Search for Resonances and High p_T Top Production

in CDF, ATLAS, and CMS

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Outline

- Introduction
- $t\bar{t}$ Resonance Searches
  - semi-leptonic channel (CDF)
  - semi-leptonic channel (ATLAS)
  - semi-leptonic & fully hadronic channels (CMS)
- Vector-like Top Partner Searches
  - T' $\rightarrow$ tH (ATLAS)
  - T' $\rightarrow$ tH, bW, tZ (CMS)
- Summary & Outlook

The top quark and new physics

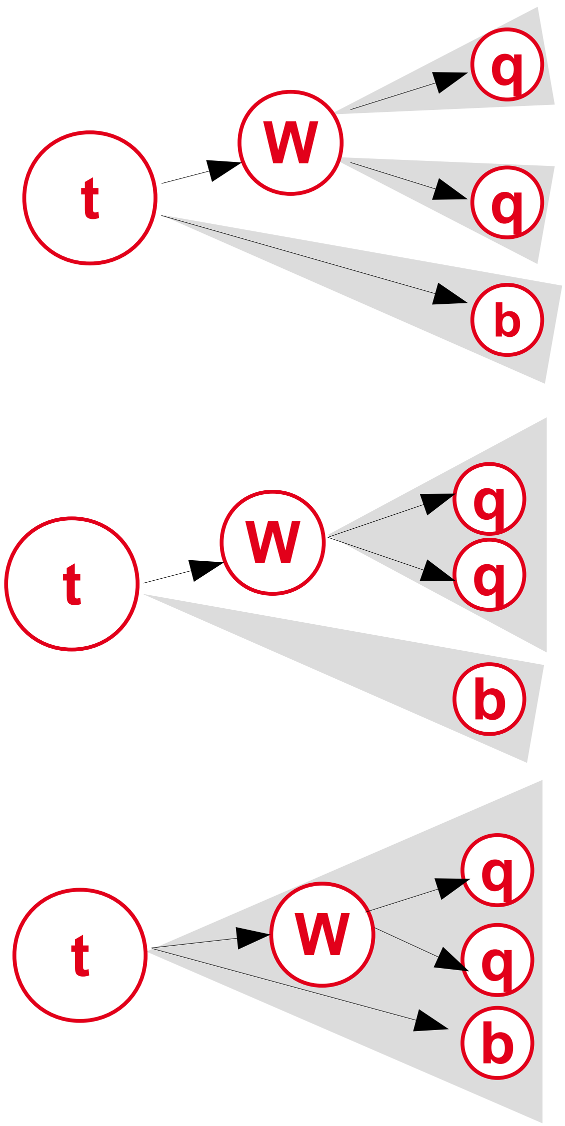
Very massive new particles

Increased couplings to 3rd generation

Decays to boosted tops

Top decay products not always resolvable

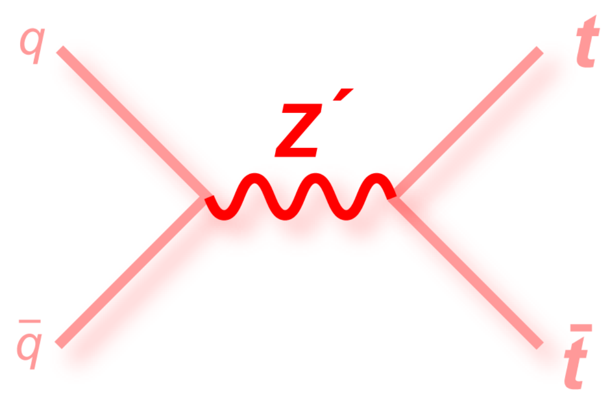
Jet substructure tools become
more and more important



$t\bar{t}$ Resonance Searches

Introduction

Two benchmark models typically considered:



- Leptophobic topcolor Z'
  → narrow resonances
- Kaluza-Klein gluons from Randall-Sundrum models
  → broad resonances

But: Other models can be tested in these searches as well

$t\bar{t}$ resonance search single lepton channel

Full CDF dataset: 9.45fb^{-1} at $\sqrt{s}$ = 1.96 TeV

PRL 110 121802 (2013)

Event Selection

Search for technicolor Z' resonance
Low mass regime: Tevatron experiments competitive with LHC experiments

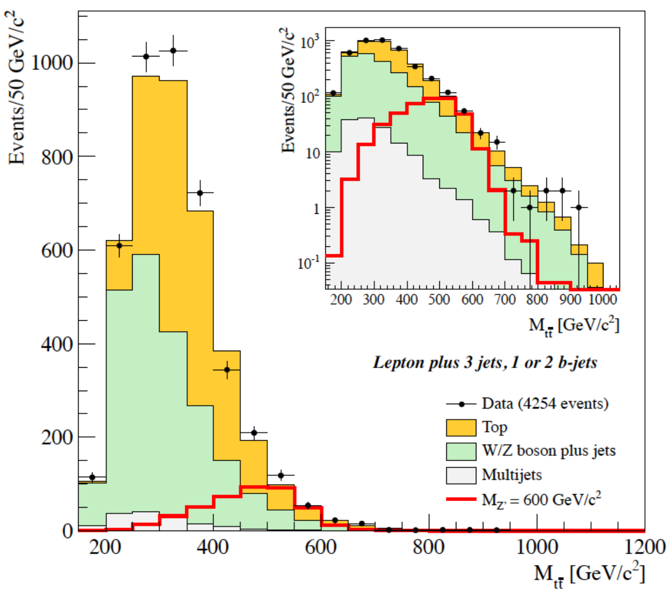
Event Selection

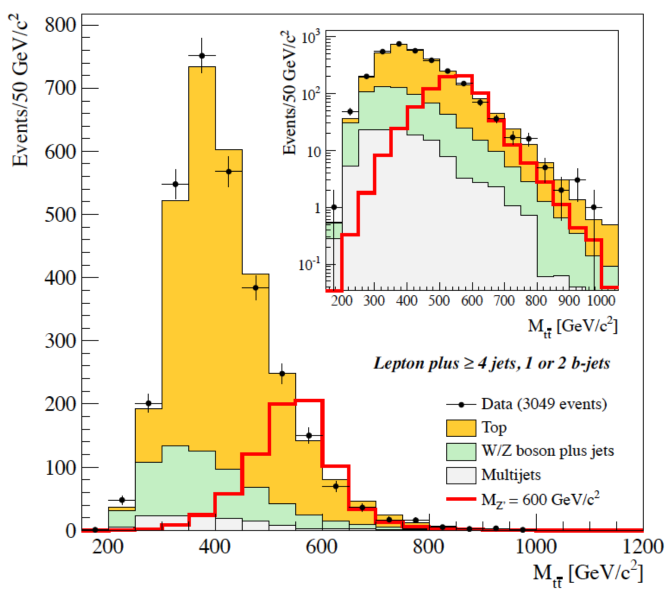
Exactly 1 lepton (p_T > 20 GeV)

$E_{T,miss}$ > 20 GeV

≥ 3 jets (E_T > 20 GeV) with 1 or 2 b-tags

Resulting mtt spectrum





$p_T(\nu)$: min. solution of

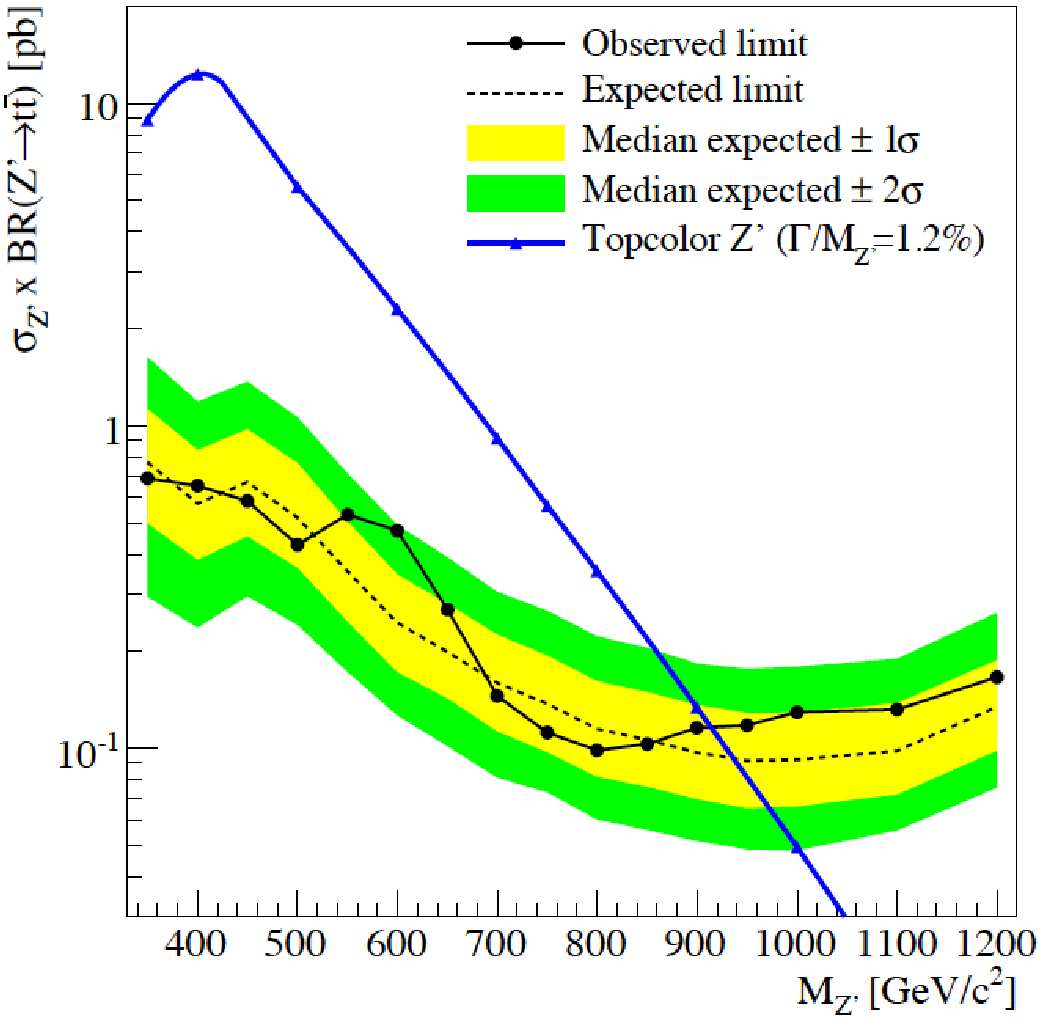
$$M_W^2 = (p^l + p^\nu)^2$$

Reconstruct m_{tt} from $p_T(\nu)$ & jets and lepton

No excess observed

Set limits

Limits



Statistical analysis in 8 categories (sort by n(b-tags), lepton flavor...)

Use combined likelihood for bayesian 95% C.L. Limits

For leptophobic topcolor Z' of width $\Gamma_{Z'} = 0.012\ M_{Z'}$:
Excluded masses below 915 GeV

Most constraining limits to date in the lower mass regime

$t\bar{t}$ resonance search
single lepton channel

14.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
ATLAS-CONF-2013-052

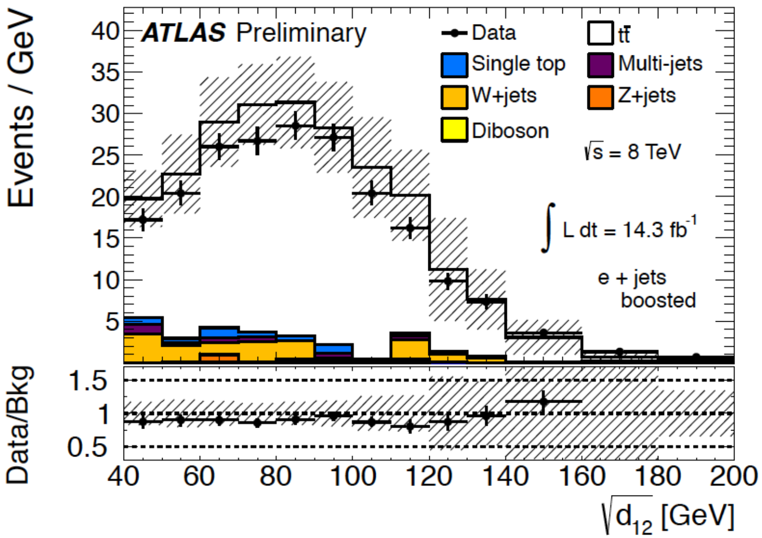
Event Selection

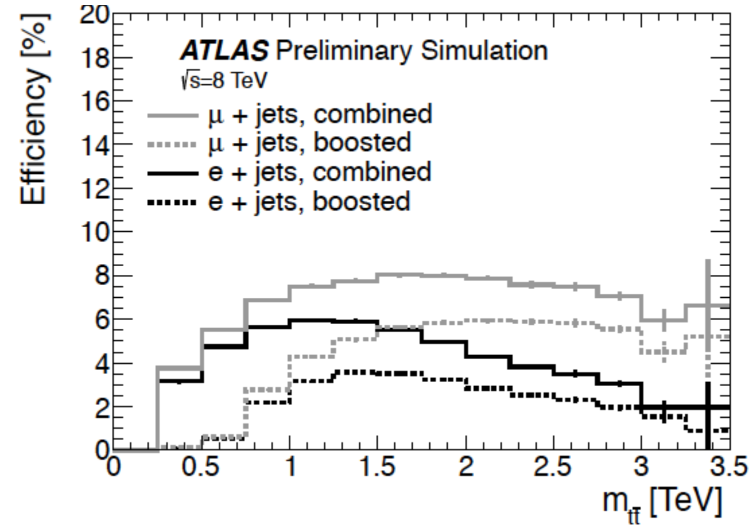
Exactly **1 isolated electron** (E_T > 25 GeV) **or muon** (p_T > 25 GeV)

Resolved selection:
≥ 4 ak4 jets pT > 25 GeV
OR
3 ak4 jets if 1 has m_{jet} > 60 GeV

Boosted selection:
1 anti-kt jet ΔR = 1. (m_{jet} > 100 GeV) with
2 hard subjets after trimming ($\sqrt{d_{12}}$ > 40 GeV)
1 anti-kt jet ΔR = .4 (ak4 jet)

Both selections:
≥ 1 b-tag on ak4 (neural network MV1 tagger)





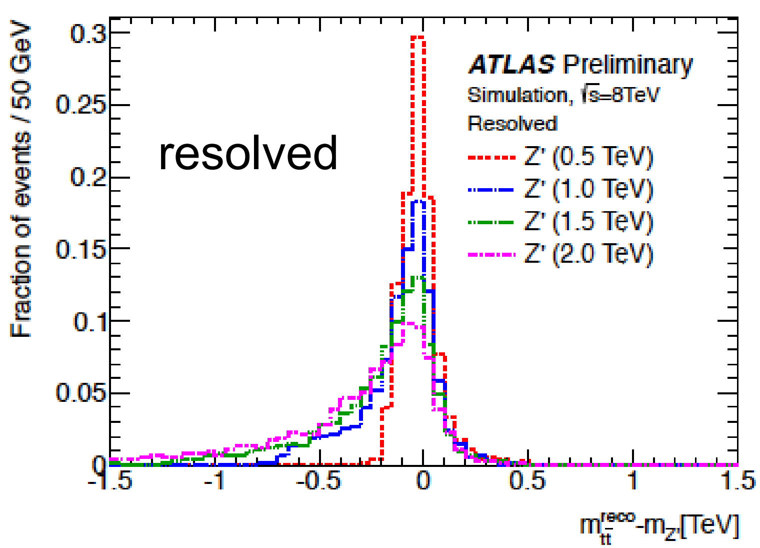
Reconstruction of $m_{t\bar{t}}$

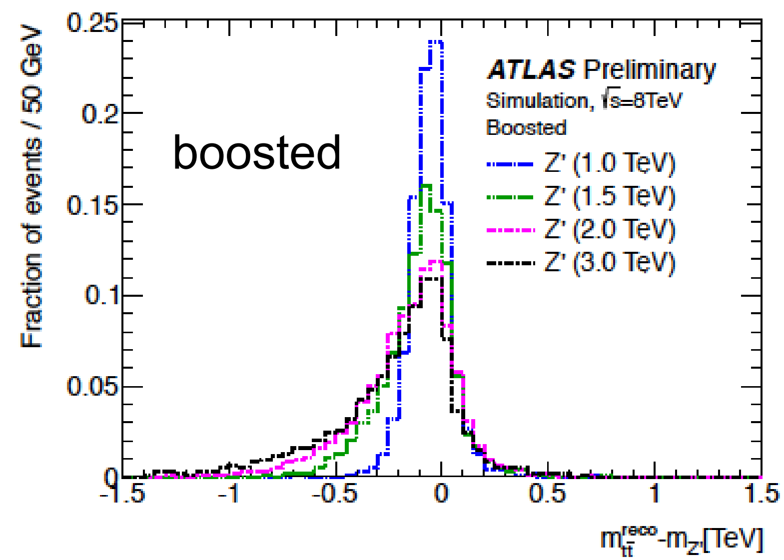
Leptonic top decay:
On-shell W constraint on lepton + $E_{T,miss}$ system → neutrino momentum p_Z

Resolved case: χ^2 algorithm → best assignment of jets to had. & lept. decay

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\mathrm{diff}\,p_T}}\right]^2$$

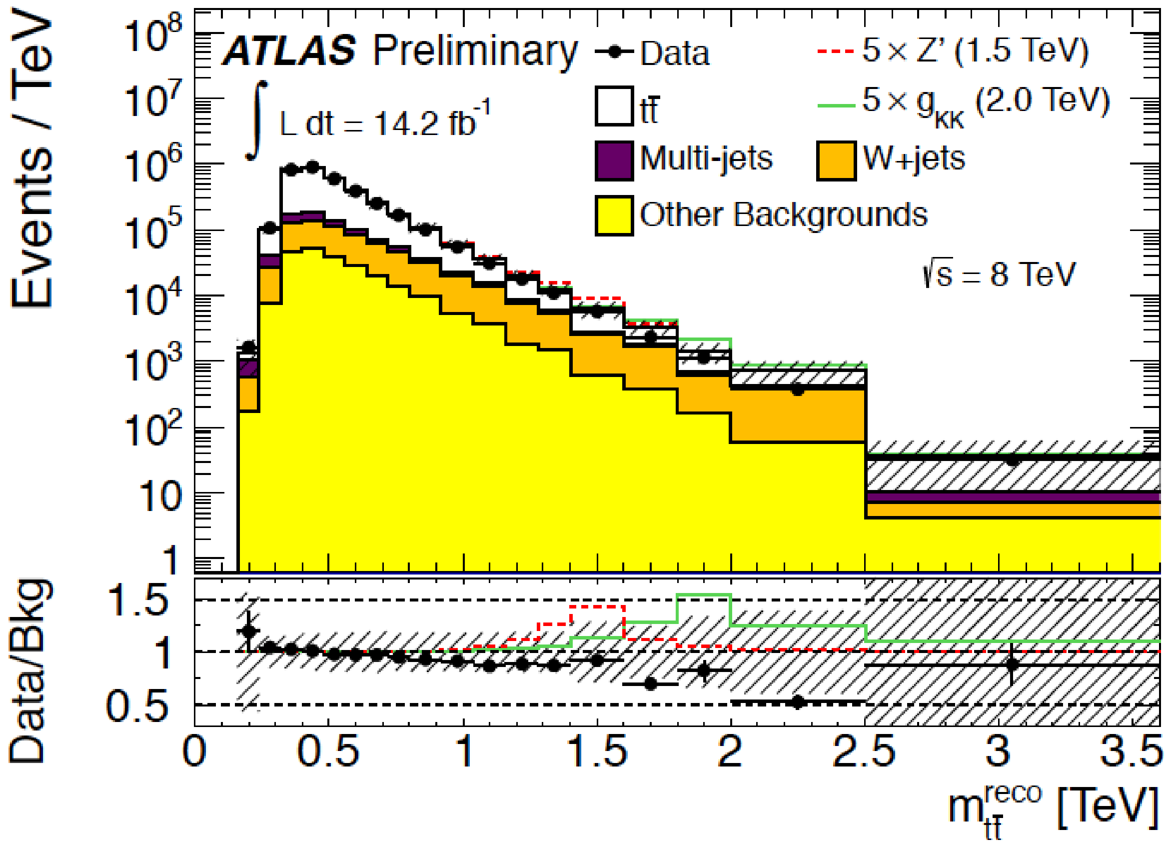
Boosted case: Decay products merged to fat jet → No ambiguity





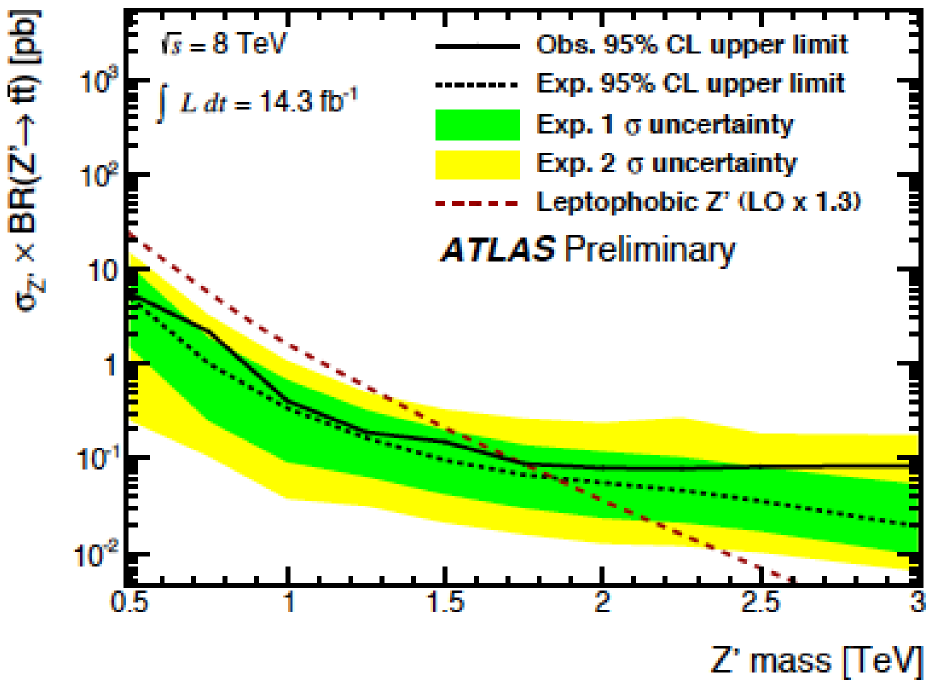
$m_{t\bar{t}}$ Spectrum

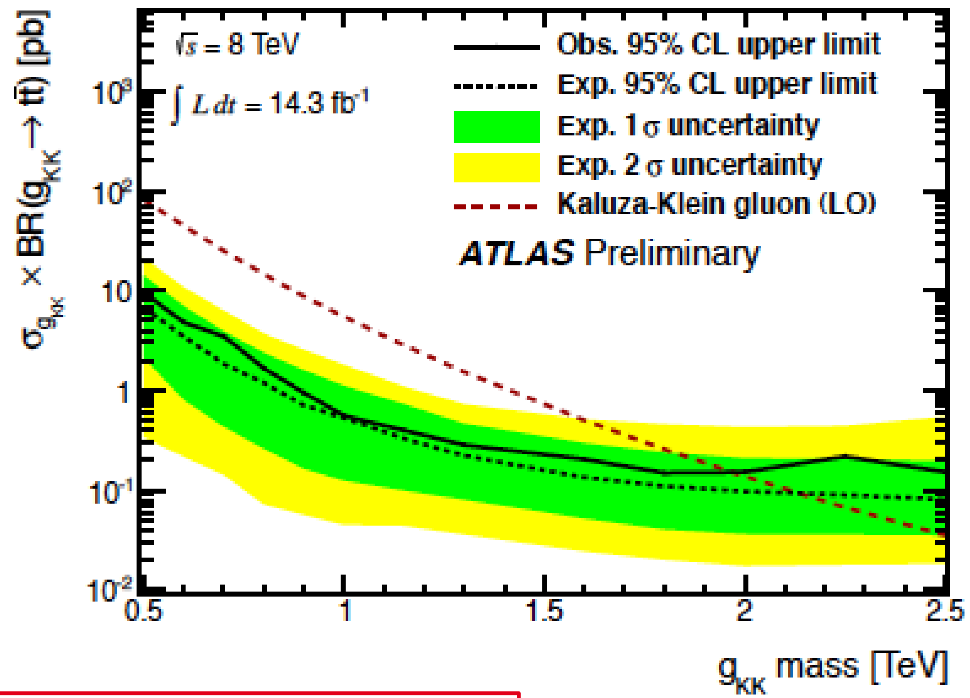
Compare data & expected background using BUMPHUNTER



No significant deviation found → Set Limits

Limits





Compute bayesian limits from the 4 uncorrelated spectra

Upper limits on masses:

- Leptophobic topcolor Z': 1.8 TeV observed 1.9 TeV expected
- KK gluon: 2.0 TeV observed 2.1 TeV expected

$t\bar{t}$ resonance search
fully hadronic & single lepton channel

19.7 fb-1 at $\sqrt{s}$ = 8 TeV

CMS PAPER B2G-13-001

CMS PAS B2G-12-005

CMS PAS B2G-12-006

arXiv: hep-ex:1309.2030

Analysis Setup

- Combination of two analyses:
  - Single lepton search channel in resolved and boosted categories
  - Fully hadronic search channel
- Search for
  - Randall-Sundrum Kaluza-Klein gluons
  - Topcolor Z' boson
  - Non-resonant enhancement of $M_{t\bar{t}}$ spectrum for $M_{t\bar{t}}$ > 1 TeV
  - Spin-zero resonance produced via gluon fusion

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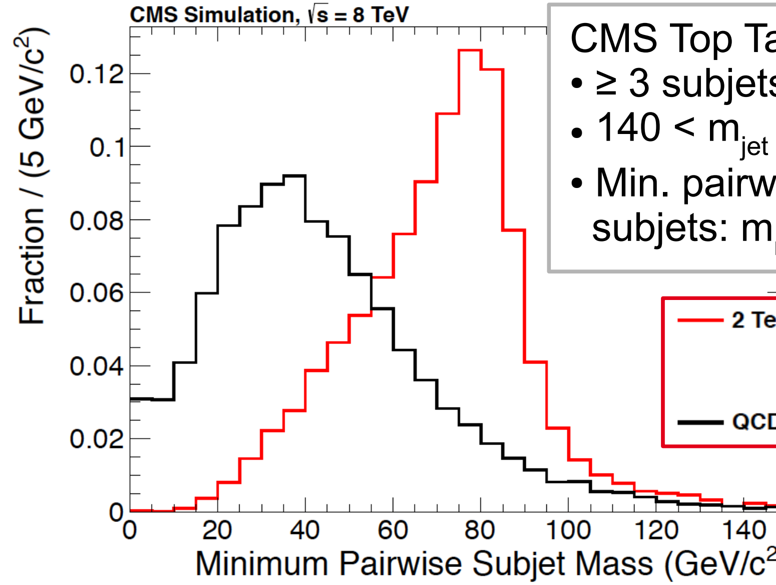
Fully Hadronic Channel

Event selection

- Trigger: HT > 750 GeV
- **≥ 2 ΔR = .8 Cambridge-Aachen jets**
- leading jets: ΔΦ > π/2 & **|Δy| < 1.**
- **≥ 2 top-tags**

→ Main backgrounds: **SM tt & multijet**



CMS Top Tagger:
- ≥ 3 subjets
- 140 < m_{jet} < 250 GeV
- Min. pairwise mass of subjets: m_{min}>50GeV

Non-top multijet background from data

1. Select events with **2 jets** (p_T > 400 GeV) & 1 **"inverted" top-tag** (m_{min}< 30 GeV) → **mistag rate**: probability to tag other jet
2. Select events with **2 jets** (p_T > 400 GeV) & 1 **standard top-tag**
   → apply mistag rate to other jet → sample of **non-top multijet events**
3. Set **mass of jet$_2$** to **random** value
   → **avoid kinematic bias** due to higher masses in signal region

Semi-leptonic Channel

Resolved selection

- Exactly **1 isolated lepton** (μ: p_T > 26 GeV, e: p_T > 30 GeV)
- **≥ 4 ak5 jets** (pT > 70, 50, 30, 30 GeV)
- $\mathbf{E_{T,miss}}$ > 20 GeV

→ 2 categories: **1 or ≥ 2 b-tag**

Boosted selection

- Exactly **1 lepton, NO isolation** (μ: p_T > 40 GeV, e: p_T > 26 GeV)
- **≥ 2 ak5 jets** (pT > 150, 50 GeV)
- $\mathbf{E_{T,miss}}$>50 GeV, $\mathbf{E_{T,miss}+p_{T,lep}}$>150 GeV

→ 2 categories: **0 or ≥ 1 b-tags**

Reconstruction of $M_{t\bar{t}}$

Assign objects to leptonic or hadronic decay via **χ^2 optimization**
Lepton & $E_{T,miss}$ assigned to leptonic side, **neutrino solution**: W-constraint

Resolved channel:
Assign **4 jets**

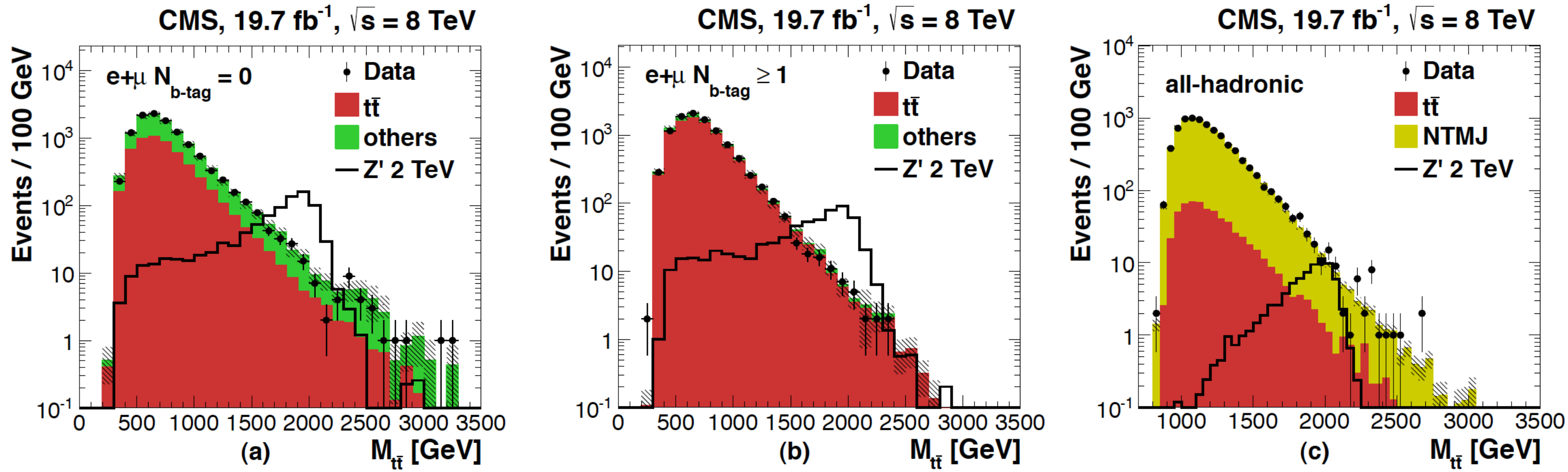
$$\chi^2 = \chi^2_{m(tlep)} + \chi^2_{m(thad)} + \chi^2_{m(whad)} + \chi^2_{p_T(t\bar{t})}$$

Boosted channel:
Assign **2 jets** (merged t-decay)

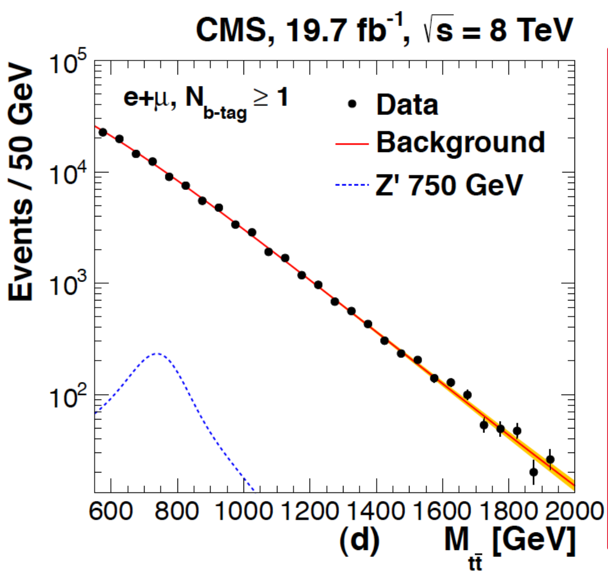
$$\chi^2 = \chi^2_{m(tlep)} + \chi^2_{m(thad)}$$

$m_{t\bar{t}}$ Spectrum

BOOSTED



RESOLVED



Joint maximum likelihood fit in all boosted channels
Fit of smoothly falling pdf in resolved channel

No excess in boosted or resolved channel

Set limits

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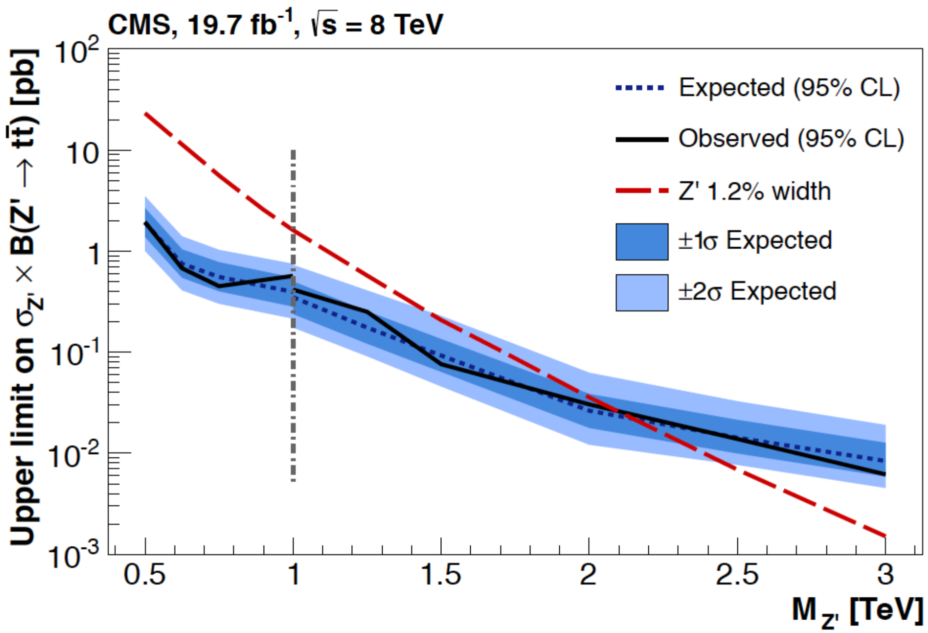
Limits



Phase space overlap between resolved and boosted semi-leptonic analysis

Transition point ≈ 1 TeV

Quote resolved result below and boosted result above 1 TeV

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

Spin-zero resonance:

Mass	Limit
500 GeV	0.8 pb
750 GeV	0.3 pb

Non-resonant enhancement:**ratio S** = (SM + BSM tt) / (SM tt)

Limit for **m$_{t\bar{t}}$ > 1TeV**: **S < 1.2 at 95% CL** with credible interval of 1.1-2.0 at 68% CL

Vector-like Top Partner Searches

(See also talk by Roman Lysak this morning)

Introduction

Vector-like quarks are part of numerous **theories**:

- Little Higgs Models
- Composite Higgs Models,
- Extra dimensions…

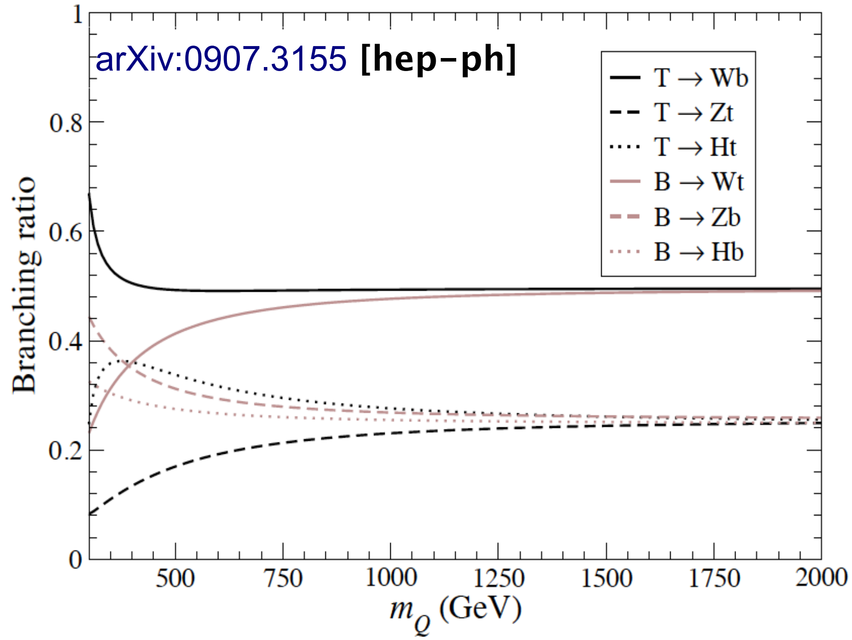
Possible solution to the hierarchy problem

Decay modes:

T' → bW, T' → tH, T' → tZ

B' → tW, B' → bH, B' → bZ

Example model:



$T_{2/3} \rightarrow$ tH, bW, tZ

single lepton channel

14.3 fb^{-1} at $\sqrt{s}$ = 8 TeV

ATLAS-CONF-2013-018

Event Selection

Event selection

- Exactly **1 isolated lepton** (e: E_T > 35 GeV, μ: p_T > 25 GeV)
- **≥ 6 ak4 jets** (p_T > 25 GeV) with **≥ 2 b-tags**
- **$E_{T,miss}$** > 20 GeV, **$E_{T,miss}$ + m_T** > 60

Background estimation

1. **Multijet events: Matrix method**

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}},$$
$$N^{\text{tight}} = \epsilon_{\text{real}} N^{\text{loose}}_{\text{real}} + \epsilon_{\text{fake}} N^{\text{loose}}_{\text{fake}}$$

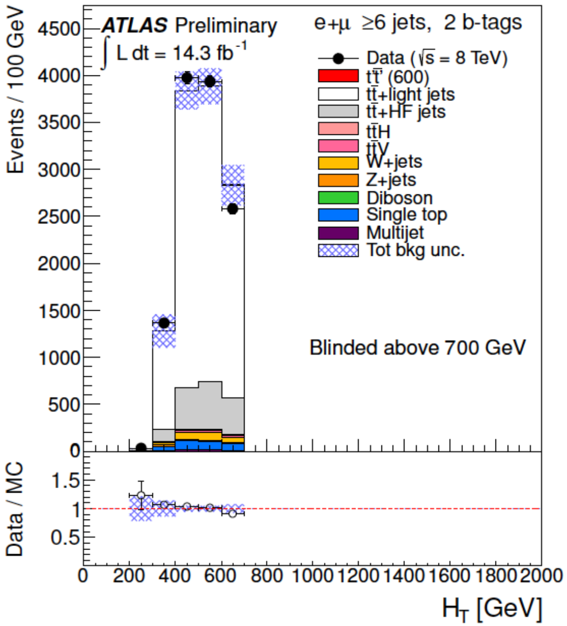
- 2 lepton selections: tight & loose
- W-enriched data sample → ϵ_{real}, multijet-enriched data sample → ϵ_{fake}

2. **W + jets events: Determine rate using charge asymmetry**

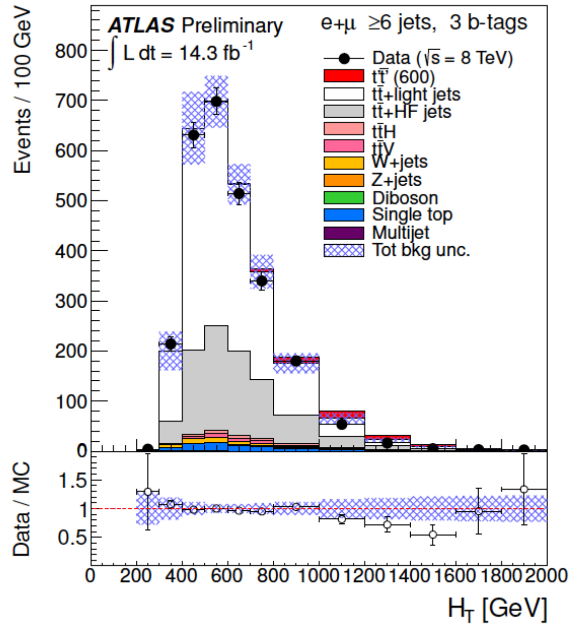
$$N_W = \underbrace{\left(\frac{r_{\text{MC}}+1}{r_{\text{MC}}-1}\right)}_{\text{from simulation}} \underbrace{(N_{W^+} - N_{W^-})_{\text{meas}}}_{\text{from data}}$$

H_T distributions

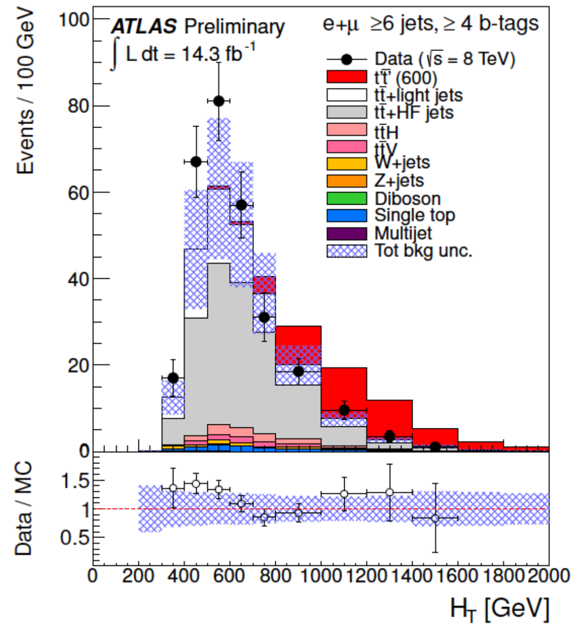
$H_T = p_T(\text{lepton}) + E_{T,\text{miss}} + p_T(\text{jets})$



2 b-tags



3 b-tags



≥ 4 b-tags

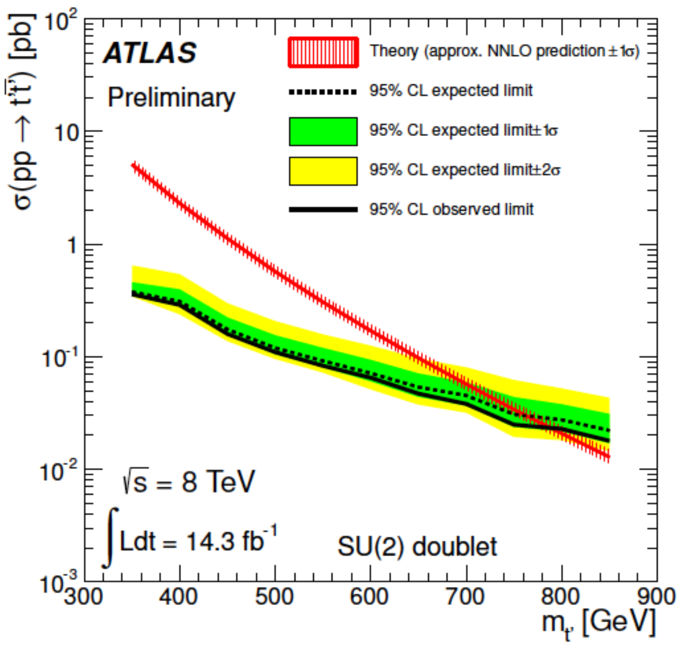
H_T < 700 GeV
(orthogonality with other analysis)

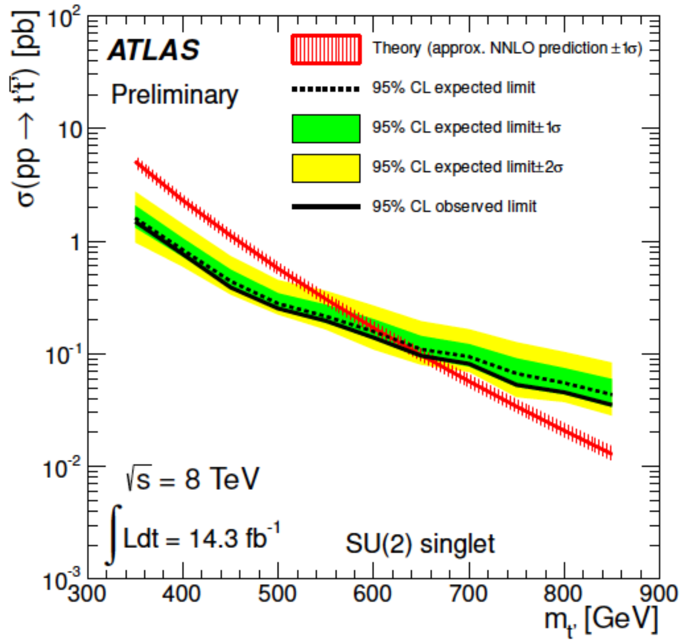
Best signal to background ratio in ≥ 4 b-tag category
→ drives sensitivity

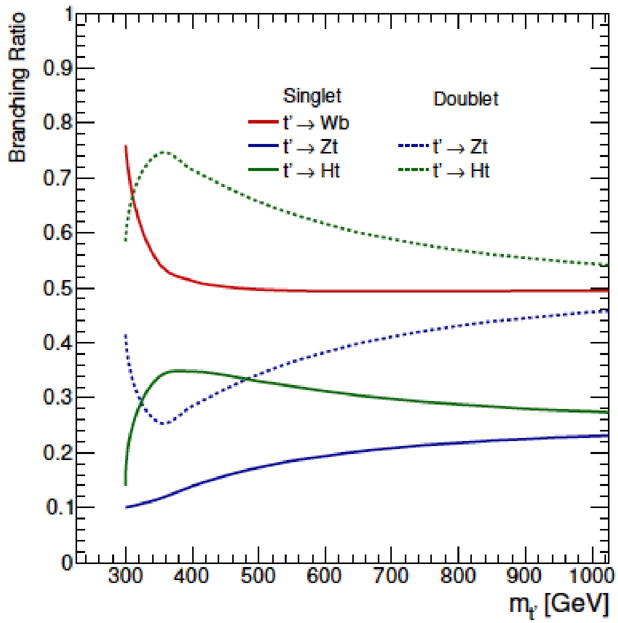
No excess observed → set limits

Limits

Derive 95% C.L. limits using CLs method:







	SU(2) doublet	SU(2) singlet
Observed	790 GeV	640 GeV
Expected	745 GeV	615 GeV

$T_{2/3} \rightarrow tH, tZ, bW$
lepton channel

19.6 fb^{-1} at $\sqrt{s}$ = 8 TeV
CMS-PAS-B2G-12-015

Analysis Setup

This Analysis:

- **all branching fractions** possible considered
- Combination of two analysis strategies:
    1. **Multivariate single lepton** channel analysis
    2. **Multilepton** channel **counting** experiment

$T'T' \rightarrow tZtZ$

$T'T' \rightarrow tZtH$

$T'T' \rightarrow tZbW$

$T'T' \rightarrow tHtH$

$T'T' \rightarrow tHbW$

$T'T' \rightarrow bWbW$

Single Lepton Analysis

Exactly **1 isolated lepton** (p_T > 32 GeV) & $\mathbf{p_{T,\,miss}}$ > 20 GeV

≥ **3 ak5 jets** (p_T > 120, 90, 50 GeV), where

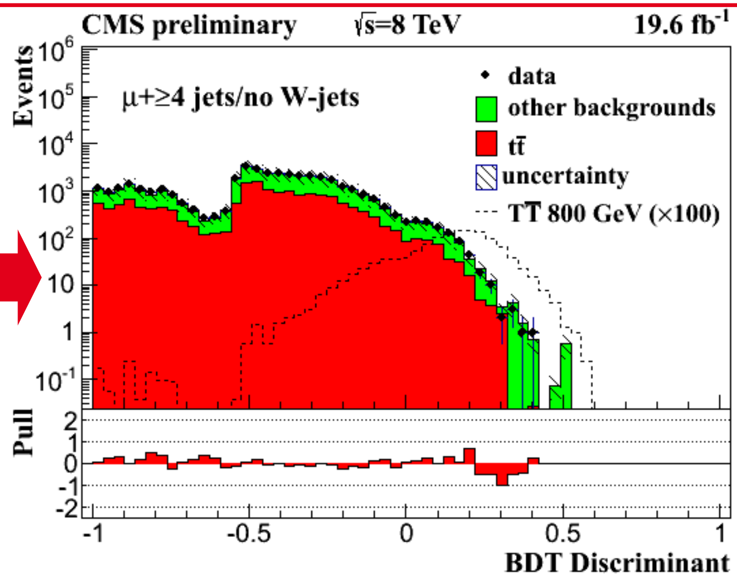
A) 4th ak5 jet with p_T > 35 GeV exists

B) ≥ 1 of the 3 jets can be matched to **W-tagged CA8 jet**

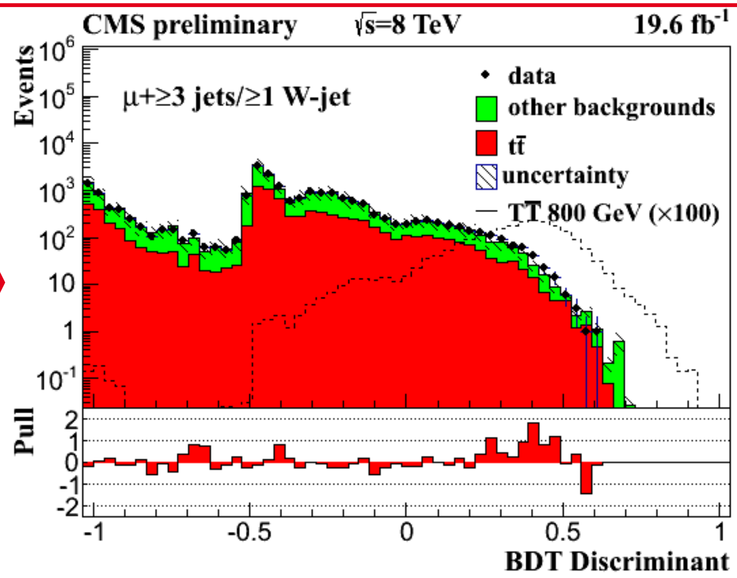
T' mass	μ	e
500 GeV	850	840
700 GeV	97	98
1500 GeV	0.1	0.1
Background	61500 ±13700	61100 ±13500

Boosted Decision Tree → separate small signal & background

7 input variables



7 input variables + 3 substructure variables



No excess seen → Compute posterior likelihood from BDT discriminant

Multilepton Analysis

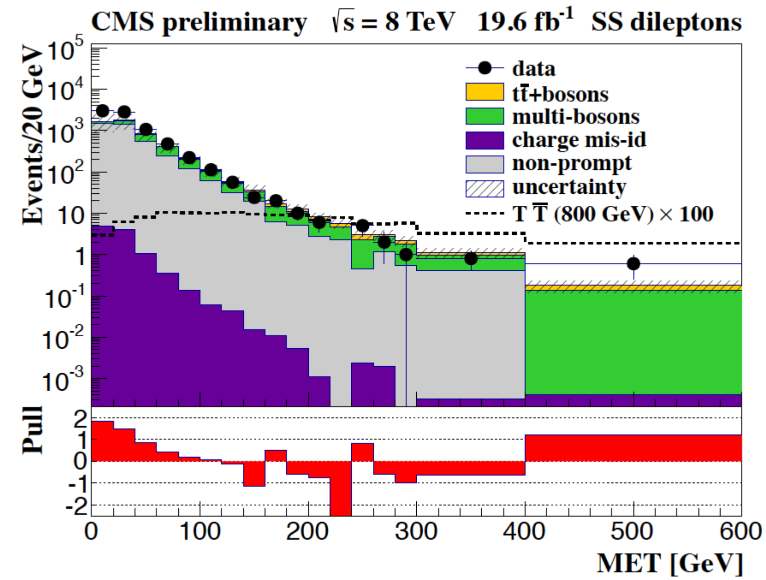
4 event categories:

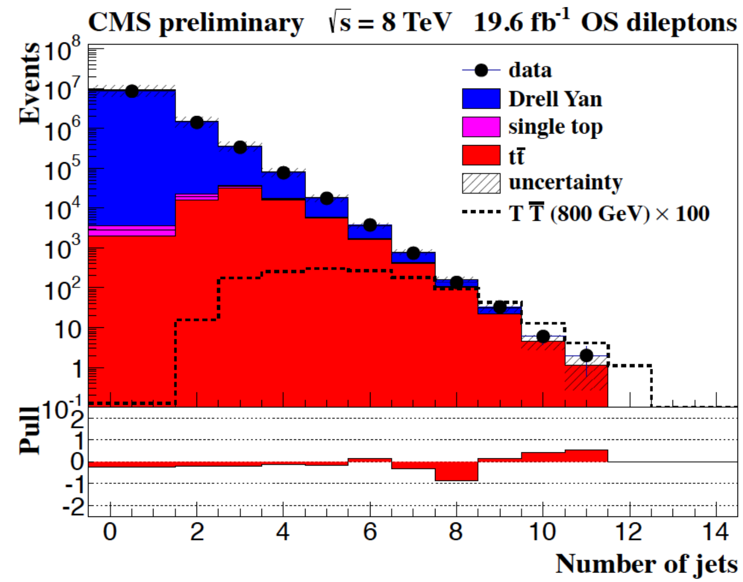
- Opposite sign dilepton with Z- & top-veto
- Opposite sign dilepton with b-tagged jets
- Same sign dilepton
- Trilepton

	Dilepton			trilepton
	OS 1	OS 2	SS	
Background	17.4 ± 3.7	84 ± 12	16.5 ± 4.8	3.7 ± 1.3
Data	20	86	18	2

No significant excess observed

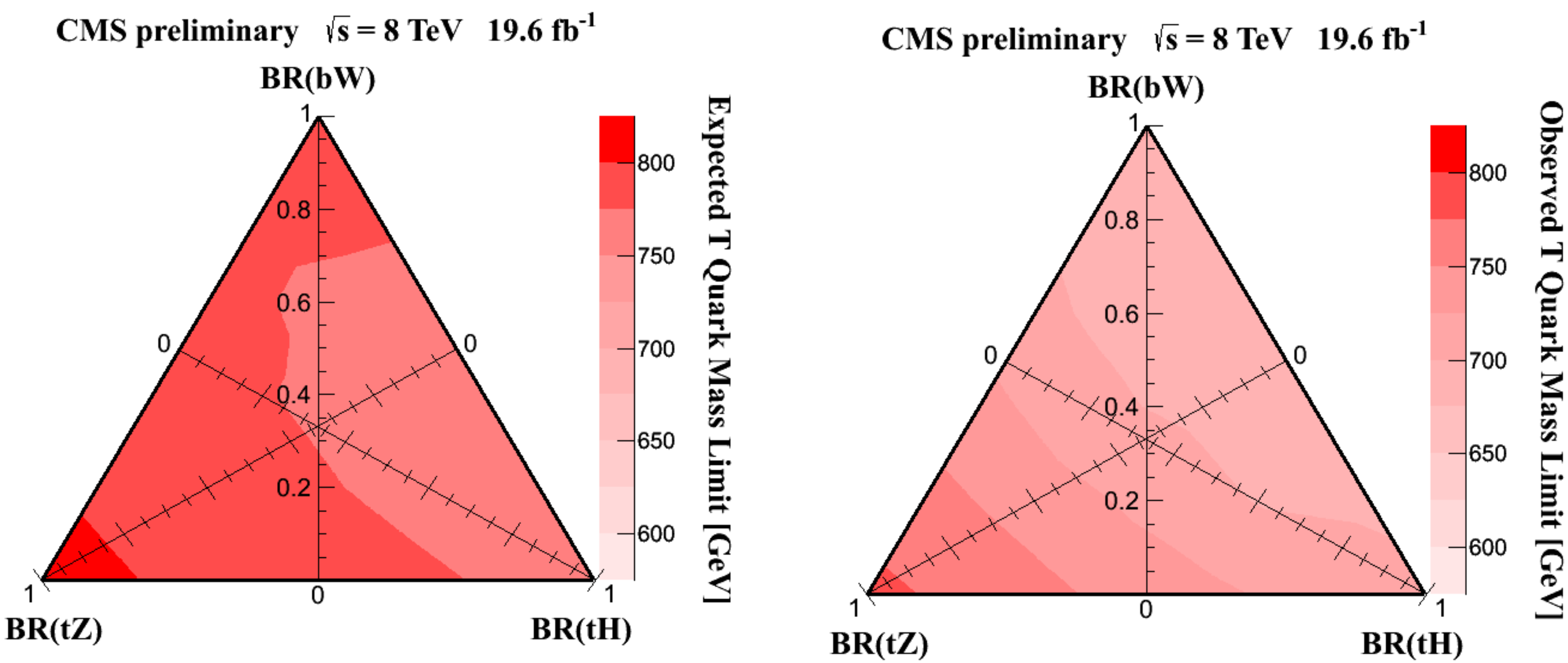
Compute likelihood from observed and predicted number of events in 12 subsamples to set limits





Limits on T' mass

Expected and observed limits on the T' quark mass for each possible branching ratio



Greatest sensitivity for T' → tZ decays
Lower limits on m(T'): between 687 and 782 GeV

Conclusion & Outlook

- Broad search program for resonances and heavy top partners in ATLAS and CMS

  → only small selection covered in this talk

  (See talk by Roman Lysak for more VLQ searches)
- Limits on new particle masses increasing

  → definite need to handle boosted topologies in the future
- Jet substructure tools
  - already used in several different aspects of some analyses
  - importance will even increase in the near future
  - newly developed tools, e.g. subjet b-tagging

More analyses making use of new substructure tools expected by the end of the year → stay tuned!

BACKUP

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MC samples tt resonances CDF

- **tt**: POWHEG + PYTHIA v6.2 showering
- **W + jets**: ALPGEN + PYTHIA showering
- **Z' signal**: PYTHIA

MC Samples tt resonances ATLAS

- **tt**: MC@NLO v4.01, HERWIG v6.520 showering, JIMMY v4.31 multiple parton scattering
- **Single top tW & s-channel**: MC@NLO/HERWIG/JIMMY
- **Single top t-channel:** ACERMC + PYTHIA showering
- **W/Z + jets**: ALPGEN v2.13, PYTHIA showering, hadronization & underlying event, matching of matrix element to parton shower with MLM method.
- **Wbb, Wcc, Wc, Zbb, Zcc**: ALPGEN
- **Massive diboson**: HERWIG v6.520 and JIMMY v4.31
- **Signal Z'**: PYTHIA v8.165
- **Signal g_{KK}**: MADGRAPH + PYTHIA showering

MC samples tt resonances CMS

- **tt**: POWHEG v1.0, PYTHIA 6 showering
- **W/Z + jets**: MADGRAPH + PYTHIA 6
- **Diboson**: PYTHIA 6
- **Signal Z'**: MADGRAPH + PYTHIA 6
- **Signal spin-zero model**: MADGRAPH + PYTHIA 6
- **Signal g_{KK}**: PYTHIA 8

Samples T' search ATLAS

- **tt + jets**: ALPGEN v2.13 + HERWIG v6.520 showering
- **W/Z + jets**: ALPGEN v2.13 + HERWIG v6.520 showering
- **Single top s- & tW-channel**: MC@NLO v4.01 + HERWIG showering
- **Single top t-channel**: ACERMC v3.8 + PYTHIA showering
- **ttV**: MADGRAPH v5 + PYTHIA showering
- **ttH**: PYTHIA 6.425
- **Signal T'**: PROTOS v2.2 + PYTHIA showering

Samples T' search CMS

- W/Z + jets, ttW, ttZ: MADGRAPH
- tt: POWHEG
- Single top: POWHEG
- Diboson: PYTHIA 6
- ttH: PYTHIA 6

- PYTHIA showering & underlying events for all samples

Systematics tt resonances CDF

- JES, b-tag eff., luminosity, lepton ID, trigger efficiency, IFSR
- W + heavy flavor jet rate: 30%
- QCD multijet normalization: 40%

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Systematics tt resonances ATLAS

Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Z'	Boosted selection yield impact [%] total bkg.	Z'
Luminosity	2.9	4	3.3	4
PDF	2.9	5	6	2.9
ISR/FSR	0.2	–	0.7	–
Parton shower and fragm.	5	–	4	–
$t\bar{t}$ normalization	8	–	9	–
$t\bar{t}$ EW virtual correction	2.2	–	4	–
$t\bar{t}$ Generator	1.5	–	1.6	–
W+jets $b\bar{b}$+$c\bar{c}$+c vs. light	0.8	–	1.0	–
W+jets $b\bar{b}$ variation	0.2	–	0.4	–
W+jets c variation	1.1	–	0.6	–
W+jets normalization	2.1	–	1.0	–
Multi-Jet norm, e+jets	0.6	–	0.3	–
Multi-Jet norm, μ+jets	1.8	–	0.3	–
JES, small-radius jets	6	2.2	0.7	0.5
JES+JMS, large-radius jets	0.3	4	17	3.3
Jet energy resolution	1.6	0.4	0.6	0.7
Jet vertex fraction	1.7	2.3	2.1	2.4
b-tag efficiency	4	1.8	3.4	6
c-tag efficiency	1.4	0.3	0.7	0.9
Mistag rate	0.7	0.3	0.7	0.1
Electron efficiency	1.0	1.1	1.0	1.0
Muon efficiency	1.5	1.5	1.6	1.6
All systematic uncertainties	14	9	22	9

Systematics tt resonances CMS

	Resolved Semi-Leptonic	Boosted Semi-Leptonic	Boosted All-Hadronic
Constraints on normalization			
Luminosity [41]	2.6%	2.6%	2.6%
Pileup	6%	6%	6%
$t\bar{t}$ [42]	–	15%	15%
Parton distribution functions [43]	1σ	1σ	1σ
Single top	–	50%	–
W+light-flavor jets	–	50%	–
W+heavy-flavor jets	–	100%	–
Z+ jets	–	100%	–
Lepton selection	0.5-3.0%	0.5-3.0%	–
Top-tagging efficiency	–	–	9%
Constraints on shape			
$t\bar{t}$ renormalization, factorization and matching scales	–	variation by $\times 2$ and $\times 0.5$	
Jet energy scale	1–6%	1–6%	1–6%
Jet energy resolution	8–10%	8–10%	8–10%
b-tagging efficiency	2–8%	2–8%	–
b-tagging mis-ID	–	20%	–
Top-tagging mis-ID	–	–	5–20%
Signal and background pdf	1σ	–	–

Systematics T' Search ATLAS

Systematic uncertainty	Type	Components	
Luminosity	N	1	3.6%
Lepton ID+reco+trigger	N	1	2.1%
Jet vertex fraction efficiency	S	1	2.2%
Jet energy scale	SN	8	
Jet energy resolution	SN	1	
b-tagging efficiency	SN	9	7-13%
c-tagging efficiency	SN	5	15-39%
Light jet-tagging efficiency	SN	1	~25%
$t\bar{t}$ cross section	N	1	+10/-11%
$t\bar{t}V$ cross section	N	1	30%
$t\bar{t}H$ cross section	N	1	+12/-17%
Single top cross section	N	1	+5/-4%
Dibosons cross section	N	1	5%
V+jets normalisation	N	1	50%
Multijet normalisation	N	1	50%
$t\bar{t}$ modelling	SN	3	
$t\bar{t}$+heavy-flavour fractions	N	1	

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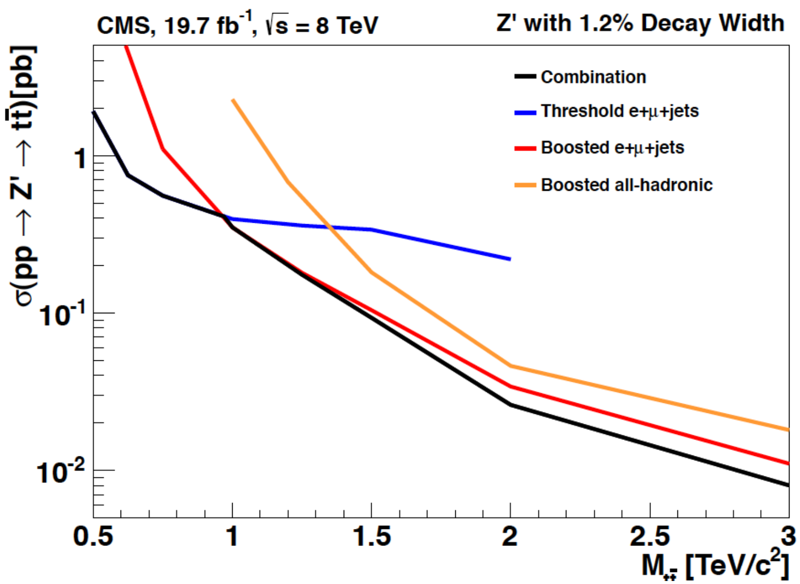
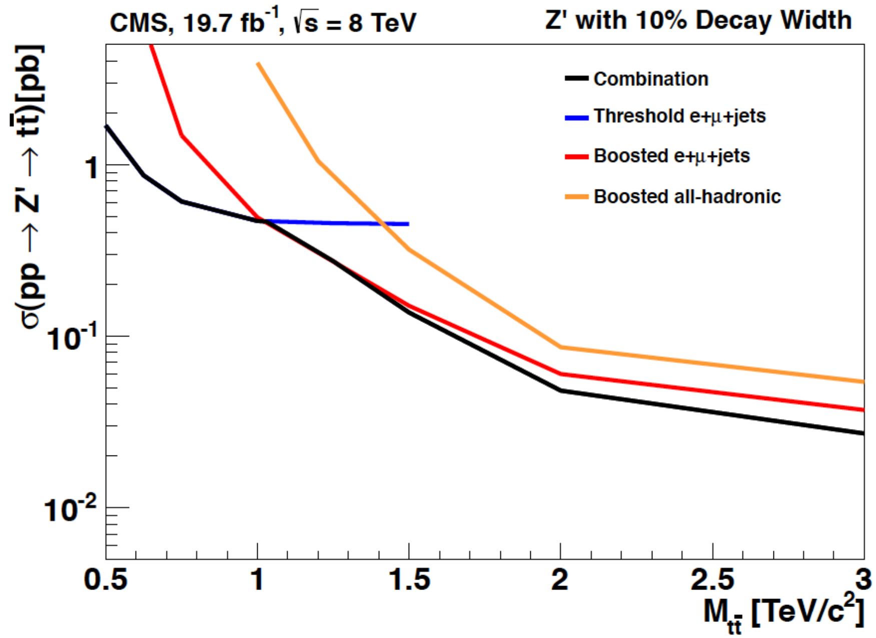
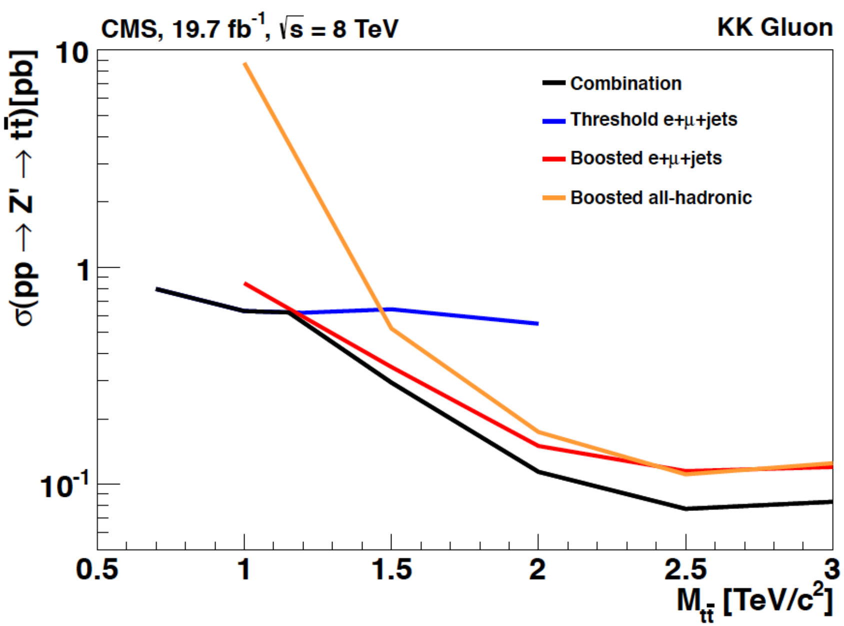
Systematics T' Search CMS

- Luminosity: 4.4%
- Diboson background: 50%
- Single top: 50%
- W/Z bosons: 50%
- tt background normalization: 8%
- Lepton trigger / ID scale factors: 3%
- JES, JER, b-tag eff. Q2 and matching scales, top pT distribution

Limits CMS tt resonances







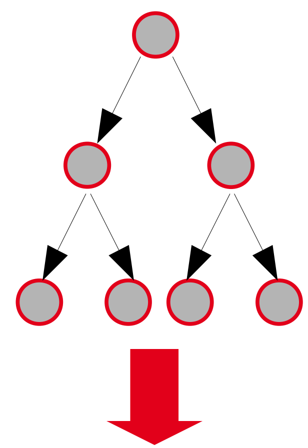
Boosted Decision Tree

1. N(jets)
2. N(b-tags)
3. H_T
4. p_{Tmiss}
5. p_T(lepton)
6. p_T(jet3)
7. p_T(jet4)

Only if W-tag:

8. N(top jets)
9. N(W jets)
10. p_T(W jets)

7 / 10 input variables used for BDT training



Single powerful discriminating variable

No excess seen

Compute posterior likelihood from BDT discriminant