Search for New Resonances with Top Quark

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Sep 17, TOP2015, Ischia

on behalf of the ATLAS and CMS collaborations

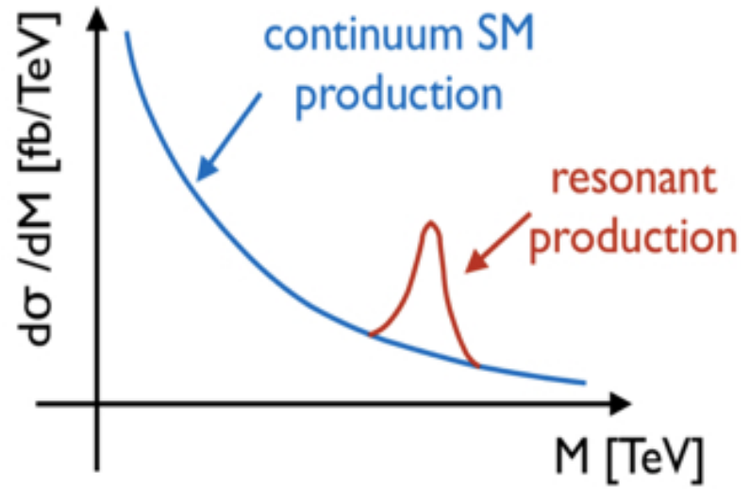
Searches with top quark

- Top quark special due to its high mass
  - Main responsible for hierarchy problem
  - Strong Yukawa couplings to Higgs boson → widow to EWSB
- Top quark plays important role in many BSM
  - Little Higgs Models and Composite Higgs Models
  - Extra dimensions...
- These models predict a number of new particles
  - This talk: searches for resonances of third generation quarks

Searches for VLQs and SUSY/DM with top quarks in next session

New Physics at LHC

- Many theories of new physics Beyond the Standard Model



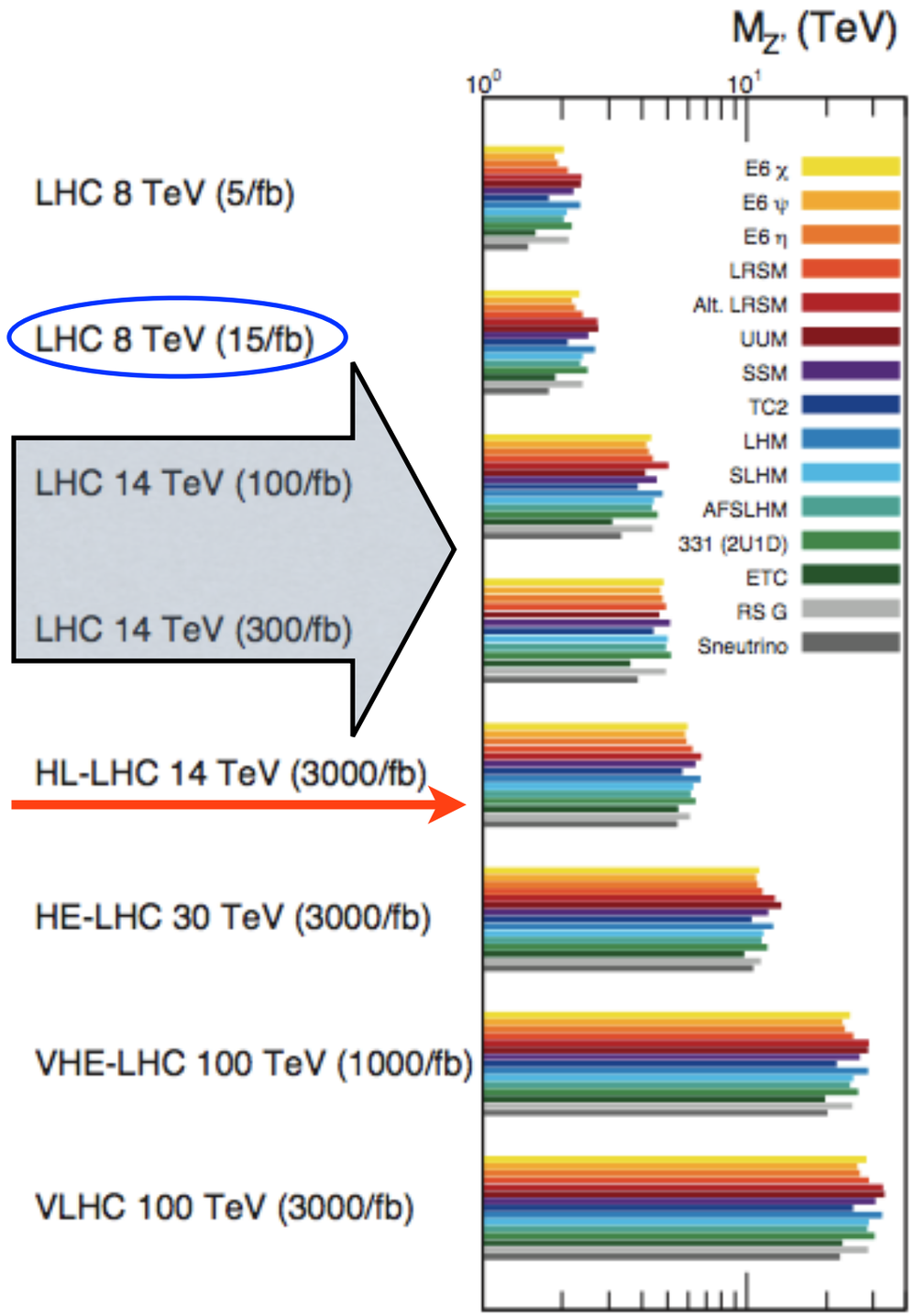
- One of the most direct ways to find new physics at TeV scale is search for new resonances

Z' and W'

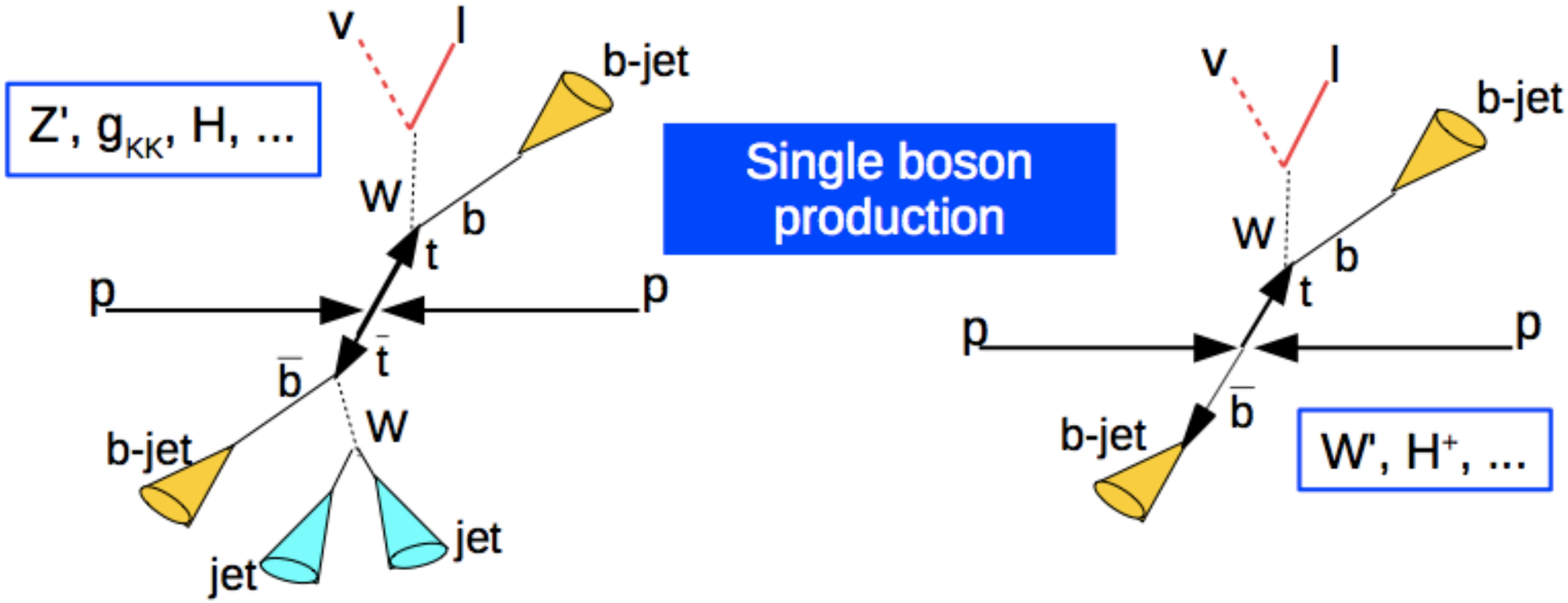
- Extra gauge bosons are a feature of many models of physics beyond the SM
- Possible that the discovery of a new gauge boson could be one of the first piece of evidence for new physics
- When the LHC reaches it's design energy and luminosity it should be able to see evidence for Z' up to ~5 TeV

Discovery limits

(arXiv:1309.1688)



Typical signatures



- (boosted) top
- (boosted) W
- many b-jets

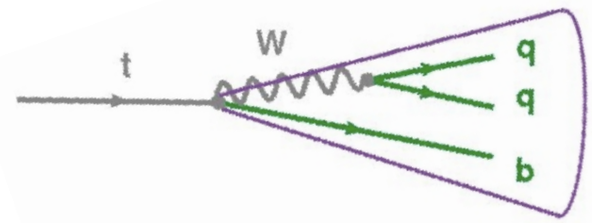
Jet substructure tools

(For details, see talks for top reconstruction and boosted top)

- Top Tagging

  → Identify 3 subjets

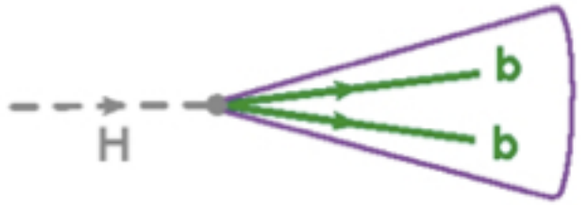
  - Apply W and top mass requirements on fat jet and subjets



- Higgs/W/Z Tagging

  → Identify 2 subjets

  - Apply mass cut



- Subjet b tagging

  → Increase QCD rejection and improve performance of top & Higgs tagging

  - b-tagging discriminator from displaced tracks & secondary vertex info

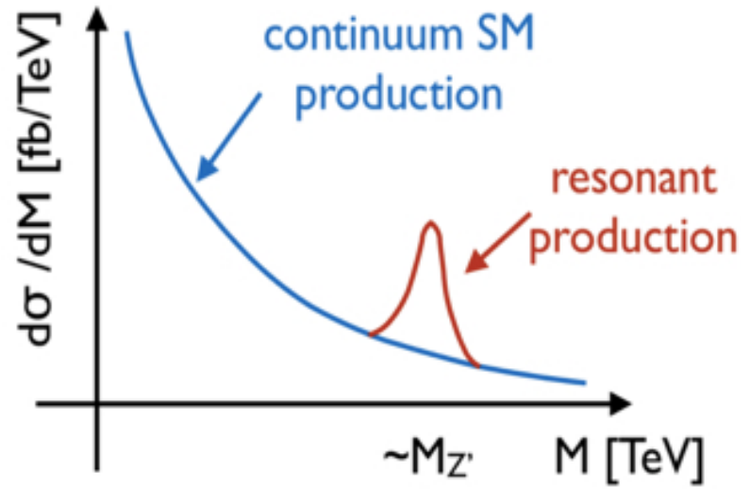
- N-subjecttiness

  → τ_n: how consistent is jet with having n subjets?

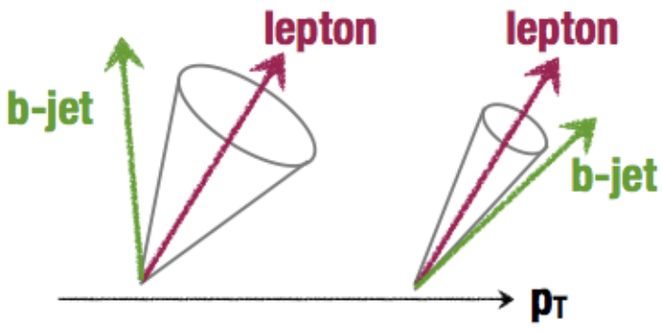
$t\bar{t}$ resonances

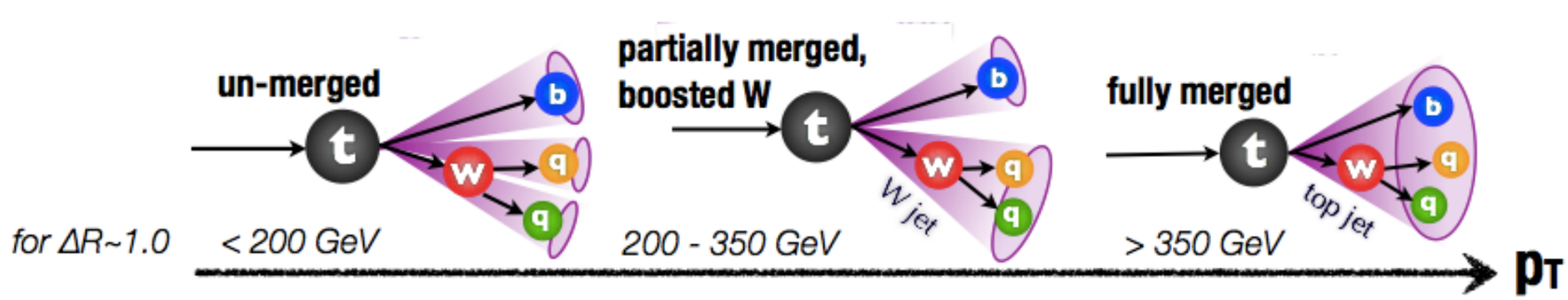
- Generically referred to as Z'
  - sensitive to topcolor Z', RS KK gluons, Etc.
  - **Z' with widths (1-10%) of mass, g_{KK} with 10-40%**

$$Z' \rightarrow t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$$

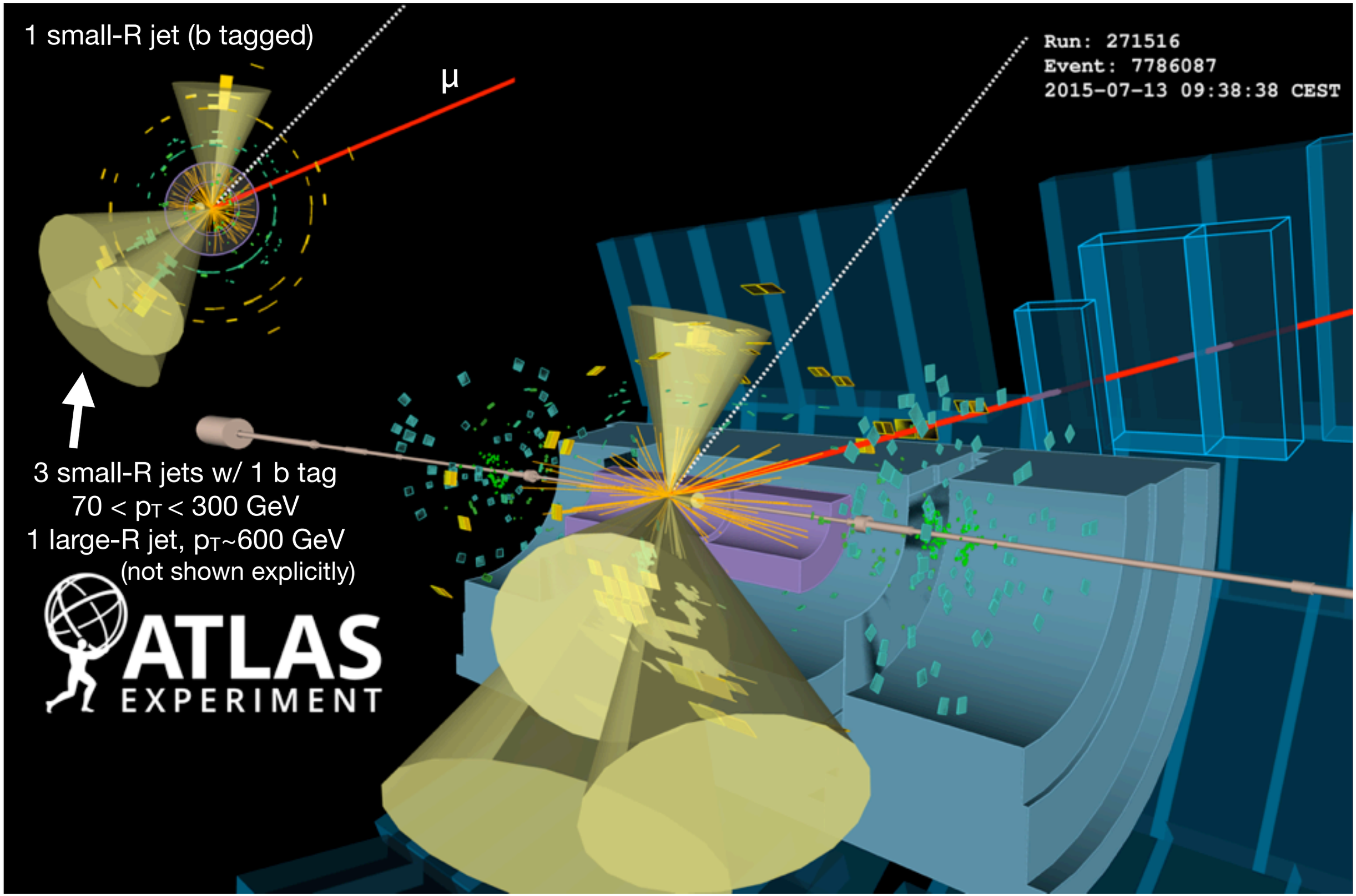


- Massive to produce highly boosted top quarks, decay products merged into single large-R jets
  - Standard lepton isolation → alternative definitions
  - Jet substructure to distinguish signal from QCD
  - Jet grooming to remove soft radiation
- Boosted top quarks: **leptonic** and **hadronic**

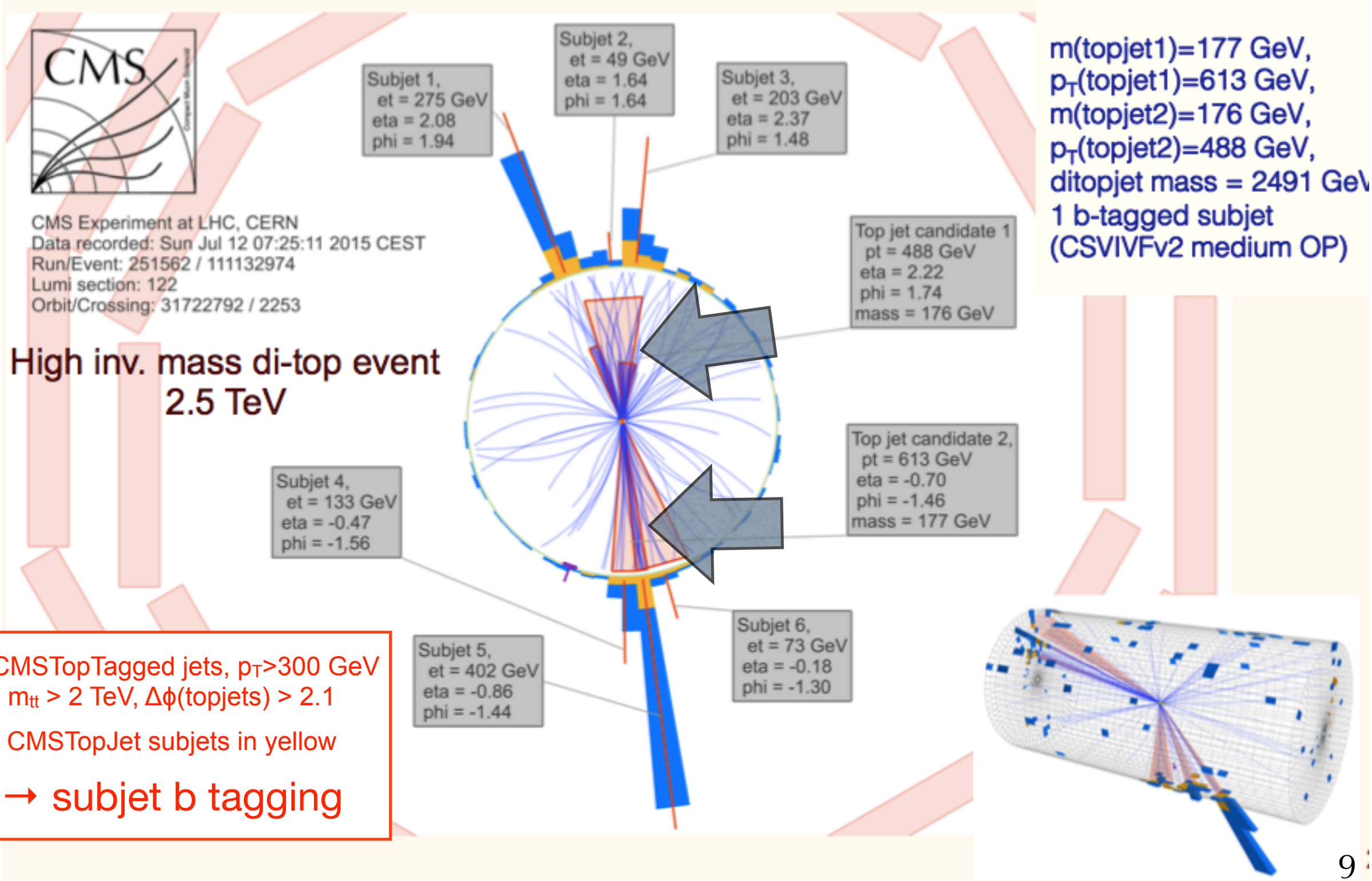




Boosted tt̄ at 13 TeV (μ+jets)



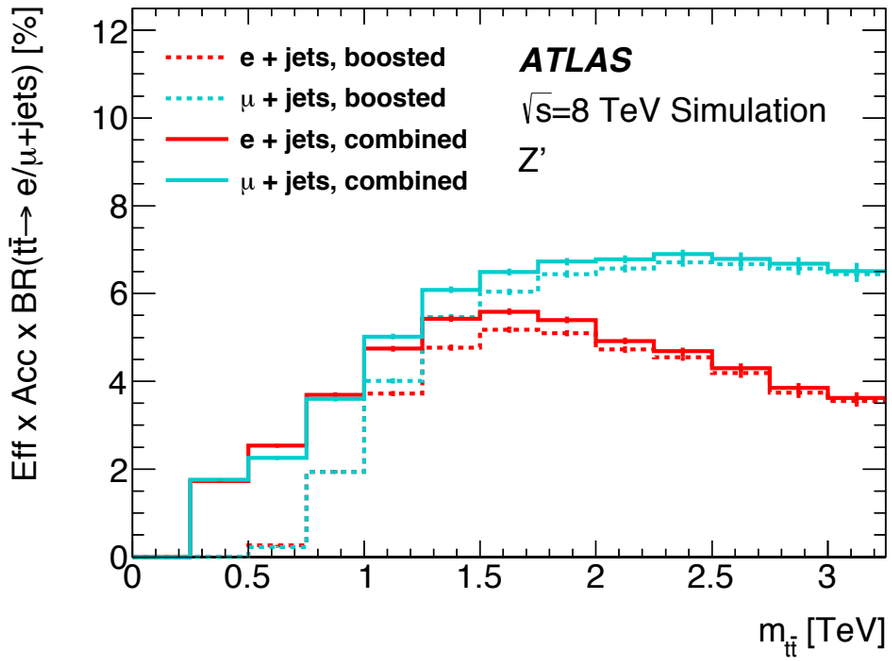
Boosted tt̄ at 13 TeV (all-jets)



$t\bar{t}$ resonances at ATLAS

JHEP 08 (2015) 148

- Semi-leptonic channel only
  - both boosted and resolved topologies
- Lepton isolation cone: $\Delta R < 10\ \text{GeV}/E_T$
  - reflects p_T dependence of separation
  - increases acceptance in boosted top decays



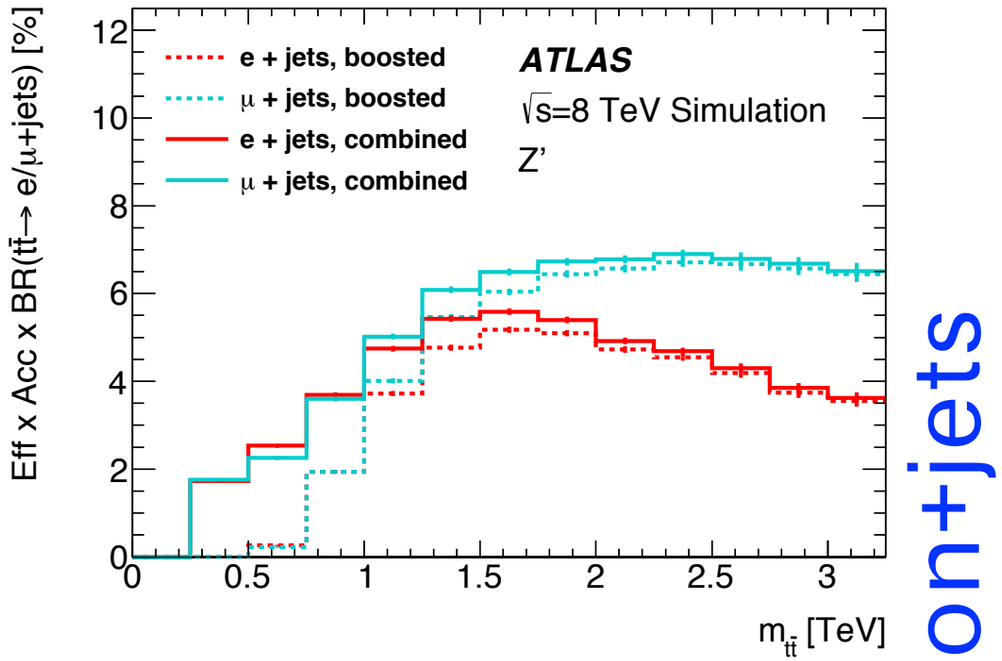
tt̄ resonances at ATLAS

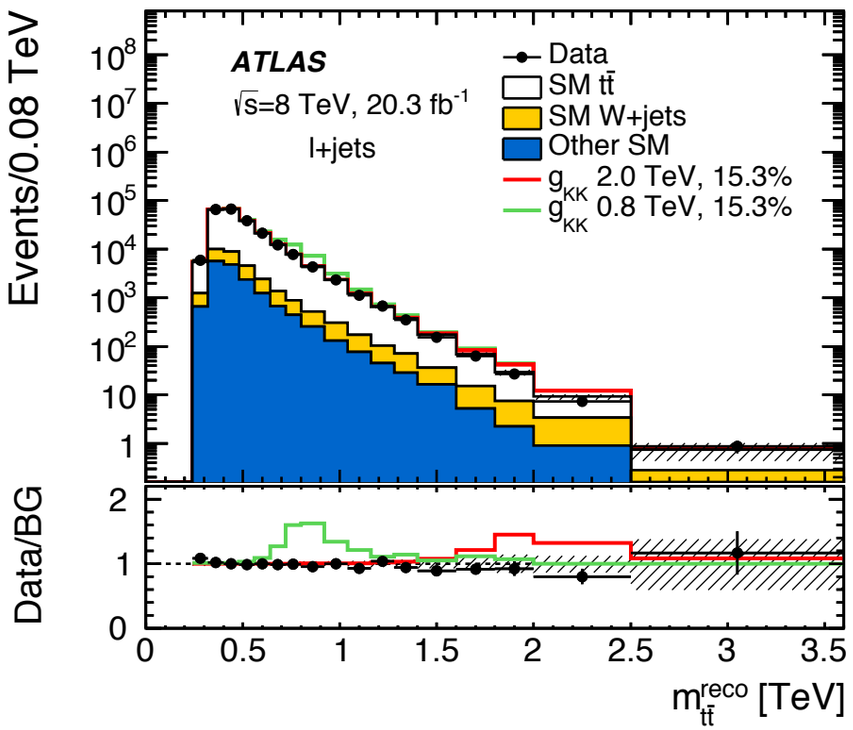
JHEP 08 (2015) 148

- Semi-leptonic channel only
  - both boosted and resolved topologies
- Lepton isolation cone: $\Delta R < 10\ \text{GeV}/E_T$
  - reflects p_T dependence of separation
  - increases acceptance in boosted top decays

Event selection

- Boosted selection (high mass)
  - ≥4 large-R jet, $p_T > 300$ GeV, AK10
  - jet mass > 100 GeV + substructure
- Resolved selection (low mass)
  - ≥4 small-R jets, combination of AK4
  - ≥1 jet w/ $\Delta R(l,j)=1.5$, ≥1 b-tag, χ^2 algorithm
- 12 categories to improve the sensitivity
  - resolved / boosted / lepton flavor (e,μ)
  - b-tag: leptonic side / hadronic side / both





Lepton+jets

$t\bar{t}$ resonances at CMS

arXiv:1506.03062, submitted to PRD

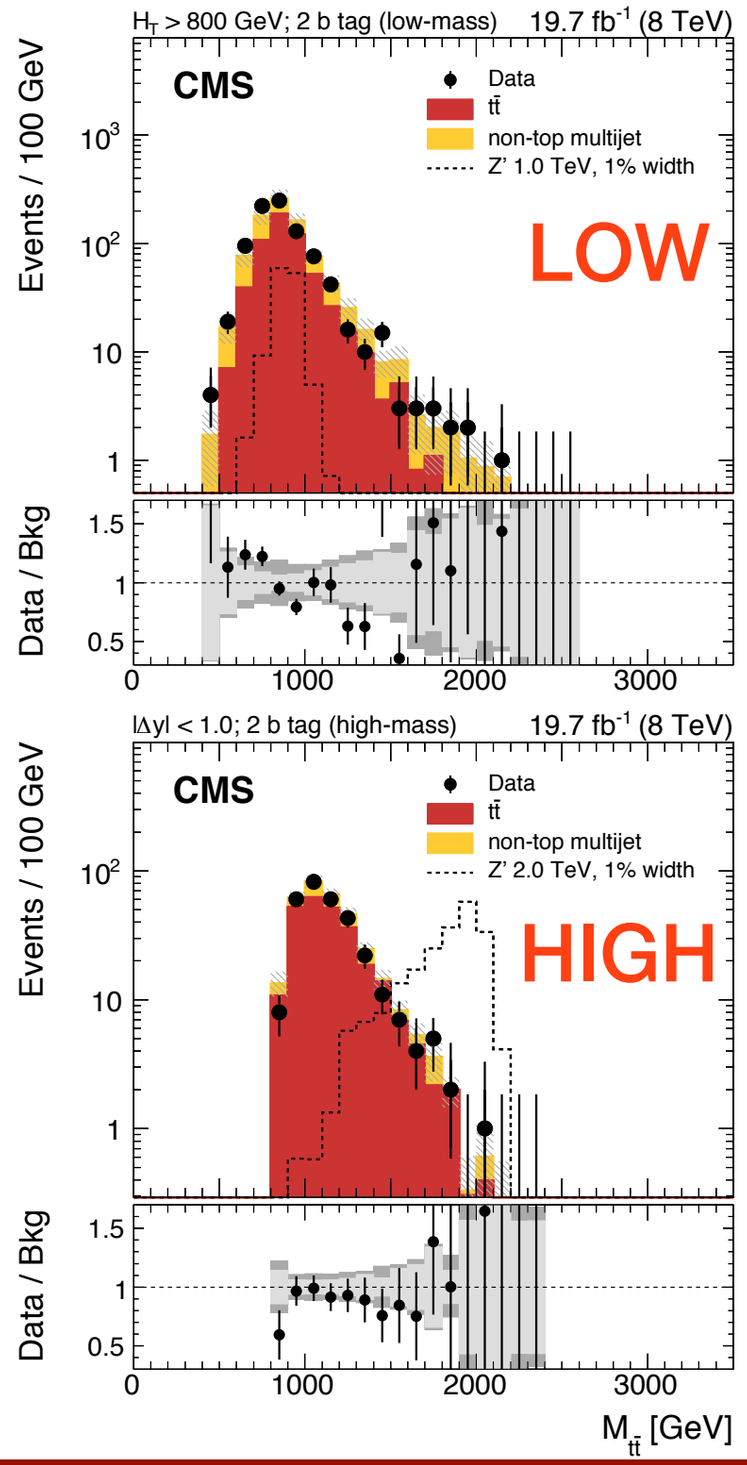
- Performed using events with three different final states, defined by num of leptons (e,μ)

Event selection

- **Di-leptonic**
  - two (non-)isolated leptons for (boosted) resolved
  - 1 or 2 b tags, background region: $\Delta R_{min}(l_2,jet)>1.5$
- **Semi-leptonic**
  - leptonic decay: (non-)isolated for (boosted) resolved
  - hadronic decay: boosted with 1 CMSTopTagger χ^2 algorithm for (partially) resolved decays
- **Full hadronic: 12 event categories**
  - if boosted, then events result in a dijet topology
  - two separate regions: low & high resonance mass

  → HepTopTagger (200-400 GeV), CMSTopTagger (> 400 GeV), n-subjecttiness + subjet b-tagging (0,1,2)

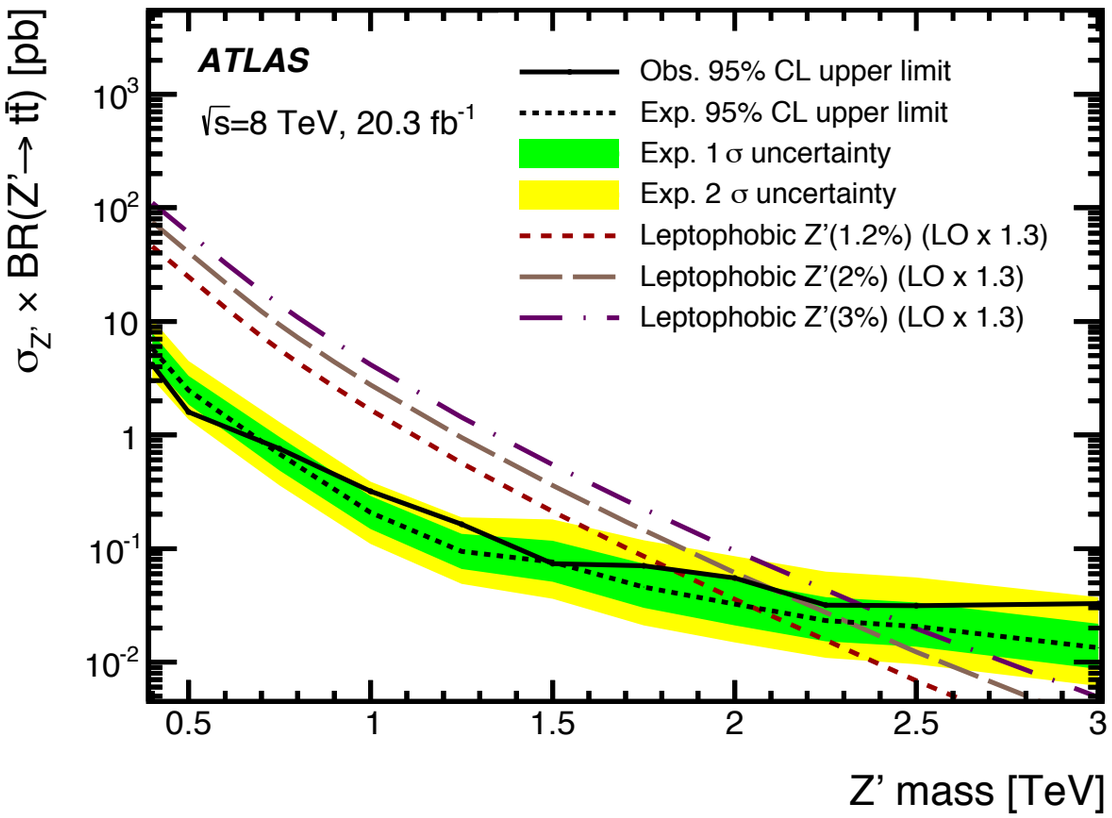
  → low: H_T < and > 800 GeV, high: $|\Delta y|$ < and > 1.0



All-jets

$t\bar{t}$ resonances limits

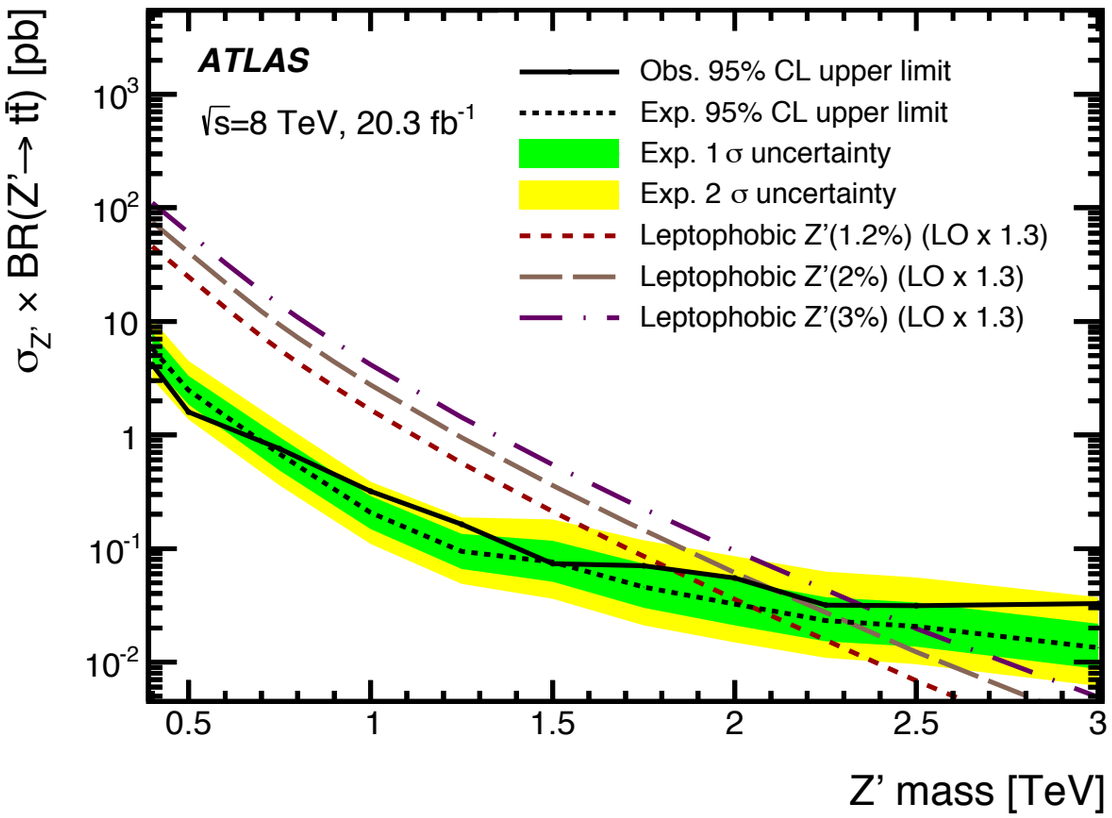
ATLAS: JHEP 08 (2015) 148



Model (a mass of 2 TeV)	Observed (expected) [TeV]		
	ATLAS		CMS
Z' narrow 1.2%	1.8 (2.0)		
Z' wide	2%: 2.0 (2.3)	3%: 2.3 (2.5)	
g_{KK} broad	15.3%: 2.2 (2.3)		

$t\bar{t}$ resonances limits

ATLAS: JHEP 08 (2015) 148



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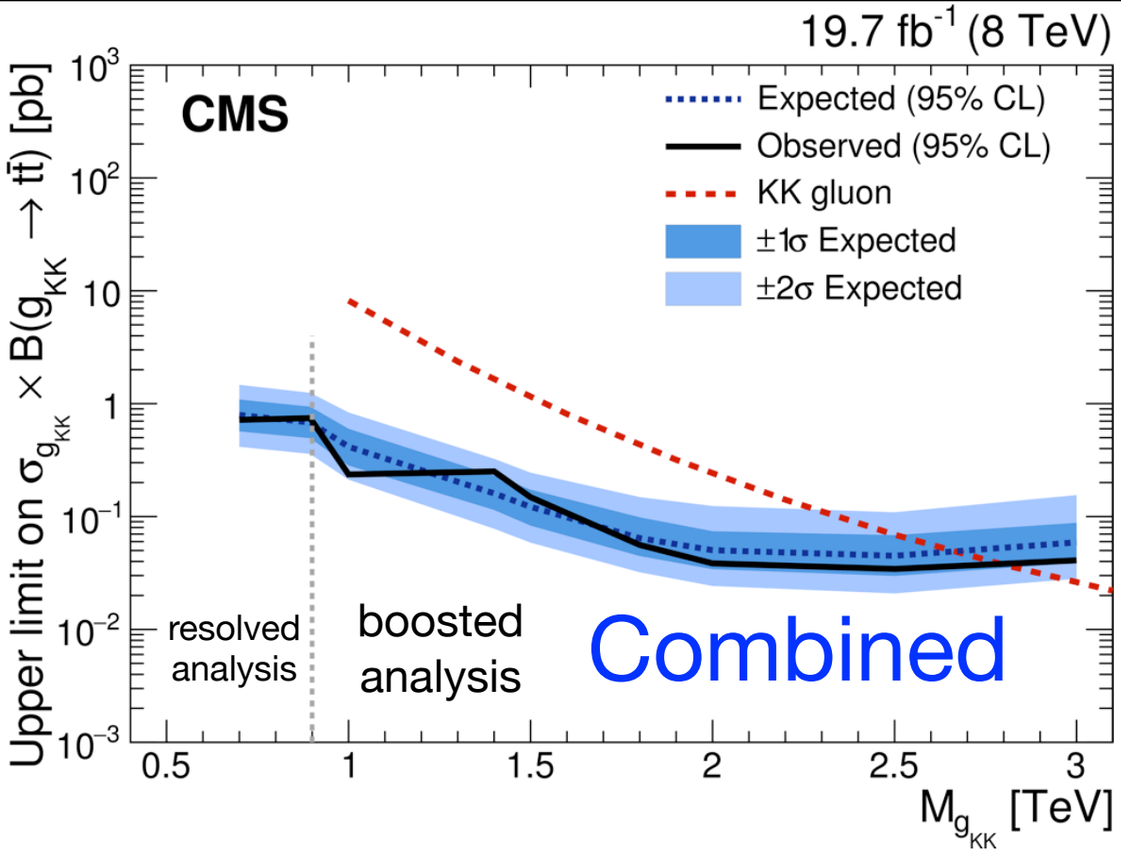
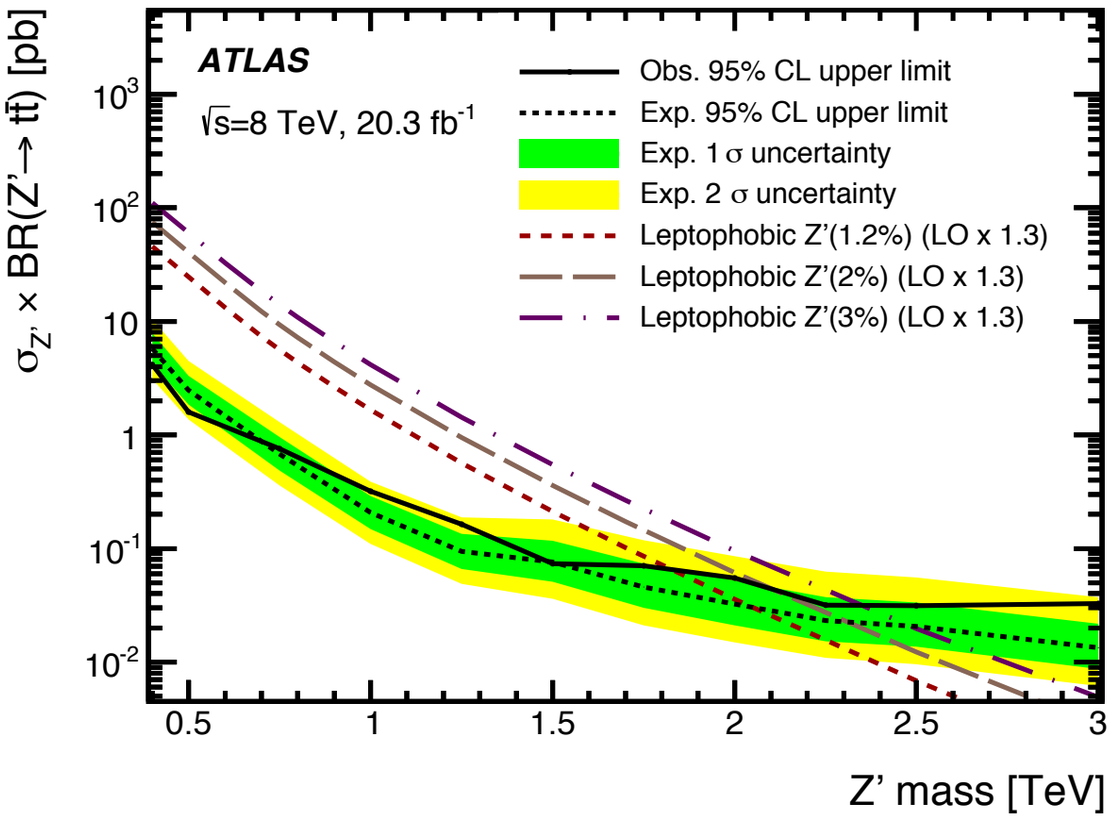


Model (a mass of 2 TeV)	Observed (expected) [TeV]	
	ATLAS	CMS
Z' narrow 1.2%	1.8 (2.0)	2.4 (2.4)
Z' wide	2%: 2.0 (2.3) / 3%: 2.3 (2.5)	10%: 2.9 (2.8)
g_{KK} broad	15.3%: 2.2 (2.3)	~20%: 2.8 (2.7)

$t\bar{t}$ resonances limits

ATLAS: JHEP 08 (2015) 148



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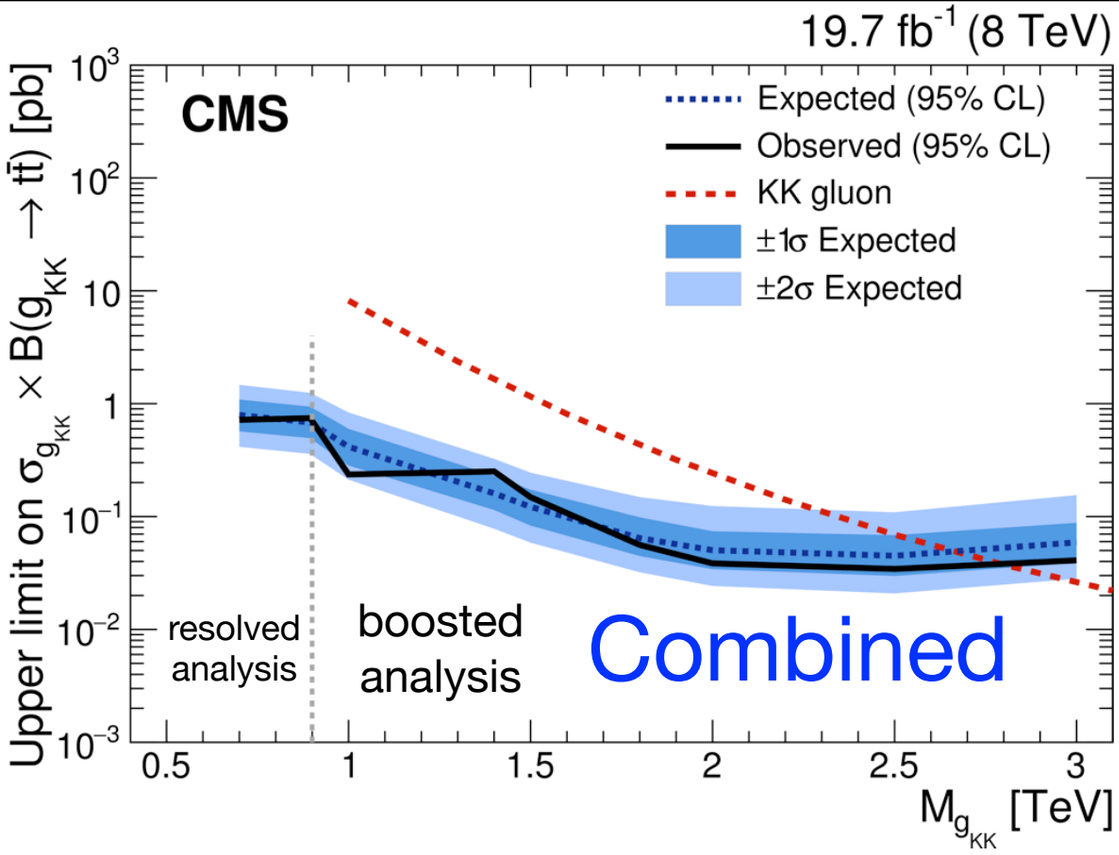

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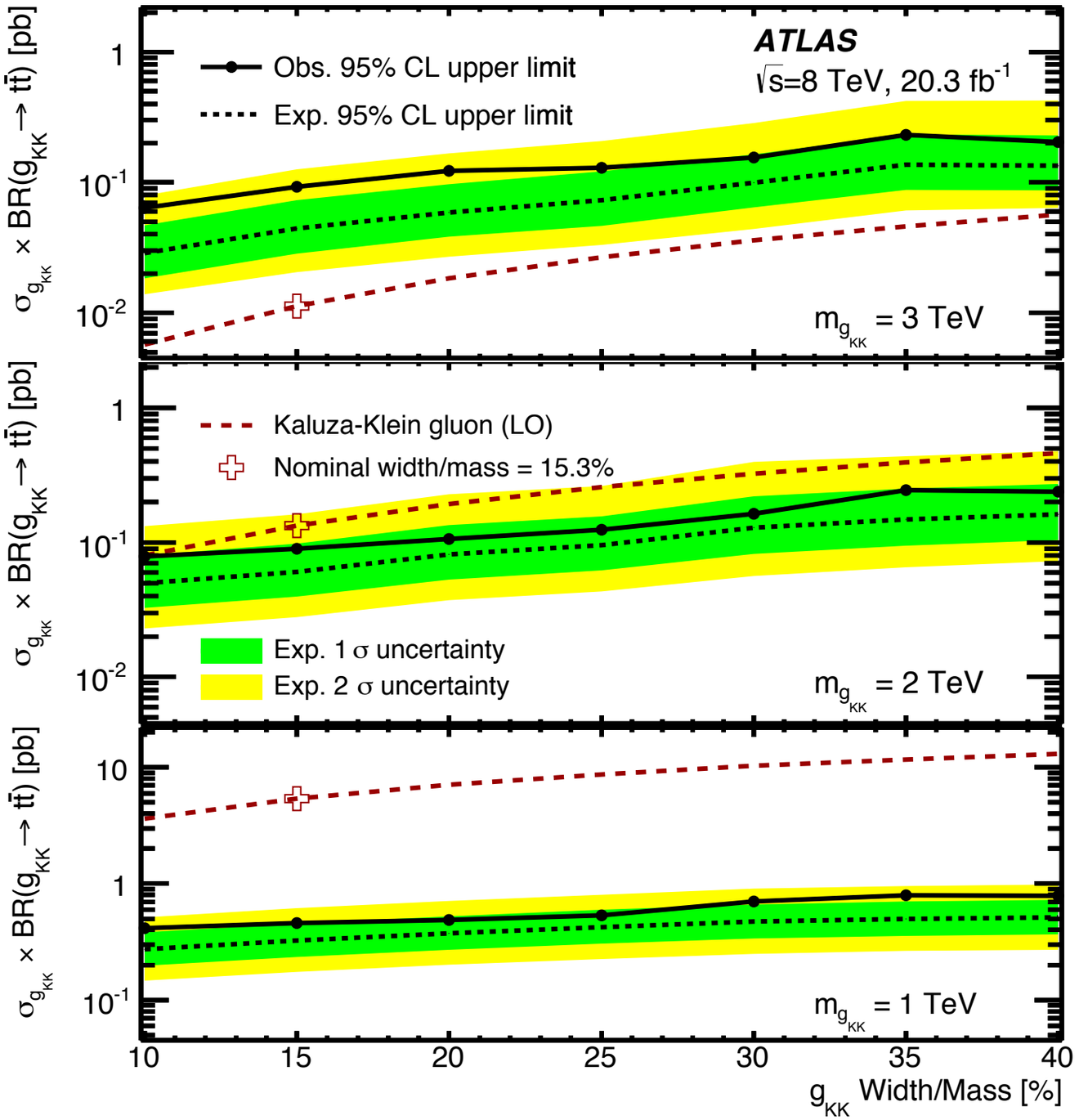
better limits due to the higher production cross-section of the wider Z' resonance

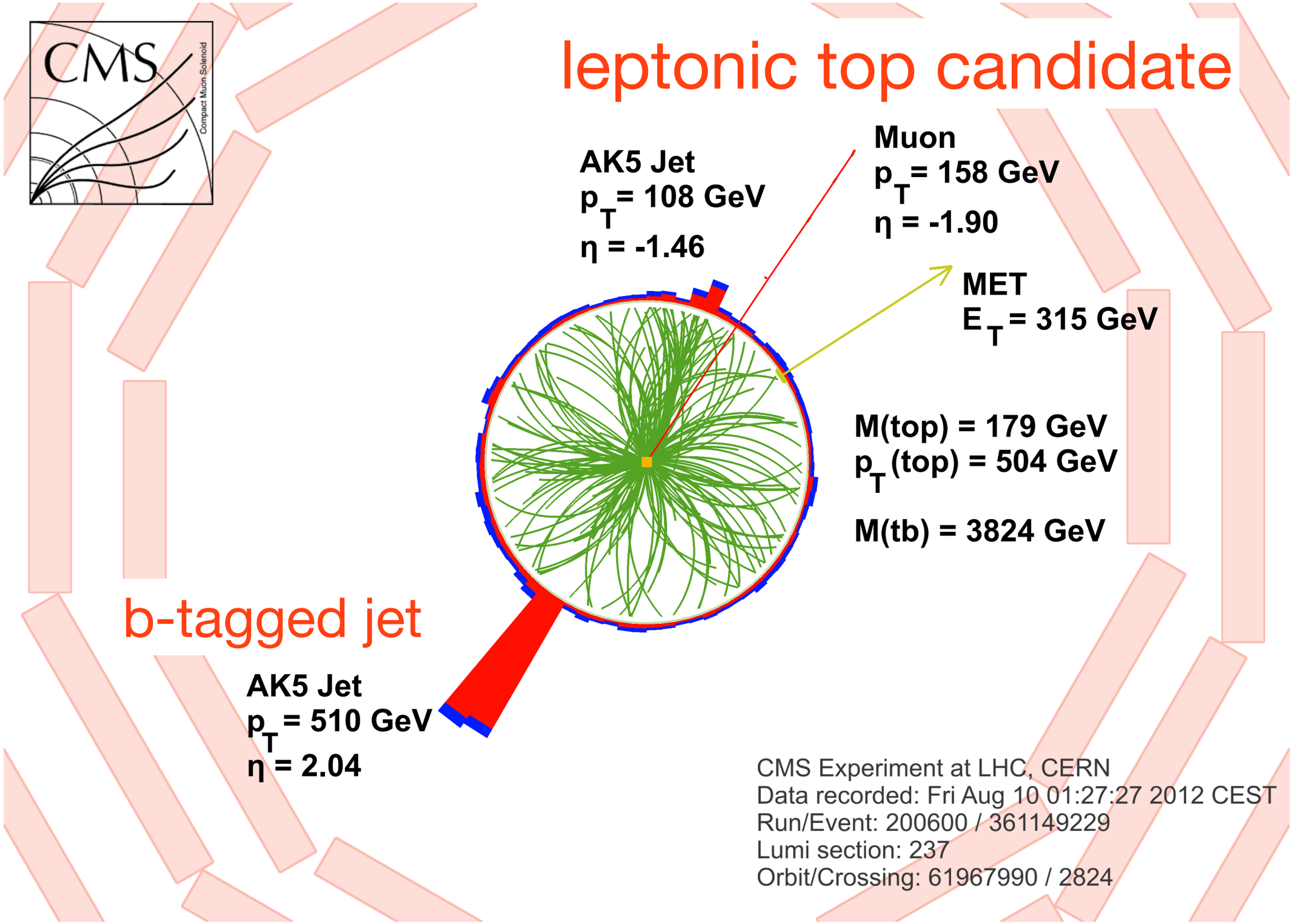
$t\bar{t}$ width dependence at ATLAS

- Width dependence also evaluated for g_{KK}
  - For a 1 TeV resonance, limits weaken by approximately a factor of two as the width increases 10%→40%
  - For 2 and 3 TeV resonances, limits weaken by a factor of three over this width range

The wider the width is
(or the heavier the resonance)
→ the weaker the limit



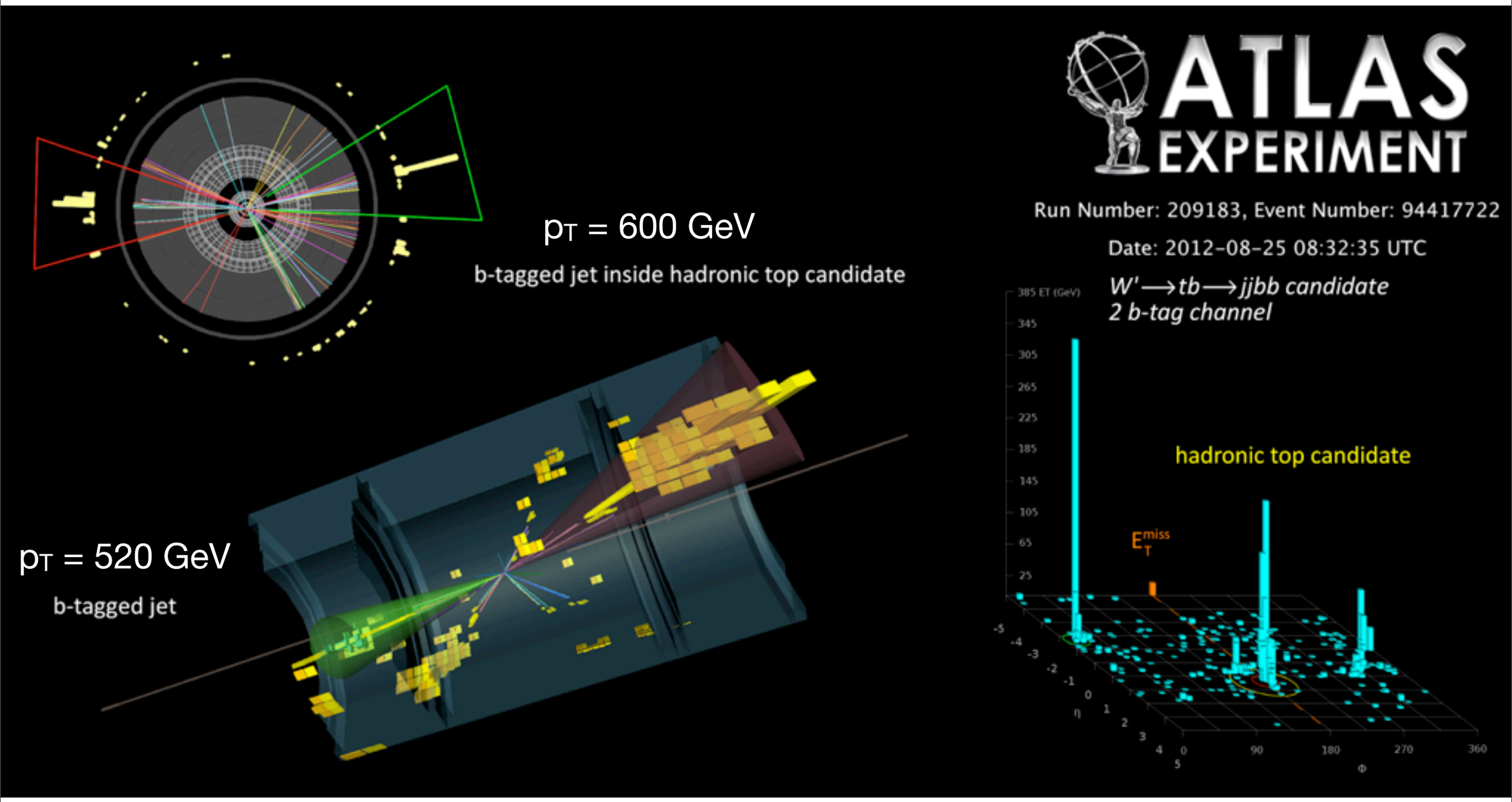
W'→tb→μνbb candidate at 8 TeV



CMS Experiment at LHC, CERN
Data recorded: Fri Aug 10 01:27:27 2012 CEST
Run/Event: 200600 / 361149229
Lumi section: 237
Orbit/Crossing: 61967990 / 2824

W’→tb→jjbb candidate at 8 TeV

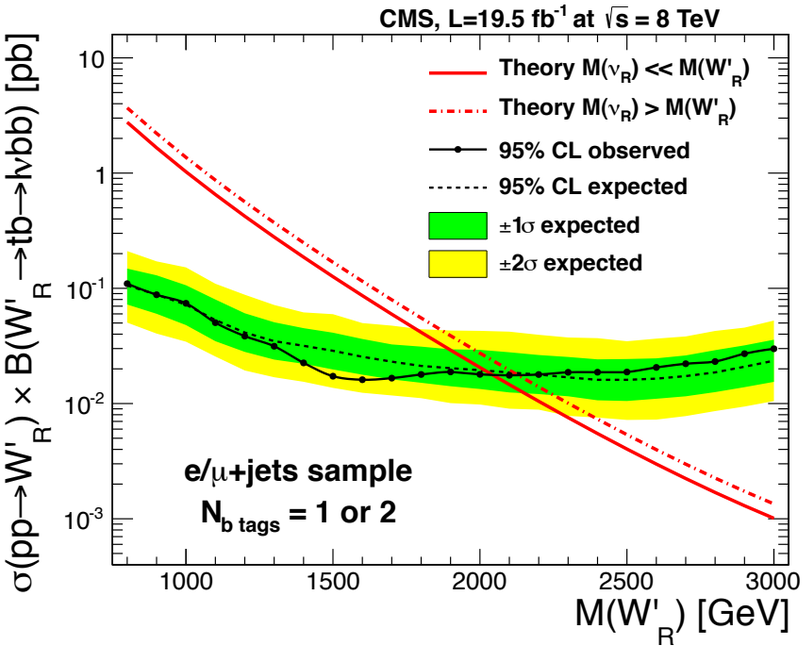
2 b-tag channel: m_{tb} = 3.3 TeV (top candidate p_T = 790 GeV, b candidate p_T = 520 GeV)



W’ resonances at CMS

JHEP 05 (2014) 108

- Lepton+jets: 4 event categories
  - resolved: lepton (e or μ), 2 leading jets, ≥1 b tag
  - W’ candidate from top candidate and leading jet
  - Total leptonic branching fraction with l = e/μ/τ
  - Search is sensitive to W’→tb→τνbb decay mode if τ→e/μ
  - Included in signal and background estimations



Lepton+jets

Channel	W'_R obs. (exp.)
Lepton+jets	2.05 (2.02)
All-jets	

- Various models of W’ are studied by allowing for an arbitrary combination of left- and right-handed couplings
- Search results when assuming light (heavy) right-handed neutrinos

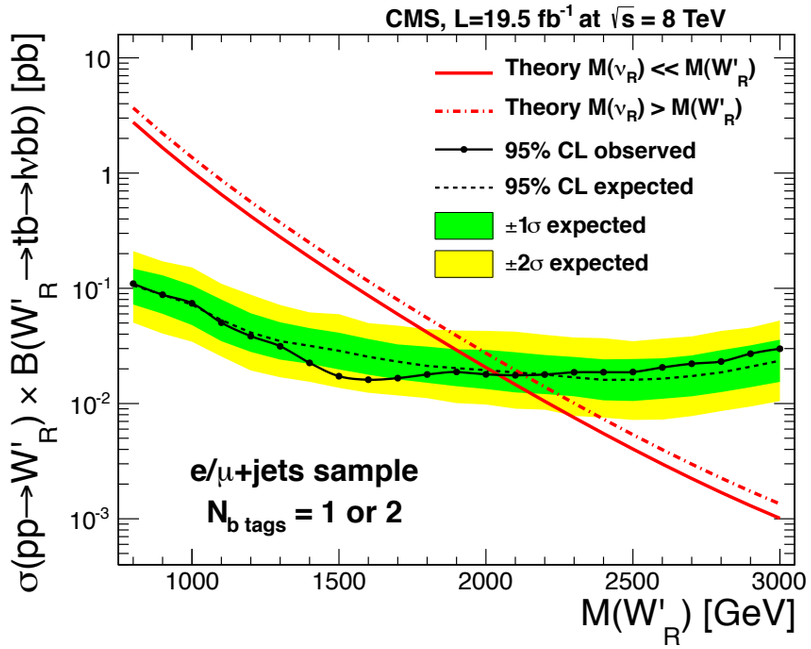
W’ resonances at CMS

JHEP 05 (2014) 108, B2G-12-009

- **Lepton+jets**
  - resolved: lepton (e or μ), 2 leading jets, ≥1 b tag
  - W’ candidate from top candidate and leading jet
- **Boosted all hadronic**
  - b candidate: b-tagged jet
    p_T > 370 GeV and mass < 70 GeV
  - top decay: p_T > 450 GeV, CMSTopTagger + 1 subjet b-tagging + n-subjettiness τ_3/τ_2 < 0.55
  - substructure: similar sensitivity as cleaner semi-leptonic final state

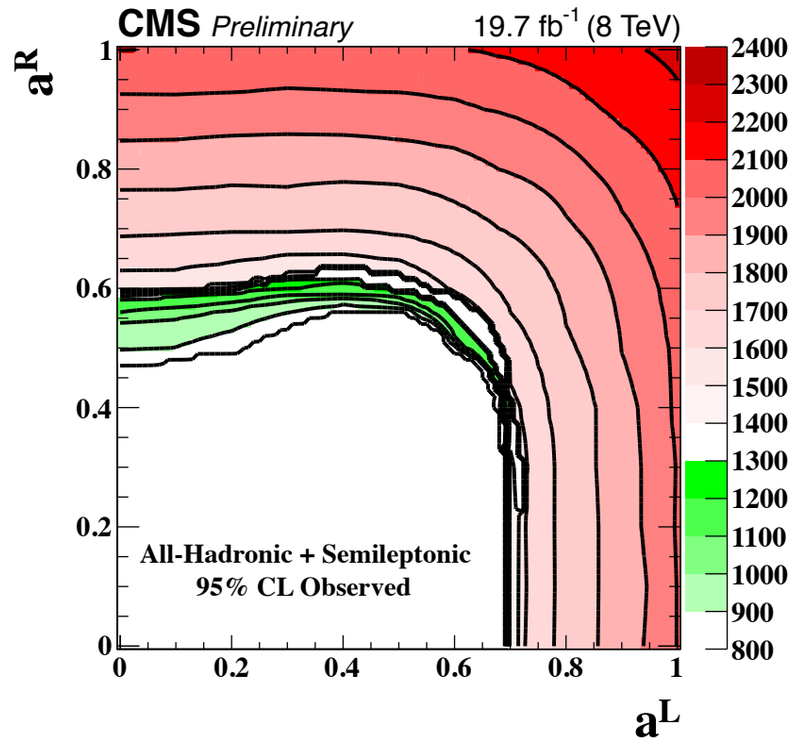
Channel	W'_R obs. (exp.)
Lepton+jets	2.05 (2.02)
All-jets	2.02 (1.99)
Combined	2.15 (2.15)

Lepton+jets



Limits on right and left couplings

Combined



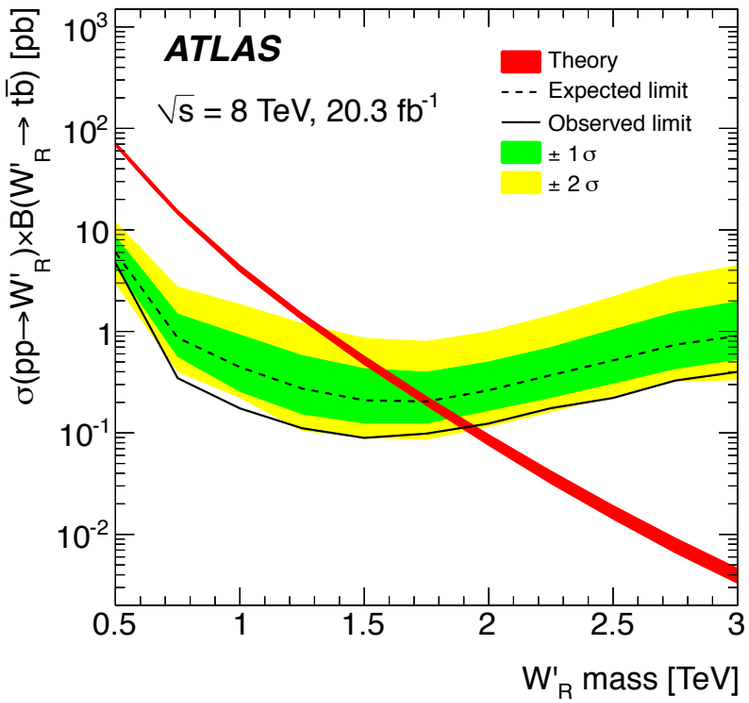
W’ resonances at ATLAS

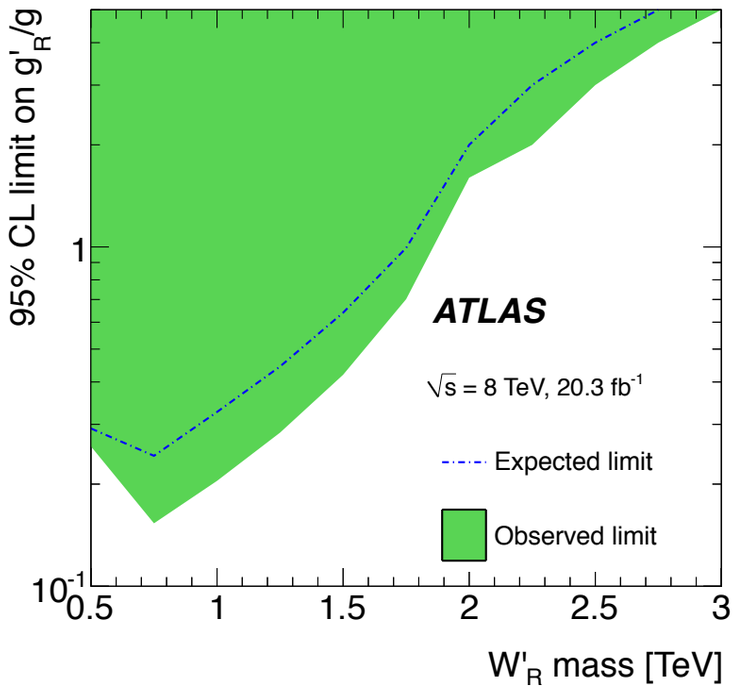
PLB 743 (2015) 235

- Lepton+jets
  - single lepton, 2 b tags
  - $m_T(W)$ + MET > 60 GeV, MET > 35 GeV
  - two categories: 2-jet and 3-jet channels
    - $\Delta R(b_t,W), \Delta\eta(l,b_t)$ ($\Delta R(l,b)$ I $\Delta\phi(b_t,MET), m_T(W)$)
    - $\Delta R(l,b_t)$, $p_T(b), m(b,b_t,j)$ ($\Delta R(b,W)$ I $\Delta\phi(b_t,MET)$)

Channel	W'_R obs. (exp.)
Lepton+jets	1.92 (1.75)
All-jets	

→ Cross-section limits also interpreted as limits on other values of the couplings: g’/g vs. m(W’) where g is the SM $SU(2)_L$ coupling





Lepton+jets

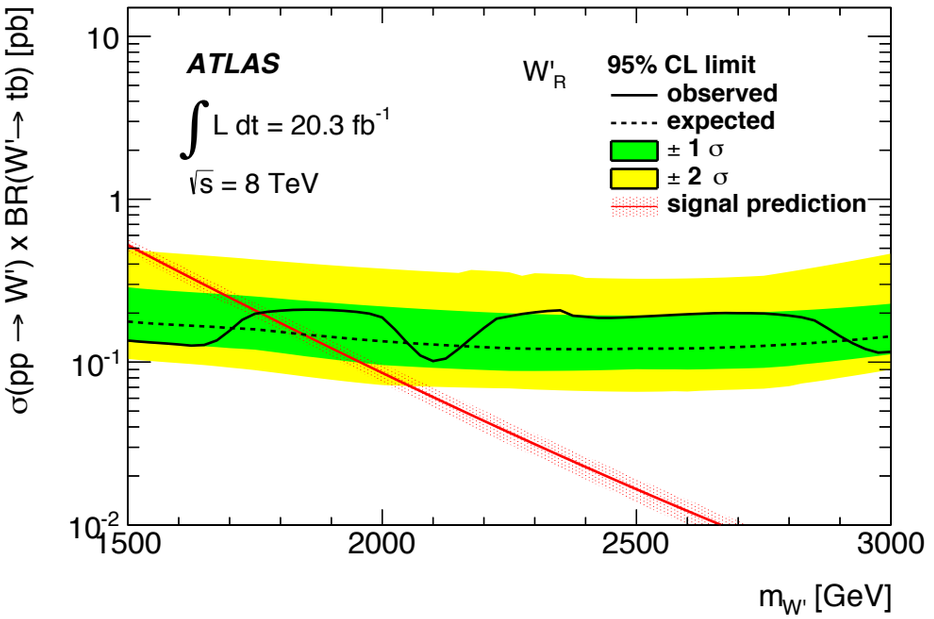
W’ resonances at ATLAS

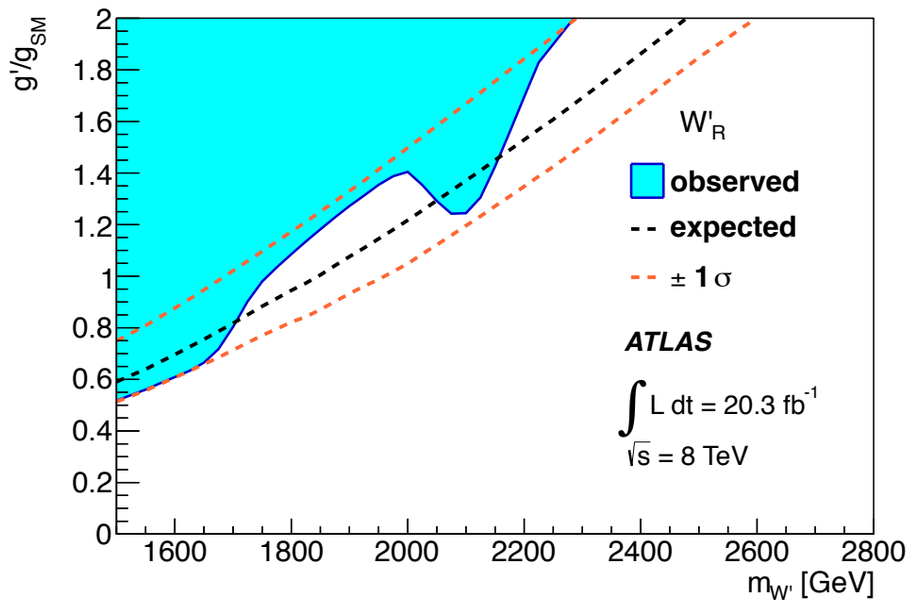
PLB 743 (2015) 235, EPJC 75 (2015) 165

- Boosted all hadronic
  - substructure: 1 top-tagged jet (large-R)
  - ΔR(top candidate,b candidate) > 2.0
  - two categories: 1 b-tag, 2 b-tag (small-R)
    - ✓ 2 b-tag category with an additional b-tagged jet close to top-tagged jet: ΔR(t,b) < 1.0

Channel	W’$_R$ obs. (exp.)
Lepton+jets	1.92 (1.75)
All-jets	1.76 (1.85)

→ Cross-section limits also interpreted as limits on other values of the couplings: g’/g vs. m(W’) where g is the SM SU(2)$_L$ coupling





All-jets

Summary table

- Limits depend on widths and channels

[TeV]

- Z’

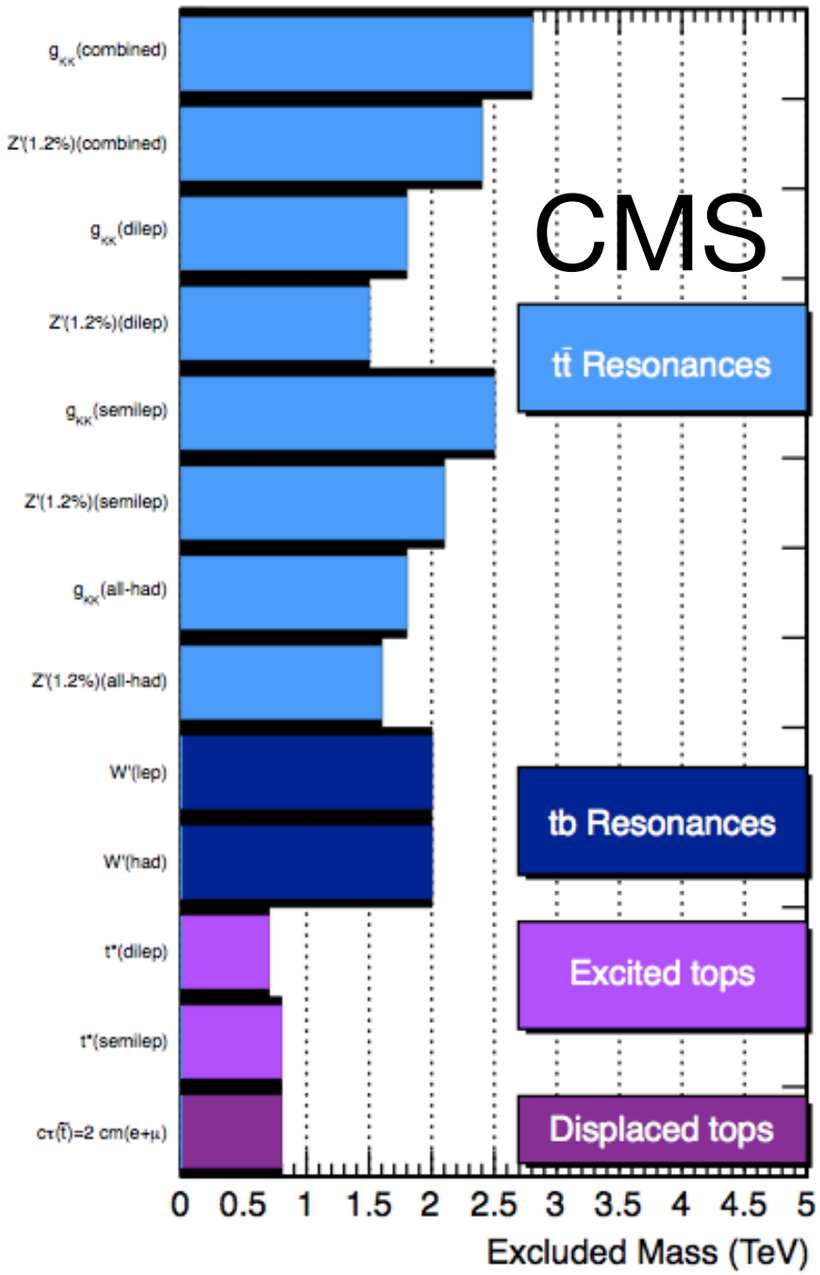
Model	Observed (expected)	
	ATLAS lepton+jets	CMS combined
Z’	1.2%: 1.8 (2.0)	1.2%: 2.4 (2.4)
	2%: 2.0 (2.3) / 3%: 2.3 (2.5)	10%: 2.9 (2.8)
KK gluon	15.3%: 2.2 (2.3)	~20%: 2.8 (2.7)

- W’

Channel	W_R’ observed (expected)	
	ATLAS	CMS
Lepton+jets	1.92 (1.75)	2.05 (2.02)
All jets	1.76 (1.85)	2.02 (1.99)
Combined		2.15 (2.15)

Conclusions

- New physics models tested in Run 1
  - Cutting edge substructure techniques to handle boosted topologies
  - No evidence for new physics, but all types of studies excluded up to 2~3 GeV
- In Run 2, it should be able to see evidence up to 4~5 GeV



95% CL Exclusions (TeV)

ATLAS

Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	20.3	Z′ mass 2.9 TeV
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z′ mass 2.02 TeV
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	20.3	W′ mass 3.24 TeV
	EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$	3 e,μ	–	Yes	20.3	W′ mass 1.52 TeV
	EGM $W' \to WZ \to qq\ell\ell$	2 e,μ	2 j / 1 J	–	20.3	W′ mass 1.59 TeV
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W′ mass 1.3-1.5 TeV
	HVT $W' \to WH \to \ell\nu bb$	1 e,μ	2 b	Yes	20.3	W′ mass 1.47 TeV
	LRSM $W'_R \to t\bar{b}$	1 e,μ	2 b, 0-1 j	Yes	20.3	W′ mass 1.92 TeV
	LRSM $W'_R \to t\bar{b}$	0 e,μ	≥ 1 b, 1 J	–	20.3	W′ mass 1.76 TeV

We are close!

Backup

Excited Top Quarks

CMS: arXiv:1311.5357 submitted to JHEP

$t^* \rightarrow t$ + jets

- Searches for pair production of top excitation
- Signature tt + jets difficult to model

  → distributions derived from data
- Dilepton event selection:
  - 2 isolated leptons
  - 4 jets with 2 b-tags
- Single lepton event selection:
  - 1 isolated lepton
  - ≥ 6 jets with ≥ 1 b-tag
- Limits on m_{t^*} from t + jets mass spectrum

Dilepton	703 GeV
Single lepton	803 GeV