



Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG



search for fermionic top partners at CMS



GEFÖRDERT VOM



SUSY2016

2016 / 07 / 03-08

Heiner Tholen
for the CMS Collaboration

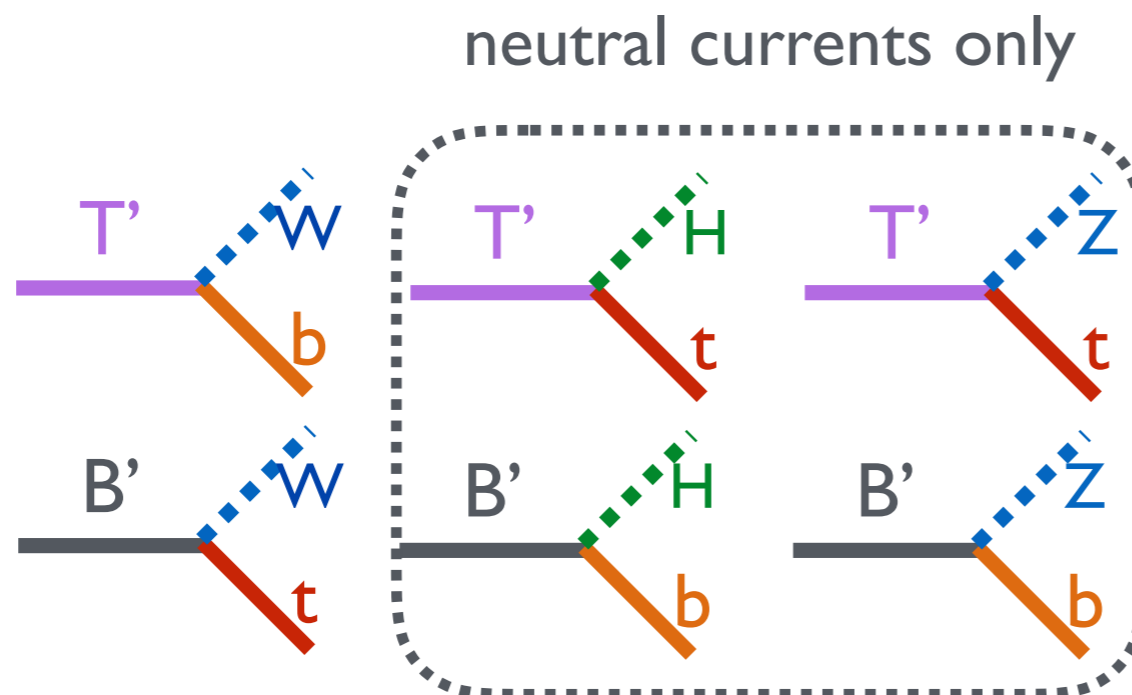
vector-like quarks (VLQ)

- **quarks!** colored, charged, spin 1/2
- **vector-like:** same coupling to lh and rh currents
=> mass terms without gauge inv. violation
- **not constrained** through Higgs discovery
(unlike chiral 4th-gen quarks)
- simplest colored extra-fermions allowed by data
- common in SM-extensions:
 - e.g. little Higgs, composite Higgs, warped/extra dimensions
 - solve the Hierarchy problem
 - stabilize the Higgs mass

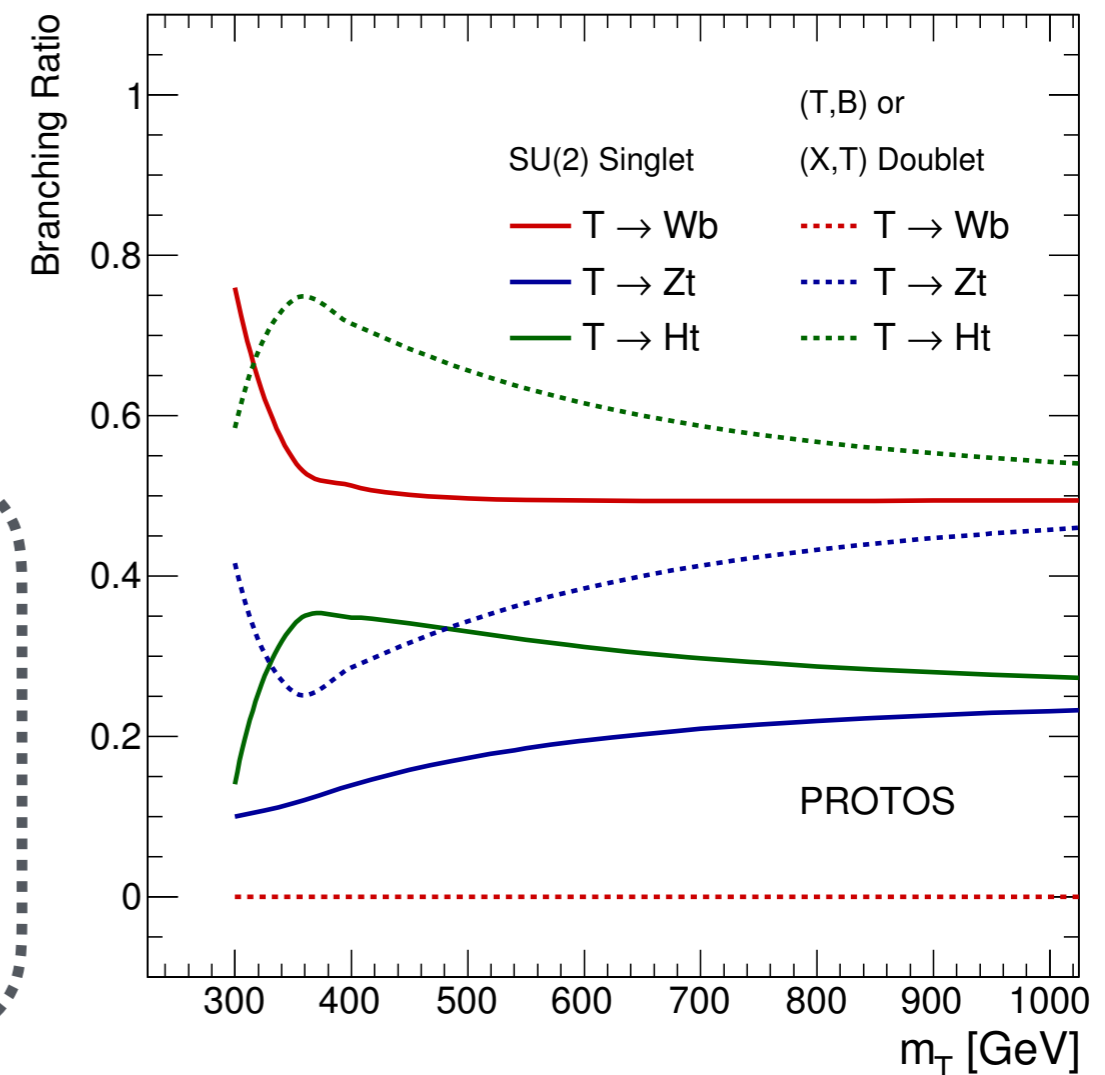
Singlets	Doublets	Triplets	Notation: $\text{Isospin}_{\text{Hypercharge}}$ $\left. \begin{array}{l} T \rightarrow +2/3 \\ B \rightarrow -1/3 \\ X \rightarrow +5/3 \\ Y \rightarrow -4/3 \end{array} \right\} \begin{array}{l} \text{charge} \\ \text{Electric} \end{array}$
$\mathbf{1}_{2/3} = T$ $\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$ $\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$ $\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$ $\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$	

vector-like quarks (VLQ)

- **quarks!** colored, charged, spin 1/2
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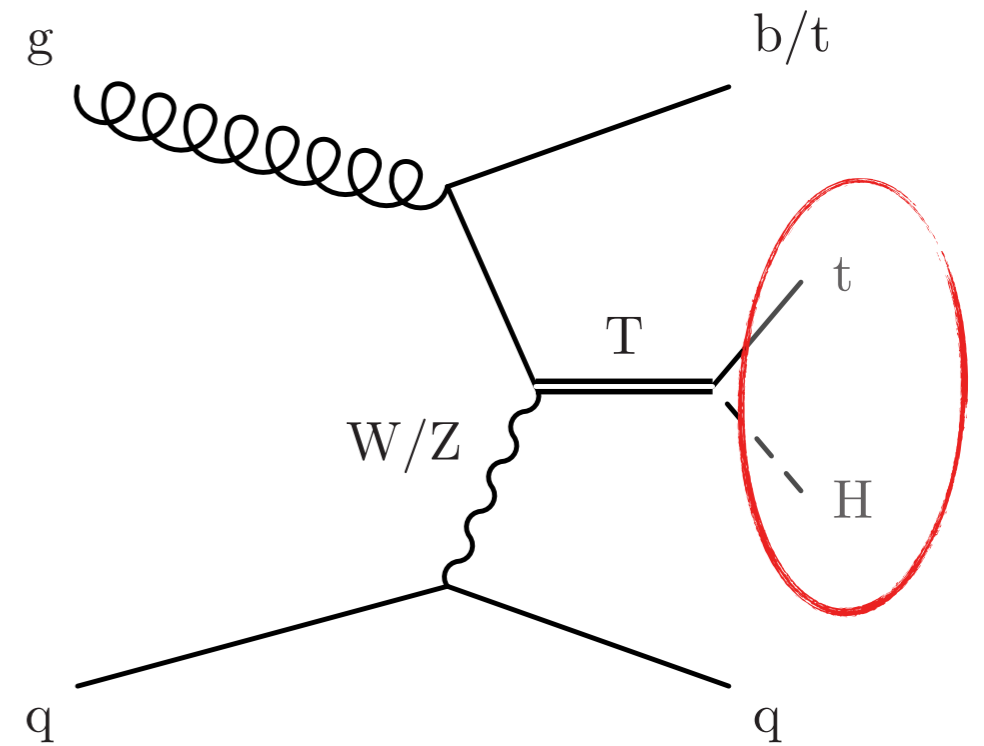
[JHEP 08 (2015) 105]



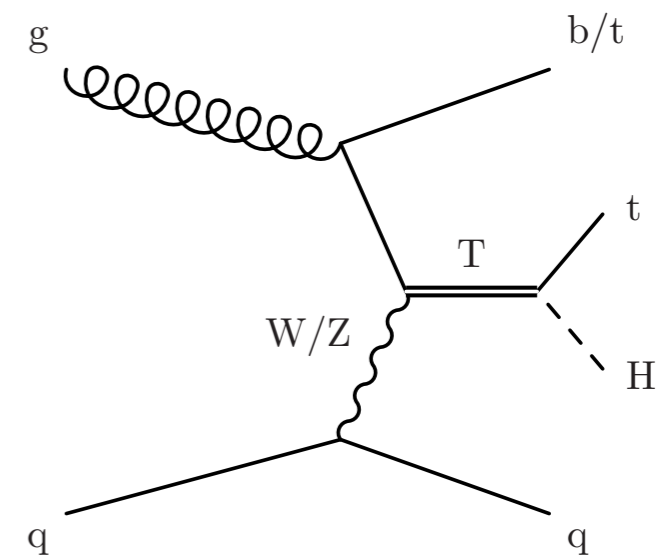
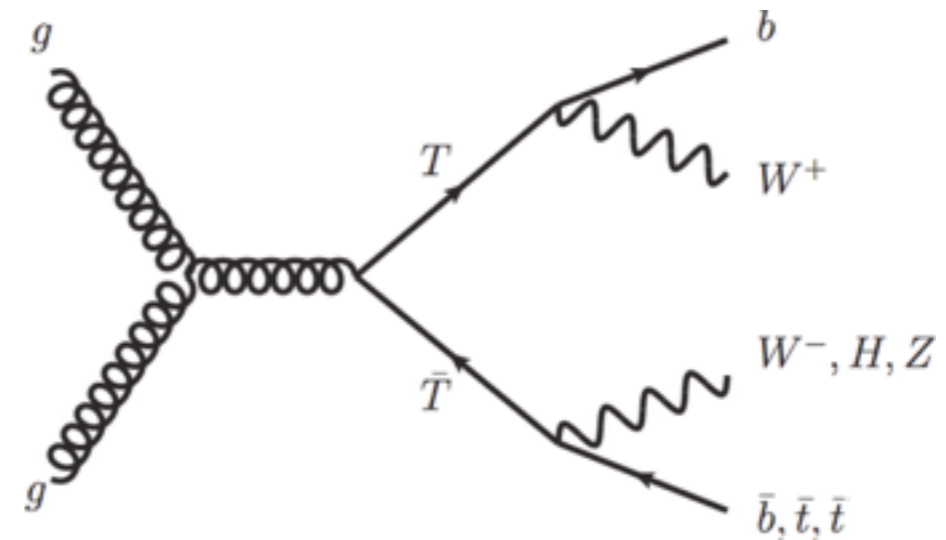
analysis techniques

- heavy vector like quarks ($> 700 \text{ GeV}$)
 - \Rightarrow heavily boosted decay products
- jet tagging
 - V (W, Z, H) tags:
 - CA8 or AK8 jets, $p_T > 200 \text{ GeV}$
 - e.g. $50 < \text{groomed mass} < 150 \text{ GeV}$
 - H tag: use b tags on soft drop subjets
 - N subjettiness: τ_2 / τ_1
 - t tags:
 - CA15 or AK8 jets, $p_T > 200 \text{ GeV}$
 - e.g. $110 < \text{groomed mass} < 210 \text{ GeV}$
 - one soft drop subjets b tagged
 - N subjettiness: τ_3 / τ_2
- lepton isolation
 - p_T dependent lepton isolation
(scales iso cone with pt)
$$R = \frac{10}{\min(\max(p_T, 50), 200)}$$

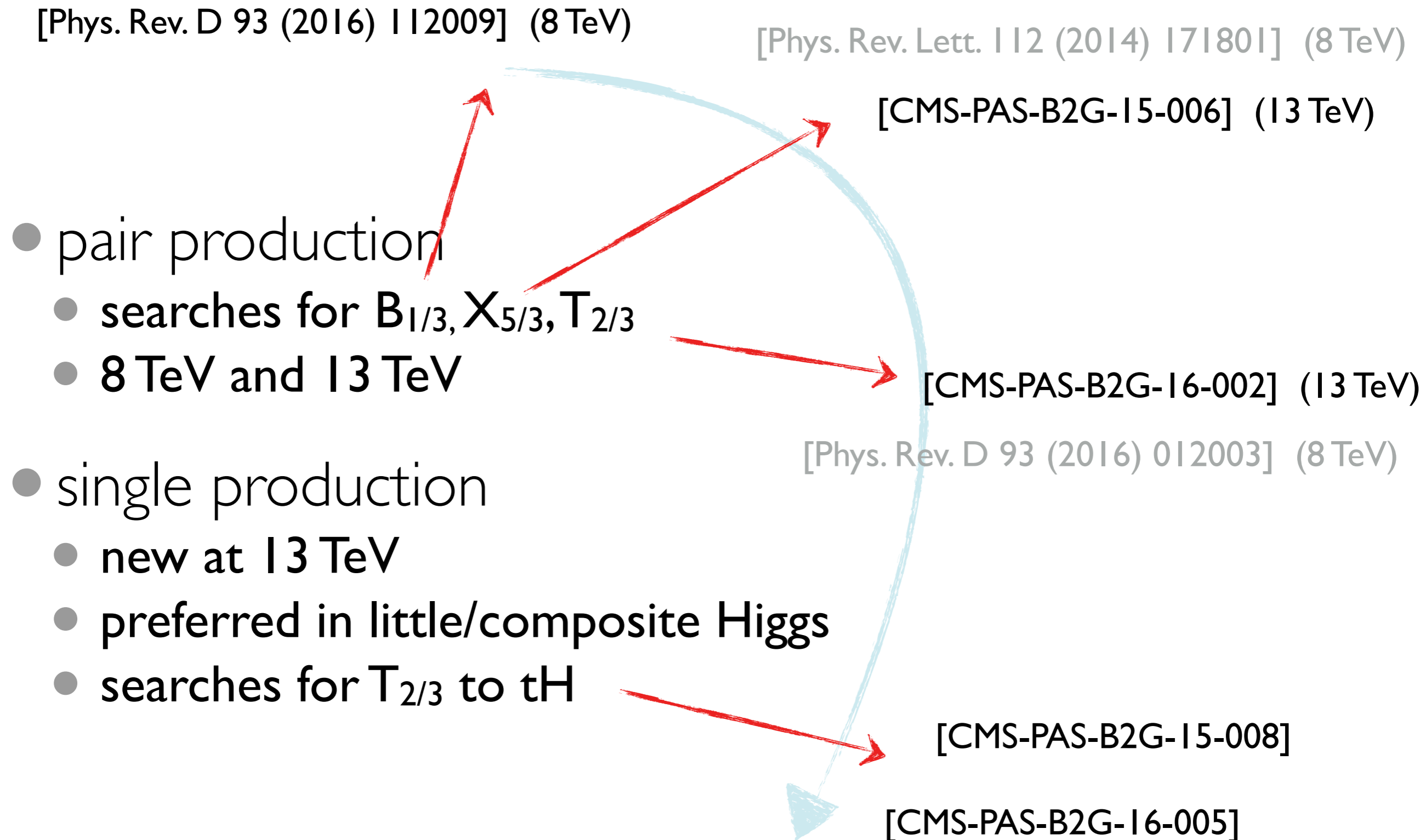
jet grooming:
pruning / soft drop



- pair production
 - searches for $B_{1/3}, X_{5/3}, T_{2/3}$
 - 8 TeV and 13 TeV
- single production
 - new at 13 TeV
 - preferred in little/composite Higgs
 - searches for $T_{2/3}$ to tH



overview of CMS analyses



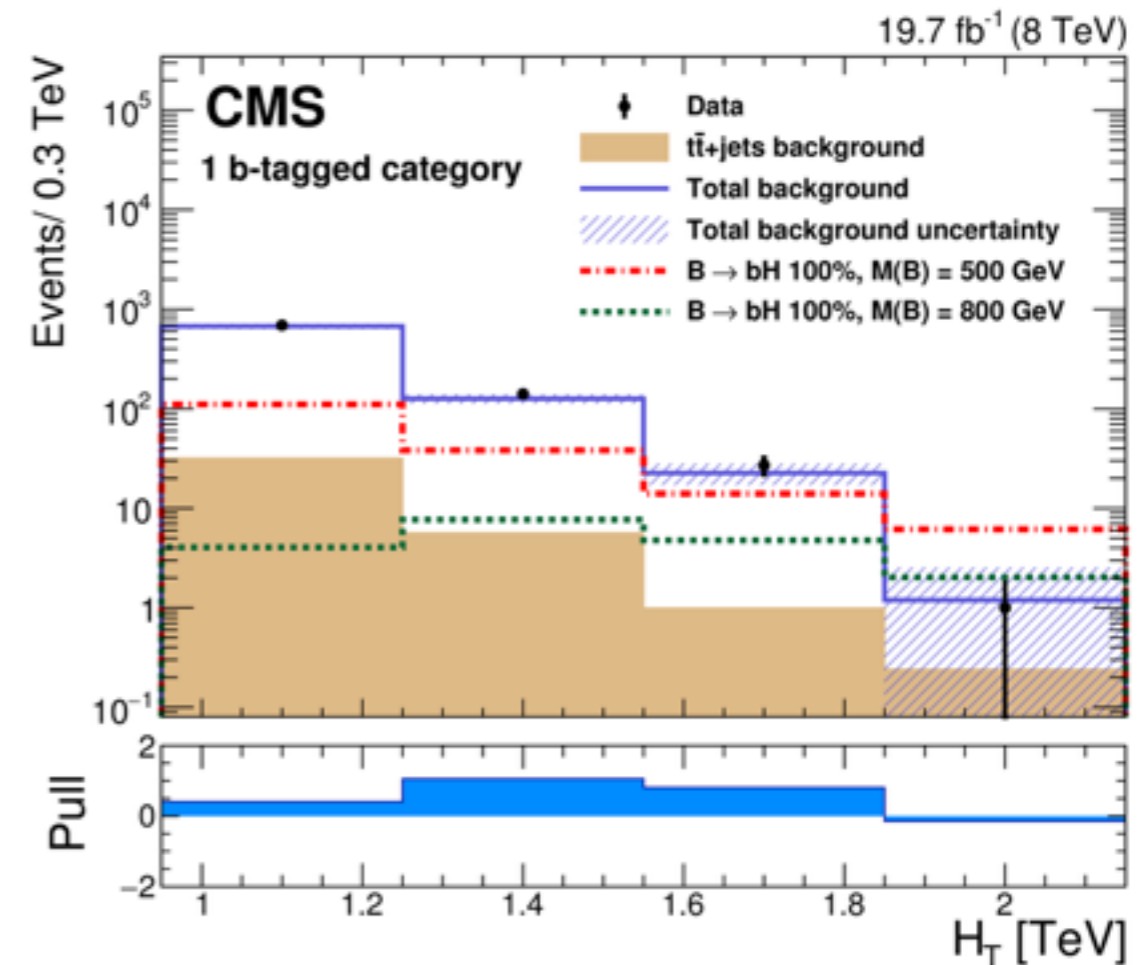
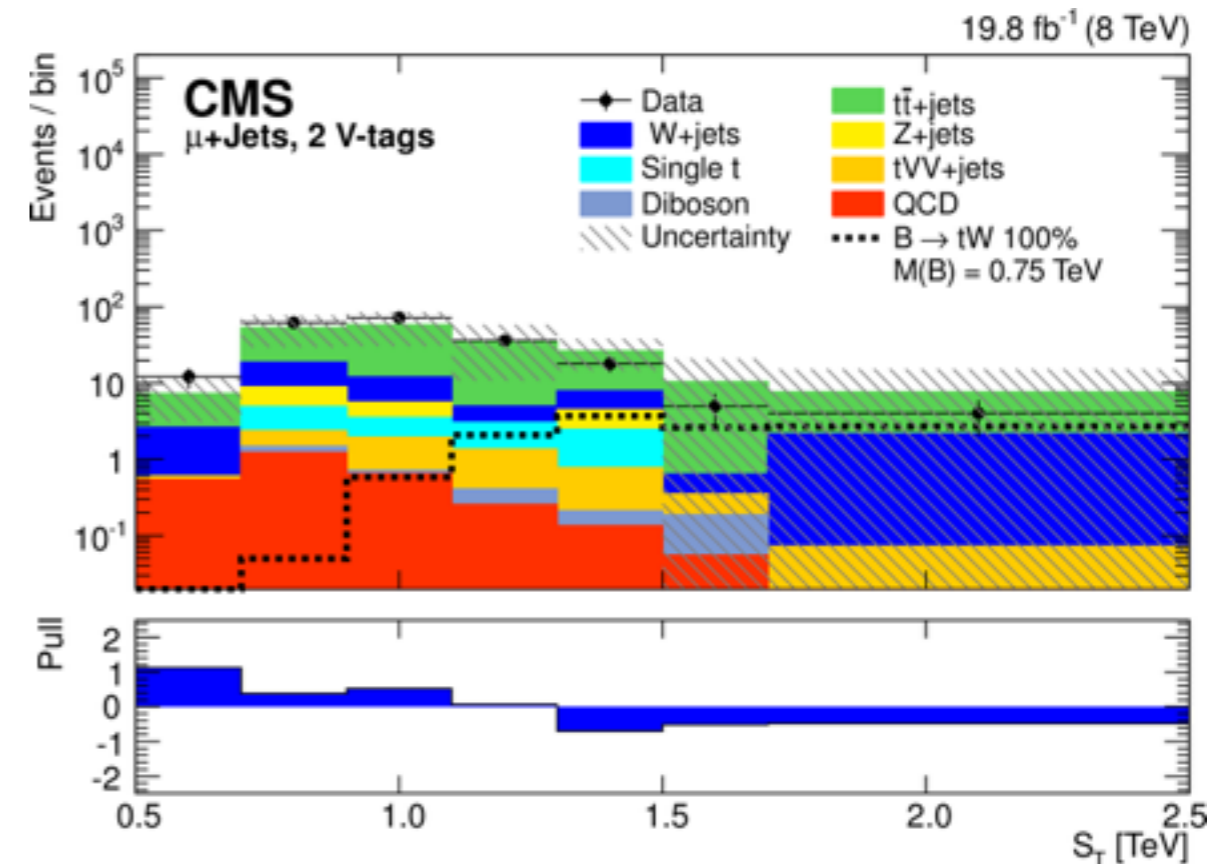
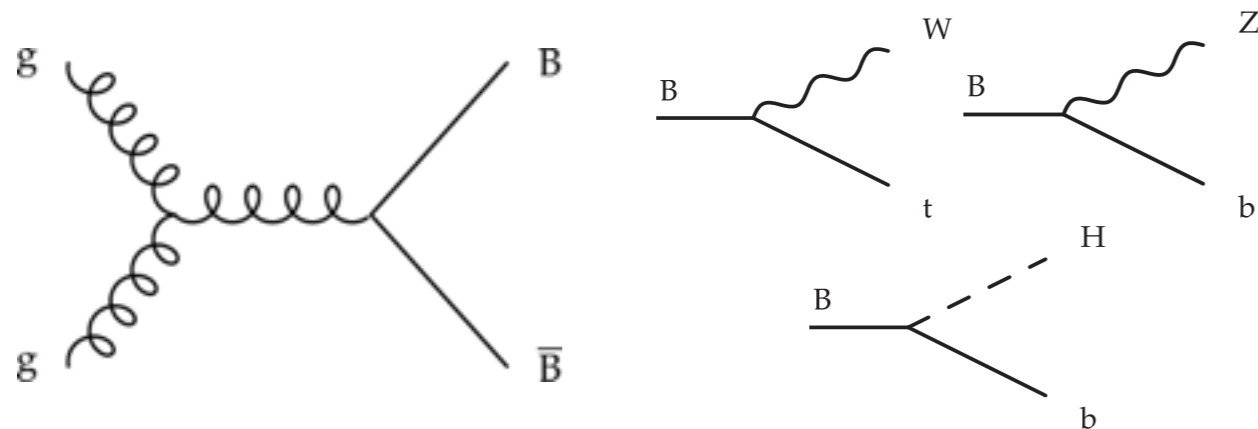
pair production

● B pair production (8 TeV) [Phys. Rev. D 93 (2016) 112009] BB production (8 TeV)

- combination of 8 TeV results
- B decay modes: tW , bZ , bH
- final states with $>2, 2, 1$ lepton; all-had;

● tagging

- lepton+jets:
 - V tag (W, Z, H)
 - S_T : scalar sum of pt of all jets and the main lepton
- all-hadronic:
 - focus on $B \Rightarrow bH$ decay
 - tighter H tag incl. $\tau_2 / \tau_1 < 0.5$
 - H_T : scalar sum of pt of all jets

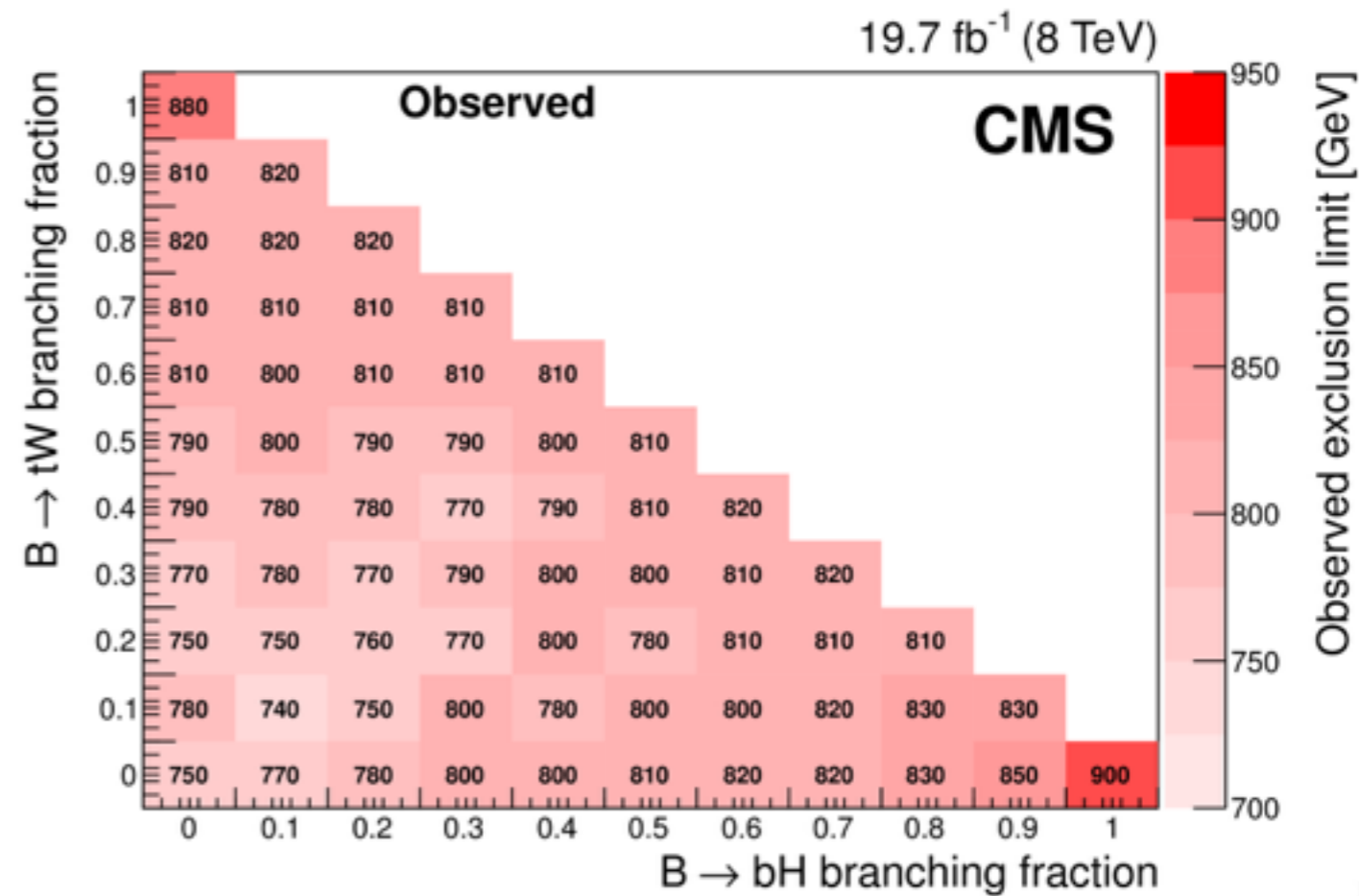
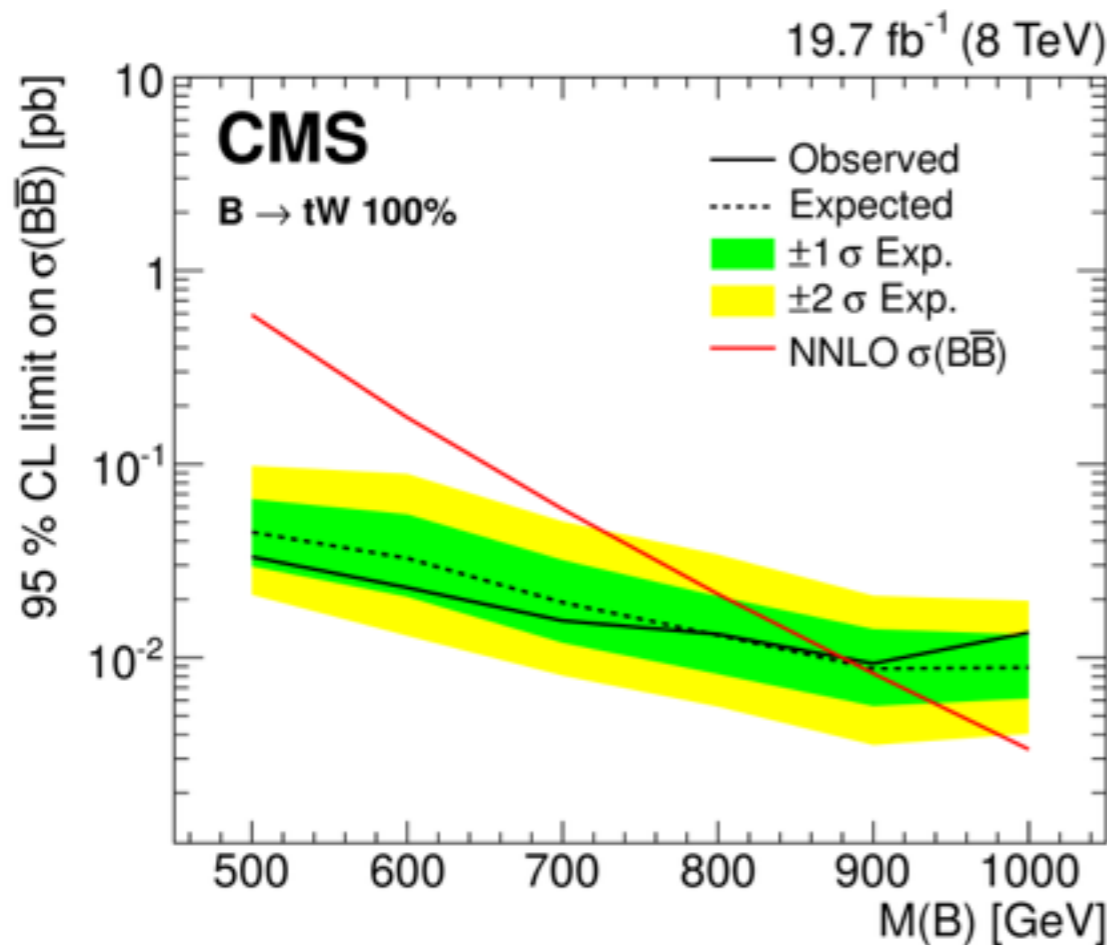
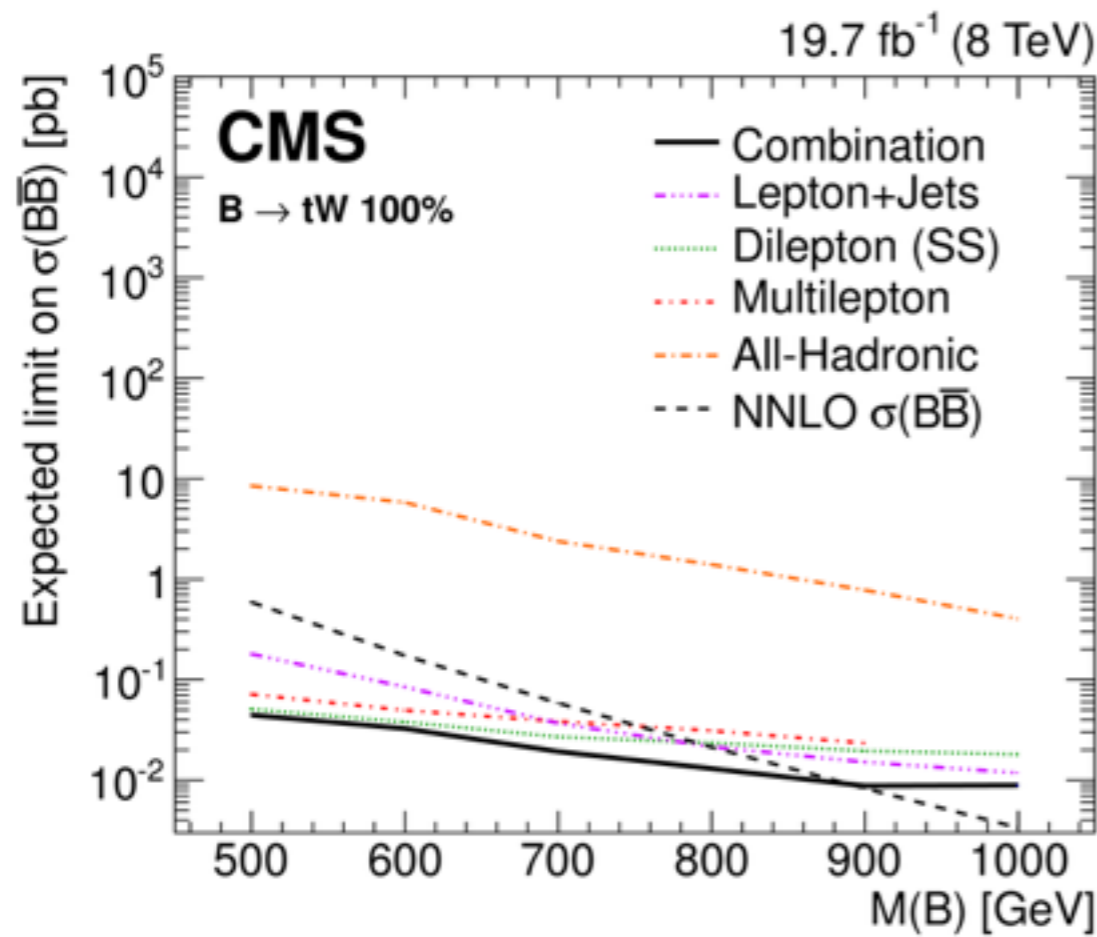


BB production (8 TeV)

[Phys. Rev. D 93 (2016) 112009]

bayesian 95% CL limits

still most stringent
results to date



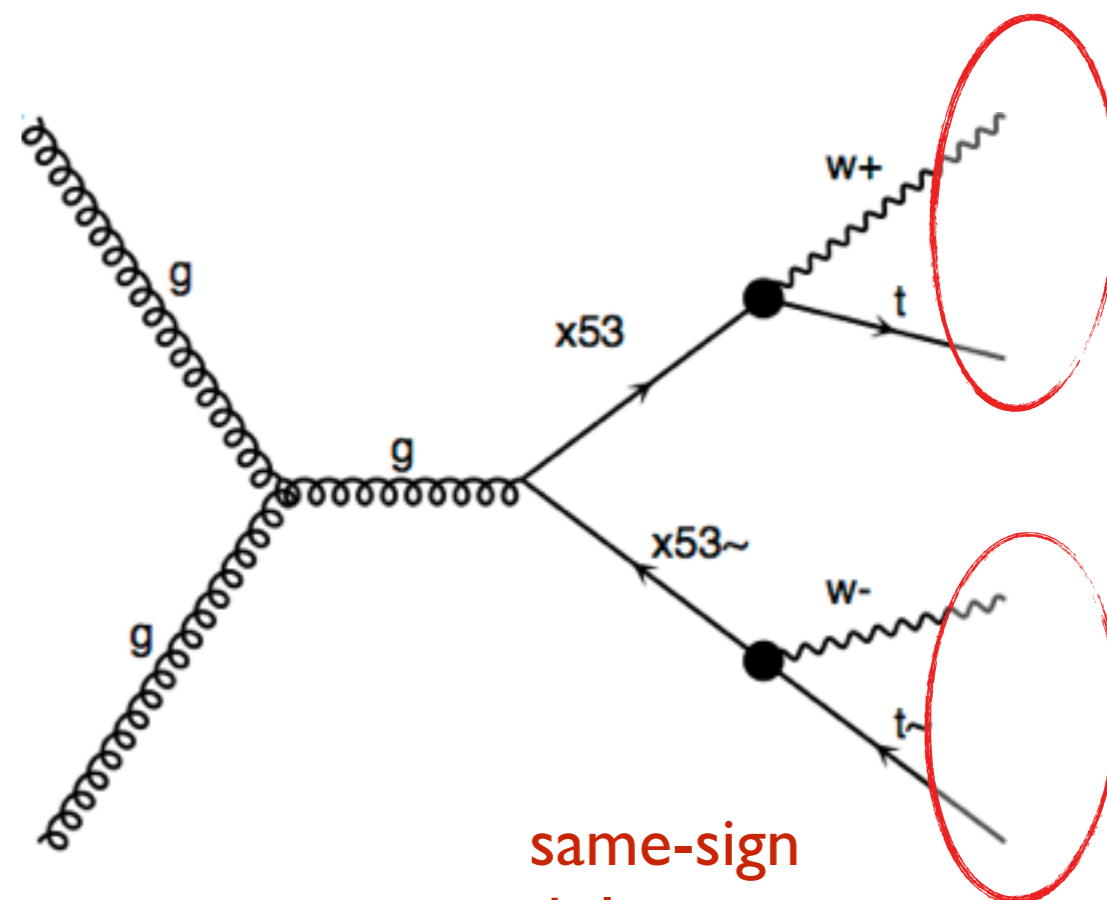
● $X_{5/3}$ pair production

[CMS-PAS-B2G-15-006] pair production (13 TeV)

- two channels
 - same sign di-leptons
 - lepton + jets
- first vector-like quark result at 13 TeV

● techniques / event selection

- p_T dependent lepton isolation
- Z-boson veto
- scalar sum of p_T of jets and leptons ($H_T^{\text{lep}} > 900 \text{ GeV}$)



same-sign
di-leptons
possible

backgrounds:

(ss di-lep) hadrons, conversions, etc.
(using tight-loose ratios)

prompt same sign
leptons (from MC)

electron charge mis-ID
($\#_{\text{opp. sign}} * \text{fake-rate}$)

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11

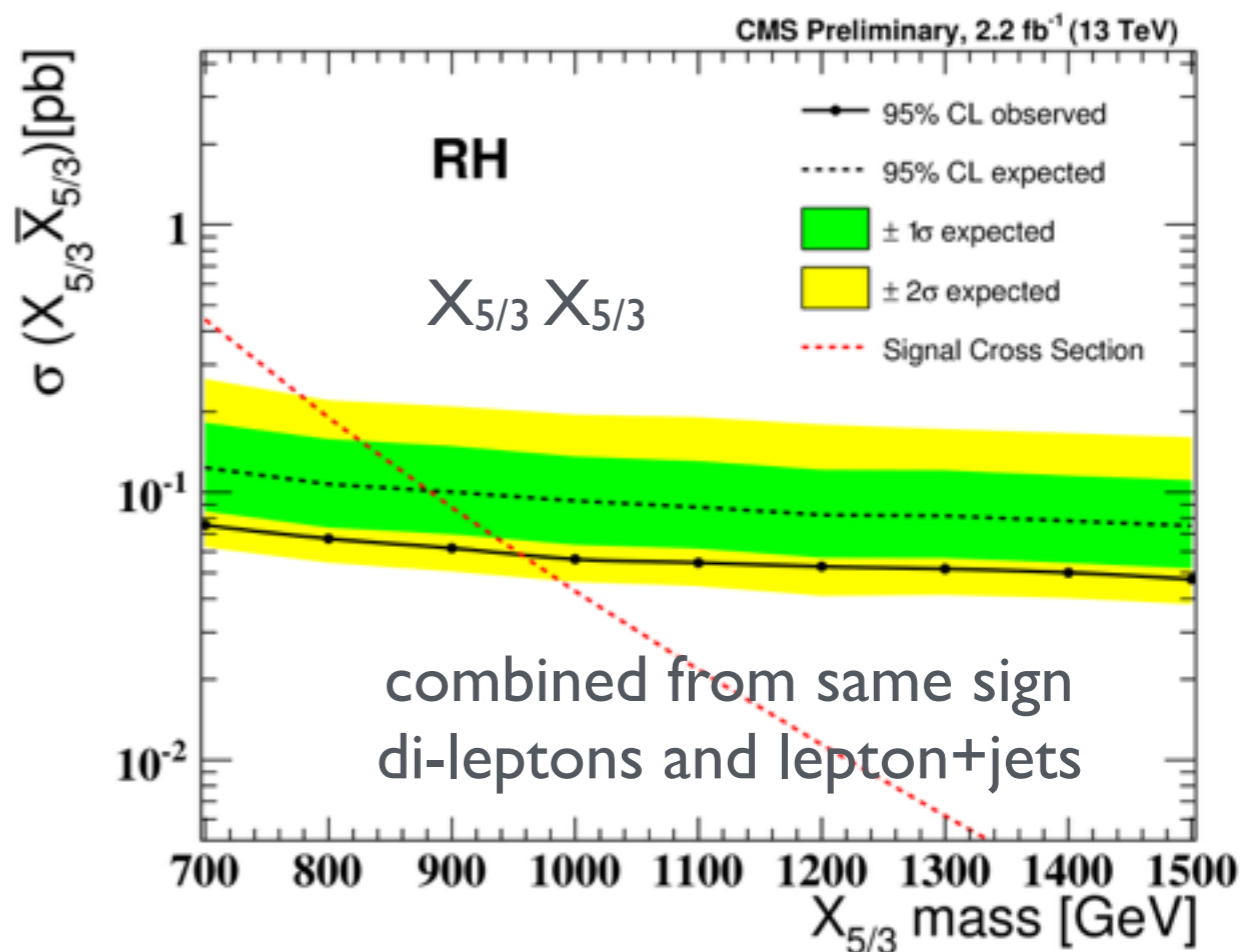
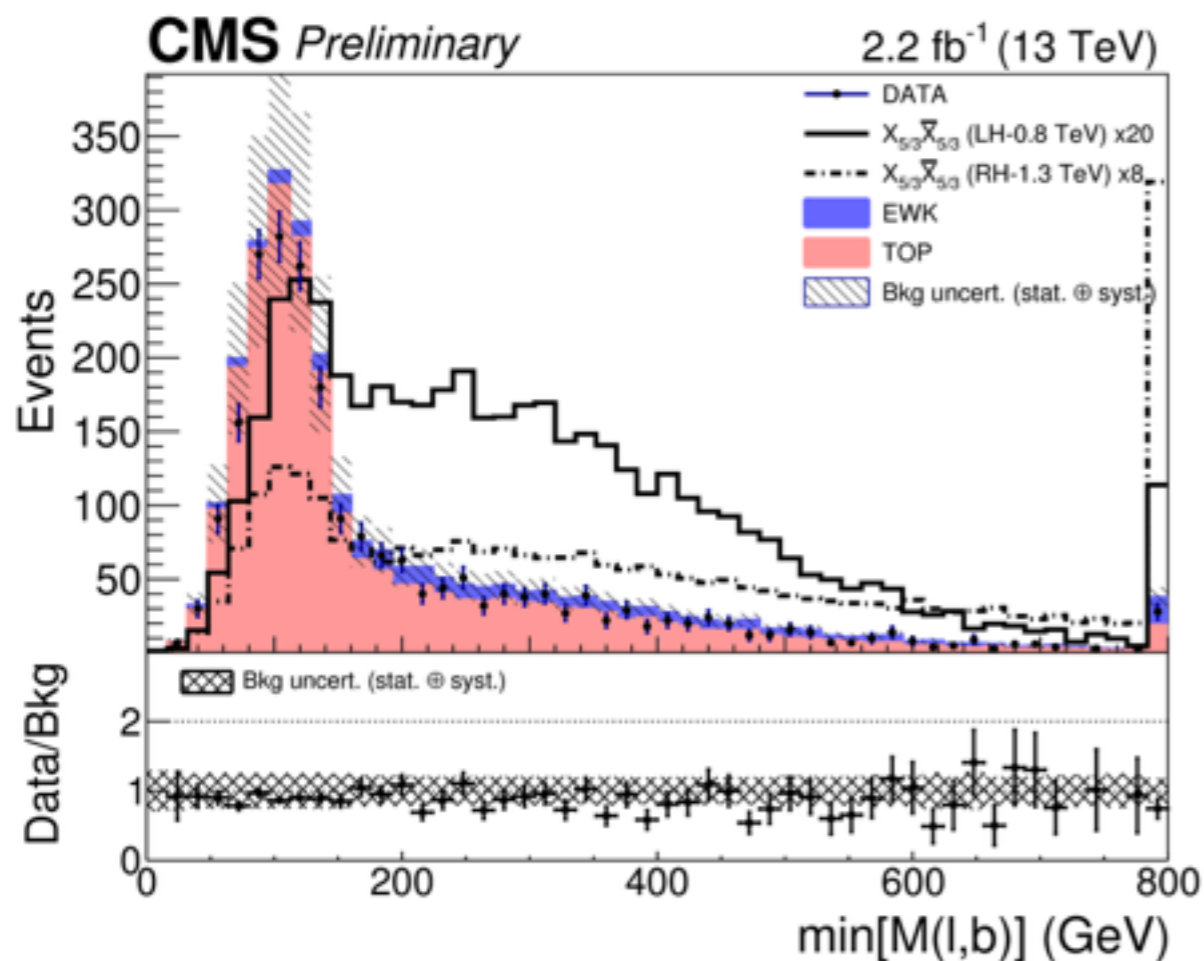
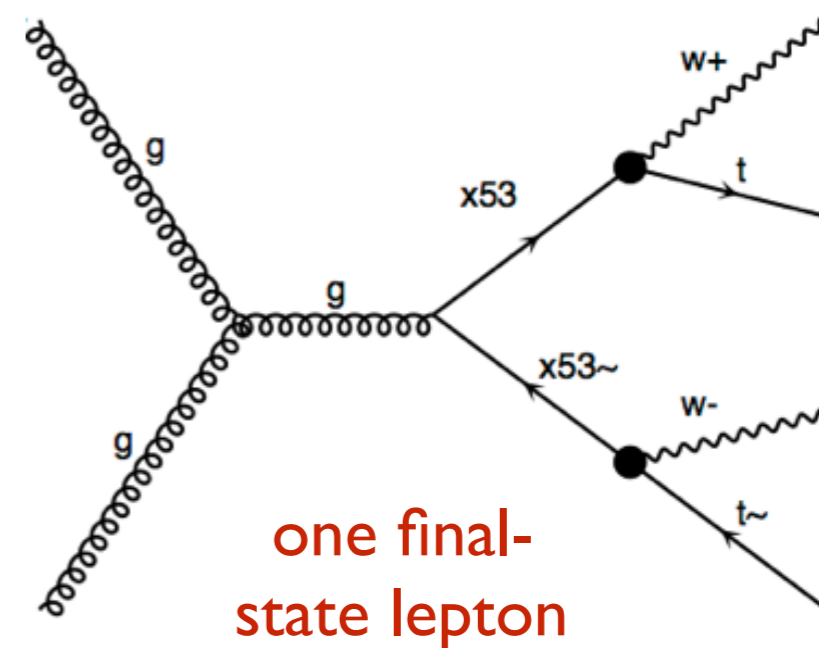
● $X_{5/3}$ pair production

[CMS-PAS-B2G-15-006] pair production (13 TeV)

- two channels
 - same sign di-leptons
 - **lepton + jets**
- first vector-like quark result at 13 TeV

● techniques / event selection

- p_T dependent lepton isolation
- Z-boson veto
- scalar sum of p_T of jets and leptons (H_T^{lep}) > 900 GeV



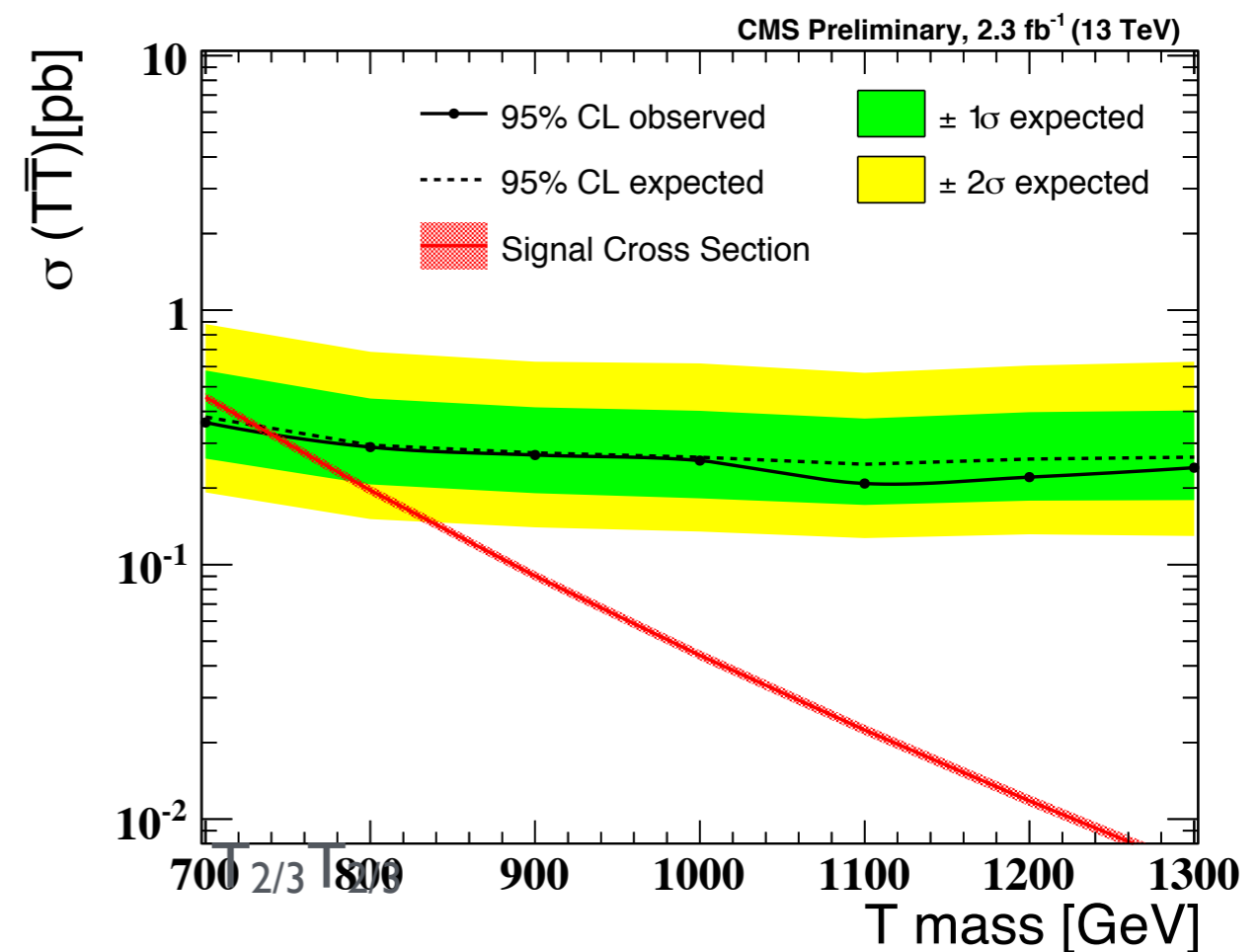
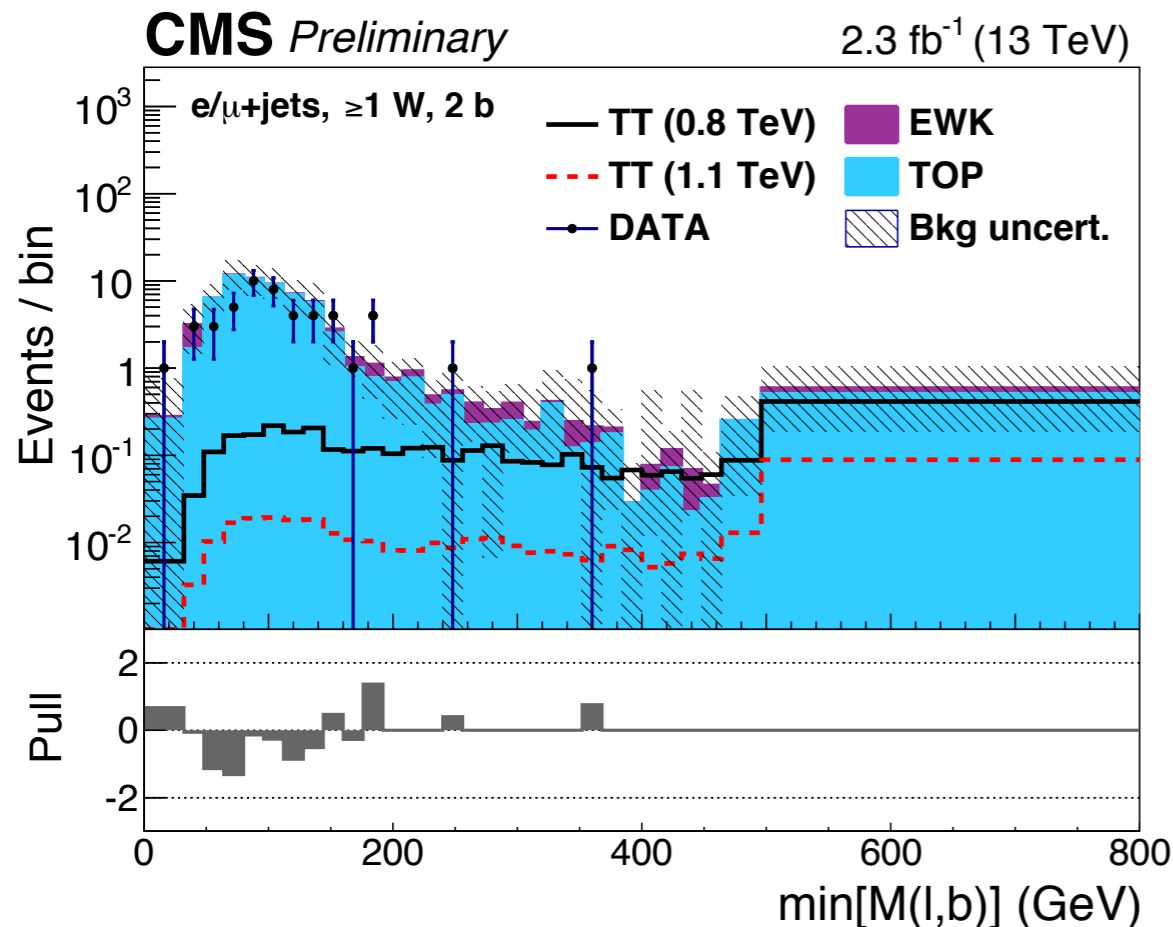
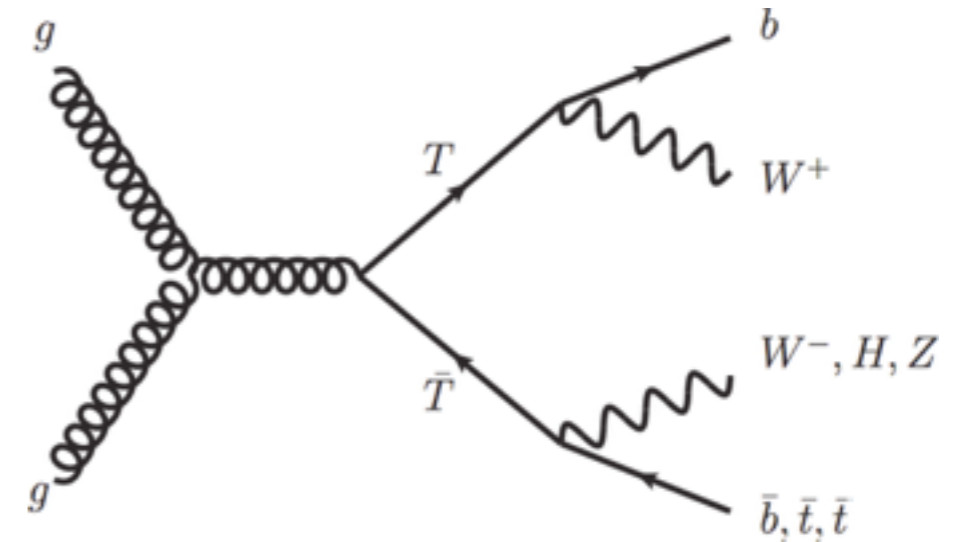
● $T_{2/3}$ pair production

[CMS-PAS-B2G-16-002] pair production (13 TeV)

- lepton + jets
- b tag categories: 0, 1, 2, ≥ 3
- W tag categories: 0, ≥ 1

● techniques / event selection

- p_T dependent lepton isolation
- W tag (incl. $\tau_2 / \tau_1 < 0.6$)



=> excluding $T_{2/3}$ up to 750 GeV (Run I: up to 690 GeV)

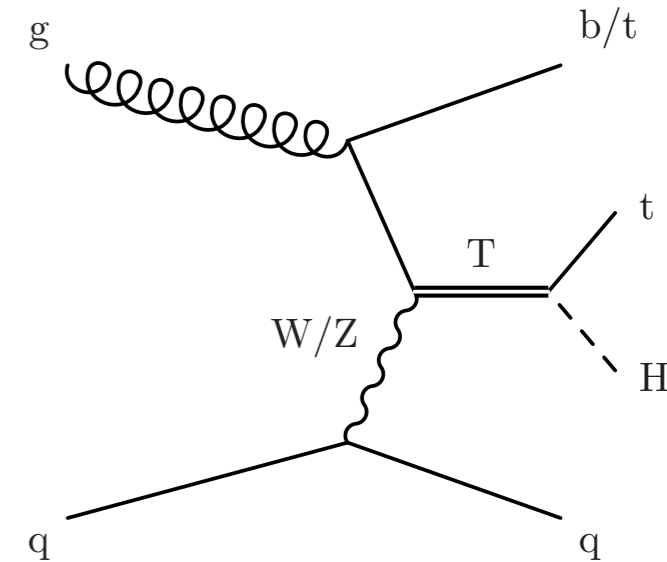
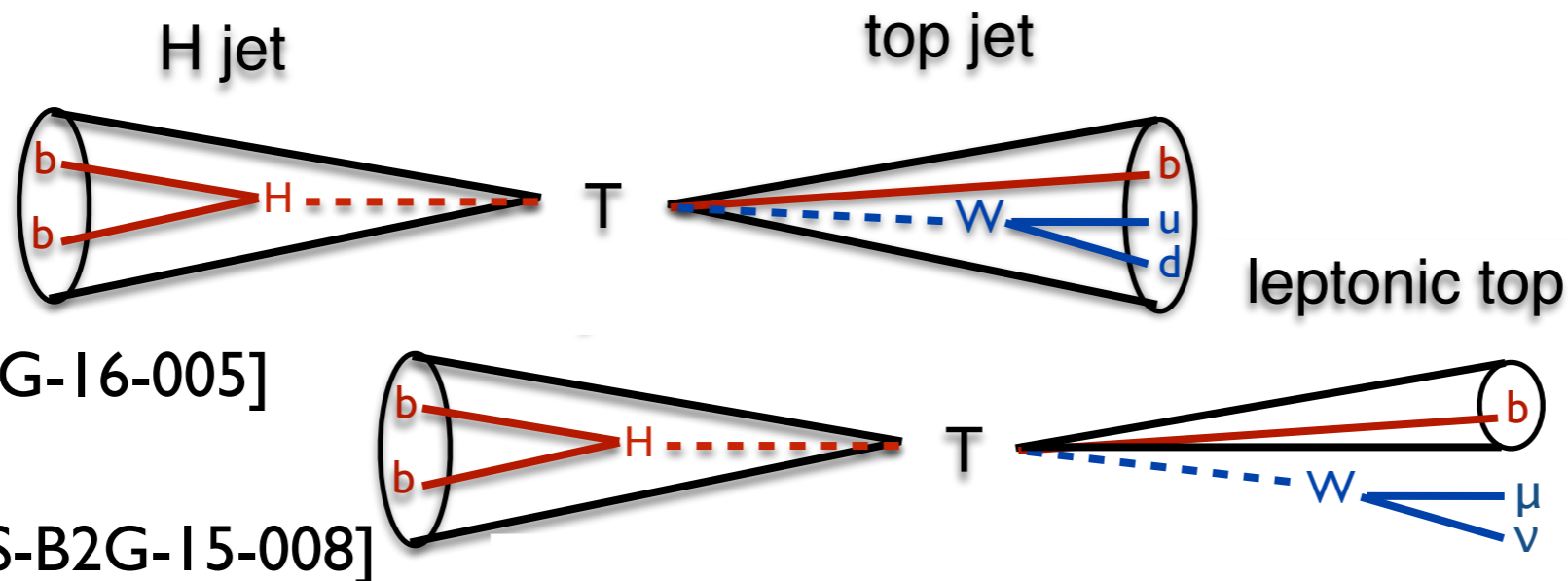
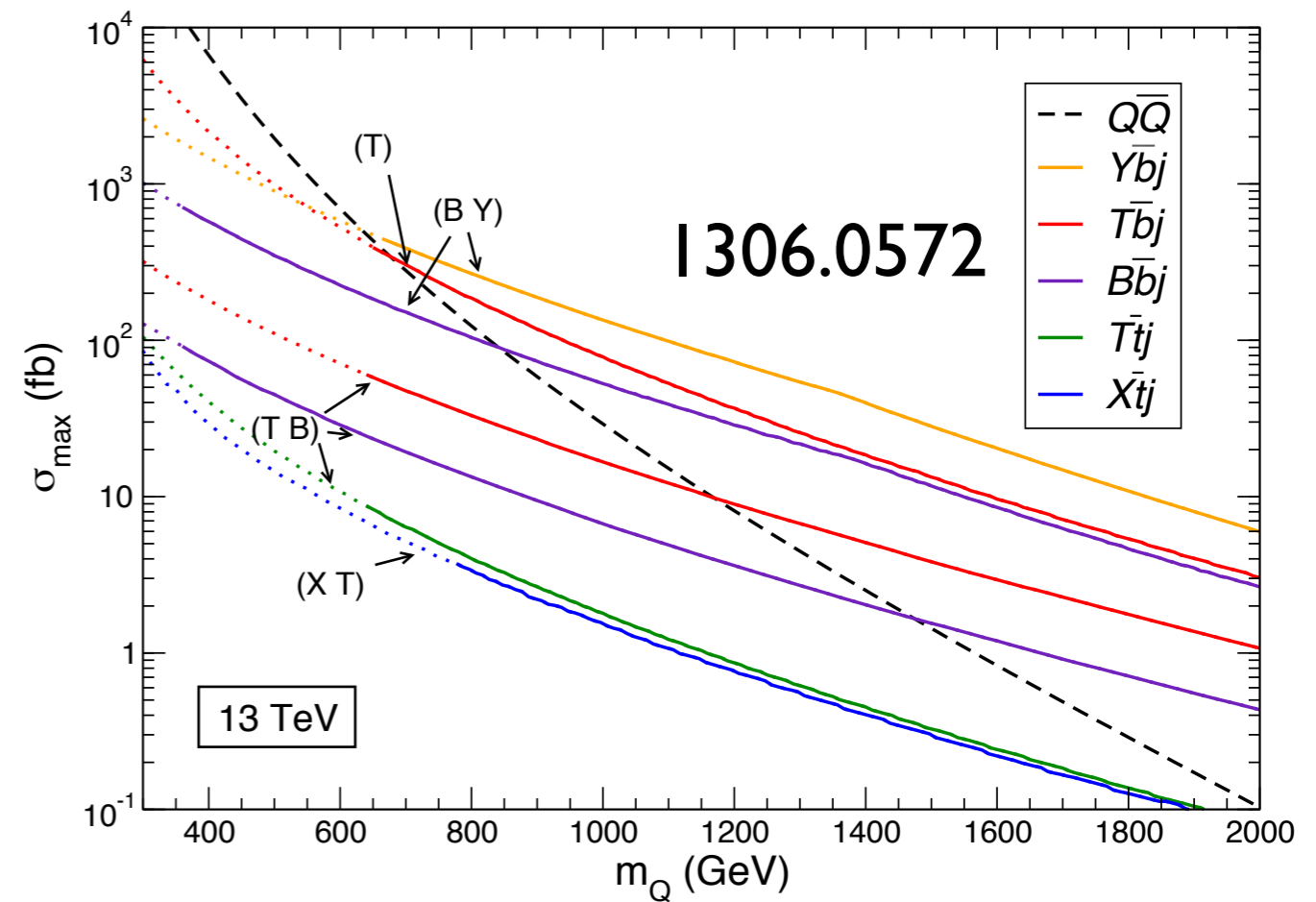
single T production

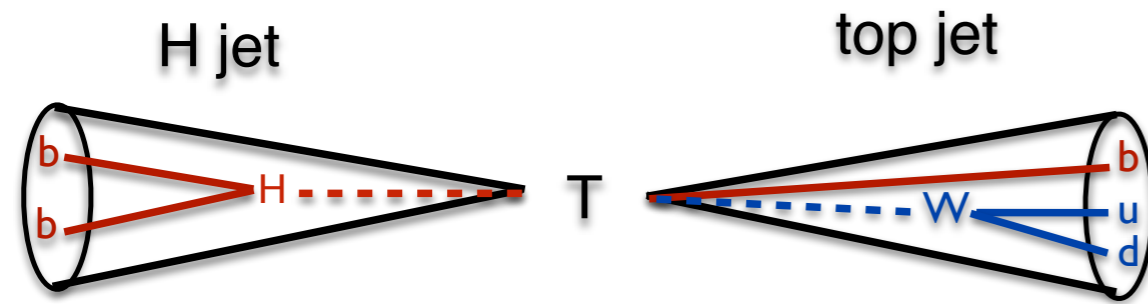
single T production

- searches
 - single vector-like T quark, charge $2/3e$
 - exclusive decay to tH
- bW / tZ coupling is needed in production
- 2.3fb^{-1} at 13 TeV (data taken in 2015)

techniques

- H / t jet tagging
- jet grooming with soft drop / pruning





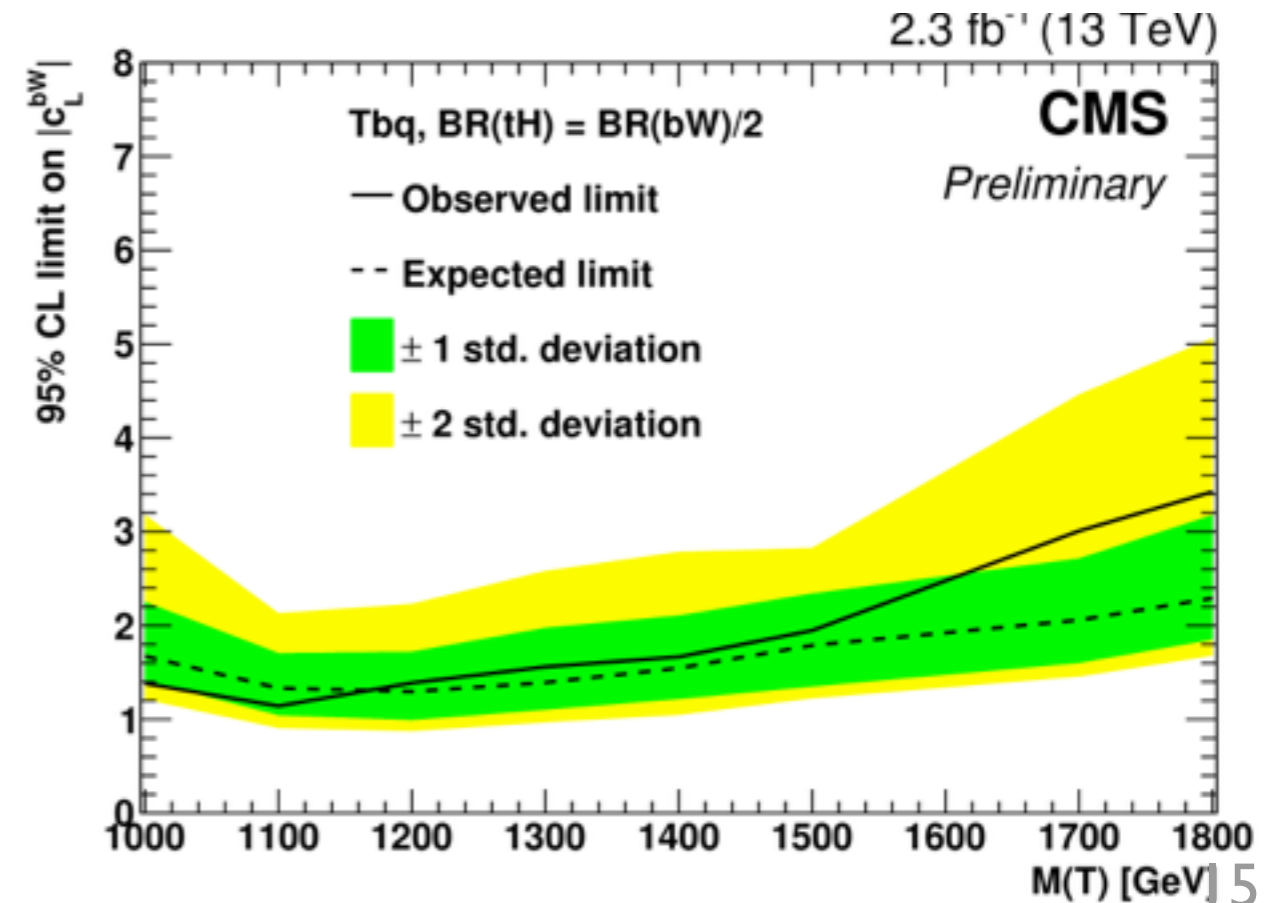
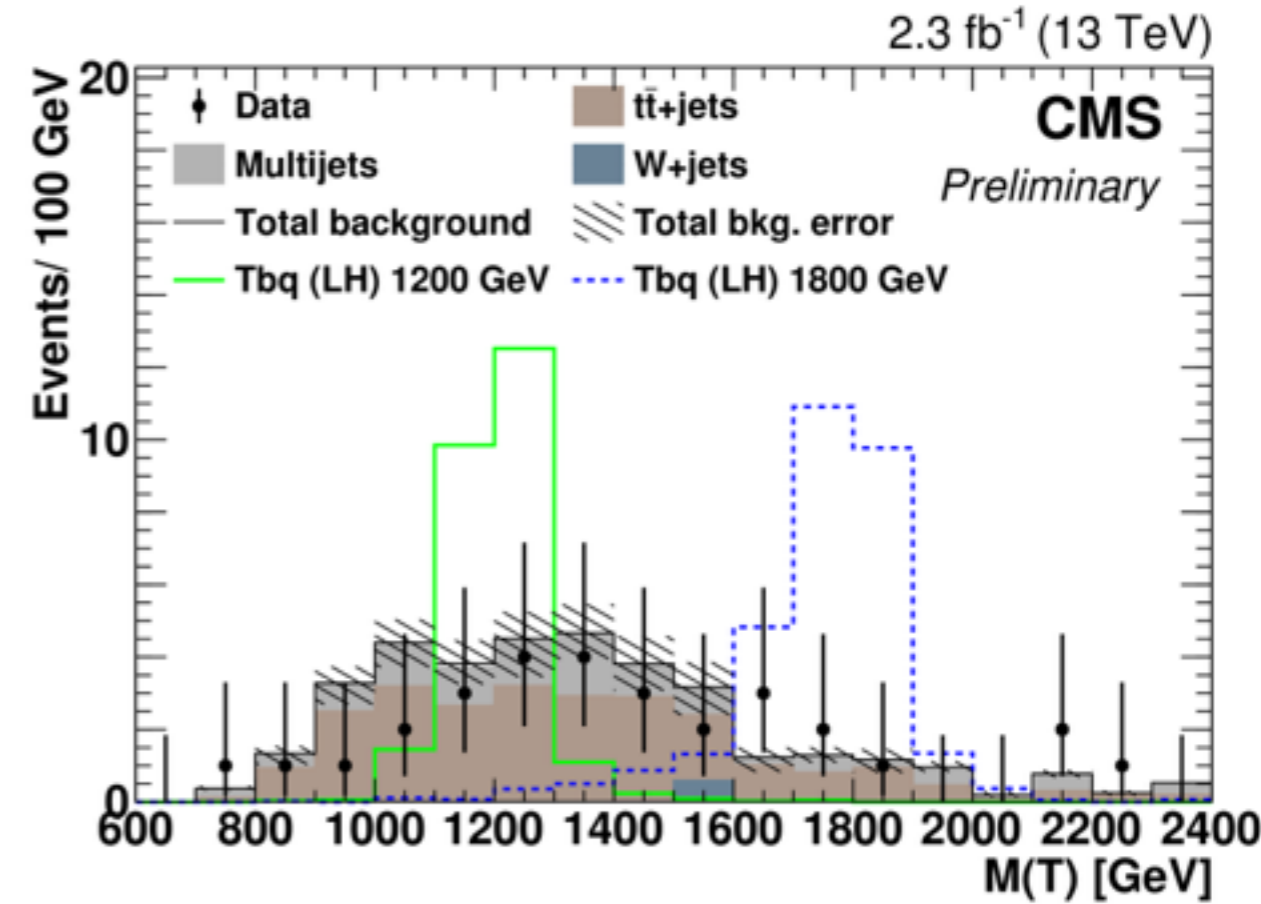
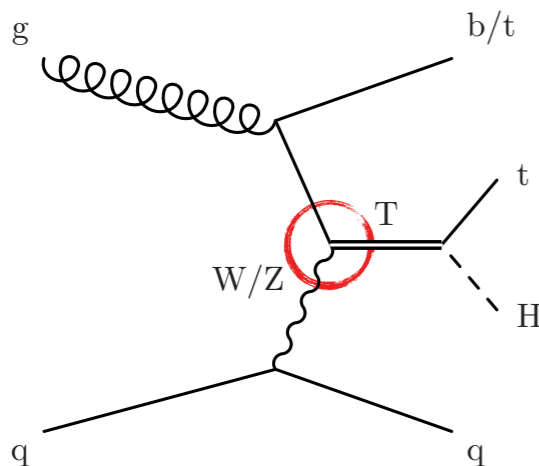
[CMS-PAS-B2G-16-005] all hadronic

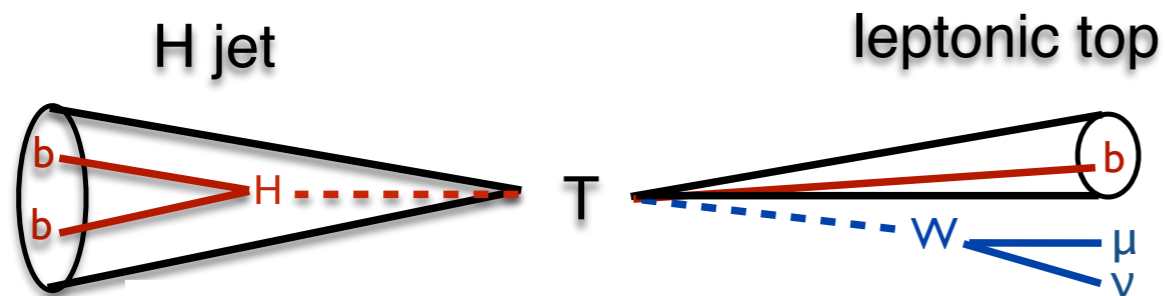
● tagging

- large multijet background
=> tight tagger working points
- H tag (incl. $\tau_2 / \tau_1 < 0.6$)
- t tag (incl. $\tau_3 / \tau_2 < 0.54$)

● coupling exclusion

$$c_{L(R)}^{qV} = \sqrt{\frac{\sigma^{obs.}}{\sigma^{theo.}}}$$

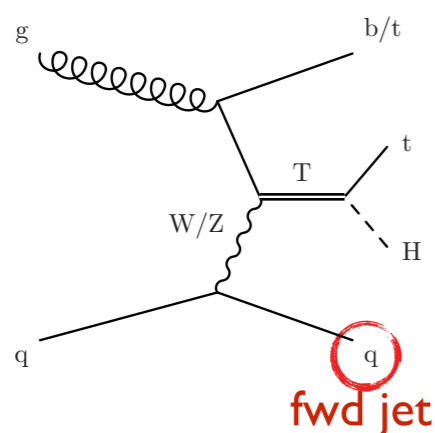




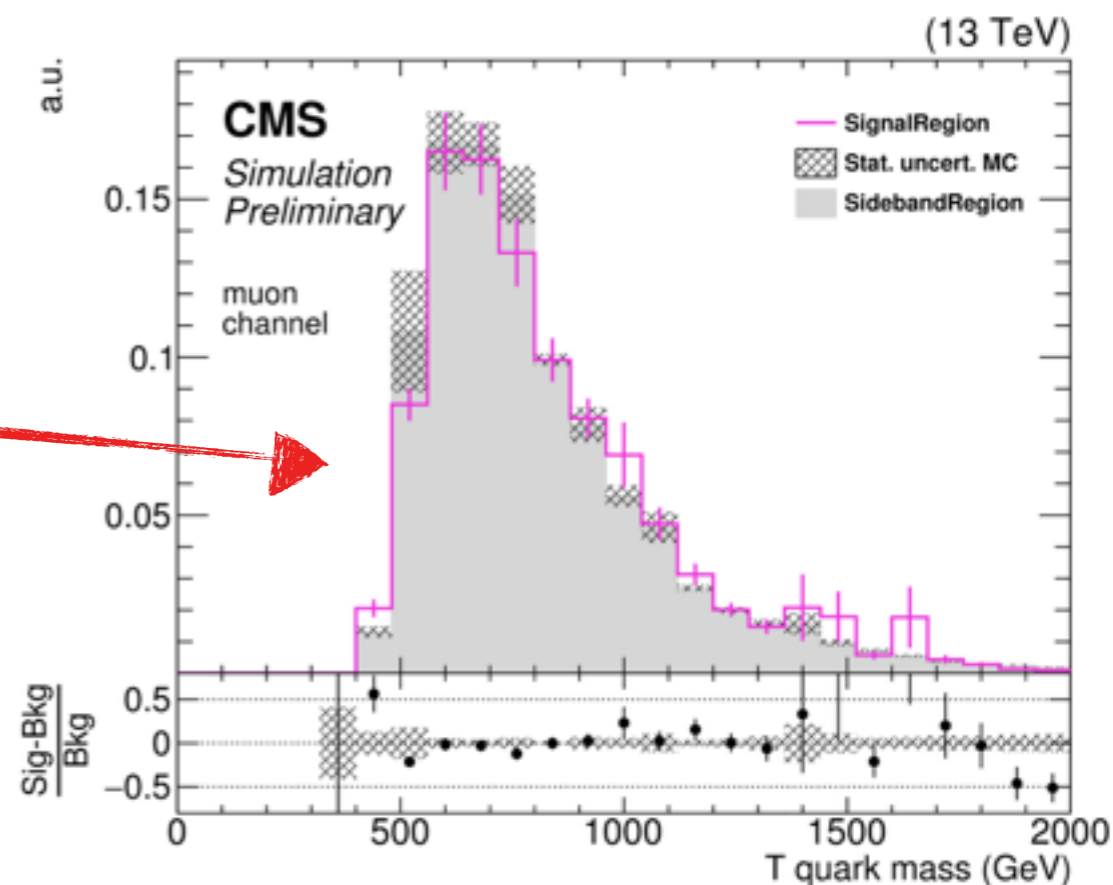
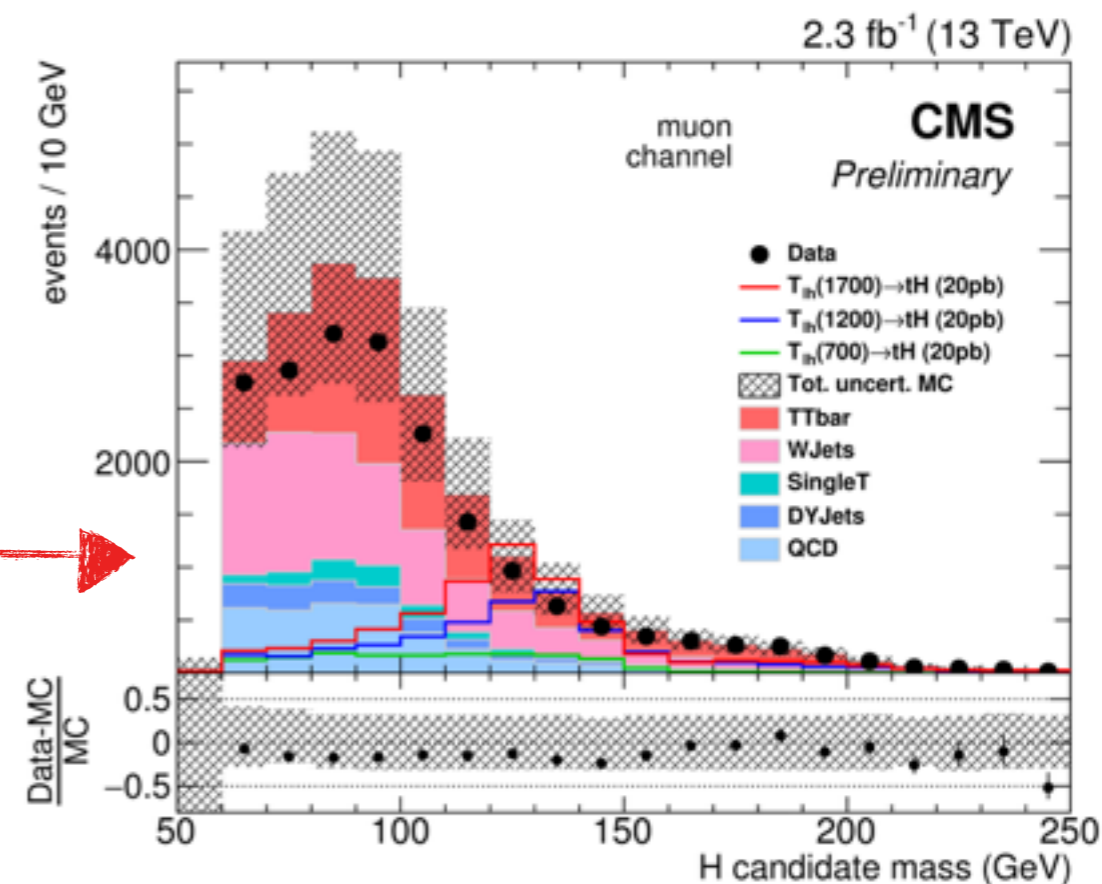
[CMS-PAS-B2G-15-008] leptonic top decay

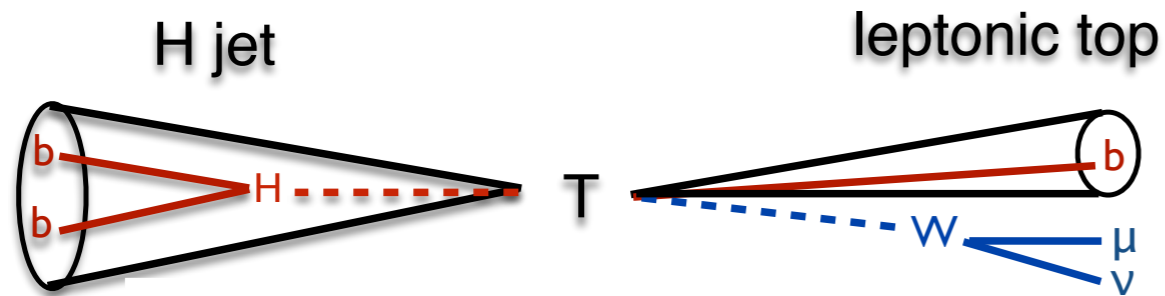
● technique

- H tag (Ak8 jets, $p_T > 200$ GeV):
 - $90 < \text{soft drop mass} < 160$ GeV
 - both soft drop subjects b tagged
- t from lepton, E_T^{miss} , jets:
 - lepton $p_T > 50$ GeV
 - lepton iso relative to closest jet
- event hypothesis:
 - many (t, H) combinations possible
 - $$\chi^2 = \left(\frac{\Delta M_H}{\sigma_{M_H}} \right)^2 + \left(\frac{\Delta M_t}{\sigma_{M_t}} \right)^2 + \left(\frac{\Delta(dR(H, t))}{\sigma_{dR(H, t)}} \right)^2$$
- bkg. shape from signal depleted region



		N subjet b tags	
N forward jets		1	2
	0	sideband region	
	≥ 1		signal region





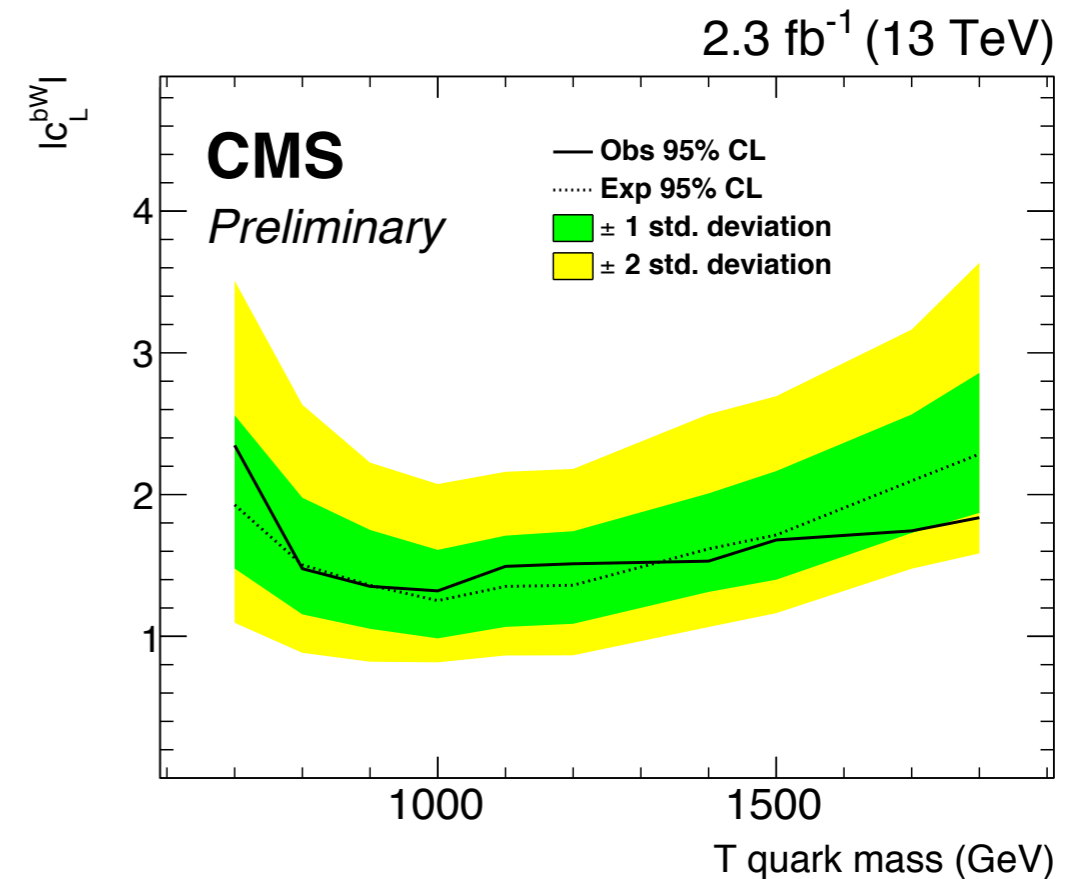
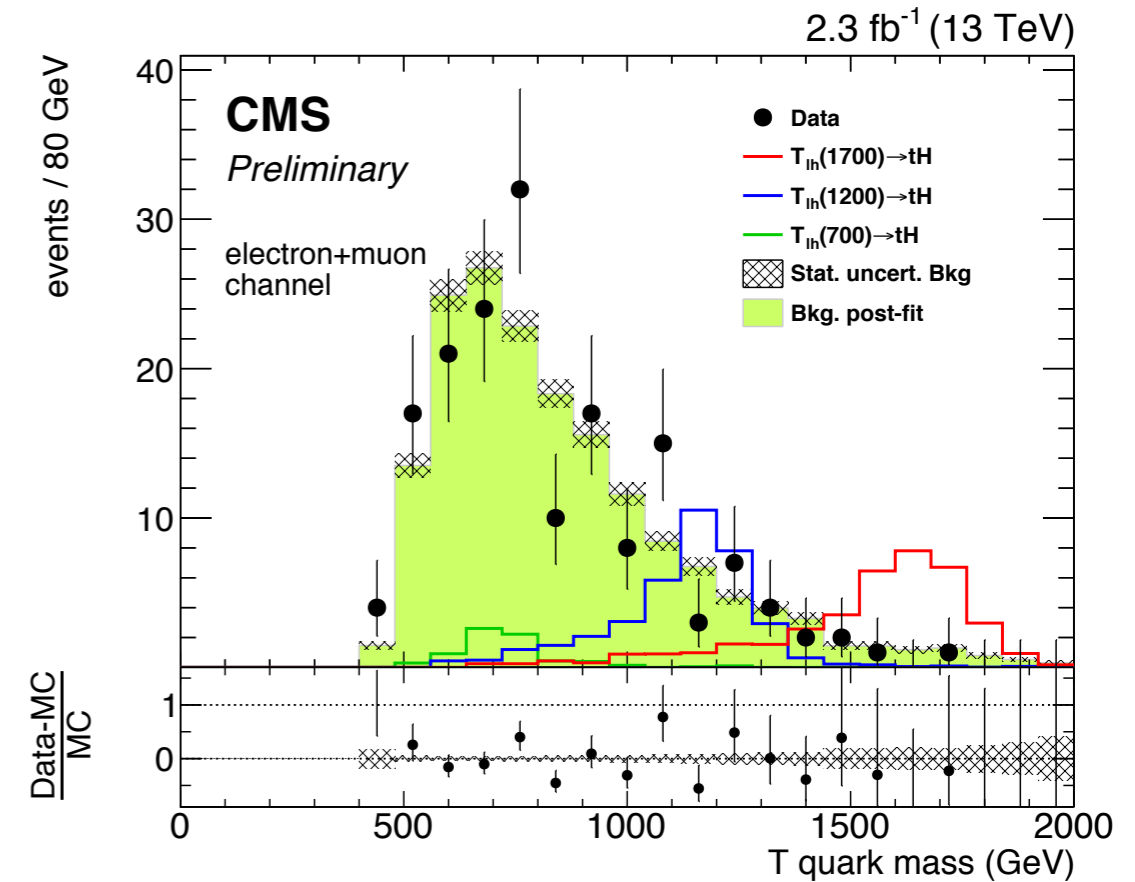
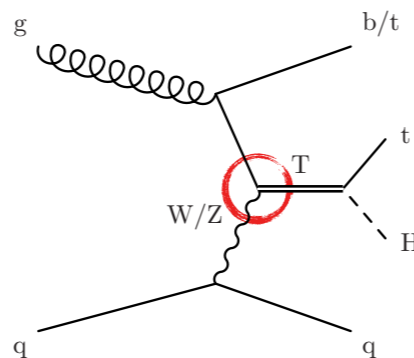
[CMS-PAS-B2G-15-008] leptonic top decay

● technique

- H tag (Ak8 jets, $p_T > 200$ GeV):
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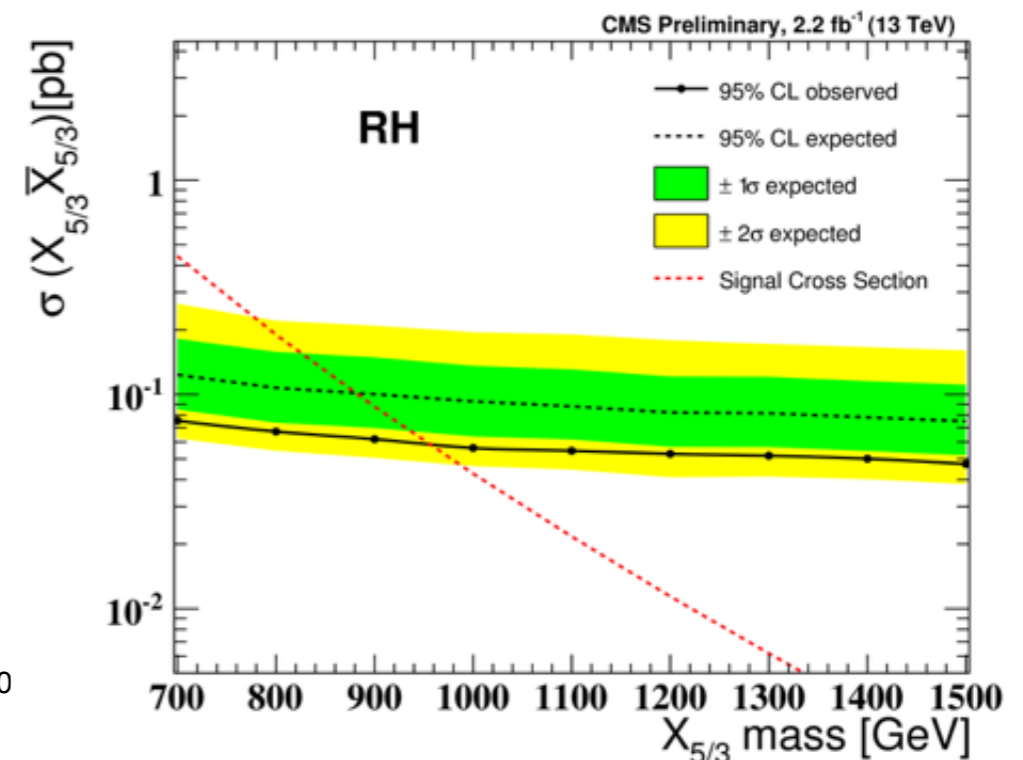
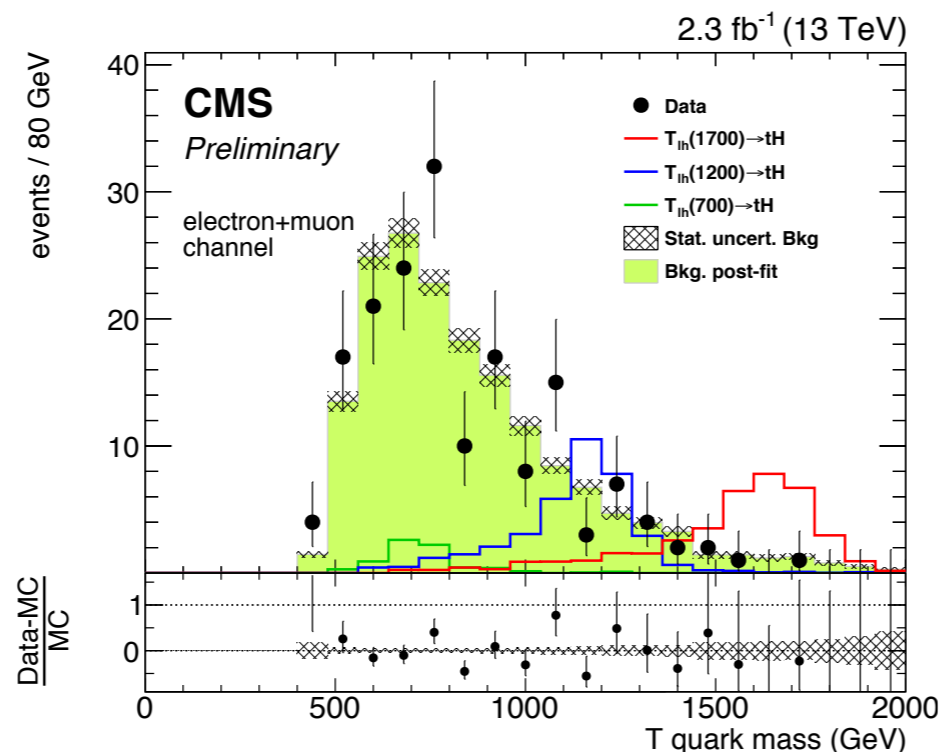
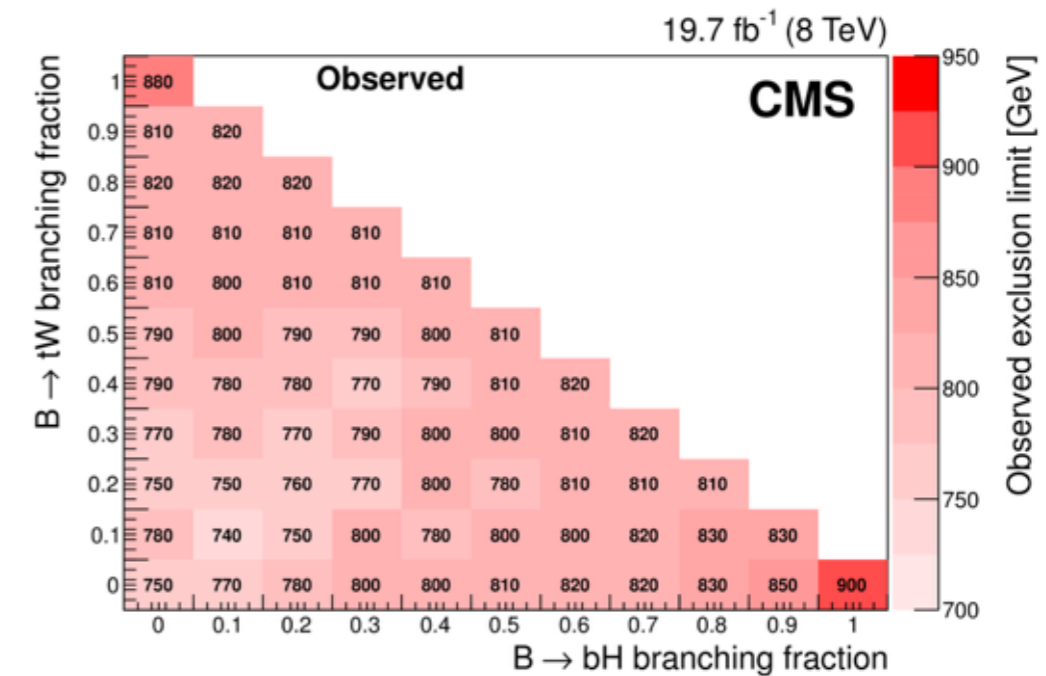
● coupling exclusion

$$c_{L(R)}^{qV} = \sqrt{\frac{\sigma^{\text{obs.}}}{\sigma^{\text{theo.}}}}$$



summary

- **vector-like quarks** are a useful search tool, comprising many BSM models
- 13 TeV begin to supersede the 8 TeV results already
- first single production results are public
- many results are coming in the near future and the full 2016 dataset will have an even larger discovery reach
=> stay tuned!



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backup

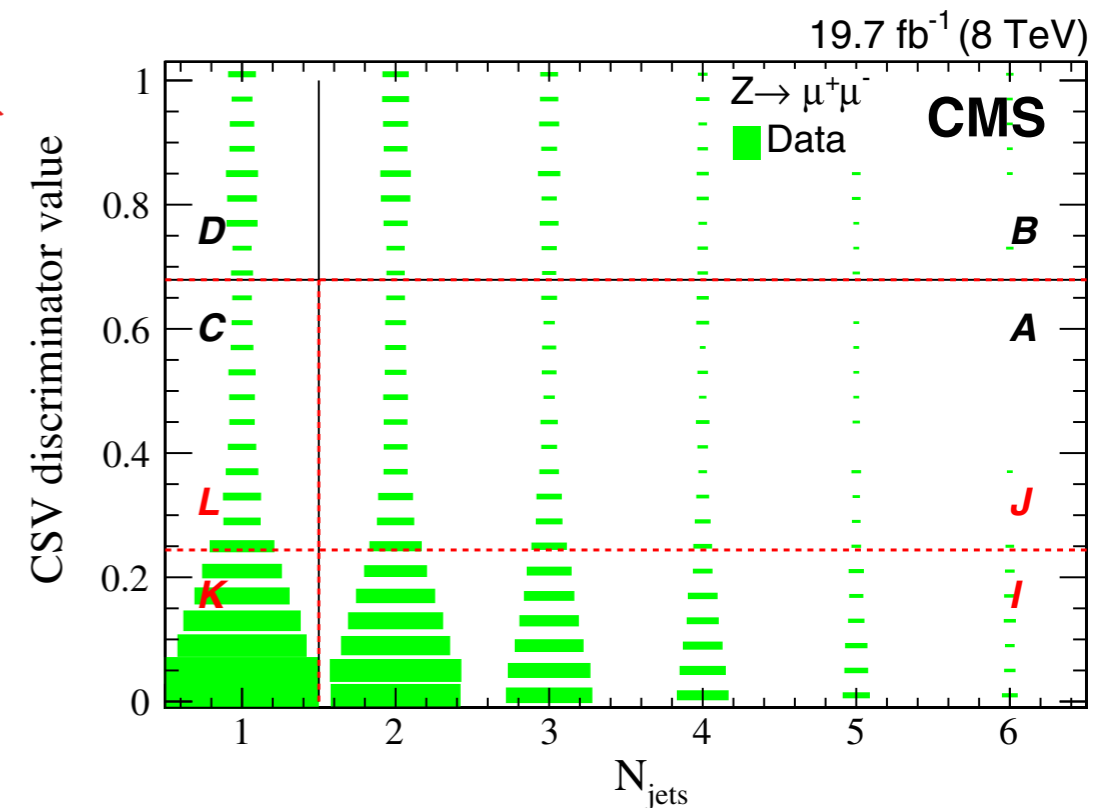
B_{1/3} pair production

channels / backgrounds

● backgrounds

- lepton+jets:
 - 77% top quark pair estimated from control regions, e.g. inverting the lepton isolation
 - other backgrounds from MC
- same sign leptons:
 - as illustrated for $X_{5/3}$ $X_{5/3}$ analysis
- opposite sign leptons:
 - Z+jets
 - top quark pair / di-boson
 - estimated with ABCD method
 - b tag discriminator
 - N_{jets}
- multileptons:
 - Z+jets and WW+jets from control regions
 - low $E_{\text{T}}^{\text{miss}}$ and low H_{T}
 - all other from simulation
- all hadronic:
 - QCD multijet production from control region
 - "anti-H-tagged"
 - pruned mass < 80 GeV

	Number of leptons	Discriminating variable	Best decay mode
Lepton + jets	1	S_{T}	tW
Same-sign dilepton	2	S_{T}	tW
Opposite-sign dilepton	2	$M(\ell\ell b)$	bZ
Multilepton	≥ 3	S_{T}	tW, bZ
All-hadronic	0	H_{T}	bH



B_{1/3} pair production

systematic uncertainties

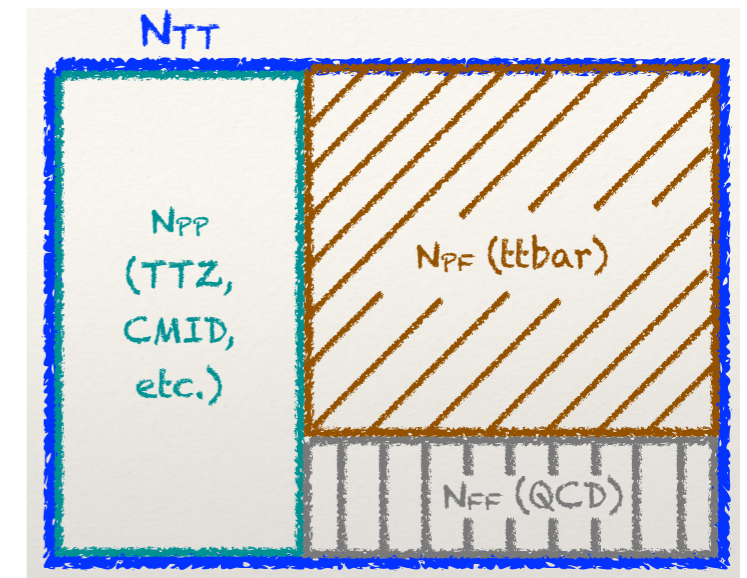
TABLE VII. Nuisance parameters applied to the statistical combination. They are listed separately for each individual channel, and the \checkmark symbol is used if they are applied to that given channel. If a nuisance parameter is taken as correlated between channels, the $\boxed{\checkmark}$ symbol is shown. In some cases, several systematic uncertainties are combined into a single nuisance parameter (for example, in the case of combined lepton categories); in such instances, the \bullet symbol is used to denote the presence of a systematic uncertainty combined with others in a distinct nuisance parameter. The \sim symbol has been used to denote systematic uncertainties that have negligible effects on the analysis results. The “Combined systematic uncertainty” entry represents a contribution composed of other sources listed in the table, applied as a single nuisance parameter during limit extraction.

	Lepton + jets	OS dilepton	SS dilepton	Multilepton	All hadronic
Jet energy scale	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$
Jet energy resolution	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	\sim	$\boxed{\checkmark}$
V-tag SF	\checkmark				\checkmark
$t\bar{t}$ matching scale	\checkmark				\bullet
$t\bar{t}$ renormalization/factorization scales	\checkmark				\bullet
b -tagging SF	$\boxed{\checkmark}$	\bullet		$\boxed{\checkmark}$	\bullet
Light-jet-tagging SF		\bullet			\bullet
Integrated luminosity	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$	$\boxed{\checkmark}$
Lepton reconstruction	\checkmark	\checkmark	\checkmark	\bullet	
$t\bar{t}$ cross section	$\boxed{\checkmark}$			$\boxed{\checkmark}$	
QCD normalization	\checkmark				
Trigger efficiency	\checkmark	\checkmark	\checkmark	\bullet	\checkmark
Pileup uncertainty	\sim	$\boxed{\checkmark}$	$\boxed{\checkmark}$	\sim	$\boxed{\checkmark}$
Background component from data		\checkmark	\checkmark	\bullet	
PDF uncertainty	\sim	\sim	\checkmark	\bullet	\checkmark
E_T resolution				\checkmark	
Initial-state radiation				\checkmark	
Combined systematic uncertainty	\checkmark		\checkmark	\checkmark	\checkmark

$X_{5/3}$ pair production

backgrounds

- relaxed charge consistency
 - electron charge from standard track, GSF track, track-to-calorimeter position
 - for $p_T > 100$ GeV, the third criterion is dropped in order to keep a high selection efficiency
- backgrounds
 - NonPrompt:
 - prompt rates $p_{\mu\mu} = 0.940 \pm 0.001$; $p_e = 0.873 \pm 0.001$
 - fake rates $f_{\mu\mu} = 0.298 \pm 0.003$; $f_e = 0.371 \pm 0.002$
 - more on tight-loose method: [10.1007 / JHEP06 (2011) 077]
 - ChargeMisID:
 - apply full selection, but with opposite sign leptons
 - weight events by mis-id probability (as function of eta)
 - binned in $p_T < 100$ GeV and $p_T > 100$ GeV



prompt same sign leptons (from MC) hadrons, conversions, etc. (using tight-loose ratios) electron charge mis-ID ($\#_{opp. sign} * \text{fake-rate}$)

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV $X_{5/3}$	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
Electron-Muon	2.98 ± 0.36	5.20 ± 3.21	0.54 ± 0.18	8.72 ± 3.24	9.14	3
Di-muon	0.70 ± 0.12	2.09 ± 1.69	0.00 ± 0.00	2.80 ± 1.70	3.55	1
All	6.09 ± 0.67	9.45 ± 5.49	2.44 ± 0.76	17.98 ± 5.58	17.06	11

X_{5/3} pair production

systematic uncertainties

- systematic uncertainties
 - two channels
 - same sign di-leptons
 - lepton + jets
 - 30% additional on charge mis-ID
 - 50% additional for fake leptons

Source	Value	Application
Electron ID	1%	per electron
Electron ISO	1%	per electron
Electron Trigger	3%	per event
Muon ID	1%	per muon
Muon ISO	1%	per muon
Muon Trigger	3%	per event
Electron-Muon Trigger	3%	per event

Background Process	JES	Theory
ttW	4%	20%
ttZ	3%	12%
ttH	8%	14%
WZ	5%	12%
ZZ	4%	12%
W+W+	4%	50%
WWZ	4%	50%
WZZ	6%	50%
ZZZ	6%	50%
tttt	6%	50%

Channel	PSS MC	NonPrompt	ChargeMisID	Total Background	800 GeV X _{5/3}	Observed
Di-electron	2.41 ± 0.29	2.16 ± 1.91	1.90 ± 0.60	6.47 ± 2.02	4.38	7
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$X_{5/3}$ pair production

systematic uncertainties

- systematic uncertainties
 - two channels
 - same sign di-leptons
 - lepton + jets

Source	Uncertainty	Signal	Background
Normalization only			
Luminosity	4.6%	Yes	All
Trigger Efficiency	3%	Yes	All
Lepton efficiencies	1%	Yes	All
“Top bkg”: $t\bar{t}$, Single top, $t\bar{t}+W/Z$ cross-sections	5.5%	No	
“EWK bkg”: W +jets, Diboson cross sections	5%	No	
“Top bkg” modeling, based on the CR	11-19%	No	
“EWK bkg” modeling, based on the CR	24%	No	
QCD multijet cross-sections	50%	No	
Shape and Normalization			
Jet Energy Scale	$\pm\sigma(p_T, \eta)$	Yes	All
Jet Energy Resolution	$\pm\sigma$	Yes	All
b tagging	$\pm\sigma$	Yes	All
W tagging: mass resolution	$\pm\sigma$	Yes	All
W tagging: mass scale	$\pm\sigma$	Yes	All
W tagging: τ_2/τ_1	$\pm\sigma$	Yes	All
Top p_T	$\Delta(\text{weighted, nominal})$	No	$t\bar{t}$
Pileup	$\sigma_{\text{minbias}} \pm 5\%$	Yes	All
Parton Shower Scale	$\pm\sigma$	No	$t\bar{t}$, single top
Shape only			
PDF	$\pm\sigma$	Yes	All
Renormalization Scale	$\pm\sigma$	Yes	All
Factorization Scale	$\pm\sigma$	Yes	All

T_{2/3} pair production

systematic uncertainties

- systematic uncertainties

Source	Uncertainty	Signal	Background
Normalization only			
Luminosity	2.7%	Yes	All
Trigger Efficiency	5%	Yes	All
Lepton efficiencies	1%	Yes	All
TOP background modeling	1-14%	No	TOP group
EWK background modeling	2-23%	No	EWK group
Shape and Normalization			
Jet Energy Scale	$\pm\sigma(p_T, \eta)$	Yes (0 – 5%)	All (0 – 20%)
Jet Energy Resolution	$\pm\sigma$	Yes (0 – 3%)	All (0 – 40%)
b tagging	$\pm\sigma$	Yes (0 – 20%)	All (0 – 40%)
W tagging: mass resolution	$\pm\sigma$	Yes (0 – 2%)	All (0 – 22%)
W tagging: mass scale	$\pm\sigma$	Yes (0 – 1%)	All (0 – 3%)
W tagging: τ_2/τ_1	$\pm\sigma$	Yes (0 – 2%)	All (0 – 2%)
Pileup	$\sigma_{\text{minbias}} \pm 5\%$	Yes (0 – 3%)	All (0 – 8%)
Jet reweighting	$\pm\sigma(p_T)$	Yes (7 – 10%)	All (0 – 18%)
Top p_T	$\Delta(\text{weighted, nominal})$	No	$t\bar{t}$ (17 – 19%)
PDF	$\pm\sigma$	No	All (2 – 15%)
Renorm./Fact. Energy Scale	envelope($\times 2, \times 0.5$)	No	All (17 – 43%)
Parton Shower Scale	envelope($\times 2, \times 0.5$)	No	$t\bar{t}$, single top (0 – 70%)
Shape only			
PDF	$\pm\sigma$	Yes	None
Renorm./Fact. Energy Scale	envelope($\times 2, \times 0.5$)	Yes	None

T_{2/3} single production

systematic uncertainties

- systematic uncertainties
 - all hadronic final state (largest uncertainties)
 - t tagging:
 - 15% (jet p_T 400 - 550 GeV)
 - 30% (jet p_T >550 GeV)
 - statistical uncertainty from ABCD sideband
 - H tag:
 - N subjettness: 12.5%
 - jet mass correction: 10%
 - subjet b tags

Process	Events
Estimated multijets (using data)	10.8 ± 5.5
Estimated t \bar{t} +jets (using MC)	24.3 ± 8.1
Estimated W+jets (using MC)	0.6 ± 0.6
Estimated total background	35.7 ± 5.6
Observed events	30

variables for ABCD method:

- 0/1 t tag
- 0/1 anti-H tag
(H tag w/ 0 subjet b tags)

- final state with one lepton

	electron channel			muon channel		
	T(0700)	T(1200)	T(1700)	T(0700)	T(1200)	T(1700)
forward jet	15.0	15.0	15.0	15.0	15.0	15.0
b tag heavy flav.	7.8	7.6	8.7	6.0	7.5	8.5
JES	8.9	4.9	4.9	3.0	5.7	4.6
lepton iso. and trg.	5.0	5.0	5.0	5.0	5.0	5.0