Searches for top/bottom partners and new phenomena in top/bottom quark pair signatures in CMS

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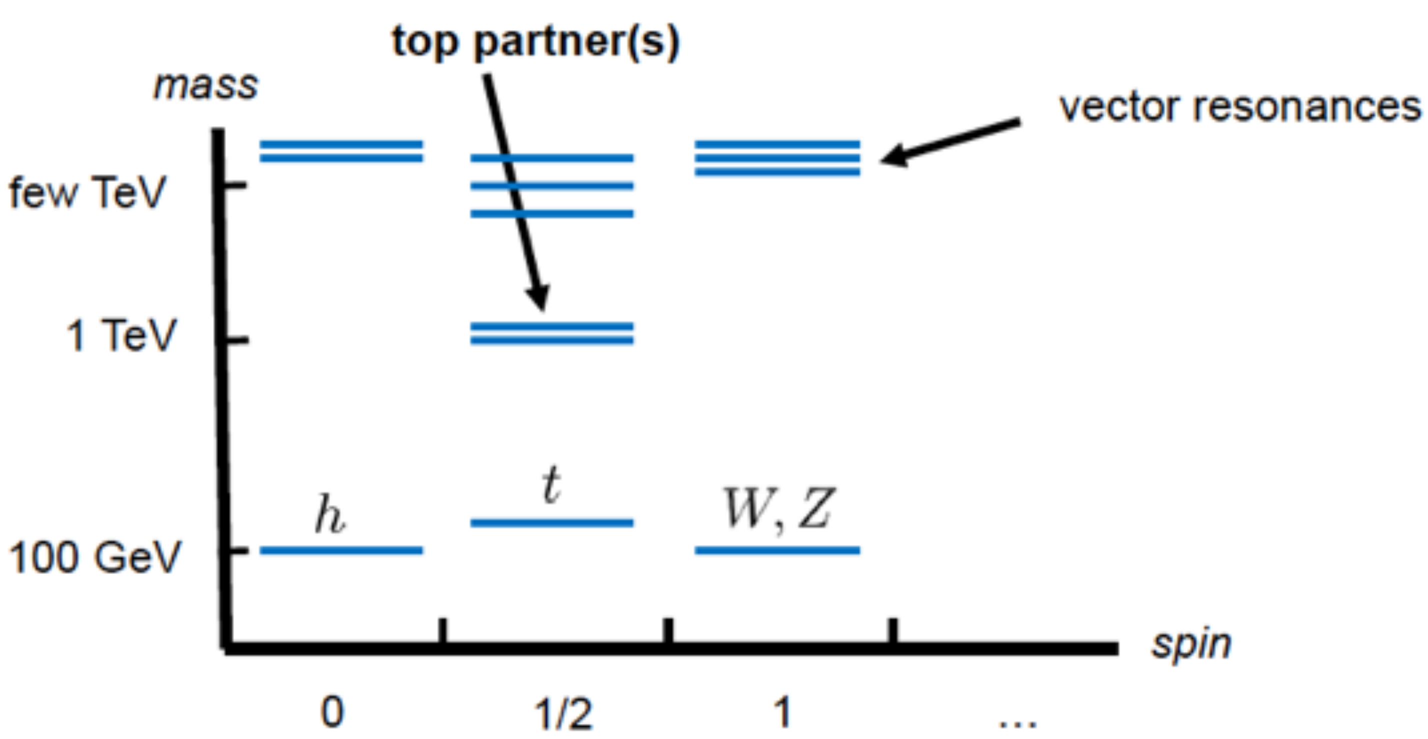
NEW PHYSICS REQUIRED

- The large mass of the top quark induces large quadratic divergencies
- Solutions to the problem involve hypothesizing the existence of top partners of bosonic (SUSY) or fermionic (Little/Composite Higgs, Extra Dimensions) nature, that automatically cancel out such divergencies
- In both scenario, several additional particles appear, providing a very rich phenomenology



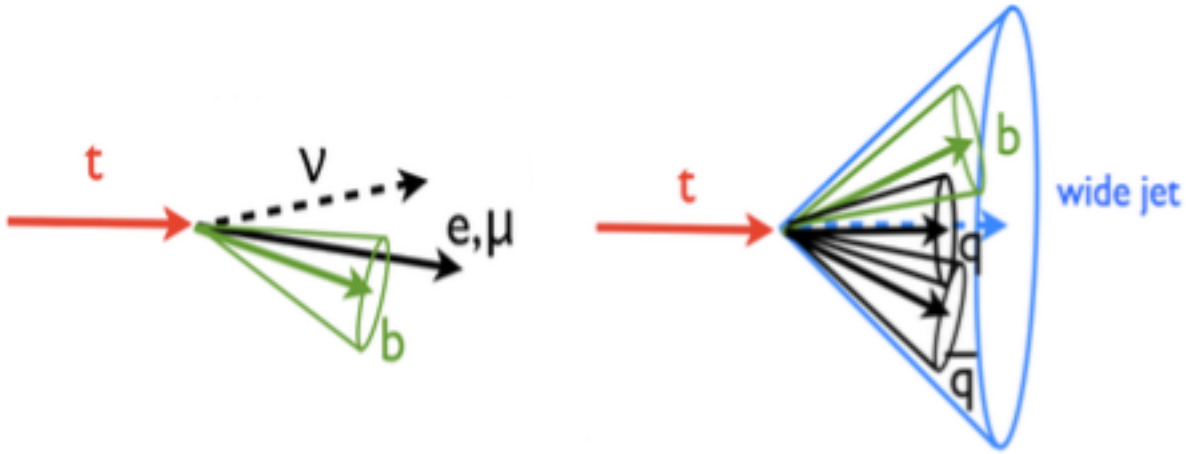
— Light (<2TeV) Top Partners are present in any « reasonably Natural » model, i.e. less than one order of magnitude cancellation

— Heavier (<10TeV) Resonances needed

— The new LHC energy opens up the discovery reach for this very interesting mass region

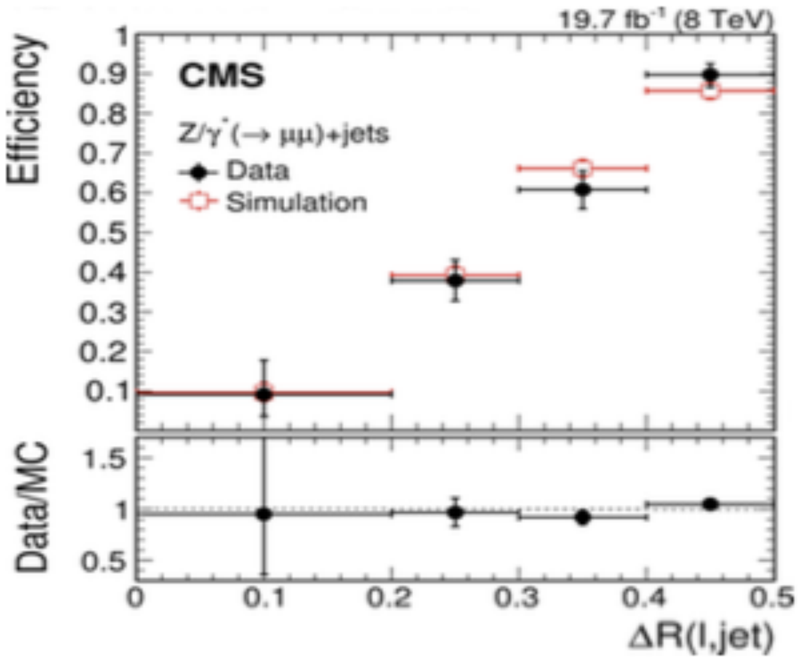
Tools and Techniques

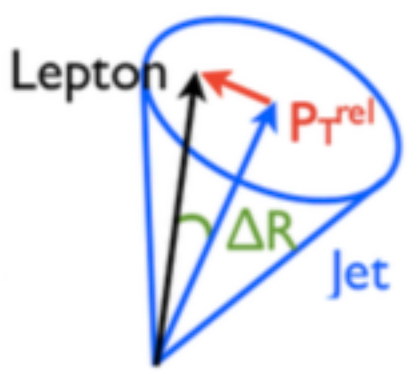
- **Classical selection methods fail**:



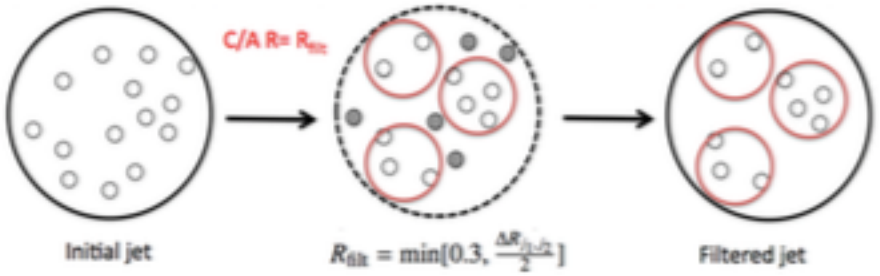
→non-isolated leptons
→hadronic decay products from heavy particles **merged into large fat-jets**

- **Leptons**: simple cone isolation fails, e.g. exploit **p_T,rel** observable

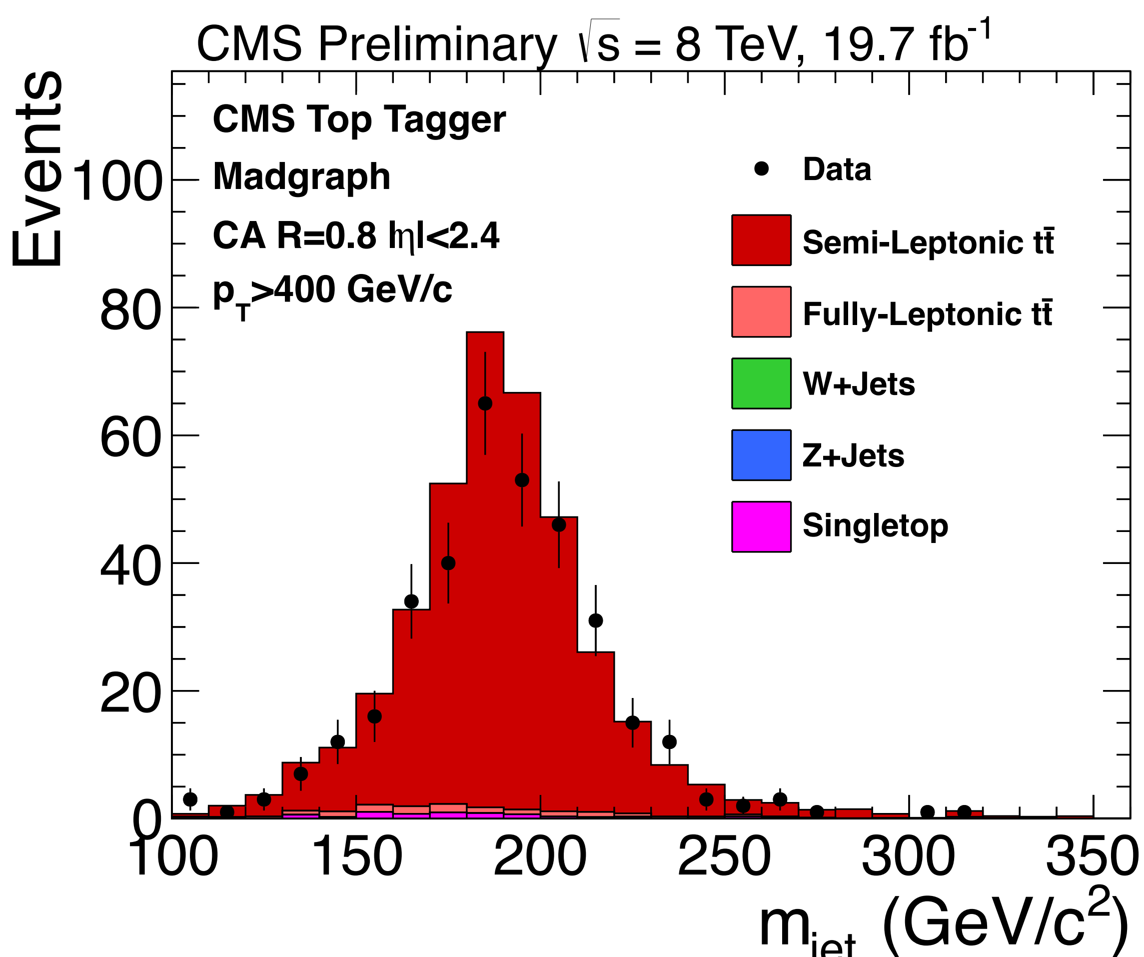




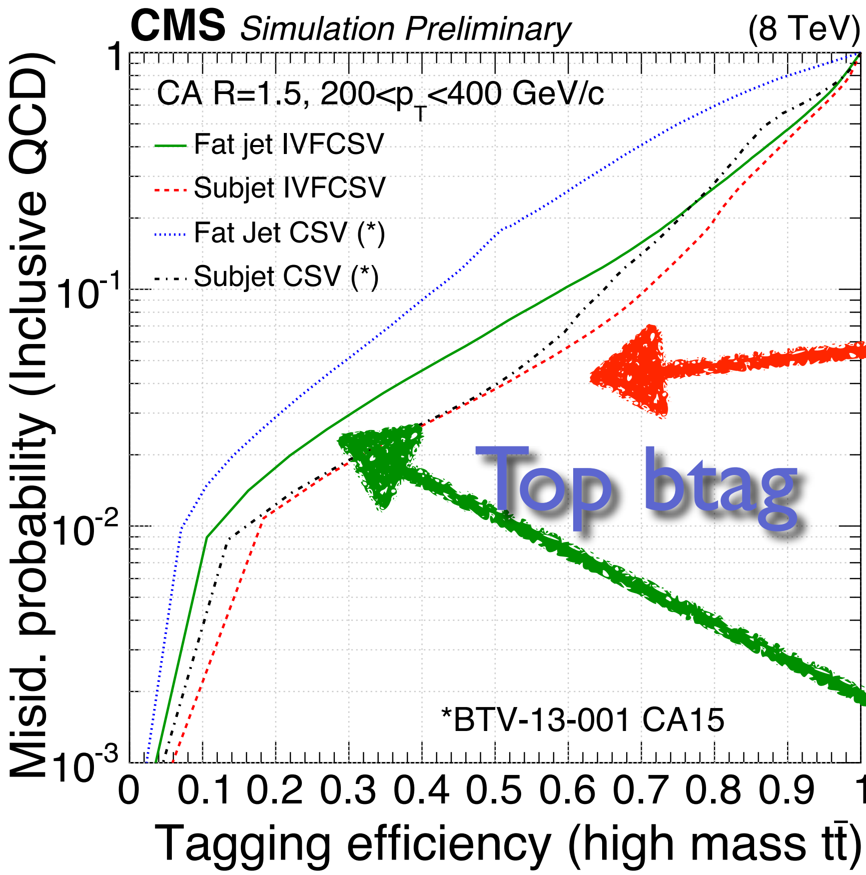
- **Jet mass**: fundamental observable to identify merged jets
  - → **grooming** (pruning, trimming, filtering, ...): remove soft/large angle radiation, protect from pile-up

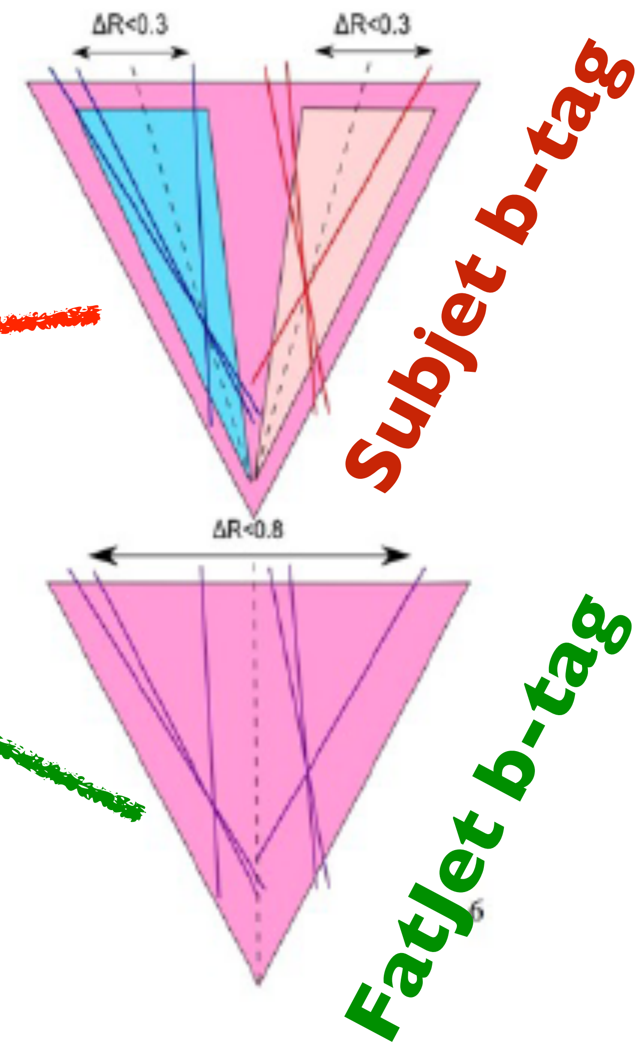


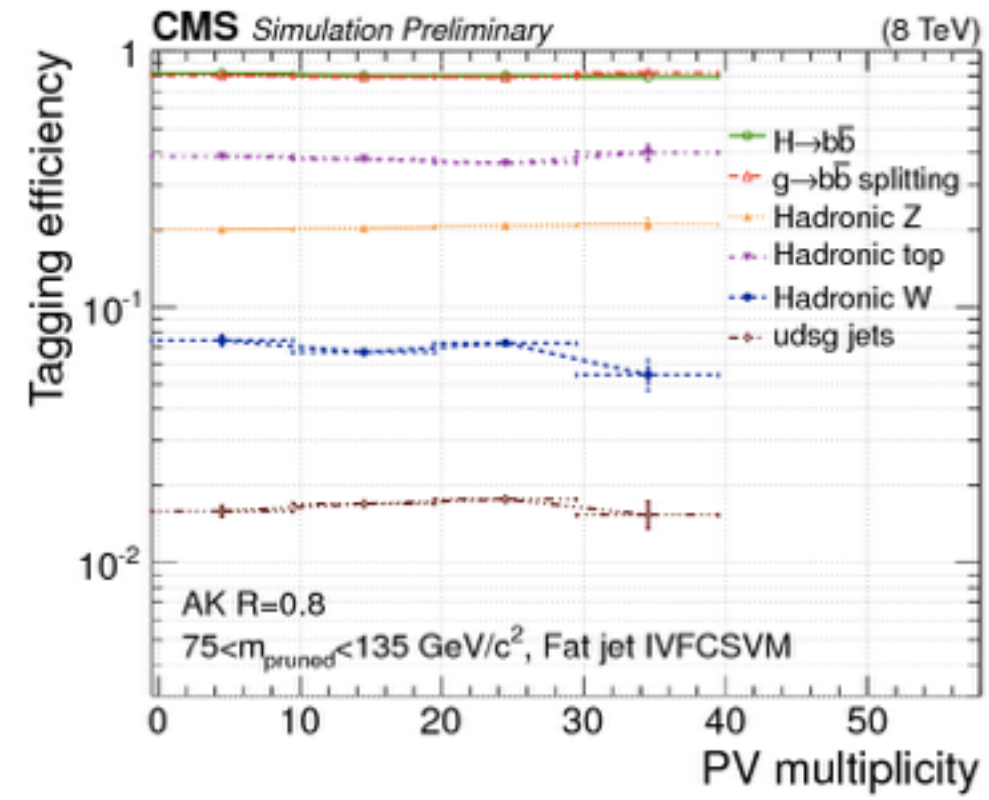
filtering, merged W candidates



TOOLS AND TECHNIQUES 2







<u>SubJet b-tagging performs better than FatJet</u>

Combing with TopTagger obtain factor 10 reduction in QCD keeping 70% efficiency (compared to TopTagger only)

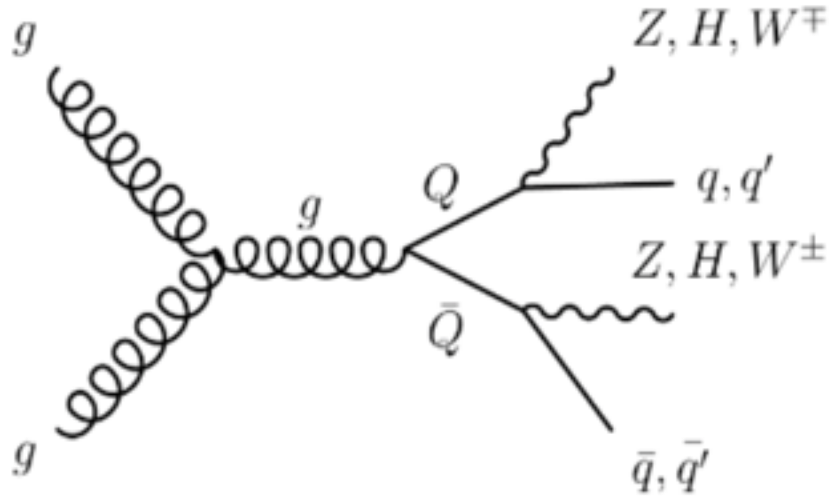
Developments in tracking and btagging will be available to cope with the track sharing due to even higher boost regime expected in Run2

CMS DP-2014/031

New heavy quarks

FERMIONIC TOP PARTNERS

- Fourth generation replica of SM quarks strongly disfavored by Higgs data

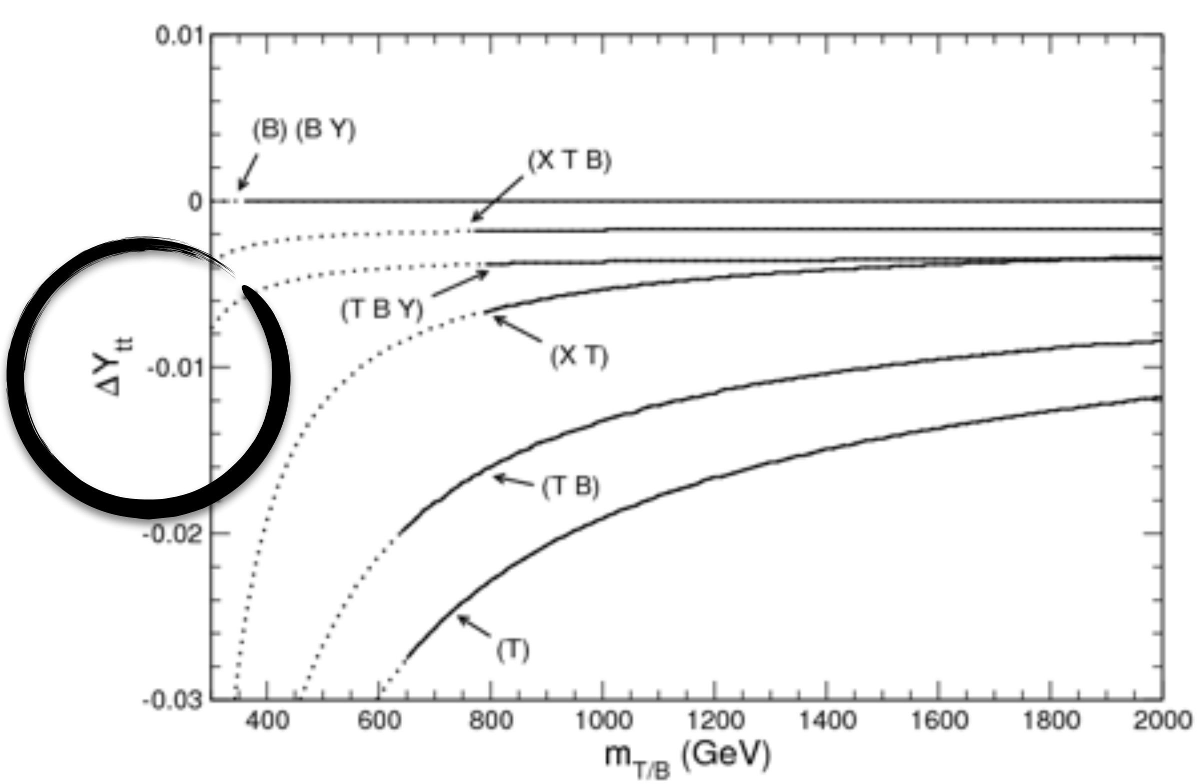


Singlets	Doublets	Triplets
$\mathbf{1}_{2/3} = T$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	
$\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$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

Notation:

Isospin$_{\text{Hypercharge}}$

$\left.\begin{array}{l} T \to +2/3 \\ B \to -1/3 \\ X \to +5/3 \\ Y \to -4/3 \end{array}\right\}$ Electric charge

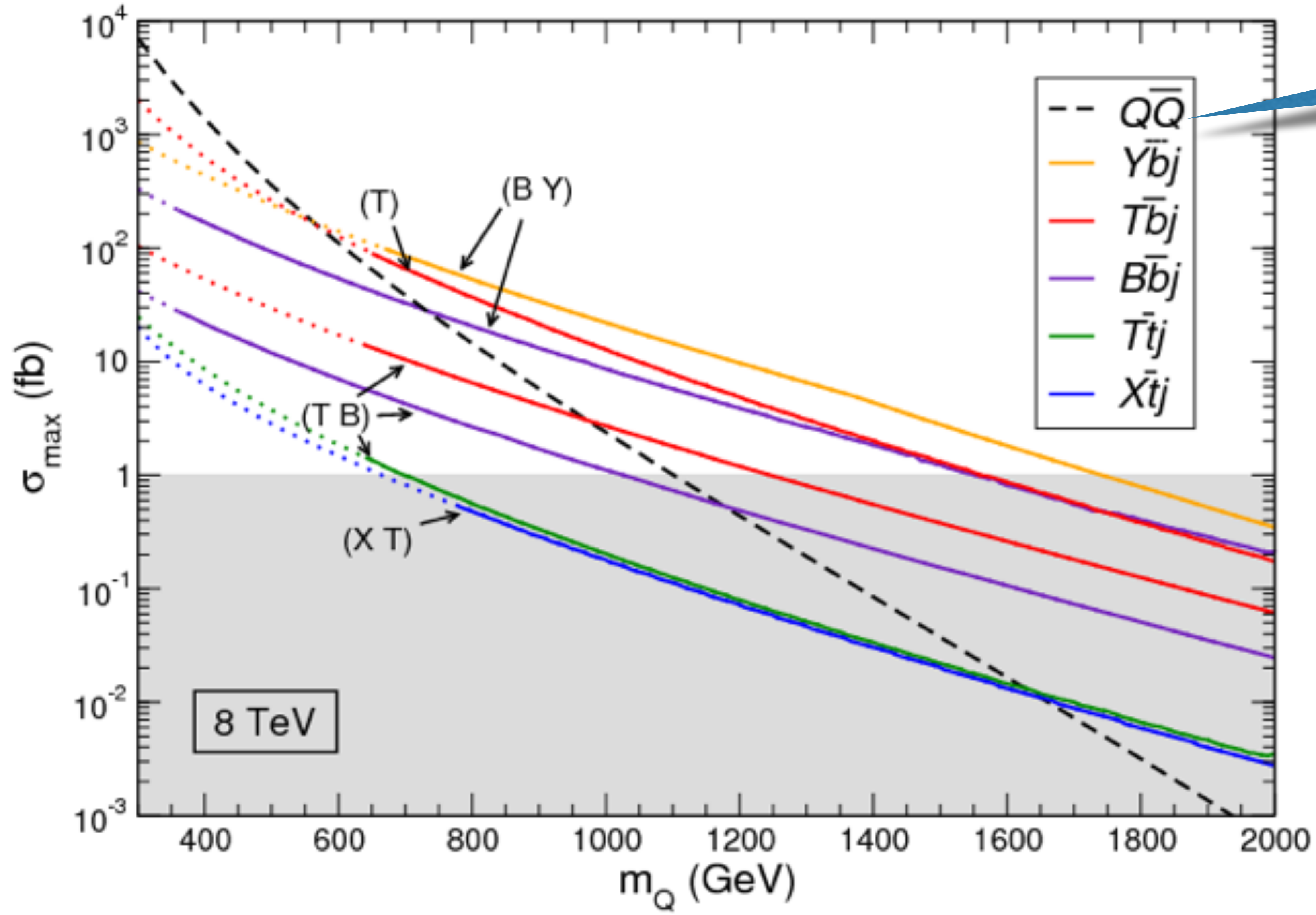


- Vector-like quarks not not acquire mass due to Yukawa coupling
- Deviation from top Yukawa too small to be visible, both in current and future collider experiments

J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Pérez-Victoria
arXiv:1306.0572

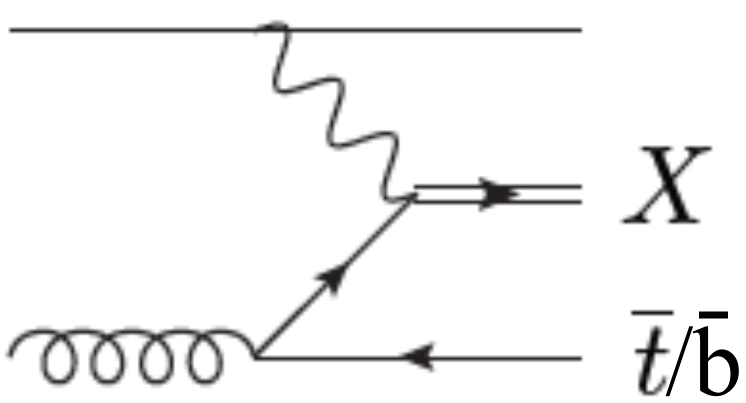
Fermionic top partners

- Pair production is a QCD process: only free parameter is the new particle mass



Q= T,B,X,Y

- single production depends on the model



- single production will be key in the new run

J.A. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, M. Pérez-Victoria
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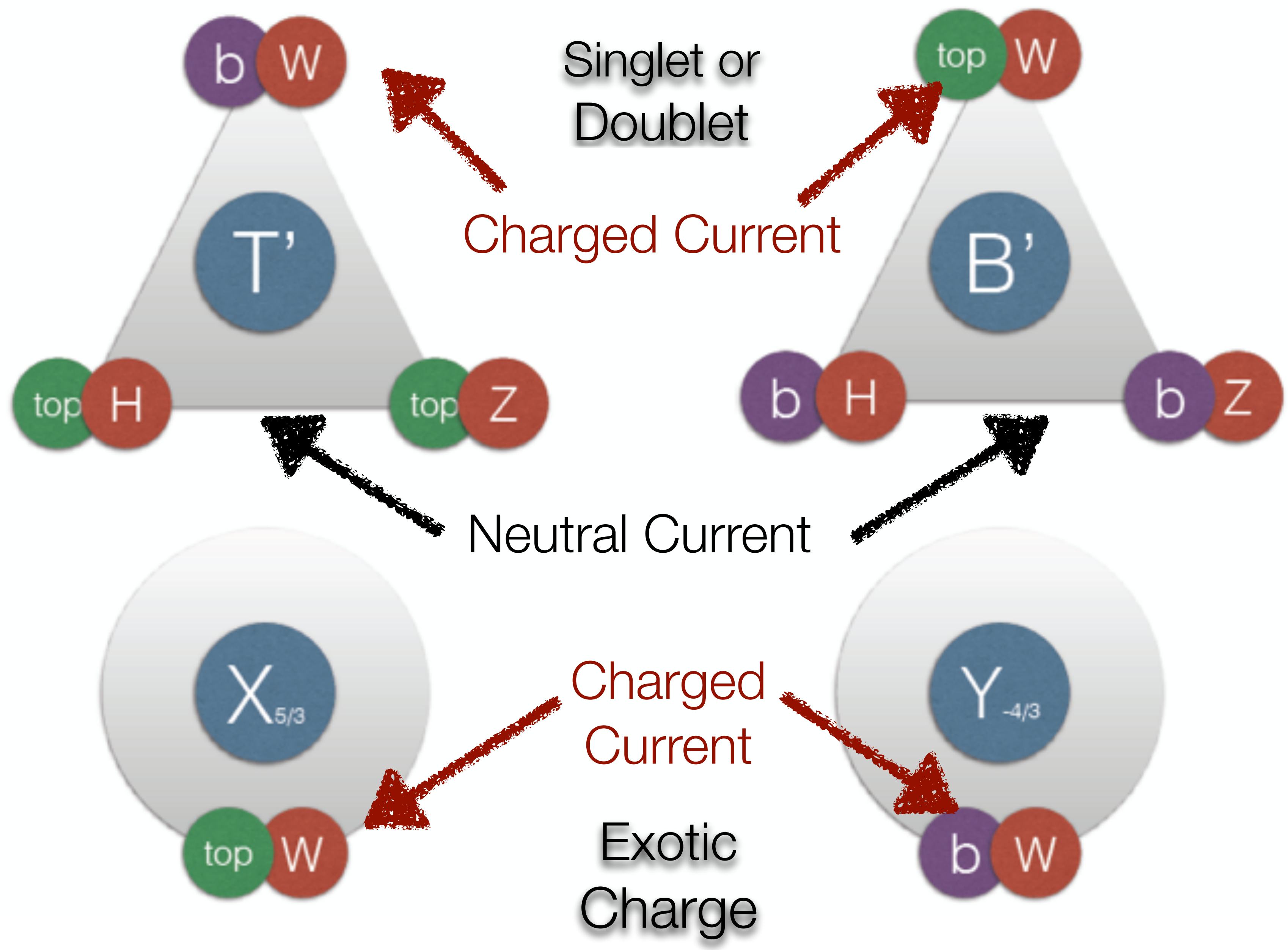
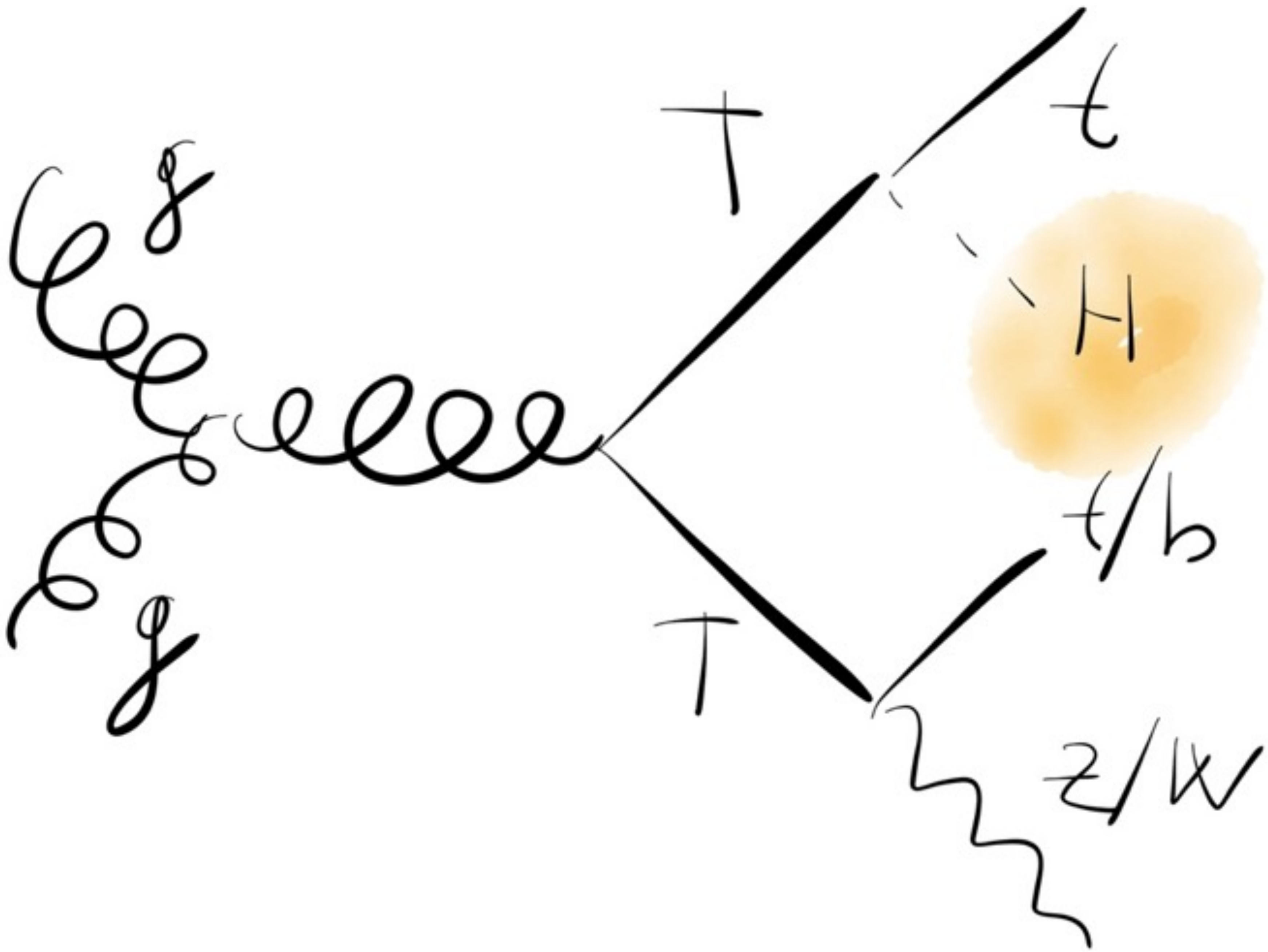
Decay modes at a glance (for 3rd generation only)



E. Usai

The exact branching ratios are model dependent, need to explore all of the above

Fermionic top partners

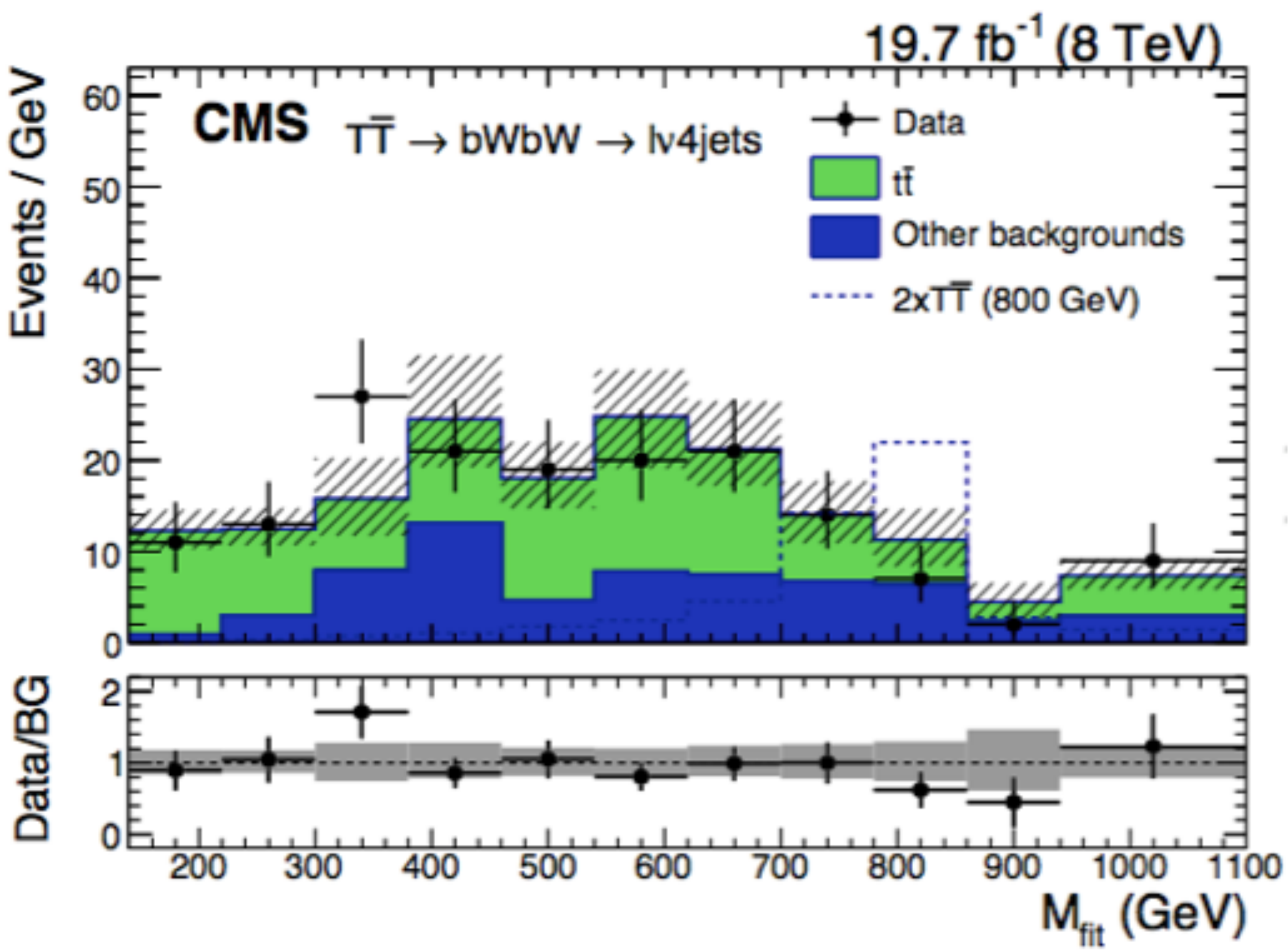


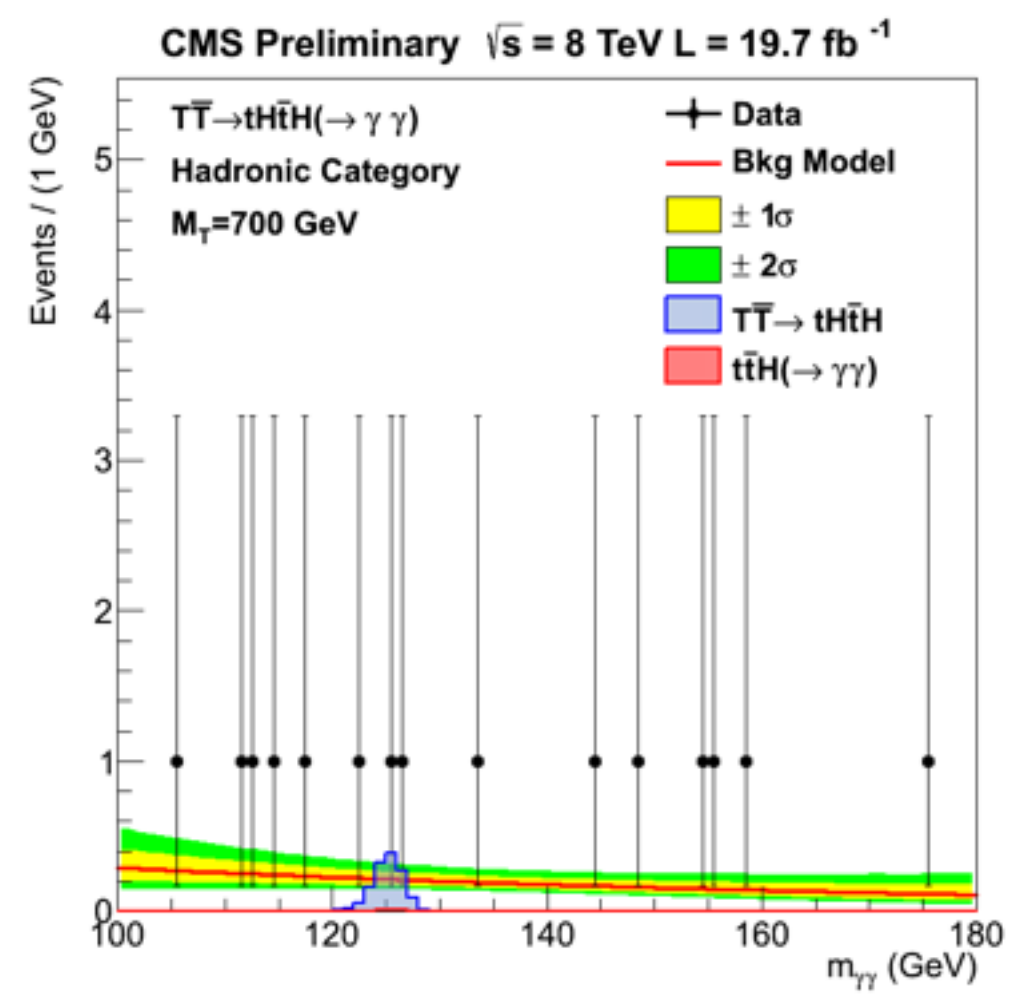
*example diagram

TOP PARTNERS

B2G-12-013, Phys. Lett. B 729 (2014) 149, B2G-12-017, JHEP 06 (2015) 080, B2G-14-003

- Take any possible final state, using any possible number/flavor of leptons, number of b-tags, identified boosted bosons. In particular:
  - single lepton, aiming specifically at $T \rightarrow tW$
  - single, di, trilepton, aiming at all final states
  - diphoton, aiming exclusively at $T \rightarrow tH$





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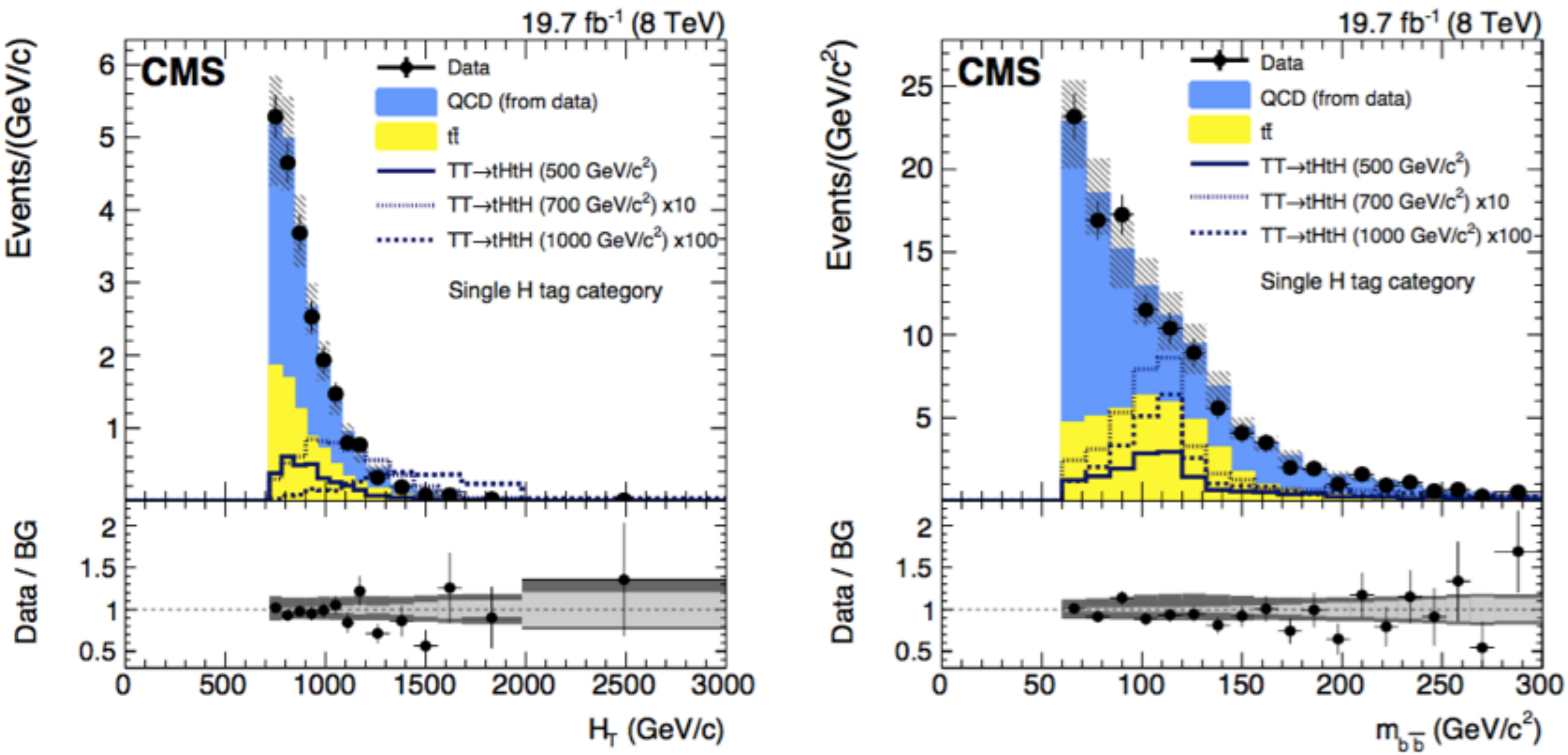
  - all-hadronic T→tH
  - all-hadronic T→tW



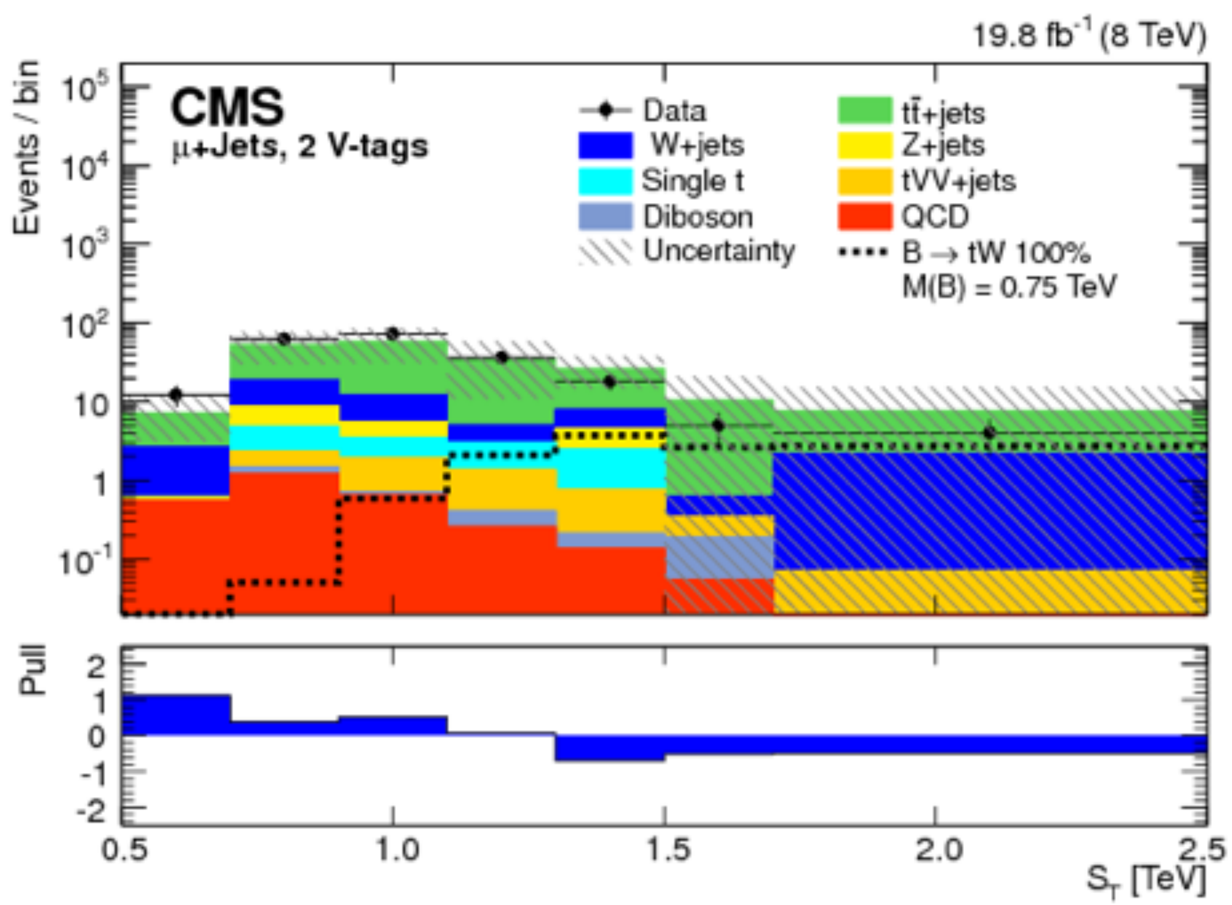
- Limits on T→qV hyp. ranging in the 700-800GeV range. Combination underway

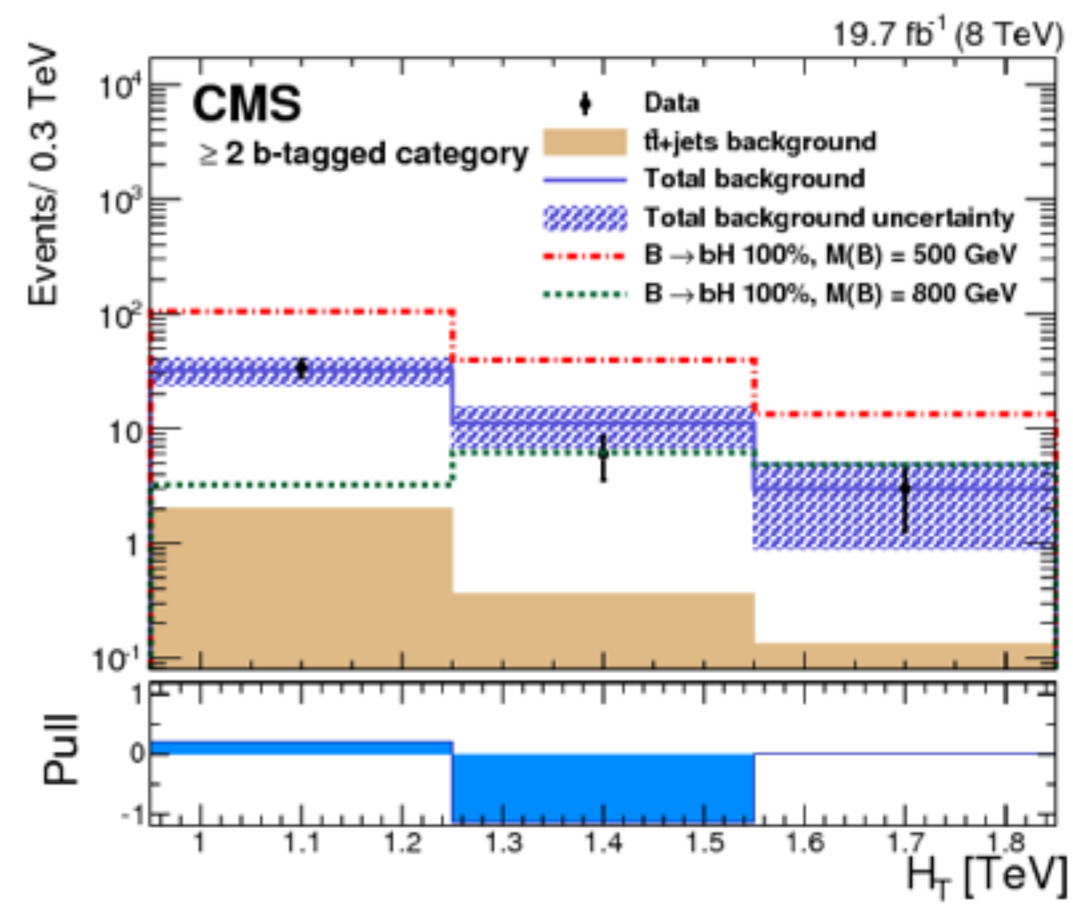
BOTTOM PARTNERS

arxiv:1507.07129

- Take any possible final state, using any possible number/flavor of leptons (including taus), number of b-tags, identified boosted bosons

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

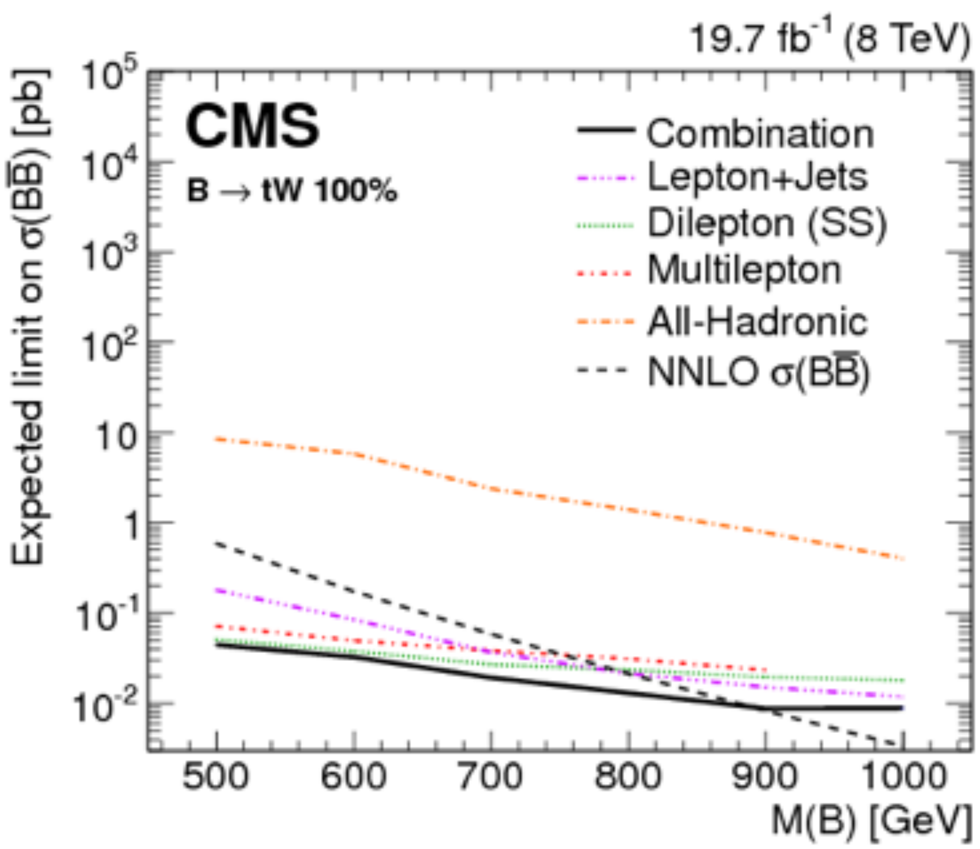


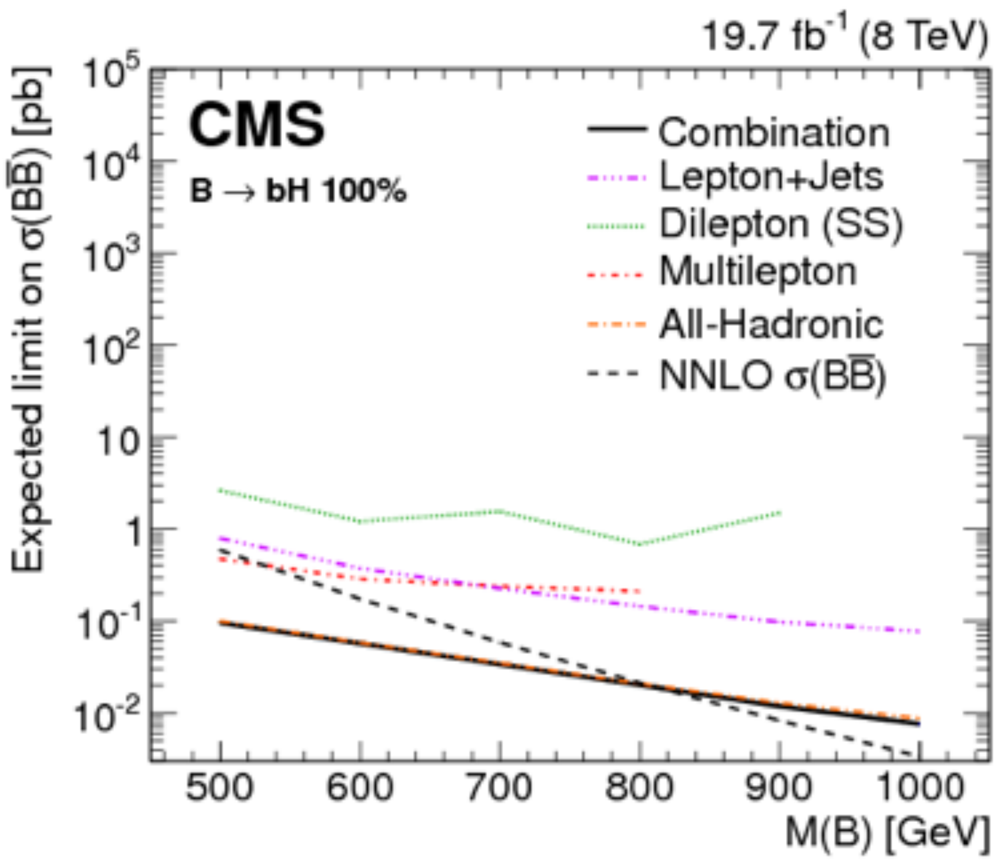


BOTTOM PARTNERS

arxiv:1507.07129

- All analyses samples are statistically independent by construction
- Maximize a joint likelihood for all channels, scan all the allowed B decay space
- no signal found, set 95% upper limits





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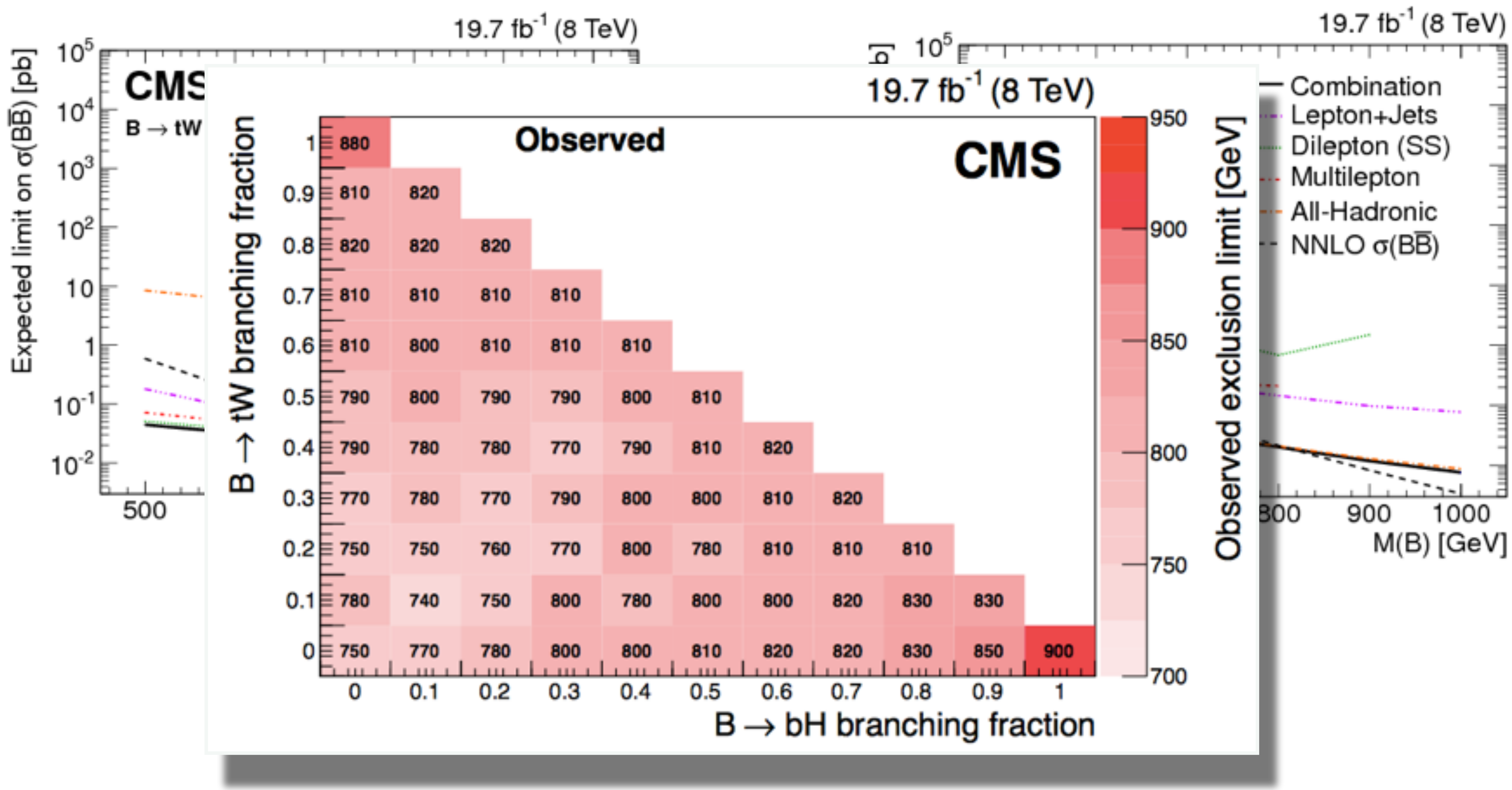


New heavy bosons

New resonances

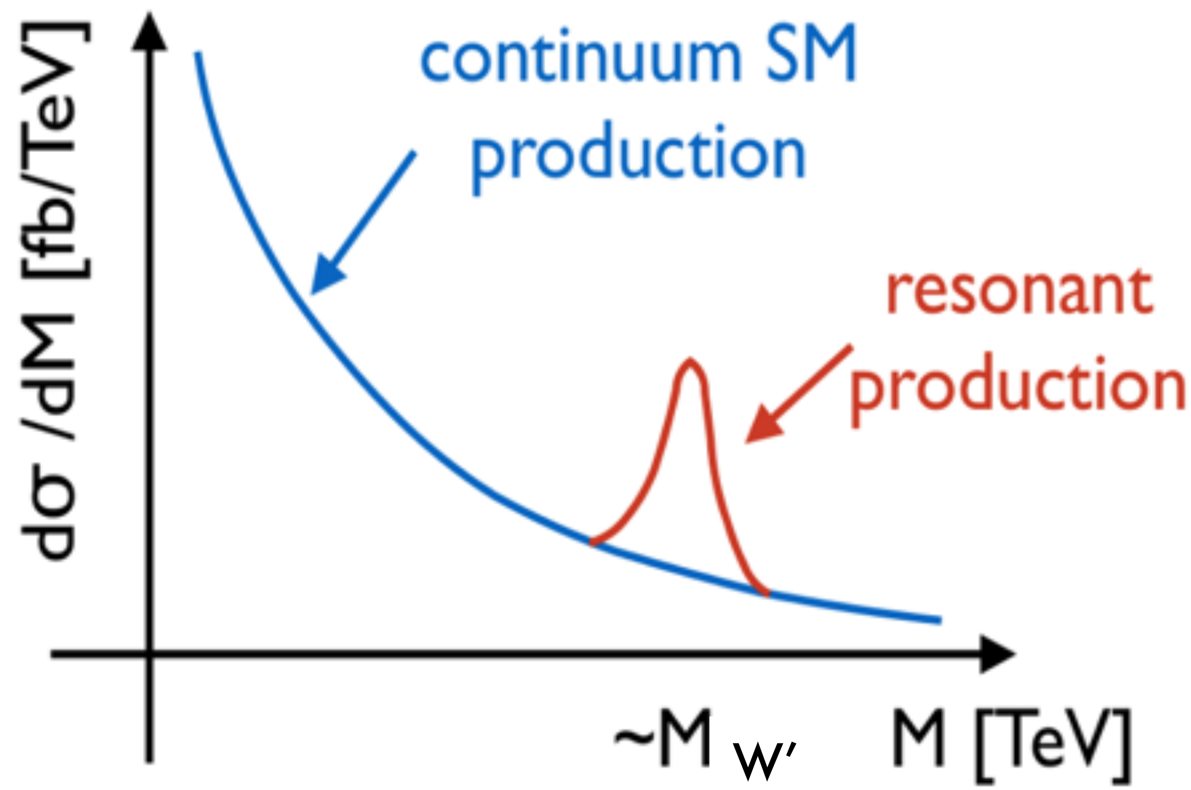
W'→tb resonances:

in some models the W’ decay to light quarks is suppressed.

Signal modeling:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^{\mathrm{R}}_{f_i f_j} (1+\gamma^5) + a^{\mathrm{L}}_{f_i f_j} (1-\gamma^5) \right) W'^{\mu} f_j + \mathrm{h.c.}$$

if left-coupling component is non-zero then **interference with SM**



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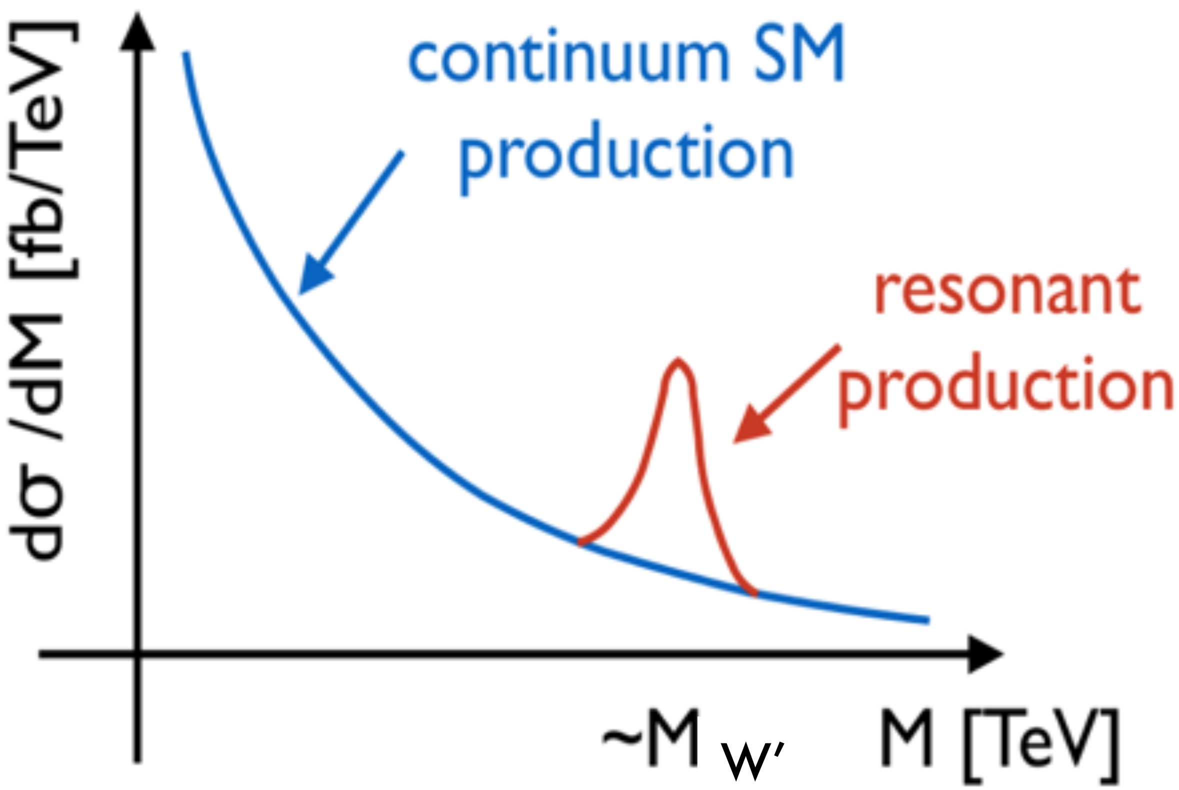
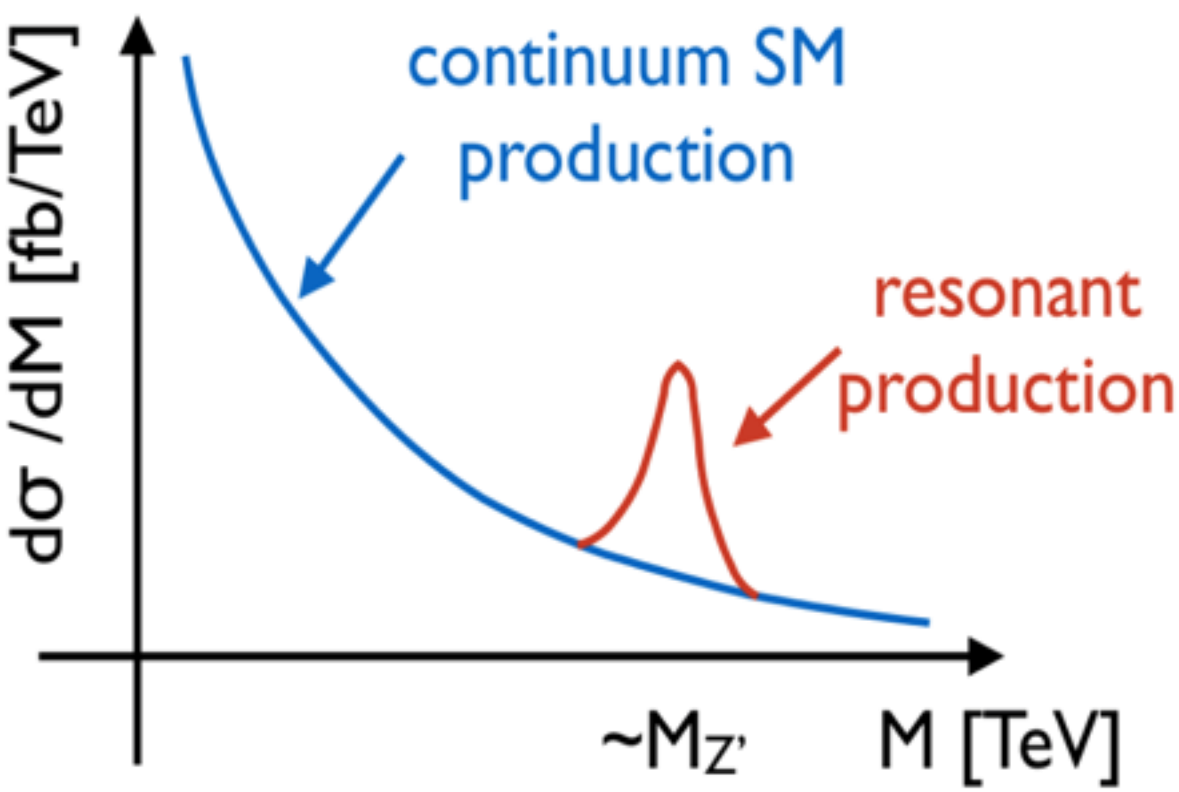


- **ttbar resonances**: predicted by several models, searches can be interpreted in any of these: extended gauge sectors top-colour condensates warped extra dimensions Kaluza-Klein excitations

  appear as a deviation from the SM in M_{tt} spectrum



JHEP 05 (2014) 108

NEW W' RESONANCES

B2G-12-009

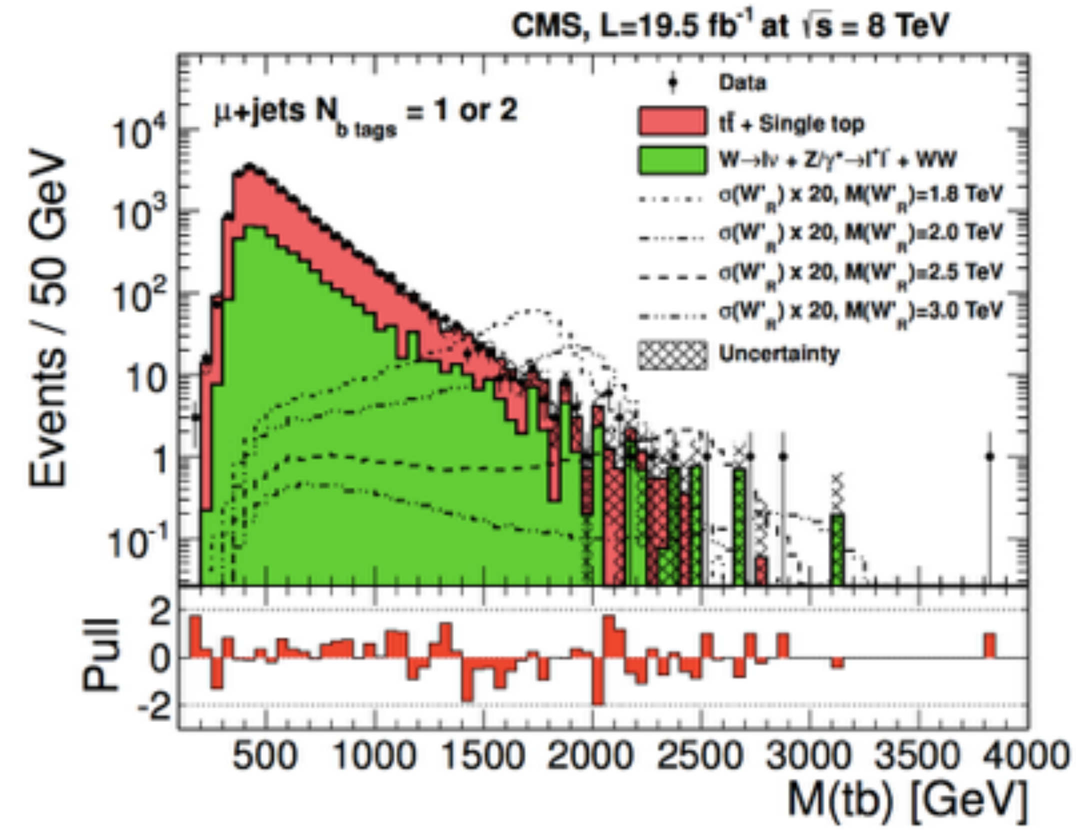
Lepton+jets:

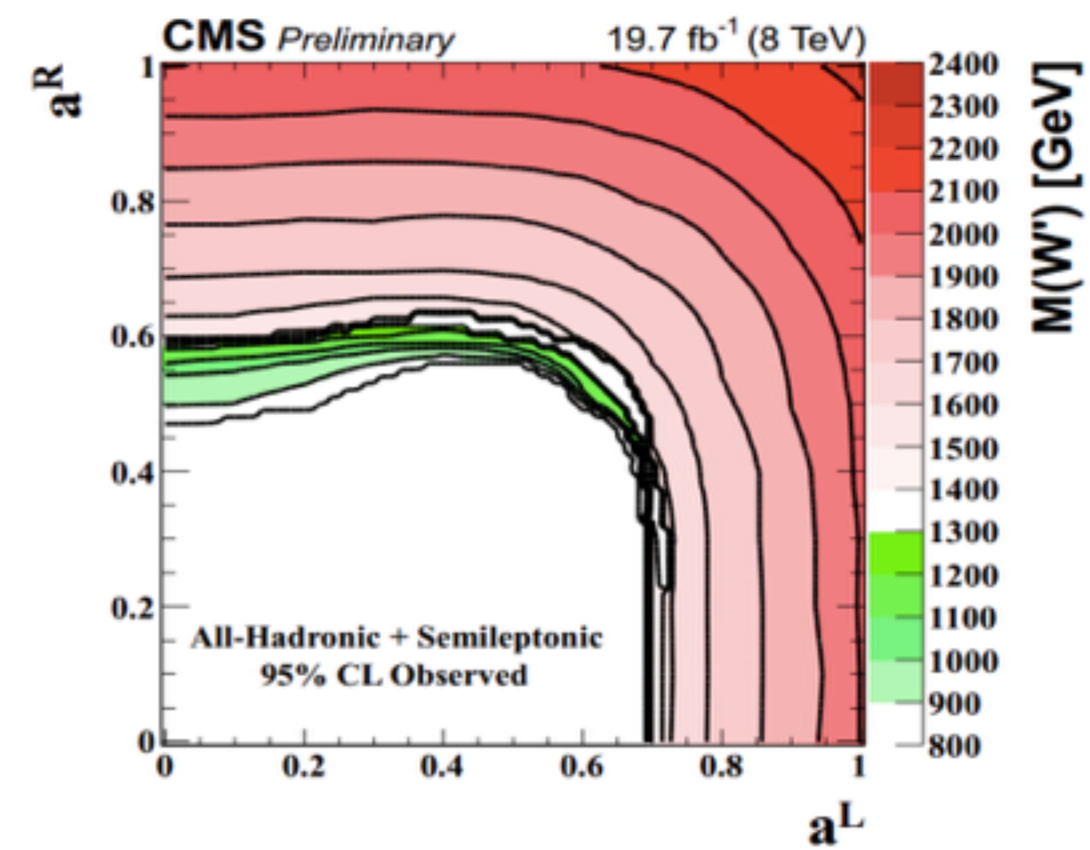
- resolved: single lepton (e, μ), 2 jets, 1 b-tag
- W' candidate from top candidate and leading jet

Boosted all hadronic:

- b-candidate: b-tag + mass < 70 GeV
- top-decay: CMSTopTagger+ n-subjettiness + subjet b-tagging
- **substructure**: similar sensitivity as cleaner semi-leptonic final state

W'_R mass limit of 2.15 GeV. Limits provided also for mixed couplings





arxiv:1506.03062

New Z' resonances

Resolved:

conventional analysis: 4 jets, 1 b-tag, isolated lepton (μ or e), $E^{miss}{}_T$

→ ttbar system reconstructed from χ^2 **assignment**

Di-leptonic

→ two (non-)isolated leptons (ee, μμ, eμ), 1 or 2 b-tags

background region: ΔR (lept 2, jet) > 1.5

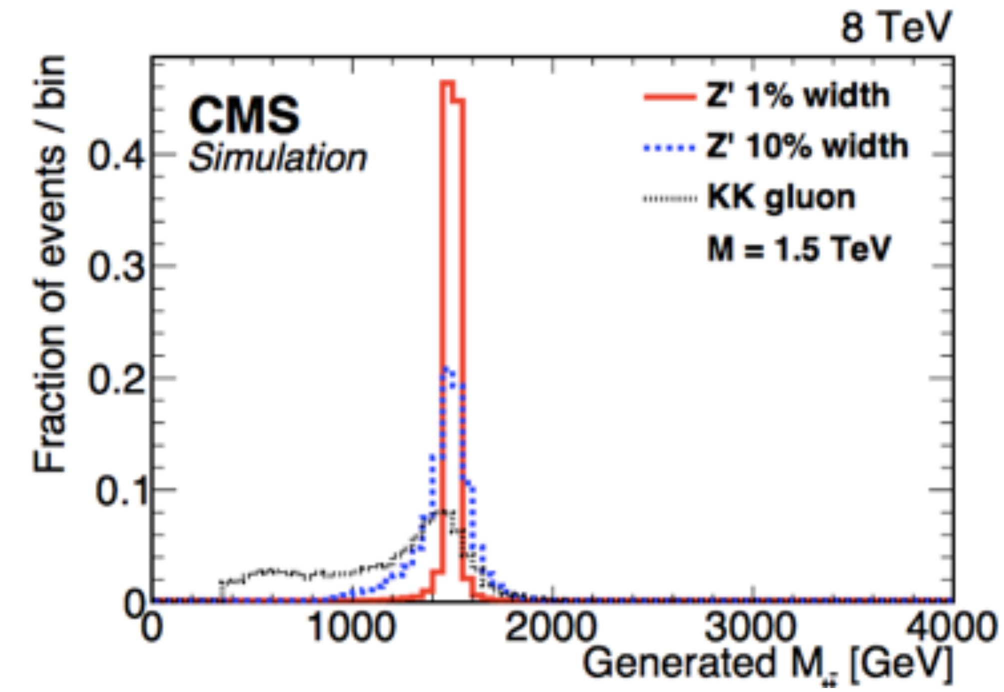
Semileptonic

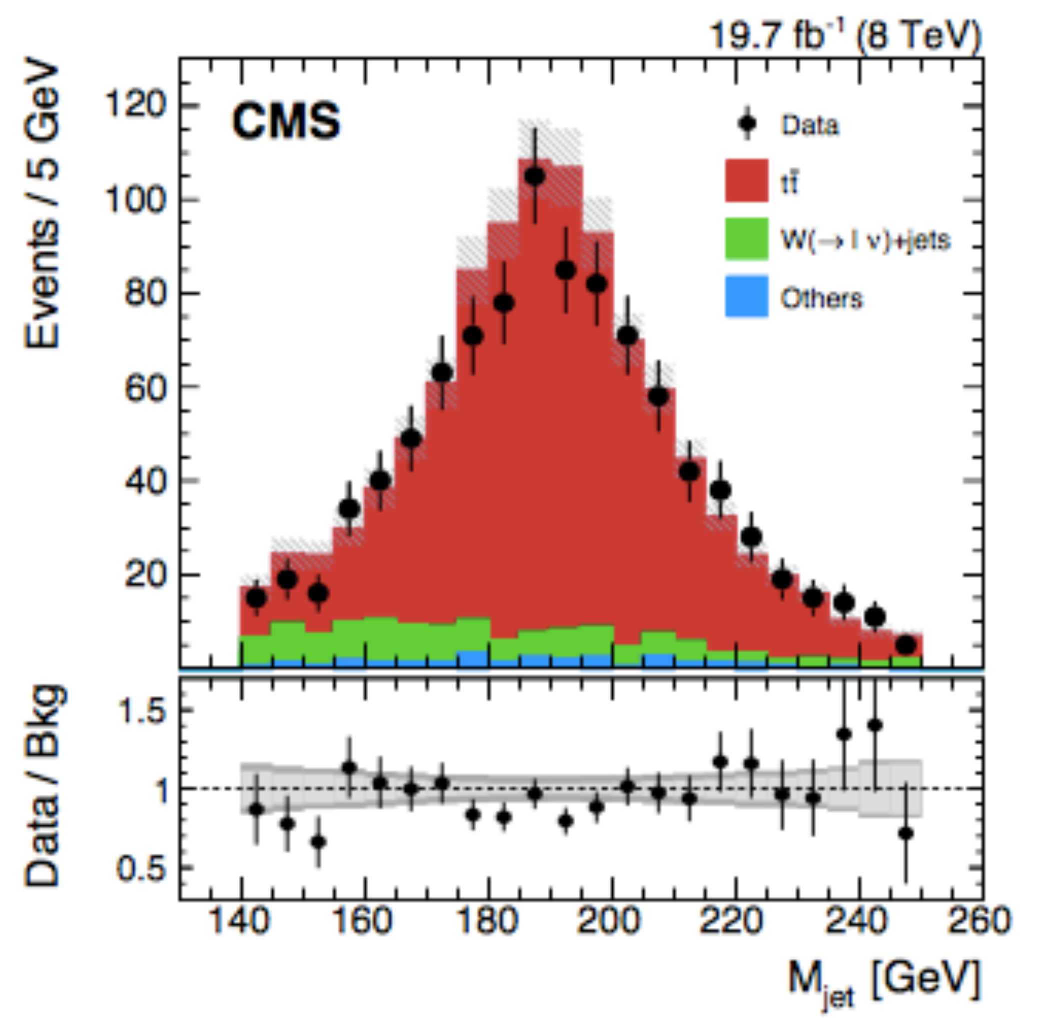
leptonic decay: (non-)isolated lepton, e or μ

→ hadronic decay:

boosted: events with 1 CMS-**top-tag**

χ^2 **assignment** for (partially) resolved decays



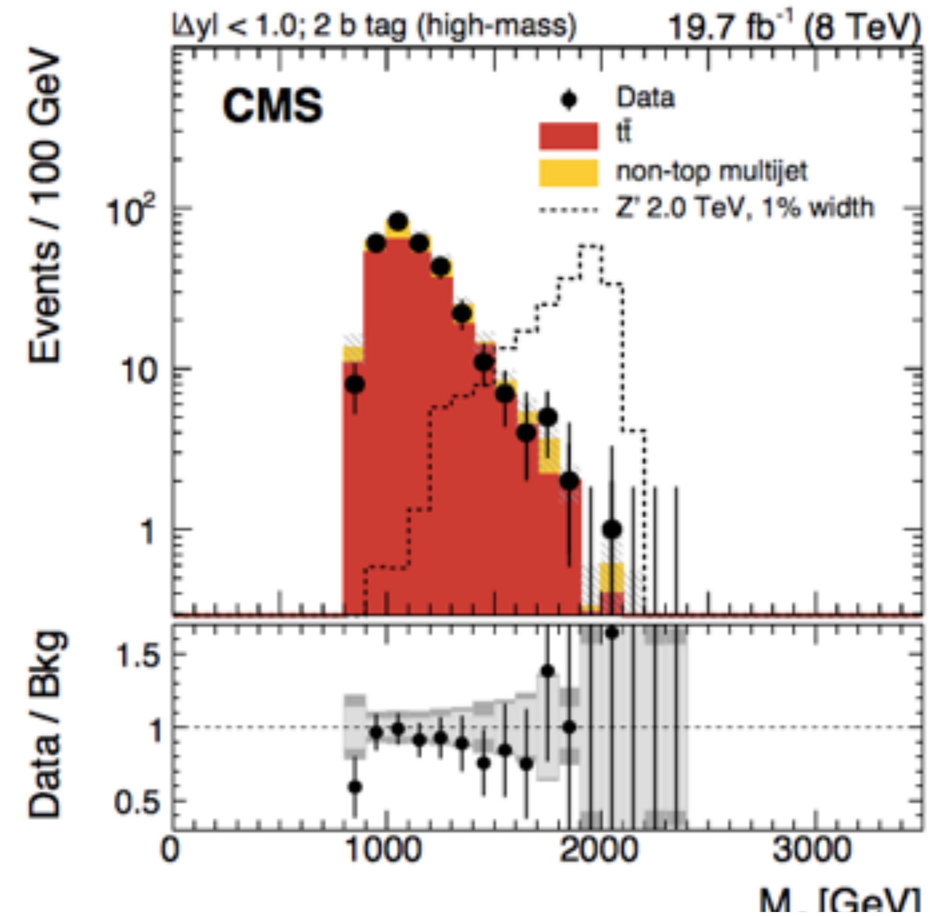


arxiv:1506.03062

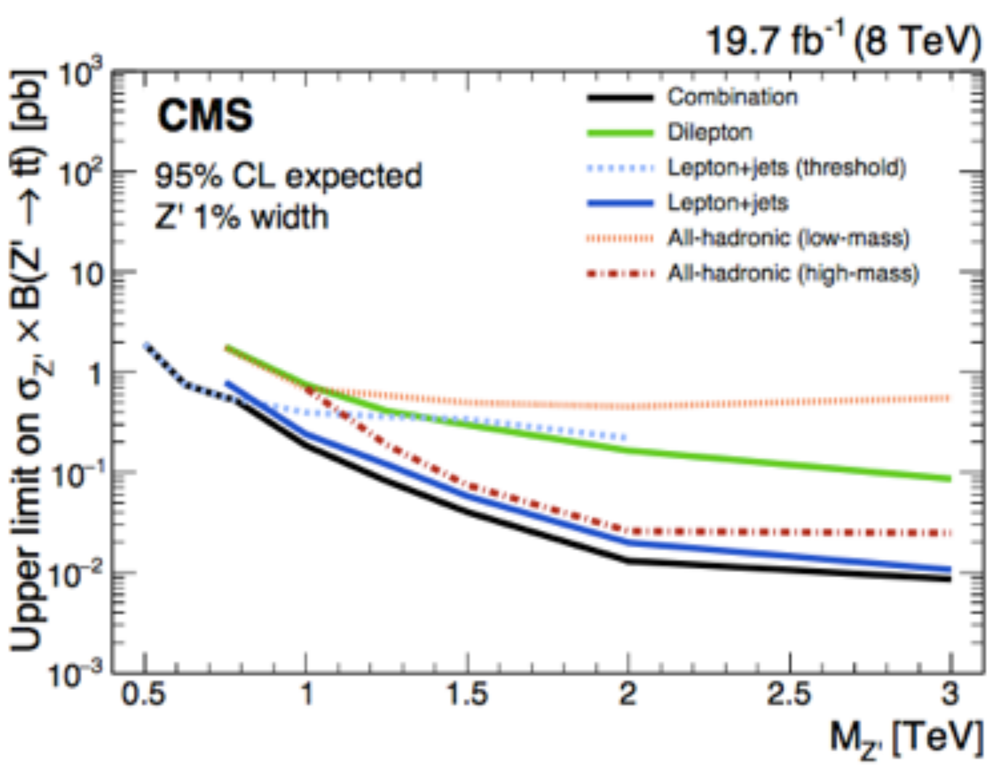
NEW Z' RESONANCES

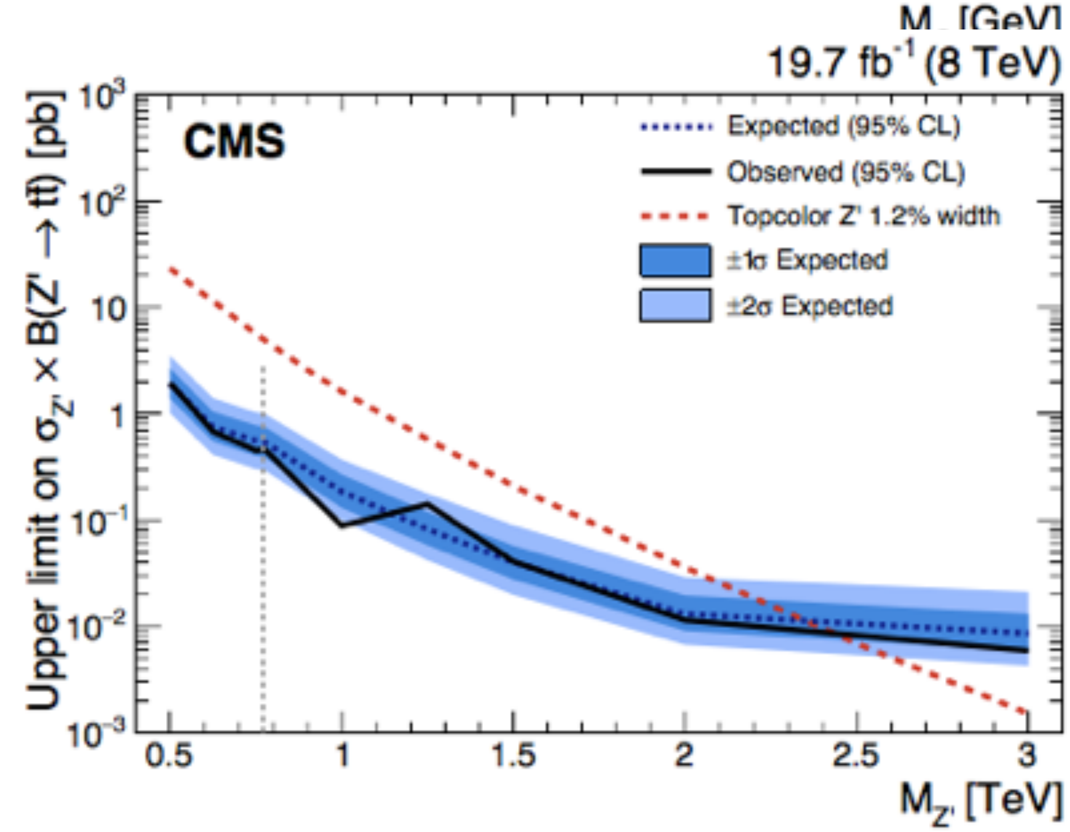
Full hadronic:

large use of **substructure:**
HepTopTagger (200-400 GeV) **and**
CMSTopTagger (>400 GeV) **subjet b-tagging**

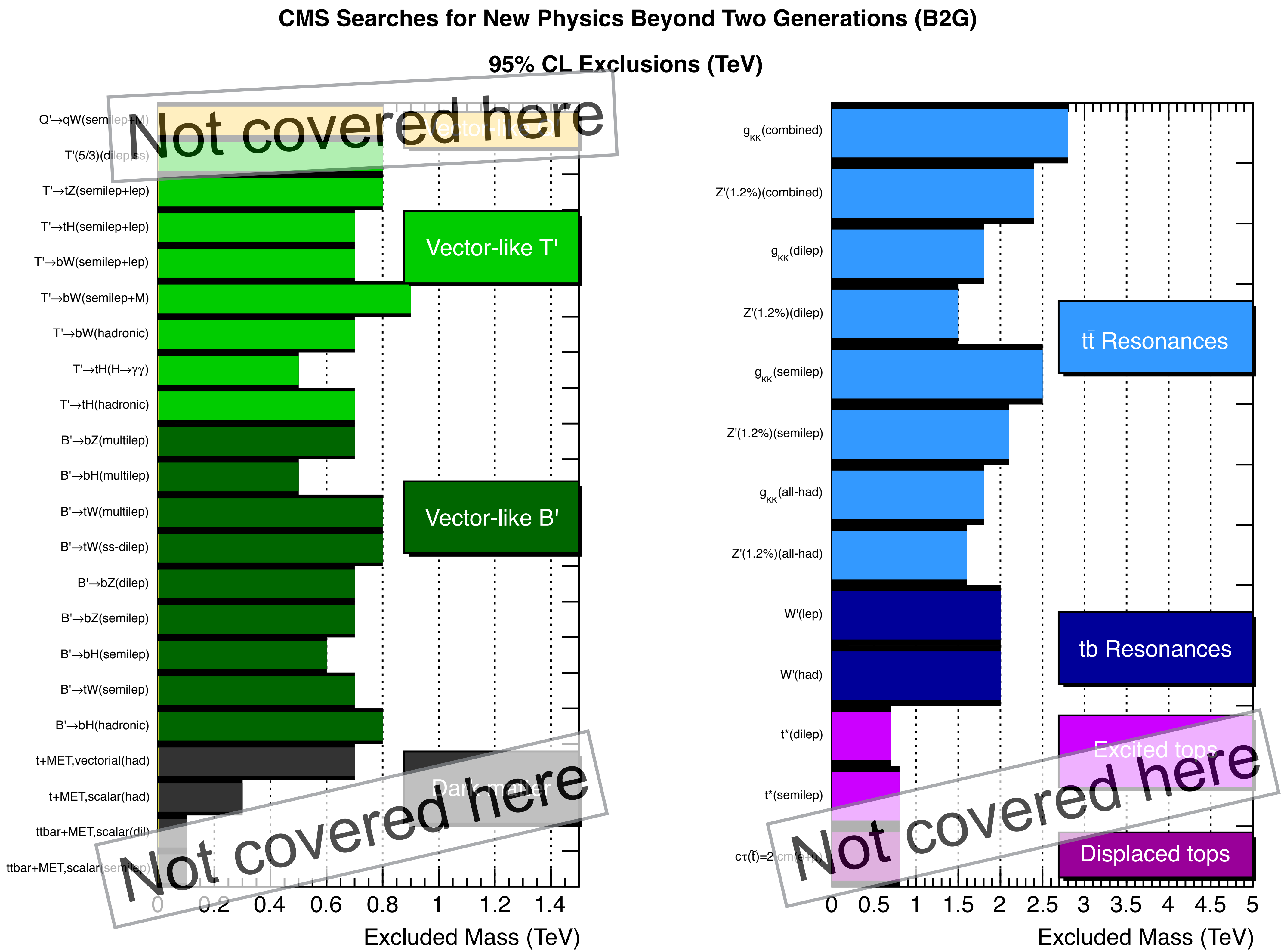


Combination of all of the above channels to obtain best limits. Here shown sensitivity to Z' with 1% width hypothesis





A VISUAL SENSITIVITY SUMMARY



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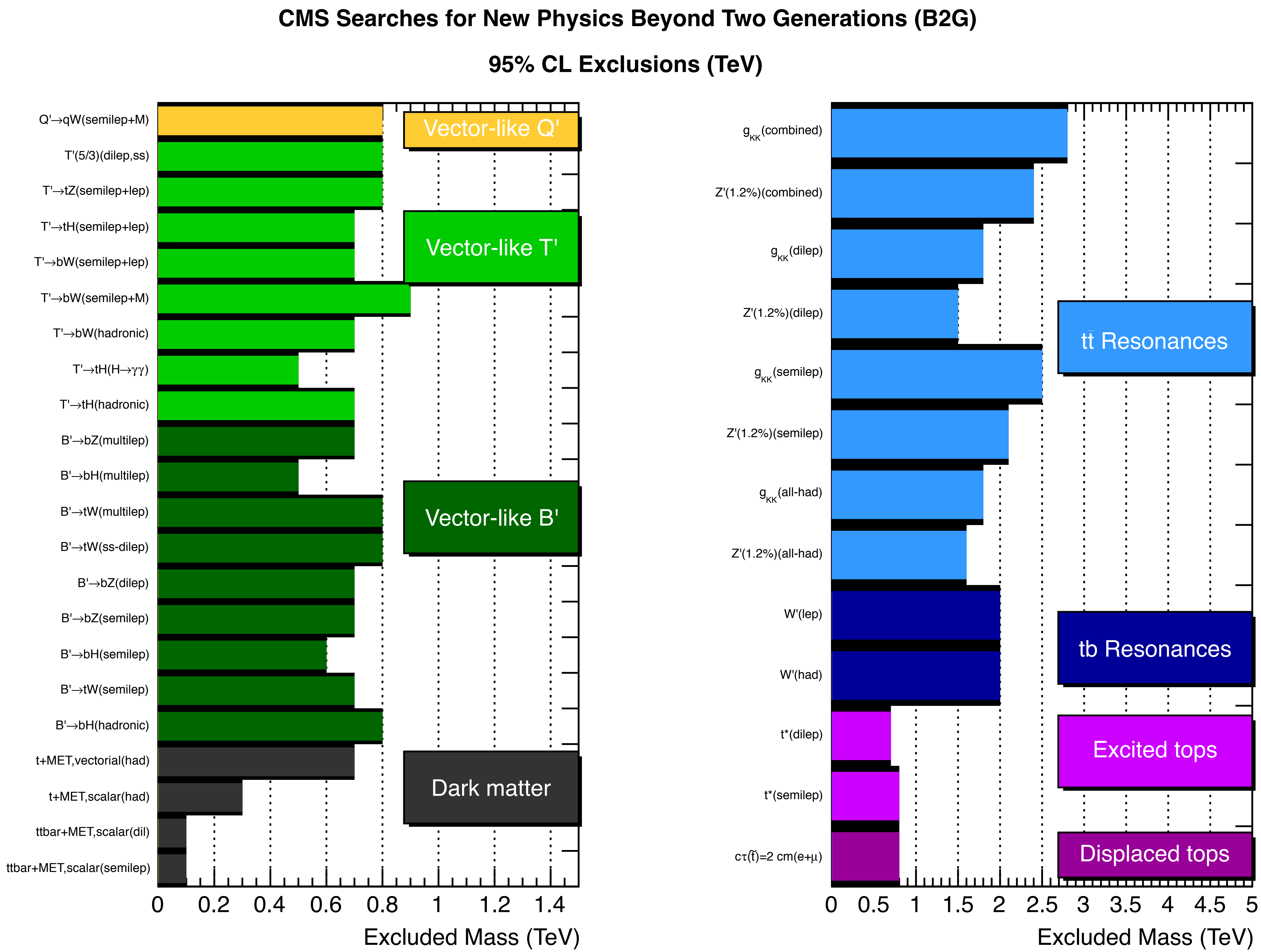
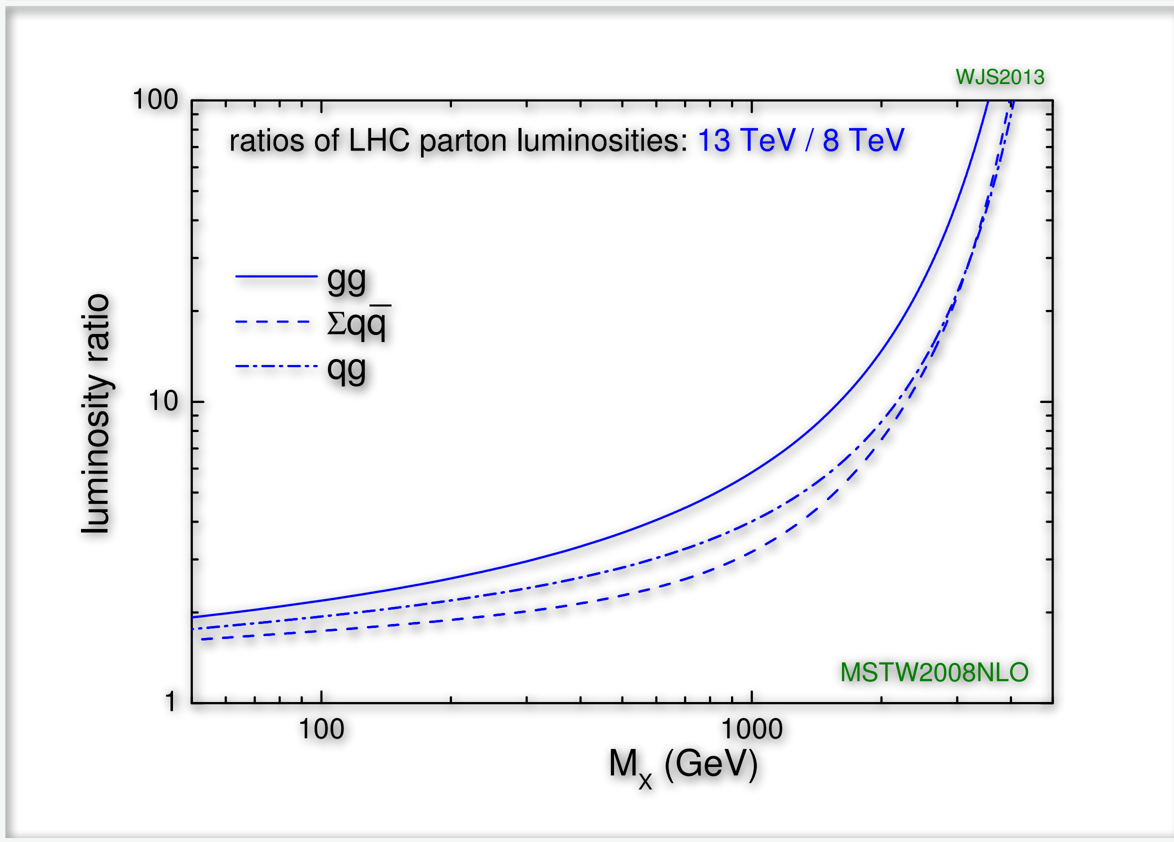
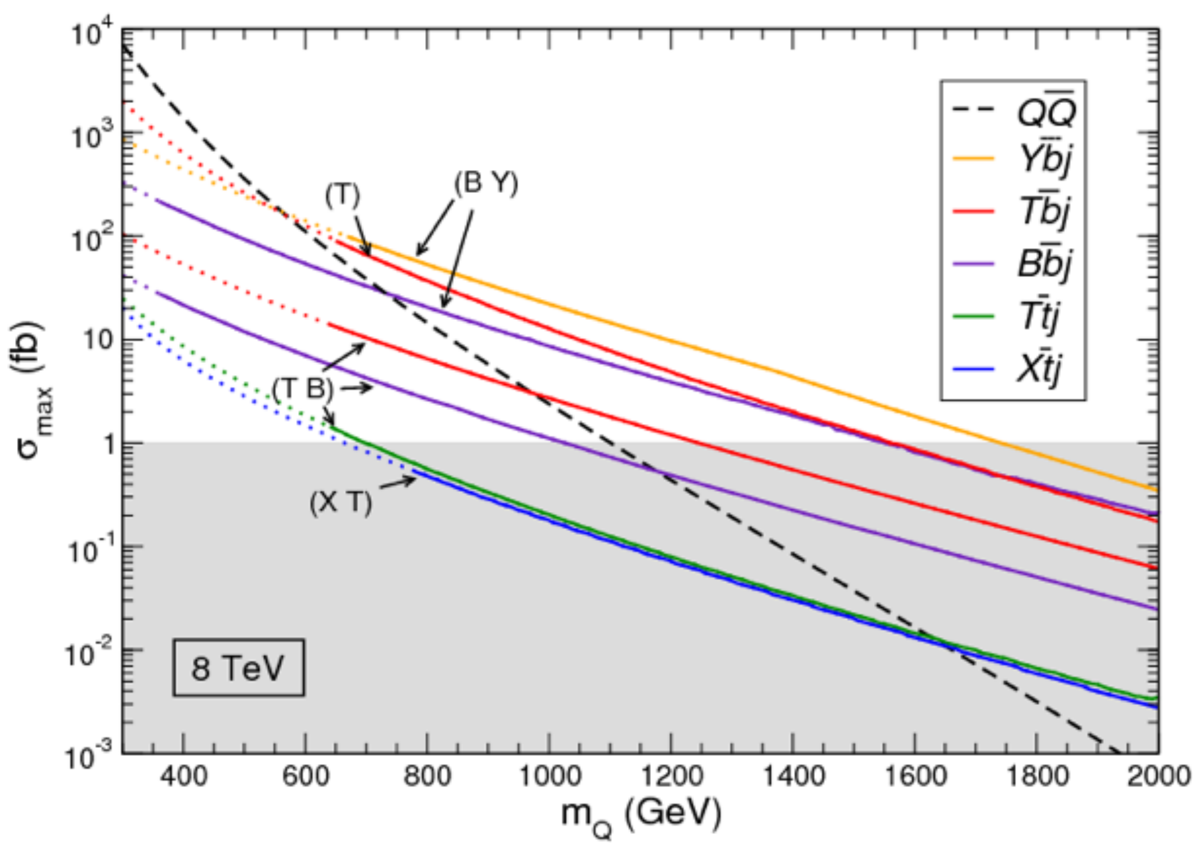


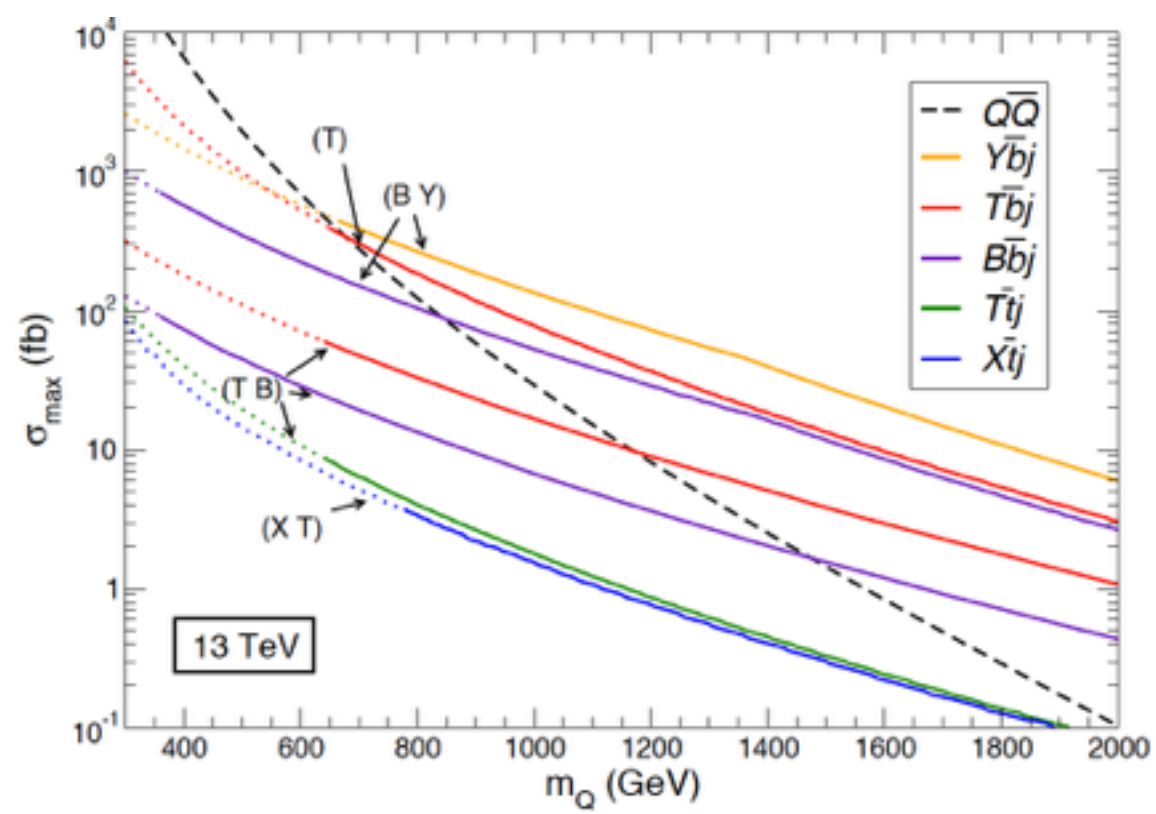
LIFE IS BETTER AT 13TEV



New energy:

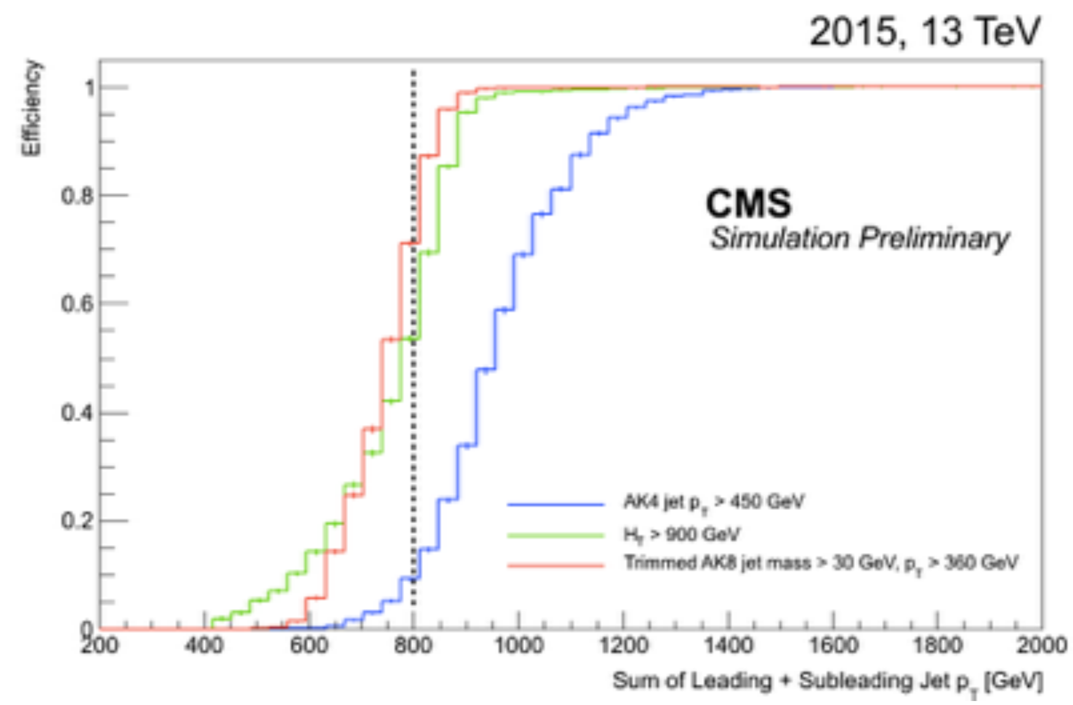
- increased parton luminosities, increased mass reach for less luminosity
- this is especially true for heavy quarks
- single heavy quark will become more important
- challenge: keep/improve performance wrt Run1



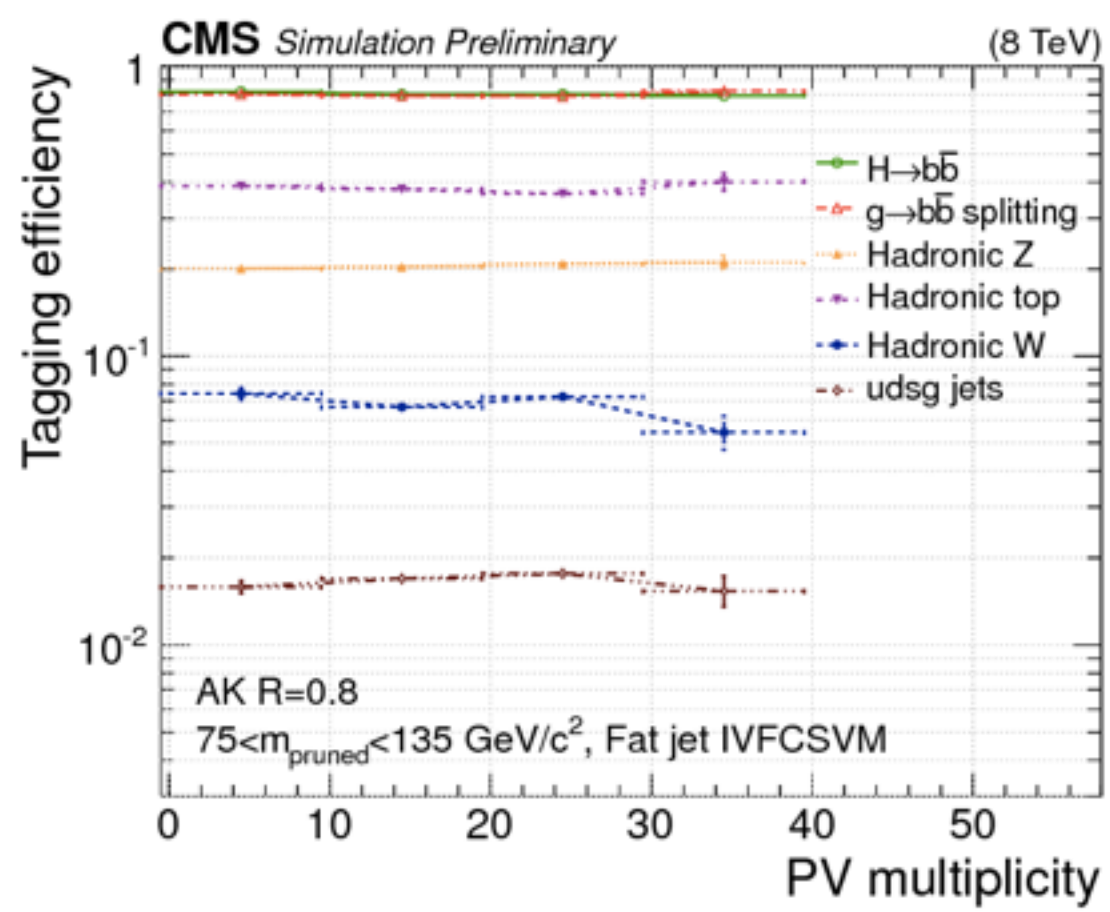


BUT IT COMES WITH ITS OWN CHALLENGES

Readiness means adapting to the new running conditions. W'/Z' cross sections do not increase so dramatically, g_{KK} resonance broadens at high masses



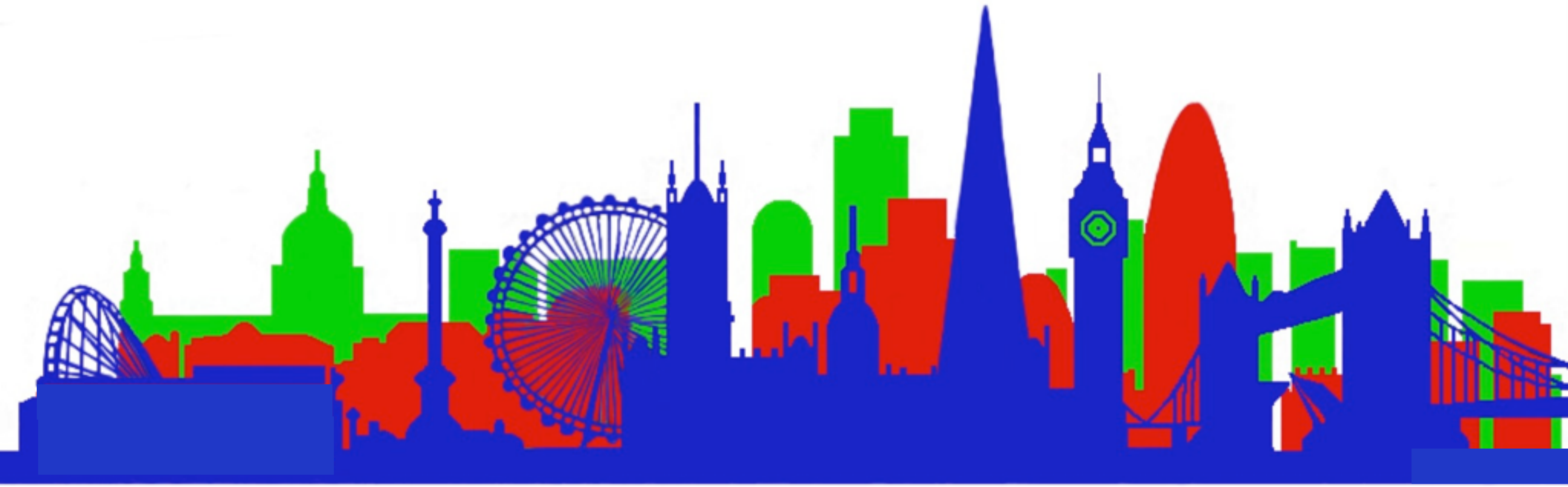
- need improved triggers to keep the rate low and the efficiency high: use substructure technique such as the Trimmed mass



- develop reconstruction variables and techniques that would not suffer from PileUp dependence

Conclusions

- The Higgs discovery calls for new, compelling questions, that need to be promptly answered
- Forcing the development of advanced tools for physics with boosted particles
- New heavy quarks/bosons with very rich phenomenology could very much lie only a few months of data-taking away



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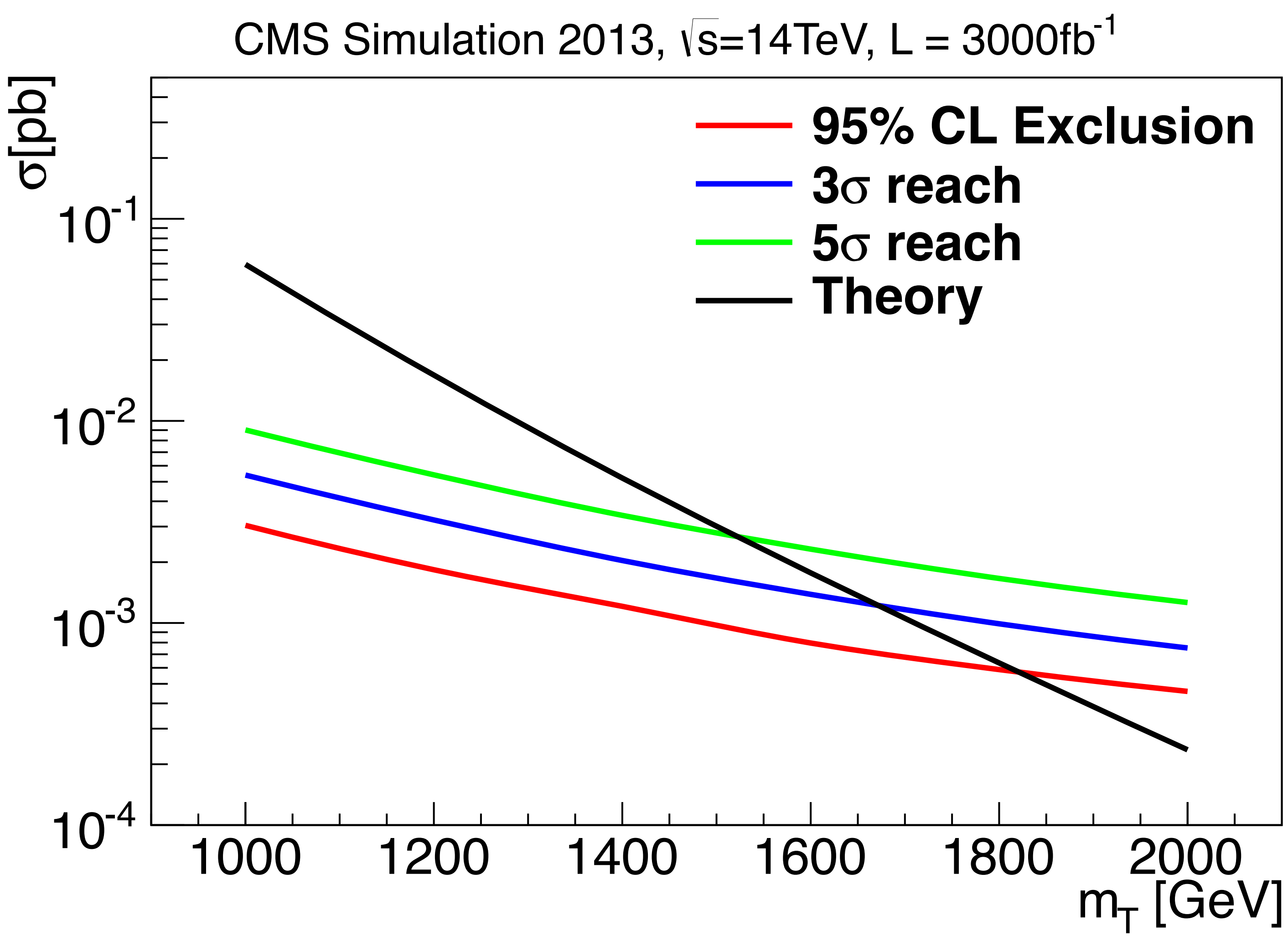
BACKUP

Fermionic top partners, projections to 3ab-1



MODELING

Heavy quarks: MadGraph + Pythia. Hathor/Top++2.0 for NNLO rates

W': CompHEP/SINGLETOP includes interference, finite mass Width ~3%

Z' MadGraph and widths of $\Gamma Z'/MZ'$ of 1% and 10%.

g* excitations are simulated using PYTHIA 8. The widths of the gKK signals are about 15–20% of the resonance mass.

The tt is modeled with POWHEG or MadGraph
W+jets, and $Z/\gamma*$+jets background processes are generated with MadGraph 5.1 + Pythia + Tune Z2* + CTEQ6L1

When using POWHEG, need NLO PDFS: CTEQ6M

Jets

Leptonic analyses:

- the usual anti-Kt AK05 jets to identify a single parton
- Cambridge-Aachen jets CA08 (CA15) to identify a boson (top quark)
- CA jets can be pruned to find subjects in them
- if looking for a boson, take CA jet, find two subjects, require small mass drop

Hadronic analyses

The use of the t tagging algorithm enhances the sensitivity of this channel at high resonance masses by about 30–40%, and leaves tt continuum production as the dominant irreducible background.

Two separate regions are explored: a search region sensitive to Z′ masses MZ′ below 1 TeV, where Cambridge-Aachen (CA) jets [with a distance parameter of R = 1.5 are considered, and a search region for high resonance masses, using CA jets with R = 0.8. Two distinct t tagging algorithms are used for these two regions.

TRIGGERS

Single lepton triggers

- one electron with $pT > 35$ GeV in conjunction with two jets that have $pT > 100$ and 25 Ge
  respectively
- single electron/muon with $Pt>27$
- single electron trigger with a pT threshold of 80 GeV and an efficiency of 90%
- single muon with $pT > 4\ 0$ GeV and $|\eta| < 2.1$. The efficiency for this trigger is 80-95%
- two e/mu with $Pt>17$ and 8GeV of any charge

A 10% increase in the signal efficiency at $MZ' = 2$ TeV is gained in the electron channel by including events that are triggered by a single jet with $pT > 320$ GeV

The all-hadronic data sample is based on two different triggers. The first requires the scalar sum of the pT of jets (HT) to be greater than 750 GeV, with an efficiency of 95% or higher after the analysis selection. The second requires four jets with $pT > 50$ GeV at trigger level, used to gain efficiency in the low mass regime with $MZ' < 1$ TeV. The efficiency of this trigger is 50% for events with the fourth leading jet having $pT > 50$ GeV, and increases to 100% for jets with $pT >100$GeV.