

# *Search for vector-like quarks and excited quarks at CMS*



**Giorgia Rauco**  
Universität Zürich  
on behalf of the **CMS** Collaboration

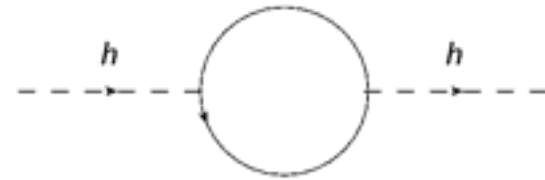
**EPS Conference on High Energy Physics 2017**  
Venice, 08.07.2017

# Motivation and phenomenology, VLQs

[arXiv:1306.0572](#), [arXiv: 1505.04306](#)



- spin 1/2, colored and charged particles
- both left- and right-handed chiralities have the same representation under the EWK group
- **receive mass through direct mass term**
  - ▶ no coupling to Higgs needed → not constrained by the Higgs discovery
- their existence could solve the **hierarchy problem**





# Motivation and phenomenology, VLQs

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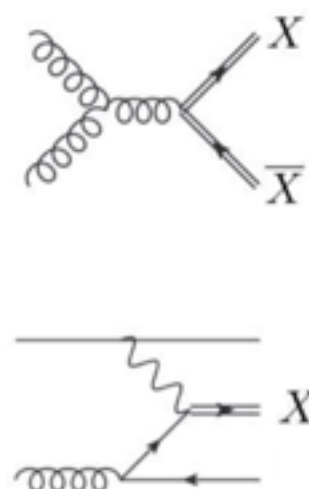
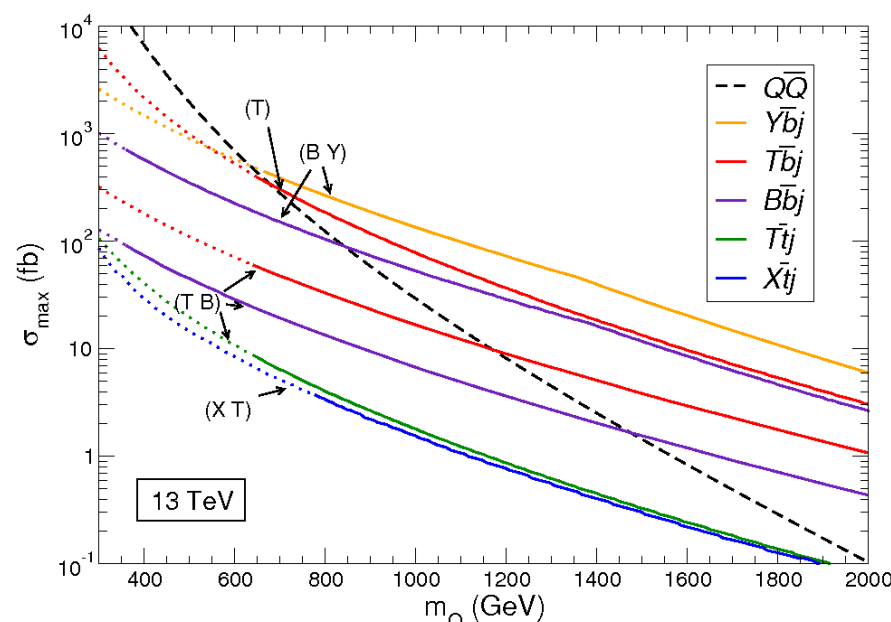
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*how can we look for them at the LHC?*

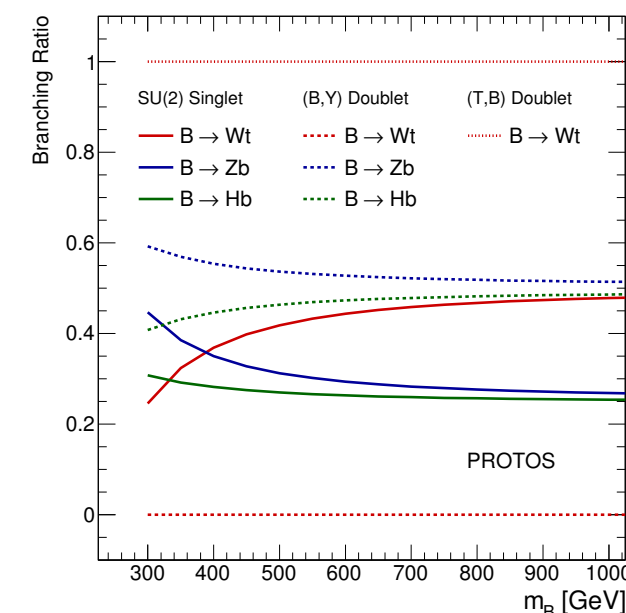
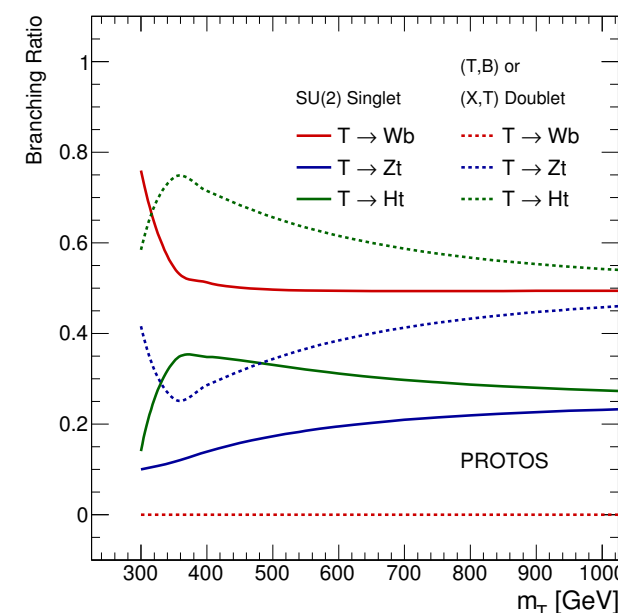
## production

- **in pair:** cross section depends on VLQ mass
- **singly:** depends also on the SM couplings



## decay

- in a boson and a massive SM quark
- BRs depend on the isospin multiplet

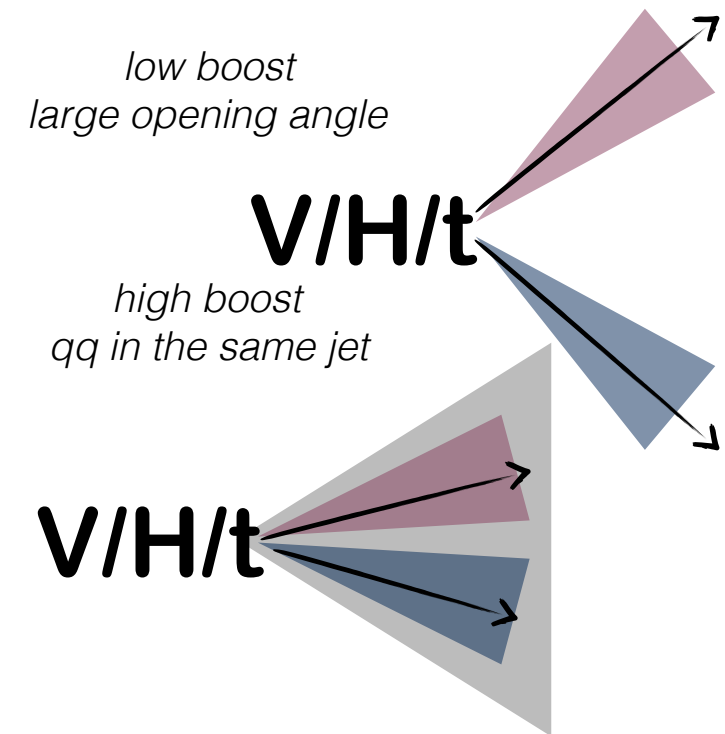


# Boosted topologies and jet substructures



[PhysRevD 81 094023](#), [JHEP 05 \(2014\) 146](#) 1, [arXiv 1707.01303](#)

- VLQs expected to appear at the **TeV scale**
  - ▶ their decay products get **high boost**



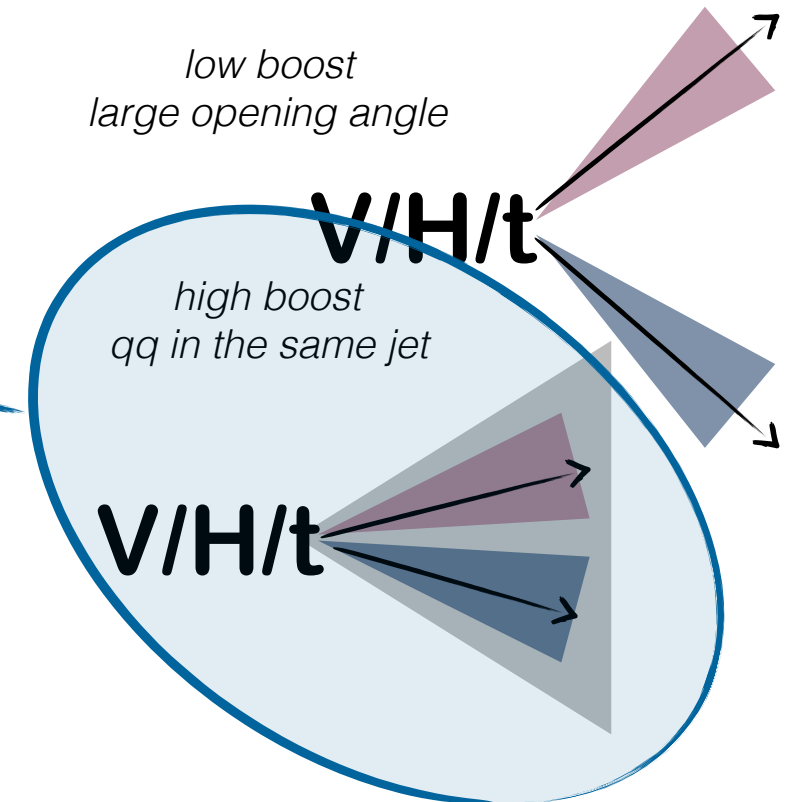
# Boosted topologies and jet substructures



PhysRevD 81 094023, JHEP 05 (2014) 146 1, arXiv 1707.01303

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*what can we do here?* ←



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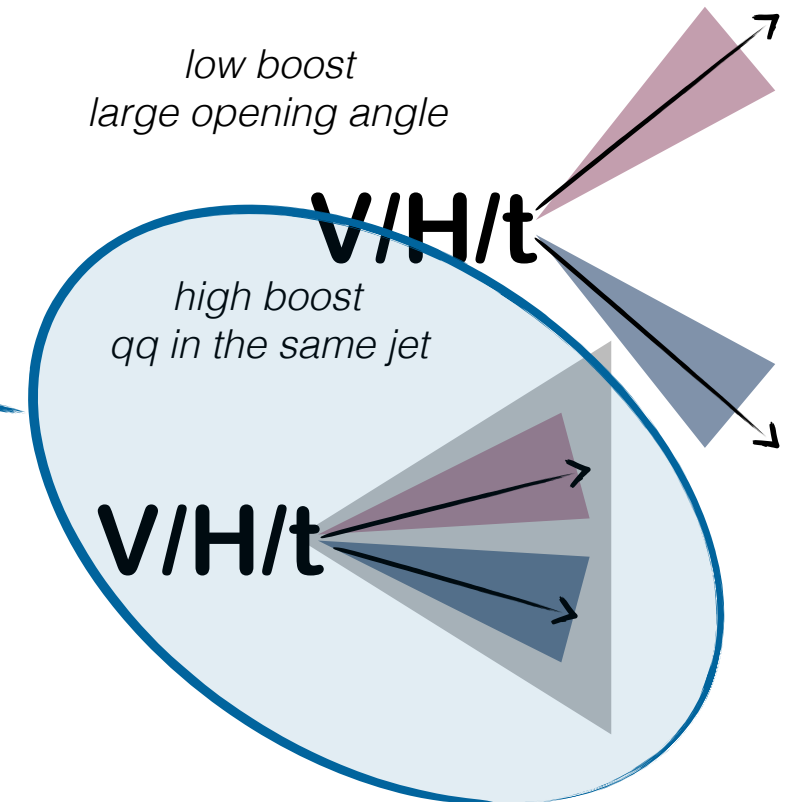


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*what can we do here?* ←

- Large-cone jets with **grooming** algorithms
- Fundamental to tag V/H bosons and top quarks



# Boosted topologies and jet substructures

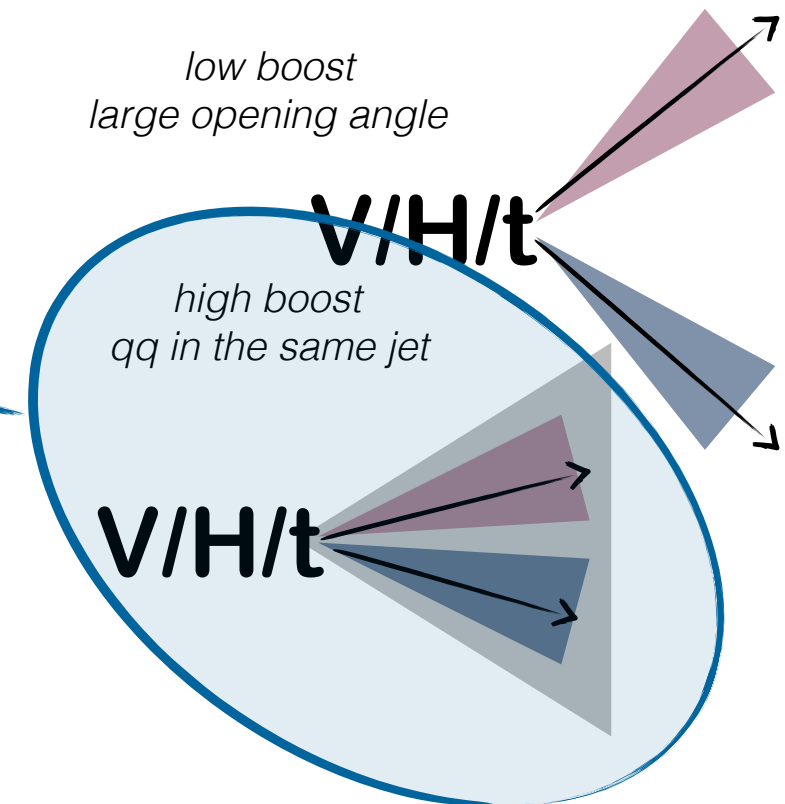


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## Pruning

PhysRevD 81 094023

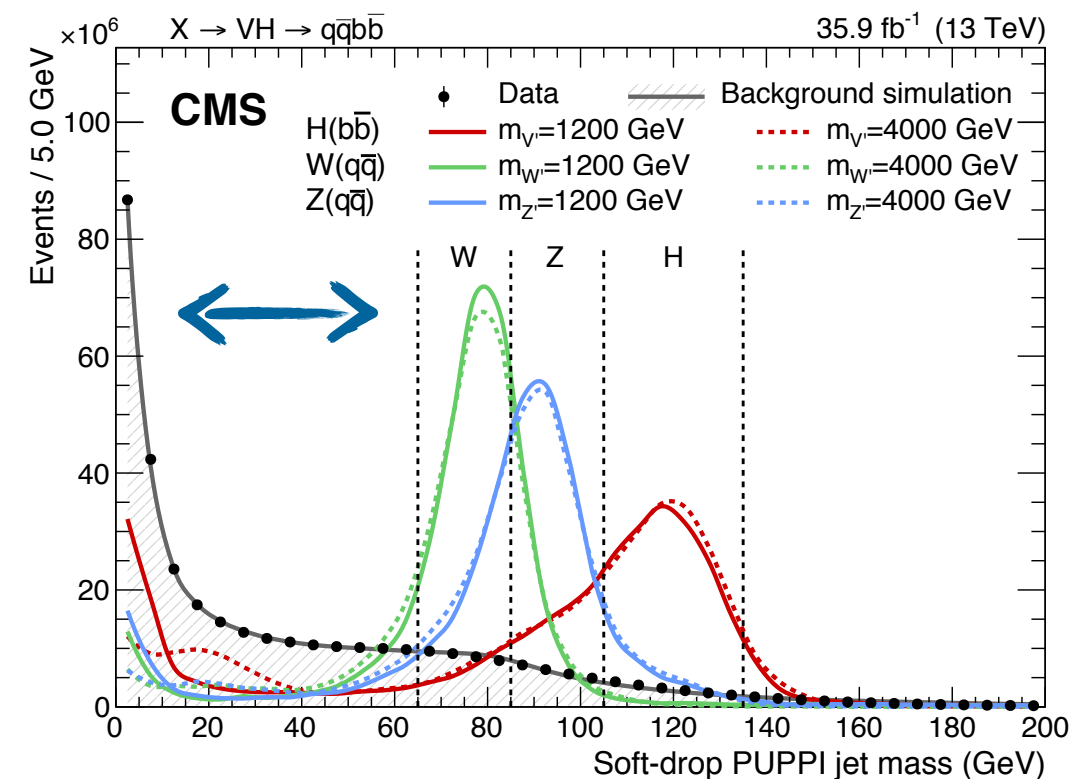
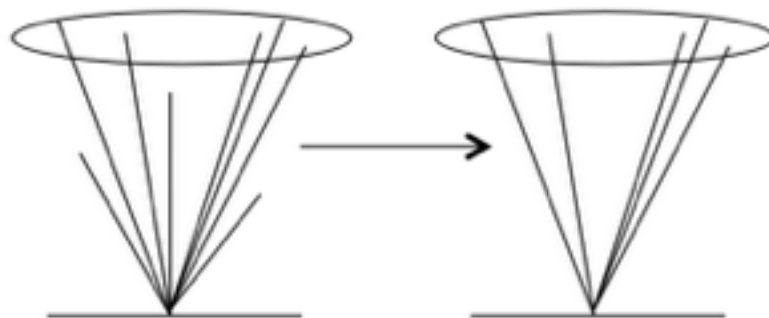
- attempts to remove from the jets those constituents that are unlikely to be associated with the jet
- removes soft and wide angle radiation

## Soft-Drop

JHEP 05 (2014) 146 1

detector and data handling

more details in  
**Mauro Verzetti's** talk



# Boosted topologies and jet substructures



PhysRevD 81 094023, JHEP 05 (2014) 146 1, arXiv 1707.01303

- VLQs expected to appear at the **TeV scale**

▶ their

*in this talk focus on the very latest results with full 2016 luminosity*

NEW

Single B,  $B \rightarrow bH$  all hadronic  
CMS-PAS-B2G-17-009

Single T,  $T \rightarrow tZ$  (II)  
CMS-PAS-B2G-17-007

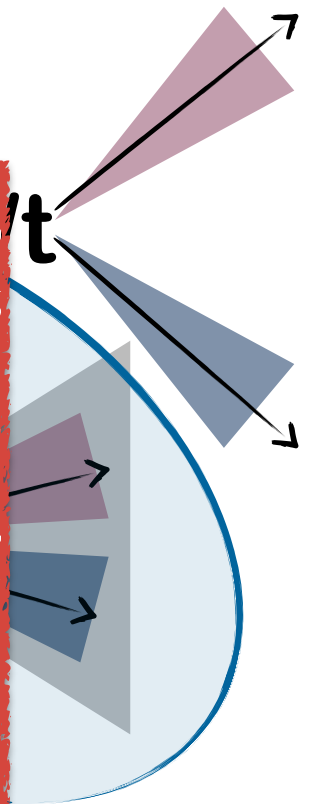
Pair T/ $Y_{-4/3}$ ,  $TT/Y_{-4/3}Y_{-4/3}$  in lepton + jets  
CMS-PAS-B2G-17-003

Pair  $X_{5/3}$ ,  $X_{5/3}X_{5/3} \rightarrow tWtW$ , single lepton  
CMS-PAS-B2G-17-008

Pair  $X_{5/3}$ ,  $X_{5/3}X_{5/3} \rightarrow tWtW$ , same sign leptons  
CMS-PAS-B2G-16-019

NEW

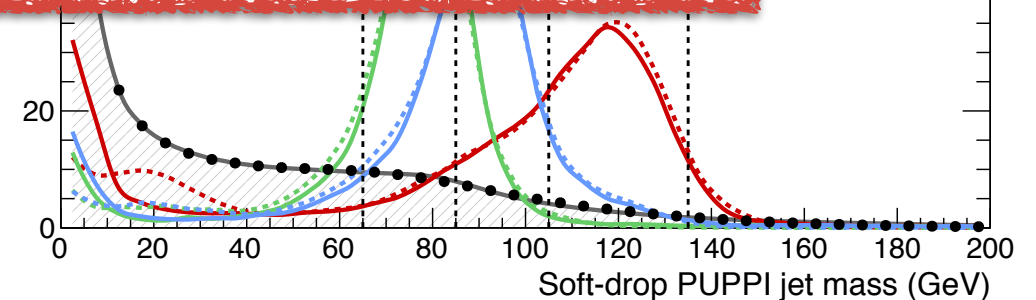
excited quarks,  $q^*/b^*$  in photon + jet  
CMS-PAS-EXO-17-002



35.9 fb<sup>-1</sup> (13 TeV)  
bound simulation  
 $m_V=4000$  GeV  
 $m_W=4000$  GeV  
 $m_Z=4000$  GeV

detector and data

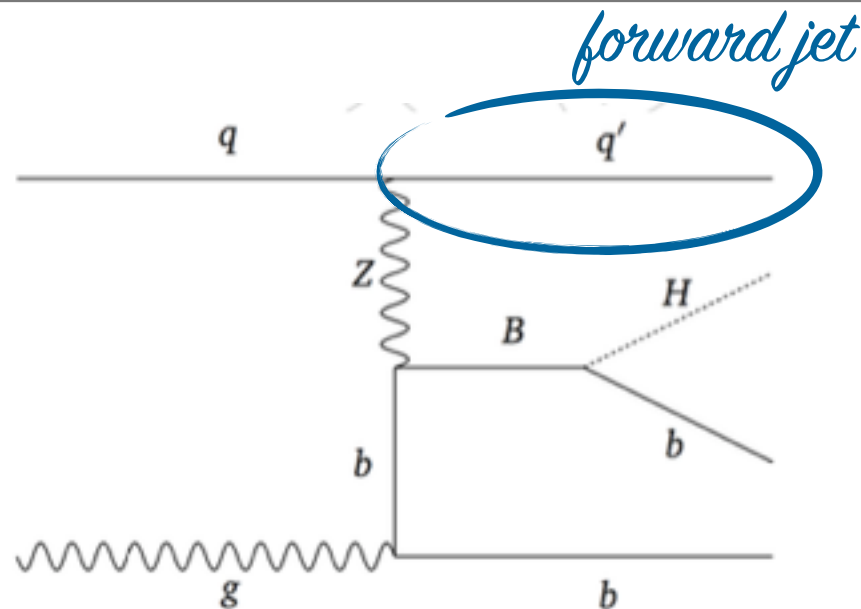
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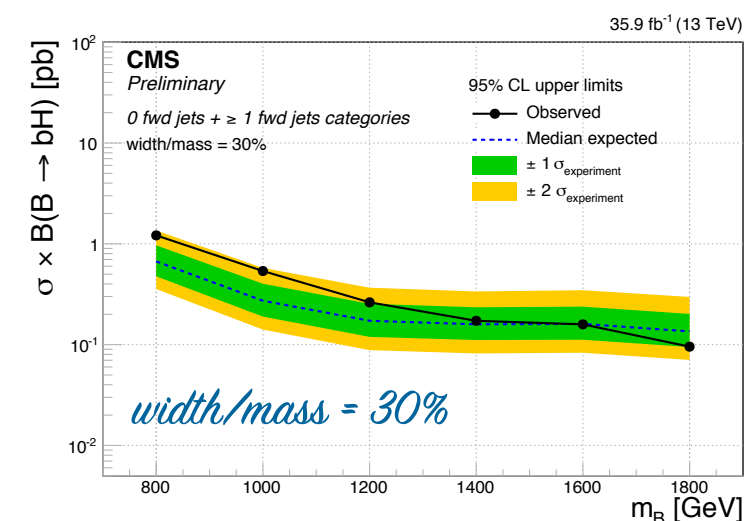
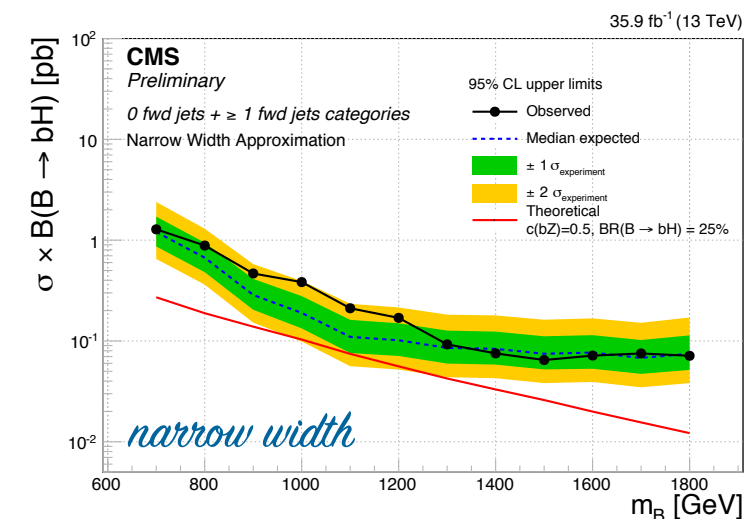
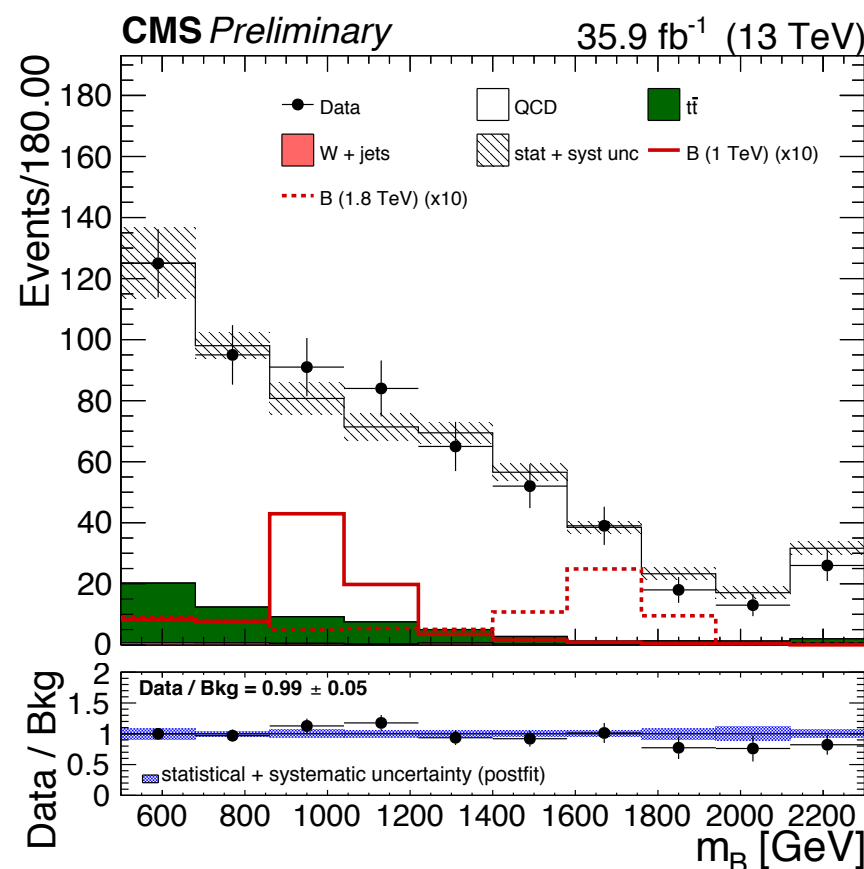
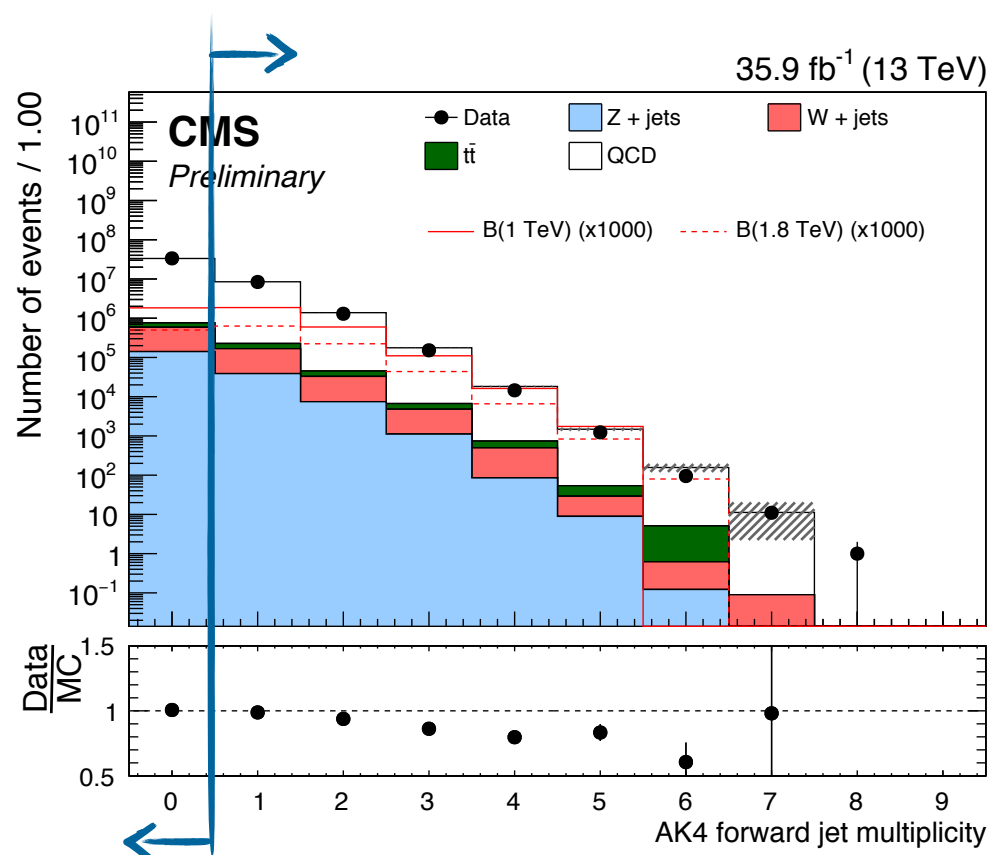


# Single B, $B \rightarrow bH$ all hadronic **NEW**

CMS-PAS-B2G-17-009

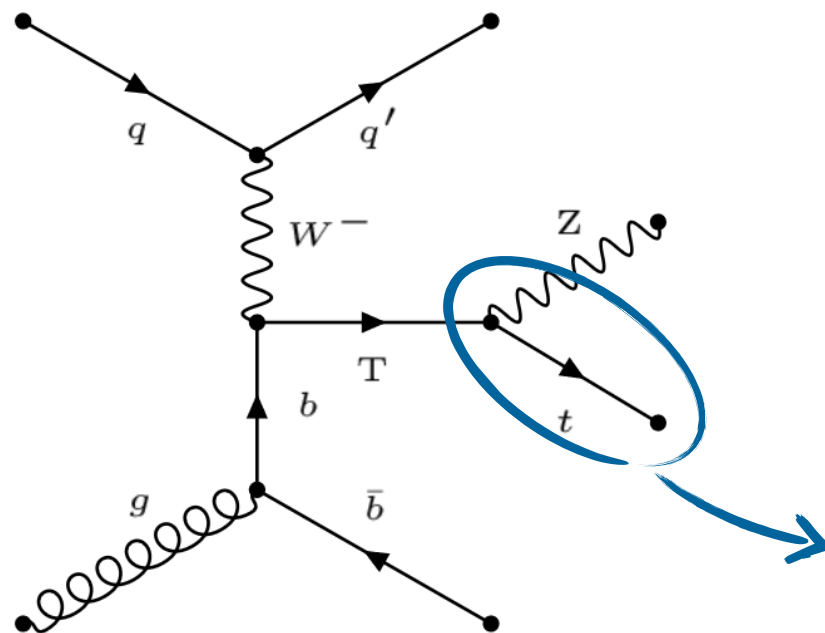


- hadronic activity used to reduce QCD multijets
  - ▶ two different selections applied, to optimize sensitivity in the whole B mass spectrum
- 2 categories based on the **forward jets multiplicity**
- **data-driven background** using signal depleted regions
- searching for an bump in the invariant  **$m(bH)$**  distribution
- **several resonance width/mass** scenarios investigated

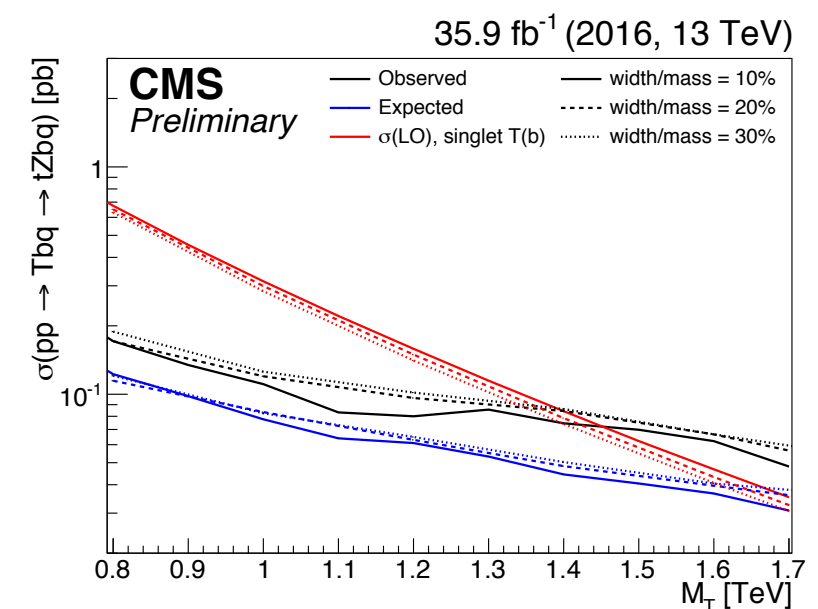
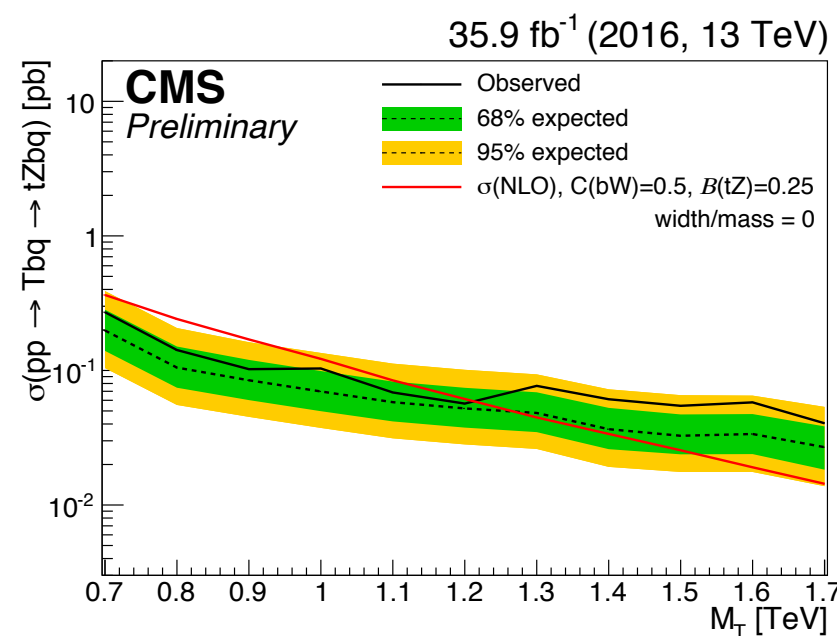
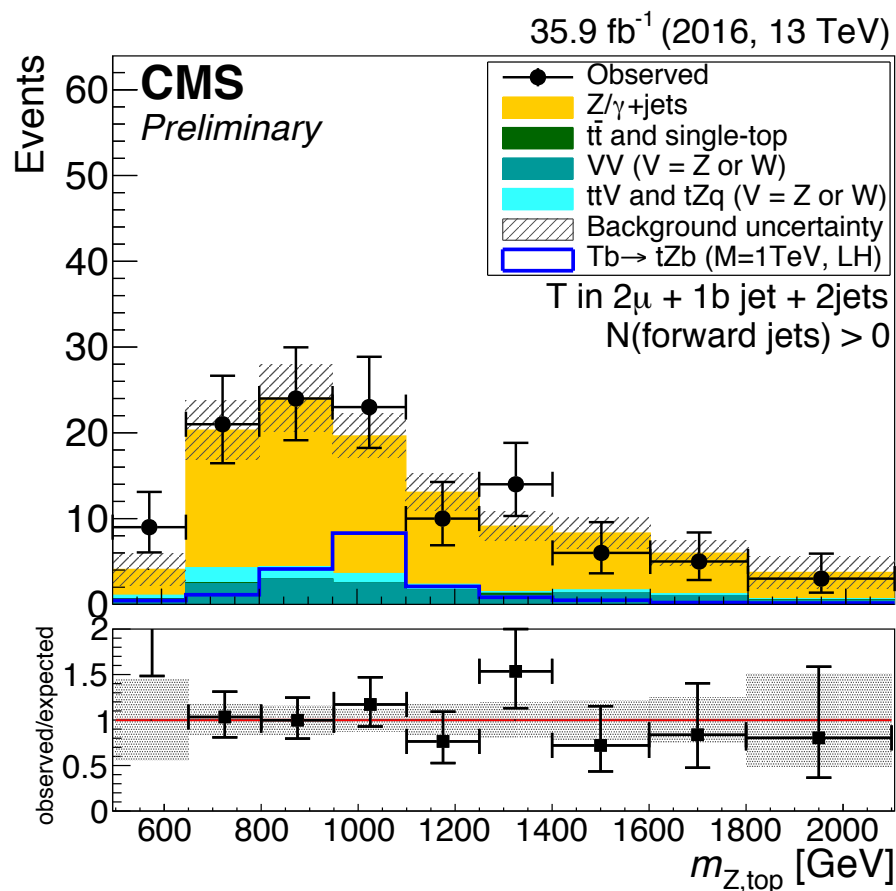
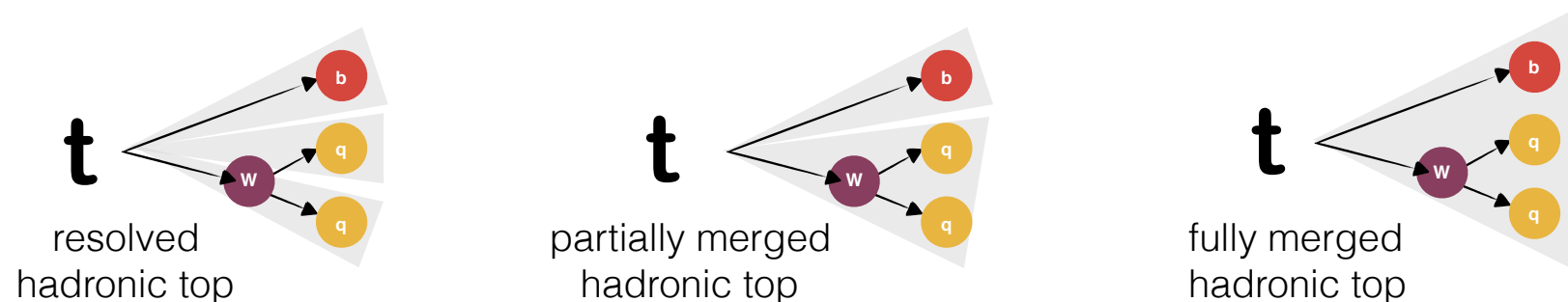


# Single T, $T \rightarrow tZ$ (II)

CMS-PAS-B2G-17-007



- leptonic Z decay and hadronic top
- categories based on the **forward jets multiplicity and t/W tag**
- searching for an excess in the  **$m(tZ)$**  distribution
- **data-driven background** in a b-jets depleted region
- **several resonance width/mass** scenarios investigated



**$M_T > 1.2$  TeV @ 95 % C.L.,  $C_{bW} = 0.5$ , BR ( $T \rightarrow tZ$ ) = 25%**

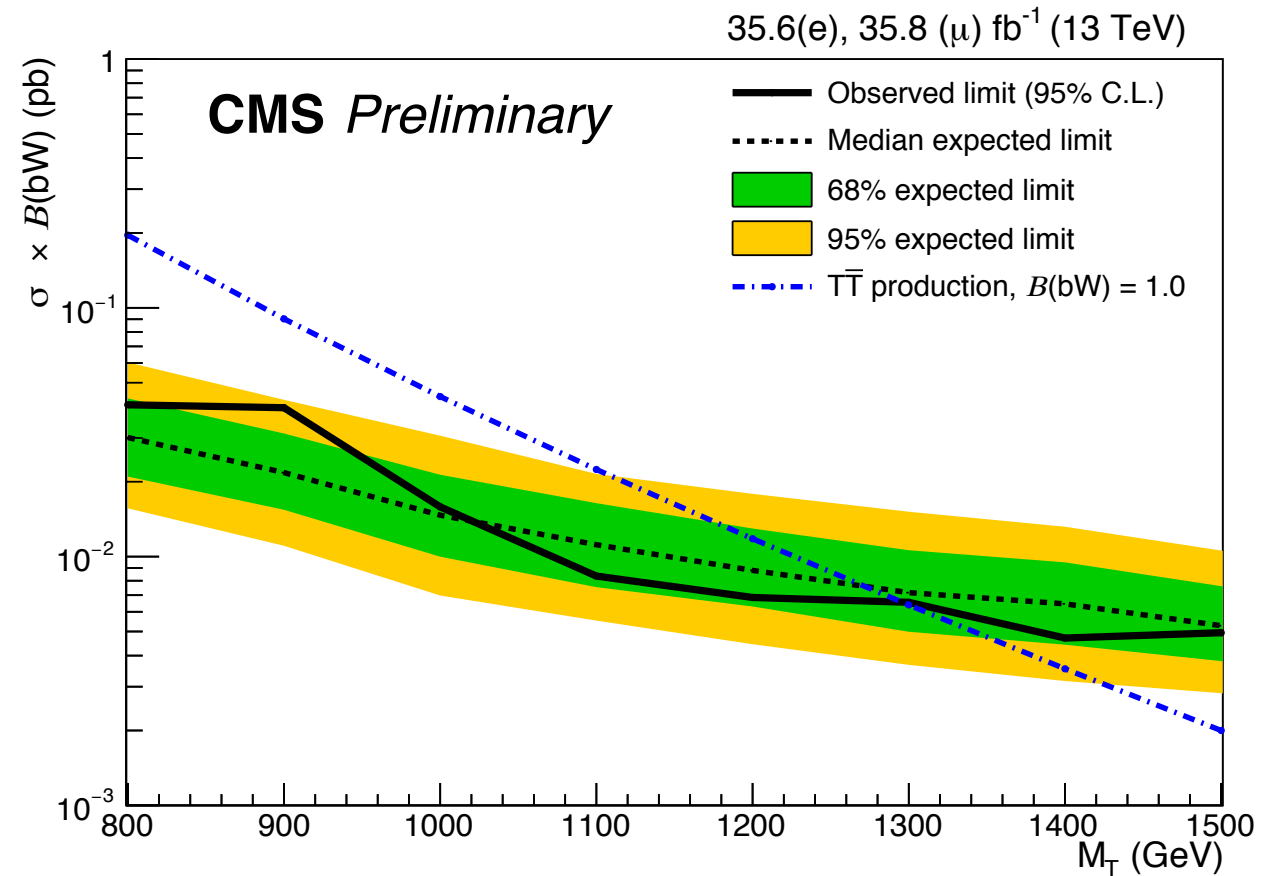
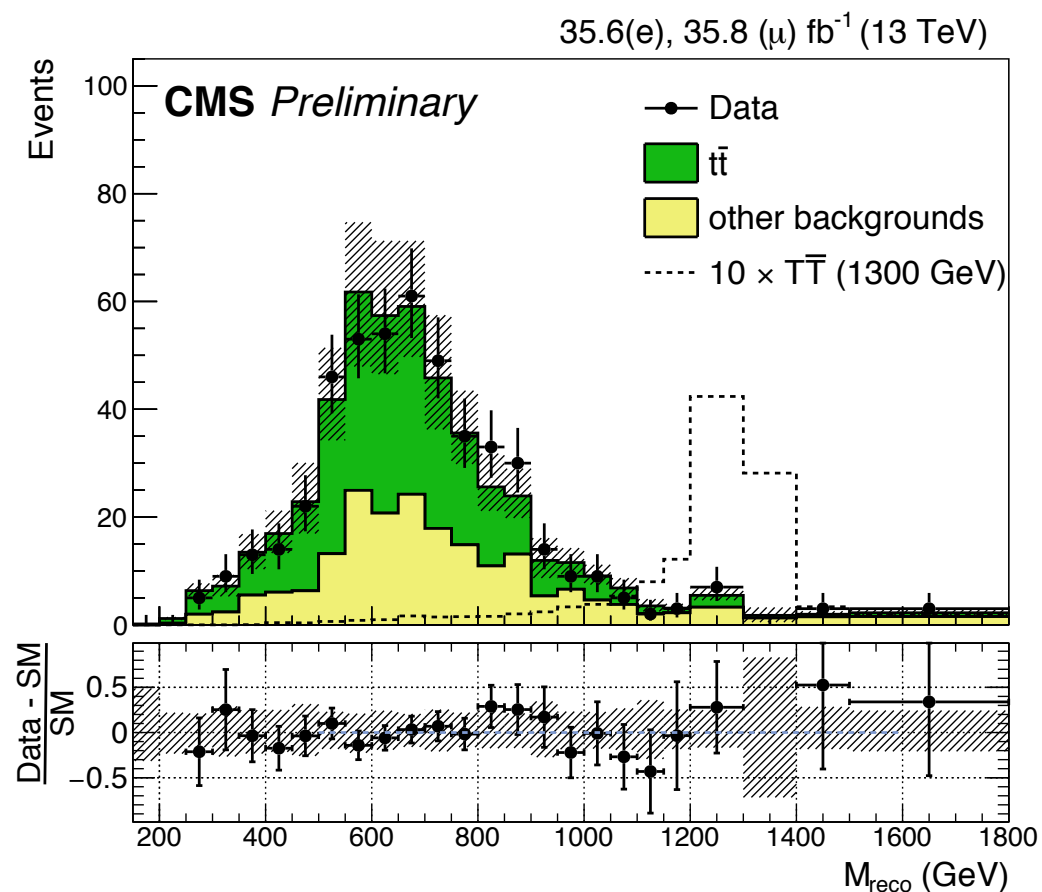
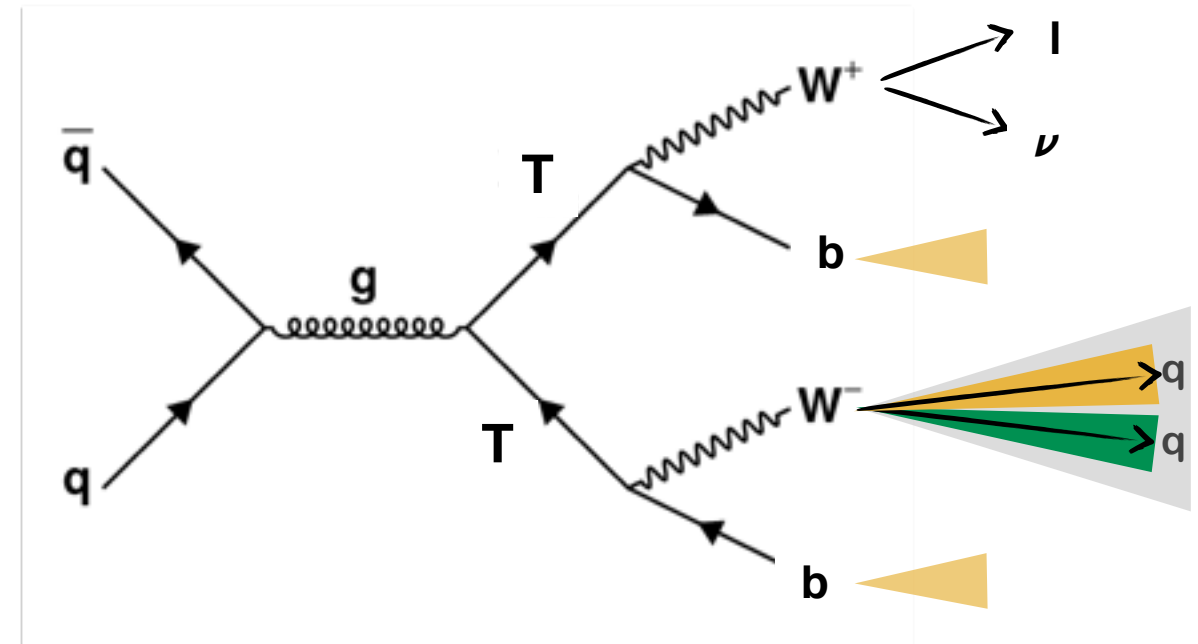
# Pair $T/Y_{-4/3}$ , $TT/Y_{-4/3}Y_{-4/3}$ in lepton + jets

CMS-PAS-B2G-17-003



- focus on  **$WbWb$  decays**, with single lepton, MET and number of jets  $\geq 4$
- a **kinematic fit** performed to fully reconstruct the final state kinematic and obtain the  $T$  mass

**$M_T > 1.375$  TeV @ 95% C.L.**  
**BR ( $T \rightarrow Wb$ ) = 100%**



# Pair $X_{5/3}$ , $X_{5/3}X_{5/3} \rightarrow tWtW$

CMS-PAS-B2G-17-008 CMS-PAS-B2G-16-019

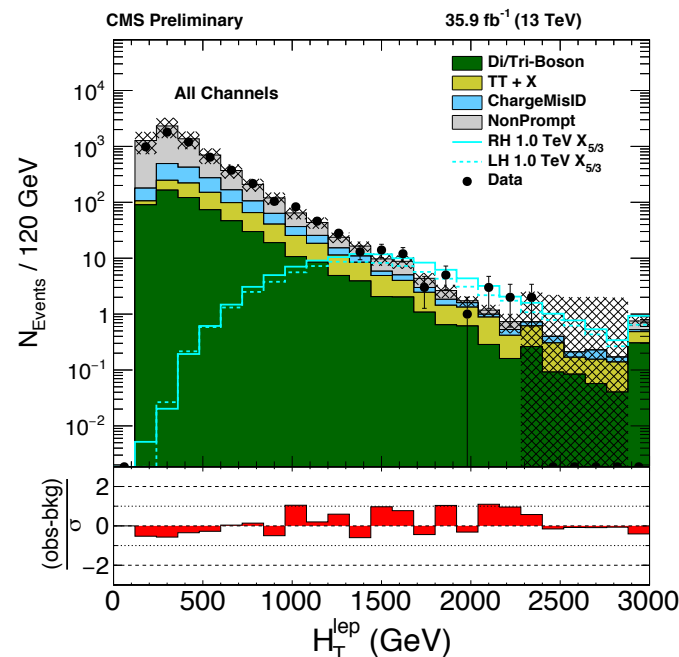
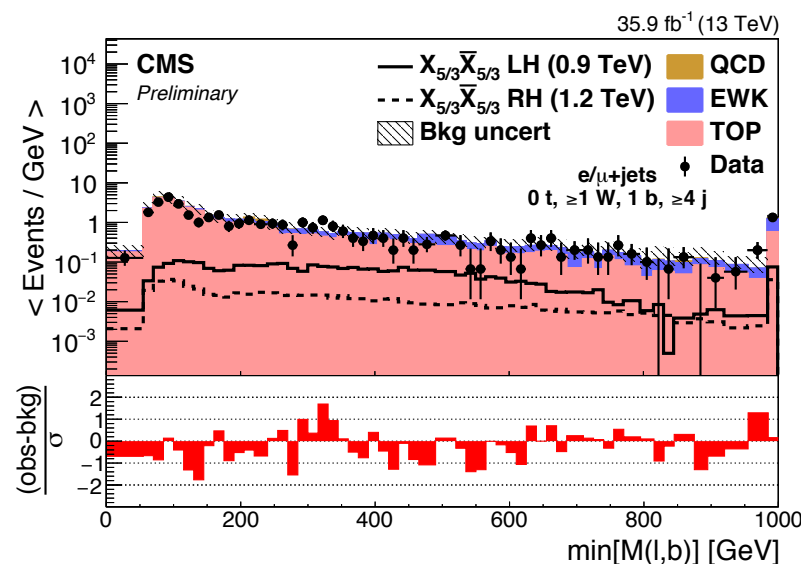
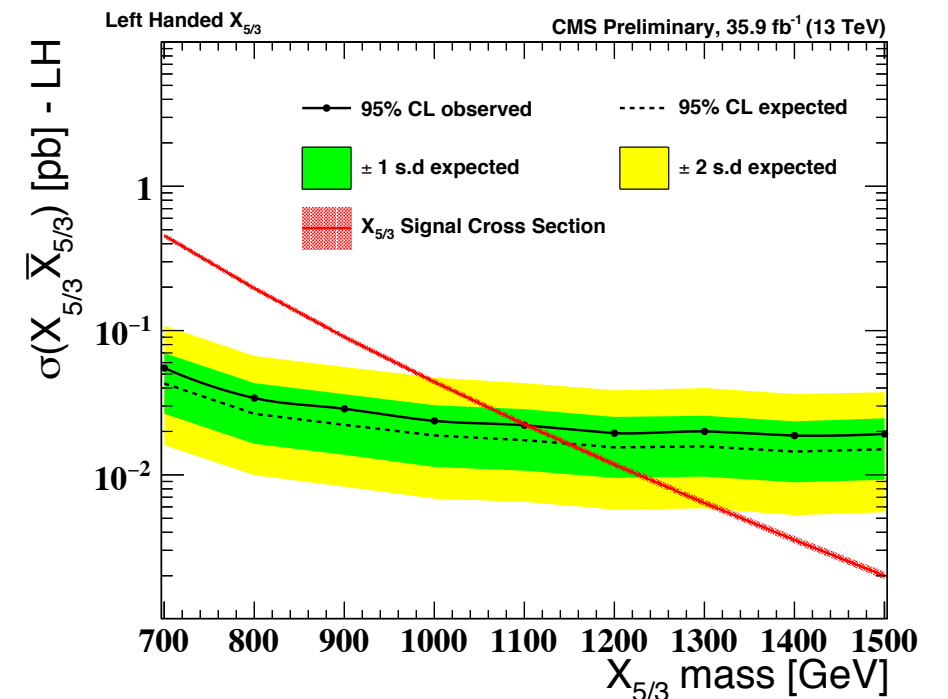
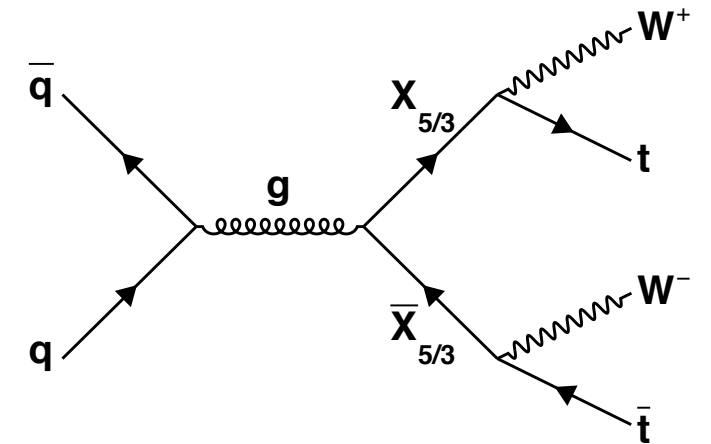


## single lepton + jets

- 1 lepton+jets,  $\geq 1$  b-tag
- 16 categories based on **W-tagged and t-tagged jet** multiplicity
- key variable is the **min(M<sub>lb</sub>)**
- MC modeling validated in **signal depleted regions**

## same-sign leptons + jets

- 2 SS leptons + jets or 3 leptons + jets
- **H<sub>T,lep</sub>**: scalar sum of the jets and leptons p<sub>T</sub>
- backgrounds:
  - ▶ same-sign prompt leptons from **simulation**
  - ▶ opposite-sign prompt leptons and same-sign events from a fake lepton estimate **from data**



**$M_X > 1.30$  LH (1.32 RH) TeV (SL)**  
 **$M_X > 1.16$  LH (1.10 RH) TeV (SSL)**  
**@ 95 % C.L.**  
**BR ( $X \rightarrow tW$ ) = 100%**



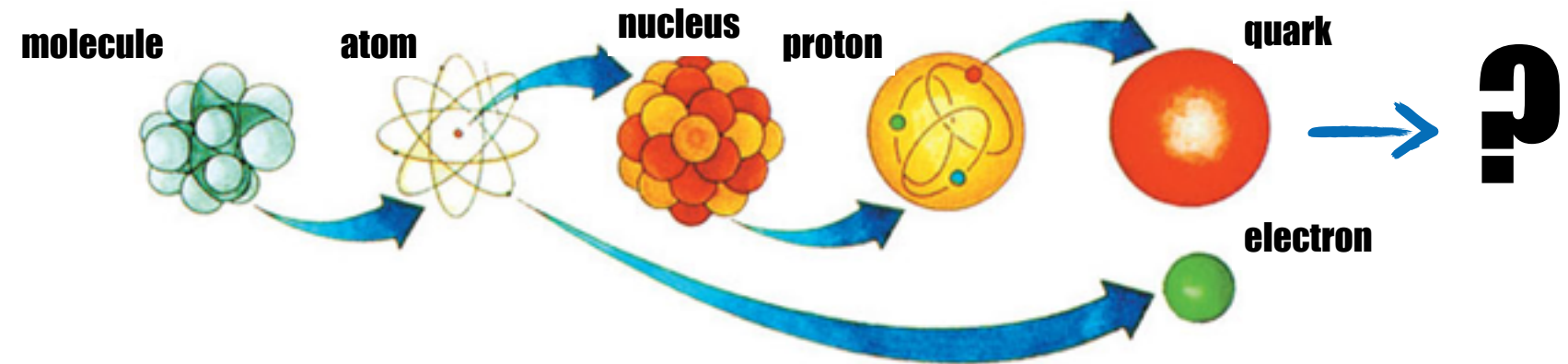
# Motivation and phenomenology, $q^*$

Int. J. Mod. Phys. A 2 (1987) 1285, Phys. Rev. D 42 (1990) 815–824



## Compositeness model

- excited states  $q^*$  would be a clear signature of composite structure
- $m^*$  expected at the TeV scale



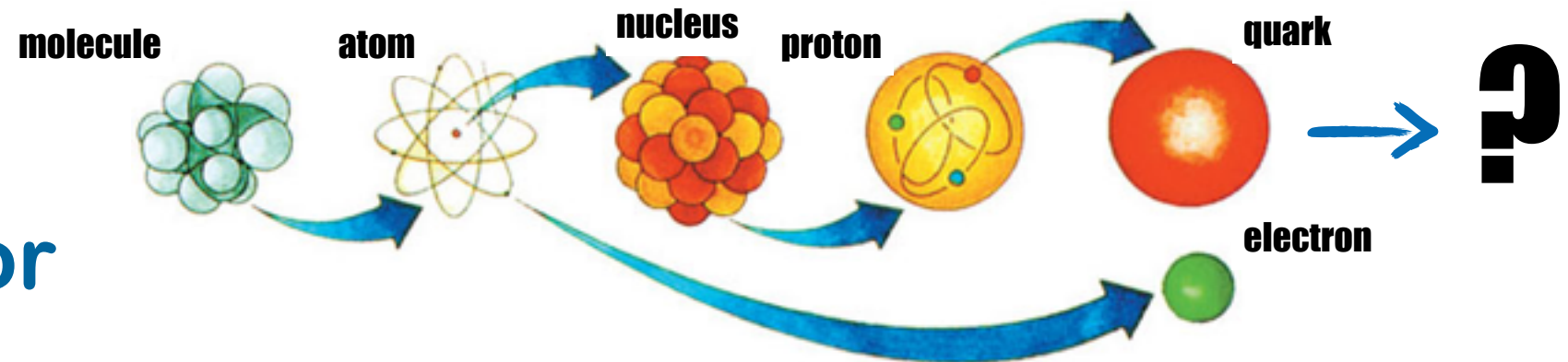
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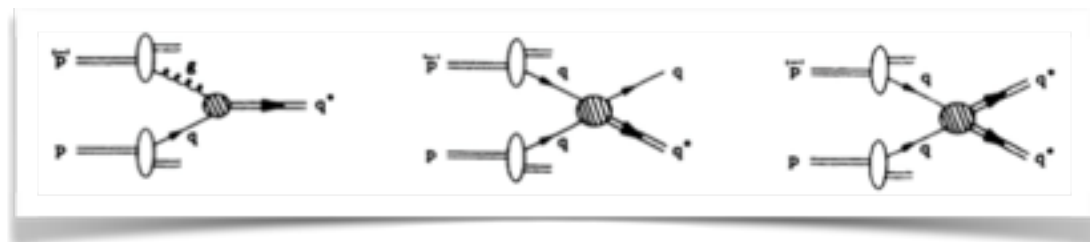
- excited states  $q^*$  would be a clear signature of composite structure
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how can we look for them at the LHC?

## production

- either produced **singly or pair-wise**
- can occur through
  - quark-antiquark annihilation and gluon-gluon fusion
  - gluonic excitation of quark

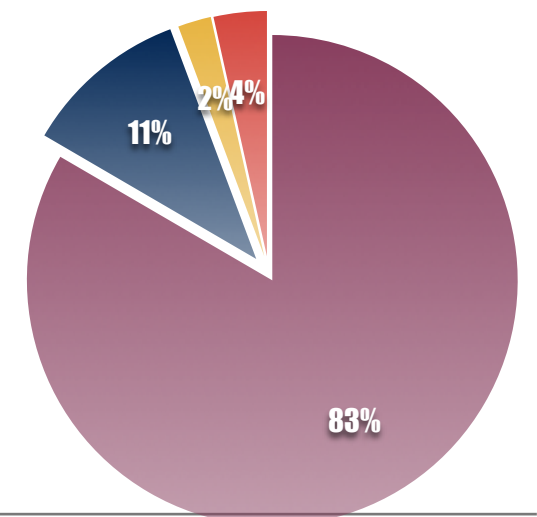


## decay

- predominant decay ordinary quarks and gluons ( $q^* \rightarrow qg$ )
- radiative transitions and decays into a weak boson also possible

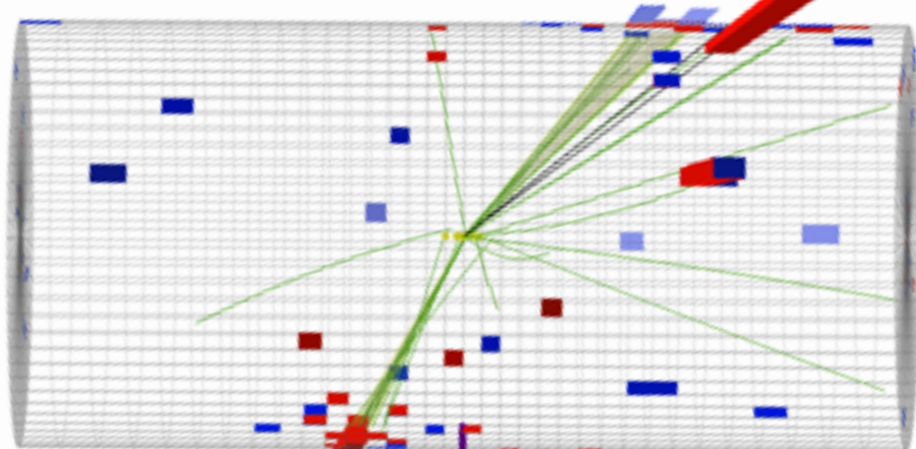


pie chart for  $u^*$  decay  
(for  $f_S=f_V'$  and  $\alpha_S=0.1$ )



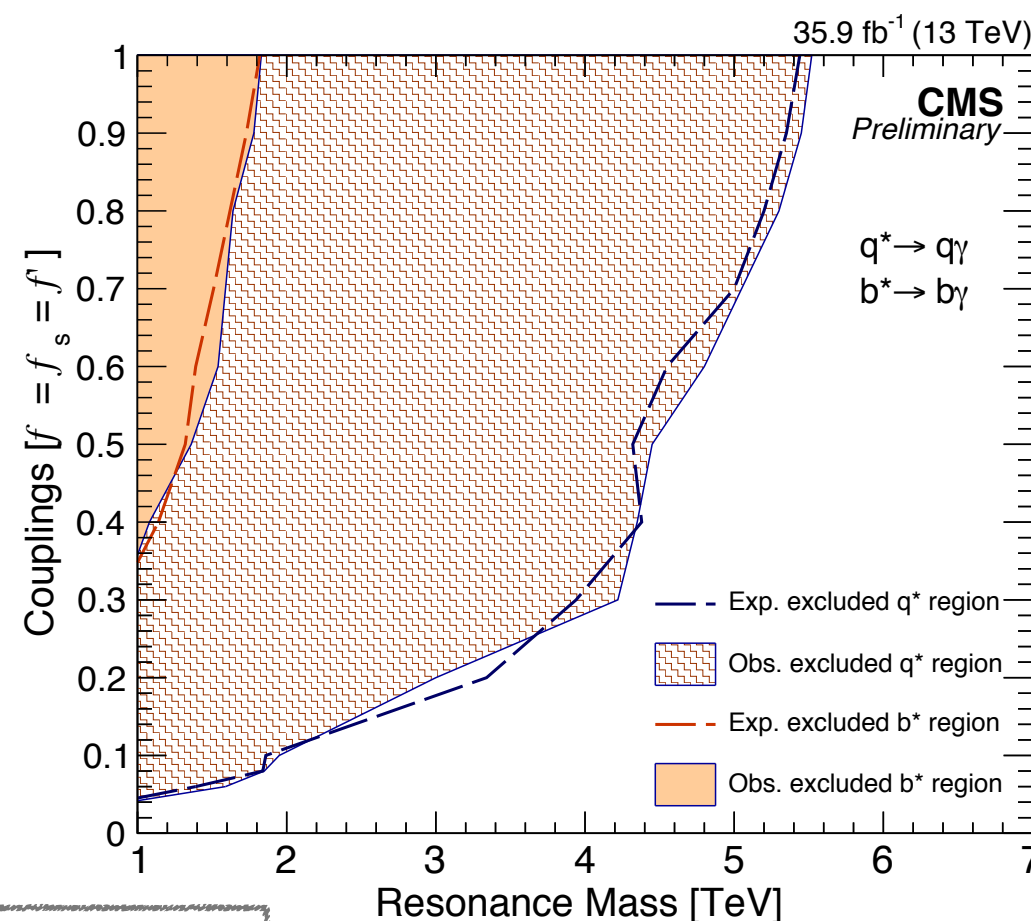
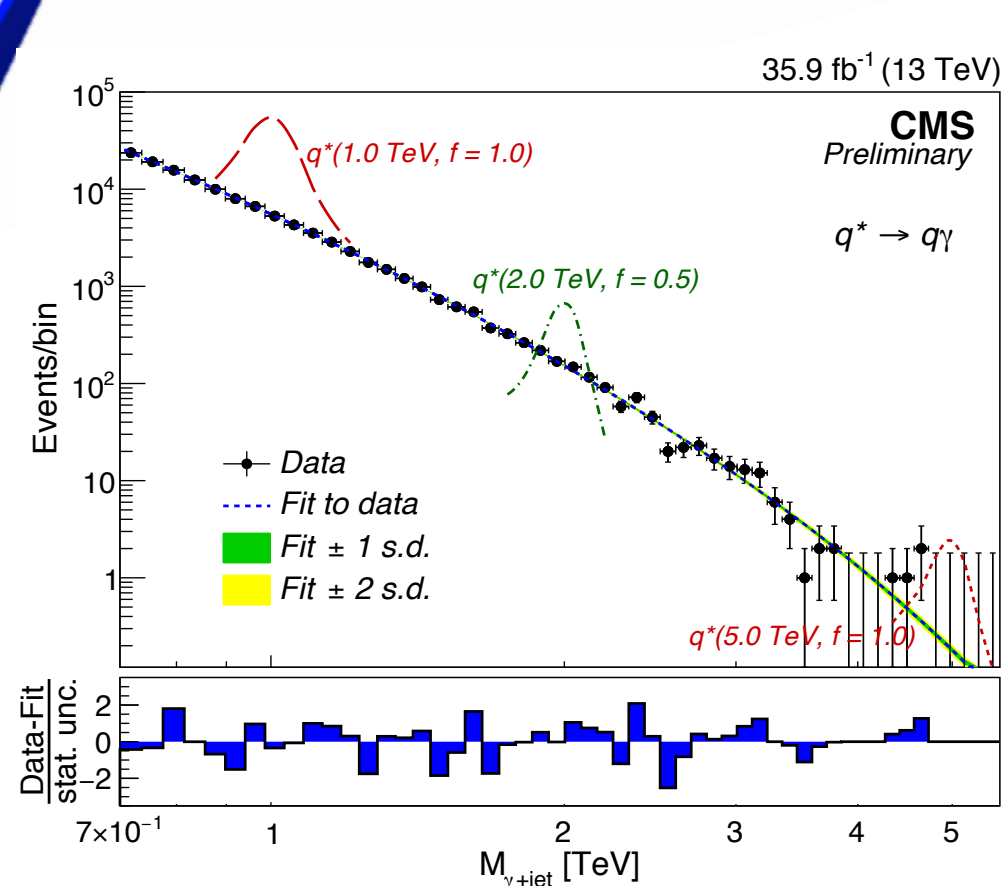
# excited quarks, $q^*/b^*$ in photon + jet **NEW**

CMS-PAS-EXO-17-002



- **bump-hunt** in the  $\gamma$  + jet mass spectrum
- **angular selections** between  $\gamma$  and the jet to reduce background
- main backgrounds are Compton scattering, quark-antiquark annihilation, predicted **from simulation**

$M_{q^*} > 5.52 \text{ TeV}$ ,  $M_{b^*} > 1.83 \text{ TeV}$  @ 95% C.L.



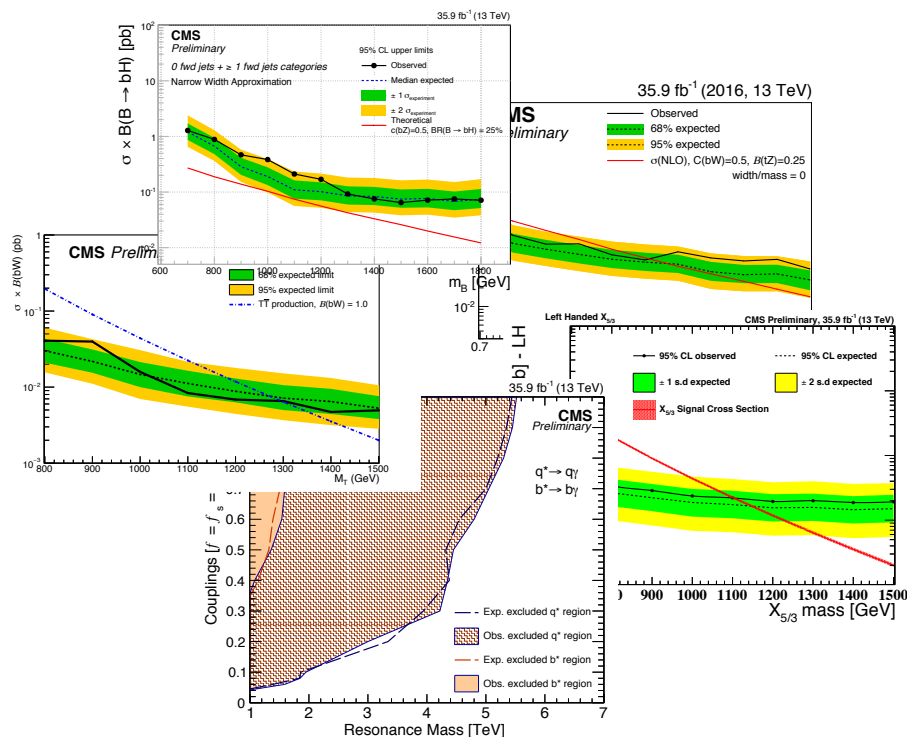
- dedicated search for  $t^*$ , see **Johannes Haller's** talk
- dijet analysis in **Federico Preiato's** talk

Higgs and new physics

# Summary and outlook



- **Successful and wide search program** conducted by CMS
  - ▶ many new searches using singly-produced VLQs
  - ▶ improvements in the boosted techniques
  - ▶ major focus on the analyses with full 2016 data, but other interesting results available at 13 TeV

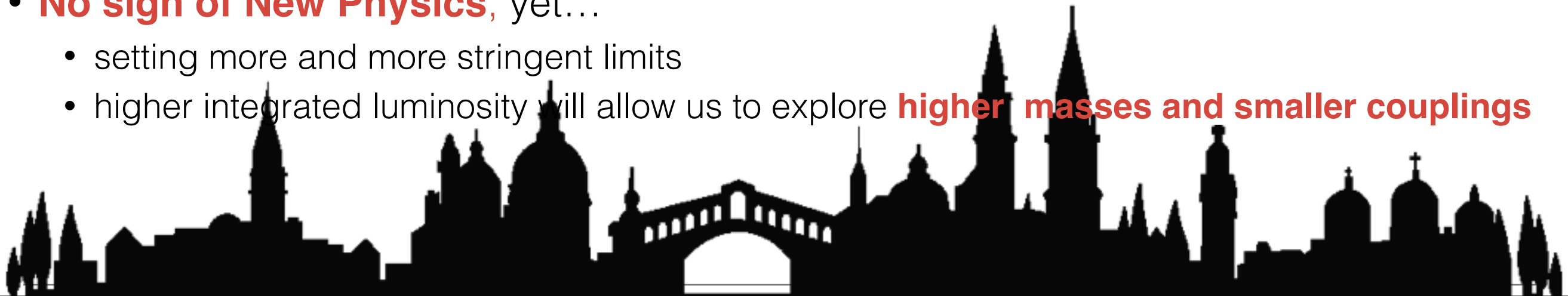


+

- B2G-16-001: Search for T, B in decays to leptonic Z final states
- B2G-16-005: Search for single production of T'->tH in hadronic final state
- B2G-16-006: Search for singly-produced Vector-like Quarks decaying to Wb, semi-leptonic channel
- B2G-15-008: Search for single production of T'->tH with a lepton and Higgs tag
- B2G-16-002: Search for VLQ pair production in leptonic final states
- B2G-16-011: Search for T pair production decaying to boosted tH in leptonic final states at 13 TeV
- B2G-16-024: Search for pair production of vector-like T quarks in leptonic final states at 13 TeV

- **No sign of New Physics**, yet...

- setting more and more stringent limits
- higher integrated luminosity will allow us to explore **higher masses and smaller couplings**





*Thanks for your attention!*



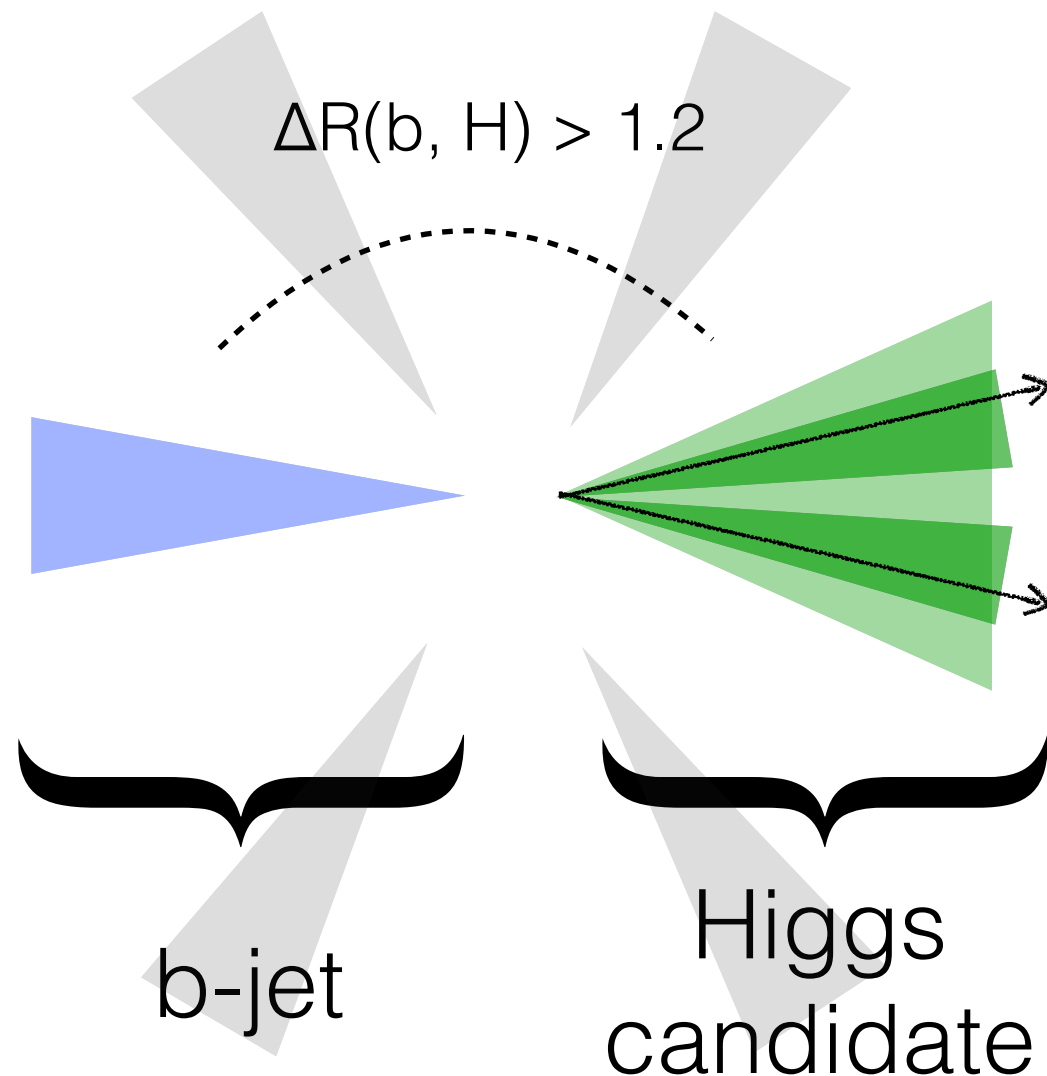
*Supporting Material*

*B2G-17-009*



## Online Selection

- $H_T > 950$  GeV
- $p_T > 450$  GeV



## Preselection

- at least one large-cone jet
- at least three narrow jets
- at least one jet has to come from the hadronization of a b quark
- lepton veto

## Hadronic Activity

- $H_T > 950$  GeV (low mass analysis)
- $H_T > 1250$  GeV (high mass analysis)

## Higgs tagging

- pruned mass in  $[105, 135]$  GeV
- 2 b-tagged subjets

## B' reconstruction

- at least 1 medium AK4
- $\Delta R(b, H) > 1.2$



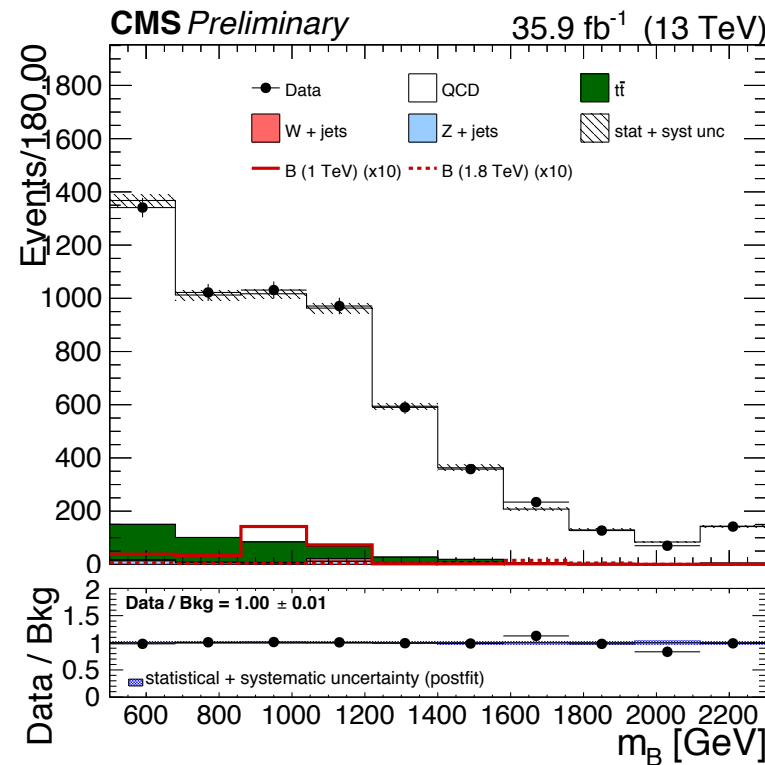
# B2G-17-009: event yields

category	source	low mass yields	high mass yields
zero forward jets category	$t\bar{t}$	$394 \pm 46$	$117 \pm 18$
	W + jets	$29 \pm 13$	$10.5 \pm 4.3$
	Z + jets	$43 \pm 15$	$23 \pm 23$
	Multijet	$5416 \pm 60$	$1612 \pm 24$
	Backgrounds	$5882 \pm 42$	$1762 \pm 26$
	Data	$5886 \pm 77$	$1753 \pm 42$
	$m_B = 1000 \text{ GeV}$	$29.3 \pm 1.1$	$7.07 \pm 0.53$
	$m_B = 1800 \text{ GeV}$	$4.88 \pm 0.15$	$4.12 \pm 0.14$
at least one forward jet category	$t\bar{t}$	$163 \pm 20$	$58 \pm 17$
	W + jets	$11.5 \pm 4.2$	$4.3 \pm 1.4$
	Z + jets	$2 \pm 10$	$0.0 \pm 0.0$
	Multijet	$1938 \pm 23$	$549 \pm 10$
	Backgrounds	$2115 \pm 21$	$612 \pm 15$
	Data	$2107 \pm 46$	$608 \pm 25$
	$m_B = 1000 \text{ GeV}$	$46.4 \pm 1.4$	$8.51 \pm 0.58$
	$m_B = 1800 \text{ GeV}$	$9.29 \pm 0.21$	$7.78 \pm 0.19$

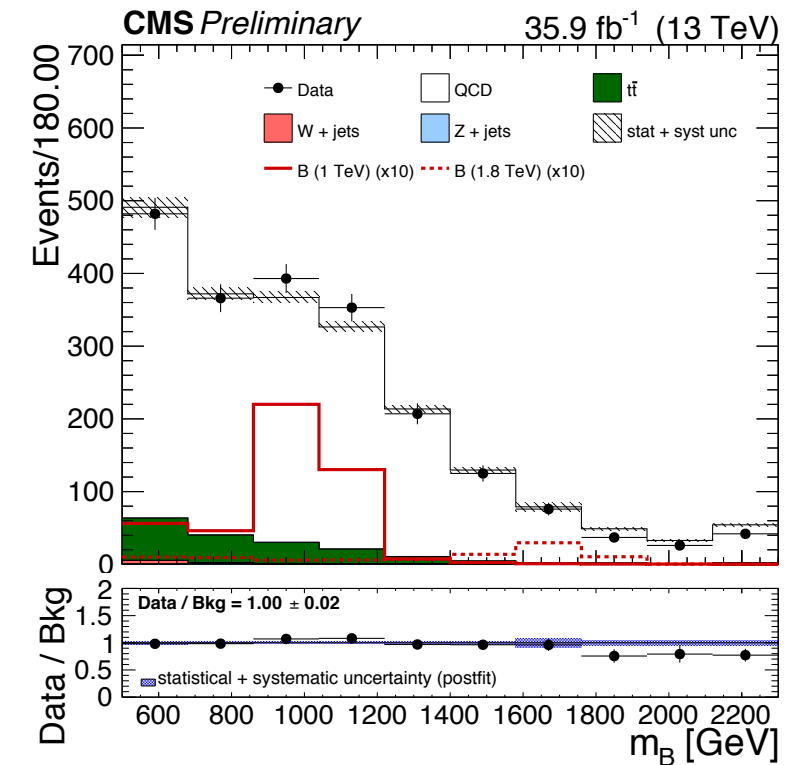
# B2G-17-009: post-fit final distributions



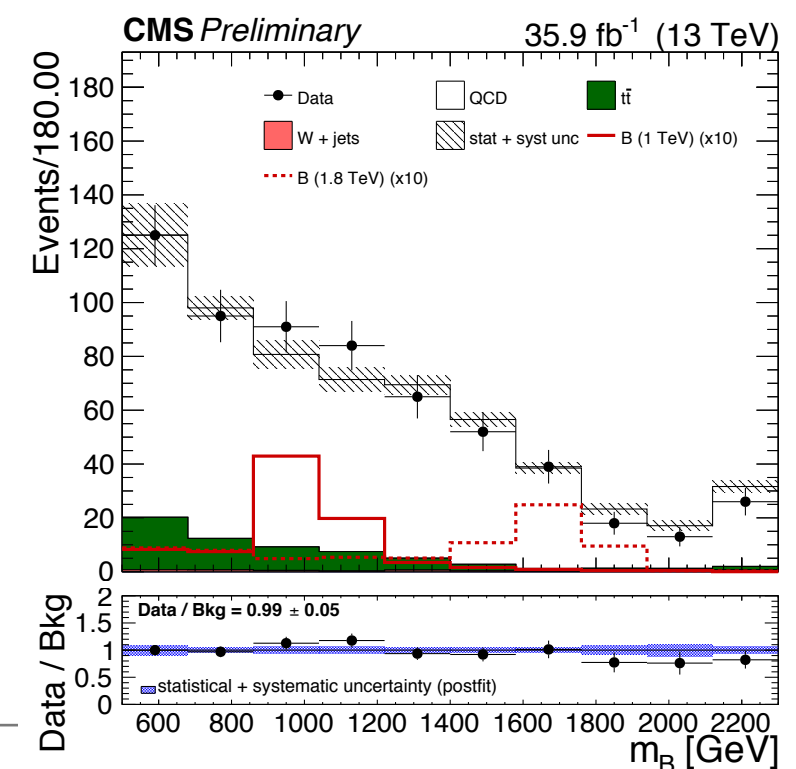
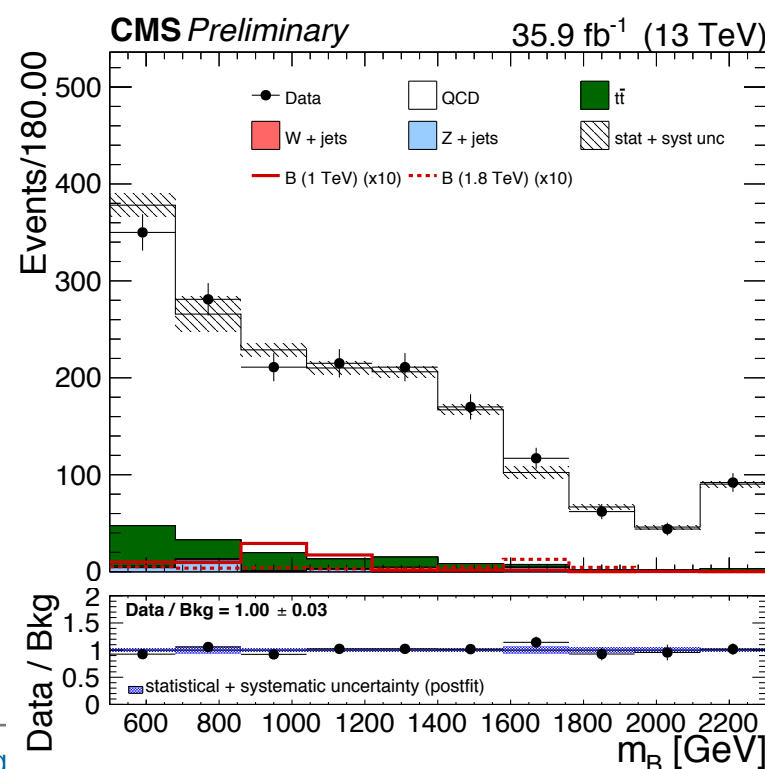
**cat 0**



**cat 1**



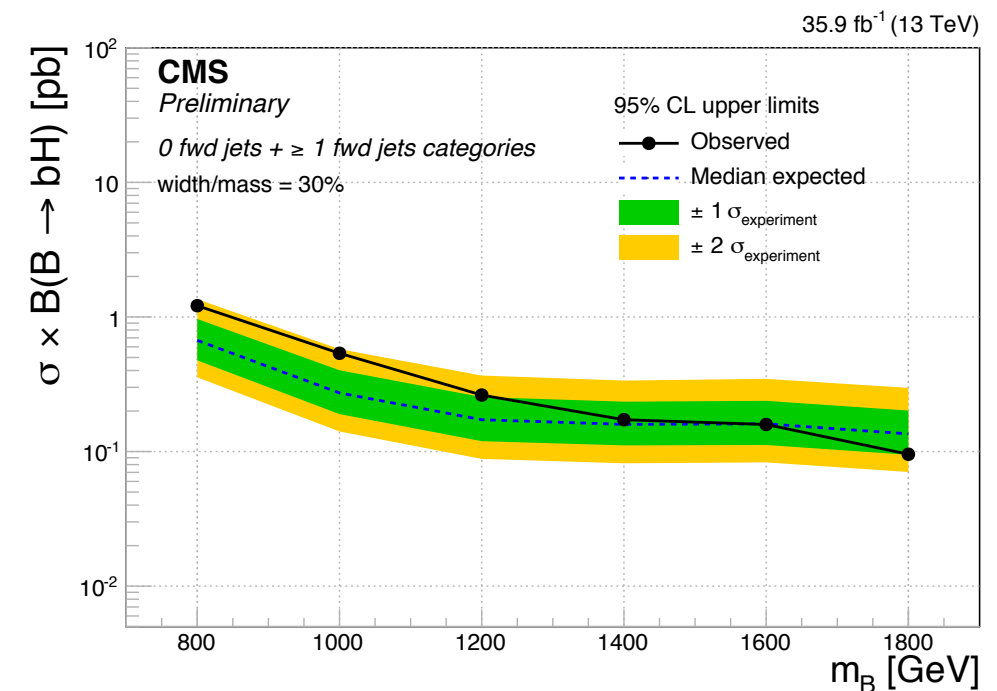
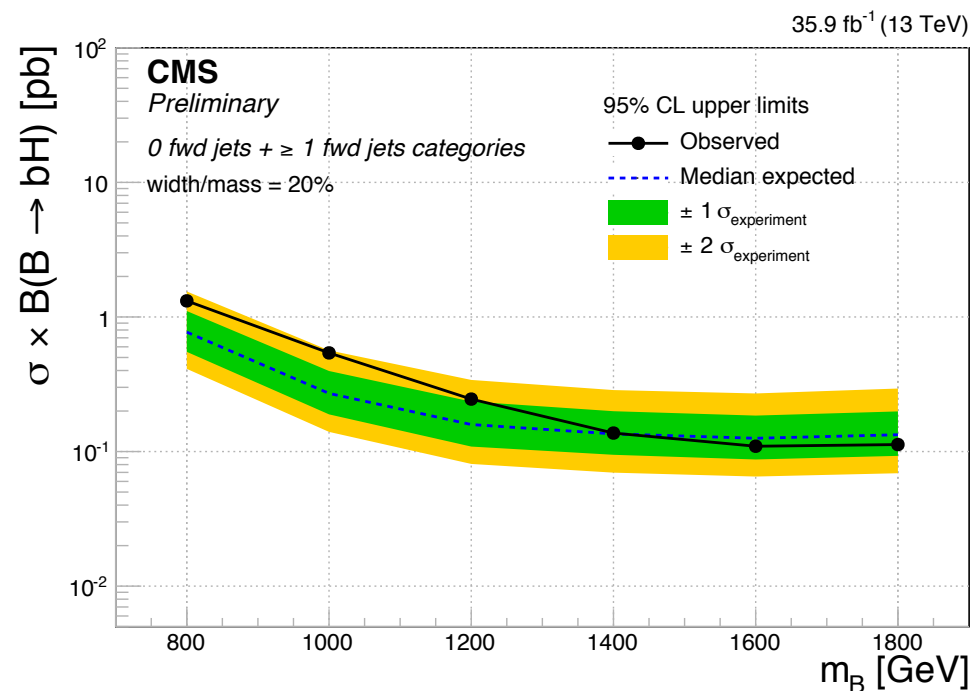
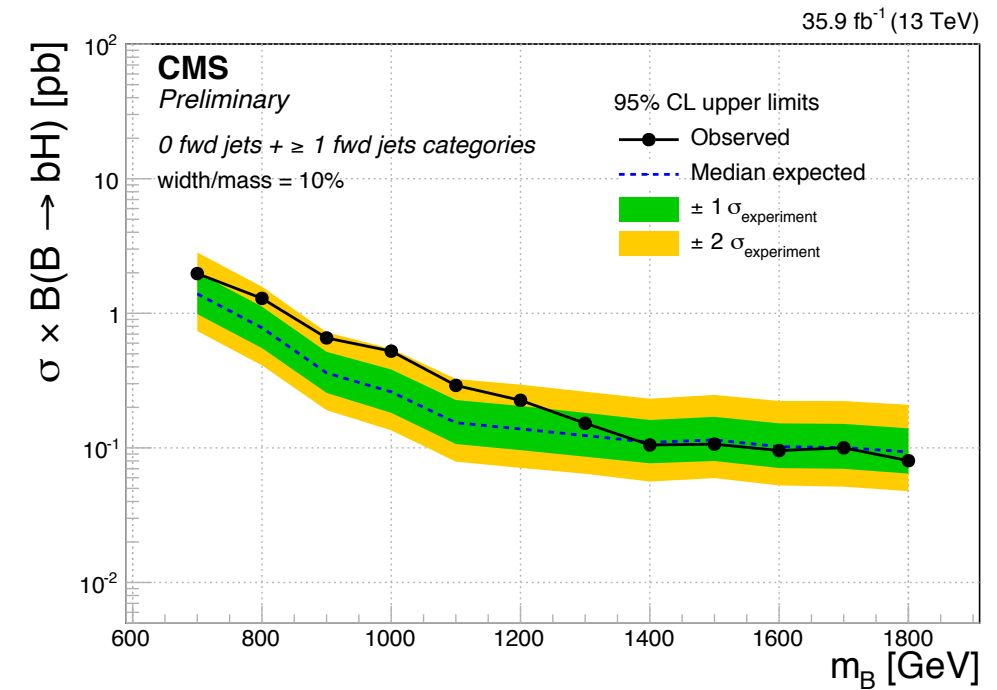
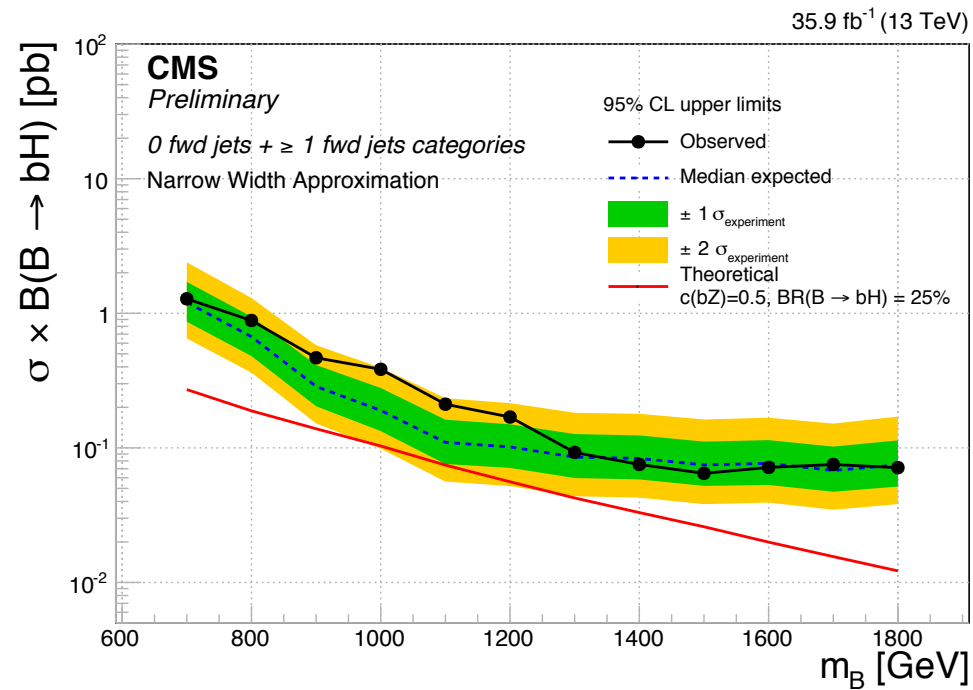
**low  
mass**



**high  
mass**

- post-fit distributions in:
  - forward jets based categories
  - low and high mass regions (depending on the hadronic activity selection)

# B2G-17-009: upper limits

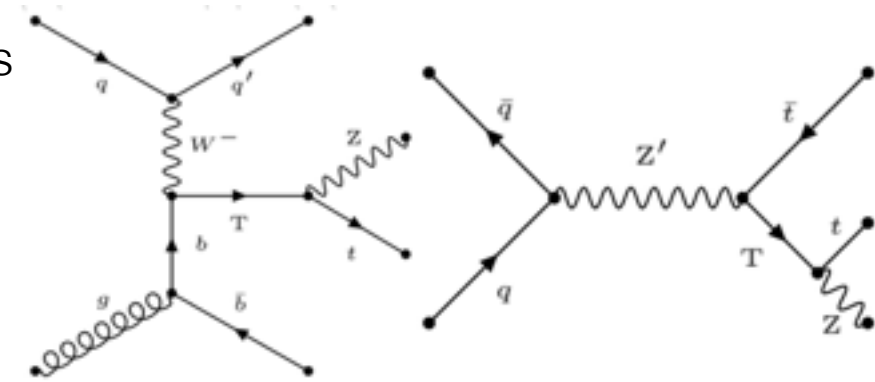


*B2G-17-007*



# B2G-17-007: intro & selection

- background dominated by Z+jets events (above 80%), with smaller contributions from other backgrounds ( $t\bar{t}+V$ ,  $tZq$ ,  $t\bar{t}$ , single  $t$ , and SM diboson production)
- large improvement in the T search sensitivity is found when compared with the previous results (increase in the size of the data set and improvements to the analysis, including categorizing according to the presence of forward jets and analysis of the mass distribution in events with top jets)
- first analysis of the effect of a non-negligible resonance width



## online selection

- Events with a Z boson decaying to muons are selected online, requiring the presence of an isolated muon with  $p_T > 24$  GeV. Events with the Z boson decaying to electrons are selected online if an electron with  $p_T > 115$  GeV is reconstructed.

## offline selection

- Electrons and muons selected with  $p_T > 20$  GeV and  $|\eta| < 2.5$  (2.4), leading electron  $p_T > 120$  GeV
- lepton isolation applied to reduce backgrounds where one hadronic jet is misidentified as a lepton (0.4 (m) - 0.3 (e))
- AK4 (AK8) jets  $p_T > 20$  (180) GeV and  $|\eta| < 2.4$
- W tagging: pruned jet mass is within 65–105 GeV and  $N$ -subjettiness  $\tau_{21} = \tau_2/\tau_1$  is less than 0.6
- top tagging:  $p_T > 400$  GeV, mass of the jet reconstructed with the modified mass drop tagger algorithm [45, 46] between 105 and 220 GeV, and  $\tau_{32} = \tau_3/\tau_2$  less than 0.81
- AK4 jets can be tagged as coming from a b quark using the combined secondary vertex algorithm. A “medium” (loose) working point with efficiency of 70% (85%) on real b jets and rejection of 99% (90%) of light-flavour jets is used
- two muons or two electrons forming a Z boson candidate with an invariant mass between 70 and 110 GeV
- one Z, one top quark and at least one b-jet
- the two leptons from the Z boson decay have to be close to each other ( $\Delta R < 0.6$ –1.4, depending on the category)
- in the resolved categories two of the three jets forming the t jet, i.e. the ones with the lowest b tagging discriminant, are required to have an invariant mass below 200 GeV

A  $t$  quark from a  $T$  quark decay can be identified in three different scenarios: fully merged (a  $t$  quark jet is identified), partially merged (a  $W$  jet and a  $b$  jet is identified), or resolved (three  $AK_4$  jets are reconstructed)

## 10 categories based on lepton type, forward jets multiplicity and $W/t$ jet

- category 0: two muons; fully-merged topology
- category 1: two electrons; fully-merged topology
- category 2: two muons; partially-merged topology; no forward jets
- category 3: two muons; partially-merged topology; at least 1 forward jet
- category 4: two electrons; partially-merged topology; no forward jets
- category 5: two electrons; partially-merged topology; at least 1 forward jet
- category 6: two muons; resolved topology; no forward jets
- category 7: two muons; resolved topology; at least 1 forward jet
- category 8: two electrons; resolved topology; no forward jets
- category 9: two electrons; resolved topology; at least 1 forward jet

# B2G-17-007: background estimation

- To reduce the dependence on the simulation, a background estimate based on control samples in data is used
- method consists of the definition of a background-enriched control region from which the number of events is extrapolated into the signal region. This control region is defined by the normal event selection, but applying a veto on the presence of any jets passing the b tagging algorithm at the “loose” working point.

**background yield in the signal region:**

Number of events in the data sample in the control region as a function of  $M_{t,Z}$

ratio for each value of  $M_{t,Z}$  of the number of events in the signal region to the number of events in the control region, taken from simulation

$$N_{bkg}(M_{t,Z}) = N_{cr}(M_{t,Z}) \cdot \alpha(M_{t,Z})$$

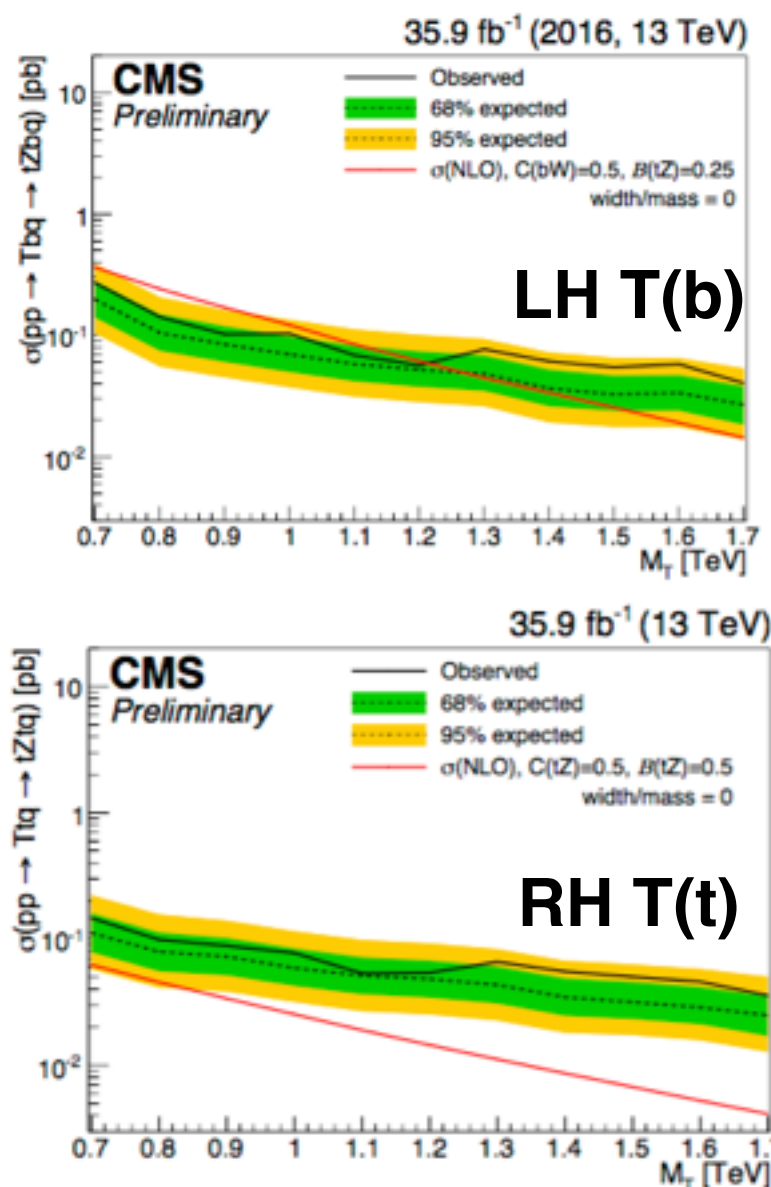
## Signal yields and efficiencies:

Channel	$2\mu+1\text{top-jet}$	$2e+1\text{top-jet}$	$2\mu+1W\text{jet}+1b\text{jet}$	$2e+1W\text{jet}+1b\text{jet}$	$2\mu+1W\text{jet}+1b\text{jet}$	$2e+1W\text{jet}+1b\text{jet}$	$2\mu+1b\text{jet}+2\text{jets}$	$2e+1b\text{jet}+2\text{jets}$	$2\mu+1b\text{jet}+1\text{jets}$	$2e+1b\text{jet}+1\text{jets}$
Estimated background	$37.3 \pm 4.6$	$25.8 \pm 4.1$	N(forward jets) = 0		N(forward jets) > 0		N(forward jets) = 0		N(forward jets) > 0	
Observation	33	31	$17.2 \pm 1.9$	$14.5 \pm 1.9$	$8.5 \pm 1.8$	$5.7 \pm 1.6$	$315.2 \pm 14.5$	$228.0 \pm 12.3$	$108.3 \pm 7.3$	$66.2 \pm 5.6$
			21	16	3	7	339	239	115	88
T(b), M = 0.8 TeV, w = 0	1.2 (0.2%)	0.9 (0.1%)	2.7 (0.5%)	1.7 (0.3%)	5.4 (0.9%)	4.3 (0.7%)	13.7 (2%)	10.0 (2%)	25.7 (4%)	18.5 (3%)
T(b), M = 0.8 TeV, w = 30 %	22.9 (1%)	17.1 (1%)	8.2 (0.5%)	5.0 (0.3%)	12.2 (0.8%)	9.5 (0.6%)	35.9 (2%)	29.7 (2%)	66.5 (4%)	52.7 (3%)
T(t), M = 0.8 TeV, w = 0	1.3 (1%)	1.0 (1%)	0.9 (0.8%)	0.8 (0.7%)	2.0 (2%)	1.5 (1%)	2.5 (2%)	2.0 (2%)	5.0 (5%)	4.0 (4%)
T(t), M = 0.8 TeV, w = 30 %	6.3 (2%)	5.4 (2%)	2.8 (0.9%)	2.1 (0.6%)	4.7 (1%)	3.9 (1%)	8.9 (3%)	6.7 (2%)	15.8 (5%)	12.0 (4%)
T(b), M = 1.6 TeV, w = 0	2.9 (6%)	2.6 (6%)	0.2 (0.3%)	0.2 (0.3%)	0.4 (0.9%)	0.3 (0.6%)	1.0 (2%)	0.9 (2%)	2.5 (5%)	2.0 (4%)
T(b), M = 1.6 TeV, w = 30 %	5.3 (5%)	4.8 (5%)	0.4 (0.4%)	0.3 (0.3%)	0.7 (0.7%)	0.6 (0.6%)	2.2 (2%)	1.9 (2%)	4.7 (5%)	3.9 (4%)
T(t), M = 1.6 TeV, w = 0	0.8 (6%)	0.7 (6%)	0.1 (0.7%)	0.1 (0.5%)	0.2 (1%)	0.2 (1%)	0.3 (3%)	0.3 (2%)	0.8 (6%)	0.7 (5%)
T(t), M = 1.6 TeV, w = 30 %	1.5 (5%)	1.4 (5%)	0.2 (0.7%)	0.2 (0.6%)	0.4 (1%)	0.4 (1%)	0.8 (3%)	0.7 (2%)	1.7 (6%)	1.5 (5%)



# B2G-17-007: results

## Narrow Width Approximation:



## Not-negligible widths:

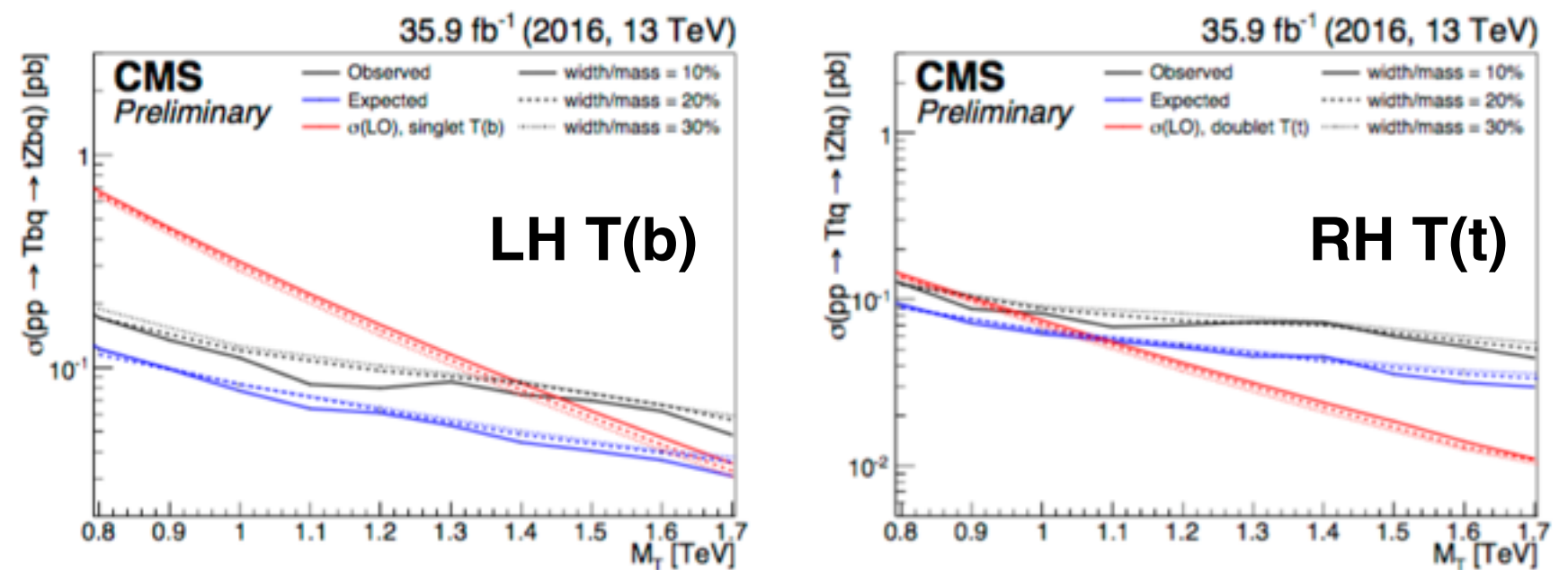


Figure 6: Observed and expected 95% CL upper limit on the product of cross section and branching fraction for the singlet LH T(b) (left) and doublet RH T(t) (right) production modes, with the T decaying to tZ, where the T has a width of 10%, 20% and 30% of the resonance mass. Theoretical cross sections have been calculated at leading order using a private version of the model constructed by the authors of [5, 31, 32] and are reported in Table 2.

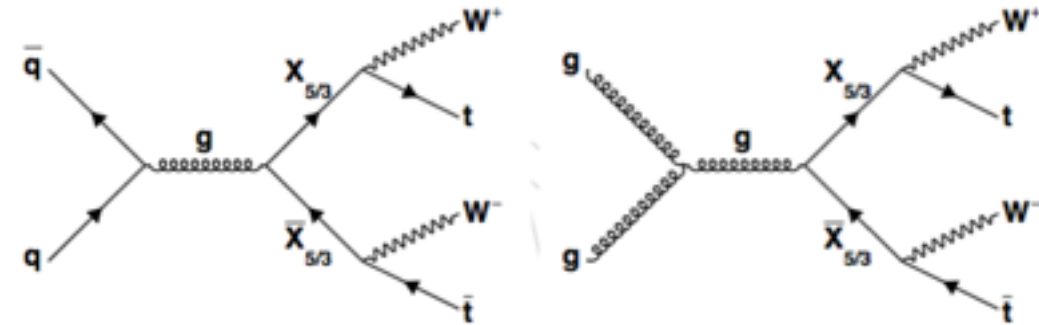


*B2G-17-008*

# B2G-17-008: selection

## online selection

- one lepton (electron or muon), passing single electron or single muon triggers within an acceptance region of  $|\eta| < 2.5$  (2.4) for electrons (muons). The single-electron triggers require an isolated electron with  $p_T > 32$  GeV or a very loosely isolated electron with  $p_T > 15$  GeV accompanied by  $H_T > 350$  GeV (the scalar sum of all reconstructed jets with  $p_T > 30$  GeV and  $|\eta| < 3.0$ ). The single-muon triggers require a muon with  $p_T > 50$  GeV or a very loosely isolated muon with  $p_T > 15$  GeV and  $H_T > 350$  GeV.



## offline selection

- The tight (loose) electrons are further required to have transverse momentum  $p_T > 30$  (10) GeV and pseudorapidity  $|\eta| < 2.5$ ,
- The tight (loose) muons are required to have  $p_T > 30$  (10) GeV and pseudorapidity  $|\eta| < 2.4$ .
- The AK8 jets are considered to be t-tagged if they have  $p_T > 400$  GeV,  $|\eta| < 2.4$ , a softdrop mass between 105 and 220 GeV, and the ratio of n-subjettiness variables  $\tau_3/\tau_2 < 0.81$
- the AK8 jets are W-tagged if they have  $p_T > 200$  GeV,  $|\eta| < 2.4$ , pruned mass between 65 and 105 GeV, and the ratio of n-subjettiness variables  $\tau_2/\tau_1 < 0.6$
- events are required to have exactly one tight lepton with  $p_T > 80$  GeV and no additional loose leptons with  $p_T > 10$  GeV
- MET  $> 100$  GeV
- at least four AK4 jets where the leading and subleading jet transverse momenta are required to be greater than 450 GeV and 150 GeV, respectively. Among these jets, at least one of them is required to be b-tagged.
- The selected lepton and its closest jet are required to be separated by either  $\Delta R(l, \text{closest jet}) > 0.4$ , or by the magnitude of the lepton  $p_T$  perpendicular to the jet axis being larger than 40 GeV.
- The final selection criteria uses the distance parameter between the lepton and the subleading jet,  $\Delta R(l, j_2)$ . It is required to be  $> 1.0$ .

# B2G-17-008: categories

Events are further split into 16 categories based on lepton flavor (e,  $\mu$ ), the number of b-tagged jets (1,  $\geq 2$ ), the number of W-tagged jets (0,  $\geq 1$ ), and the number of t-tagged jets (0,  $\geq 1$ )

Sample	0 t, 0 W, 1 b	0 t, 0 W, $\geq 2$ b	0 t, $\geq 1$ W, 1 b	0 t, $\geq 1$ W, $\geq 2$ b
LH $X_{5/3}$ (0.9 TeV)	$5.6 \pm 1.3$	$4.9 \pm 1.2$	$43.6 \pm 2.3$	$36.5 \pm 2.3$
RH $X_{5/3}$ (1.2 TeV)	$1.1 \pm 0.3$	$0.8 \pm 0.24$	$10.4 \pm 0.66$	$7.7 \pm 0.6$
TOP	$609 \pm 120$	$370 \pm 81$	$536 \pm 110$	$349 \pm 74$
EWK	$362 \pm 54$	$53.7 \pm 8.7$	$111 \pm 18$	$19.0 \pm 3.8$
QCD	$28.6 \pm 9.5$	$10.2 \pm 5.8$	$13.9 \pm 7.2$	$0.7 \pm 2.7$
Total bkg	$1000 \pm 140$	$434 \pm 82$	$661 \pm 110$	$369 \pm 74$
Data	984	416	577	321
Data/Bkg	$0.98 \pm 0.14$	$0.96 \pm 0.19$	$0.87 \pm 0.15$	$0.87 \pm 0.18$

Sample	1+ t, 0 W, 1 b	1+ t, 0 W, 2+ b	1+ t, 1+ W, 1 b	1+ t, 1+ W, 2+ b
LH $X_{5/3}$ (0.9 TeV)	$17.6 \pm 1.6$	$15.5 \pm 1.5$	$39.7 \pm 2.4$	$34.5 \pm 2.2$
RH $X_{5/3}$ (1.2 TeV)	$4.2 \pm 0.5$	$3.4 \pm 0.5$	$13.8 \pm 0.8$	$11.8 \pm 0.8$
TOP	$423 \pm 92$	$306 \pm 68$	$151 \pm 35$	$117 \pm 28$
EWK	$109 \pm 18$	$19.4 \pm 3.3$	$21.2 \pm 4.8$	$2.6 \pm 0.7$
QCD	$10.2 \pm 5.1$	$1.7 \pm 0.8$	$1.6 \pm 1.1$	$0.7 \pm 0.5$
Total bkg	$543 \pm 94$	$327 \pm 68$	$174 \pm 35$	$121 \pm 28$
Data	465	285	135	123
Data/Bkg	$0.86 \pm 0.15$	$0.87 \pm 0.19$	$0.78 \pm 0.17$	$1.02 \pm 0.25$

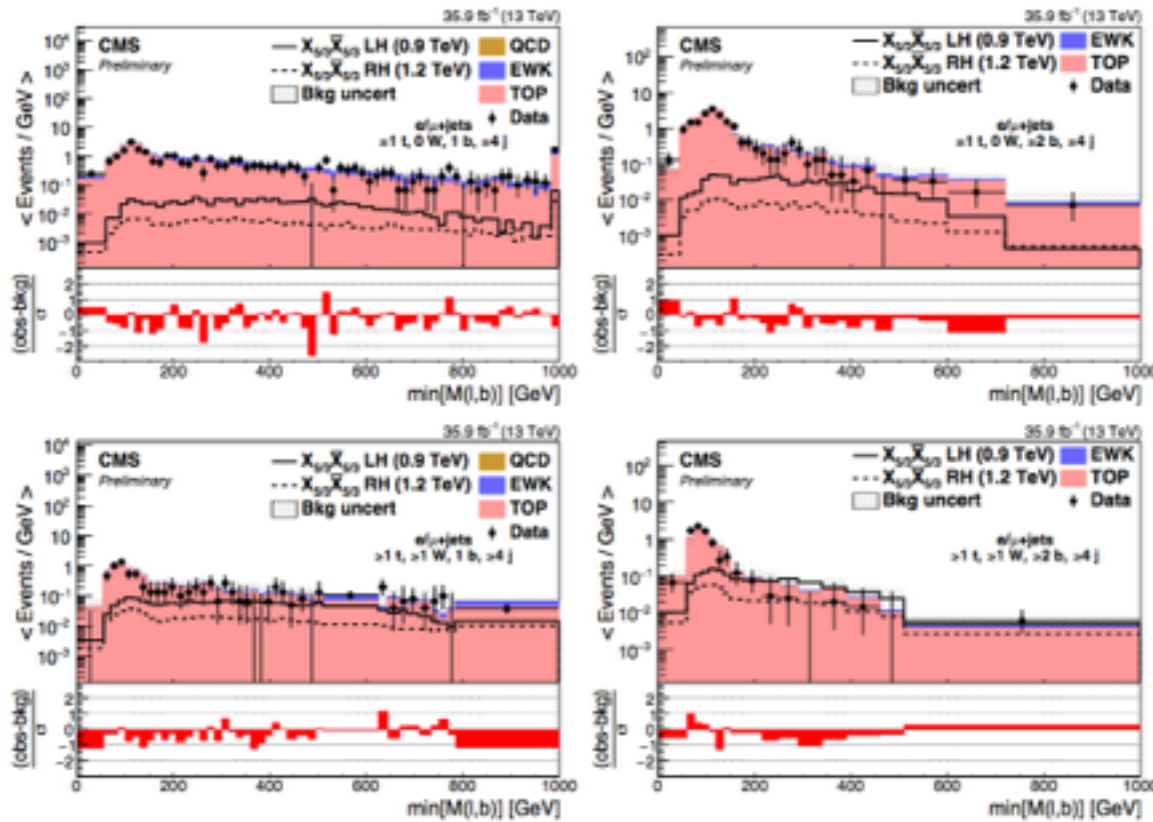


Figure 4: Distributions of  $\min[M(\ell, b)]$  in events with  $\geq 1$  t-tagged jet, (top) 0 or (bottom)  $\geq 1$  W-tagged jets and (left) 1 or (right)  $\geq 2$  b-tagged jets for combined electron and muon samples in the signal region. The events in the overflow bin are added to the last bin of the distributions. The distributions are given variable sized bins in each category so that the statistical uncertainty on the total background in each bin is less than 30%. The bottom panel on all plots shows the difference between the observed and the predicted number of events in that bin divided by the total uncertainty ( $\sigma$ ). The total uncertainty is calculated as the sum in quadrature of the statistical uncertainty on the observed measurement and statistical and systematic uncertainties on the background.

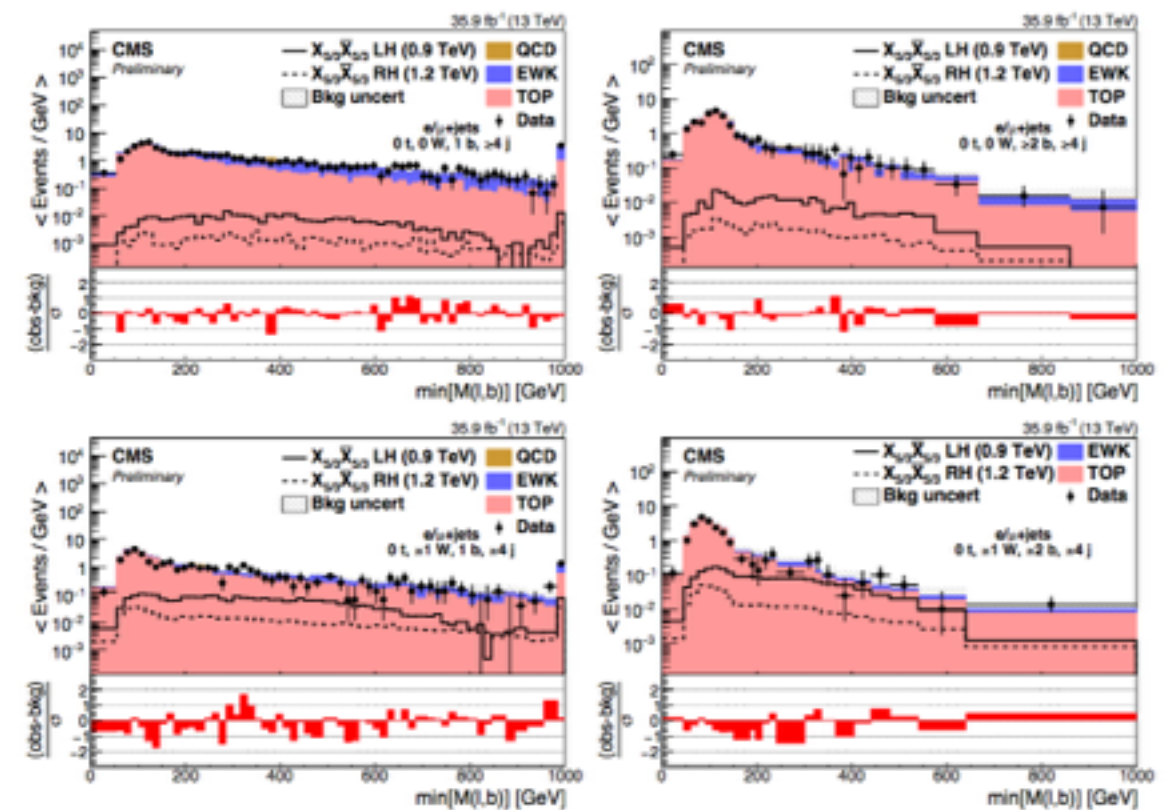


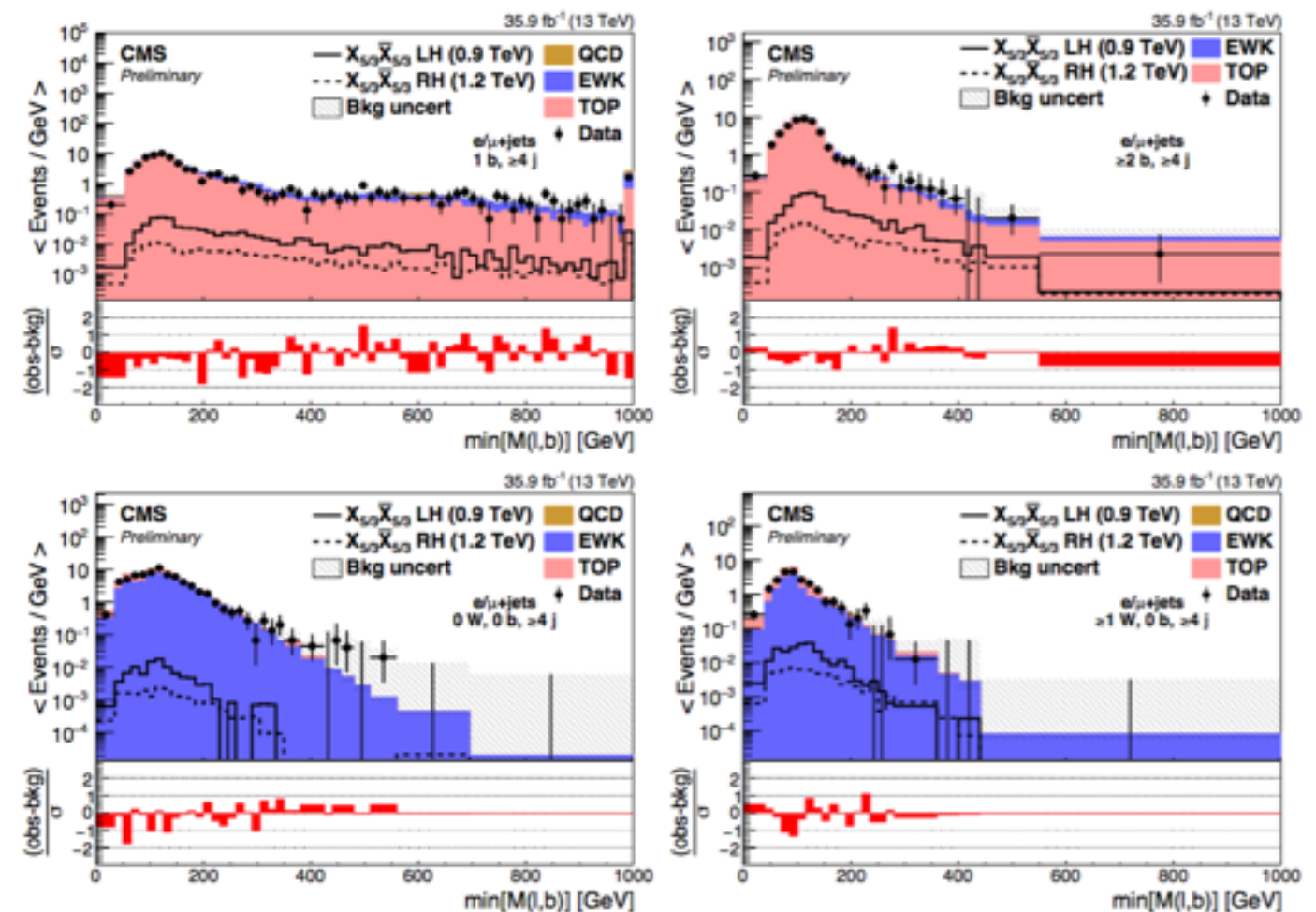
Figure 3: Distributions of  $\min[M(\ell, b)]$  in events with 0 t-tagged jet, (top) 0 or (bottom)  $\geq 1$  W-tagged jets and (left) 1 or (right)  $\geq 2$  b-tagged jets for combined electron and muon samples in the signal region. The events in the overflow bin are added to the last bin of the distributions. The distributions are given variable sized bins in each category so that the statistical uncertainty on the total background in each bin is less than 30%. The bottom panel on all plots shows the difference between the observed and the predicted number of events in that bin divided by the total uncertainty ( $\sigma$ ). The total uncertainty is calculated as the sum in quadrature of the statistical uncertainty on the observed measurement and statistical and systematic uncertainties on the background.



# B2G-17-008: background

- all the background processes are estimated using MC simulations.
- cross checks of the background modeling are performed for the leading background process  $t\bar{t}$  and the subleading background process  $W$  +jets by imposing the same event selection as described in the previous section, but reverting the selection on  $\Delta R(l, j_2)$ , required to be less than 1.0.
- The modeling check is performed separately in different event categories. For the  $t\bar{t}$  background control region, we divide events into 1 and 2 or more b-tagged jet categories. The  $W$ +jets control region is split into 0 and 1 or more W-tagged jet categories, while requiring 0 b-tagged jets. Because of the absence of b-tagged jets in the  $W$ +jets control region, we modify the mass discriminant to the minimum mass of all lepton and jet pairs in the event and denote it as  $\min[M(l, j)]$ .

Figure 5: Distributions of  $\min[M(l, b)]$  in the  $t\bar{t}$  control region, for 1 b-tagged jet (top left) and  $\geq 2$  b-tagged jets (top right) categories, and of  $\min[M(l, \text{jets})]$  in the  $W$  + jets control region, for 0 W-tagged (bottom left) and  $\geq 1$  W-tagged jet (bottom right) categories. Electron and muon event samples are combined. The events in the overflow bin are added to the last bin of the distributions. The distributions are given variable sized bins in each category so that the statistical uncertainty on the total background in each bin is less than 30%. The bottom panel on all plots shows the difference between the observed and the predicted number of events in that bin divided by the total uncertainty ( $\sigma$ ). The total uncertainty is calculated as the sum in quadrature of the statistical uncertainty on the observed measurement and statistical and systematic uncertainties on the background.





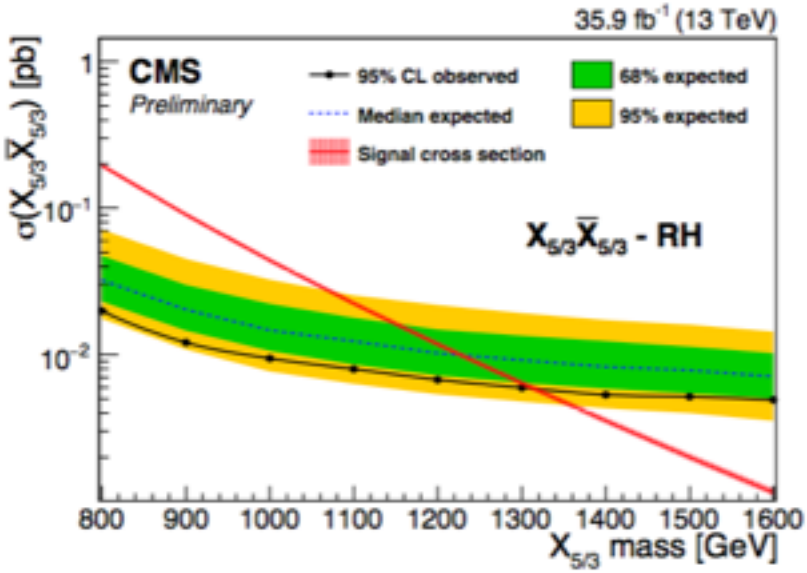
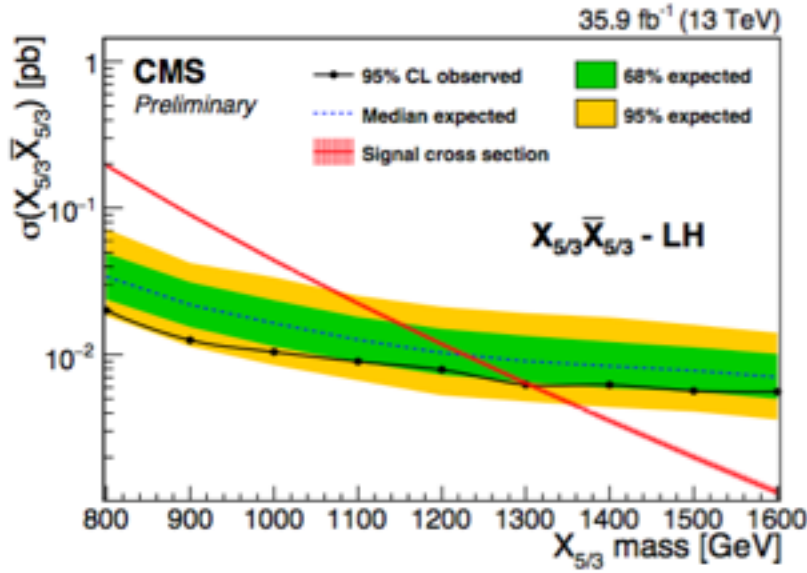
# B2G-17-008: results



Source	Uncertainty	Signal	Background
Normalization only			
Luminosity	2.6%	Yes	All
Electron identification/isolation	2%/1%	Yes	All
Muon identification/isolation	3%/1%	Yes	All
Shape and normalization			
Trigger efficiency	$\pm\sigma(p_T, \eta)$	Yes	All (2 – 5%)
Jet energy scale	$\pm\sigma(p_T, \eta)$	Yes	All (0.5 – 52%)
Jet energy resolution	$\pm\sigma(\eta)$	Yes	All (0 – 3%)
b/c tagging	$\pm\sigma(p_T)$	Yes	All (0 – 5%)
udsg mistagging	$\pm\sigma$	Yes	All (0 – 4%)
W tagging: mass resolution	$\pm\sigma(\eta)$	Yes	All (0 – 13%)
W tagging: mass scale	$\pm\sigma(p_T, \eta)$	Yes	All (0 – 21%)
W tagging: $\tau_2/\tau_1$	$\pm\sigma$	Yes	All (0 – 2%)
W tagging: $\tau_2/\tau_1$ extrapolation	$\pm\sigma(p_T)$	Yes	All (0 – 2%)
t tagging	$\pm\sigma$	Yes	All (0 – 4%)
Top $p_T$	$\Delta(\text{weighted, unweighted})$	No	$t\bar{t}$ (0 – 19%)
W+jets $H_T$	$\pm 2\sigma(H_{T\text{gen}})$	No	W+jets (0.2 – 0.3%)
Pileup	$\sigma_{\text{inel.}} \pm 4.6\%$	Yes	All (0 – 4%)
PDF	$\pm\sigma$	No	All (2 – 9%)
QCD renormalization/factorization scale	envelope( $\times 2, \times 0.5$ )	No	All (12 – 36%)
Shape only			
PDF	$\pm\sigma$	Yes	None
QCD renormalization/factorization scale	envelope( $\times 2, \times 0.5$ )	Yes	None

← Systematics table

95% C.L.



*B2G-17-003*

# B2G-17-003: selection

## online selection

- The trigger providing the muon data sample is based on the presence of at least one muon with  $p_T > 50$  GeV and  $|\eta| < 2.5$ . For the electron data sample we require events to pass a single isolated electron trigger with  $p_T > 32$  GeV and  $|\eta| < 2.1$ .

## offline selection

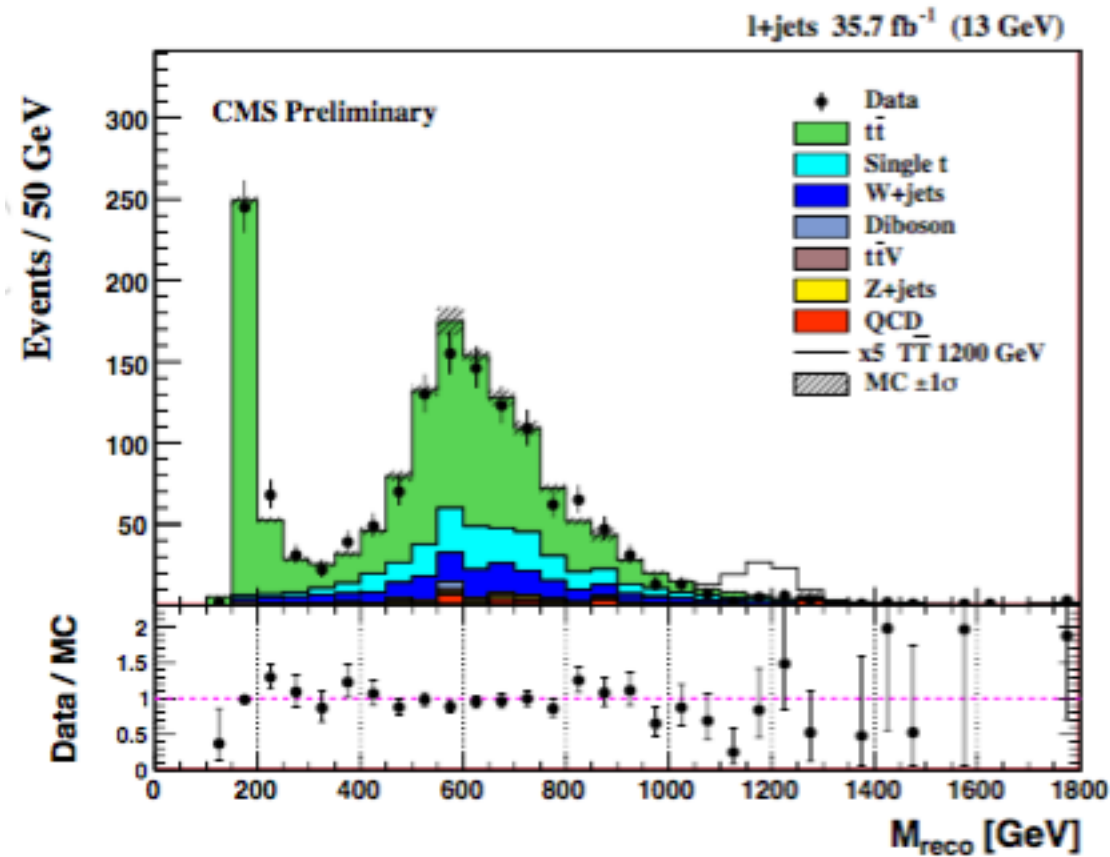
- exactly one charged lepton (muon or electron) and at least four jets, comprising AK4 jets and subjects of W-tagged AK8 jet
- at least four AK4 jets or three AK4 jets and one AK8 jet. AK4 jets should have  $p_T > 30$  GeV and  $|\eta| < 2.4$ , AK8 jets- $p_T > 200$  GeV and  $|\eta| < 2.4$
- Muon candidates are required to have transverse momentum  $p_T > 55$  GeV (above value given by trigger), and  $|\eta| < 2.4$ . Relative muon isolation is  $I_{rel} < 0.15$ . Selected electrons should have  $|\eta| < 2.1$ . In order for the electron channel to cover similar kinematic domain as the muon channel, electron candidates are required also to have  $p_T > 55$  GeV. Events with just one (so called “tight”) muon or electron are accepted, events with a second (so called “loose”) electron or muon are vetoed. Loose muons and electrons have  $p_T > 20.0$  GeV and  $|\eta| < 2.5$ .
- An AK8 jet is labeled “W-tagged”, if its mass ( $M_{AK8}$ ) satisfies requirement  $60 \text{ GeV} < M_{AK8} < 100 \text{ GeV}$ . The W-tagged AK8 jets are then deconstructed into subjects, which then replace AK4 jets, matching the AK8 jet. For each W-tagged AK8 jet we search for overlapping with AK4 jet or with a pair of AK4 jets, considering nearby jets satisfying  $\Delta R(AK8, AK4) < 0.8$ . Matching is accepted if difference between directions of AK8 jet and AK4 jet (or pair of AK4 jets) is  $\Delta R < 0.05$ . Matched one or two AK4 jets are replaced with the two subjects of the W-tagged AK8 jet, and they are considered as jets from the W decay.
- The resulting jet collection consists of AK4 jets left unmatched plus the subjects of W-tagged AK8 jets. This collection is used as an input to the kinematic fit.
- After the hybrid jet collection is composed, a set of preselection requirements is applied on the event:
  - Lepton-jet cleaning of the hybrid jet collection is performed by discarding jets for which  $\Delta R(Jet, l) < 0.4$ .
  - The two highest  $p_T$ -ordered jets must satisfy the requirements  $p_T > 100$  GeV, 70 GeV.
  - Select events with at least 4 jets left in the hybrid jet collection.
  - Transverse missing energy in the event must be  $E^{miss} > 30$  GeV.
- $S = p^L + E^{miss} + p^{J_1} + p^{J_2} + p^{J_3} + p^{J_4} > 1000$  GeV

# B2G-17-003: kinematic fit

- Events, which pass all these requirements, are input into a kinematic fit \*HitFit package
- The reconstructed objects in the event are the charged lepton,  $E^{\text{miss}}$  and jets. The four quarks  $\tau$  in the final state are presented as jets, and their measured momenta are used as estimates of quark momenta. The missing transverse energy in the event is used as an estimate of the transverse component of the neutrino momentum. The z component of the neutrino momentum is calculated from the kinematic constraint (3) below.
- The fit is performed by minimizing the  $\chi^2$  quantity, constructed from the differences between the measured momentum components (absolute value,  $\eta$  and  $\phi$  of momentum vector) and their fitted values, divided by the corresponding uncertainties, summed over all reconstructed objects in final state ([36]). Fit is a subject of constraints:  $m(l\nu) = M_W$ ,  $m(qq') = M_W$ ,  $m(l\nu b) = m(qq' b) = M_{\text{reco}}$
- After one constraint is used for calculation of longitudinal neutrino momentum, two constraints are left (2C fit). To check to what extent the assumed kinematic hypothesis is compatible with the fitted particles, the so called “goodness-of-the-fit” is calculated, given by the probability of the  $\chi^2$  value obtained after its minimization, for the case of 2C fit  $Prob(\chi^2) = \exp(-\chi^2/2)$ .
- First step is assignment of reconstructed objects to the final state objects, second step - kinematic fit for given assignment.
- If there are more than four jets in the selected jet collection, then the five jets with highest  $p_T$  are considered, and all permutations of four jets out of five are used as input to the fitter.
- To reduce a number of accidental combinatoric assignments we use information on b-tagging, on W-tagging and some additional requirements.
- In all this sequence of selection, first, combinations containing W-tagged subjects are considered. If no combination with W tag passes the selection criteria, then the rest of combinations, which do not contain W-tagged subjects, is considered.



Event Yields table



Systematics table

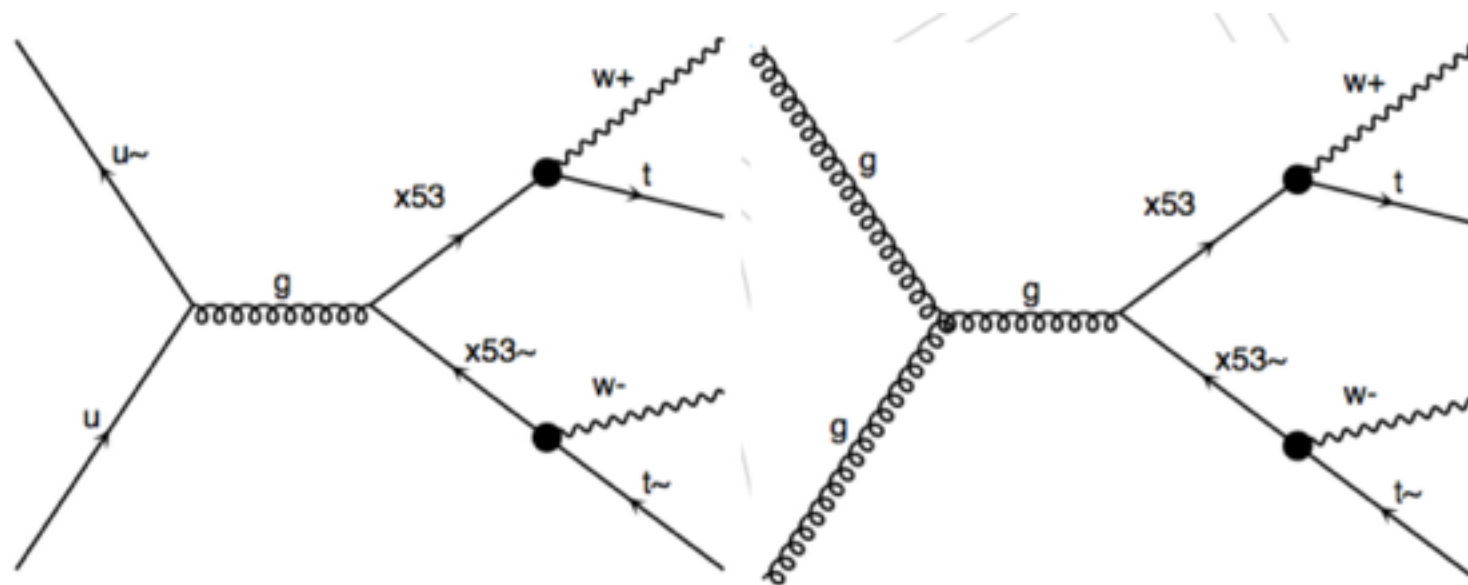
	signal	BG
JES	+0.2% -2.5%	17%
JER	+0.02% -0.3%	0.03%
b tag heavy flavour	2.5%	+2.8% -1.4%
b tag light flavour	0.2%	0.8%
Q <sup>2</sup> scale	1.1%	+18% -14%
Pileup	0.05%	0.2%
PDF	0.3%	2.0%
Top reweighting	-	11%
W+jets reweighting	-	+4.9% -3.3%
$\Delta R_{match}$	+0% -0.8%	+0% -1.9%

Efficiencies table

Channel	$\mu$ + jets		$e$ + jets	
Mass [ GeV ]	Efficiency	Events	Efficiency	Events
800	0.0237 ± 0.0005	166.1 ± 3.7	0.0220 ± 0.0005	153.5 ± 3.5
900	0.0271 ± 0.0006	87.8 ± 1.9	0.0236 ± 0.0005	75.8 ± 1.8
1000	0.0297 ± 0.0006	46.7 ± 0.9	0.0269 ± 0.0006	42.2 ± 0.9
1100	0.0308 ± 0.0006	24.7 ± 0.5	0.0277 ± 0.0006	22.1 ± 0.4
1200	0.0314 ± 0.0006	13.3 ± 0.3	0.0280 ± 0.0006	11.8 ± 0.24
1300	0.0310 ± 0.0007	7.09 ± 0.15	0.0279 ± 0.0006	6.34 ± 0.14
1400	0.0314 ± 0.0006	3.98 ± 0.08	0.0277 ± 0.0006	3.50 ± 0.07
1500	0.0321 ± 0.0006	2.30 ± 0.04	0.0276 ± 0.0006	1.96 ± 0.04
1600	0.0301 ± 0.0006	1.24 ± 0.02	0.0284 ± 0.0006	1.16 ± 0.02

*B2G-16-019*

# B2G-16-019: selection



## online selection

- For the first half of the dataset the  $p_T$  requirements are 40 (35) GeV on the leading (sub-leading) lepton, while for the second half the requirements are 40 (30) GeV for the leading (sub-leading) lepton.

## offline selection

- The isolation variable ( $I_{\text{mini}}$ ) is defined as the sum of energy around the electron in a varying cone size divided by the transverse momentum ( $p_T$ ) of the electron. The radius used for the isolation cone ( $R$ ) is defined as:  $R = 10/\min(\max(p_T, 50), 200)$ . We define a “tight” electron to have  $I_{\text{mini}} < 0.1$  while a “loose” electron has  $I_{\text{mini}} < 0.4$ .
- Jets (radius 0.4) are required to have  $p_T > 30$  GeV,  $|\eta| < 2.4$
- The analysis takes advantage of the same-sign dilepton final state as well as the significant amount of jet activity due to the presence of the two bottom quarks and the possibility of hadronic decays for the W bosons arising from one of the top-quark partners
- After requiring two tight, same-sign leptons we impose the following requirements:
  - QuarkoniaVeto:  $M_{ll} > 20$  GeV
  - Associated Z Boson Veto: veto any event where either of the leptons in the same-sign pair reconstructs to within 15 GeV of the mass of the Z boson with any other lepton in the event not in the same-sign pair.
  - Primary Z Boson Veto: invariant dilepton mass ( $M_{ll}$ )  $> 106.1$  or  $< 76.1$  GeV for dielectron channel only. If the muon charge is mismeasured, its momentum will also be mismeasured so a selected muon pair from a Z Boson will not fall within this invariant mass range.
  - Number of Constituents  $\geq 5$
  - $H^{\text{lep}} > 1200$  GeV



# B2G-16-019: background

1. **Same-sign prompt leptons:** standard model processes leading to prompt, same-sign dilepton signatures. Their contribution is obtained from theoretical predictions.
  - contributions from diboson production (WZ and ZZ) and rarer processes like ttW, ttZ, ttH, WWZ, ZZZ, WZZ,  $W^\pm W^\pm$ , etc.
  - contribution obtained from simulation.
2. **Opposite sign prompt leptons:** prompt leptons could be mis-reconstructed with the wrong charge leading to a same-sign dilepton final state.
  - Processes with two prompt leptons that are oppositely charged can contribute to the top partners background if the charge of one of these leptons is incorrectly identified.
  - We measure the probability of charge misidentification using di-electron events that reconstruct to within 10 GeV of the Z-boson mass, as a function of  $|\eta|$ .
  - The number of expected same-sign events due to charge misidentification is estimated by considering the total number of events passing the full selection but having oppositely charged leptons, weighted by the charge misidentification probability
3. **Same-sign events arising from the presence of one or more non-prompt leptons:** this is the primary instrumental background arising from jets being mis-identified as leptons, non-prompt leptons passing tight isolation selection criteria, etc.
  1. This contribution is estimated using a data driven method
  2. non-prompt leptons that come from heavy flavor decays, decays in flight, jets misidentified as leptons, or conversions. These contributions are estimated using the Tight-Loose method (<https://link.springer.com/article/10.1007%2FJHEP06%282011%29077>)
  3. Any lepton passing either the tight or the loose selection can originate either from a prompt decay (i.e. a W or a Z boson) or from a non-prompt source such as a heavy flavor hadron or a photon converting to electrons.
  4. The background is estimated by using events with one or more loose leptons weighted by the ratios of the numbers of tight leptons to the numbers of loose leptons expected for prompt and non-prompt leptons.



# B2G-16-019: results

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	1000 GeV $X_{5/3}$	Observed
Di-electron	$4.1 \pm 0.6$	$3.5 \pm 2.1$	$2.4 \pm 0.8$	$10.0 \pm 2.3$	11.6	10
Electron-Muon	$10.7 \pm 1.4$	$8.5 \pm 4.6$	$1.7 \pm 0.5$	$20.9 \pm 4.8$	26.9	26
Di-muon	$5.9 \pm 0.8$	$3.8 \pm 2.2$	-	$9.7 \pm 2.4$	16.1	12
All	$20.7 \pm 2.6$	$15.8 \pm 8.2$	$4.1 \pm 1.3$	$40.6 \pm 8.7$	54.6	48

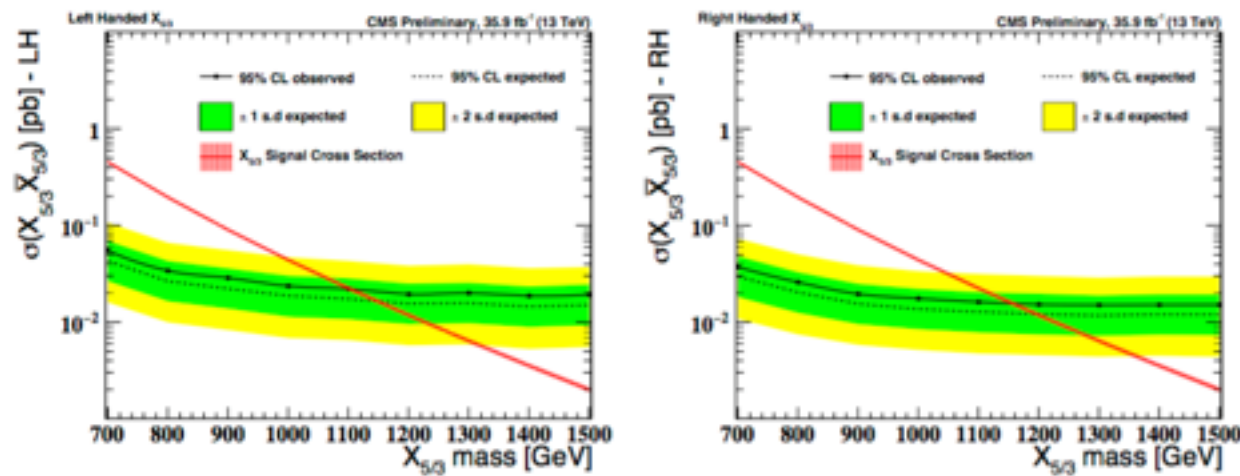


Figure 3: 95% CL observed and expected limits for a left-handed (left) and right-handed (right)  $X_{5/3}$  for all channels combined. The theoretical uncertainty on the signal cross section is shown as a red band around the central prediction.

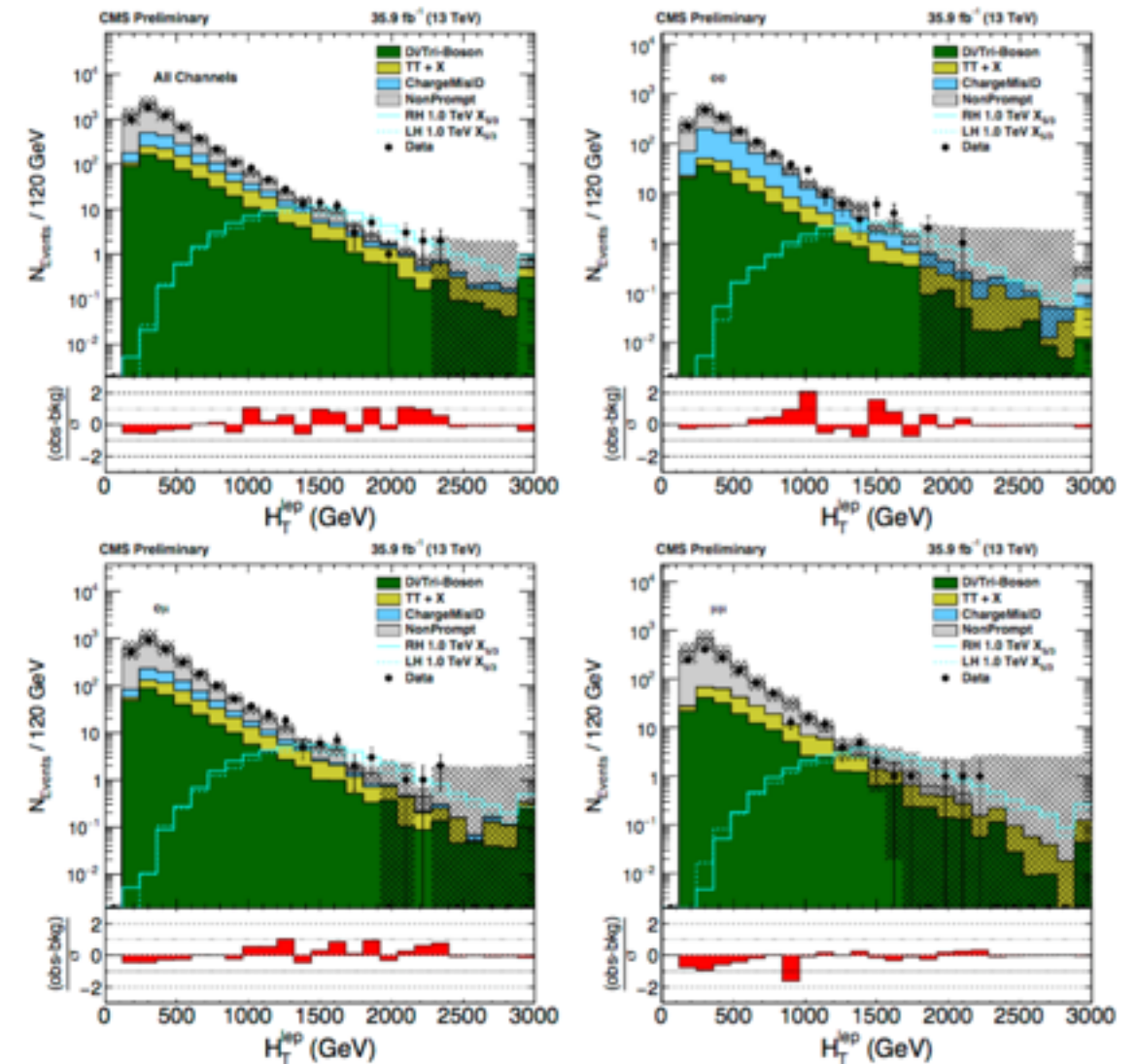


Figure 2: The  $H_T^{lep}$  distributions after the same-sign dilepton selection,  $Z$ /quarkonia lepton invariant mass vetoes, and requiring at least two AK4 jets in the event. The bottom panel on all plots shows the difference between the observed and the predicted number of events in that bin divided by the total uncertainty ( $\sigma$ ). The total uncertainty is calculated as the sum in quadrature of the statistical uncertainty on the observed measurement and the uncertainty, including both statistical and systematic, on the background.

*EXO-17-002*



# EXO-17-002: selection

## online selection

The data sample used in this analysis consists of events that pass a photon trigger with a photon energy threshold of 165 GeV with an additional requirement on the ratio of the hadronic over electromagnetic energy of the photon candidate.

## offline selection

- The photon should be isolated from any of identified electrons in the detector [19]. The photon is also required to be well isolated from other photons and hadrons within a cone of  $\Delta R = 0.3$  around its axis within the supercluster. The photon should have  $p_T^\gamma > 200$  GeV and should lie in central barrel region ( $|\eta^\gamma| < 1.4442$ ). Among the selected photons passing the above criteria in each event, the one with highest transverse momentum is used as the final photon candidate to reconstruct the mass of photon + jet system in the event.
- Jets separated from the selected photon candidate by  $\Delta R > 0.5$  and satisfying the tight jet identification criteria [21] are selected as possible jet candidates. The jet identification criteria have requirements on the number of constituents, and on the fraction of the jet energy held by each constituent type. The jet is required to be within the pseudorapidity region  $|\eta^{\text{jet}}| < 2.4$  and must have a transverse momentum  $p_T^{\text{jet}} > 170$  GeV. The angular separation between the selected photon and jet is restricted by applying a requirement of  $\Delta\eta(\gamma, \text{Jet}) < 1.5$ .
- To have full efficiency due to the photon and jet  $p_T$  and  $\eta$  requirements, the invariant mass of the  $\gamma + \text{jet}$  ( $\gamma + b \text{ jet}$ ) system evaluated using the selected photon and jet ( $b \text{ jet}$ ) is required to be  $M_{\gamma, \text{jet}} > 700$  GeV.



# EXO-17-002: fitting procedure

These distributions are modelled using an empirical parametrization, widely used in similar previous searches

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2 + P_3 \ln(m/\sqrt{s})}}$$

In order to examine the presence of a possible systematic bias due to the choice of background fitting function, **tests are performed using alternate functional forms**. In order to perform these tests, an invariant mass distribution is obtained using MC simulation. This invariant mass distribution is fitted with alternate test functions and the results of the fit, considered the truth model, is used to generate a large number of pseudo-data distributions following the Poisson distribution. A signal with a cross section close to the expected sensitivity is also injected in the pseudo-data distributions. These distributions are then fitted using the default background function along with a signal model, and the signal cross section is extracted. Pull distributions defined as the difference between the true and predicted signal cross section divided by the estimated statistical uncertainty, for the obtained signal cross sections are constructed. The deviation of the mean in the pull distribution from the input value is a measure of expected bias present in the model. **The shapes of pull distribution, for  $q^*$  and  $b^*$  scenarios over the mass range under study, are found to be consistent with a normal distribution with medians deviating by no more than 0.5 from zero, and widths consistent with unity for the full mass range. Therefore, the conclusion that the possible statistical bias from the choice of parametric function is small as compared to the statistical uncertainty of the fit, is made.**

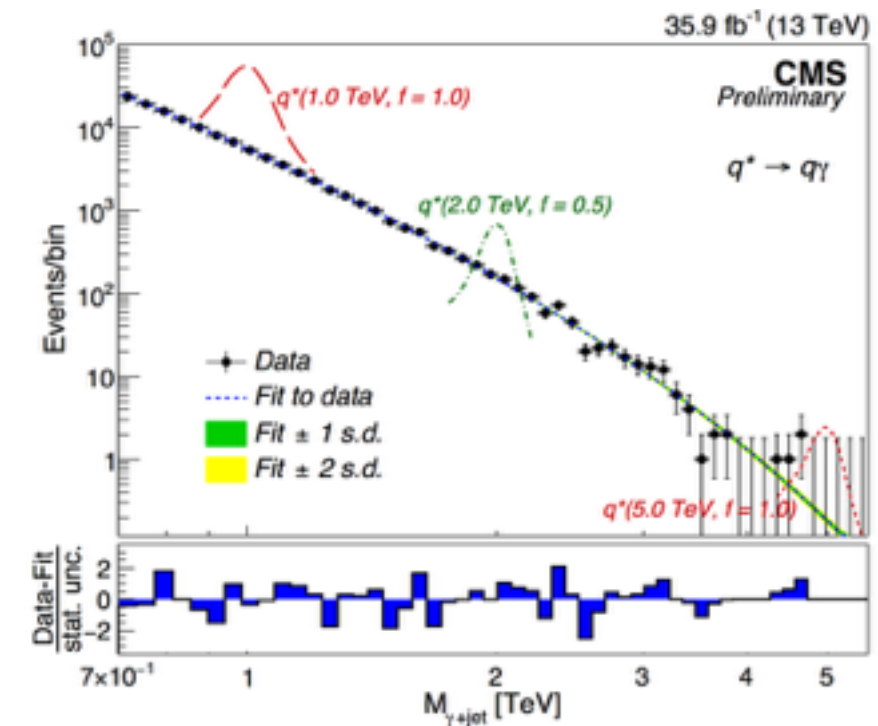
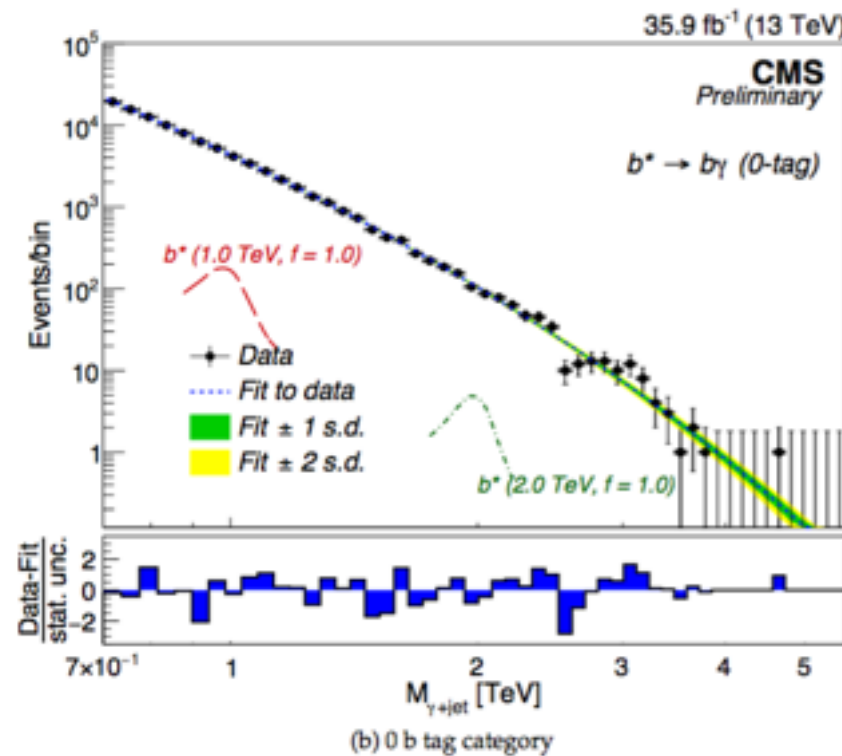
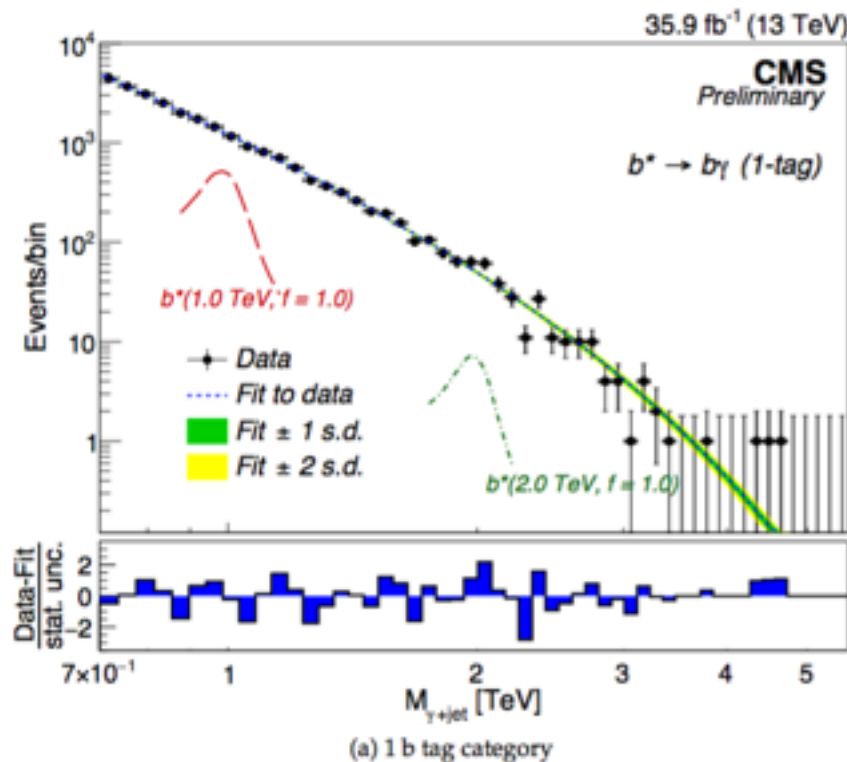
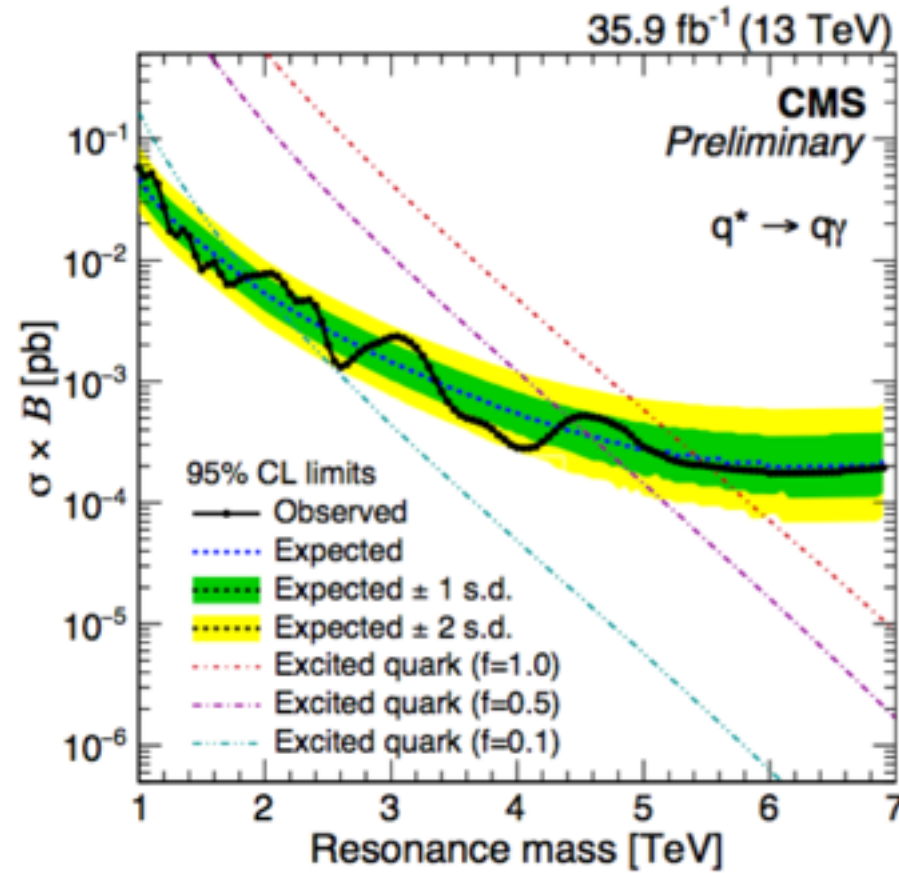
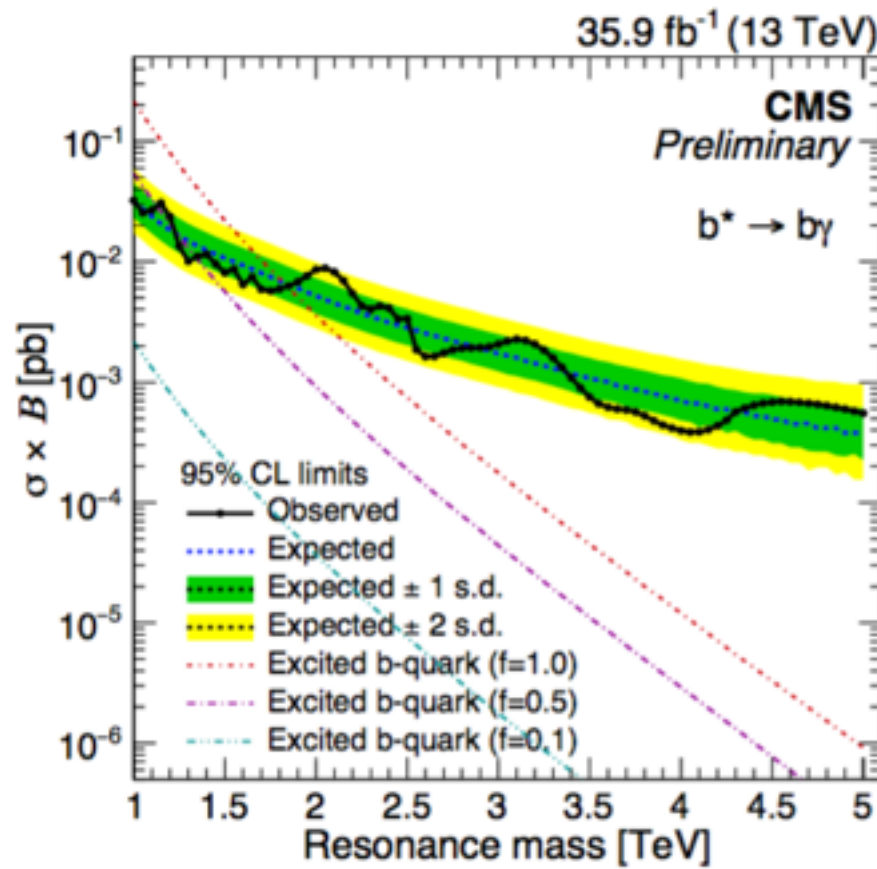


# EXO-17-002: systematics

Table 1: Summary of the dominant sources of uncertainties and their effect on yield.

Source	Effect on yield	Applicable for ( $q^*/b^*$ )
Luminosity	2.5%	Both
Jet energy scale	$\sim 1.0\%$	Both
Jet energy resolution	0.2-0.4%	Both
Photon energy scale	$\sim 0.6\%$	Both
Photon energy resolution	0.2-0.4%	Both
Pileup	1.0-2.0%	Both
Photon ID efficiency	$\sim 2.0\%$	Both
HLT Trigger efficiency	5.0%	Both
Signal shape interpolation	0.5-1.0%	Both
b-tag SF uncertainty on signal shape	1.0%	Only $b^*$
b-tag SF uncertainty on signal normalization	2.0%	Only $b^*$

# EXO-17-002: results



*phenomenology*

# Vector Like Quarks (I)

VLQs: The left-handed and right-handed chiralities of a vector-like fermion  $\psi$  transform in the same way under the SM gauge groups  $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L} = \frac{g}{\sqrt{2}} (J^{\mu+} W_{\mu}^{+} + J^{\mu-} W_{\mu}^{-}) \quad \text{charged current lagrangian}$$

**SM chiral quarks: only left-handed charged currents**

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} \quad \begin{cases} J_L^{\mu+} = \bar{u}_L \gamma^{\mu} d_L = \bar{u} \gamma^{\mu} (1 - \gamma^5) d = \textcolor{red}{V} - \textcolor{red}{A} \\ J_R^{\mu+} = 0 \end{cases}$$

**vector like quarks: both left-handed and right-handed charged currents**

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



# Vector Like Quarks (II)

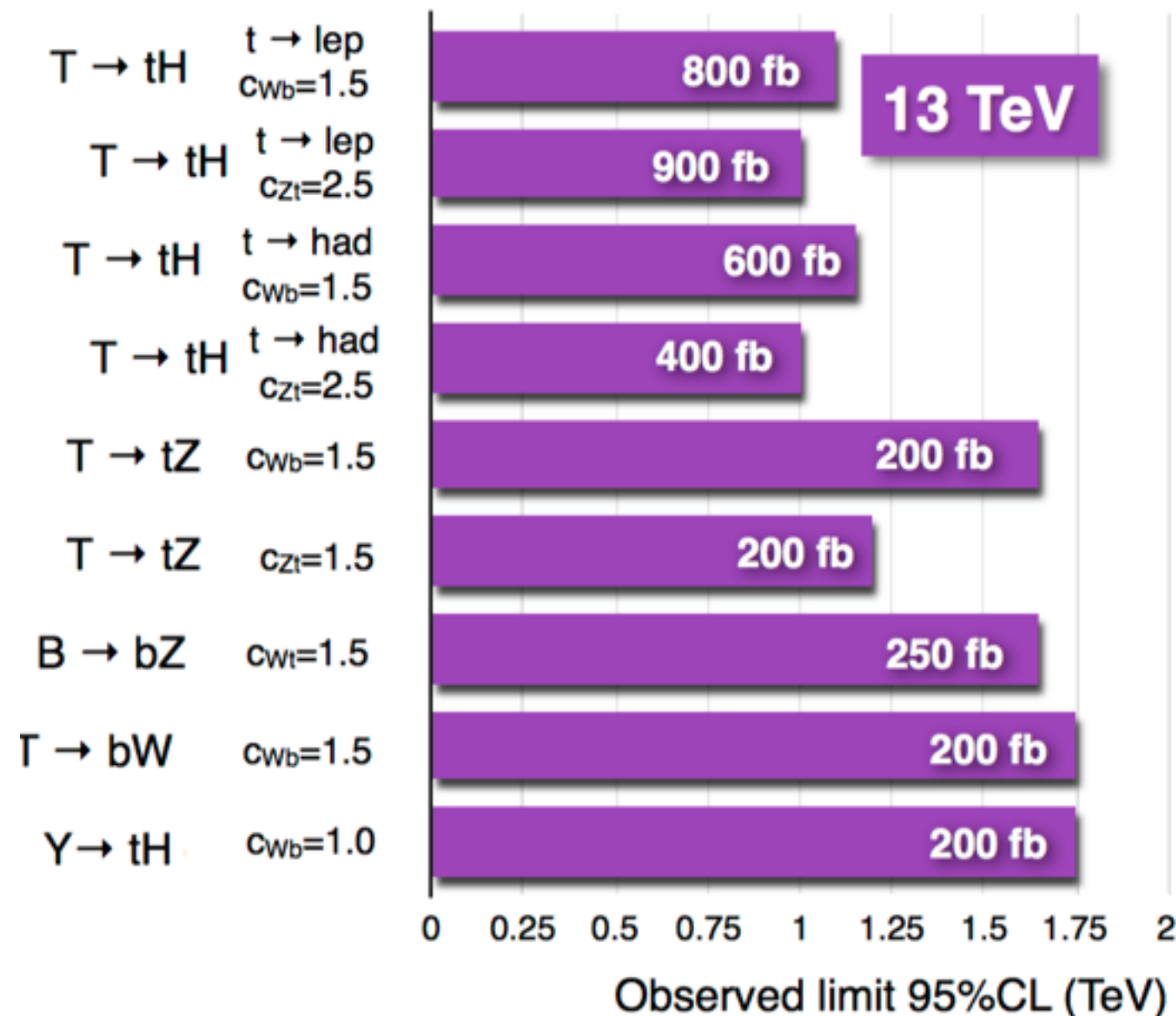
	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	$\begin{pmatrix} t' \\ b' \end{pmatrix}$	$\begin{pmatrix} X \\ t' \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix} \begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	$2/3 \quad -1/3$	$7/6 \quad 1/6 \quad -5/6$	$2/3 \quad -1/3$
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}} \bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}} \bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}} \bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}} \bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$

from a talk by L. Panizzi

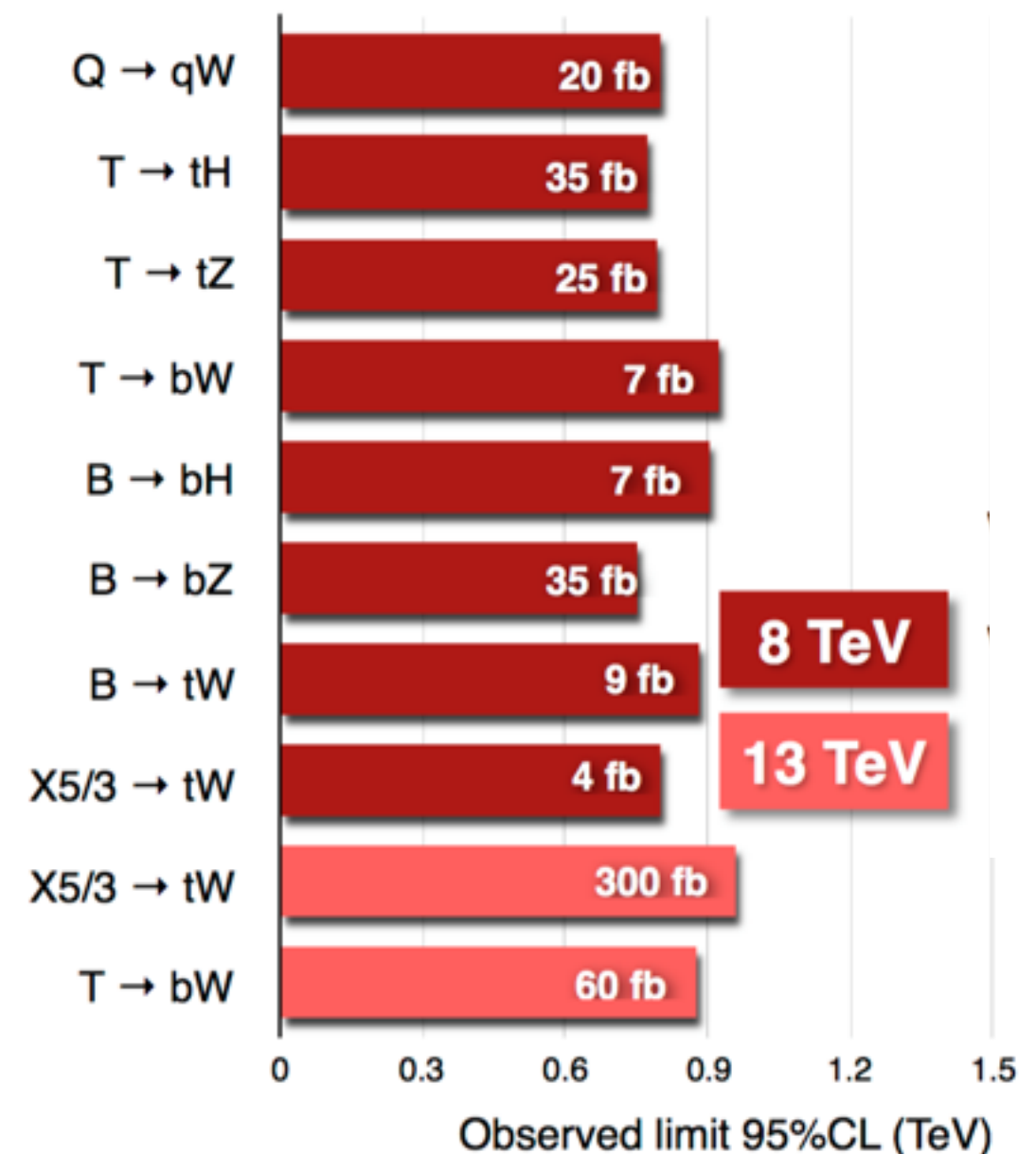
# Vector Like Quarks (III)

<http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html>

**Vector-like quark single production**



**Vector-like quark pair production**



# excited quarks (I)

**effective Lagrangian:** 
$$\mathcal{L}_{eff} = \frac{1}{2M^*} \bar{Q}^* \sigma^{\mu\nu} \left[ g_s f_s \frac{\lambda^a}{2} F_{\mu\nu}^a + g f \frac{\vec{\tau}}{2} \vec{W}_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q_L + h.c. .$$

**$Q^*$  decay widths:**

$$\Gamma(Q^* \rightarrow gq) = \frac{1}{3} \alpha_s f_s^2 M^* , \quad (2)$$

$$\Gamma(Q^* \rightarrow \gamma q) = \frac{1}{4} \alpha f_\gamma^2 M^* , \quad (3)$$

$$\Gamma(Q^* \rightarrow Vq) = \frac{1}{8} \frac{g_V^2}{4\pi} f_V^2 M^* \left(1 - \frac{m_V^2}{M^{*2}}\right)^2 \left(2 + \frac{m_V^2}{M^{*2}}\right) . \quad (4)$$

Here

$$f_\gamma = f T_3 + f' \frac{Y}{2} , \quad (5)$$

$$f_Z = f T_3 \cos^2 \theta_W - f' \frac{Y}{2} \sin^2 \theta_W , \quad (6)$$

decay mode	br. ratio [%]	decay mode	br. ratio [%]
$U^* \rightarrow ug$	83.4	$D^* \rightarrow dg$	83.4
$U^* \rightarrow dW$	10.9	$D^* \rightarrow uW$	10.9
$U^* \rightarrow u\gamma$	2.2	$D^* \rightarrow d\gamma$	0.5
$U^* \rightarrow uZ$	3.5	$D^* \rightarrow dZ$	5.1

$$f_W = \frac{f}{\sqrt{2}} , \quad (7)$$

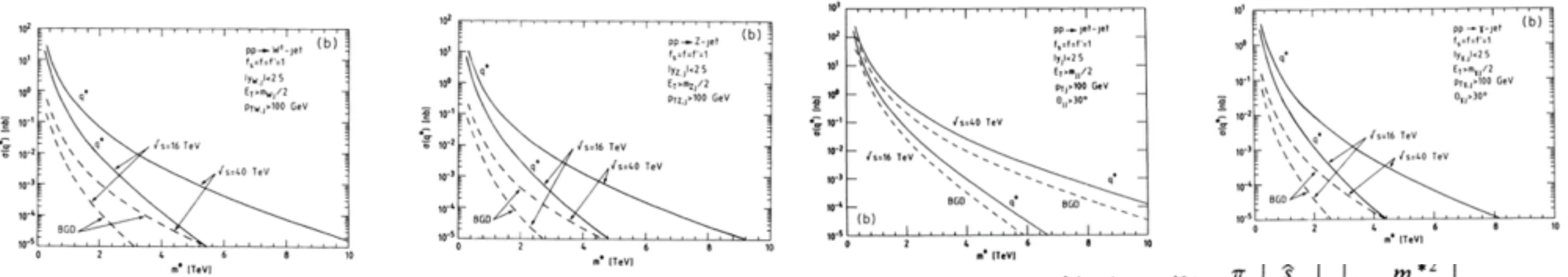
# excited quarks (II)

## Gauge interactions:

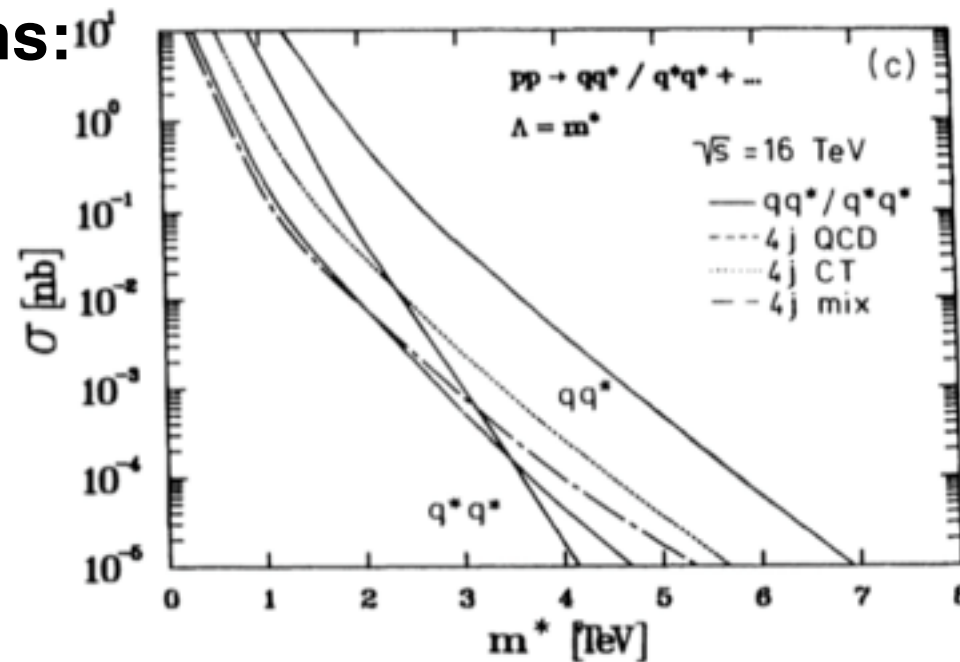
$$\sigma = \frac{\alpha_s \pi^2}{3\Lambda^2} f_s^2 \tau \frac{d\mathcal{L}^{8q}}{d\tau}$$

with

$$\tau = \frac{m^{*2}}{s}$$



## Contact interactions:



$$\hat{\sigma}(qq' \rightarrow qq'^*) = \frac{\pi}{\hat{s}} \left| \frac{\hat{s}}{\Lambda^2} \right| \left| 1 - \frac{m^{*2}}{\hat{s}} \right|,$$

$$\hat{\sigma}(qq \rightarrow qq^*) = \frac{8}{3} \hat{\sigma}(qq' \rightarrow qq'^*)$$

and

$$\hat{\sigma}(q\bar{q} \rightarrow q'\bar{q}'^*) = \frac{\pi}{4\hat{s}} \left| \frac{\hat{s}}{\Lambda^2} \right|^2 \left[ 1 + \frac{v}{3} \right] \times \left[ 1 - \frac{m^{*2}}{\hat{s}} \right]^2 \left[ 1 + \frac{m^{*2}}{\hat{s}} \right],$$

$$\hat{\sigma}(q\bar{q}' \rightarrow q\bar{q}'^*) = \hat{\sigma}(q\bar{q} \rightarrow q'\bar{q}'^*),$$

$$\hat{\sigma}(q\bar{q} \rightarrow q\bar{q}^*) = \frac{8}{3} \hat{\sigma}(q\bar{q} \rightarrow q'\bar{q}'^*)$$



*tools*

# pruning

- remove soft, large angle constituents from the jet
- it reclusters the jet using Cambridge-Aachen algorithm, requiring each recombination to be satisfying:

$$\frac{\min(p_{T1}, p_{T2})}{p_{Tp}} > 0.1 \quad \Delta R_{12} < 0.5 \times \frac{m_{\text{jet}}}{p_T}$$

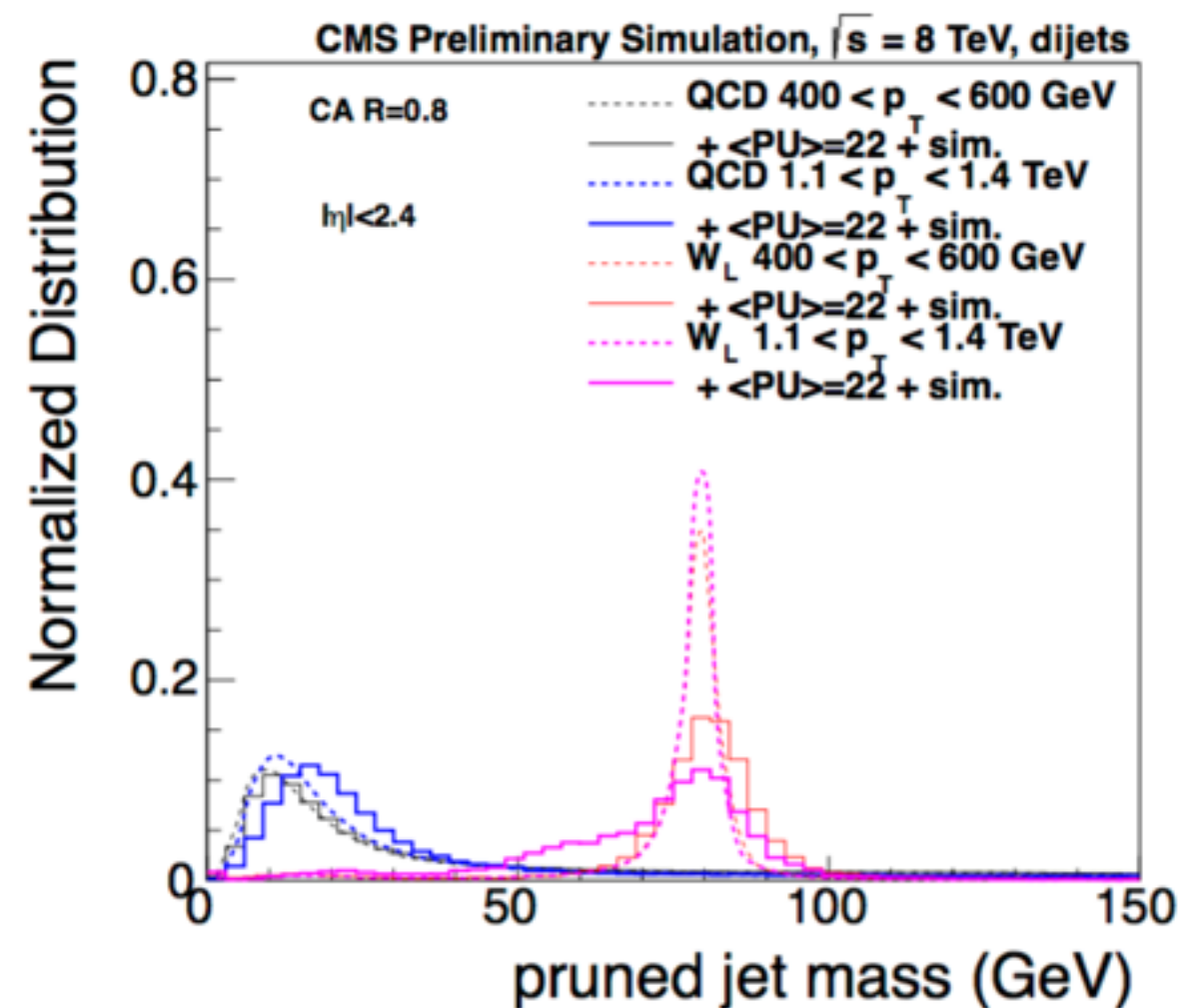
Removes soft particles

Removes wide angle particles

- QCD jet mass peaking to zero

*Ellis, Stephen, Vermilion, Christopher and Walsh*  
 10.1103/PhysRevD.81.094023

JME-13-006



# soft-drop

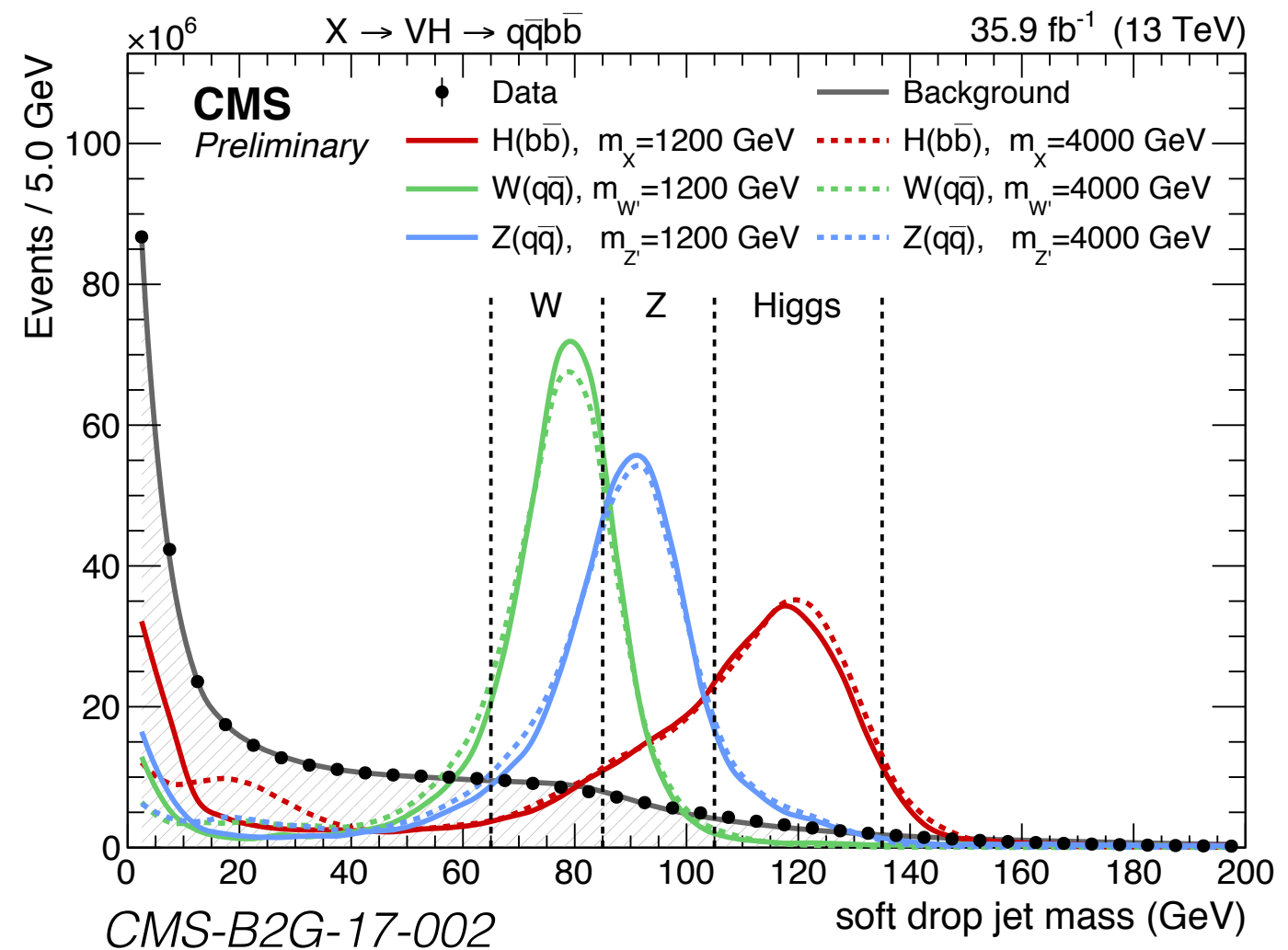
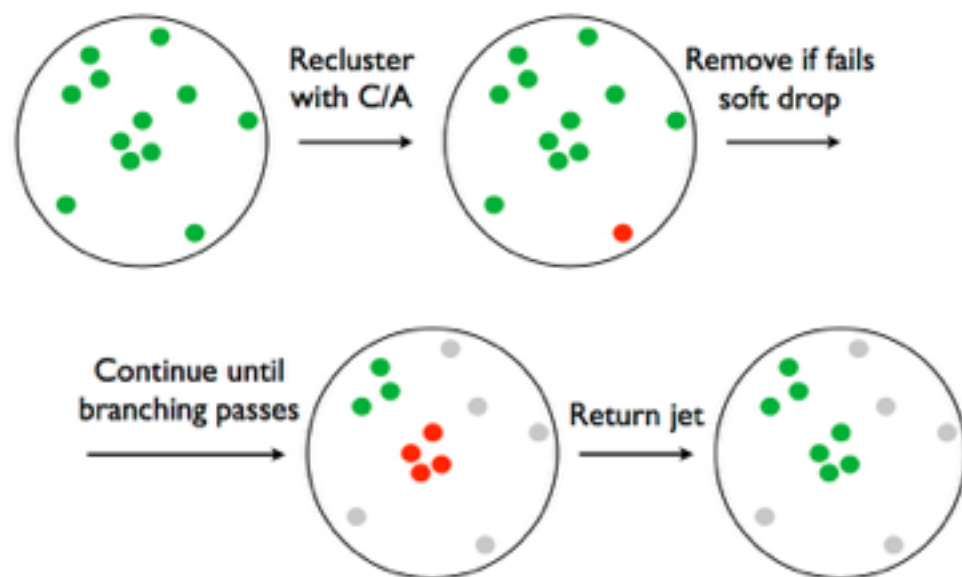
- remove soft, large angle constituents from the jet
- it reclusters the jet using Cambridge-Aachen algorithm and then declusters if the jet pass the requirements

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta$$

Soft threshold

Angular exponent

tuning parameters are  $z_{\text{cut}}$  and  $\beta$



Larkoski, Marzani, Soyez, Thaler  
JHEP 05 (2014) 146 16

# N-subjetiness

- $p_T$ -weighted sum over all jet constituents of the distance w.r.t the closest of  $N$  axes in a jet
  - Axes are obtained by undoing last  $(N-1)$  steps of jet clustering algorithm
  - Small  $\tau_N$  indicates compatibility with  $N$  axes hypothesis

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

Distance between momentum of constituent  $k$  w.r.t momentum of rest-frame subjet  $N$

Each constituent assigned to nearest subjet!

- To discriminate 2 prong W/Z/H jets from 1 prong q/g jets the ratio  $\tau_2/\tau_1$  is used
- To discriminate 3 prong t jets  $\tau_3$  is used

