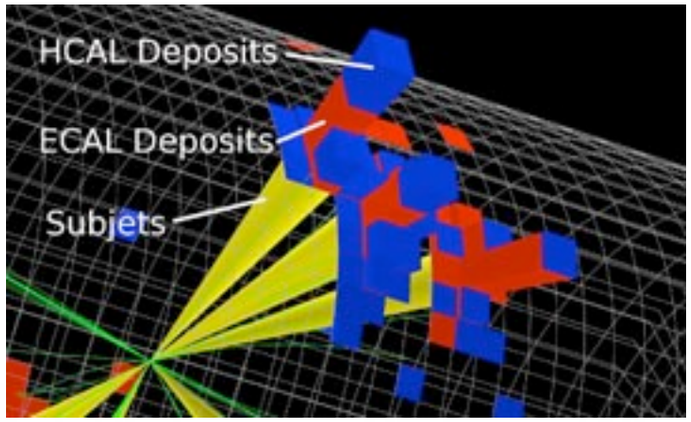
Experimental Results in the Boosted Regime

DISCLAIMER

this talk is about techniques and analysis strategies, not about the final result plot



Johannes Erdmann

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prepared with the help of Emanuele Usai
on behalf of the ATLAS and CMS Collaborations

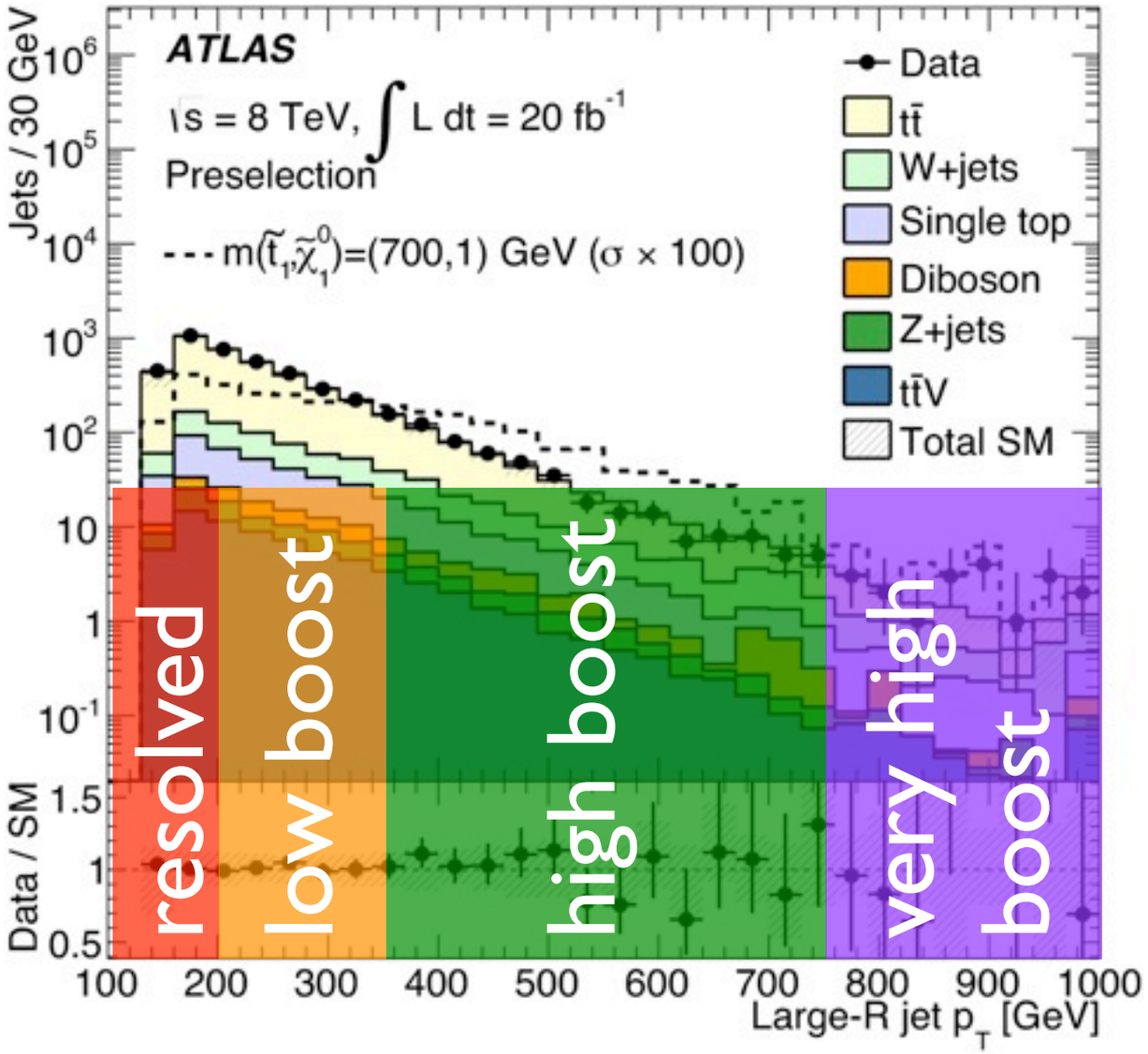
Top 2014, Cannes

related presentations:
Carmen Diez Pardos (4)
Emanuele Usai (8)
Till Eifert (11)
Florencia Canelli (11')

Outline

- continuous transition
  resolved → high boost
- non-trivial analysis optimization
- run I :
  - few purely boosted analyses
  - typical scenario (Run1) :
    - top ID for high boost
    - W ID for low boost
    - complementary resolved analysis

$\tilde{t}\tilde{t}^* \rightarrow l + \text{jets} + E_T^{\text{miss}}$



Organized by final states

(1) fully hadronic [stop, $t\bar{t}$ and tb and tH resonances]

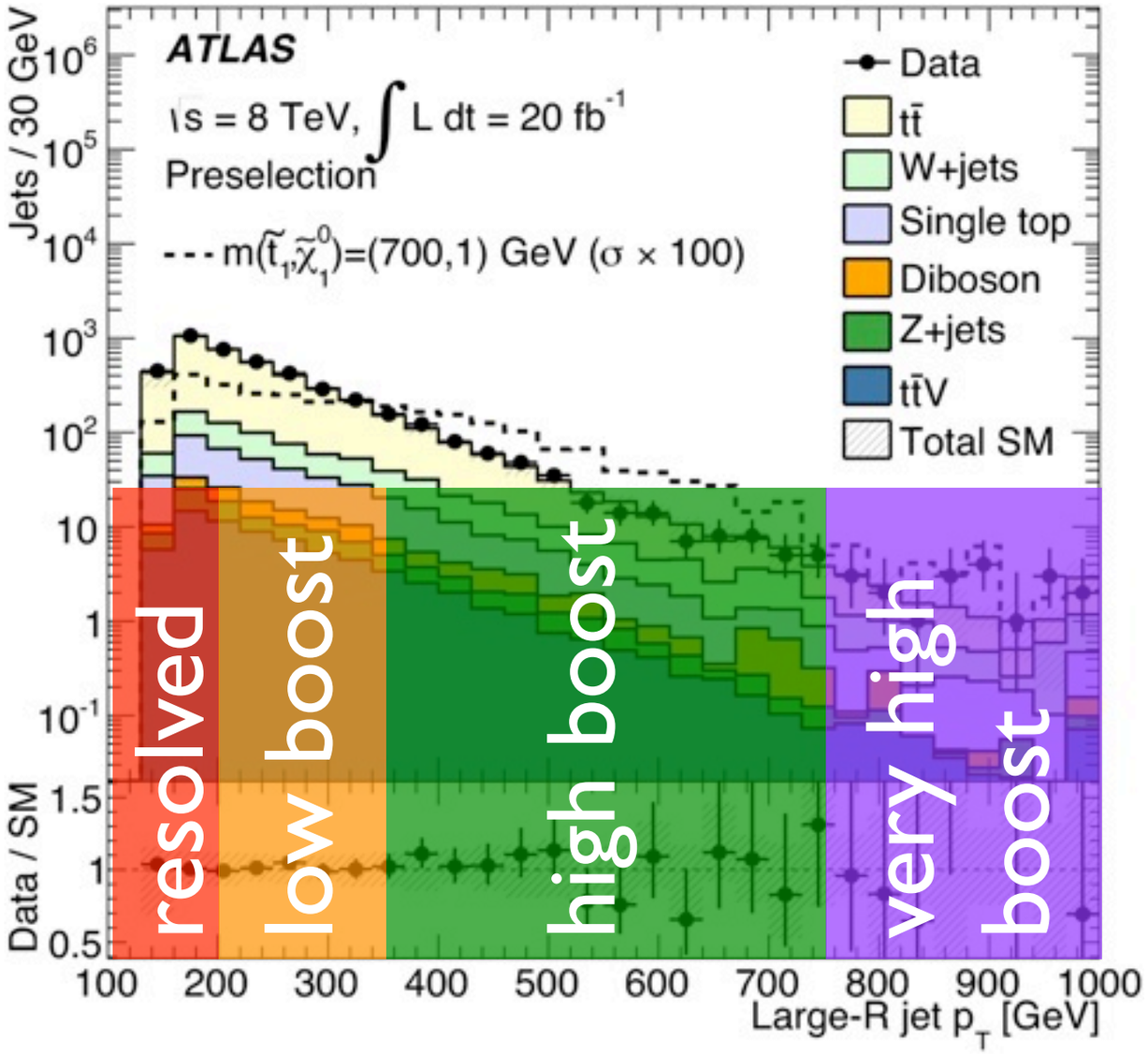
(2) ≥ 1 lepton [VLQ b', stop, VLQ T, $t\bar{t}$ resonances, diff. Xsec, $T_{5/3}$]

Outline

Models for searches

- Searches for stop quarks
  - low mass top partners favored in various flavors of SUSY
- Searches for vector-like quarks (VLQ)
  - excellent candidates for heavy non-chiral top partners
- Searches for $t\bar{t}$ and tb resonances
  - searches for narrow resonances

$\tilde{t}\tilde{t}^* \rightarrow l + \text{jets} + E_T^{\text{miss}}$



All-Hadronic Final States

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$

$\tilde{t} \rightarrow t + \text{LSP}$

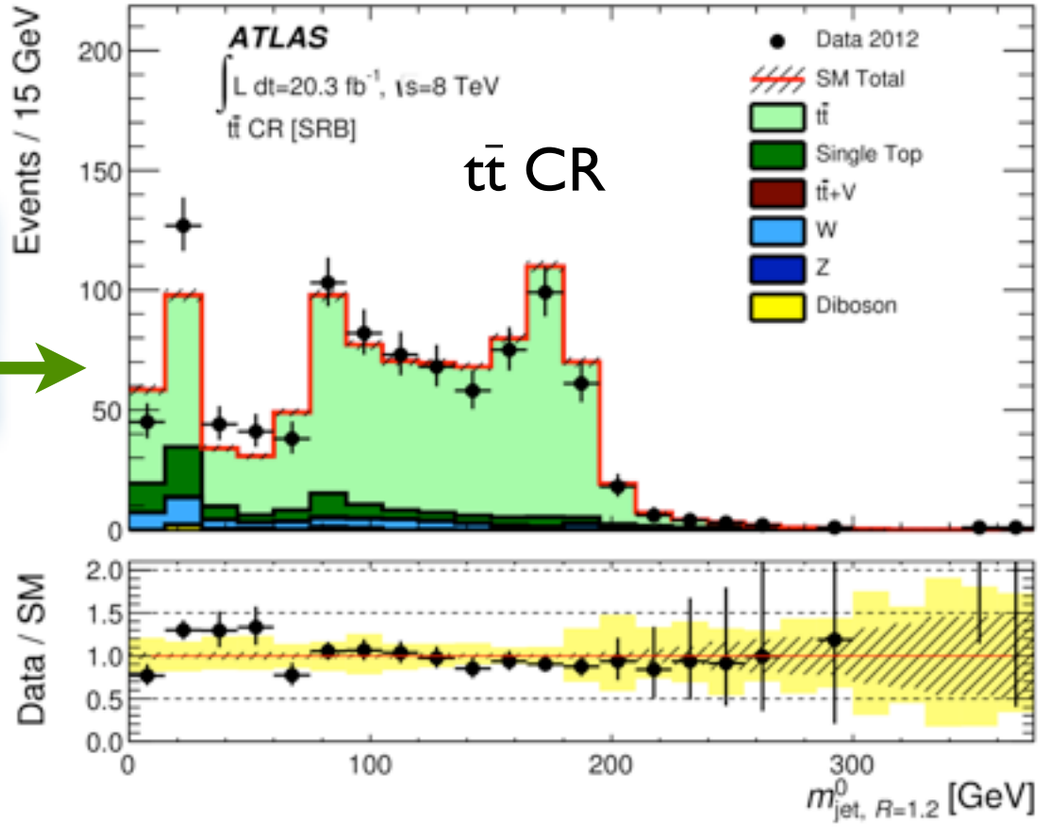
- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost ($m_{\tilde{t}}$ ~ O(few 100 GeV))
- resolved selections : 6jets/5jets, 2 b-tags, E_T^{miss}

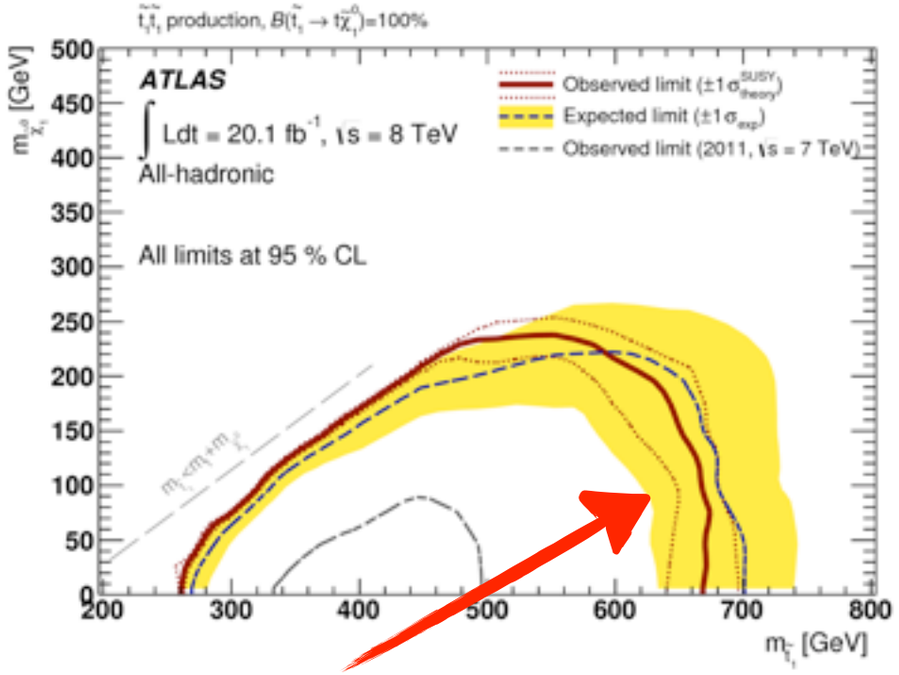
additional partially boosted selection :

- recluster jets to top jets (R=1.2) and W jets (R=0.8)
- make use of jet masses for loose tagging
- also use top jet mass asymmetry to distinguish topologies (asymmetric → only 1st top, > E_T^{miss})

bkg. from CRs

$t\bar{t}$: 4/5jets





partially boosted selection

JHEP 1409 (2014) 015

Low boost → loose mass requirements

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$

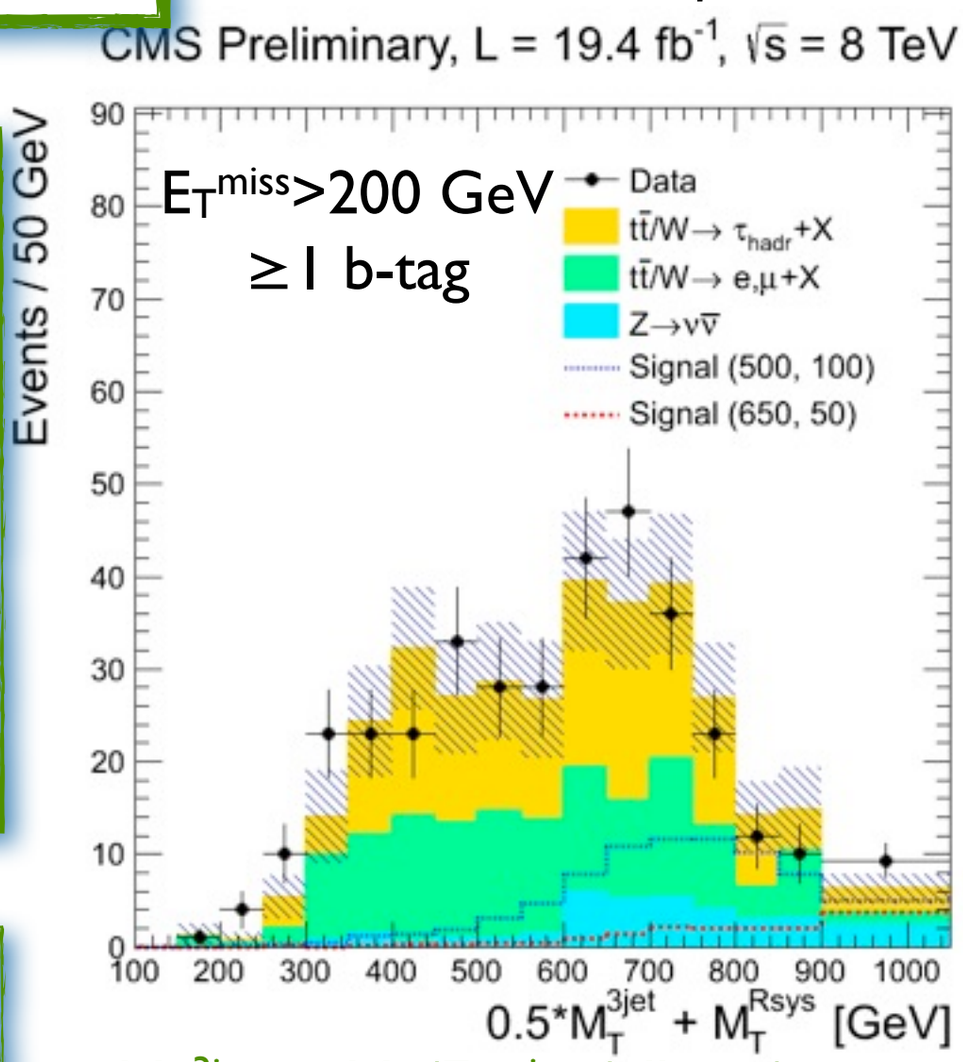
$\tilde{t} \rightarrow t + \text{LSP}$

- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost
- preselection : 5jets, 1 b-tag, E_T^{miss}

partially boosted selection :

- one "full top" : HEPTopTagger(HTT)-like 3-jet selection
  - $\Delta R < 1.5$, $m_{jjj} \in [80,270]$ GeV, HTT inv. mass cuts
- + one "partial top" :
  - 3 jets left : use m_{jjj} and m_{jj}
  - failing or just 2 jets : use m_{jj}
  - failing or just 1 jet : use remaining b-tagged jet

- kinematic requirements on full/partial tops
- #b-tags and E_T^{miss} categories
- bkg. estimated using data-driven techniques



$M_T^{3jet} = M_T(E_T^{miss}, \text{full top})$

$M_T^{Rsys} = M_T(E_T^{miss}, \text{partial top})$

CMS PAS SUS-13-015

low boost → partial reco. for 2nd top

low boost

tH Resonances (all-hadronic)

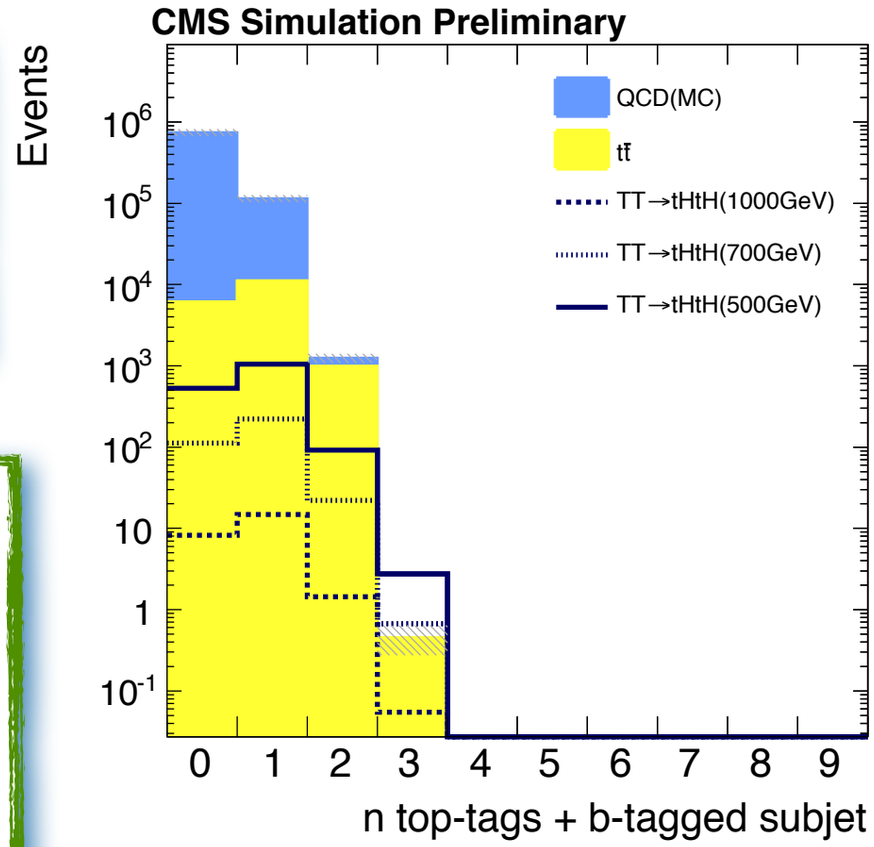
full 8 TeV

$$T\bar{T} \rightarrow tH\bar{t}H \rightarrow \text{jets}$$

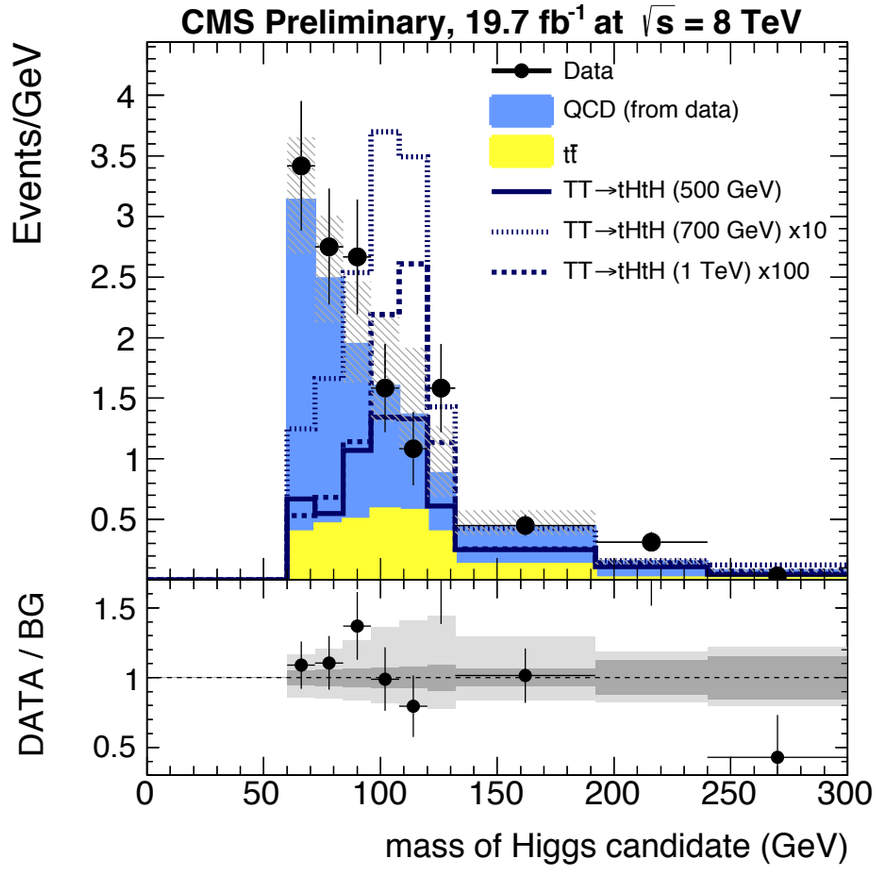
- moderate boost given high-mass final state
- preselection : ≥ 2 C/A R=1.5 jets, p_T > 150 GeV
- ≥ 1 top candidate : HTT-tag + ≥ 1 b-tagged subjet
- ≥ 1 Higgs candidate : Higgs-tag
  - 2 subjet b-tags and m_{bb} > 60 GeV

- QCD from data (inverted tagging)
- $t\bar{t}$ from MC

- categorized in #Higgs-tags
- final discriminant uses H_T and m_{bb}



multi-Higgs category



CMS PAS B2G-14-002

Johannes Erdmann

top- + b- + Higgs-tagging against QCD

low boost

high boost

ttbar Resonances (all-hadronic)

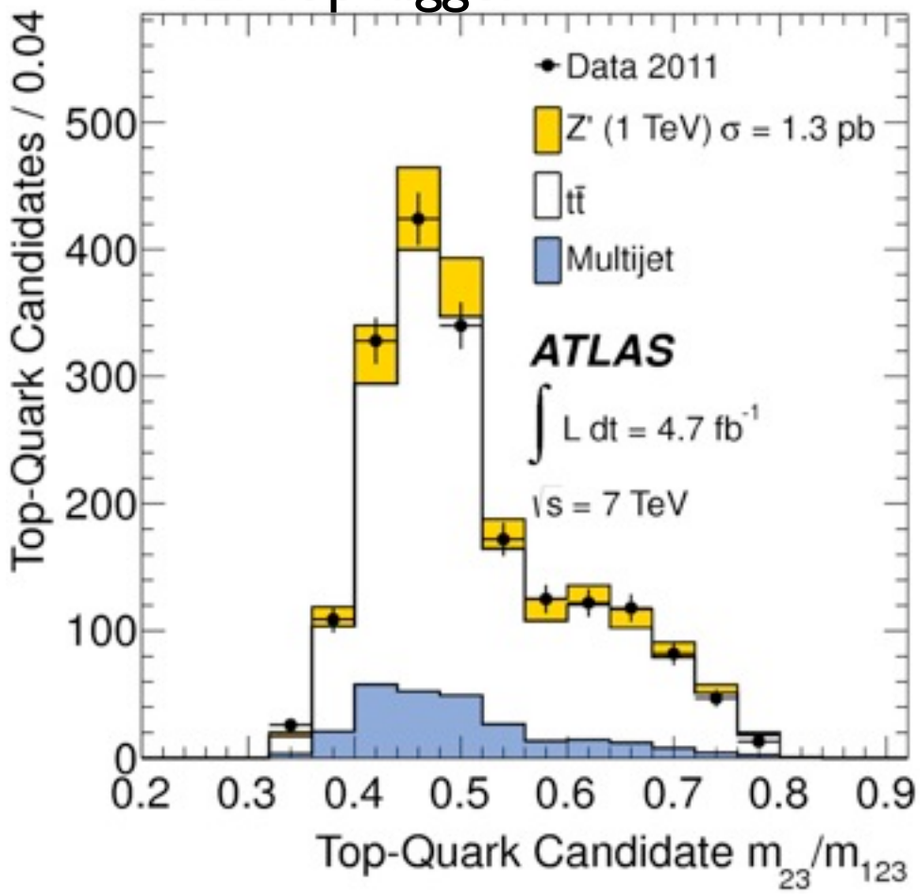
full 7 TeV

$$X \rightarrow t\bar{t}$$
$$\rightarrow \text{jets}$$

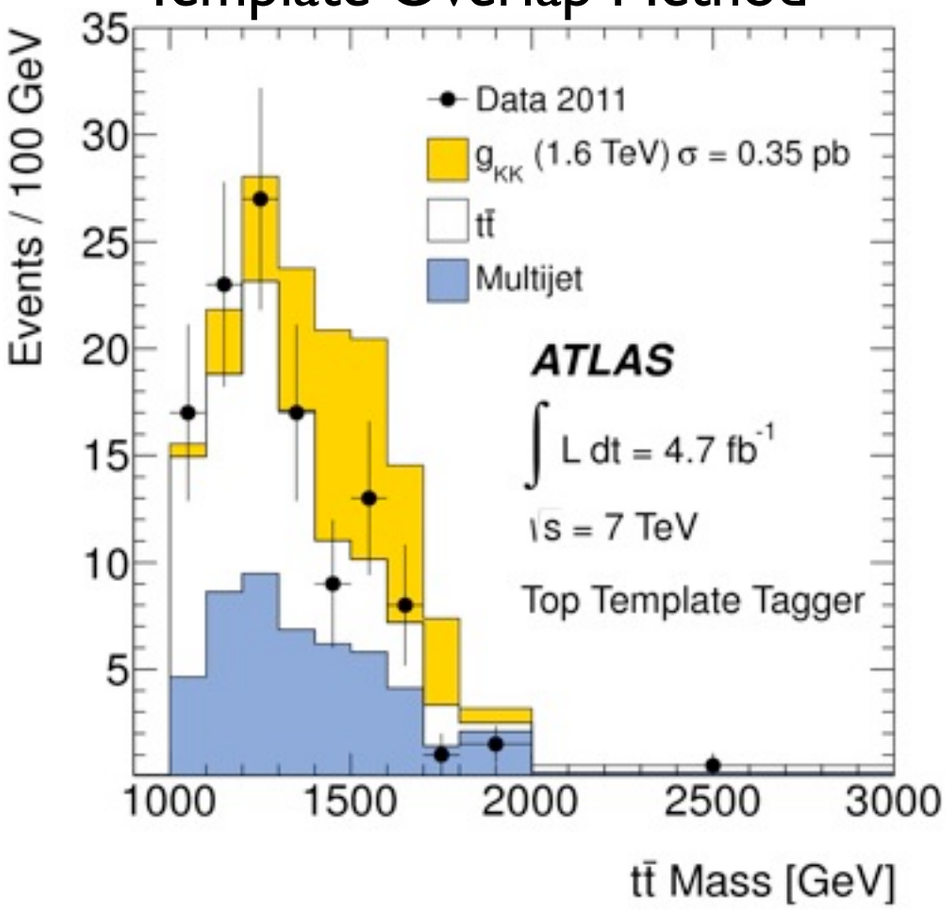
- fully boosted analysis
- low boost (p_T>200 GeV) : HEPTopTagged-C/A 1.5 jets
- high boost, i.e. high mass resonances (p_T>500/450 GeV) : Template Overlap Method (anti-k_t 1.0) + pile-up corr. mass
- matched small-R b-tagged jet

- QCD bkg. from data (inverted b-tag and top-tag requirements)
- $t\bar{t}$ from MC

HEPTopTagger



Template Overlap Method



JHEP 1301 (2013) 116

tagger choice p_T dependent

high boost

ttbar Resonances (all-hadronic)

full 8 TeV

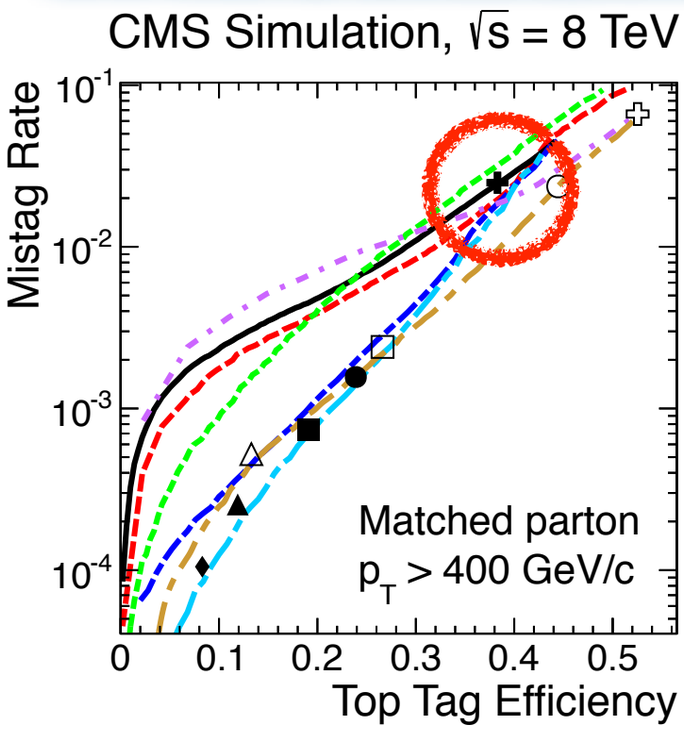
$X \rightarrow t\bar{t}$

$\rightarrow$ jets

- fully boosted analysis
- complemented by l+jets analyses (resolved and boosted)

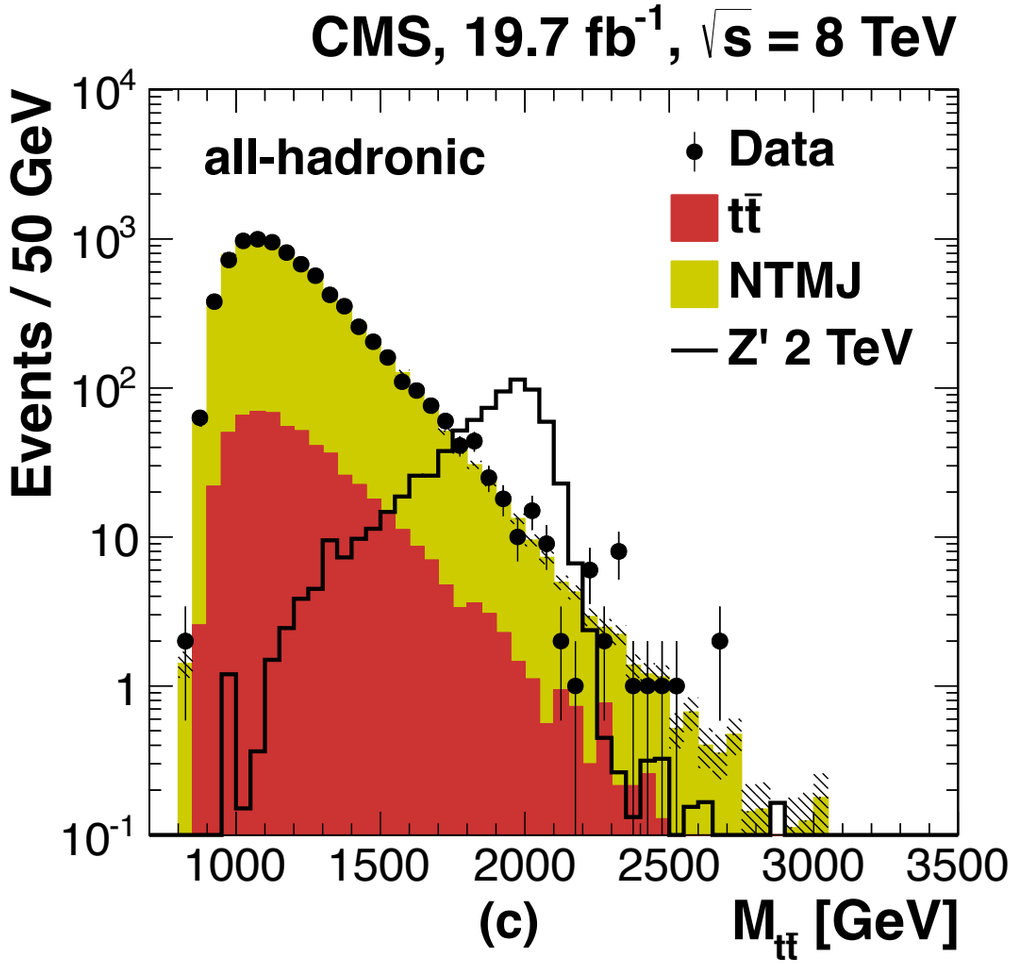
- 2 C/A R=0.8 jets
- p_T > 400 GeV
- CMS-tagged, no b-tags
- $\Delta\Phi_{jj} > \pi/2$, $|\Delta\eta_{jj}| < 1.0$

- QCD estimated with measured top-tag fake rate



CMS PAS JME-13-007

- CMS Top Tagger
- subjet b-tag
- N-subjettiness ratio τ_3/τ_2
- CMS + subjet b-tag
- CMS + τ_3/τ_2 + subjet b-tag
- HEP Top Tagger
- HEP + τ_3/τ_2 + subjet b-tag
- CMS WP0
- CMS Comb. WP1
- CMS Comb. WP2
- CMS Comb. WP3
- CMS Comb. WP4
- HEP WP0
- HEP Comb. WP1
- HEP Comb. WP2
- HEP Comb. WP3



PRL 111 (2013) 211804

CMS PAS B2G-12-005

tight top-tagging against QCD

high boost

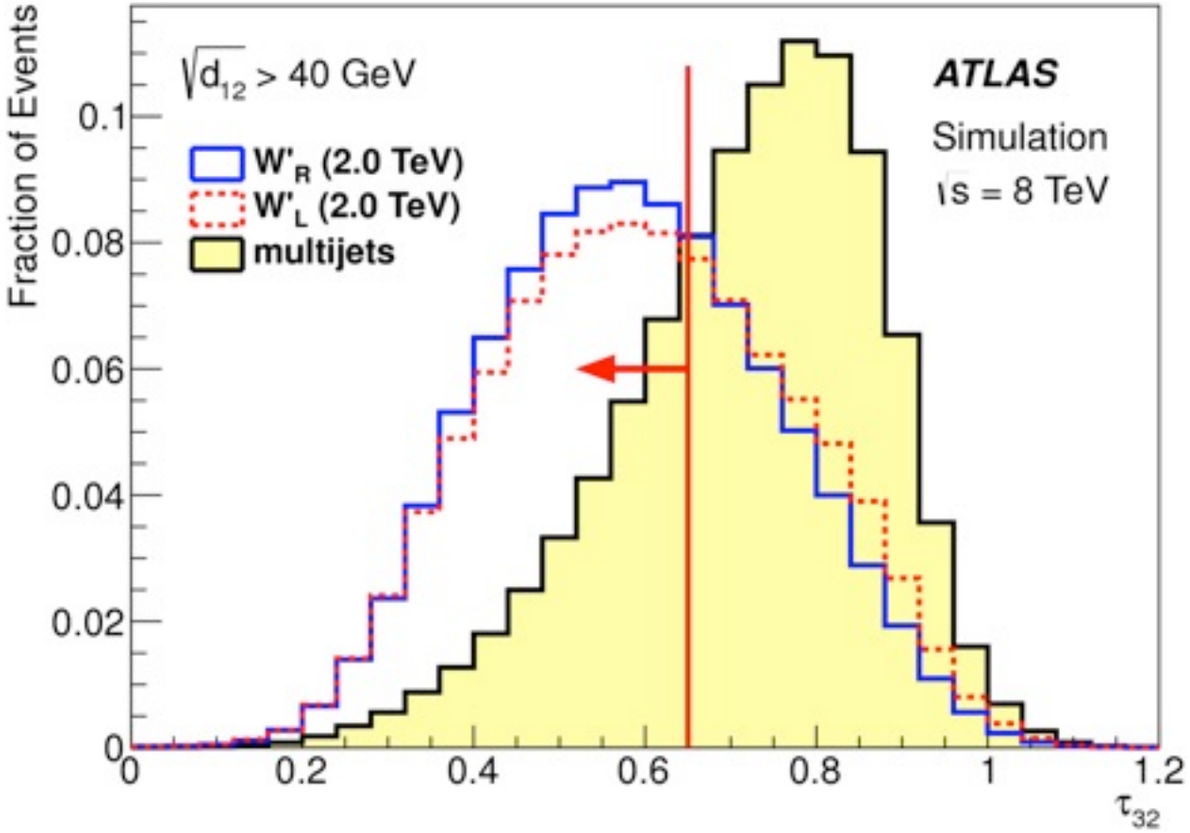
tb Resonances (all-hadronic)

full 8 TeV

$W' \rightarrow tb$

$\rightarrow$ jets

- fully boosted analysis
- 1 trimmed anti-k_t 1.0 jet with p_T > 350 GeV, and substructure-tag (split. scale $\sqrt{d_{12}}$ & N-subjettiness τ_{21}, τ_{32})
- 1 anti-k_t 0.4 jet with p_T > 350 GeV and b-tagged
- m_{tb} > 1100 GeV → only high boosts
- difference in tagging efficiency from W' handedness



Process	One b-tag	Two b-tag
Multijet	16100 ± 800	2600 ± 300
Hadronic $t\bar{t}$	130 ± 30	210 ± 60
Leptonic $t\bar{t}$	60 ± 20	90 ± 30
Other	60 ± 60	8 ± 8
Total SM prediction	16400 ± 800	2900 ± 300
Data	16601	2925

- 2 #b-tag categories for large-R jet
- total bkg. from data fit

August '14

arXiv:1408.0886

suppress QCD with classical substructure

high boost

tb Resonances (all-hadronic)

full 8 TeV

$W' \to tb$

$\to$ jets

- fully boosted analysis
- 1 trimmed anti-k_t 1.0 jet with p_T > 350 GeV, and substructure-tag (split. scale $\sqrt{d_{12}}$ & N-subjettiness τ_{21}, τ_{32})
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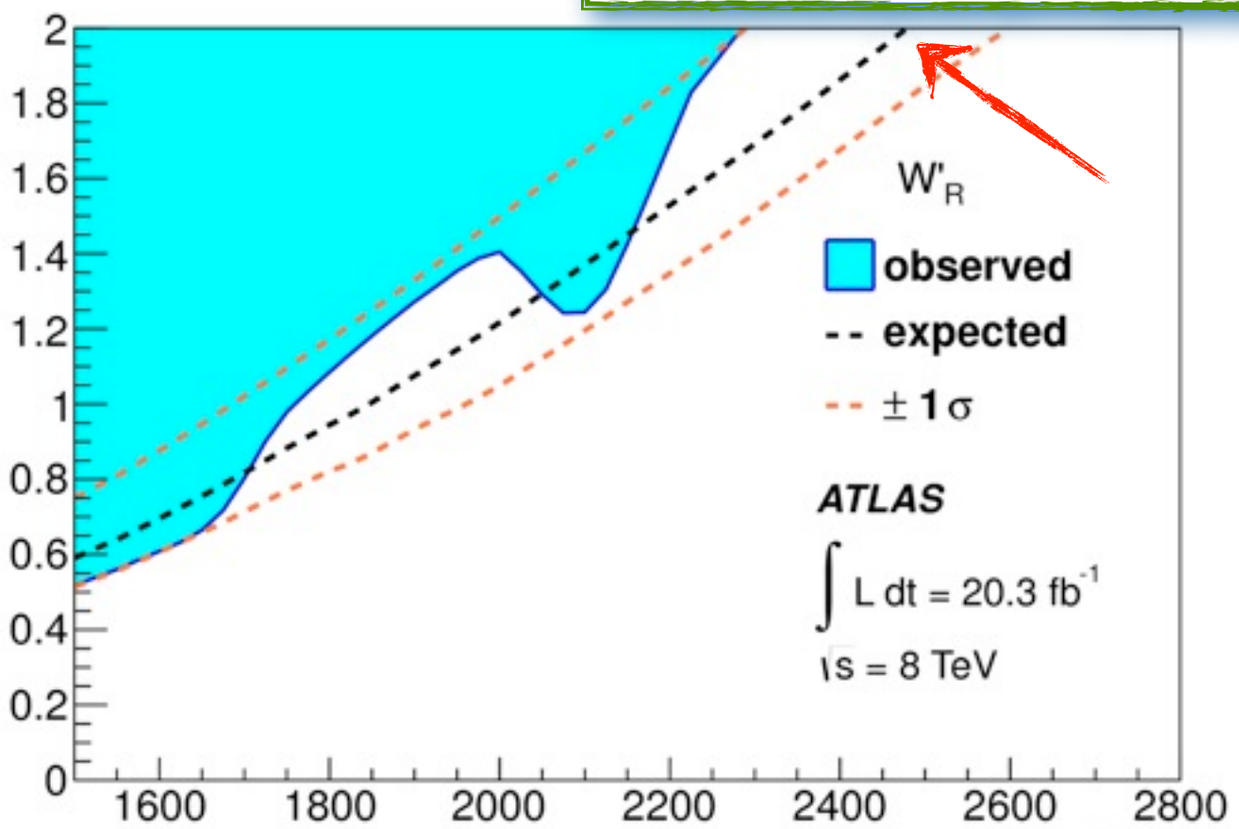
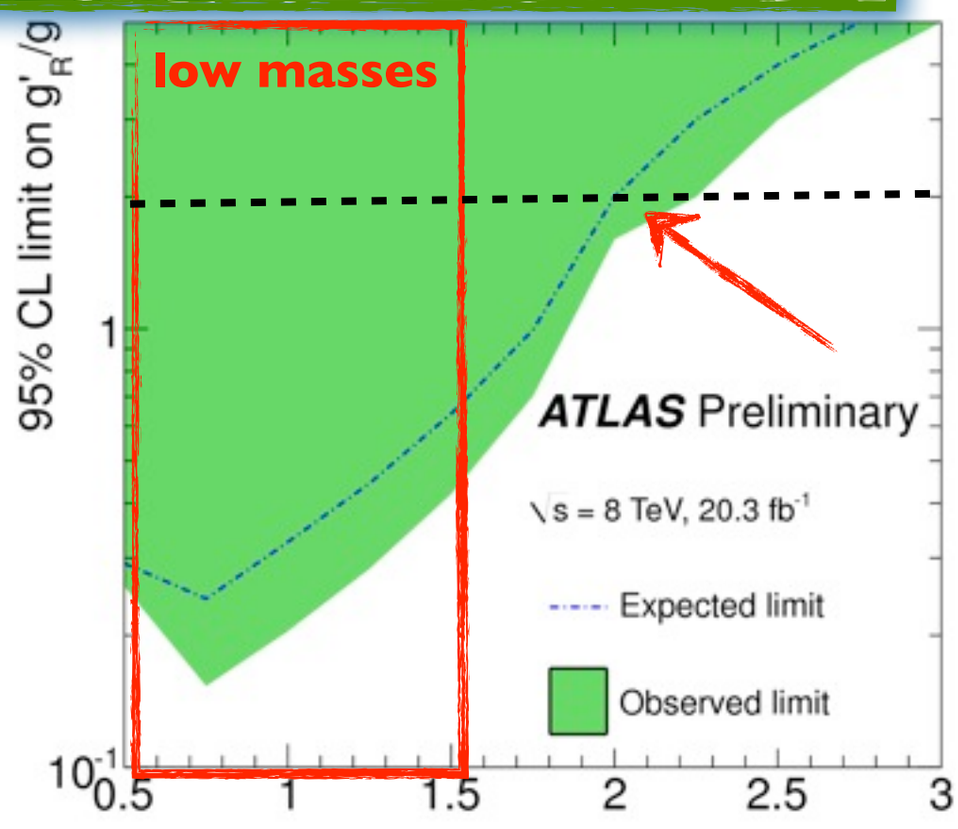


boosted hadronic search



hot off the press leptonic search (see poster by G. Gilles)

arXiv:1408.0886

high boost

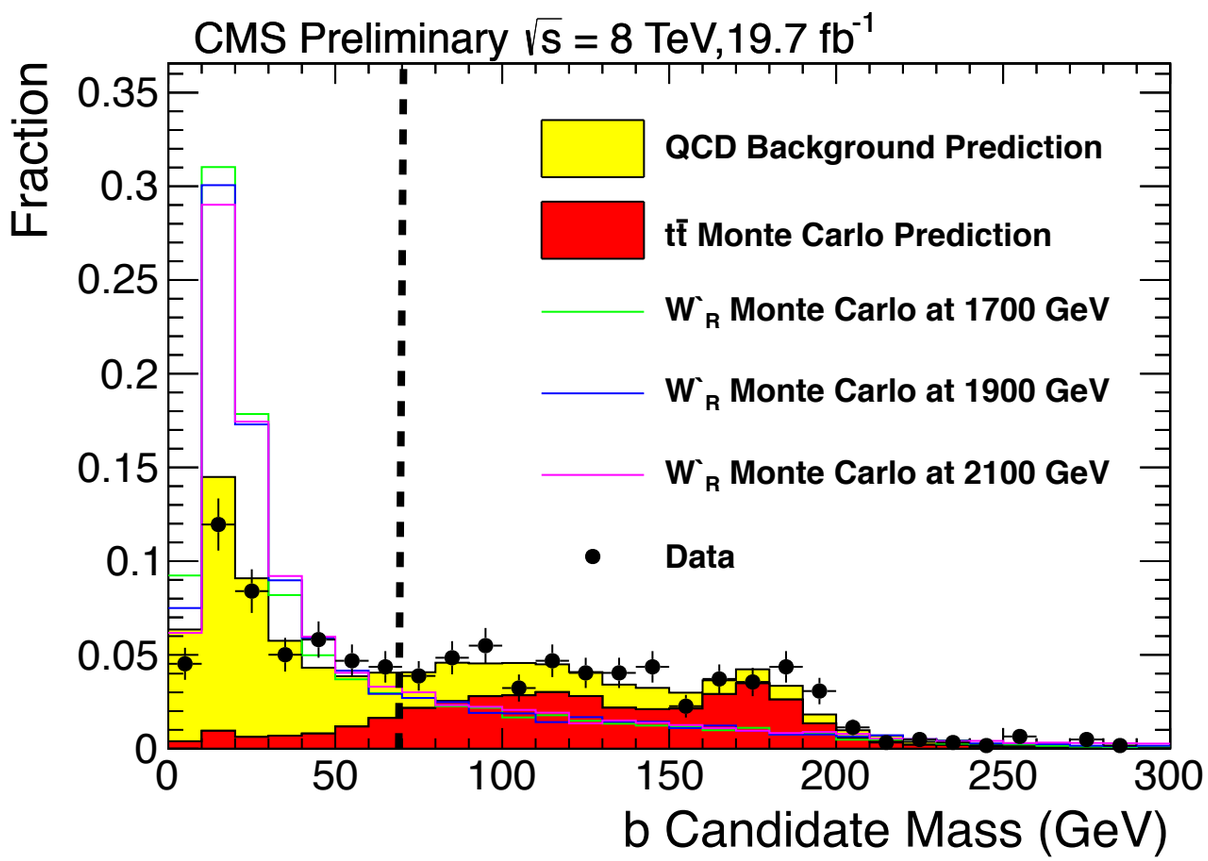
tb Resonances (all-hadronic)

full 8 TeV

$W' \rightarrow tb$

$\rightarrow$ jets

- fully boosted analysis
- 1 C/A 0.8 jet with p_T > 450 GeV
  - top-tagged (CMS-tag + τ_{32} < 0.55 + subjet b-tag)
- 1 C/A 0.8 jet with p_T > 370 GeV, b-tagged
  - mass < 70 GeV
- angular separation between the two jets



Sample	Yield
Data	277
QCD	248
ttbar	37
M(W'$_R$ = 1300 GeV)	251
M(W'$_R$ = 1700 GeV)	41
M(W'$_R$ = 2100 GeV)	6

- QCD from sideband
- ttbar shape from MC
- ttbar yield from CR

August '14

CMS PAS B2G-12-009

CMS tagging + τ_{32} ; high mass veto

tb Resonances (all-hadronic)

full 8 TeV

$W' \to tb$

$\to$ jets

- fully boosted analysis
- 1 C/A 0.8 jet with p_T > 450 GeV
  - top-tagged (CMS-tag + τ_{32} < 0.55 + subjet b-tag)
- 1 C/A 0.8 jet with p_T > 370 GeV, b-tagged
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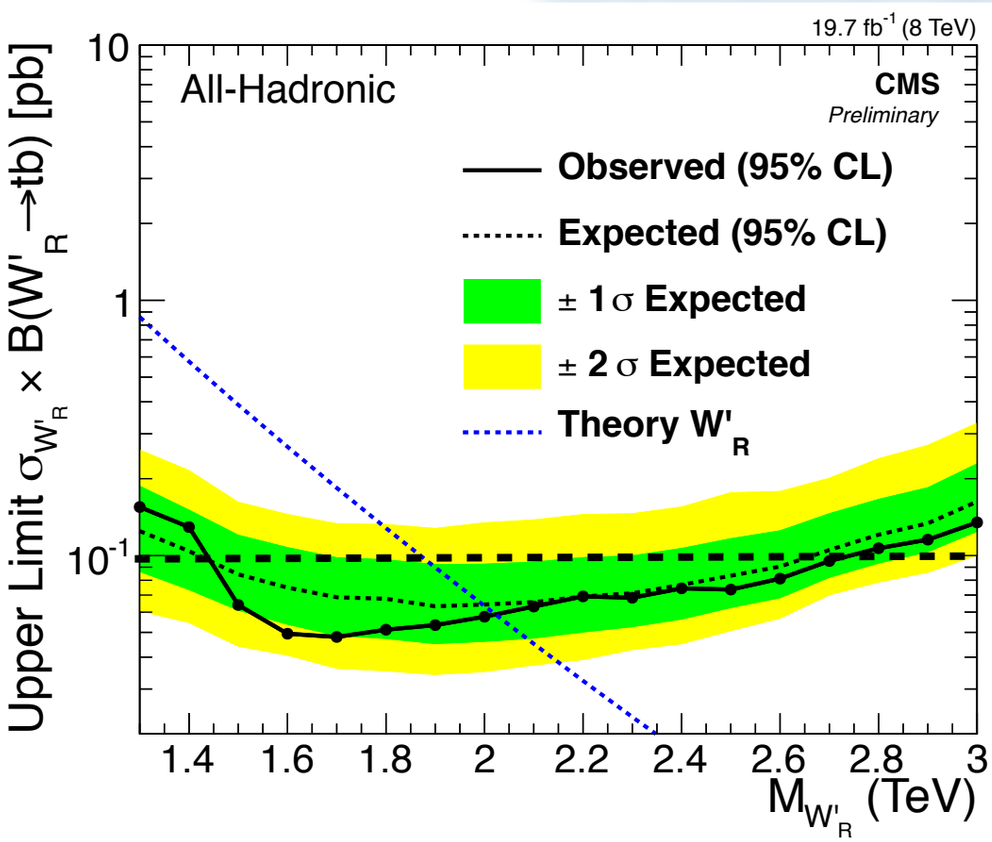
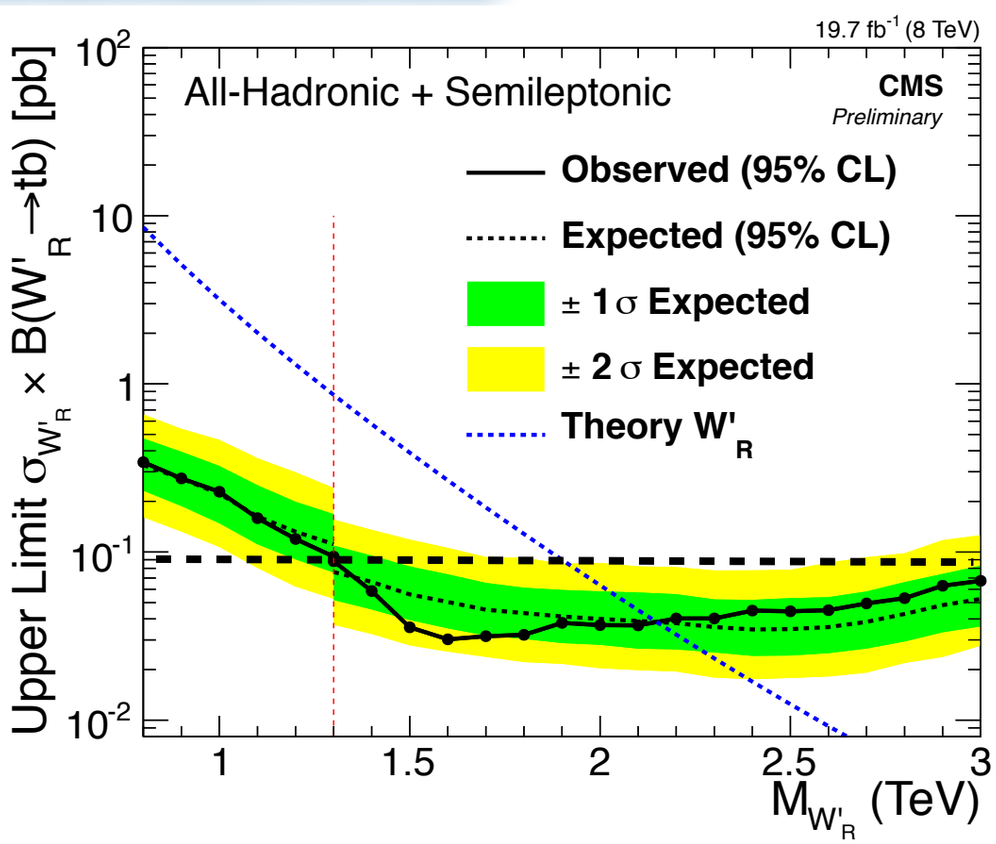


combination with leptonic search



CMS PAS B2G-12-009

CMS tagging + τ_{32} ; high mass veto

≥ 1 Lepton Final States

resolved
low boost

Stop Pair Production (1 lepton)

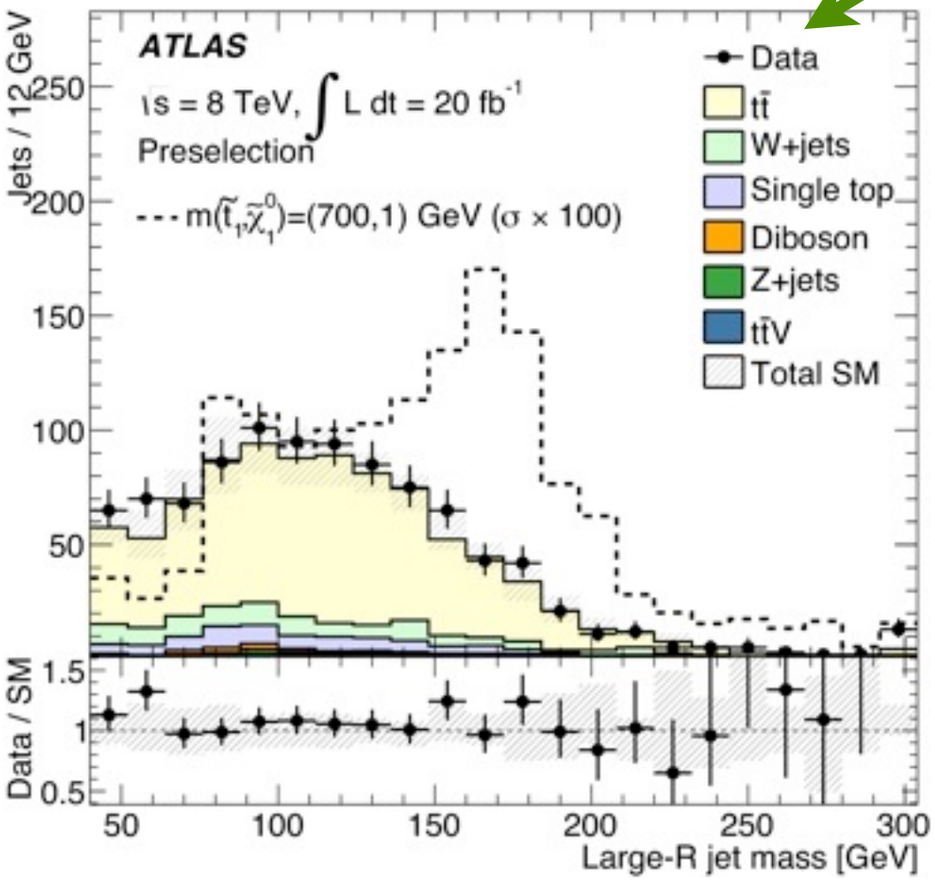
full 8 TeV

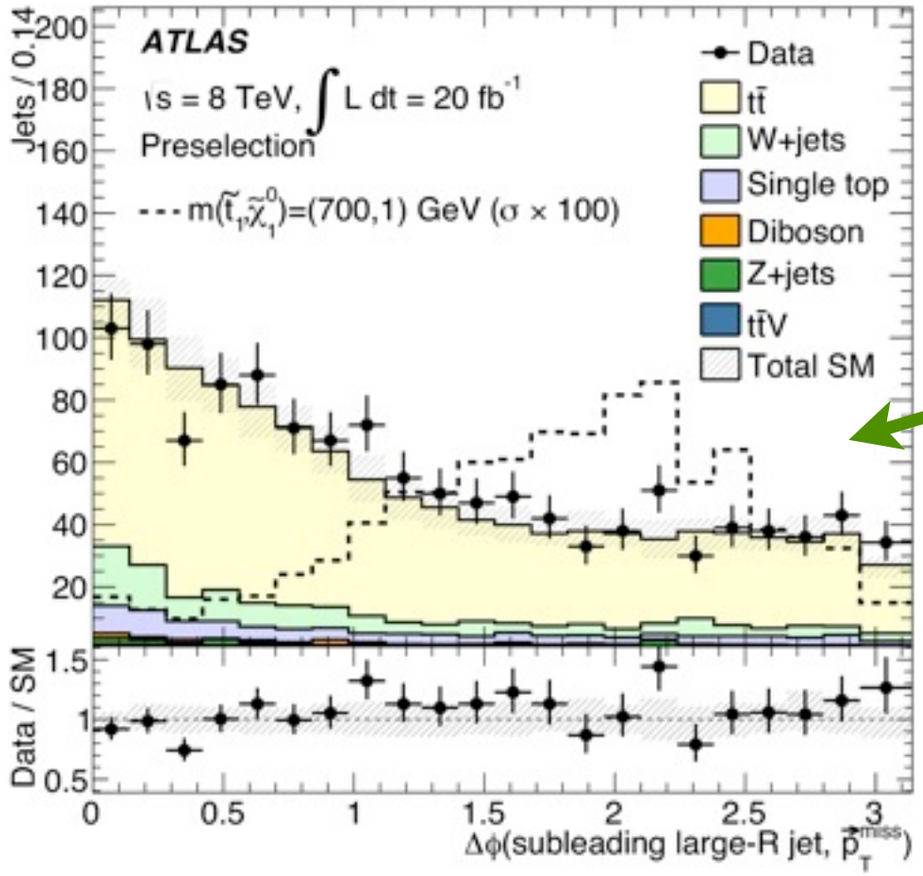
$$\tilde{t}\tilde{t}^* \to \ell + \text{jets} + E_T^{\text{miss}}$$
$$\tilde{t} \to t + \text{LSP}$$

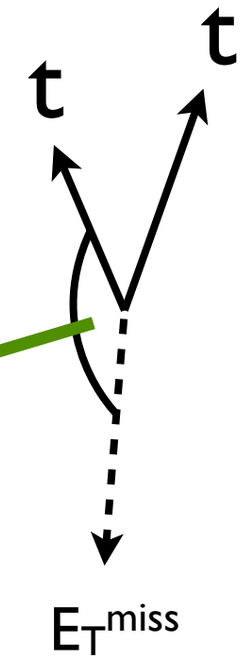
- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost ($m_{\tilde{t}}$ ~ O(few 100 GeV))
- preselection: 1 e / μ, E_T^{miss}, ≥ 4 jets, ≥ 1 b-tag

- 15 signal regions, one targeting boosted tops
- trimmed anti-k_t 1.0 jet, p_T > 270 GeV, m > 75 GeV

boosted strategy shown to improve on optimized resolved strategy







July '14

arXiv:1407.0583

Johannes Erdmann

l+jets + low boost → very loose tagging

low boost

VLQ Searches (≥ 1 lepton)

full 8 TeV

$b'\bar{b}'$

$b' \to tW$

$b' \to bZ$

$b' \to bH$

- 1 lepton, ≥ 4 high-p_T jets, ≥ 1 b-tagged, E_T^{miss}
- pruned C/A 0.8 V-tag (m∈[50,150]GeV, mass drop)
- categorize in boson tags

CMS PAS B2G-12-019

$T\bar{T}$

$T \to bW$

$T \to tZ$

$T \to tH$

- resolved and partially boosted selection
  - 1 e/μ + 3 high-p_T jets, E_T^{miss}
  - C/A 0.8 jet, p_T > 200 GeV, m ∈ [60,130] GeV
- BDT inputs : #W-tags, #top-tags

PLB 729 (2014) 149

$T_{5/3}\bar{T}_{5/3} \to tWtW$

- same-sign lepton search
- top ID : R=0.8 CMS top-tagger (p_T > 400 GeV)
- W ID : R=0.8 (pruned) 2 subjets + W mass
- jet ID : R=0.5, away from top or W ID-ed jets
- use #top-tags, #W-tags, #jets

PRL 112 (2014) 171801

using W-tagging to reject background

low boost
high boost

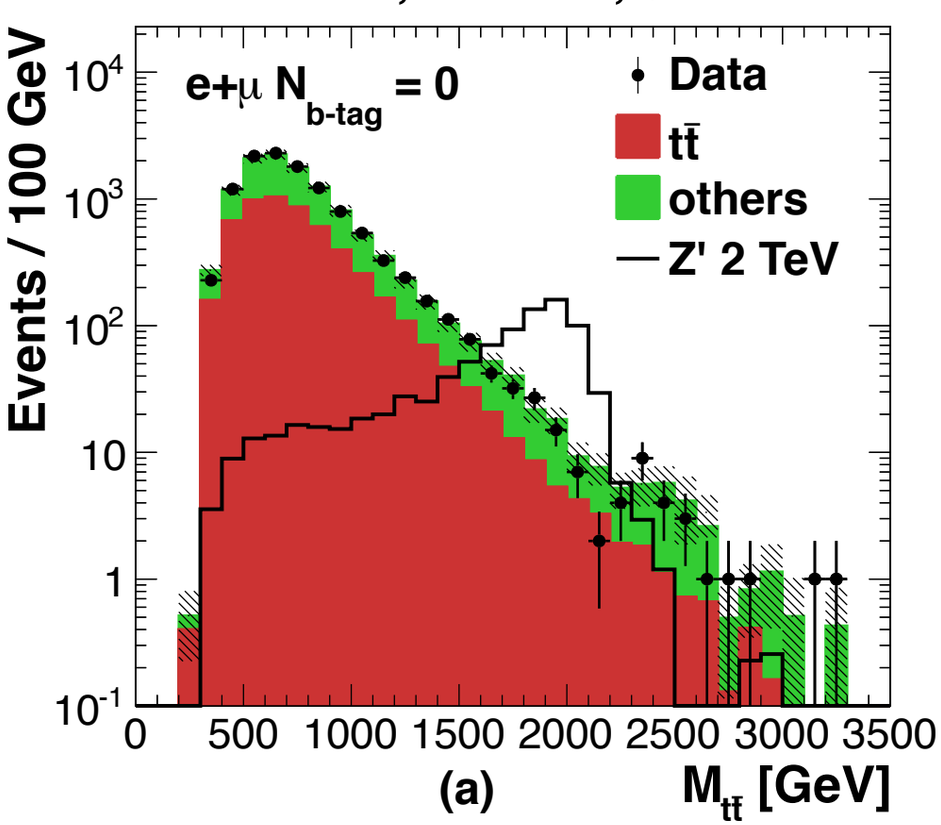
ttbar Resonances (1 lepton)

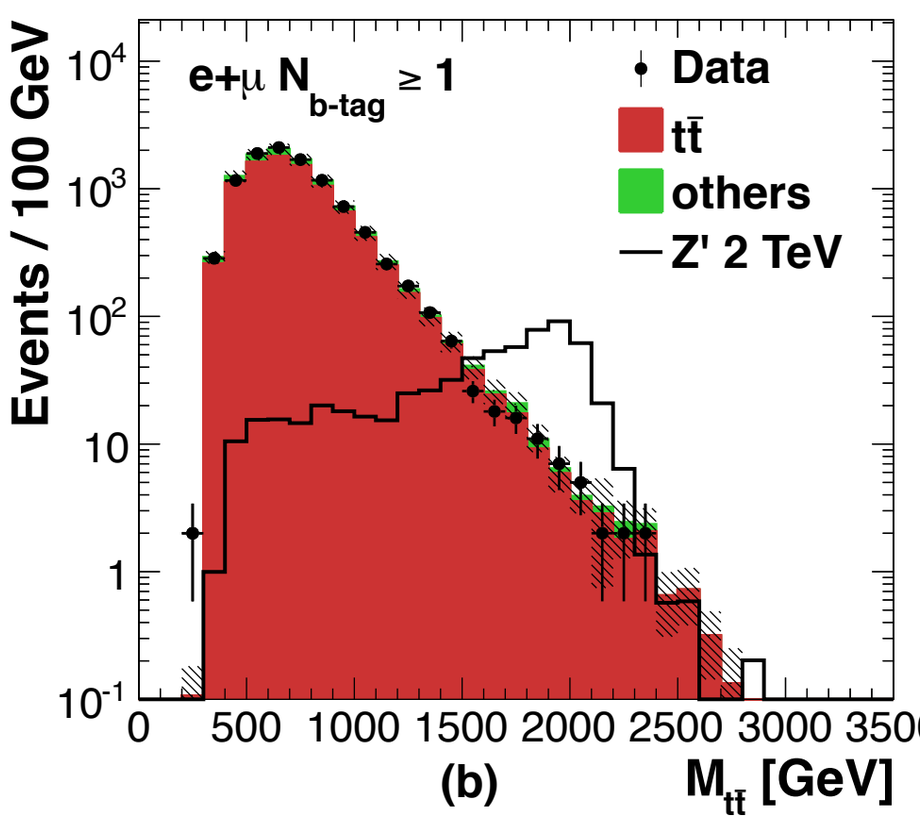
full 8 TeV

$$X \to t\bar{t}$$
$$\to \ell + \text{jets}$$

- boosted selection complementary to resolved :
  - 1 e or μ (no isolation requirements)
  - ≥ 2 anti-k_t 0.5 jets with p_T > 150/50 GeV
  - E_T^{miss} and topological requirements

- require good boosted χ^2 reconstruction with leptonic/hadronic mass constraints
- one jet in leptonic hemisphere & at least one jet in hadronic hemisphere





main "other" bkg.
- 0-tag : W+jets
- 1-tag : single top

PRL 111 (2013) 211804

CMS PAS B2G-12-006

χ^2 reconstruction modified for boosted

low boost

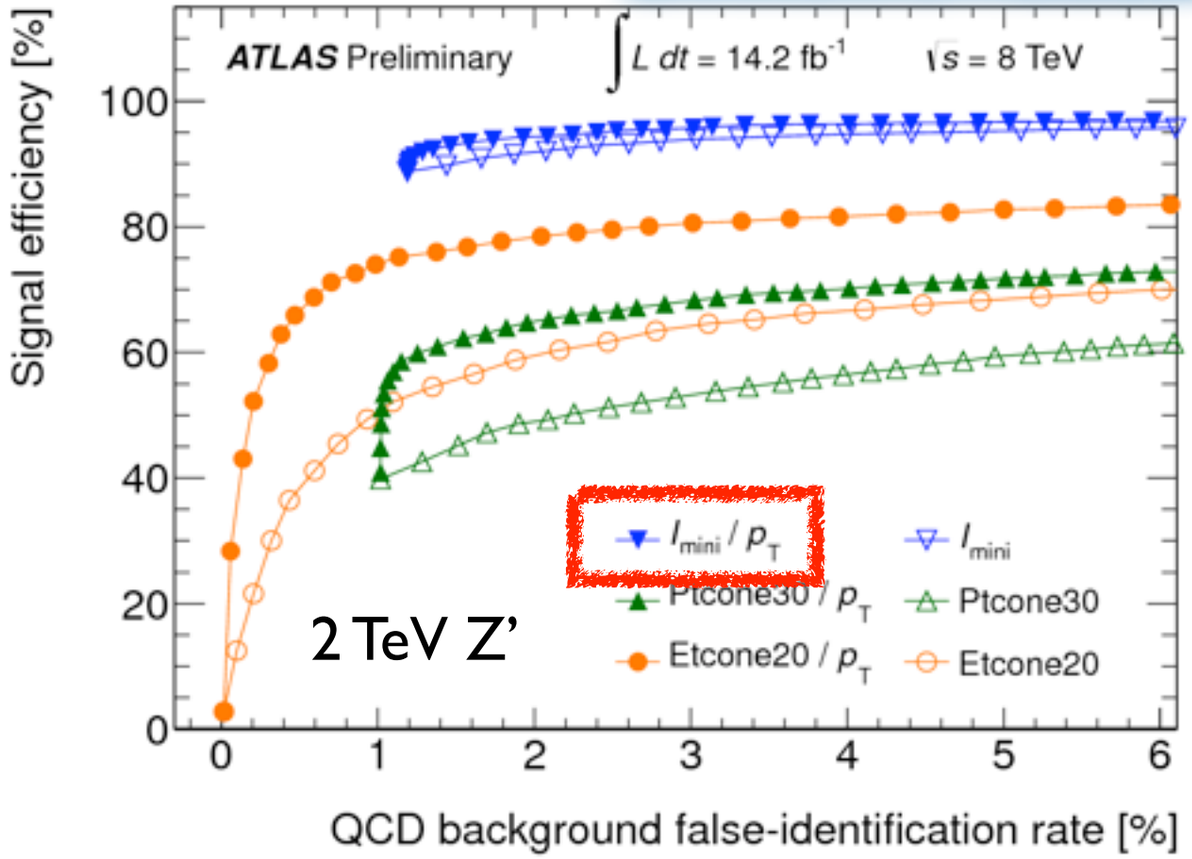
high boost

ttbar Resonances (1 lepton)

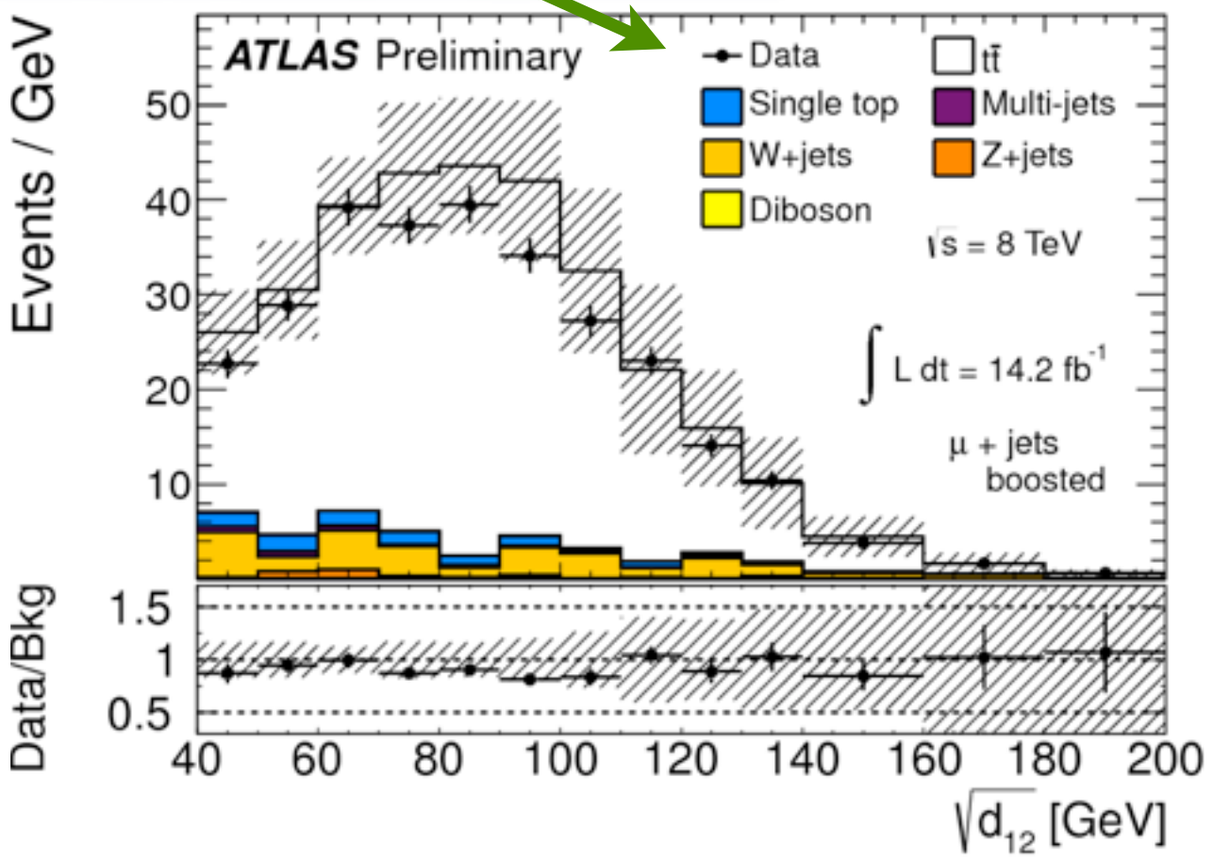
8 TeV (14 fb^{-1})

$$X \to t\bar{t}$$
$$\to \ell + \text{jets}$$

- boosted selection complementary to resolved :
  - 1 e or μ with mini-isolation (shrinking cone)
  - 1 anti-k_t 0.4 jet close to lepton
  - ≥ 1 b-tag & E_T^{miss} and m_T^W requirements
  - 1 trimmed anti-k_t 1.0 jet :
    - p_T > 300 GeV, m > 100 GeV, $\sqrt{d_{12}}$ > 40 GeV



isolation cone size = 10 GeV / E_T



ATLAS-CONF-2013-052

l+jets → mini-isolation + loose tagging

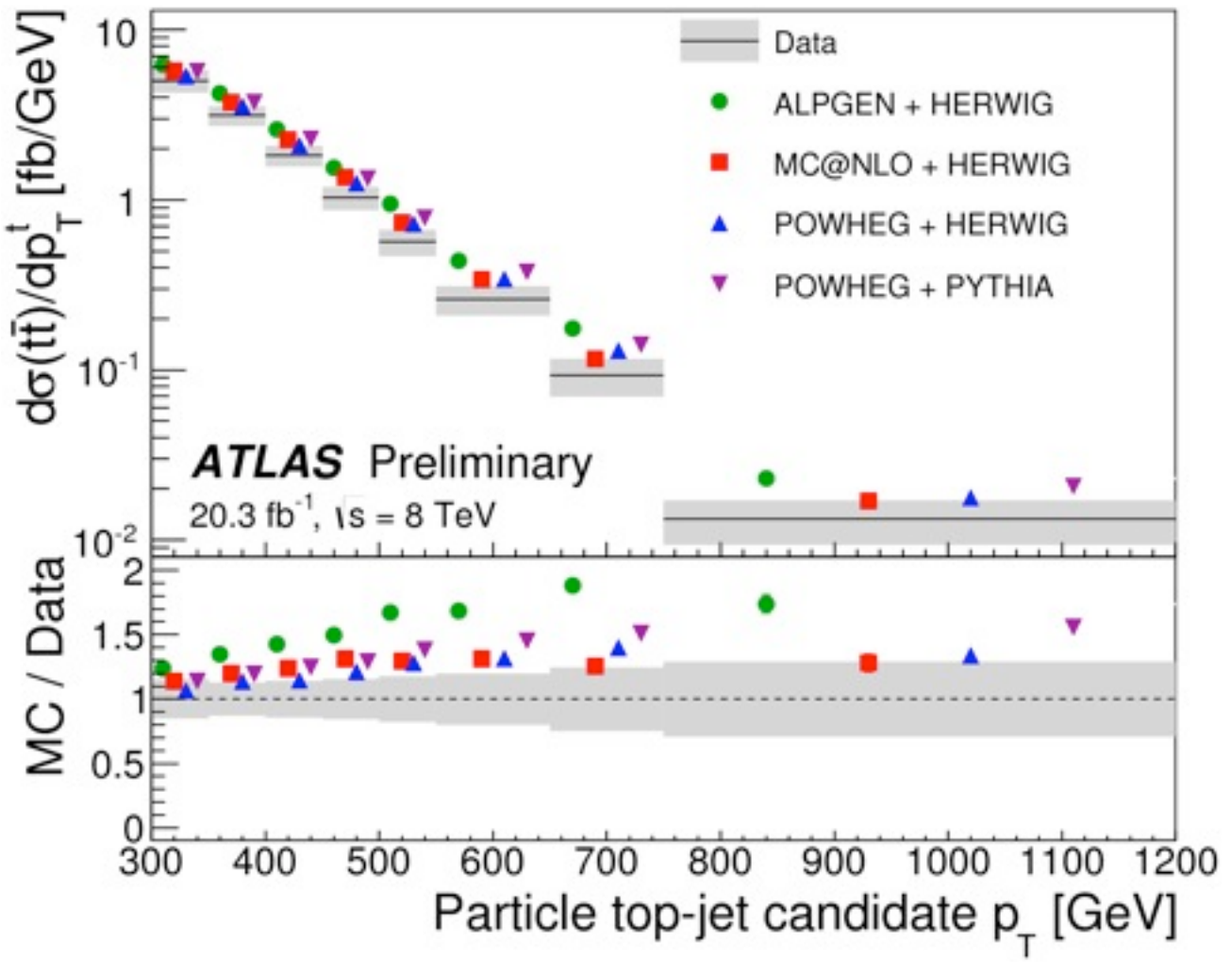
low boost
high boost

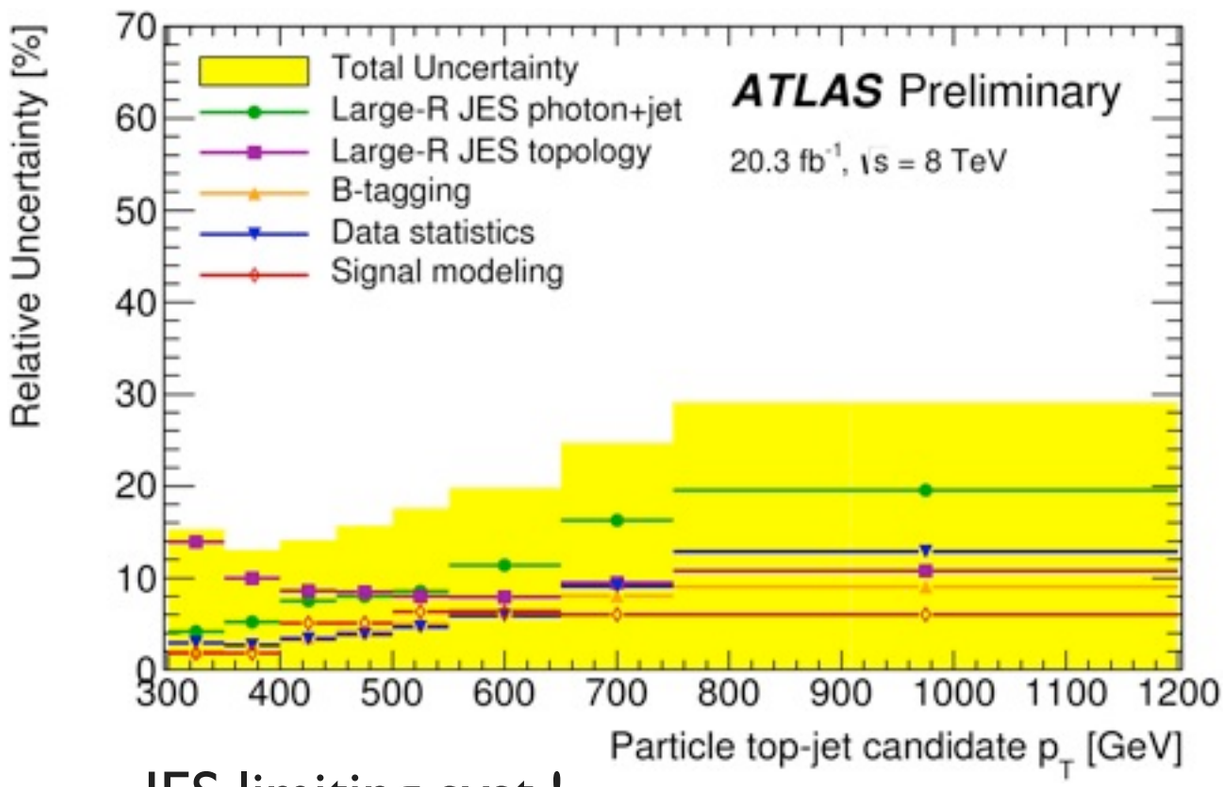
Boosted Differential Cross Section

full 8 TeV

$t\bar{t} \to \ell + \text{jets}$

- aim : measure p_T of hadronic top candidate
  - recover high p_T efficiency with boosted techniques
- this is a background for most searches presented here !
- same selection as l+jets $t\bar{t}$ resonance search
- MC fails to model high p_T regime well





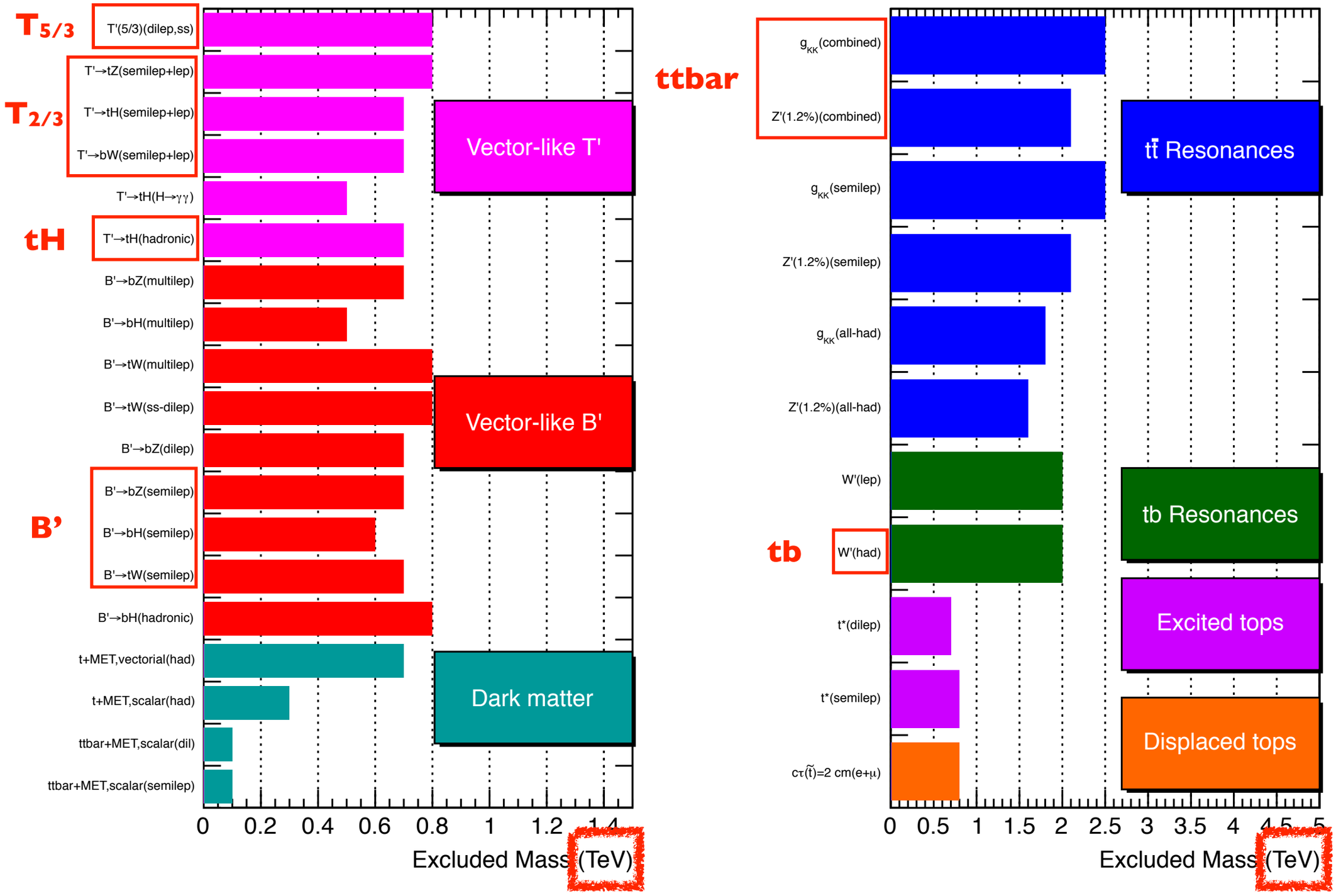
JES limiting syst.!

hot off the press

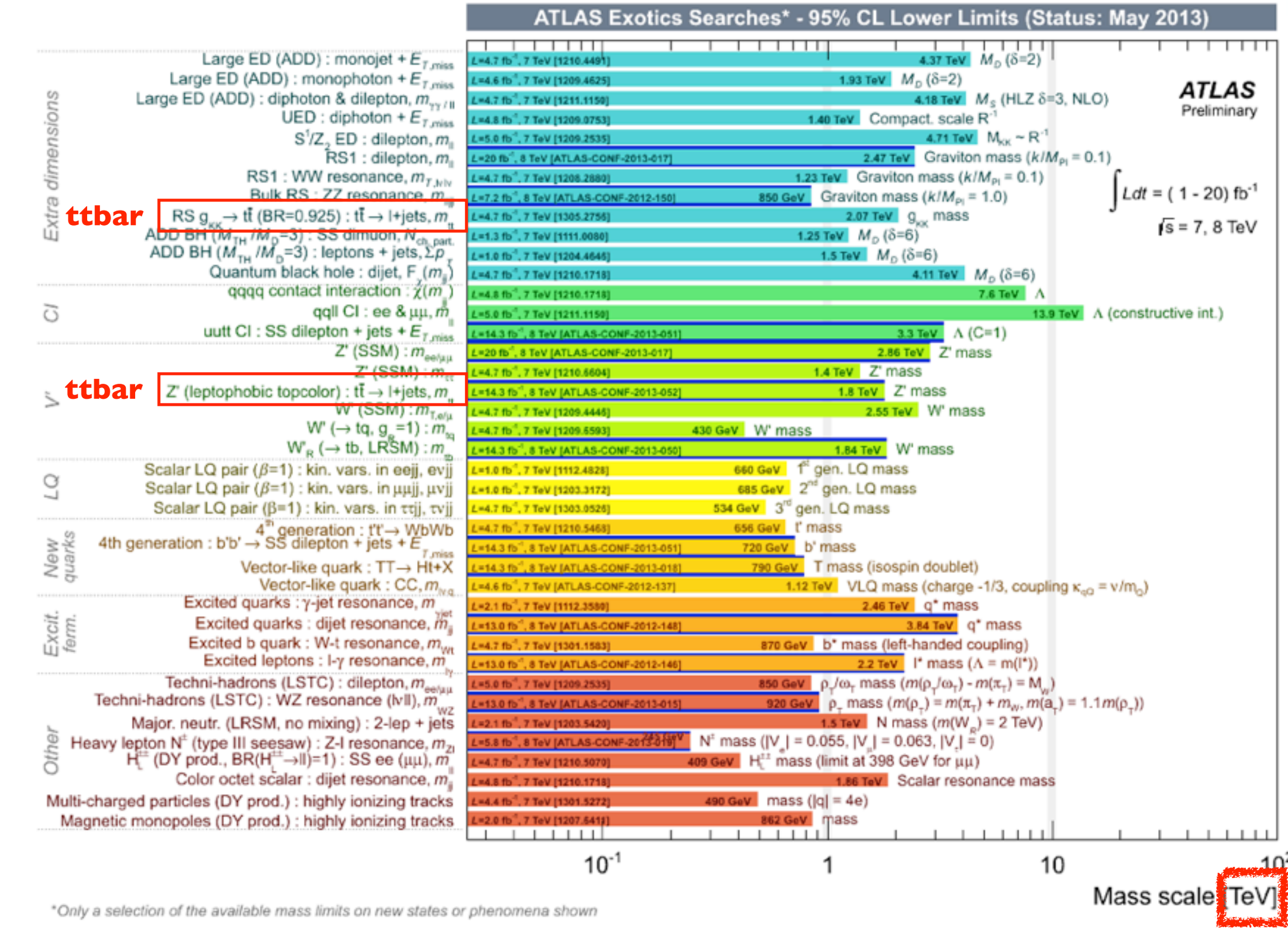
ATLAS-CONF-2014-057

l+jets → mini-isolation + loose tagging

Pushing the TeV Scale



Pushing the TeV Scale



*Only a selection of the available mass limits on new states or phenomena shown

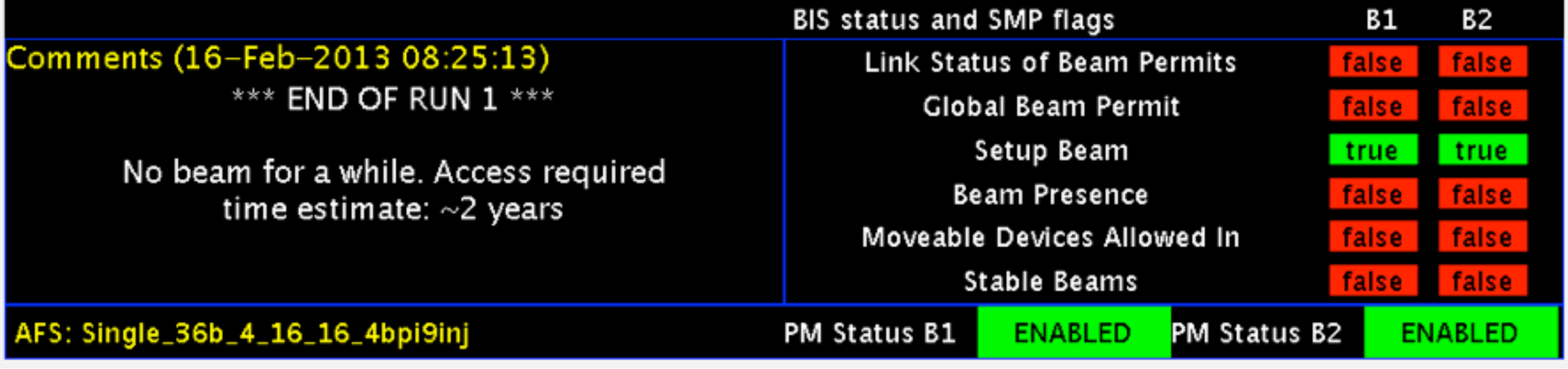
W'R → tb (had.): 1.8 TeV

Summary

SHUTDOWN: NO BEAM

- Variety of analysis strategies developed in run 1
  - different p_T regimes
  - targeting different backgrounds
  - optimized for different signals
- Exciting times ahead in run 2 !
  - boosted techniques will play a crucial role

high-mass searches + high-p_T SM top + ttH + ???



Bonus

Johannes Erdmann

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$

$\tilde{t} \rightarrow t + \text{LSP}$

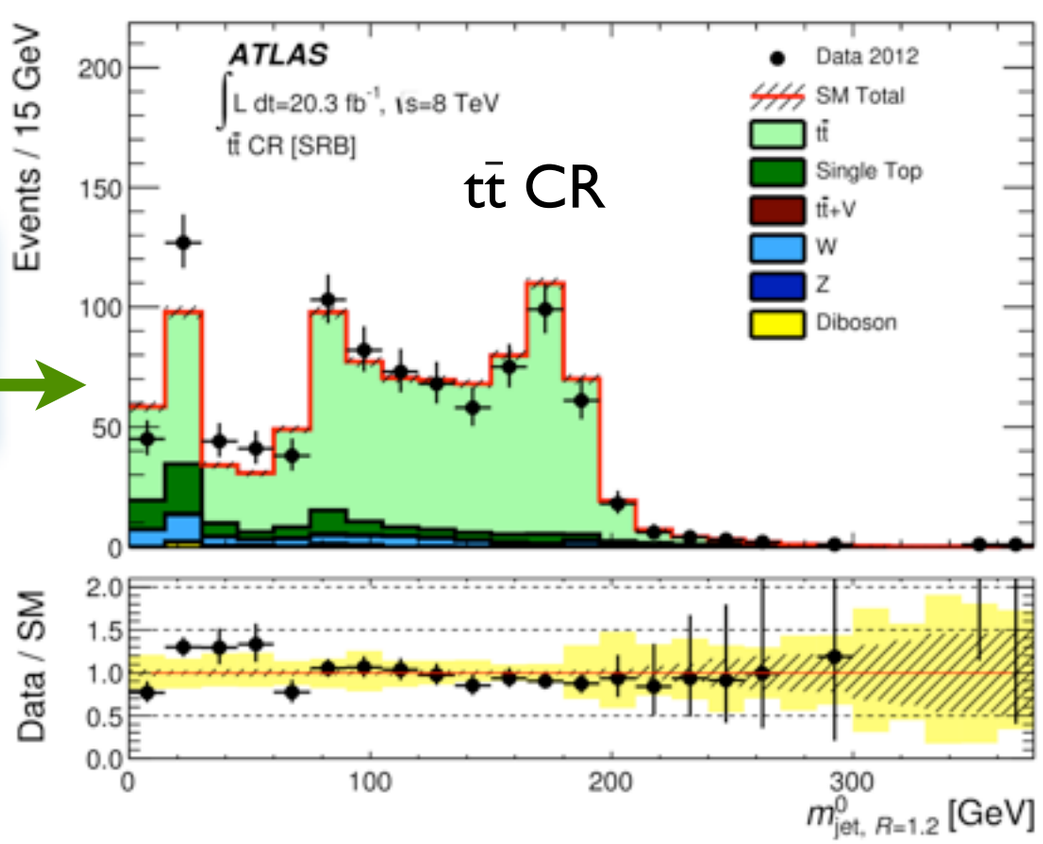
- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost ($m_{\tilde{t}}$ ~ O(few 100 GeV))
- resolved selections : 6jets/5jets, 2 b-tags, E_T^{miss}

additional partially boosted selection :

- recluster jets to top jets (R=1.2) and W jets (R=0.8)
- make use of jet masses for loose tagging
- also use top mass asymmetry to distinguish topologies (asymmetric → only 1st top, > E_T^{miss})

bkg. from CRs

$t\bar{t}$: 4/5jets



partially boosted signal region

	SRB
Observed events	2
Total SM	2.4 ± 0.7
$t\bar{t}$	$0.10^{+0.14}_{-0.10}$
$t\bar{t} + W/Z$	0.47 ± 0.17
Z + jets	1.23 ± 0.31
W + jets	0.49 ± 0.33
Single top	0.08 ± 0.06
Diboson	0.02 ± 0.01
Multijets	< 0.001

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Low boost → loose mass requirements

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$

$\tilde{t} \rightarrow t + \text{LSP}$

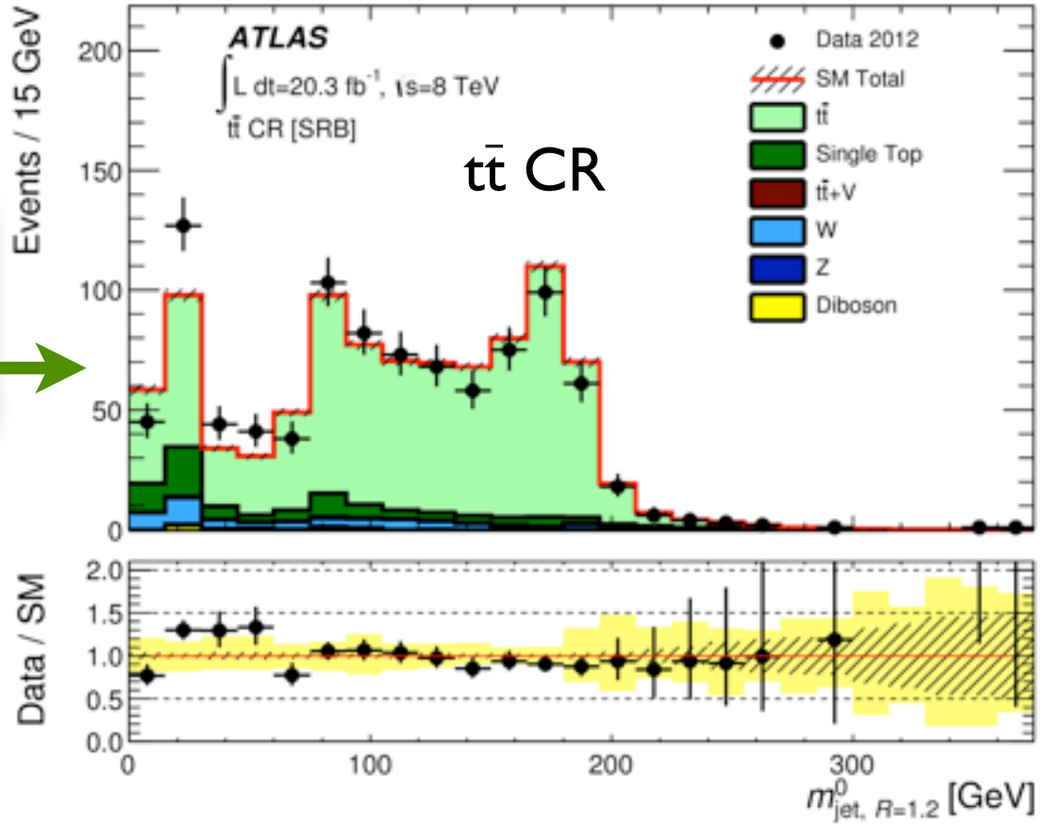
- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost ($m_{\tilde{t}}$ ~ O(few 100 GeV))
- resolved selections : 6jets/5jets, 2 b-tags, E_T^{miss}

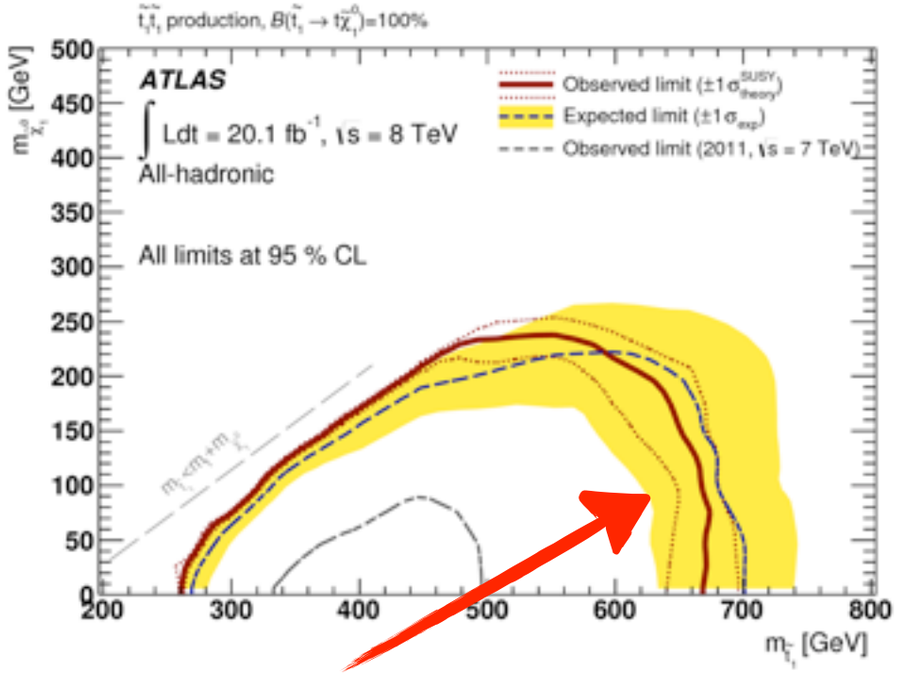
additional partially boosted selection :

- recluster jets to top jets (R=1.2) and W jets (R=0.8)
- make use of jet masses for loose tagging
- also use top jet mass asymmetry to distinguish topologies (asymmetric → only 1st top, > E_T^{miss})

bkg. from CRs

$t\bar{t}$: 4/5jets





partially boosted selection

JHEP 1409 (2014) 015

Low boost → loose mass requirements

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$$
$$\tilde{t} \rightarrow t + \text{LSP}$$

$$\mathscr{A}_{m_t} = \frac{|m^0_{\text{jet},R=1.2} - m^1_{\text{jet},R=1.2}|}{m^0_{\text{jet},R=1.2} + m^1_{\text{jet},R=1.2}}.$$

Table 3. Selection criteria for SRB, the partially resolved topology, with four or five anti-k_t $R = 0.4$ jets, reclustered into anti-k_t $R = 1.2$ and $R = 0.8$ jets.

	SRB1	SRB2
anti-k_t $R = 0.4$ jets	4 or 5, $p_{\text{T}} > 80, 80, 35, 35, (35)$ GeV	5, $p_{\text{T}} > 100, 100, 35, 35, 35$ GeV
$\mathscr{A}_{m_t}$	< 0.5	> 0.5
$p^0_{\text{T,jet},R=1.2}$	–	> 350 GeV
$m^0_{\text{jet},R=1.2}$	> 80 GeV	$[140, 500]$ GeV
$m^1_{\text{jet},R=1.2}$	$[60, 200]$ GeV	–
$m^0_{\text{jet},R=0.8}$	> 50 GeV	$[70, 300]$ GeV
$m^{\text{min}}_{\text{T}}$	> 175 GeV	> 125 GeV
$m_{\text{T}}\left(\text{jet}^3, \mathbf{p}^{\text{miss}}_{\text{T}}\right)$	> 280 GeV for 4-jet case	–
$E^{\text{miss}}_{\text{T}}/\sqrt{H_{\text{T}}}$	–	$> 17\sqrt{\text{GeV}}$
$E^{\text{miss}}_{\text{T}}$	> 325 GeV	> 400 GeV

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resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

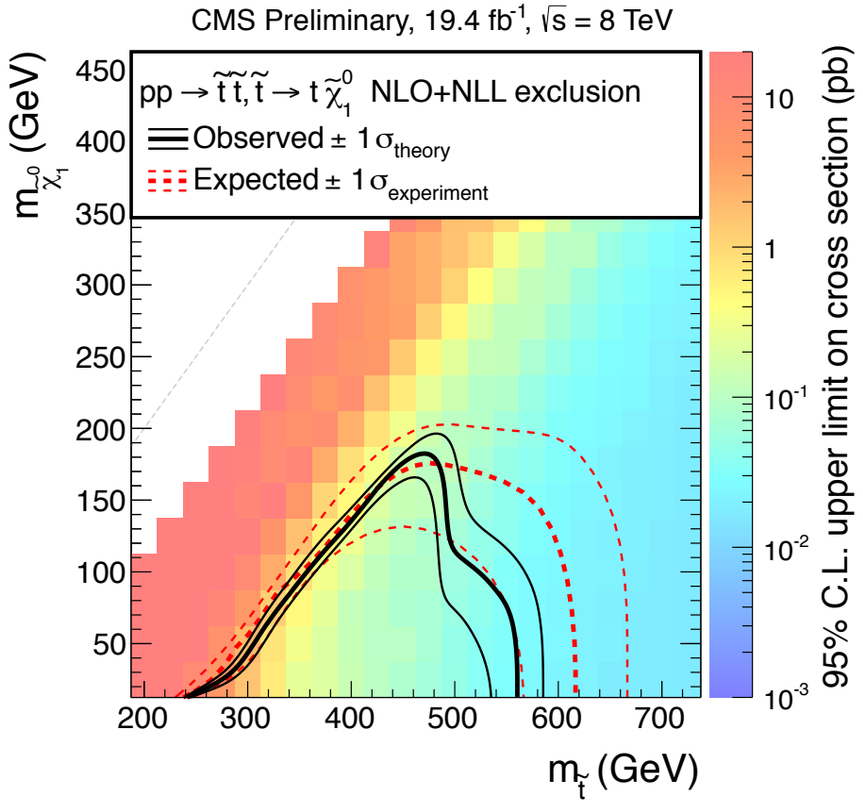
$$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$$
$$\tilde{t} \rightarrow t + \text{LSP}$$

- $m_{\tilde{t}} - m_{\text{LSP}}$ defines boost
- only low boost
- preselection : 5jets, 1 b-tag, E_T^{miss}

partially boosted selection :

- one "full top" : HEPTopTagger(HTT)-like 3-jet selection
  - $\Delta R < 1.5$, $m_{jjj} \in [80,270]$ GeV, HTT inv. mass cuts
- + one "partial top" :
  - 3 jets left : use m_{jjj} and m_{jj}
  - failing or just 2 jets : use m_{jj}
  - failing or just 1 jet : use remaining b-tagged jet

- kinematic requirements on full/partial tops
- #b-tags and E_T^{miss} categories
- bkg. estimated using data-driven techniques



CMS PAS SUS-13-015

low boost → partial reco. for 2nd top

resolved
low boost

Stop Pair Production (all-hadronic)

full 8 TeV

$$\tilde{t}\tilde{t}^* \rightarrow \text{jets} + E_T^{\text{miss}}$$
$$\tilde{t} \rightarrow t + \text{LSP}$$

- backgrounds :
  - W → τ+X, τ → had.
    - W → μν selection and replace μ by jet with p_T^{jet} / p_T^{τ} from MC
  - lost leptons (60% non-reco., 10% non-iso., 30% not in acceptance)
    - apply inefficiencies for reco. and iso.
  - Z → inv. + X
    - Z → dilep. + HF and add leptons to MET
  - QCD
    - low angle between jet and MET CR
    - extrapolate into SR

CMS PAS SUS-13-015

tH Resonances (all-hadronic)

$$T\bar{T} \to tH\bar{t}H$$
$$\to \text{jets}$$

full 8 TeV

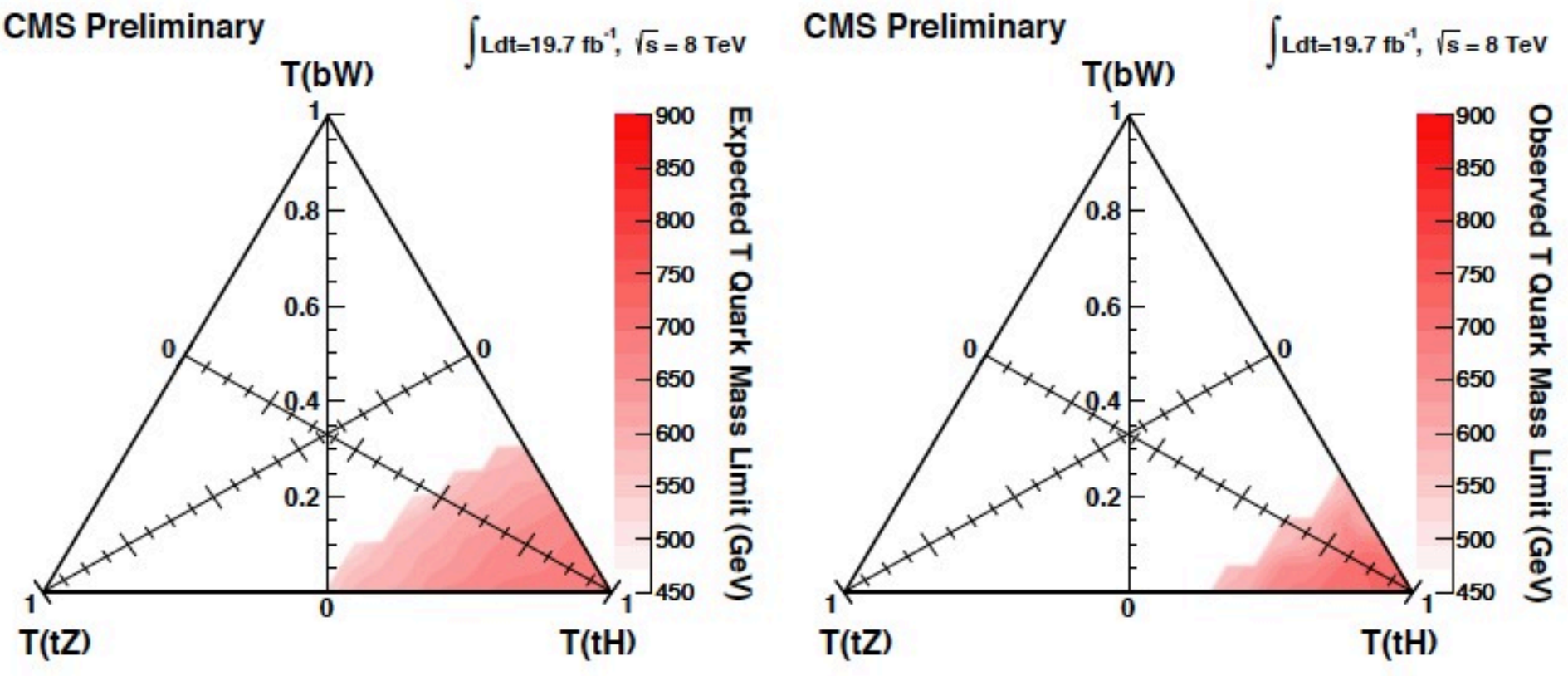


Figure 12: Branching fraction triangle with expected limits (left) and observed limits (right) for the T quark mass. Every point in the triangle corresponds to a particular set of branching fraction values subject to the constraint that all three add up to one. The branching fraction for each mode decreases from one at the corner labelled with the decay mode to zero at the opposite side of the triangle.

CMS PAS B2G-14-002

low boost
high boost

ttbar Resonances (all-hadronic)

full 7 TeV

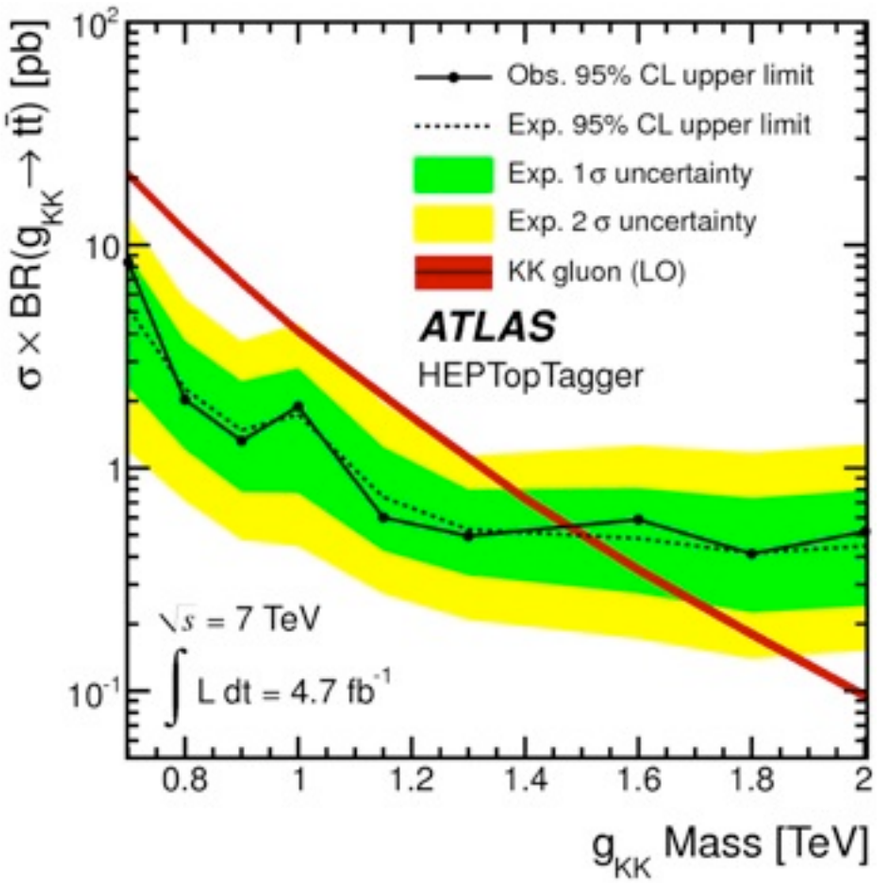
$X \rightarrow t\bar{t}$

$\rightarrow$ jets

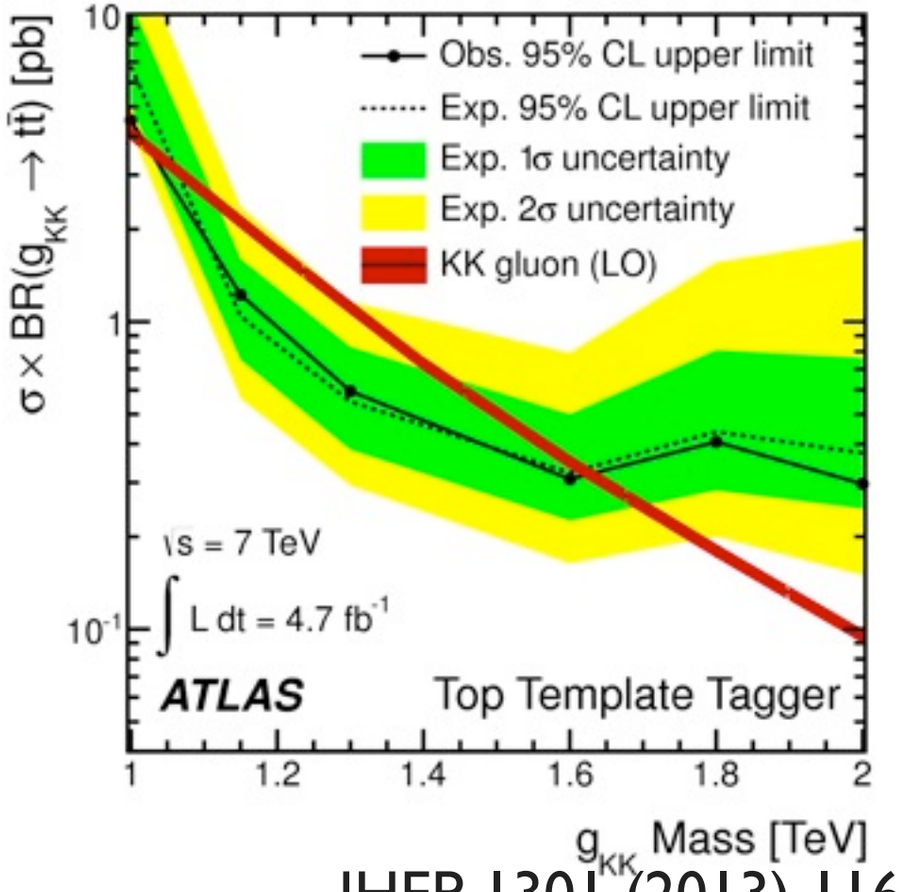
- fully boosted analysis
- low boost (p_T>200 GeV) : HEPTopTagged-C/A 1.5 jets
- high boost, i.e. high mass resonances (p_T>500/450 GeV) : Template Overlap Method (anti-k_t 1.0) + pile-up corr. mass
- matched small-R b-tagged jet

- QCD bkg. from data (inverted b-tag and top-tag requirements)
- $t\bar{t}$ from MC

HEPTopTagger



Template Overlap Method



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tagger choice p_T dependent

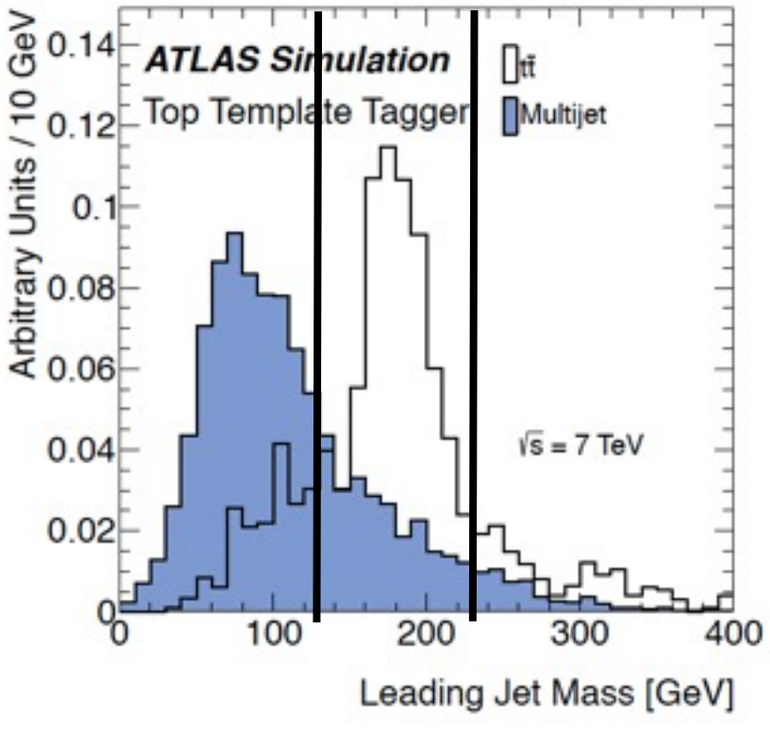
Template Overlap Method

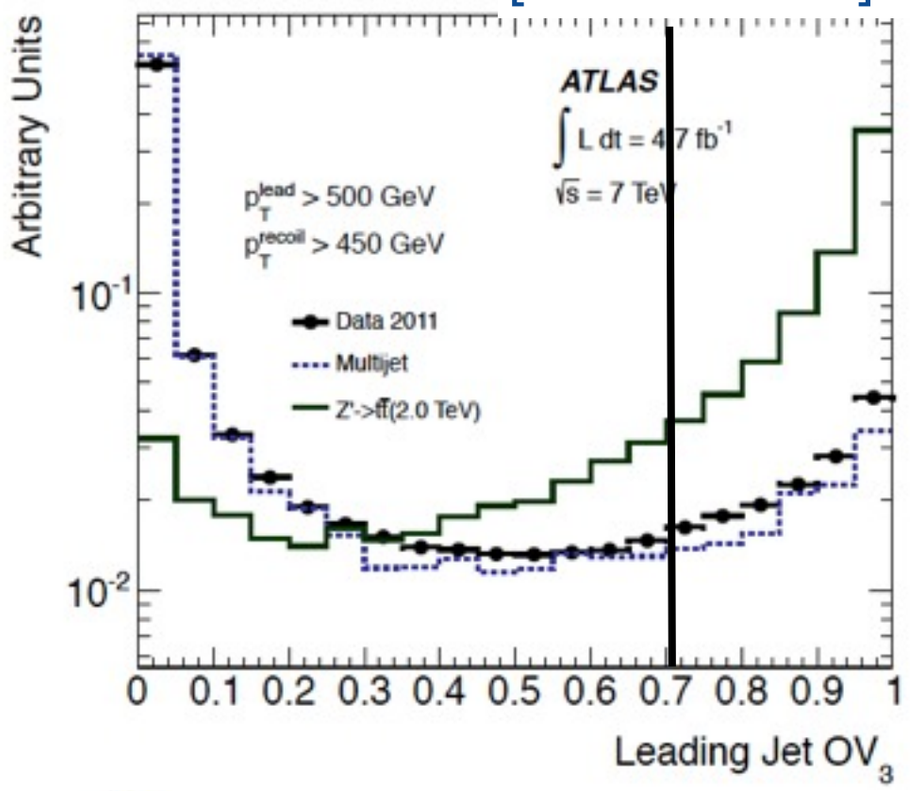
[hep-ph/1006.2035]
[hep-ph/1112.1957]
[arXiv:1211.2202]

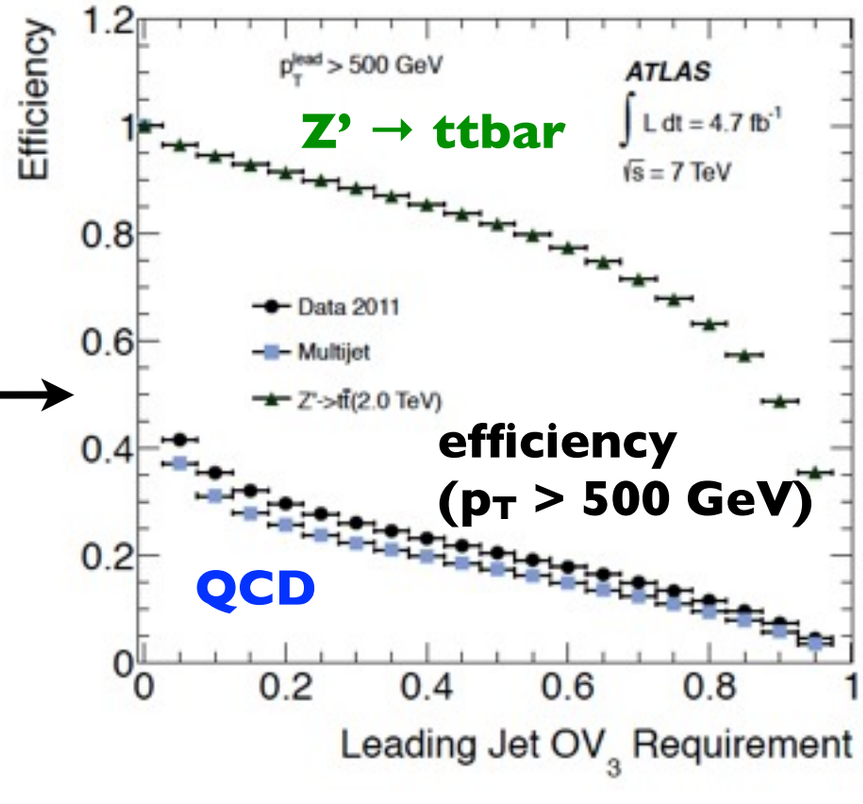
define "overlap" (= observable quantifying match of energy distributions in η-Φ space) OV_3 of topo clusters with first 3 partons in each template τ_n (large library)

$$OV_3 = \max_{\{\tau_n\}} \exp\left[-\sum_{i=1}^{3} \frac{1}{2\sigma_i^2}\Big(E_i - \sum_{\substack{\Delta R(\text{topo},i) \\ <0.2}} E_{\text{topo}}\Big)^2\right], \quad \sigma_i = E_i/3.$$

combine with cut on (pile-up corrected) jet mass







low boost

high boost

ttbar Resonances (all-hadronic)

full 8 TeV

$$X \to t\bar{t}$$

$$\to \text{jets}$$

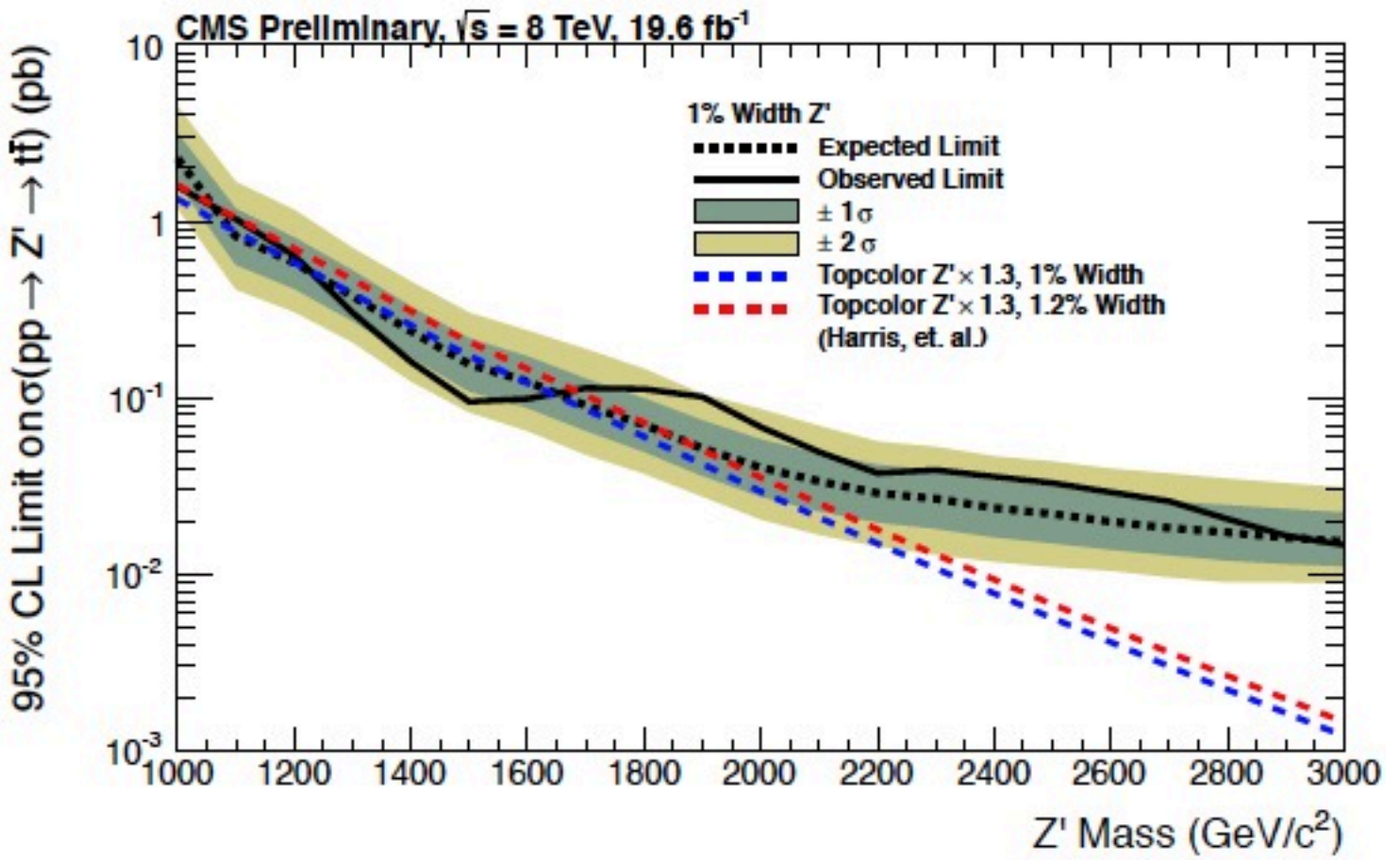


Figure 9: Preliminary expected and observed limits, in logarithmic scale, for the narrow Z′ hypothesis. The theory expectation is shown in the dashed curve, scaled by a factor of 1.3 to account for next-to-leading order effects.

PRL 111 (2013) 211804

CMS PAS B2G-12-005

high boost

tb Resonances (all-hadronic)

full 8 TeV

$$W' \to tb$$
$$\to \text{jets}$$

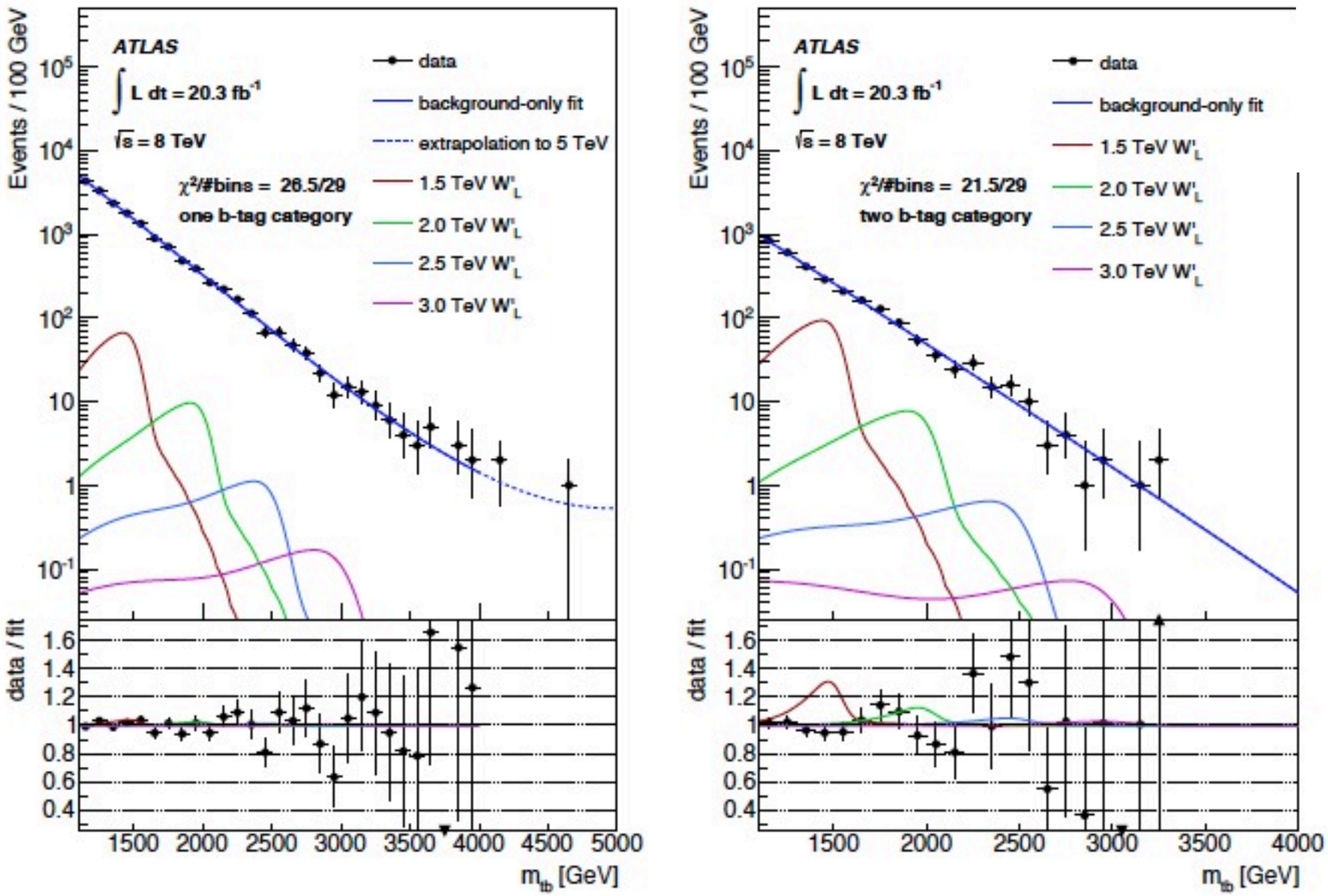


Fig. 4: m_{tb} distributions in data in the one b-tag (left) and the two b-tag category (right). Background-only fits are shown, and the bottom plots show the ratio of the data and the fit. The left plot shows an extrapolation of the background fit into the region 4 – 5 TeV. The ratio plot, however does not show the three data points in this range, because they are beyond the range considered for this analysis. Potential W'_L signal shapes in the hadronic top-quark decay channel with $g' = g_{\mathrm{SM}}$ are also overlaid for resonance masses of 1.5, 2.0, 2.5 and 3.0 TeV.

arXiv:1408.0886

tb Resonances (all-hadronic)

full 8 TeV

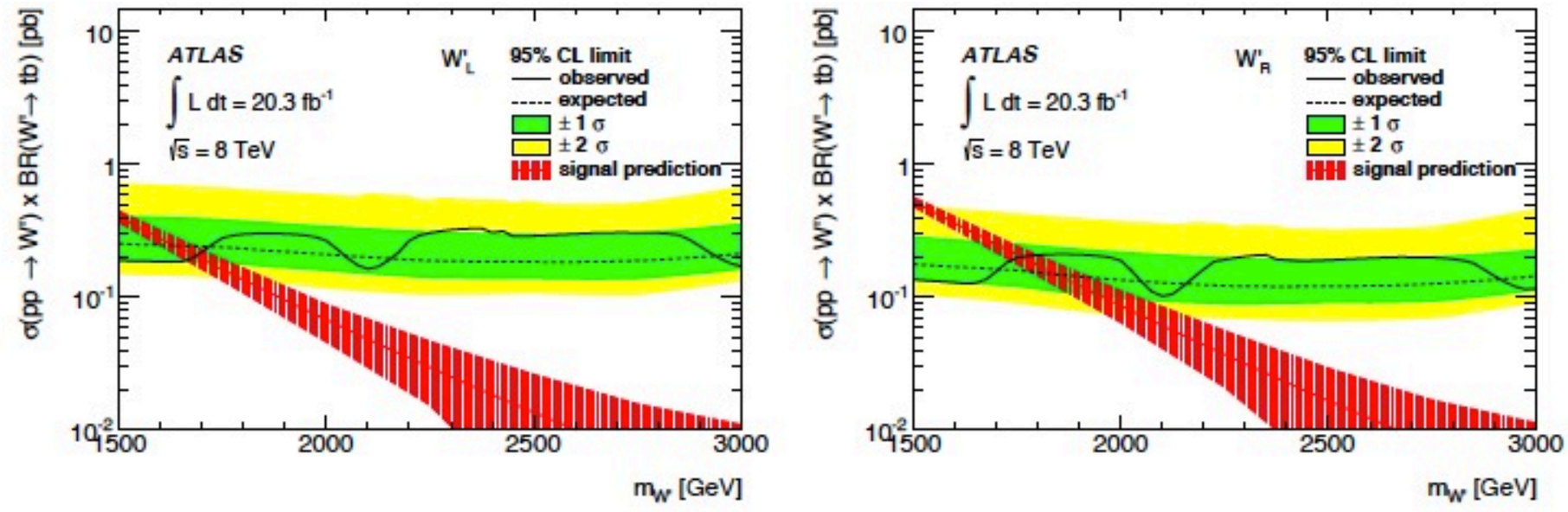


Fig. 6: Limits at 95% CL on the cross section times branching ratio to tb for the left-handed (left) and for the right-handed (right) W' model. The expected cross section for W' production with $g' = g_{SM}$ is also shown.

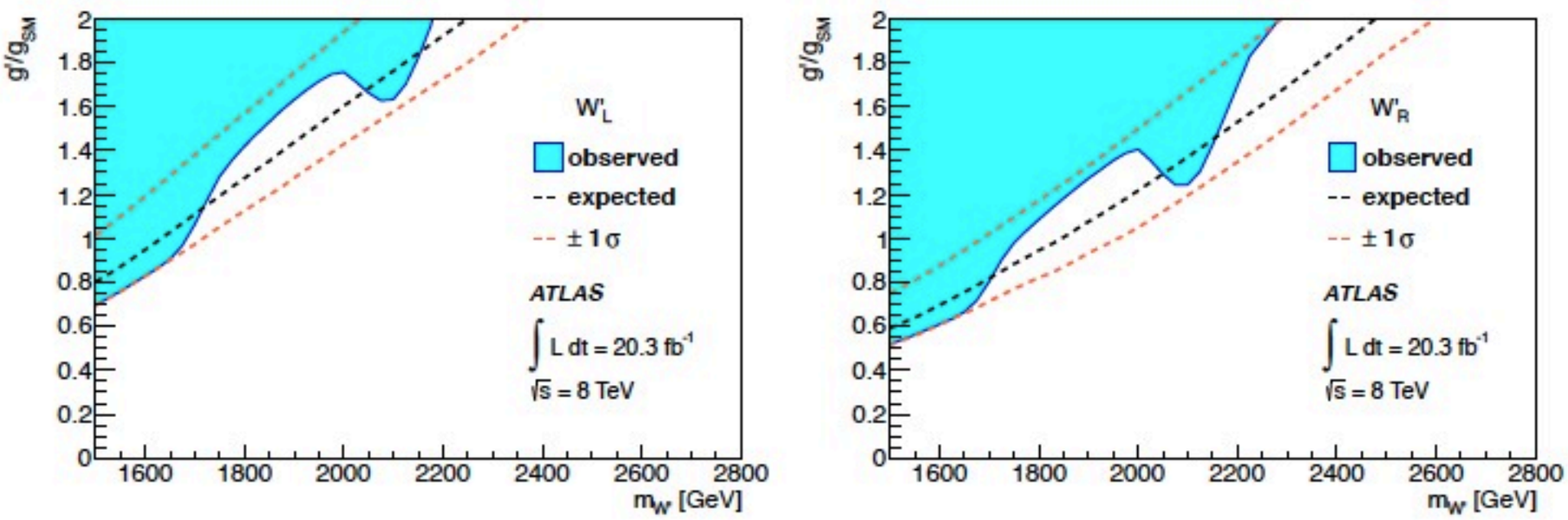
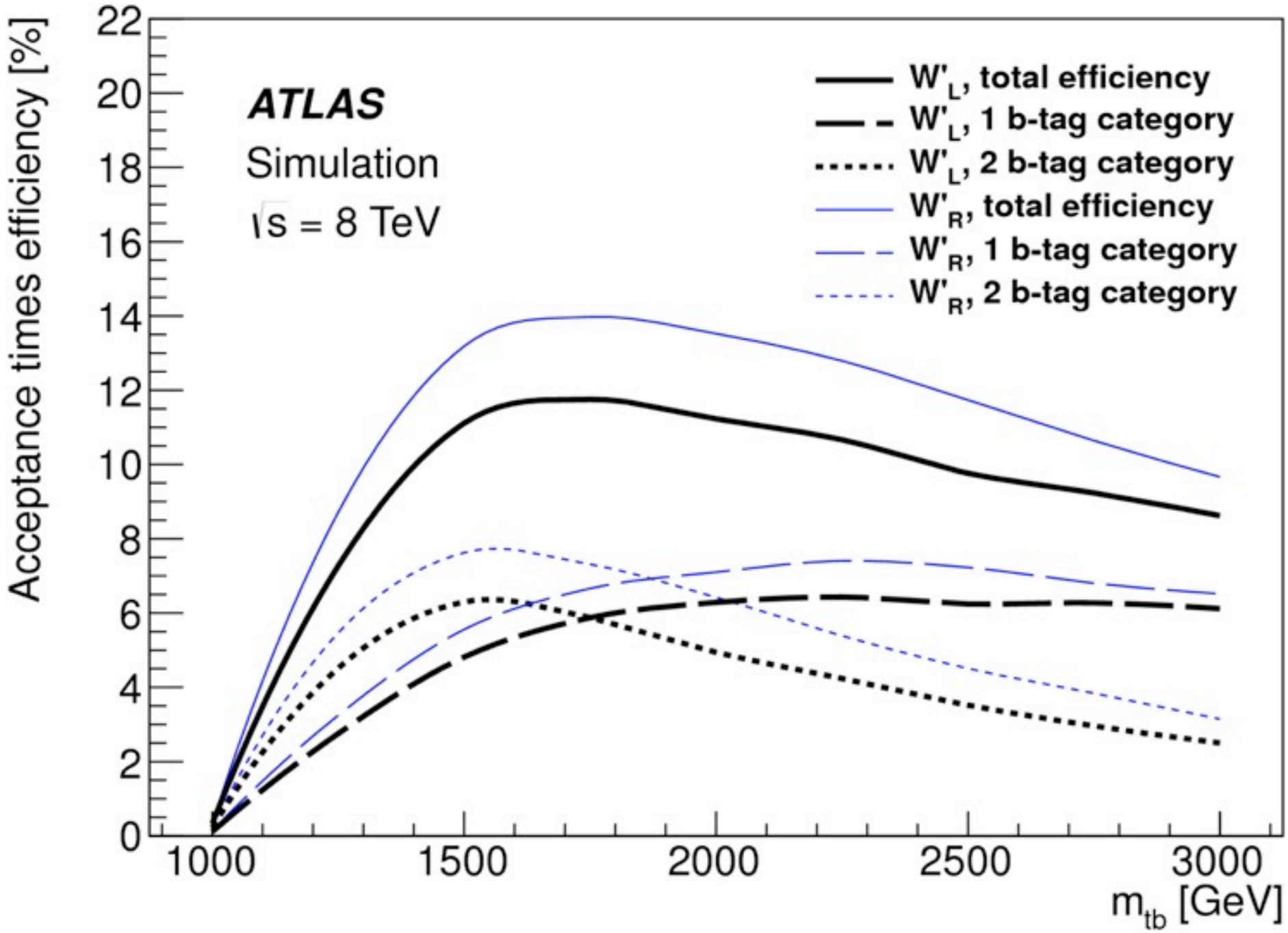


Fig. 7: Observed and expected 95% CL limits on the ratio of coupling g'_L/g_{SM} (g'_R/g_{SM}) of the W'_L (W'_R) model as a function of the W' mass.

arXiv:1408.0886

high boost

tb Resonances (all-hadronic)



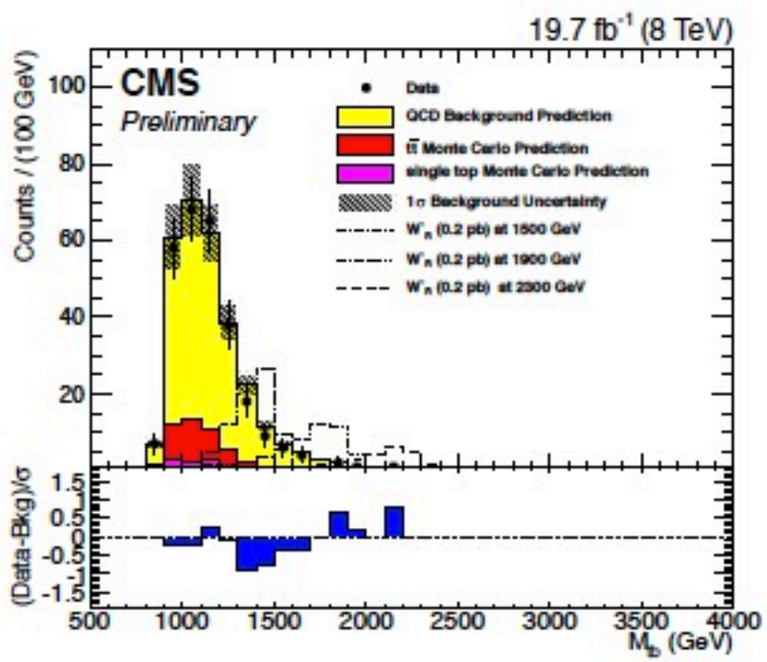
full 8 TeV

arXiv:1408.0886

tb Resonances (all-hadronic)

$W' \to tb$

$\to$ jets



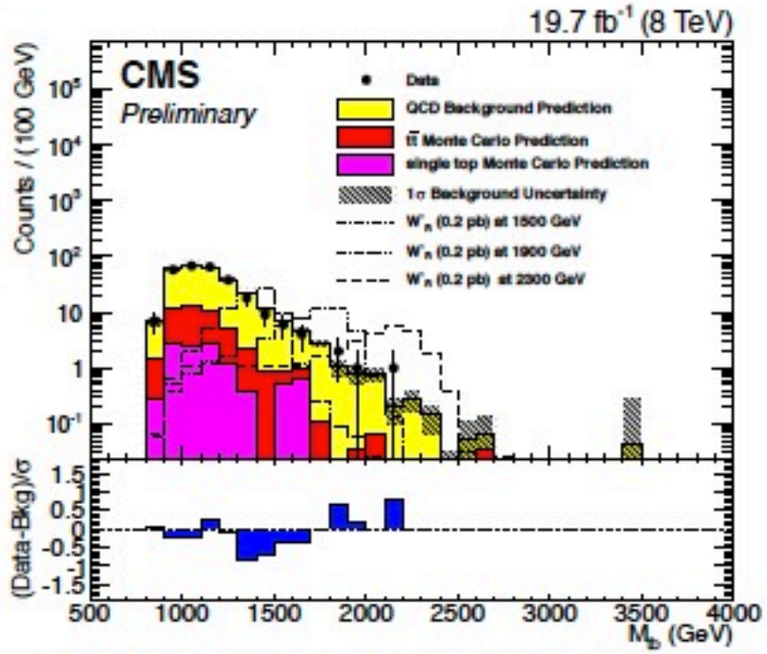


Figure 7: A plot of the full selection comparing data, signal and background. The single top quark contribution is not considered when setting limits. The normalization for the signal samples is set to a cross-section of 0.2pb. Top and bottom plots are the same but with linear and log y-axis scale.

full 8 TeV

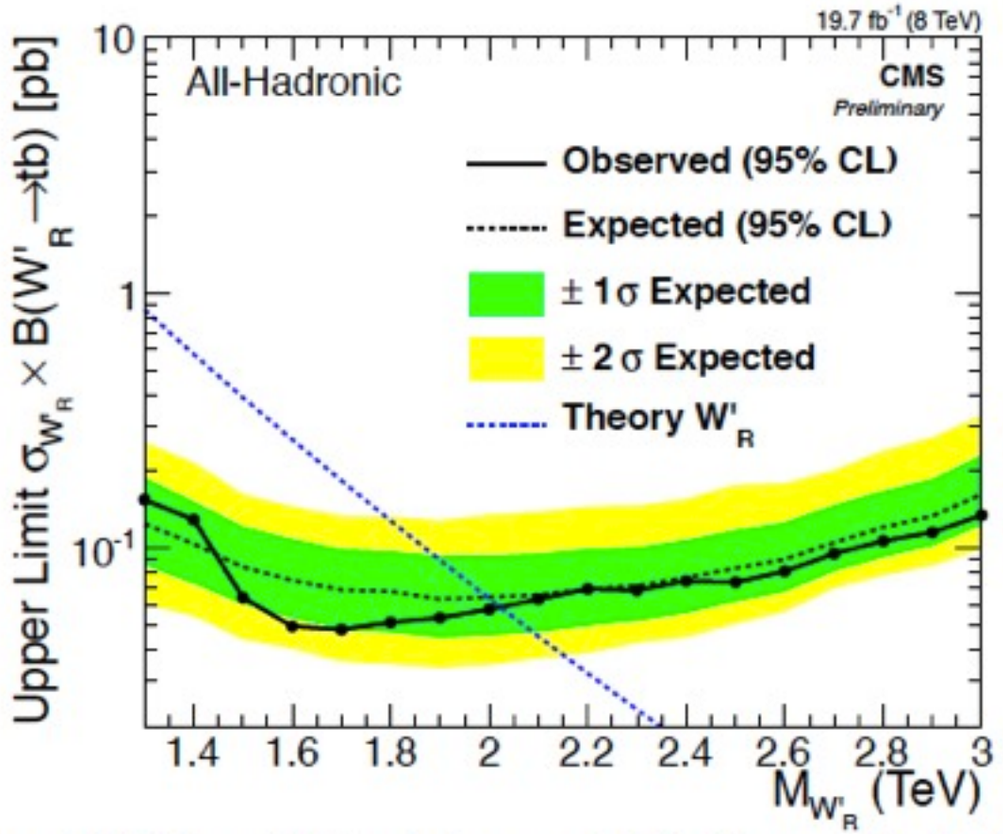


Figure 8: The W'_R boson 95% C.L. production cross-section limits. The expected (black) and observed (red) limits as well as W'_R boson theoretical cross-section (blue) are plotted for comparison. The uncertainty in the expected limit band is shown in light ($\pm 1\sigma$) and dark grey ($\pm 2\sigma$). These limits were extracted using the Theta limit setting framework.

CMS PAS B2G-12-009

CMS tagging + τ_{32} ; high mass veto

resolved

low boost

Stop Pair Production (1 lepton)

full 8 TeV

	tN_diag	tN_med	tN_high	tN_boost
Preselection	Default preselection criteria, cf. table 3.			
Lepton	$= 1$ lepton			
Jets	≥ 4 with $p_{\mathrm{T}} >$ 60, 60, 40, 25 GeV	≥ 4 with $p_{\mathrm{T}} >$ 80, 60, 40, 25 GeV	≥ 4 with $p_{\mathrm{T}} >$ 100, 80, 40, 25 GeV	≥ 4 with $p_{\mathrm{T}} >$ 75, 65, 40, 25 GeV
***b*-tagging**	≥ 1 b-tag (70% eff.) amongst four selected jets			
large-R jet	–			≥ 1, $p_{\mathrm{T}} > 270$ GeV and $m > 75$ GeV
$\Delta\phi(\mathrm{jet}_2^{\text{large-}R}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$	–			> 0.85
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 100 GeV	> 200 GeV	> 320 GeV	> 315 GeV
m_{T}	> 60 GeV	> 140 GeV	> 200 GeV	> 175 GeV
am_{T2}	–	> 170 GeV	> 170 GeV	> 145 GeV
m_{T2}^{τ}	–	–	> 120 GeV	–
topness	–	–	–	> 7
$m_{\mathrm{had-top}}$	$\in [130, 205]$ GeV	$\in [130, 195]$ GeV	$\in [130, 250]$ GeV	
τ-veto	tight	–	–	modified, see text.
$\Delta R(b\text{-jet}, \ell)$	< 2.5	–	< 3	< 2.6
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	> 5 GeV$^{1/2}$	–		
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	–	> 12.5		> 10
$\Delta\phi(\mathrm{jet}_i, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$	> 0.8 $(i = 1, 2)$	> 0.8 $(i = 2)$	–	$> 0.5, 0.3$ $(i = 1, 2)$

arXiv:1407.0583

l+jets + low boost → very loose tagging

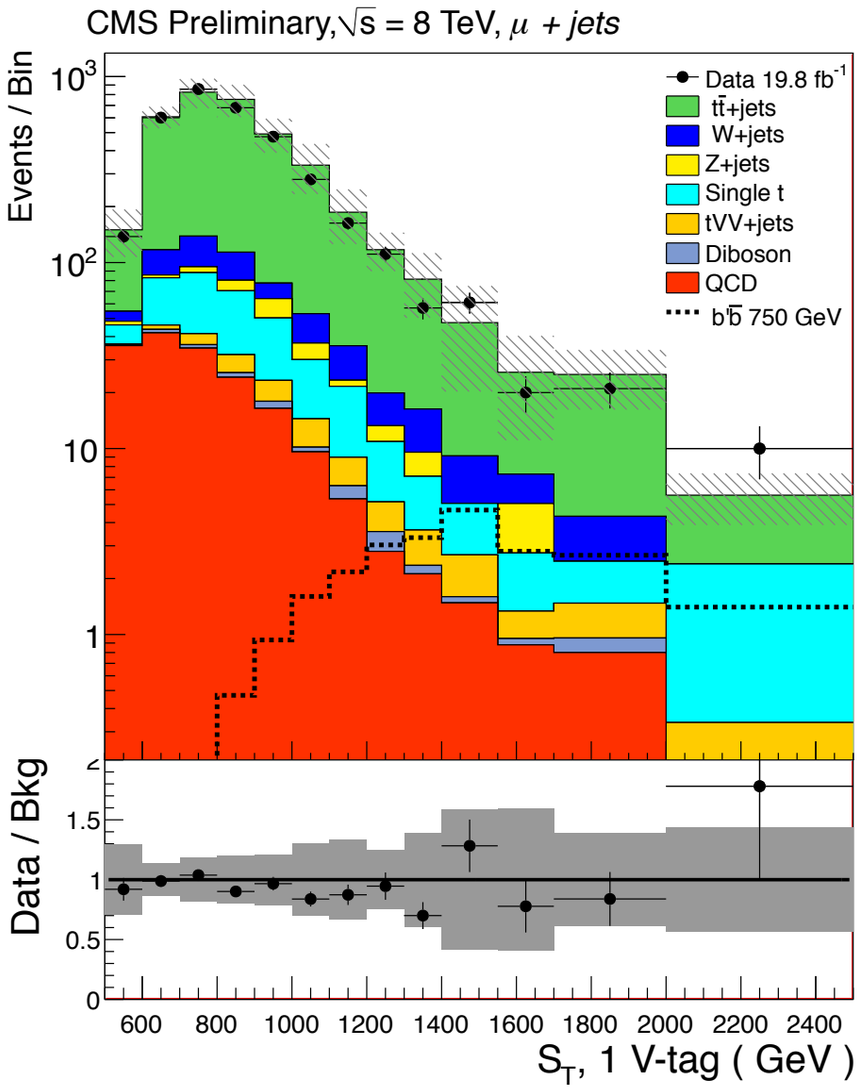
low boost

VLQ b' Pair Production (1 lepton)

full 8 TeV

$$b'\bar{b}'$$
$$b' \to tW$$
$$b' \to bZ$$
$$b' \to bH$$

- selection targeting all possible final states
  - one e or μ
  - ≥ 4 high-p_T jets (anti-k_t 0.5), ≥ 1 b-tagged, E_T^{miss}
  - pruned C/A 0.8 V-tag (m∈[50,150]GeV, mass drop)



- categorize in boson tags
- most sensitive to tW final state (more taggable bosons)
- $S_{\mathrm{T}} = \sum_{\text{anti-}k_t 0.5} p_{\mathrm{T}}^{\mathrm{jet}} + p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}$

μ+jets

Background process	0 V-tag	1 V-tag	≥ 2 V-tags
$t\bar{t}$	6400.5 ± 64.4	3001.8 ± 44.1	147.7 ± 9.8
W+jets	932.2 ± 34.7	178.5 ± 11.7	25.9 ± 6.4
Z+jets	179.5 ± 19.7	50.9 ± 10.5	8.0 ± 4.2
Single top	471.8 ± 13.6	203.1 ± 9.2	7.6 ± 1.8
$t\bar{t}$V+jets	46.8 ± 1.0	31.8 ± 0.8	3.9 ± 0.3
Diboson (WW,WZ,ZZ)	24.3 ± 1.6	9.4 ± 1.0	0.7 ± 0.3
Multijet	325.5 ± 2.8	176.2 ± 2.7	2.9 ± 0.1
Total background	8380.7 ± 77.0	3651.7 ± 47.8	196.6 ± 12.6
Data	8013	3473	209

CMS PAS B2G-12-019

categorize in tight boson-tags

low boost

VLQ $T_{2/3}$ Pair Production (≥1 lepton)

full 8 TeV

$T\bar{T}$

$T \to bW$

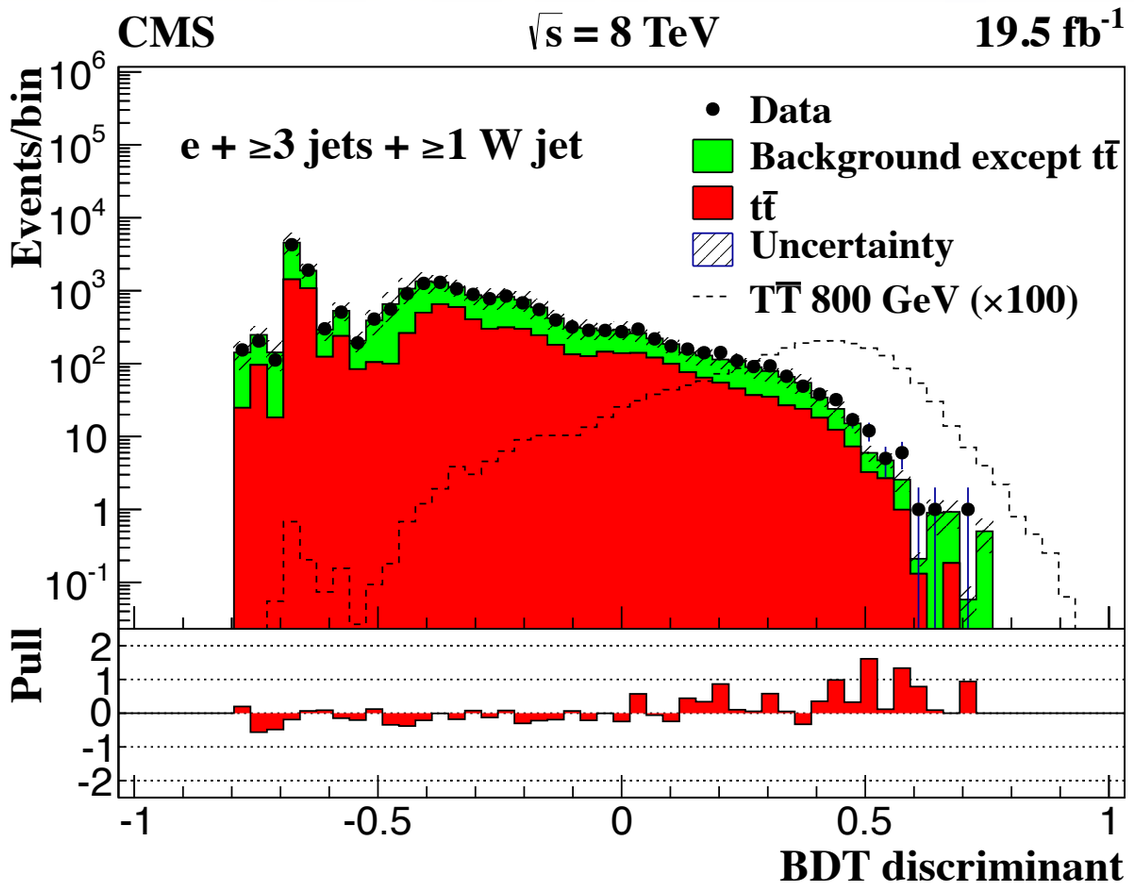
$T \to tZ$

$T \to tH$

- multi-lepton and single lepton
- single lepton : resolved and partially boosted
  - one e/μ + 3 jets with p_T > 120/90/50 GeV, E_T^{miss}
    - resolved : 4th jet with p_T > 35 GeV
    - partially boosted (tagged W) :
      C/A 0.8 jet, p_T > 200 GeV, m ∈ [60,130] GeV

BDT inputs

- # W-jets
- p_T of W-jets
- # top-jets (CMS tagger)
- # anti-k_t 0.5 jets
- # b-tags
- H_T & E_T^{miss},
- p_T of lepton
- p_T of third jet



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W- and top-tagging as inputs to BDT

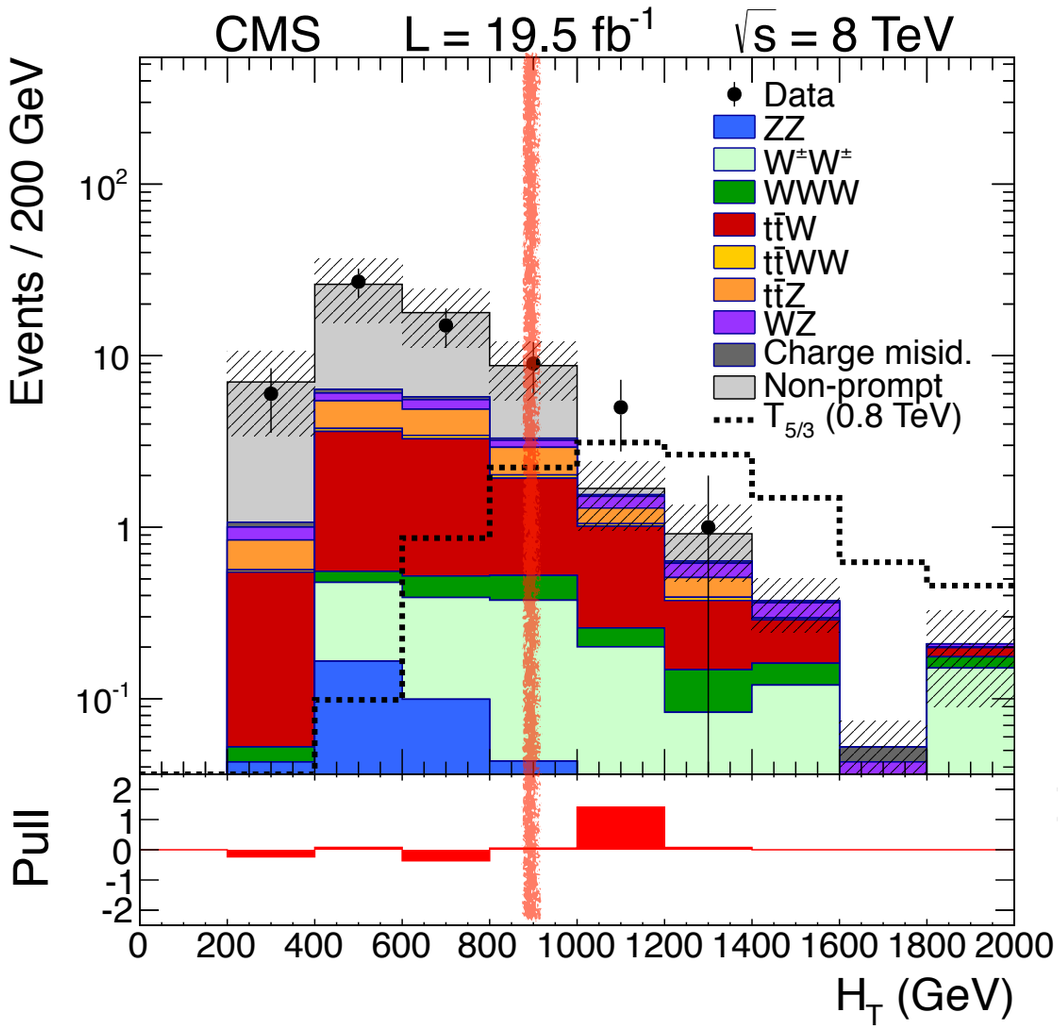
low boost

VLQ $T_{5/3}$ (dilepton)

full 8 TeV

$$T_{5/3}\bar{T}_{5/3} \to tWtW$$

- same-sign lepton search
- top ID : R=0.8 CMS top-tagger (p_T > 400 GeV)
- W ID : R=0.8 (pruned) 2 subjets + W mass
- jet ID : R=0.5, away from top or W ID-ed jets



selection :

- $Z \to ll$ veto
- cover various boosted regimes by counting final state objects :

$$3 \cdot N_t + 2 \cdot N_W + N_{\text{jet}} + N_\ell \geq 7$$

- counting experiment in H_T > 900 GeV

boosted techniques shown to improve limits

PRL 112 (2014) 171801

counting of final state objects