IAS Program on “The Future of High Energy Physics”
HKUST Jockey Club IAS, Hong Kong, Jan 18-21, 2016

Searches for top and Higgs compositeness at the LHC and beyond

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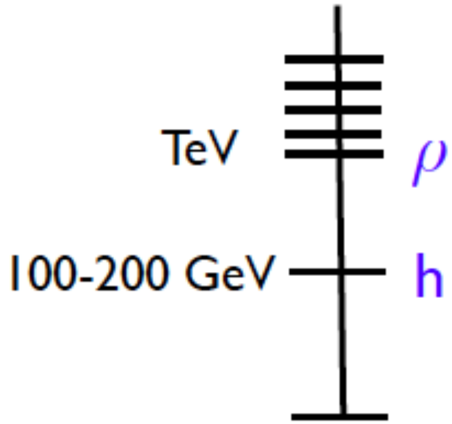
Composite Higgs Paradigm

- Models where the Higgs boson is a composite state give a natural solution to the hierarchy problem.
- The Higgs boson can be light if it is a PNGB emerging from the breaking of a global symmetry (e.g. SO(5)→SO(4)).
- Partial compositeness:
  - SM fermions mix linearly with composite fermions.
  - Fermion mass generation needs separate composite partner for each SM fermion.



- Basic phenomenology:
  - Deviations in Higgs couplings to fermions and vector bosons.
  - New heavy gauge bosons (since vector boson scattering not fully unitarized by the composite Higgs).
  - New fermionic resonances ➔ searches for top/bottom partners.
  - Partially composite top quark can be strongly coupled to the composite sector ➔ anomalous four-top-quark production.
  - Indirect effects: deviations in top couplings to EW gauge bosons, and in precision EW observables.

Outline

- Introduction
- Direct searches for vector-like quarks at the LHC
  - Overview of Run 1 results
  - Run 2 plans and prospects
- Constraints from precision measurements
  - Higgs and top couplings
  - Precision EW observables
- Summary and outlook

Vector-Like Quarks: Production and Decay

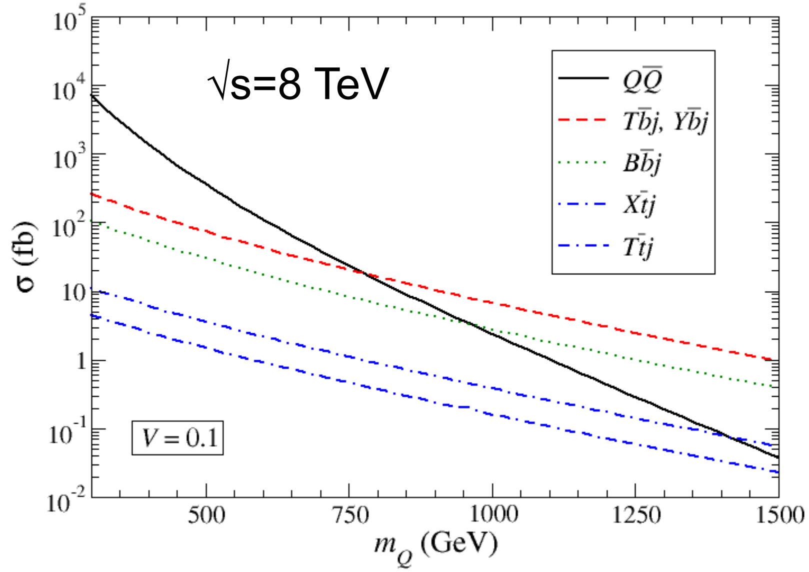
- Top/bottom partners are vector-like quarks (left and right components transform the same under $SU(2)_L$). VLQs present in many BSM scenarios.
- Production:
  - Pair production via QCD: "universal" mode (just depends on m_Q).

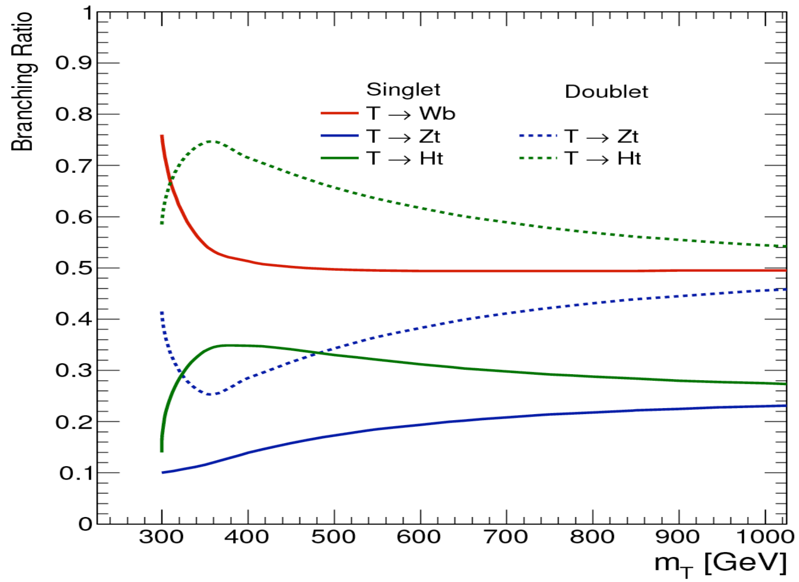
    ➔ Focus of Run 1 searches
  - Single production via EW: potentially important at high m_Q (depends on coupling strength).

    ➔ Important to consider in Run 2
- Decay: Q→Wq, Zq, Hq all with sizable BR

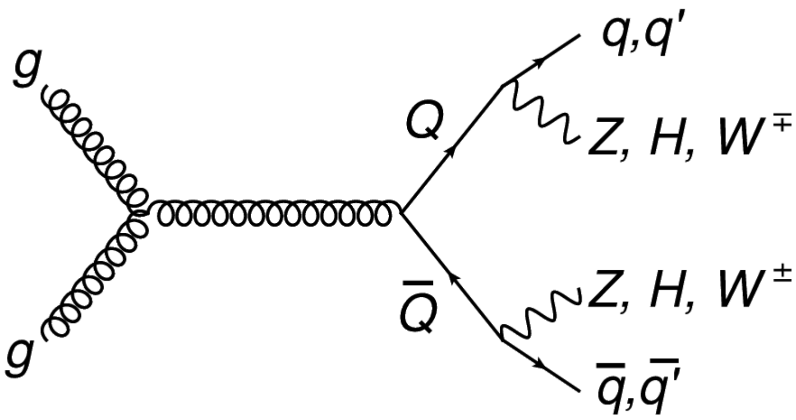
JHEP 11, 030 (2009) *(triplets not included)*

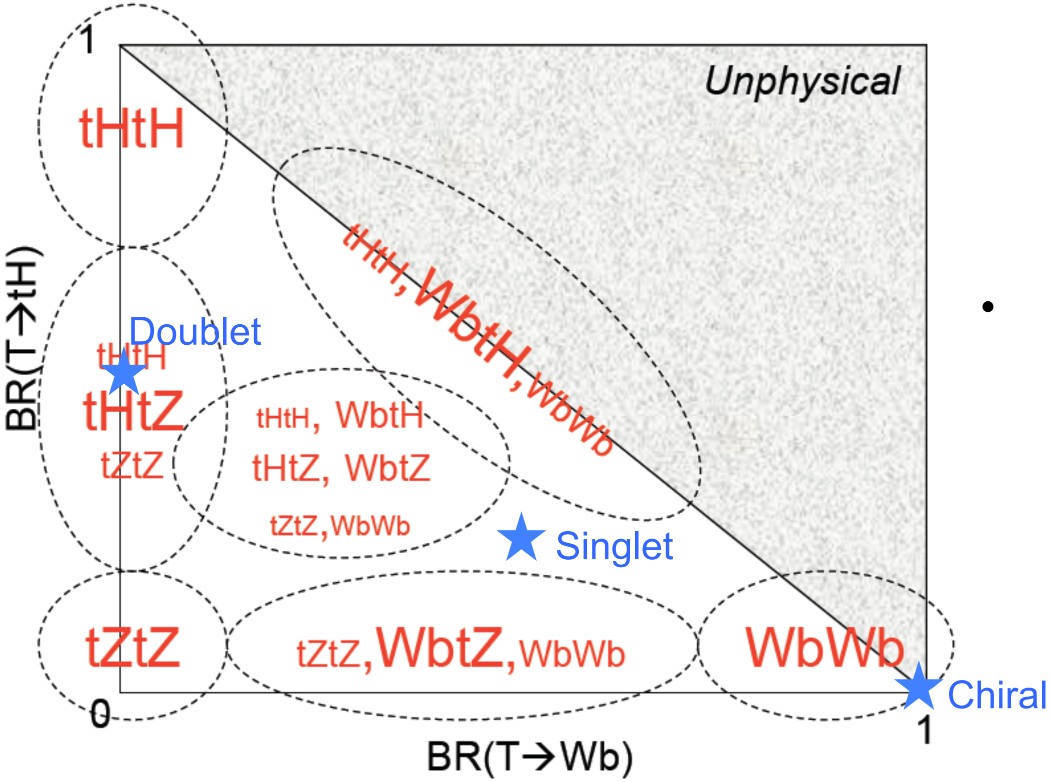
	Label	Charge	Decay mode
T singlet	T_S	+2/3	T→W⁺b, Zt, Ht
B singlet	B_S	-1/3	B→W⁻t, Zb, Hb
(T,B) doublet	TB_d	(+2/3, -1/3)	T→Zt, Ht B→W⁻t
(X,T) doublet	XT_d	(+5/3, +2/3)	X→W⁺t T→Zt, Ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	B→Zb, Hb Y→W⁻b





Strategies





- Very rich phenomenology, depending on the heavy quark mass and quantum numbers.
- Goal is to probe full BR plane in as model independent possible way.

  ➔ Searches specialized on particular heavy quark decay modes, but also able to probe part of the plane.

  ➔ Multiple searches required, ideally overlapping in the plane.
- Searches typically have considered one heavy quark at a time, assuming other resonances do not contribute to the signature. Single production typically neglected.

  ➔ Something to improve upon for Run 2.

Signatures

- There are many signatures that could be exploited, and which are ultimately needed both to enhance discovery potential and model discrimination. Just looking at pair-production:

		SU(2) singlet		*SU(2) doublet*		
		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$	$B\overline{B}$
	4l (1Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$	$B\overline{B}$
	4l (0Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$,$X\overline{X}$	$B\overline{B}$
3 leptons	3l (1Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$	
	3l (0Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$,$X\overline{X}$	
OS dileptons	l^+l^- (1Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$	$B\overline{B}$
	l^+l^- (0Z)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$,$X\overline{X}$	$B\overline{B}$,$Y\overline{Y}$
SS dileptons	$l^\pm l^\pm$		$B\overline{B}$	$B\overline{B}$	$X\overline{X}$	
lepton+jets	$l^\pm$ (4j)	$T\overline{T}$		$T\overline{T}$	$T\overline{T}$	$Y\overline{Y}$
	$l^\pm$ ($\geq$6j)	$T\overline{T}$	$B\overline{B}$	$T\overline{T}$,$B\overline{B}$	$T\overline{T}$,$X\overline{X}$	

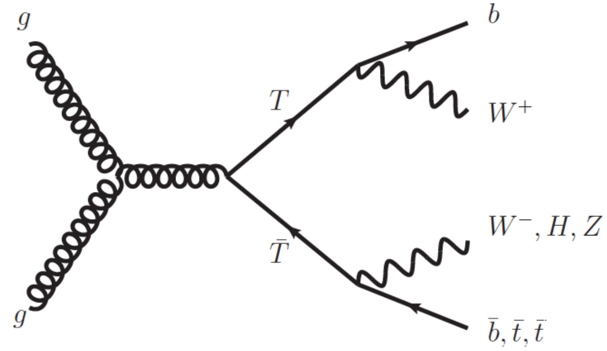
And not even including all-hadronic final state and Higgs tagging!

- Of course, some of them are more challenging and/or powerful than others…

Overview of Run 1 Results

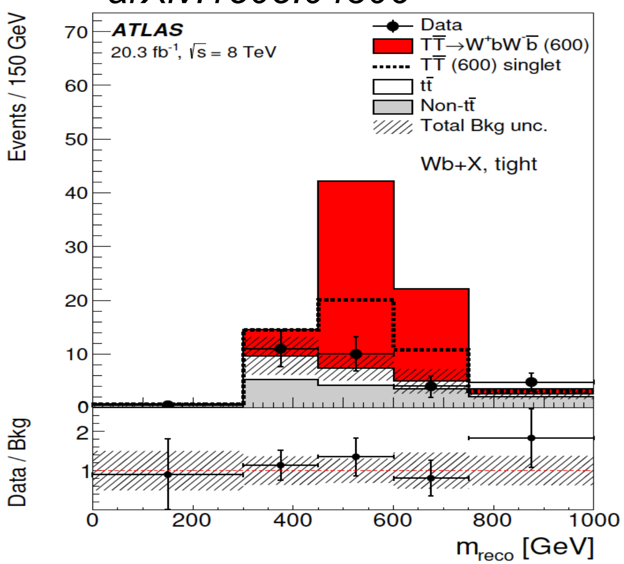
Vector-Like Top: 1-lepton Searches

- Searches targeting high BR($T_{2/3} \rightarrow W^+b$), but also sensitive to other decay modes.
- Most sensitive searches exploit lepton+jets final state. Also searches on all-hadronic mode but lower sensitivity.
- Basic strategy:
  - Presel: 1 lepton, high E_T^{miss}, ≥4 jets/≥1 b-tags.
  - Reconstruct boosted hadronic W boson.
  - Tight cuts: high H_T (*), additional cuts to exploit boosted topology for W bosons.
  - Uses reconstruct heavy quark mass.
  - All BRs tested. Best exclusion for BR($T \rightarrow Wb$)=1.

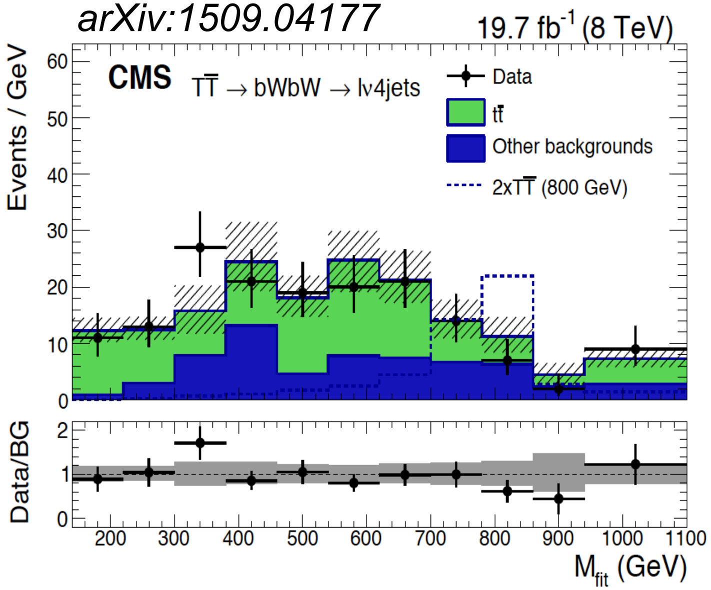


(*) $H_T = \sum p_T^{\text{jets}} + p_T^{\text{lep}} + E_T^{\text{miss}}$

arXiv:1505.04306



arXiv:1509.04177



95% CL obs (exp) limits [100% WbWb]:

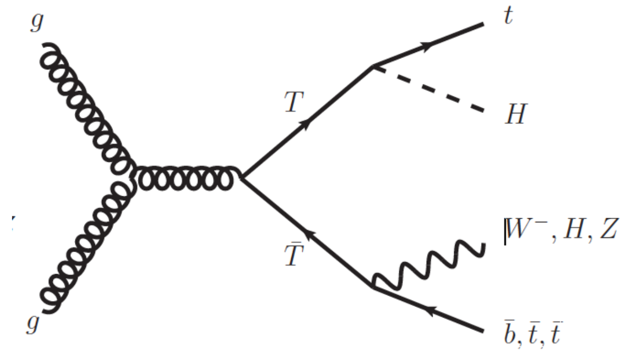
ATLAS: m_T>**770** (795) GeV

CMS: m_T>**912** (851) GeV

Limits also apply to $Y_{-4/3}$, since BR($Y_{-4/3} \rightarrow W^-b$)=1.

Vector-Like Top: 1-lepton Searches

- Search targeting high BR($T_{2/3}$→Ht), but designed as broad-band search sensitive to multiple decay modes: TT→HtHt, HtWb, HtZt, ZtZt, ZtWb
- Basic strategy:
  - Presel: 1 lepton, high E_T^{miss}, ≥5 jets/≥2 b-tags.
  - Analyze H_T spectrum across 8 channels:
    (5 jets, ≥6 jets) x (2 b-tags, 3 b-tags, ≥4 b-tags)
    ≥6 jets/≥3 b-tags channels split in low/high M_{bb}
  - Signal-depleted channels used to constrain in-situ bkg uncert. through likelihood fit to data.
- All BRs tested. Best exclusion for BR(T→Ht)=1.



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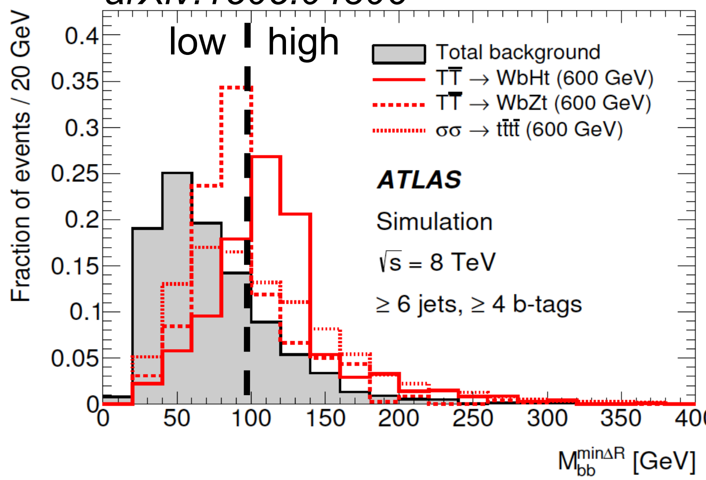

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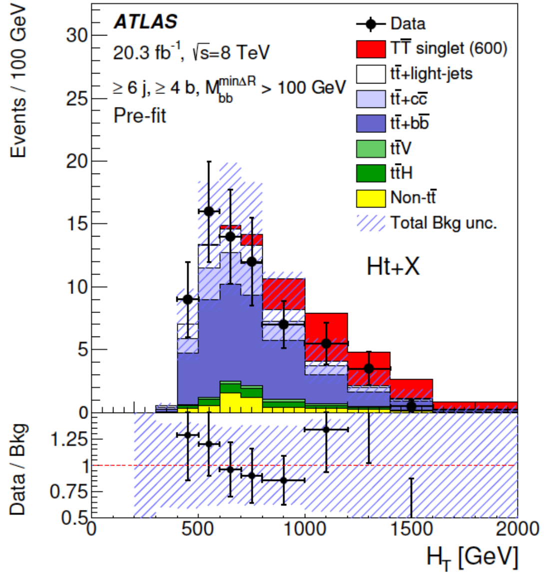
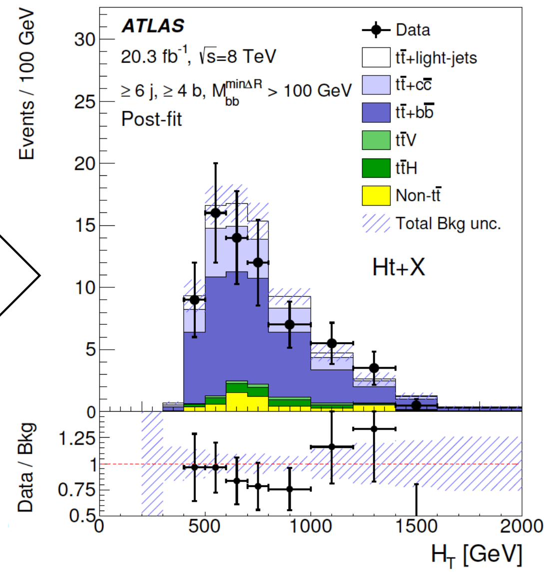




95% CL obs (exp) limits:

Singlet: m_T>**765** (720) GeV

Doublet: m_T>**855** (820) GeV

BR(T→Ht)=1: m_T>**950** (885) GeV

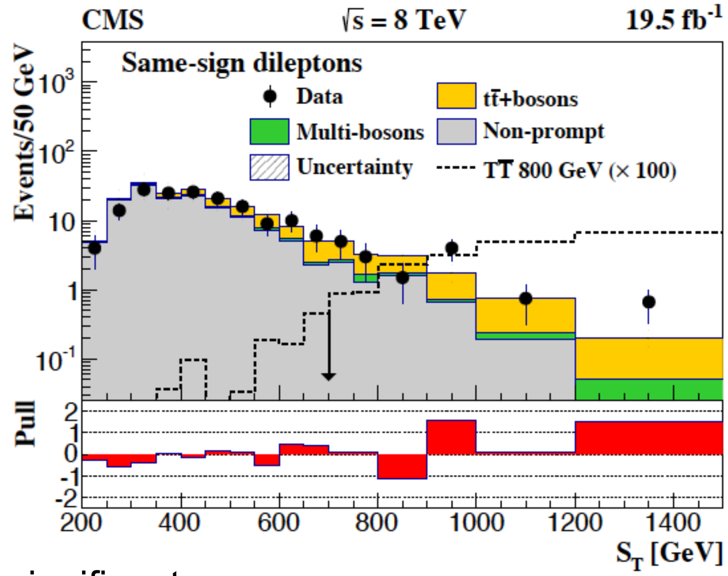
Vector-Like Top: Multilepton Searches

- Inclusive multilepton searches. Consider multiple search channels that are eventually combined.
- CMS search:

	OS1	*OS2*	*SS*	Multileptons
H_T (GeV)	>300	>500	>500	>500
S_T (GeV)	>900	>1000	>700	>700
Number of jets	2 or 3	≥ 5	≥ 3	≥ 3
b tags	≥ 1	≥ 2	≥ 1	≥ 1
E_T^{miss} (GeV)	>30	>30	>30	>30
$M_{b\ell}$ (GeV)	>170	—	—	—
$M_{\ell\ell}$ (GeV)	>20	>20	>20	>20
Z boson veto	yes	no	no	no

	OS1	*OS2*	*SS*	Multileptons
Total background	17.4 ± 3.7	84 ± 12	16.5 ± 4.8	3.7 ± 1.3
Data	20	86	18	2

arXiv:1311.7667

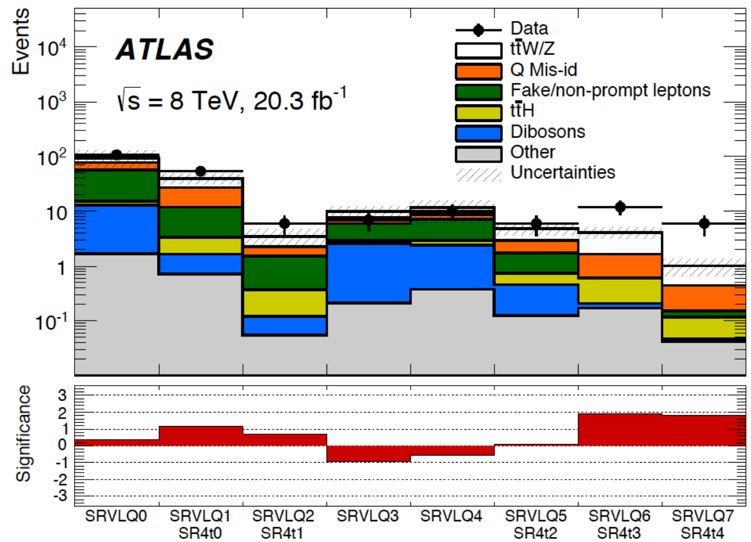


➔ No significant excess

- ATLAS search:

Definition				
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_T < 700$ GeV	$N_b = 1$	$E_T^{miss} > 40$ GeV		SRVLQ0
	$N_b = 2$			SRVLQ1
	$N_b \geq 3$			SRVLQ2
$H_T \geq 700$ GeV	$N_b = 1$	$40 < E_T^{miss} < 100$ GeV		SRVLQ3
		$E_T^{miss} \geq 100$ GeV		SRVLQ4
	$N_b = 2$	$40 < E_T^{miss} < 100$ GeV		SRVLQ5
		$E_T^{miss} \geq 100$ GeV		SRVLQ6
	$N_b \geq 3$	$E_T^{miss} > 40$ GeV		SRVLQ7

arXiv:1409.5500



Apparent excess in VLQ6 and VLQ7 SRs 🡐

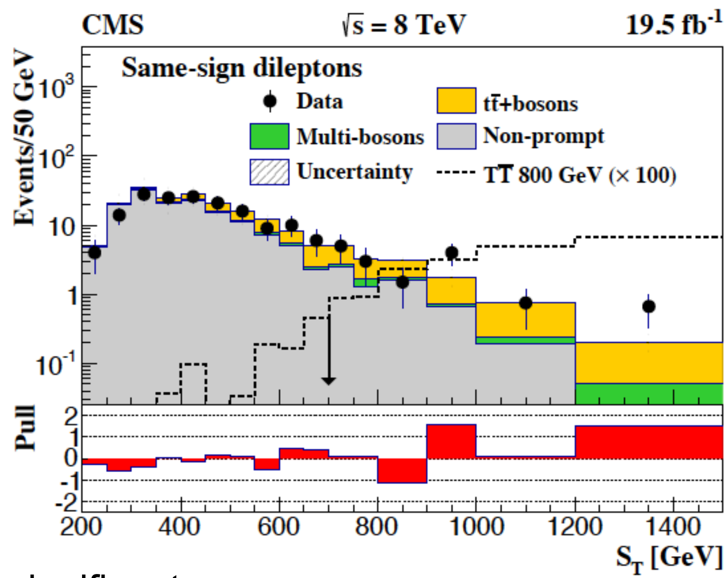
Vector-Like Top: Multilepton Searches

- Inclusive multilepton searches. Consider multiple search channels that are eventually combined.
- CMS search:

	OS1	*OS2*	*SS*	Multileptons
H_T (GeV)	>300	>500	>500	>500
S_T (GeV)	>900	>1000	>700	>700
Number of jets	2 or 3	≥ 5	≥ 3	≥ 3
b tags	≥ 1	≥ 2	≥ 1	≥ 1
E_T^{miss} (GeV)	>30	>30	>30	>30
$M_{b\ell}$ (GeV)	>170	—	—	—
$M_{\ell\ell}$ (GeV)	>20	>20	>20	>20
Z boson veto	yes	no	no	no

	OS1	*OS2*	*SS*	Multileptons
Total background	17.4 ± 3.7	84 ± 12	16.5 ± 4.8	3.7 ± 1.3
Data	20	86	18	2

arXiv:1311.7667



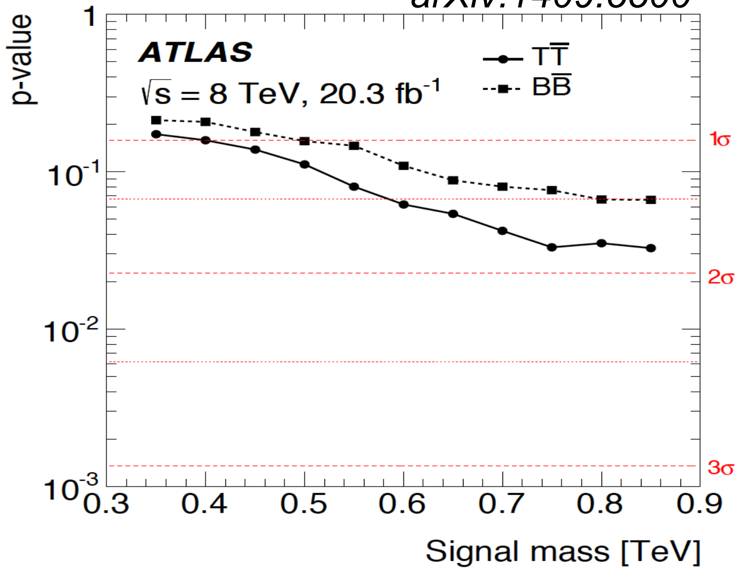
➔ No significant excess

- ATLAS search:

	SRVLQ5/SR4t2	SRVLQ6/SR4t3	SRVLQ7/SR4t4
$t\bar{t}W/Z$	$1.87 \pm 0.09 \pm 0.80$	$2.46 \pm 0.11 \pm 1.06$	$0.57 \pm 0.05 \pm 0.25$
$t\bar{t}H$	$0.31 \pm 0.04 \pm 0.05$	$0.44 \pm 0.04 \pm 0.06$	$0.08 \pm 0.02 \pm 0.02$
Dibosons	$0.33 \pm 0.14 \pm 0.10$	$0.04 \pm 0.12 \pm 0.03$	$0.00 \pm 0.12 \pm 0.00$
Fake/Non-prompt	$1.03 \pm 0.97 \pm 0.60$	$0.00 \pm 1.02 \pm 0.28$	$0.04 \pm 0.83 \pm 0.24$
Q mis-Id	$1.17 \pm 0.16 \pm 0.38$	$1.09 \pm 0.14 \pm 0.34$	$0.30 \pm 0.09 \pm 0.10$
Other bkg.	$0.16 \pm 0.08 \pm 0.02$	$0.23 \pm 0.08 \pm 0.05$	$0.14 \pm 0.08 \pm 0.08$
Total bkg.	$4.9 \pm 1.0 \pm 1.0$	$4.3 \pm 1.1 \pm 1.1$	$1.1 \pm 0.9 \pm 0.4$
Data	6	12	6
p-value	0.46	0.029	0.036

1.9σ 1.8σ

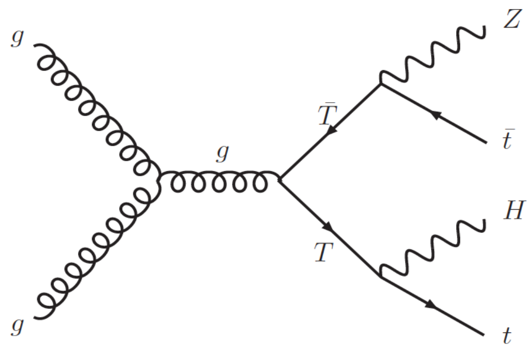
arXiv:1409.5500



Vector-Like Top: Multilepton Searches

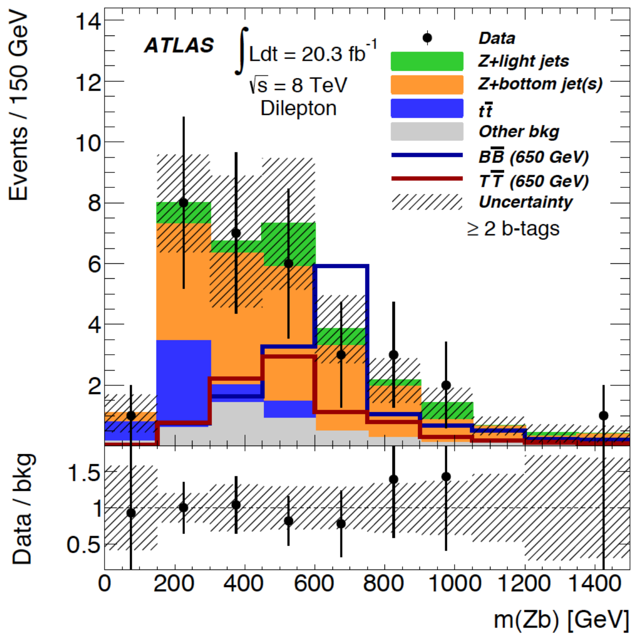
- Dedicated search probing TT→Zt+X (*).
- Multiple search channels that are eventually combined.

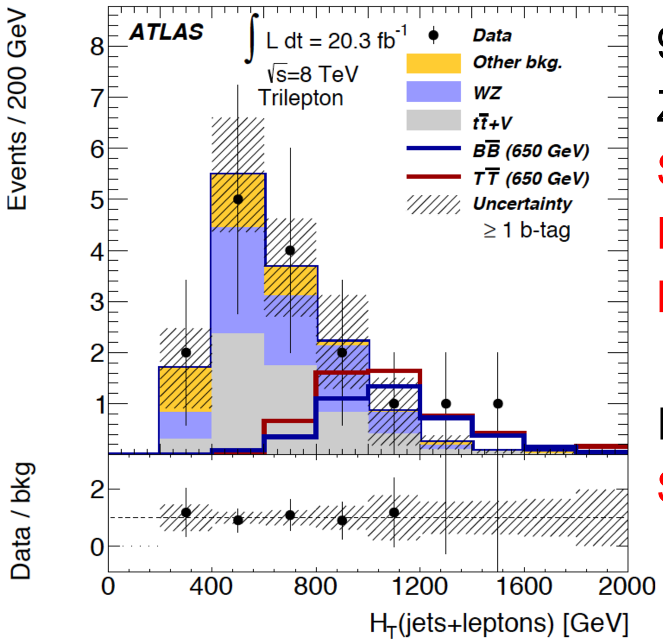
Event selection			
Z boson candidate preselection ≥ 2 central jets $p_{\mathrm{T}}(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_{\mathrm{T}}(\text{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		$H_{\mathrm{T}}(\text{jets+leptons})$	



(*) Not orthogonal to inclusive multilepton search.

arXiv:1409.5500





95% CL obs (exp) limits:

Zt+X search:

Singlet: m_T>**655** (625) GeV

Doublet: m_T>**735** (720) GeV

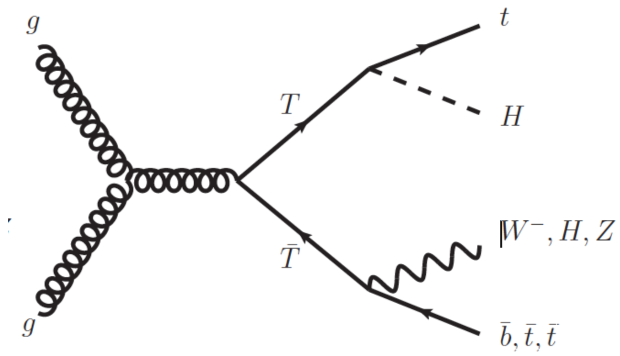
BR(T→Zt)=1: m_T>**810** (810) GeV

Inclusive multilepton search

Singlet: m_T>**590** (660) GeV

Vector-Like Top: All-Hadronic Searches

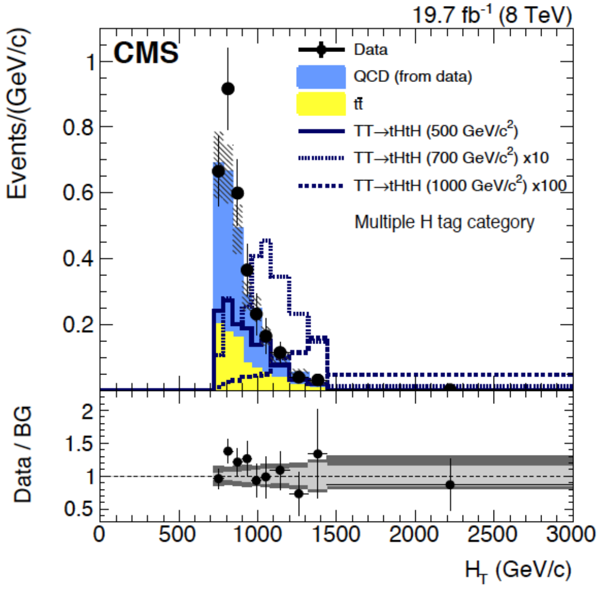
- CMS has performed several VLQ searches in the all-hadronic final state using jet substructure techniques.

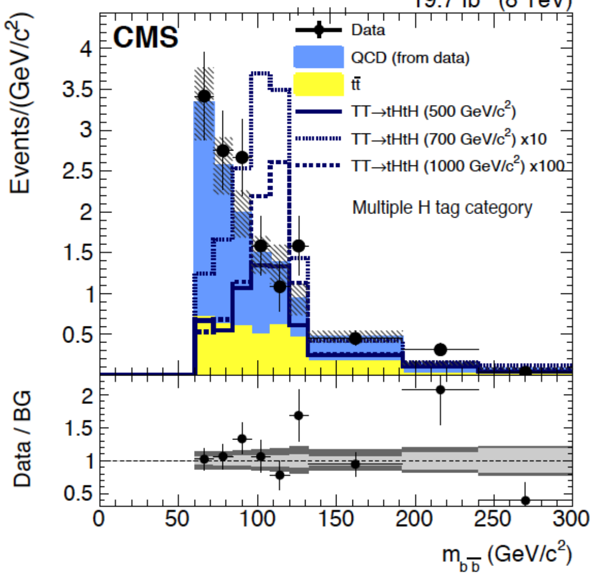


TT→Ht+X, H→bb

- CA R=1.5 jets used as input to HepTopTagger and Higgs tagging (based on subjet b-tagging)
- ≥1 HTT candidate (p_T>200 GeV).
- ≥1 Higgs candidate (p_T>150 GeV), m_j>60 GeV
- Categorize events depending on number of Higgs candidates (=1 and ≥2).
- Uses likelihood discriminant based on H_T and Higgs invariant mass.

arXiv:1503.01952



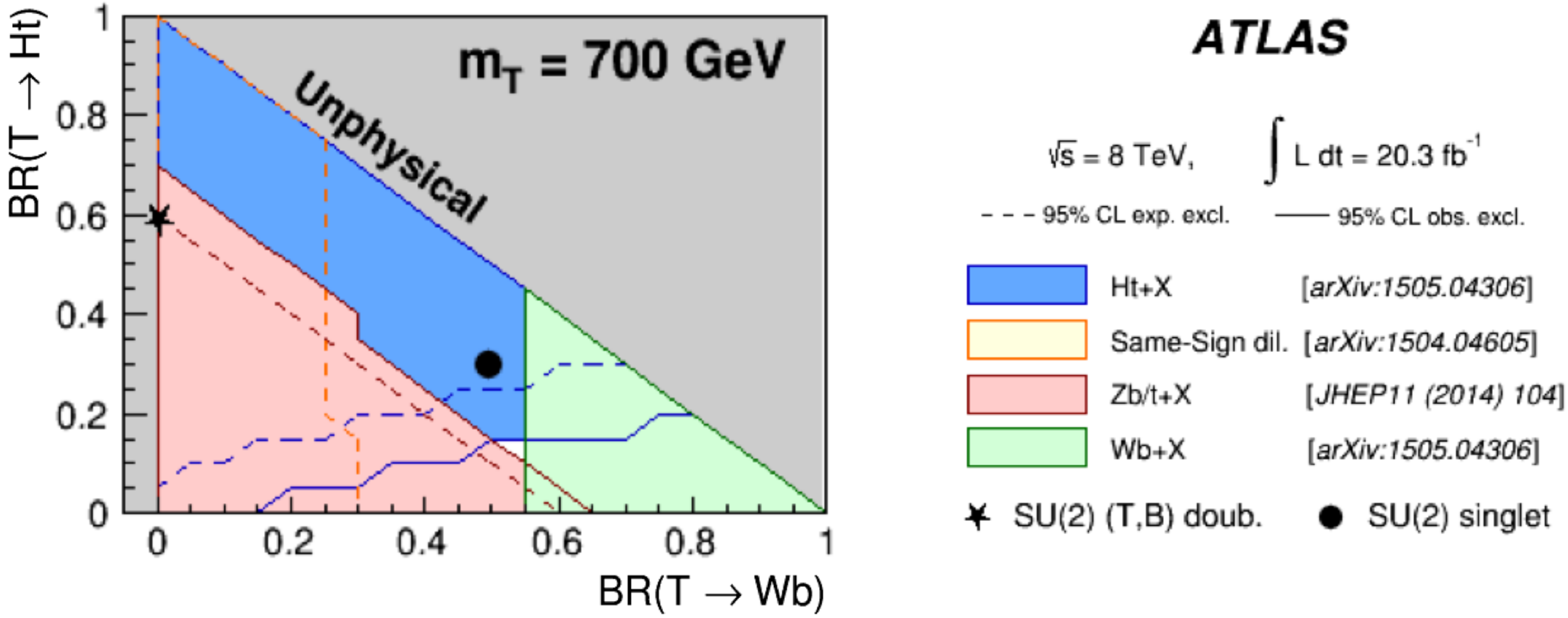


95% CL obs (exp) limits [100% HtHt]:
m_B>**900** (810) GeV

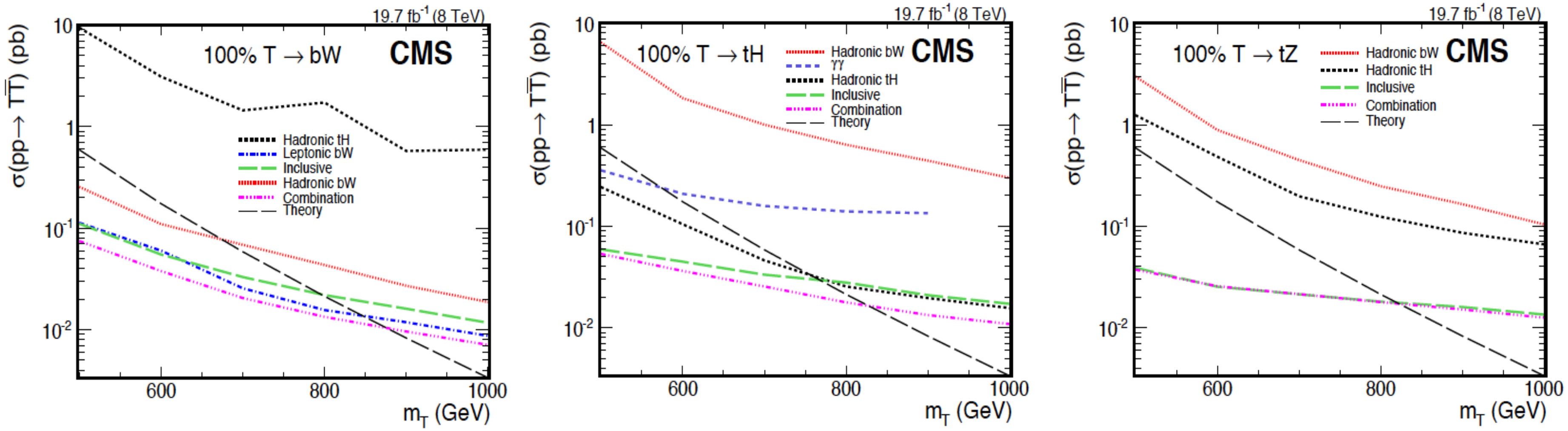
Competitive with inclusive CMS search, which combines 1-lepton and multilepton searches

arXiv:1311.7667

Vector-Like Top: Complementarity

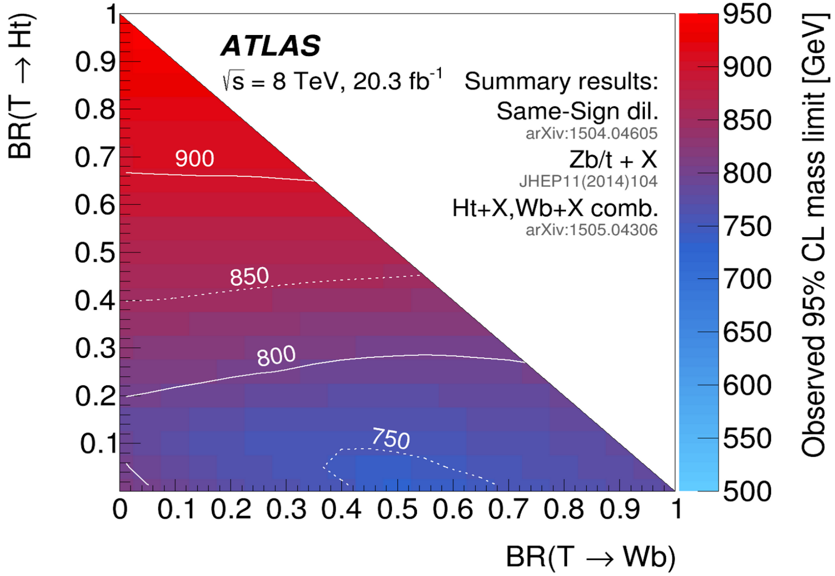


arXiv:1509.04177



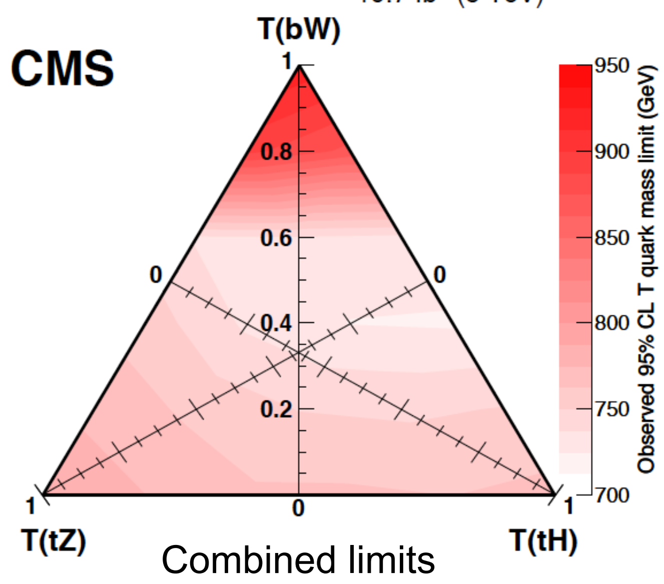
Vector-Like Top Summary

arXiv:1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

arXiv:1509.04177

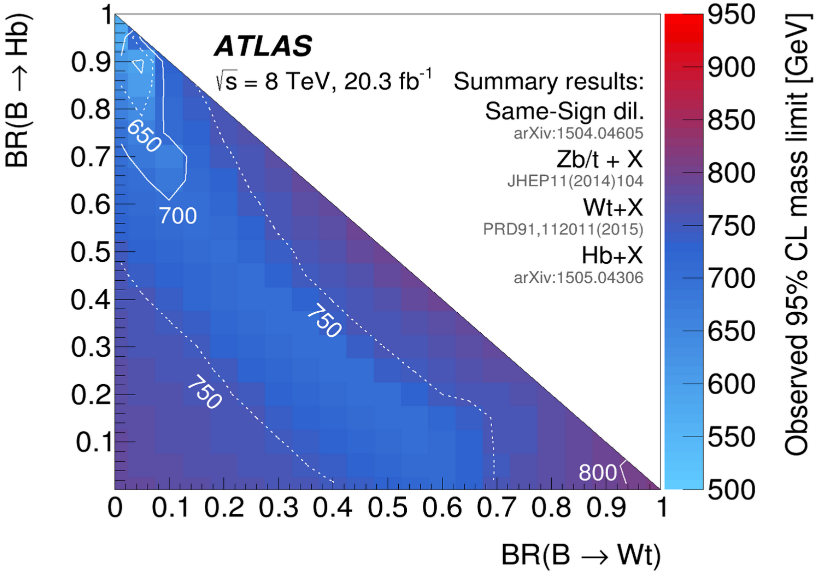


Vector-like top masses below ~720 GeV excluded for any possible combination of BRs.

Vector-like T BR Hypothesis	ATLAS (*) 95% CL Limit on m_T (GeV) obs (exp)	CMS 95% CL Limit on m_T (GeV) obs (exp)
100% Wb (chiral, Y)	**770** (795)	**920** (890)
100% Zt	**810** (810)	**790** (830)
100% Ht	**950** (885)	**770** (840)
T singlet	**800** (755)	**740** (800)
T in (T, B) doublet	**855** (820)	**760** (820)

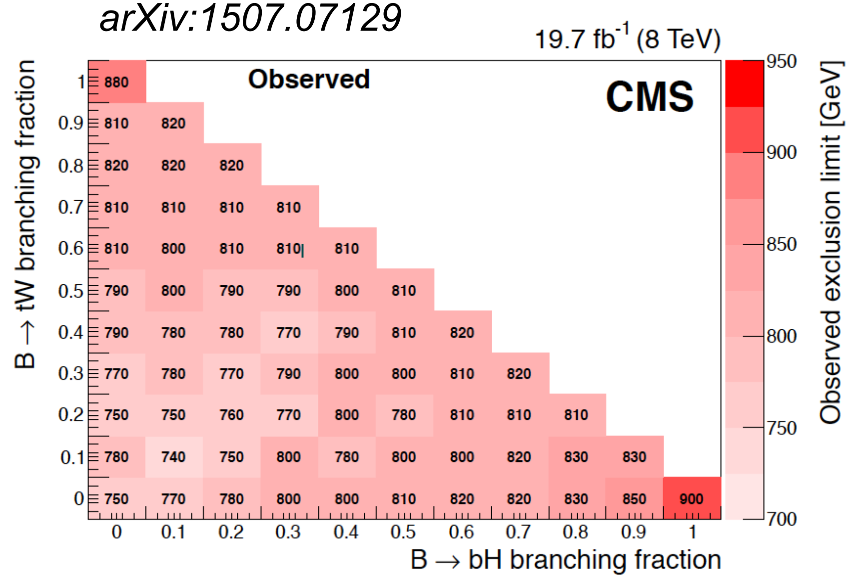
Vector-Like Bottom Summary

arXiv:1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

arXiv:1507.07129



Combined limits

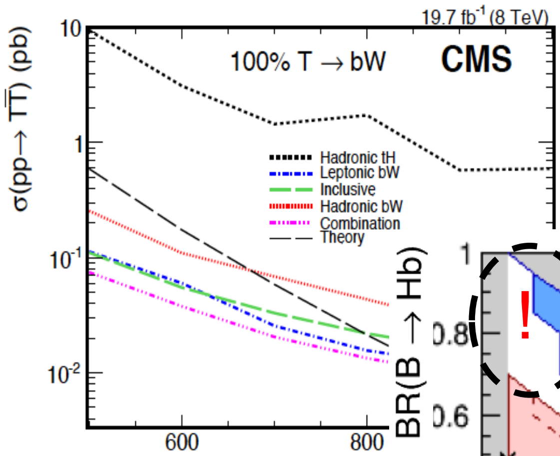
Vector-like bottom masses below ~740 GeV excluded for any possible combination of BRs.

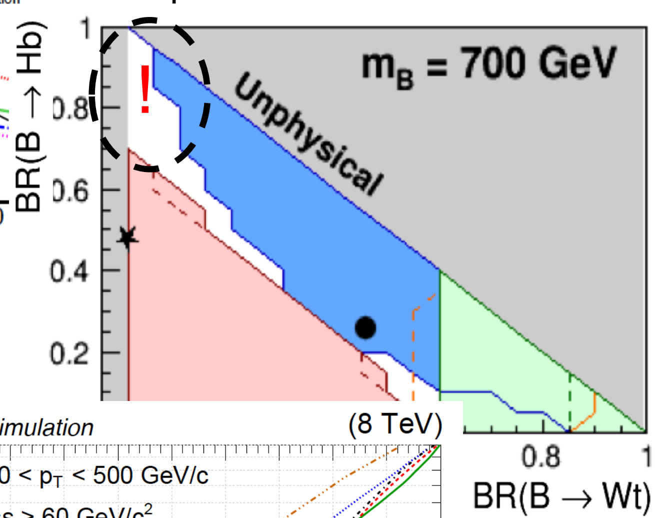
Vector-like B BR Hypothesis	ATLAS (*) 95% CL Limit on m_B (GeV) obs (exp)	CMS 95% CL Limit on m_B (GeV) obs (exp)
100% Wt (chiral, X)	**730** (790)	**880** (890)
100% Zb	**790** (800)	**750** (740)
100% Hb	**700** (625)	**900** (810)
B singlet	**685** (670)	**780** (760)
B in (B, Y) doublet	**755** (755)	**810** (800)

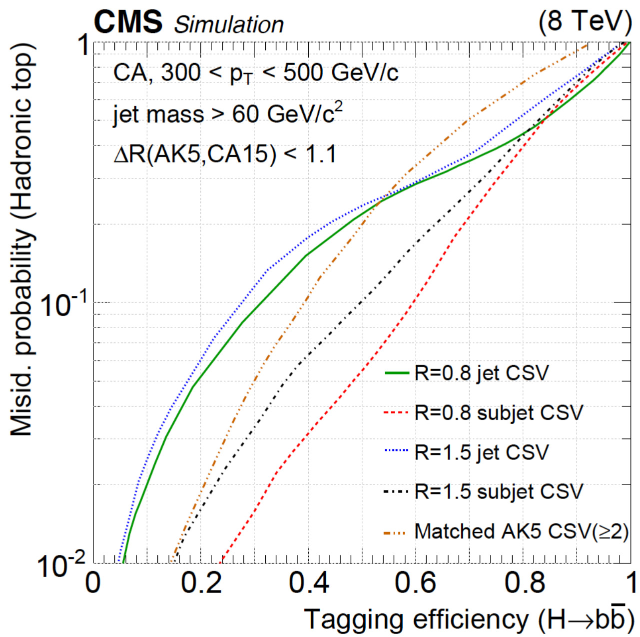
Run 2 Plans and Prospects

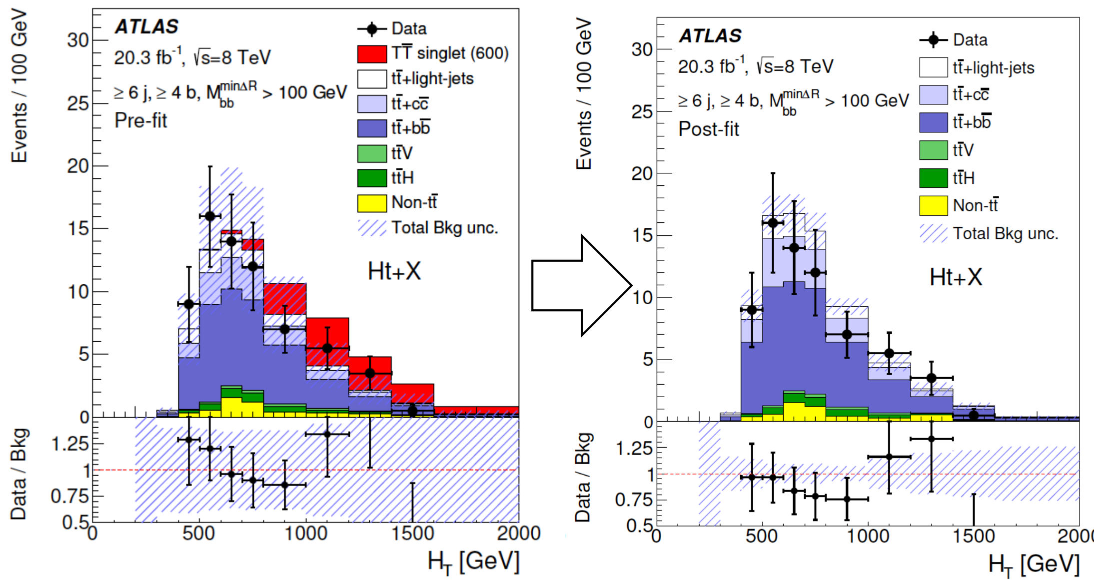
Basic Plan for Run 2

- **Capitalize on Run 1 experience**
  - Most sensitive channels
  - Complementary channels
  - Missing channels
  - Most powerful experimental strategies
  - Improved background estimation techniques
  - Reducing the impact of systematic uncertainties
  - …



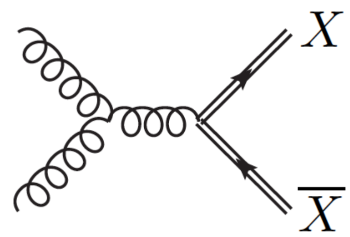




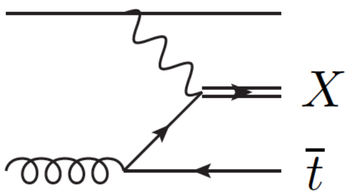


Basic Plan for Run 2

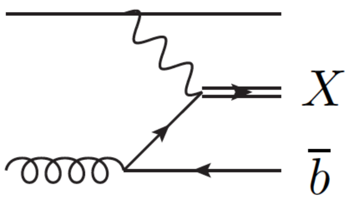
- Capitalize on Run 1 experience
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Continue to exploit pair production above 1 TeV
  - Add single production above 1 TeV
  - Optimize strategy at high mass



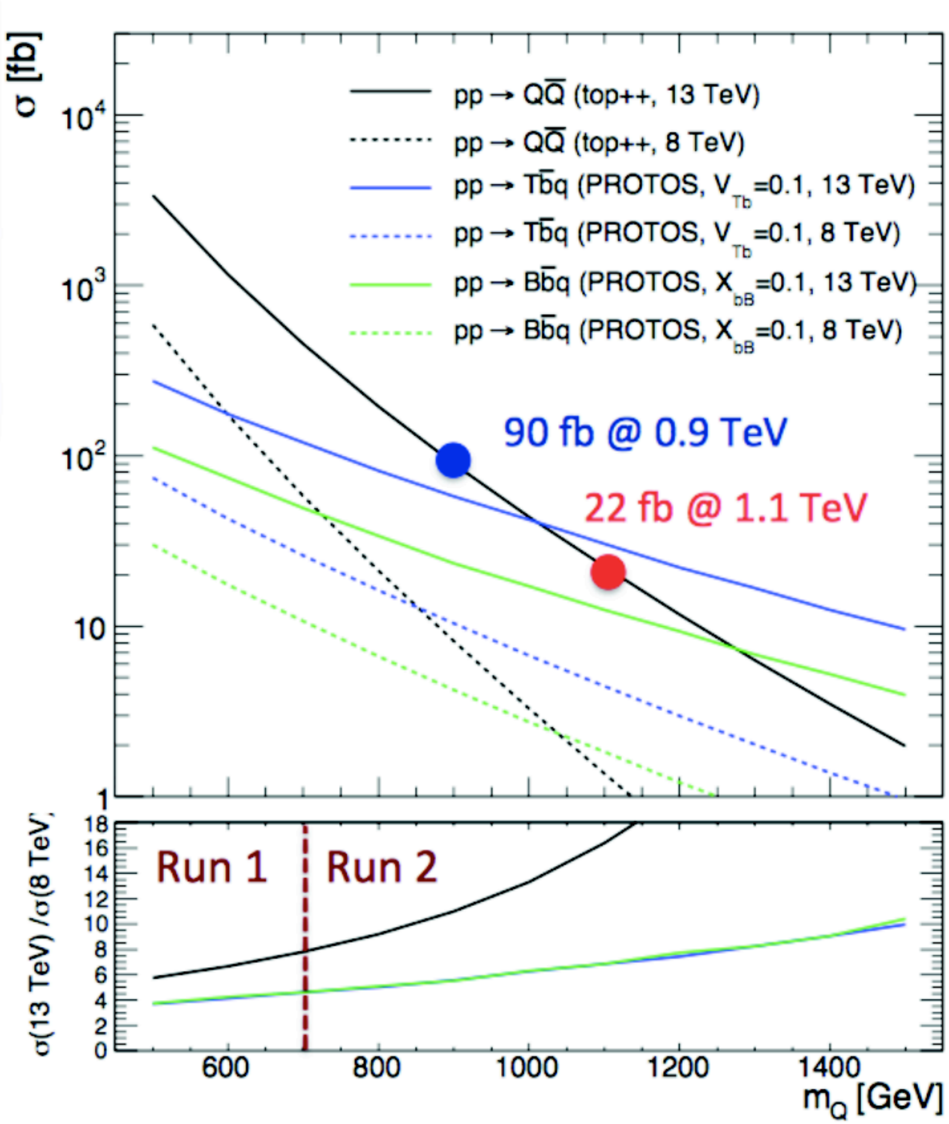
QCD **pair prod.**
model indep.,
relevant at low mass



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



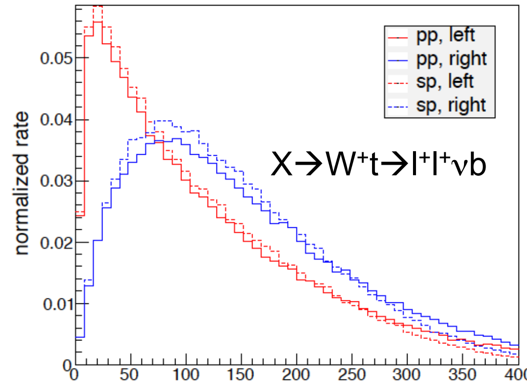
single prod. with **b**
favoured by small b mass
dominant when allowed



Basic Plan for Run 2

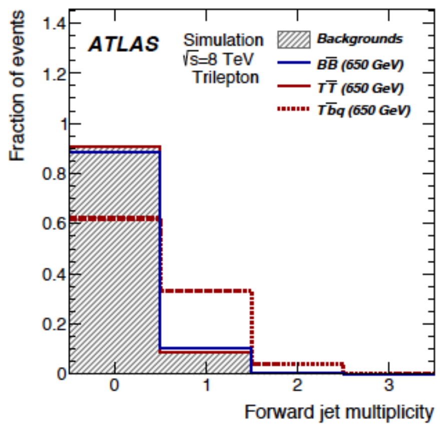
- Capitalize on Run 1 experience
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Continue to exploit pair production above 1 TeV
  - Add single production above 1 TeV
  - Optimize strategy at high mass

arXiv:1409.0100

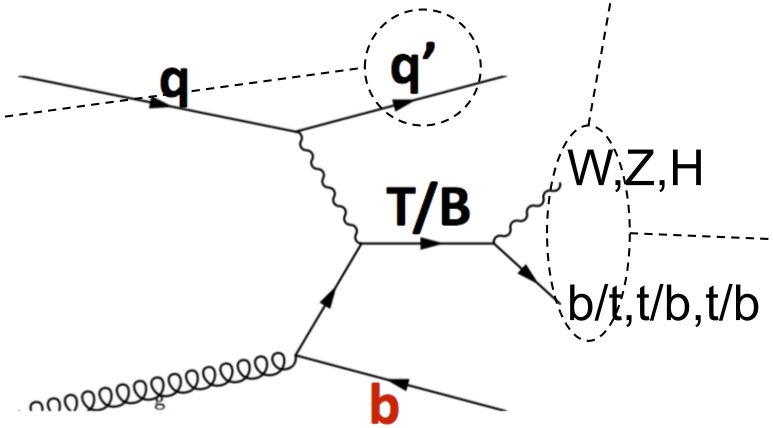


p_T(SS leptons)

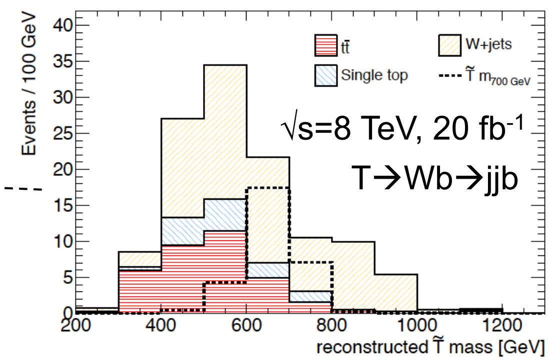
arXiv:1409.5500



Forward jet:
p_T>35 GeV, 2.5<|η|<4.5



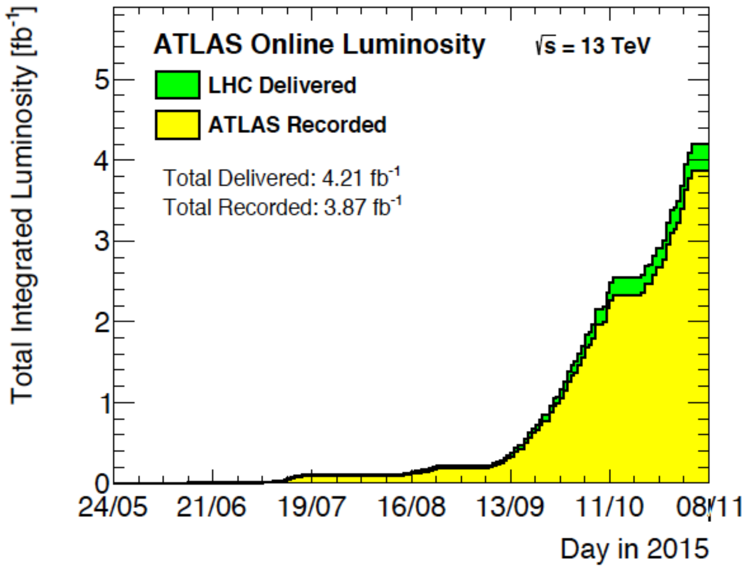
arXiv:1403.7490



- Forward jet tagging critical.
- Many channels, with and without leptons.
- Boosted techniques for all-hadronic modes crucial.
- Must ensure proper helicity propagation in decay.

Basic Plan for Run 2

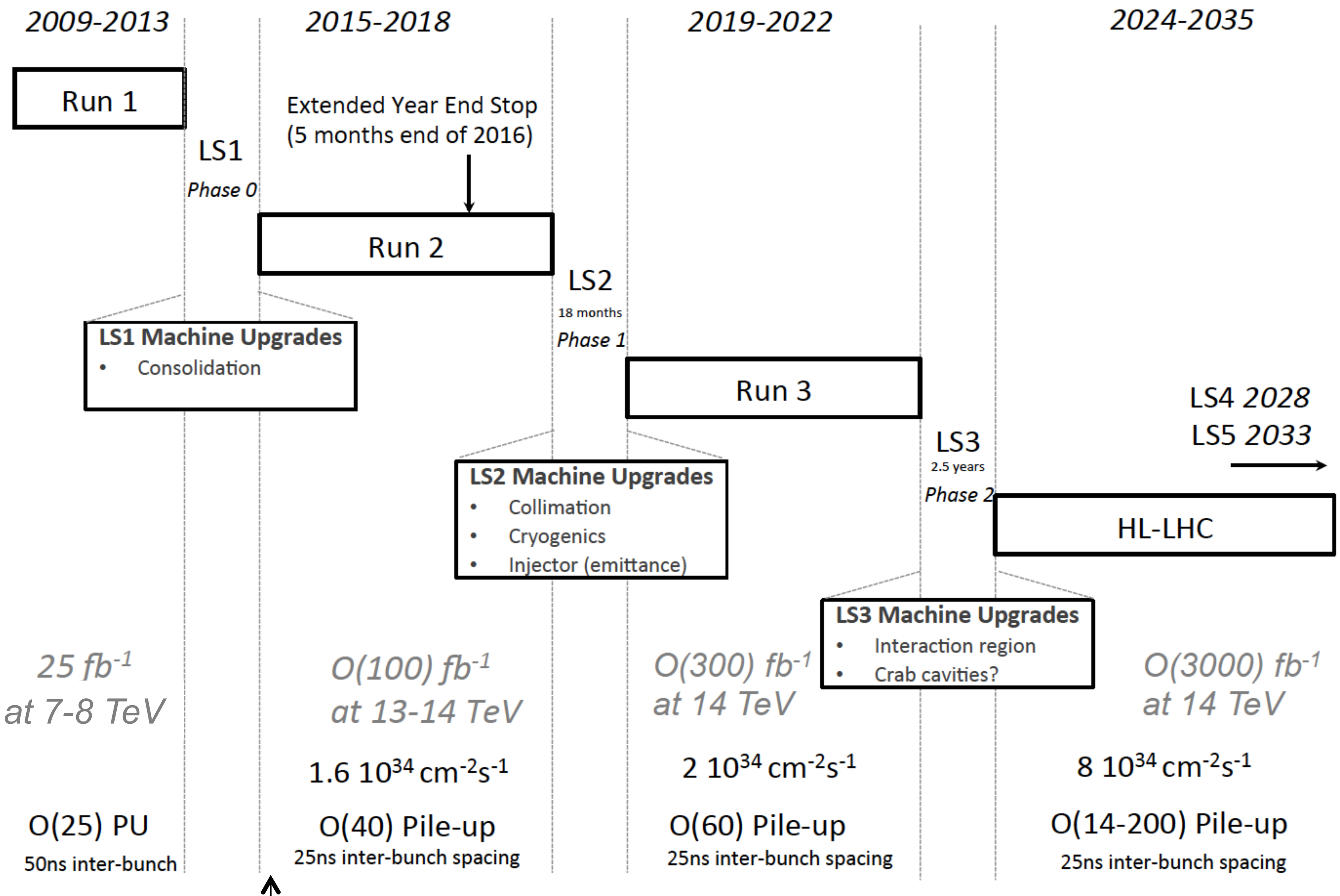
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**
  - **2015**:
    - Recorded 3.9 fb^{-1}
    - For the most part Run 1-style analyses with early data.
    - *Expect to exceed Run 1 sensitivity*.
    - High-priority to checking Run 1 excesses.
    - Optimize searches for discovery!
  - **2016**:
    - Collisions restart on April 25, 2016.
    - Expect ~20-35 fb^{-1}
  - **Full Run 2 (2015-2018):**
    - Expect ~100 fb^{-1}



- <μ>=13
- Reached 5.1×10^{33} $cm^{-2}s^{-1}$ (Run 1: $7\text{-}8 \times 10^{33}$ $cm^{-2}s^{-1}$)

The LHC Run 2 and Beyond

Eventually will multiply by x1000 the 2015 dataset!



We are at the beginning of a ~20 year program!

Basic Plan for Run 2

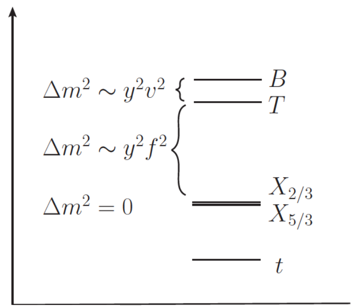
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Use of simplified models
  - Combination of pair and single production
  - Take into account effect of extra resonances in some cases
  - …

arXiv:1211.5663

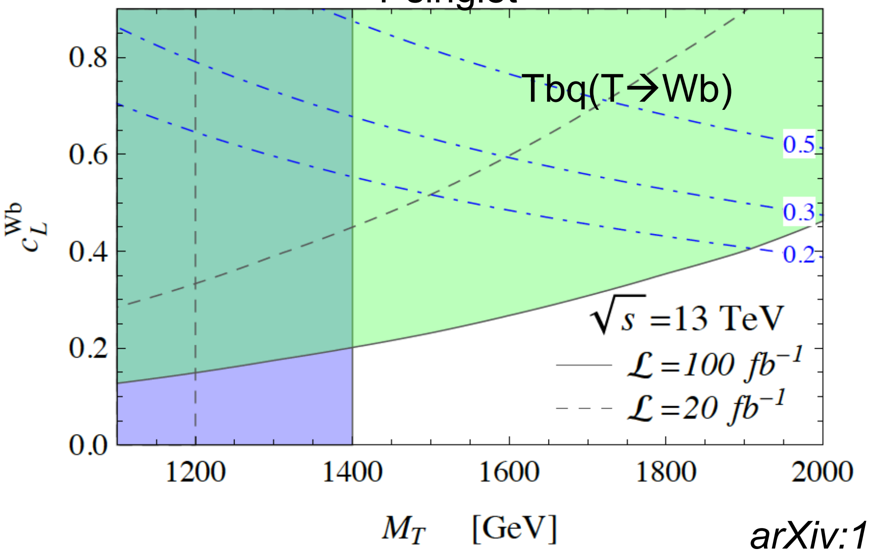
$$\mathcal{L} = \frac{g_w}{2}\left[c_R^{XV}\,\overline{X}_R \not{V} t_R + c_L^{XV}\,\overline{X}_L \not{V} t_L\right] + \frac{g_w}{2}\left[c_L^{XV}\,\overline{X}_L \not{V} b_L + c_R^{XV}\,\overline{X}_R \not{V} b_R\right] + \left[c_R^{Xh}\,h\,\overline{X}_L t_R + c_L^{Xh}\,h\,\overline{X}_R t_L\right] + \left[c_L^{Xh}\,h\,\overline{X}_R b_L + c_R^{Xh}\,h\,\overline{X}_L b_R\right] + \text{h.c.}\,,$$

		couplings			
partner (MG name)	Q	$W^\pm$	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	2/3	c_L^{TW}, c_R^{TW}	c_L^{TZ}, c_R^{TZ}	c_L^{Th}, c_R^{Th}	—
$B_{1/3}$ (B13)	-1/3	c_L^{BW}, c_R^{TW}	c_L^{BZ}, c_R^{BZ}	c_L^{Bh}, c_R^{Bh}	—
$X_{5/3}$ (X53)	5/3	c_L^{XW}, c_R^{XW}	—	—	—
$Y_{4/3}$ (Y43)	-4/3	c_L^{YW}, c_R^{YW}	—	—	—
$V_{8/3}$ (V83)	8/3	—	—	—	c_L^{VW}, c_R^{VW}

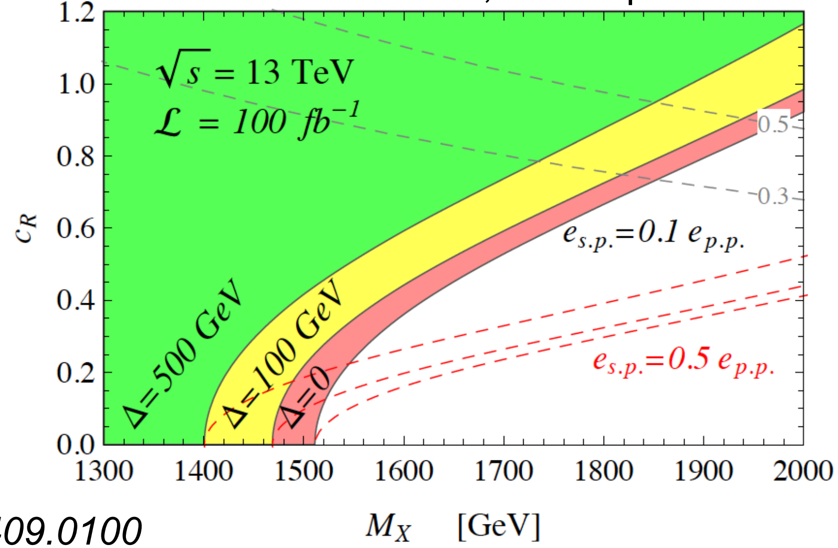
Typical spectrum in minimal coset SO(5)/SO(4)



T singlet



X→W⁺t + B→W⁻t, SS dileptons

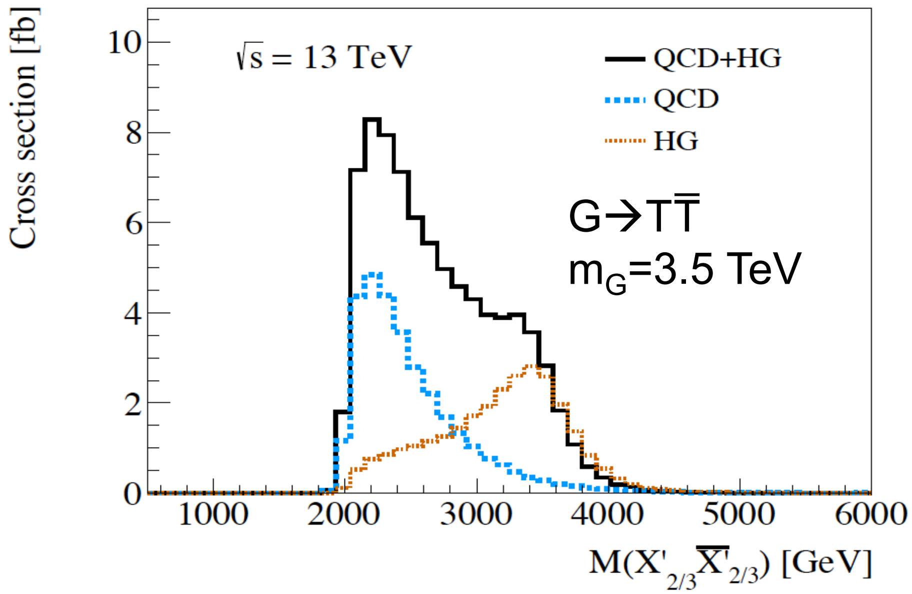


arXiv:1409.0100

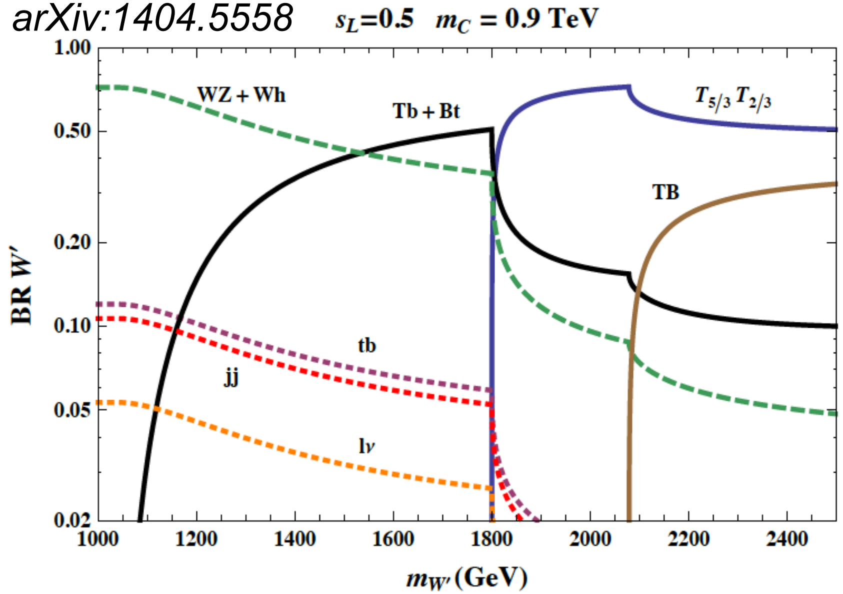
Basic Plan for Run 2

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production
    - Heavy gluon:
      $G \rightarrow Q\bar{Q}$, $m_G \geq 2m_Q$
      $G \rightarrow Q\bar{q}$, $m_Q + m_q < m_G < 2m_Q$
    - Heavy W'/Z':
      W'→Tb, Bt, XT, depending on custodian mass and mixing
    - …

arXiv:1507.05628



arXiv:1404.5558

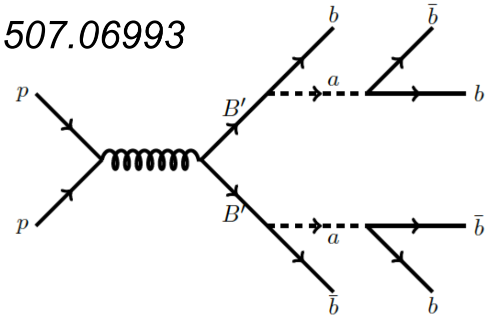


Basic Plan for Run 2

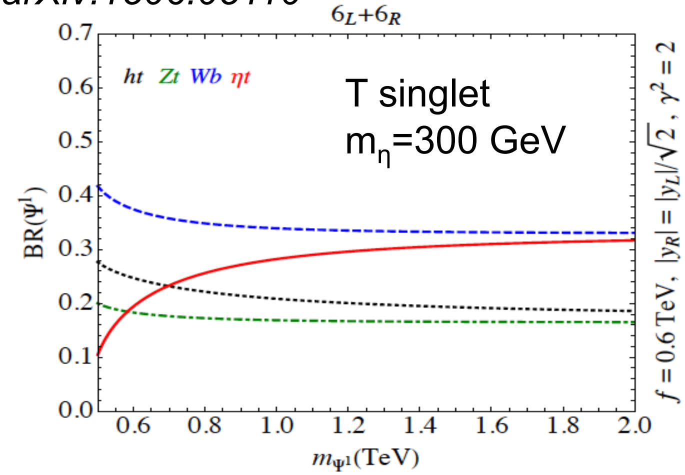
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production
  - Non-standard decays
    - BR(Q→Wq)+BR(Q→Zq)+BR(Q→Hq)<1
    - Examples:
      - Q→q+inv
      - Q→q+η, η CP-odd scalar
      - …
    - If exotic BRs dominant, signal may be picked by existing searches (e.g. direct sbottom searches for $B\bar{B} \rightarrow b\bar{b}+E_T^{miss}$).
    - For comparable BRs, it becomes difficult as signal split into challenging channels such as $T\bar{T} \rightarrow W^+ b\bar{t} gg$.

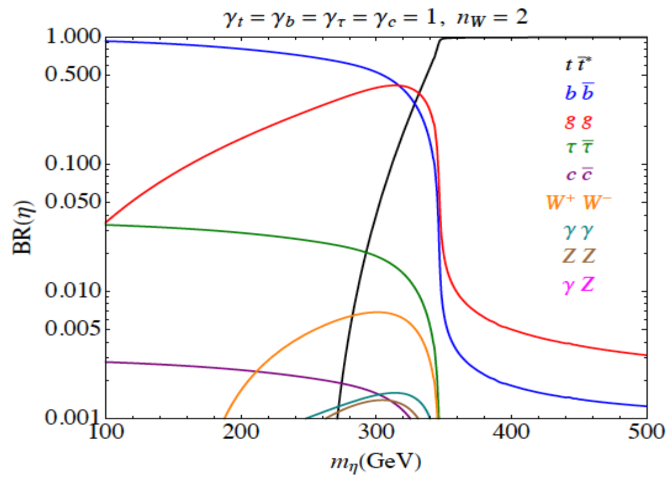
      But also promising channels: $T\bar{T} \rightarrow W^+ b\bar{t} t\bar{t}$.

arXiv:1507.06993



arXiv:1506.05110





Precision Measurements

The Role of Precision Measurements

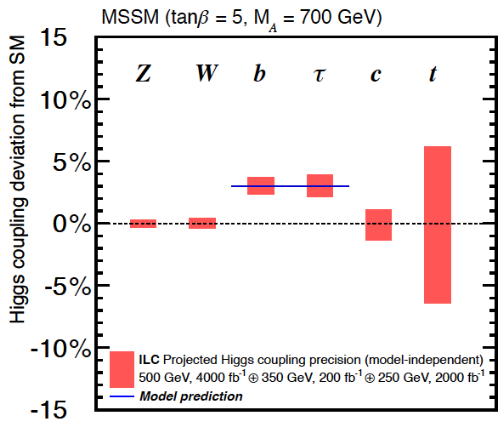
- Non-linear Nambu-Goldstone structure and composite resonances:

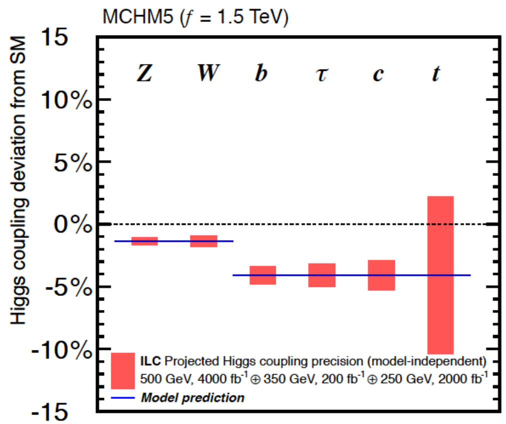
  ➔ peculiar pattern of distortions to the Higgs couplings:

$$\kappa_V \sim 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2,$$

$$\kappa_F \sim 1 - (3-9)\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2.$$

Need ≤1% measurements!





  ➔ deviations in a number of electroweak observables sensitive to the interactions between light SM fermions and gauge fields (e.g. Z pole observables, top EW couplings, etc).

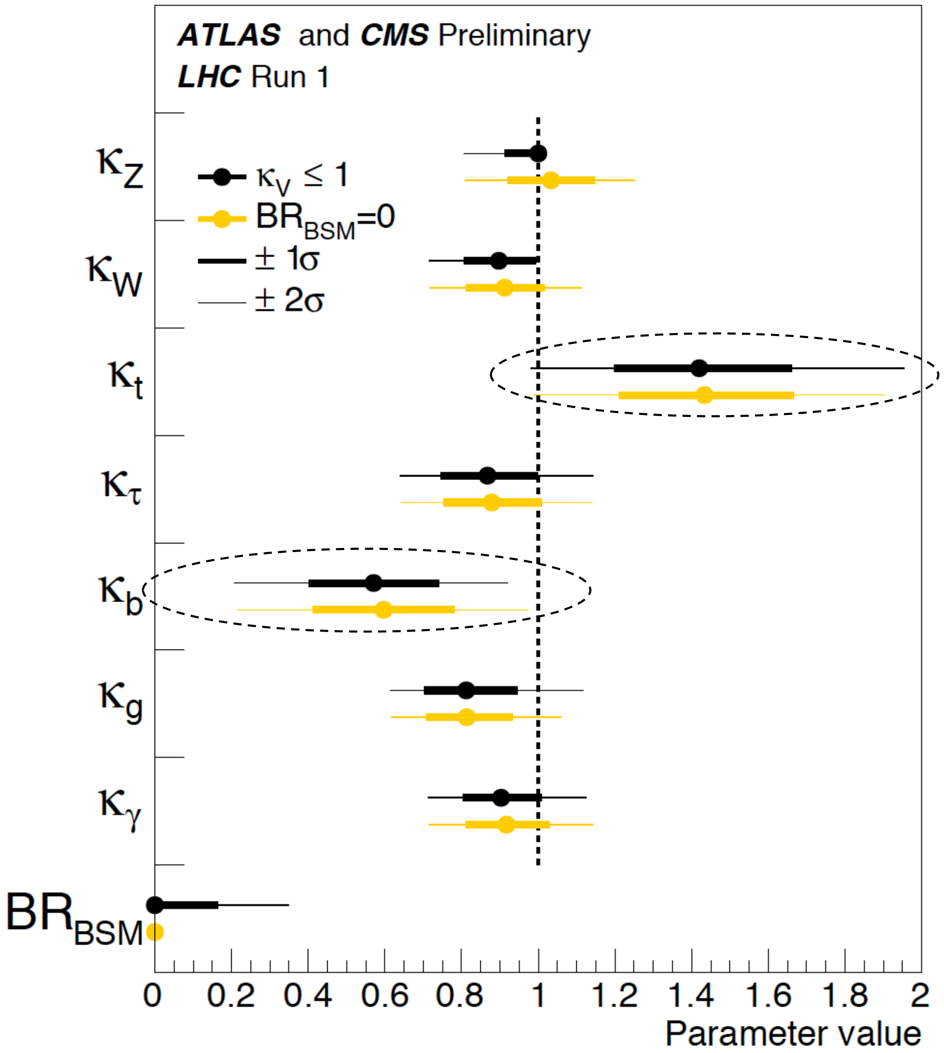
- Future e^+e^- colliders will allow to make a quantum leap in the precision in these observables. E.g. expected statistics in FCC-ee:

arXiv:1510.09056

$\sqrt{s}$ (GeV)	90	160	240	350	350+
$\mathscr{L}$(ab^{-1}/year)	86.0	15.2	3.5	1.0	1.0
Events/year	3.6×10^{12}	6.1×10^7	7.0×10^5	4.2×10^5	2.5×10^4
Event type	Z	WW	HZ	$t\bar{t}$	WW → H
Years	0.3 (2.5)	1	3	0.5	3

Higgs Couplings: LHC Run 1

ATLAS-CONF-2015-044



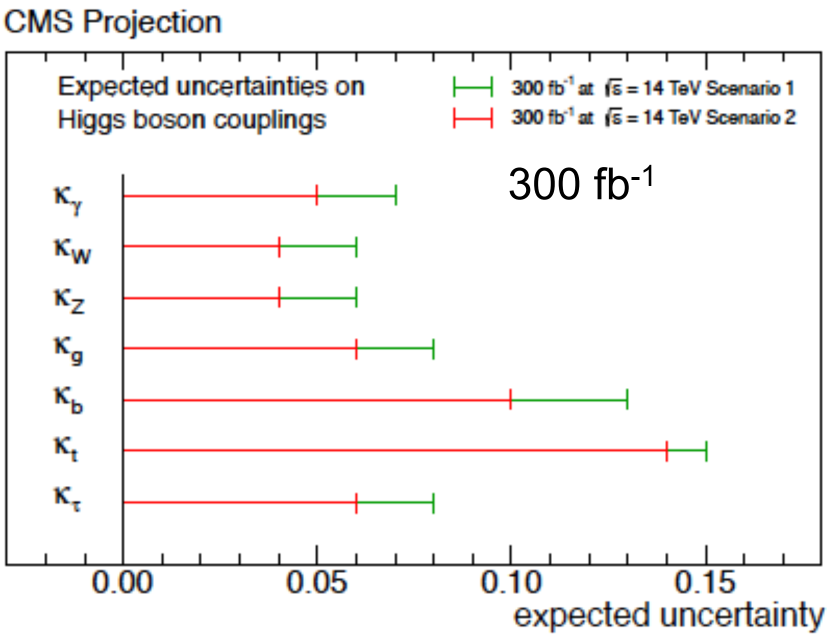
- Combination of Run 1 Higgs analyses by ATLAS and CMS.
- Express expected number of signal events in each channel in terms of scaling factors to Higgs couplings as given by effective Lagrangian (assuming narrow width and $J^{CP}=0^{++}$).
- So far consistent with SM although some small "tensions" present for couplings to 3rd generation quarks.
- Run 1 accuracy: ~10-20%.

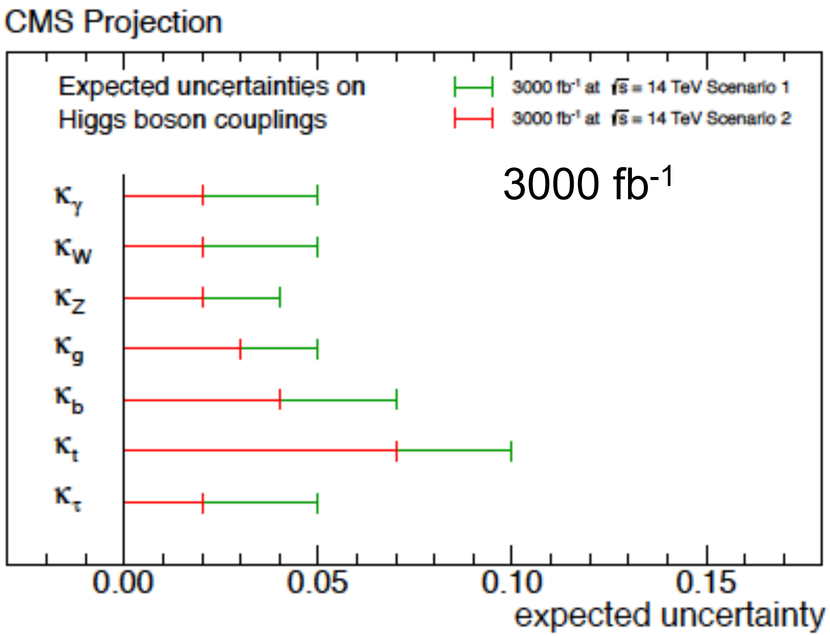
Higgs Couplings: LHC Prospects

arXiv:1307.7135

- Extrapolation of global fit to Higgs couplings based on CMS Higgs analyses existing at the time (*).

  (*) For ttH only considered H→γγ and H→bb searches. Will improve after including multileptons.
- Consider two scenarios:
  - Scenario 1: all systematic uncertainties are left unchanged.
  - Scenario 2: theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity.

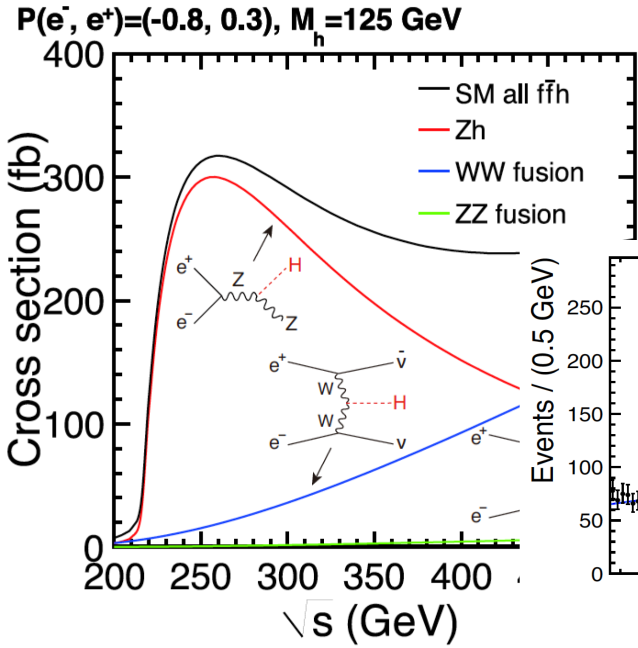




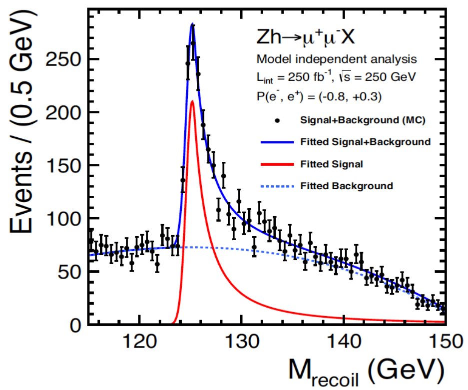
Higgs Couplings: Future e^+e^- Colliders

- Much lower Higgs boson production cross section than at hadron colliders.
- Ability to exploit recoil method to tag Higgs events independently of decay mode.
- Experimental and theoretical precision allows percent-level precision on most Higgs boson couplings.

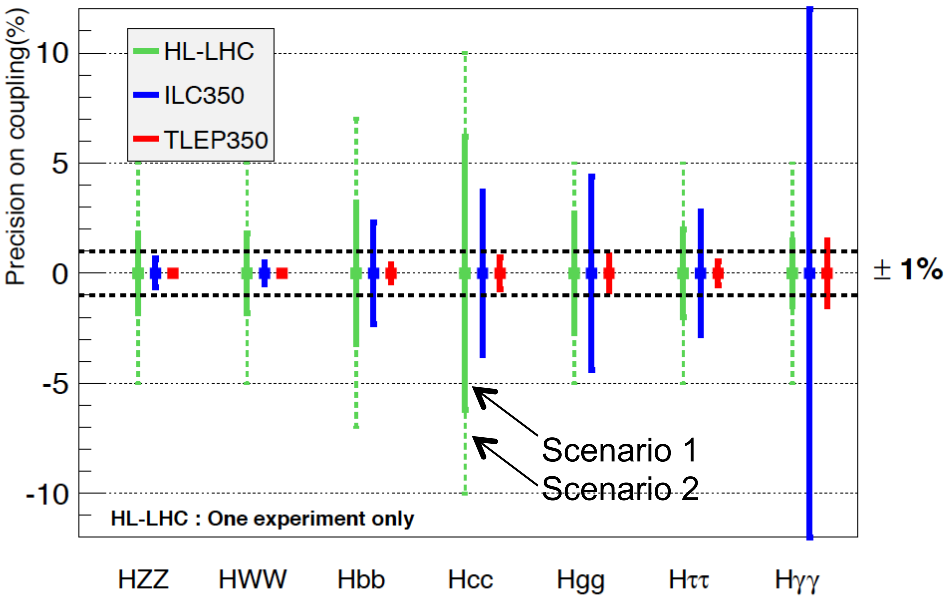
  ➔ Significant constraints on composite Higgs models!



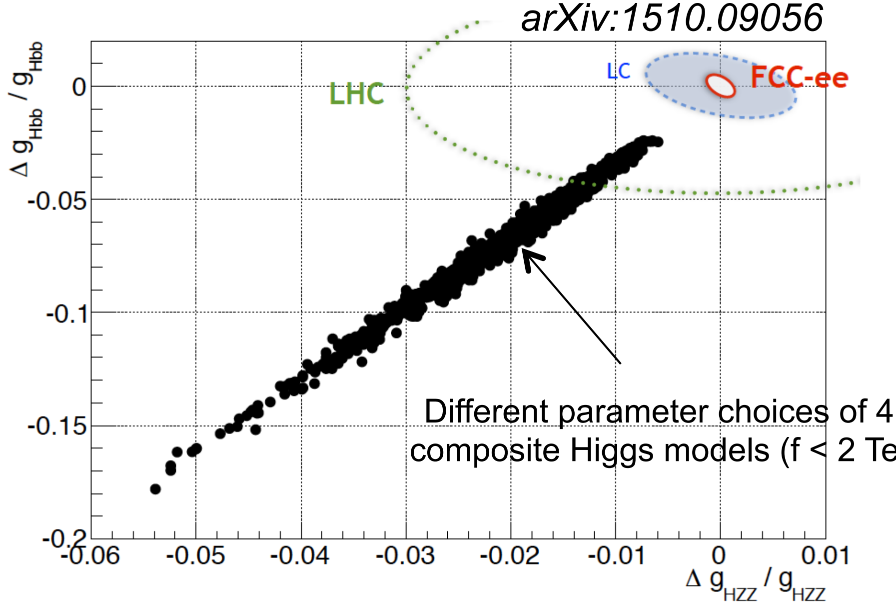
arXiv:1506.05992



arXiv:1308.6176



arXiv:1510.09056



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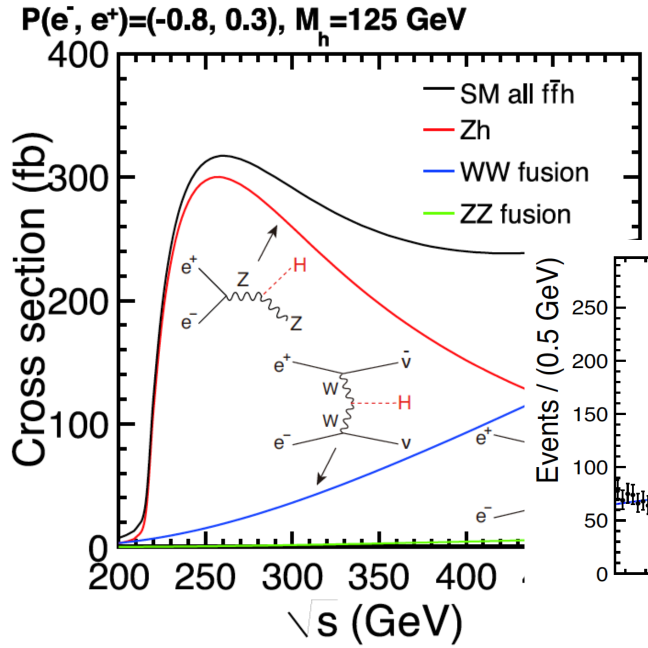

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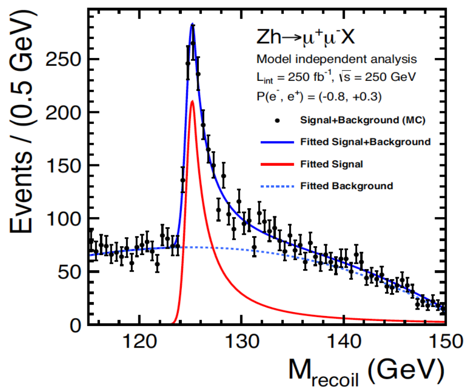

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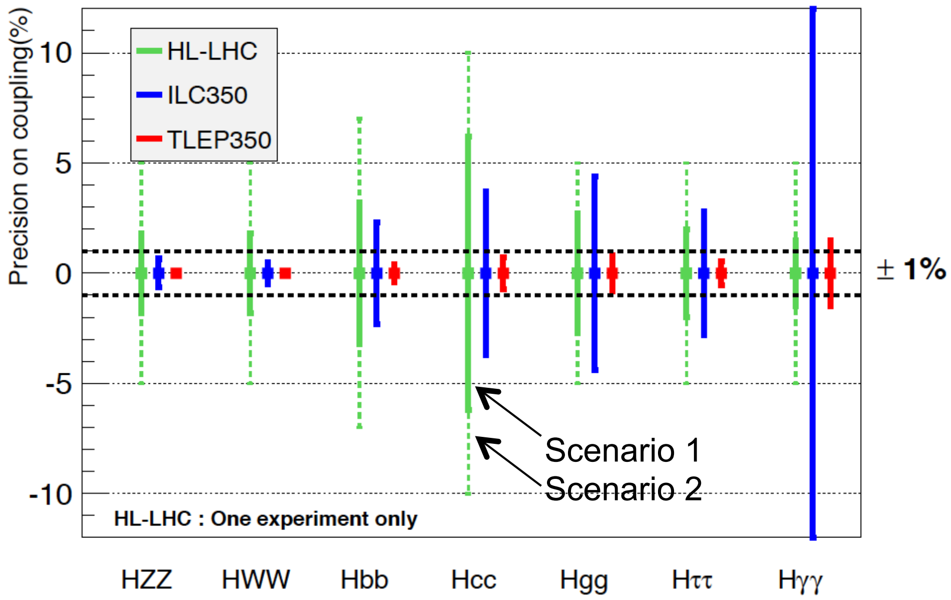


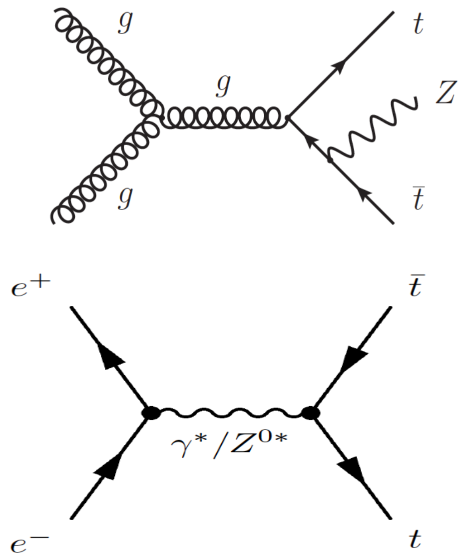
arXiv:1411.1054

Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

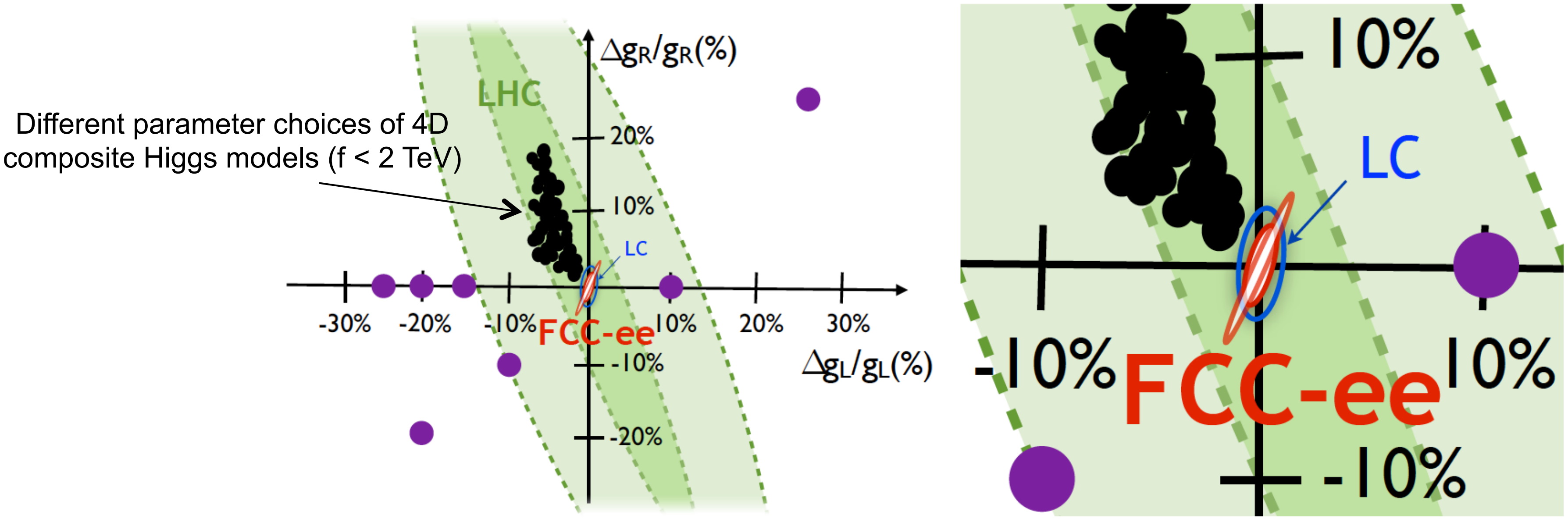
Precision Top Couplings

- New fermions and vector bosons arising in composite Higgs models affect a number of top observables:
  - Deviations on EW couplings of the top quark (via mixing).
  - Direct contributions from new vector bosons (e.g. $e^+e^- \rightarrow Z'^* \rightarrow t\bar{t}$).
- Observables:
  - LHC: $t\bar{t}Z$ differential cross sections
  - e^+e^-: $\sigma(t\bar{t})$, A_{FB}^t, lepton/b angular and energy distributions

➔ Significant constraints expected from top couplings measurements at e^+e^- colliders!



arXiv:1510.09056



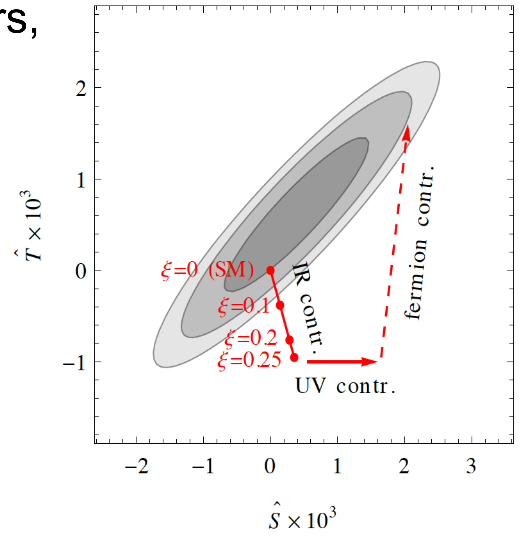
Precision EW Parameters

- Contributions to oblique EW parameters, S and T, that encode the corrections to the 2-point function of the EW bosons. Three sources:
  - Goldstone nature of the Higgs
  - EW vector resonances (mixing)
  - Fermionic resonances (loops)

  Observables:

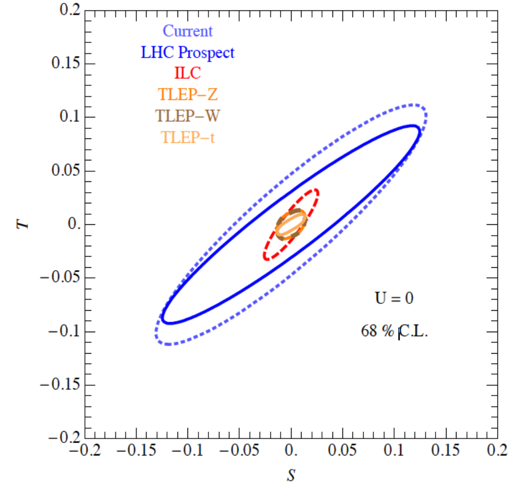
$$\Delta m_W, \Delta\Gamma_W \propto S - 1.54T$$
$$\Delta \sin^2\theta^\ell_{\rm eff}, \Delta R_\ell, \Delta\sigma^0_{\rm had} \propto S - 0.71T$$
$$\Delta\Gamma_Z \propto S - 2.76T.$$

arXiv:1306.4655



$$S = 4s_W^2\hat{S}/\alpha \approx 119\,\hat{S},\ T = \hat{T}/\alpha \approx 129\,\hat{T}$$

arXiv::1411.1054



arXiv::1411.1054

	Present data	TLEP-t
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [36]	$\pm 1.0 \times 10^{-4}$ [37]
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [38]	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	91.1875 ± 0.0021 [27]	$\pm 0.0001_{\rm exp}$ [2]
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [39] $\pm 0.5_{\rm th}$ [23]	$\pm 0.02_{\rm exp} \pm 0.1_{\rm th}$ [2, 23]
m_h [GeV]	125.14 ± 0.24 [23]	$< \pm 0.1$
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [36] $\pm 0.004_{\rm th}$ [24]	$(\pm 1.2_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [20, 40]
$\sin^2\theta^\ell_{\rm eff}$	$(23153 \pm 16) \times 10^{-5}$ [27]	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [20, 40]
Γ_Z [GeV]	2.4952 ± 0.0023 [27]	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [2, 26]

Impressive improvements in precision expected!

arXiv:1411.1054

Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

➔ Less stringent constraints than from Higgs couplings

Summary and Outlook

- Broad program of direct searches for top and Higgs compositeness at LHC Run 1.
  - No evidence for composite resonances found.
  - VLQs with mass below ~800 GeV excluded in typical MCHM scenarios.
  - Serves as a stepping stone for more incisive tests during Run 2.

- Great potential for discovery in Run 2:
  - First results exceeding Run 1 sensitivity by Winter 2016.
  - With 100 fb^{-1} should be able to probe VLQ masses up to 1.5 TeV via pair production and even beyond depending of the electroweak couplings.
  - Should also target bosonic resonances!

- Future colliders would provide critical information to unravel a new strongly-interacting sector:
  - e^+e^- colliders: indirectly via precise coupling measurements (top, Higgs) and other EW parameters.
  - 100 TeV pp collider: directly probing most a large fraction of the spectrum of composite resonances (fermionic and bosonic).

Backup

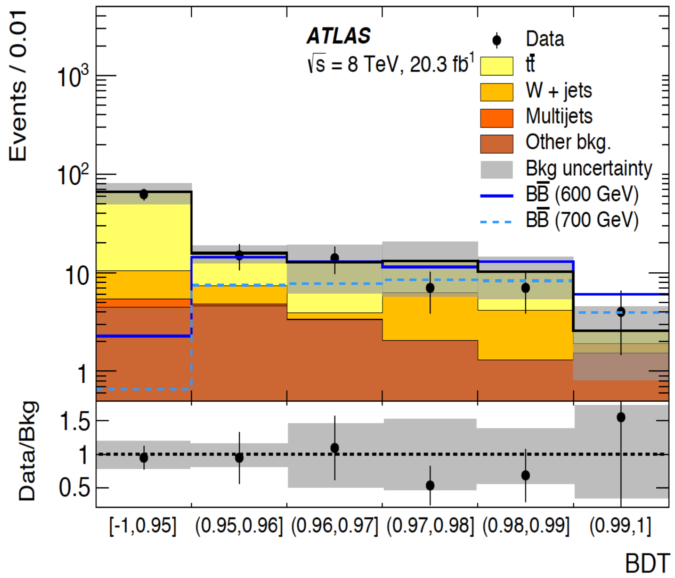
Vector-Like Bottom: 1-lepton Searches

- Searches targeting high BR($B_{-1/3}$→$W^{-}t$), but also sensitive to other decay modes.
- Basic strategy:

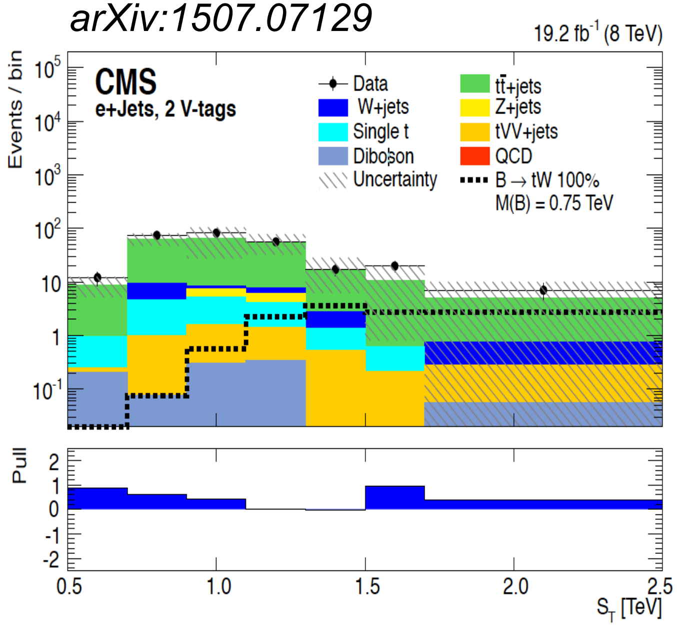
ATLAS
- Preselection: 1 lepton, ≥6 jets w/ p_T>25 GeV ≥1 b-tags, H_T>500 GeV
- ≥1 hadronic W/Z candidate
  - Dijet pair with ΔR_{jj}<1.0, $p_{T,jj}$>200 GeV, 60<m_{jj}<110 GeV
- Uses BDT as final discriminant variable.

CMS
- Preselection: 1 lepton, ≥4 jets w/ p_T>200,60,40,30 GeV, ≥1 b-tags
- Categorize events in 0, 1, ≥2 tagged W/Z candidates
  - CA R=0.8 jets, p_T>200 GeV, pruned/mass drop, 50<m_j<150 GeV
- Uses S_T as final discriminant variable.

arXiv:1503.05425



arXiv:1507.07129



95% CL obs (exp) limits [100% WtWt]:

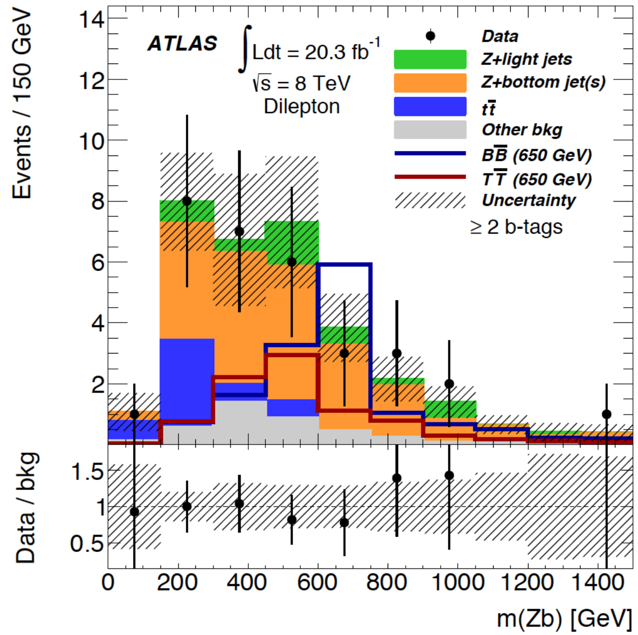
ATLAS: m_B>**810** (760) GeV

CMS: m_B>(~800) GeV

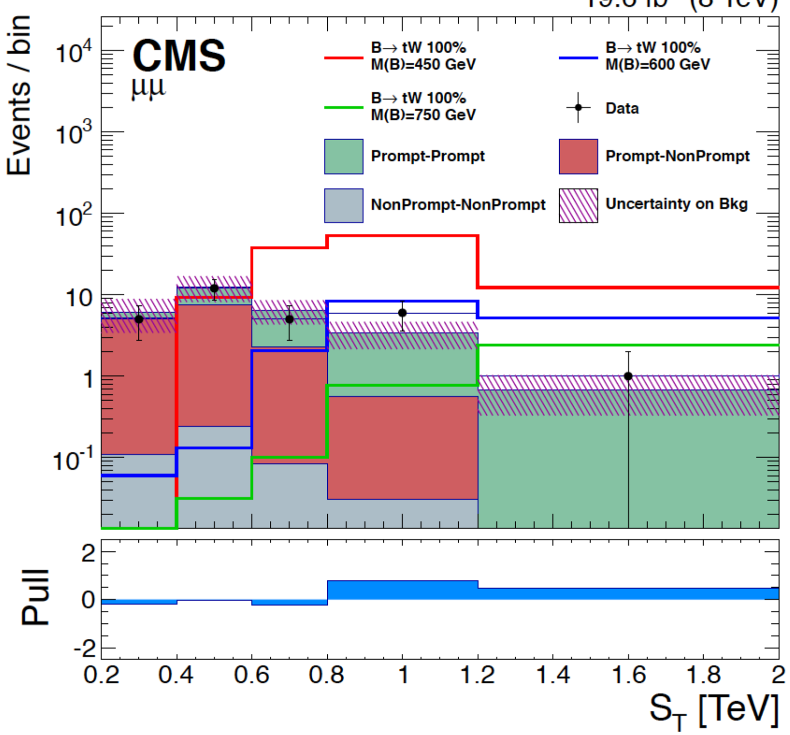
Vector-Like Bottom: Multilepton Searches

- ATLAS: same multilepton searches used for vector-like top interpreted in the context of vector-like bottom (sometimes even better optimized for the latter, e.g. Zb+X).
- CMS: several analysis channels
  - SS 2l, ≥4 jets, E_T^{miss}>30 GeV; uses S_T
  - OS 2l, Z candidate, ≥1 b-jet, $p_{T,Z}$>150 GeV; uses M(Zb)
  - Multileptons: ≥3 leptons (incl τ), several categories depending on number of leptons and flavor; uses S_T

arXiv:1409.5500



arXiv:1507.07129



95% CL obs (exp) limits:

ATLAS:

BR(B→Wt)=1: m_B>**730** (790) GeV [Multilepton]

BR(B→Zb)=1: m_B>**790** (800) GeV [Zb+X]

CMS multilepton combination:

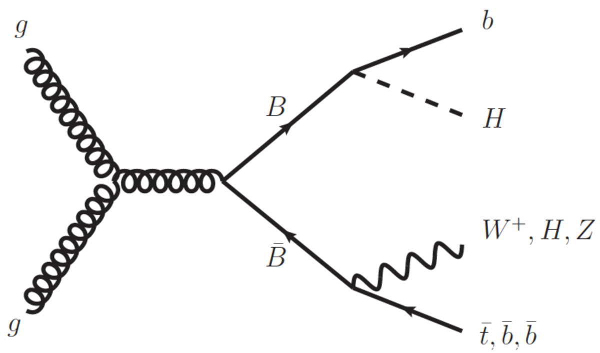
BR(B→Wt)=1: m_B>(~800) GeV

BR(B→Zb)=1: m_B>(740) GeV

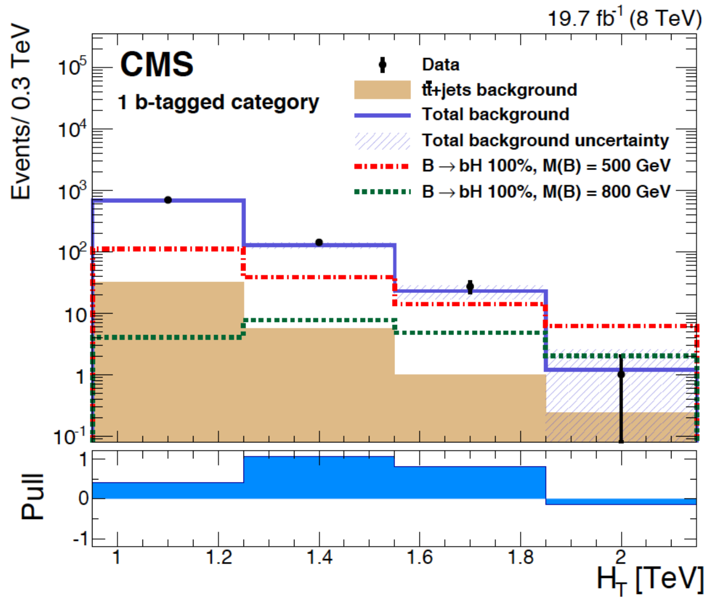
Vector-Like Bottom: All-Hadronic Searches

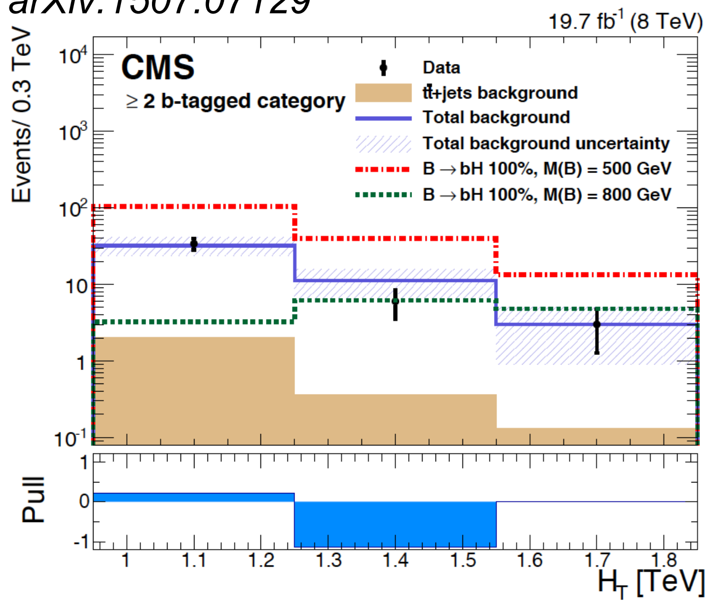
BB→Hb+X, H→bb

- Search targeting high BR(B→Hb), with H→bb.
- Strategy:
  - ≥1 Higgs-tagged jet
    - CA R=0.8, p_T>300 GeV, pruned, 90<m_j<140 GeV
    - 2-prong-like (τ_2/τ_1<0.5), 2 b-tagged subjets
  - H_T>950 GeV (from AKT5 jets with p_T>50 GeV)
  - ≥1 additional b-tagged AKT5 jet
  - Events categorized into =1 and ≥2 additional b-tagged jets
  - Uses H_T as final discriminant



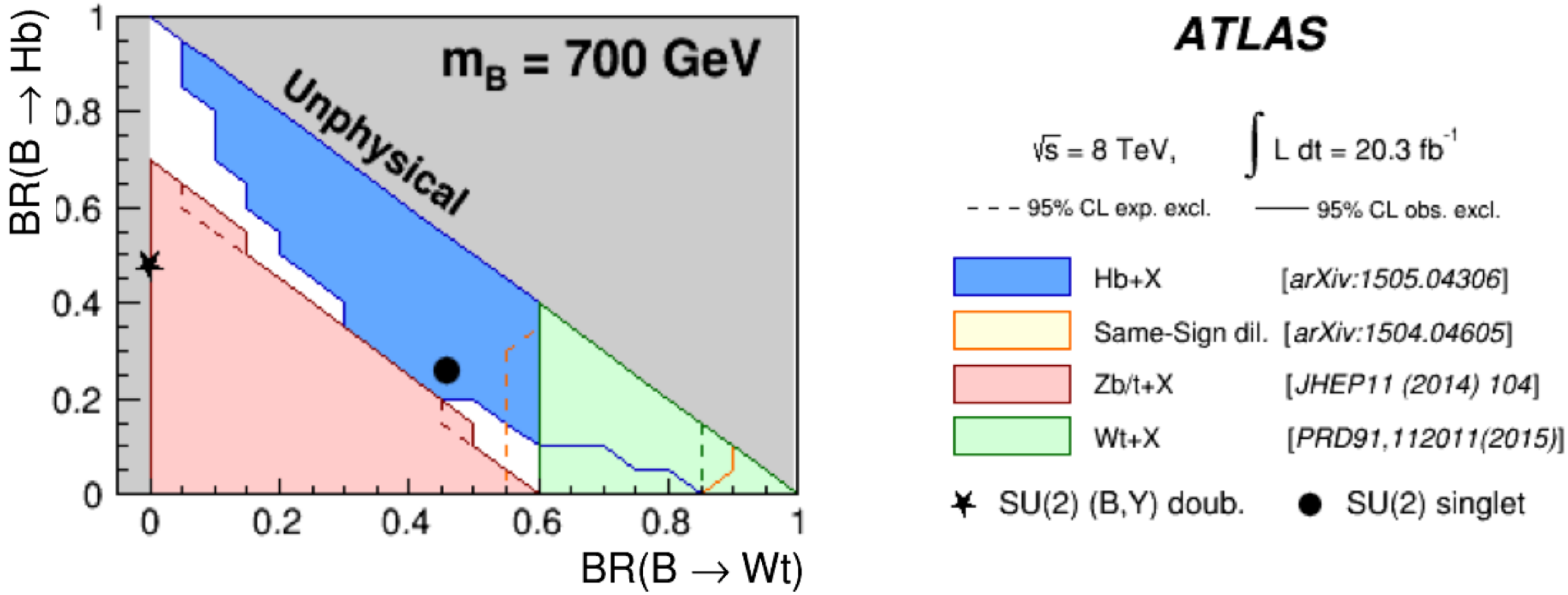
arXiv:1507.07129





95% CL obs (exp) limits [100% HbHb]:
m_B>**900** (810) GeV

Vector-Like Bottom: Complementarity



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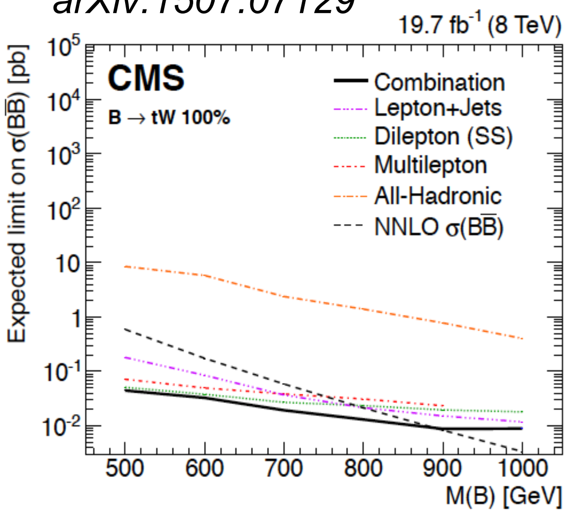
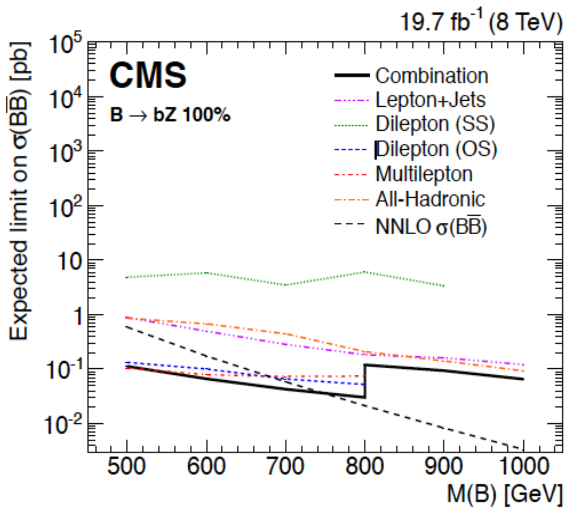
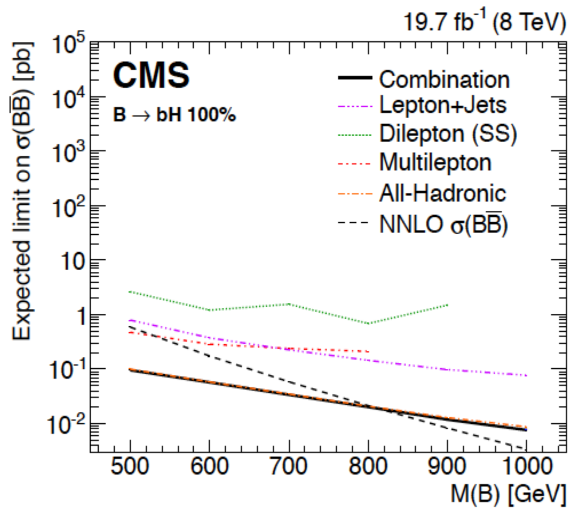






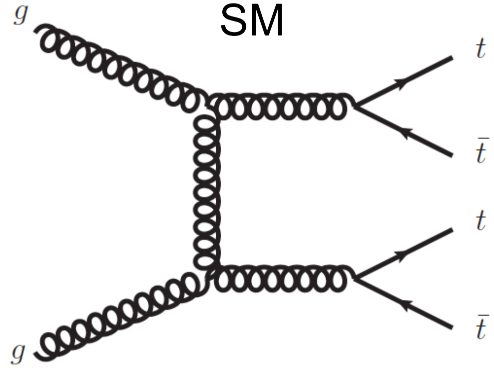
Four-Top-Quark Production

- Production cross section for 4-top within the SM very small (~1 fb).
- (Partially) composite top quark strongly coupled to composite sector. Most economical solution is to have composite t_R:

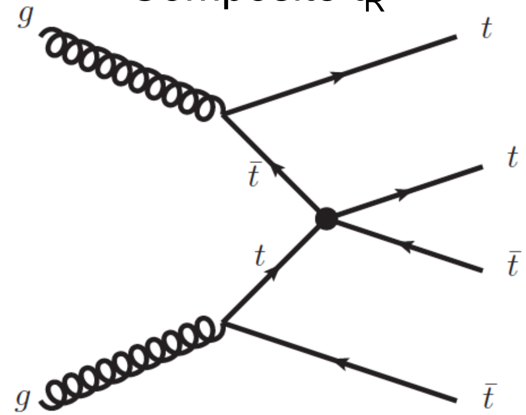
  ➔ anomalous four-top-quark production that can be orders of magnitude larger than the SM prediction.

- Other BSM scenarios that can lead to enhanced 4-top production:
  - Sgluon pair production
  - Universal extra-dimensions
  - etc

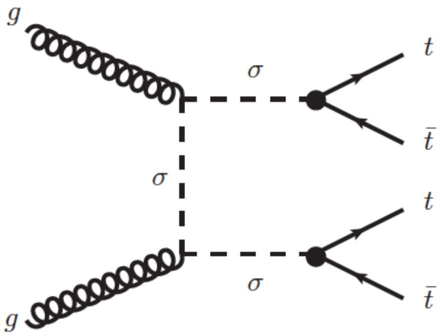
SM

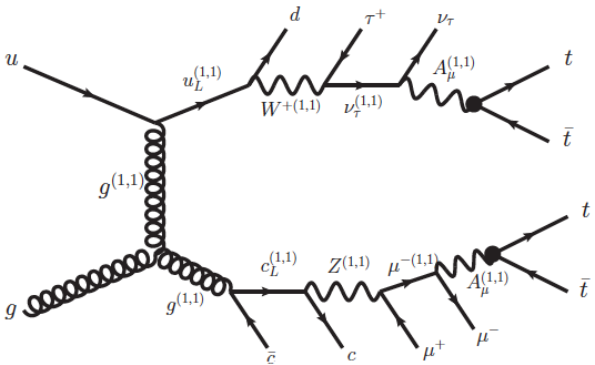


Composite t_R



$$\mathcal{L}_{4t} = \frac{|C_{4t}|}{\Lambda^2}(\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$$





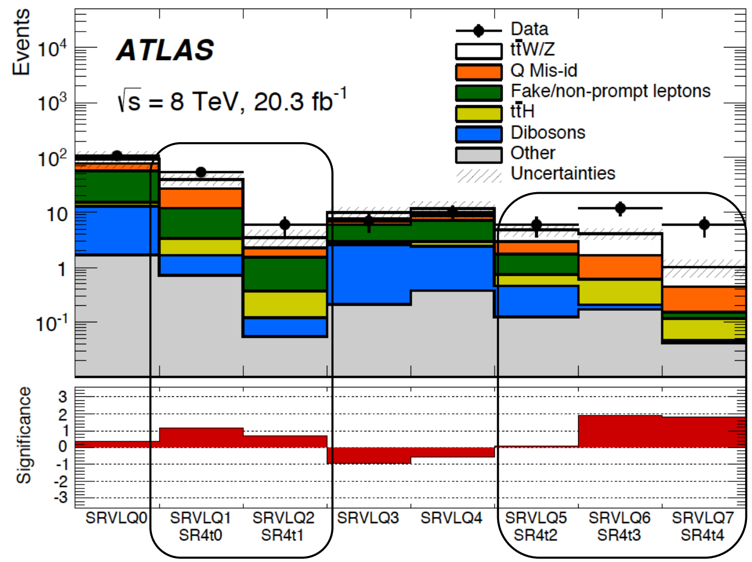
Four-Top-Quark Production: Searches

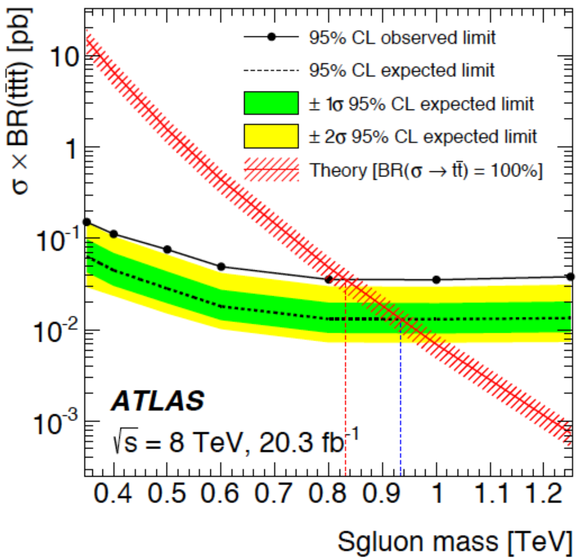
- VLQ searches for SS dileptons/trileptons and TT→Ht+X reinterpreted in the context of SM and BSM 4-top production.

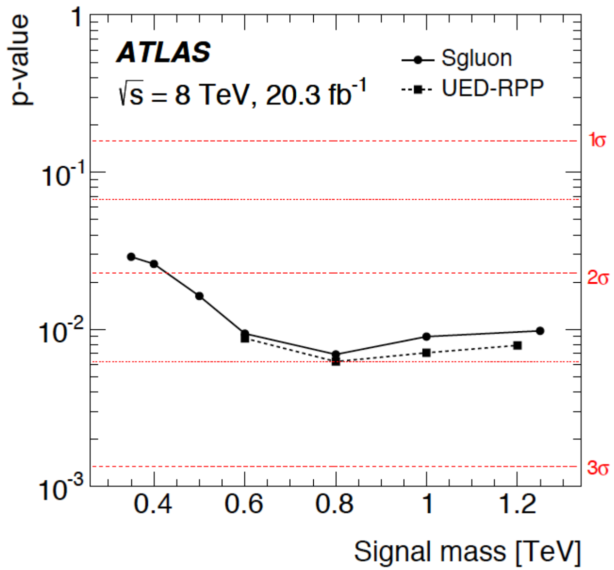
arXiv:1409.5500

ATLAS SS dilepton/trileptons:

- Most search channels in common with VLQ search ➔ **excess**
- 95% CL obs (exp) limits:
  SM 4-top: $\sigma_{SM\text{-}4t}$<**70** (27) fb
  EFT 4-top: $\sigma_{EFT\text{-}4t}$<**61** (22) fb
  Sgluon: m_σ>**0.83** (0.94) TeV







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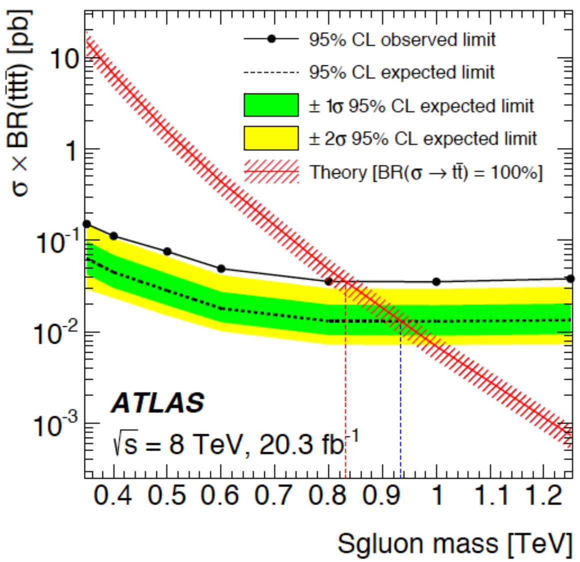

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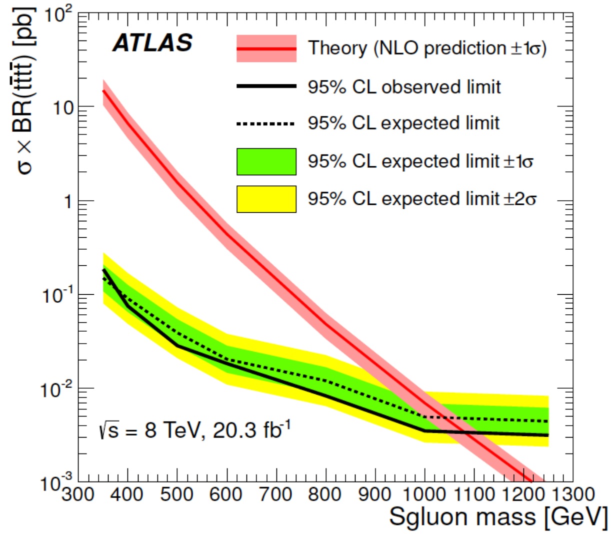
ATLAS TT→Ht+X (lepton+jets):

- Comparable or better sensitivity to same BSM scenarios.
- 95% CL obs (exp) limits:
  SM 4-top: $\sigma_{SM\text{-}4t}$<**23** (32) fb
  EFT 4-top: $\sigma_{EFT\text{-}4t}$<**12** (16) fb
  Sgluon: m_σ>**1.06** (1.02) GeV



- **Rules out 4-top interpretation for multilepton search.**