Heavy T' searches @ LHC

José David Ruiz-Alvarez

On behalf of the ATLAS and CMS collaborations

Outline

- General overview

- Pair production searches
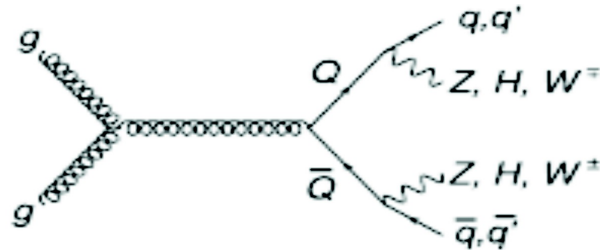
- Single production searches

- Conclusion

Heavy Quarks

- Fourth generation → Sequential T, B added to SM

- Vector Like Quarks → Not sequential generation.
  - Generic T, B, X, Y, …
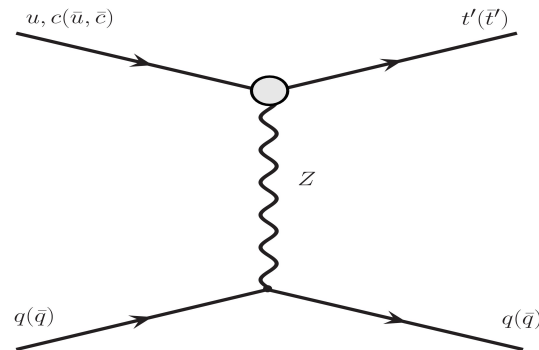 - Equal under left or right transformations (Vector)

Production/Decay Modes
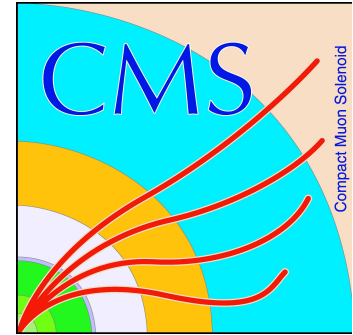
- Production:
  - Pair:
  - Single:

- Decay: T → bW, tH, tZ
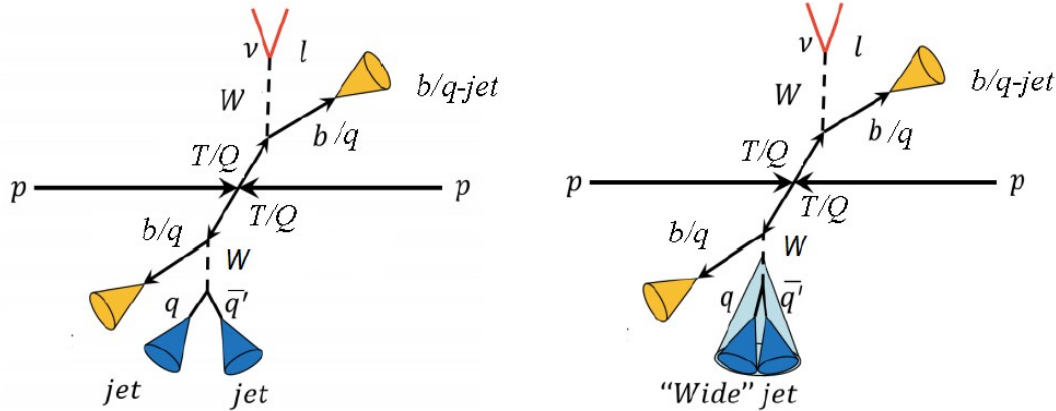- Searches commonly focused on a production channel with a specific decay

Pair production searches

T → bW

CMS PAS B2G-12-017

Main bkgs:
SM top
V + jets
VV
Multijets

Selection:
Muons: pT(mu) > 45 GeV,
|eta(mu)|<2.1, ET^{MIS} > 20 GeV
Electrons: pT(e) > 30 GeV,
|eta(e)|<2.5, ET^{MIS} > 30 GeV
All events:
1 CA8 jet with 2 subjets and
60 GeV < M < 100 GeV
All AK5 jets pT>30 GeV,
CA8 jet pT>200 GeV
pT(j1) > 120 GeV, pT(j2) > 90 GeV
pT(j3) > 50 GeV

CMS Preliminary, $L=19.7$ fb^{-1} l+jets, $\sqrt{s}=8$ TeV

- observed limit (95% C.L.)
- expected limit (95% C.L.)
- central 1σ expected limit
- central 2σ expected limit
- NNLO $T\bar{T}$

Limit on $T\bar{T}$ cross section [pb]

M_T [GeV]

T → bW
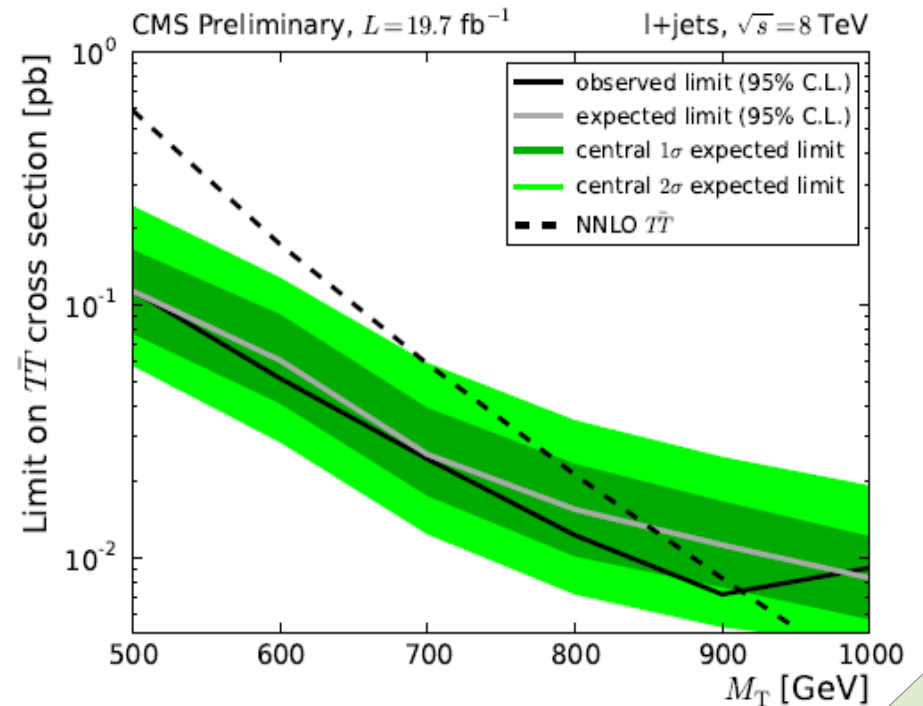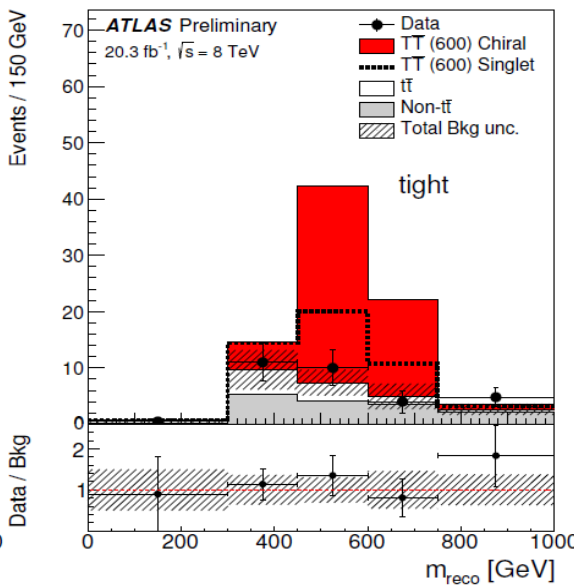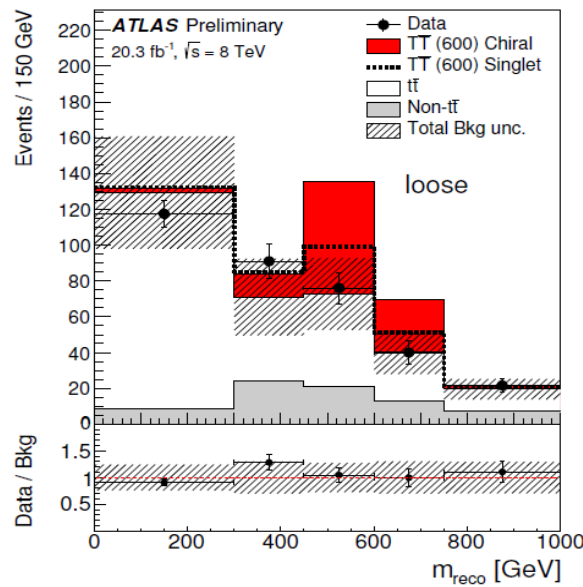
Search for generic TT → Wb+X
optimized for TT → WbWb case
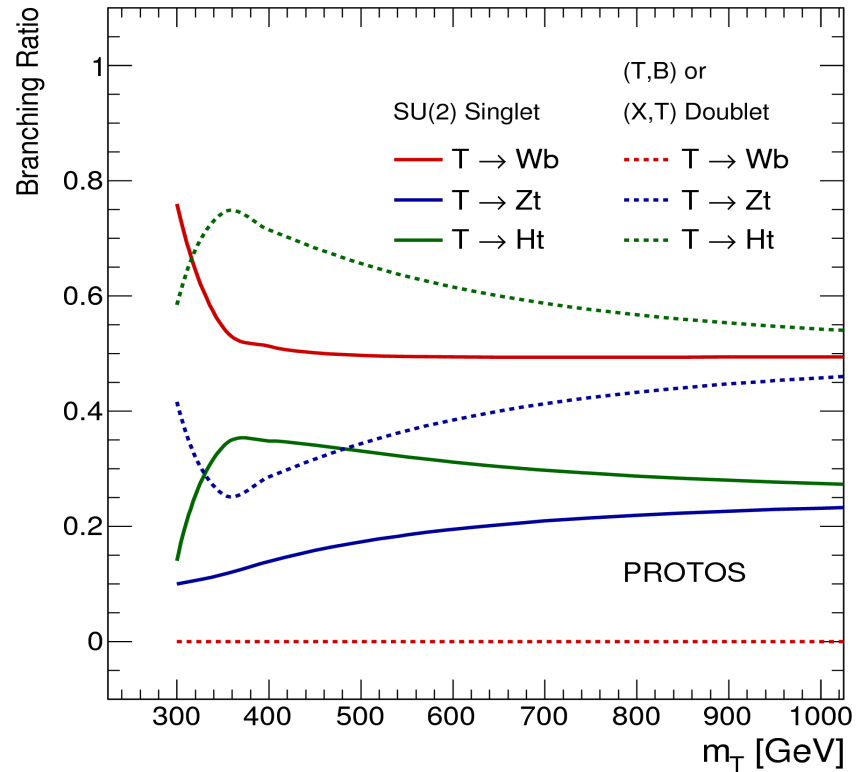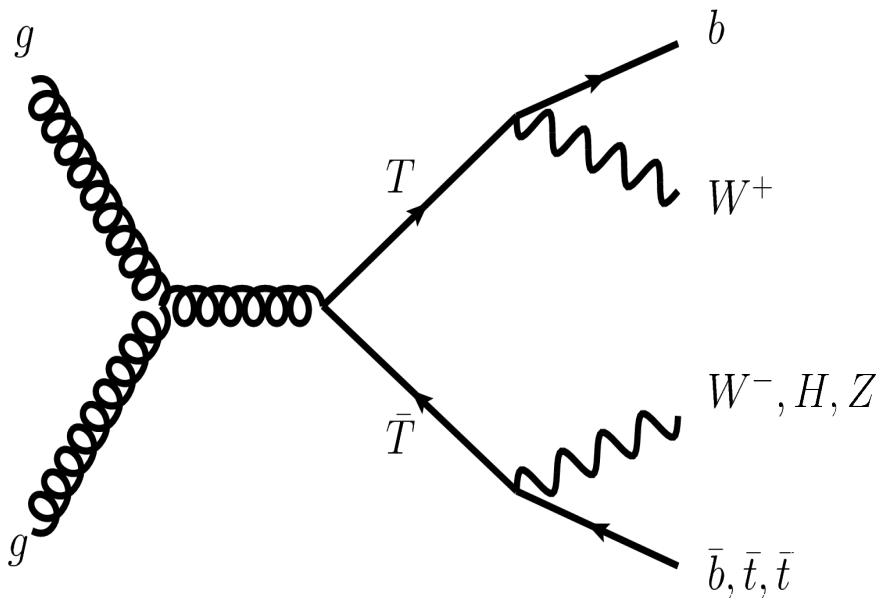
Branching ratio for the different decay modes
as a function of a vector-like T quark mass

- 1 leptonic W, 1 hadronic W
- Hadronic W: Type I → boosted, Type II → resolved
- m_{RECO}: from hadronic W and one b-jet

| Selection	Requirements
Preselection	One electron or muon $E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T > 60$ GeV ≥ 4 jets, ≥ 1 b-tagged jets
Loose selection	Preselection ≥ 1 W_{had} candidate (type I or type II) $H_T > 800$ GeV $p_T(b_1) > 160$ GeV, $p_T(b_2) > 110$ GeV (type I) or $p_T(b_2) > 80$ GeV (type II) $\Delta R(\ell, v) < 0.8$ (type I) or $\Delta R(\ell, v) < 1.2$ (type II)
Tight selection	Loose selection $\min(\Delta R(\ell, b_{1,2})) > 1.4$, $\min(\Delta R(W_{had}, b_{1,2})) > 1.4$ $\Delta R(b_1, b_2) > 1.0$ (type I) or $\Delta R(b_1, b_2) > 0.8$ (type II) $\Delta m < 250$ GeV (type I)

Event selection for TT → Wb+X analysis

T → tH

Search for generic TT → tH + X
not optimized for a specific case

Main bkgs:
SM top
V + jets
VV
Multijets
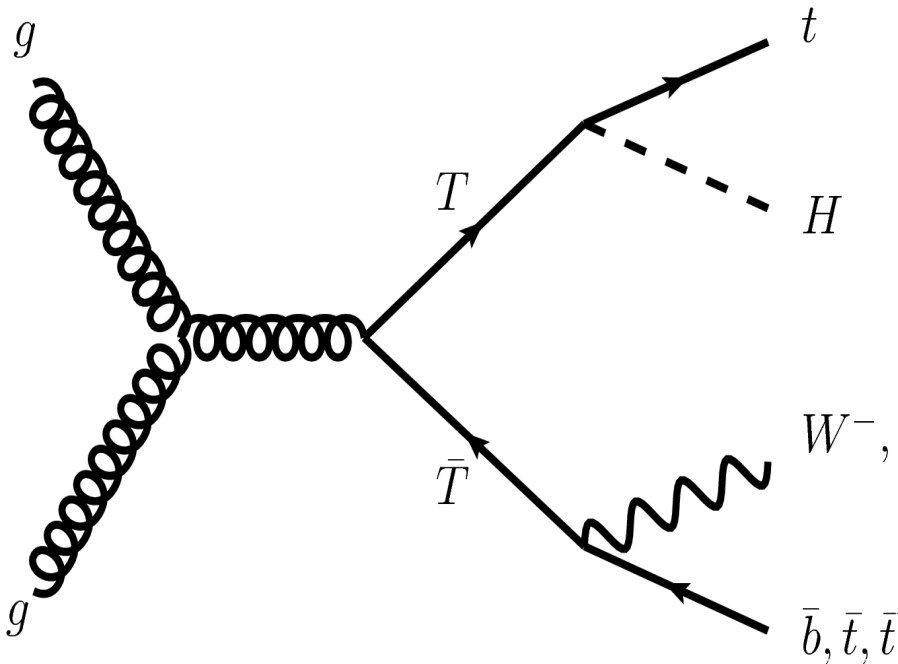
Selection:
Several categories to increase sensitivity
to different channels: TT → HtHt, ZtHt, WbHt
Used definition:

$$M_{bb}^{\mathrm{min}\Delta R} < 100 \text{ GeV } (\text{"low } M_{bb}^{\mathrm{min}\Delta R}\text{"})$$
$$M_{bb}^{\mathrm{min}\Delta R} > 100 \text{ GeV } (\text{"high } M_{bb}^{\mathrm{min}\Delta R}\text{"})$$

To split categories.
Eight total categories:

$(5\,\mathrm{j}, 2\,\mathrm{b})$ $(5\,\mathrm{j}, 3\,\mathrm{b})$ $(5\,\mathrm{j}, \geq 4\,\mathrm{b})$

$(\geq 6\,\mathrm{j}, 2\,\mathrm{b})$

$(\geq 6\,\mathrm{j}, 3\,\mathrm{b}, \text{low } M_{bb}^{\mathrm{min}\Delta R})$, $(\geq 6\,\mathrm{j}, 3\,\mathrm{b}, \text{high } M_{bb}^{\mathrm{min}\Delta R})$

$(\geq 6\,\mathrm{j}, \geq 4\,\mathrm{b}, \text{low } M_{bb}^{\mathrm{min}\Delta R})$, $(\geq 6\,\mathrm{j}, \geq 4\,\mathrm{b}, \text{high } M_{bb}^{\mathrm{min}\Delta R})$
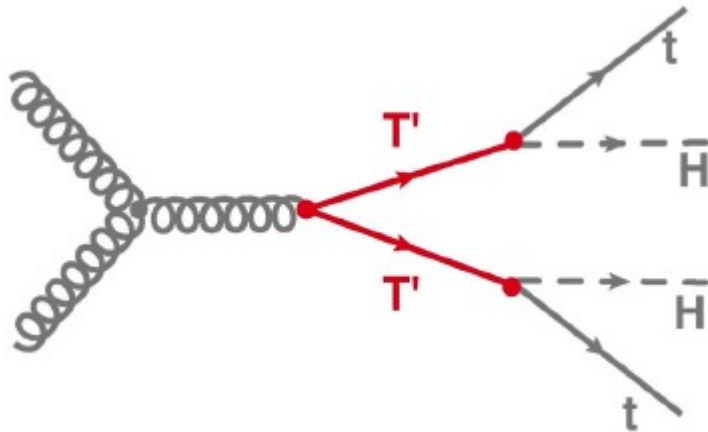

Discriminating variable: HT(jets+leptons)
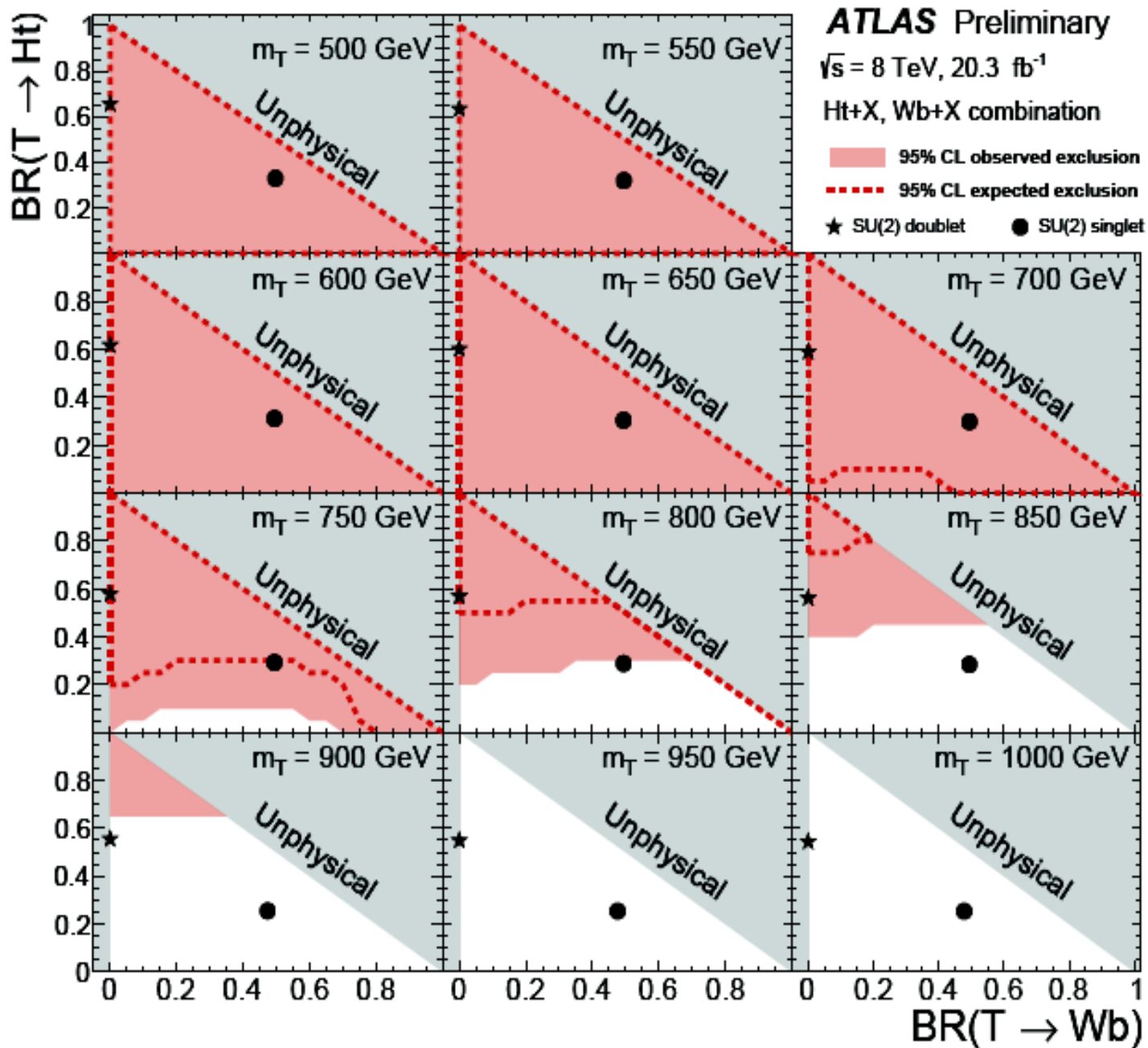
Observed (red filled area) and expected (red dashed line) at 95% CL exclusion from the combination of TT → Wb+X and TT → Ht+X searches for different values of the vector-like T mass.

T → tH

T' → tH, T' → tZ, and T' → bW

(Optimized for T'T' → tHtH)

top jet   Higgs jet

Boosted topologies

Selection:
HT > 720 GeV
At least 2 CA15 jets with pT >150 GeV
and |eta| < 2.5
At least 1 CA15 jet top tagged with
at least 1 b subjet
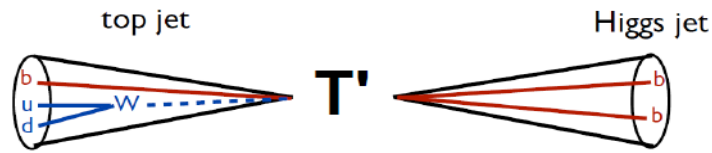At least 1 CA15 jet Higgs tagged with
at least 2 b subjets, and M > 60 GeV
Two categories:
    1 Higgs-tagged CA15 jet
    At least 2 Higgs-tagged CA15 jets

Main bkgs:
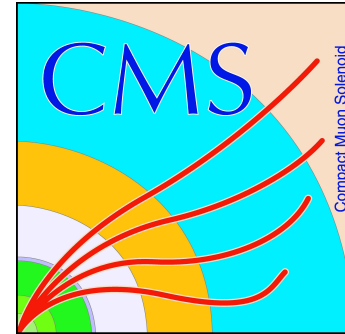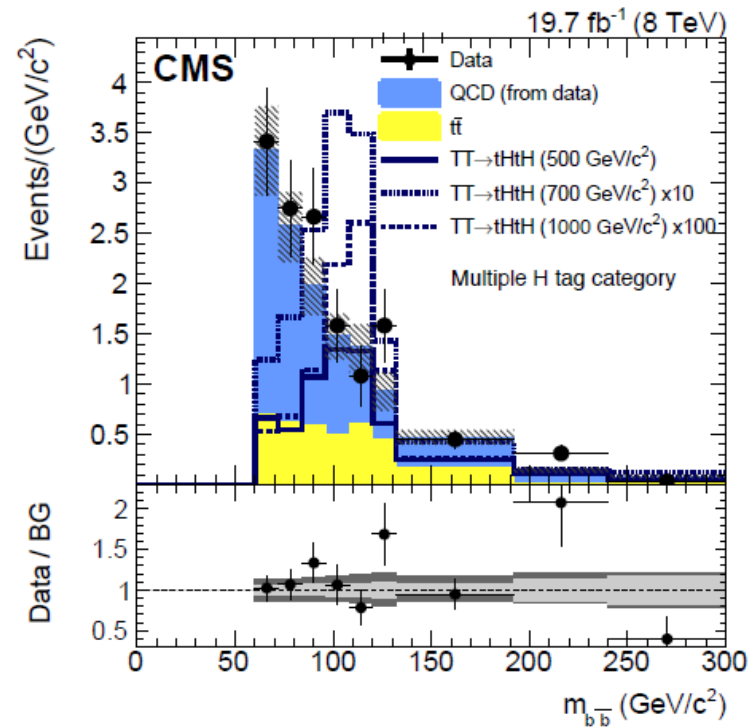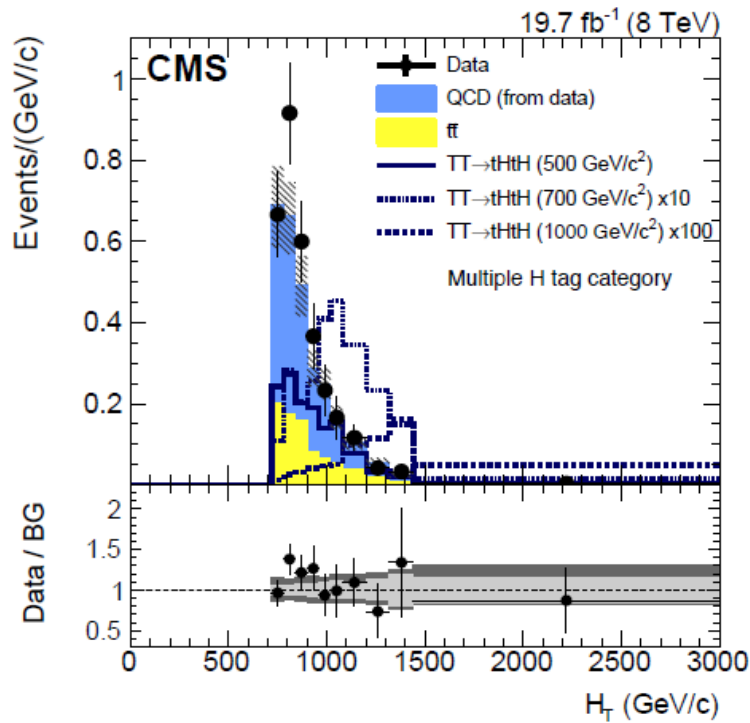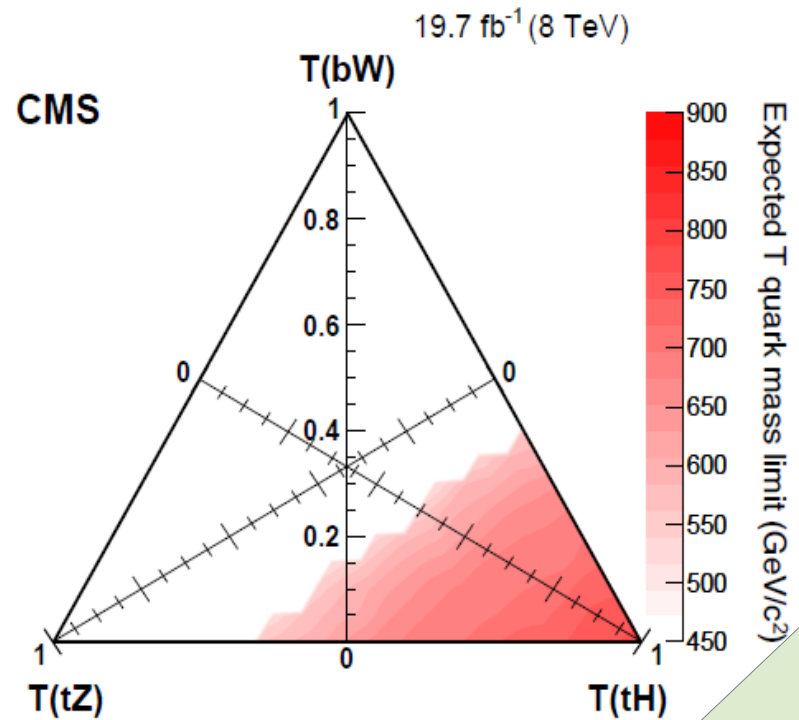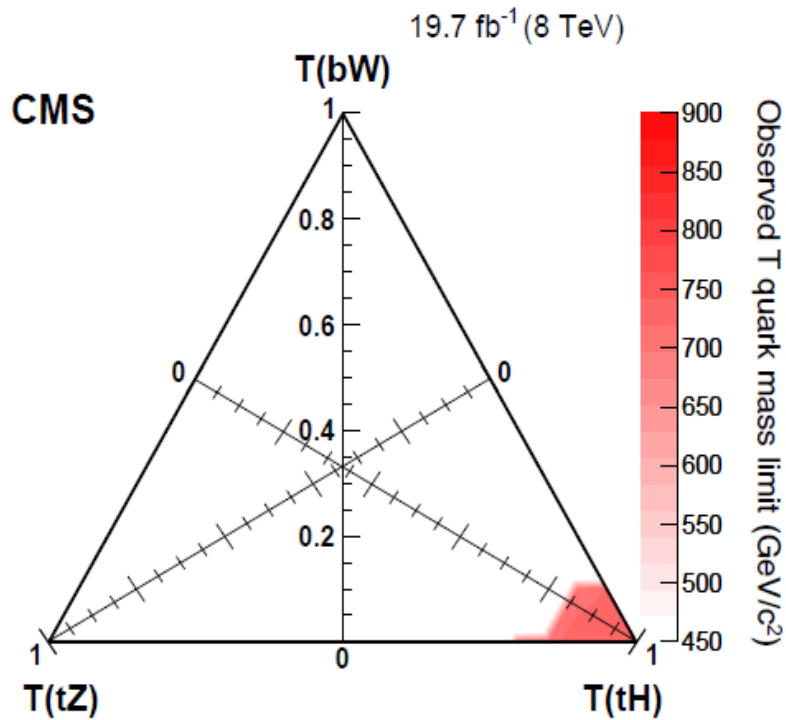SM top (ttbar mainly)
Multijets

Multijet bkg estimation:
ABCD method inverting
Higgs and top tagging

Multi-Higgs tagged category discrimination variables

T → tH

TT → tH + X, H → γγ
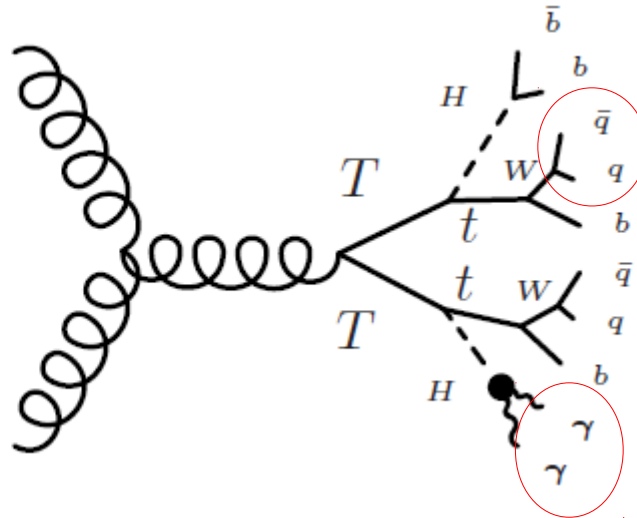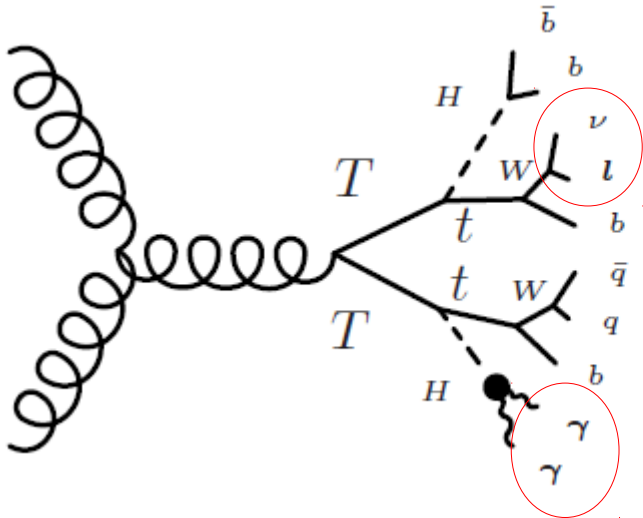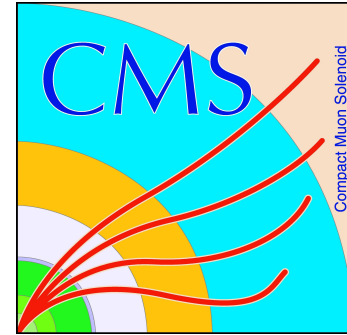
Main bkgs:
γγ+jets
γγ+top
ttbarH

Bkg estimation:
Control sample from one loose photon not passing the selection

Table 1: Final selection for hadronic and leptonic channel

Variable	Hadronic channel	Leptonic channel
$p_T(\gamma_1)$	$> \frac{3}{4}m_{\gamma\gamma}$ GeV	$> \frac{1}{2}m_{\gamma\gamma}$ GeV
$p_T(\gamma_2)$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-

Scalar sum of the pT of all objects

CMS Preliminary √s= 8 TeV L=19.7 fb⁻¹

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T → tZ
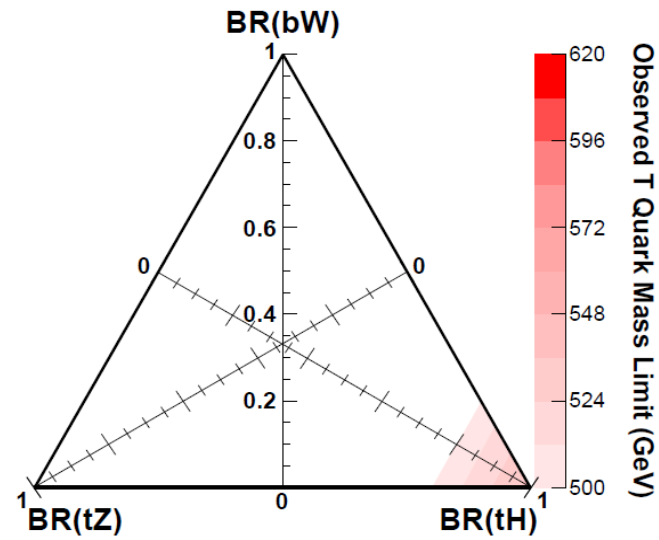
Search for generic TT → tZ + X
not optimized for a specific decay

l+l- → |m(ll)-m(Z)|<10 GeV

Main bkgs:
SM top
Z+jets
VV

Event selection			
Z boson candidate preselection			
≥ 2 central jets			
$p_T(Z) \geq 150$ 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
$H_T(\text{jets}) \geq 600$ GeV	≥ 1 fwd. jet	–	≥ 1 fwd. jet
Final discriminant			
$m(Zb)$		$H_T(\text{jets+leptons})$	

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T → tZ, tH, bW

Selection:

→ Single lepton channel

pT(mu) > 32 GeV, |eta(mu)| < 2.1

pT(e) > 32 GeV,

|eta(e)| < 1.44, 1.57 < |eta(e)| < 2.5

pT(j1) > 120 GeV, pT(j2) > 90 GeV

pT(j3) > 50 GeV

From j1, j2, j3 one should be a W-jet (CA8, pT>200 GeV, 60 GeV<M<130 GeV) or there is a j4 with pT(j4) > 35 GeV

|eta(jets)| < 2.4, ΔR(jj) > 0.4

pT^{Miss} > 20 GeV

+ BDT

→ Multi-lepton channel (4 categories)

pT(l) > 20 GeV, M(ll)>20 GeV,

pT^{Miss} > 30 GeV, at least one b-jet

Dilepton (Opp. Sign): (bWbW) 2,3 jets

Dilepton (Opp. Sign): (Z → ll) >=5 jets 2 b-jets

Dilepton (Sam. Sign): (tZ, tH) >= 3 jets

Trilepton: (tZ, tH) >= 3 jets

All decays:

TT → tZtZ, tZtH, tZ bW, tHtH, bWtH, bWbW

Main bkgs:

SM top (ttbar mainly)

V+jets

ttbar + V

VV

Multijets

CMS preliminary $\sqrt{s}$ = 8 TeV 19.6 fb^{-1}

Expected T Quark Mass Limit [GeV]

CMS preliminary $\sqrt{s}$ = 8 TeV 19.6 fb^{-1}

Observed T Quark Mass Limit [GeV]
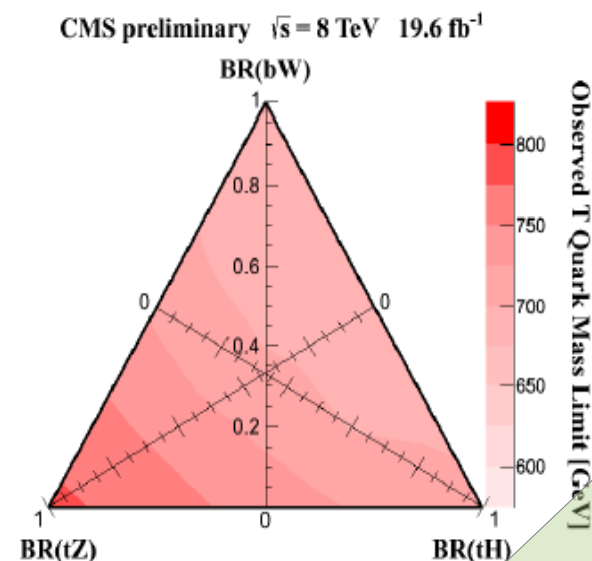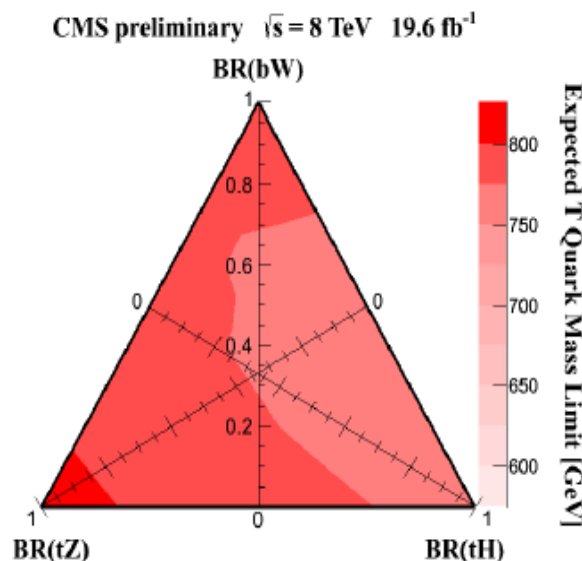
T → tH,tZ,bW

B-jets + a pair of same charge leptons (T pairs or $T_{5/3}$ single or pair)

Covered by Romain Kukla in SS talk

Main bkgs:

SM →
VV, VVjj, VVtt,
Vtt, VH, ttH, tH, ───► MC

Instrumental →
Misidentified jets
Misidentified l-charge ───► Matrix method
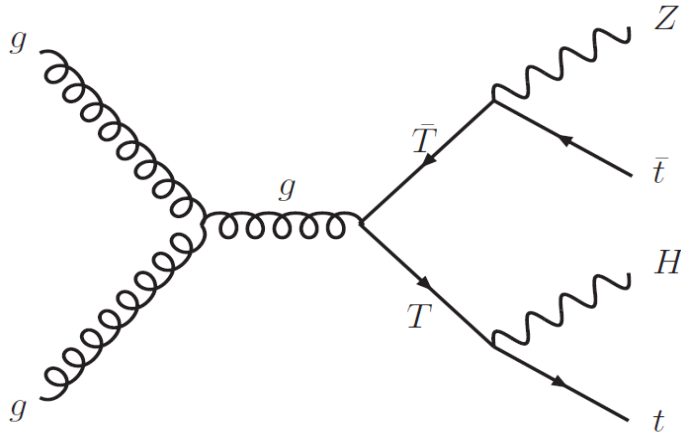
Selection:

2 leptons with same charge, no veto extra leptons

N(j) >= 2

N(b) >= 1

pT(Iso e,mu)>24 GeV

pT(NonIso e)>60 GeV

pT(NonIso mu)>36 GeV

ET^{Miss} > 40 GeV

HT > 400 GeV

m_{ee} >15 GeV

$|m_{ee}-m_Z|$ > 10 GeV

───► Jets + leptons

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

Categories to optimize the selection for the different BSM processes: VLQ, 4-tops and 2-tops
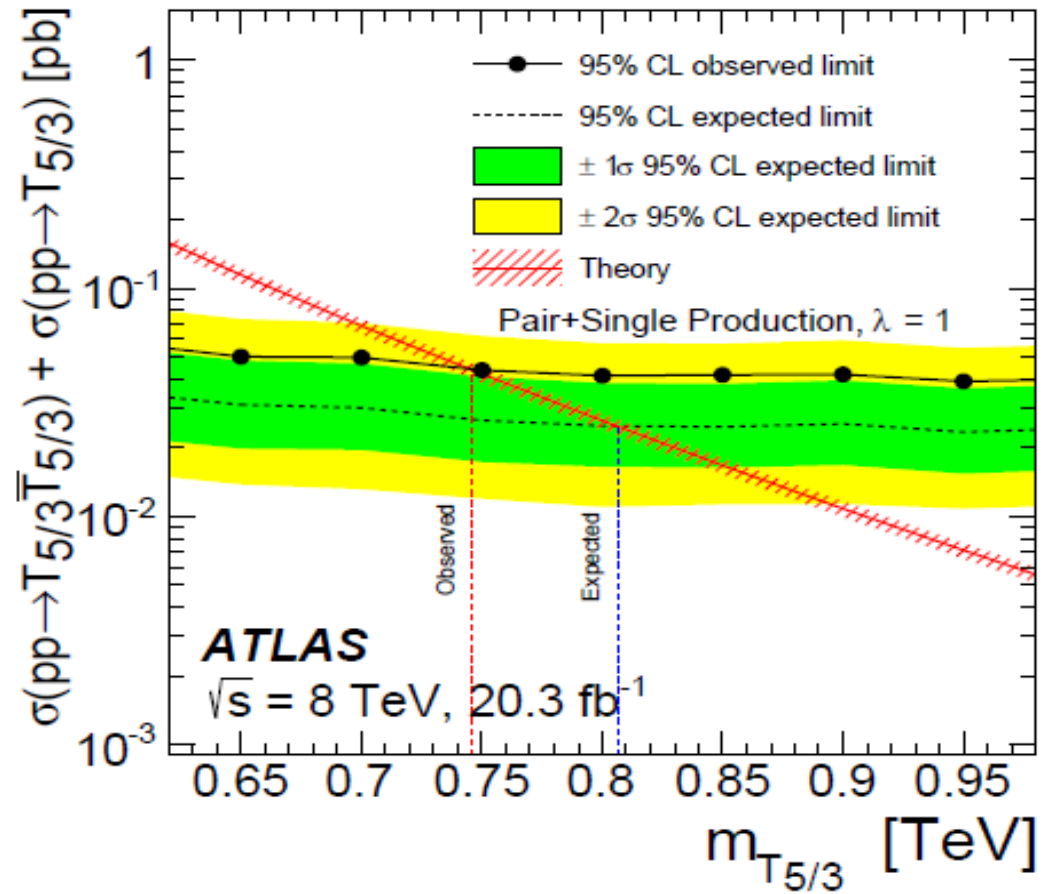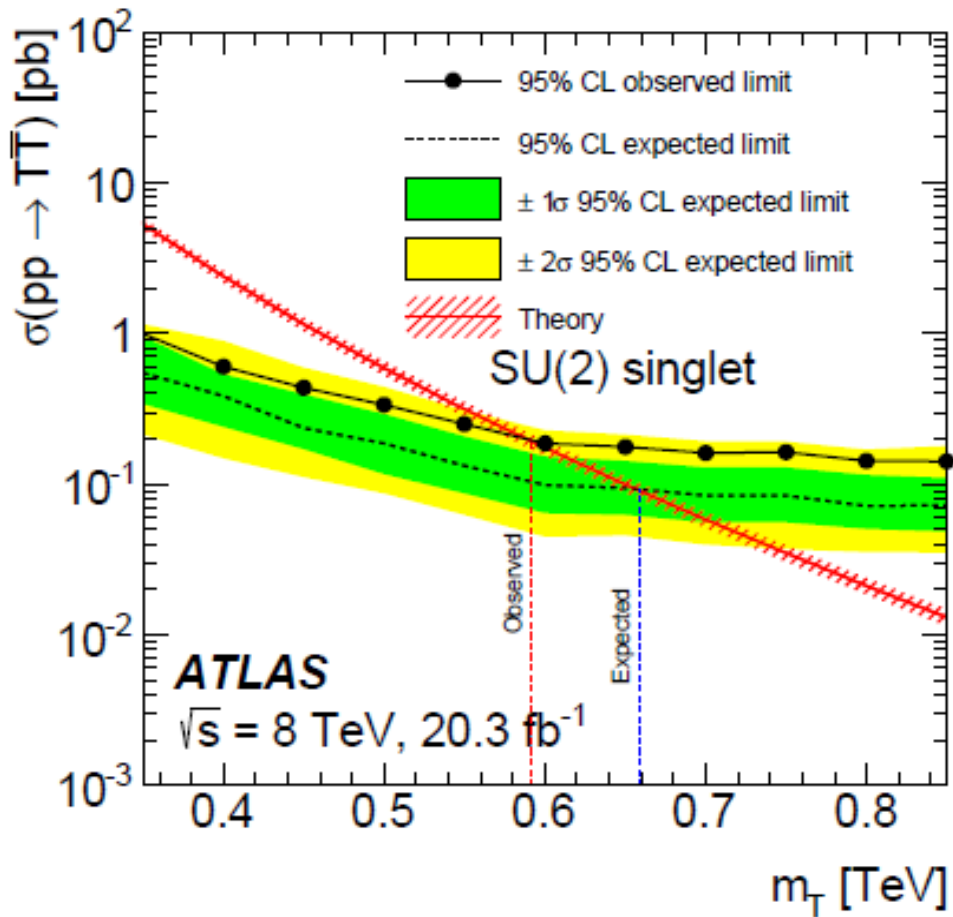
Observed and expected limits on the cross section of pair produced vector-like T-quark and on the sum of the cross section of single and pair produced vector-like $T_{5/3}$-quark as function of the mass. λ parameter control the interaction between $T_{5/3}$ and SM top.

$T_{5/3} \to tW$

Limits using same analysis for B → Wt + X

Process:
BB → Wt,Wt/Zb/Hb
One lepton:
Electron and muon events

Preselection:
$pT(lepton) > 25$ GeV
$ET^{Miss} > 20$ GeV
$ET^{Miss}+MT > 60$ GeV
At least 4 jets:
$pT(j) > 25$ GeV
$HT > 300$ GeV
V: $pT(jj)>120$, $\Delta R(jj)<1.0$

Main bkgs:
Multijets
W+jets
Ttbar
Z+jets, VV
ttbar+V

Data Region	N_{jets}	N_V	N_{bjets}	H_T (GeV)
SR (cuts-based)	≥ 6	≥ 1	≥ 1	> 800
SR (BDT)	≥ 6	≥ 1	≥ 1	> 500
WCR1	$= 4, 5$	-	$= 0$	-
TCR1	$= 4, 5$	-	≥ 1	-
WCR2	≥ 6	-	$= 0$	-
TCR2	≥ 6	-	≥ 1	< 500
TCR3	≥ 6	$= 0$	≥ 1	-

signal regions (SR) control regions (CR) number of hadronic W/Z candidates (N_V)

TCR1 through TCR3 → modeling and estimation of → $t\bar{t}$ background

WCR1 and WCR2 → modeling and estimation of → W+jets

ATLAS
$\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
$T_{5/3}T_{5/3} \to WbWb$

— Observed 95% CL limit
···· Expected 95% CL limit
Expected ±1 σ
Expected ±2 σ
Theory (NNLO+NNLL)
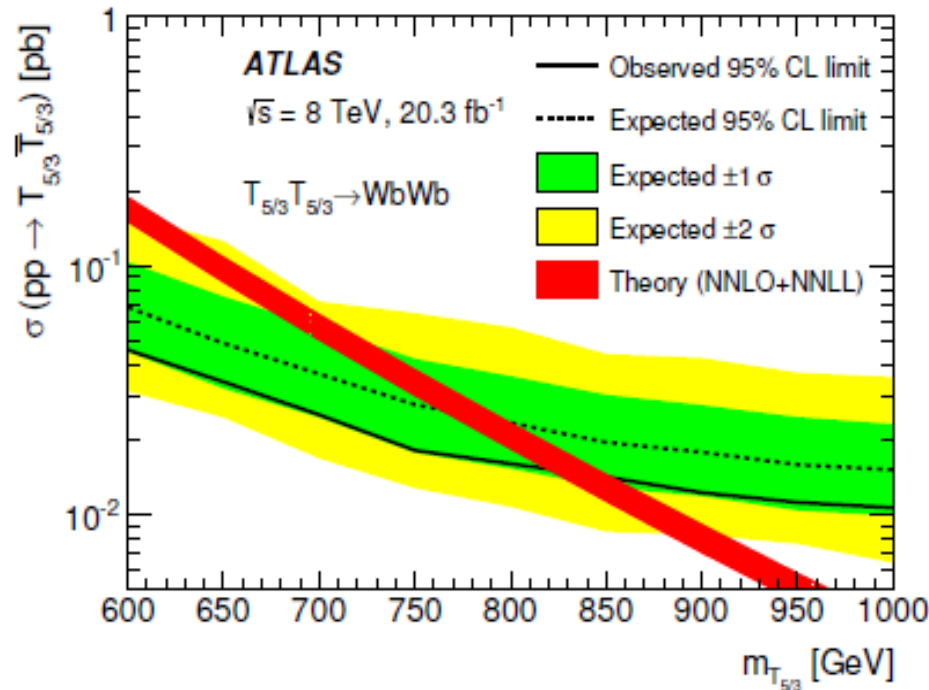
BDT analysis:
12 variables
HT, pT(l),
Njets, MT,...

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$T_{5/3} \rightarrow tW$
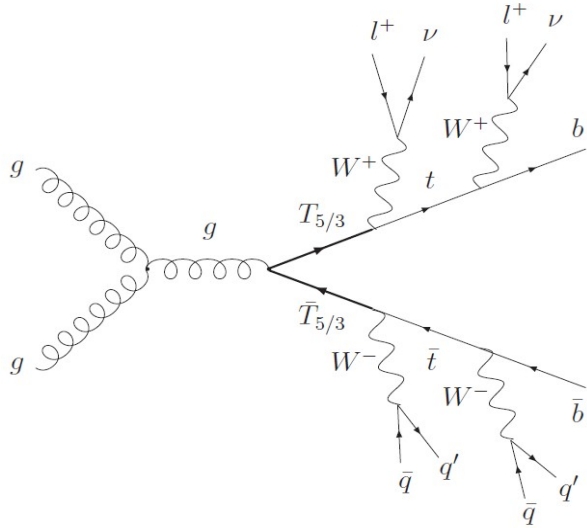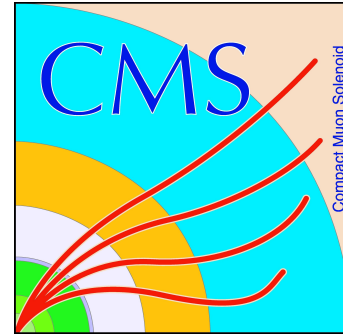
Main bkgs:

SM →
VV, VVV,
VVtt, Vtt → MC

Prompt-leptons (mis)
Non-prompt leptons → Tight-loose method

Selection:
At least 2 SS leptons
Quarkonia veto: M(ll) > 20 GeV
M(ll) < 76 GeV or M(ll) > 106 GeV
N(constituents) >= 5
e or mu → 1 constituent
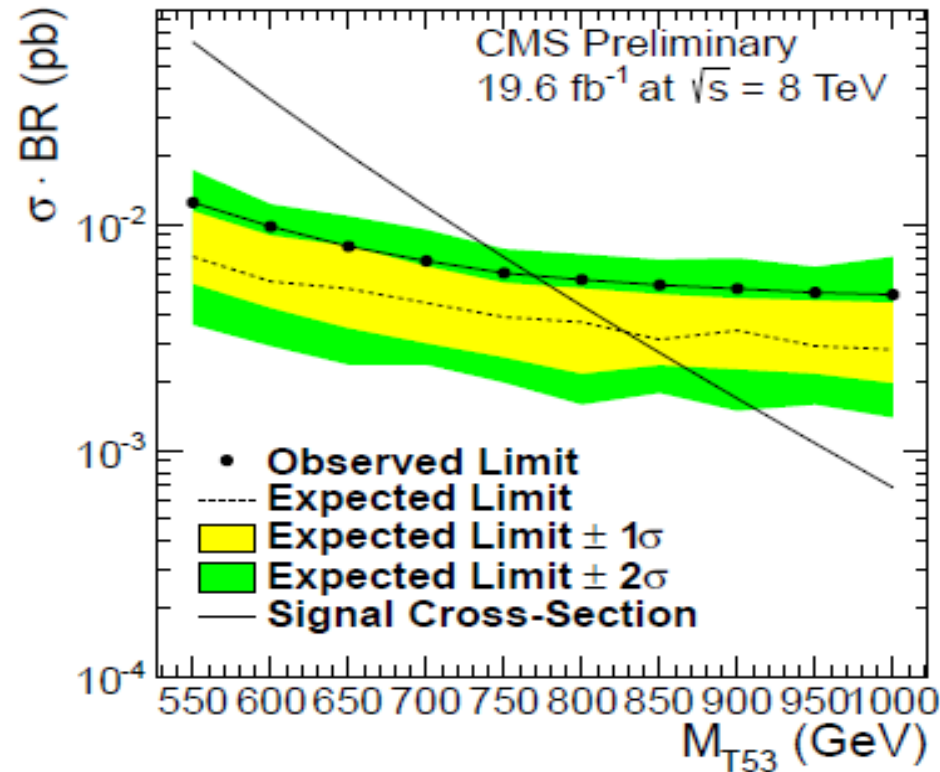AK5 jet → 1 constituent
CA8 W-tagged jet → 2 constituents
CA8 top-tagged jet → 3 constituents
HT > 900 GeV

→ Jets + leptons

Single production searches
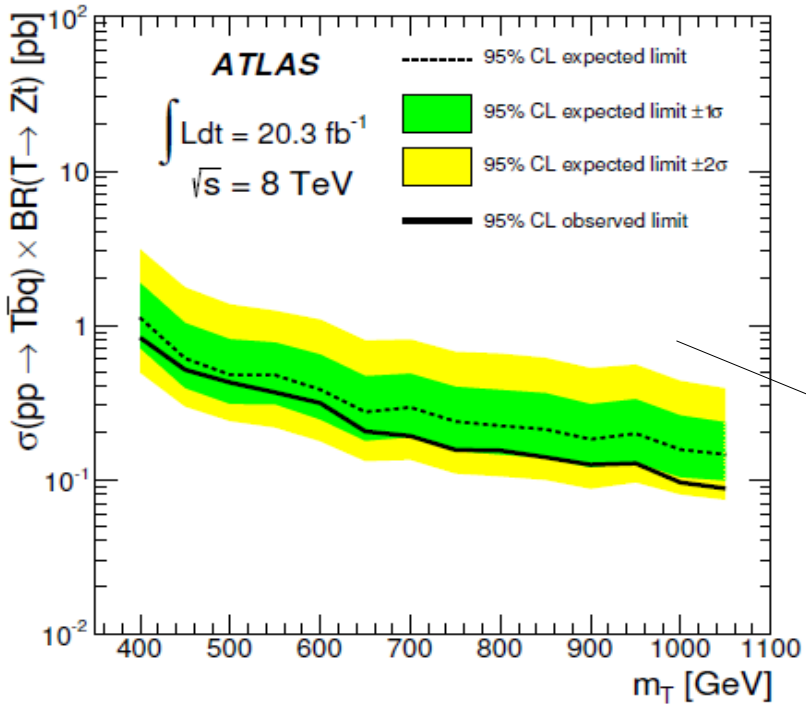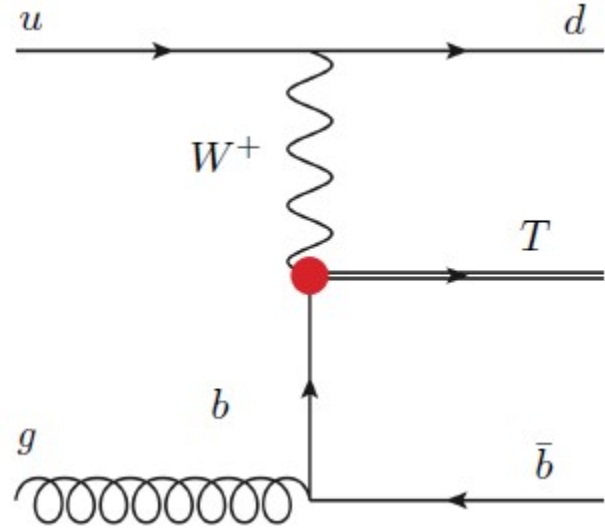
T → tZ

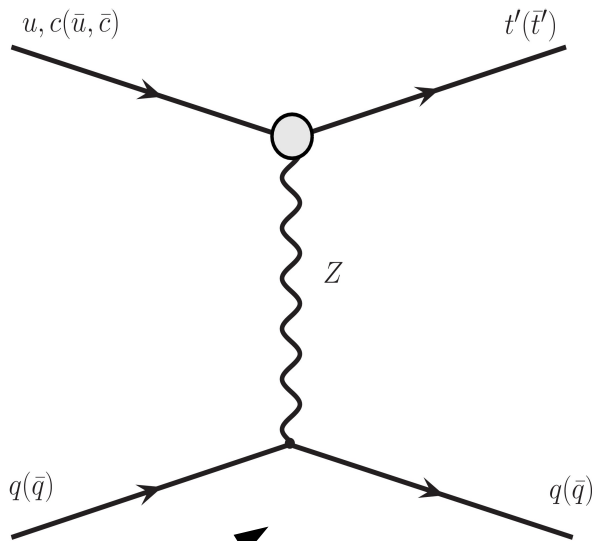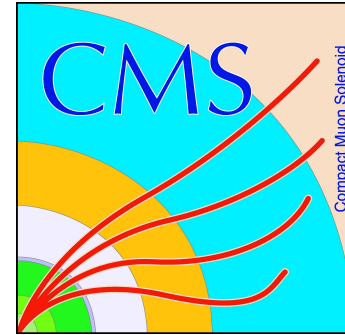| Event selection			
Z boson candidate preselection			
≥ 2 central jets			
$p_T(Z) \geq 150$ GeV			
Dilepton channel		Trilepton channel	
= 2 leptons		≥ 3 leptons	
≥ 2 b-tagged jets		≥ 1 b-tagged jet	
Pair production	Single production	Pair production	Single production
$H_T(\text{jets}) \geq 600$ GeV	≥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

Main bkgs:
WZ
ttbar+V
Z+jets

Upper limits on specific model parameters controlling production and decay

T → tH

Full hadronic final state:
T → tH → bWbb → bjjbb

Main bkgs:
SM top (ttbar mainly)
Multijets
VV

$u, c(\bar{u}, \bar{c})$

$t'(\bar{t}')$

Z

$q(\bar{q})$

$q(\bar{q})$

Different production
than ATLAS

Discrimination variable:
5 jets invariant mass

Forward jet

Pheno study

Five jets invariant mass for backgrounds and signal (stacked) after full event selection.
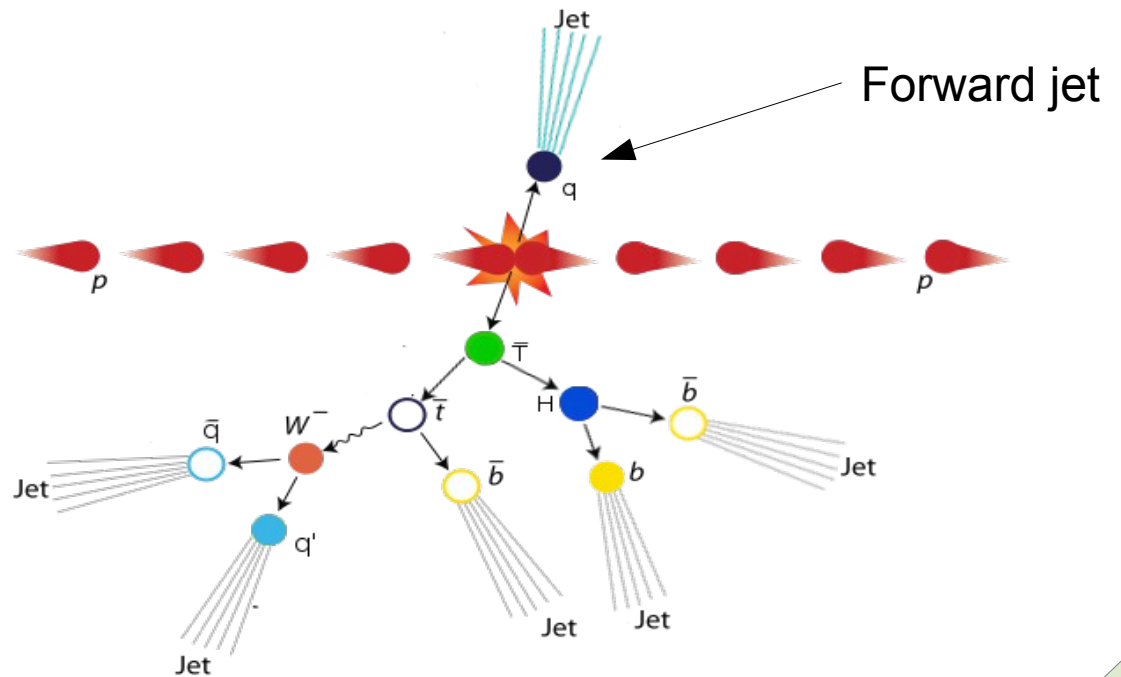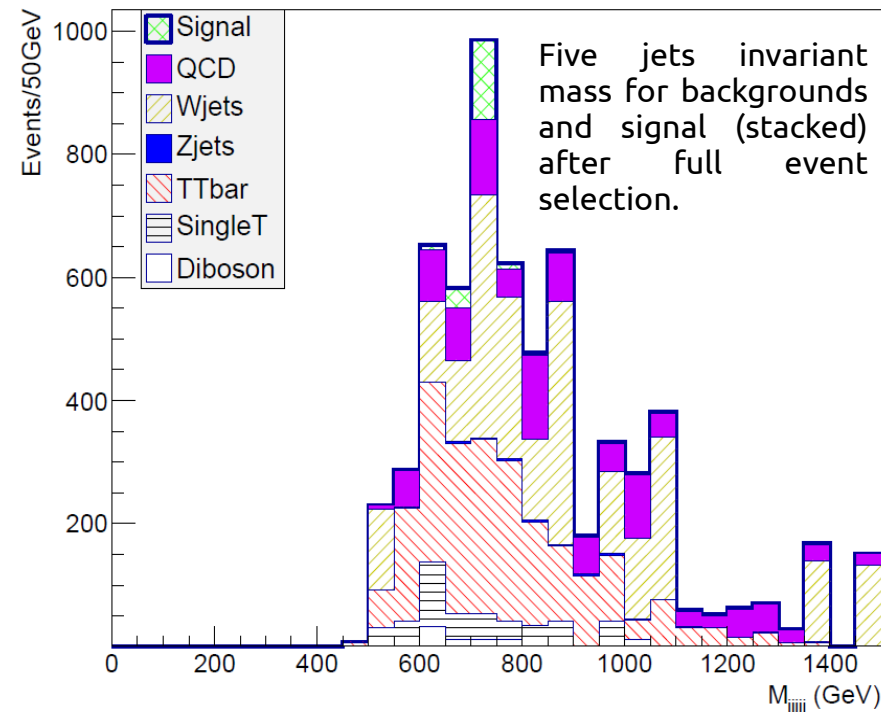
- 20 fb^{-1} @ 8 TeV → Full hadronic channel: Highest expected number of events for the signal [~1000 events] → Full mass reconstruction of T'
- Background reduction: Higgs and top as handles.
- Event selection: Keep high efficiencies on signal.

S. Beauceron, G. Cacciapaglia, A. Deandrea, J. Ruiz-Alvarez
Phys.Rev. D90 (2014) 11, 115008. arXiv: 1401.5979
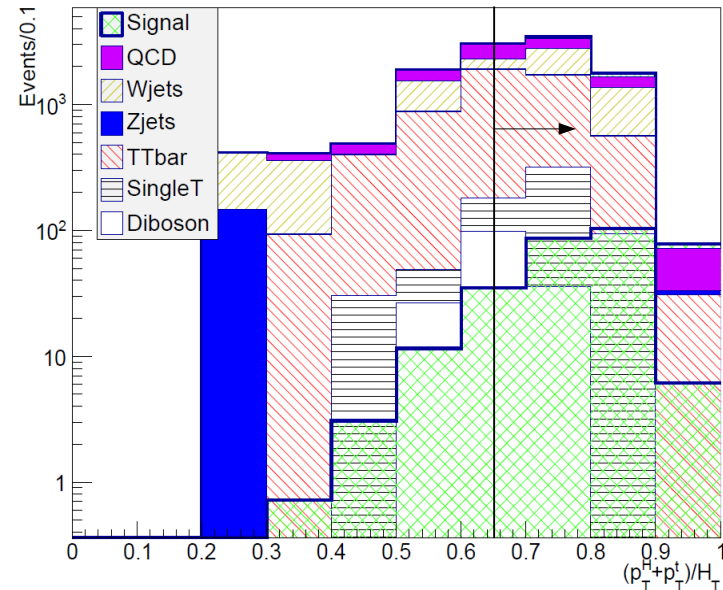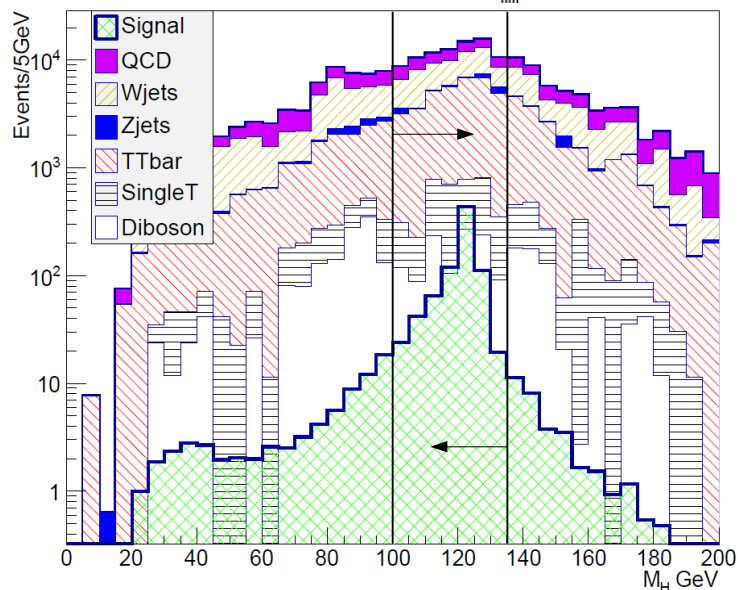
Reconstructed Higgs mass (left) and Relative HT (right) for backgrounds and signal

Strategy @ CMS

- ## Preselection:
  - pT(j1), HT, at least 3 b jets

- ## Reconstruction:
  - Reconstruct each object (W, H, top) from 3b's and 2j's
  - Keep smallest chi2 combination:

$$\chi^2 = \frac{(M_H - M_{bb})^2}{\sigma_H^2} + \frac{(M_W - M_{jj})^2}{\sigma_W^2} + \frac{(M_t - M_{bjj})^2}{\sigma_t^2}$$

- ## Object selection:
  - $\Delta R((bb)^H)$
  - M(H)
  - 1 forward jet
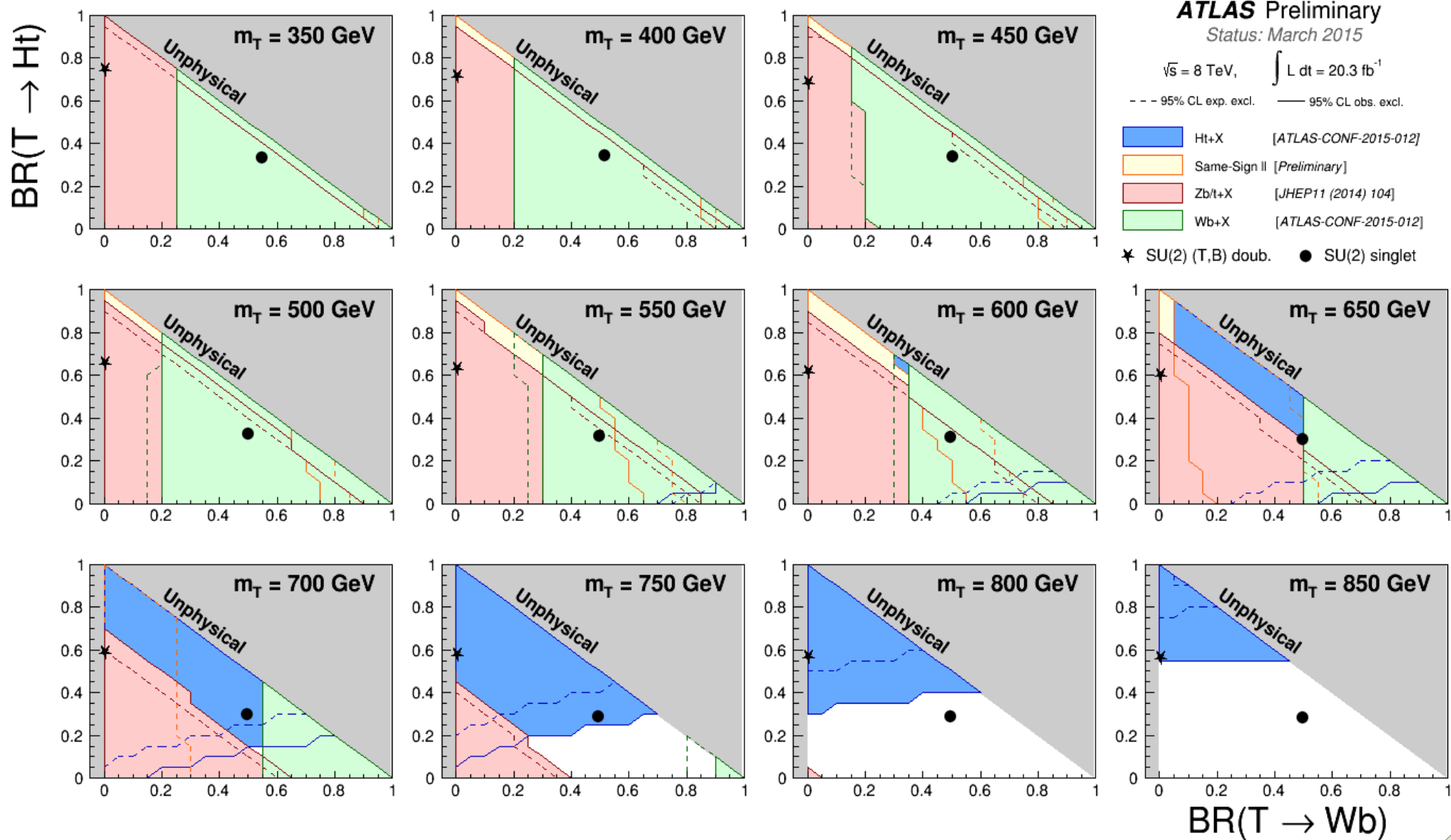 - Among others variables

Background estimation
- Driven from data: Multijets + ttbar
- Control sample:
  – Loosening of b-tagging (Enrich bkgs)
  – Keep all combinations (Enrich stats)
- Validation comparing to signal sample, cut per cut (MC and Data)

Exclusion limits summary on ATLAS results for vector-like T-quark

Conclusion

- T' searches → Aid to answer to the hierarchy problem

- Stringent limits from Run I of LHC → Waiting for more on Run II !

  - Masses higher than 1 TeV completely unconstrained

- Still coming new results from Run I data

- Ongoing discussion between ATLAS and CMS to synchronize MC production and benchmarks for Run II analysis

THANKS!
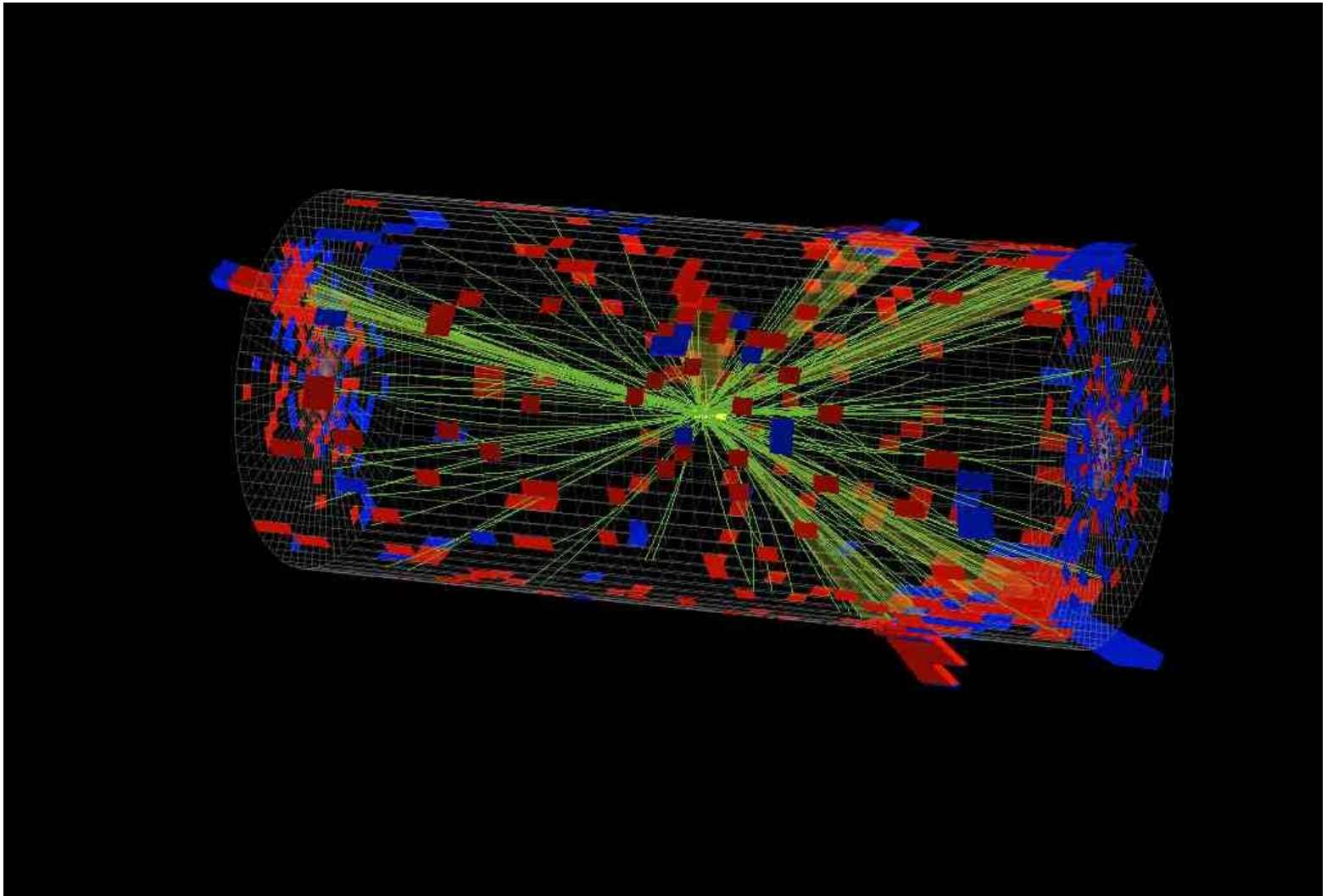
Backup

A word on systematics

ATLAS	JES	JER	B-tagging	BKG estimation
Signal	2%-10%	<2%	6%-13%	-
BKG	2%-15%	1%-12%	4%-10%	Up to 50%

CMS	JES	JER	B-tagging	BKG estimation
Signal	2%-5%	<2%	3%-7%	-
BKG	~5%	<10%	2%-7%	Up to 30%