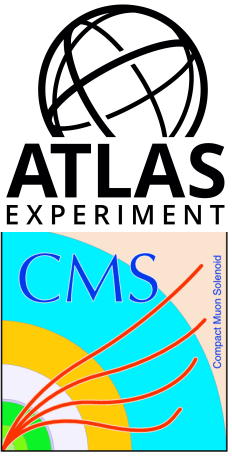

Searches for resonances in the ttbar final state at the LHC with ATLAS and CMS

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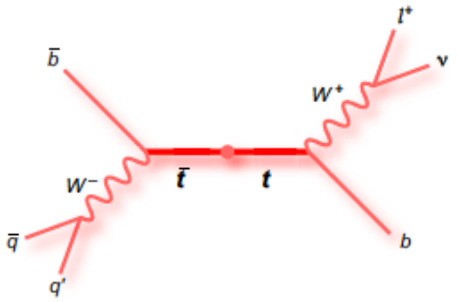
University of Glasgow
On behalf of ATLAS & CMS
CKM16

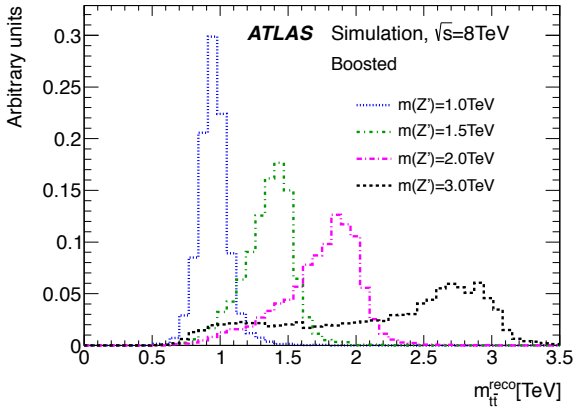
Outline

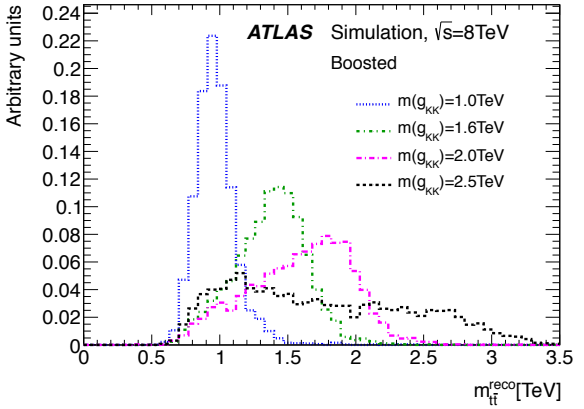
- Introduction
  - Physics
  - Low and high mass topologies
  - backgrounds
- Analyses
  - ATLAS 8TeV resonance searches
  - ATLAS 8TeV search for heavy Higgs updated to include interference
  - CMS 8TeV resonance searches
  - ATLAS & CMS searches at 13TeV
- Projections for the HL-LHC
- Summary

Physics

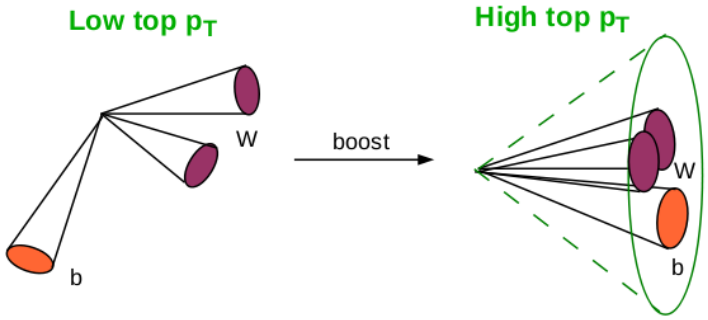
- Many BSM predict high mass particles decaying to ttbar because of its yukawa coupling ~1
- Experiments search for resonances on top of non-resonant standard model backgrounds
  - Analysis is a generic bump-hunt looking for significant deviations from the SM
- Interpret in terms of physics models to establish limits:
  - Techicolour Z' - spin-1 colour singlet
  - Extra dimension models Kaluza-Klein gluons – spin -1 colour octet
  - Extra dimensions Kaluza-Klein gravitons – spin-2 colour singlets
  - Heavy Higgs – spin-0 scalar
- In general interference is not implemented in the models, except for search for heavy Higgs' bosons







A tale of two topologies



- Two topologies: high mass and low mass
- High mass:
  - jets from hadronic decays of highly boosted top quarks merge and are treated as single large-R jets
- Low mass:
  - Match jets to t-decay using χ^2-function
- Lepton isolation is p_t dependent

- Handling Large-R (fat) jets
- Identify jets using anti-k_t algorithm
- Recluster using k_t or Cambridge-Aachen (CA) algorithms to measure jet substructure
- Use substructure within jets to tag as t-jets and/or reject jets not associated with a top
  - τ32 subjettiness: measures whether a jet is well described by 2-subjets or 3-subjets: a value →1 indicated two subjets, lower indicates 3 jets
  - d12, last splitting: large value indicates two high mass jets, small value indicated light quark/gluon jets with radiation.
  - Pairwise jet mass
  - Mass drop

General comments on the analyses

- Search for resonances in non-resonant SM ttbar-mass spectrum
- Backgrounds:
  - SM ttbar
  - W+jets
  - Single top
  - Z+jets
  - QCD
- In general, backgrounds are simulated using MC
- QCD background is significantly reduced by using leptonic decay channels of the top
- QCD background determined from data
  - Both normalisation and shape can be determined
- W+jets normalisation from data

Semi-leptonic channel at 8TeV

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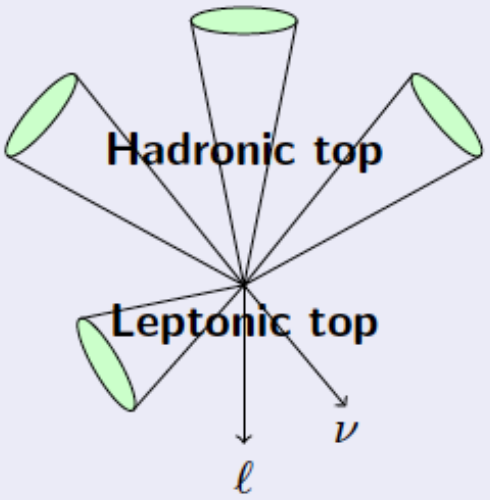
- Exactly one isolated electron or muon with p_t>25GeV
- ET_{miss} > 20GeV and $ET_{miss}+M_{T,W}$ > 60GeV
- ≥ 1 b-tagged jet (anti-kt R=0.4 calorimeter jet)
- Anti-kt R=0.4 jets wth p_t > 25GeV and $|\eta| < 2.5$
- Test even against boosted selection, if not boosted → resolved selection
  - If boosted and resolved → boosted

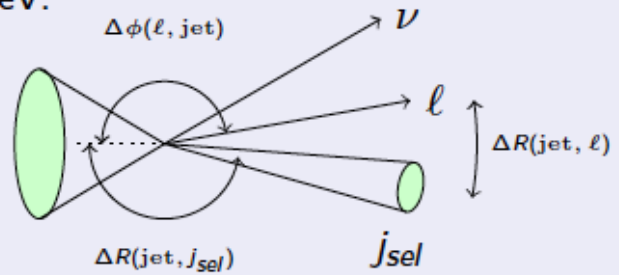
Resolved channel

- ≥ 4 anti-k_t calorimeter $R = 0.4$ jets required.



Boosted channel

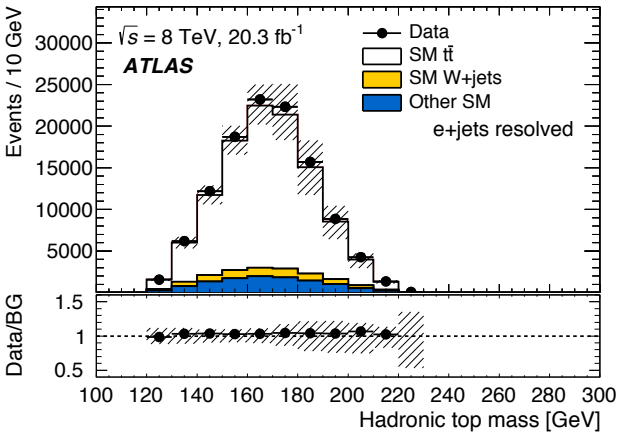
- ≥ 1 anti-k_t calo. $R = 0.4$ jet ($p_T > 25$ GeV) that has $\Delta R(\text{jet}, \ell) < 1.5$ (j_{sel}).
- ≥ 1 top-tagged anti-k_t calo. $R = 1.0$ jet ($p_T > 300$ GeV, $|\eta| < 2.0$) with $\Delta\phi(\ell, \text{jet}) > 2.3$ and $\Delta R(\text{jet}, j_{\text{sel}}) > 1.5$.
- Top-tagging: $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV.



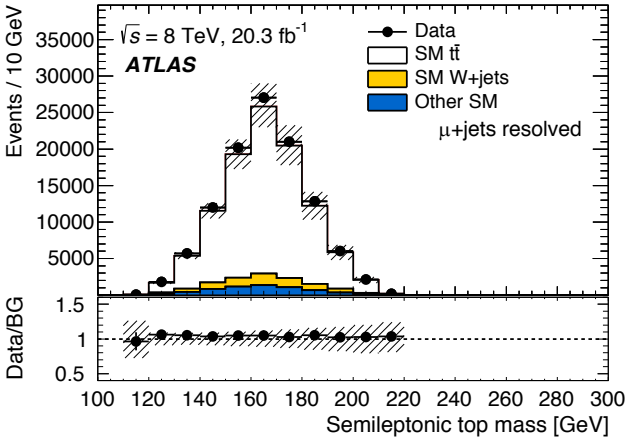
Semi-leptonic channel at 8TeV

- For resolved analysis, assign jets to the t-quarks using χ^2 function

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



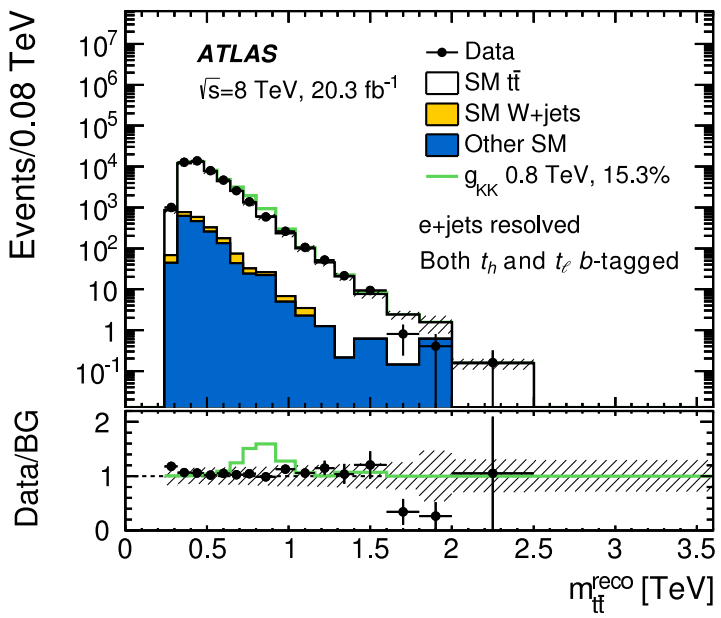
- Principal systematics :
- Common to both boosted and resolved
  - Paron distribution function and luminosity
  - ttbar background normalization
- Boosted channel
  - JES & JMS of large-R jets
  - b-tagging
- Resolved channel
  - JES of small-R jets



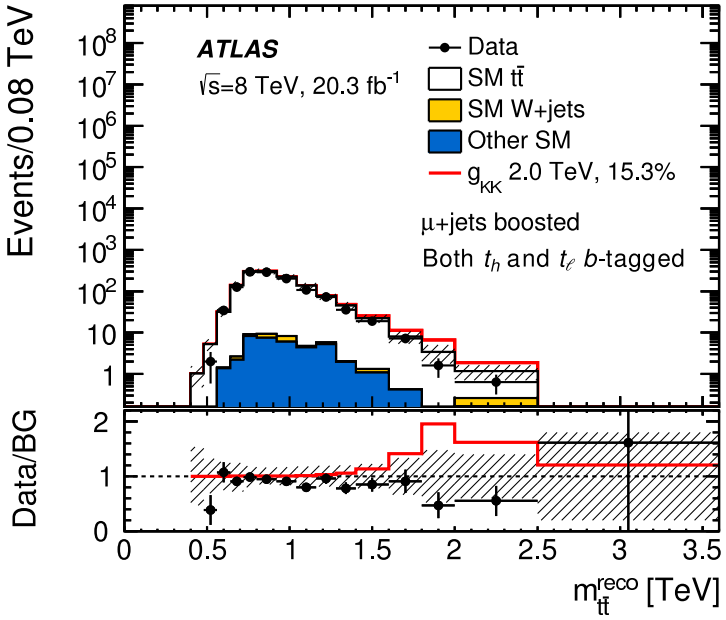
Semi-leptonic channel at 8TeV

- Reconstruct ttbar system mass
  - 3 categories: b-tag matched in dR to: leptonic t, hardonic t, leptonic & hadronic t
- No significant deviation from the standard model is found

Resolved channel

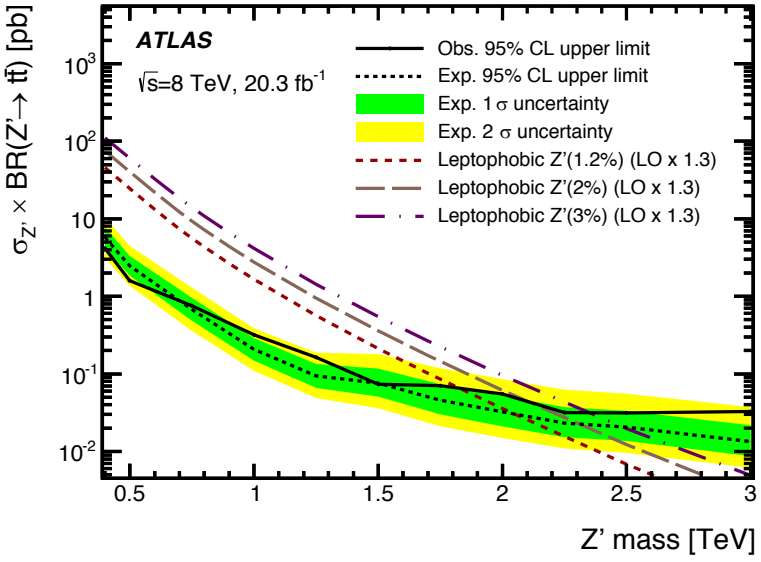


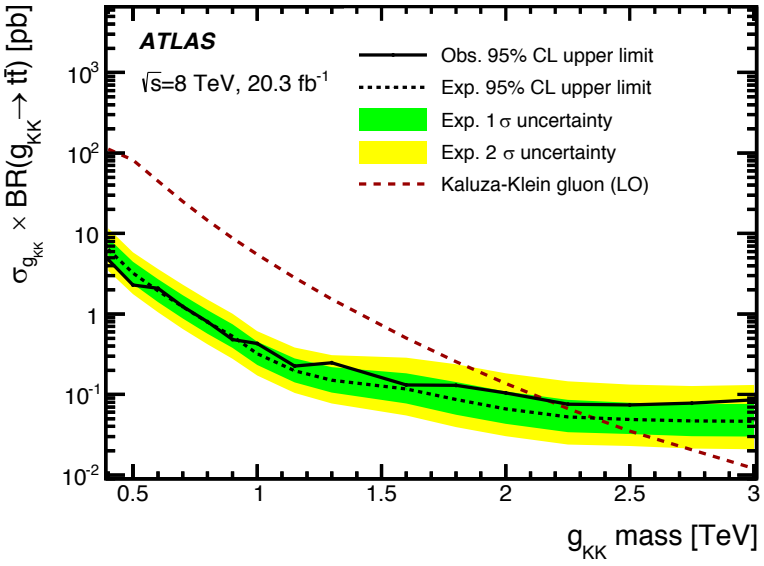
Boosted channel:



Semi-leptonic channel at 8TeV

- No deviations → set limits using models
  - Z'_{TC2} and Bulk RS Kaluza-Klein gluon



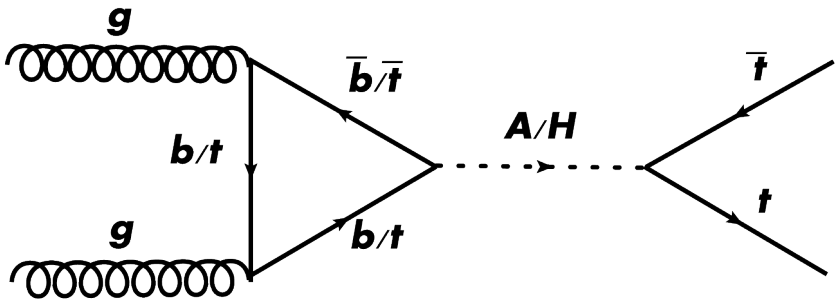


Z'_{TC2} A narrow resonance with mass below 2.0TeV (expected) is excluded

KK-gluon: A broader resonance with mass below 2.3TeV (expected) is excluded

Revisiting the search for heavy scalars: including interference

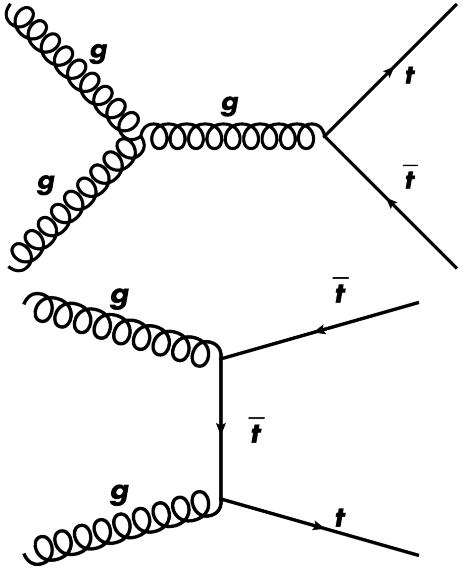
ATLAS-CONF-2016-073



$Signal\ (S)$

+

SM

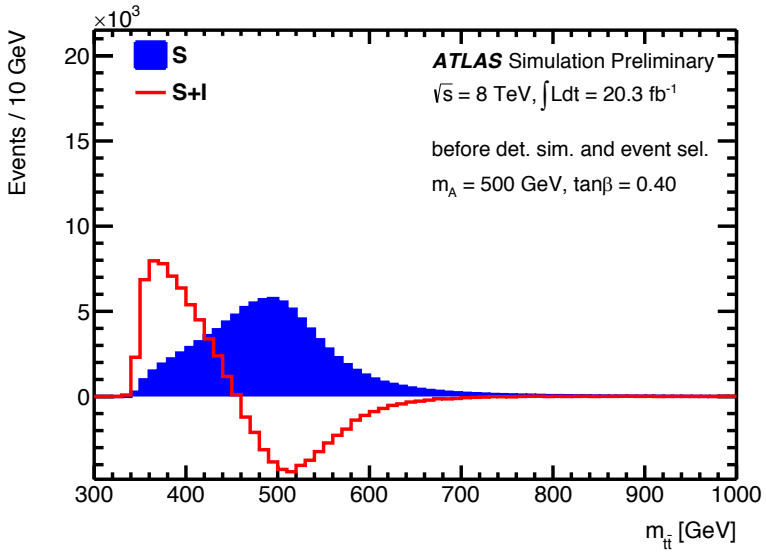


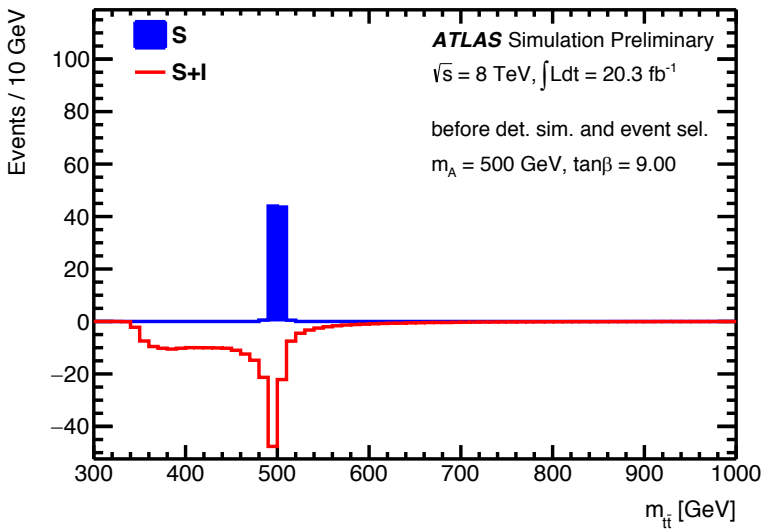
$Background\ (B)$

- Interference between gluon initiated signal and background
- Previous analyses assume no interference, but processes with gluon initial state will interfere with SM top production
- New analysis reinterprets in terms of 2HDM type-II H/A->ttbar
- Probe mass range 400<M<800 GeV and low tanβ
  - Events are tested against boosted and resolved categories, if both treat as resolved

Effect of interference

- Modify Madgraph5_aMC@NLO to generate events without SM ttbar background i.e. generate signal+interference only
  - Keep good description of background at NLO (Powheg+Pythia)
  - Efficient generation
  - Cross check with full S+I+B generation

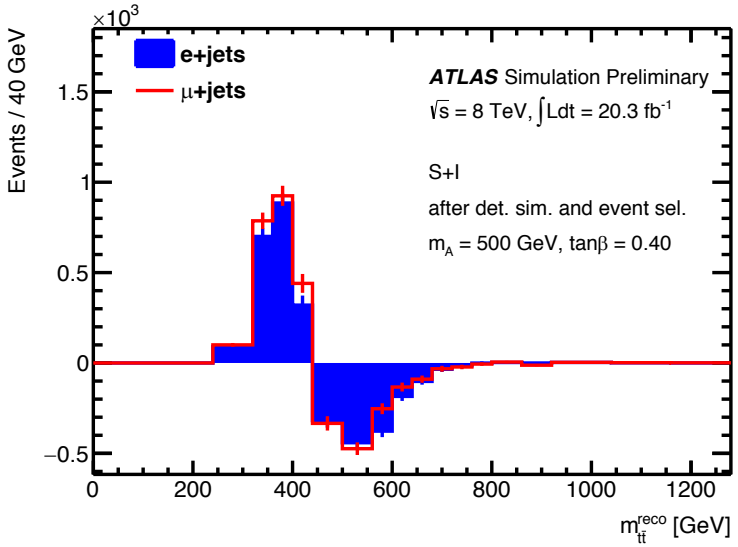


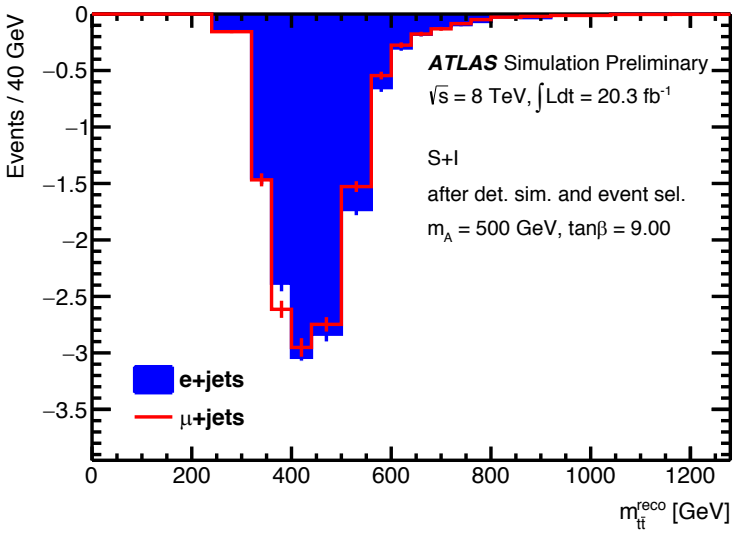


Parton level simulation

Effect of interference

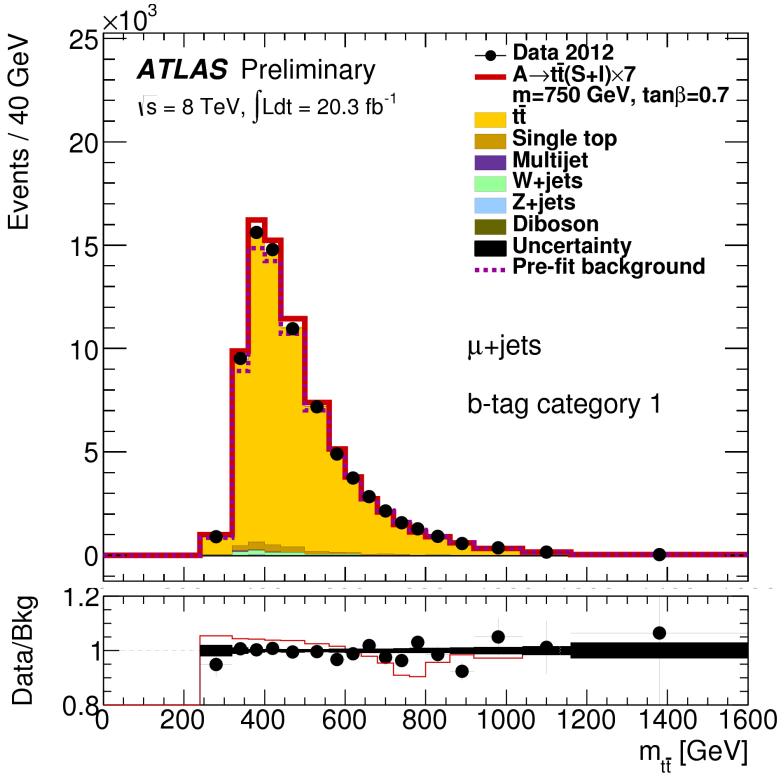
- S+I for e and μ channels after reconstruction and event selection
- Effect of interference remains but distorted relative to parton level.
  - In some cases strong or even completely negative component

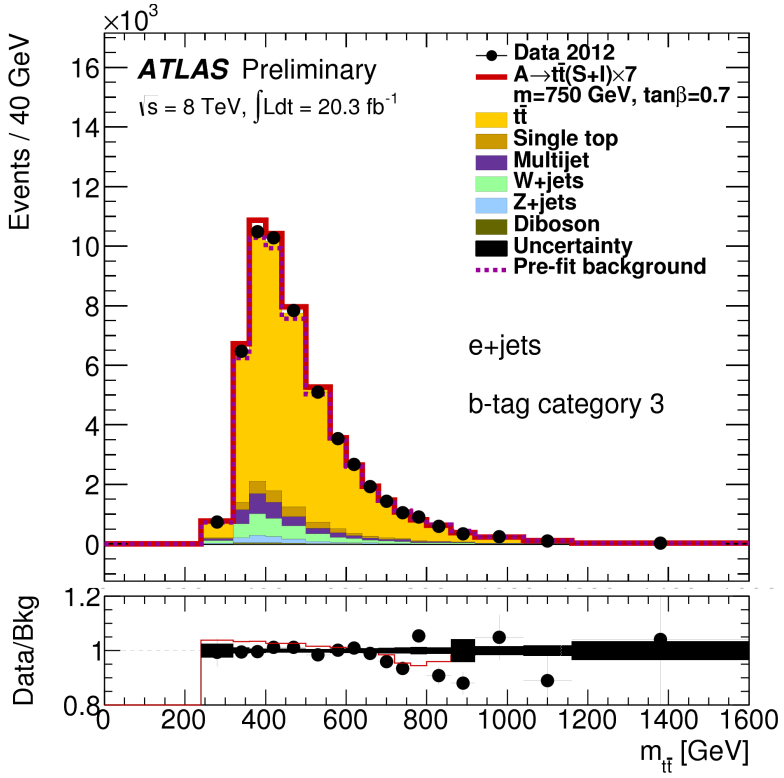




Interference

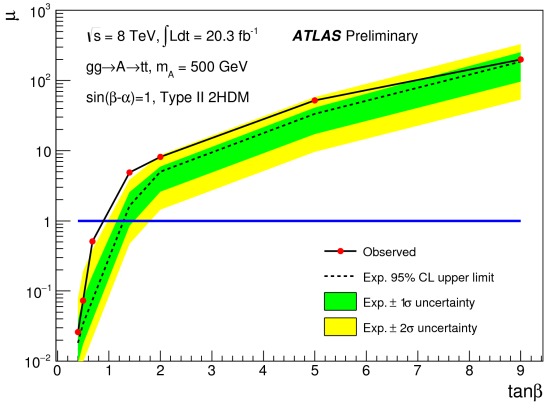
- Add signal+interference to Powheg+Pythia ttbar SM background
- No deviation from SM observed
- Set limits on Scalar model



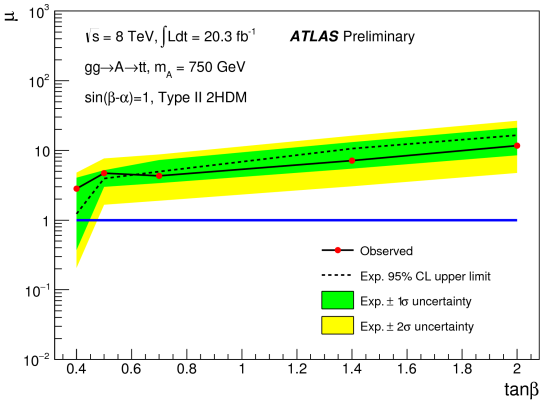


Scalar limits

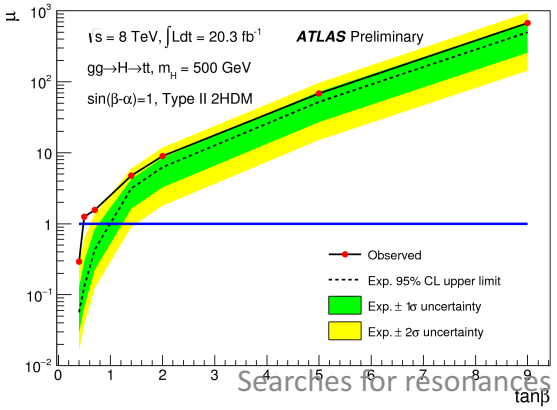
- Limits are set parameterising S+I and S as function of $\sqrt{\mu}$
  - $\mu S + \sqrt{\mu}\, I + B = \sqrt{\mu}(S + I) + (\mu - \sqrt{\mu})S + B$
  - (μ=1 for 2HDM type II)

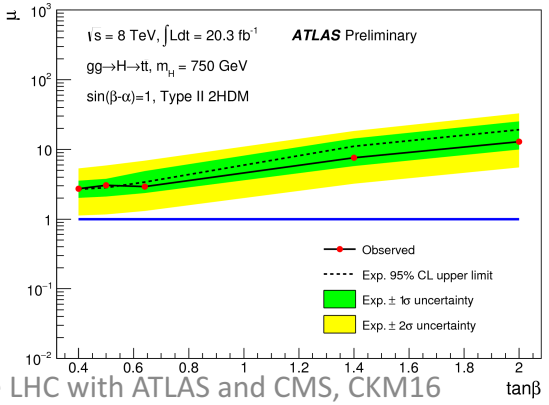


$M_{H/A}$=500GeV
Excluded region for pseudoscalar: tanβ<0.85
For scalar tanβ<0.45



No limit on tanβ for $M_{H/A}$=750GeV

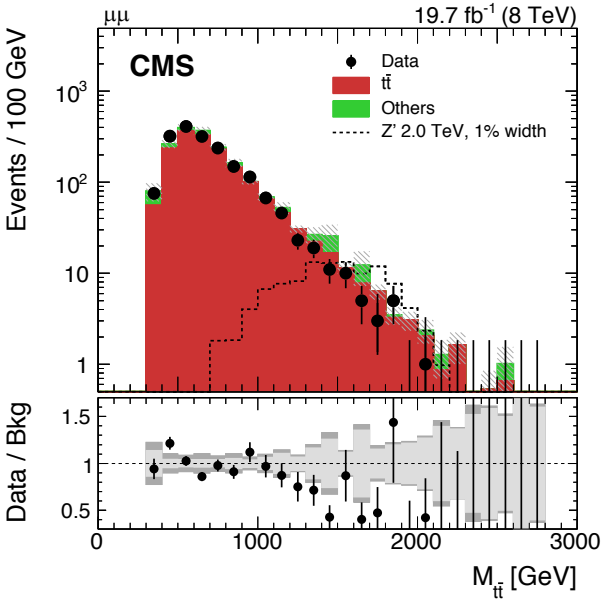


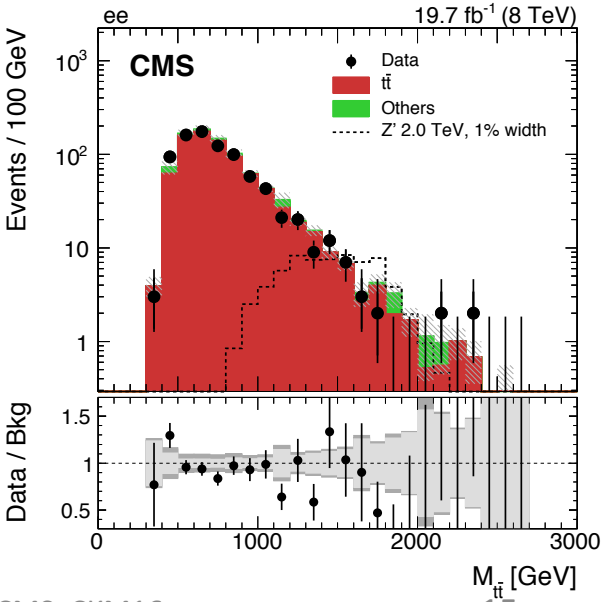


Di-leptonic analysis at 8TeV

Phys. Rev. D 93 (2016) 012001

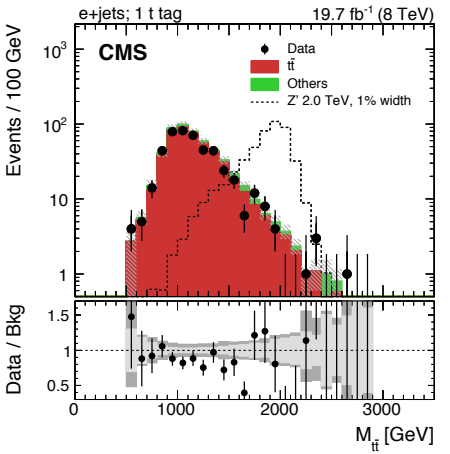
- 2 opposite charged leptons
  - No isolation
  - ee: p_t>85 GeV & 20GeV $|\eta|$<2.5
  - eμ: p_t^m>45GeV $|\eta|$<2.1 & p_t^e>20GeV $|\eta|$<2.5
  - μμ: p_t>45GeV $|\eta|$<2.1 & 20GeV $|\eta|$<2.4
- ≥ 2 Anti-kt R=0.5 (AK5) jets
- Lepton isolation
  - $\Delta R(l,jet)>0.5$ or $\Delta p_t^{rel}(l,jet)>15GeV$
  - $\Delta R(l^{leading},jet)<1.2$ and $\Delta R(l^{subleading},jet)<1.5$
- E_T-miss > 30GeV
  - Veto Z+jet & multi-jet backgrounds
- Approximate M_{ttbar} reconstructed
  - Assign E_T-miss to total E_T-miss of neutrinos
  - p_z of neutrino = 0

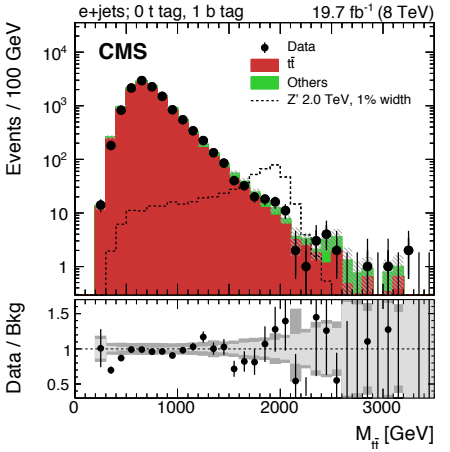


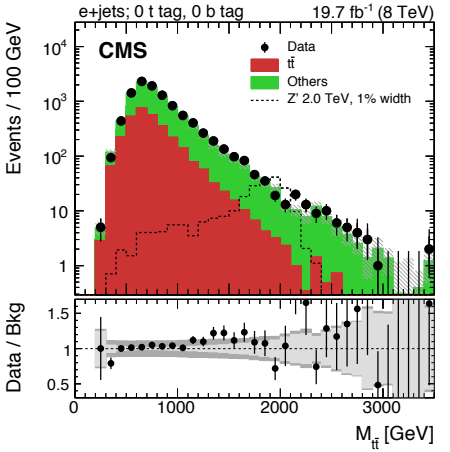


Semi-leptonic at 8TeV

- Exactly 1 electron or muon
  - Avoid overlap with dilepton channel
  - p_t^{μ}>45GeV $|\eta|$<2.1 or p_t^{e}>35GeV $|\eta|$<2.5
- ≥ 2 jets
  - $p_t^{leading}$>150GeV and $p_t^{subleading}$>50GeV
  - AK5 and Cambridge-Aachen jets with R=0.8 (CA8) for boosted top-quark decays
  - Events with ≥ 2 CA R=0.8 jets are rejected to prevent overlap with all-hadronic analysis
- Lepton isolation
  - $\Delta R(l,jet)>0.5$ or $\Delta p_t^{rel}(l,jet)>25GeV$
- E_T-miss > 50GeV
  - Multi-jet backgrounds
- M_{ttbar} reconstructed
  - Minimise $\chi 2(M_{tl}, M_{th}, M_W, pt_{tt})$ to select and assign correct jets
  - If event has a single CA8 t-tagged, this is taken as the hadronic jet
- Split into different tagging categories for each lepton flavour
  - 1 CA8 t-tagged jet
  - 0 CA8 t-tagged jet, 1 b-tagged jet
  - 0 CA8 t-tagged jet, 0 b-tagged jets



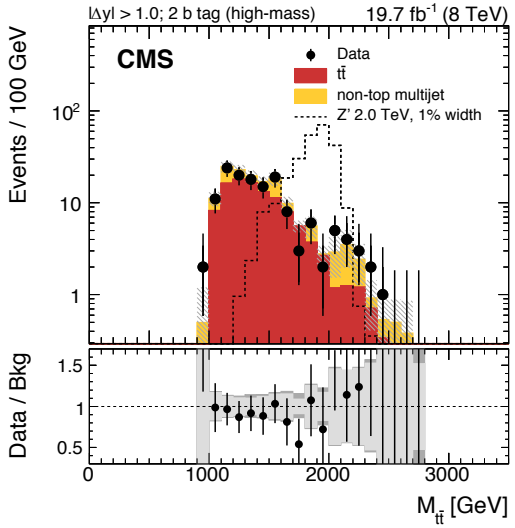


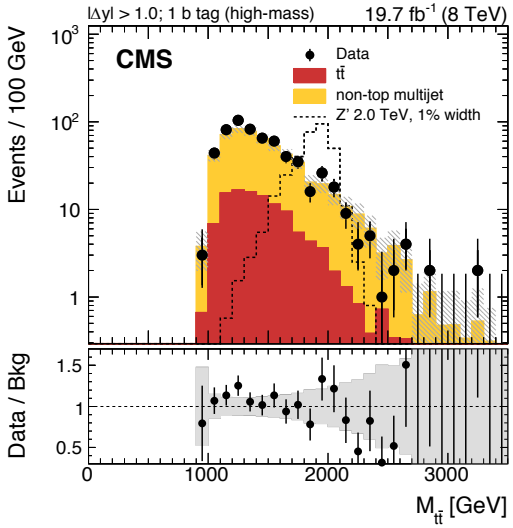


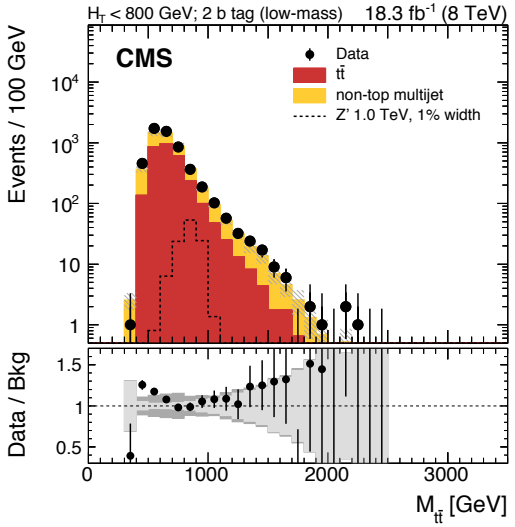
All-hadronic at 8TeV

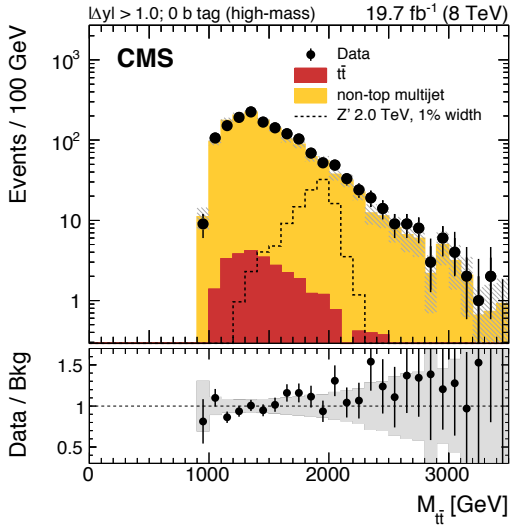
- Determine if high mass, if not treat as low mass event
- High mass
  - 2CA8 jets t-tagged p_t>400GeV, $|\eta|$<2.4, $\Delta\phi$ < 2.1
  - Consider two regions: $\Delta|y|$<1.0 and $\Delta|y|$>1.0 (dominated by multi-jets)
- Low mass
  - 2CA15 jets t-tagged p_t>200GeV
  - Split in $H_T=\Sigma|p_T|$<800GeV and H_T>800GeV
- Multi-jet background calculated from data
- Categorised according to number of b-tagged sub-jets

All-hadronic at 8TeV



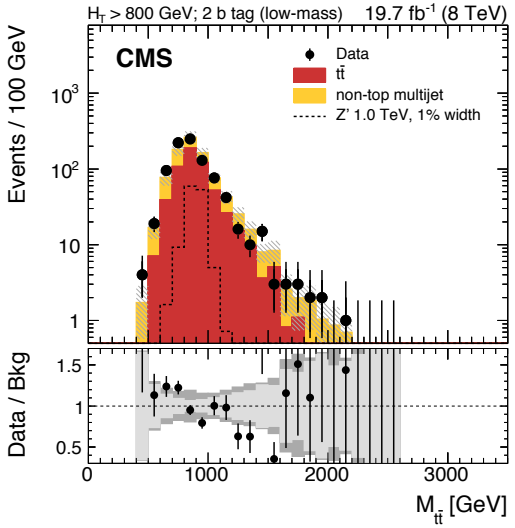






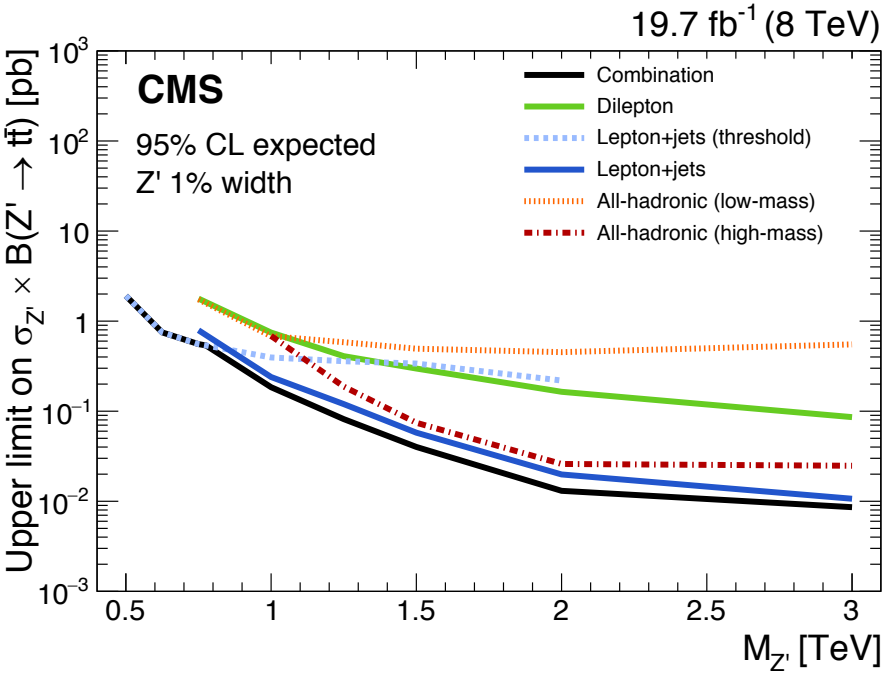
High mass

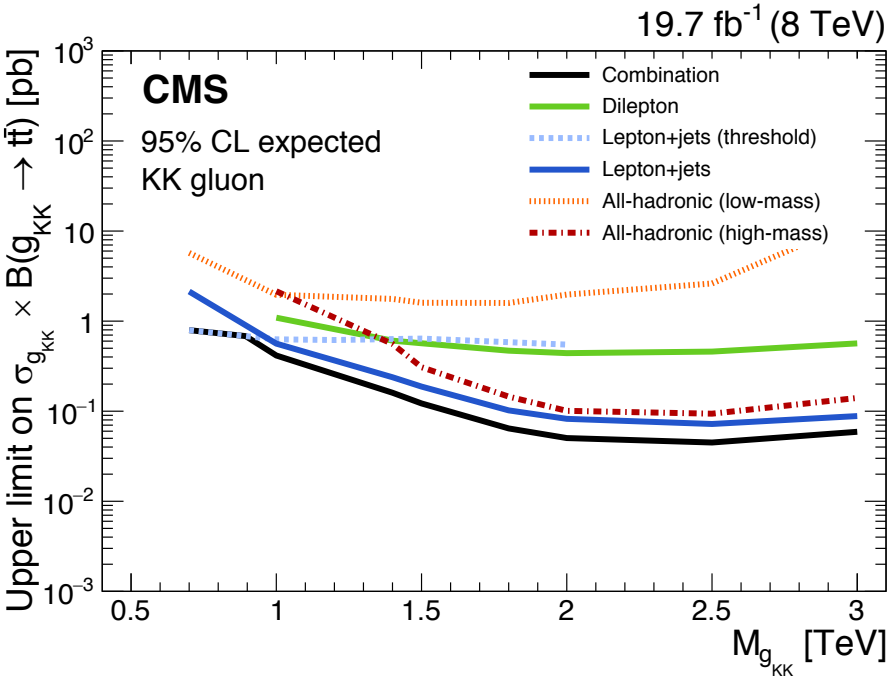
No significant deviations from standard model observed



Low mass

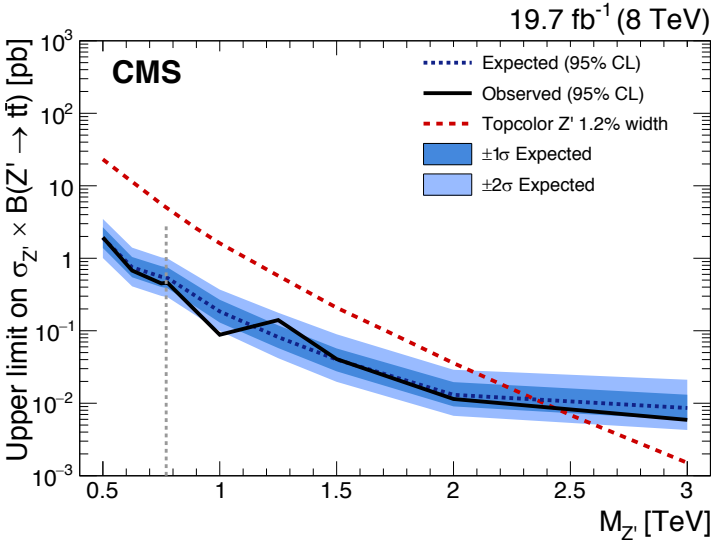
Results at 8TeV

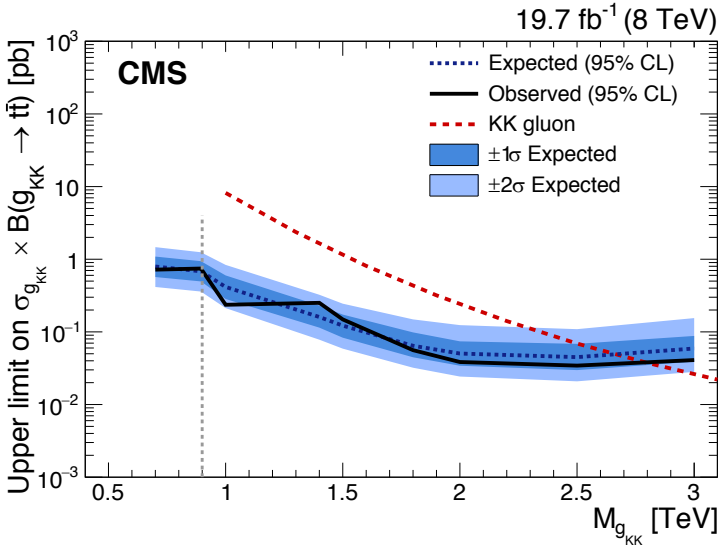


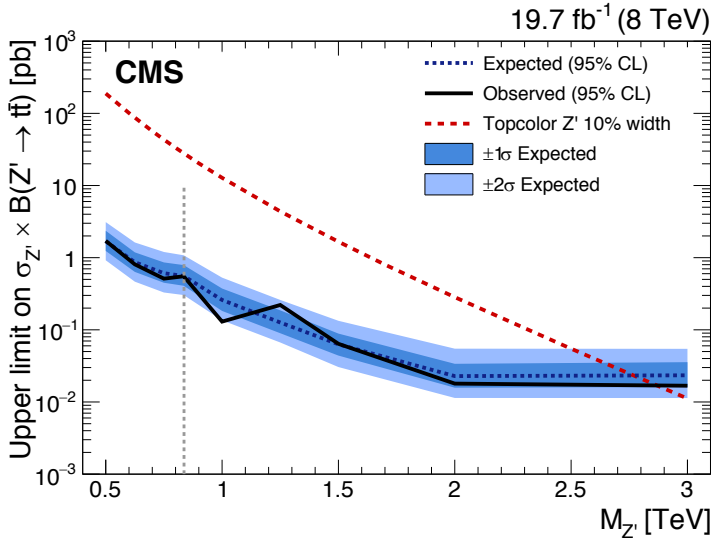


95% CL upper limits on cross-section X branching ratio for Z’ and KK gluon

Combined Results at 8TeV



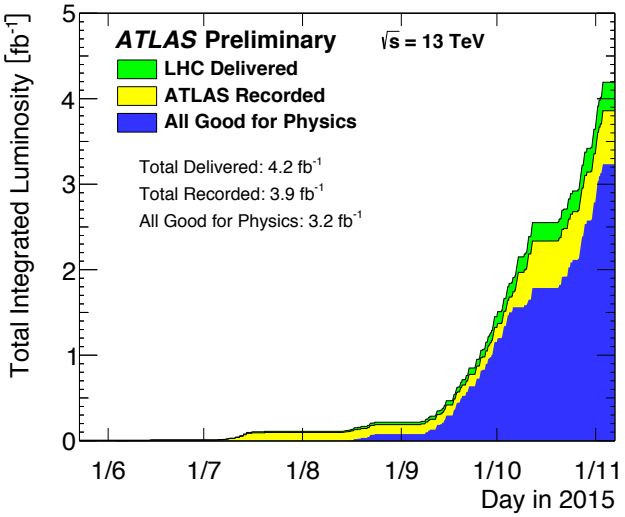


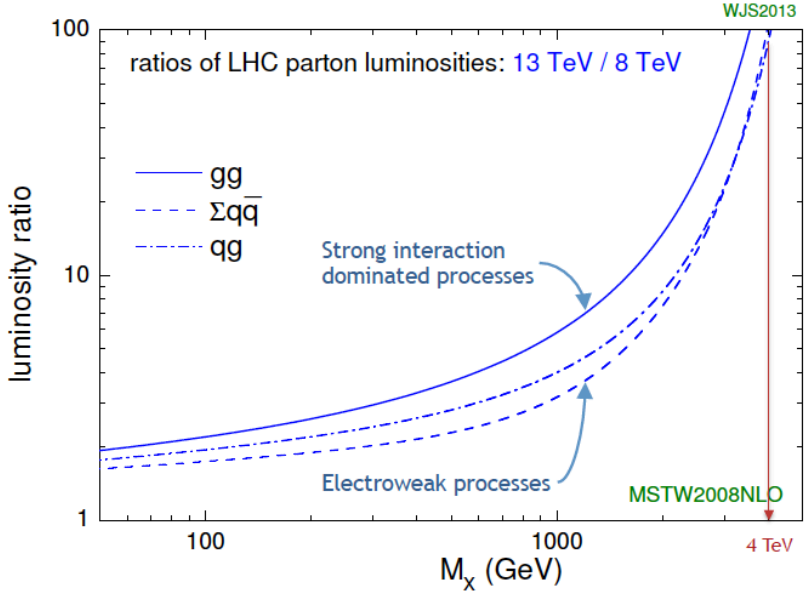


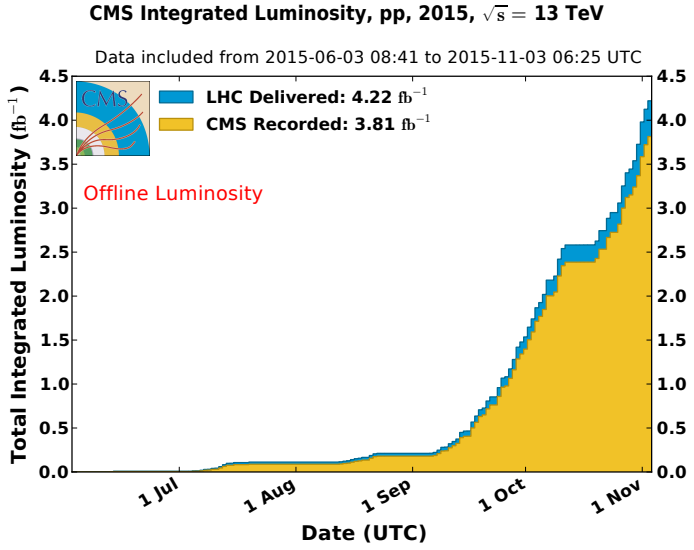
	Mass limit [TeV]							
	Dilepton channel		Lepton+jets channel		All-hadronic channels		Combined	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	1.4	1.5	2.2	2.3	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.1	2.2	2.7	2.8	2.5	2.5	2.8	2.9
RS KK gluon	1.8	2.0	2.5	2.5	2.4	2.3	2.7	2.8

Run-2 at 13TeV

- 2015 very successful for rebooting LHC at 13TeV, and ATLAS & CMS after long shutdowns
  - 2016 luminosities:
    ATLAS: 36fb^{-1}
    CMS:32.87fb^{-1} (preliminary)
- Significant increase in parton luminosity of heavy particles
  - >10 increase for ~3TeV mass object



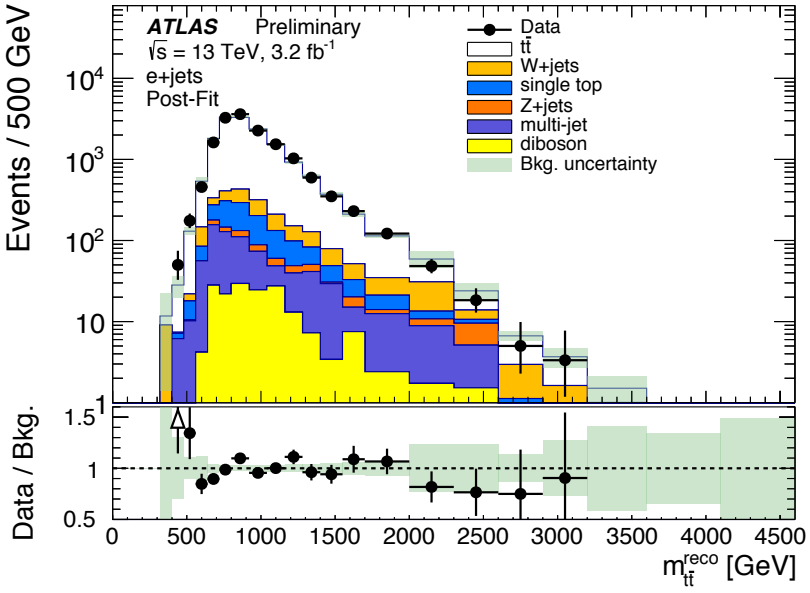


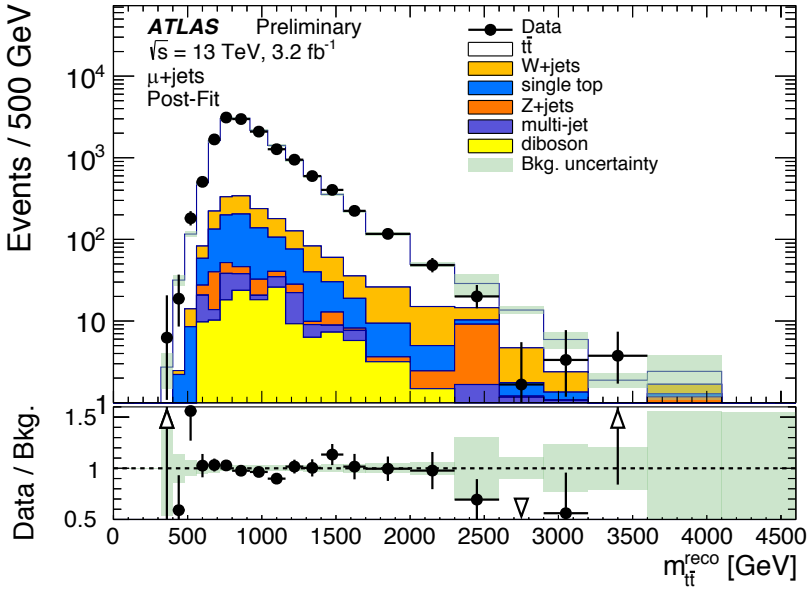


Semi-leptonic channel at 13TeV

ATLAS-CONF-2016-014

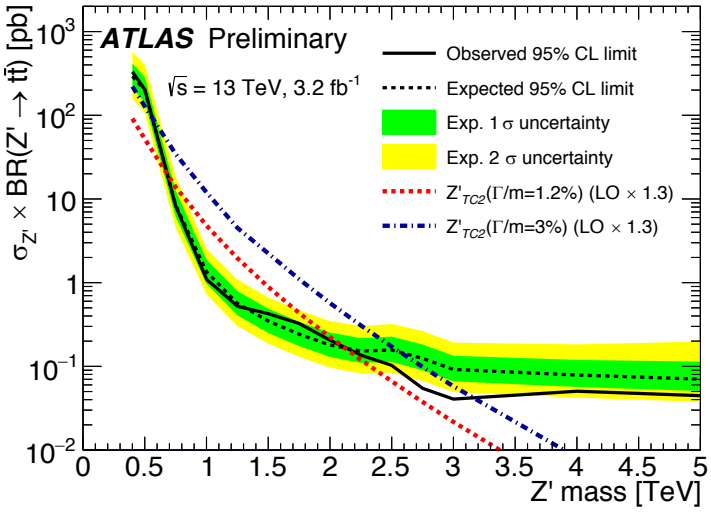
- Focus on highly boosted top quarks with 3.2fb^{-1} at 13TeV (2015 data)
- Similar analysis to 8TeV
  - Improved b-tagging
  - Use Anti-kt R=0.2 track jets as higher efficiency at heavier masses





Semi-leptonic channel at 13TeV

	e+jets	μ+jets
$t\bar{t}$	3000 ± 700	3000 ± 700
W+jets	200 ± 140	200 ± 40
Single top	190 ± 40	180 ± 40
Z+jets	33 ± 12	26 ± 12
Multi-jet	130 ± 70	19 ± 11
Diboson	46 ± 11	37 ± 8
Total	3700 ± 800	3400 ± 800
Data	3352	3074

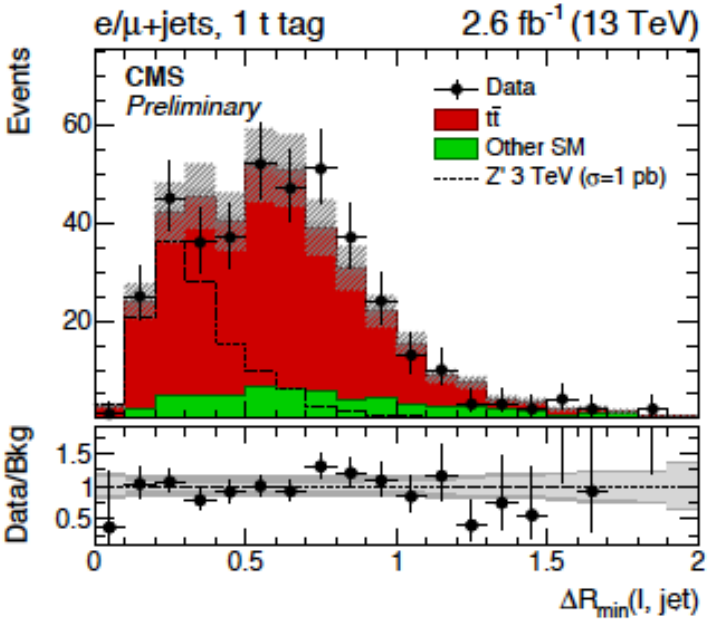


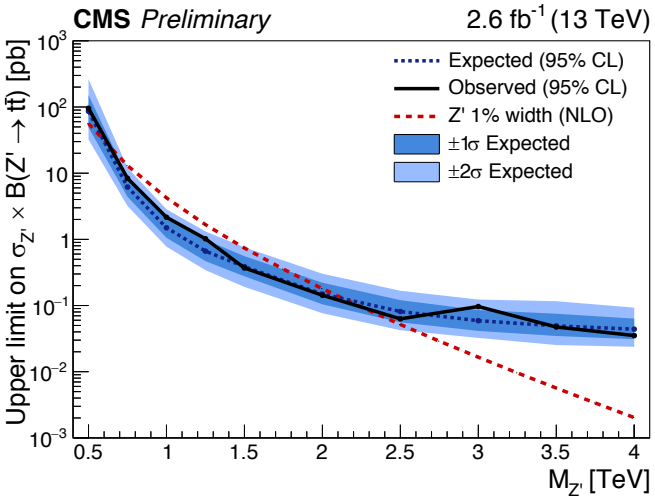
- No significant deviations from SM found
- Use Z'_{TC2} to set limits
  - $\Gamma/M_{Z'}$ =1.2%: 0.7TeV < M < 2.1TeV expected
    (0.7TeV < M < 2.0TeV observed)
  - $\Gamma/M_{Z'}$ =3%: 0.7TeV < M < 2.5TeV expected
    (0.7TeV < M < 3.2 TeV observed)

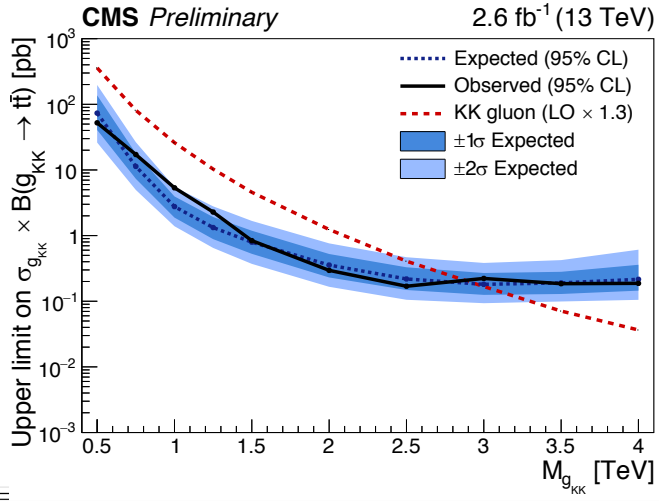
Semi-leptonic channel at 13TeV

CMS-PAS-B2G-15-002

- 2.6fb^{-1} (2015 data)
- Highly boosted analysis to focus on high Mtt
- No significant deviation from SM is found





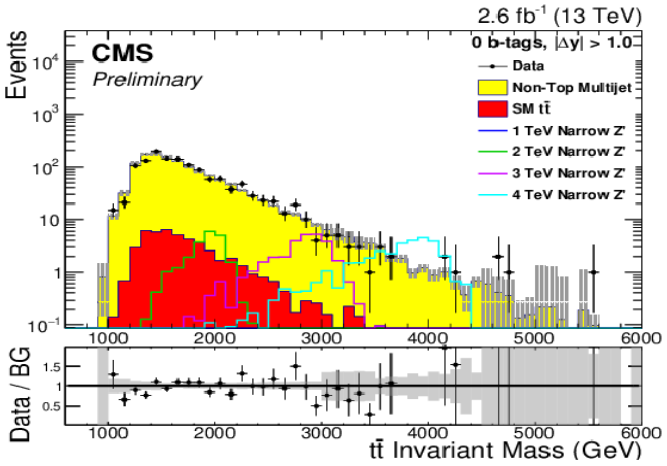


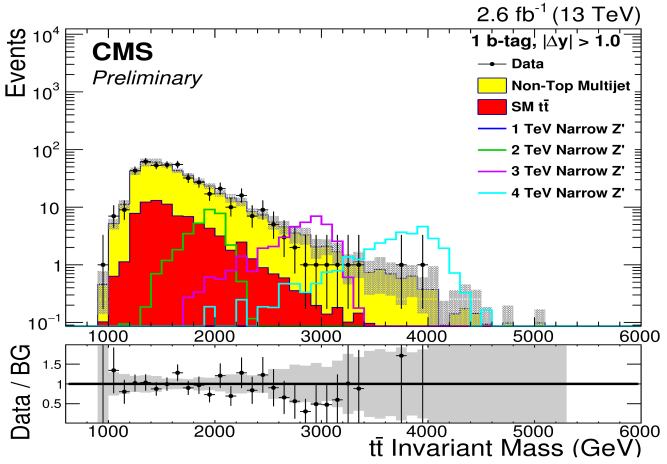
signal	excluded mass regions [TeV]		
	μ + jets observed (expected)	e + jets observed (expected)	combination observed (expected)
Z' (1% width)	0.5 – 1.8 (0.6 – 1.9)	1.0 – 1.1, 1.3 – 2.2 (0.9 – 1.7)	0.6 – 2.3 (0.6 – 2.1)
Z' (10% width)	0.5 – 3.2 (0.5 – 3.3)	0.5 – 3.2 (0.5 – 3.2)	0.5 – 3.4 (0.5 – 3.5)
Z' (30% width)	0.5 – 3.9 (0.5 – 4.0)	0.5 – 3.8 (0.5 – 3.8)	0.5 – 4.0 (0.5 – 4.0)
KK gluon	0.5 – 2.7 (0.5 – 2.8)	0.6 – 2.7 (0.6 – 2.5)	0.5 – 2.9 (0.5 – 2.9)

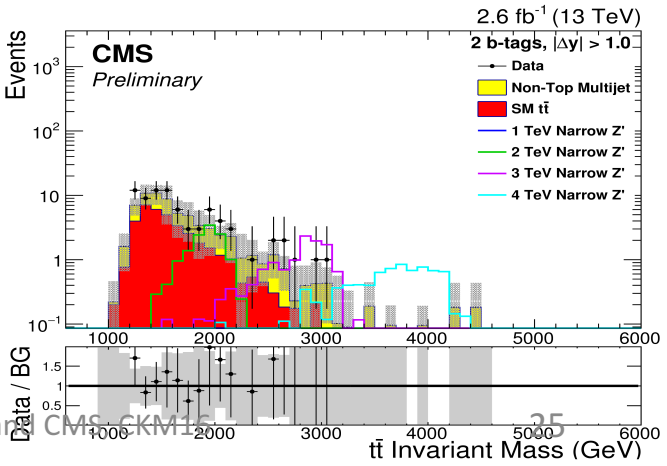
All-hadronic channel at 13TeV

CMS-PAS-B2G-15-003

- All-hadronic final state
- Identify two large-R jets (Anti-kt R=0.8) as top candidates
- Tag t-quark jets using
- Event categories:
  - 0,1,2-b-tags
  - $\Delta\eta(j_1,j_2)>0.1$ and $\Delta y(j_1,j_2)<0.1$

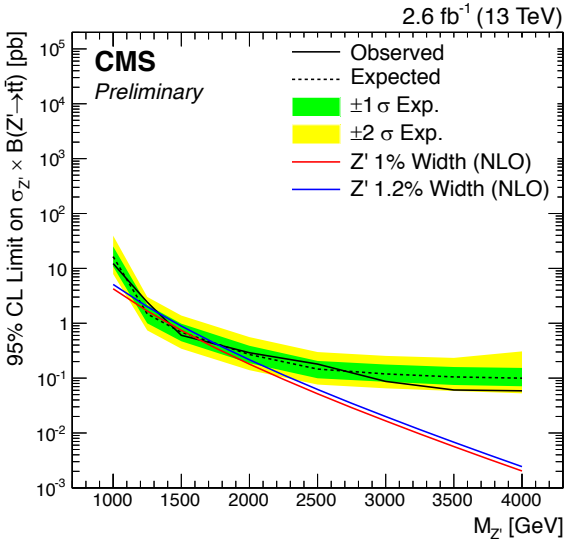


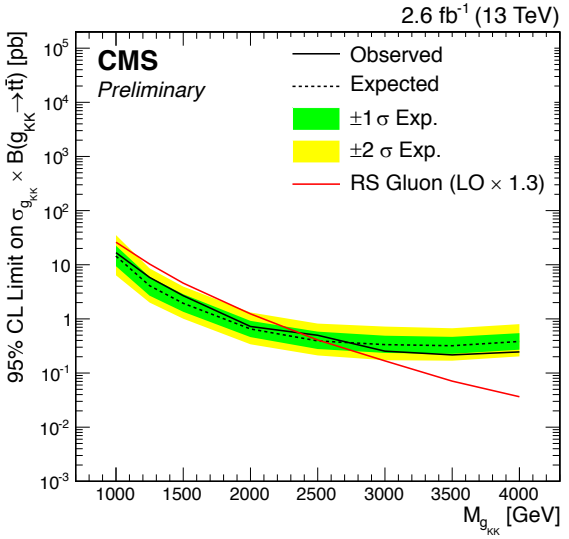




CMS 13TeV: all-hadronic

- No significant deviations from SM found
- Set limits for Z'_{TC2} and KK-gluon

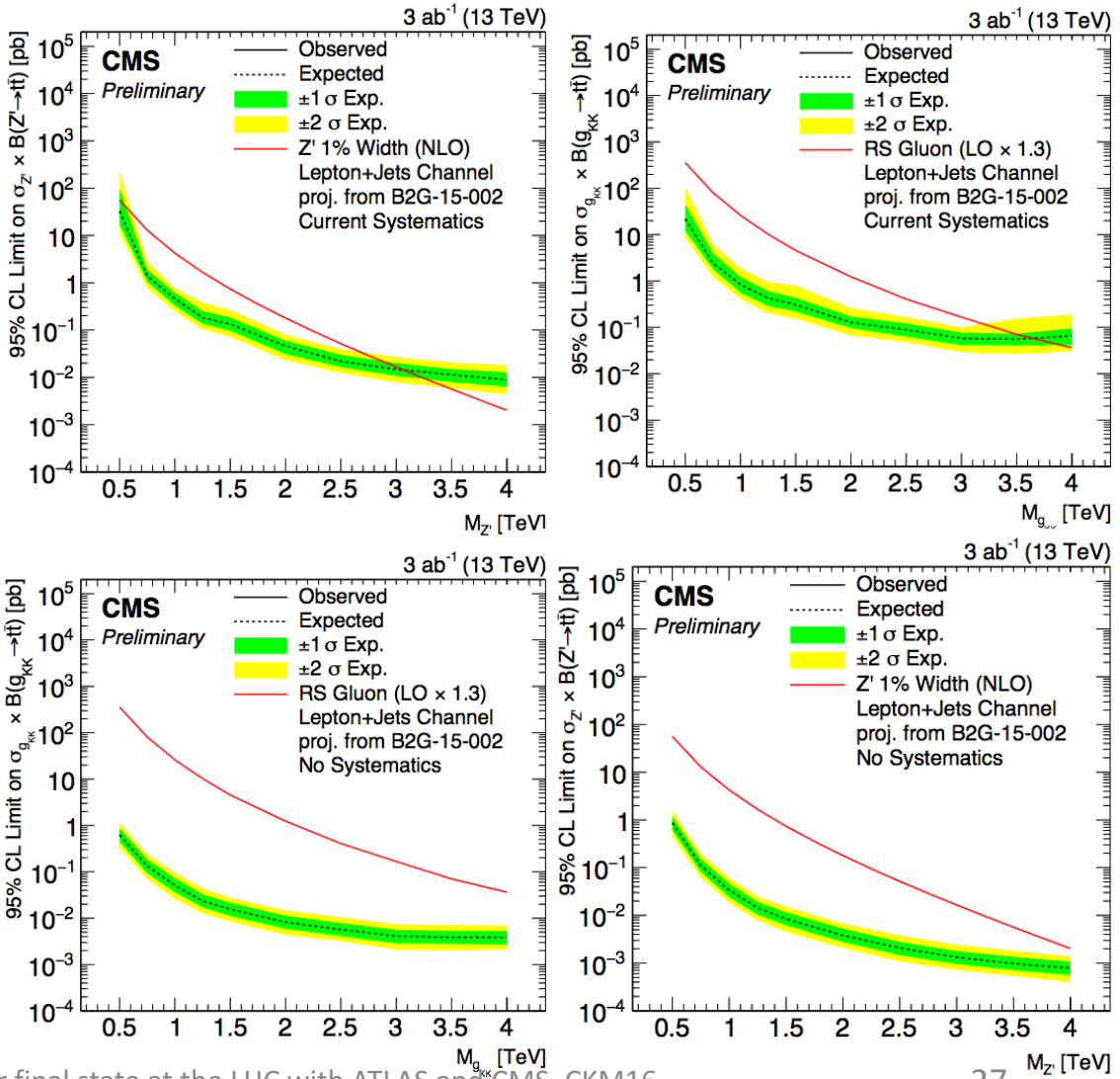




Signal Model	Exclusion Ranges (TeV)	
	Expected	Observed
Z′ (1% Width)	1.2 – 1.6	1.4 – 1.6
Z′ (10% Width)	1.0 – 3.1	1.0 – 3.3
Z′ (30% Width)	1.0 – 3.7	1.0 – 3.8
RS Gluon	1.0 – 2.5	1 – 2.4

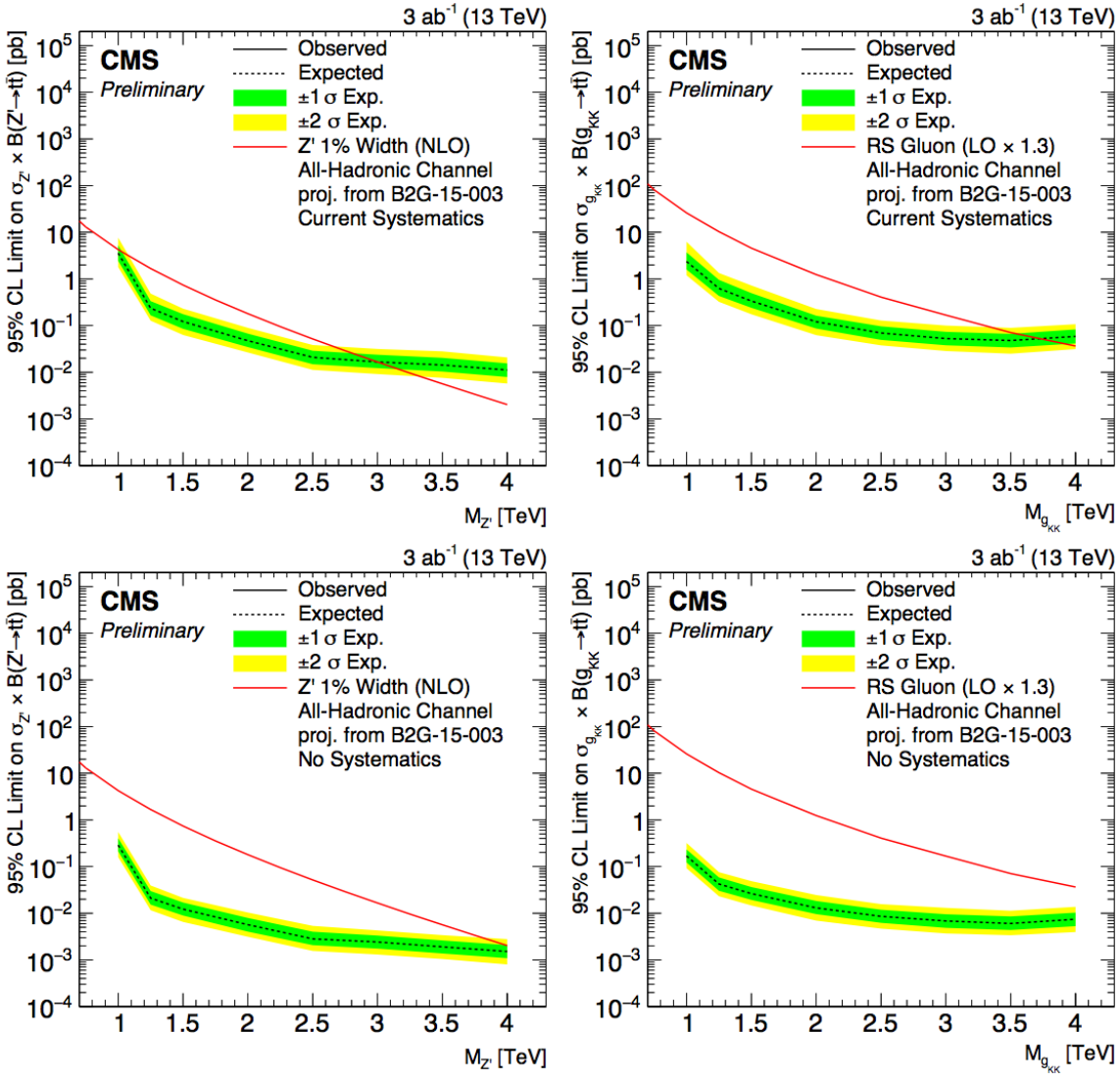
HL-LHC projections

- Performance extrapolations for 3000fb^{-1} at HL-LHC
- Extrapolate with current systematics
- Extrapolate with no systematics
- Project semi-leptonic
- Limits extended to 3 TeV for Z’ and 3.5Tev for KK-gluon



HL-LHC projections

- Performance extrapolations for 3000fb^{-1} at HL-LHC
- Extrapolate with current systematics and with no systematics (most optimistic results)
- Project all hadronic
- Limits extended to 3 TeV for Z’ and 3.5Tev for KK-gluon



Summary of results at 8 and 13 TeV

13TeV		Mass limit (95% CL upper limit on σxBr)
ATLAS 3.2fb^{-1} semi-leptonic	Z' 1.2% width	0.7<M<2.0 TeV
CMS 2.6fb^{-1} all-hadronic	Z' 1% width	1.2<M<1.6 TeV
	RS KK-gluon	1.0<M<2.5 TeV (17pb @ 1TeV– 0.25pb @ 4TeV)
CM 2.6fb^{-1} semi-leptonic	Z' 1% width	0.6<M<2.1 TeV
	RS KK-gluon	0.5<M<2.9 TeV 73.4pb @ 0.5TeV– 0.22pb @ 4TeV)
8TeV		
ATLAS 20.3fb^{-1} semi-lpetonic	Z' 1.2% width	M<2.0 TeV
	RS KK-gluon	M<2.3TeV (4.8pb @ 0.4TeV – 0.09 pb @ 3TeV
CMS 19.7fb^{-1} (Combined)	Z' 1% width	M<2.4TeV
	RS KK-gluon	M<2.7 TeV (17pb @ 0.7TeV– 0.059pb @ 3TeV)

CMS result at 8TeV, combination of di-leptonic, semi-leptonic, all-hadronic channels

Summary

- Results on ttbar resonance searches at 8TeV and 13TeV from ATLAS & CMS
  - Complementary analyses covering all decay channels of ttbar events
- Search for resonances on non-resonant SM background show no significant deviations from the Standard Model
- Limits are set using specific physics models: up to ~2TeV for Z' (colour singlets) and ~2.7TeV for RS KK-gluons (colour octet)
- 13TeV limits using 2015 data only, ~3fb^{-1}, agree with current 8TeV limits
  - Expect full 13TeV dataset with ~20fb^{-1}, to significantly extend mass limits
- *Watch this space for new results from LHC run 2*
- In the future HL-LHC will allow limits to be extended

BACKUP

References

ATLAS-CONF-2016-014

- ATLAS 8-TeV analysis: *JHEP 1508 (2015) 148*
- ATLAS 8-TeV H/A re-interpretation: *ATLAS-CONF-2016-073*
- CMS 8-TeV analysis : *Phys. Rev. D 93 (2016) 012001*

- ATLAS 13-TeV analysis: *ATLAS-CONF-2016-014*
- CMS 13-TeV analysis: *CMS-PAS-B2G-15-002*; *CMS-PAS-B2G-15-003*

ATLAS 8TeV systematics on the yield

Systematic Uncertainties	Resolved selection yield impact [%] total bkg.	Resolved selection yield impact [%] Z'	Boosted selection yield impact [%] total bkg.	Boosted selection yield impact [%] Z'
Luminosity	2.5	2.8	2.6	2.8
PDF	2.4	3.6	4.7	2.3
ISR/FSR	3.7	–	1.2	–
Parton shower and fragmentation	4.8	–	1.5	–
$t\bar{t}$ normalisation	5.3	–	5.5	–
$t\bar{t}$ EW virtual correction	0.2	–	0.5	–
$t\bar{t}$ generator	0.3	–	2.6	–
$t\bar{t}$ top quark mass	0.6	–	1.4	–
W+jets generator	0.3	–	0.1	–
Multi-jet normalisation, e+jets	0.5	–	0.2	–
Multi-jet normalisation, μ+jets	0.1	–	< 0.1	–
JES+JMS, large-radius jets	0.1	2.1	9.7	2.8
JER+JMR, large-radius jets	< 0.1	0.3	1.0	0.2
JES, small-radius jets	5.6	2.6	0.4	1.4
JER, small-radius jets	1.8	1.4	< 0.1	0.2
Jet vertex fraction	0.8	0.8	0.2	< 0.1
b-tagging b-jet efficiency	1.1	2.0	2.9	17.1
b-tagging c-jet efficiency	0.1	0.7	0.1	2.1
b-tagging light-jet efficiency	< 0.1	< 0.1	0.5	0.2
Electron efficiency	0.3	0.6	0.6	1.3
Muon efficiency	0.9	1.0	1.0	1.1
MC statistical uncertainty	0.4	6.0	1.3	1.8
All systematic uncertainties	10.8	8.8	13.4	18.0