
Prompt-Prompt	13.61	0.99	4.97	4.13	2.84	0.68
Prompt-NonPrompt	15.09	5.04	7.30	2.23	0.53	0.00
NonPrompt-NonPrompt	0.46	0.11	0.24	0.08	0.03	0.00
Charge Flip	0.00	0.00	0.00	0.00	0.00	0.00
ee	Total Events Yield	$200 \le S_T < 400$	$400 \le S_T < 600$	$600 \le S_T < 800$	$800 \le S_T < 1200$	$S_T \ge 1200$
Data	33	5	19	5	4	0
Background Estimation	34.84 ± 1.68 (stat.) ± 12.05 (sys.)	5.49 ± 0.73 (stat.) ± 2.11 (sys.)	14.91 ± 1.14 (stat.) ± 5.26 (sys.)	8.67 ± 0.79 (stat.) ± 2.83 (sys.)	4.52 ± 0.56 (stat.) ± 1.43 (sys.)	1.24 ± 0.25 (stat.) ± 0.42 (sys.)
Prompt-Prompt	12.42	1.11	4.52	3.58	2.42	0.79
Prompt-NonPrompt	17.93	3.25	8.30	4.31	1.66	0.41
NonPrompt-NonPrompt	1.29	0.39	0.62	0.15	0.14	0.00
Charge Flip	3.20	0.74	1.47	0.63	0.30	0.05
μe	Total Events Yield	$200 \le S_T < 400$	$400 \le S_T < 600$	$600 \le S_T < 800$	$800 \le S_T < 1200$	$S_T \ge 1200$
Data	57	10	28	9	8	2
Background Estimation	65.55 ± 3.16 (stat.) ± 21.94 (sys.)	9.32 ± 1.37 (stat.) ± 3.46 (sys.)	29.27 ± 2.19 (stat.) ± 10.21 (sys.)	14.14 ± 1.33 (stat.) ± 4.31 (sys.)	10.77 ± 1.15 (stat.) ± 3.28 (sys.)	2.05 ± 0.46 (stat.) ± 0.67 (sys.)
Prompt-Prompt	25.41	2.03	9.13	7.14	5.86	1.25
Prompt-NonPrompt	37.62	6.58	19.10	6.55	4.62	0.77
NonPrompt-NonPrompt	0.77	0.41	0.11	0.13	0.13	0.00
Charge Flip	1.74	0.30	0.94	0.32	0.15	0.03

B-1/3 quark, SS dilepton

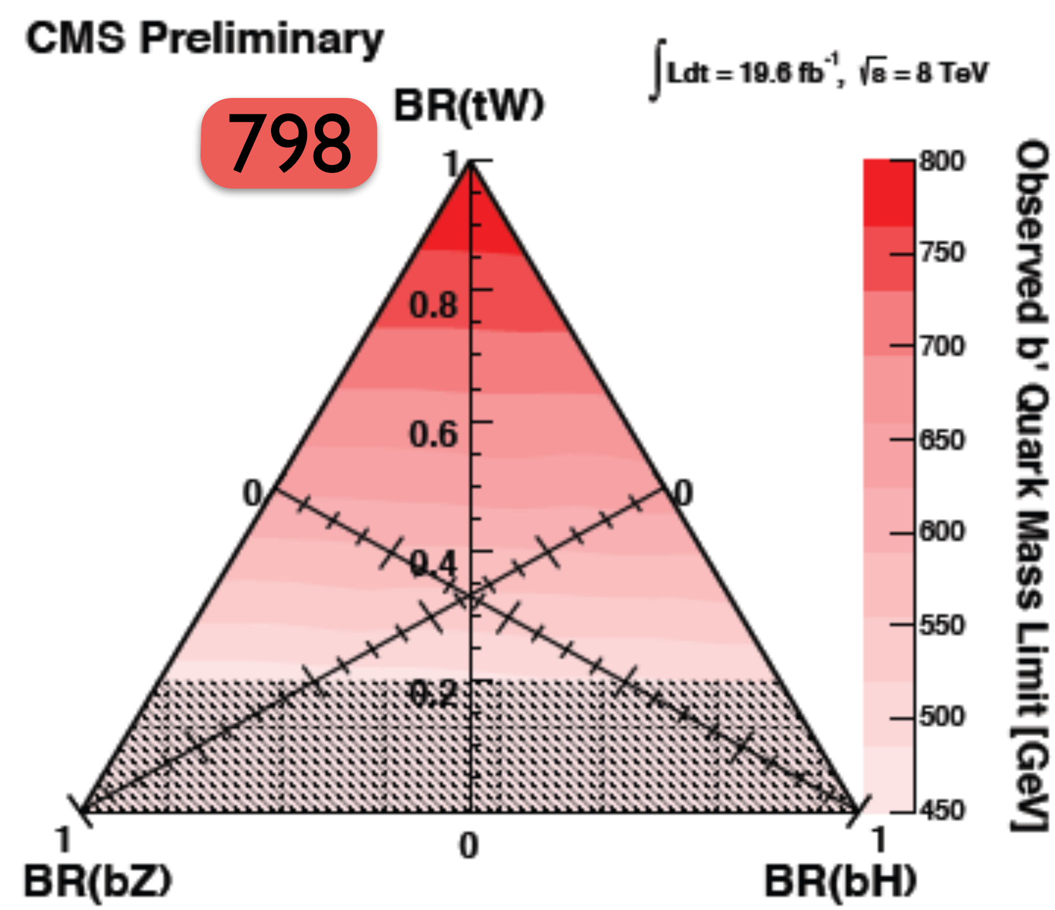
CMS-PAS-B2G-12-020

B→tW, bZ, bH (SS dilepton channel)

Expected



Observed



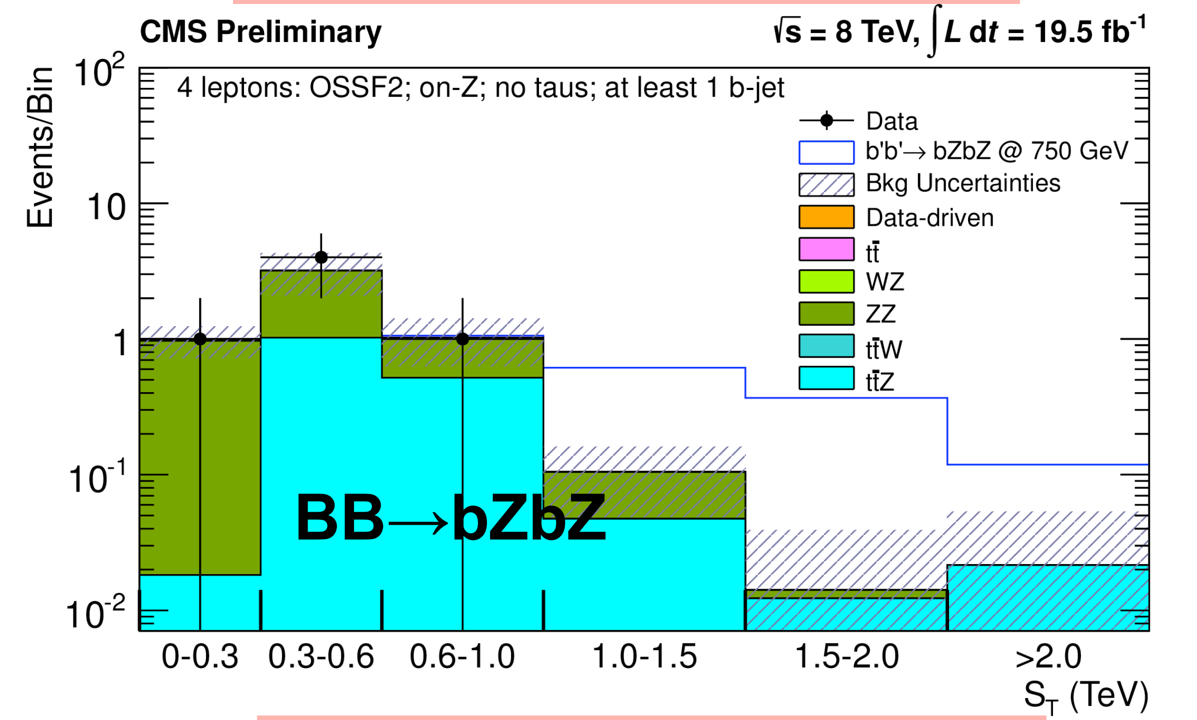
Benchmark point, tW:bZ:bH=0.50:0.25:0.25 : 641(Obs), 646(Exp)

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

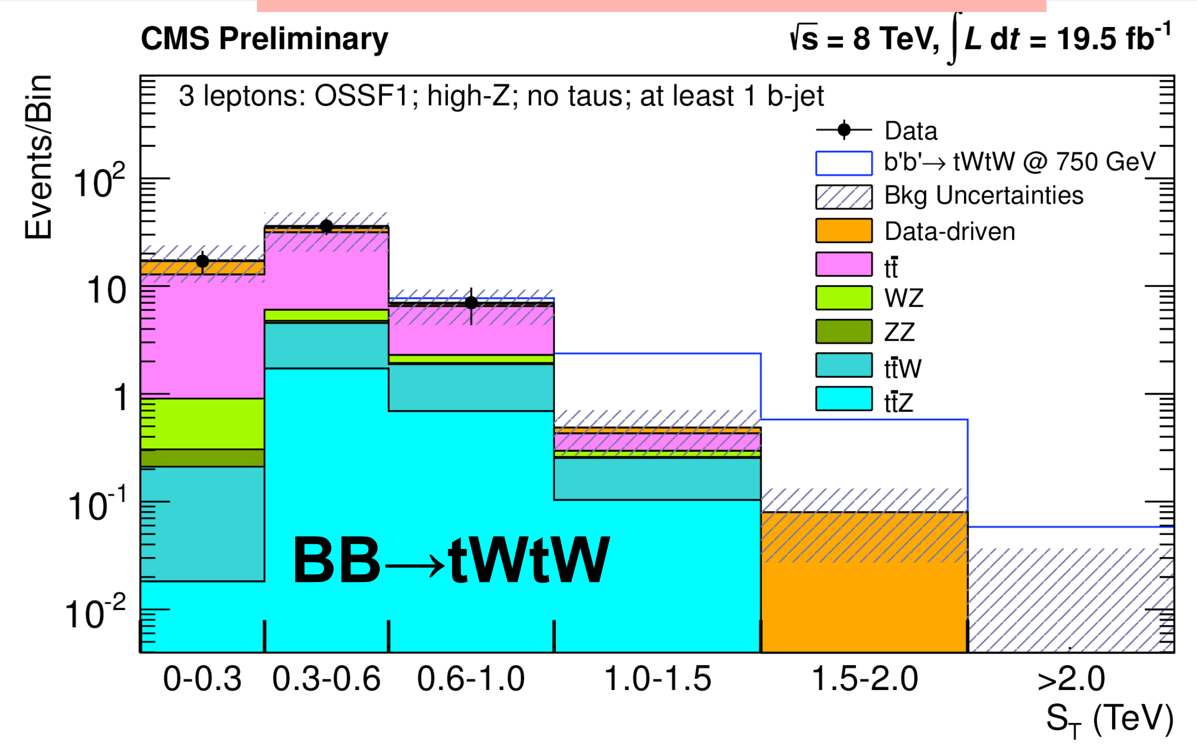
CMS-PAS-B2G-13-003

- Event selection:
  - ≥ 3 isolated leptons (τ_l = e or μ, ≤1τ_h)
  - M(ll)>12 GeV: quarkonia veto
  - |M(lll)-MZ|<15 GeV: conversion veto
  - ≥ 1 b-tagged jet (P_T>80 GeV)
- 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

4 lep, ≥1b-tag, OSSF on Z



3 lep, ≥1b-tag, OSSF off Z

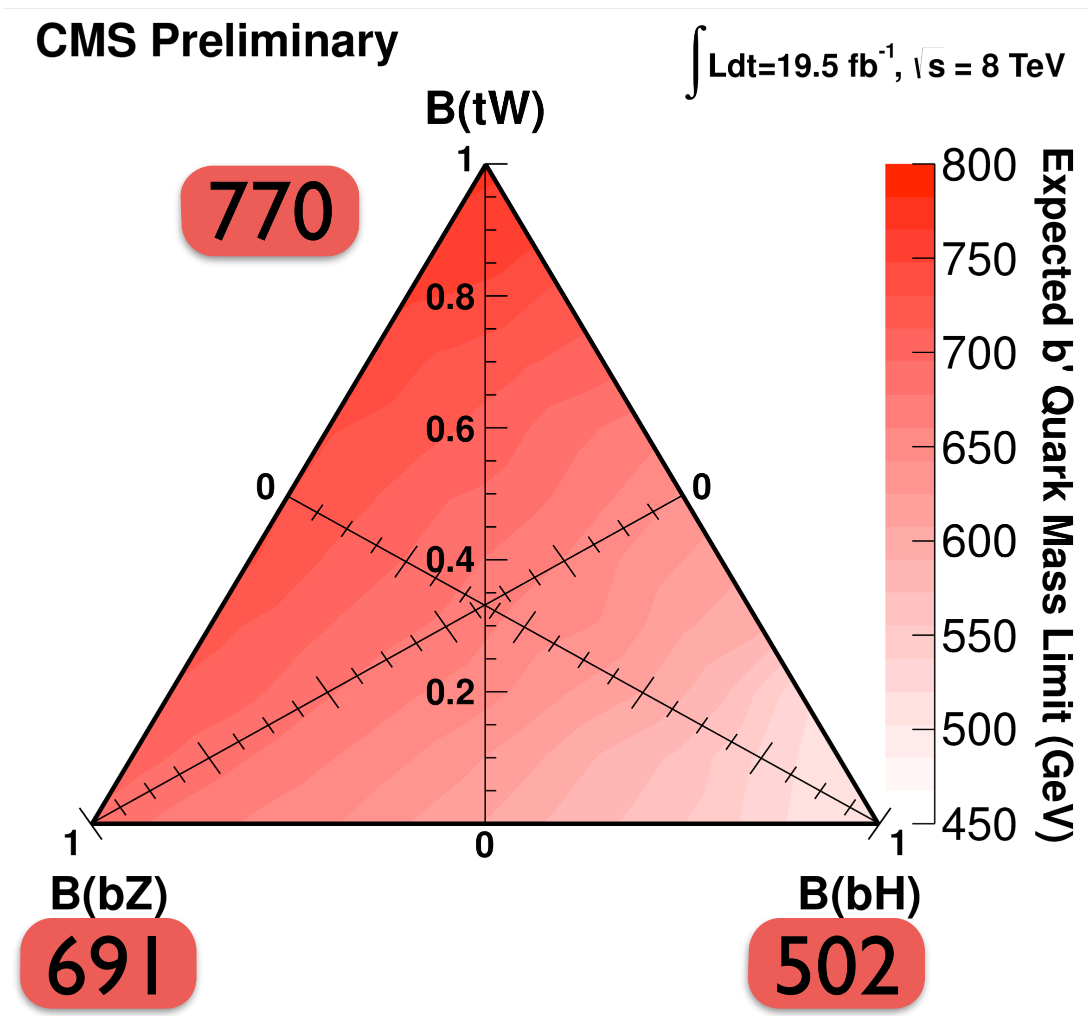


B-1/3 quark, multileptons

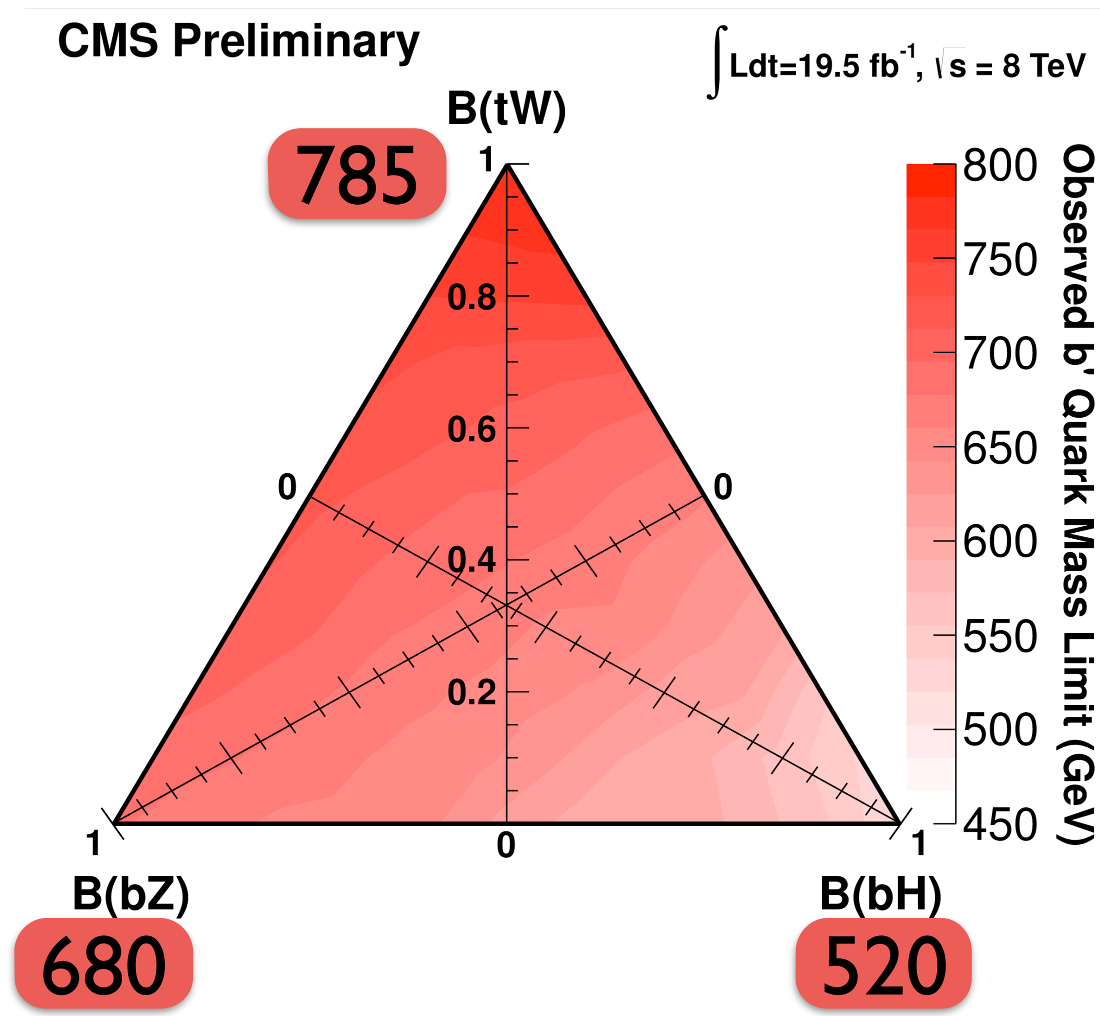
CMS-PAS-B2G-13-003

B→tW, bZ, bH

Expected



Observed



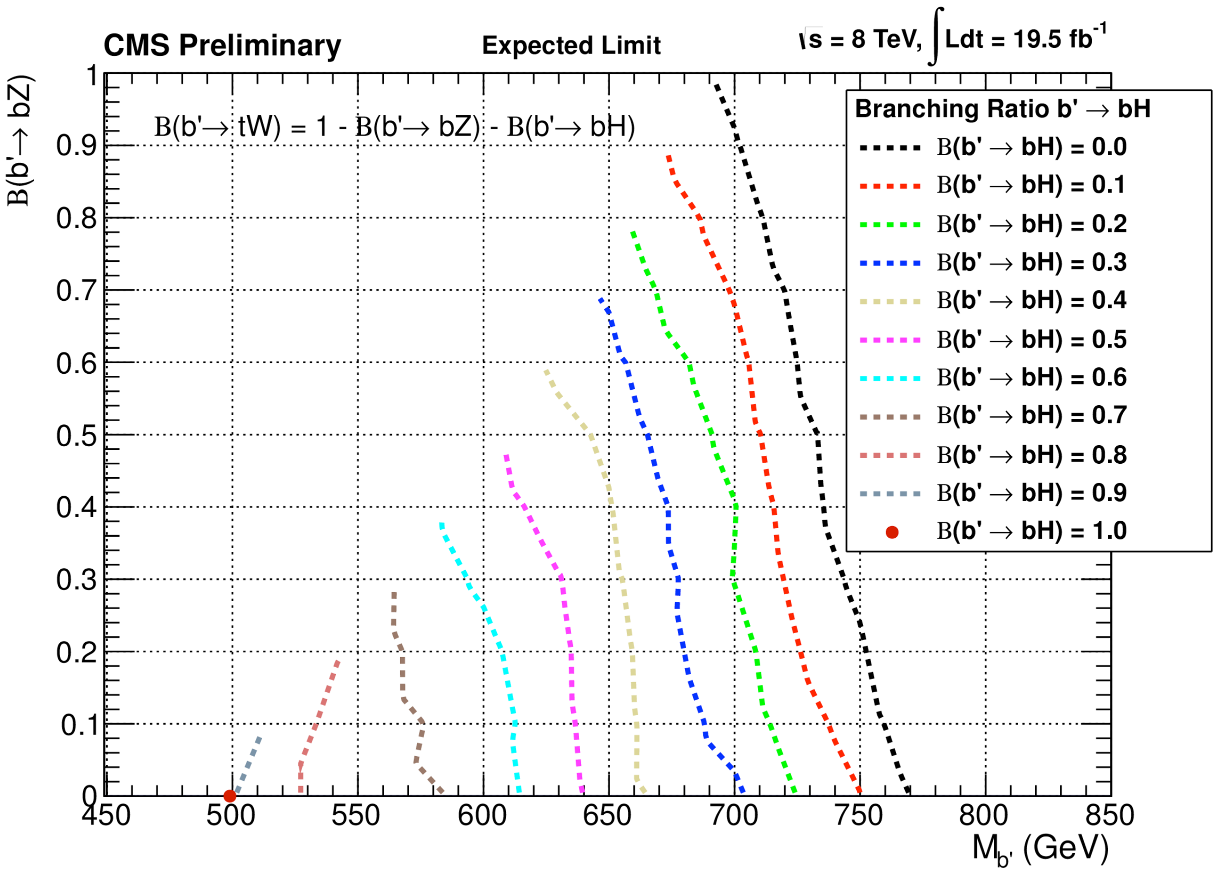
A mass bound of **[520, 785] GeV** is set at 95% CL for all possible BR.

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

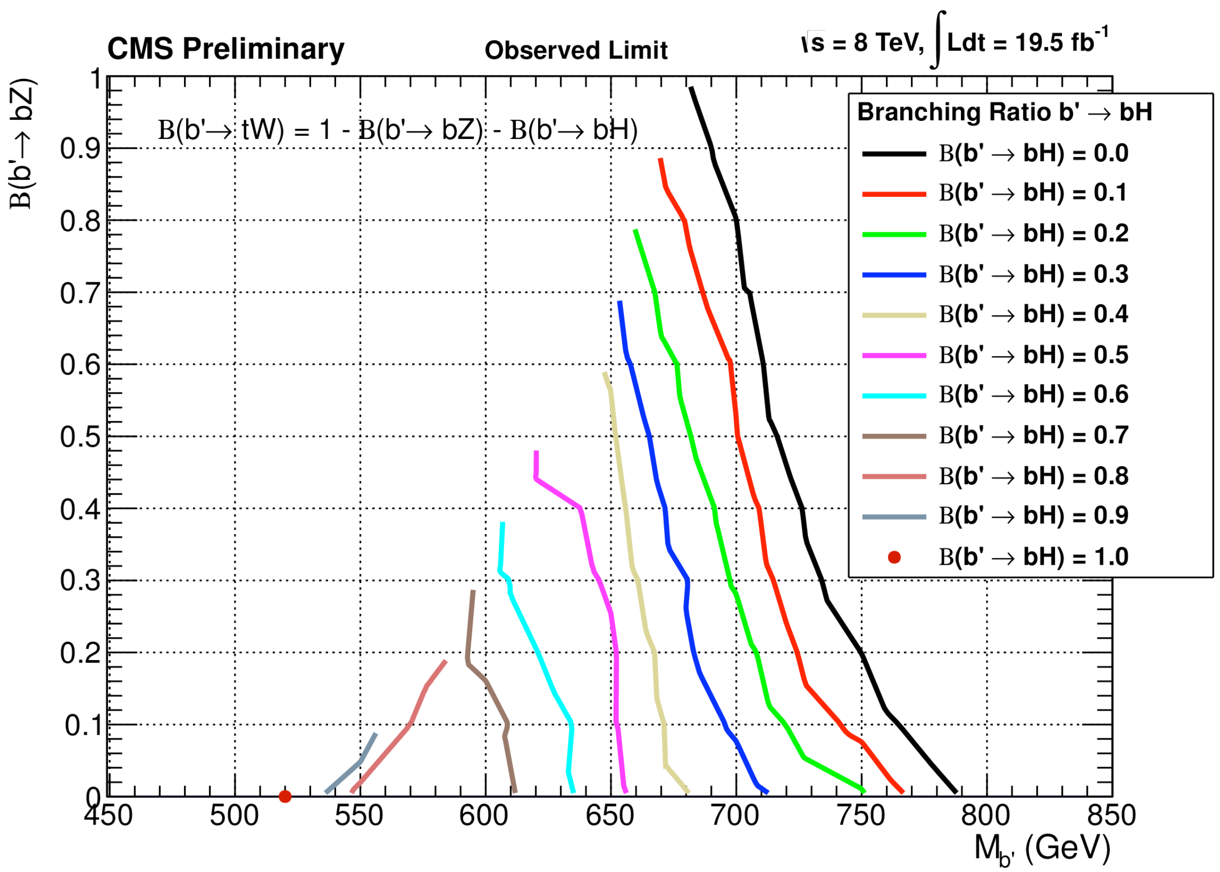
CMS-PAS-B2G-13-003

B→tW, bZ, bH

Expected



Observed



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

$B_{-1/3}$ quark: Grand Combination

CMS-PAS-B2G-13-003

- Five different analyses for a legacy publication using 8 TeV data
  - Lepton+jets
  - Dileptons(OS, SS)
  - Multilepton
  - Boosted H→bb

Stay Tuned!

Run 2 Preparation

General Description

- Generic 'broad' assumption consistent with realistic models are:
  - New fermions interact with the SM fermions via Yukawa interactions.
  - The Quantum-numbers of the new fermions under the weak $SU(2)_L \times U(1)_Y$ gauge group are limited by interaction with the SM Higgs doublet and one of the SM fermions.

G Cacciapaglia, A. Deandrea (arXiv:1007.2933)

- Possible Q-numbers :
  - 1 SM-like singlet
  - 3 doublets : 1 with SM hypercharge Y, the others Y+/-1
  - 2 triplets with Y+/-1

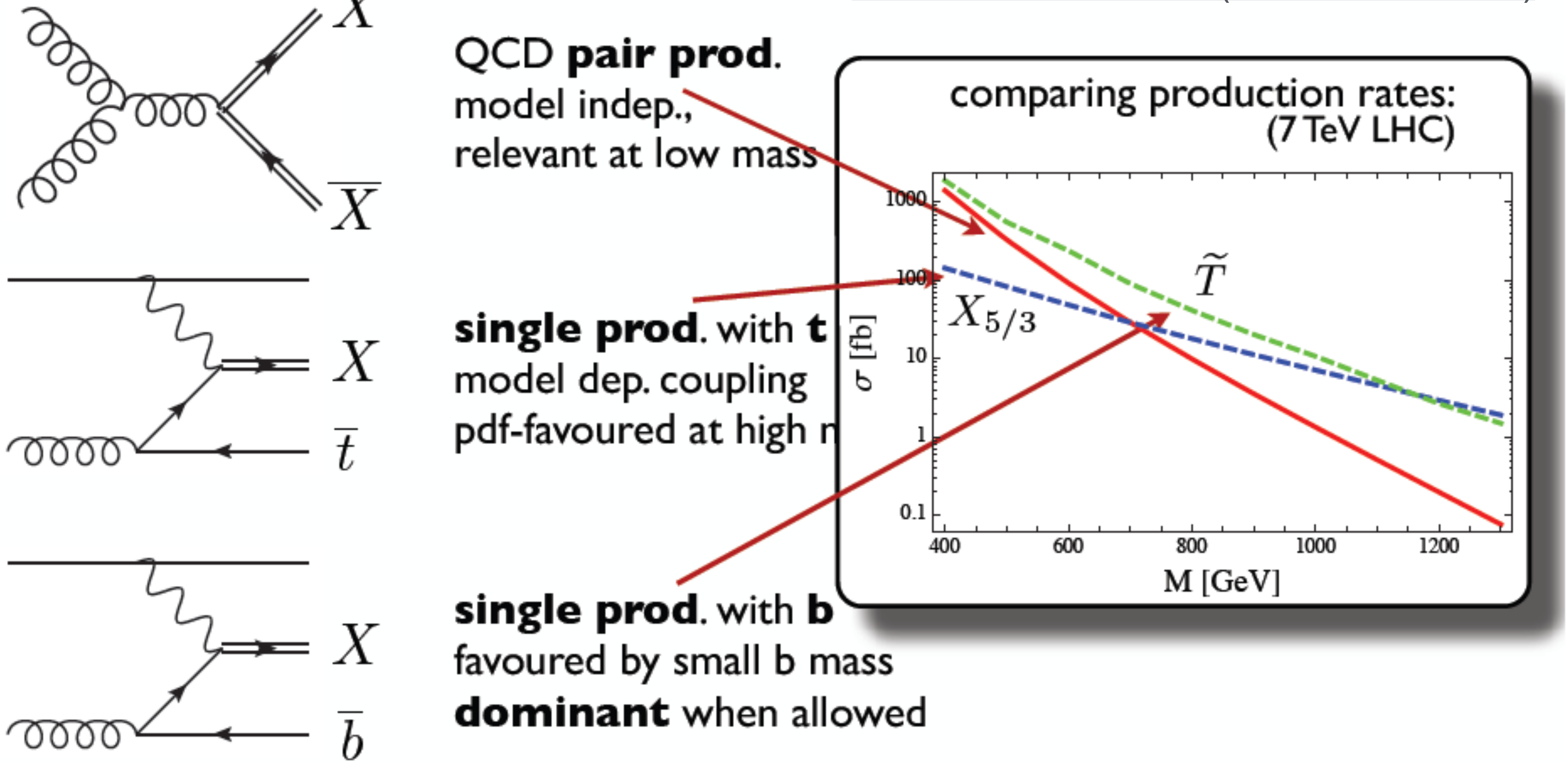
	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix}u\\d\end{pmatrix}$ $\begin{pmatrix}c\\s\end{pmatrix}$ $\begin{pmatrix}t\\b\end{pmatrix}$	(t') (b')	$\begin{pmatrix}X\\t'\end{pmatrix}$ $\begin{pmatrix}t'\\b'\end{pmatrix}$ $\begin{pmatrix}b'\\Y\end{pmatrix}$	$\begin{pmatrix}X\\t'\\b'\end{pmatrix}$ $\begin{pmatrix}t'\\b'\\Y\end{pmatrix}$
$SU(2)_L$	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
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}}\bar{u}_L^i u_R^i$ $-\frac{y_d^j v}{\sqrt{2}}\bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}}\bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$
$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)		
Free parameters		4 $M + 3 \times \lambda^i$	4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$	4 $M + 3 \times \lambda^i$

VLQ Production

- LHC Run1 has focused more on pair production of VLQ, with typical constraints of m_Q~ 750 GeV

Three possible production mechanisms

- Andrea Wulzer et.el (arXiv:1211.5663)



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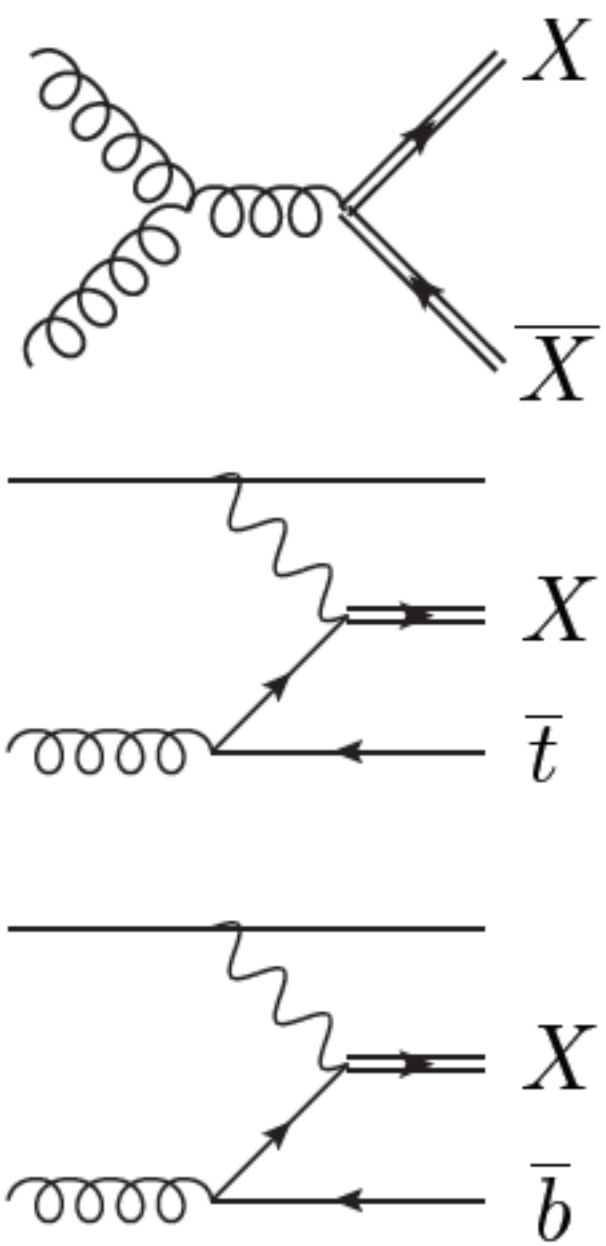
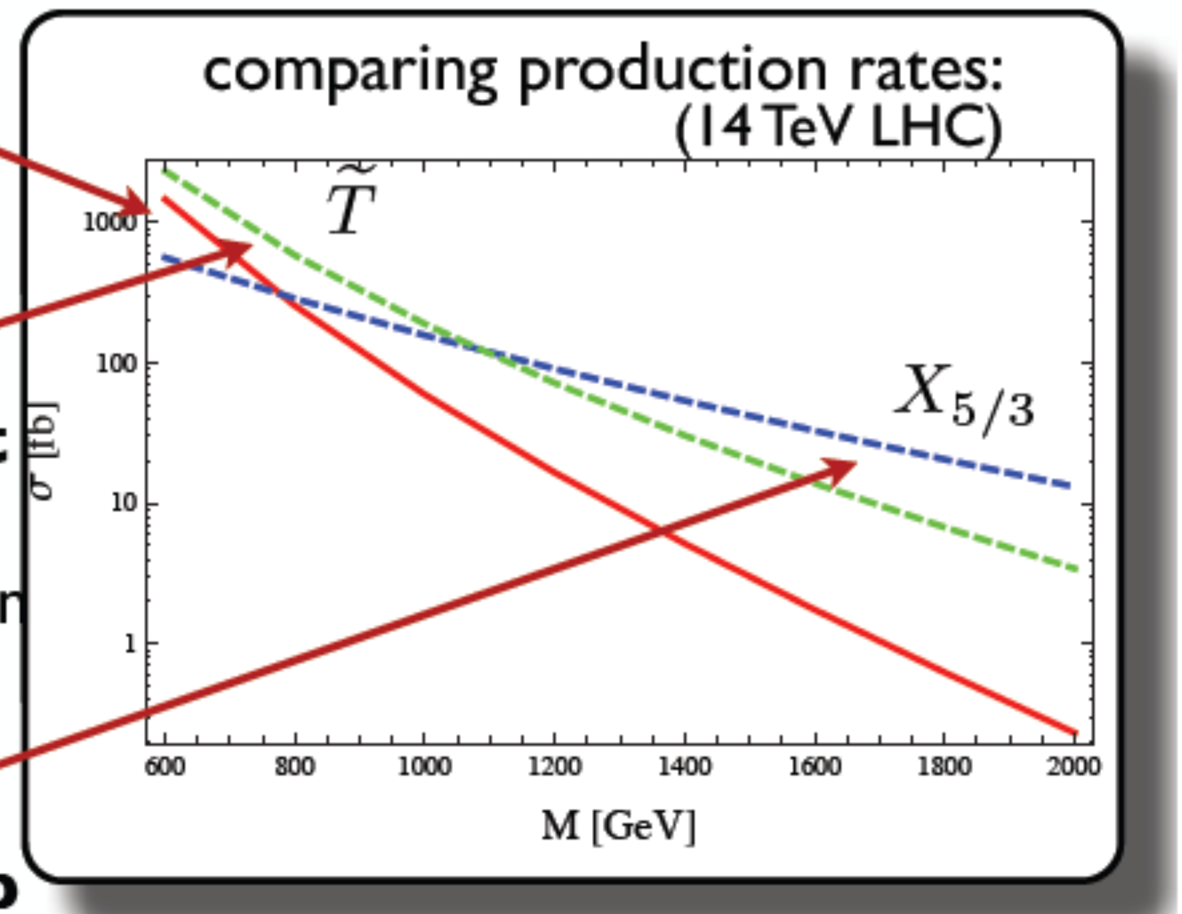


QCD **pair prod**.
model indep.,
relevant at low mass

single prod. with **t**
model dep. coupling
pdf-favoured at high m

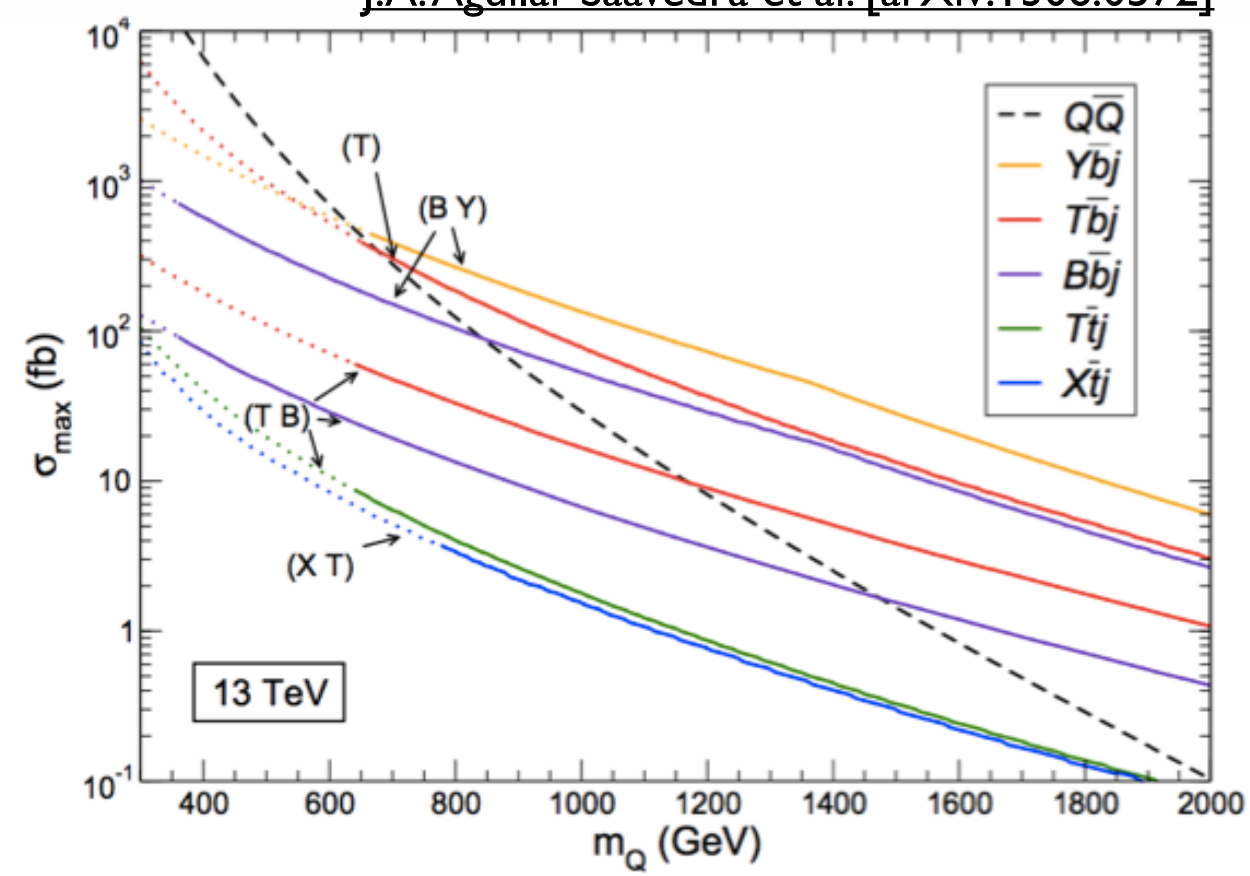
single prod. with **b**
favoured by small b mass
dominant when allowed



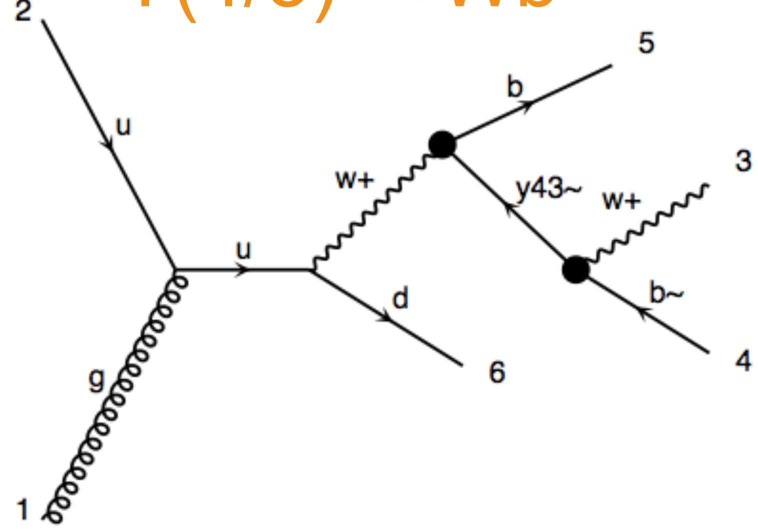
Benchmark Models

J.A. Aguilar-Saavedra et al. [arXiv:1306:0572]

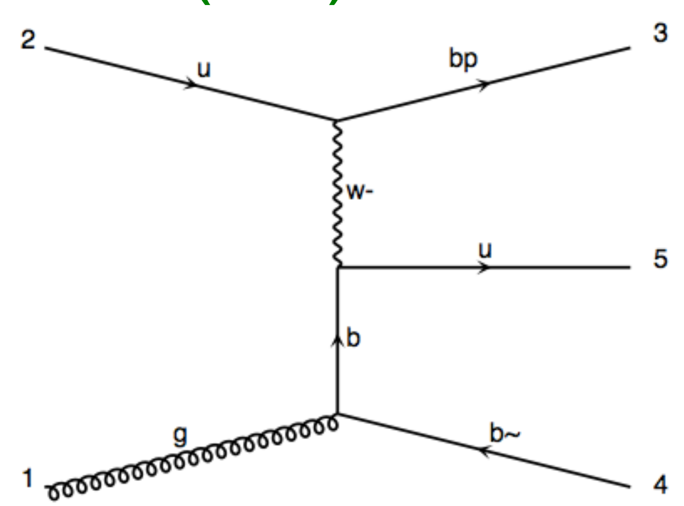
- Few interesting benchmark models to focus on for Run2 startup
  - Single Y(4/3) quark (Y →Wb) production in an association with b
  - Single B(4/3) quark (B →Wb) production in an association with b quark or top quark (other decay modes also feasible)



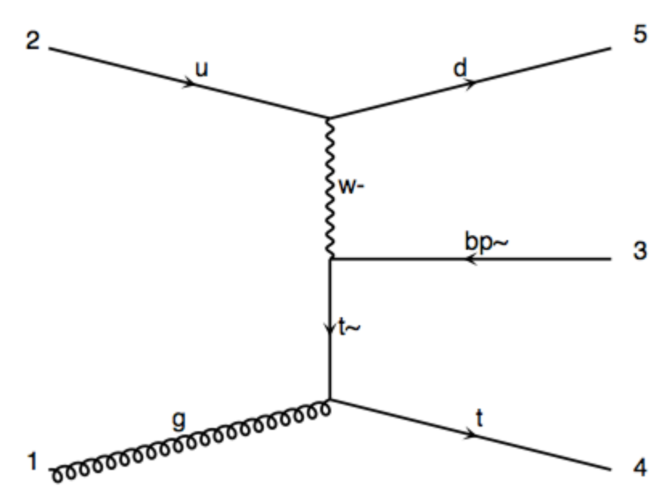
Y(4/3) →Wb



B(1/3) →Wt



B(1/3) →Wt



W+bb (+j)

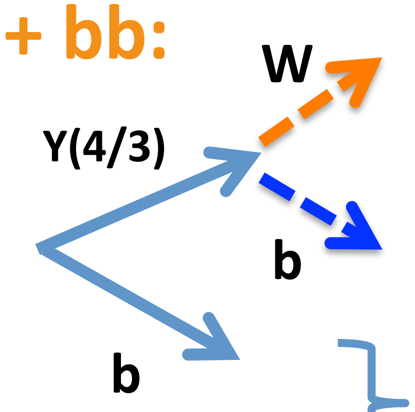
W+t+b (+j)

W+tt (+j)

Benchmark Models

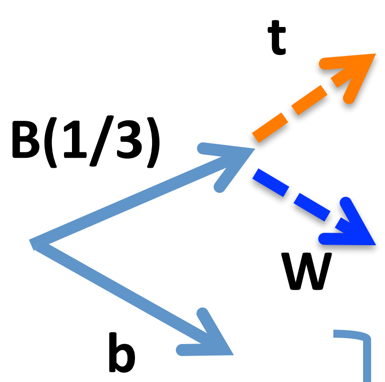
- Search Strategies

W + bb:



- Both **W** and **b** carry half of Y(4/3)-quark mass energy and are boosted for heavier Y(4/3)-quark
- **W-** and **t**-tagging using CA8 jet selection is essential
- recoiled b-quark is soft due to gluon splitting

W + t + b:

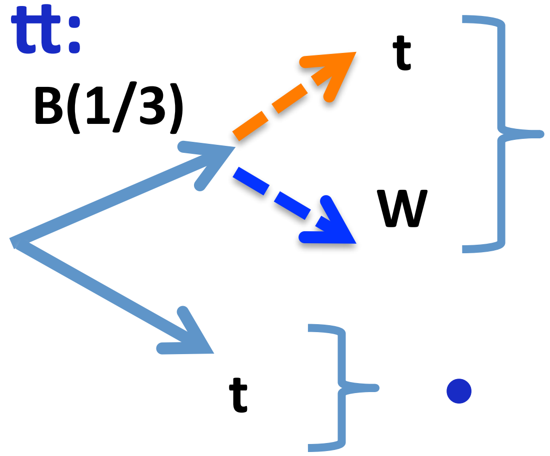


- Both **W** and **b** carry half of Y(4/3)-quark mass energy
- **W-** and **t**-tagging using CA8 jet selection is essential
- Single lepton can be the best way to go + **BDT** but all hadronic is also very sensitive
- recoiled b-quark is soft due to gluon splitting

Benchmark Models

- Search Strategies

W + tt:



- Both **W** and **b** carry half of Y(4/3)-quark mass energy and are boosted for heavier Y(4/3)-quark
- **A combination of multiple final state can be used**
- t quark is relatively soft

- Variety of final states
  - Single lepton + boosted W/t
  - SS and OS dileptons
  - All hadronic

- MC Production
  - Testing production using MG5 and 5F scheme

Conclusion

- CMS is very actively pursuing the search program in the top-like sector
- Many interesting analyses
  - with more and more stringent limits
  - useful for generic searches
- Extensive use of jet substructure techniques @ 8TeV analyses
- Final legacy results to come, stay tuned :

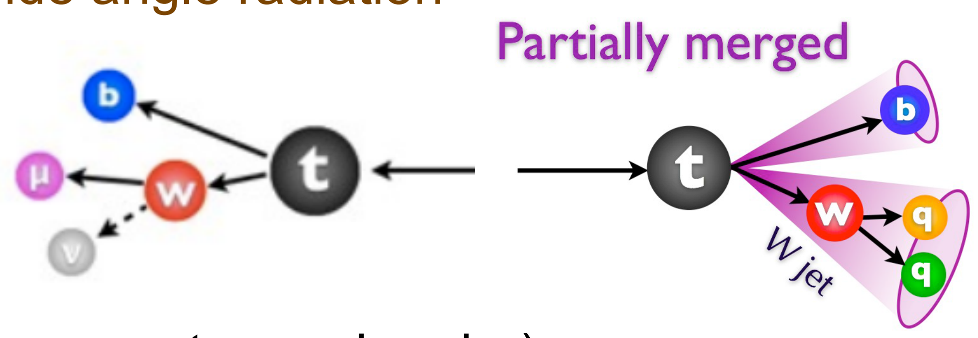
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- Getting ready for more data at higher energy !
  - MC is a challenge: Many more new channels (Bt, Bq, BW, BZ, BH)

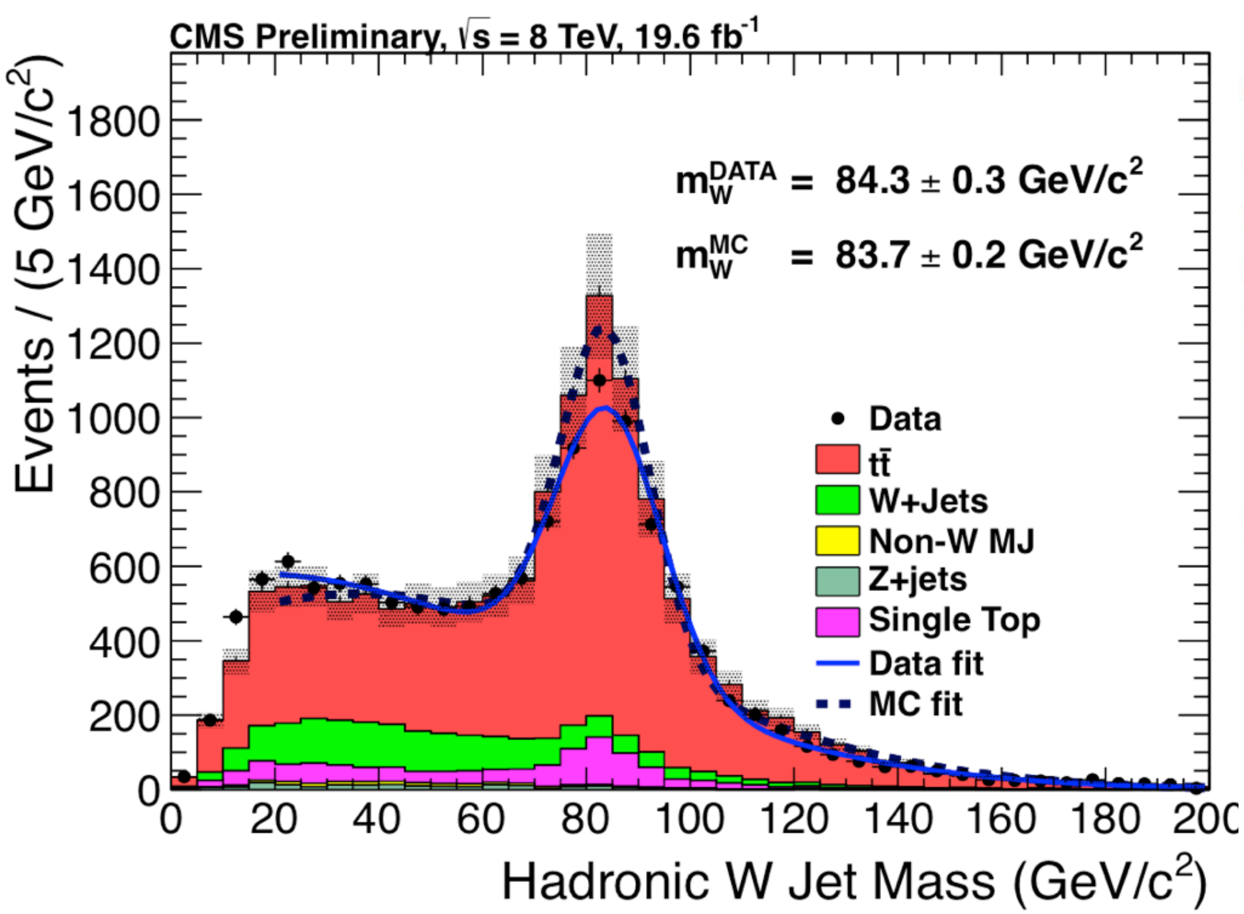
Thank you

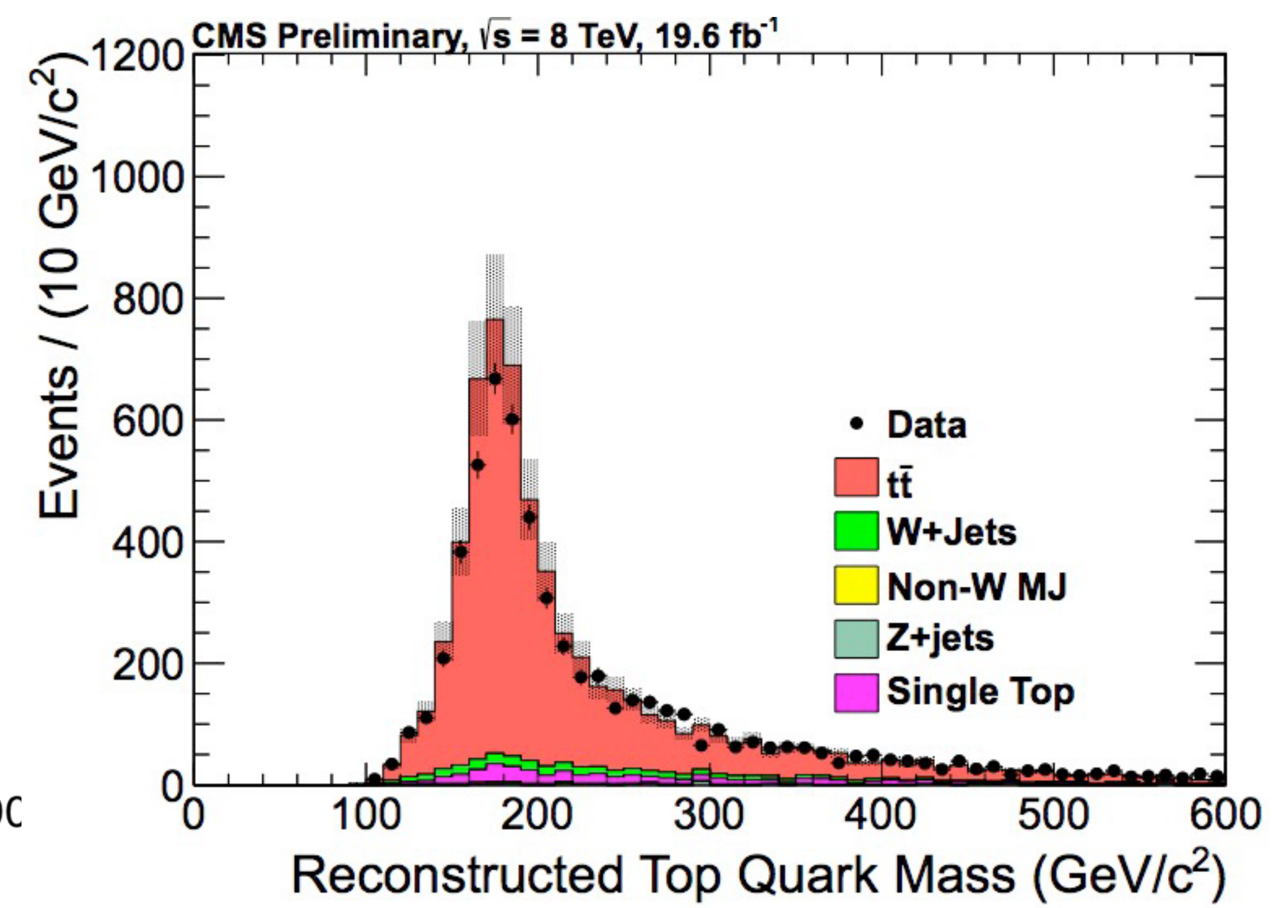
Backup

Common tools: W-tagging

- W tagging uses pruning algo: http://arxiv.org/abs/0912.0033
  - Recluster jets from its constituents removing soft and wide angle radiation
- W Selection
  - $N_{subjets} = 2$
  - 60 GeV < m_{jet} < 130 GeV
- Validated on semileptonic tt events (leptonic and hadronic legs are tag and probe)
  - W mass peak serves as a calibration of the subjet energy scale

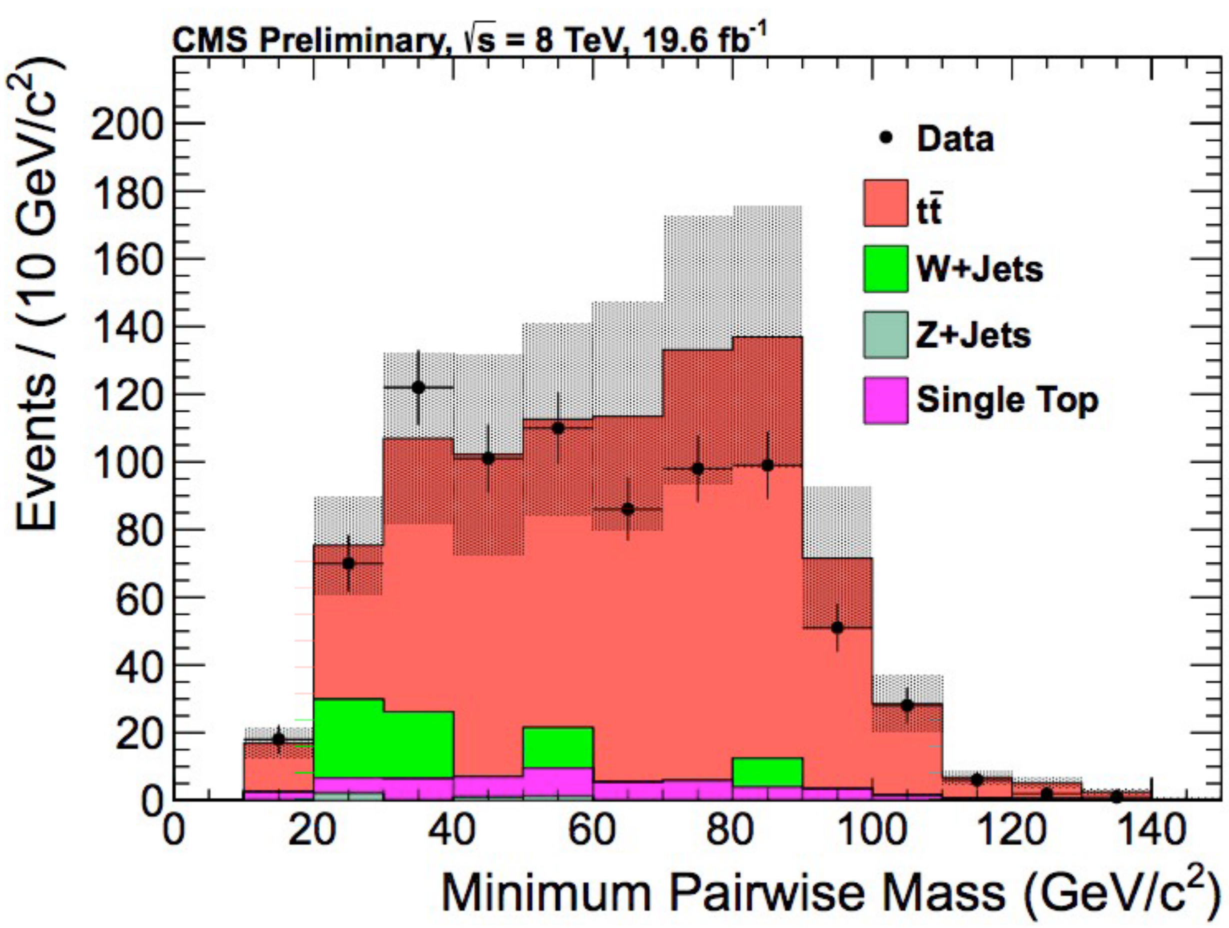


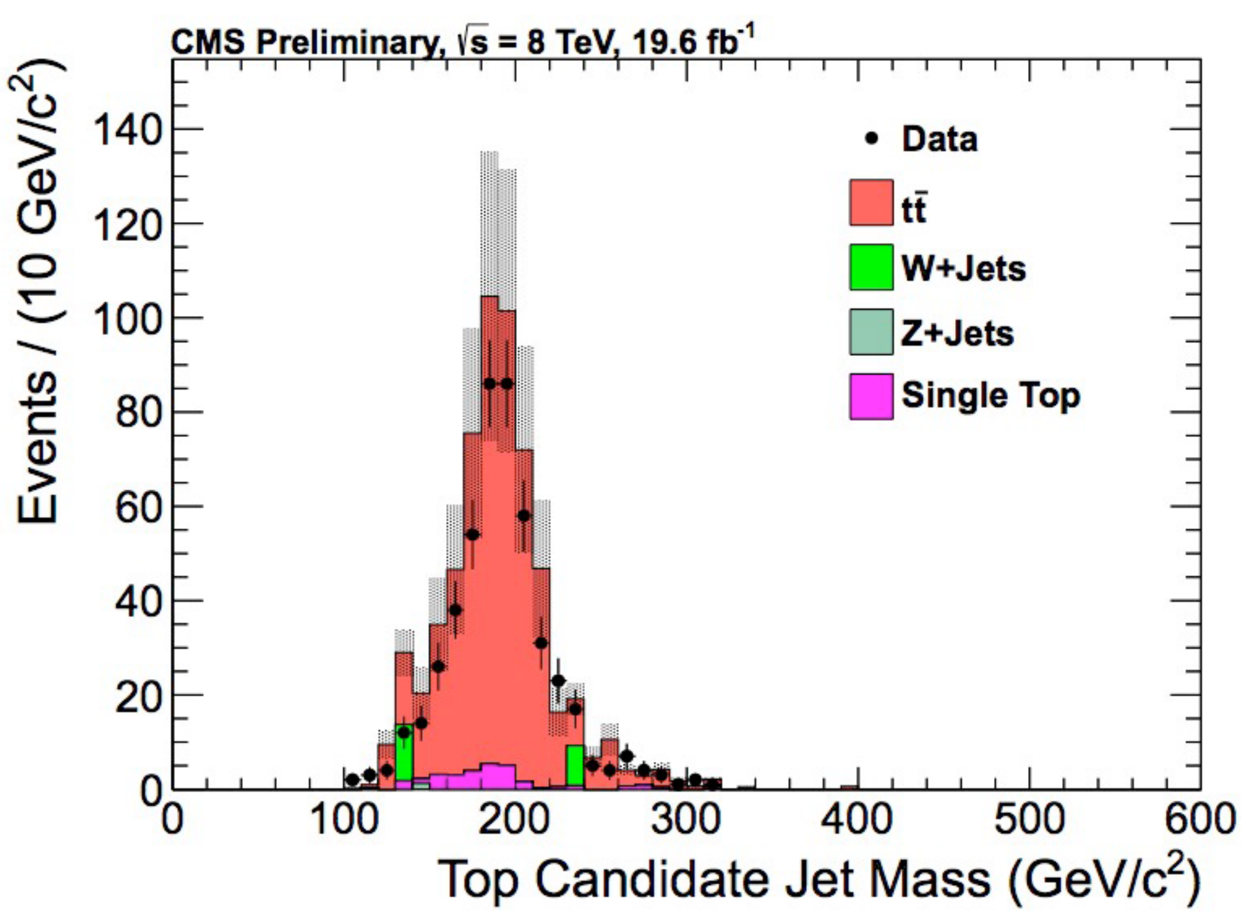




Common tools: top tagging

- Top tagging algo: http://arxiv.org/abs/0806.0848
  - Invert the last steps of CA algo removing soft objects
- Top Selection
  - $N_{subjets} \geq 3$
  - $m_{min} > 50$ GeV
  - 140 GeV < m_{jet} < 250 GeV
- Validated on semileptonic tt events (leptonic and hadronic legs are tag and probe)

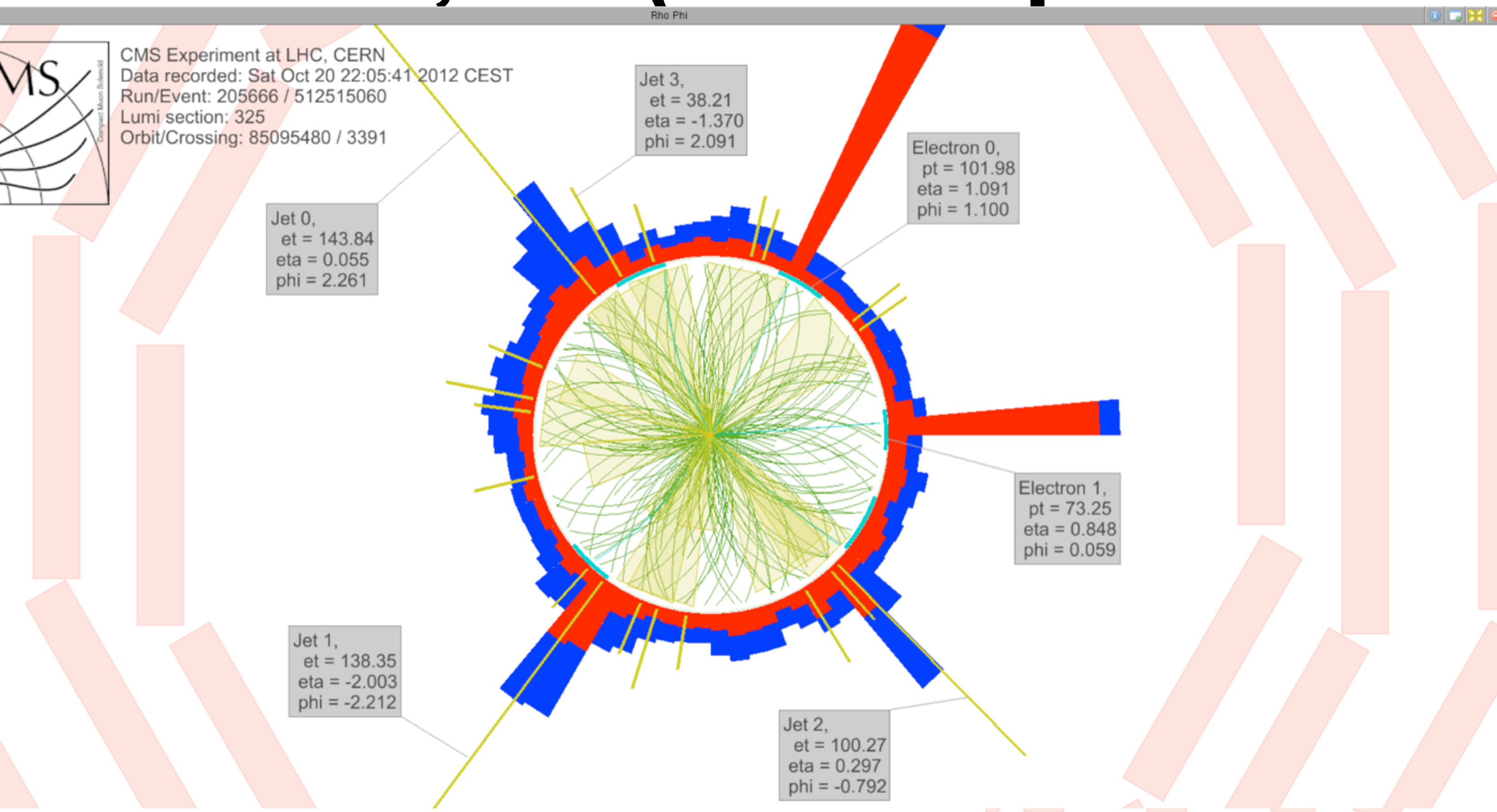




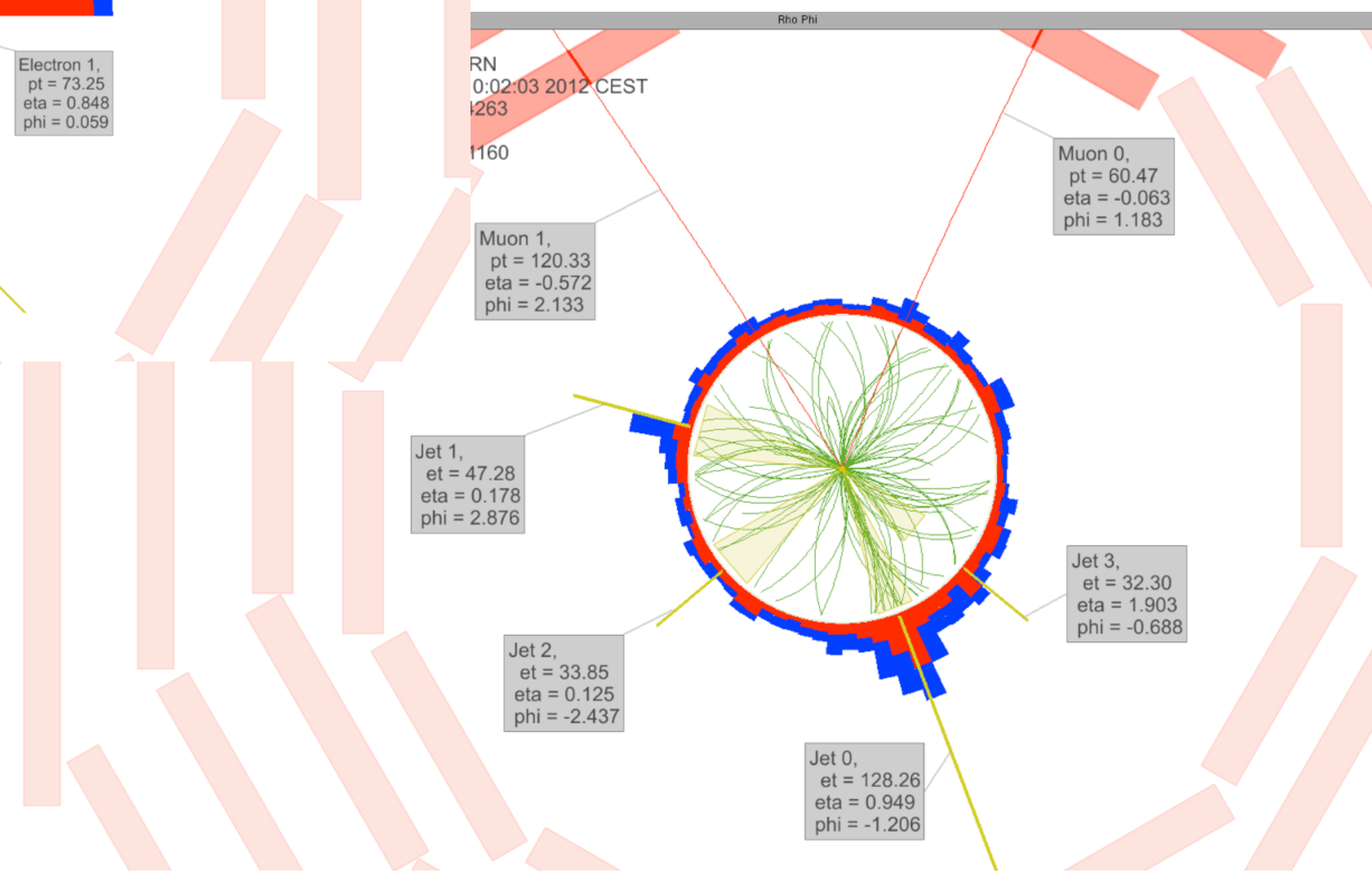
B quark searches

CMS-PAS-B2G-12-021

B→tW, bZ (OS dilepton channel)



→ B→bZ, Z→ee

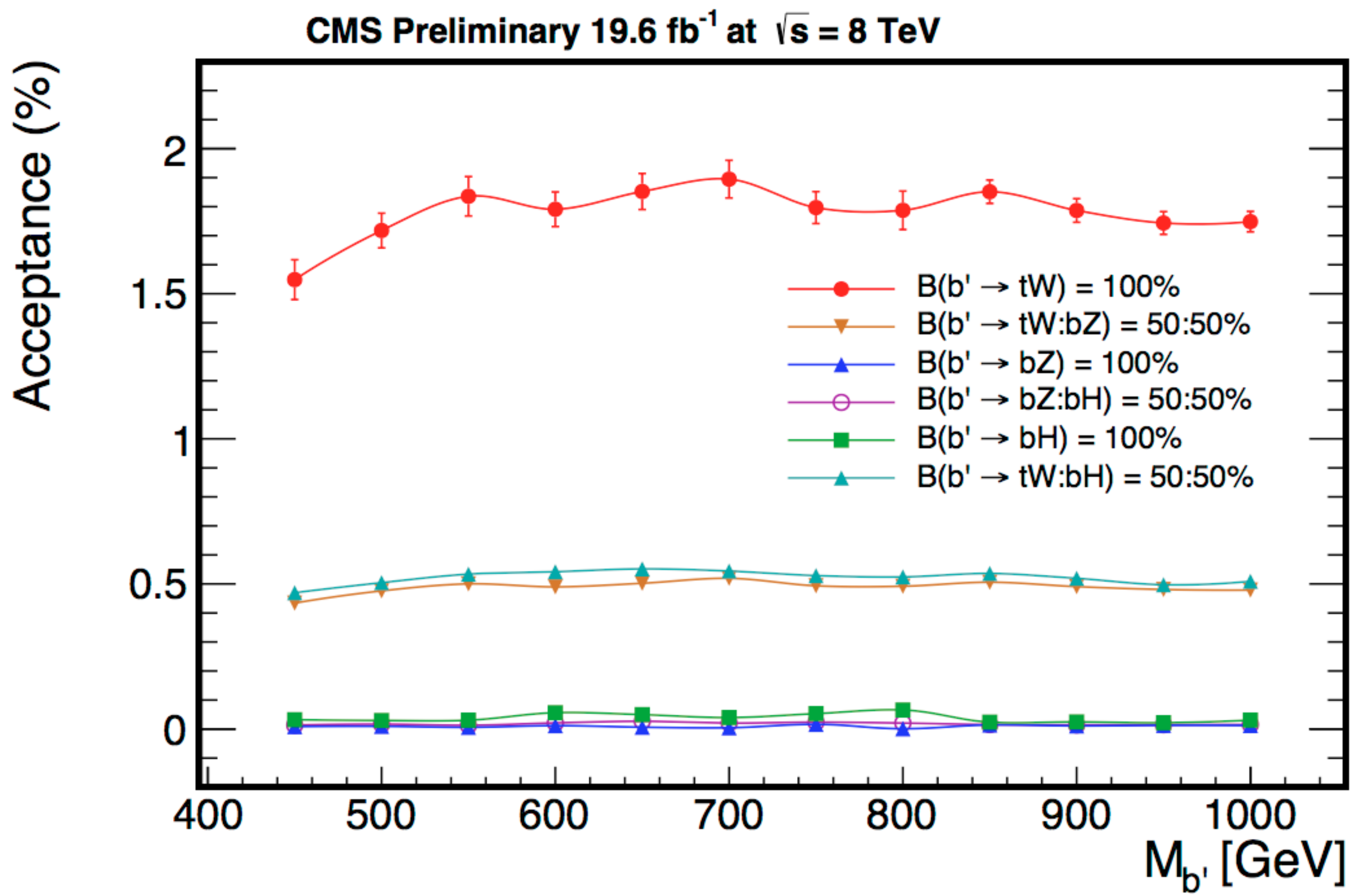


B→bZ, Z→μμ ←

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

CMS-PAS-B2G-12-020

Signal Acceptance



B search with multileptons

CMS-PAS-B2G-13-003

- Systematic Uncertainty

Source of Uncertainty	Uncertainty (%)
Luminosity	2.6
E_T^{miss} Resolution (0-50 GeV, 50-100 GeV, > 100 GeV)	(–3, +4, +4)
Jet Energy Scale WZ	0.5
b-tagging Scale Factor	0.1 (WZ), 6 ($t\bar{t}$)
Muon ID/Isolation at 10 (100) GeV	11 (0.2)
Electron ID/Isolation at 10 (100) GeV	14 (0.6)
Tau ID/isolation at 10 (100) GeV	2 (1.1)
Dilepton trigger efficiency	5
$t\bar{t}$ cross section	5
$t\bar{t}$ fake contribution	50
WZ normalization	6
ZZ normalization	12
Asymmetric Internal conversion fake rate	50
Internal Photon Extrapolation for muons (electrons)	0.1 (0.3)
Fake Muons (electrons) contribution	0.2 (0.2)

B search with multileptons

- Event counts for 3 leptons

CMS-PAS-B2G-13-003

N_{OSSF}	$m(\ell^+\ell^-)$ (GeV)	S_T (TeV)	$N_{\tau_h} = 0$, $N_{b\text{-jets}} = 0$		$N_{\tau_h} = 1$, $N_{b\text{-jets}} = 0$		$N_{\tau_h} = 0$, $N_{b\text{-jets}} \geq 1$		$N_{\tau_h} = 1$, $N_{b\text{-jets}} \geq 1$	
			obs	exp	obs	exp	obs	exp	obs	exp
0	-	> 2.0	0	< 0.02	0	0.04 ± 0.05	0	0 ± 0.02	0	0 ± 0.22
0	-	1.5 – 2.0	0	0.07 ± 0.06	0	0.18 ± 0.19	0	0.05 ± 0.06	0	0.46 ± 0.28
0	-	1.0 – 1.5	0	0.21 ± 0.18	2	2.6 ± 1.2	0	0.36 ± 0.14	2	3.9 ± 2
0	-	0.6 – 1.0	†3	3.1 ± 1	†26	28 ± 12	2	4.9 ± 1.9	†46	58 ± 28
0	-	0.3 – 0.6	32	27 ± 10	289	290 ± 129	42	39 ± 17	410	480 ± 241
0	-	0 – 0.3	72	79 ± 22	1194	1324 ± 330	37	32 ± 15	316	331 ± 160
1	> 105	> 2.0	0	0.001 ± 0.02	0	0 ± 0.21	0	0 ± 0.03	0	0 ± 0.21
1	< 75	> 2.0	0	0.004 ± 0.02	0	0 ± 0.21	0	0.01 ± 0.04	0	0 ± 0.21
1	onZ	> 2.0	0	0.2 ± 0.12	0	0.009 ± 0.21	0	0.04 ± 0.06	0	0.04 ± 0.05
1	> 105	1.5 – 2.0	0	0.15 ± 0.09	0	0.22 ± 0.22	0	0.08 ± 0.05	0	0.2 ± 0.18
1	< 75	1.5 – 2.0	1	0.11 ± 0.08	0	0.03 ± 0.05	0	0.07 ± 0.05	0	0.06 ± 0.07
1	onZ	1.5 – 2.0	3	1.1 ± 0.6	0	0.31 ± 0.17	1	0.28 ± 0.18	0	0.25 ± 0.12
1	> 105	1.0 – 1.5	2	1 ± 0.4	1	1.3 ± 0.6	0	0.5 ± 0.22	1	2.1 ± 1.2
1	< 75	1.0 – 1.5	0	1.1 ± 0.38	1	0.9 ± 0.44	†1	0.6 ± 0.27	0	1 ± 0.7
1	onZ	1.0 – 1.5	11	15 ± 6.9	9	5.9 ± 1.6	2	3.3 ± 1.2	1	1.7 ± 0.6
1	> 105	0.6 – 1.0	13	10 ± 2.4	21	23 ± 7.2	†7	7.4 ± 2.4	23	28 ± 14
1	< 75	0.6 – 1.0	14	10 ± 3.6	21	11 ± 3.4	†4	8.3 ± 2.6	†14	12 ± 6
1	onZ	0.6 – 1.0	106	111 ± 40	108	70 ± 17	†16	24 ± 7	17	17 ± 4.7
1	> 105	0.3 – 0.6	63	65 ± 12	285	372 ± 96	36	35 ± 13	169	187 ± 94
1	< 75	0.3 – 0.6	84	86 ± 21	290	279 ± 71	52	56 ± 22	167	171 ± 87
1	onZ	0.3 – 0.6	*669	735 ± 166	*2099	2705 ± 772	122	108 ± 24	325	284 ± 73
1	> 105	0 – 0.3	180	195 ± 33	1620	1712 ± 482	17	17 ± 6.4	97	79 ± 35
1	< 75	0 – 0.3	617	644 ± 102	10173	9211 ± 2694	62	74 ± 28	297	288 ± 97
1	onZ	0 – 0.3	*4255	4439 ± 691	*49916	49192 ± 14670	*140	149 ± 24	795	826 ± 229
Total3	All	All	6125	6430 ± 916	66055	65233 ± 19038	541	564 ± 150	2680	2774 ± 903

B search with multileptons

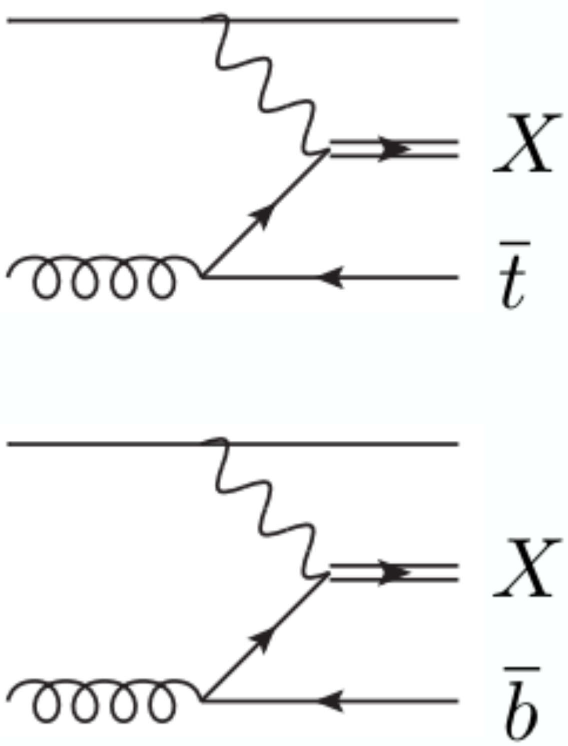
- Event counts for 4 leptons

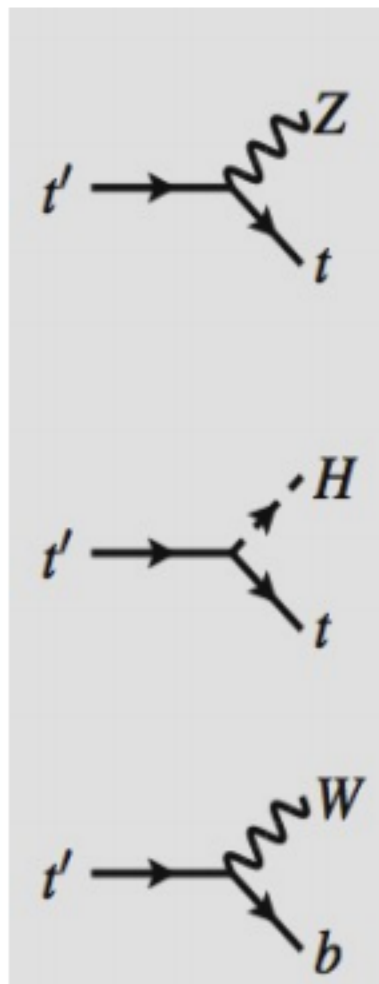
CMS-PAS-B2G-13-003

N_{OSSF}	on- or off-Z	S_T (TeV)	$N_{\tau_h}=0$, $N_{b\text{-jets}}=0$		$N_{\tau_h}\geq 1$, $N_{b\text{-jets}}=0$		$N_{\tau_h}=0$, $N_{b\text{-jets}}\geq 1$		$N_{\tau_h}\geq 1$, $N_{b\text{-jets}}\geq 1$	
			obs	exp	obs	exp	obs	exp	obs	exp
0	-	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
0	-	$1.5-2.0$	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
0	-	$1.0-1.5$	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0.007 ± 0.02
0	-	$0.6-1.0$	0	< 0.02	0	0.12 ± 0.11	0	0.05 ± 0.05	†0	0.12 ± 0.1
0	-	$0.3-0.6$	0	0.09 ± 0.06	1	0.5 ± 0.19	0	0.001 ± 0.02	0	0.28 ± 0.12
0	-	$0-0.3$	0	0.05 ± 0.05	2	1.1 ± 0.45	0	0.0003 ± 0.02	0	0.25 ± 0.16
1	offZ	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	onZ	> 2.0	0	< 0.02	0	0 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	offZ	$1.5-2.0$	0	< 0.02	0	0.007 ± 0.02	0	0 ± 0.02	0	0 ± 0.02
1	onZ	$1.5-2.0$	0	< 0.02	0	0.02 ± 0.03	0	0.01 ± 0.03	0	0.007 ± 0.02
1	offZ	$1.0-1.5$	0	0.002 ± 0.02	0	0.12 ± 0.07	†0	0.03 ± 0.04	0	0.02 ± 0.02
1	onZ	$1.0-1.5$	1	0.06 ± 0.06	0	0.1 ± 0.07	0	0.11 ± 0.08	0	0.04 ± 0.04
1	offZ	$0.6-1.0$	0	0.06 ± 0.04	2	0.48 ± 0.17	0	0.06 ± 0.07	†0	0.3 ± 0.13
1	onZ	$0.6-1.0$	0	0.43 ± 0.15	0	1.7 ± 0.6	0	0.5 ± 0.29	†0	0.7 ± 0.33
1	offZ	$0.3-0.6$	0	0.27 ± 0.11	4	2.1 ± 0.5	0	0.33 ± 0.17	0	1.2 ± 0.43
1	onZ	$0.3-0.6$	5	1.8 ± 0.47	10	12 ± 3	2	1 ± 0.5	2	1.6 ± 0.5
1	offZ	$0-0.3$	2	0.48 ± 0.18	18	8.3 ± 2.1	0	0.04 ± 0.04	1	0.6 ± 0.3
1	onZ	$0-0.3$	2	3 ± 0.9	43	41 ± 10	2	0.07 ± 0.04	2	1 ± 0.4
2	offZ	> 2.0	0	$1e-05 \pm 0.02$	-	-	0	0 ± 0.02	-	-
2	onZ	> 2.0	0	0.002 ± 0.02	-	-	0	0.02 ± 0.03	-	-
2	offZ	$1.5-2.0$	0	0.0002 ± 0.02	-	-	0	0 ± 0.02	-	-
2	onZ	$1.5-2.0$	0	0.05 ± 0.03	-	-	0	0.01 ± 0.02	-	-
2	offZ	$1.0-1.5$	0	0.01 ± 0.02	-	-	0	0 ± 0.02	-	-
2	onZ	$1.0-1.5$	1	0.6 ± 0.26	-	-	†0	0.1 ± 0.05	-	-
2	offZ	$0.6-1.0$	0	0.11 ± 0.04	-	-	0	0.14 ± 0.08	-	-
2	onZ	$0.6-1.0$	4	5.9 ± 2.0	-	-	1	1 ± 0.39	-	-
2	offZ	$0.3-0.6$	3	1 ± 0.3	-	-	1	0.22 ± 0.1	-	-
2	onZ	$0.3-0.6$	26	42 ± 10	-	-	4	3.2 ± 1	-	-
2	offZ	$0-0.3$	7	8.2 ± 2.3	-	-	0	0.18 ± 0.07	-	-
2	onZ	$0-0.3$	*135	122 ± 29	-	-	1	1 ± 0.26	-	-
Total4	All	All	186	187 ± 39	80	68 ± 15	11	8.3 ± 2.7	5	6.3 ± 1.6

SingleVLQ Production

- LHC Run1 has focused more on pair production of VLQ, with typical constraints of m_Q~ 750 GeV





Decay

Production	$W+t$	$W+b$	$Z/h+t$
Pair Production	$X_{5/3}, B$	$\tilde{T}$	$X_{2/3}, T, \tilde{T}$
Single + top	$X_{5/3}, B$		$X_{2/3}, T$
Single + bottom		$\tilde{T}$	$\tilde{T}$

- Similar decays for B