ATLAS Searches in Run I

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On behalf of the ATLAS Collaboration

BOOST, August 10-14, 2015

Outline

- Many nice boosted results presented last year
  - https://indico.cern.ch/event/302395/session/13/contribution/27/attachments/571615/787333/bchow_BOOST14.pdf
  - https://indico.cern.ch/event/302395/session/13/contribution/29/attachments/571625/787344/ATLAS_Searches_Boosted_Tops_BOOST2014.pdf

- Focus this year on most recent results
  - Diboson searches covered in Chris Delitzsch's talk

Topics Covered

1. Di-Higgs production

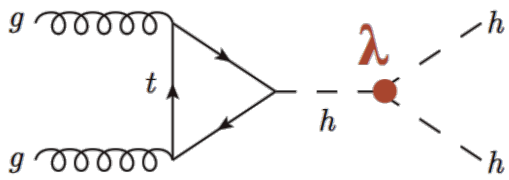
2. R-Parity Violating (RPV) Supersymmetry
   - RPV Stop
   - RPV multi-jets

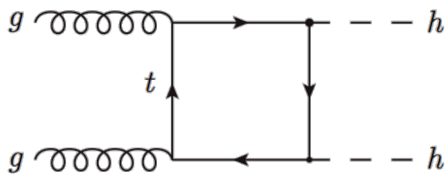
3. Heavy Resonances Decaying to top quarks / Heavy Tops
   - $t\bar{t}$ resonances
   - VLT→Wb

HH production

hh Motivation

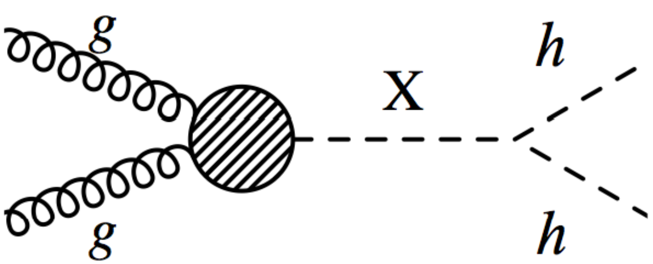
- SM hh production
  - Direct test of Higgs potential
  - Small cross section: O(40 fb) at 14 TeV





- BSM hh production
  - Higgs sector may be more complex than SM
    - Additional Higgs, modified λ or new vertices, new particles in loop, …
  - **New resonances could greatly enhance hh production**
    - E.g. KK-Gravitons, H in 2HDM, new scalar in Higgs portal, …

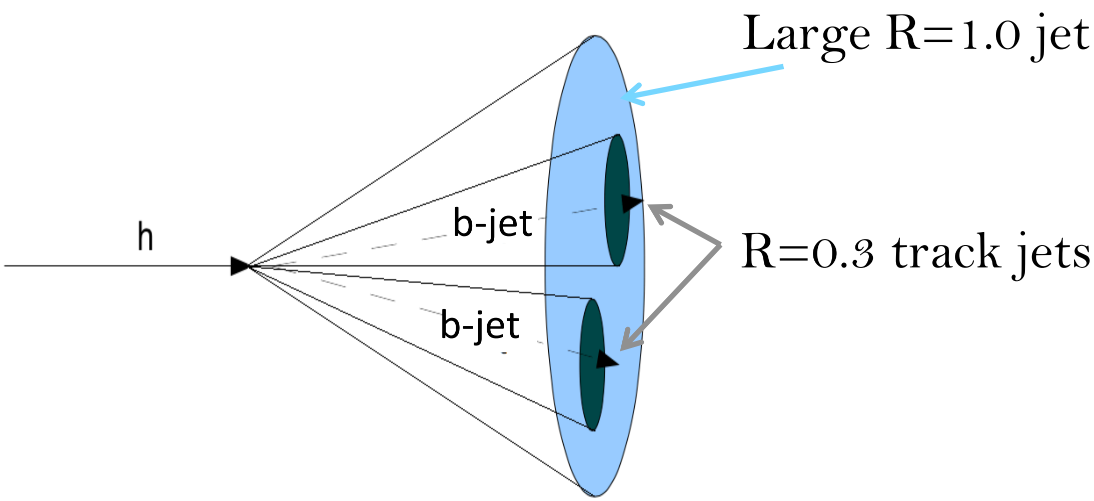
- Focus on hh→4b channel
  - Largest BR~33%
  - Heavy resonances produce **boosted Higgs-jets**
  - Must combine jet substructure with heavy flavor identification

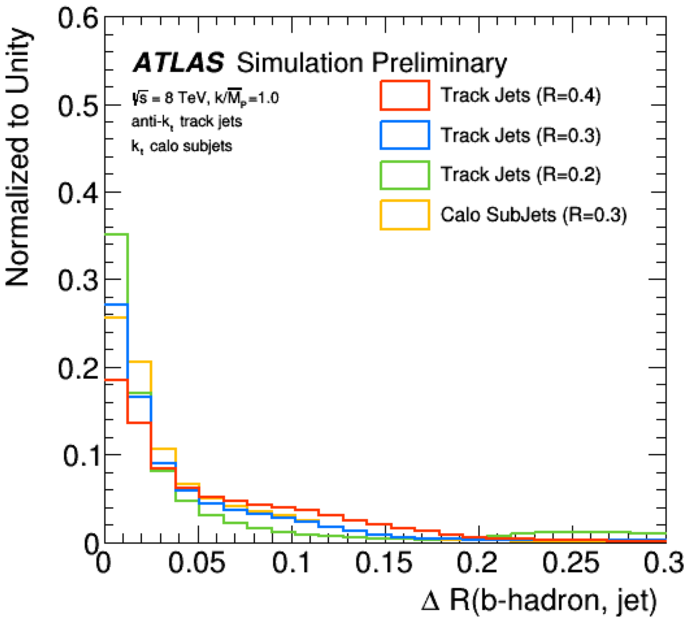


Run-I Higgs (→bb) Tagging

- R=1.0 calorimeter jets trimmed with k_T R=0.3 subjets and f_{cut}=0.05, to measure kinematics / substructure

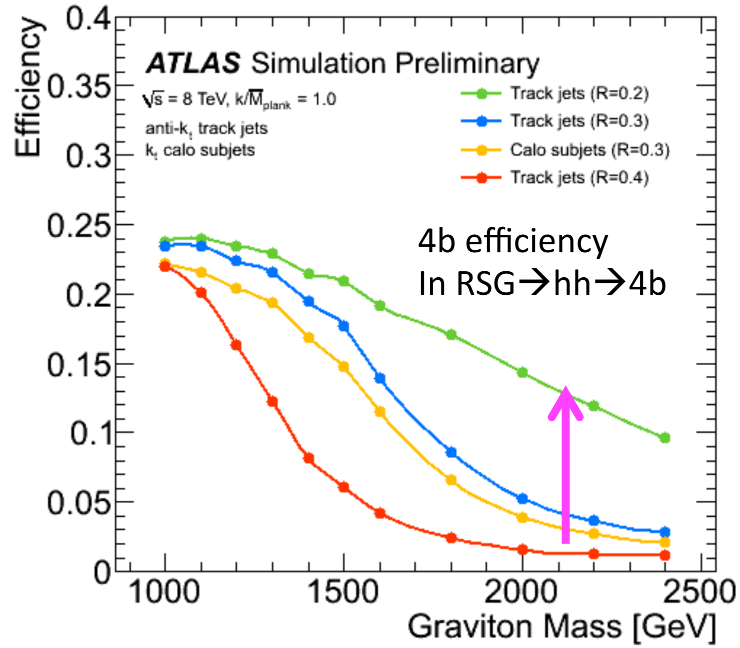
- b-tagging with small R=0.3 track jets to resolve close-by b-hadrons





Run-I Higgs (⟶bb) Tagging

- R=1.0 calorimeter jets trimmed with k_T R=0.3 subjets and f_{cut}=0.05, to measure kinematics / substructure
- b-tagging with small R=0.3 track jets to resolve close-by b-hadrons
- Ghost association of track jets to large-R to provide b-tagging
  - Matching to ungroomed parent jet area provides large improvement in acceptance to find b-hadron
- Large improvements in efficiency to find boosted Higgs Jets!



hh→4b Analysis Overview

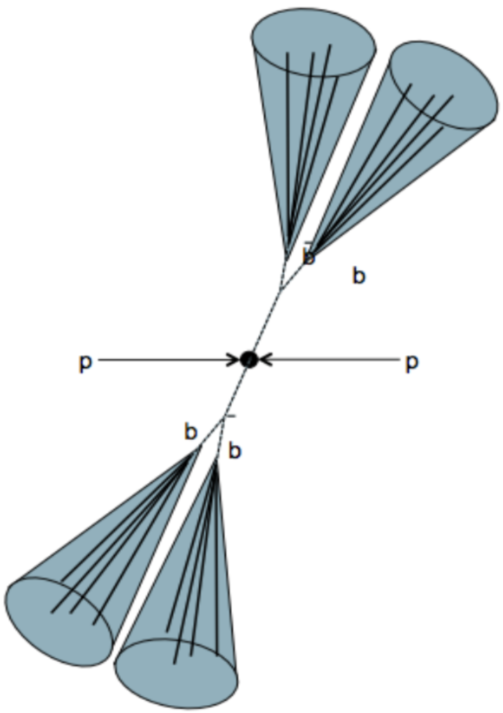
arXiv:1506.00285

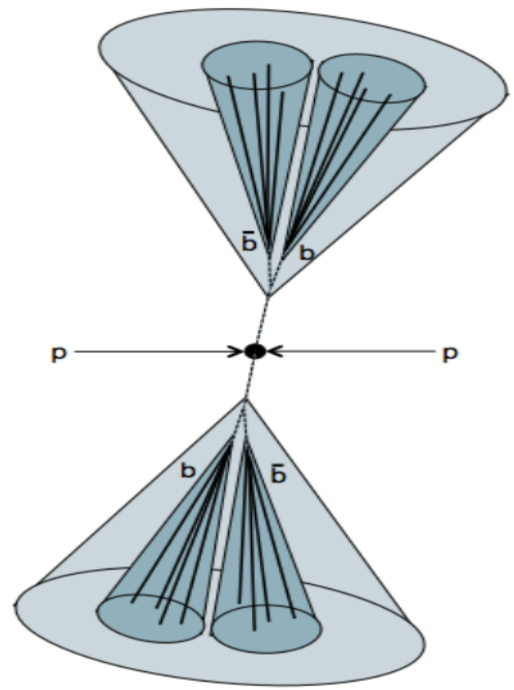
Resolved analysis:

1. Four b-tagged anti-k_T R=0.4 jets
2. Arrange into close-by pairs, $\Delta R<1.5$
3. Mass dependent p_T and $|\Delta\eta|$ cuts
4. ttbar veto, using 5^{th} jet to test consistency with m_W / m_{top}

Boosted analysis:

1. Two anti-k_T R=1.0 jets, trimmed with R_{sub}=0.3 and f_{cut}=0.05
2. Each with 2 b-tagged R=0.3 track jets
3. p_T and $|\Delta\eta|$ cuts





Signal region: $X_{hh} = \sqrt{\left(\frac{m_{\text{lead}} - 124}{0.1 \times m_{\text{lead}}}\right)^2 + \left(\frac{m_{\text{subl}} - 115}{0.1 \times m_{\text{subl}}}\right)^2} < 1.6$

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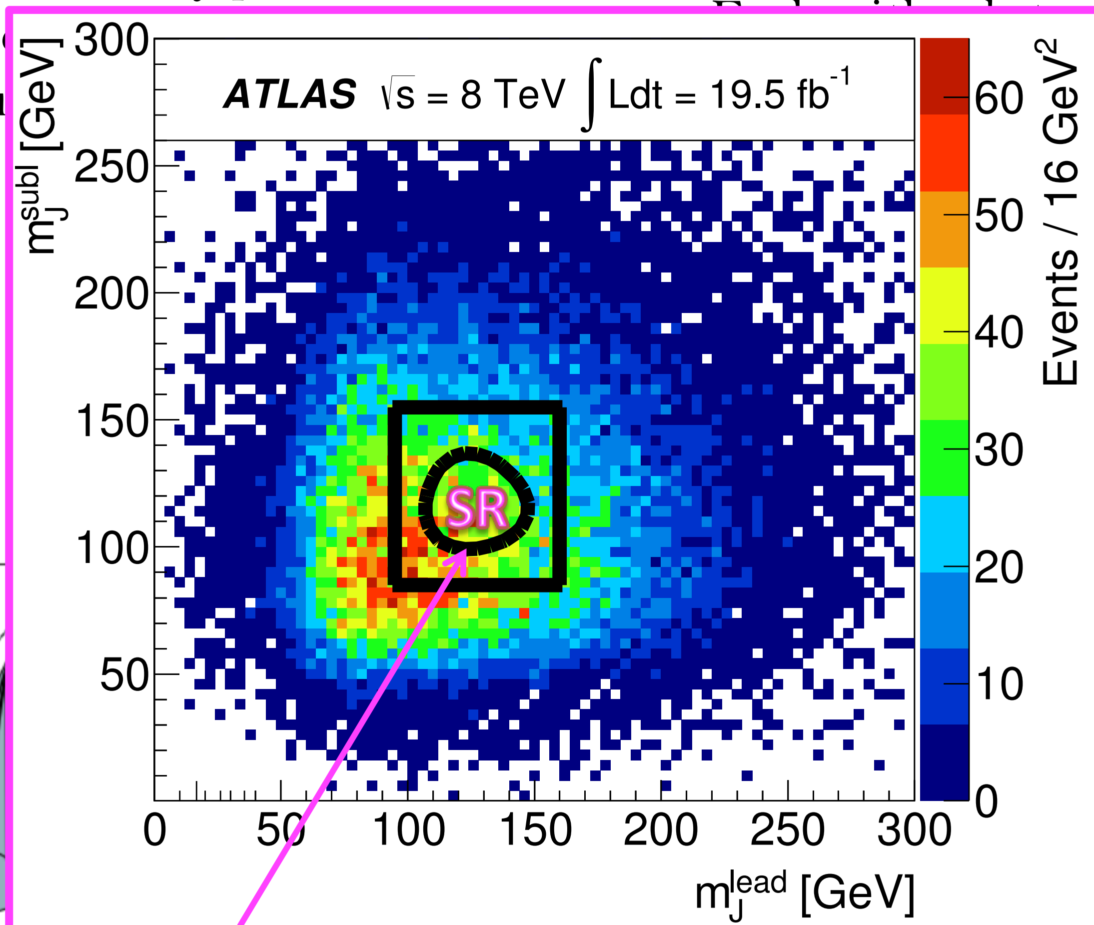

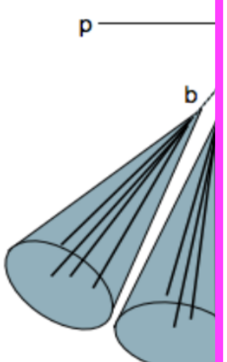

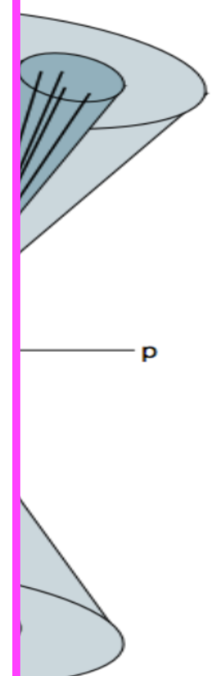

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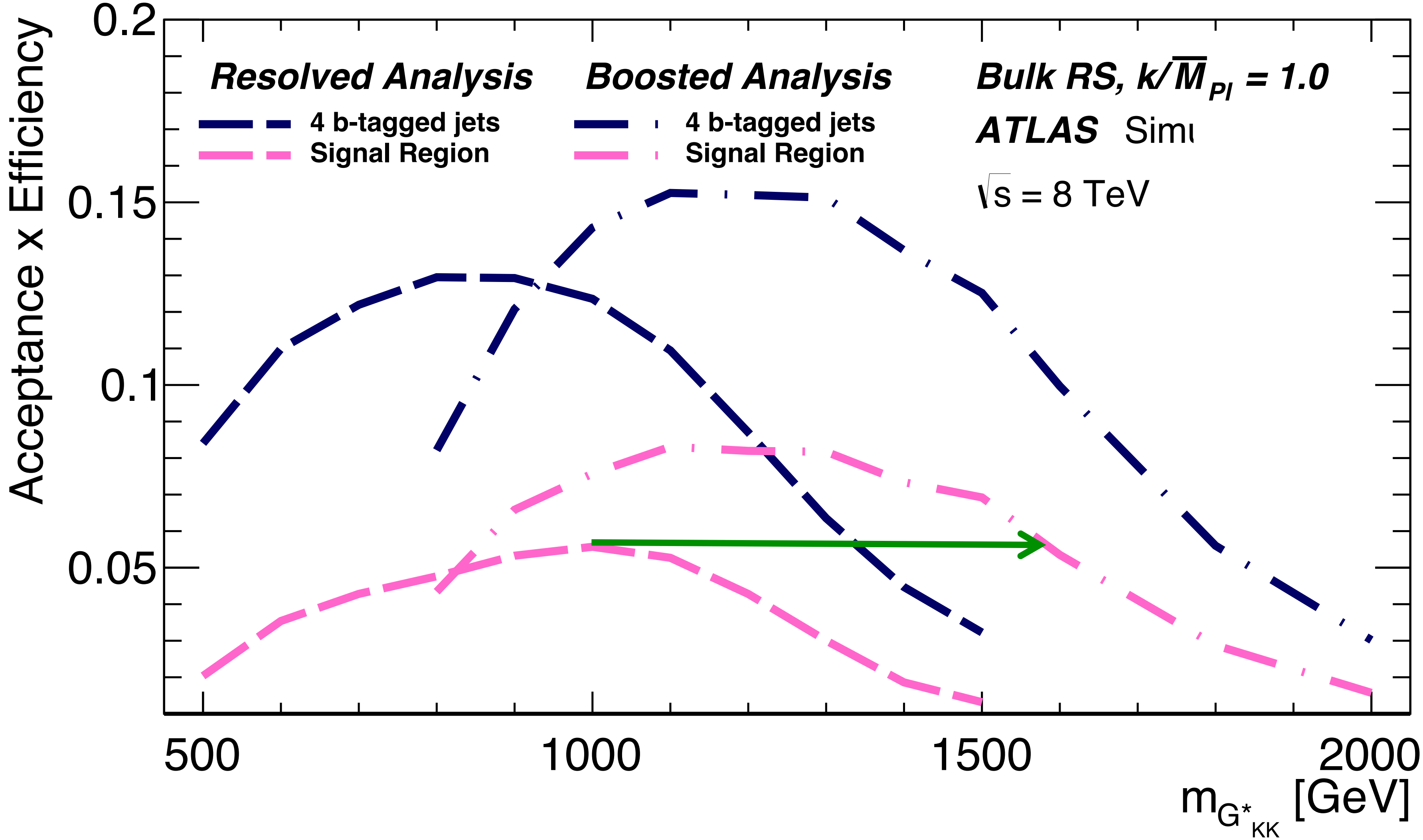
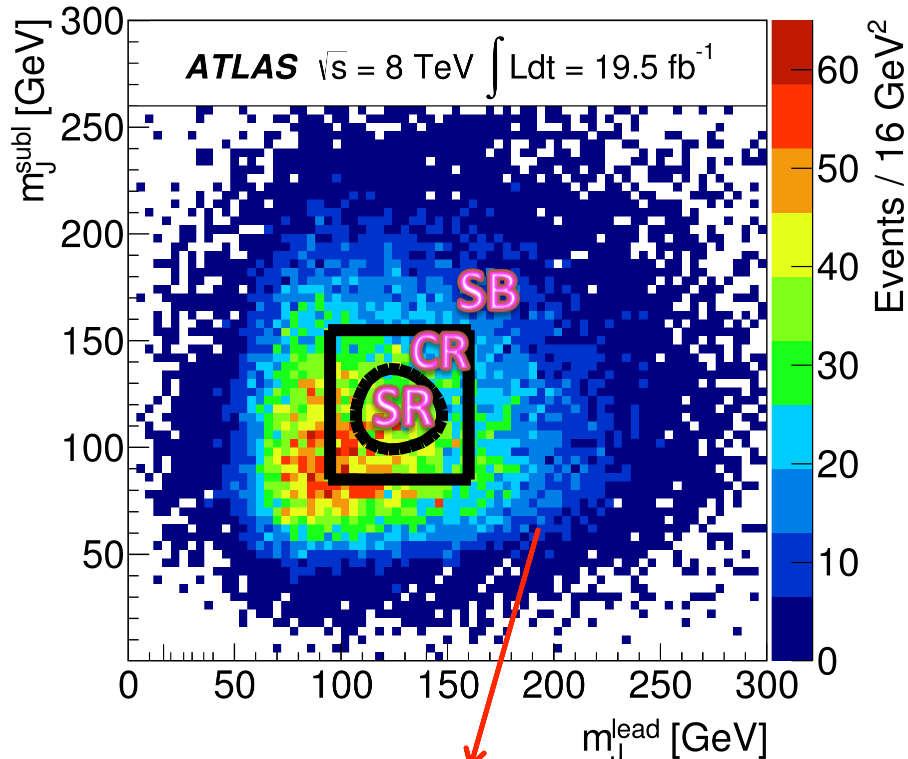
hh Boosted and Resolved Complementarity

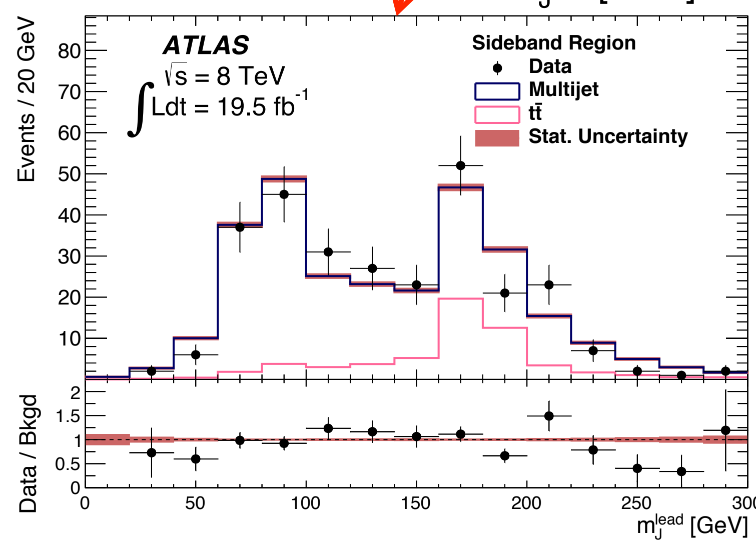
arXiv:1506.00285



hh Boosted Background Estimation

- Background: 90% QCD, 10% $t\bar{t}$
- QCD:
  - Use orthogonal control region with reduced number of b-tags
  - Shapes from 2(+3)-b-tag sample
- Top:
  - Shape from MC
- QCD and top normalizations from fit to leading jet mass in 4b-tag **SideBand** region





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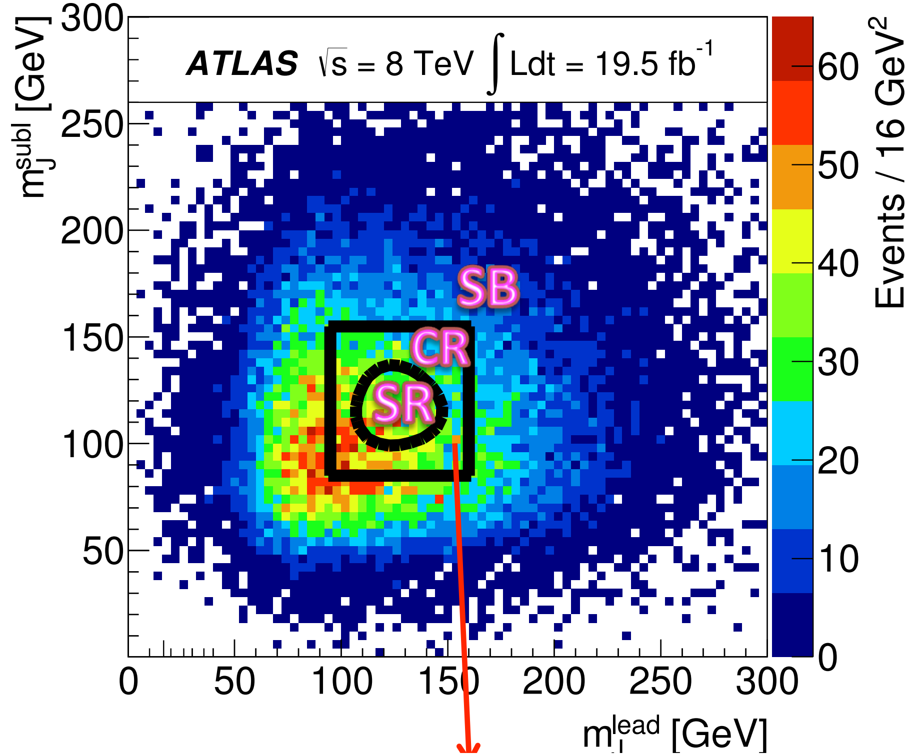
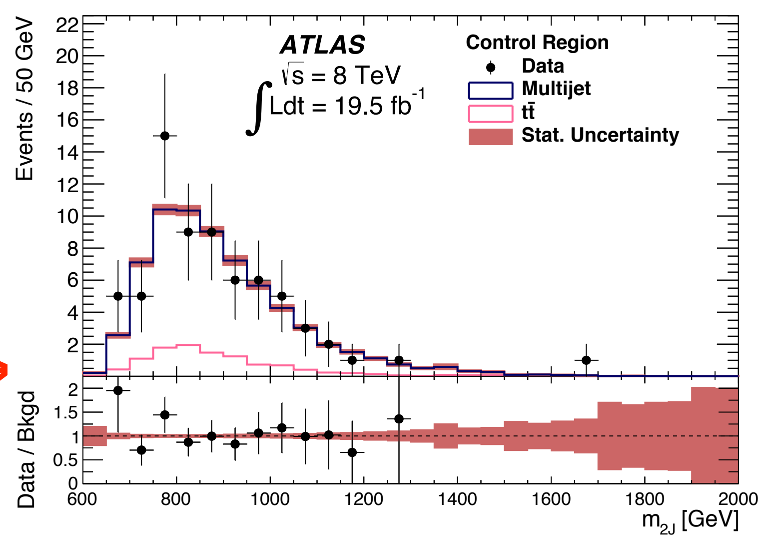
  - **Shapes from 2(+3)-b-tag sample**
- Top:
  - Shape from MC
- QCD and top normalizations from fit to leading jet mass in 4b-tag SideBand region
- Validate normalizations / shapes in **Control Region**





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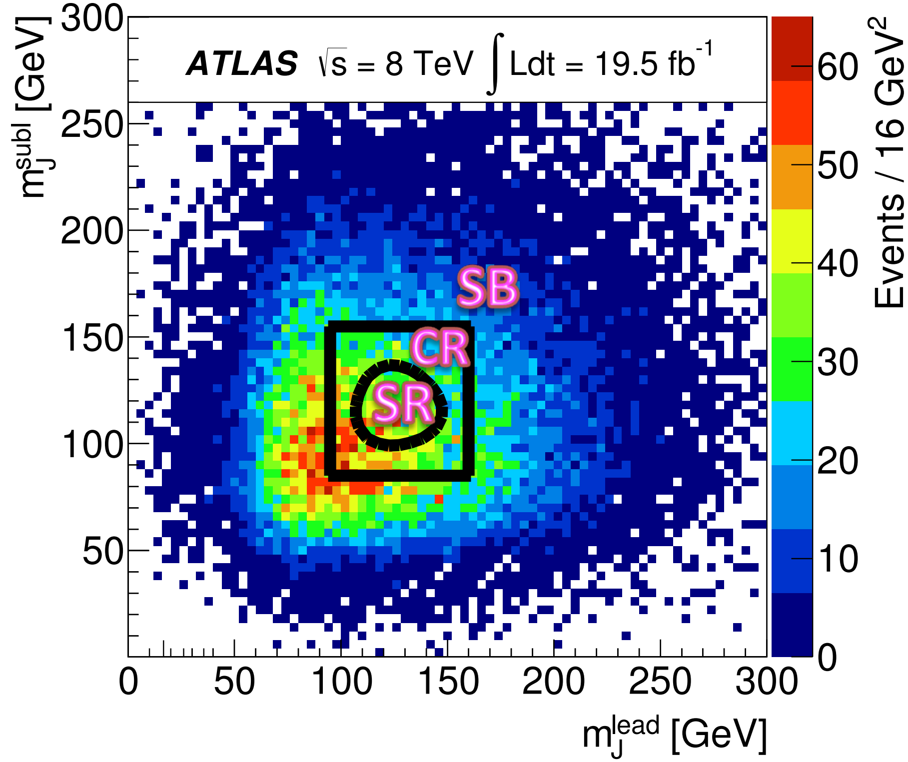
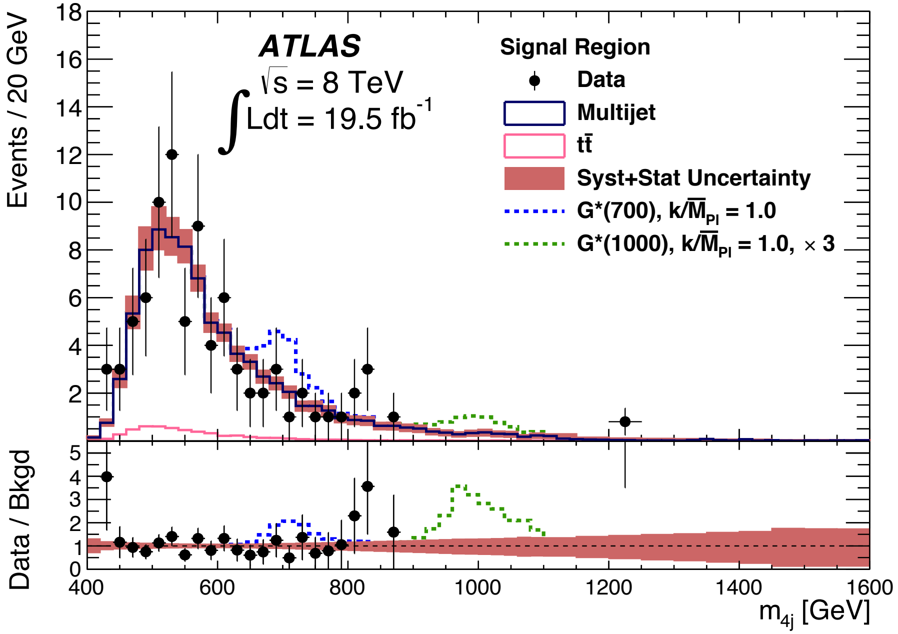


b-tagging relatively independent of jet mass

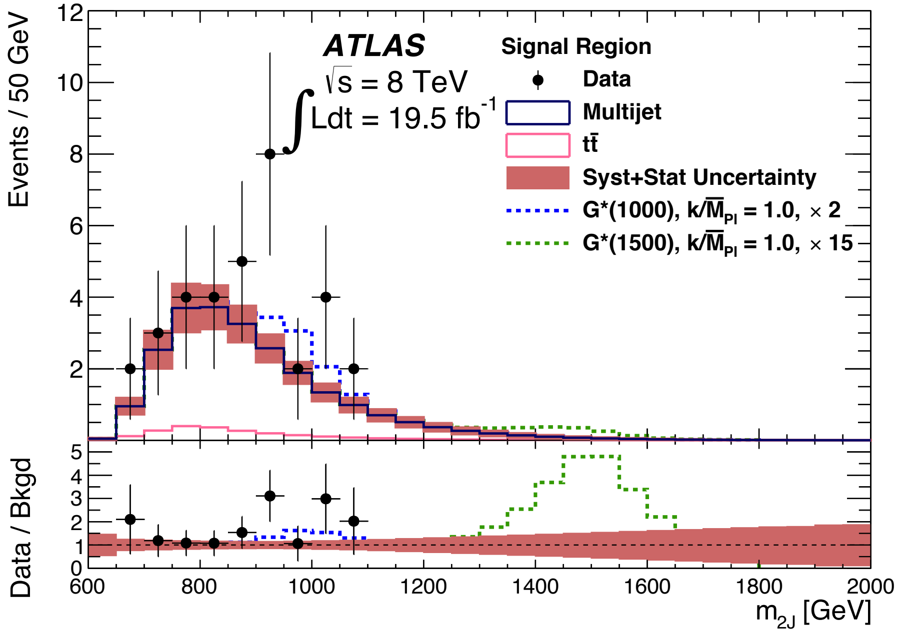
- Powerful handle on multi-jet backgrounds!

hh Results

Resolved analysis



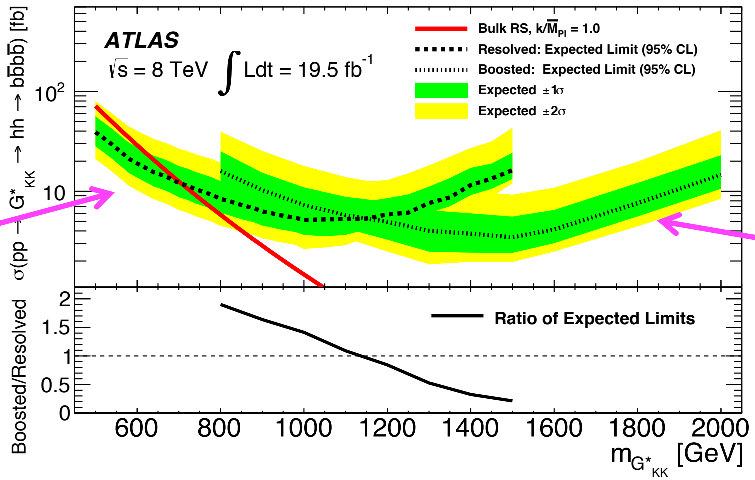
Boosted analysis



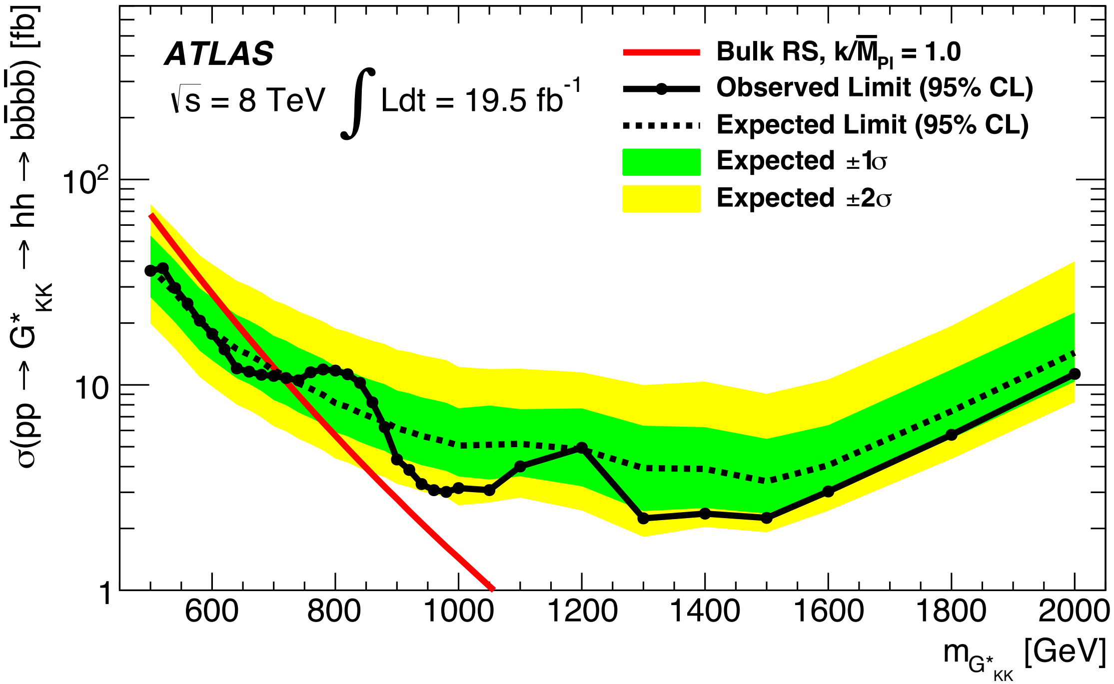
hh Results – RS Gravitons

arXiv:1506.00285

Resolved analysis



Boosted analysis

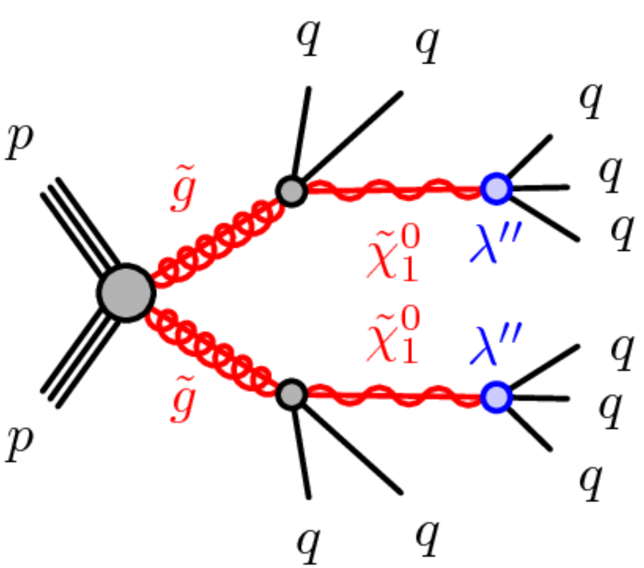


- Reaching O(fb) sensitivity in ~1 TeV range

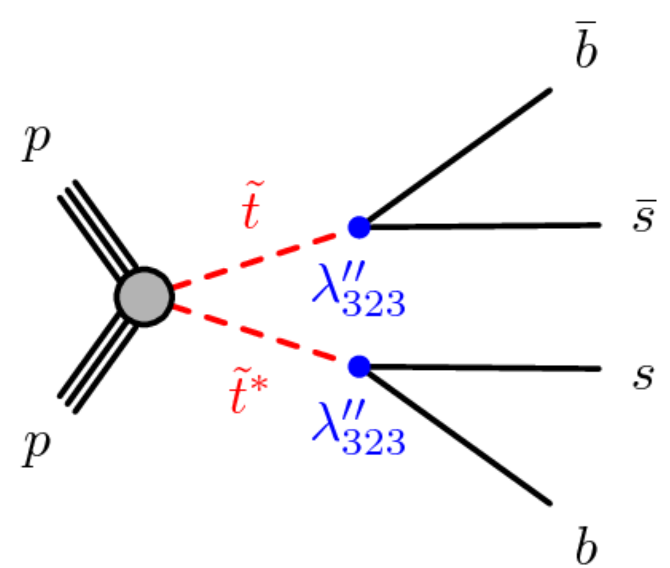
RPV SUSY

- Expand the scope of the SUSY search program to explore RPV signatures where the LSP decays
  - Focus on all hadronic modes → UDD models (no other RPV)
  - No missing energy in final state
  - Large multi-jet backgrounds, difficult to model and suppress

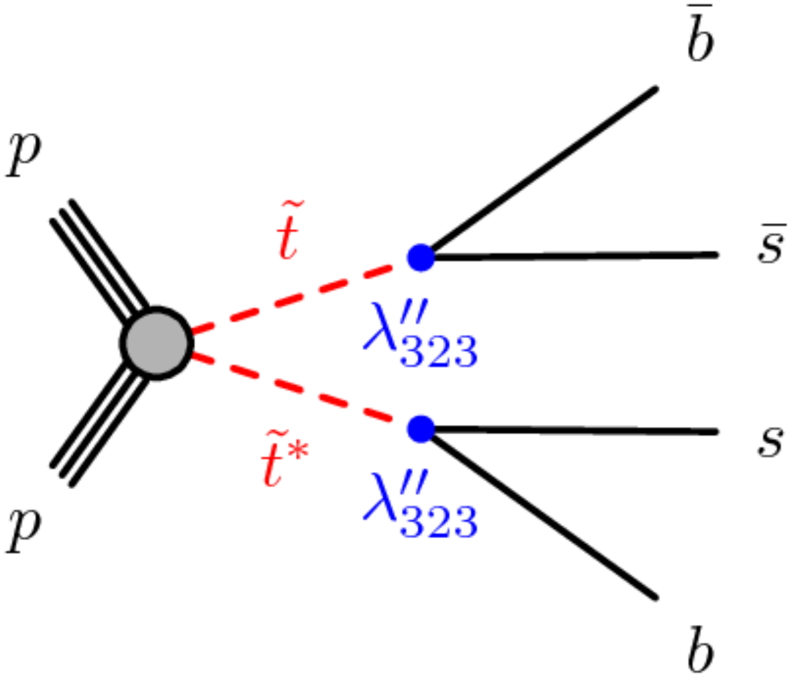
- New analysis methods needed!

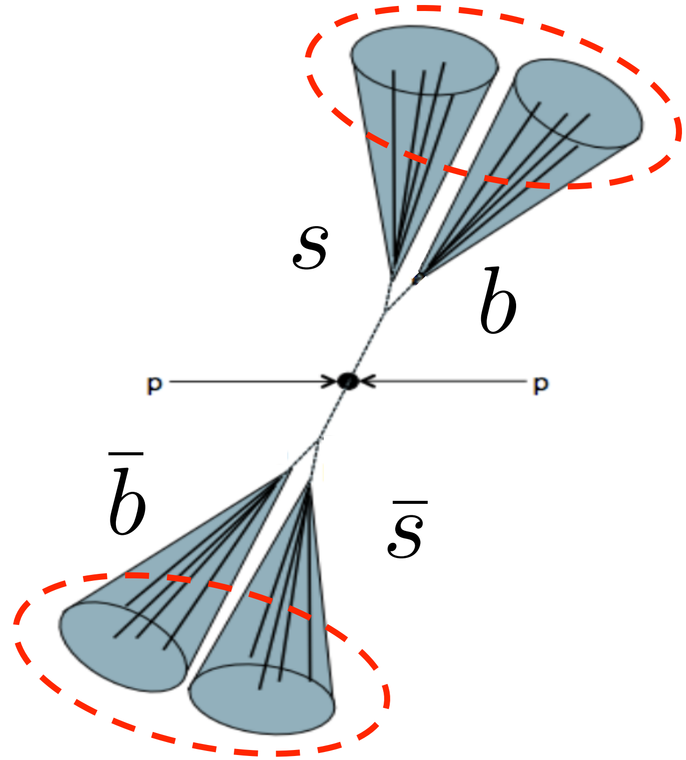


$$\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$$



RPV Stop

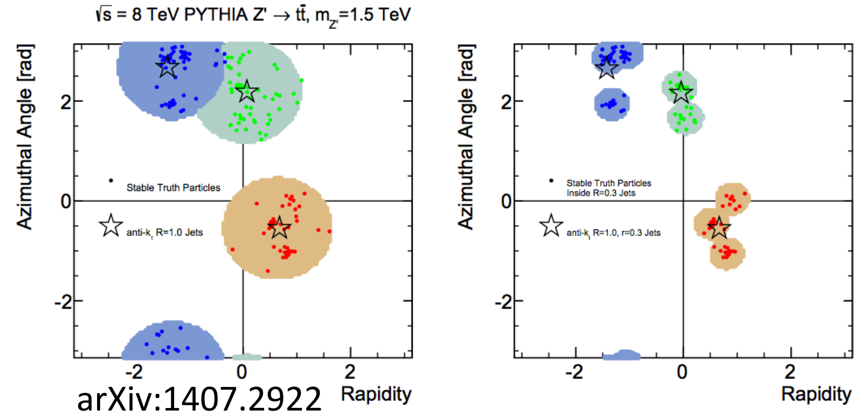




- Light stop needed to solve hierarchy problem in SUSY
  - R-Parity conserving stop (mostly) ruled out below mass of $\sim$650 GeV
- Benchmark model: Stop LSP, only $\lambda''_{323} \neq 0$
- Focus on mass range $m_{\tilde{t}} \sim \{100, 400\}$ GeV
- To reduce multi-jet background, focus on events with $p_{T,\tilde{t}} \gg m_{\tilde{t}}$
  - i.e. events with boosted stop→(bs) jets! Topology similar to HH!

RPV Stop Jet Reconstruction

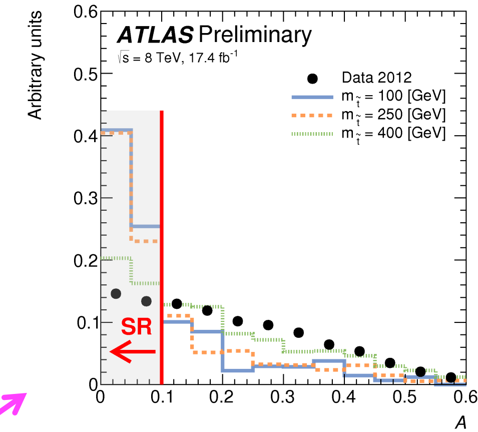
- Hadronic stop candidates from jet re-clustering
  - Use anti-k_T R=0.4 jets as input to anti-k_T R=1.5 jet algorithm
  - Benefit from calibrations and uncertainties of small-R jets

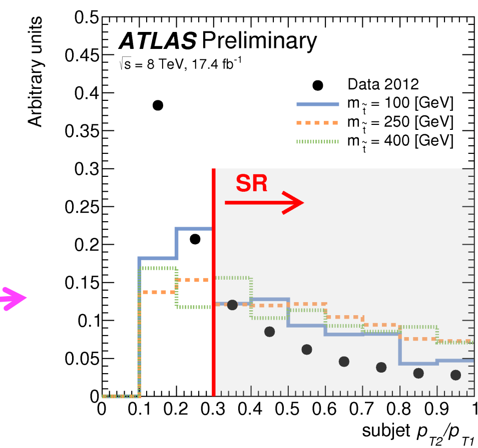


- Require two jets, p_T> 200 GeV, satisfying splitting criteria
  - Process constituents with C/A algorithm
  - Undo one step, require branches "a" and "b" satisfy

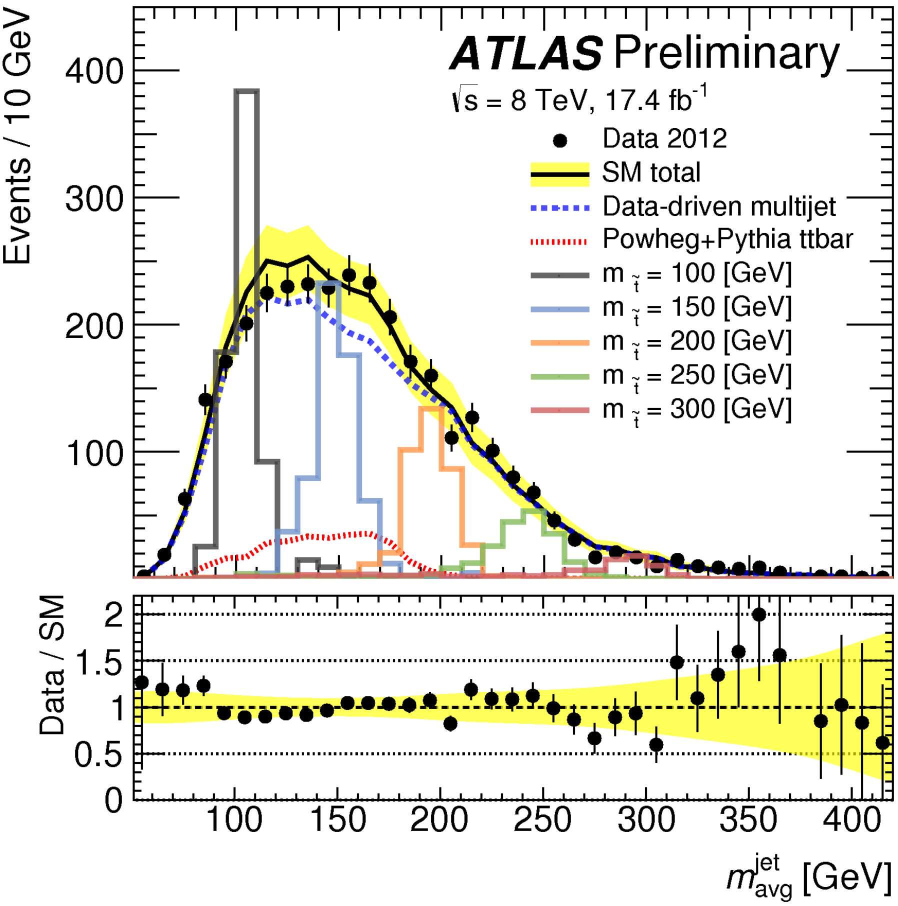
$$\frac{\min[p_T(a), p_T(b)]}{p_T(\text{large}-R)} > 0.1 \qquad \frac{m(i)}{p_T(i)} < 0.3, \quad i = a, b$$

- Signal region:
  - Event level / "Substructure" cuts
  - At least 2 b-tags in event





RPV Stop Results

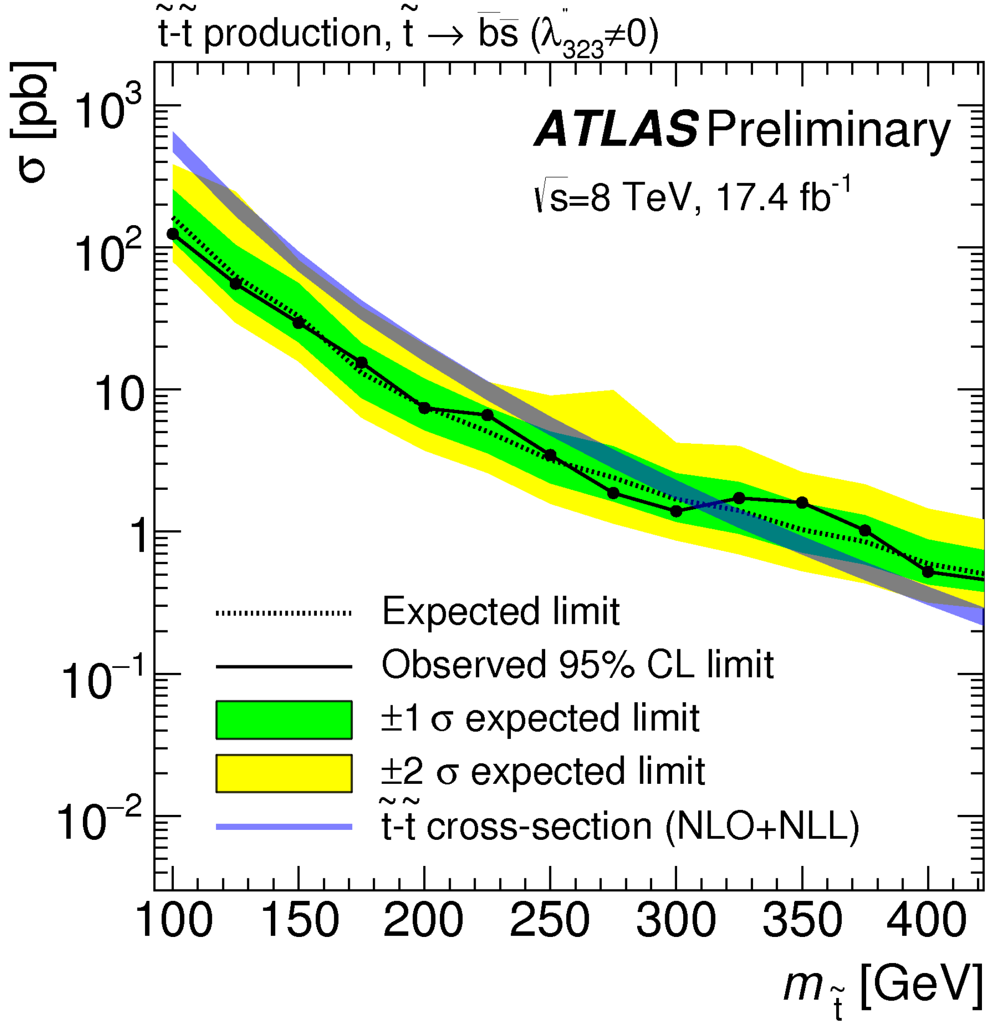


- Data driven multi-jet background
  - Shape from zero-b-tag events
  - Control regions from inverted event selection / substructure cuts to estimate normalization
- $t\bar{t}$ from MC (~10% of total)
- Approach similar to HH

- b-tagging relatively independent of jet mass
  - Powerful handle on multi-jet backgrounds!

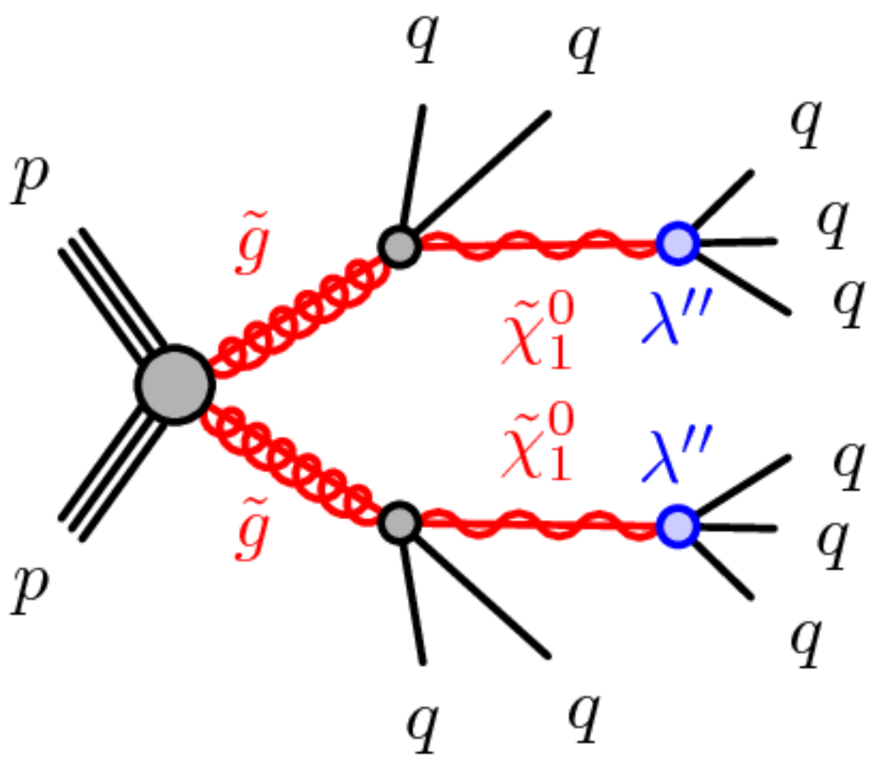
RPV Stop Results

- Stops with masses $100 < m_{\tilde{t}} < 310\ GeV$ excluded
- Fills in gap between CDF and CMS
  - CDF excludes $m_{\tilde{t}} \lesssim 100\ GeV$
  - CMS excludes $200 \lesssim m_{\tilde{t}} \lesssim 385\ GeV$



RPV Multi-Jets

arXiv:1502.05686



- Between 10 (light quarks only) and 22 (top decays) partons

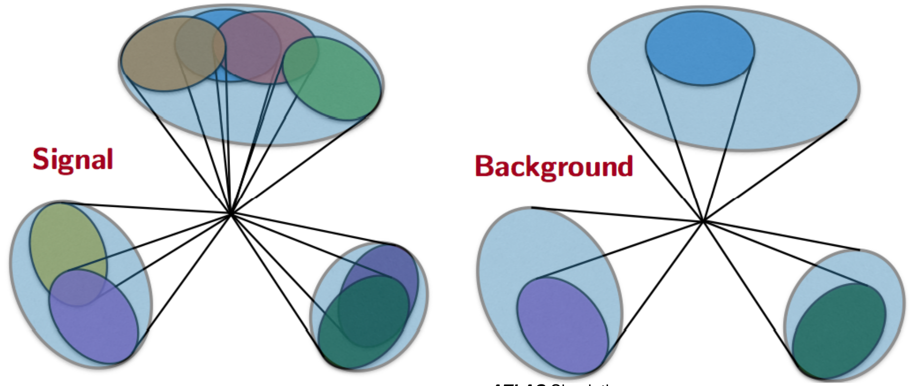
RPV Multi-Jets Analysis Overview

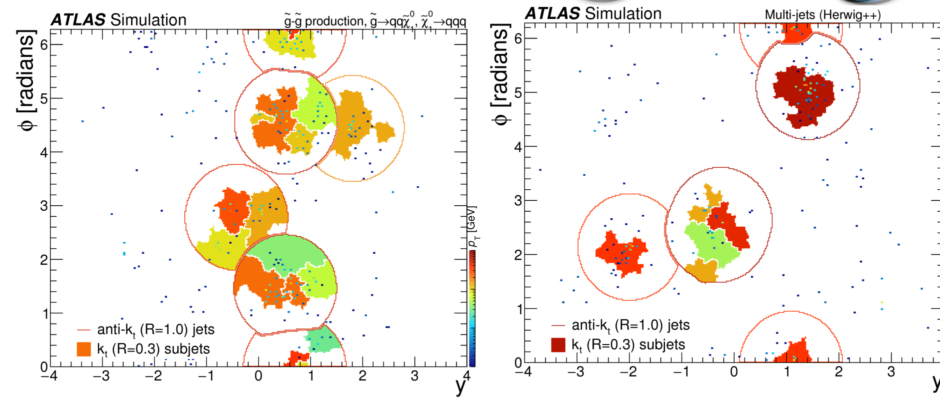
arXiv:1502.05686

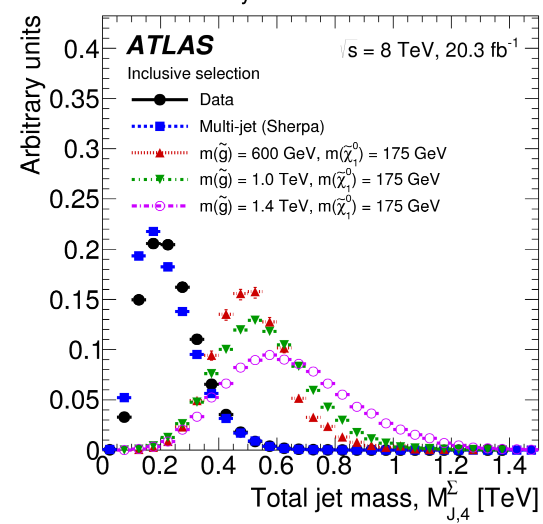
- High multiplicity → significant "accidental" overlap
- Use large-R jets to capture this **accidental substructure**
  - Multi-parton jets with large mass
  - Method based on: arXiv:1402.0516
- Require 4 anti-k_T R=1.0 trimmed (R_{sub}=0.3, f_{cut}=0.05) jets, p_T > 100 GeV
- Excellent discrimination with

$$M_{J,4}^{\Sigma} = \sum_{i=1}^{4} M_{J,i}$$

- Background estimation
  - 3-jet events to build jet templates
  - Jet templates sampled for each jet to build PDF of $M_{J,4}^{\Sigma}$ for each event
  - http://arxiv.org/abs/1402.0516







RPV Multi-Jets Results

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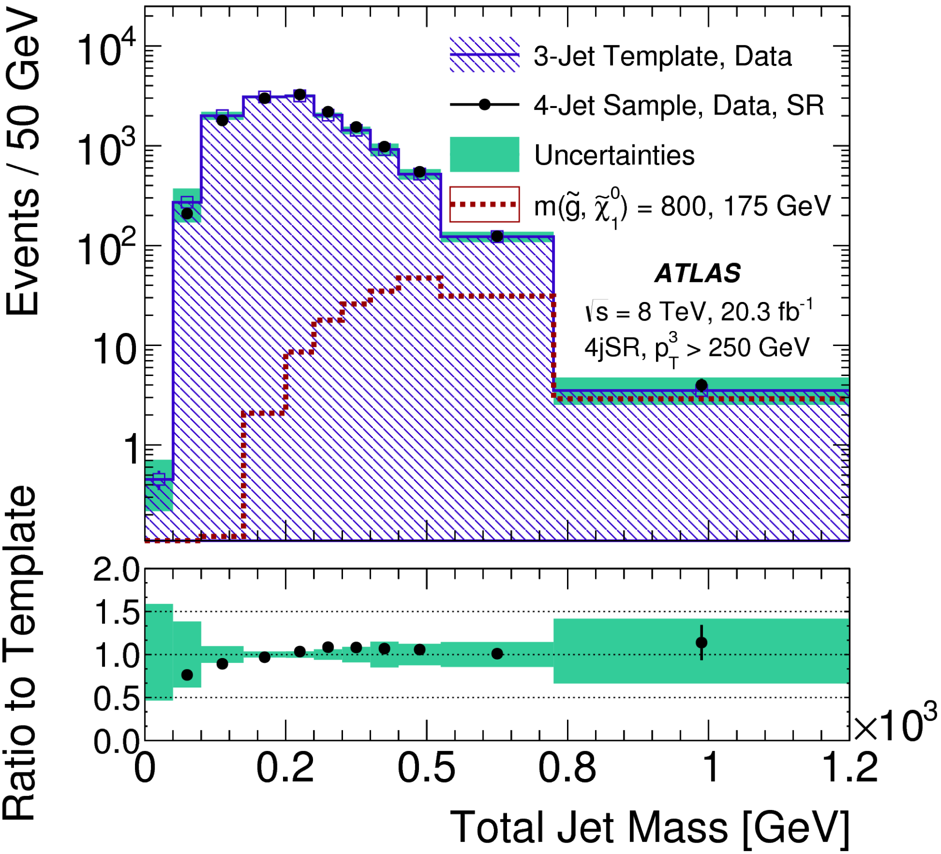
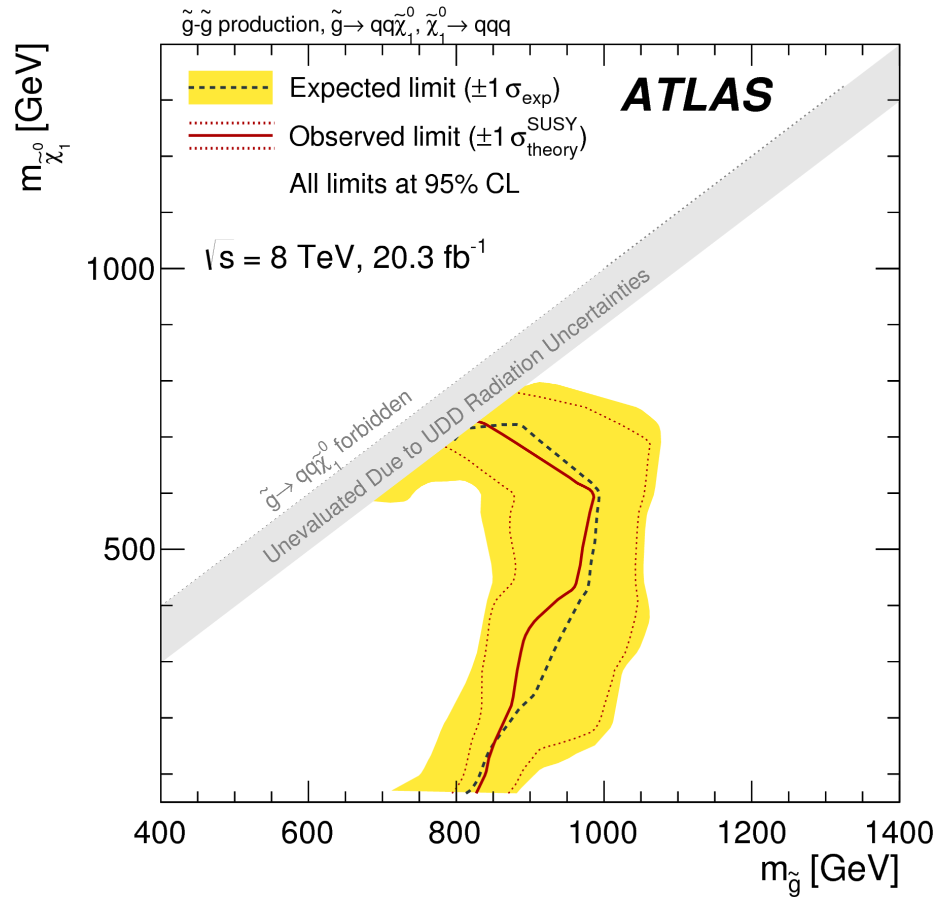




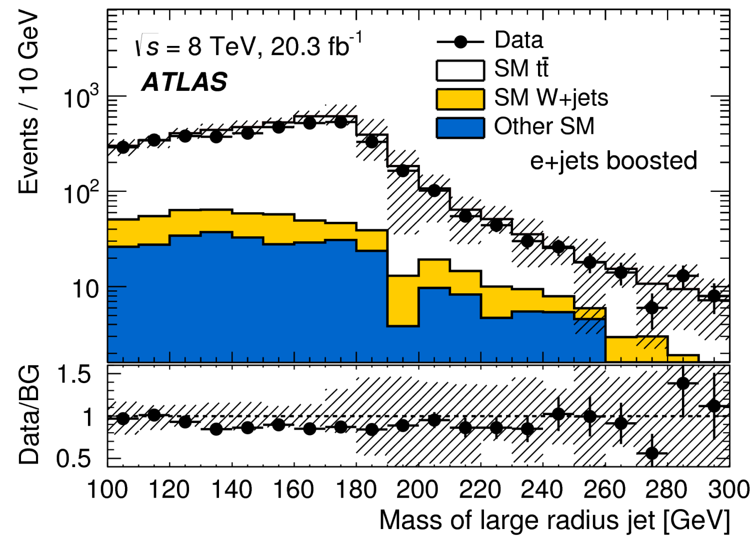
- Strong limits out to $m_{gluino} \sim 1$ TeV
- Entirely new final state explored!

This analysis has been discussed at BOOST from the theory perspective several times, and this is the result of excellent collaboration between the theoretical and experimental community at BOOST!

$t\bar{t}$ Resonances / Heavy Tops

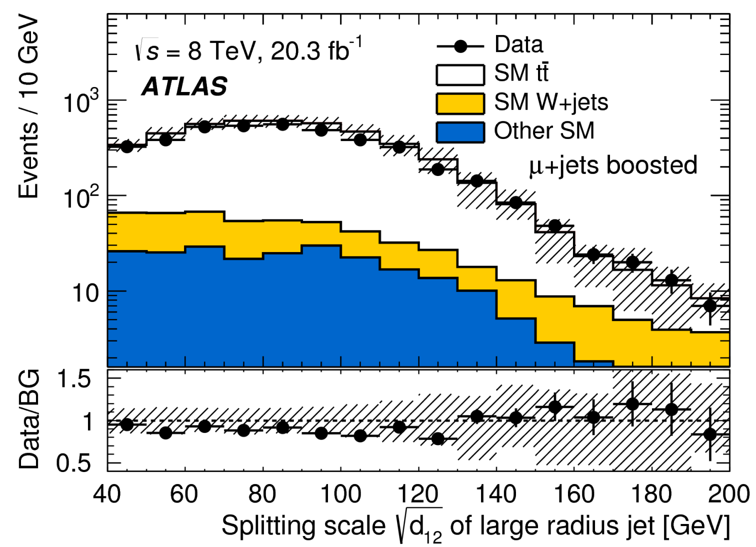
$t\bar{t}$ Resonances

- BSM physics and tops
  - Large top mass ⇒ special role in EWSB
  - New particles that preferentially couple to mass like to decay to tops!
  - Many models with $t\bar{t}$ resonances
  - TeV scale resonance produce boosted tops
  - Many of these ruled out ⇒ push to higher masses!



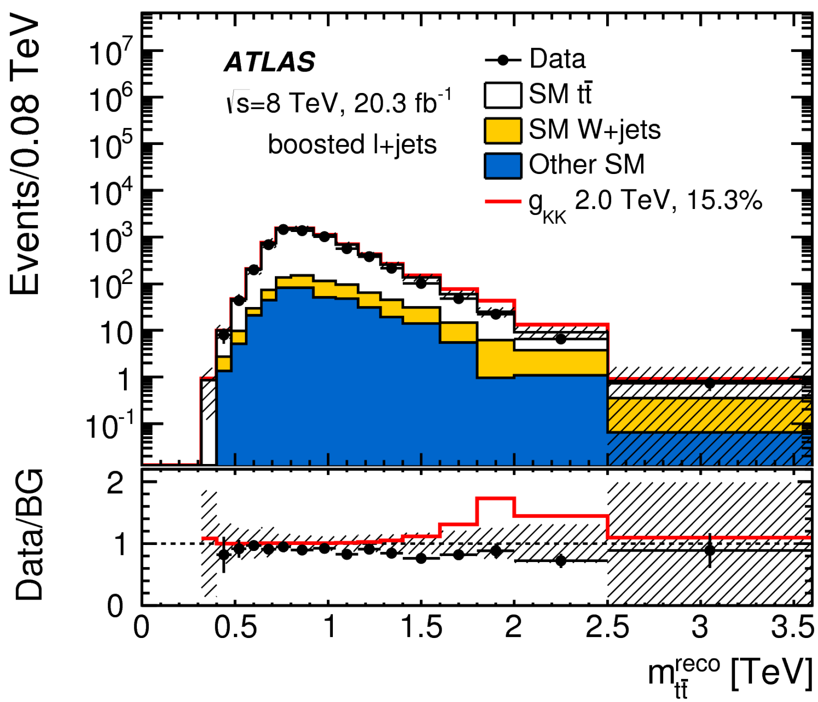
- Search in semi-leptonic $t\bar{t}$ events
  - Resolved and boosted selections
  - Categorize by number of b-jets

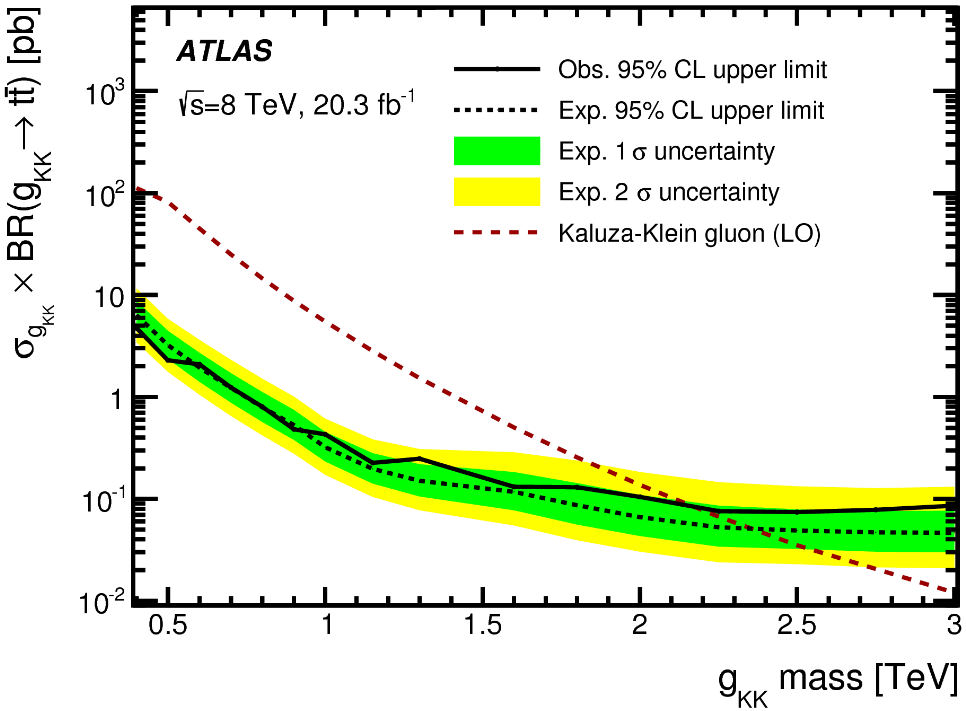
- Boosted hadronic top jets
  - Anti-kt R=1.0, trimmed with R_{sub}=0.3 and f_{cut} = 0.05
  - $p_T > 300$ GeV
  - Mass > 100 GeV
  - Splitting scale: $\sqrt{d_{12}} > 40$ GeV



$t\bar{t}$ Resonances Results

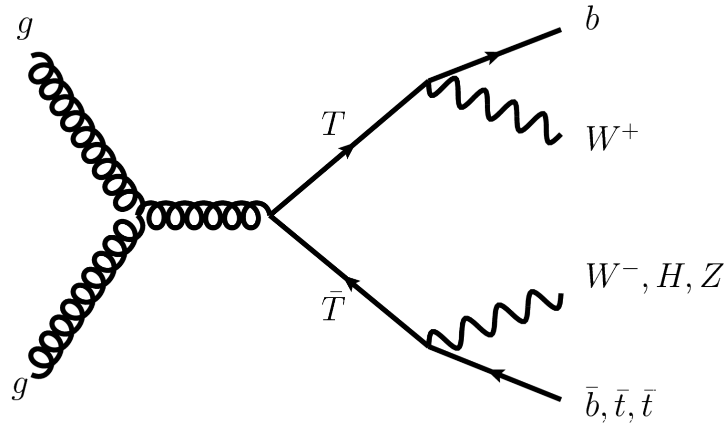
- KK Gluons ruled excluded below 2.2 TeV
  - Limits also set as function of resonance width
- Limits also set on Z' and color octets

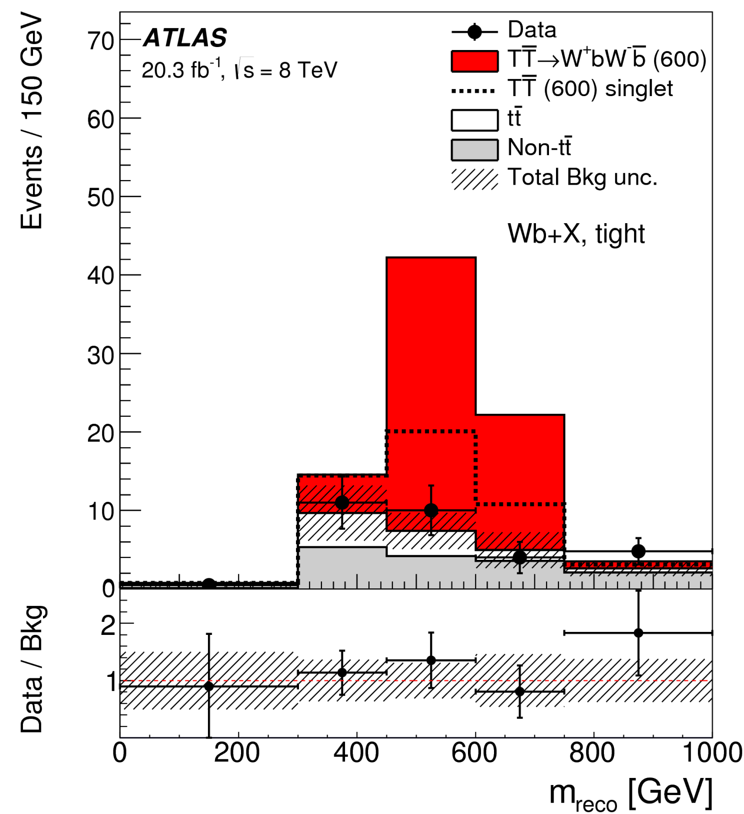




VLT→Wb

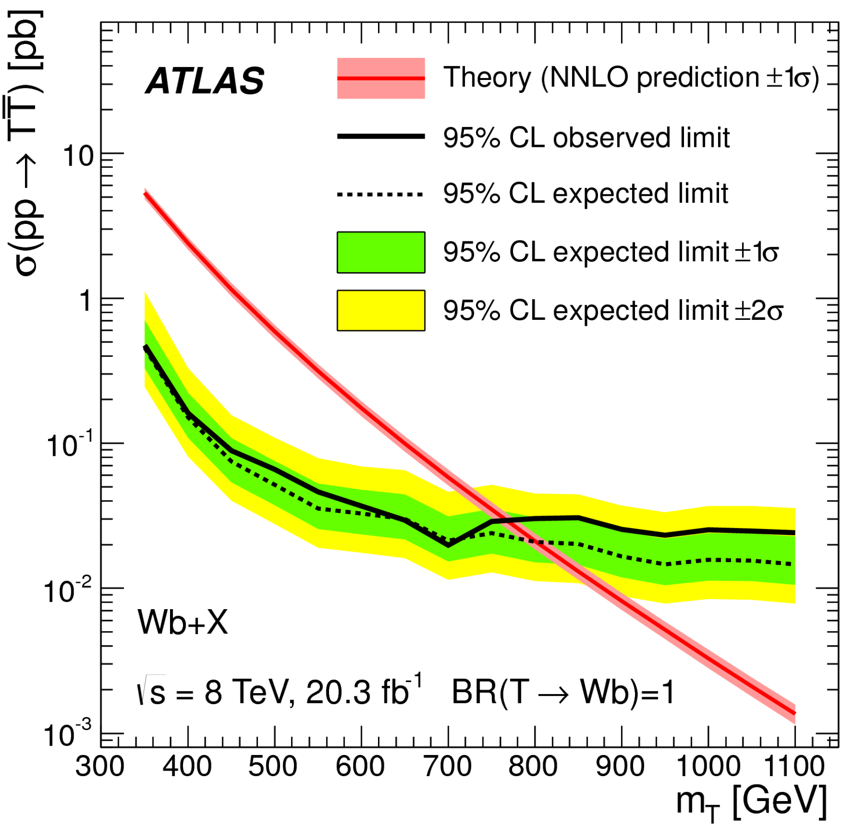
- New heavy quark states
  - Vector like coupling to weak currents (both left and right handed charge current)
  - Singlet / doublet / triplet SU(2) representations possible
- Aim to be as model independent as possible
  - But focus on enhanced 3rd generation coupling
  - Decays to (W/Z/H) + (t/b) quarks
  - Search in several decay channels to cover BR plane
- High mass T →decay products boosted!
- Search for T→Wb+X with at least 1 lepton
  - Using R=0.4 anti-k_T jets, with at least 2 b-jets
  - H_T>800 GeV
  - Angular requirements
  - Boosted: W contained in one jet p_T>400 GeV
  - Resolved: W from two jets with 80<m_{jj}<120 GeV
  - Combine W with b-jet to reconstruct T

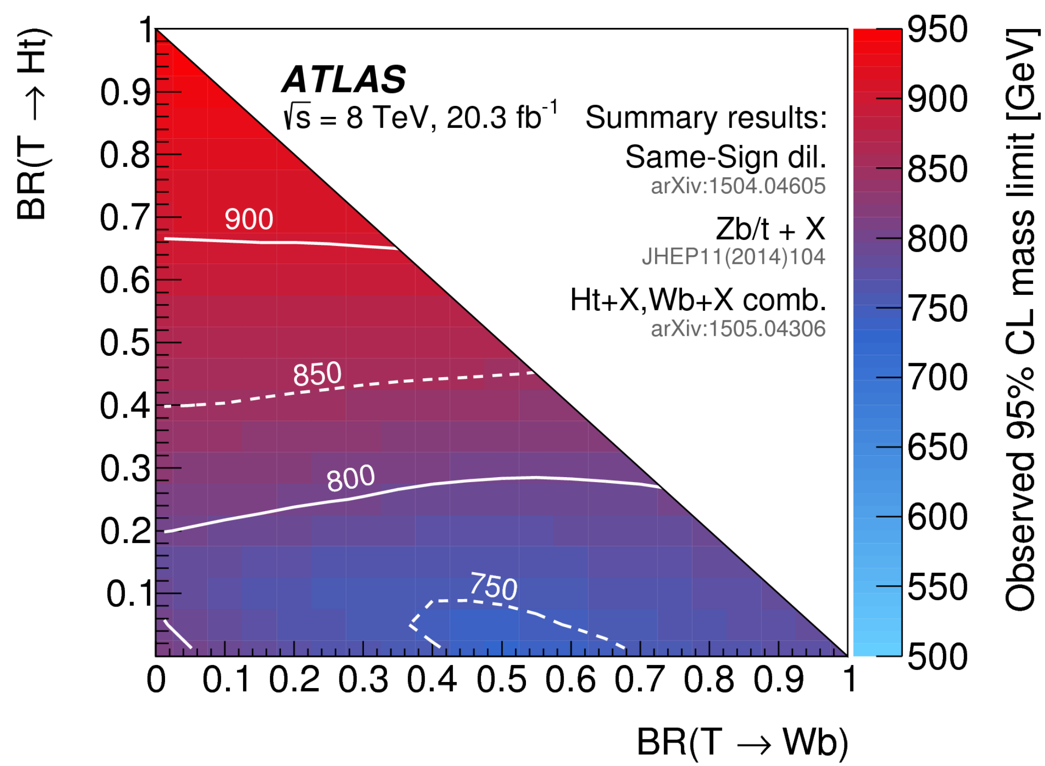




VLT Results

- Limits set assuming BR(T→Wb)=1
- Other complementary searches are used to cover the full BR plane
  - Limits set in BR(T→Ht) vs BR(T→Wb) plane
- Exclude T masses below 750-950 GeV (depending on BR)





Summary

- Pushing to high mass for a wide variety of new physics signals
  - In some cases, e.g. stop, boosted techniques give us access to the low / medium mass range as well!
- Boosted techniques are working very well
  - And can be integrated with b-tagging
- Many new techniques developed and put to use

References

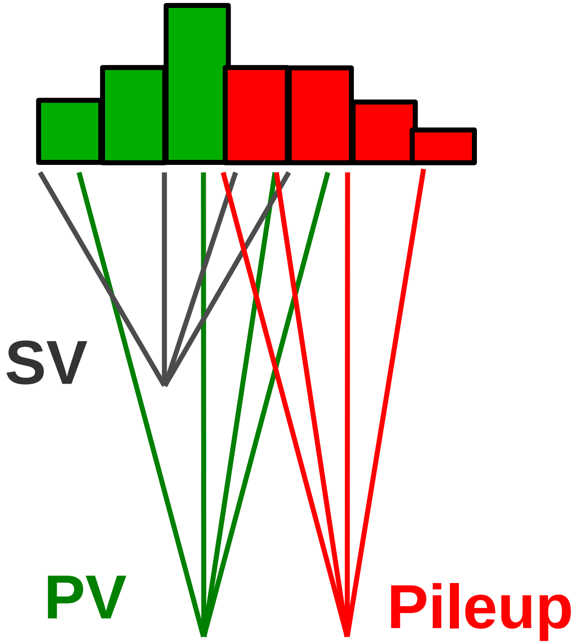
- **Run 1 Track jet b-tagging:**
  - http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-013/
- **hh→4b:**
  - http://arxiv.org/abs/1506.00285
- **RPV Stop**:
  - https://cds.cern.ch/record/2037653
- **RPV Multi-jets**:
  - http://arxiv.org/abs/1502.05686
  - http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.112016
- $t\bar{t}$ **Resonances:**
  - http://arxiv.org/abs/1505.07018
- **VLT →Wb:**
  - http://arxiv.org/abs/1505.04306

Backup

Track Jet b-tagging

- Use the charged particle tracks to build track jets

- B-tagging using track jets
  - Insensitive to pileup
  - Small radius to identify close-by objects
  - Can be optimized for b-tagging
  - Independent of calorimeter
  - Good angular resolution w.r.t. b-hadron

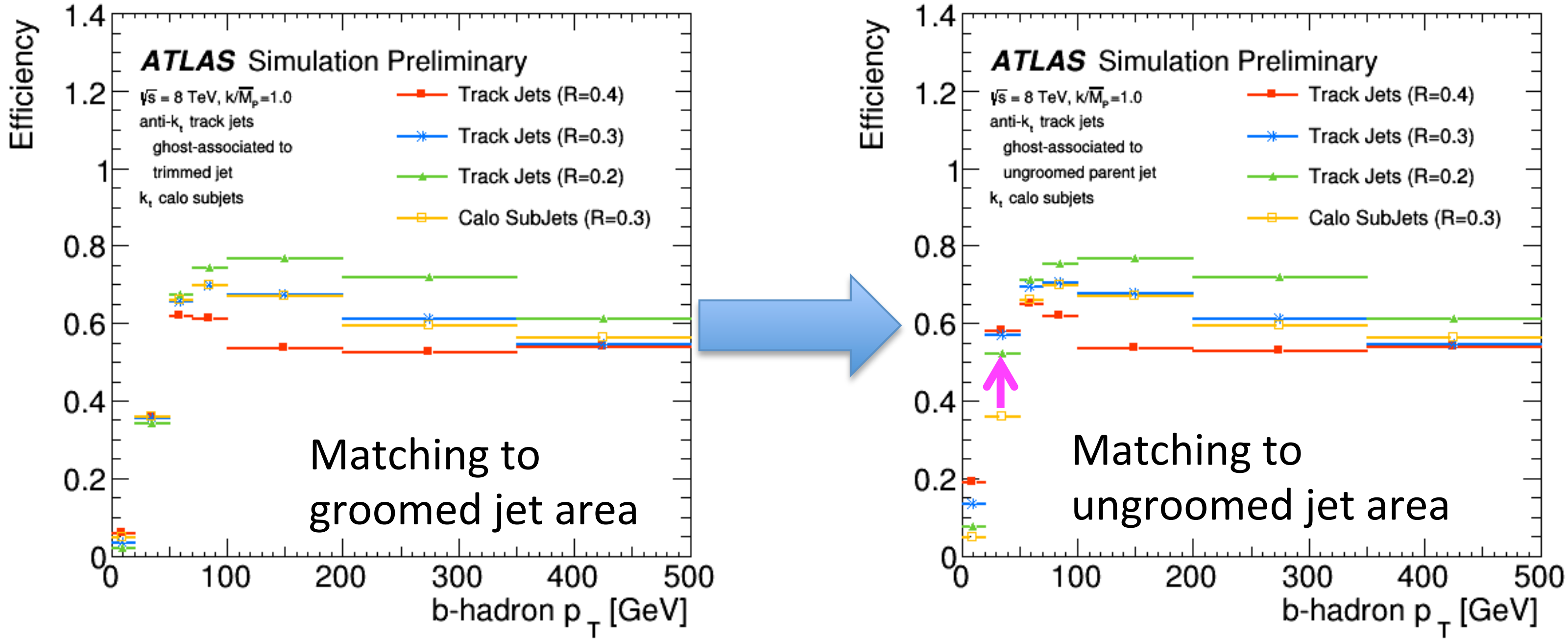


- Ghost association:
  - associate track jets to calorimeter jets, thus providing b-tag information

Run-I Higgs (→bb) Tagging

ATL-PHYS-PUB-2014-013

- R=1.0 calorimeter jets trimmed with k_T R=0.3 subjets and f_{cut}=0.05, to measure kinematics / substructure
- b-tagging with small R=0.3 track jets to resolve close-by b-hadrons
- Ghost association of track jets to large-R to provide b-tagging
  - Matching to ungroomed parent jet area provides large improvement in acceptance to find b-hadron



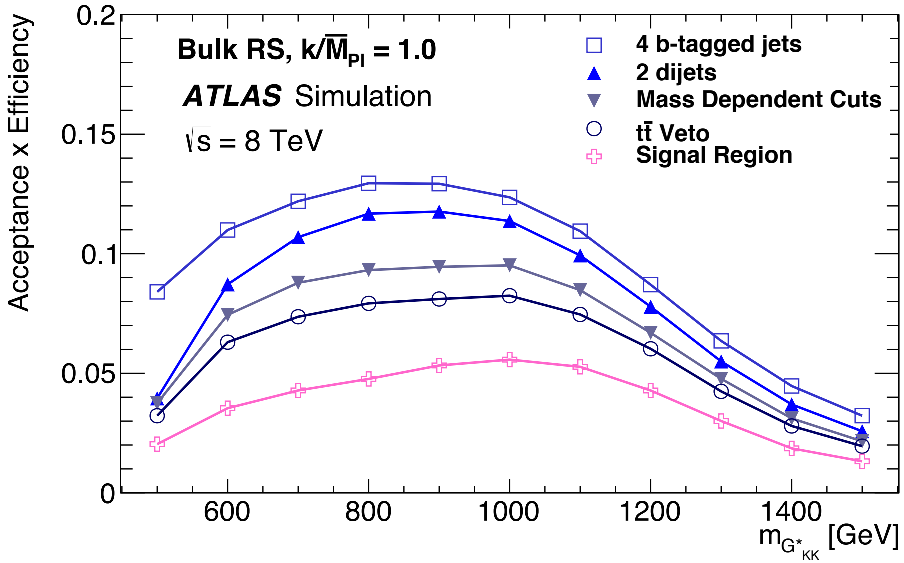
HH Analysis Overview

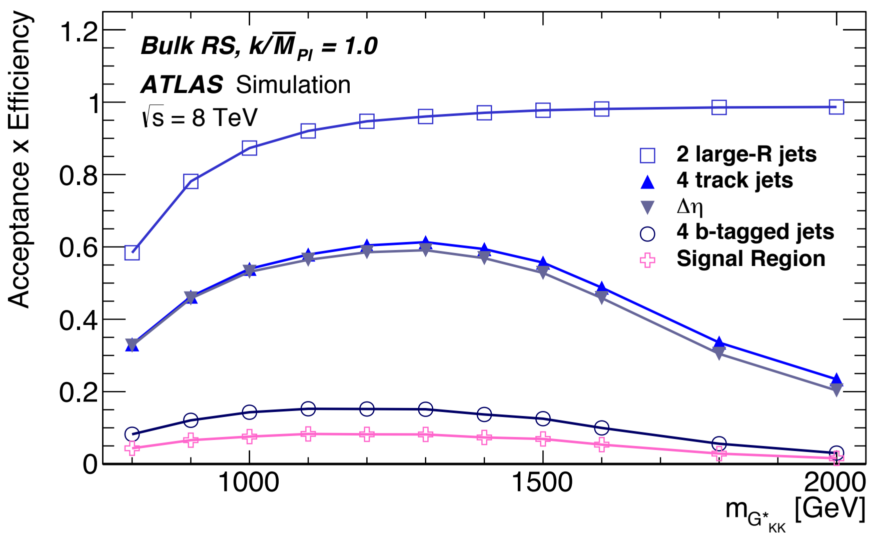
Resolved analysis:

1. Four b-tagged anti-k_T R=0.4 jets
2. Arrange into close-by pairs, $\Delta R<1.5$
3. Mass dependent p_T and $|\Delta\eta|$ cuts
4. ttbar veto, using 5[th] jet to test consistency with m_W / m_{top}

Boosted analysis:

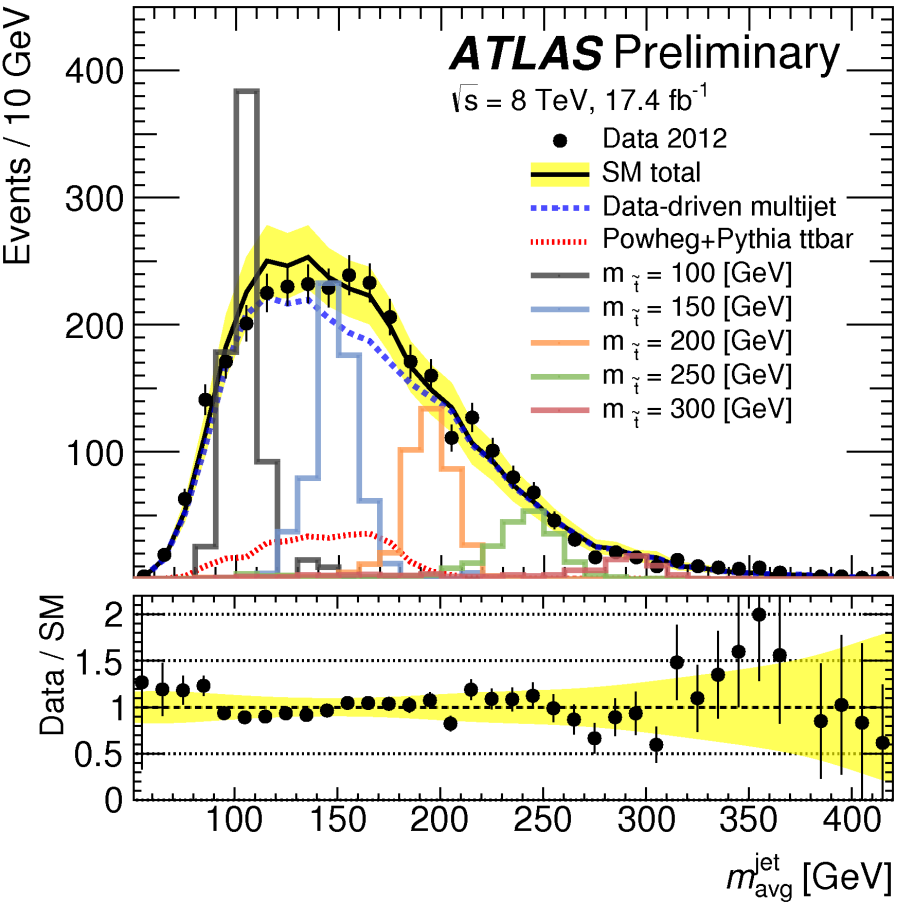
1. Two anti-k_T R=1.0 jets, trimmed with R_{sub}=0.3 and f_{cut}=0.05
2. Each with 2 b-tagged R=0.3 track jets
3. p_T and $|\Delta\eta|$ cuts

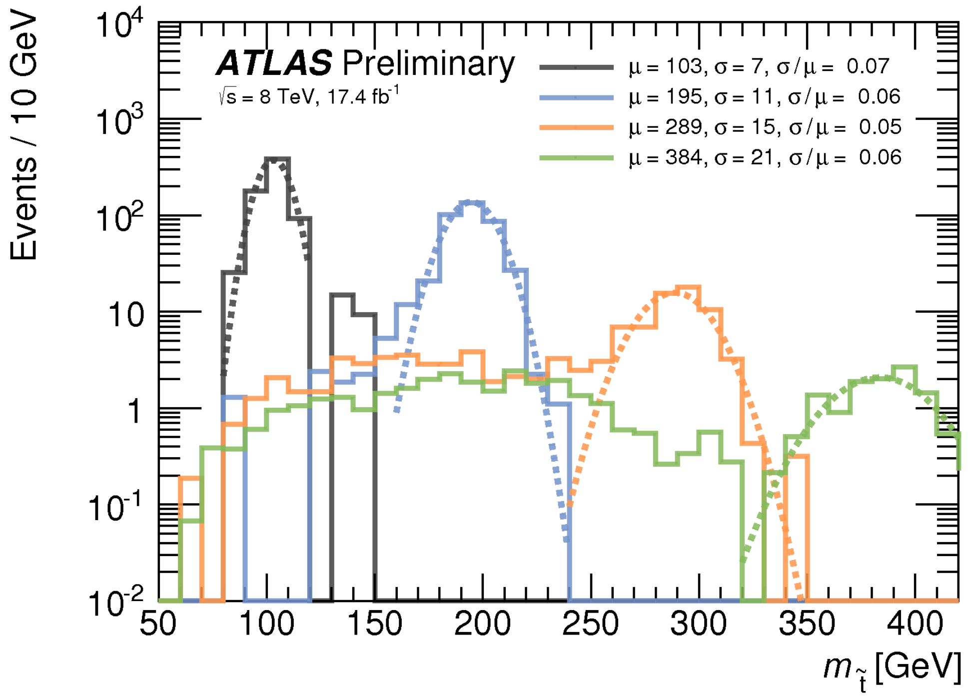




Signal region: $X_{hh} = \sqrt{\left(\frac{m_{\rm lead}-124}{0.1\times m_{\rm lead}}\right)^2+\left(\frac{m_{\rm subl}-115}{0.1\times m_{\rm subl}}\right)^2} < 1.6$

RPV Stop Results

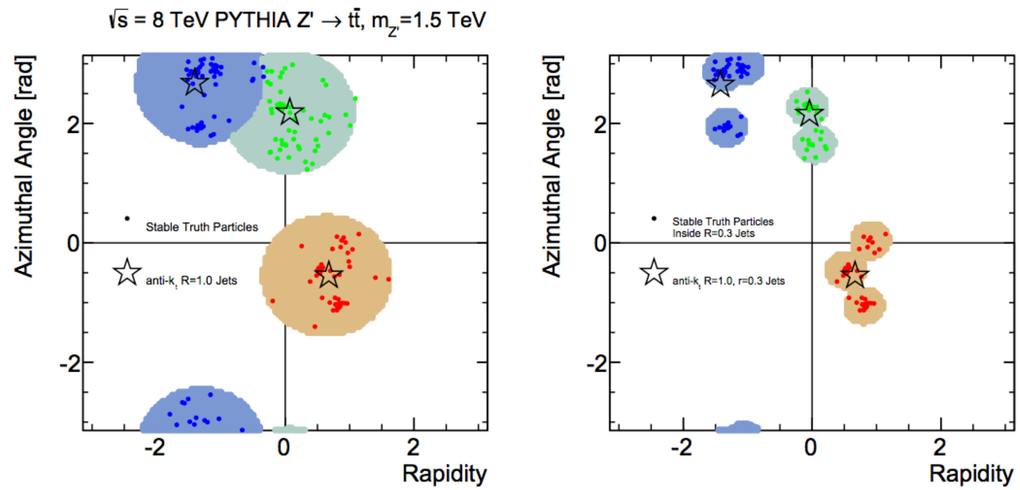




- Excellent resolution in core of signal mass distributions
- At high stop masses, large fraction of decays not contained in one jet
  - Leads to long low-mass tail

RPV Stop Jet Reconstruction

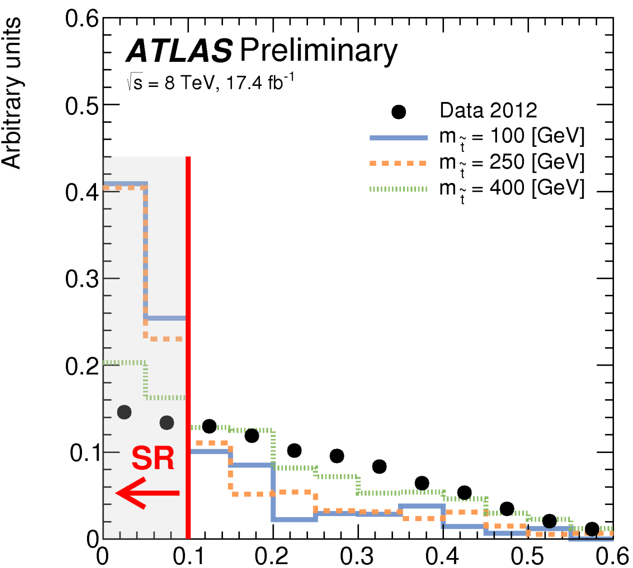
- Hadronic stop candidates from jet re-clustering
  - Use anti-k_T R=0.4 jets as input to anti-k_T R=1.5 jet algorithm
  - Benefit from calibrations and uncertainties of small-R jets



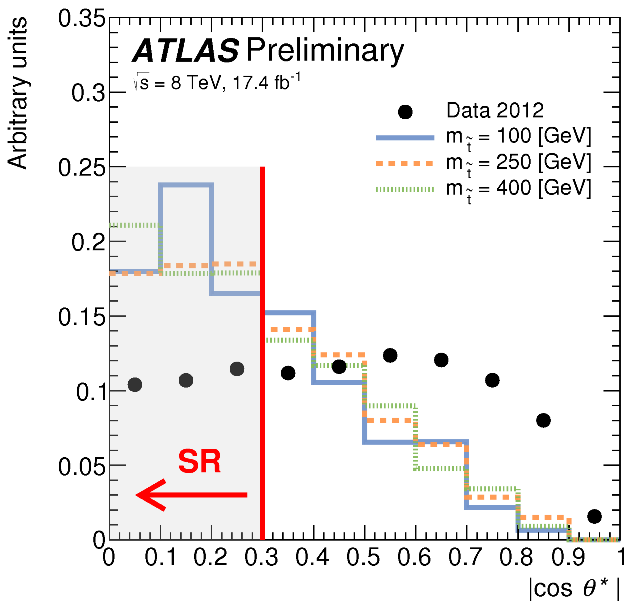
- Further suppress background with splitting criteria
  - Process jet constituents with C/A algorithm, undo one step
  - Require branches "a" and "b" satisfy
  - $\frac{\min[p_T(a), p_T(b)]}{p_T(\mathrm{large}-R)} > 0.1$ and $\frac{m(i)}{p_T(i)} < 0.3, \quad i = a, b$

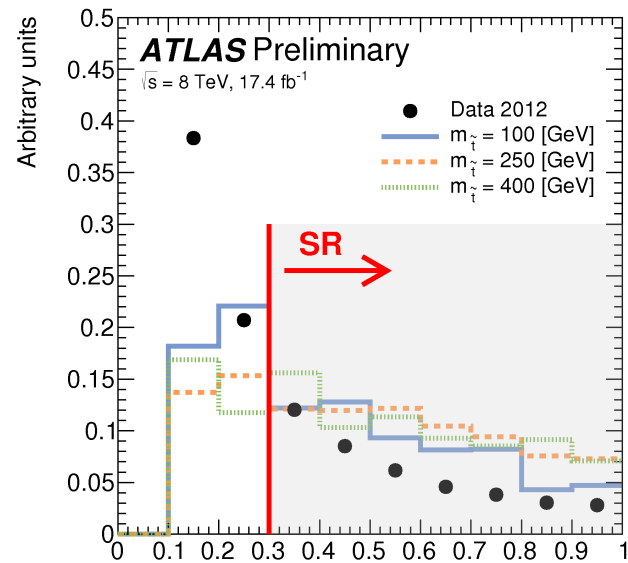
RPV Stop Signal Selection

- Require two large-R jets with p_T>200 GeV
- Signal region:
  - Event level / “Substructure” cuts
  - At least 2 b-tags in event



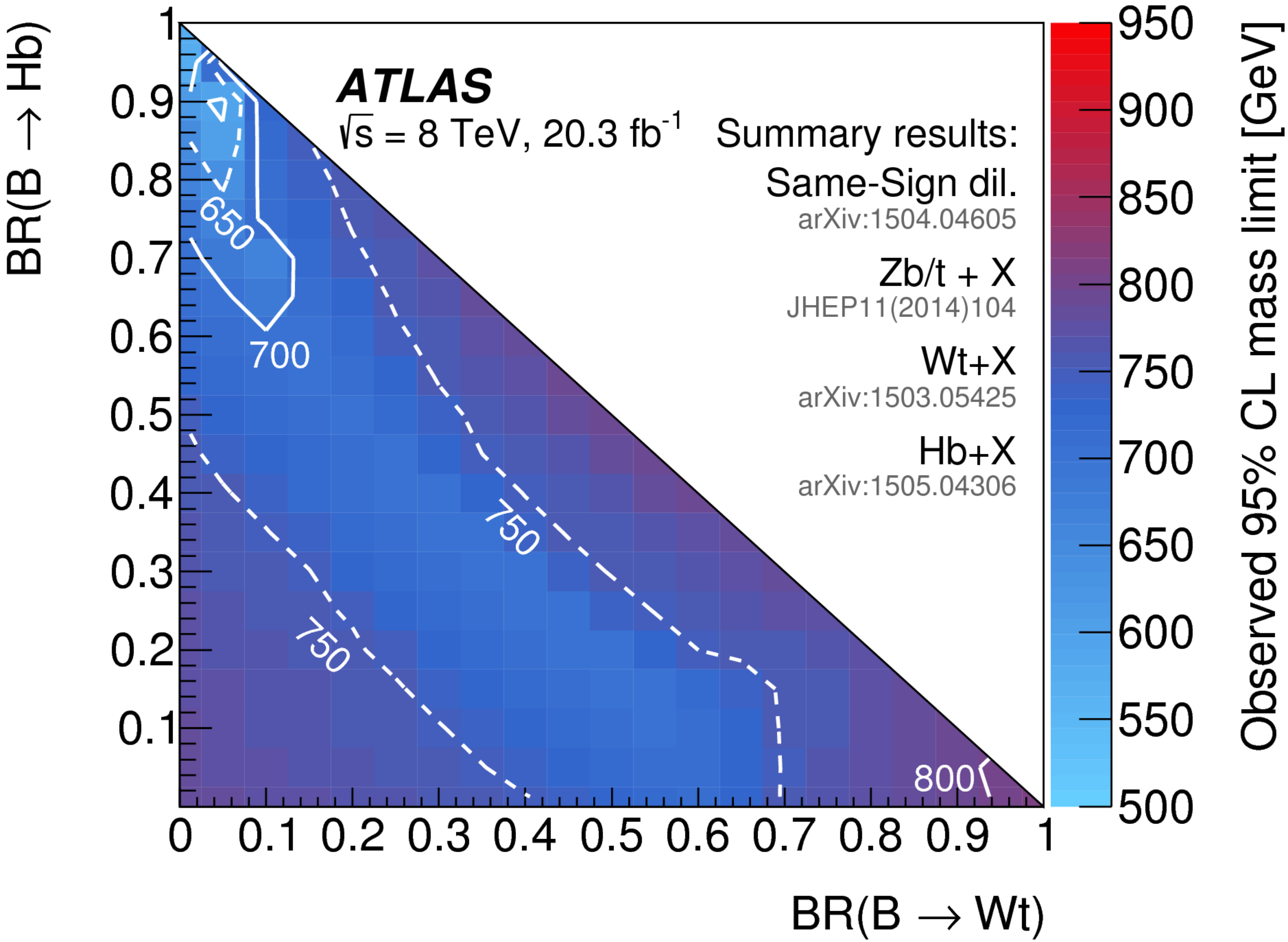
$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2},$$





$$\text{subjet } p_{T2}/p_{T1} = \frac{\min[p_T(a), p_T(b)]}{\max[p_T(a), p_T(b)]}.$$

VLB Results


ATLAS
√s = 8 TeV, 20.3 fb-1
Summary results:
Same-Sign dil.
arXiv:1504.04605
Zb/t + X
JHEP11(2014)104
Wt+X
arXiv:1503.05425
Hb+X
arXiv:1505.04306
650
700
750
750
800
BR(B → Hb)
BR(B → Wt)
Observed 95% CL mass limit [GeV]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
550
600
650
700
750
800
850
900
950