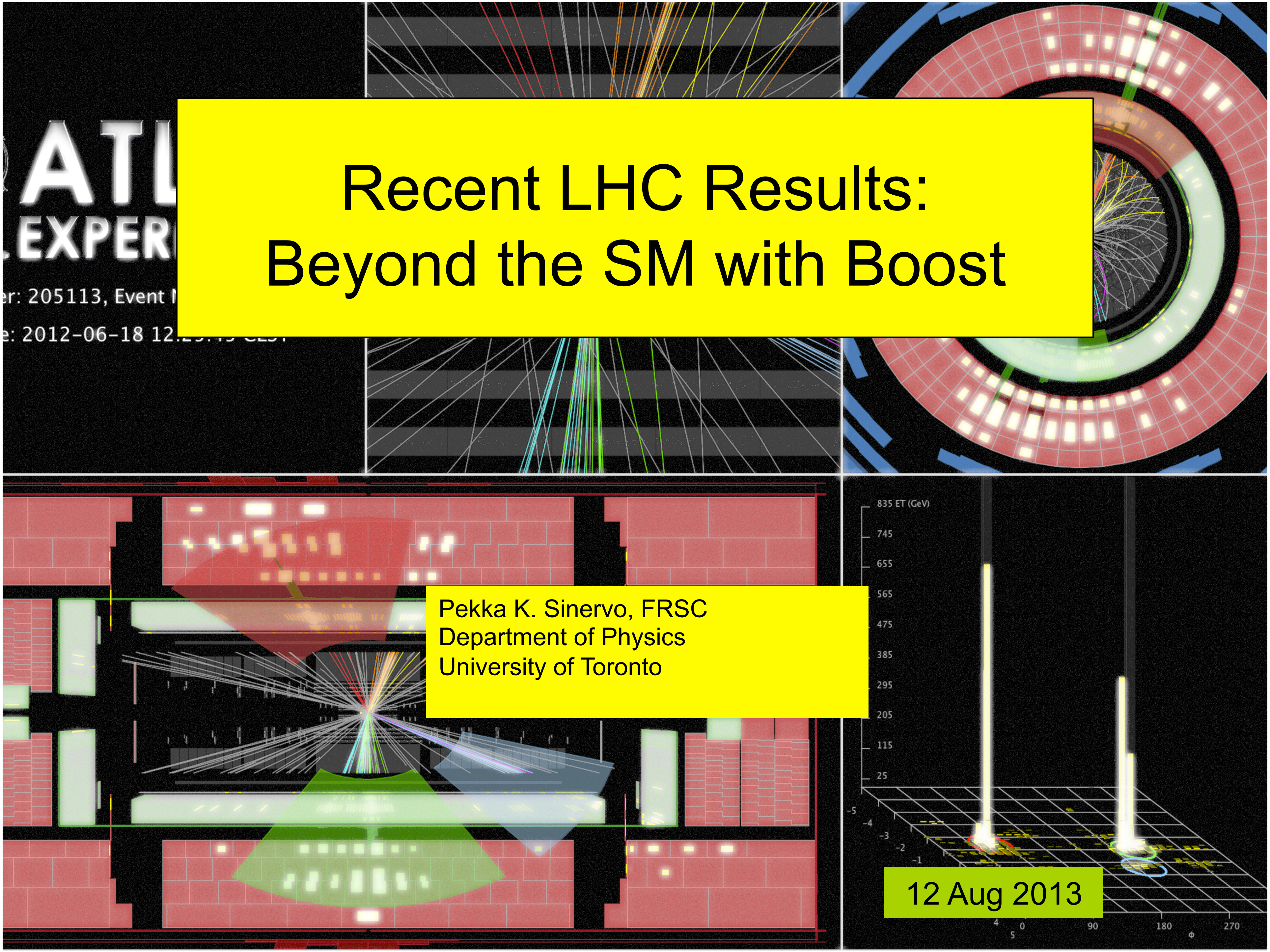
Recent LHC Results: Beyond the SM with Boost



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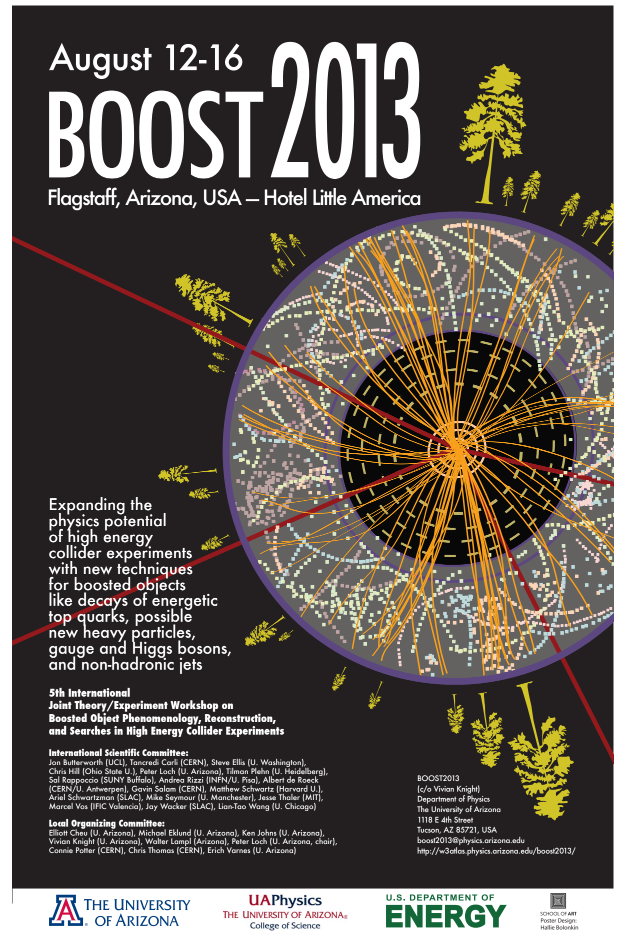
12 Aug 2013

Outline

1. Strategies and techniques – role of boost
2. Dijet searches with light quarks & gluons
3. Dijet searches with heavy quarks
4. Searches with jets and leptons
5. Monojets
6. W’→ tb search
7. Summary & Conclusions



A Perspective on LHC Results

Over the last year, Higgs boson on centre stage

- Measured mass, couplings, spin
- Fits well with SM

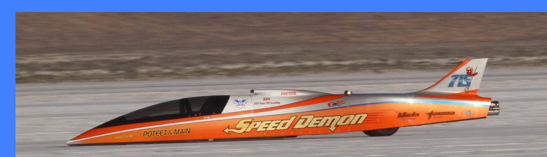
Concerted effort to look beyond SM

- Extending earlier searches with more data
- Development of new techniques

BOOST2013 will highlight many of these new techniques and searches

- So I'll help set some of the context
- Give a taste of the more detailed talks to come

Similar to pushing the world land speed record



Speed Demon: 707 km/h (2012)

ThrustSSC: 1227 km/h

Techniques and Strategies (1)

Many beyond-SM phenomena result in quarks and gluons

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

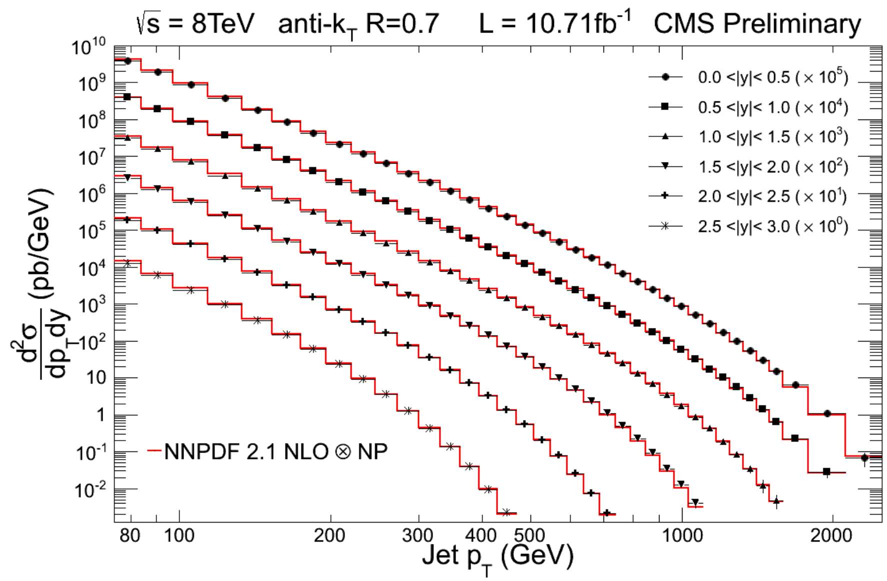
Natural to search for new particles with jet final states

- Invariant mass “bumps”
- Threshold phenomena

Experimental challenge is high rate of multijet final states from SM QCD

Cross section for inclusive jets

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



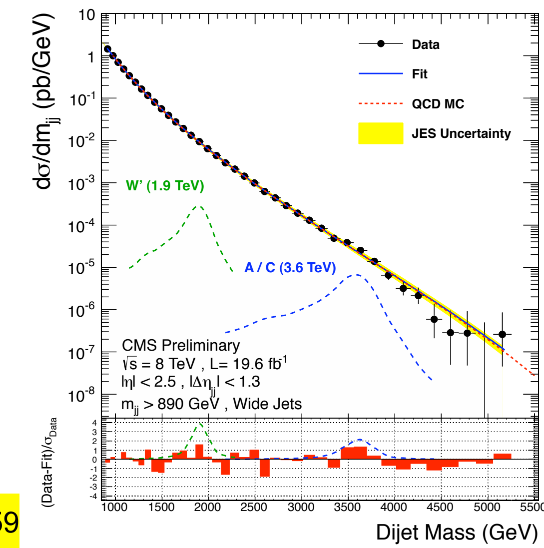
CMS-PAS-SMP-12-012

Techniques and Strategies (2)

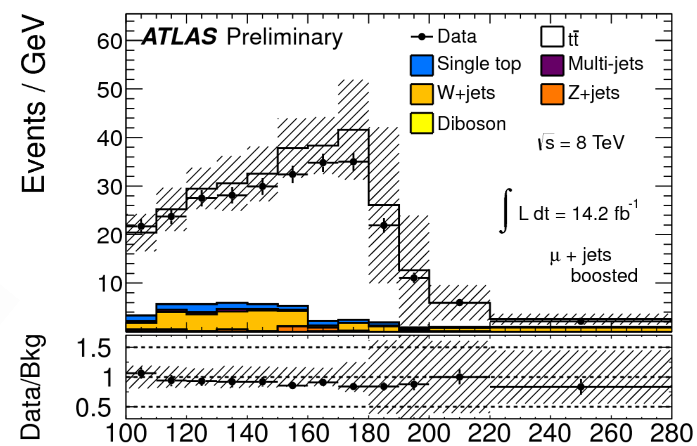
To tackle this background:

1. Develop reliable background estimation tools, e.g.
   - Dijet resonance searches

2. Develop techniques to reject light quark and gluon jets
   - Use b-tagging and “boosted” jet substructure techniques
   - Examples are the Z’ and g_{KK} “boosted” top quark searches



CMS-EXO-12-059



ATLAS-CONF-2013-052

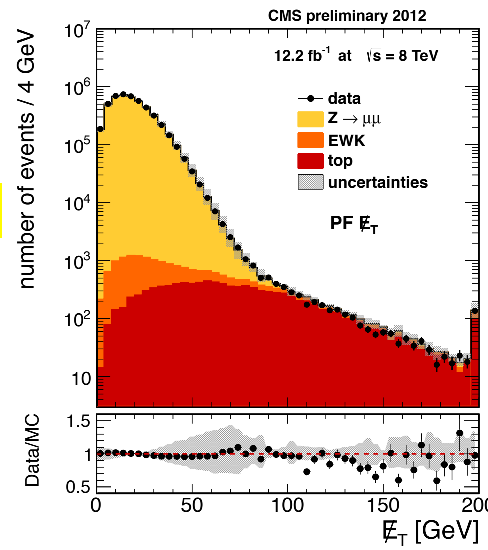
Techniques and Strategies (3)

LHC has run extraordinarily well

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

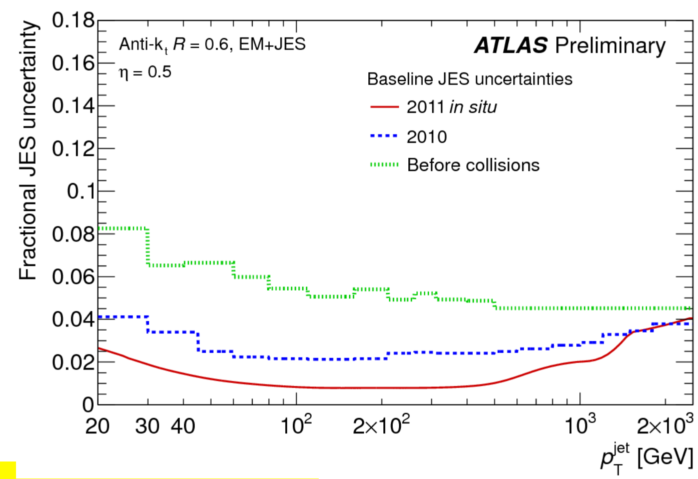
$Z \rightarrow \mu^+\mu^- X$

CMS JME-12-002



Have enabled both CMS and ATLAS to develop well-understood 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
- Efficient techniques for tagging heavy flavour jets (>70% efficiency)



These and other innovations basis for new exotics searches

ATLAS-CONF-2013-004

Validation of Boost Techniques (I)

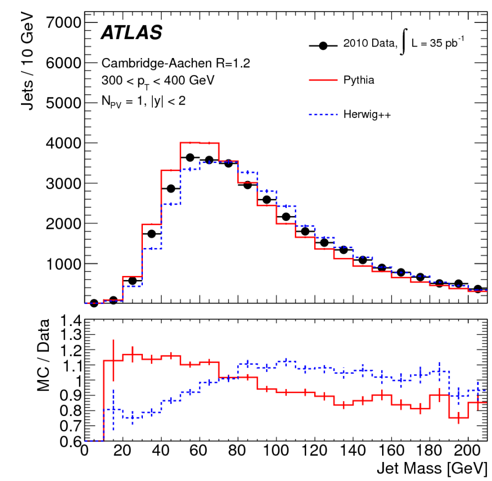
High mass objects decay primarily into high-p_T "boosted" objects

- Substructure techniques have been shown to improve S/B
  - Initial experimental work was to validate QCD predictions
  - Show that jet physics without pileup makes sense

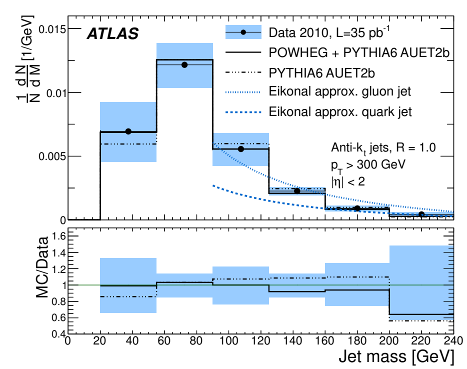
Early results confirmed general picture painted by pQCD

- Though mostly data compared with detailed MC predictions

Earliest Studies Reported Last Year



ATLAS-STDM-2011-19

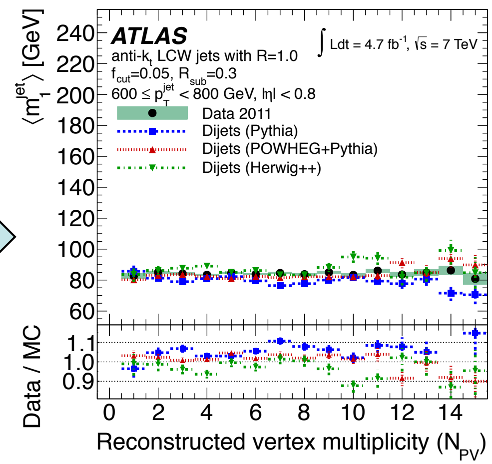


ATLAS-STDM-2011-38

Validation of Boost Techniques (II)

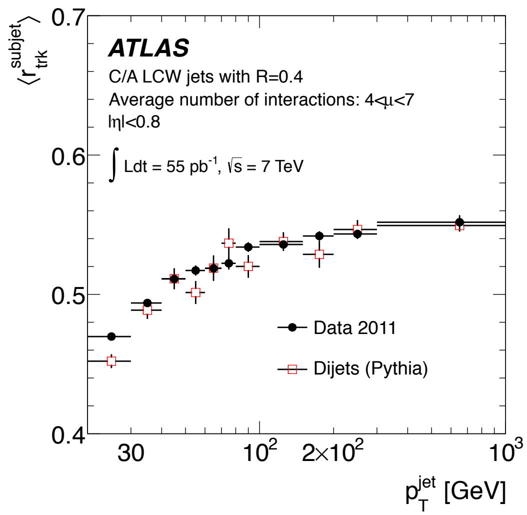
Some new results from past year:

1. "Pileup" is a managable complication
   - Physics variables such as mass and subjet structure can be extracted
   - Resolution is not compromised fully



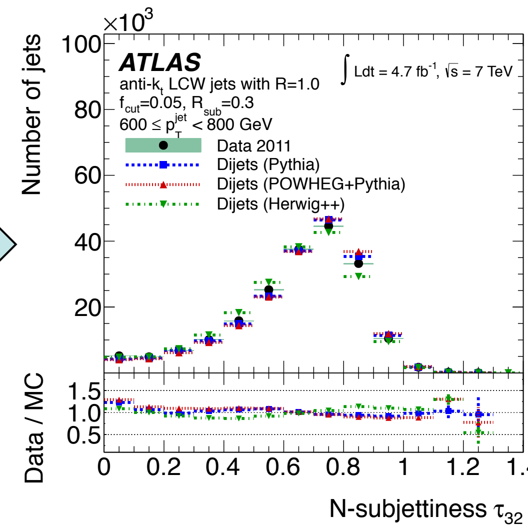
ATLAS: arXiv:1306.4945v1

2. Energy scale systematics can be controlled
   - Large R and subjet energy scales under good control



ATLAS: arXiv:1306.4945v1

3. Comparison of complementary approaches:
   - Jet mass
   - N-subjettiness
   - Splitting scale $\sqrt{d_{23}}$



Selection of Results

I'll focus on a subset of all possible results

- Reflect where jets play key role
- Illustrate the wide range of topics and techniques that are employed, some of them from the "boosted" toolbox

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 evidence of Jet Extinction
5. Search for W' bosons decaying to t-bbar

ATLAS Dijet Resonance Search

Dijets are "work-horse" for exotics searches

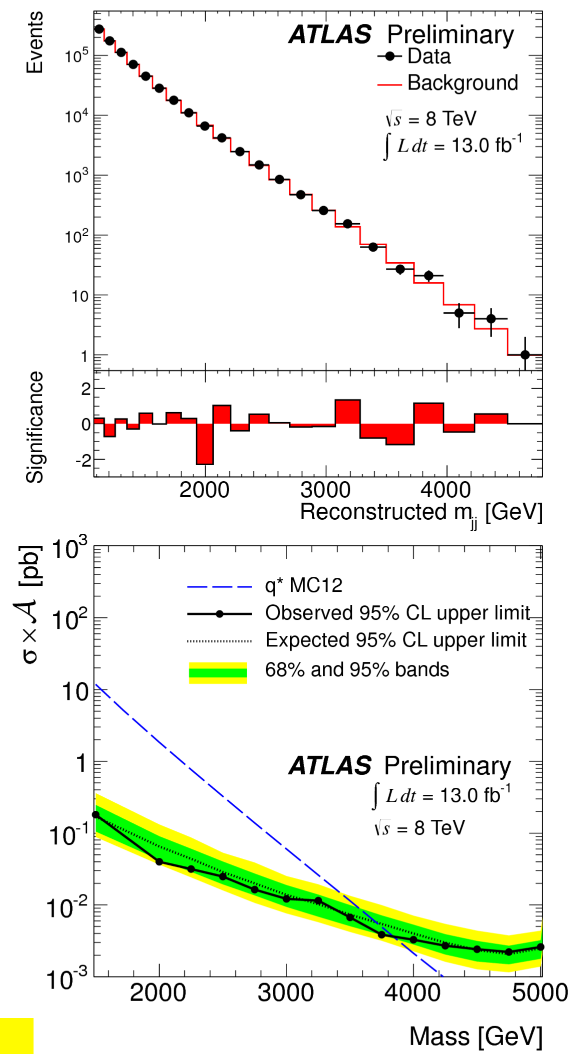
- Many possible models: e.g., excited quarks q*, black holes, and quark substructure

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

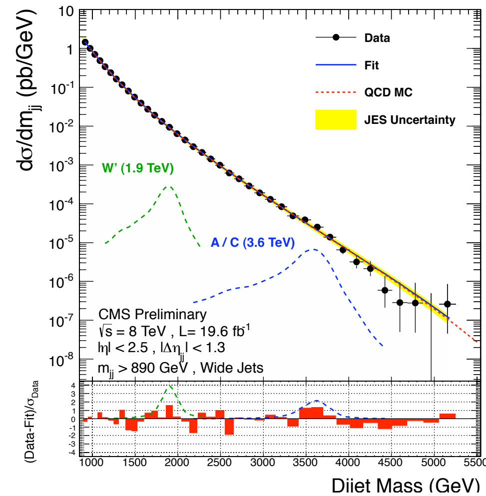
CMS Dijet Resonance Search

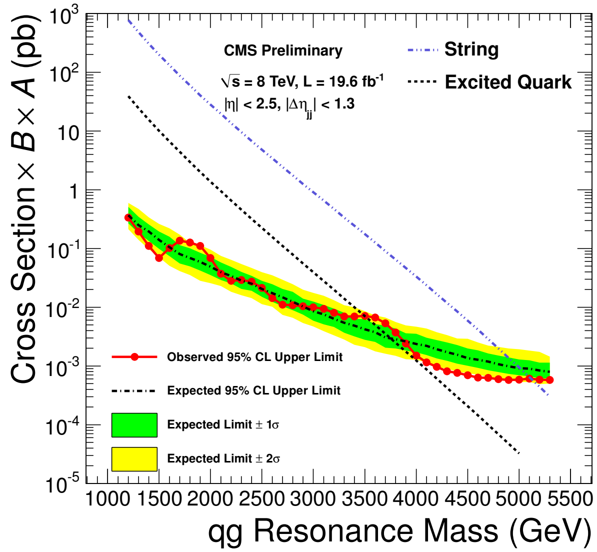
CMS has performed similar searches using a 19.6 fb^{-1} data set of 8 TeV collisions

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





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]

CMS EXO-12-059

Searches for X->ttbar

A number of theories beyond the SM predict resonance states

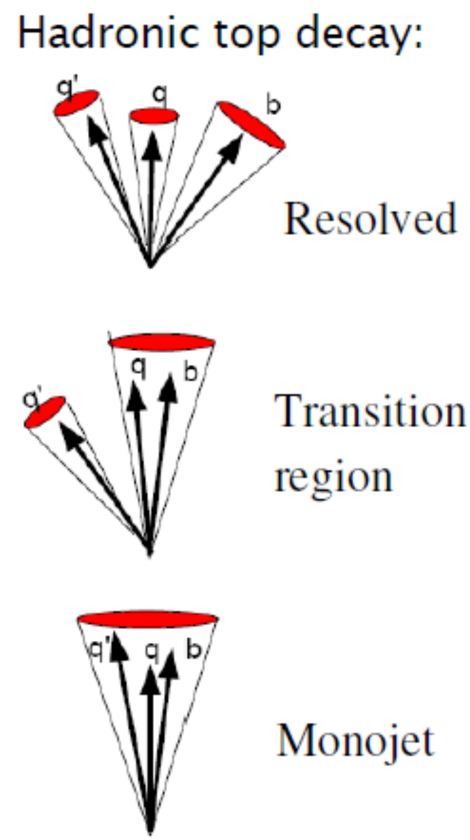
- Masses > 0.5 TeV with widths ranging from 1-2% to 10-20%
- Decay preferentially to ttbar final states

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 hadronic top quark signature
- Led to "lepton+jets" with boosted topologies and fully hadronic boosted searches

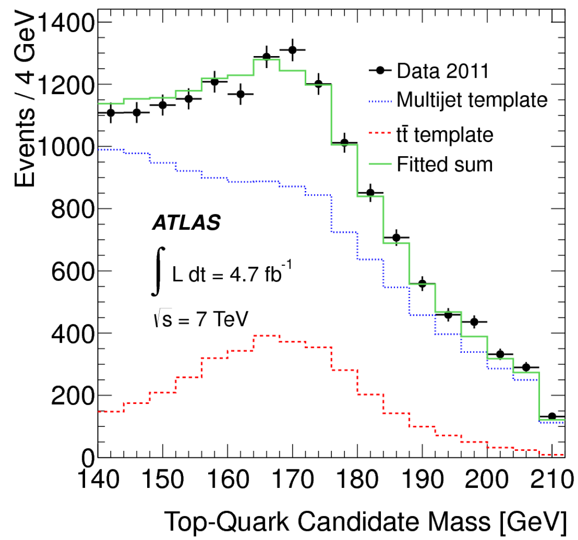


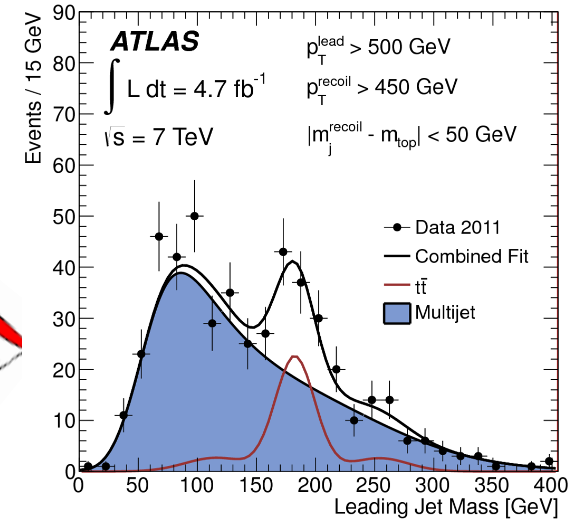
ATLAS Boosted Hadronic Search (I)

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 $|\eta|$<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 $|\eta|$<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



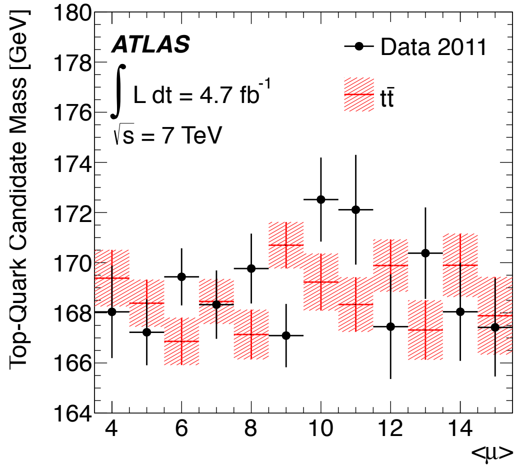


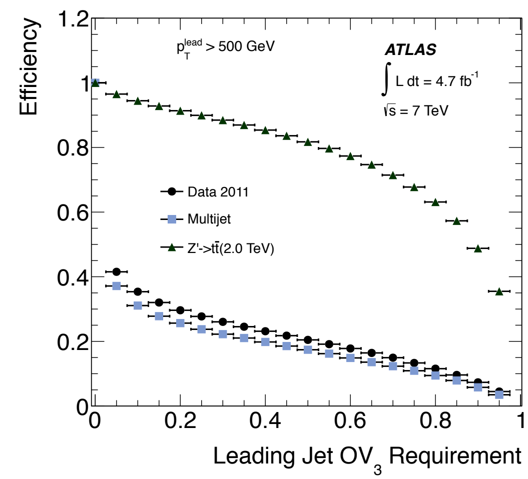
Multijet backgrounds estimated from data

- Limited by SM ttbar background

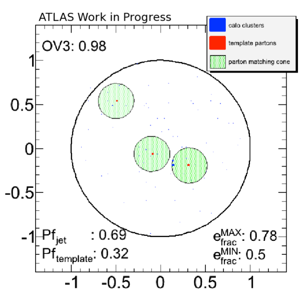
Two Taggers Compared

1. HEPTopTagger
   - Robust against large pileup
     - See average reconstructed top candidate mass
   - Retains good kinematic resolution
   - Large p_T range – p_T > 200 GeV
2. Top Template Tagger
   - Optimized for p_T > 500 GeV and $|\eta|$<2.0
   - Search for best overlap of observed energy deposits with top quark decay hypothesis
     - Good rejection (~5) with high efficiency (~0.75)
   - Work underway to optimize for p_T > 1 TeV
     - Scaling of parton cone with p_T appears promising





ATLAS, JHEP 01 (2013) 116



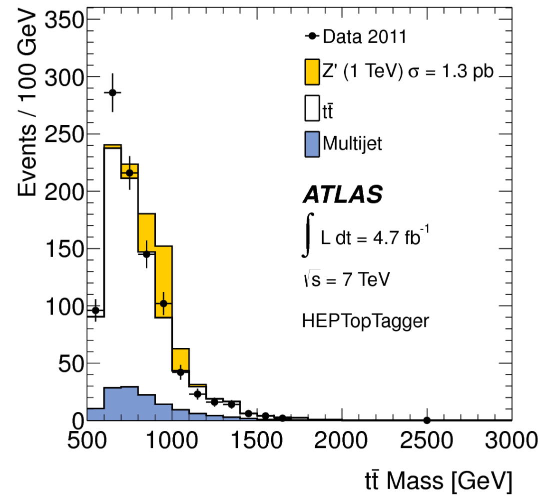
ATLAS Boosted Hadronic Search (2)

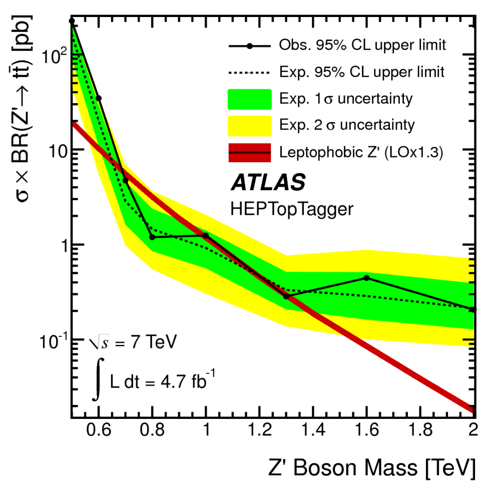
Backgrounds estimated using data-driven and MC calculations

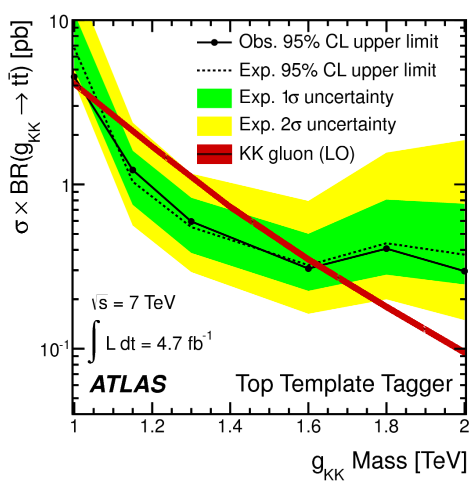
1. Multijet backgrounds estimated by mistag rates
2. SM ttbar estimated with MC@NLO+HERWIG showers

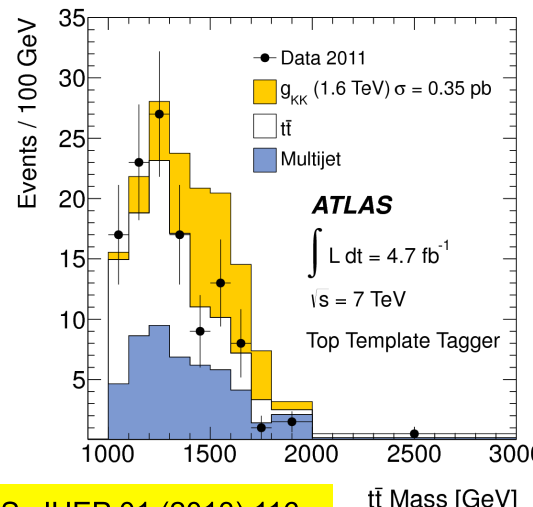
Set 95% CL limits using Bayesian calculation

- Systematic uncertainties incorporated as priors









$$M_{Z'} > 1.32 \text{ TeV for } \Gamma / M = 1.2\%$$
$$M_{gKK} > 1.62 \text{ TeV}$$

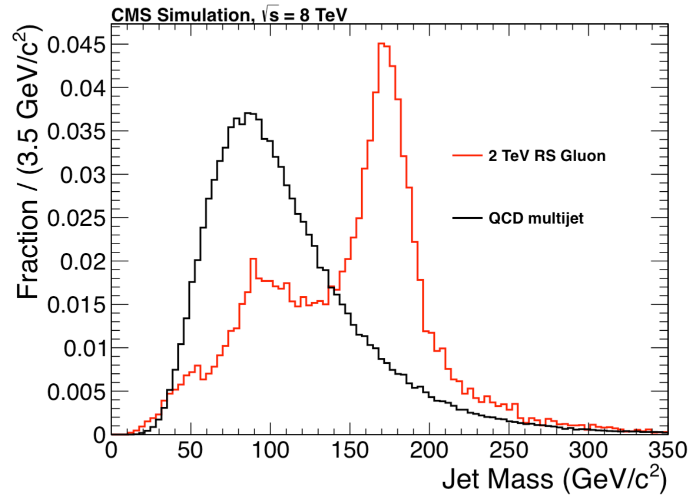
ATLAS, JHEP 01 (2013) 116

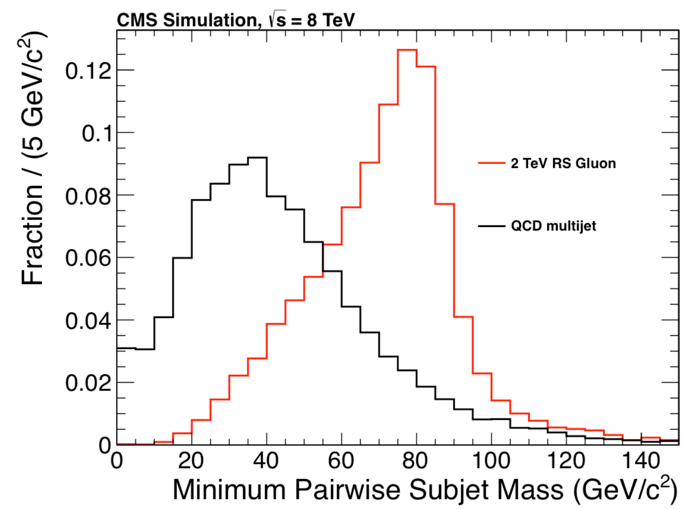
Latest CMS Hadronic Search (I)

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

Selecting two jets ("1+1")

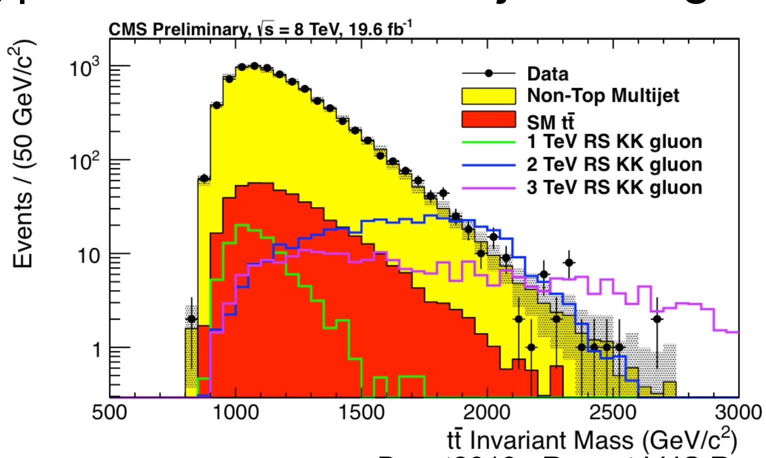
- Use Cambridge-Achen D=0.8 clusters
- Require 2 jets with p_T>400 GeV and |y|<2.5
  - Each jet has to have 3 sub-jets, m_{jet} consistent with top quark (140-250 GeV)
  - Min pair-wise mass of 2 sub-jets > 50 GeV





Several other kinematical cuts

|Δy|<1.0 to reduce multijet background



CMS B2G-12-005

Latest CMS Hadronic Search (2)

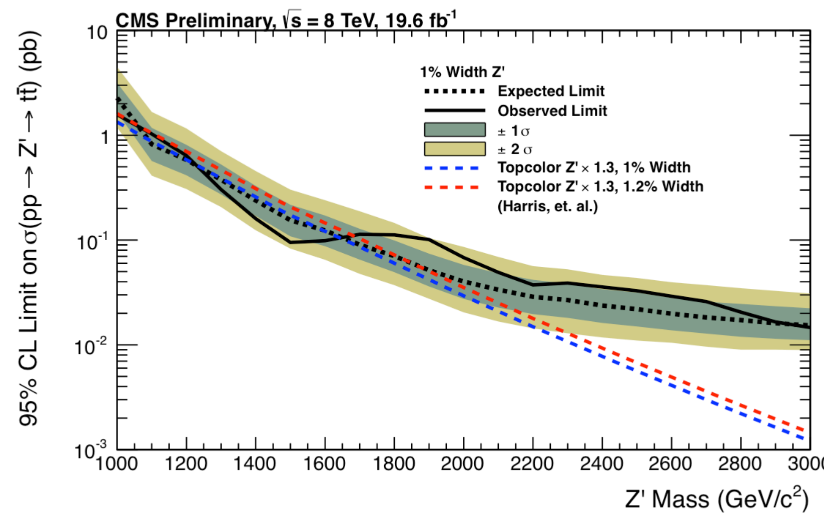
Backgrounds come from:

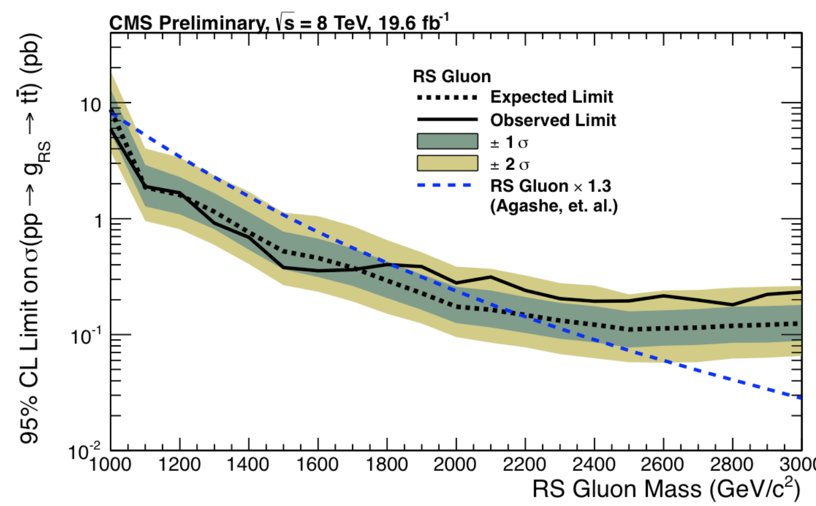
1. Multijet final states – estimated using data-driven mis-tagging probability
   - Folded in with observed multijet events
2. Standard Model ttbar
   - Estimated using MADGRAPH+HERWIG showers

Systematic uncertainties dominated by multijet bkgd, ttbar normalization

- Set 95% CL limits using Bayesian calculation

$$m_{Z'} > 1.70 \text{ TeV for } \Gamma / m = 1.2\%$$
$$m_{gKK} > 1.80 \text{ TeV}$$





CMS B2G-12-005

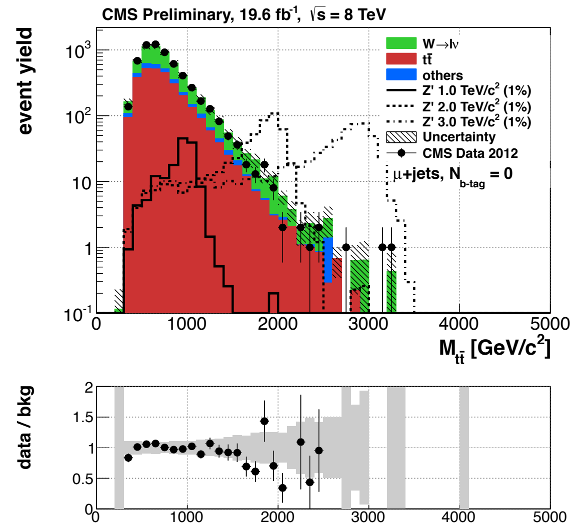
CMS Boosted l+jets Search (I)

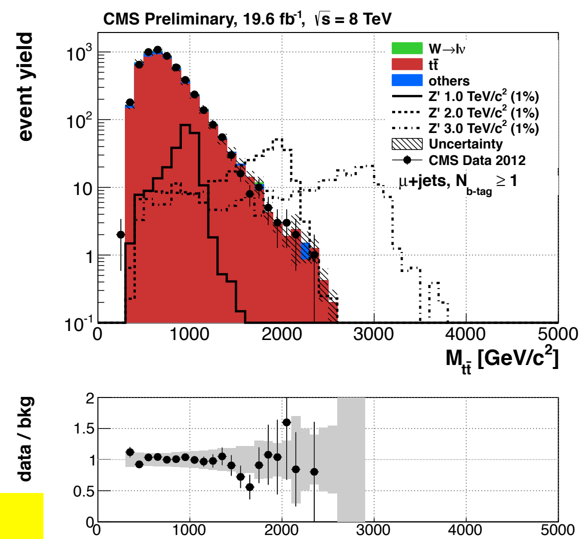
CMS has performed search in lepton+jets channel with two analyses

1. Threshold analysis:
   - Isolated e candidate with p_T>30 GeV and $|\eta|$<2.5
     Isolated μ candidate p_T>26 GeV and $|\eta|$<2.1
   - E_T^{miss}>20 GeV
   - Four jets with D=0.5, p_T>30 GeV and $|\eta|$<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 $|\eta|$<2.5
     μ candidates p_T>45 GeV and $|\eta|$<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 $|\eta|$<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

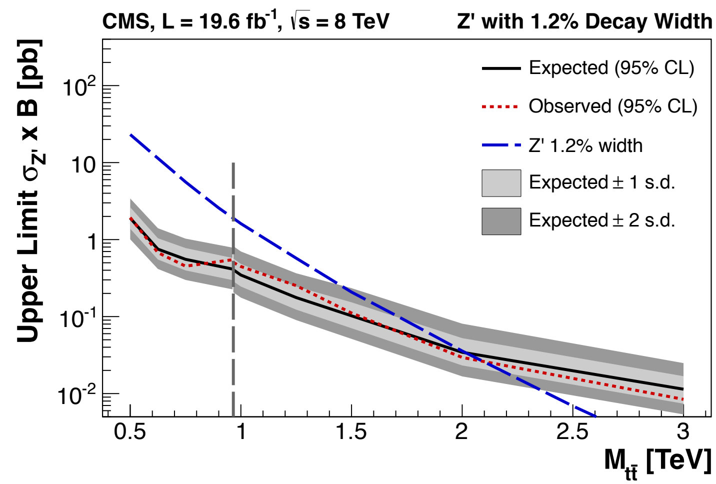
1. Threshold analysis:
   - Use data to determine SM backgrounds (no use of MC for background rate)
2. Boosted analysis:
   - Estimate SM backgrounds using POWHEG with PYTHIA showering & MADGRAPH with PYTHIA

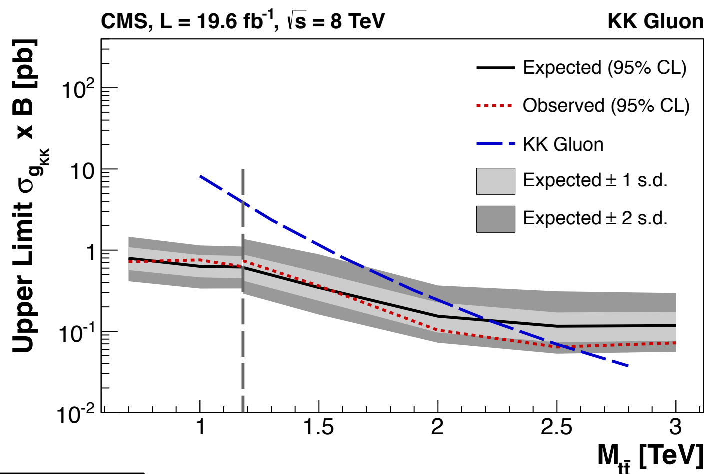
Estimate systematic uncertainties

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

Set 95% CL limits using Bayesian calculation

- Systematics incorporated as nuisance parameters





$$m_{Z'} > 2.10\ (2.68)\ \text{TeV for}\ \Gamma / m = 1.2\%\ (10\%)$$
$$m_{gKK} > 2.54\ \text{TeV}$$

CMS B2G-12-006

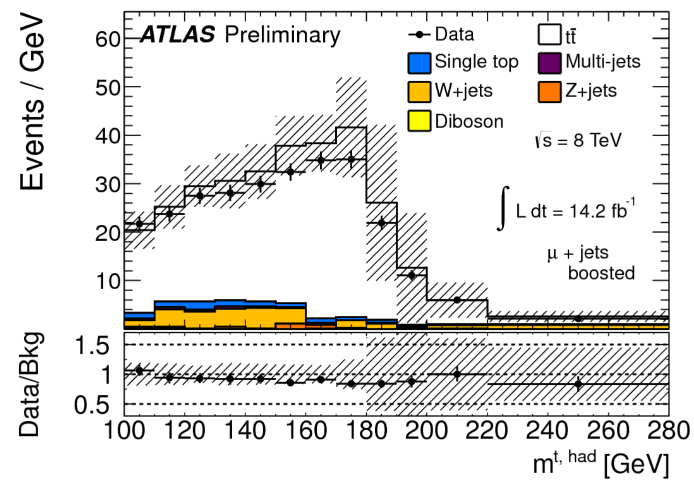
ATLAS Boosted l+jets Search (I)

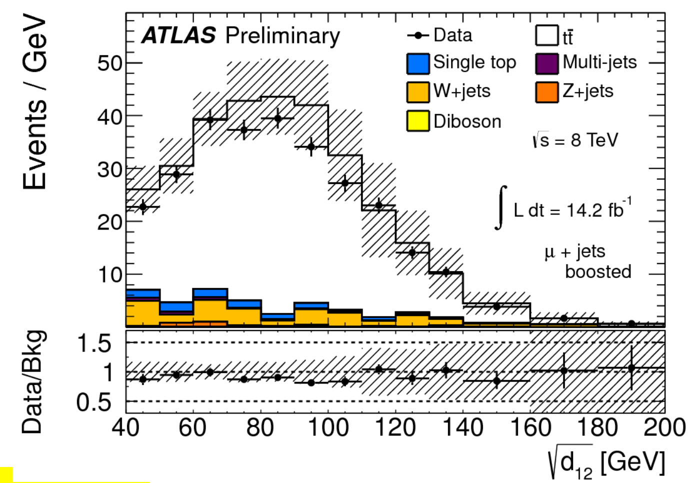
ATLAS has searched in 14.2 fb^{-1} of 8 TeV data using lepton+jets channel with 2 analyses

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

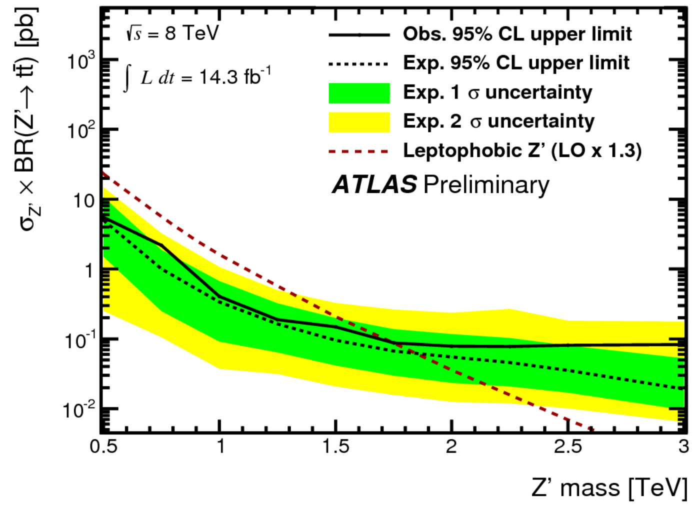
Estimate systematic uncertainties

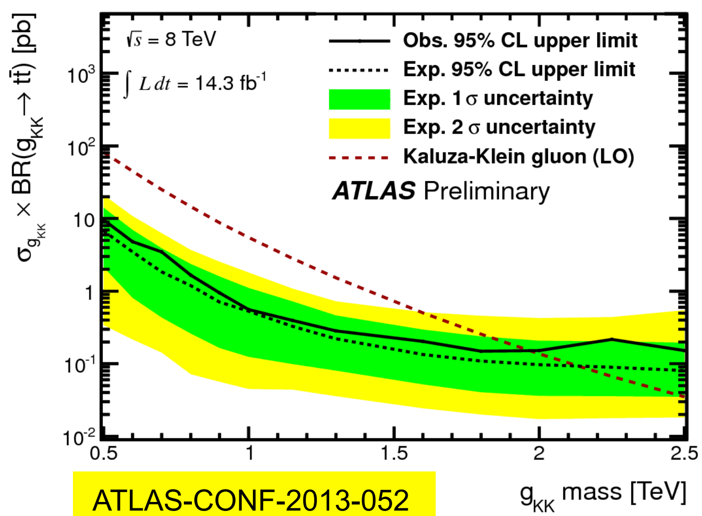
- Largest sources are JES, ttbar normalization, PDFs

Set 95% CL limits using Bayesian calculation

- Systematics incorporated as nuisance parameters

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

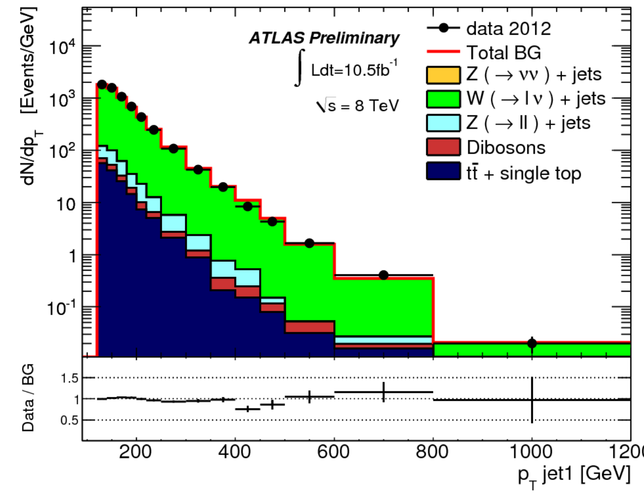
Search is a traditional one

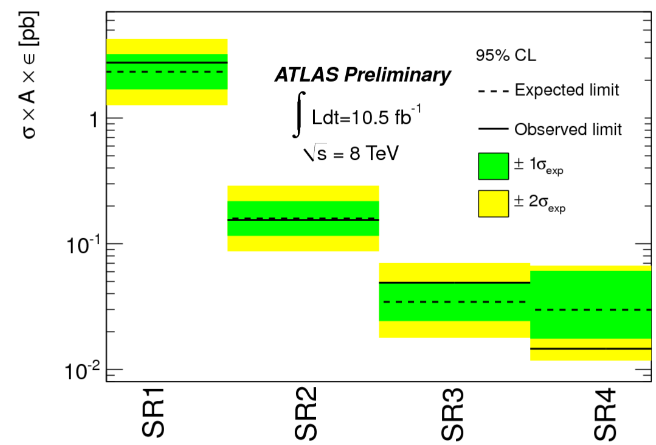
- Look at events with ≥ 1 jet & large E_T^{miss}
- Compare with expected backgrounds

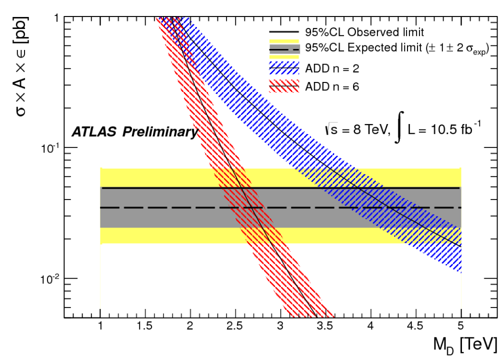
ATLAS has studied 10.5 fb^{-1} of 8 TeV pp data

- Consider 4 regions with E_T^{miss} >120, 220, 350 & 500 GeV
- Requires leading jet p_T with same p_T 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}

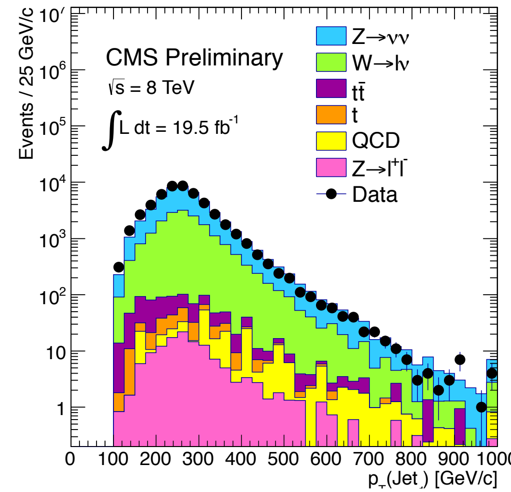
- Look in 7 regions with E_T^{miss} >250 GeV to E_T^{miss}>550 GeV in 50 GeV steps

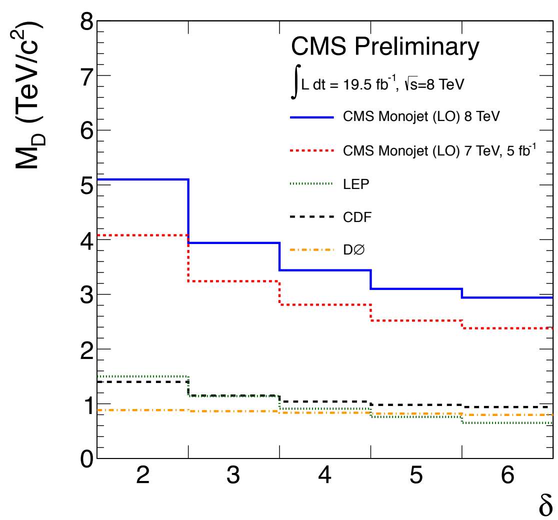
Looks at events with only one recoil jet

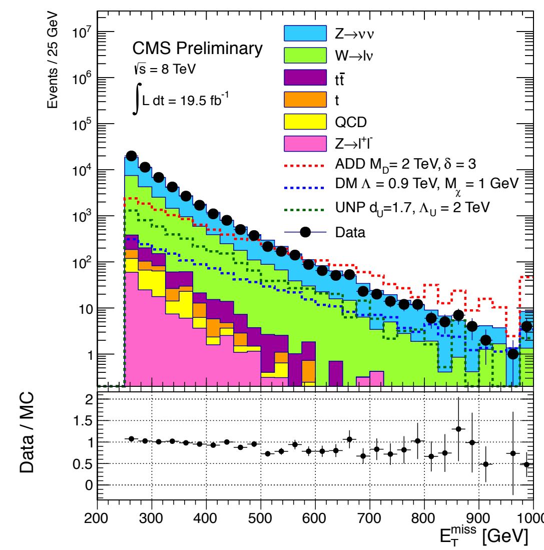
- Leading jet pT distributions is used as control

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

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

Some Terascale gravity models predict reductions of high p_T jet production

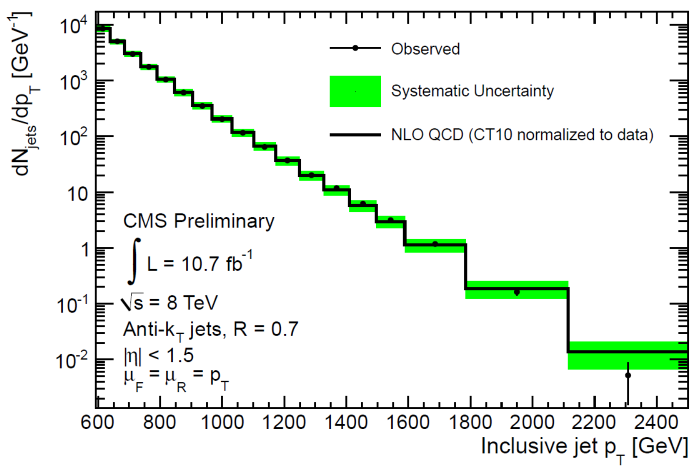
- Look for reduction of high p_T jets relative to QCD predictions

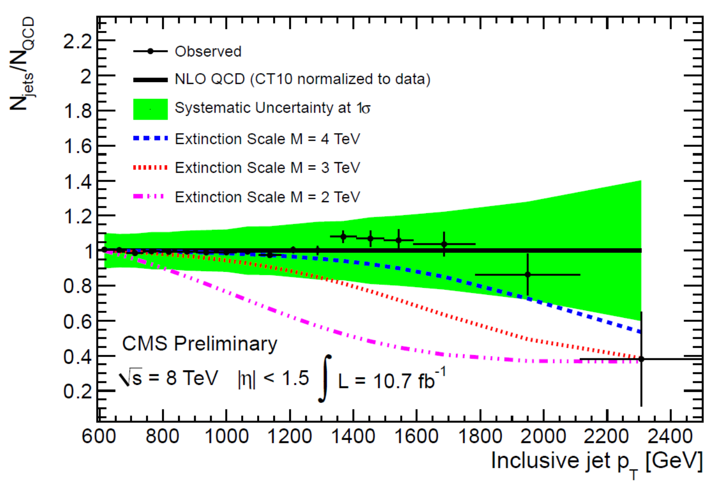
CMS searched in 10 fb^{-1} of 8 TeV collisions

- 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





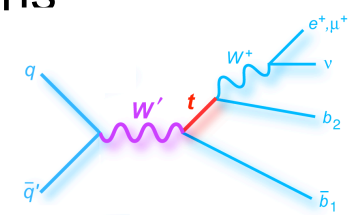
$M > 3.3$ TeV

CMS EXO-12-051

CMS Search for W'→t-bbar

Numerous models predict W' bosons

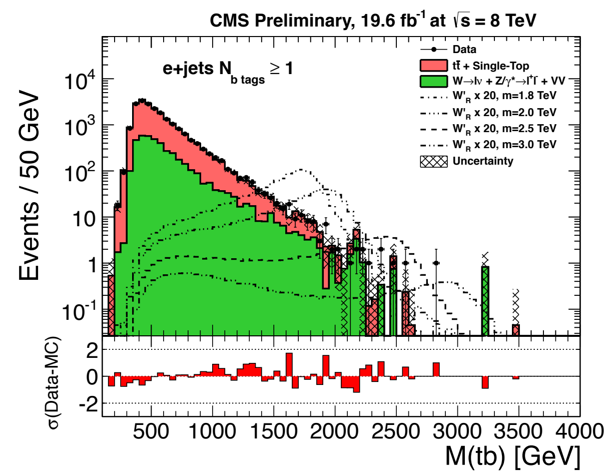
Most sensitive searches look for hadronic decay W'→t-bbar

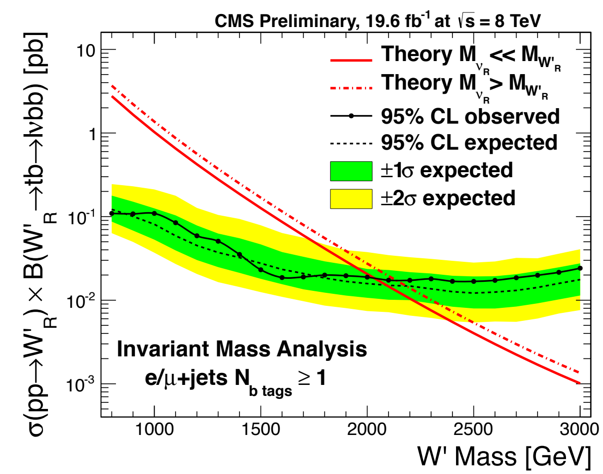


CMS searched in 19.6 fb^{-1} of 8 TeV pp collisions

- 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

$$M_{RH} > 2.03 \text{ TeV}$$





CMS B2G-12-010

ATLAS Search for W'→t-bbar

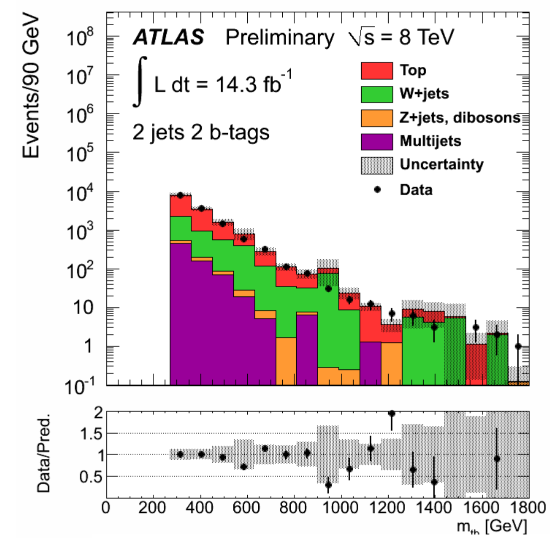
ATLAS has performed similar search in 14.3 fb^{-1} of 8 TeV pp collisions

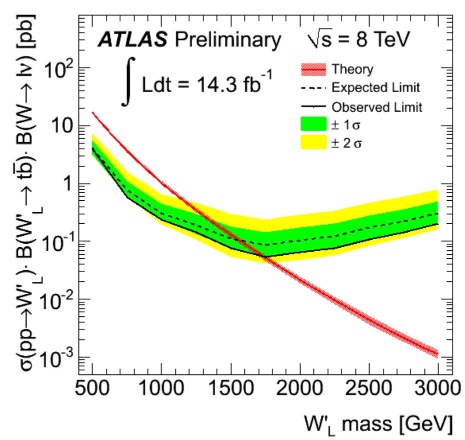
- Require e/μ with p_T>25 GeV and E_T^{miss}>35 GeV
- Require ≥ 2 jets with pT>25 GeV and |η|<2.5
  - At least 1 b-tagged jet
- Use Boosted Decision Tree analysis on 2-jet & 3-jet samples

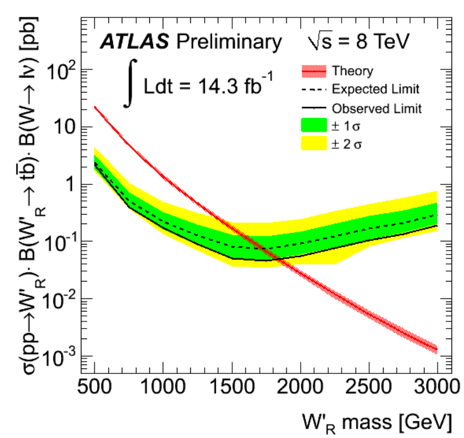
Systematic uncertainties dominated by b-tagging, bkgds

Set Bayesian 95% CL limits

$$M_{LH} > 1.74\ \text{TeV} \quad M_{RH} > 1.84\ \text{TeV}$$

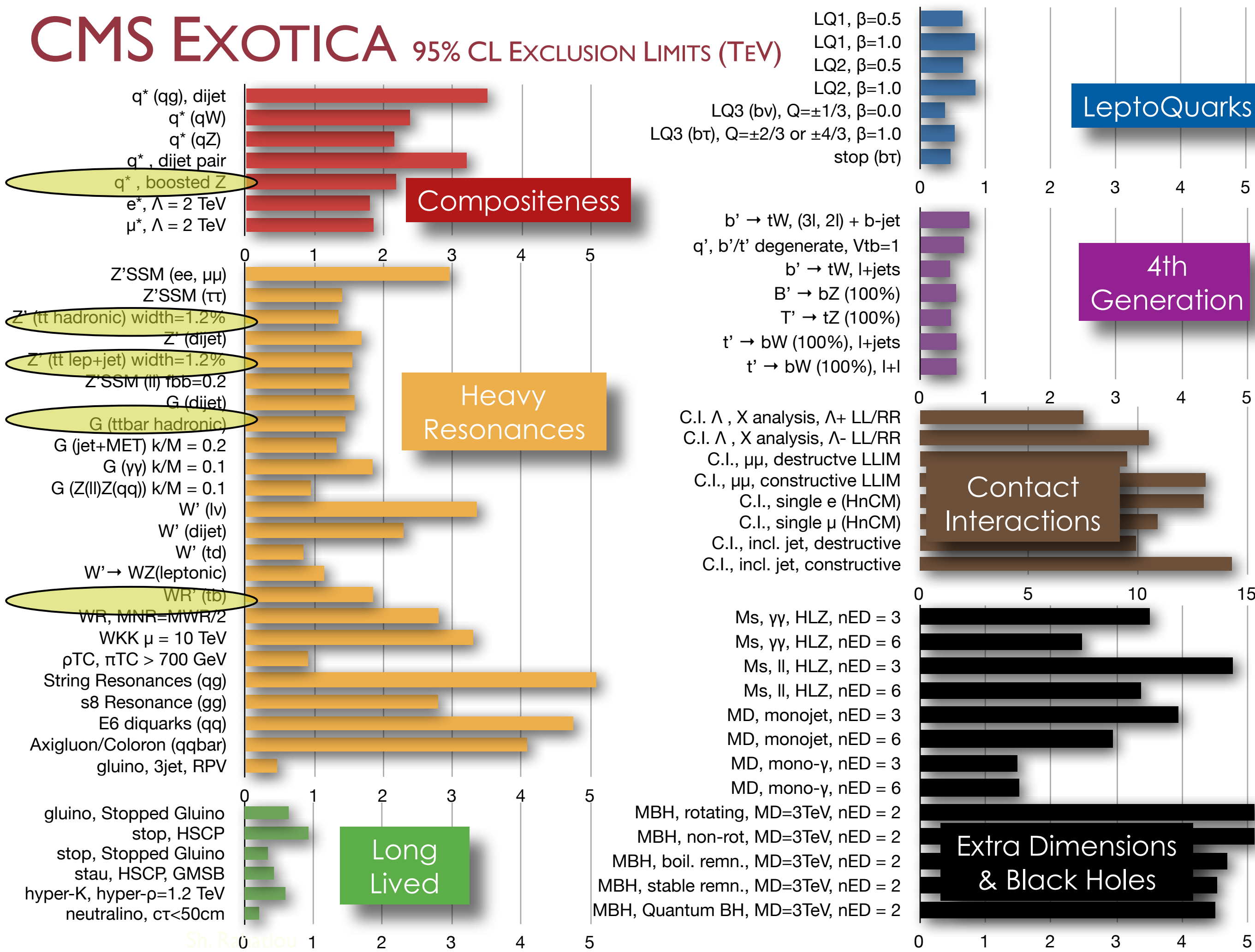




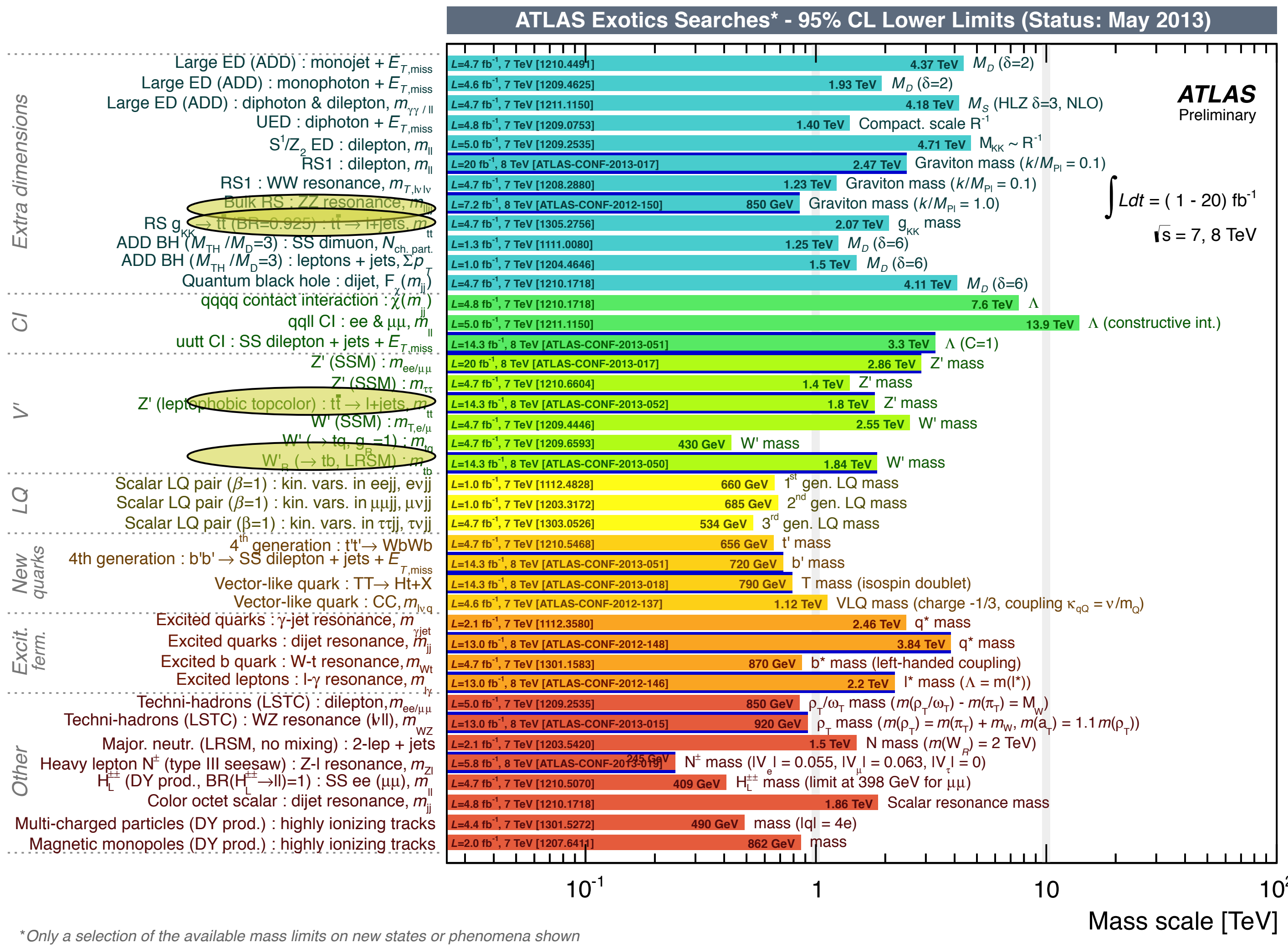


ATLAS-CONF-2013-050

CMS Exotica Summary



ATLAS 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
- See many new results this week

Next step is increase pp energy and L and upgrade detectors

- Coming in 2015!

“Boosted” techniques now maturing

- Studies over last 3 years have validated theoretical predictions
- Top quark ID works, even with high pileup

Next steps will come from similar theory-experiment interaction

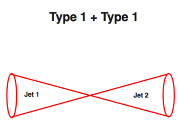
- Push calculations
- Anticipate even higher pileup -- μ ~ 100 interactions/crossing?
- Expect talks this week will move this agenda further

Backup Slides

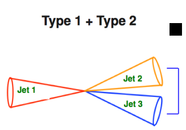
CMS Initial Hadronic Search (I)

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

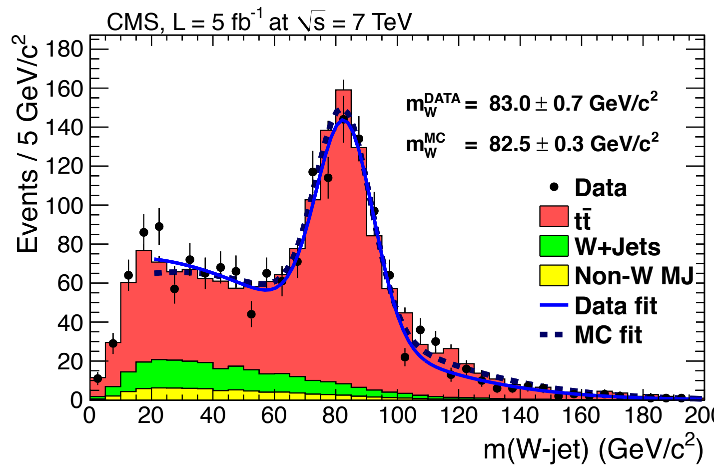


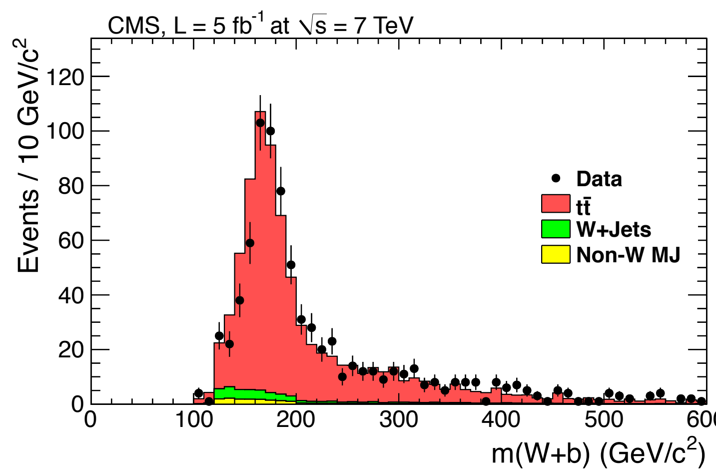
2. Three jets ("1+2")
   - As above, but only one jet satisfying the substructure criteria
   - Recoiling against 2 jets, one with p_T>200 GeV, with 2 sub-jets, m_{jet} consistent with W boson



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

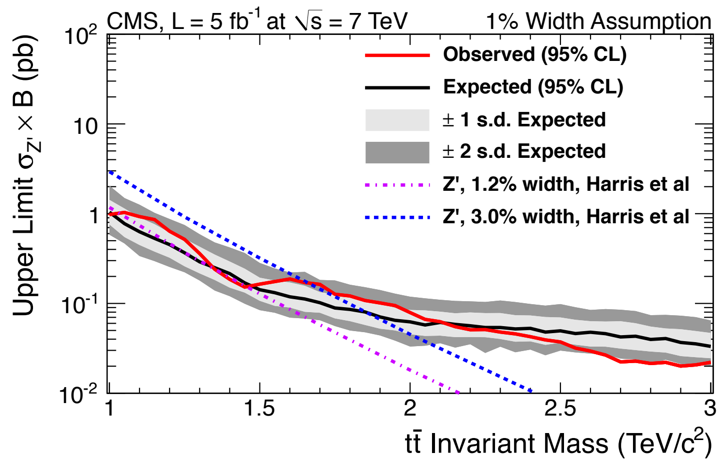
Estimate systematic uncertainties

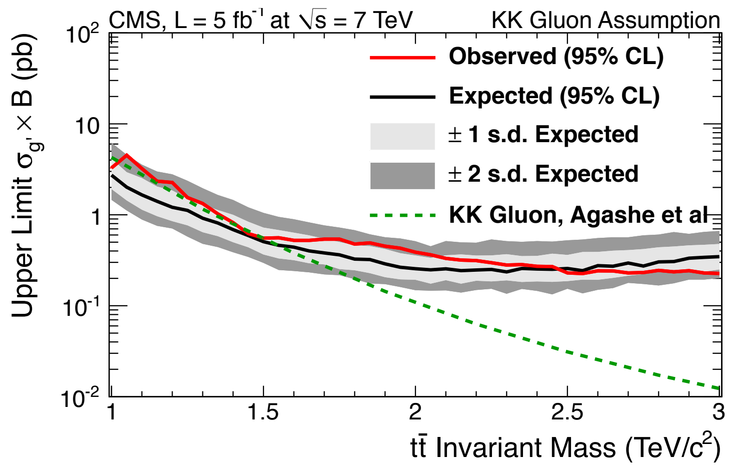
Largest sources are sub-jet efficiency, JES and integrated luminosity at high M_{tt}

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



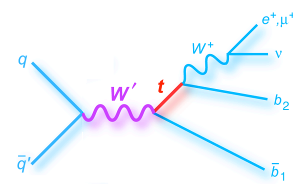


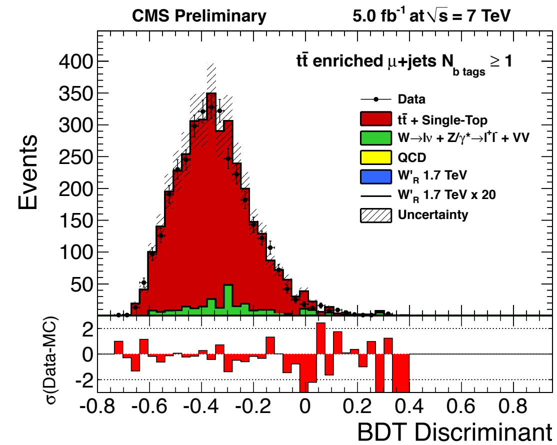
CMS EXO-11-006, JHEP 09 (2012) 029

CMS 7 TeV Search for W'→t-bbar

CMS performed an earlier search for hadronic W' decays

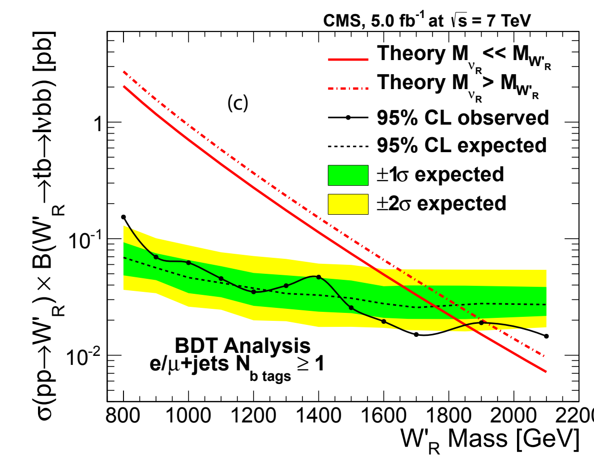
W'→t-bbar





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