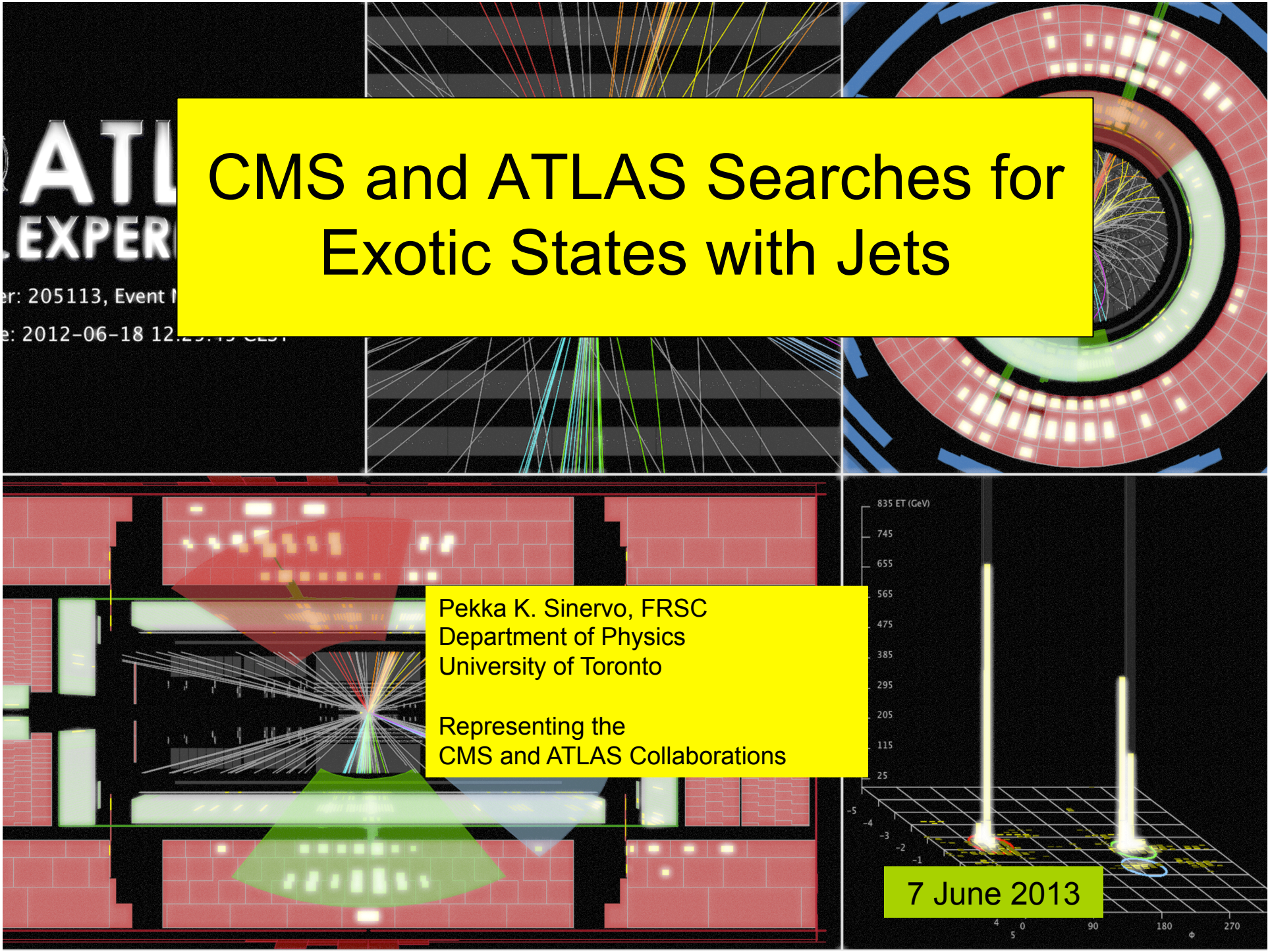

CMS and ATLAS Searches for Exotic States with Jets

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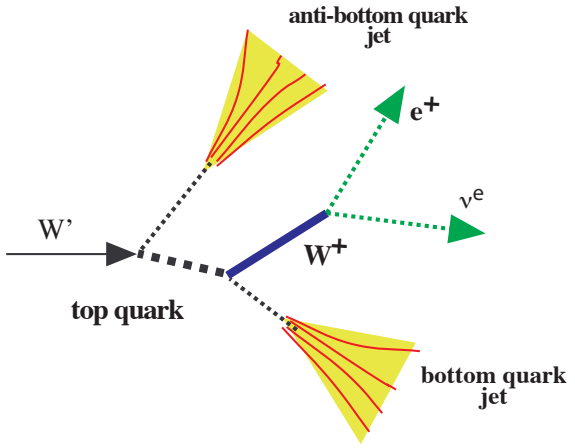
Department of Physics
University of Toronto

Representing the
CMS and ATLAS Collaborations

7 June 2013

Outline

1. **Strategies and techniques**
2. **Dijet searches with light quarks & gluons**
3. **Dijet searches with heavy quarks**
4. **Searches with jets and leptons**
5. **Monojets**
6. **Jet Extinction**
7. **W'→ tb search**
8. **Summary & Conclusions**



Techniques and Strategies (1)

Many beyond-SM phenomena result in final states with quarks and gluons

- Manifest themselves as states with one or more jets
- Also have states with jets, charged leptons and neutrinos

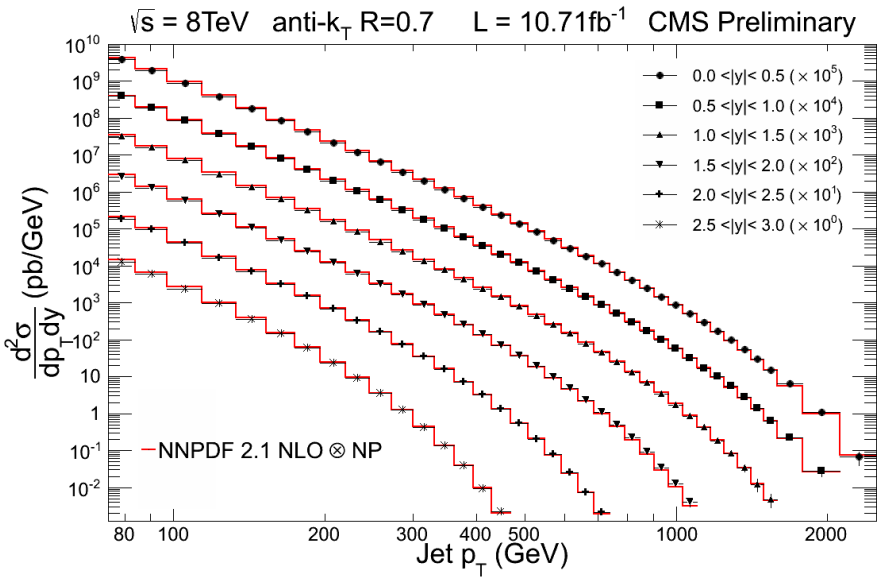
So very natural to search for new particles with jet final states

- Invariant mass “bumps”
- Signals in angular distributions
- Threshold phenomena

Fundamental challenge is the very high rate of multijet final states from SM QCD

Cross section for inclusive jets

- $\sigma \sim 0.5$ μb for $p_T > 1$ TeV
- Gives intrinsic QCD background for objects with masses > 2 TeV of order
  - 7-10 million multijet events

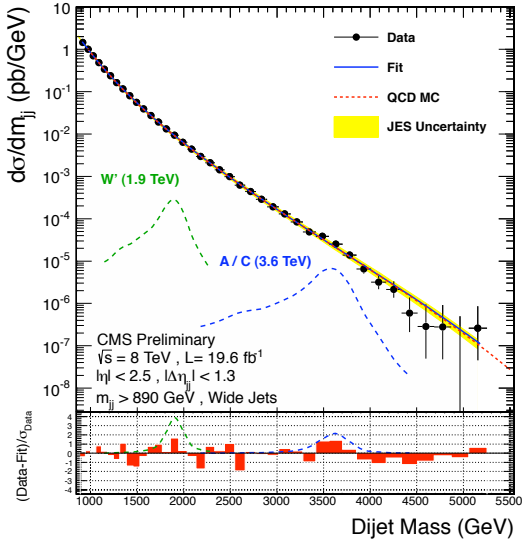


CMS-PAS-SMP-12-012

Techniques and Strategies (2)

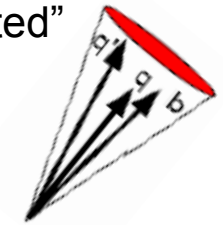
Searches for exotic phenomena have to overcome this large background

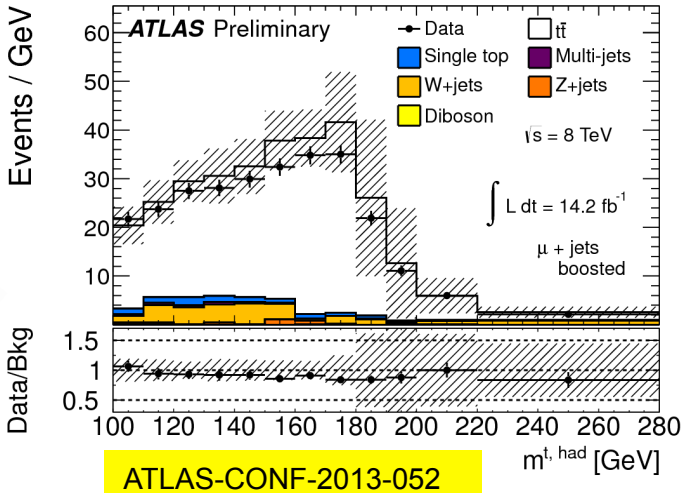
- Develop reliable background estimation tools
  - Look for kinematic signal above a background
  - Examples are dijet resonance searches



CMS-EXO-12-059

- Develop techniques to reject light quark and gluon jets
  - Use b-tagging and jet substructure techniques
  - Examples are the Z' and g_{KK} "boosted" top quark searches





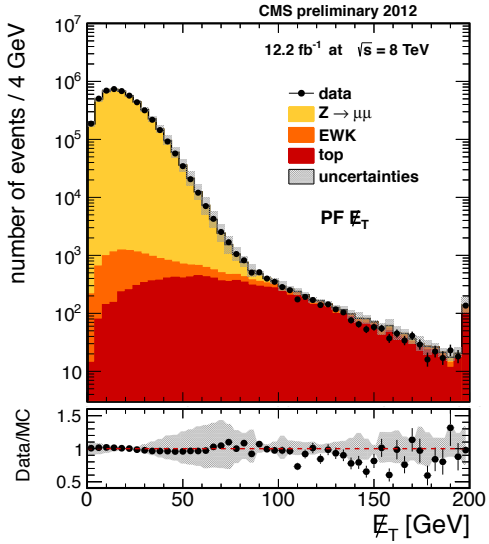
ATLAS-CONF-2013-052

Techniques and Strategies (3)

LHC has run extraordinarily well

- Have ~5 fb^{-1} sample at 7 TeV
- Have ~20 fb^{-1} sample at 8 TeV

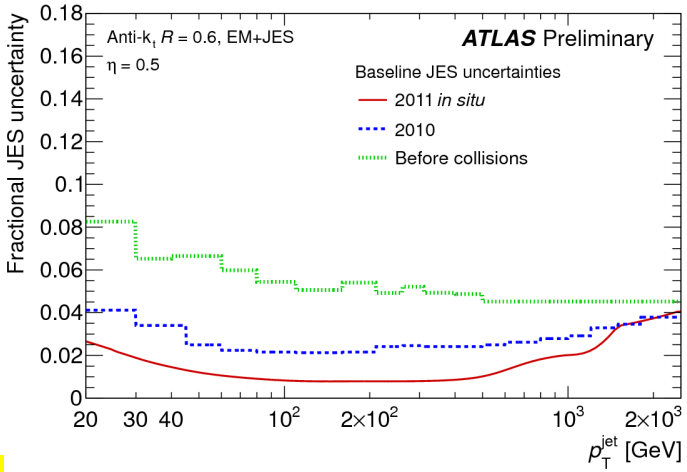
CMS JME-12-002



These data samples have enabled both CMS and ATLAS to develop detailed jet and E_T^{miss} reconstruction

- CMS has shown "particle-flow" techniques are very powerful
- Jet energy scale (JES) uncertainties are now 1-4% for $40<p_T<750$ GeV in ATLAS
- Many new techniques for tagging heavy flavour jets

These and other innovations have opened up many avenues for exotics searches



ATLAS-CONF-2013-004

Selection of Jet+X Results

I've chosen to focus on a subset of all possible "Jet+X" results

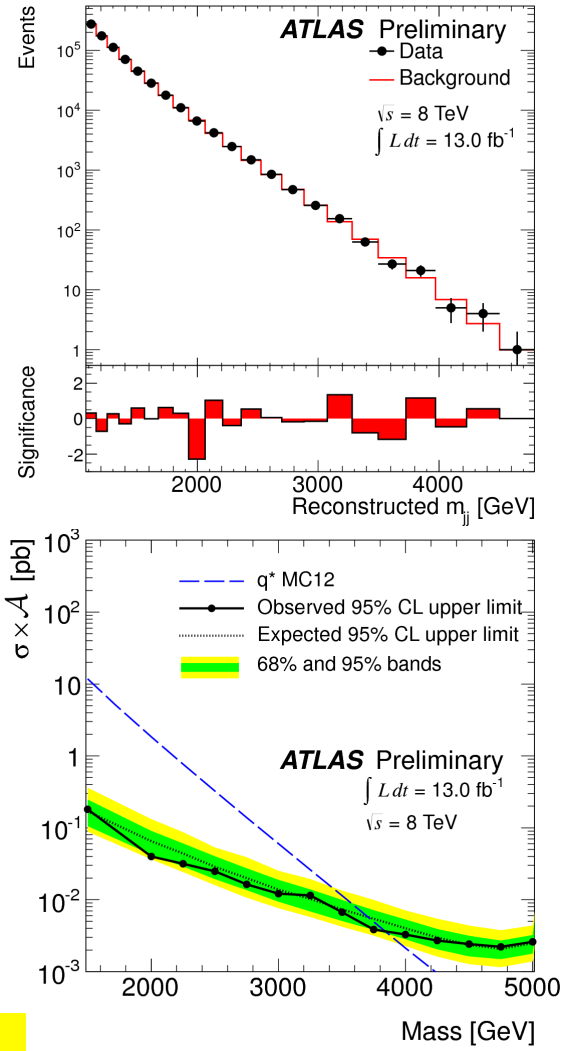
- Reflect where I believe advances are still occuring
- Illustrate the wide range of topics and techniques that are employed

1. Search for resonances in dijet events
2. Search for Z' and g_{KK} resonances in fully hadronic t-tbar decays
3. Search for Z' and g_{KK} resonances in lepton+jets t-tbar decays
4. Search for Dark Matter (DM) in monojets
5. Search for evidence of Jet Extinction
6. Search for W' bosons decaying to t-bbar

ATLAS Dijet Resonance Search

Expect dijet resonances if massive particles are produced in pp collisions

- The "work-horse" final state for exotics searches
  - Many possible models: e.g., excited quarks q*, black holes, and quark substructure
- ATLAS analysis has been updated to 13 fb^{-1}
  - Require m_{jj} > 1 TeV, $|y_{jet}|$<2.8 and |y*|<0.6
    - Acc > 48% for m_{jj} > 2 TeV
  - Use "BumpHunter" technique to look for any significant signal above smoothly falling background
- ATLAS excludes m_{q^*} < 3.84 TeV at 95% CL
  - Also provides more model-independent limits assuming Gaussian signals of various widths

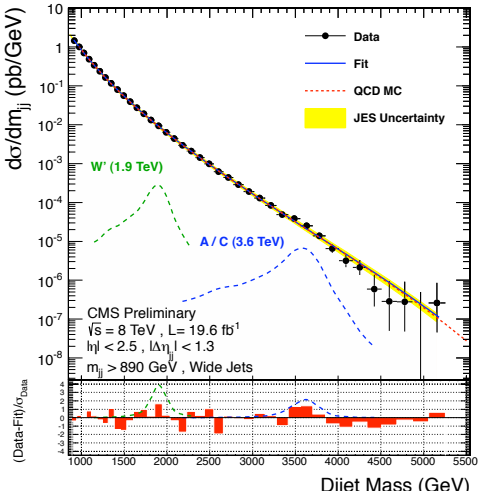


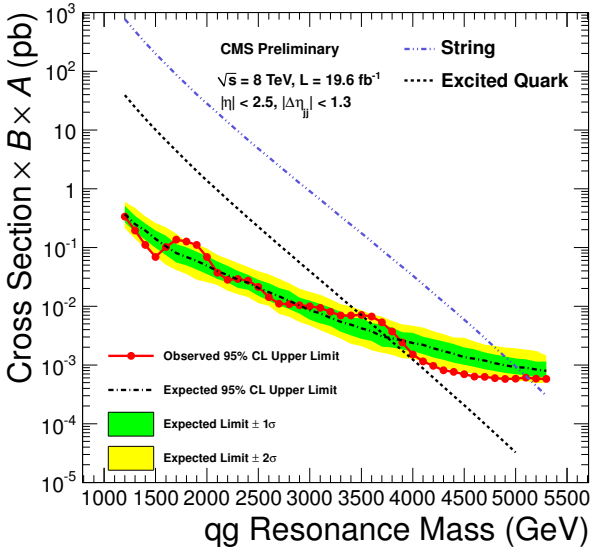
ATLAS-CONF-2012-148

CMS Dijet Resonance Search

CMS has performed similar searches using a 19.6 fb^{-1} data set of 8 TeV collisions

- Selection designed to reduce QCD backgrounds
  - Require m_{jj} > 1 TeV, $|y_{jet}|$<2.5 and $|\Delta\eta|$<1.3
    - Start with Anti-k_T jets with D=0.5
    - Recluster with D=1.1 to reduce effects of final state radiation
  - Look for signal above smooth background
- Test various models – m_{q^*}<3.50 TeV at 95 % CL





CMS EXO-12-059

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

Searches for X->ttbar

A number of theories beyond the SM predict resonance states

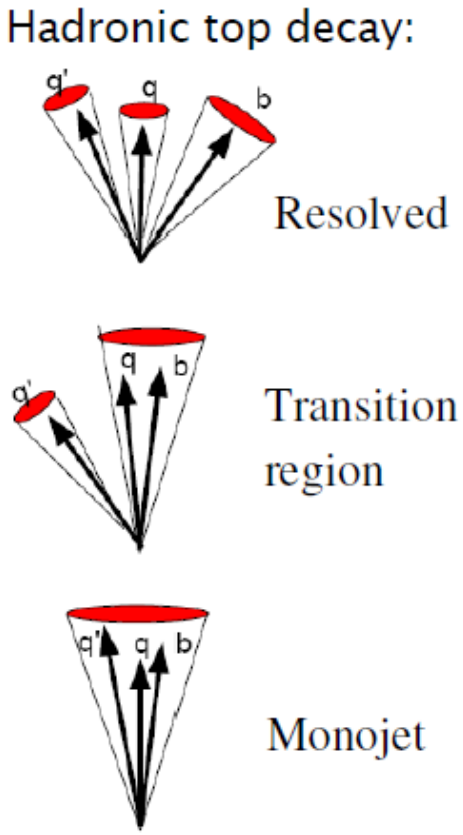
- Masses > 0.5 TeV with widths ranging from 1-2% to 10-20%
- Decay preferentially to ttbar final states

Two "benchmark" scenarios have been used

- A narrow Top Colour Z' boson (Γ/m = 1.2%)
- A broader Kaluza-Klein excitation of gluon (Γ/m = 17%)
- Expected σ's are 2 pb at m=1 TeV to 5 fb for m=2 TeV
- Experimental mass resolution is about 10%

Lead to top-quark pair final states characterized by high-p_T, "boosted" top quarks

- p_T of top quark determines signature for hadronic top decays
- Searches have used "lepton+jets" with boosted topologies and fully hadronic boosted searches



ATLAS Boosted Hadronic Search (I)

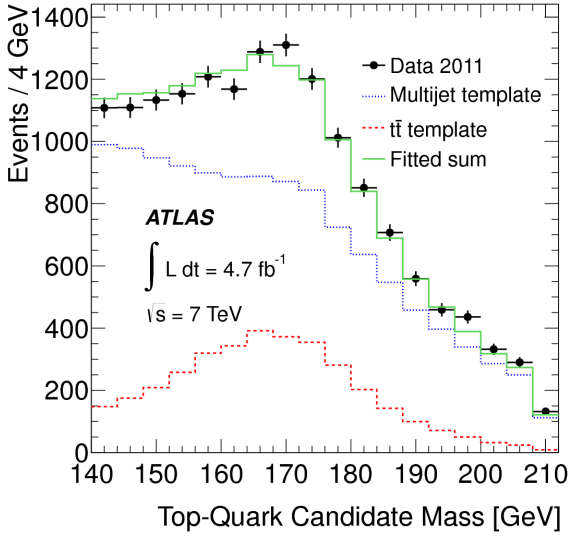
ATLAS implemented several top-tagging techniques in 7 TeV pp data

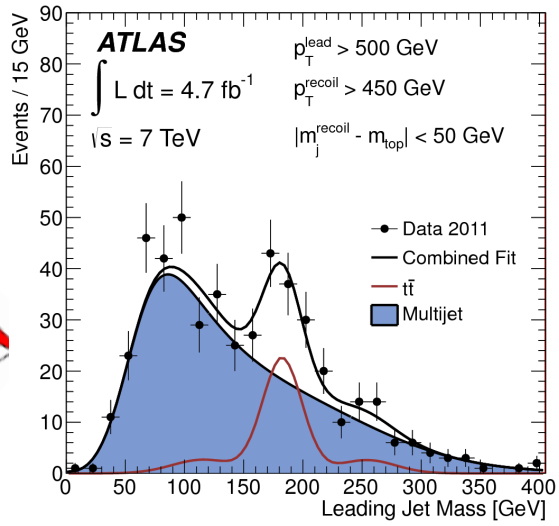
ATLAS, JHEP 01 (2013) 116

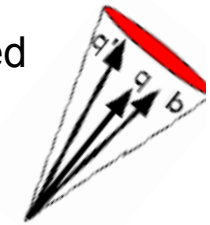
1. HEPTopTagger
   - Two CA jets with D=1.5, p_T>200 GeV and |η|<2.5, split into sub-jets (up to five retained)
   - Reclustered into three sub-jets required to be consistent with top quark (140 < m_{jet} < 210 GeV)
   - Require a D=0.4 anti-k_T cluster to be b-tagged
2. Top Template Tagger
   - Two anti-k_T jets with D=1.0, p_T>450 GeV and |η|<2.0, leading jet p_T>500 GeV
   - Require jet to be consistent with top quark through "template overlap" technique
   - Require a D=0.4 anti-k_T cluster to be b-tagged

Multijet backgrounds estimated from data

- Limited by SM ttbar background







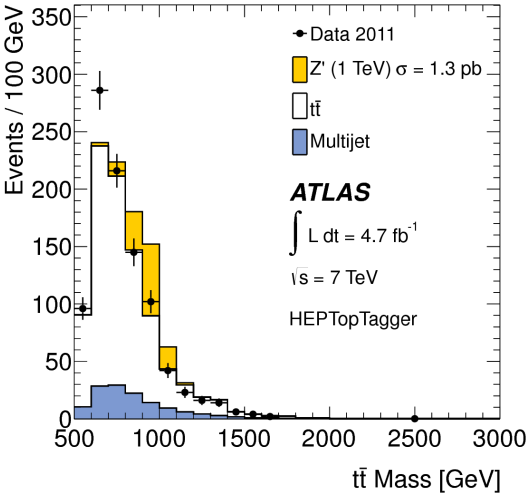
ATLAS Boosted Hadronic Search (2)

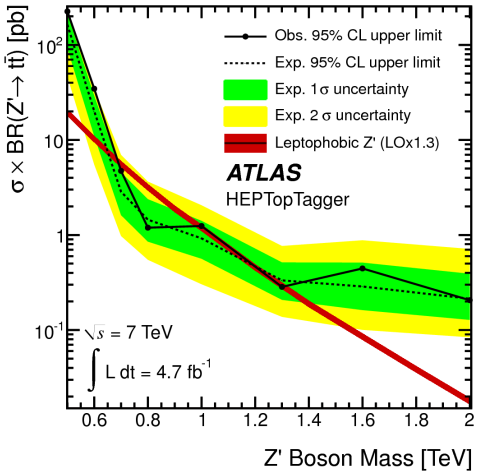
Backgrounds estimated using data-driven and MC calculations

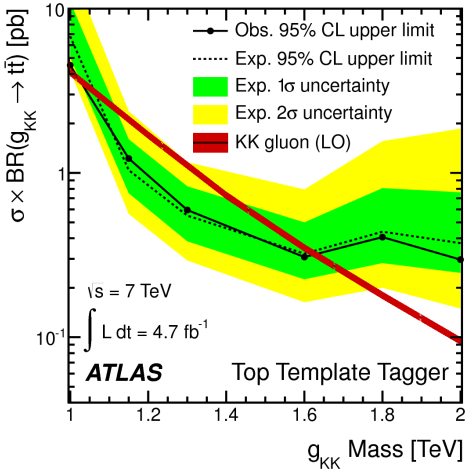
- Multijet backgrounds estimated by mistag rates
- SM ttbar estimated with MC@NLO+HERWIG showers

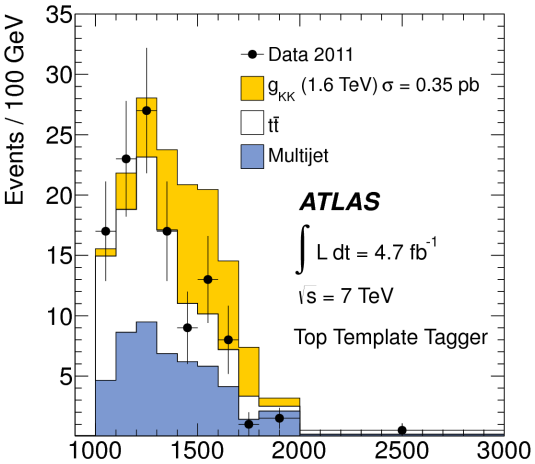
Estimate systematic uncertainties

- Set 95% CL limits using Bayesian calculation









$M_{Z'} > 1.32$ TeV for $\Gamma / M = 1.2\%$

$M_{gKK} > 1.62$ TeV

ATLAS, JHEP 01 (2013) 116

Latest CMS Hadronic Search (I)

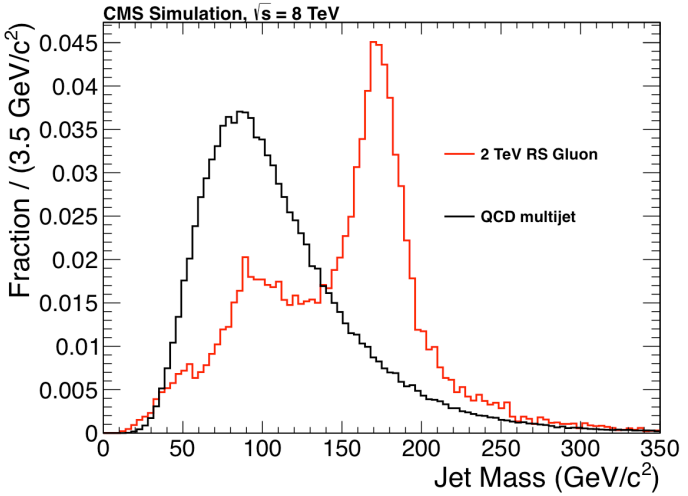
CMS has completed Z'/g_{KK} search in 19.6 fb^{-1} of 8 TeV collisions

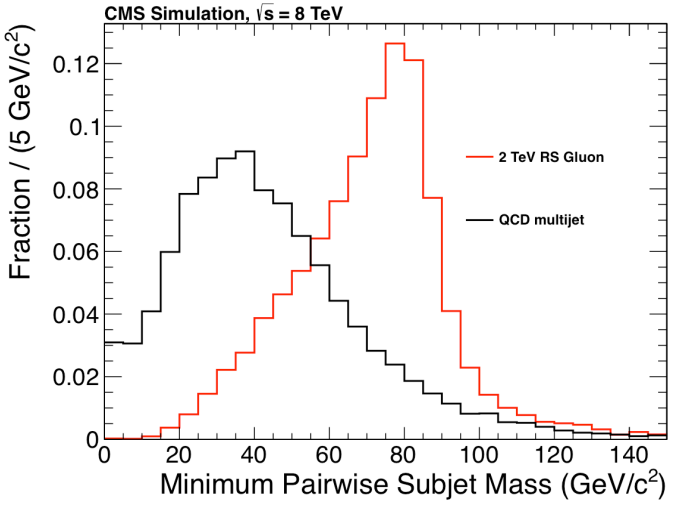
Selecting two jets ("1+1")

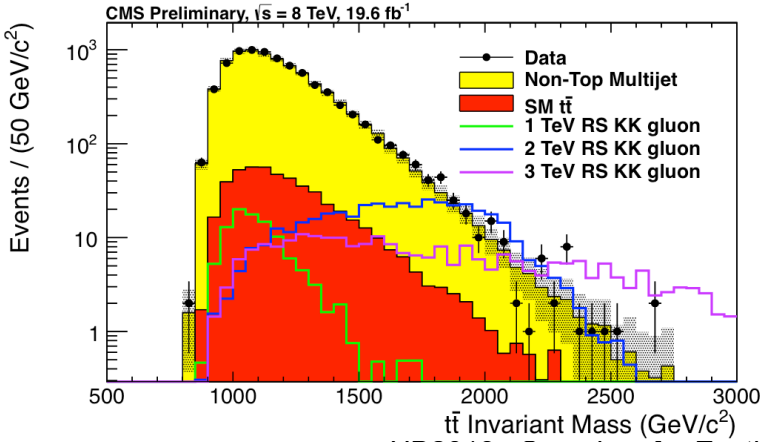
- Use Cambridge-Achen D=0.8 clusters
- Require 2 jets with p_T>400 GeV and |y|<2.5
  - Each jet has to have 3 sub-jets, m_{jet} consistent with top quark (140-250 GeV)
  - Min pair-wise mass of 2 sub-jets > 50 GeV

Several other kinematical cuts

- |Δy|<1.0 to reduce multijet background







CMS B2G-12-005

Latest CMS Hadronic Search (2)

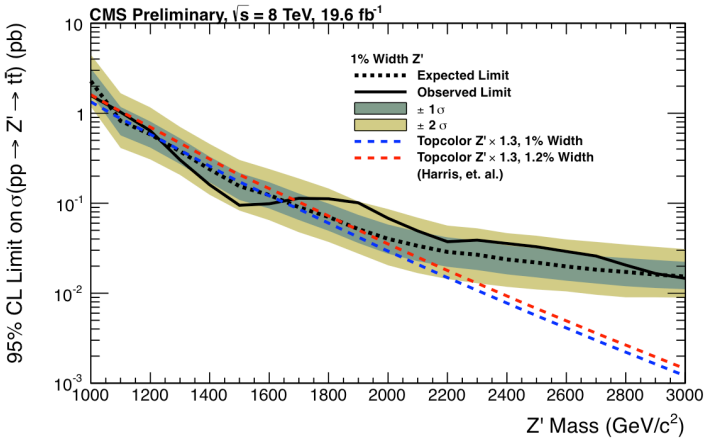
Backgrounds come from

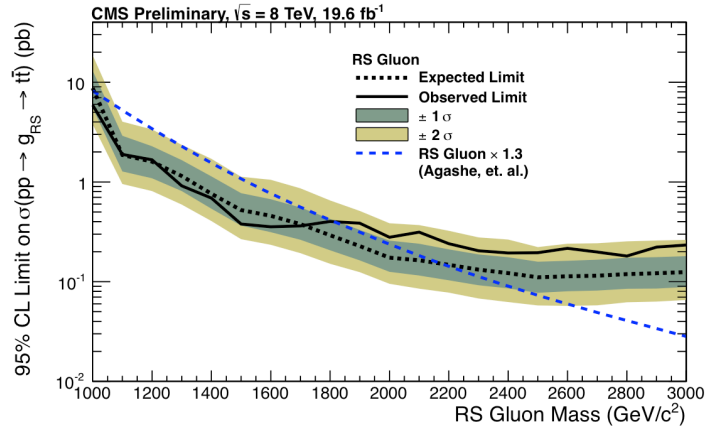
- Multijet final states – estimated using data-driven mis-tagging probability
  - Folded in with observed multijet events
- Standard Model ttbar
  - Estimated using MADGRAPH+HERWIG showers

Estimate systematic uncertainties

- Dominant sources are multijet background, ttbar normalization

Set 95% CL limits using Bayesian calculation





$m_{Z'} > 1.70$ TeV for $\Gamma / m = 1.2\%$

$m_{gKK} > 1.80$ TeV

CMS B2G-12-005

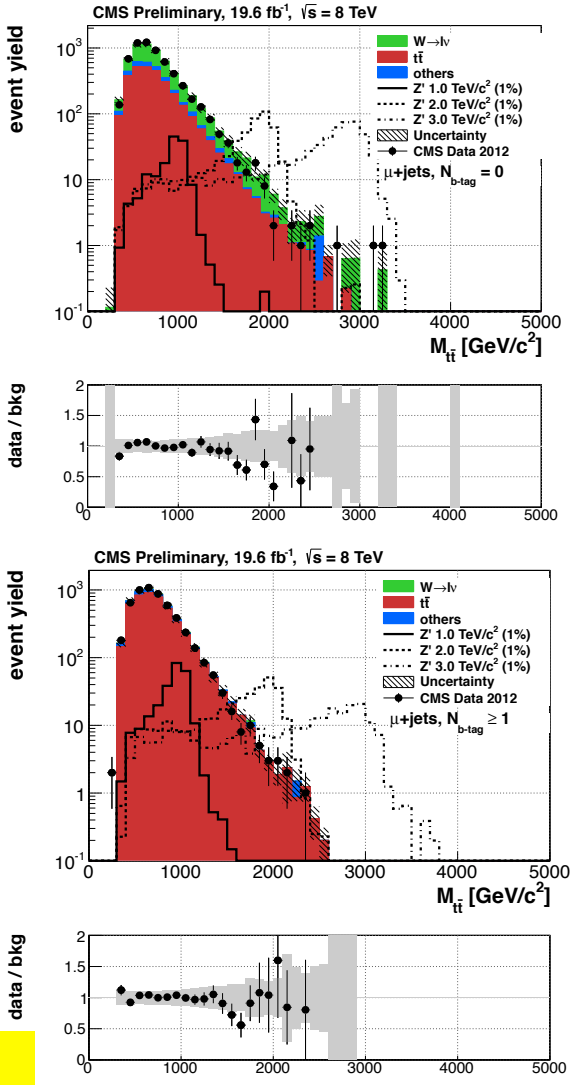
CMS Boosted l+jets Search (I)

CMS has performed search in lepton+jets channel with two analyses

1. Threshold analysis:
   - Isolated e candidate with p_T>30 GeV and |η|<2.5
     Isolated μ candidate p_T>26 GeV and |η|<2.1
   - E_T^{miss}>20 GeV
   - Four jets with D=0.5, p_T>30 GeV and |η|<2.4
     - Leading jet p_T>70 GeV and 2nd jet p_T>50 GeV
2. Boosted analysis:
   - e candidates with p_T>35 GeV and |η|<2.5
     μ candidates p_T>45 GeV and |η|<2.1
   - E_T^{miss}>50 GeV and $H_T^{lep} = p_T^{lep} + E_T^{miss}$>150 GeV
   - Two jets with D=0.5, p_T>50 GeV and |η|<2.4
     - Leading jet p_T>150 GeV

Several other kinematical cuts, jet b-tagging

- Limited by SM ttbar background



CMS B2G-12-006

CMS Boosted l+jets Search (2)

Backgrounds estimated in different ways

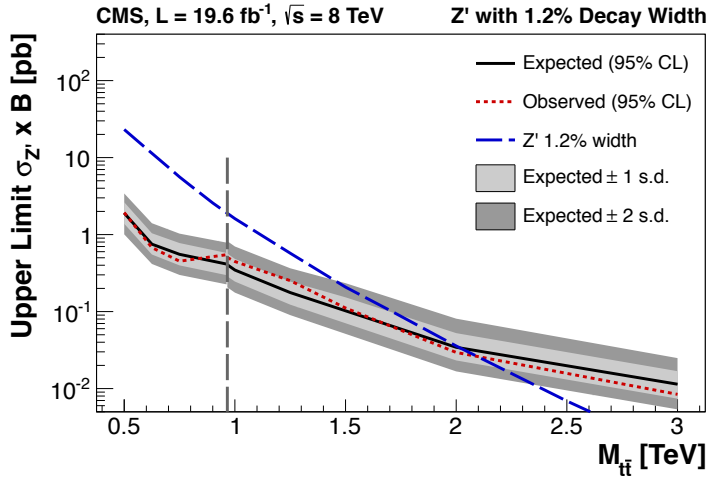
1. Threshold analysis:
   - Use data to determine SM backgrounds (no use of MC for background rate)
2. Boosted analysis:
   - Estimate SM backgrounds using POWHEG with PYTHIA showering & MADGRAPH with PYTHIA

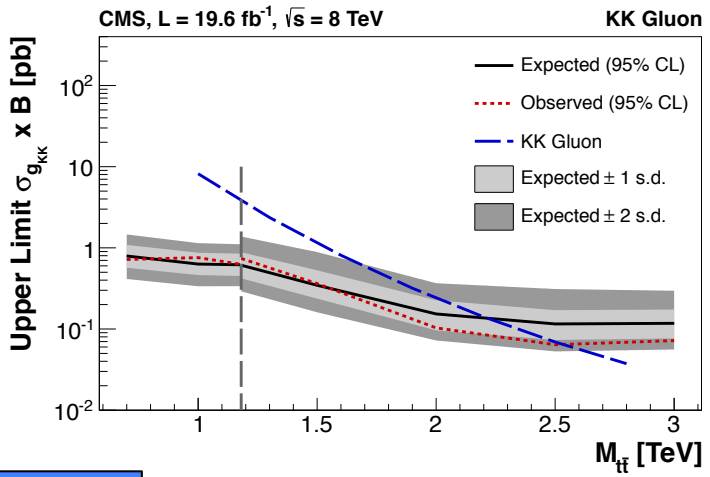
Estimate systematic uncertainties

- Largest sources are b-tagging, jet energy scale and resolution, integrated luminosity

Set 95% CL limits using Bayesian calculation

- Systematics incorporated as nuisance parameters





$m_{Z'} > 2.10\ (2.68)$ TeV for $\Gamma / m = 1.2\%\ (10\%)$

$m_{gKK} > 2.54$ TeV

CMS B2G-12-006

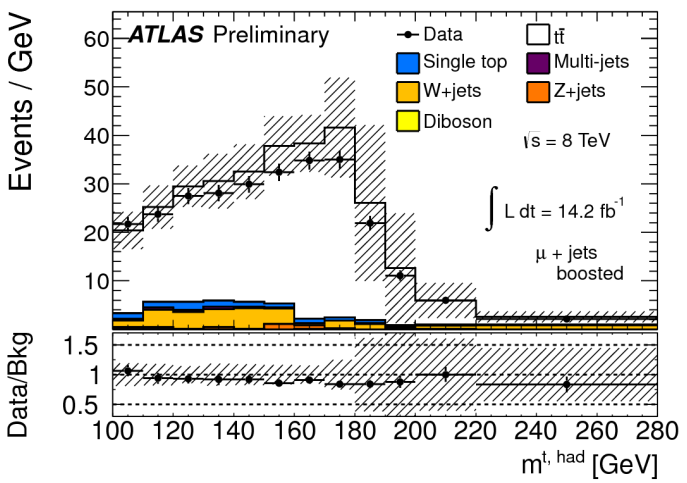
ATLAS Boosted l+jets Search (I)

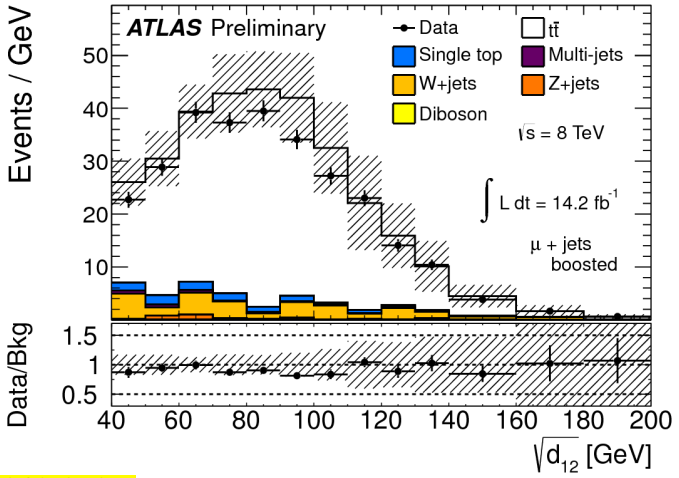
ATLAS has searched in 14.2 fb^{-1} of 8 TeV data using lepton+jets channel with 2 analyses

1. Boosted analysis:
   - Isolated e candidate with p_T>25 GeV and |η|<2.47, with E_T^{miss}>30 GeV and m_T>30 GeV
   - Isolated μ candidate p_T>25 GeV and |η|<2.5, with E_T^{miss}>20 GeV and E_T^{miss}+m_T>60 GeV
   - ≥ 1 D=0.4 jet with p_T>25 GeV and |η|<2.5
   - 1 D=1.0 jet with p_T>300 GeV and |η|<2.0
     - Must also have 1st k_T splitting scale $(d_{12})^{0.5}$ > 40 GeV and m_{jet} > 100 GeV
2. Resolved analysis:
   - Same lepton requirements
   - 3 or 4 D=0.4 jets with p_T>25 GeV and |η|<2.5
     - If only 3 jets, one must have m_{jet}>60 GeV

Also require at least one b-tagged jet

- Limited by SM ttbar background





ATLAS-CONF-2013-052

ATLAS Boosted l+jets Search (2)

Backgrounds estimated using data-driven and MC calculations

- W+jets determined using W+/W- charge asymmetry to separate from other sources
- Multijet background estimated by relaxing lepton ID requirements
- SM ttbar estimated using MC@NLO+HERWIG showering

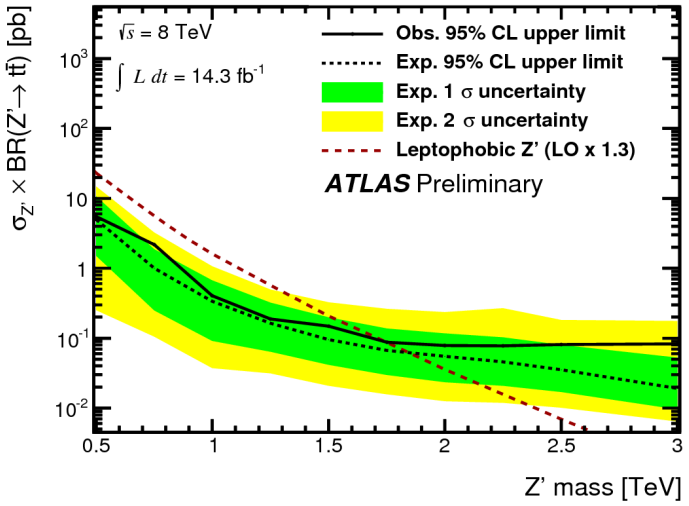
Estimate systematic uncertainties

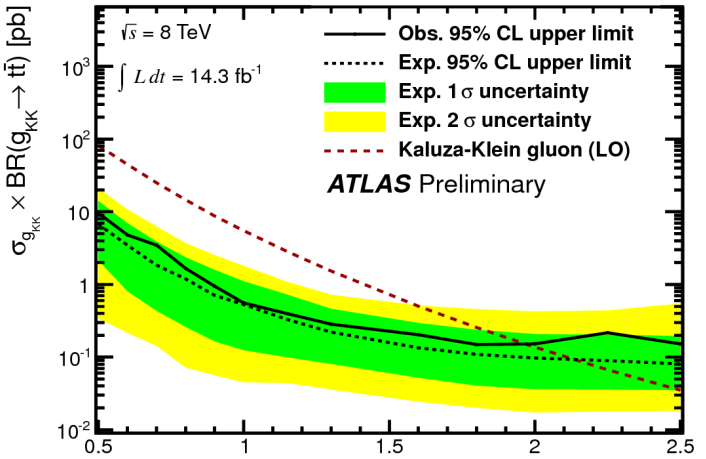
- Largest sources are JES, ttbar normalization, PDFs

Set 95% CL limits using Bayesian calculation

- Systematics incorporated as nuisance parameters

$$m_{Z'} > 1.80 \text{ TeV for } \Gamma / m = 1.2\%$$
$$m_{gKK} > 2.00 \text{ TeV}$$





ATLAS-CONF-2013-052

ATLAS Monojet Search

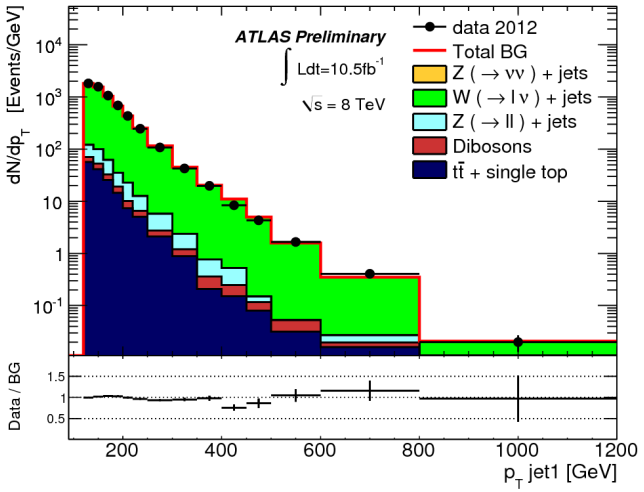
Monojets arise in a number of theories, e.g.

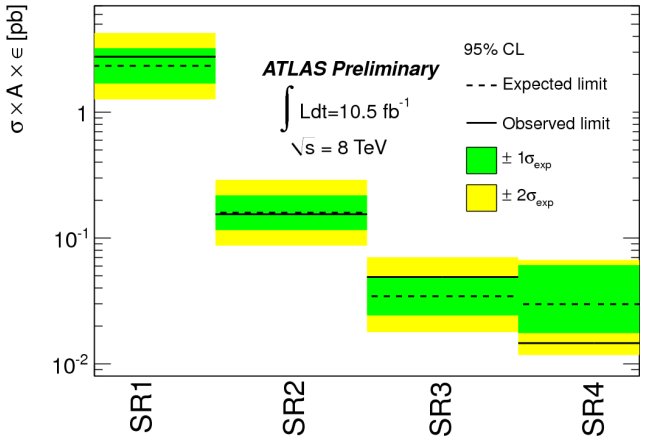
- Dark Matter (DM) -- more generally WIMPs
- Gauge-mediated SUSY-breaking models

Search is a traditional one

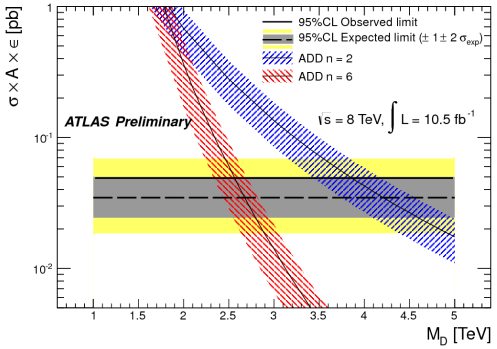
- Look at events with ≥ 1 jet & large E_T^{miss}
- Compare with expected backgrounds
- ATLAS has studied 10.5 fb^{-1} of 8 TeV pp data
  - Consider 4 regions with E_t^{miss} >120, 220, 350 & 500 GeV
  - Requires leading jet p_T with same pT threshold

See excellent agreement with expected SM backgrounds





ATLAS-CONF-2012-147



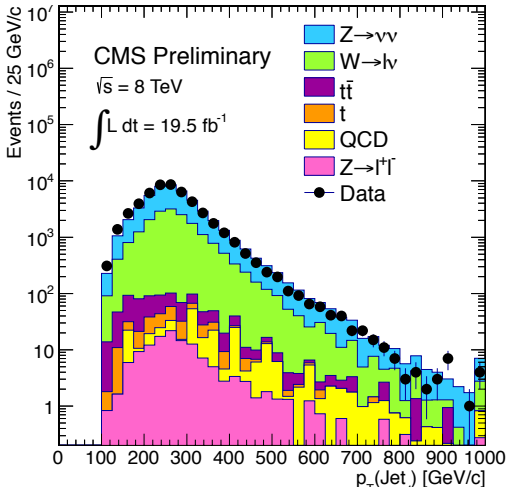
CMS Monojet Search

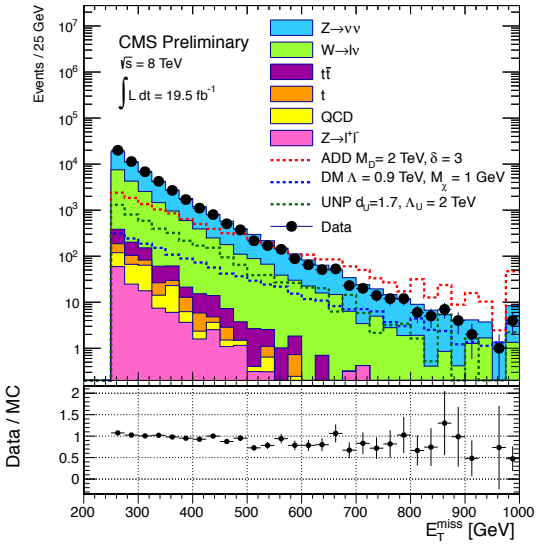
CMS has looked at monojets in 19.5 fb^{-1}

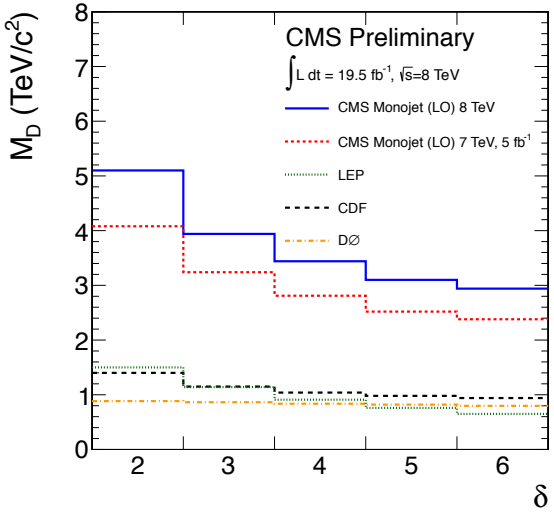
- Look in 7 regions with E_T^{miss} >250 GeV to E_T^{miss}>550 GeV in 50 GeV steps
- Looks at events with only one recoil jet
  - Leading jet pT distributions is used as control

Compare with expected SM backgrounds

- Set 95% CL limits on possible DM yield as a function of M_D and δ (number of extra dimensions)







N.B. ATLAS has similar exclusion plot

CMS EXO-12-048

CMS Search for Jet Extinction

Some Terascale gravity models predict reductions of high p_T jet production

- Look for reduction of high p_T jets relative to QCD predictions

CMS searched in 10 fb^{-1} of 8 TeV collisions

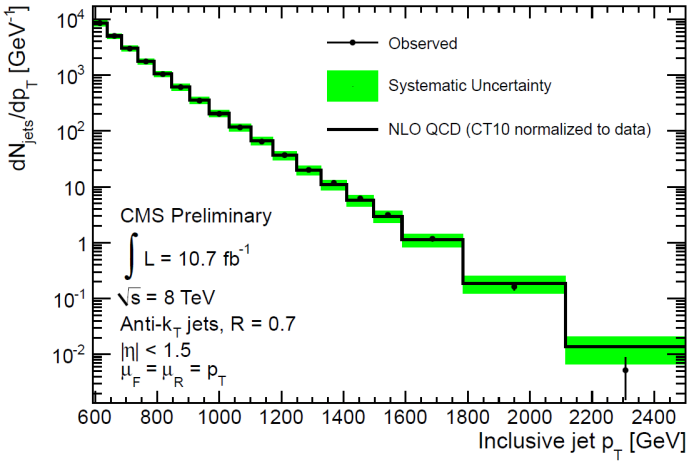
- Looked for evidence of a reduction in yield
  - Modelled this with a PYTHIA MC, using a Veneziano-type form factor
  - Extinction occurs beyond scale M
- Compared rate with NLOJet++ NLO calculation with CT10 PDFs

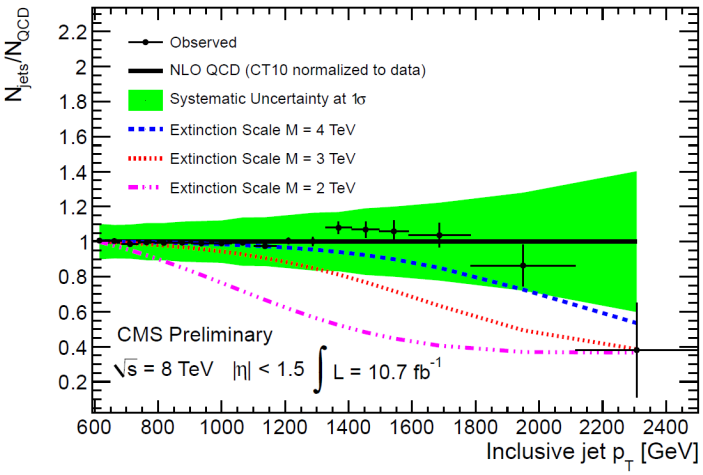
Systematic uncertainties dominated by JES and PDFs

- Set frequentist 95% CL limits

$M > 3.3$ TeV

See, for example, Banks & Fischler, arXiv:hep-th/9906038v1



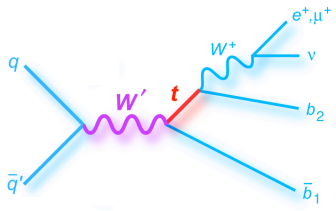


CMS EXO-12-051

CMS Search for W'→t-bbar

Numerous models predict W' bosons

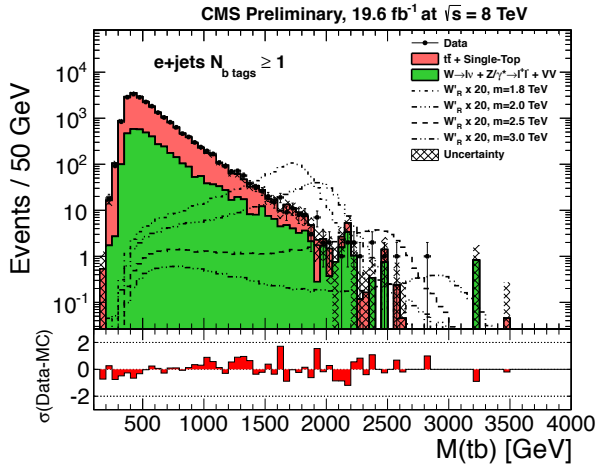
- Most sensitive searches look for hadronic decay **W'→t-bbar**

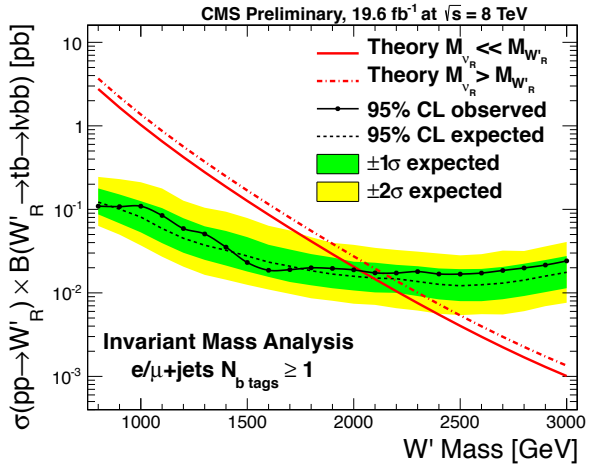


CMS searched in 19.6 fb^{-1} of 8 TeV pp collisions

- Require e/μ with p_T>50 GeV and E_t^{miss}>20 GeV
- Require ≥ 2 jets with D=0.5, $pT_{1(2)}$>120(40) GeV and |η|<2.4
  - At least 1 b-tagged jet
- Require top quark candidate with p_T>85 GeV and mass between 130 and 210 GeV
- Set Bayesian 95% CL limits fitting M(tb) distribution

$M_{RH} > 2.03$ TeV





CMS B2G-12-010

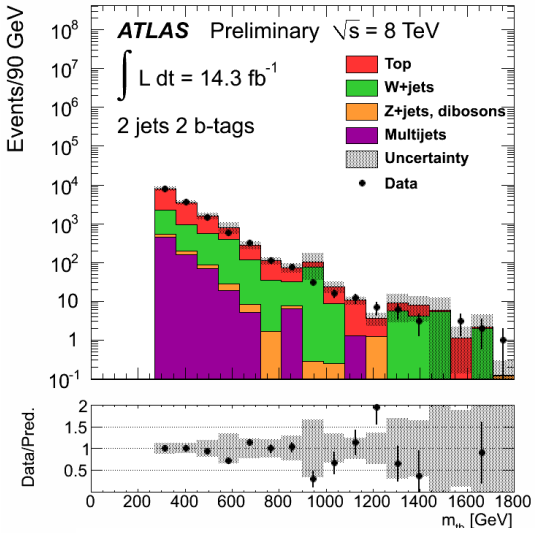
ATLAS Search for W'→t-bbar

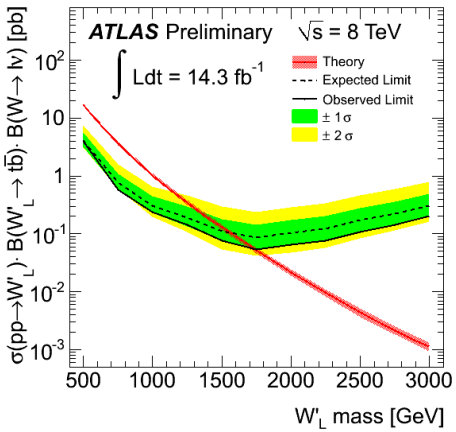
ATLAS has performed similar search in 14.3 fb^{-1} of 8 TeV pp collisions

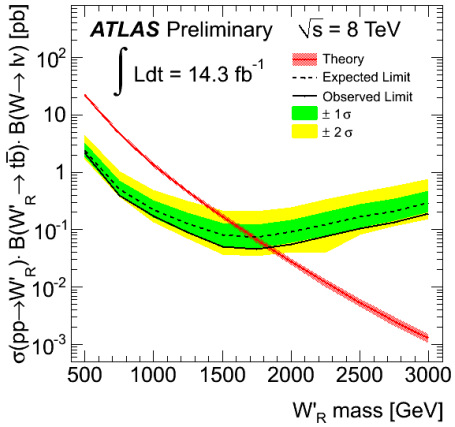
- Require e/μ with p_T>25 GeV and E_T^{miss}>35 GeV
- Require ≥ 2 jets with pT>25 GeV and |η|<2.5
  - At least 1 b-tagged jet
- Use Boosted Decision Tree analysis on 2-jet & 3-jet samples

Systematic uncertainties dominated by b-tagging, bkgds

- Set Bayesian 95% CL limits



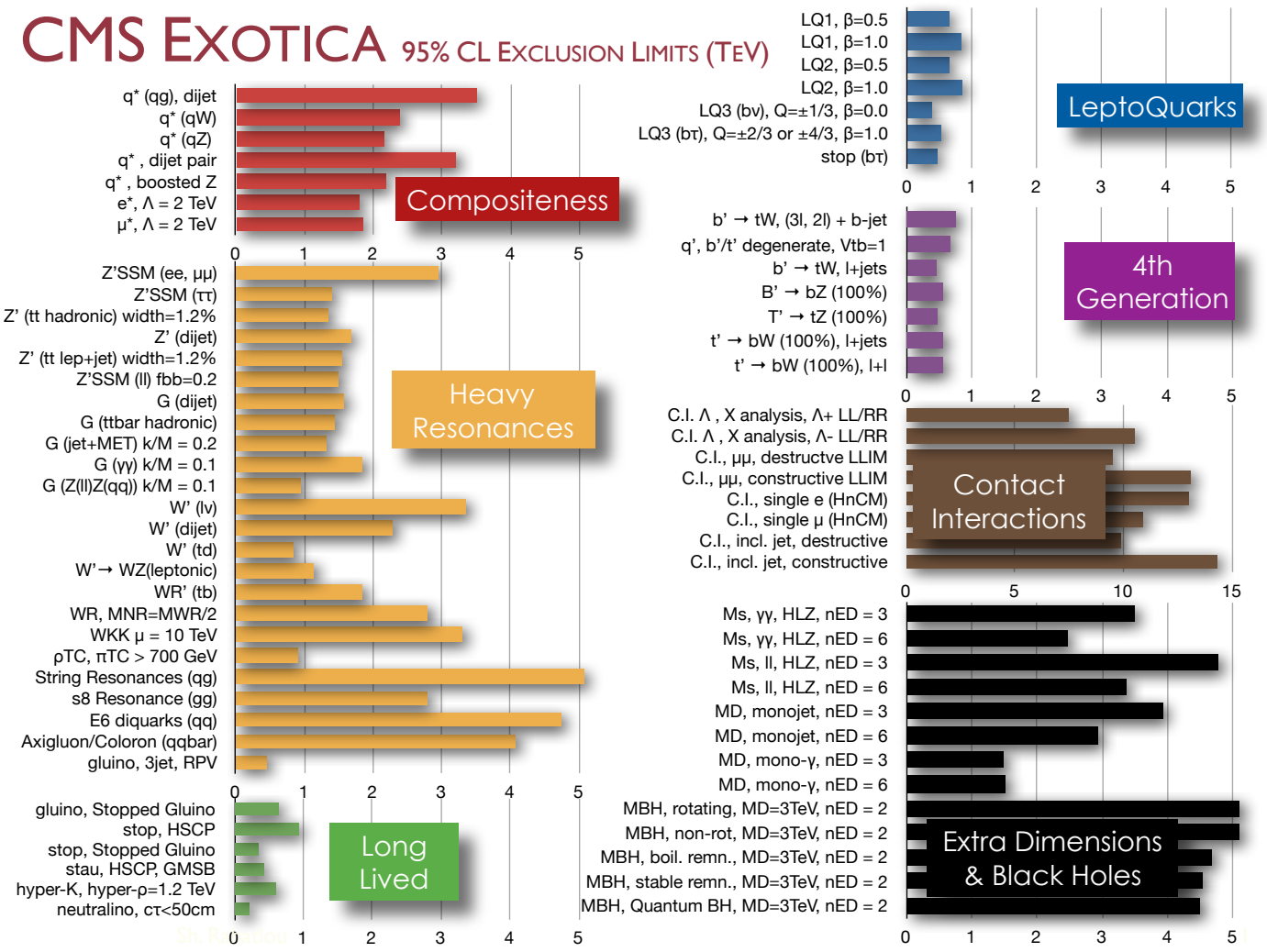




$M_{LH} > 1.74$ TeV $M_{RH} > 1.84$ TeV

ATLAS-CONF-2013-050

CMS Exotica Summary

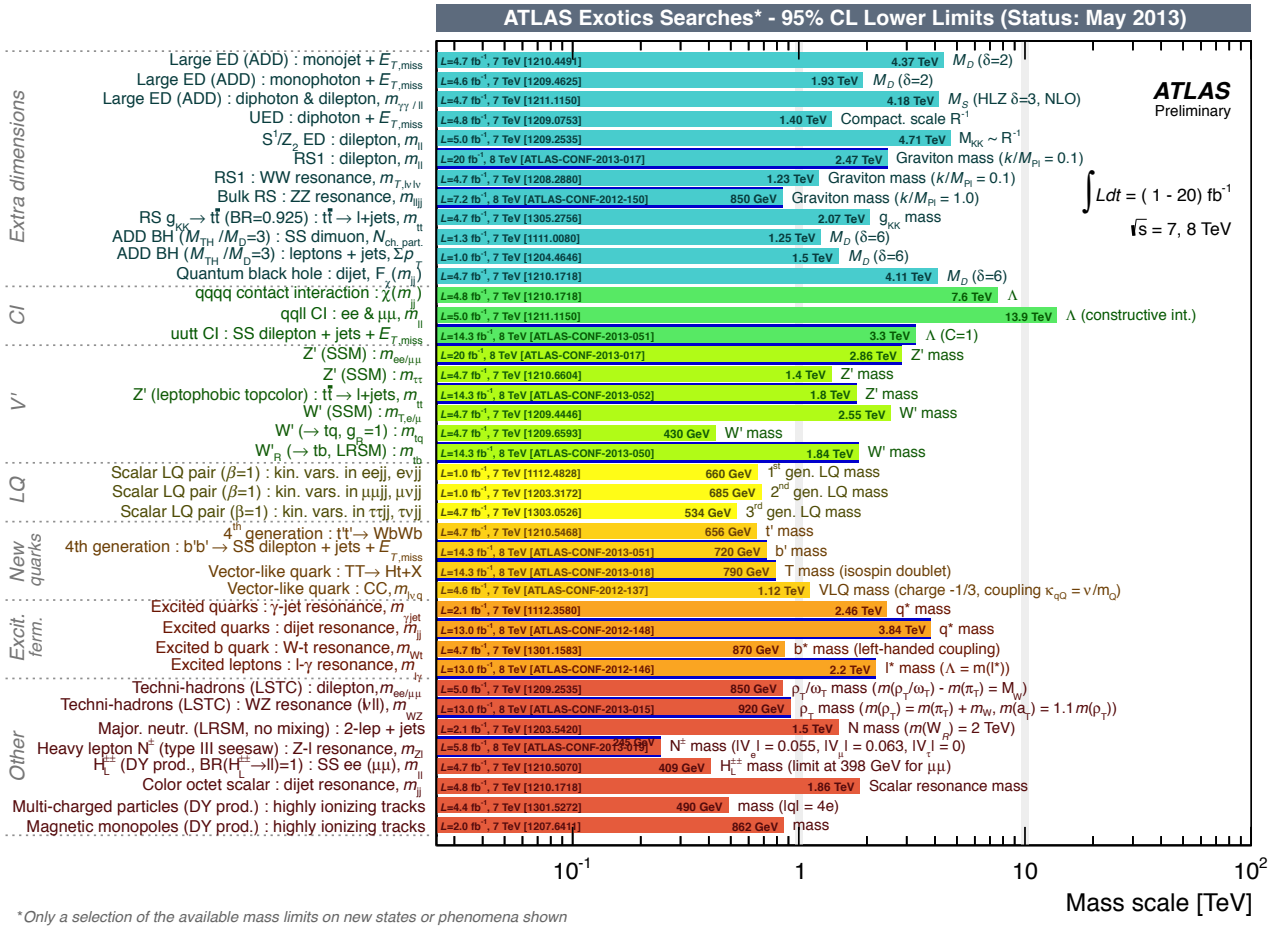


Summary and Conclusions

CMS and ATLAS successfully probing multi-TeV regime

- Summaries show that a large number of hypotheses tested
- Many analyses still underway with full 7/8 TeV samples

Next step is increase in pp energy and L coming in 2015

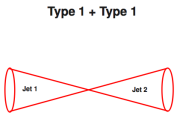


Backup Slides

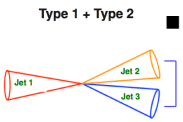
CMS Initial Hadronic Search (I)

CMS performed the first fully hadronic search at the LHC

1. Two jets ("1+1")
   - Use Cambridge-Achen D=0.8 clustering
   - Require 2 jets with p_T>350 GeV and |y|<2.5
     - Each jet has to have 3 sub-jets, m_{jet} consistent with top quark mass
     - Min pair-wise mass of 2 sub-jets > 50 GeV

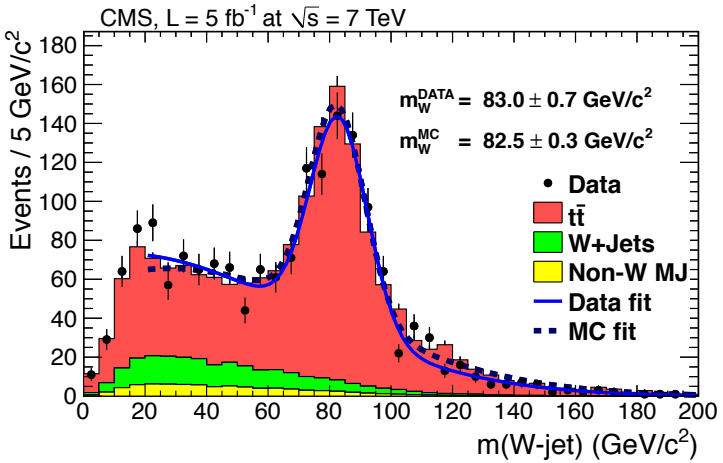


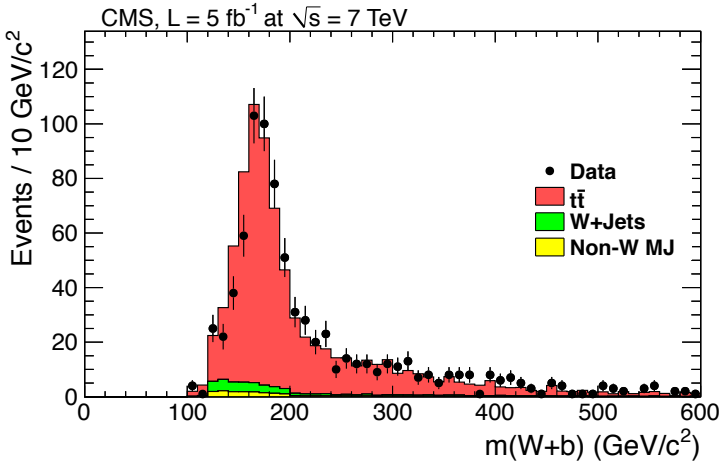
2. Three jets ("1+2")
   - As above, but only one jet satisfying the substructure criteria
   - Recoiling against 2 jets, one with p_T>200 GeV, with 2 sub-jets, m_{jet} consistent with W boson



Several other kinematical cuts, no b-tagging

- Limited by multijet background





CMS EXO-11-006, JHEP 09 (2012) 029

CMS Initial Hadronic Search (2)

Top-tagging eff 50-60% for p_T>500 GeV

Backgrounds come from

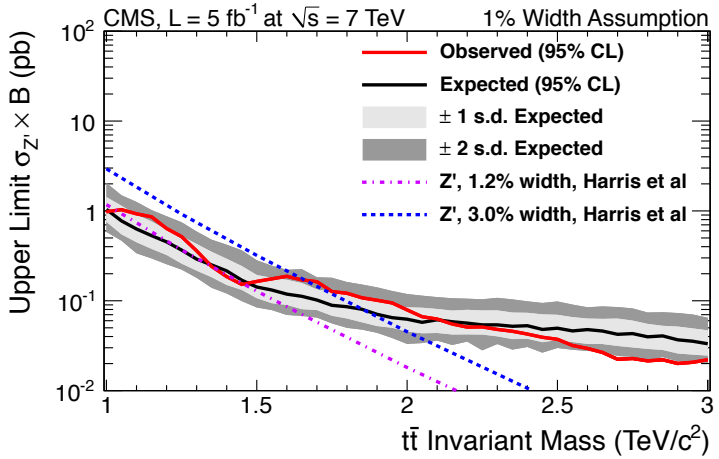
- Multijet final states – estimated using data-driven mis-tagging probability
  - Folded in with observed multijet events
- Standard Model ttbar
  - Estimated using MADGRAPH+HERWIG showers

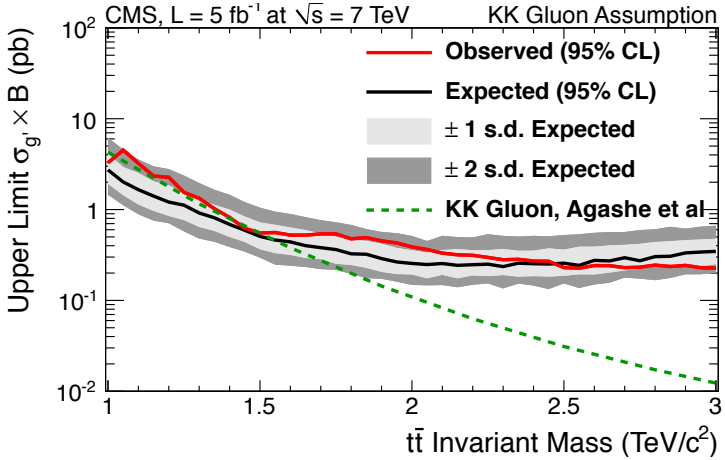
Estimate systematic uncertainties

- Largest sources are sub-jet efficiency, JES and integrated luminosity at high M_{tt}

Set 95% CL limits using Bayesian calculation

- Systematics incorporated as nuisance parameters
- Cross section limits, but not strong enough to exclude Z' or g_{KK} models



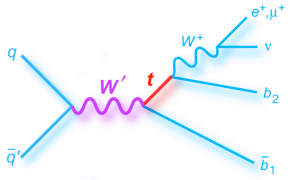


CMS EXO-11-006, JHEP 09 (2012) 029

CMS 7 TeV Search for W'→t-bbar

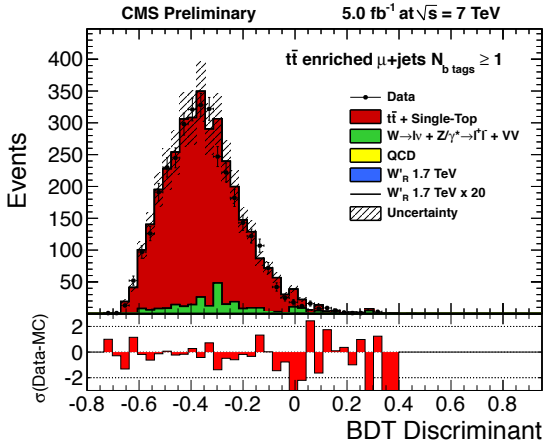
CMS performed an earlier search for hadronic W' decays

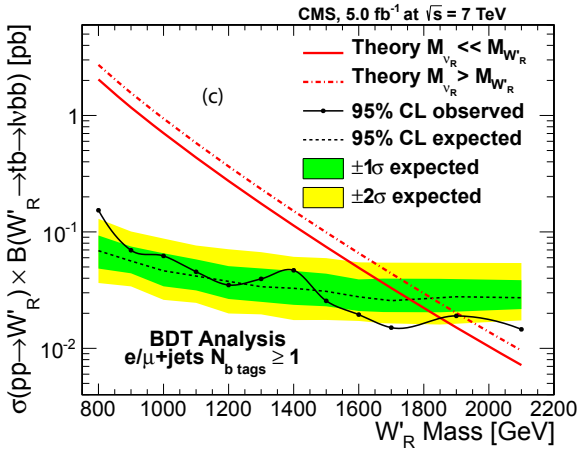
- **W'→t-bbar**



CMS has searched in 5.0 fb^{-1} of 7 TeV pp collisions

- Require e(μ) with p_T>35(32) GeV and E_T^{miss}>35(20) GeV
- Require ≥ 2 jets with D=0.5, $pT_{1(2)}$>100(40) GeV and |η|<2.4
  - At least 1 b-tagged jet
- Use Boosted Decision Tree analysis
- Set Bayesian 95% CL limits using CL_s method





$M_{RH} > 1.85$ TeV

CMS PLB 719, 1229 (2013). EXO-12-001