The Search for Heavy Top Partners

Rencontres des Blois 2015

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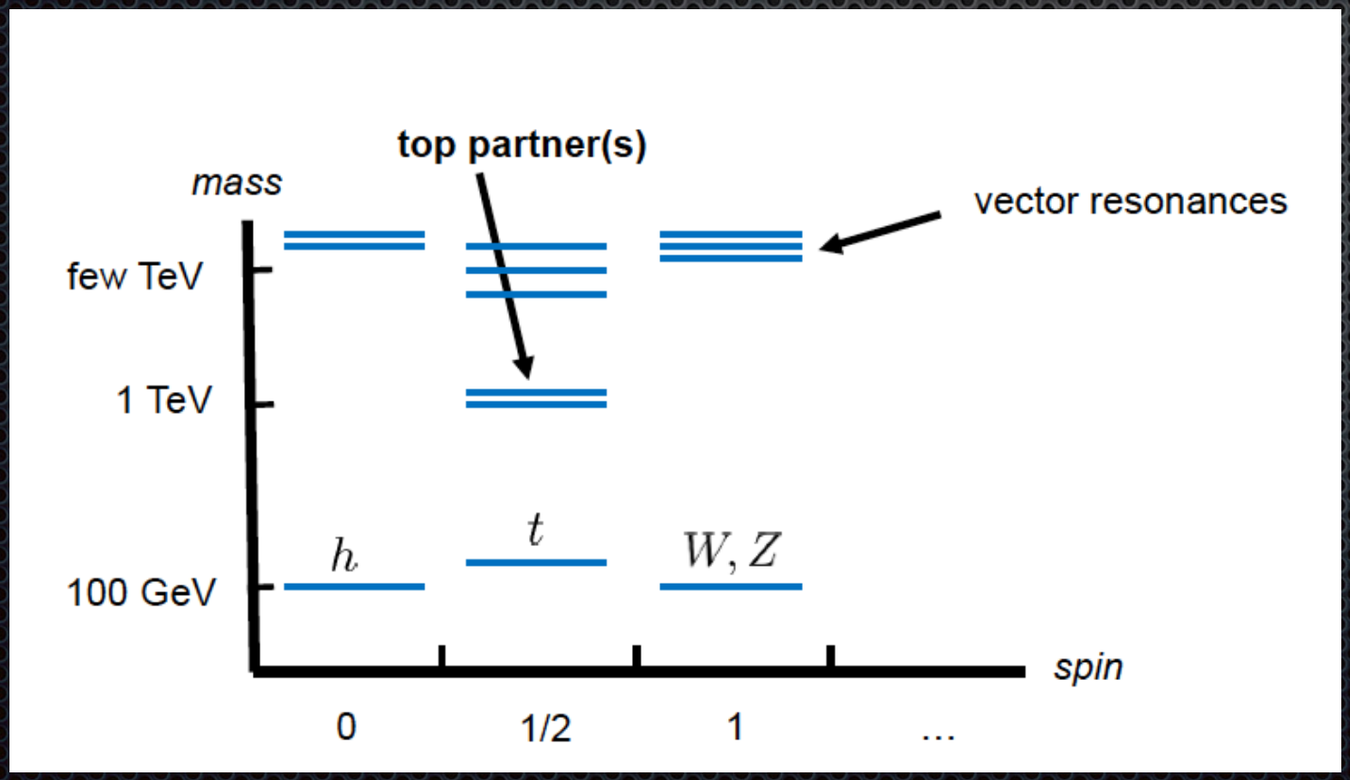
discussing results from CMS and ATLAS

Why Top Partners?

- **Top quark is a window on the microscopic origin of the EWSB: large y_T**
- Top Partners are colored fermions with vector-like properties, associated to the top quark:
  - Control the level of fine-tuning (analog to the scalar top partners in SUSY) in NP scenarios where Top-Higgs interactions (Yukawas) are generated by Partial Compositeness
    - Present also in several other SM extensions (Little Higgs, 2HDM, Extra Dimensions…)

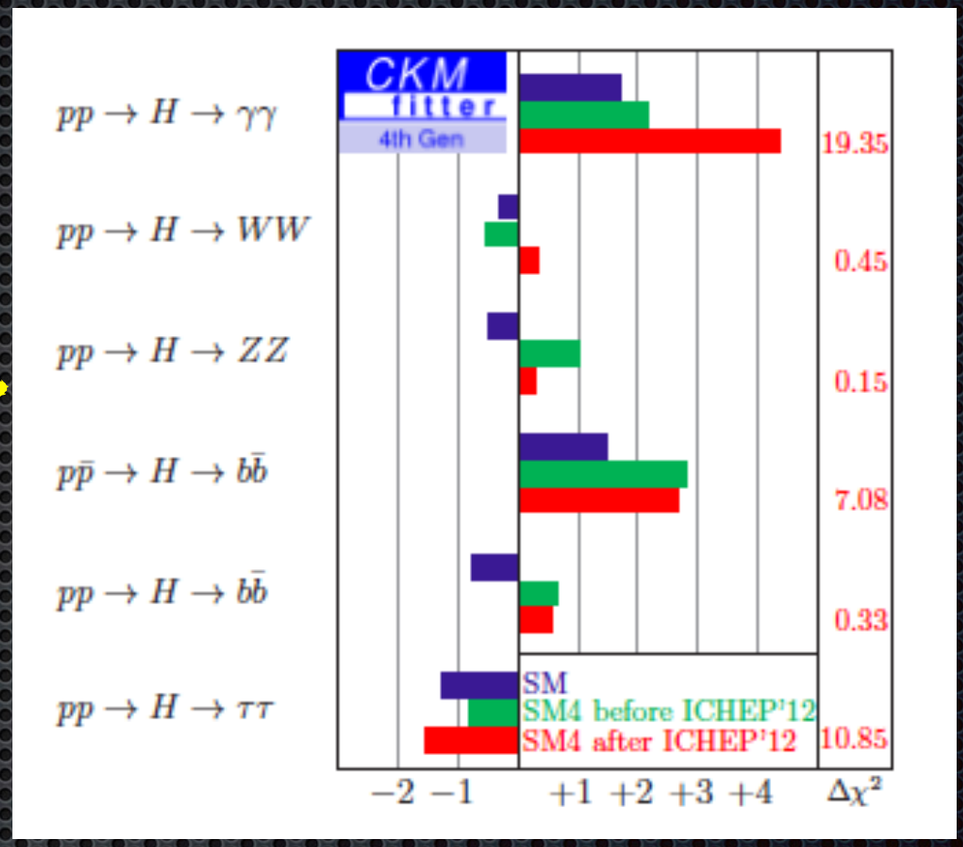


— Light (<2TeV) Top Partners are present in any « reasonably Natural » model, i.e. less than one order of magnitude cancellation

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

VLQ phenomenology

- Not a simple chiral 4th generation
  - Excluded at >5σ by Higgs properties measurements (arXiv:1209.1101)
- Do not get mass via Yukawa coupling
  - no (large) effect on Higgs measurements and EW variables
- In all models Vector Like Quarks come in SM multiplets



- Couplings to **light quarks** are possible but heavily constrained by flavor physics arguments

- **Experimental focus on 3rd generation couplings**

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

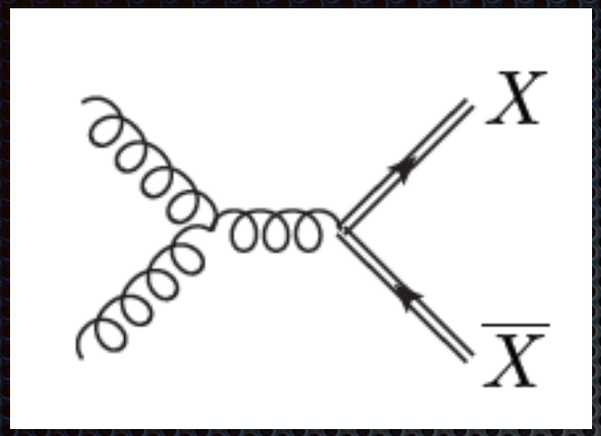
Notation:

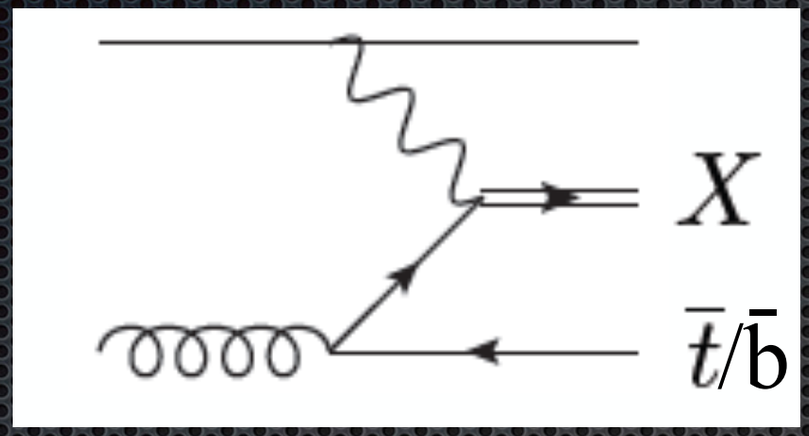
$\text{Isospin}_{\text{Hypercharge}}$

$T \to +2/3$
$B \to -1/3$
$X \to +5/3$
$Y \to -4/3$

} Electric charge

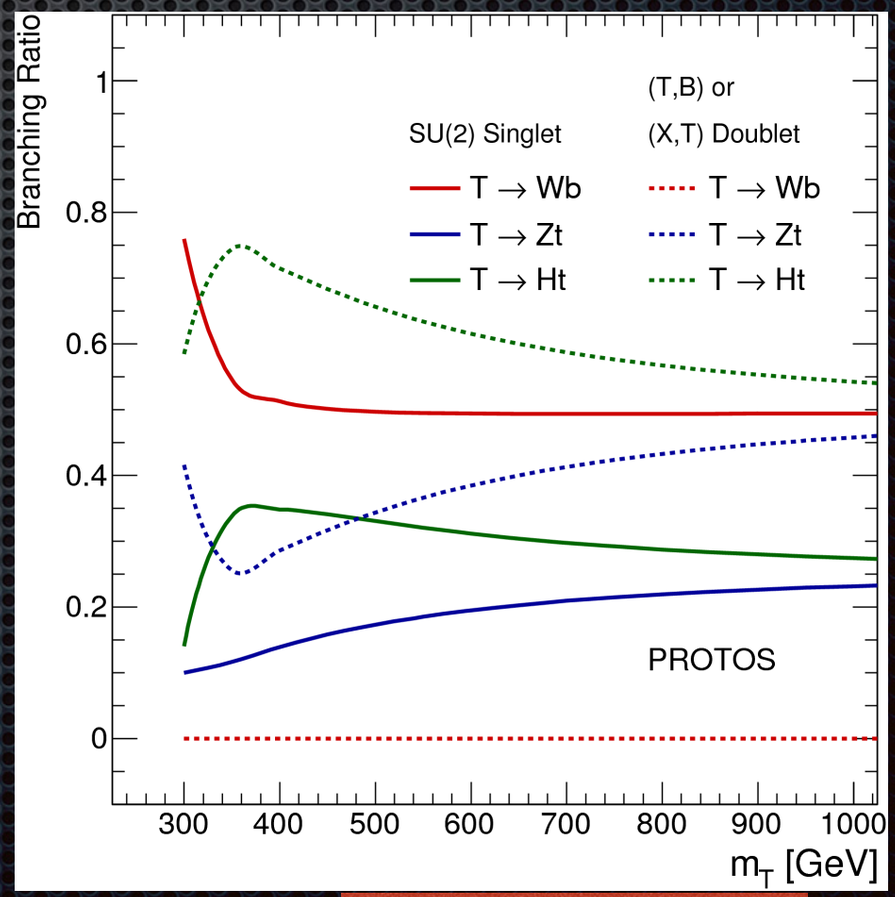
Production modes at LHC





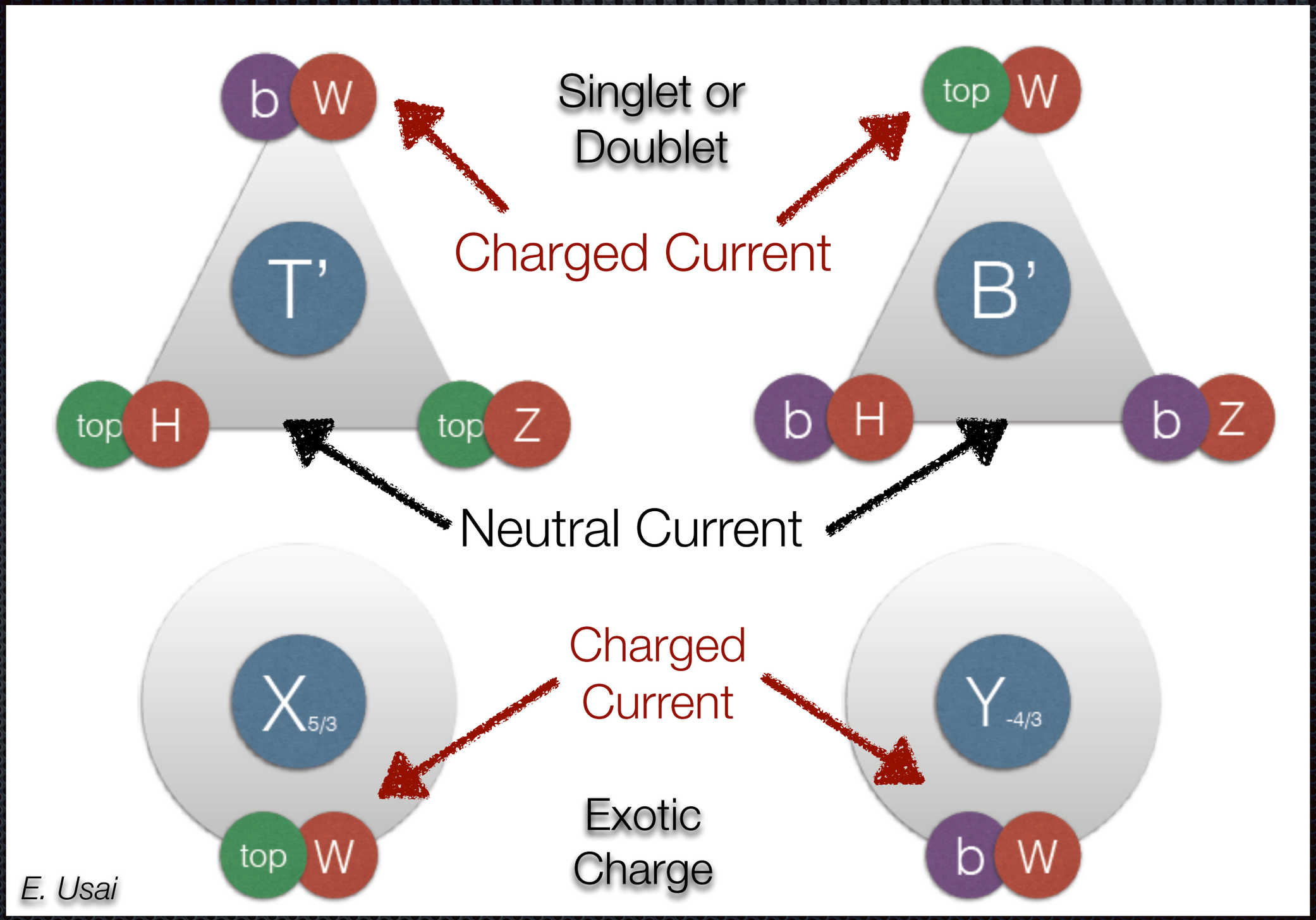
Contino, Kramer, Son, Sundrum2006
Contino, Servant2008
Mrazek, Wulzer 2009
DeSimone, Matsedonskyi, Rattazzi,Wulzer2012

- In Run1 pair production has been the default production process considered as it dominates at lower masses:
  - Pair production cross section only driven by QCD (model-independent)
  - Single production becomes significant in Run2 (model-dependent)
- Decay branching ratios instead are dependent on multiplet type and mass.



arXiv:0907.3155

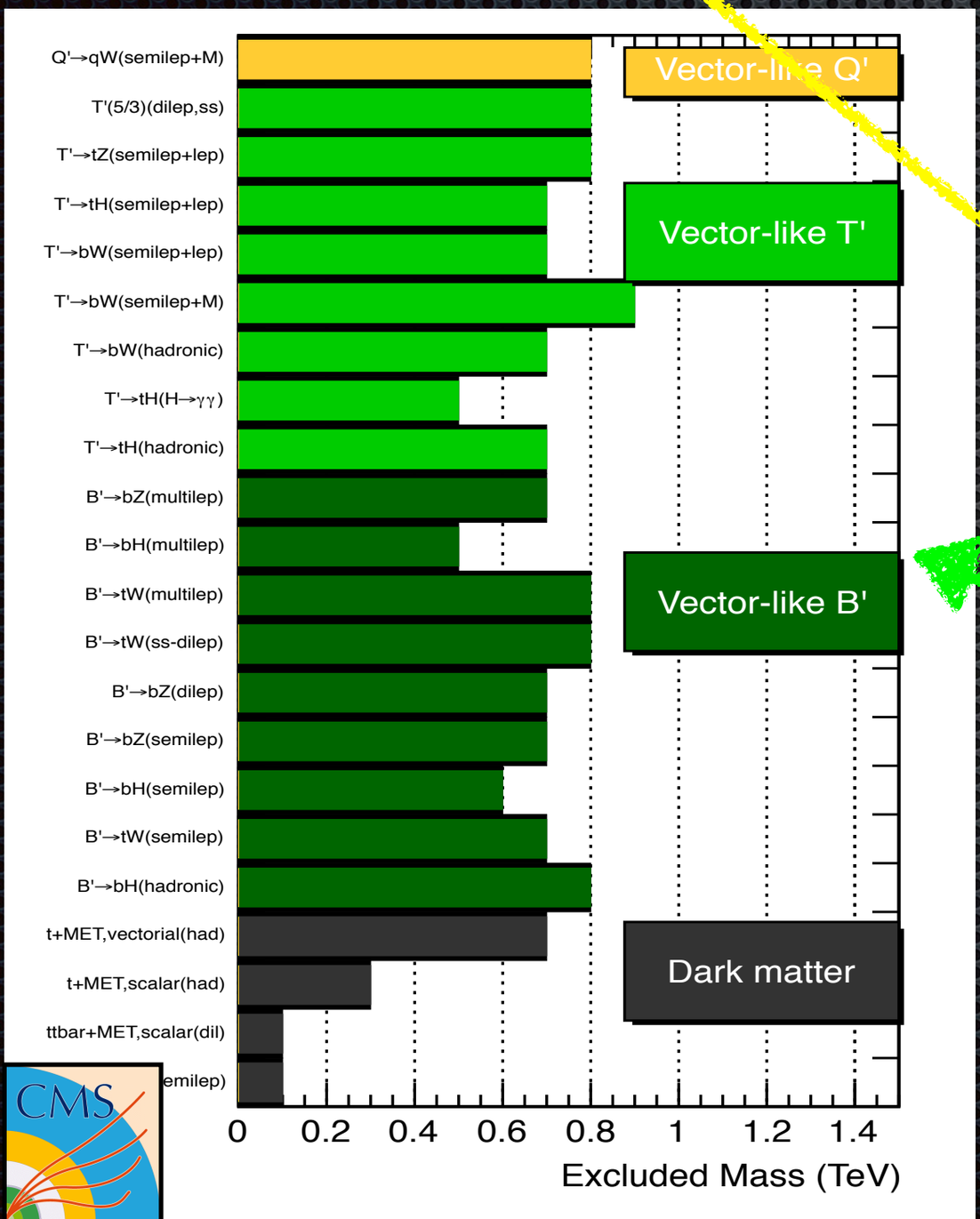
Decay modes at a glance (for 3rd generation only)



The Run1 result in a page

Heavy quarks	VLQ $TT \to Ht + X, Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3
	VLQ $TT \to Zt + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3

T mass	785 GeV
T mass	735 GeV
B mass	755 GeV
B mass	640 GeV
$T_{5/3}$ mass	840 GeV

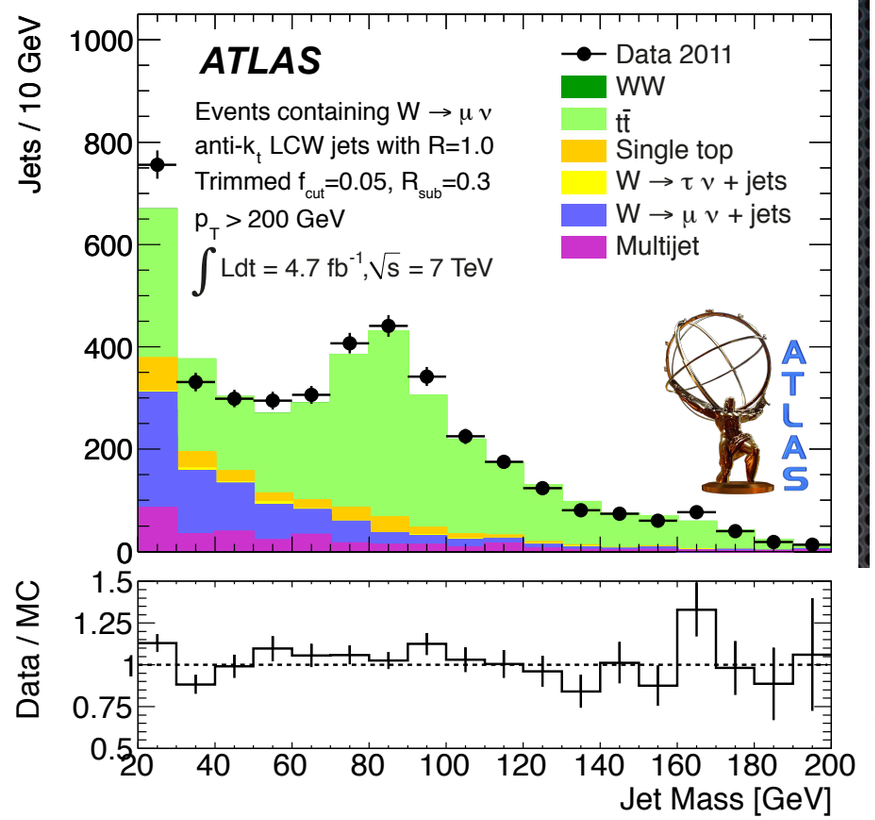


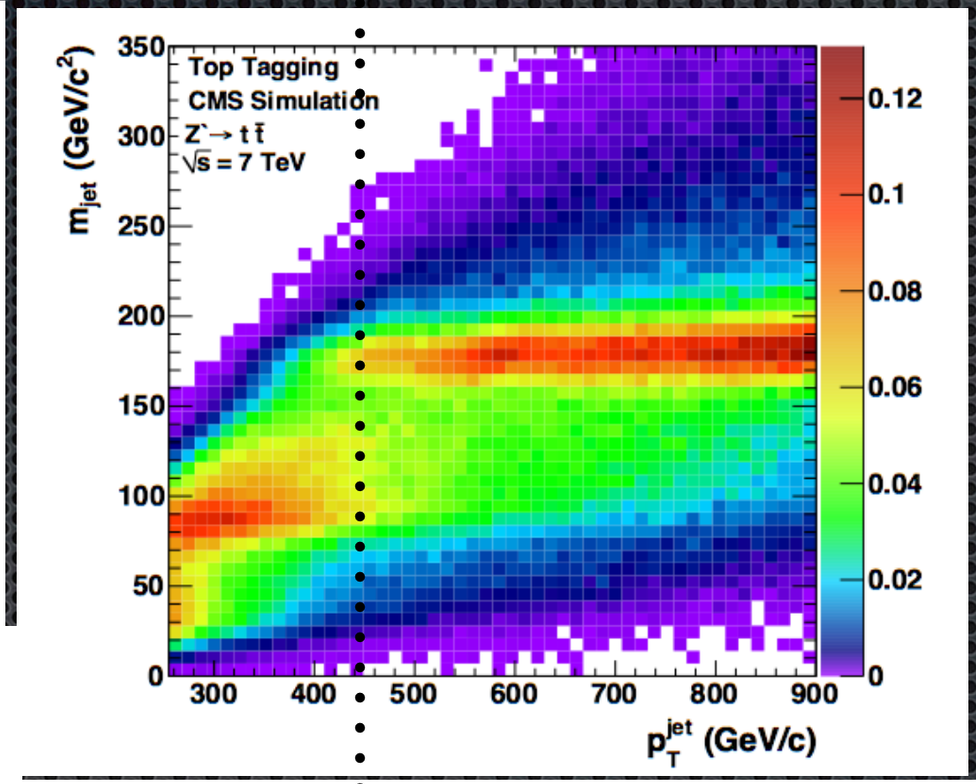
- Same signals (different MC generator):
- different approach in the searches
  - ATLAS more inclusive and signature based, unique analyses to target single production process
  - CMS more optimized for specific processes, tested advanced techniques for boosted reconstruction early on
- *different presentation of the results*
- **overall reach very similar**

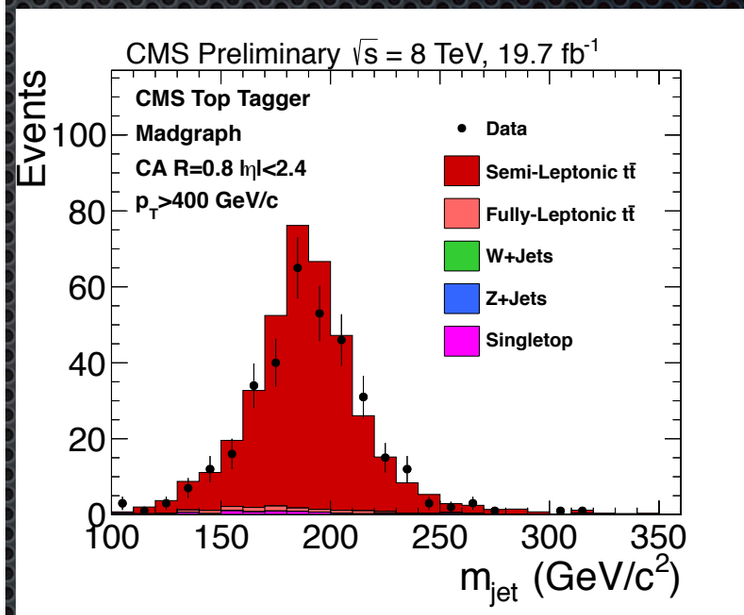
New kinematic regime: boosted top and W/Z/H bosons reconstruction

JME-13-007, JME-14-002

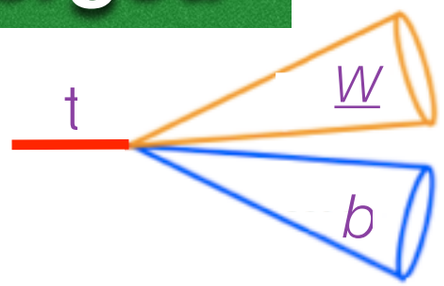
ATLAS : JHEP 1309 (2013) 076



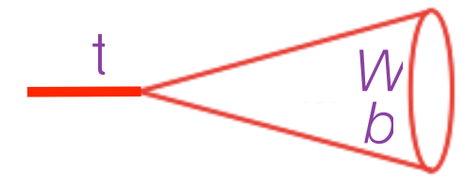


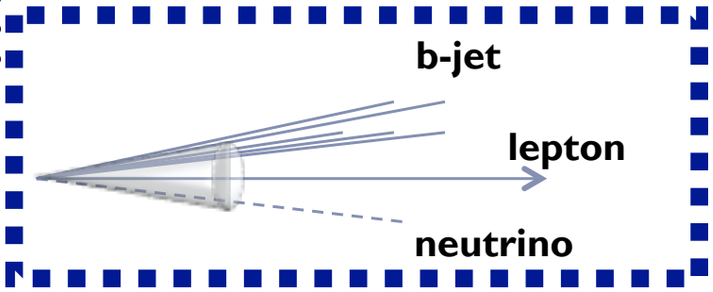


partially merged

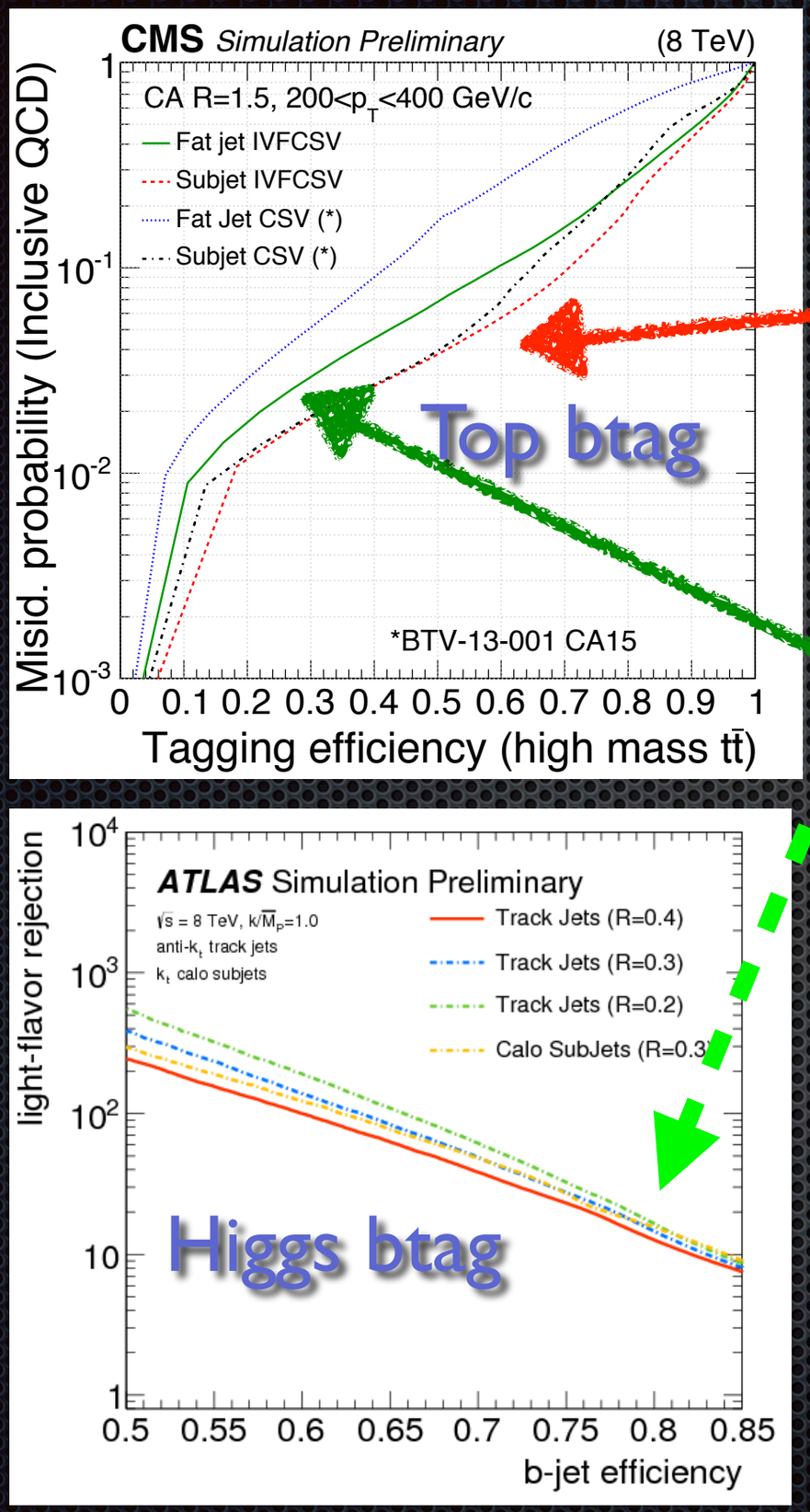


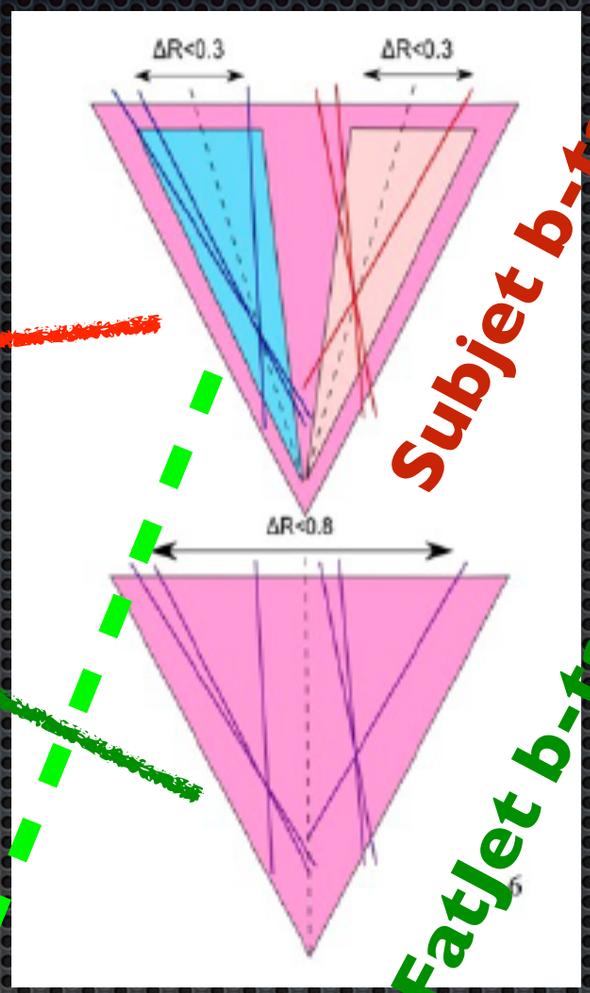
fully merged



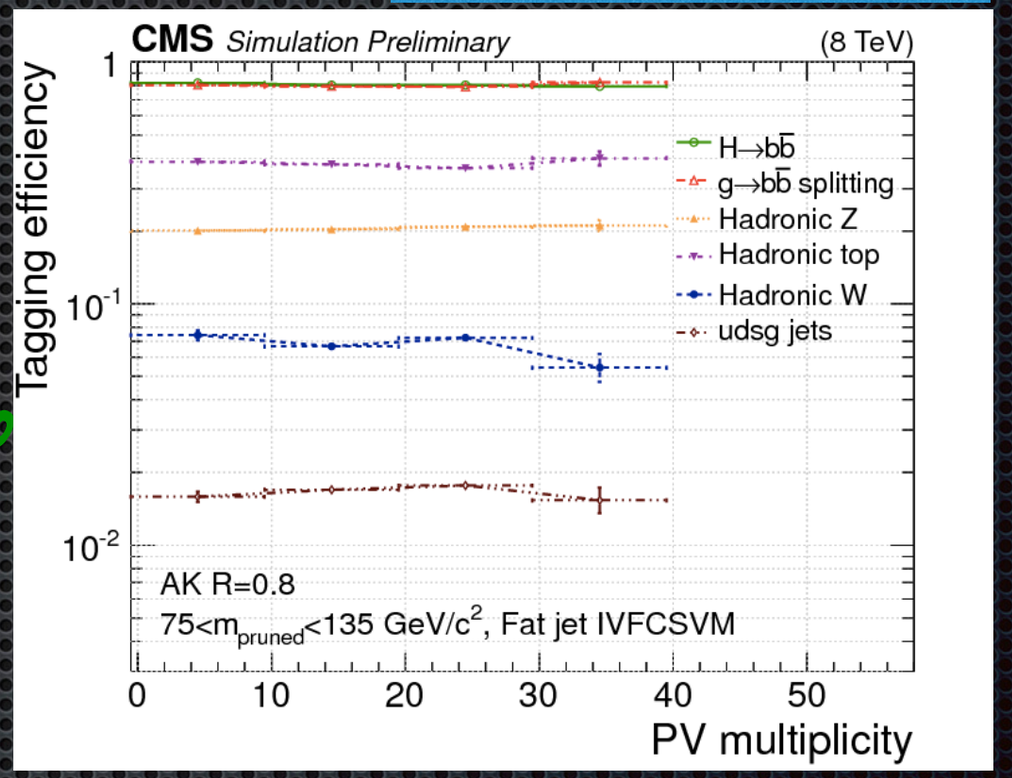


New techniques: b-tagging boosted objects





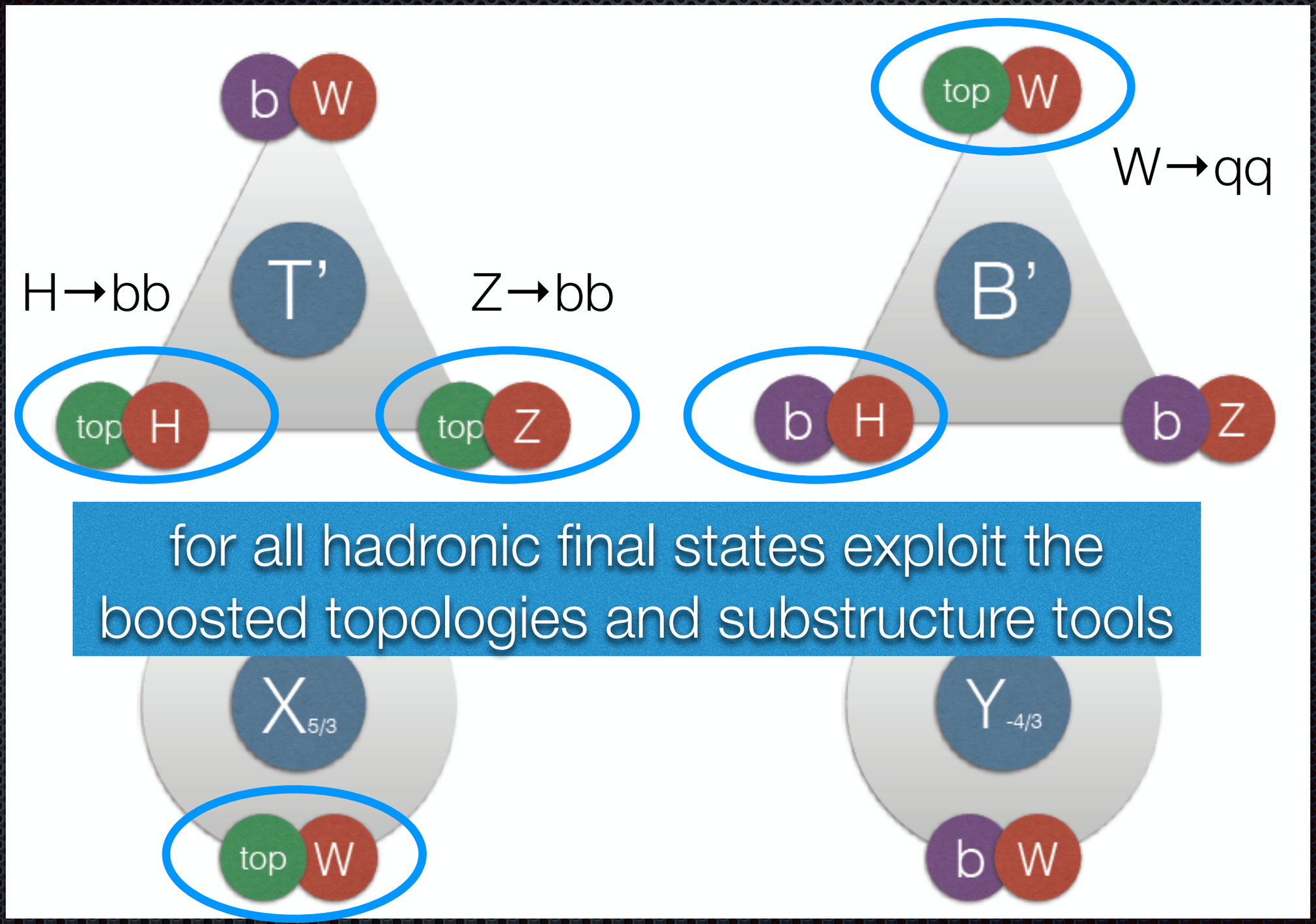
Stable with PU



- SubJet b-tagging performs better than FatJet
- 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
ATL-PHYS-PUB-2014-013

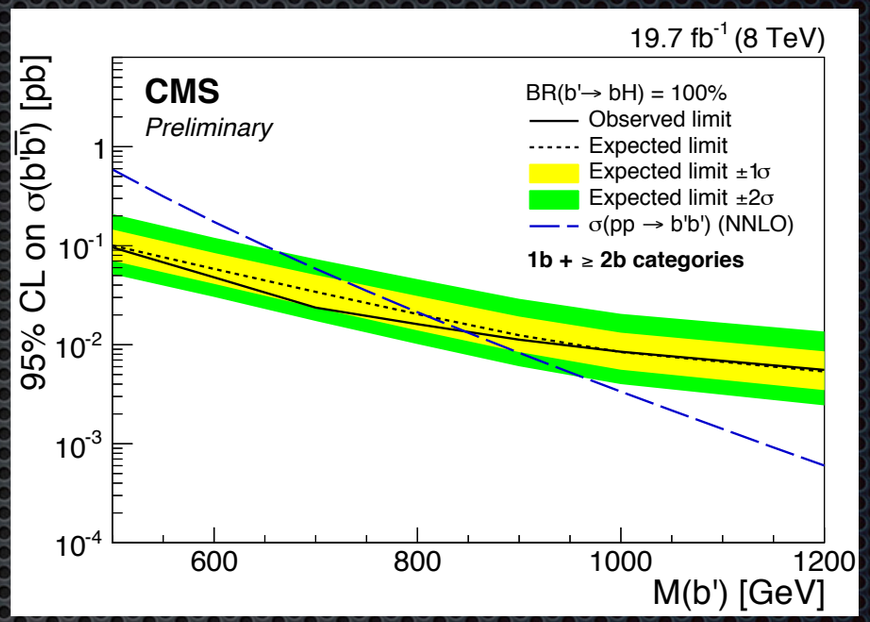
Final states: all hadronic

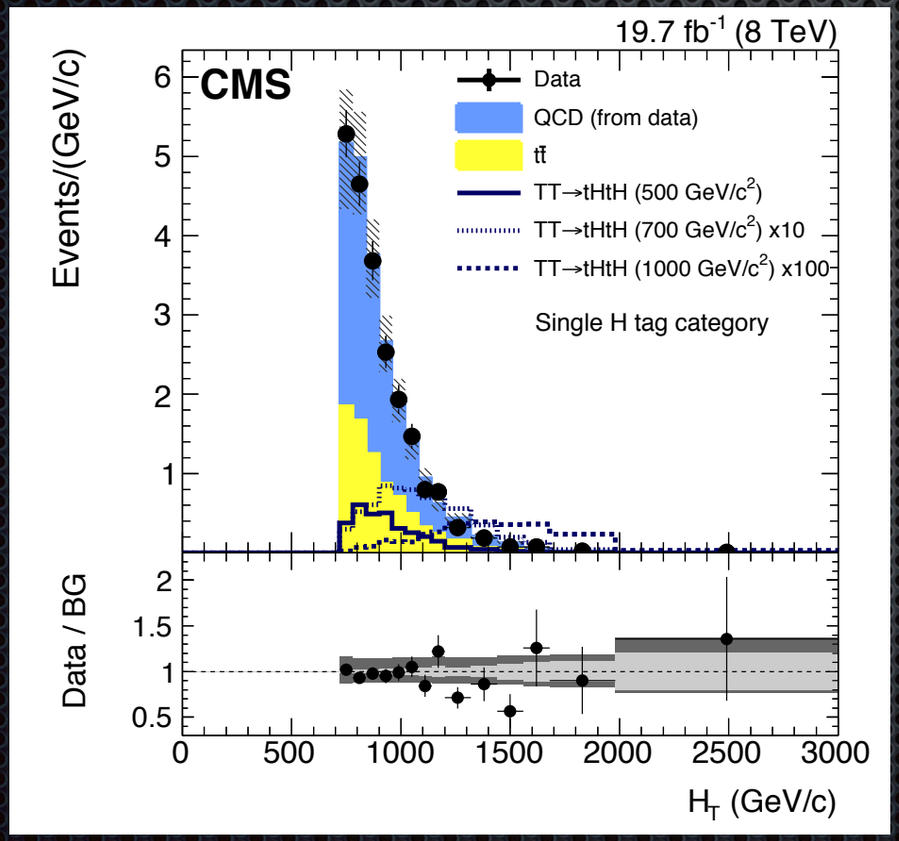


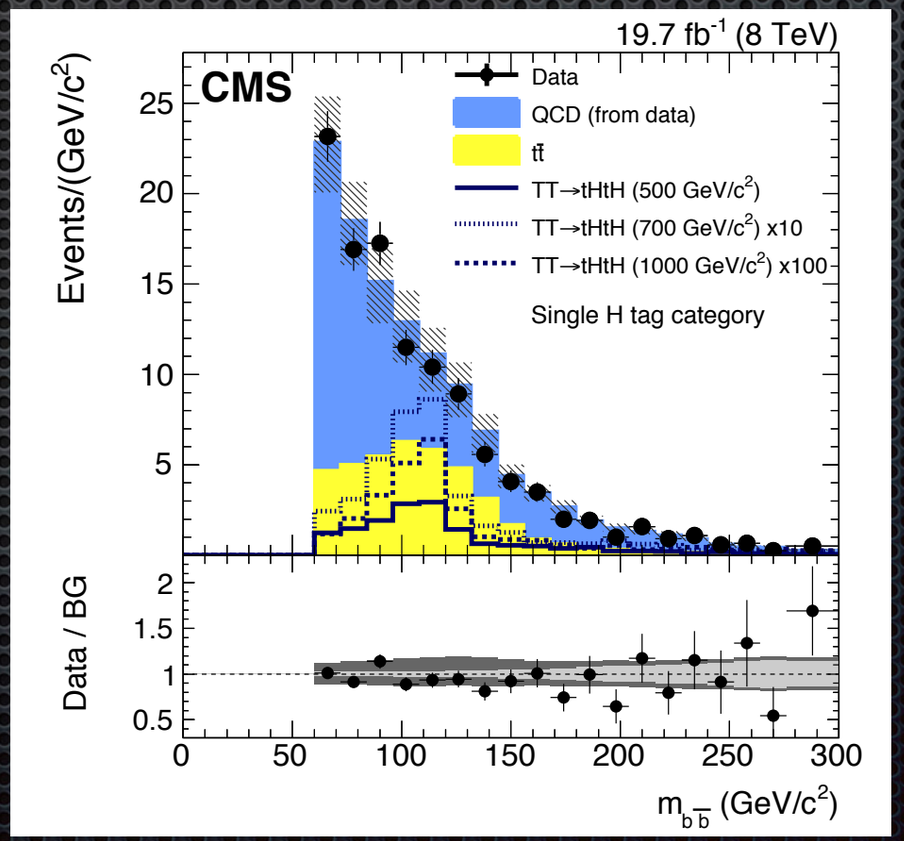
TT→tHtH, BB→bHbH: all hadronic

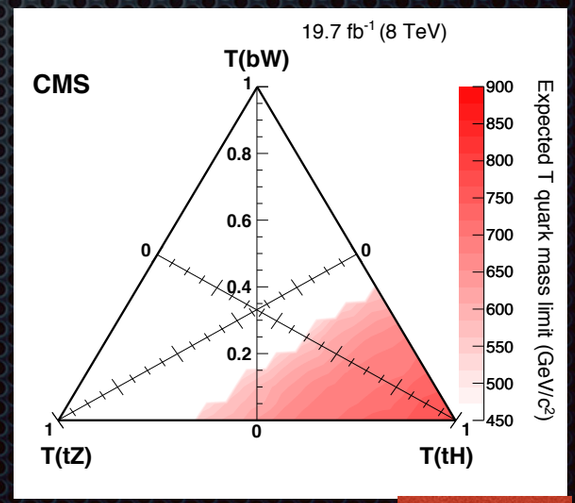
arXiv:1503.01952
B2G-14-001

- Here the power of the newly developed substructure tools has been put to the test:
  - Boosted top-tag with one sub-jet b-tagging
  - Boosted Higgs-tag and two sub-jet b-tagging







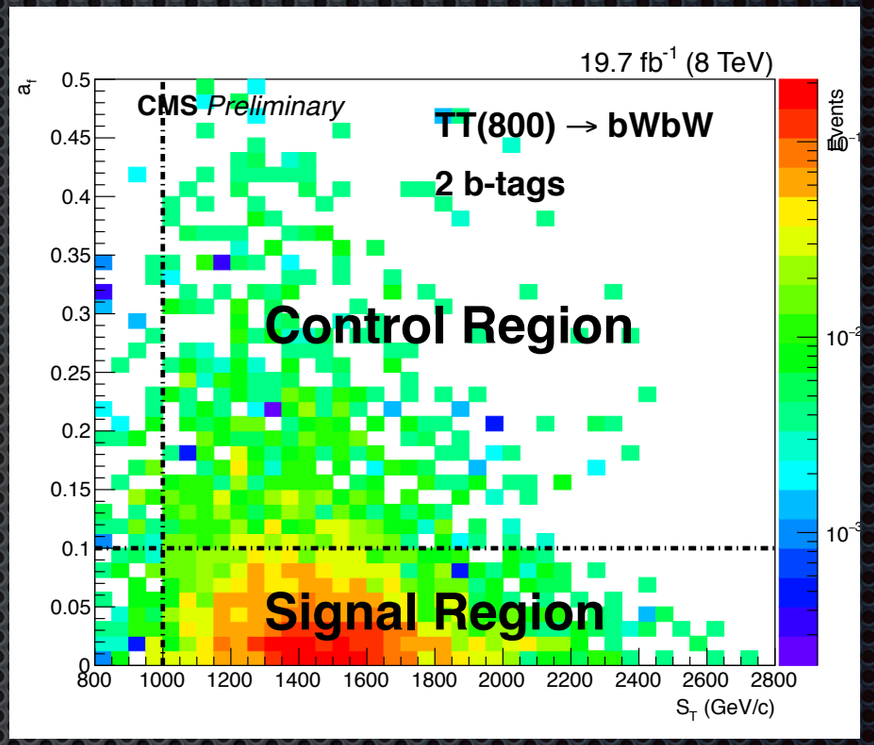


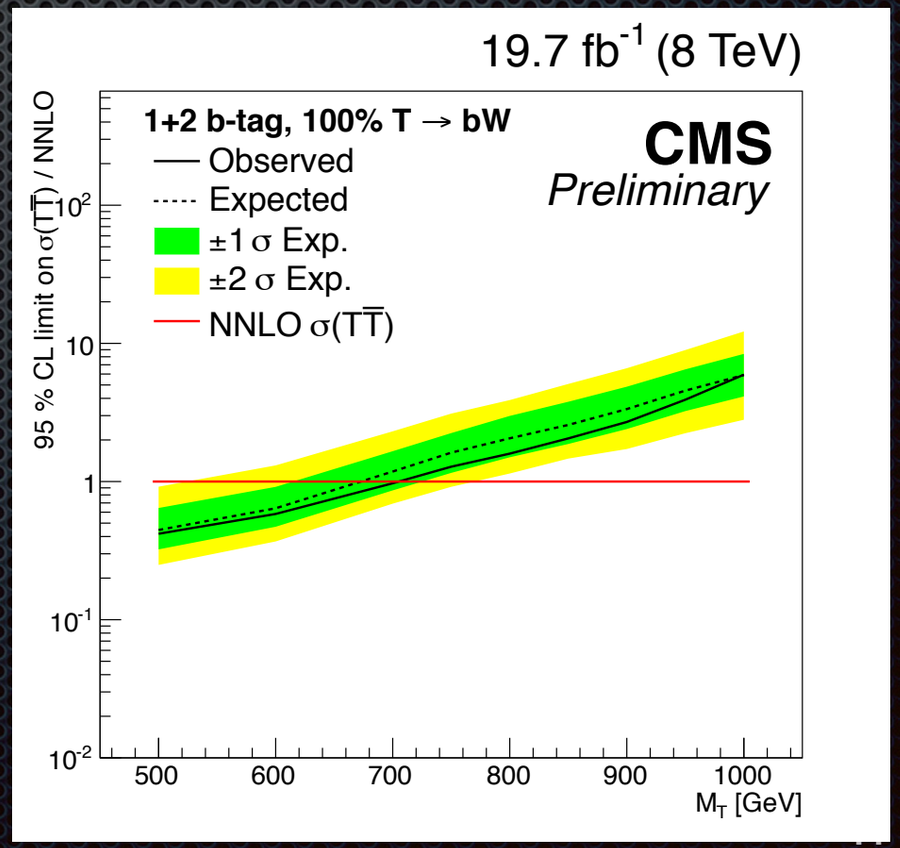
773

TT→WbWb: all hadronic

B2G-12-013

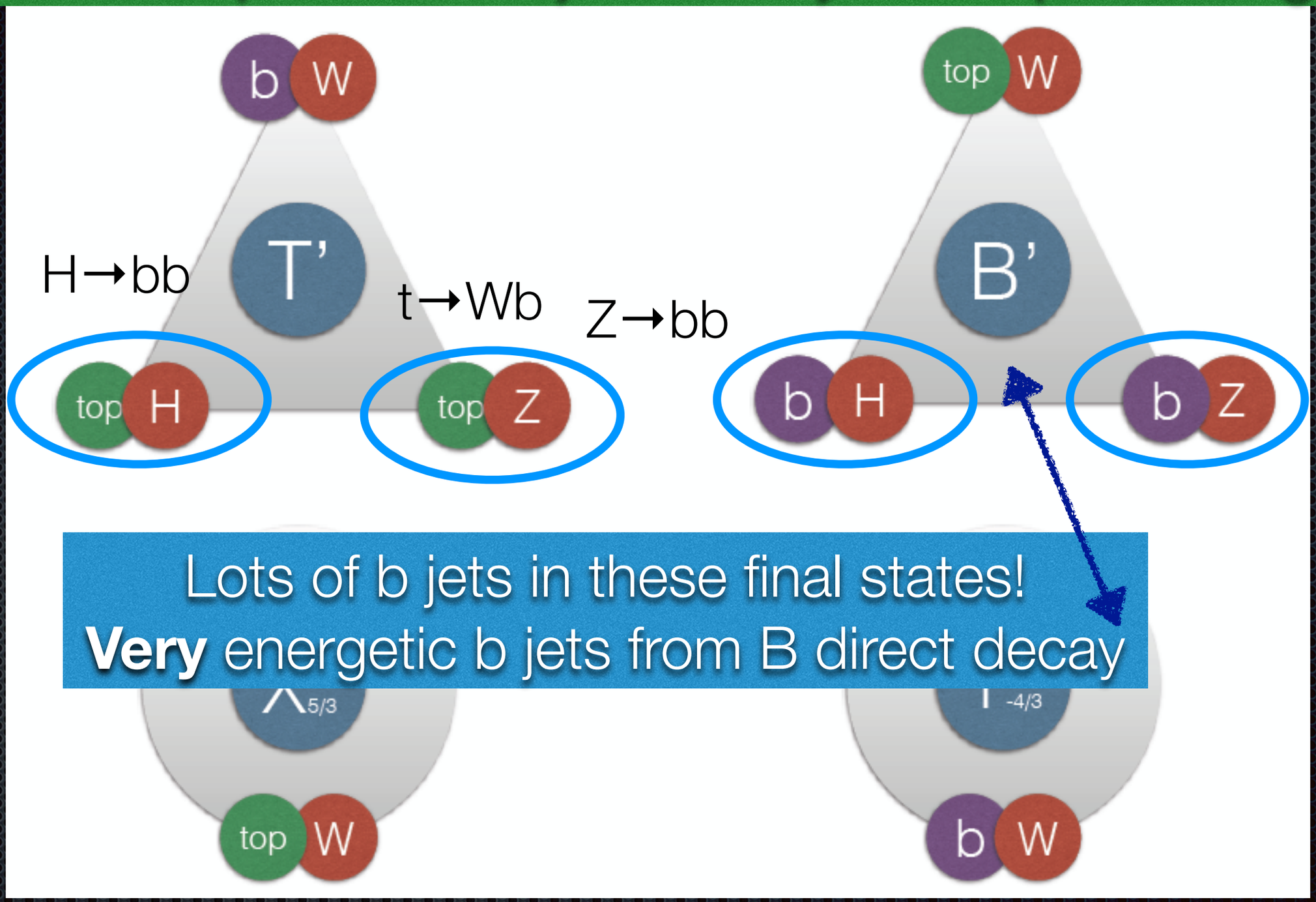
- Fully hadronic and fully boosted final state: 2 W-tags and 2 b-tags
- Exploit the mass reconstruction of the two Ts in the event
  - α_f represents the fractional difference between the two pairs
  - S_T, scalar sum of the 4 objects
- Main background is from QCD multijet which is estimated from data.
- This approach will be very important in Run2 due to the larger fraction of boosted events and larger statistics and new techniques for background estimates





Final states: lepton+boosted Higgs/Z and b-tags

Lepton+X exploits tt→l+jets decay and leptonic triggers

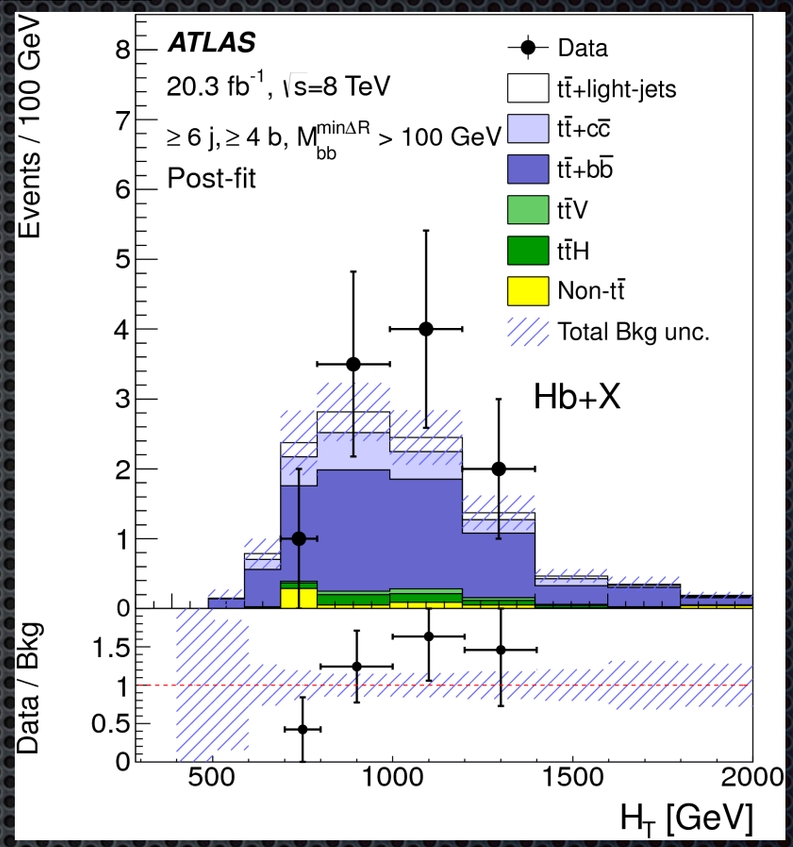


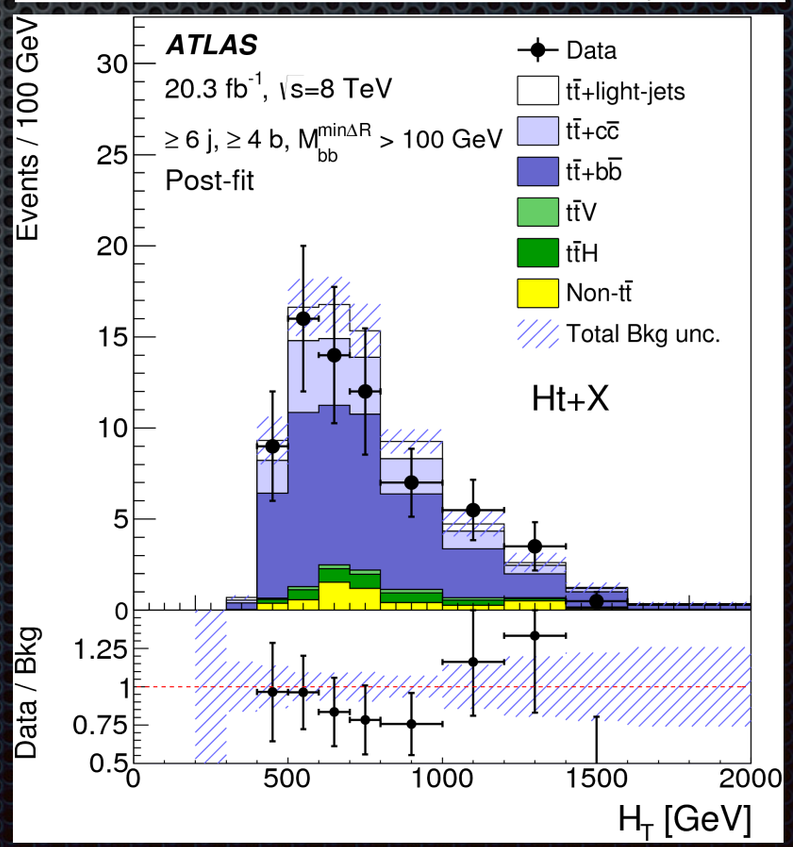
lepton+ boosted H/Z+b-tag

arXiv:1505.04306v2

- **TT→HtHt,ZtHt,WbHt : H→bb means lots of b's**
- **BB→HbHb: H→bb and H→WW (lep)**
  - the b-jet from direct B decay is very energetic
  - the sub-leading b-jet is also harder than SM tt+jets
  - always lepton trigger to select the event

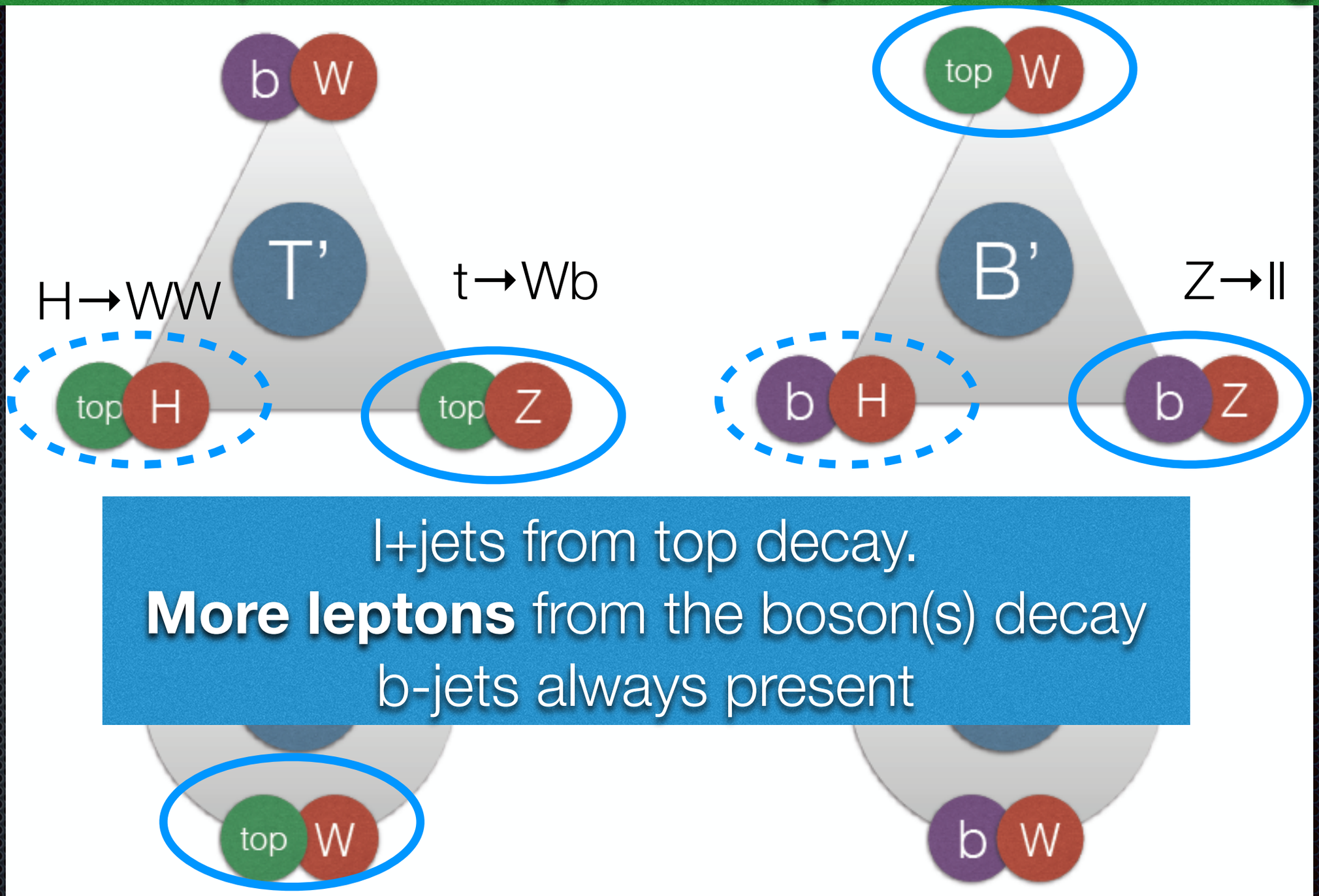
- **many signal regions with different S/B all fit at the same time.** Better background prediction.
- Tricky points:
  - extrapolation of b(mis)tagging efficiency at high pt
  - normalization of tt+HF backgrounds





Final states: « l+jets » an inclusive approach

Lepton+X exploits tt→l+jets decay and leptonic triggers



l+jets from top decay.
More leptons from the boson(s) decay
b-jets always present

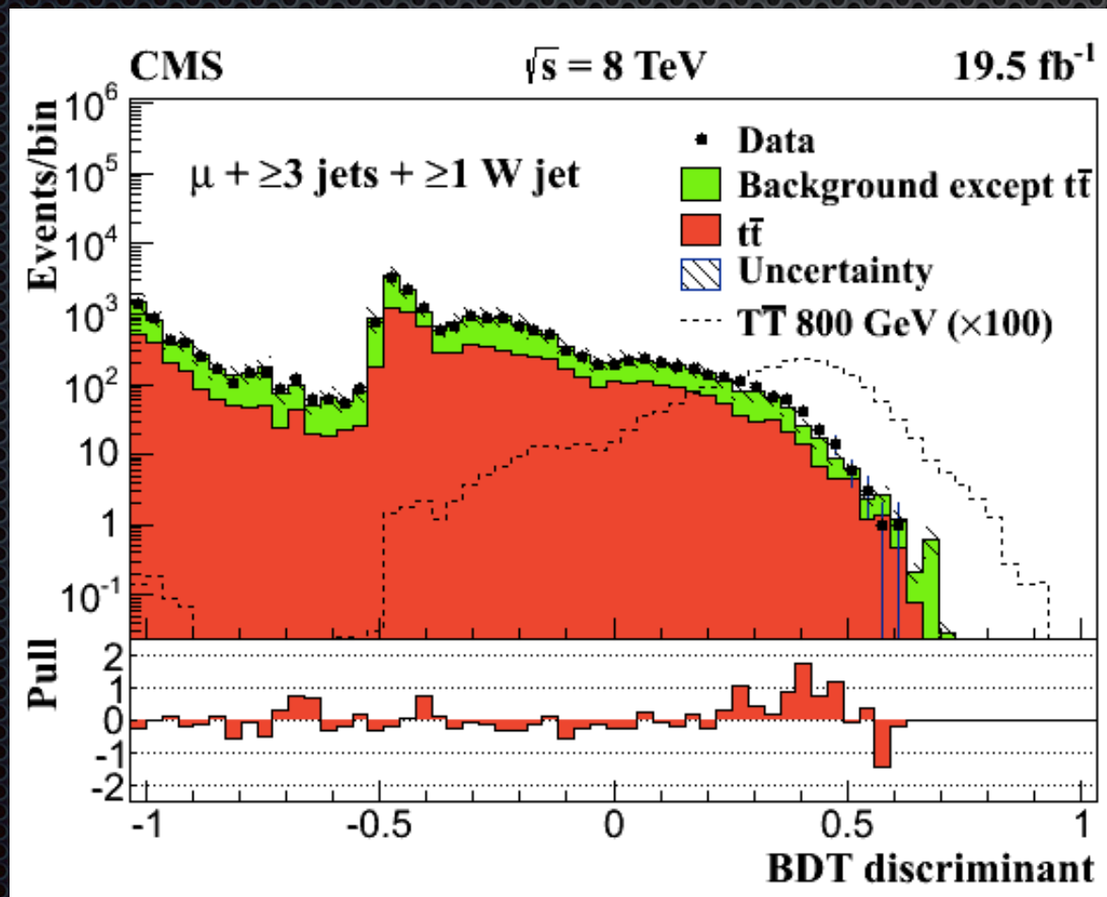
inclusive analyses

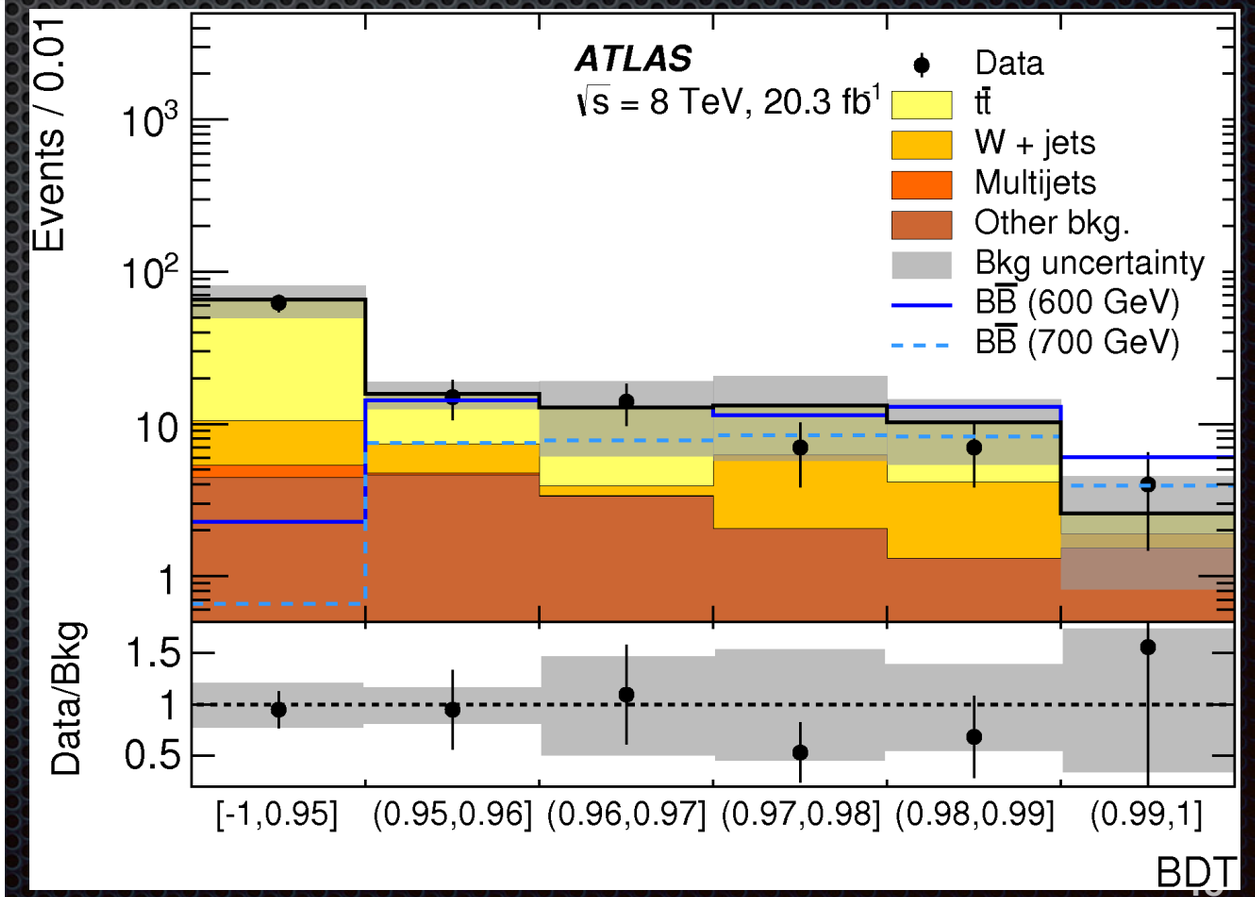
PLB 729(2014)149
B2G-12-019
arXiv: 1503.05425

Inclusive searches for TT and BB in the leptonic channel. *Not optimized for a specific BR*, but on the doublet scenario.

- 0 W: N_{jets}, N_{btags}, S_T, MET, $p_T(l)$, $p_T(j_3)$ and $p_T(j_4)$
- ≥ 1 W: 0 W + N_{Wjet}, p_T(WJet), $N_{tt+jets}$

- Events binned by # of boosted V-tags (=0,1,≥2)
- Used BDT strategy





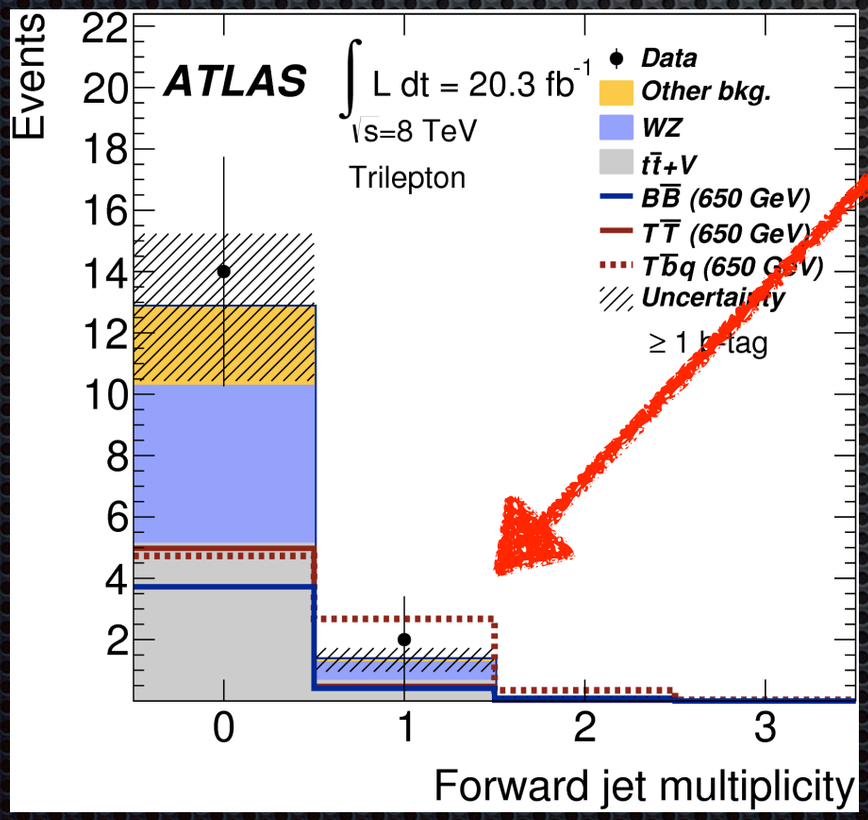
Multilepton, multipurpose

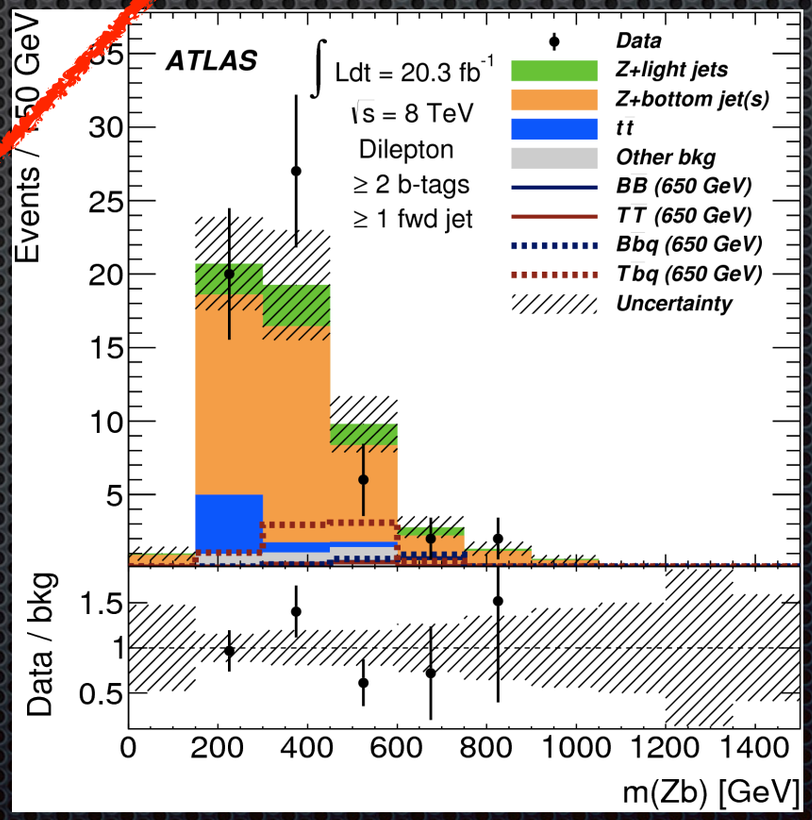
JHEP11(2014)104

- Optimization for single production: unique in Run1!

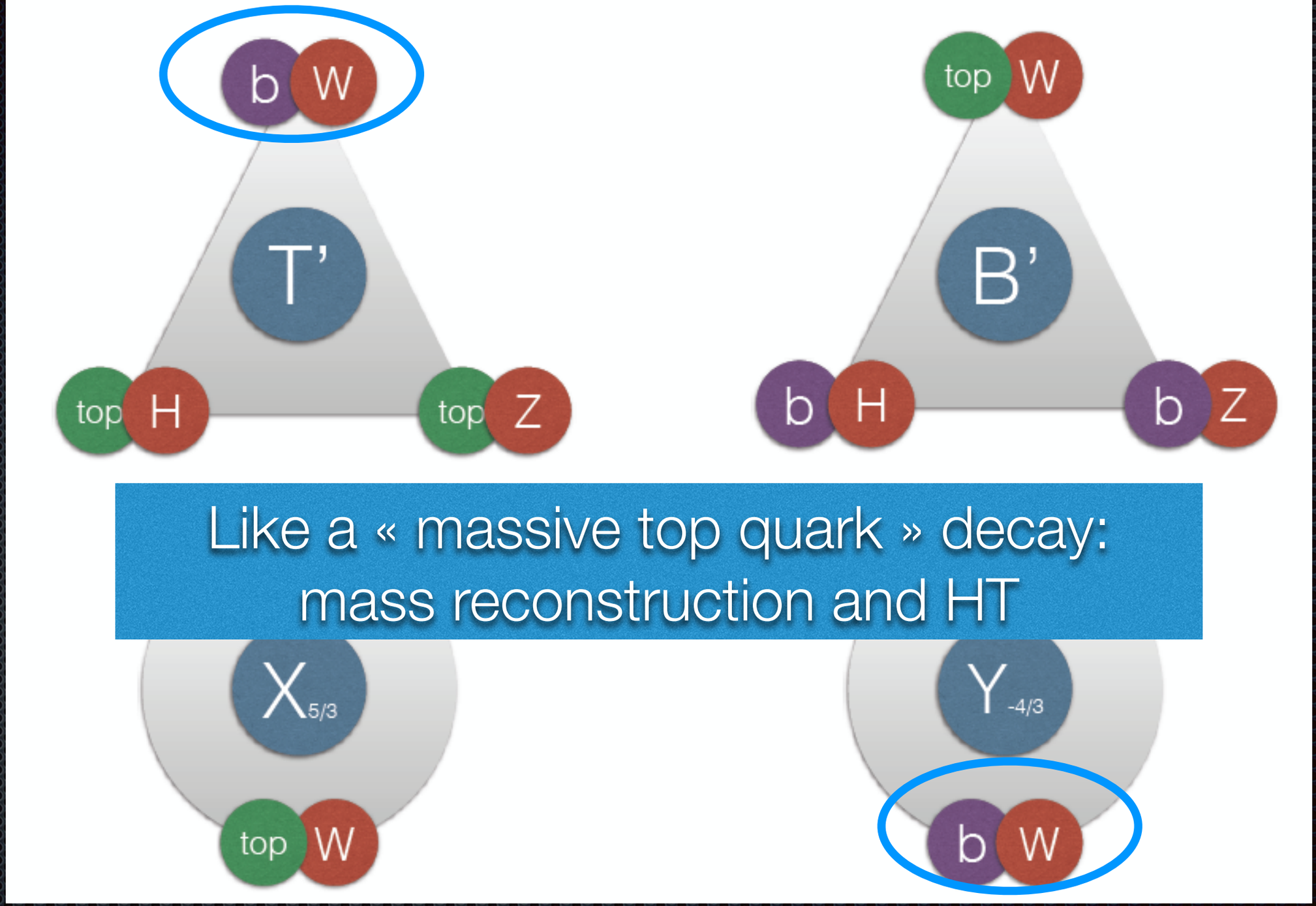
Event selection			
Z boson candidate preselection ≥ 2 central jets $p_{\mathrm{T}}(Z) \geq 150$ GeV			
Dilepton channel		**Trilepton channel**	
$= 2$ leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	**Single production**	**Pair production**	**Single production**
$H_{\mathrm{T}}(\mathrm{jets})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

More details in Loic Valéry talk





Final states: l+jets of a « heavy top »



Like a « massive top quark » decay: mass reconstruction and HT

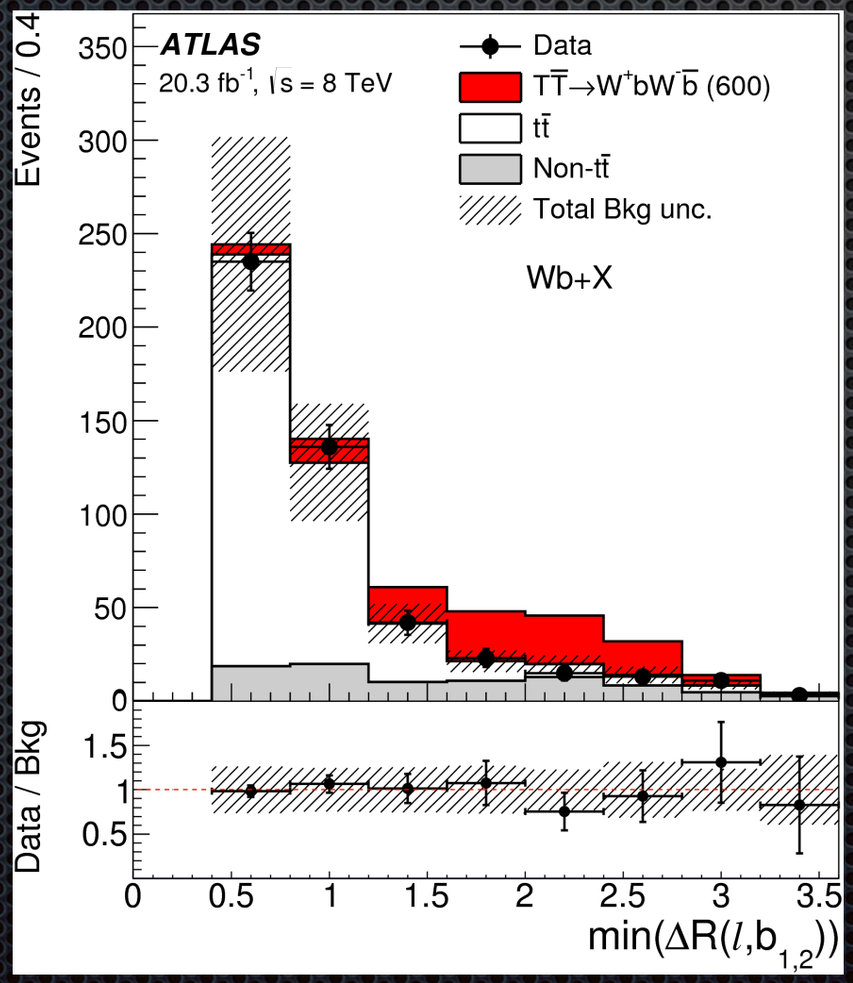
l+jets of a « heavy top »

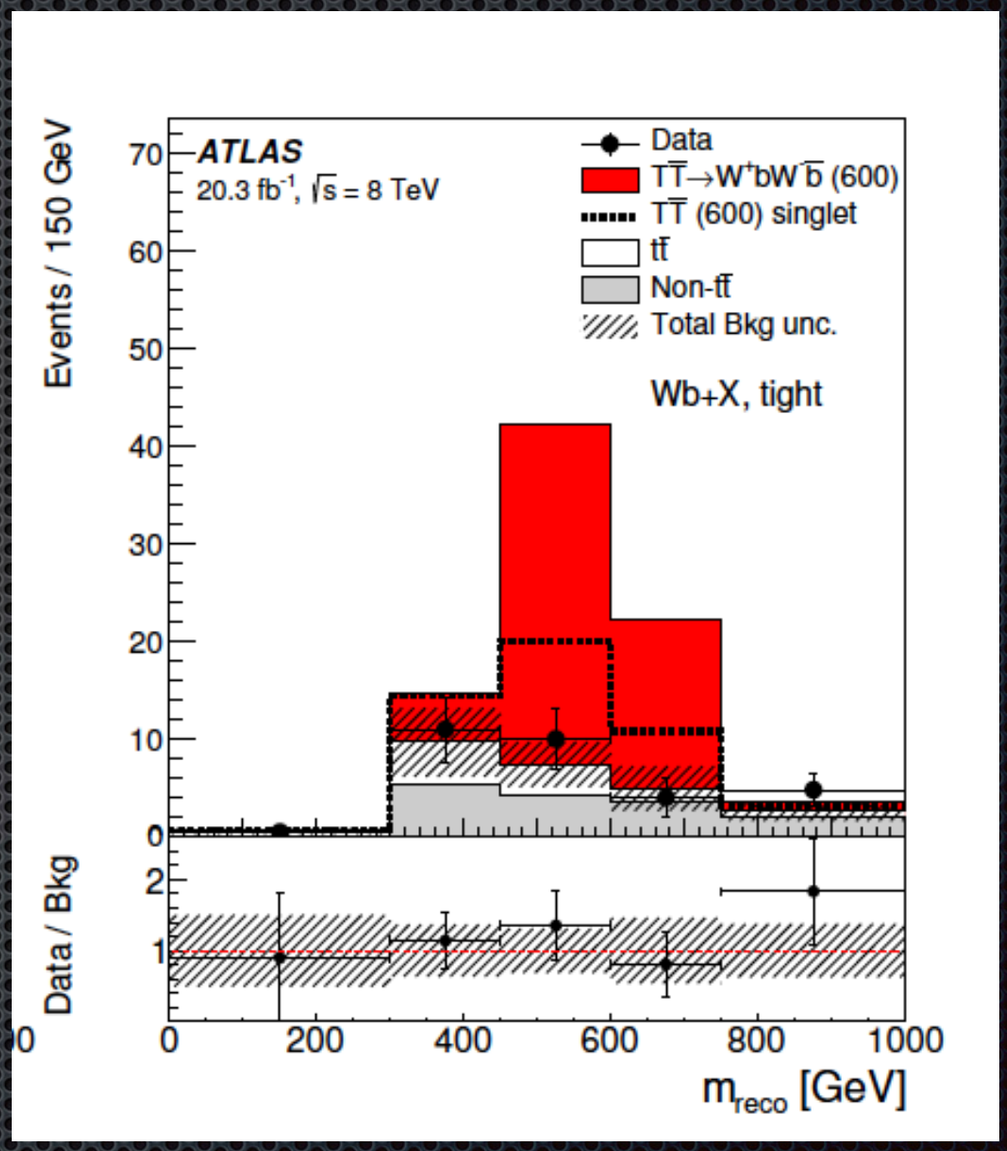
arXiv:1505.04306

B2G-12-017

TT→Wb+X

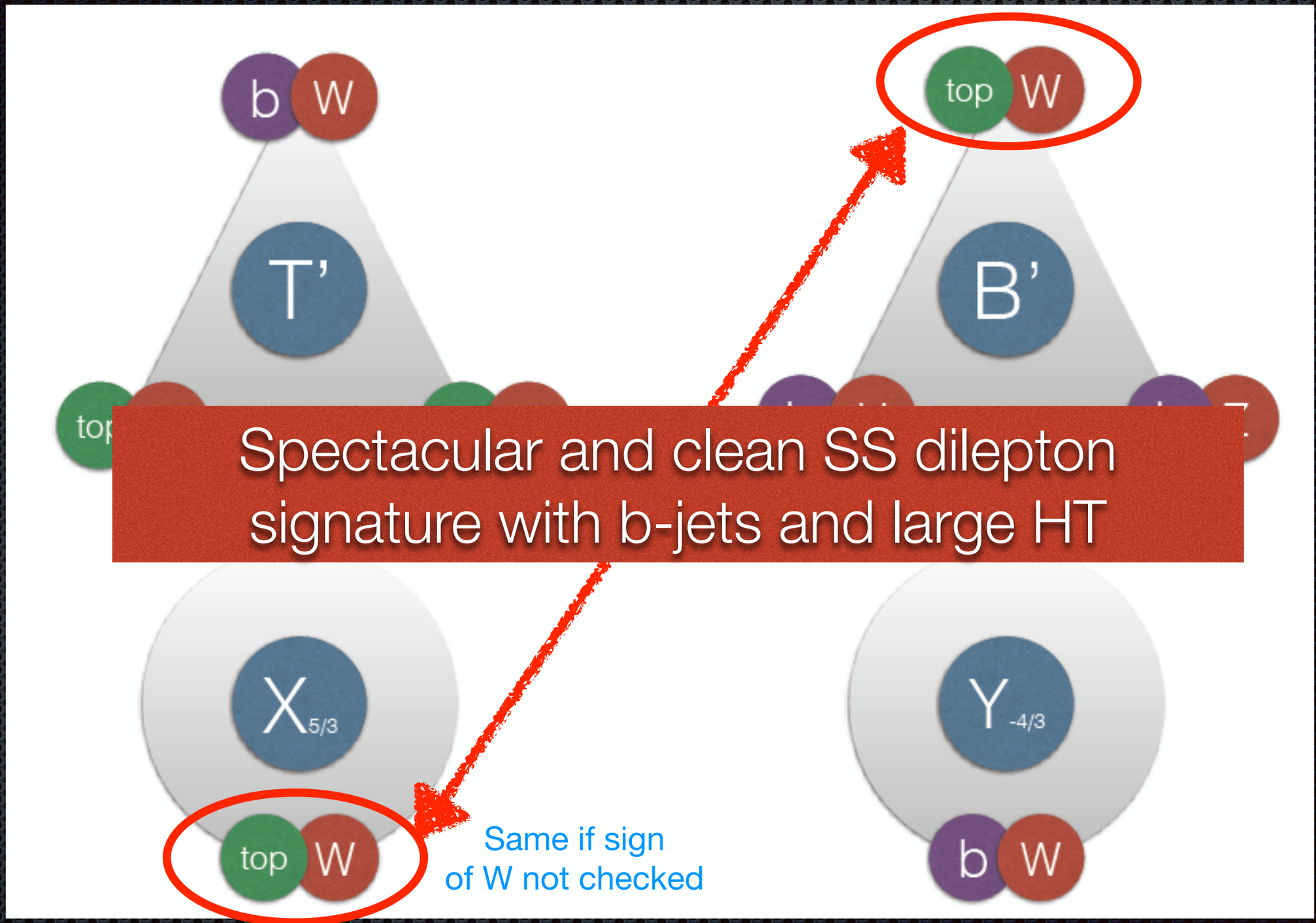
- optimized for TT→WbWb
- one W→lν, one W→had
- profit of different kinematic from SM top events





Use full mass reconstruction as discriminant

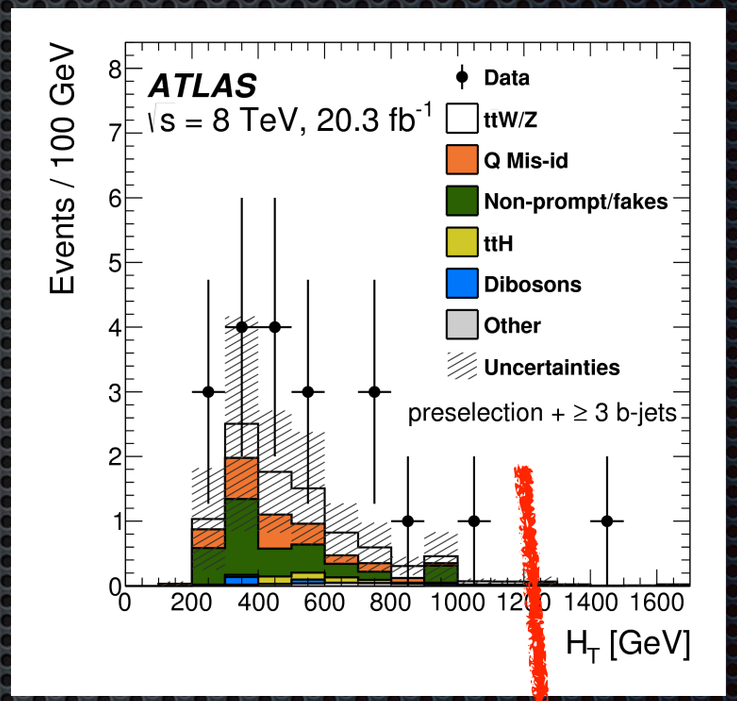
Final states: SS dileptons

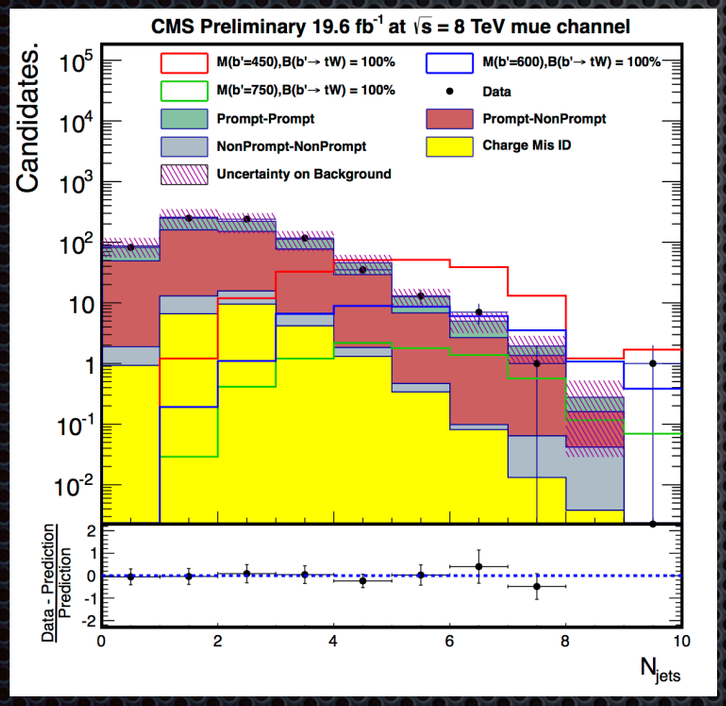


XX(BB)→tW pair production

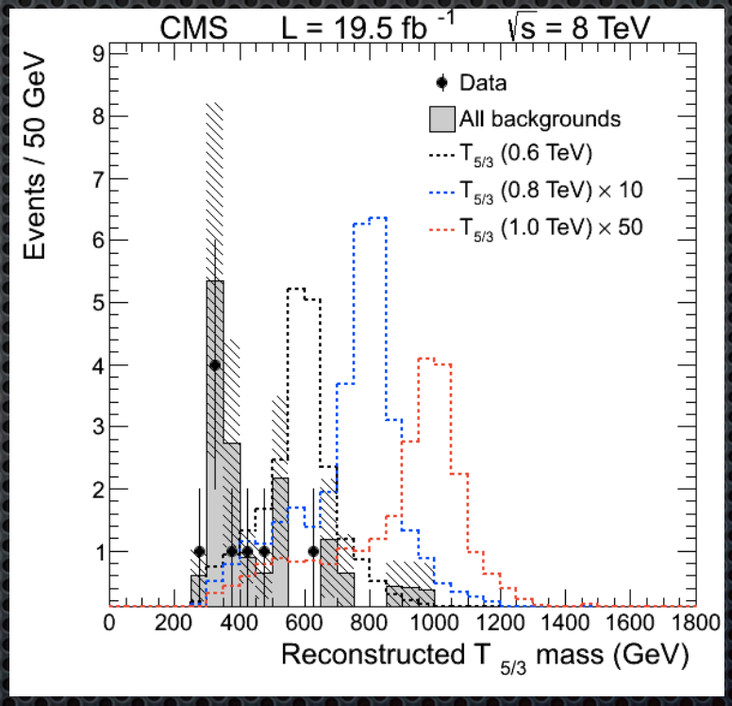
PRL 112(2014)171801
B2G-12-020
1504.040605v1

- Very clean signature as few SM processes competing
  - Main issue: fakes background estimate
- Presence of many jets and large HT. Analyses exploit:
  - b-jet content
  - W-tag or Top-tag content

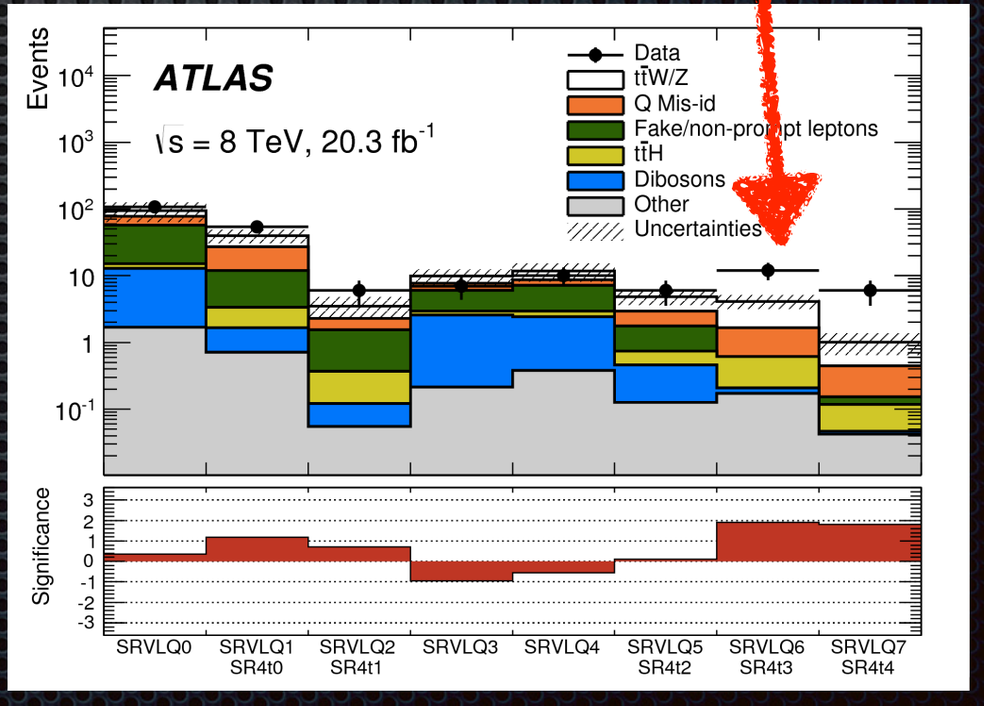




No b-jets

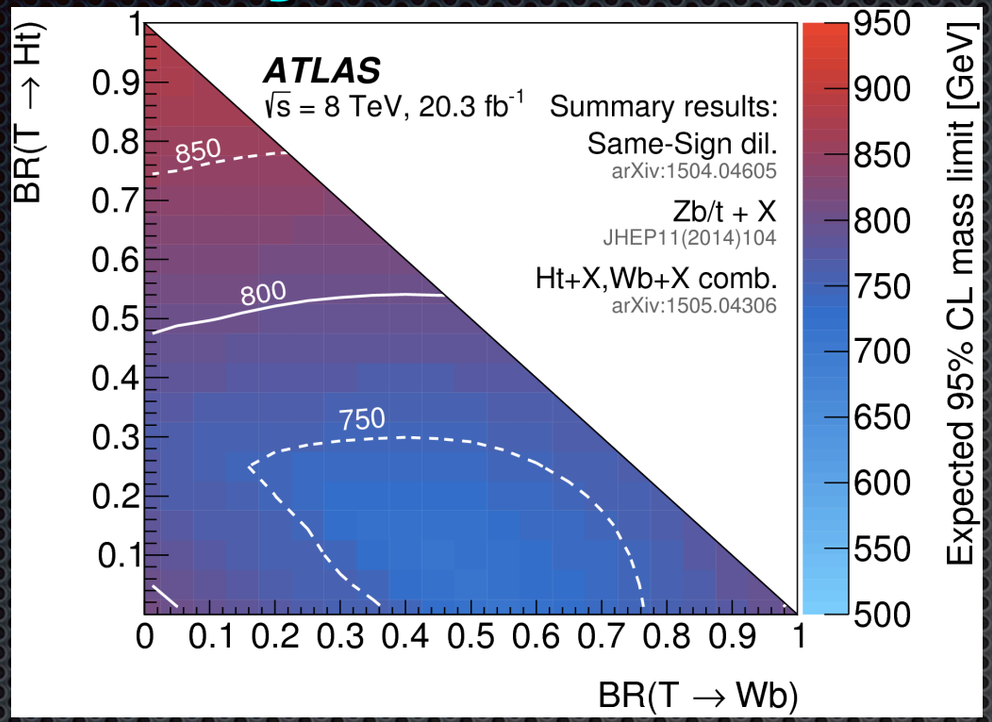


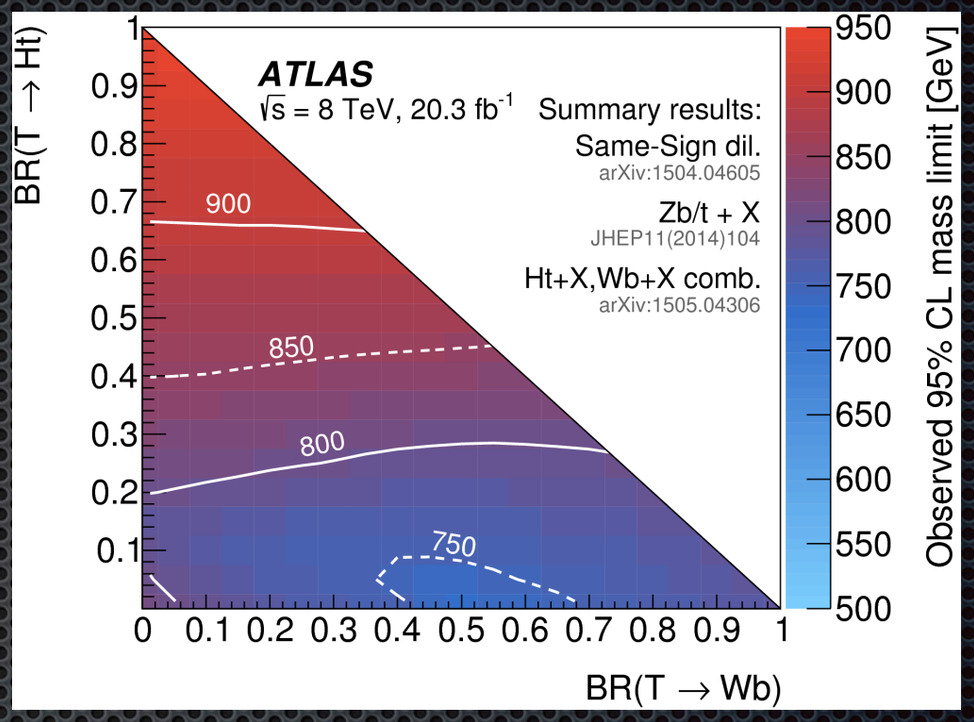
T5/3 reco

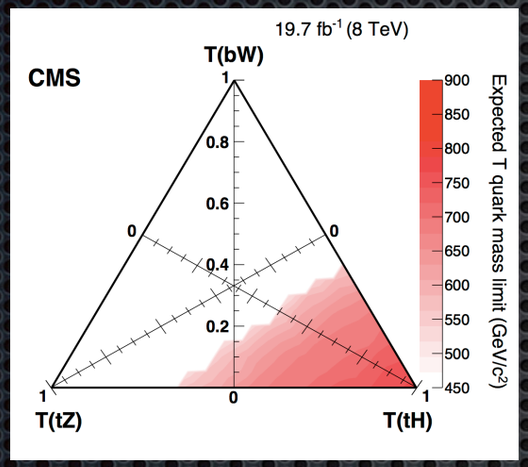


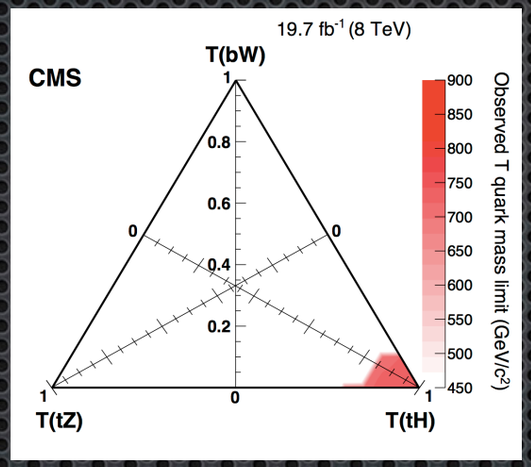
Many signal regions
(excess when requiring b-jets)

Summary of Run1: TT





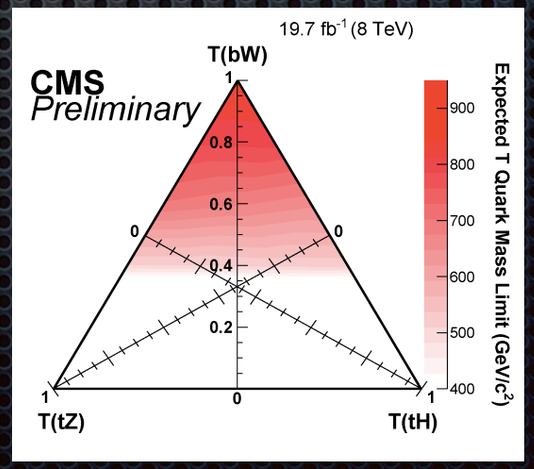


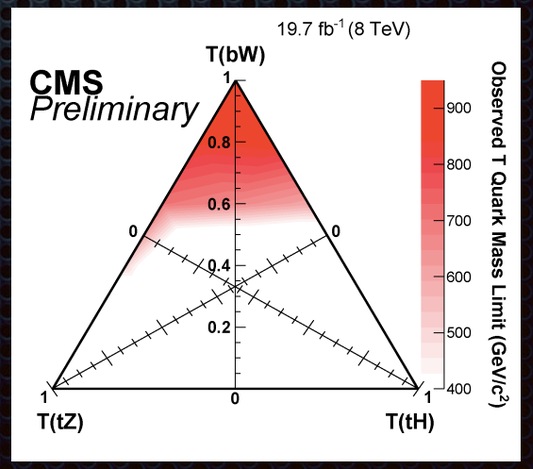


- ATLAS plots contain the most restrictive limit for the different TT searches

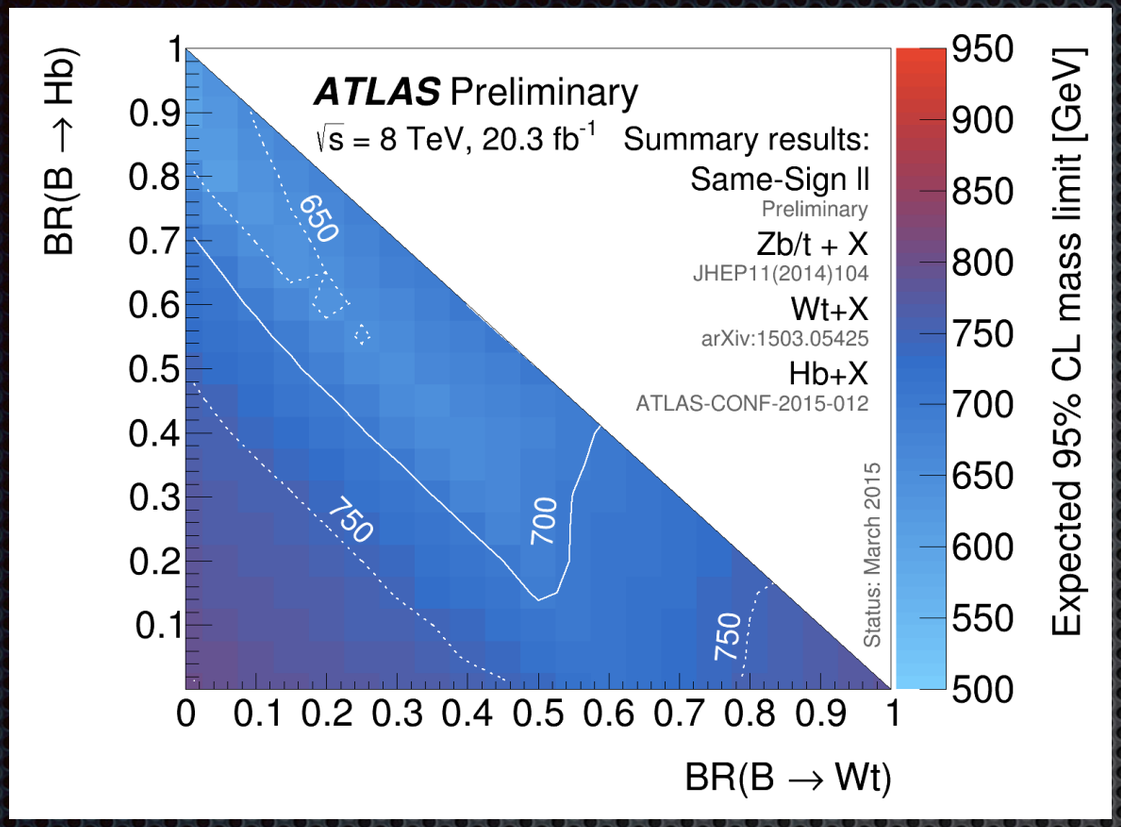
CMS (for BR=100%)

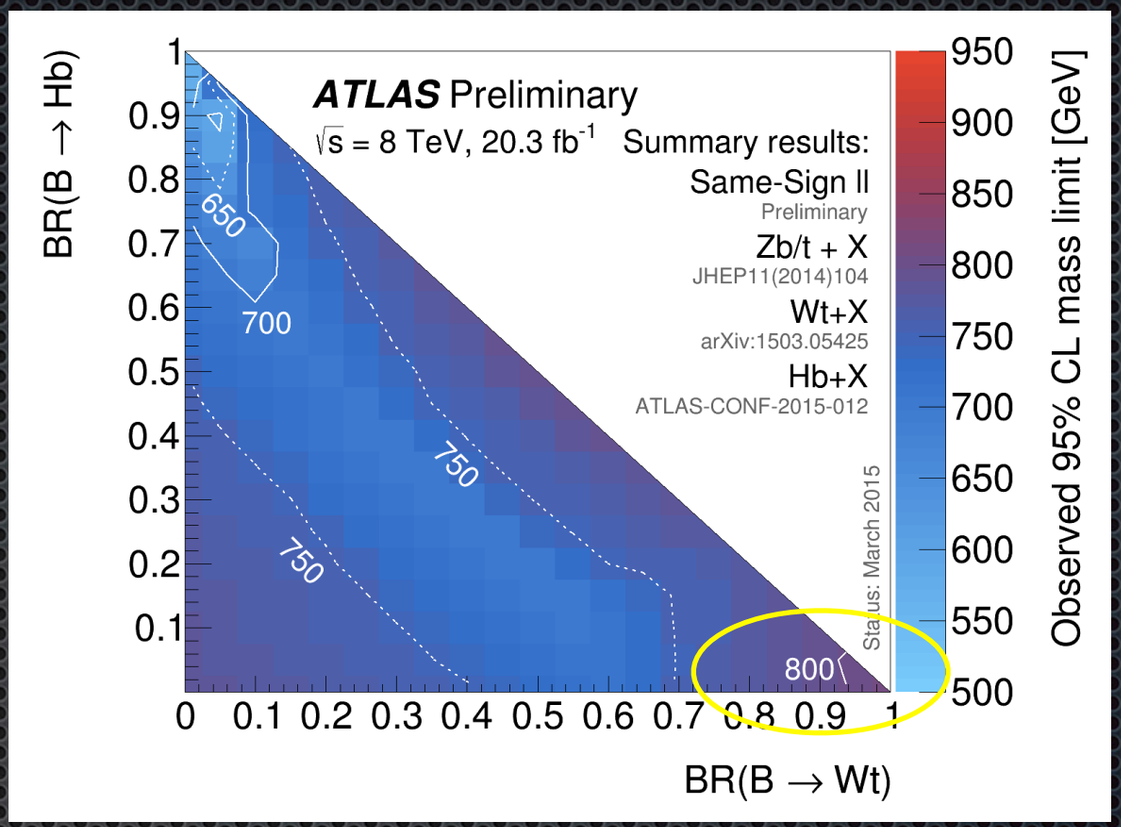
Ch	Obs(Exp)
bW	785(700)
tH	745(773)
tZ	813(782)





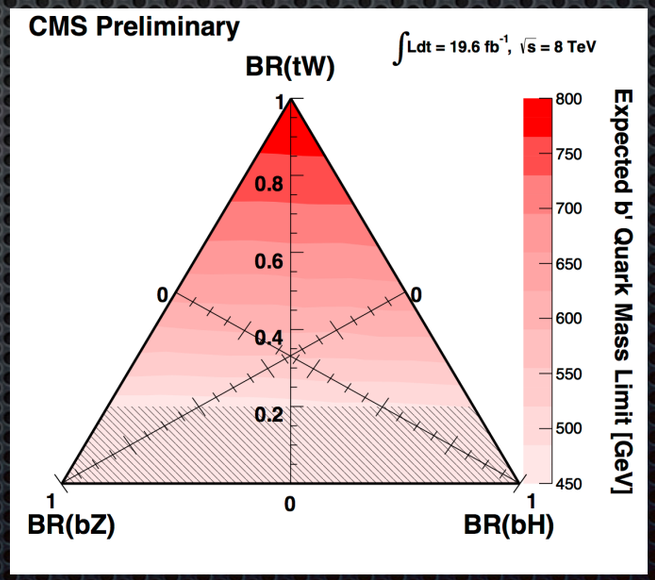
Summary of Run1: BB

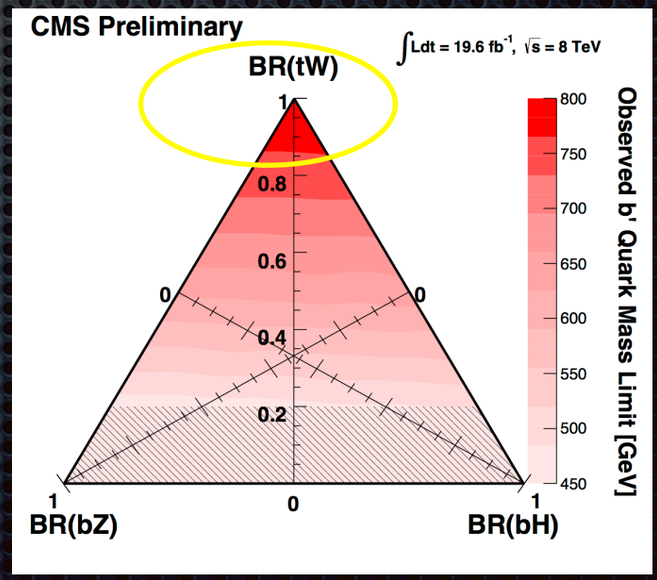




ATLAS plots contain the most restrictive limits for the different BB searches

CMS(for BR=100%)	
Ch	**Obs(Exp)**
tW	798(800)
bH	839(782)
bZ	700(680)





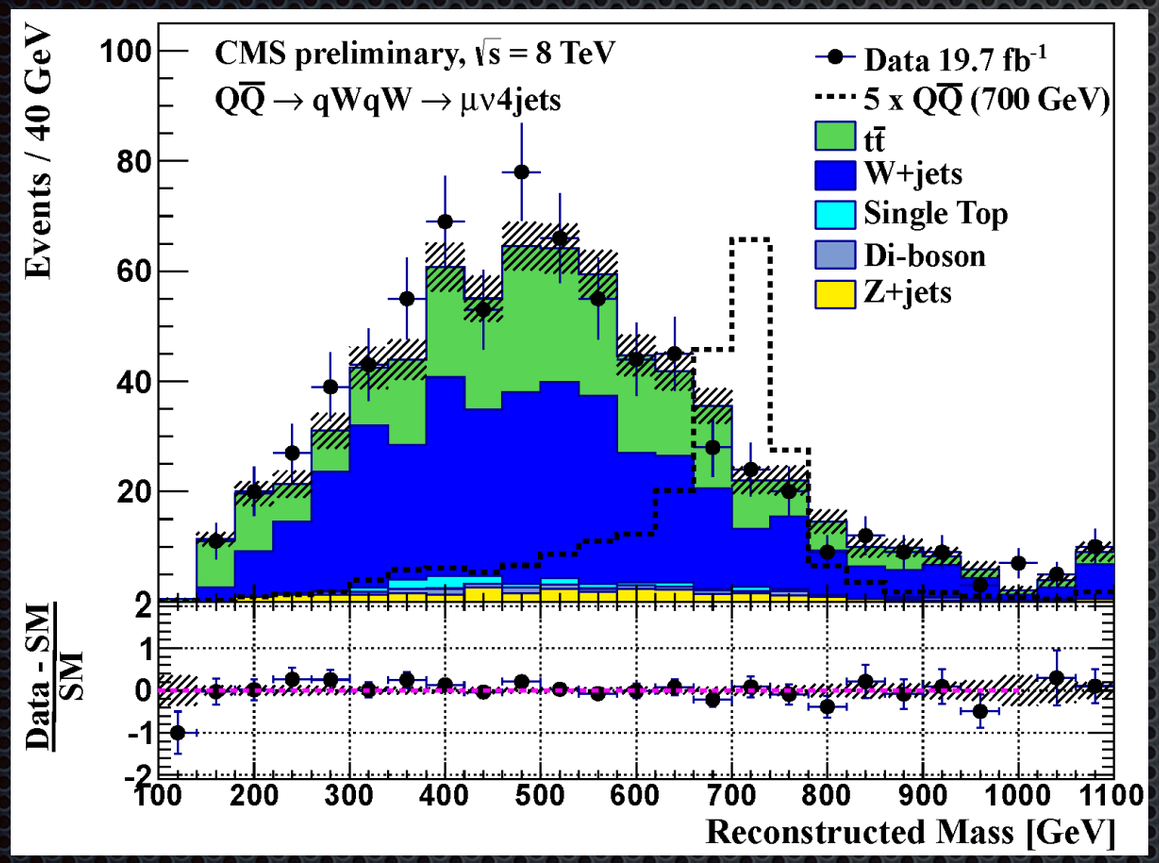
chosen the best tW corner for CMS

Light Flavor VLQ

B2G-12-017
PRD86 (2012)012007
ATLAS-CONF-2012-137

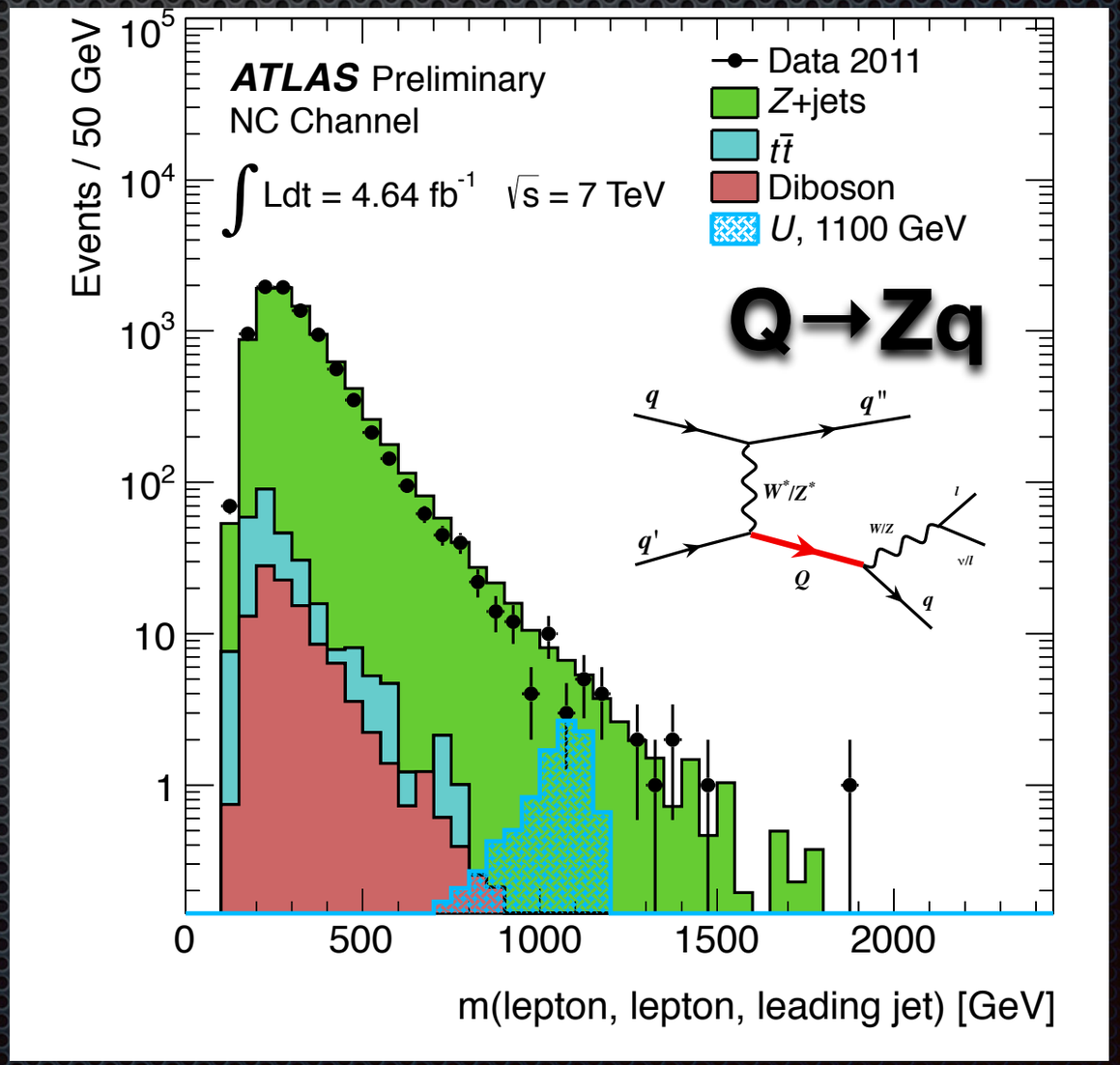
Pair production: QQ→WqWq

one W→lν
one W→had
Veto b-tag
W+jets main background



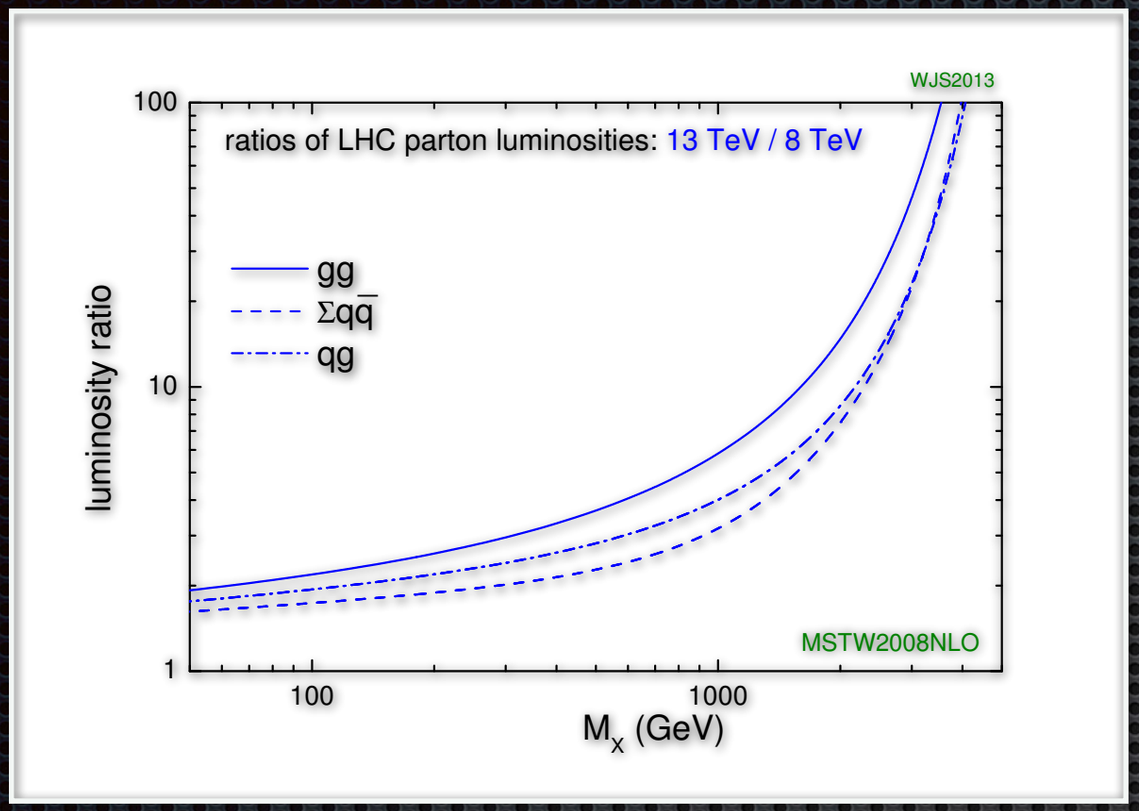
Single Production: Q→W/Zq

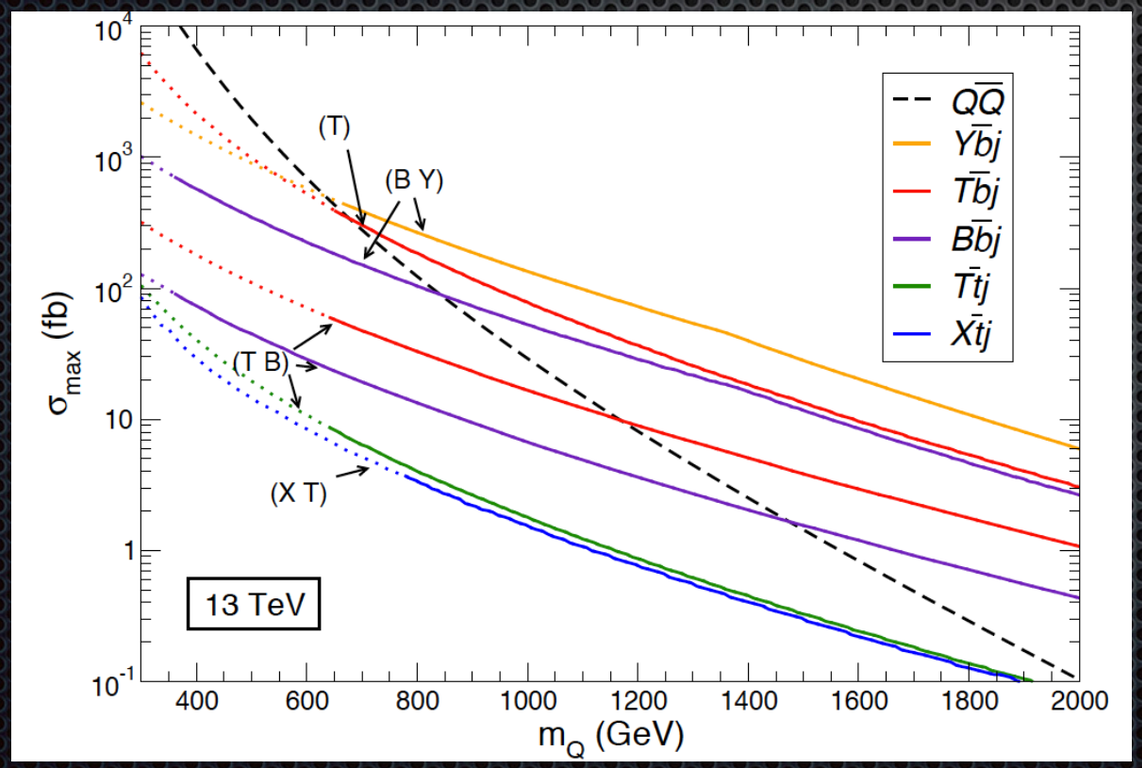
one/two leptons from V decay
W/Z+jets main background



Use full mass reconstruction as discriminant

Life at 13 TeV





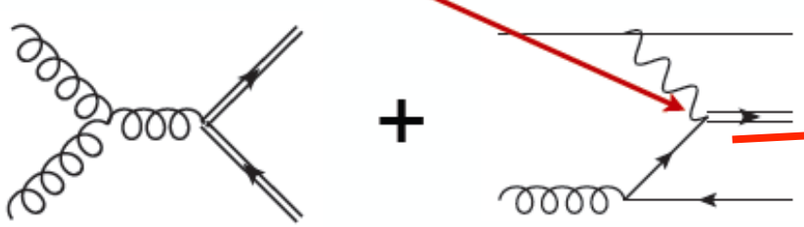
- New energy:
  - increased parton luminosities, increased mass reach for less luminosity
  - challenge: keep/improve performance wrt Run1
- VLQ physics hot topic: ATLAS and CMS opened a discussion channel with theorist to setup common benchmarks for VLQ signal generation
  - this helps future interpretations of the results
- **Single production will become more important:**
  - opens a range of new targeted analyses
- **Pair production always fundamental as less model dependent**

Ideas for interpretation of Run2 results

- Effective operators approach: all possible couplings are free parameters
- Example: X5/3

		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}

$$\mathcal{L}_{5/3} = \frac{g_w}{2} c_R \overline{X}_{5/3R} \not{W} t_R + \text{h.c.}$$



$$S = \mathcal{L} \sum_n \text{BR}_n \, \epsilon_n \, \sigma_n(M_n)$$

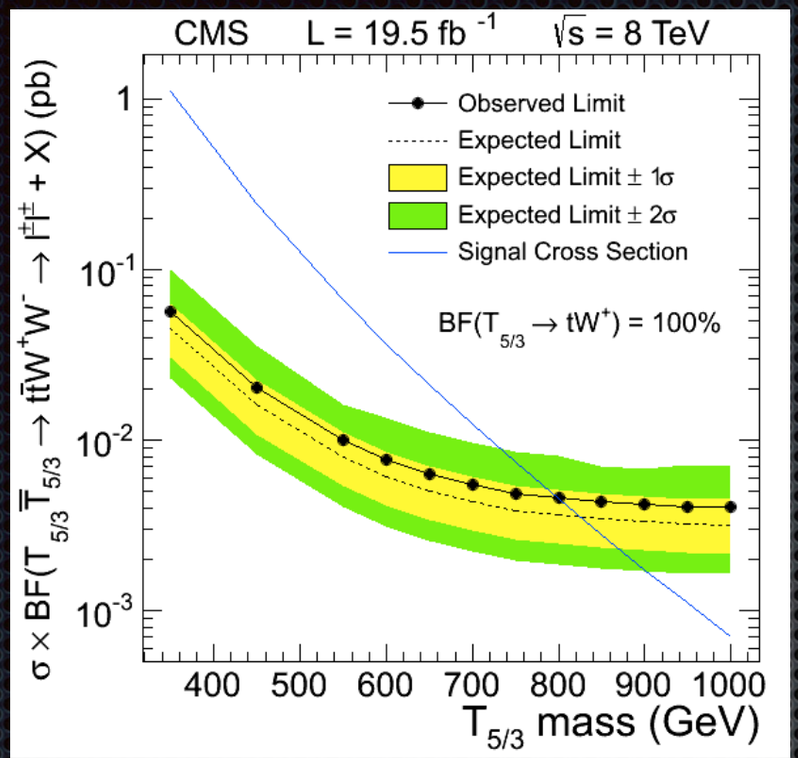
$\sigma_{pair}(M_X)$ Universal QCD pair from MC

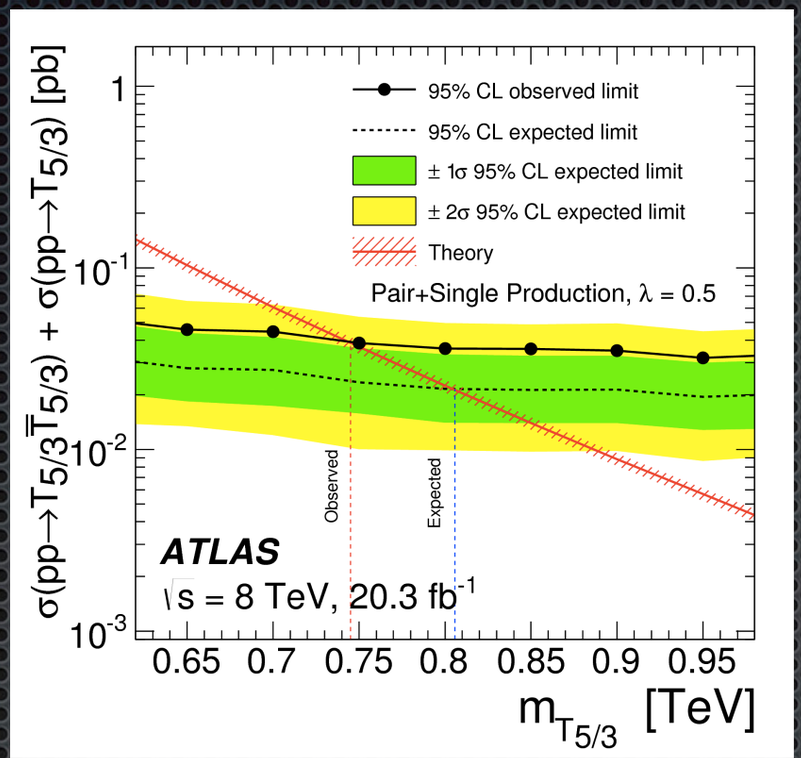
$$\sigma_{\text{sing}}(X\bar{t}) = c_R^2 \, \sigma_{Wt}(M_X)$$

factorize out the couplings

While expressing the results in terms of coupling vs mass different theory interpretations can be tried without the need of recasting.

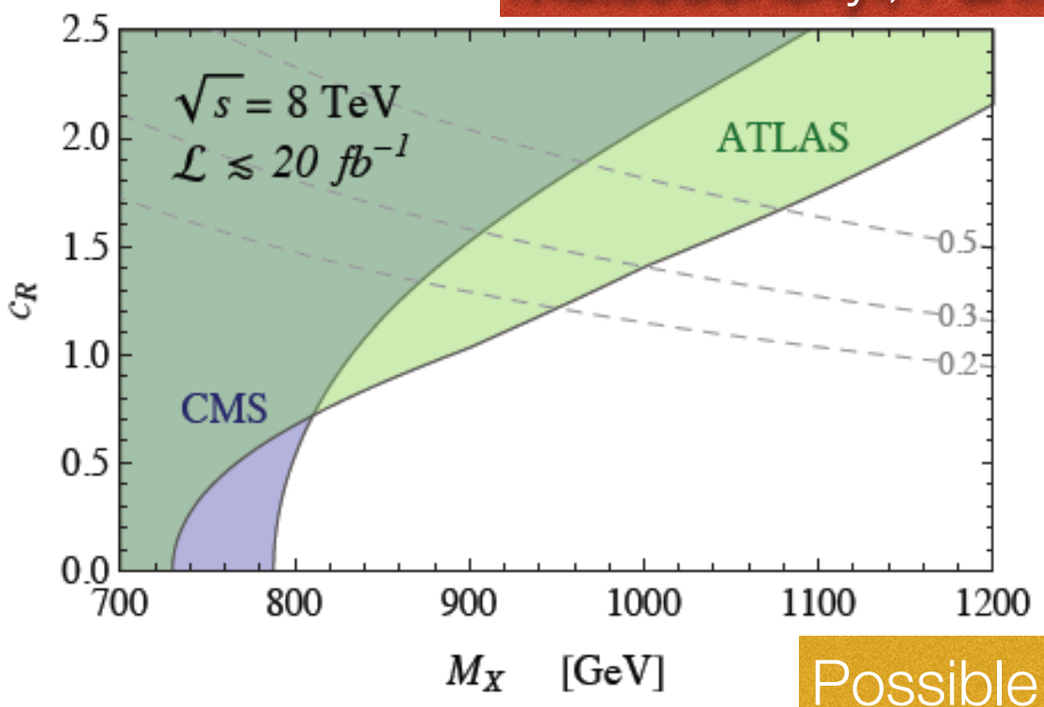
Practical examples: $X_{5/3}$

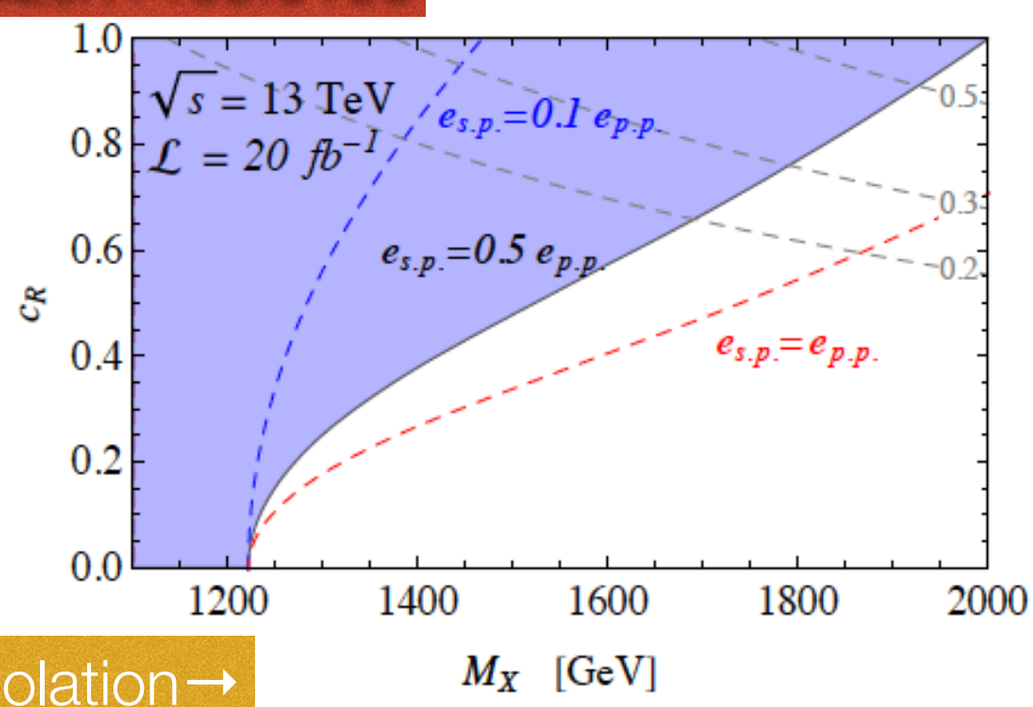




When interpreted in the simplified model approach the acceptance of the ATLAS analyses to single production helps extend the exclusion limit as a function of the coupling

Matsedonskyi, Panico, Wulzer:1409.0100

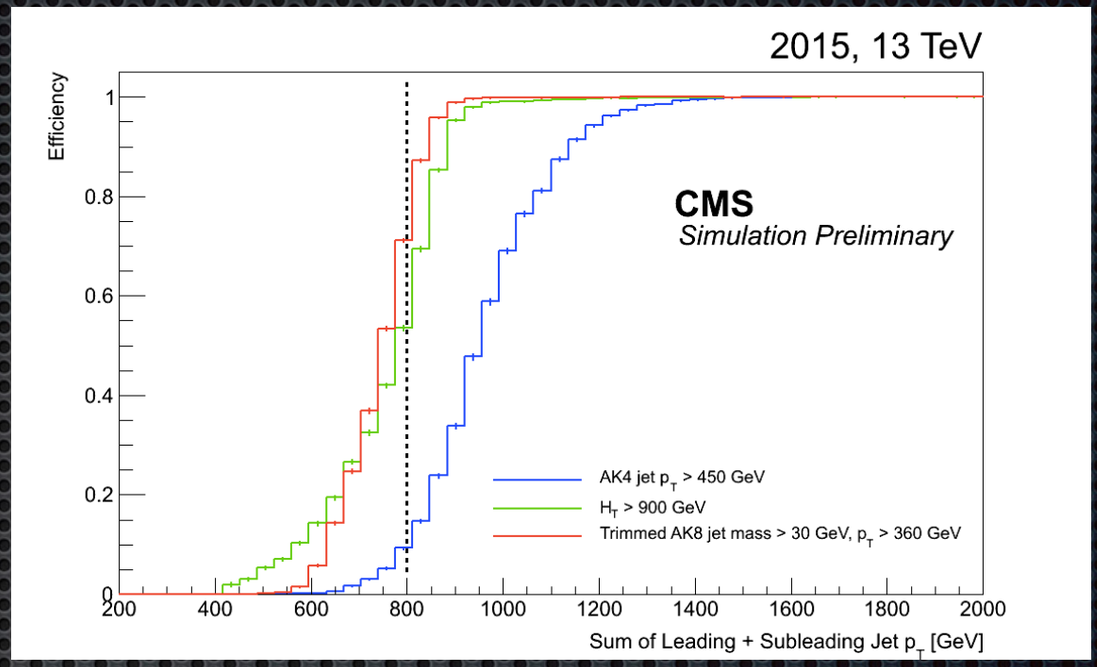


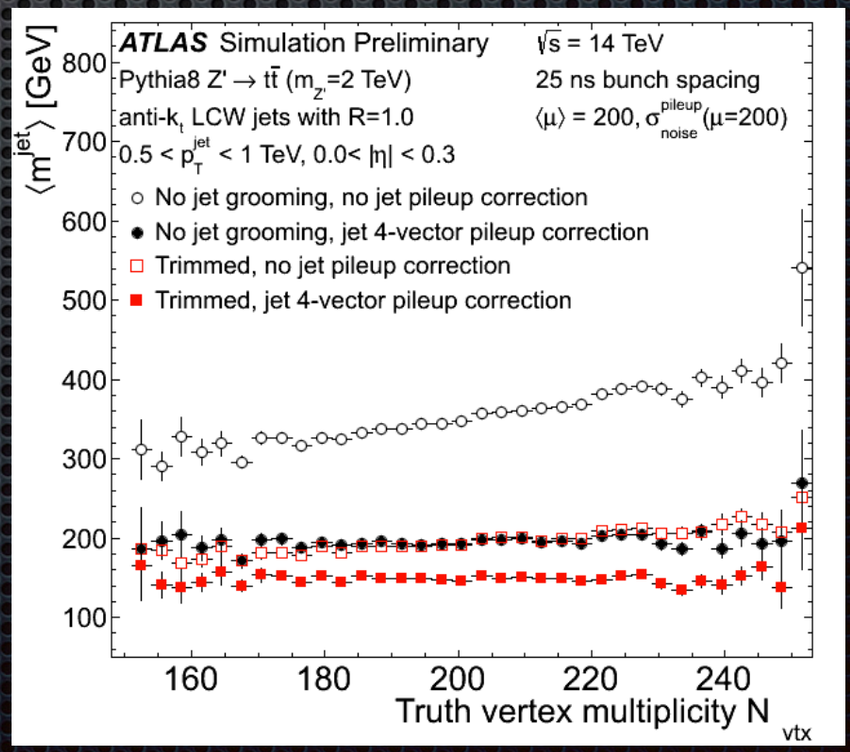


Possible extrapolation→

Experimental challenges in Run2

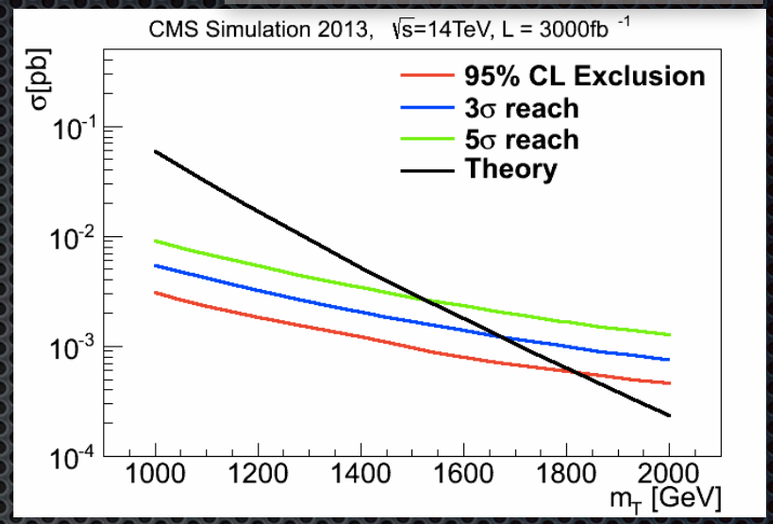
- Readiness means adapting to the new running conditions:
  - need improved triggers to keep the rate low and the efficiency high: use substructure technique such as the Trimmed mass
  - develop reconstruction variables and techniques that would not suffer from PileUp dependence





Future reach

TT→WbWb l+jets and multilepton

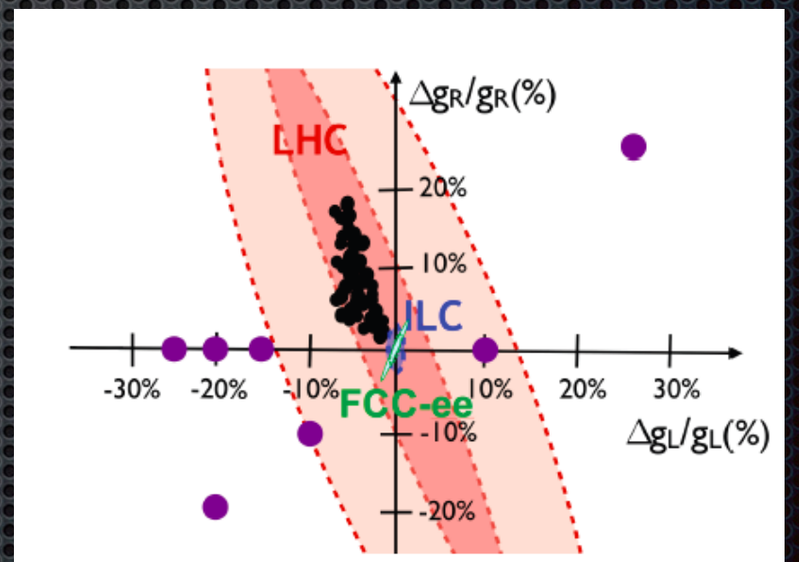


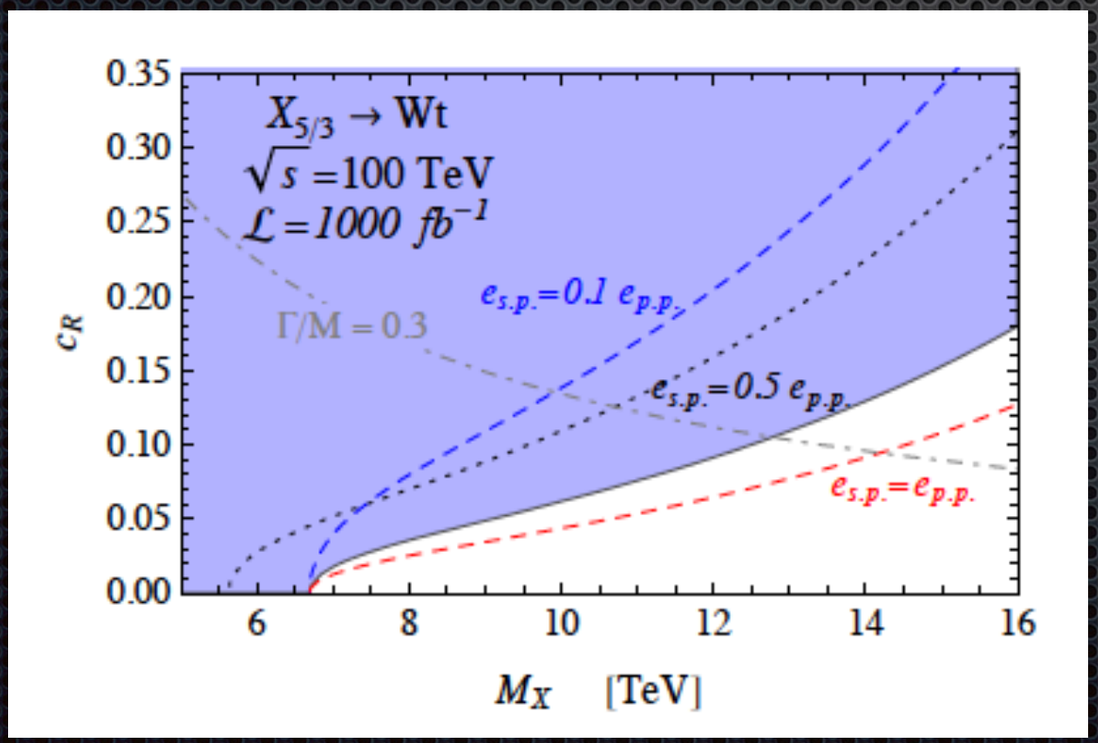
The HL-LHC program is not expected to extend much the reach for direct search wrt Run2

FTR-13-026

Better hopes for finding the scale of new physics, especially Composite Higgs scenarios, with indirect measurement at a high luminosity e+e- collider (FCC-ee): effect on top couplings from CH models

Barducci, De Curtis, Moretti, Pruna 1504.05407





Direct search will benefit of the higher center of mass energy of a FCC-hh 100TeV pp collider

Possible extrapolation at 100 TeV collider

Matsedonskyi, Panico, Wulzer:1409.0100

Conclusions

- Top Partners and Composite Higgs models are currently a very interesting new physics option
- **Strenght of the VLQ searches is the tt+X final state without large missing energy which is ~orthogonal to Susy searches**
- VLQ searches can be an excellent portal to new physics, with even more complex phenomenology:
  - **VLQ might appear in the decay of heavy resonances in the process Z'→Tt**
  - **VLQ might appear in DM searches as in single production of T→Zt, Z→νν**
- The higher Run2 energy and the higher mass search regions are pushing the development of sophisticated tools for reconstruction and identification of very boosted objects in dense pileup environment to maximize the sensitivity of the new analyses at 13 TeV

There is more VLQ @Blois:
Loic Valéry talk Wed in BSM session
Thomas D. Flacke Tue in Top+Higgs Session

Backup

Theory bibliography (non comprehensive)

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[6] S. De Curtis, M. Redi and A. Tesi, JHEP **1204** (2012) 042 [arXiv:1110.1613 [hep-ph]].

[7] O. Matsedonskyi, G. Panico and A. Wulzer, JHEP **1301** (2013) 164 [arXiv:1204.6333 [hep-ph]].

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[11] A. De Simone, O. Matsedonskyi, R. Rattazzi and A. Wulzer, JHEP **1304** (2013) 004 [arXiv:1211.5663 [hep-ph]].

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[14] G. Panico, M. Redi, A. Tesi and A. Wulzer, JHEP **1303** (2013) 051 [arXiv:1210.7114 [hep-ph]].

Run I Analyses referenced

ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

arXiv:1505.04306

arxiv:1503.05425

arxiv:1504.04605

arXiv:1409.5500

ATLAS-CONF-2015-012

ATLAS-CONF-2014-036

CMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Phys. Rev. Lett. 112 (2014) 171801

Physics Letters B 729 (2014) 149

B2G-12-013

B2G-12-017

B2G-14-001

B2G-12-020

B2G-14-003

B2G-13-003

B2G-12-019

B2G-12-021

T′T′COMBINATION

- In preparation for the combination for a T′T′ legacy paper
  - T′T′→bW, tZ, tH (leptons+jets; CMS-PAS-B2G-12-015)
  - T′T′→bW (lepton+jets; CMS-PAS-B2G-12-017)
  - T′T′→tH; H→bb (all hadronic, CMS-PAS-B2G-14-002)
  - T′T′→tH; H→γγ (all hadronic, leptonic; CMS-PAS-B2G-14-00)
  - T′T′→bW (all hadronic; CMS-PAS-B2G-12-006)

B′B′ COMBINATION

- In preparation for the combination for a B′B′ legacy paper
  - B′B′→tW, bZ, bH (lepton+jets; CMS-PAS-B2G-12-019)
  - B′B′→tW, bZ, bH (multi-lepton+jets; CMS-PAS-B2G-13-003)
  - B′B′→tW, bZ (OS dilepton+jets; CMS-PAS-B2G-12-021)
  - B′B′→tW, bZ (SS dilepton+jets; CMS-PAS-B2G-12-020)
  - B′B′→tW (all hadronic; CMS-PAS-B2G-14-001)

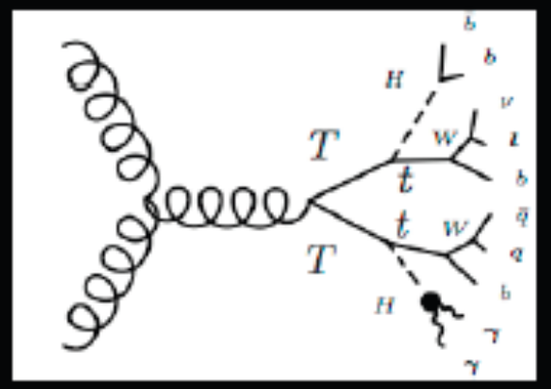
TT→tHtH, H→γγ

B2G-14-003

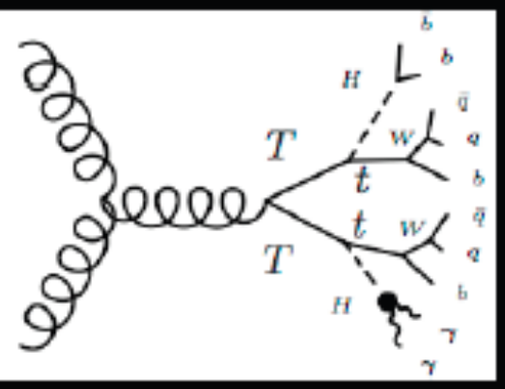
- Event Selection

Variable	Hadronic channel	Leptonic channel
$p_T^{lead\ photon}$	$> \frac{3}{4} m_{\gamma\gamma}$ GeV	$> \frac{1}{2} m_{\gamma\gamma}$ GeV
$p_T^{sublead\ photon}$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-

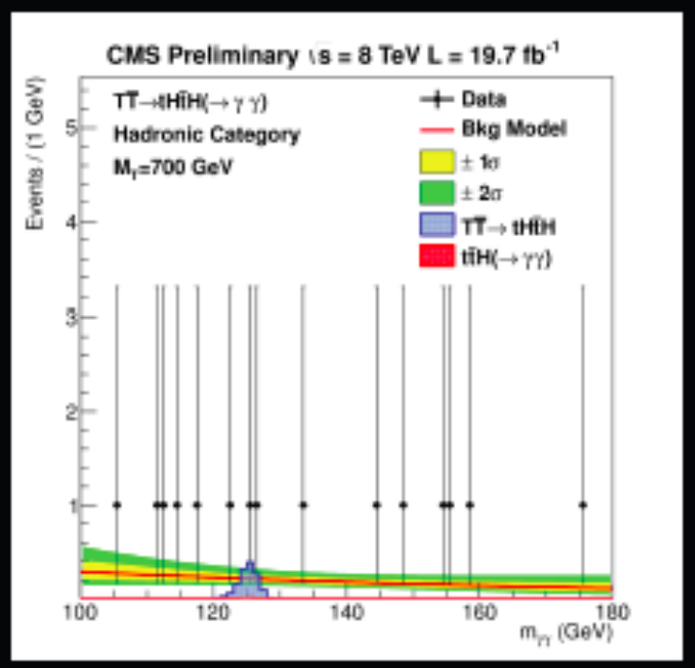
l+jets

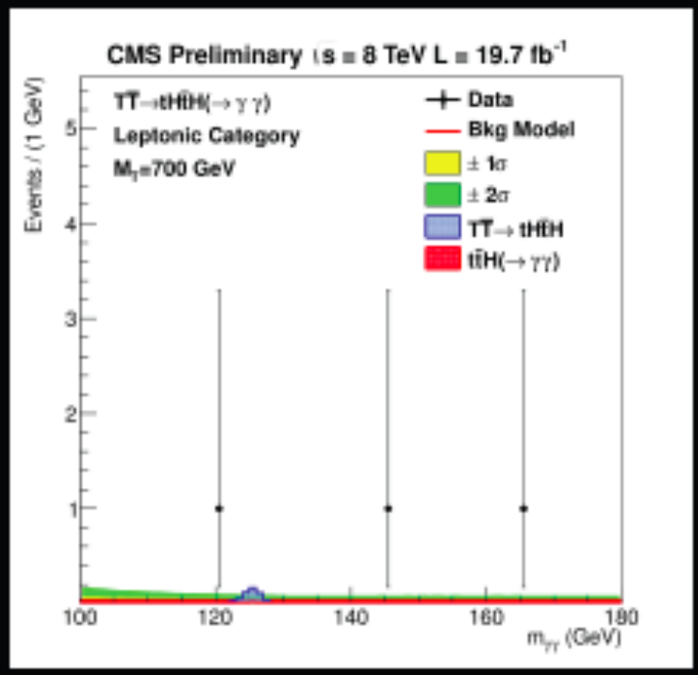


hadronic



- Exploit the **narrow resonance** of H→γγ, by fitting the peak in Mγγ distribution
- $S_T > 1000$ GeV

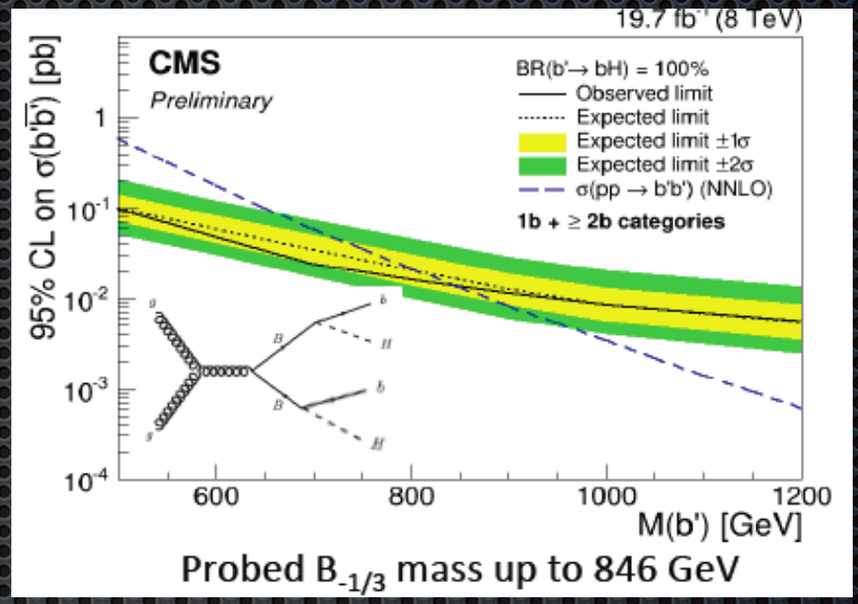


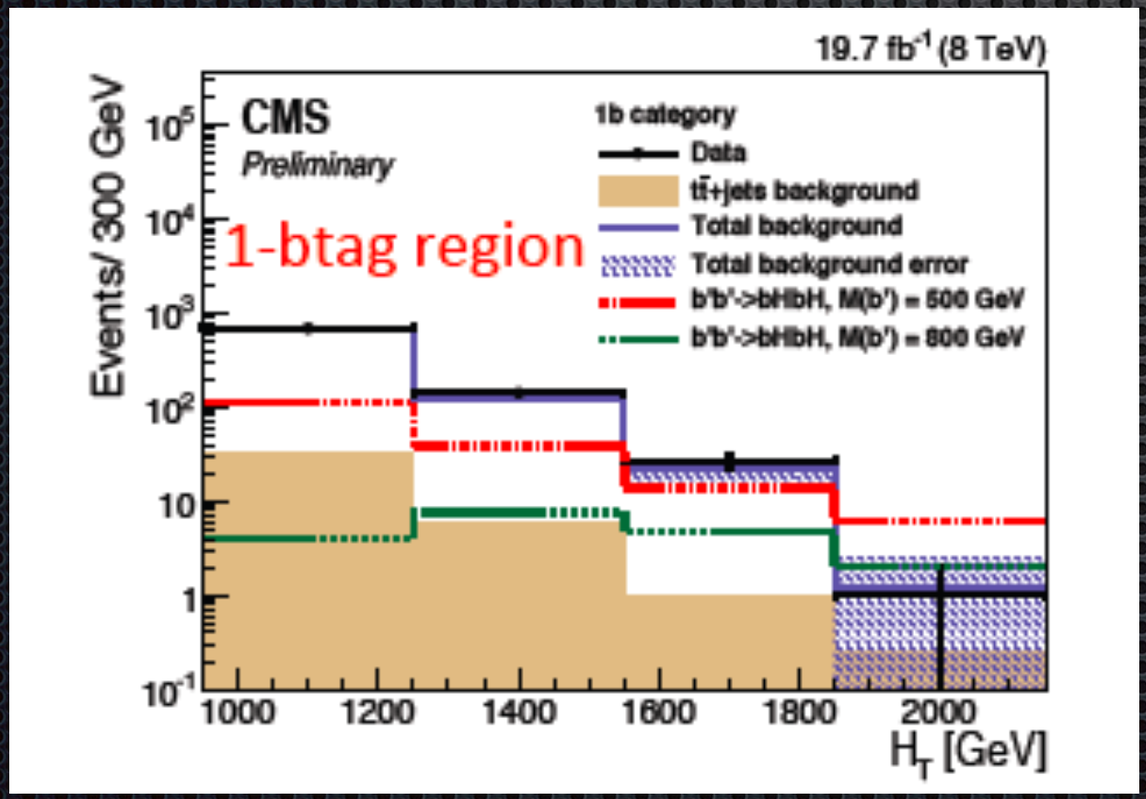


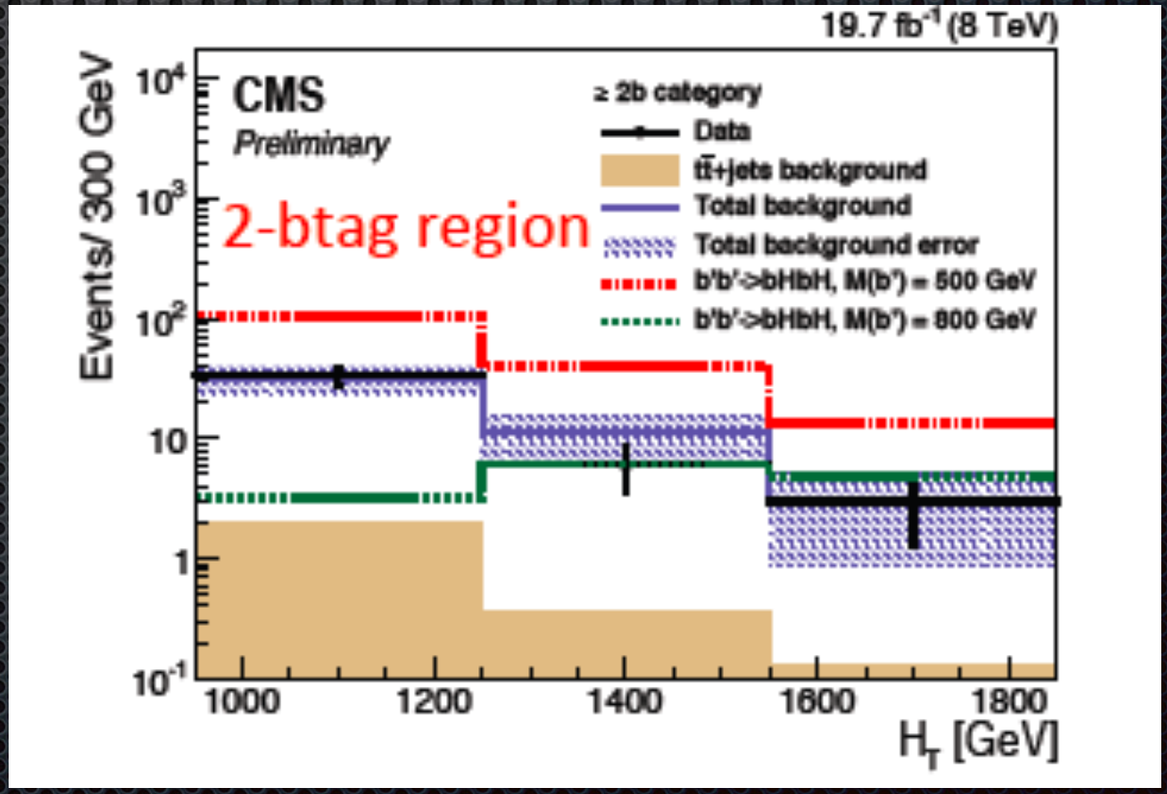
BB→bHbH

B2G-14-001

- Boosted Higgs-tag and two sub-jet b-tags
- ≥1 additional high pt b-jet (small cone)
- H_T discriminant variable







ATLAS SS dilepton analysis regions

Definition			Name	
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$				
$400 < H_{\mathrm{T}} < 700GeV$	$N_b = 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ0	
	$N_b = 2$		SRVLQ1	SR4t0
	$N_b \geq 3$		SRVLQ2	SR4t1
$H_{\mathrm{T}} \geq 700\ GeV$	$N_b = 1$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ3	
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ4	
	$N_b = 2$	$40 < E_{\mathrm{T}}^{\mathrm{miss}} < 100GeV$	SRVLQ5	SR4t2
		$E_{\mathrm{T}}^{\mathrm{miss}} \geq 100\ GeV$	SRVLQ6	SR4t3
	$N_b \geq 3$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	SRVLQ7	SR4t4
$e^{+}e^{+}$, $e^{+}\mu^{+}$, $\mu^{+}\mu^{+}$, $N_j \in [2,4]$, $\Delta\phi_{\ell\ell} > 2.5$				
$H_{\mathrm{T}} > 450\ GeV$	$N_b \geq 1$	$E_{\mathrm{T}}^{\mathrm{miss}} > 40\ GeV$	SRttee, SRtt$e\mu$, SRtt$\mu\mu$	

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

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

Notation:

$\mathbf{Isospin}_{\text{Hypercharge}}$

$T \to +2/3$
$B \to -1/3$
$X \to +5/3$
$Y \to -4/3$

} Electric charge

A general MG model for VLQ, coupling expressed as BR:

Full Lagrangian for $X_{5/3}$, T, B, $Y_{-4/3}$

$$\mathcal{L} = \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{T}_L Z_\mu \gamma^\mu u_L^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} [\bar{T}_L H t_R] \right\}$$

$$+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} [\bar{B}_R H d_L^i] \right\}$$

$$+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} + \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} + h.c.$$

Model-dependency "factored out"

$$\mathrm{BR}(Q \to V q_i) = \xi_V \, \zeta_i$$

$$\xi_W + \xi_Z + \xi_H = 1$$

$$\zeta_1 + \zeta_2 + \zeta_3 = 1$$

# of parameters:

- T : 5
- B : 5
- X : 3
- Y : 3

Feynrules, MadGraph & CalcHEP public implementations:

- http://feynrules.irmp.ucl.ac.be/
- http://hepmdb.soton.ac.uk/

(complete model, and specific representations).

T pair production $\longrightarrow$ 6 possible decays: W^+j W^+b Zj Zt Hj Ht

$$PP \to T\bar{T} \to \begin{pmatrix} W^+jW^-j & W^+jW^-\bar{b} & W^+jZj & W^+jZ\bar{t} & W^+jHj & W^+jH\bar{t} \\ W^+bW^-j & W^+bW^-\bar{b} & W^+bZj & W^+bZ\bar{t} & W^+bHj & W^+bH\bar{t} \\ ZjW^-j & ZjW^-\bar{b} & ZjZj & ZjZ\bar{t} & ZjHj & ZjH\bar{t} \\ ZtW^-j & ZtW^-\bar{b} & ZtZj & ZtZ\bar{t} & ZtHj & ZtH\bar{t} \\ HjW^-j & HjW^-\bar{b} & HjZj & HjZ\bar{t} & HjHj & HjH\bar{t} \\ HtW^-j & HtW^-\bar{b} & HtZj & HtZ\bar{t} & HtHj & HtH\bar{t} \end{pmatrix}$$

(only) 36 possible combinations of decays into SM particles!

each one with its peculiar kinematics

Example: doublet $2_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$ coupled to third family

2 parameters
M , λ_t

trade for

Physical parameters:
Heavy mass m_T (or m_X)
Mixing angle $s_R = \sin\theta_R \sim \lambda_t \dfrac{v}{m_T}$

heavy-light couplings

$X_L t_L W \to -s_L$
$X_R t_R W \to -s_R$
$T_L b_L W \to s_L$
$T_L t_L Z \to 2 s_L c_L$
$T_R t_R Z \to -s_R c_R$
$T_L t_R H \to s_R c_R$
$T_R t_L H \to \dfrac{m_t}{m_T} s_R c_R$

Correlations!

light-light couplings

$t_L b_L W \to c_L$
$t_L t_L Z \to c_L^2 - s_L^2$
$t_R t_R Z \to -s_R^2$
$ttH \to c_R^2$

s_L further suppressed and not independent:

$$\tan\theta_L = \frac{m_t}{m_T} \tan\theta_R$$