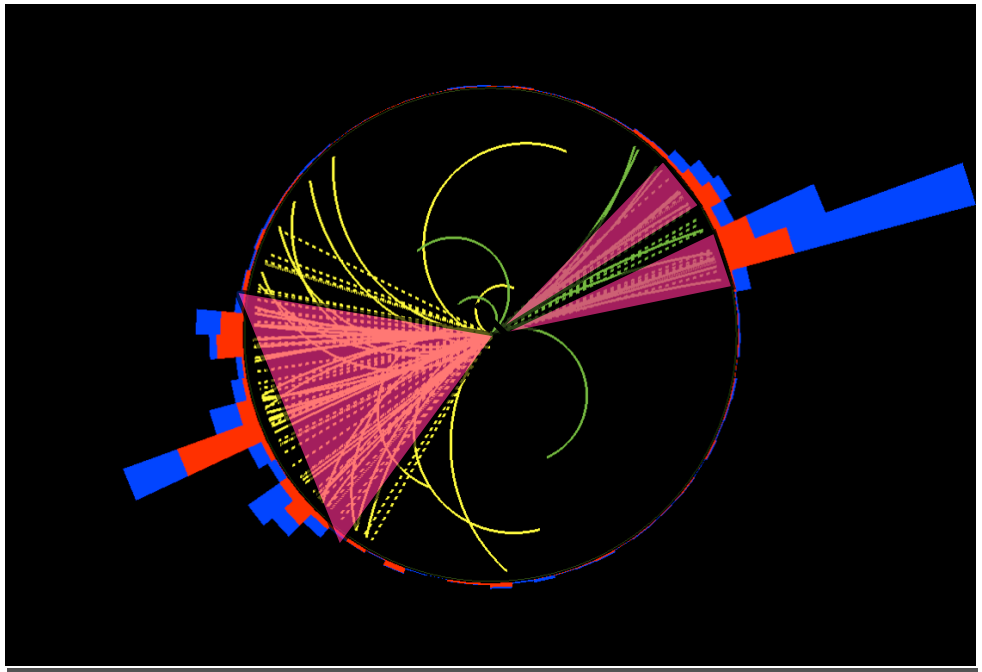
Searches for New Physics with Top-Like Signatures

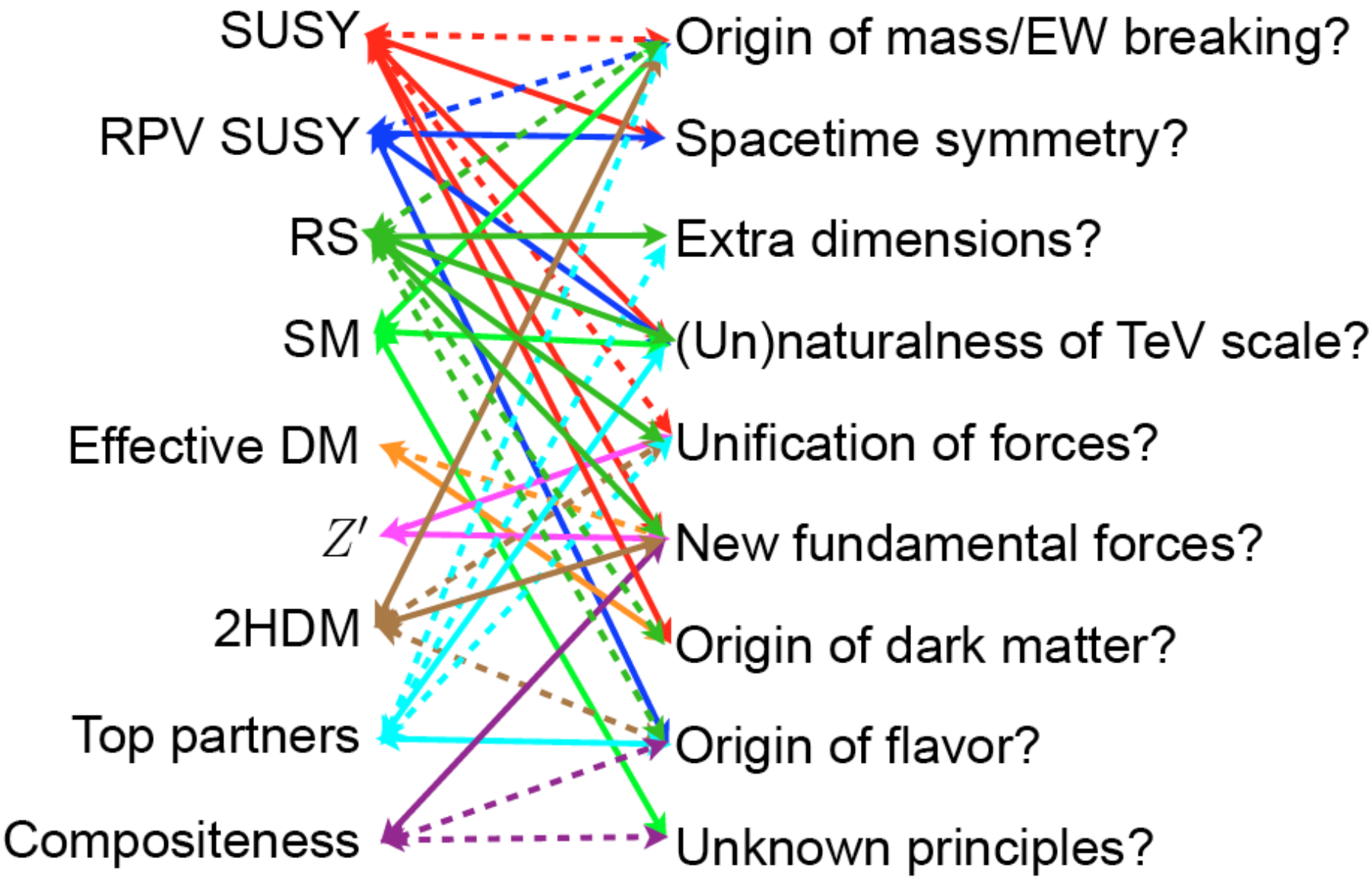


Robin Erbacher - U.C. Davis

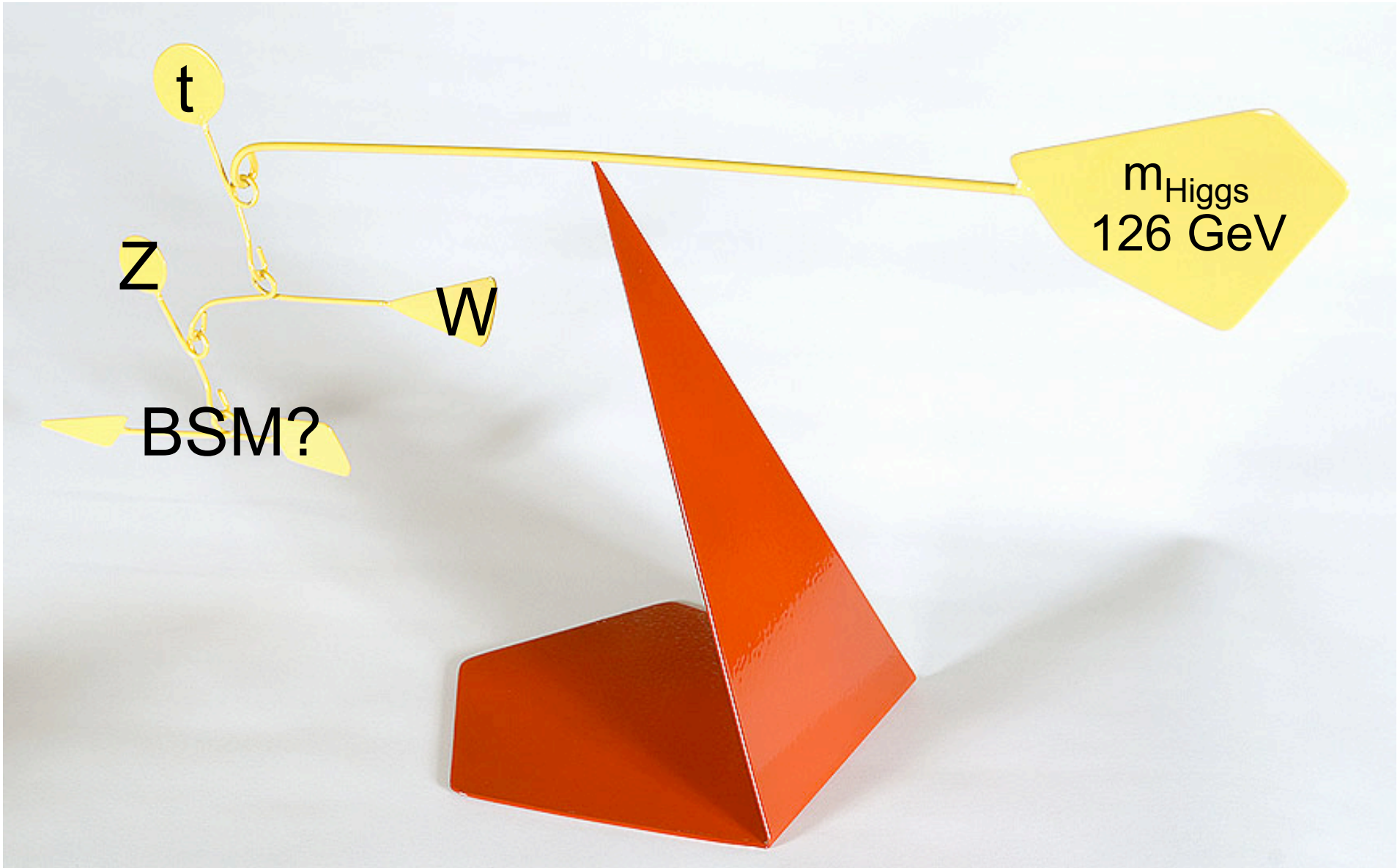
Frontiers in Particle Physics - Aspen Winter Conference

January 19, 2014

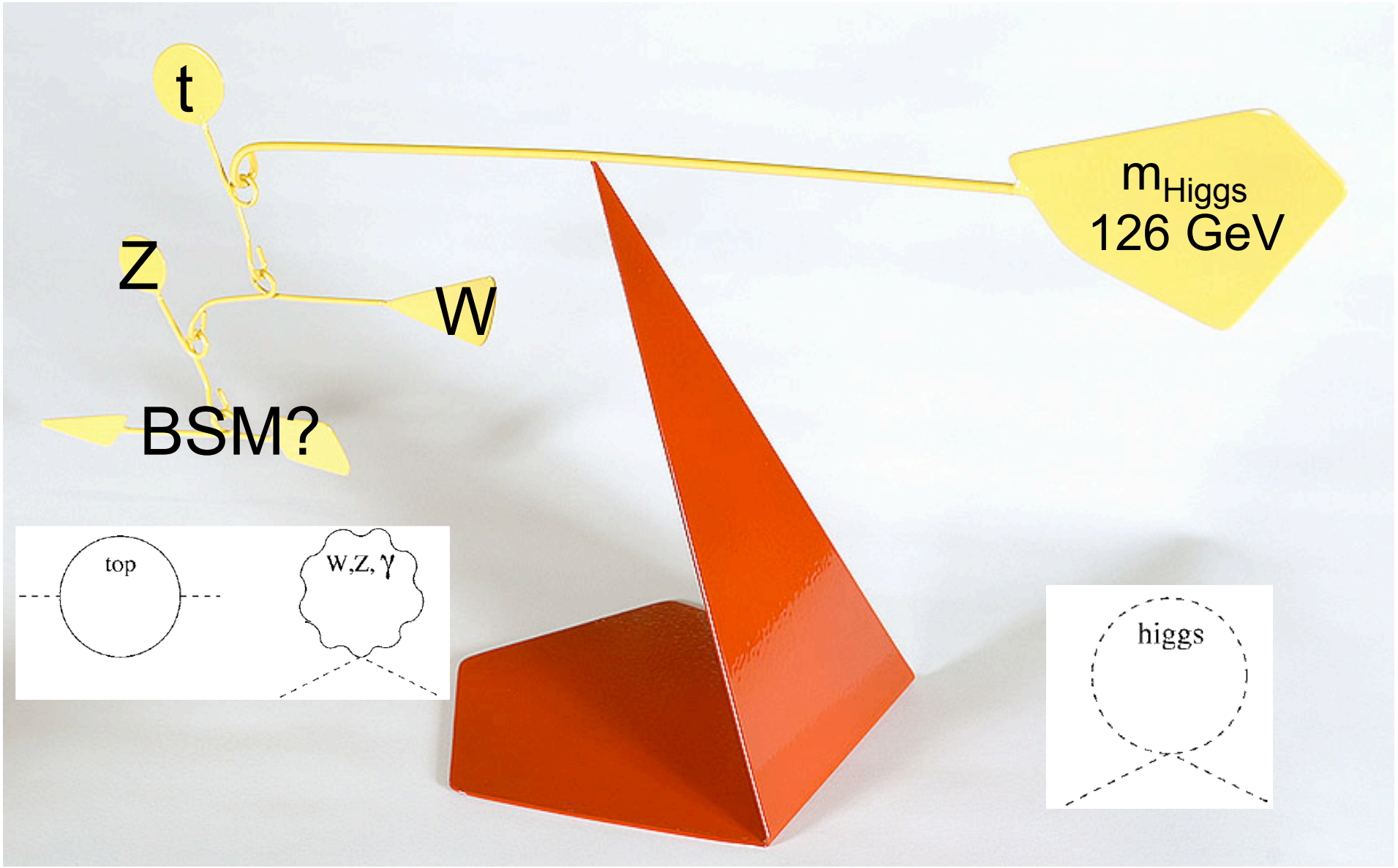
17 SM parameters, still many questions...



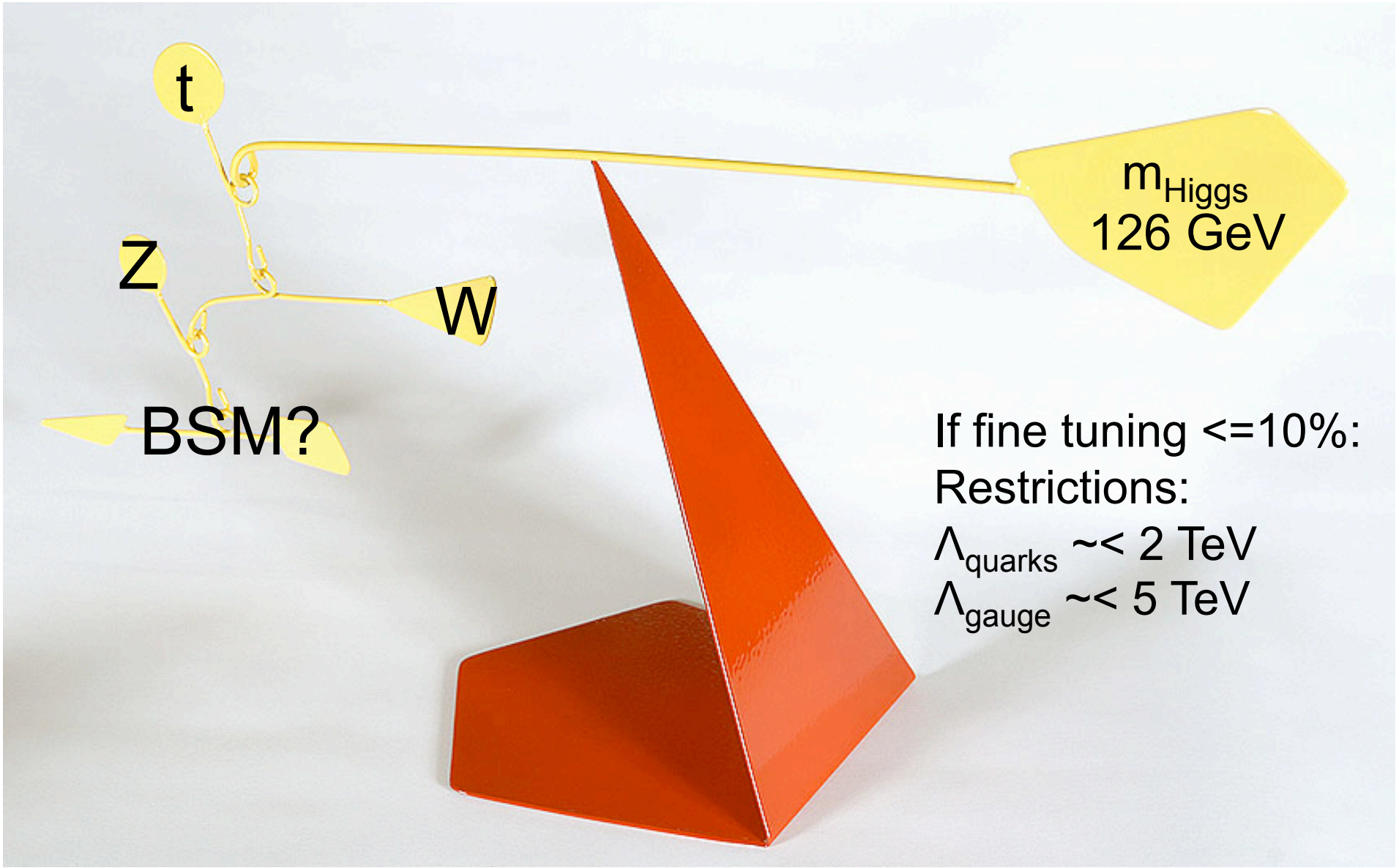
Little Hierarchy Problem: Naturalness



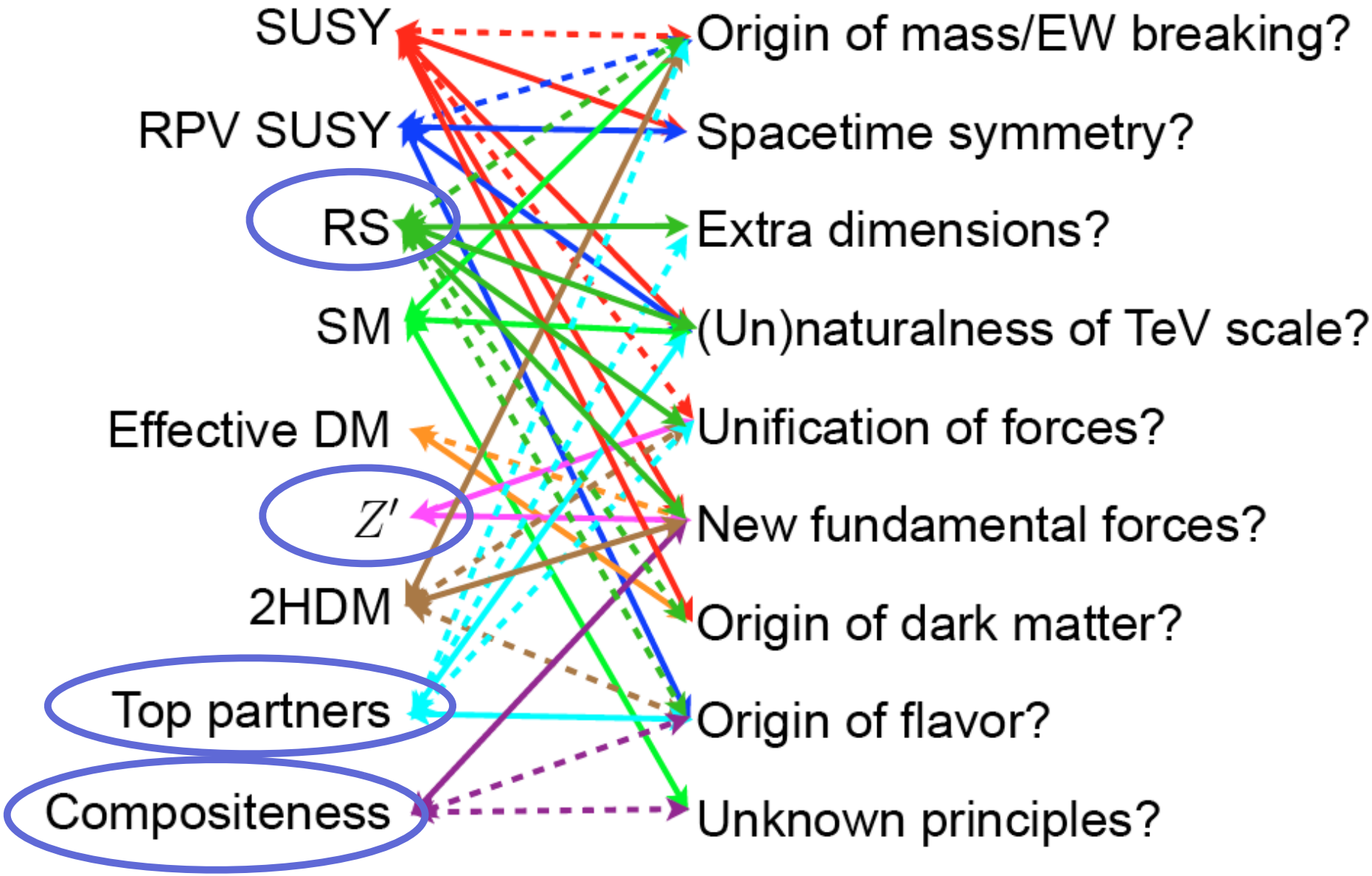
Little Hierarchy Problem: Naturalness



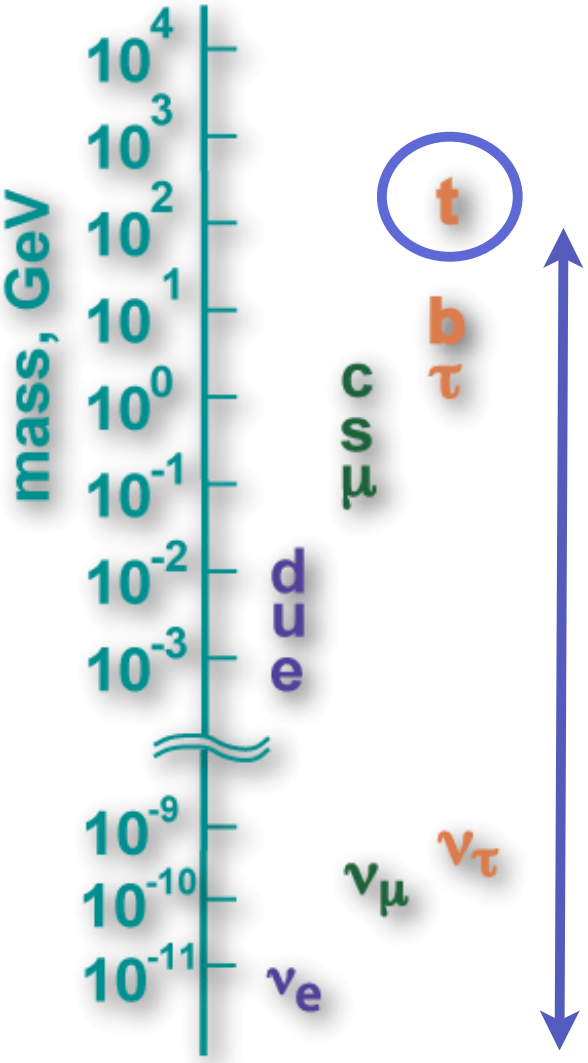
Little Hierarchy Problem: Naturalness



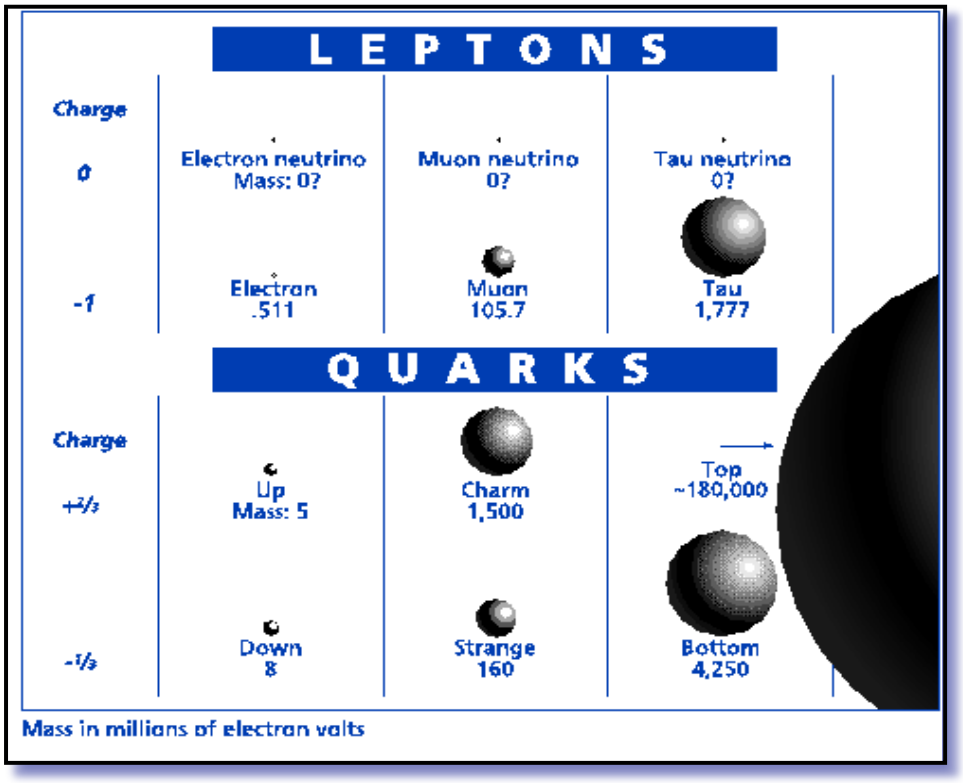
17 SM parameters, still many questions...



Searches with Top



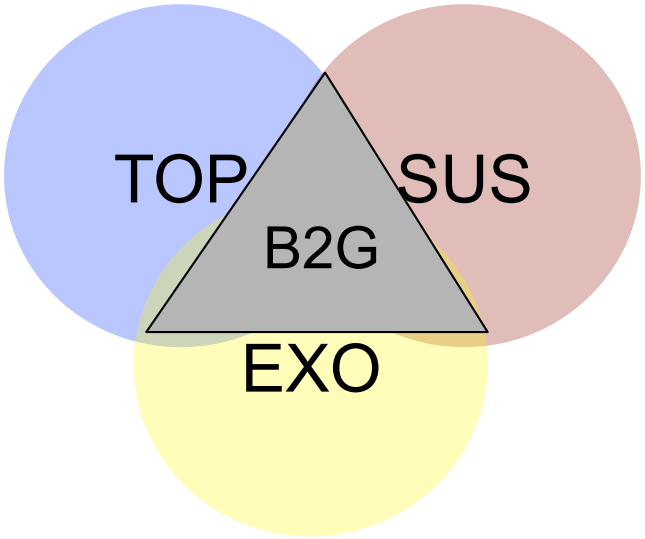
~5 orders of magnitude!



- Top quark is only fermion with a mass of order the EWK scale.
- Large mass suggests it may couple to physics beyond the SM.

New Physics in Top: Popular!

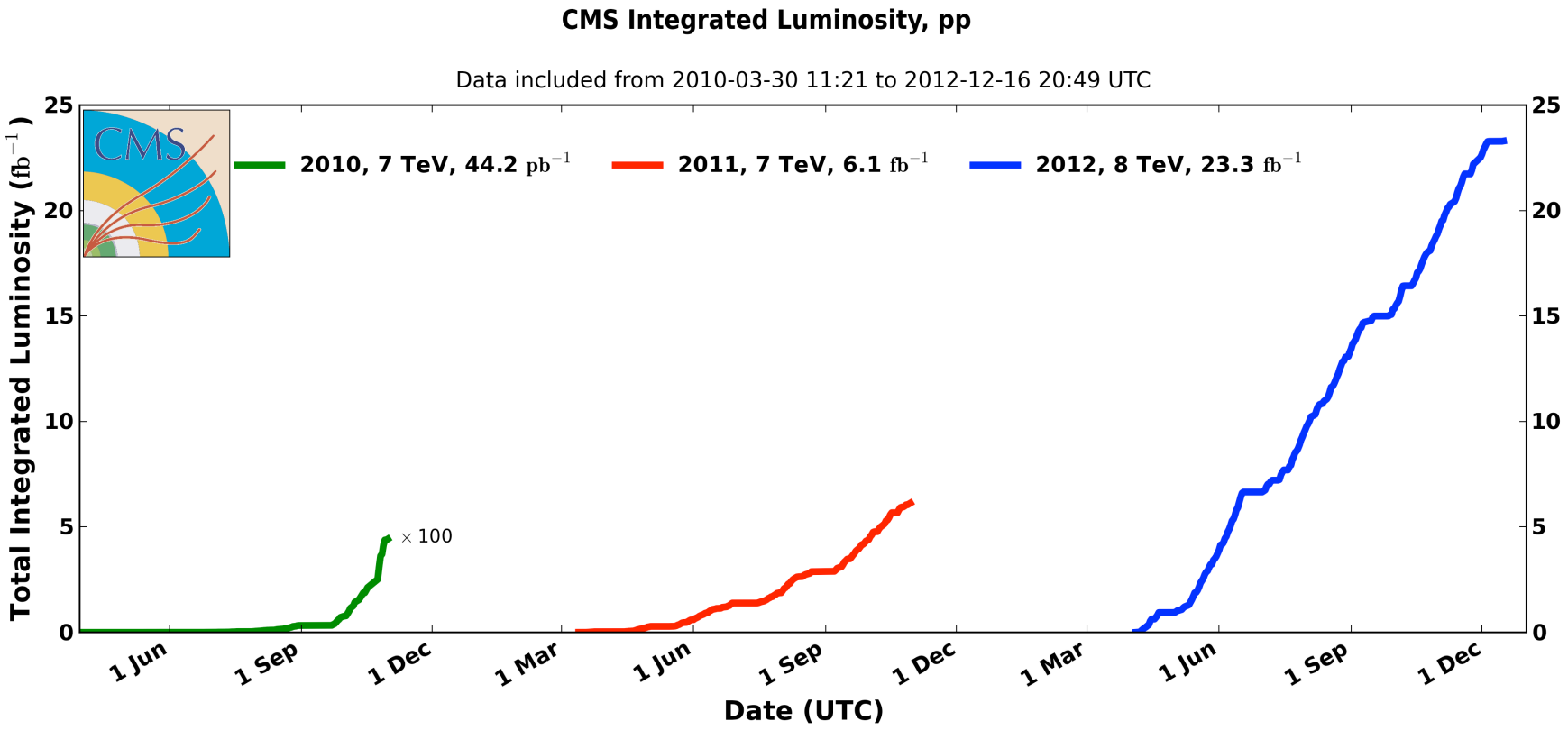
CMS



ATLAS

- Top BSM searches span many groups and categories.
- Focusing here on most recent results, LHC only.
- [B2G = Beyond 2nd Generation (Physics Analysis Group)]

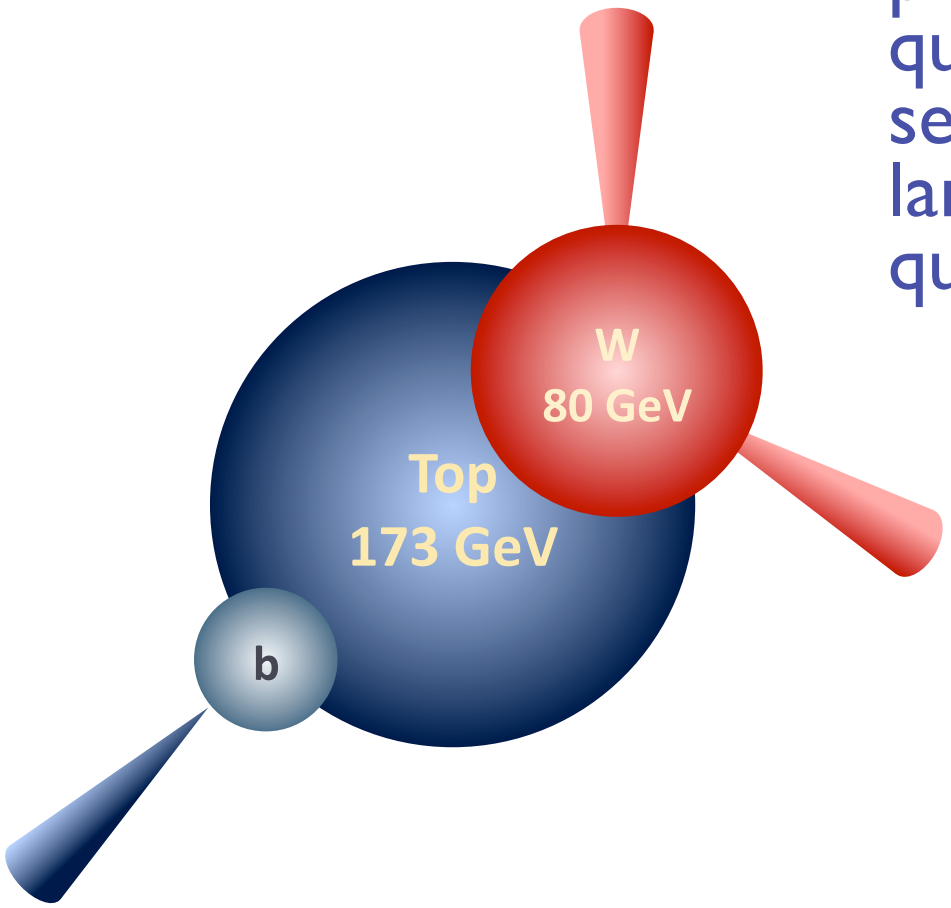
LHC Performance so far...



Outstanding LHC performance thus far.

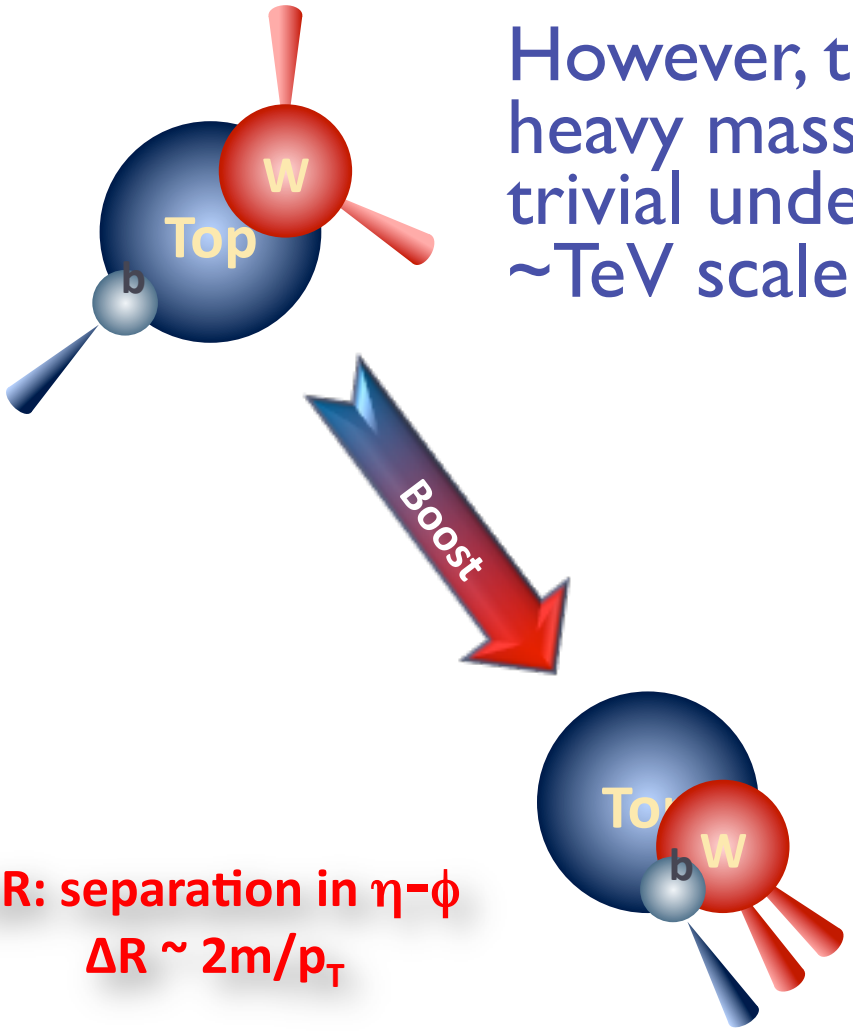
High hopes for 2015!

Top Quark Reconstruction



Traditionally, decay products from the top quark are clearly separated due to the large mass of the top quark and W boson...

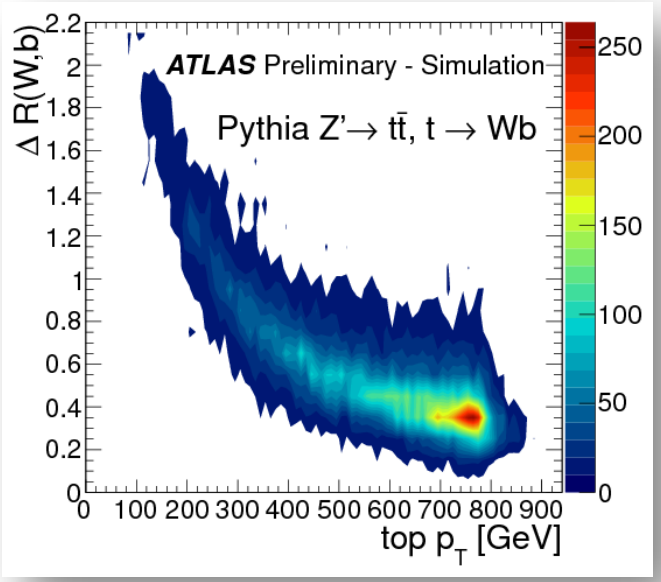
Challenge of Boosted Tops

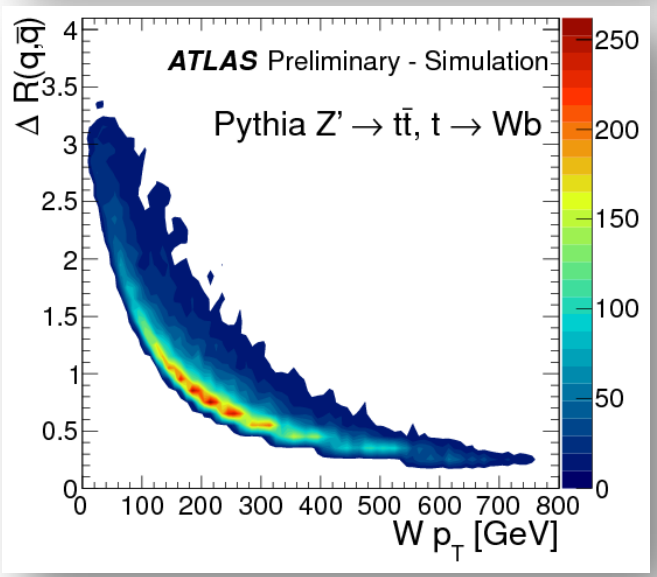


However, these heavy masses are trivial under ~TeV scale boost

ΔR: separation in η−ϕ

$\Delta R \sim 2m/p_T$





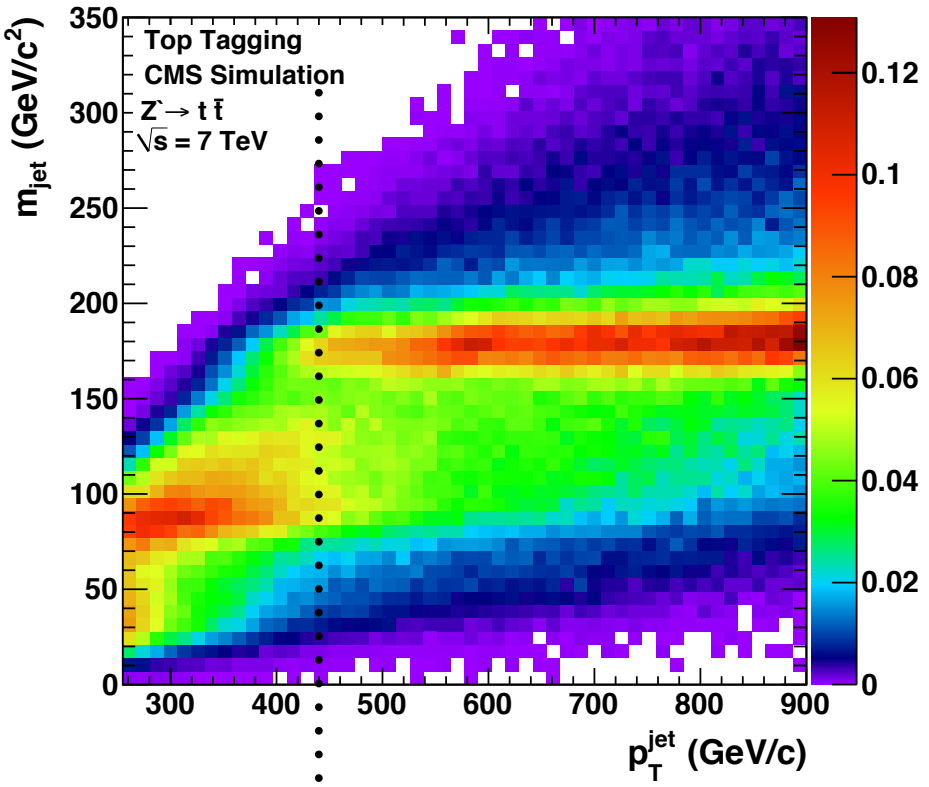
Kinematic Regimes

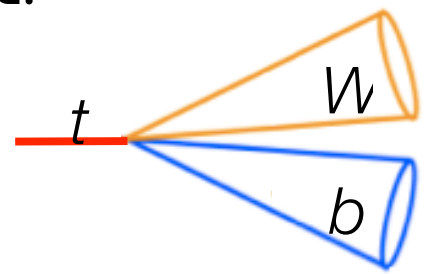
- Searches at different mass ranges need different strategies (eg: X→ttbar)

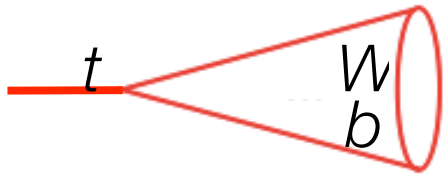
- Low-mass searches (<~1TeV)
  - Decay products well-separated
  - Standard top reco used

- High-mass searches (>~2TeV)
  - Boosted tops, collimated decays
  - Special reco algorithms needed:
  - Jet substructure!

- Intermediate mass range
  - Partially merged, mix of techniques





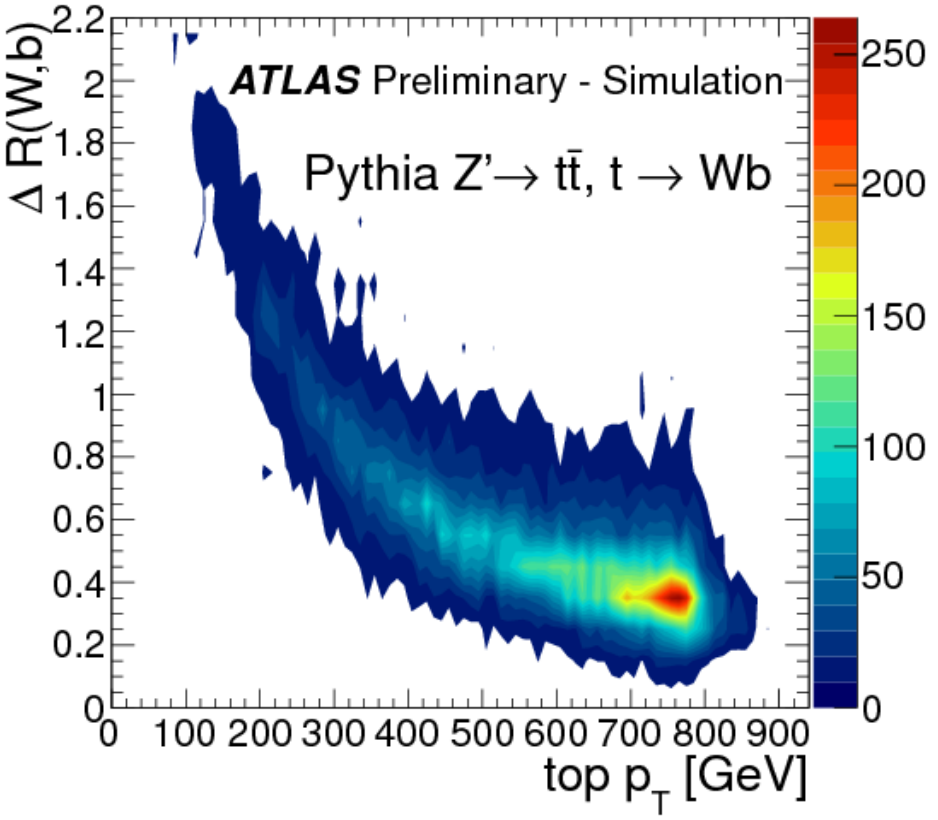


CMS-PAS-JME-10-013

"Fat" Jets

- Choose large jet size for reconstruction to catch all decay products.
- ATLAS & CMS have studied R=0.8,1.0,1.2,1.5.
- Use specific algorithms to identify the collimated decay products within this large-R jet. (C-A jets)

ATLAS-CONF-2012-065



A large amount of work is ongoing in ATLAS and CMS on "tagging" boosted tops, W/Z ("V-tags"), boosted Higgs. Stay tuned....

Boosted top references:

ATLAS-CONF-2012-065

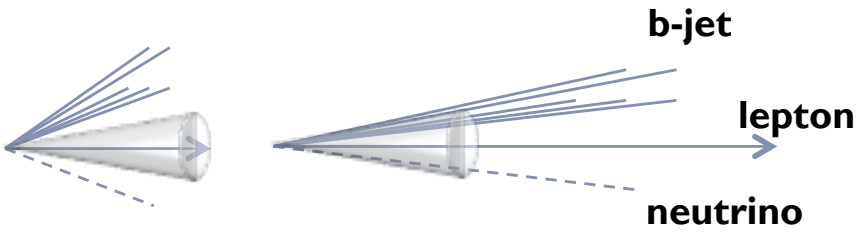
ATLAS-CONF-2013-084

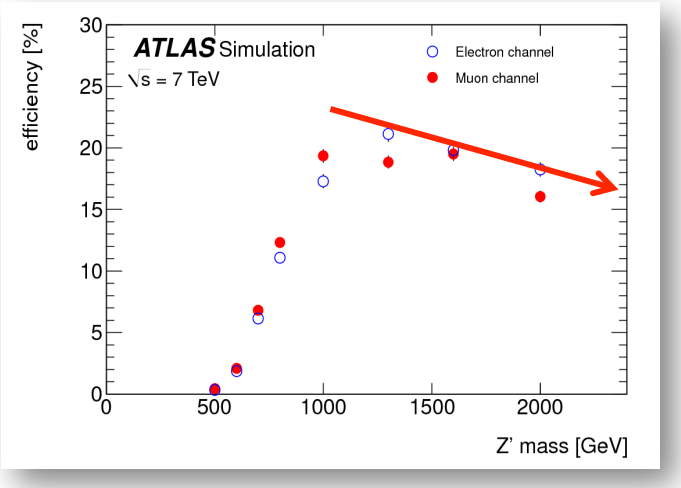
CMS-PAS-JME-10-013

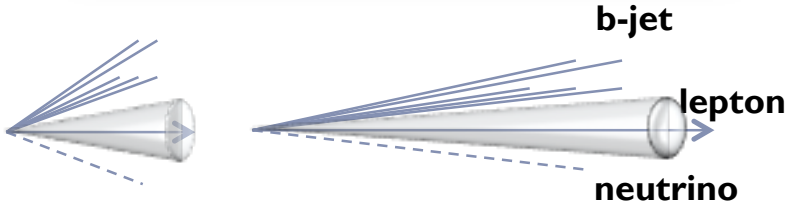
CMS-PAS-JME-13-007

Lepton Isolation

- lepton and b-jet from boosted top highly collimated: lose isolation efficiency.
- But even boosted, leptons from tops have larger separation than those from light quark jets.
- Loss in efficiency can be recovered in part: variable p_T-dependent cone size, "mini isolation", ...

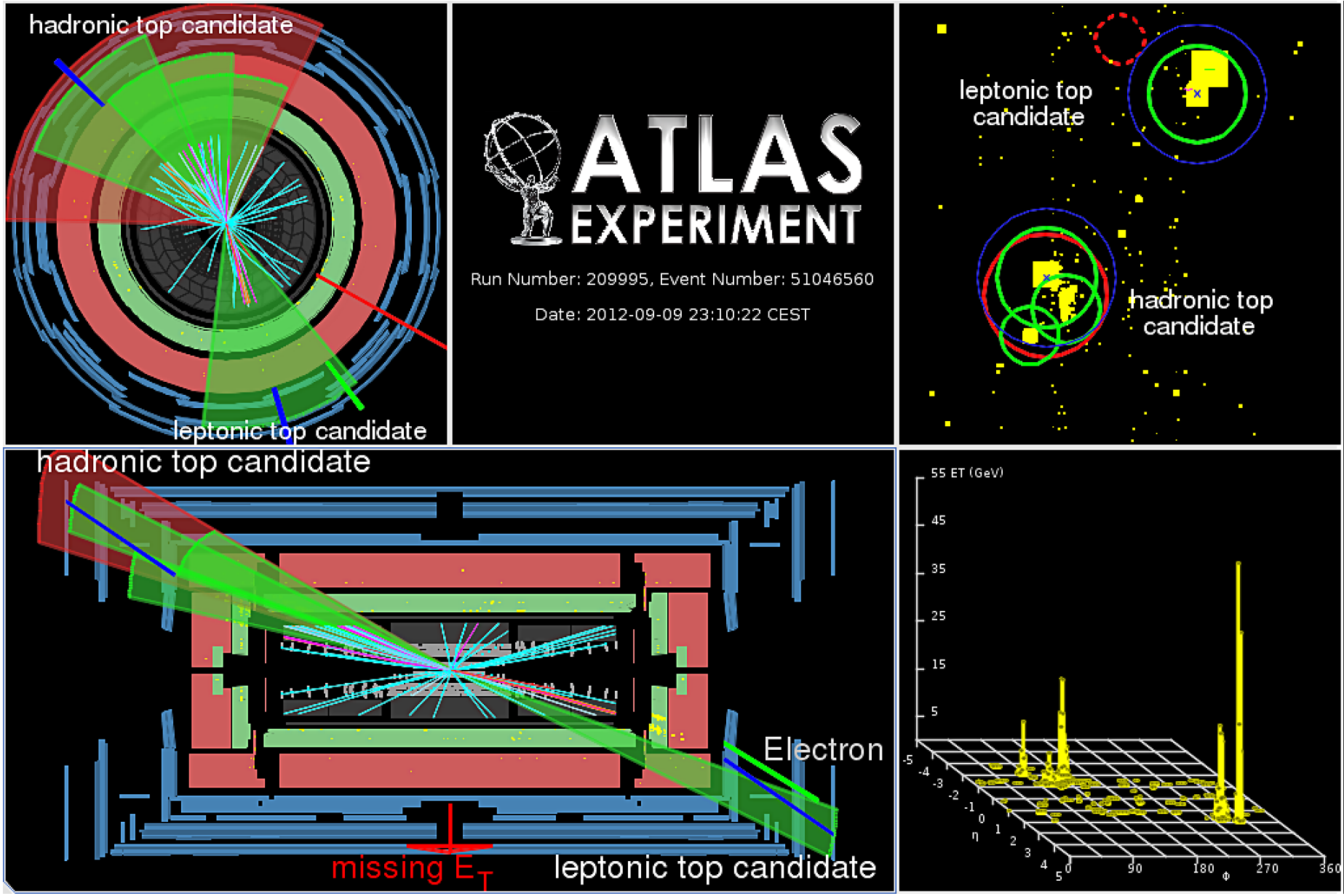




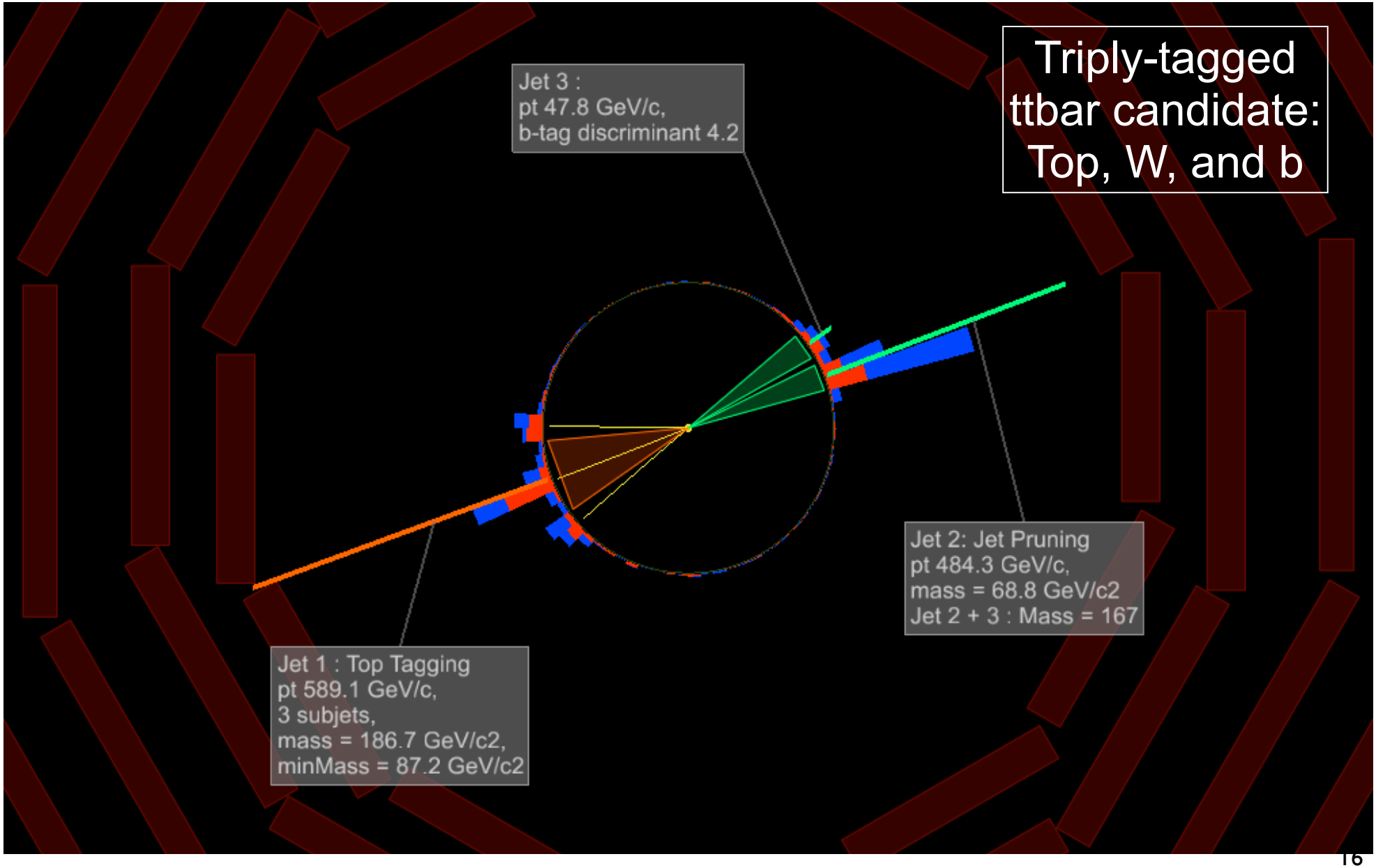


JHEP 1103:059 (2011)
Rehermann, Tweedie

Candidate Top Quark Jets



Candidate Top Quark Jets

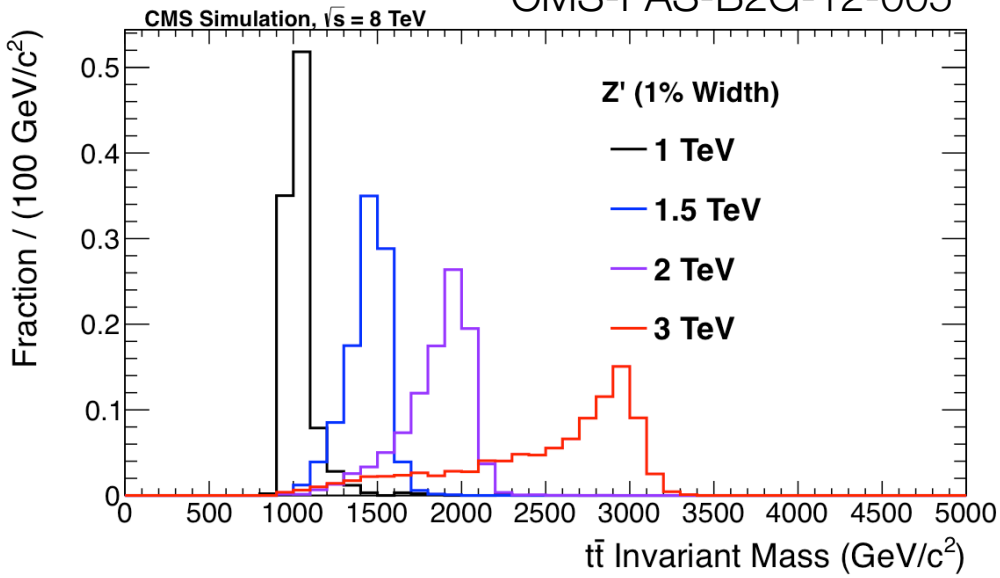


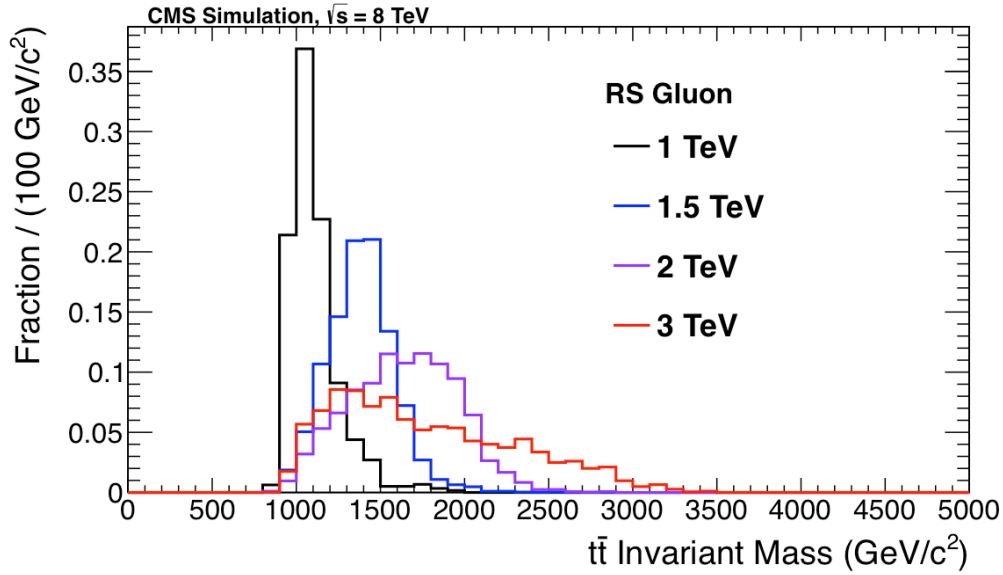
Massive resonances decaying to top pairs

Top Pair Resonances

- Both ATLAS and CMS search for resonances in the M_{tt} spectrum:
  - $Z' \rightarrow tt$, $\Gamma/m_{Z'} = 1\%, 10\%$, xs $\propto$width but SM couplings
  - RS KK gluon $\rightarrow tt$
- Searches use mix of techniques
  - Low mass $\rightarrow$ "threshold" analysis, standard reco
  - High mass $\rightarrow$ boosted analysis, jet substructure
- All channels analyzed during Run 1. I will focus on the most recent results only.

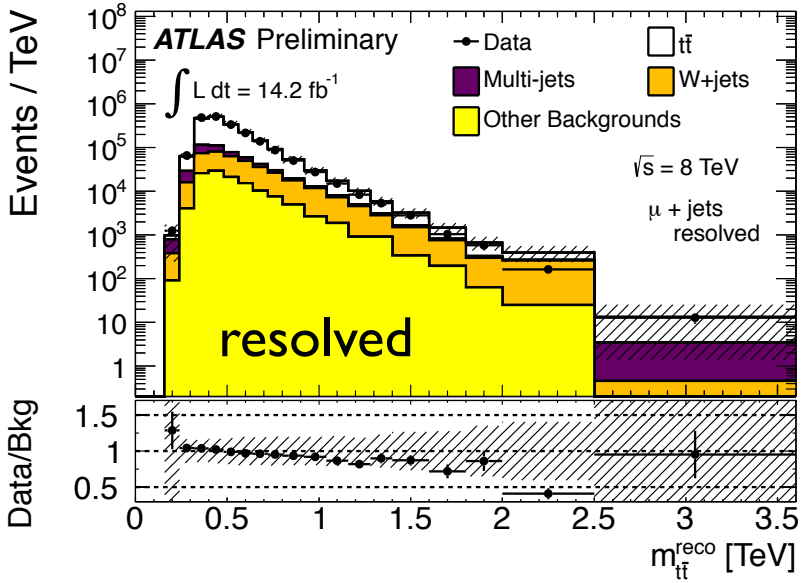
CMS-PAS-B2G-12-005

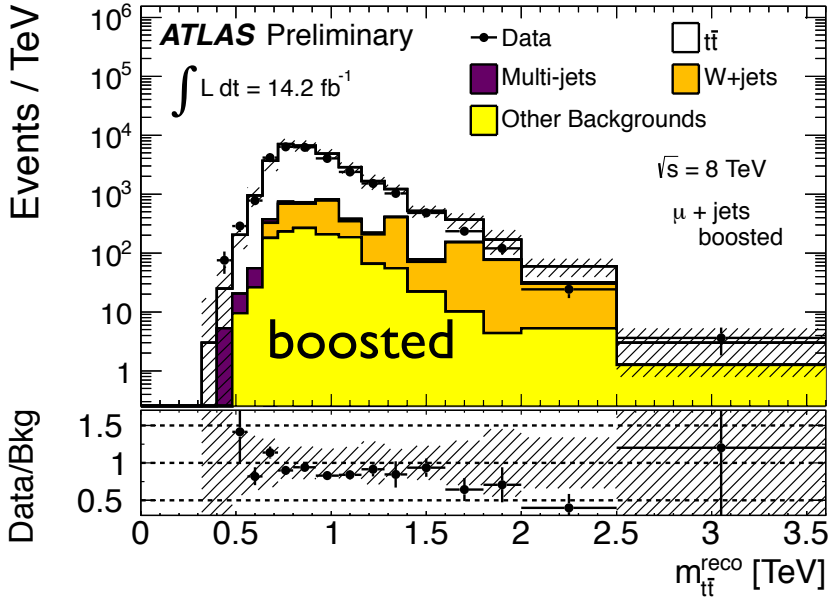




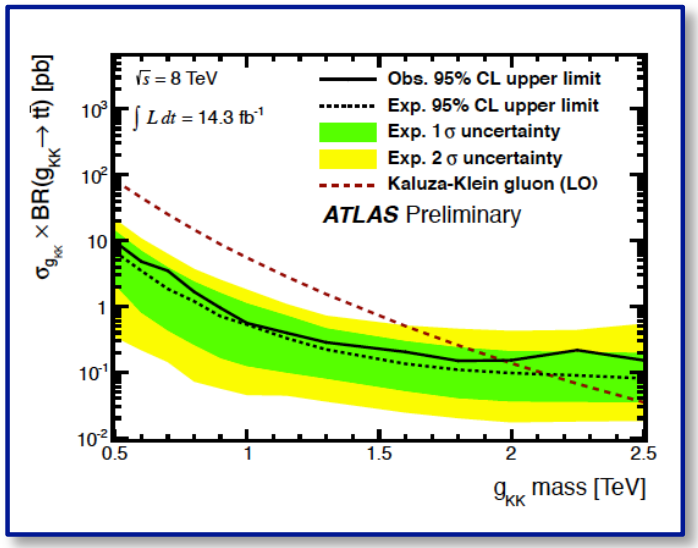
Semi-leptonic Searches

Atlas uses both resolved and boosted selections.





ATLAS-CONF-2013-052



$M_{g(KK)} > 2.0$ TeV

$M_{Z'} > 1.8$ TeV (not shown)

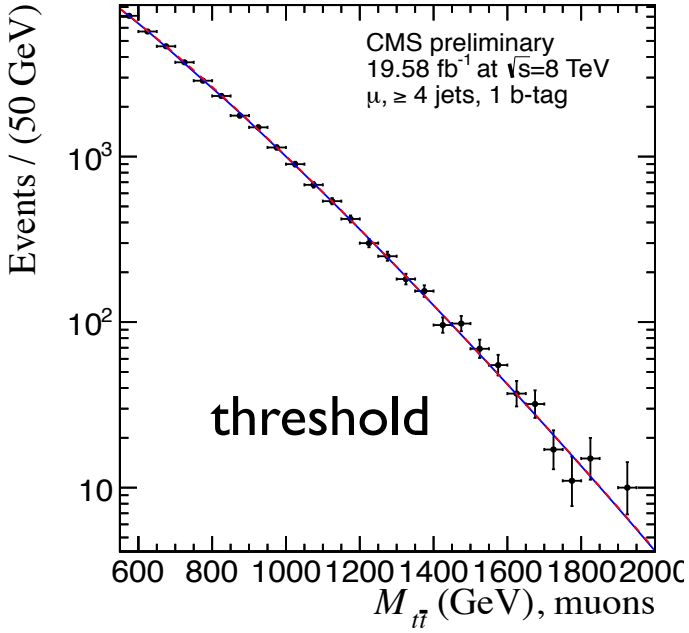
Complements previous all-hadronic search:

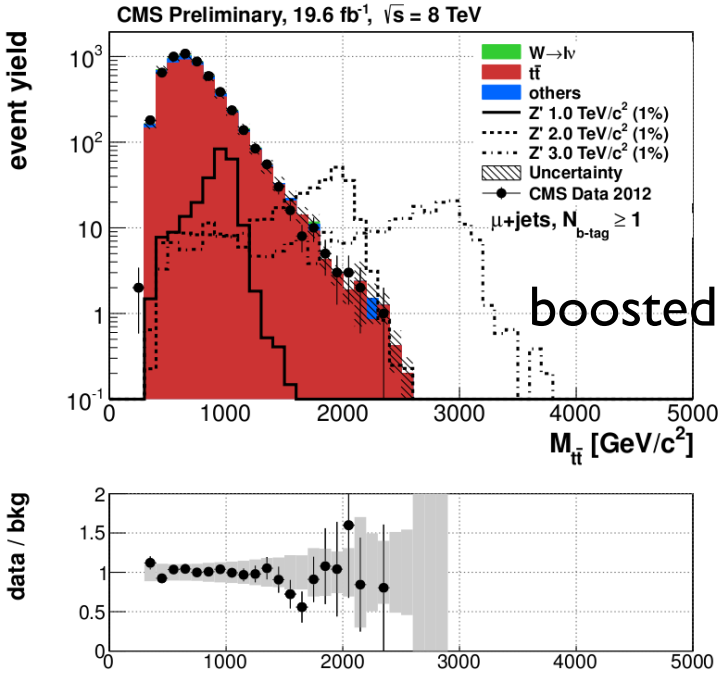
Phys.Rev. D88 (2013) 012004

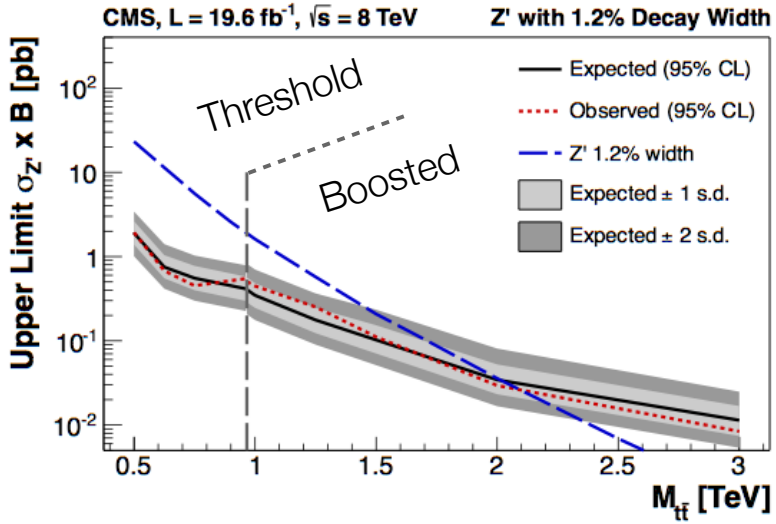
JHEP 1301 (2013) 116

Semi-leptonic Searches

CMS also uses both "threshold" & boosted selection





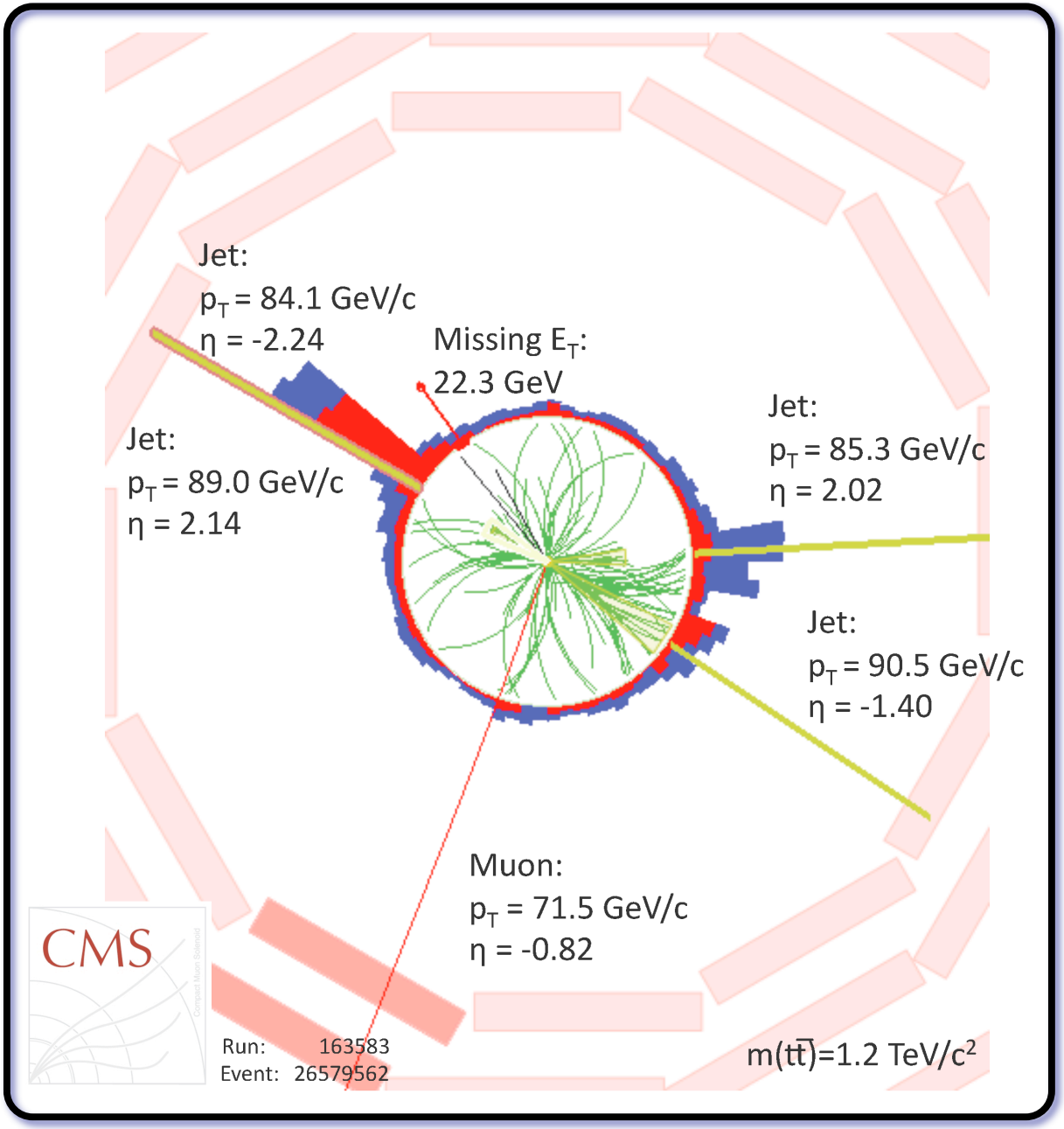


CMS excludes:

- Narrow (1%) Z' up to 2.1 TeV
- Wide(10%) Z' up to 2.68 TeV
- RS KK gluon up to 2.5 TeV

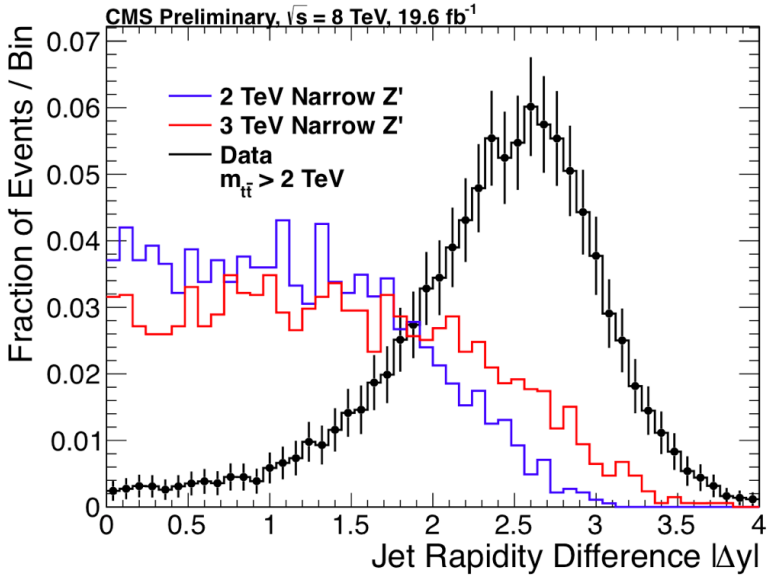
CMS-PAS-B2G-12-006

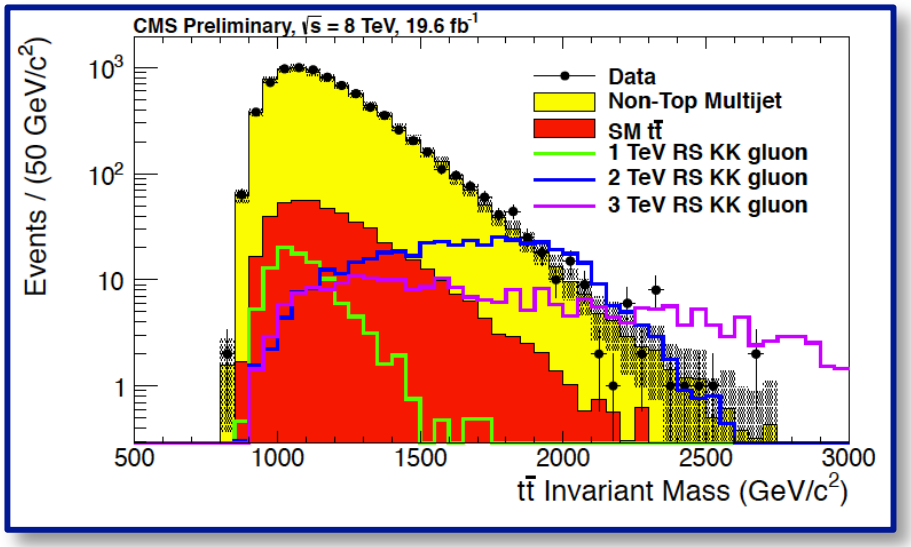
Invariant mass of t-tbar system



All-hadronic Searches

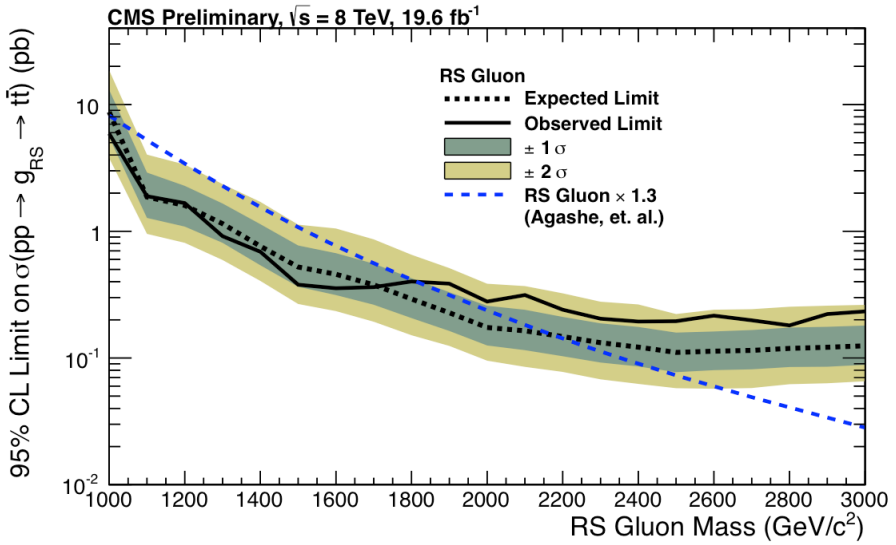
Dijet bump hunt with 2 boosted top fat jets, CMS tagger





jet rapidity separation reduces QCD at high mass

- Narrow (1%) Z' exclusion to 1.65 TeV
- Wide (10%) Z' exclusion to 2.35 TeV
- RS KK gluon exclusion to 1.8 TeV



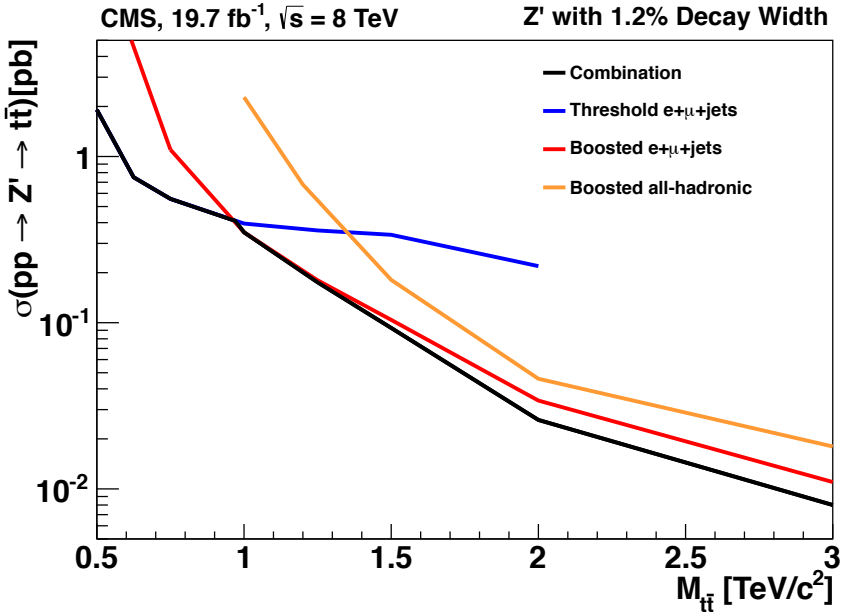
CMS-PAS-B2G-12-005

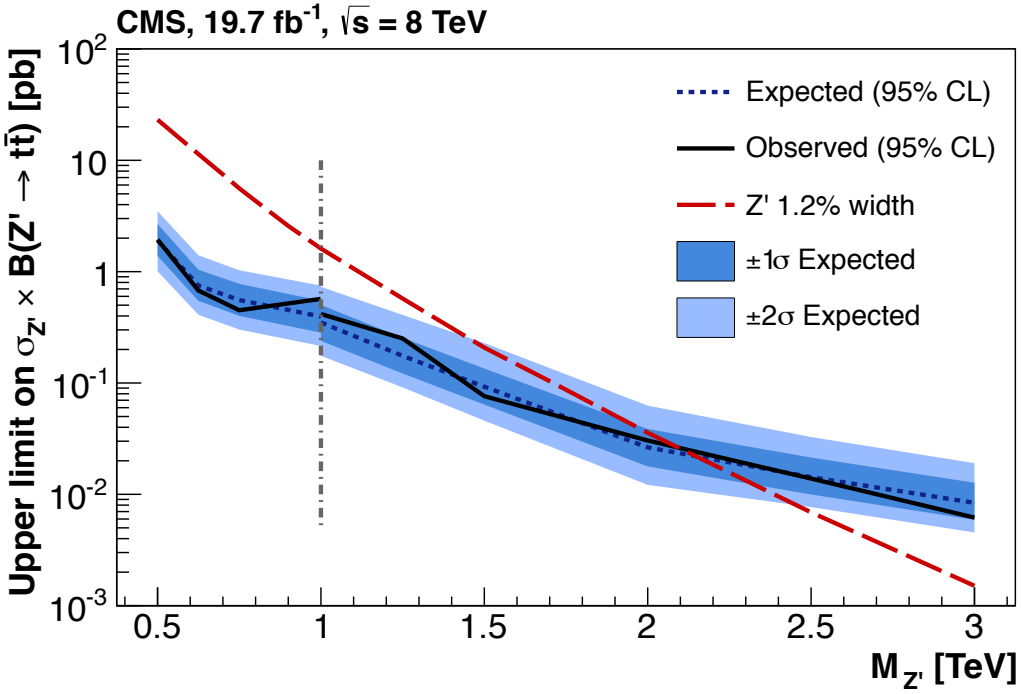
CMS Combined Results

Statistical combination of 4 channels:

- Threshold
- Boosted 0 btag
- Boosted 1 btag
- All-hadronic

Model	Observed Limit	Expected Limit
Z', $\Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
Z', $\Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV





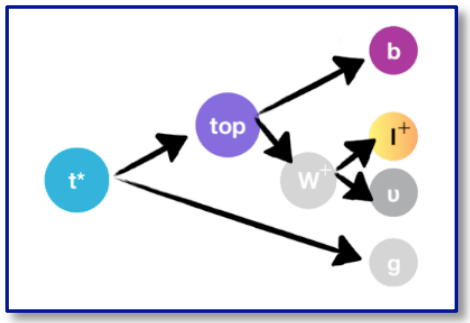
PRL 111, 211804 (2013)

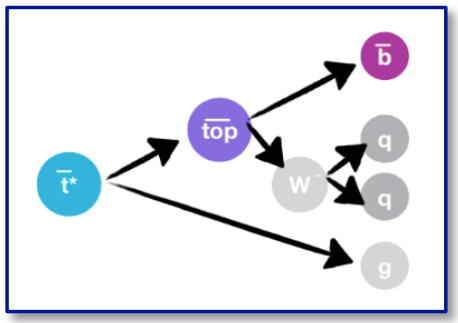
Excited Top Search

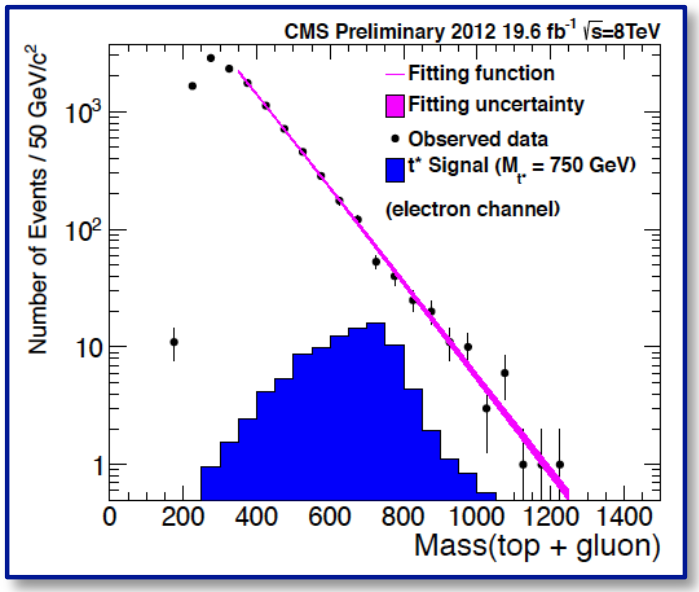
T* → top + gluon: Result given for spin 3/2 RS T*

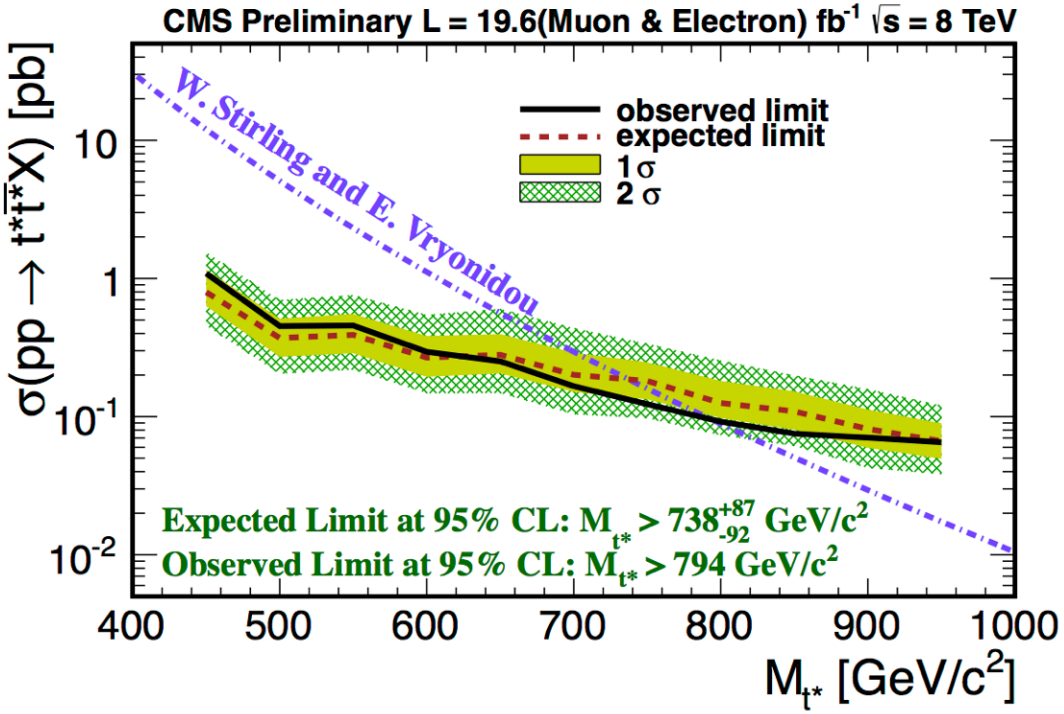
Fermi-like function modeling SM background sources:

$$f(x) = \frac{a}{1 + e^{\frac{x-b}{c}}},$$









CMS-PAS-B2G-12-014
arXiv:1311.5357

Massive resonances decaying to top + bottom

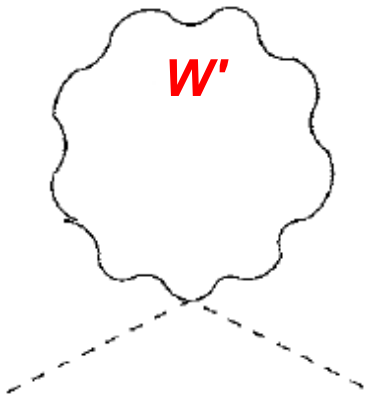
Resonances W′ → tb

- Could possibly solve hierarchy problem by canceling loops. Little Higgs, Extra Dimensions, Technicolor, L-R Symmetry

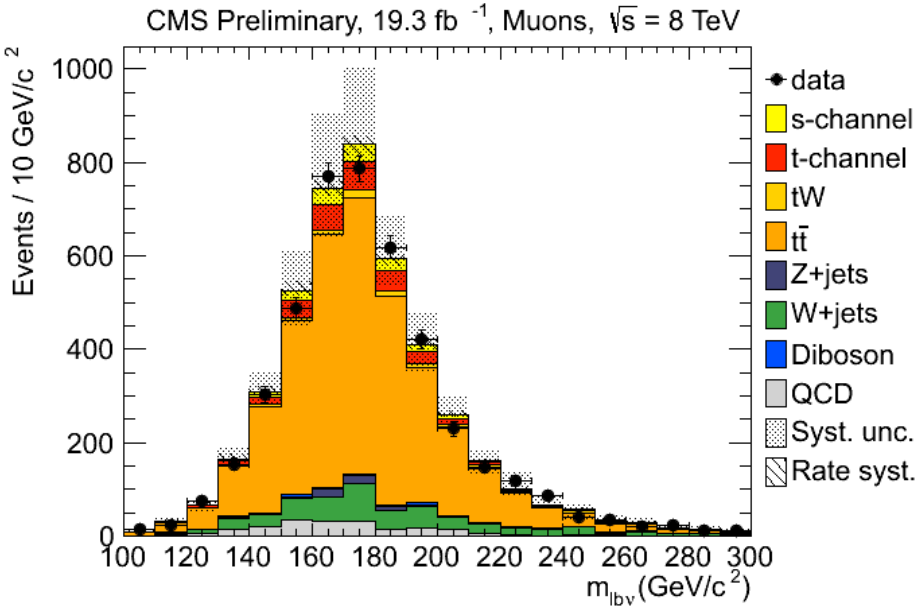
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^R_{f_i f_j} (1+\gamma^5) + a^L_{f_i f_j} (1-\gamma^5) \right)^\mu f_j + \text{H.c.}$$

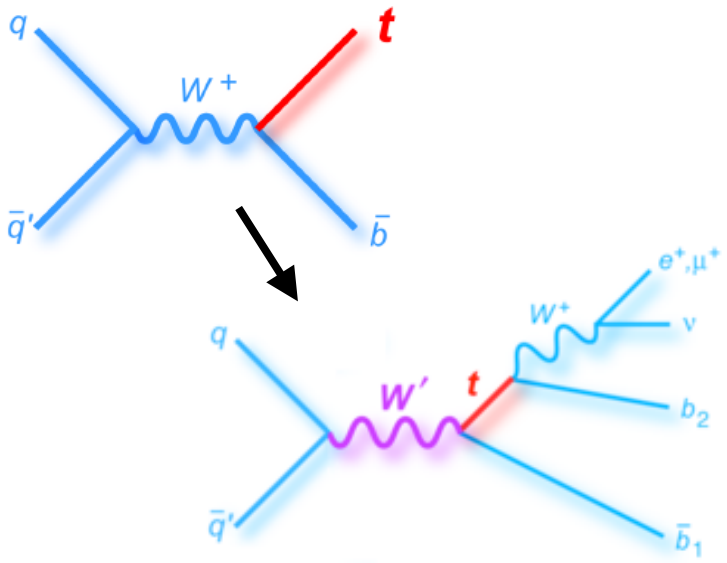
Non-0 → interference with SM

src:Z.Sullivan, Phys.Rev.D 66 075011

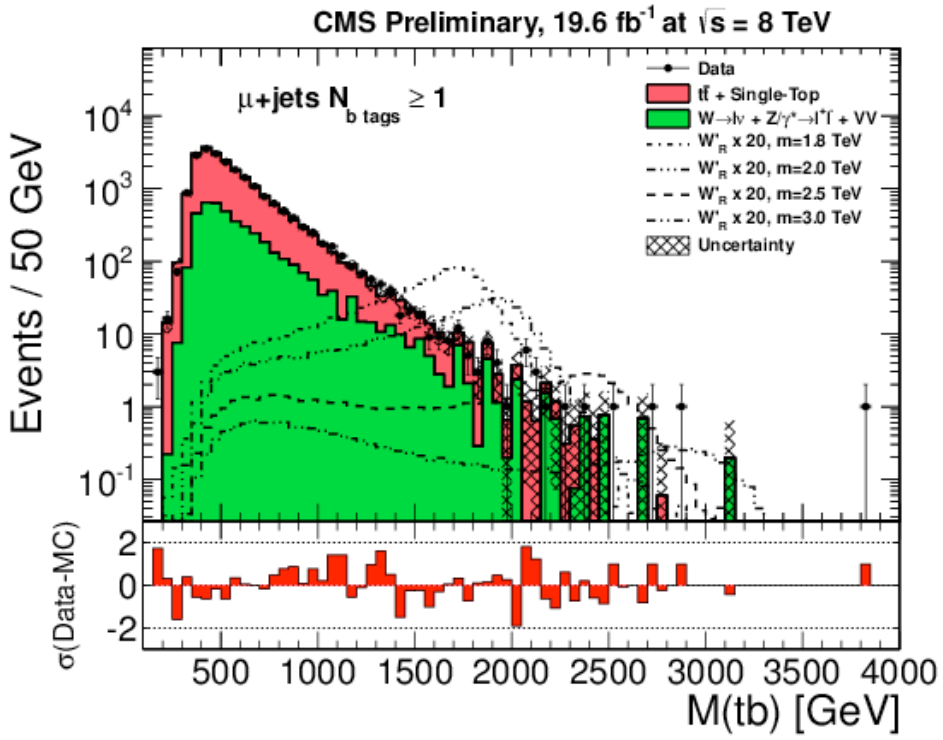


- Signature similar to single top s-channel

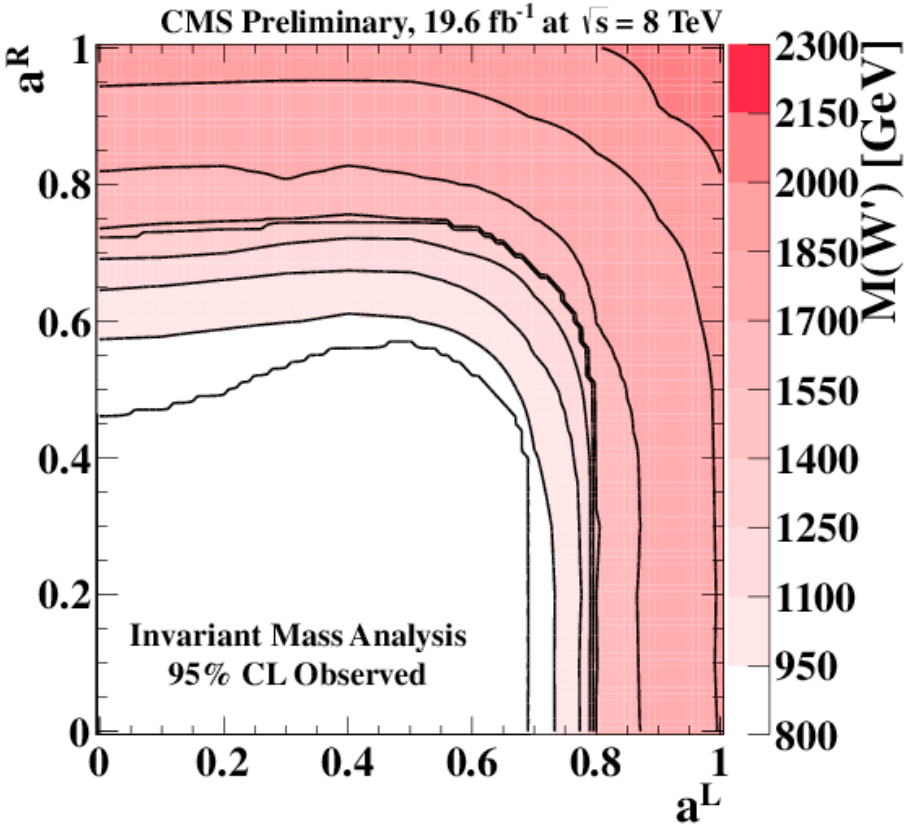




Search for W′ → tb



- lepton+MET+2b jets with mass reconstruction



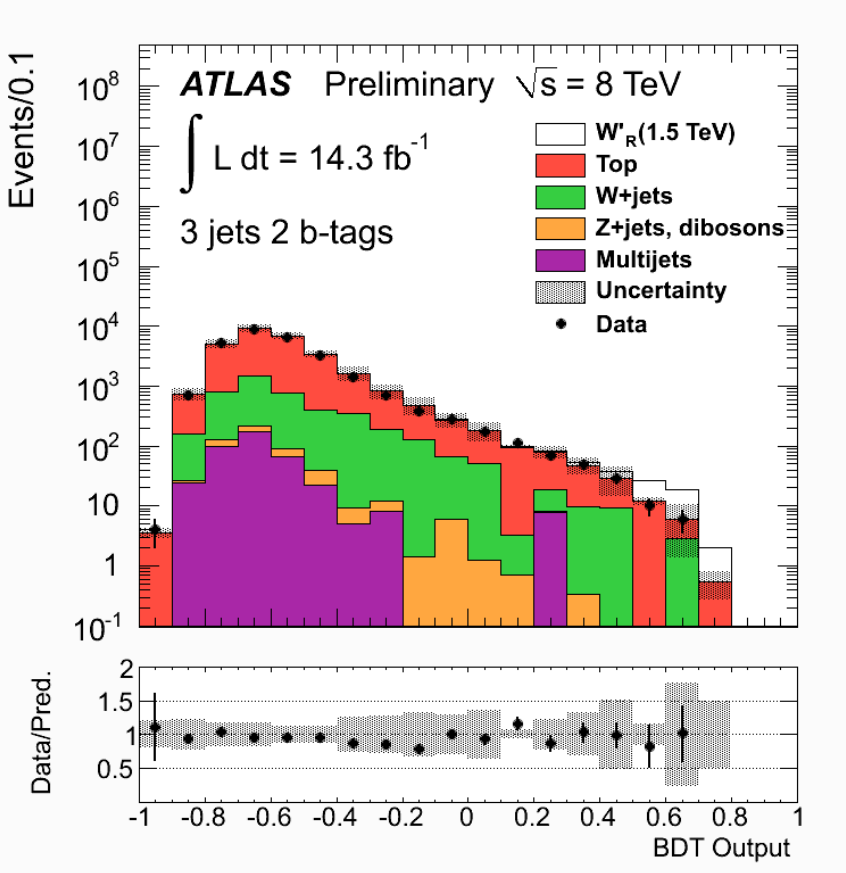
- no excess: interpret L- and R- handed W′ scenarios

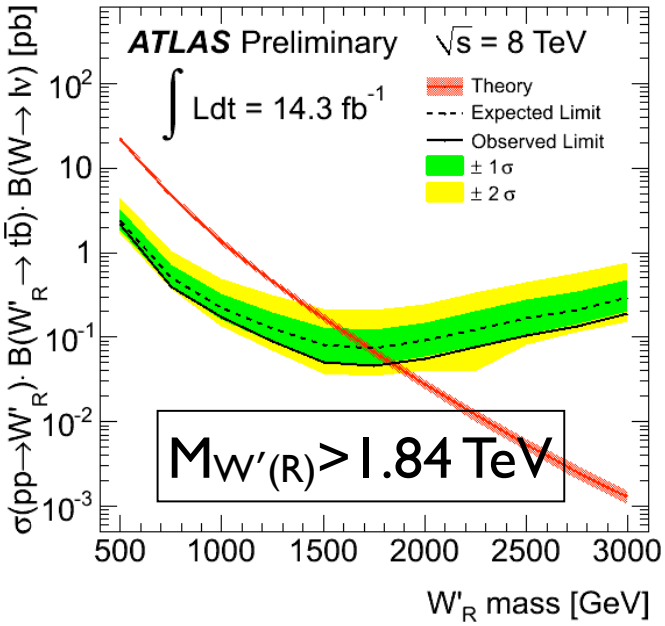
$M_{W'} > 2.03$ TeV for W'_R

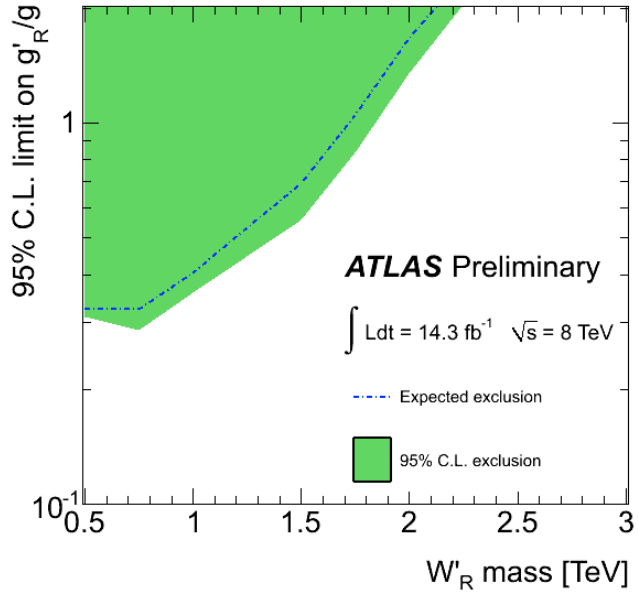
CMS-PAS-B2G-12-010

Search for W′ → tb

- 2 jets, 2 btags & 3 jets, 2 btags
- Boosted Decision Tree discriminant
- Both L- & R-handed W′ limits



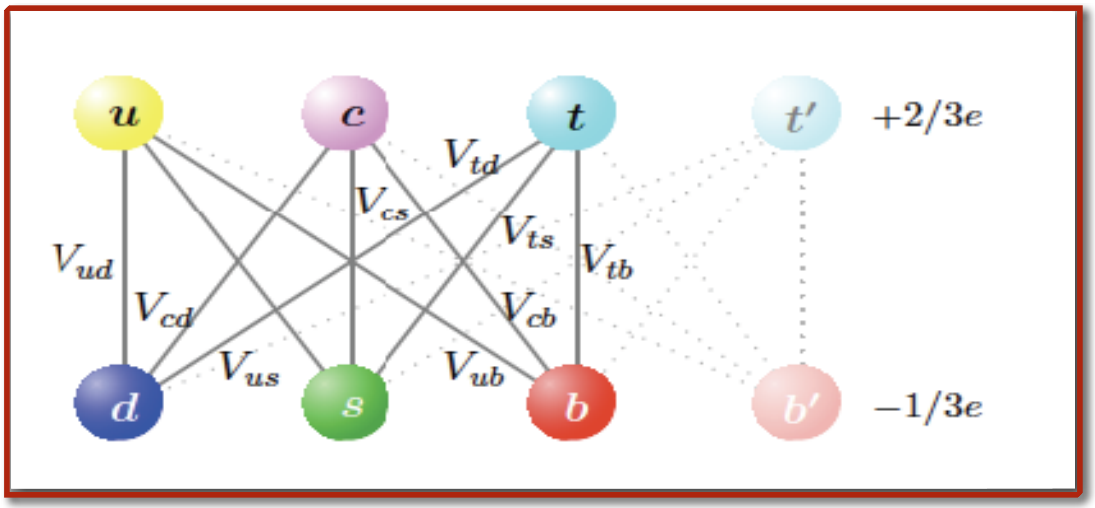




ATLAS-CONF-2013-050

Fourth Generation or Vector-Like Quarks

Is there a 4th Generation?

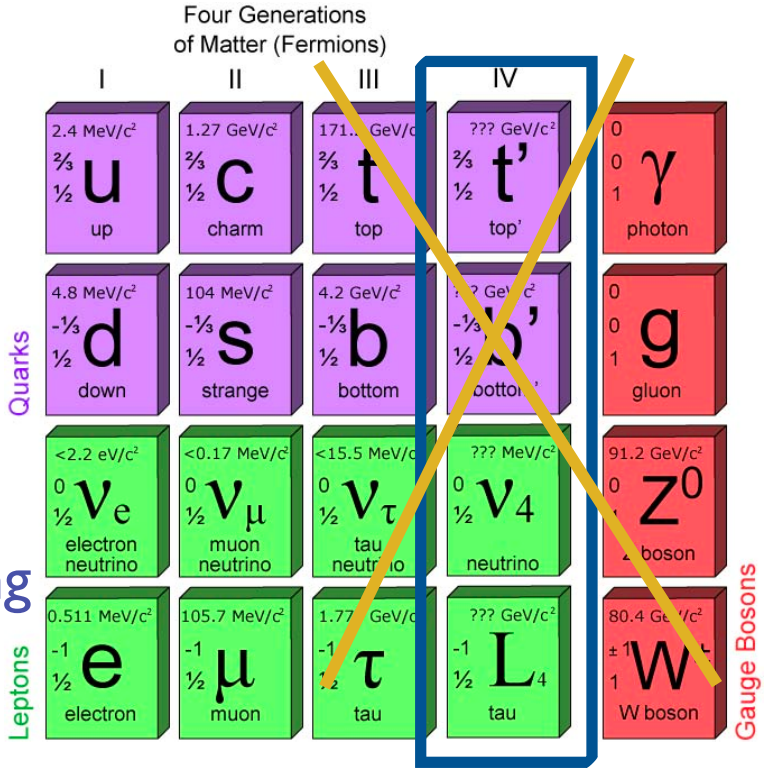


- A very compelling SM extension, but simplest models have been excluded directly or indirectly (eg- Higgs cross section).
- Elaborate models are still alive and are popular topics:

- 2 Higgs doublet models, some predicting heavy top partners
- vector-like top and bottom quark partners or exotic top partners with different charge
- non-SM 4th gen can enhance CP violation, and heavy ν is DM candidate
- if CKM is diagonal, $t' \rightarrow Wb$ and $b' \rightarrow tW$ due to GIM mechanism

Vector-like Quarks

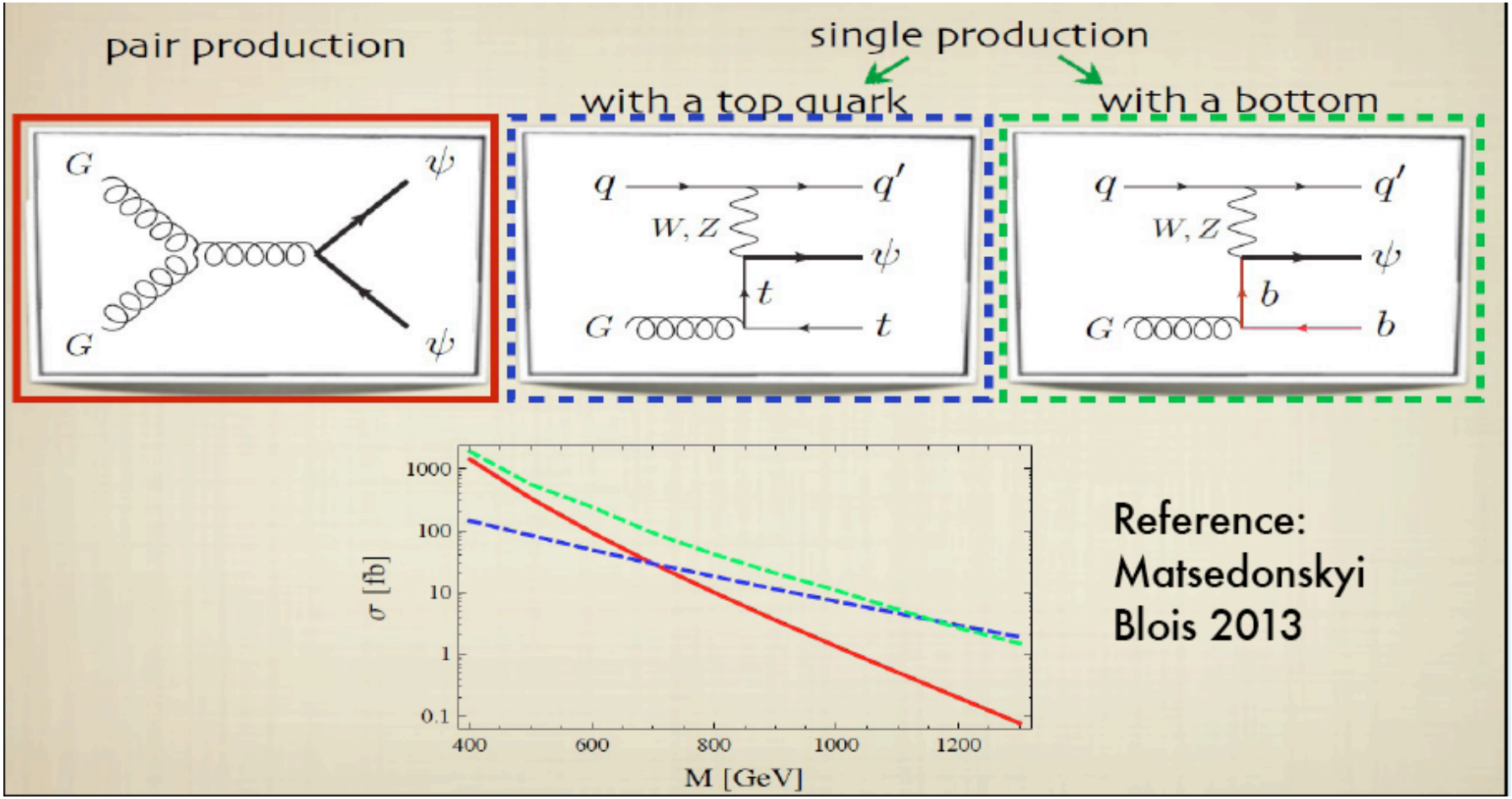
- Not your uncle's 4th generation! L- and R-handed components transform identically under SU(2) weak isospin gauge symmetry
  - don't enhance Higgs prod, unlike 4th gen.
  - appear in Little Higgs & Extra Dimensions
  - cancel quadratic divergences from loops



- Can have same charge as b, t (B, T) or exotic charge ($X_{5/3}$ or $Y_{-4/3}$).
- Can be isospin singlet, doublet, triplet
- Interact with 3rd gen (naturalness): mixing proportional to SM quark mass. Light quark coupling sometimes enhanced.
- Charged and neutral decay, branching depends on mass and model.
- Pair production is mediated by the strong interaction
- Single production can be more pronounced at high masses

Vector-like Quarks

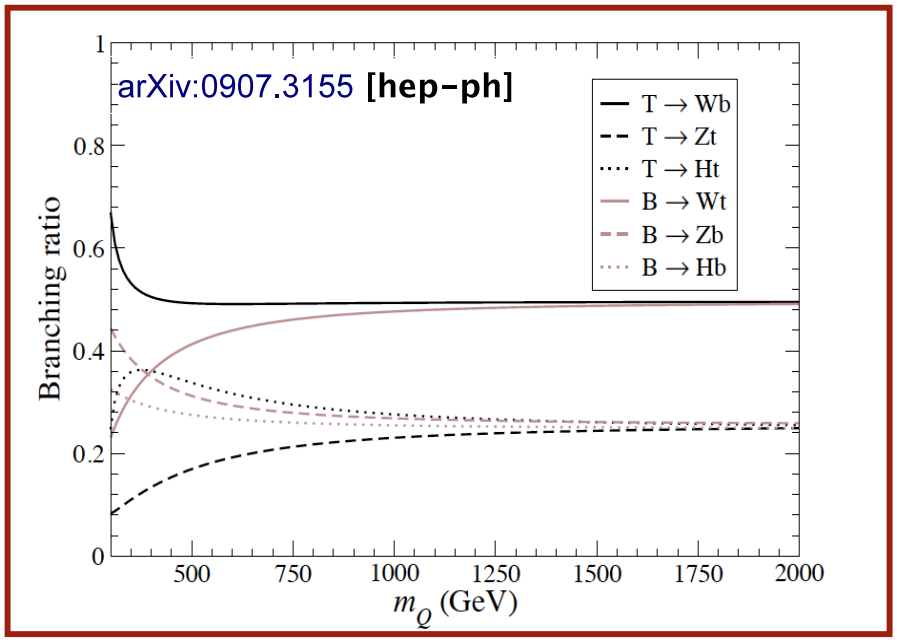
VLQ example: Partial compositeness

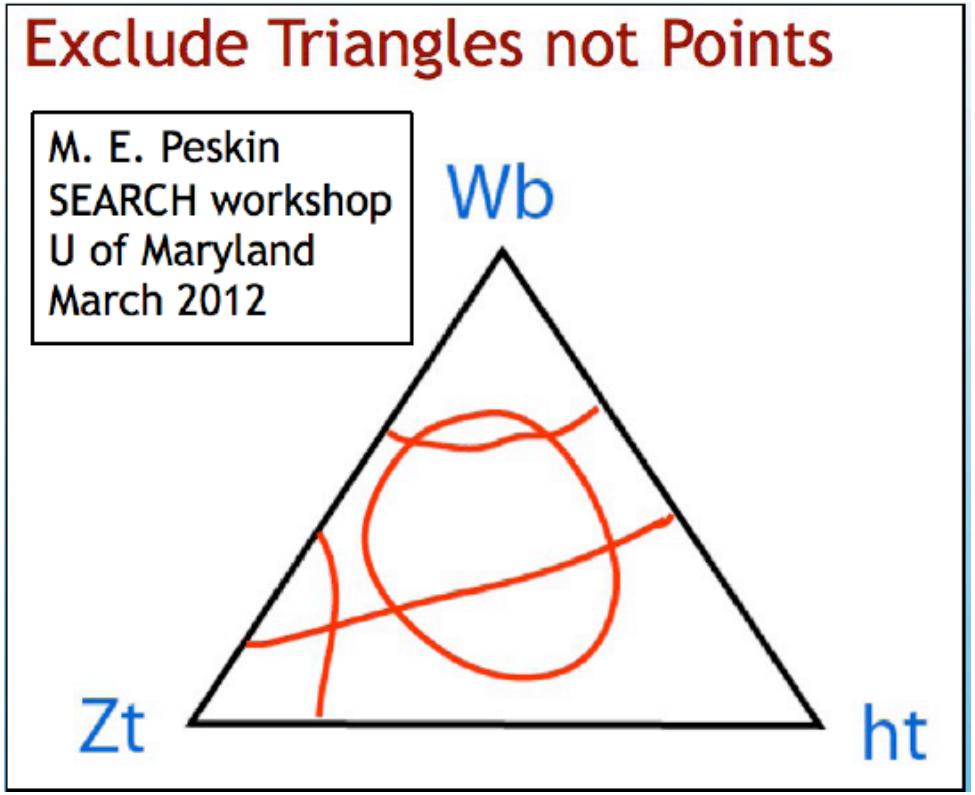


Vector-like Quarks

VLQs can have CC and NC decays: the branching ratios are constrained by the relation:

BR(Wb)+BR(tZ)+BR(tH)=1





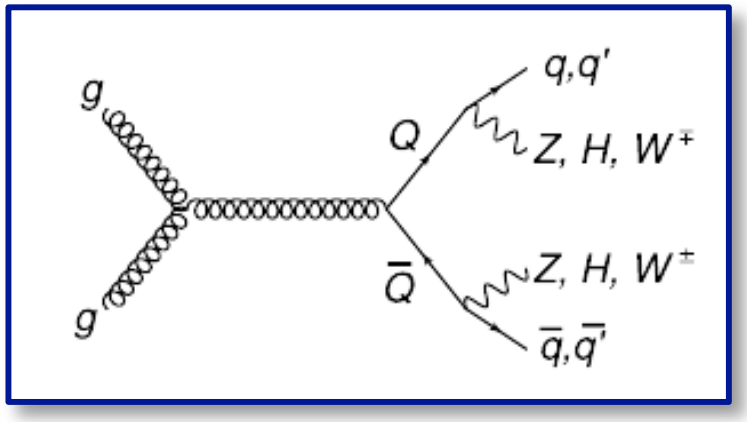
3 varying branching ratios describe the triangle

Partner Quark Topologies

Many distinct event topologies to consider:

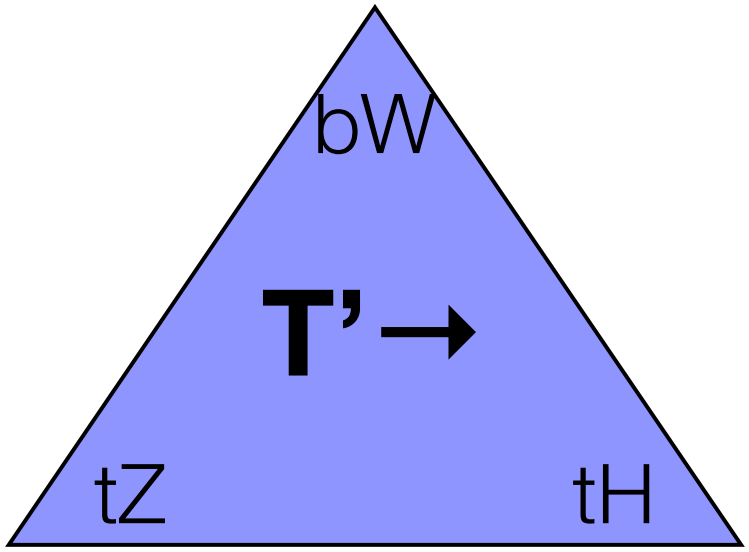
$B' \rightarrow tW, bZ, bH$

$T' \rightarrow bW, tZ, tH$



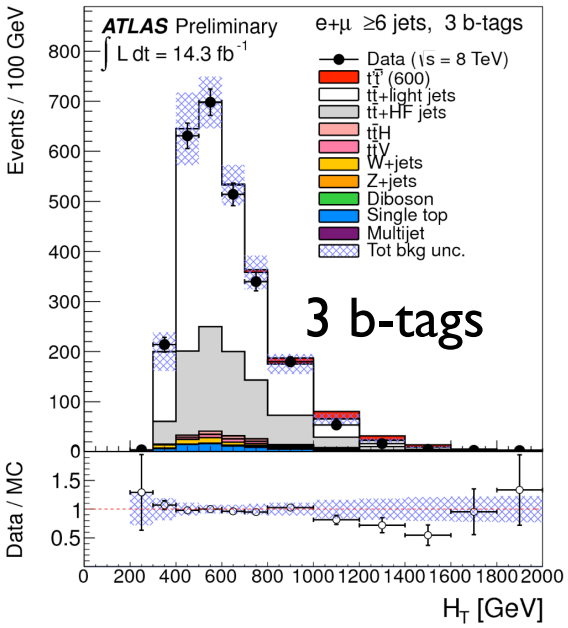
- Leptons, b-jets, (boosted) top, (boosted) W/Z, boosted H are all possible final states.
- Use standard (threshold) identification, and use boosted b-tag and V-tag algorithms as well.
- Set limits at 100% BR and also scan over all possible fractions.

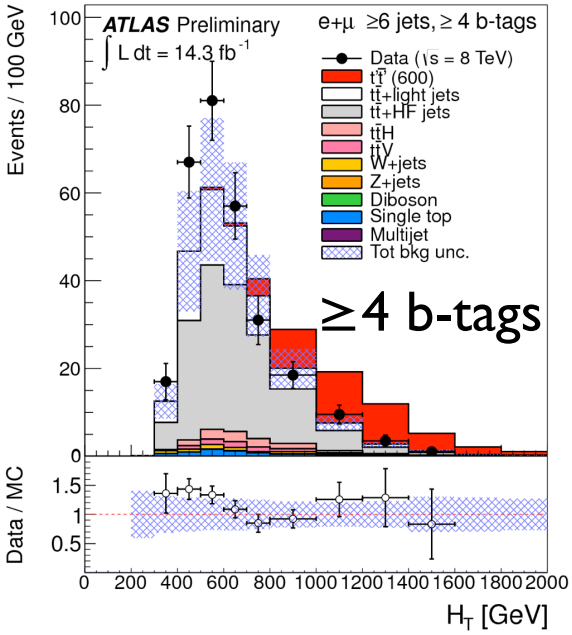
Top Partner Searches



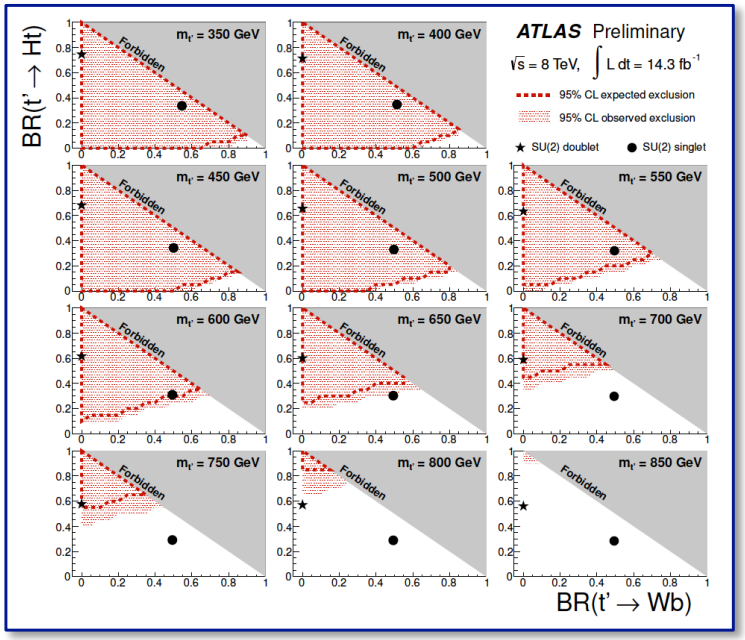
Searches for T→tH (H→bb)

- Semi-leptonic decays, Missing energy +≥6 jets.
- Sensitive to T→tHtH, tHbW, tHtZ.





Observed/expected exclusion in plane of BR(t′→bW) & BR(t′→tH)
(Protos event generator)

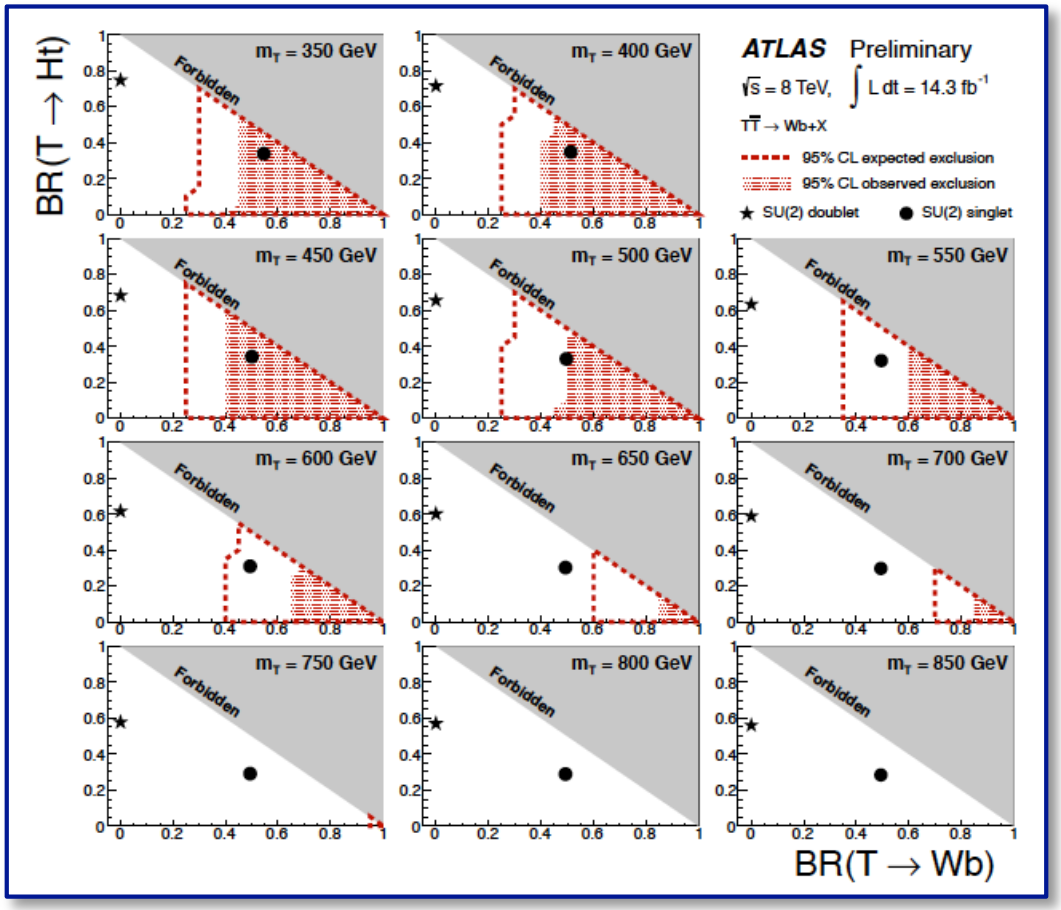


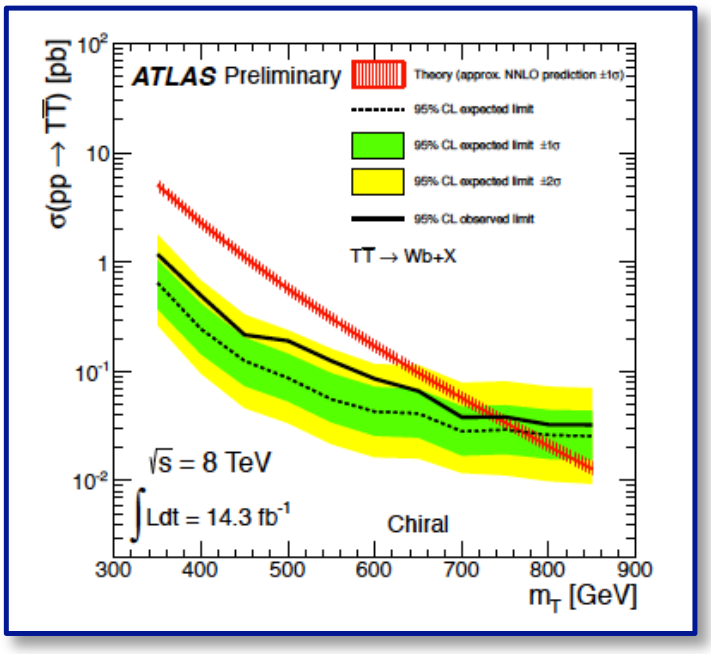
M(T′$_{doublet}$)>790 GeV
M(T′$_{singlet}$)>640 GeV

ATLAS-CONF-2013-018

Chiral 4th Gen. t′ or VLQ T

- Semi-leptonic decays with ≥1 b-jet in bW final state.
- Complements previous result with ≥6jets.
- Utilizes boosted W-tagging to extend acceptance.





M(T′)>740 GeV *valid also for Y(-4/3)*

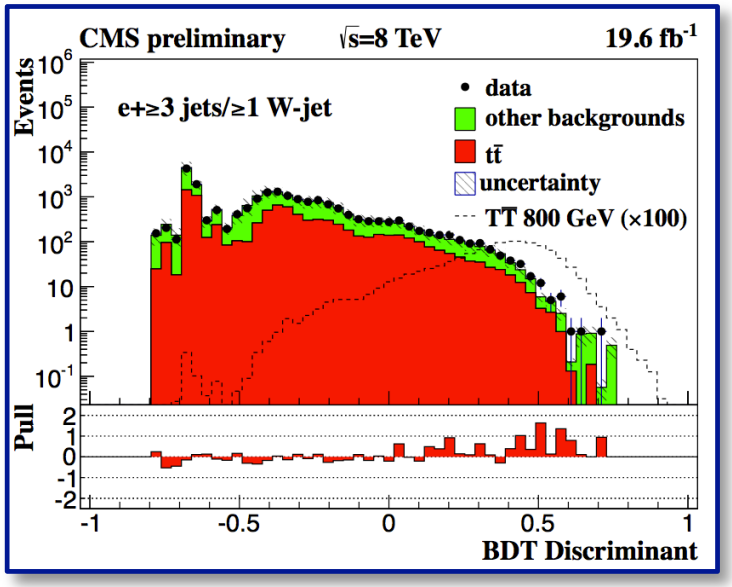
M(T′$_{singlet}$)>505 GeV

M(T′$_{singlet}$)>670 GeV → combined with previous result

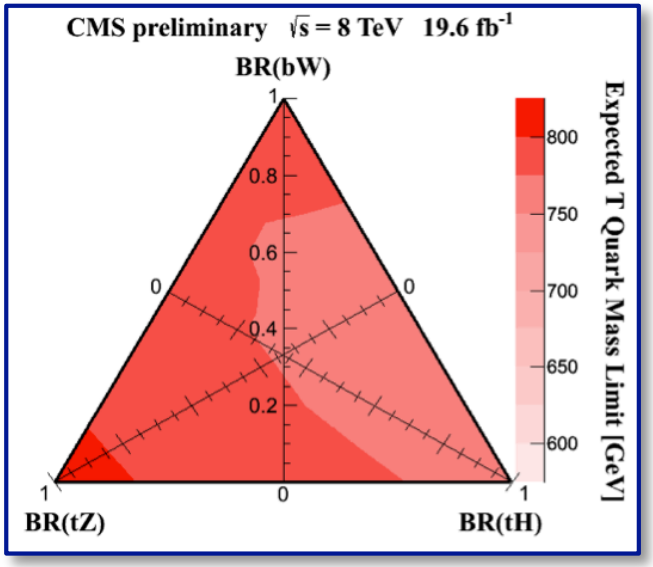
ATLAS-CONF-2013-060

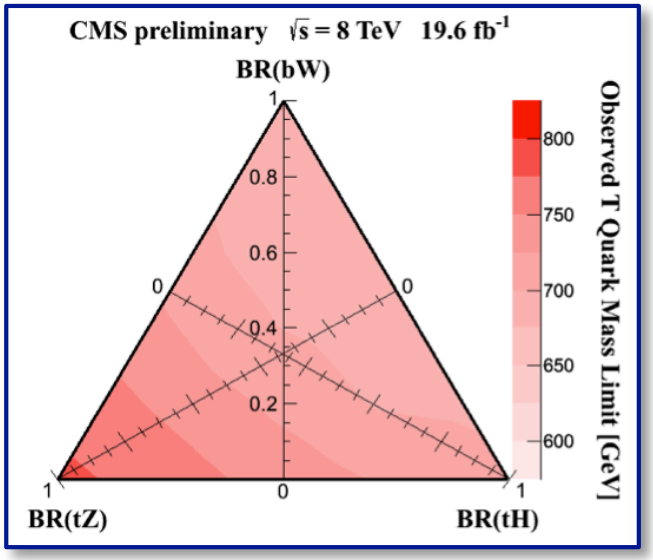
Inclusive Search for T (VLQ)

- Single-lepton, OS and SS dileptons, and tri-lepton channels.
- Multi-lepton channels fairly clean. Use boosted decision tree to reject backgrounds in single lepton channel.



Observed exclusion limits are between:
M(T′)>782 GeV
M(T′)>687 GeV



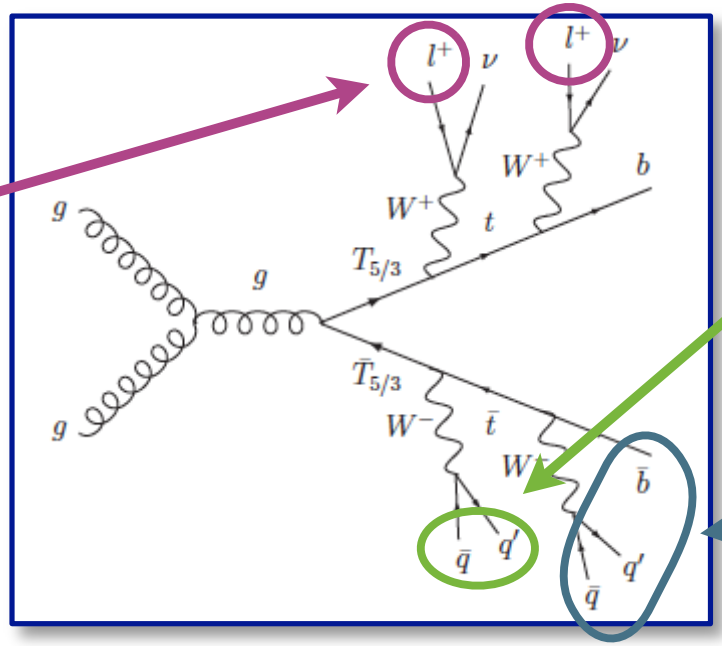


- BDT discriminant used for single-lepton channel based on:
Jet multiplicity, b-tag multiplicity, H_T, missing p_T, lepton p_T, p_T of the 3rd jet & p_T of the 4th jet

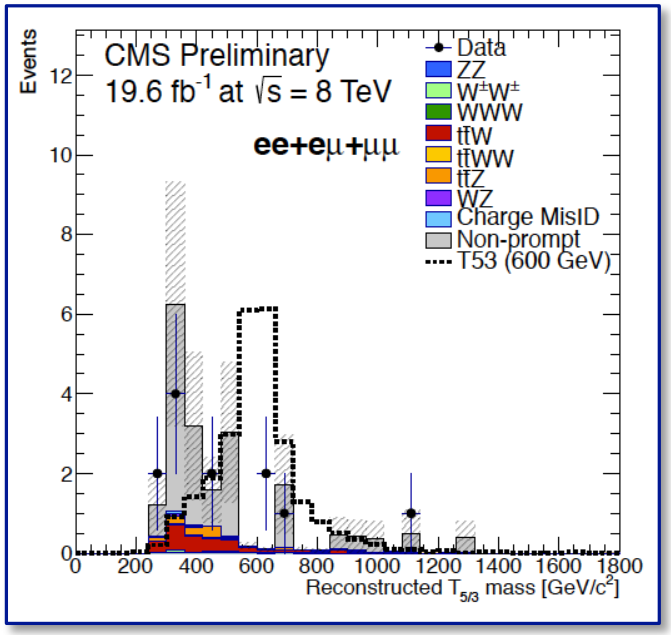
CMS-PAS-B2G-12-015
arXiv:1311.7667

Peculiar Partners: $T_{5/3}$

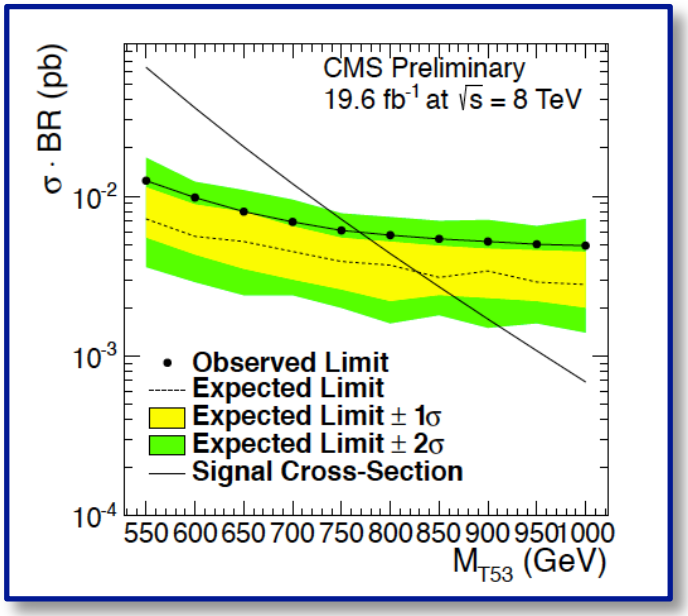
- same-sign dileptons
- boosted W tag: 2 subjets, M_j[60,130]
- CMS top tag



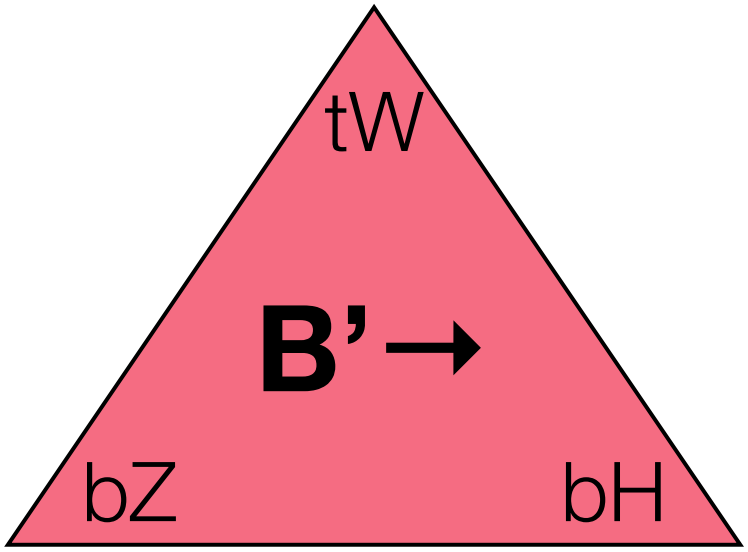
CMS-PAS-B2G-12-012



$M_{T(5/3)} > 770$ GeV

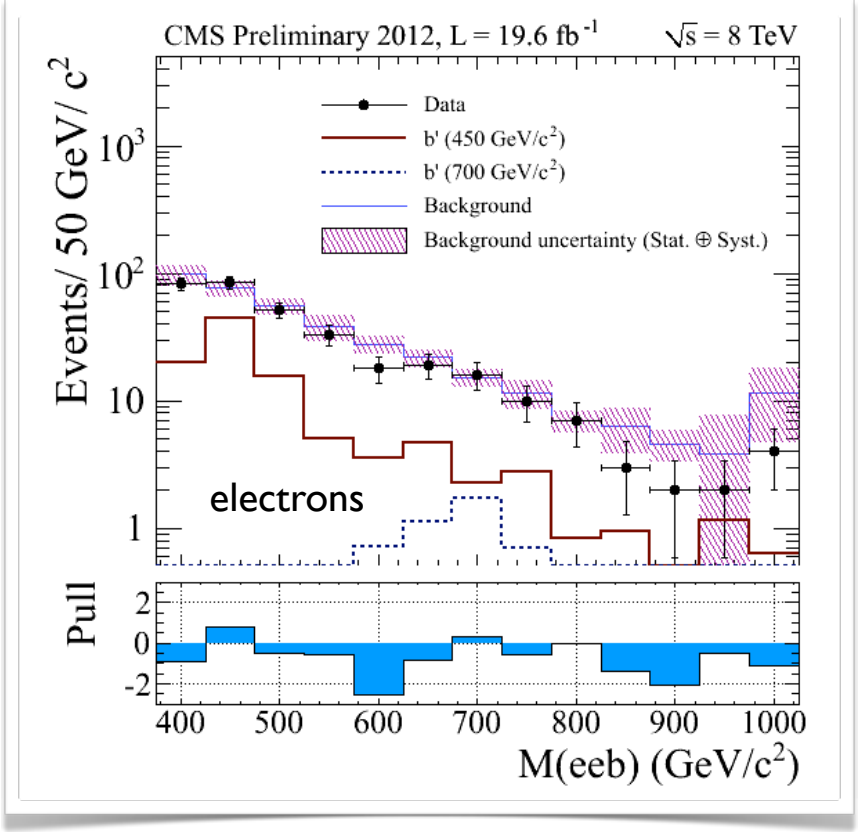


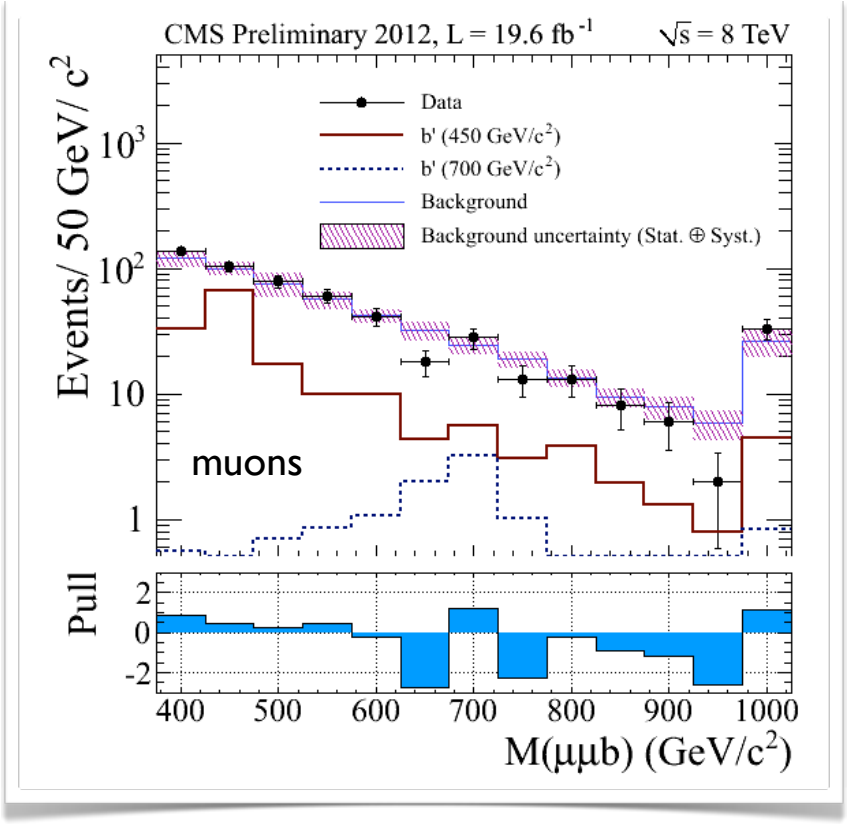
Bottom Partner Searches



Bump Hunt: B′→bZ

- Look for pair production of charge -1/3 B′ quarks, one of which decays to bZ, where Z→ee, μμ. Use OS dilepton events with at least one b-tag.





Combined limits:

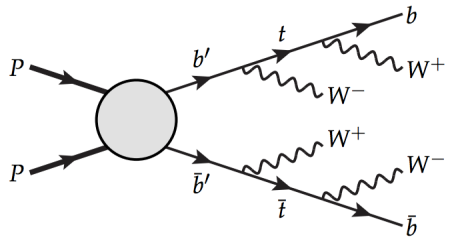
M(B′)>680 GeV (expected)

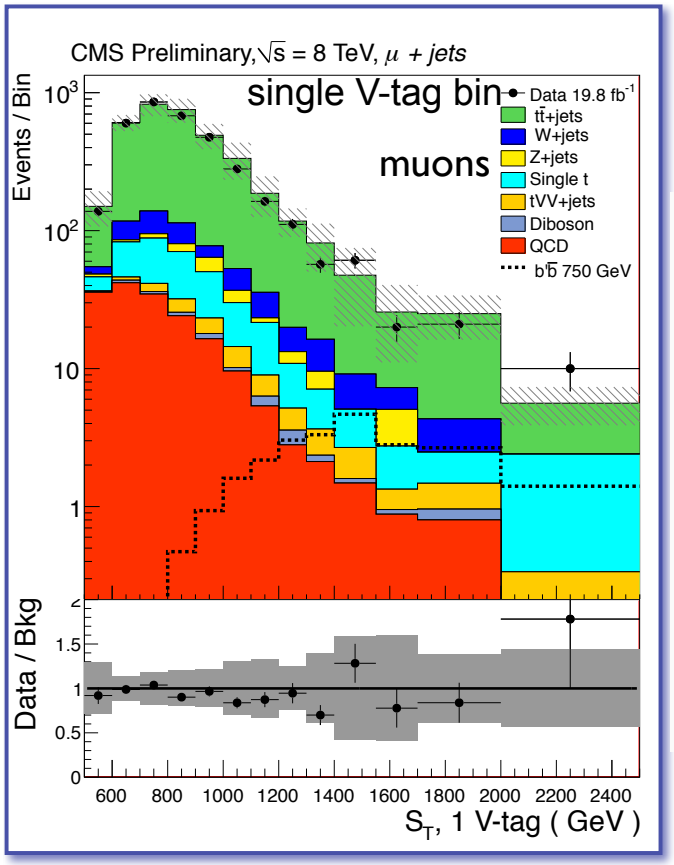
M(B′)>700 GeV (observed)

CMS-PAS-B2G-12-021

Search for B′→tW, bZ, bH

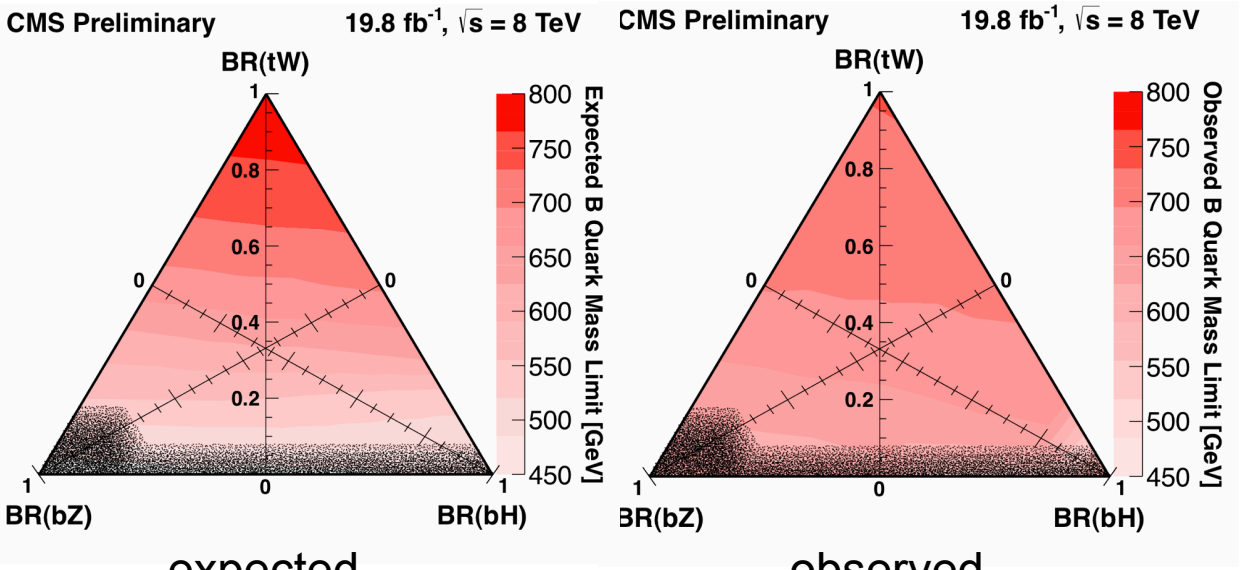
Search in semi-leptonic channel decaying to tW, bZ, bH: uses fit to total energy S_T, binned by # of boosted V-tags.





S_T distribution for single V-tag bin

Most sensitive to B′→tW channel.
Grey shade indicates no sensitivity.



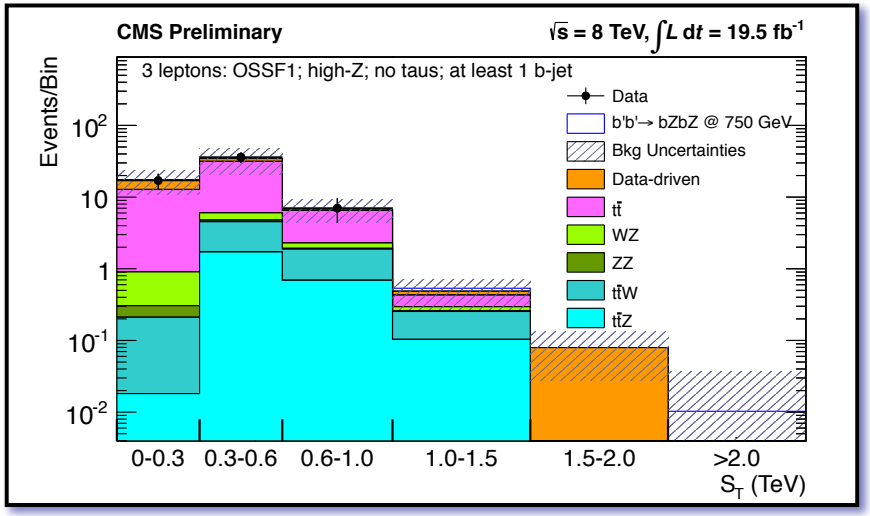
expected observed

M(B′)>732 GeV (for 100% BR to tW)

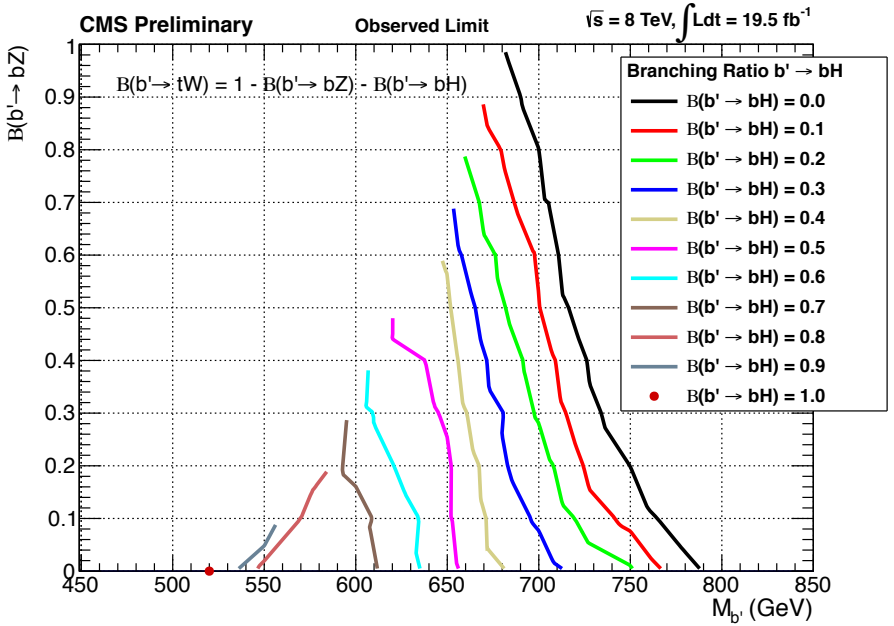
CMS-PAS-B2G-12-019

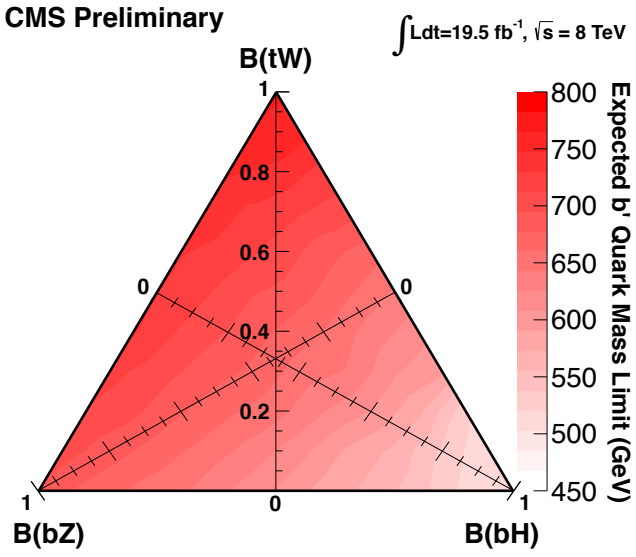
Searches for B′→tW, bZ, bH

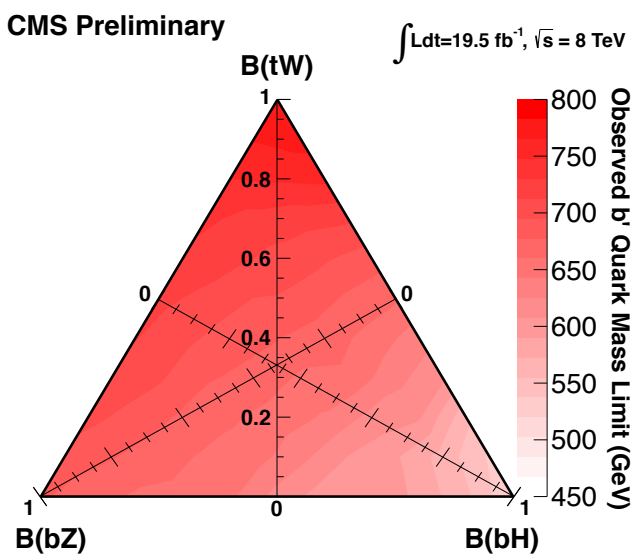
- Search in multi-lepton channel: multi-binned counting expt.



3 leptons, OSSF1, high Z, no taus, 1 b-jet



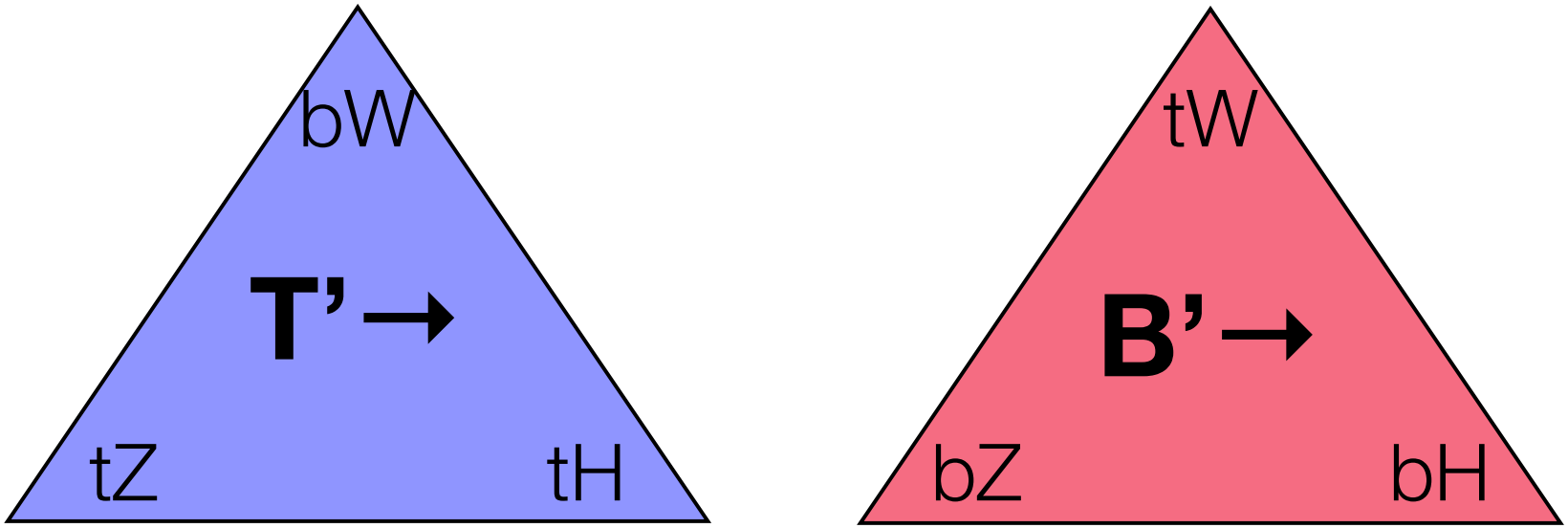




M(B′)>785 GeV
(for 100% BR to tW)

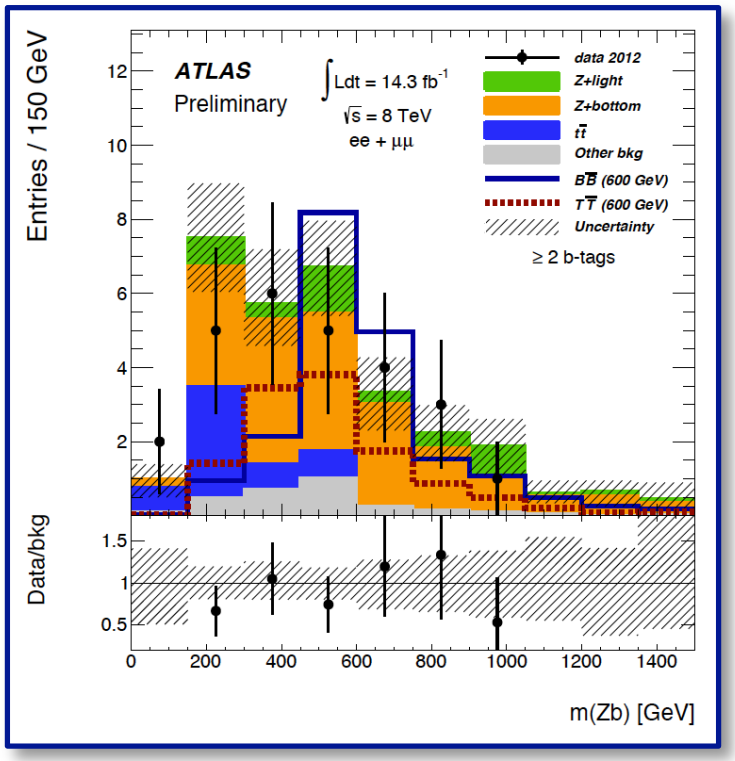
CMS-PAS-B2G-13-003

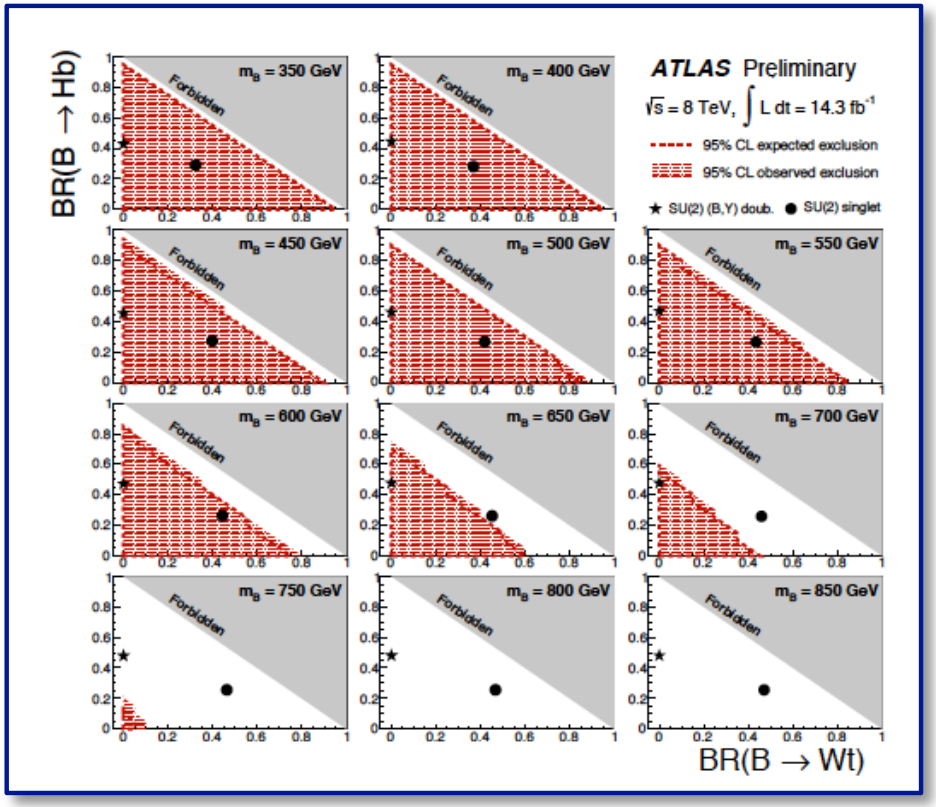
Top and Bottom Partners Together



Search for T′→tZ, B′→bZ

- Search in Z→ℓℓ candidate events with ≥2 b-tags.
- Search for weak isospin singlet T, B and doublet T of (X,T), B of (B,Y), with X(+5/3) and Y(-4/3)





Plots shown for B→bZ case

M(T′)>585 GeV (BR for singlet)

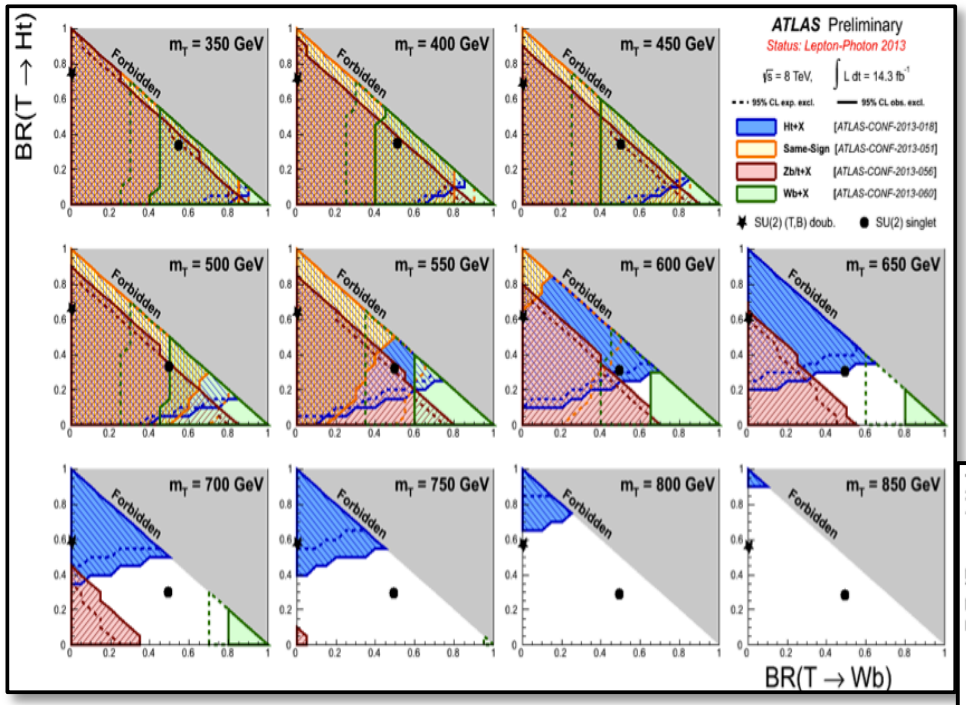
M(B′)>645 GeV (BR for singlet)

M(T′)>680 GeV (BR for doublet)

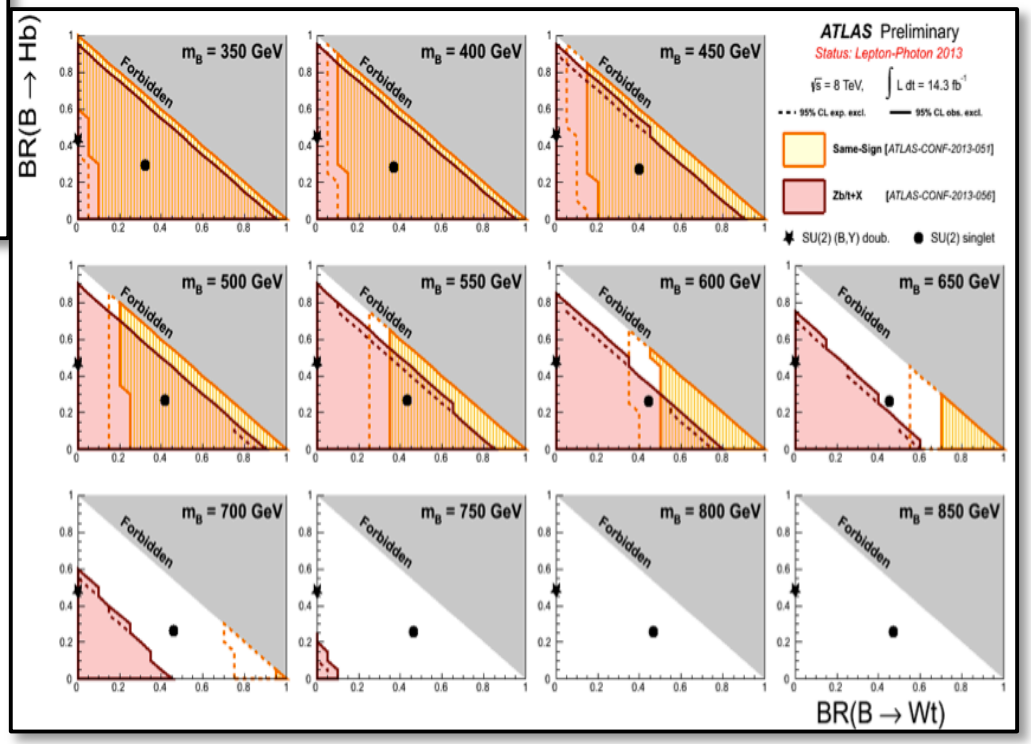
M(B′)>725 GeV (BR for doublet)

ATLAS-CONF-2013-056

ATLAS Partner Quark Summary



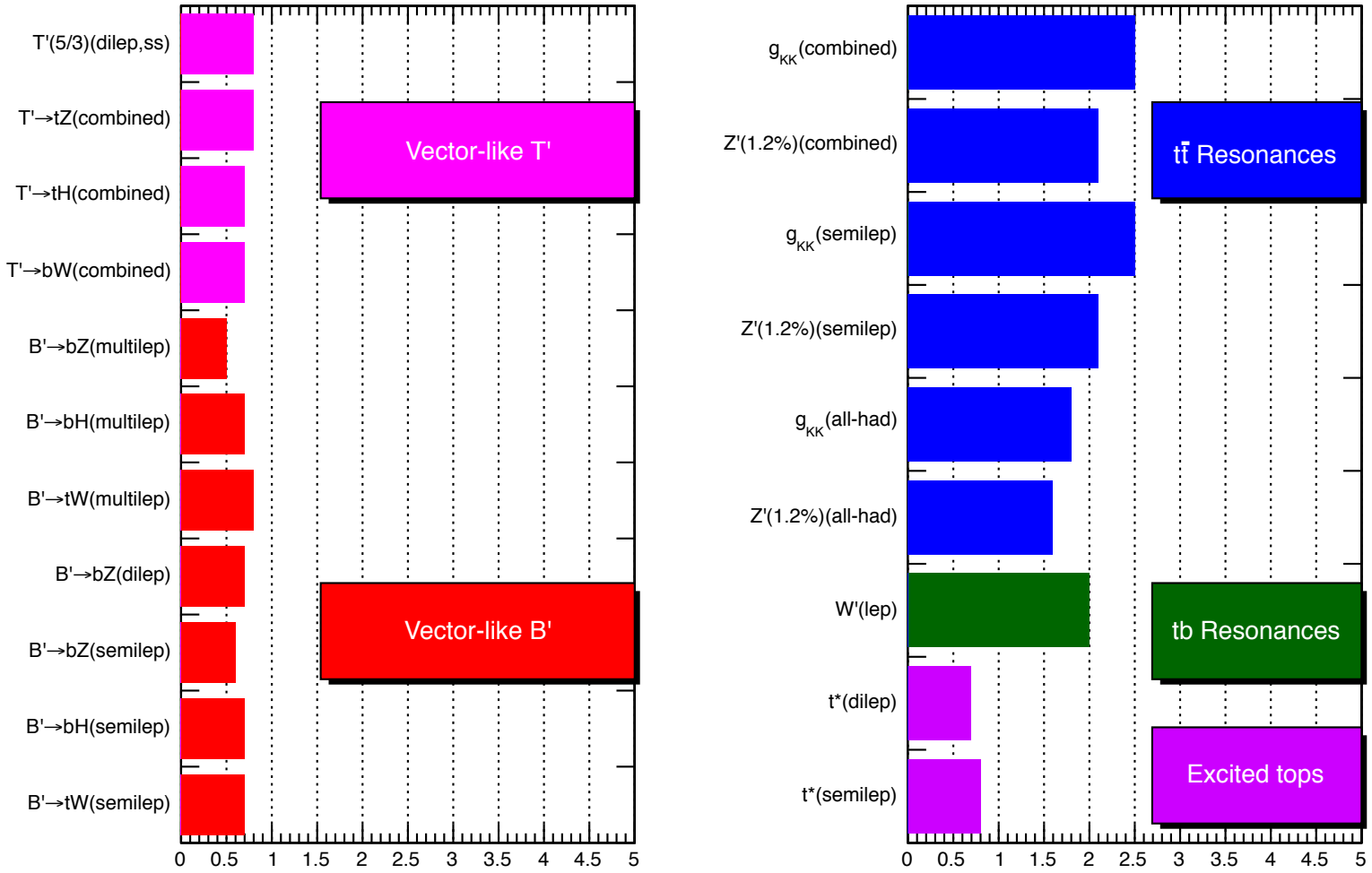
Top Partner
Exclusion Limits



Bottom Partner
Exclusion Limits

CMS Summary

CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)



Summary

- ATLAS and CMS have a rich program in searches for solutions to the hierarchy problem, many of which could involve decays to top quarks or top-like signatures.
- More results on resonances and top and bottom partners from Run 1 (and utilizing more boosted particle identification) coming soon.
- Boosted top tagging and V-tagging (jet substructure) will be increasingly important in new physics searches as we move to higher mass scales.

Stay Tuned!