IMPROVING IDENTIFICATION OF DIJET RESONANCES AT THE LHC

Brian Shuve

Perimeter Institute for Theoretical Physics

In collaboration with Eder Izaguirre, Itay Yavin

arXiv:1407.7037 & work in progress

Rutgers University

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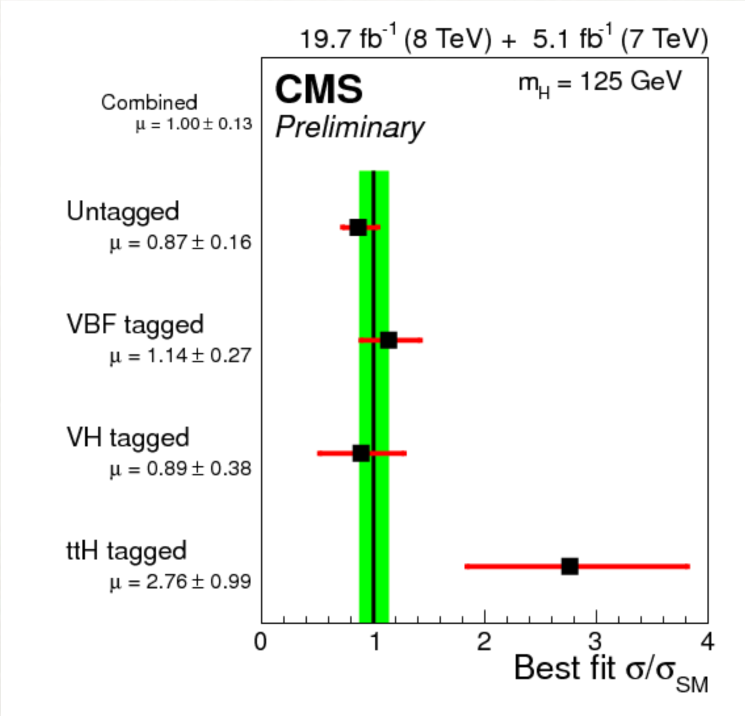
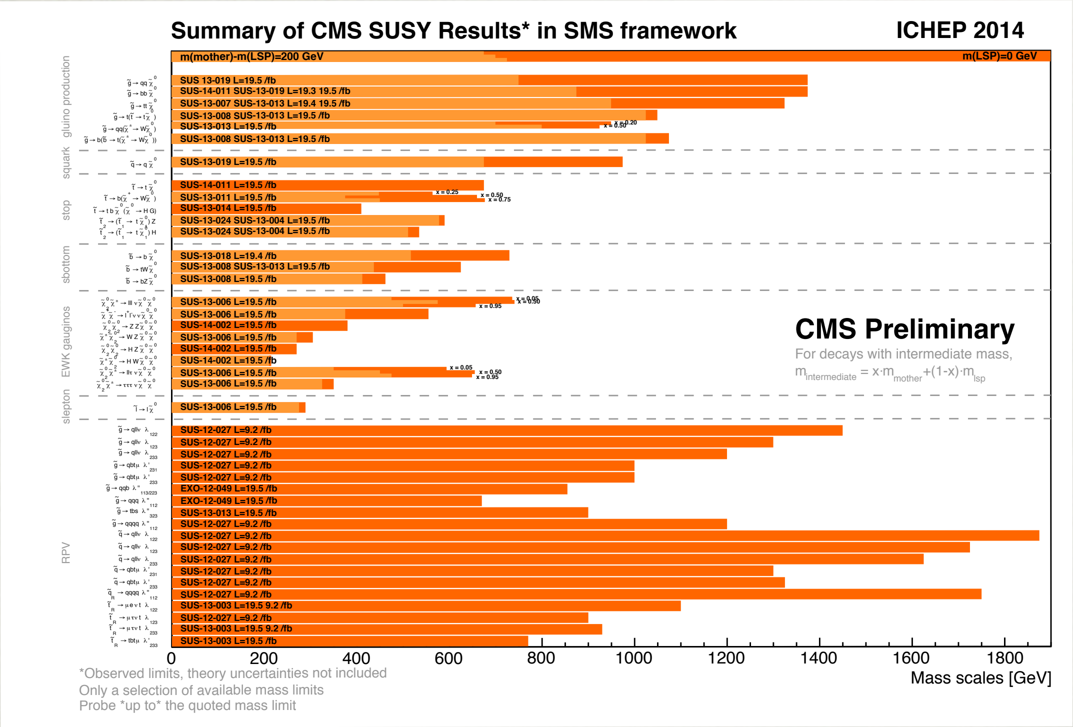
Summary of LHC Run I

- Entered the era of **precision Higgs physics**

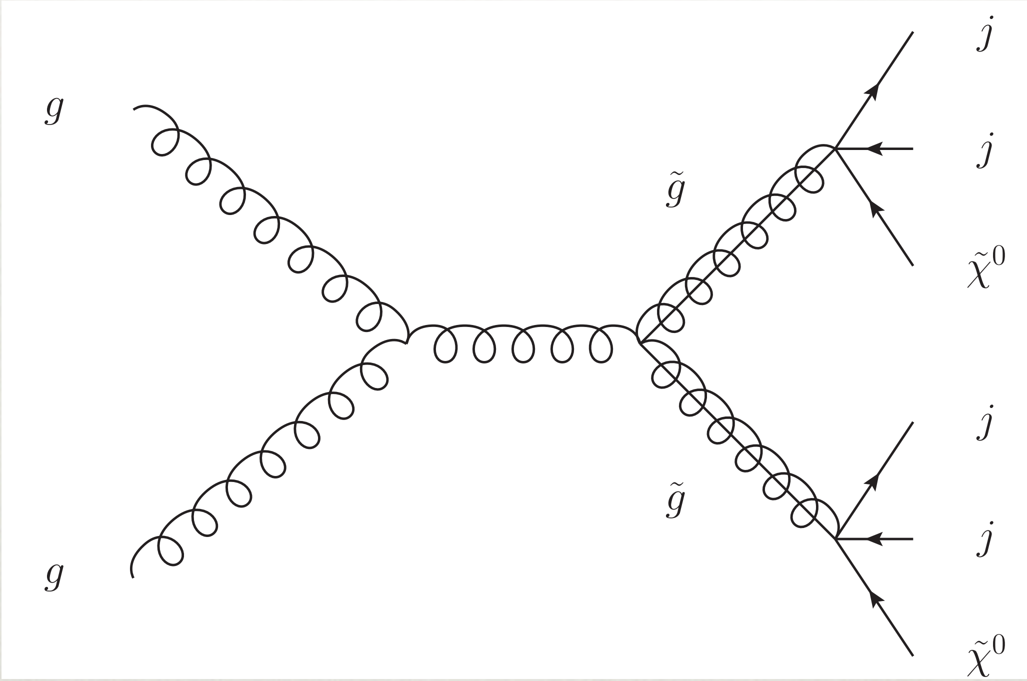




- Still no signs of
  - SUSY
  - Exotic EWSB mechanisms
  - Dark matter
  - ...

Looking forward to Run II+

- Reach improved due to **higher energies**
    - Not much to do here: scale up cuts and look for obvious signs of new physics



Looking forward to Run II+

- What if new physics lies around the electroweak scale?
    - Can look very similar to SM physics

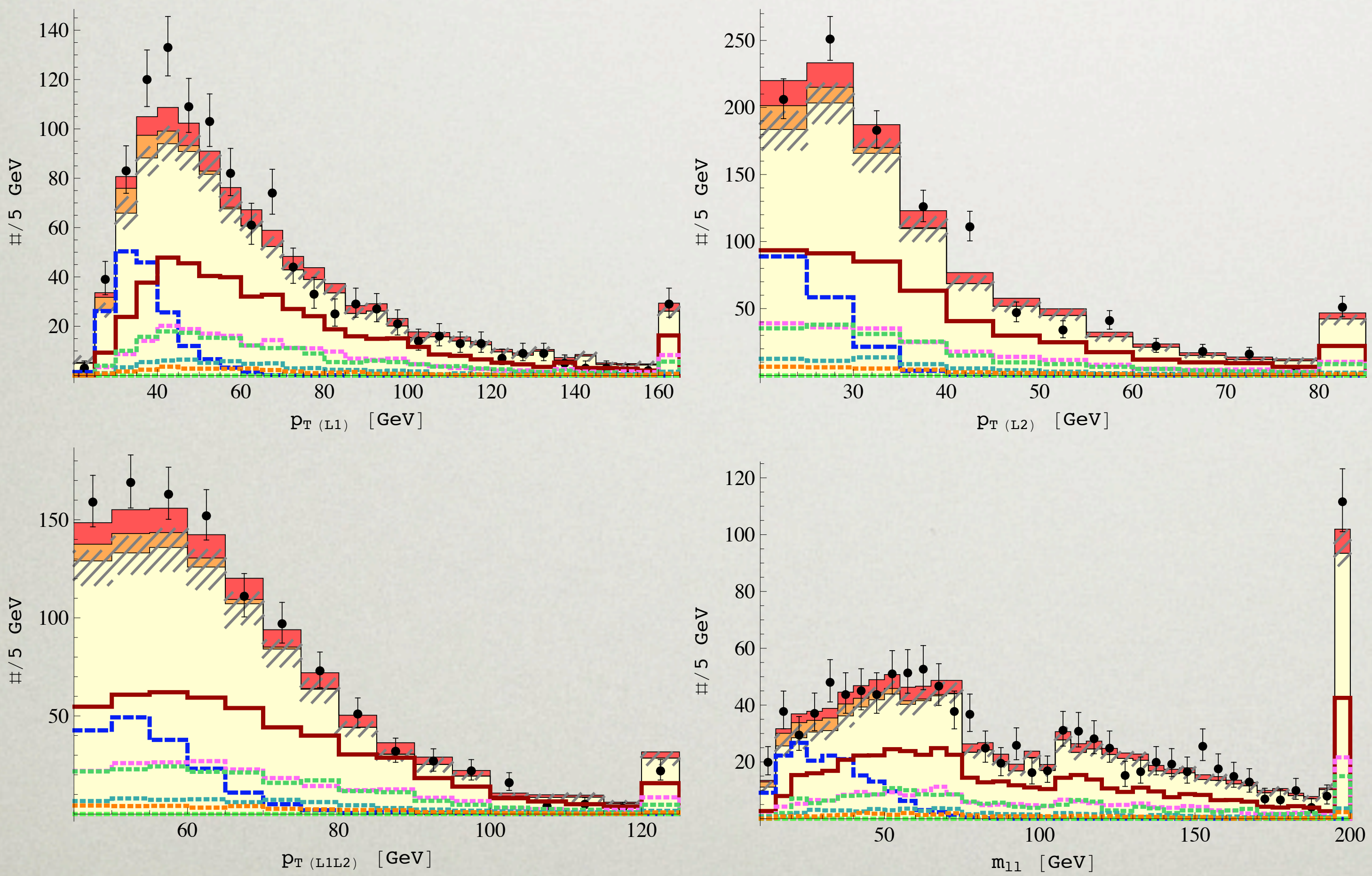
- **High integrated luminosity** gives a lot of signal events but....
    - **Trigger thresholds** are higher
    - **SM backgrounds** are higher
    - **Pile-up** is higher

- Cutting out the SM background cuts out most of the signal, too
    - Study BSM physics via precision SM physics

- Requires dedicated strategies to ensure we don't miss anything

Hadronic resonances

- Ubiquitous in the Standard Model
    - W/Z/H/t
    - SM resonances can also decay leptonically, but suffer from smaller branching fractions
    - Want as many handles as possible on SM rates
    - (Possible) discrepancy in fully leptonic WW cross section



Taken from Curtin, Jaiswal, Meade, arXiv:1206.6888

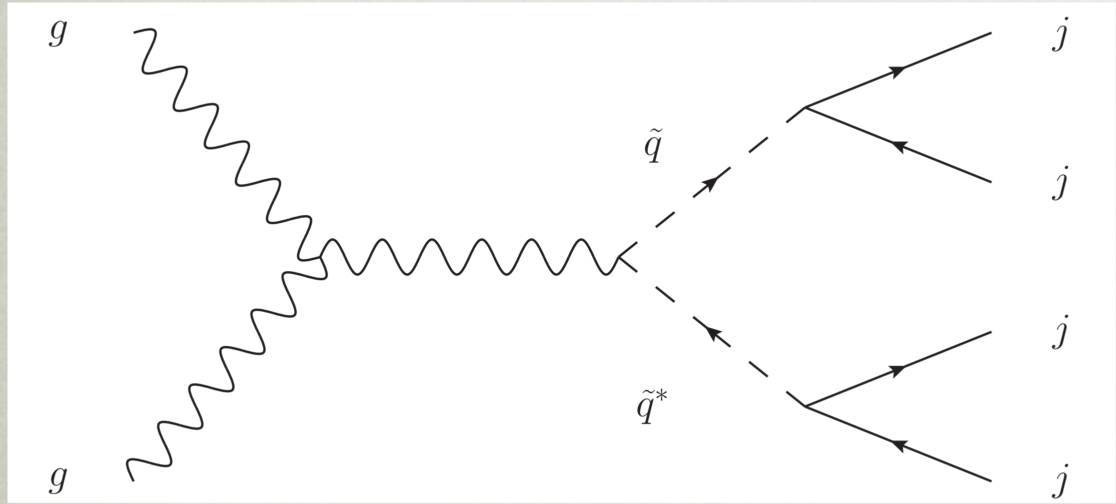
But see:

Meade, Ramani, Zeng
arXiv:1407.4481

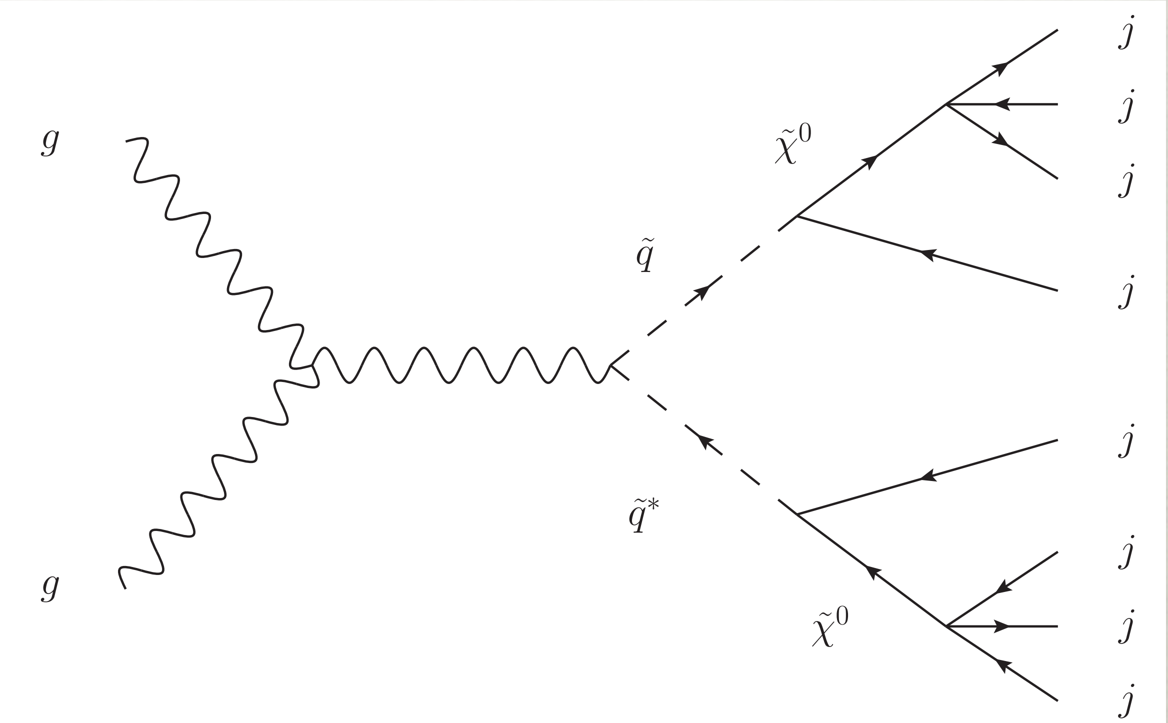
Jaiswal, Okui
arXiv:1407.4537

Hadronic resonances

- Also ubiquitous **beyond** the Standard Model
  - Extended Higgs sectors
  - R-parity-violating supersymmetry
  - Supersymmetric cascade decays
  - Extra dimensions
  - New gauge interactions



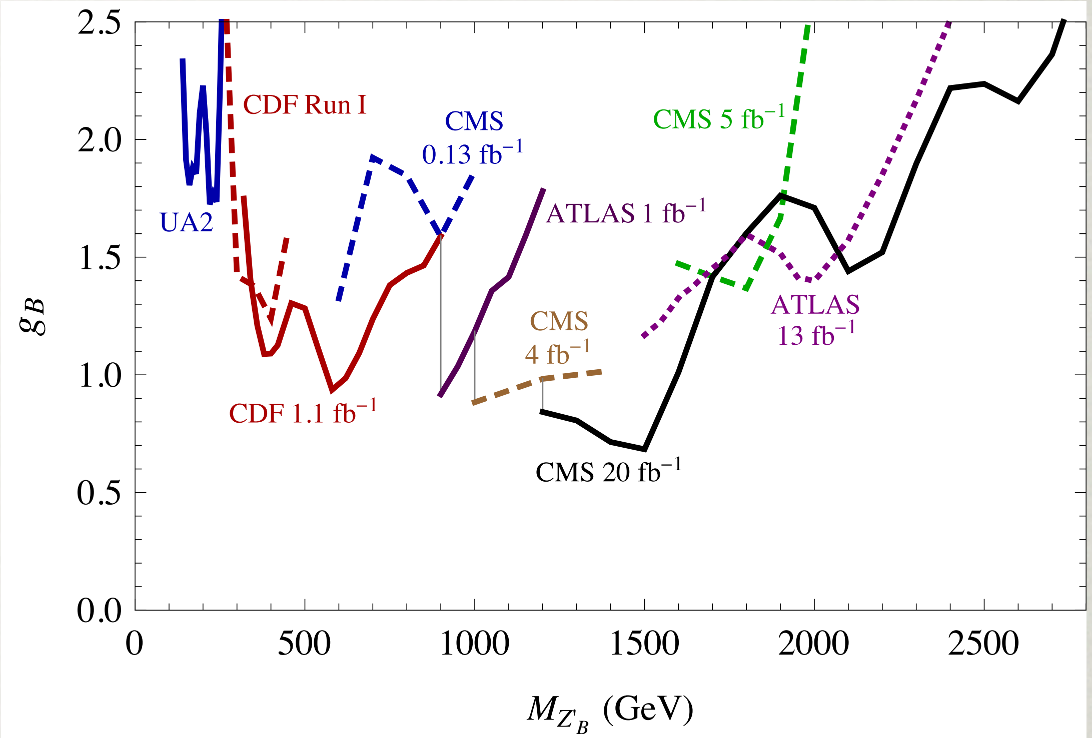
(threshold)



(boosted)

Hadronic resonances

- We are not guaranteed to do better at the LHC
- Extreme example: baryonic Z′

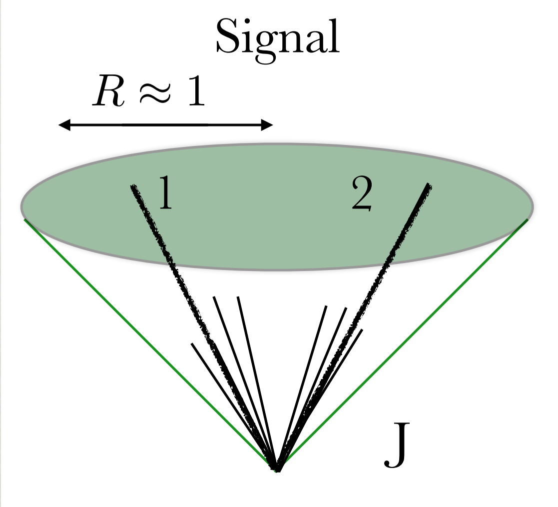


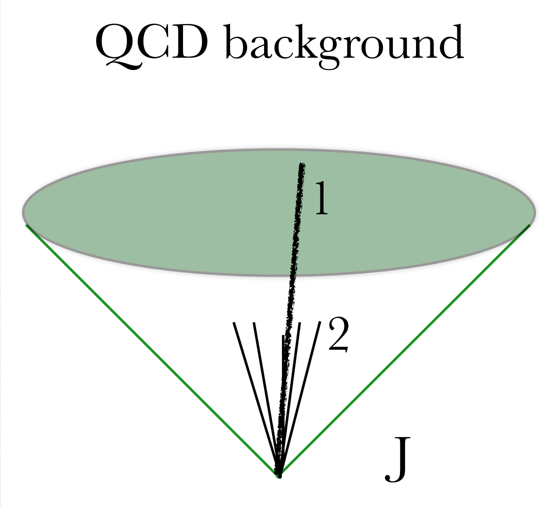
(taken from Dobrescu, Yu arXiv:1306.2629)

- Current approaches:
  - Some searches highly optimized, using sophisticated multivariable techniques (H to bb searches)
  - Others place simple cuts on jet kinematics and do a bump hunt (Z′→WW semileptonic, SM WW+WZ semileptonic,...)
  - Can we do better?

Hadronic resonances

- One method to improve sensitivity: move to new kinematic regime
  - Large boost means resonance decay products merge into "fat jet"
  - QCD jet looks nothing like t/W/Z/H jet - much recent progress on this!
  - Good for highly boosted regime, but suffer large kinematic penalties
  - Extra sensitivity to pile-up, underlying event (~ R^3)

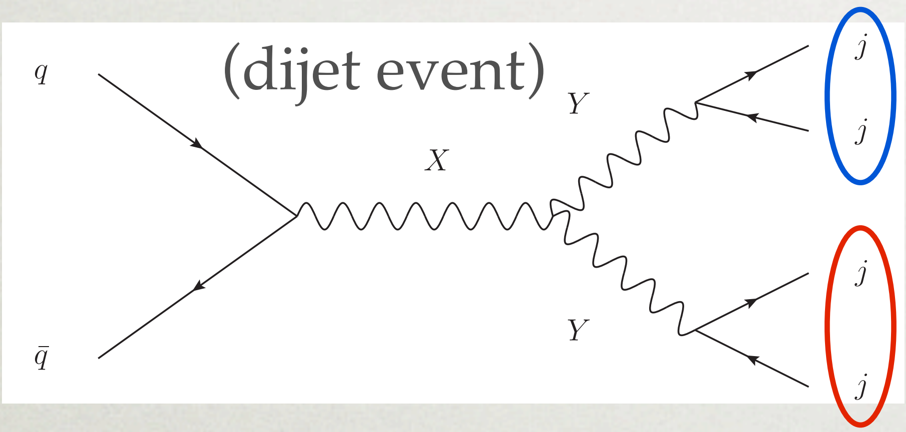


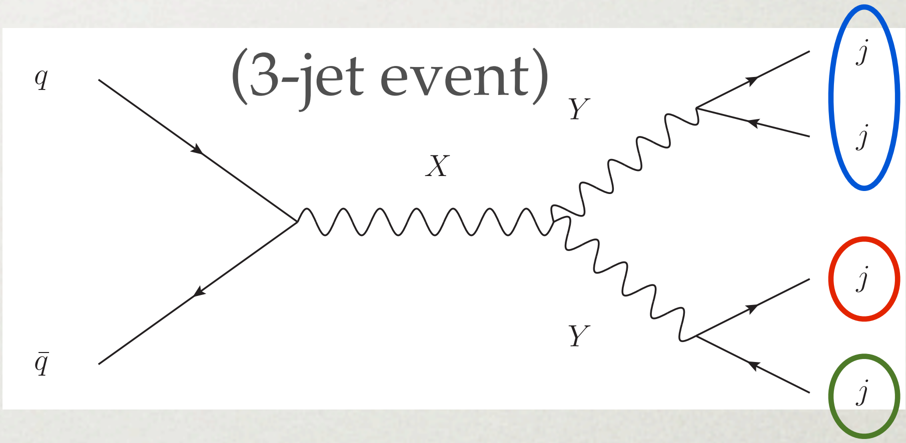


- Can we still use some of the same strategies to improve identification of **moderately boosted** resonances?
  - In this case, the decay products of the resonance are separately resolved

Hadronic resonances

- Past work attempted to combine resolved and substructure searches
  - Gouzevitch *et al.*, arXiv:1303.6636
  - Look at pair production of dijet resonances in 2j, 3j, 4j final states
  - Use substructure when decay products merged, apply similar cuts to resolved jets when not
  - Find that jet substructure observables don't give much discriminating power away from highly boosted regime





- Are there still ways to separate resonance decay from "hard" QCD splitting?
  - We define a new observable that can be added to existing searches with a factor 2-6 gain in S/B
  - Outperforms other possible cuts; includes resolved jet masses

Outline

1. Jet substructure and the highly boosted regime

2. Resonance tagging in the mildly boosted regime

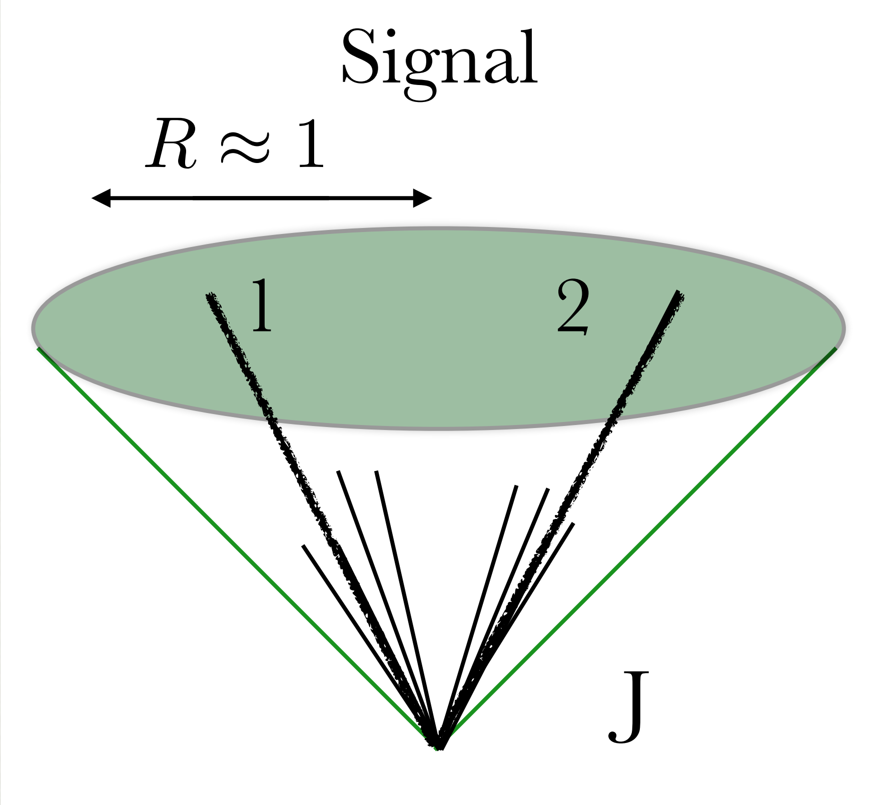
3. Examples
    - SM: WW+WZ
    - SM: $V(H \to bb)$
    - BSM: $Z' \to WW$

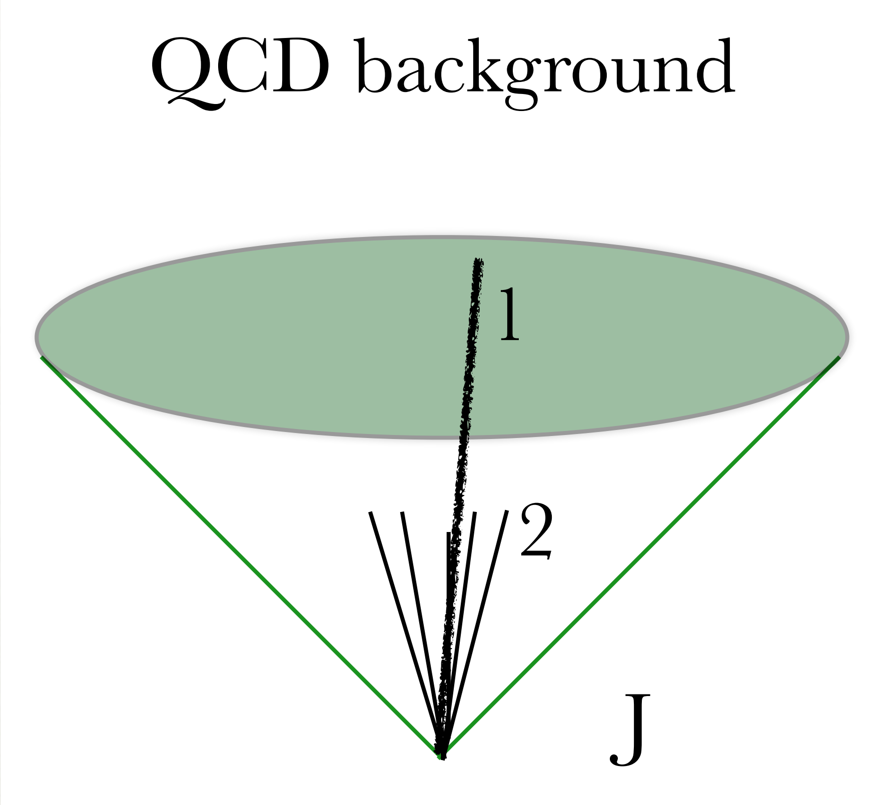
4. Future directions

Jet substructure at high boost

- When an object is highly boosted, its decay products are collimated
    - Can be clustered together into a single, "fat" jet

$$p_{\mathrm{T}} \gtrsim (\mathrm{few}) \times m_{\mathrm{resonance}}$$

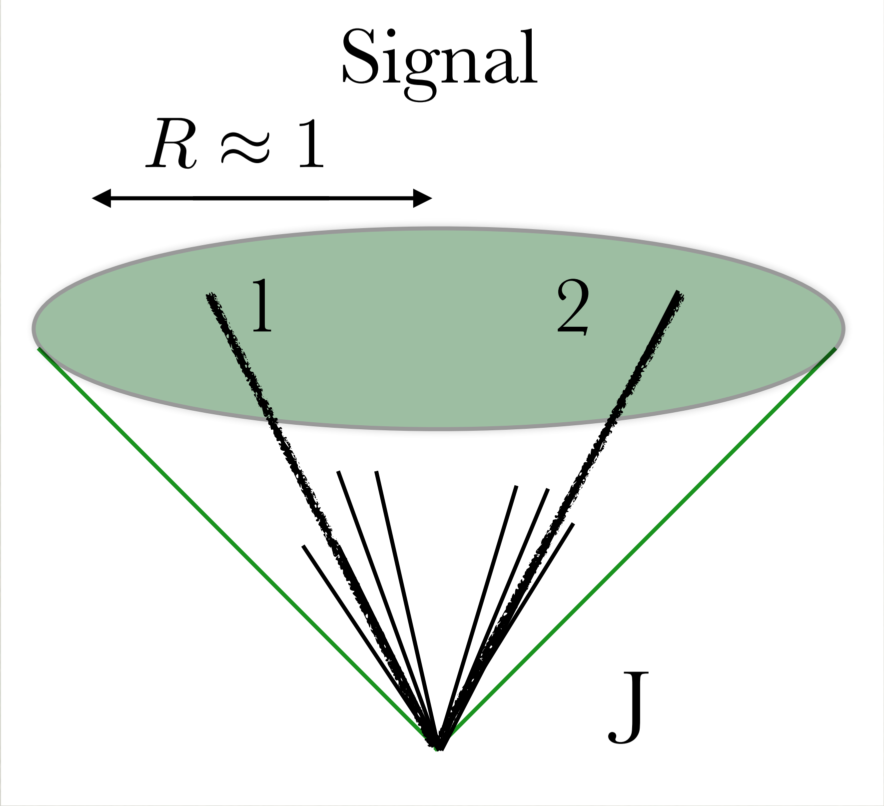


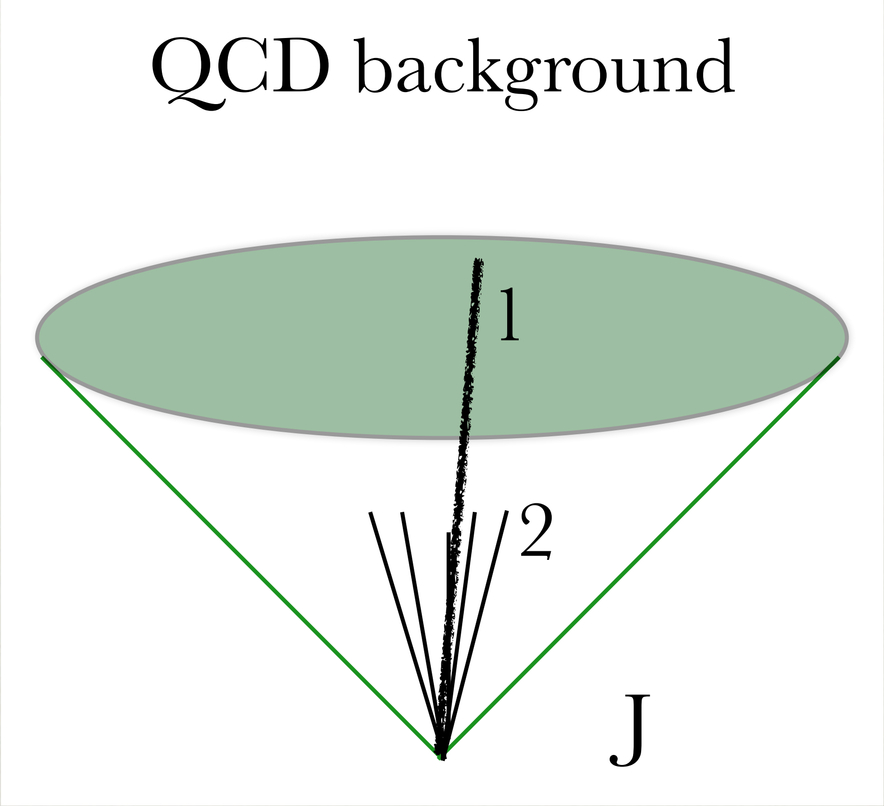


- Dominant background originates from a single QCD parton

Jet substructure at high boost

- The signal typically gives two hard **subjets** from the decay of a resonance, while the QCD subjets typically come from parton shower
    - Can take either a **decomposition** approach or **energy-flow** approach





Decomposition Approach

- Canonical example: BDRS mass-drop tagger (arXiv:0802.2470) (similar mass-drop procedure in HEPTopTagger)

1. Cluster a jet j with the Cambridge/Aachen algorithm ($R = 1.2$)
2. Undo the last step, splitting j into subjets j_1, j_2 with $m_{j1} > m_{j2}$
3. Discard j_2, set $j = j_1$, and continue de-clustering until **both**:

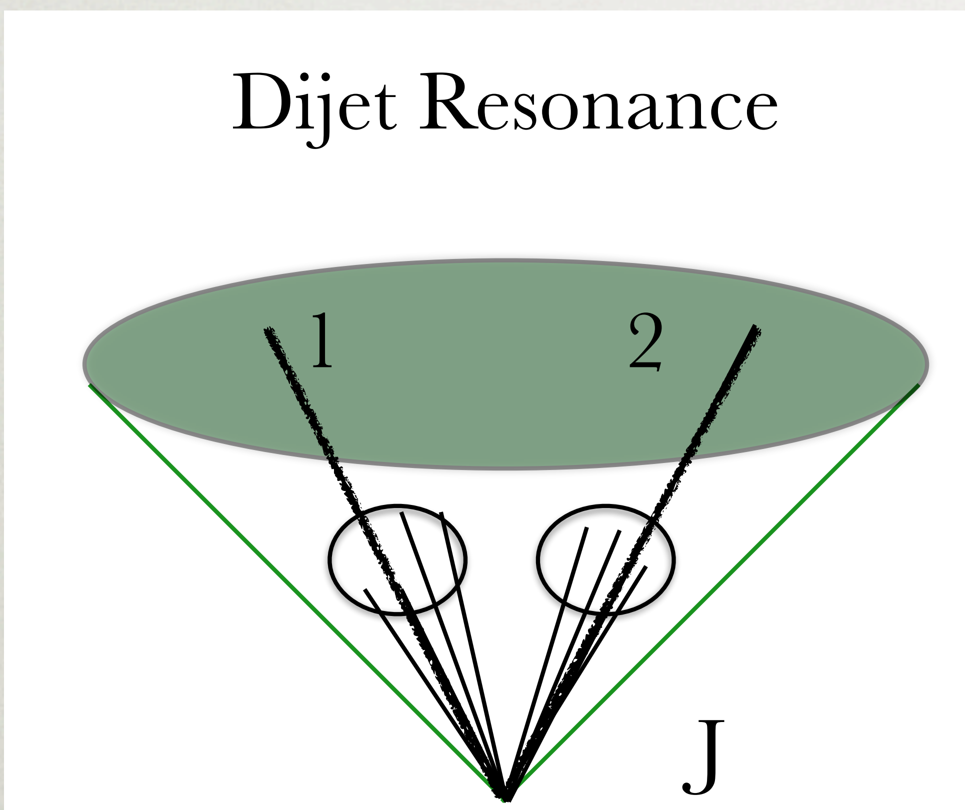
$$\frac{m_1}{m_j} < 0.67 \qquad \text{(mass drop)}$$

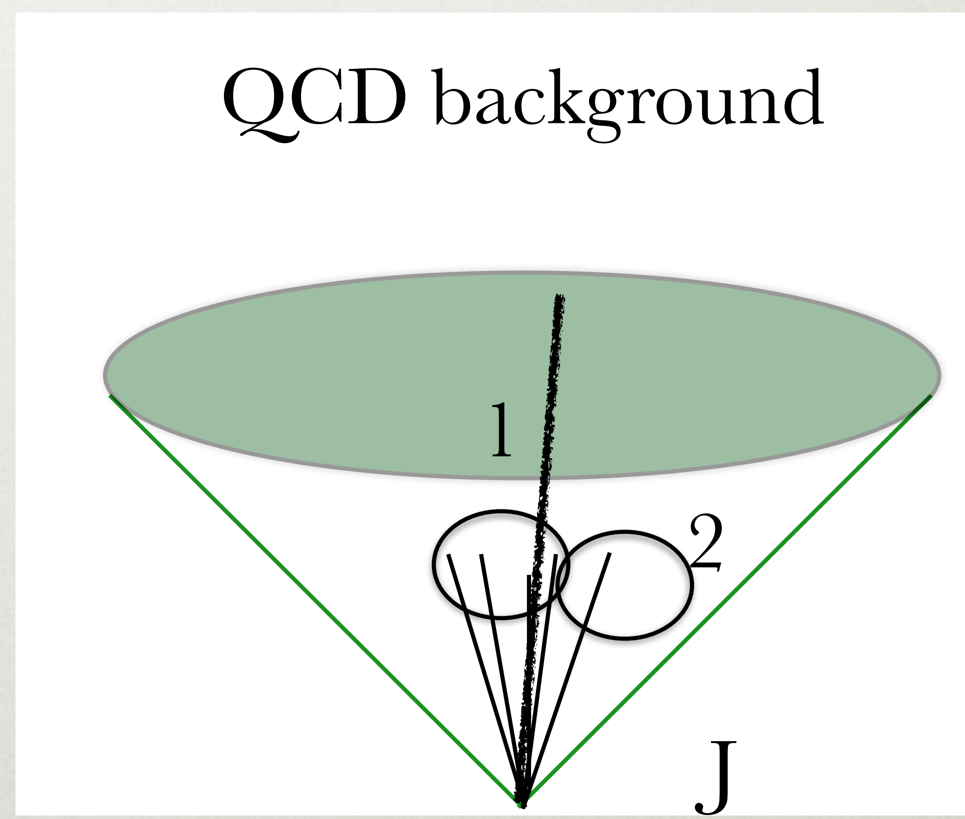
$$\frac{\min(p_{T1}^2, p_{T2}^2)}{m_j^2} > 0.09 \qquad \text{(symmetric splitting)}$$

Decomposition Approach

- This works because of their respective origins of jet masses
  - QCD masses come largely from sequences of asymmetric, wide-angle splittings
  - Signal masses come from the hard resonance decay

$$\frac{m_1}{m_j} \ll \mathcal{O}(1)$$





$$\frac{m_1}{m_j} \sim \mathcal{O}(1)$$

Energy-flow approach

- Uses inclusive, energy-flow information (algorithm-independent)
  - ex. *N*-subjettiness (Thaler, van Tilburg, arXiv:1011.2268)
  - To compute *N*-subjettiness, define *N* axes (denoted by Greek letters) and associate each particle *i* in the jet to the closest axis

$$\tau_N^\beta = \frac{1}{\mathcal{N}} \sum_{i \in j} p_{\mathrm{T}i} \, \Delta R_{i\alpha}^\beta$$

- This gives a measure of how well the radiation is aligned along *N* axes
  - For dijet resonances, τ_2/τ_1 performs better than τ_2
  - Combines information from hard and soft radiation
- Generally, both approaches work well and are complementary
  - See upcoming BOOST 2013 working group report

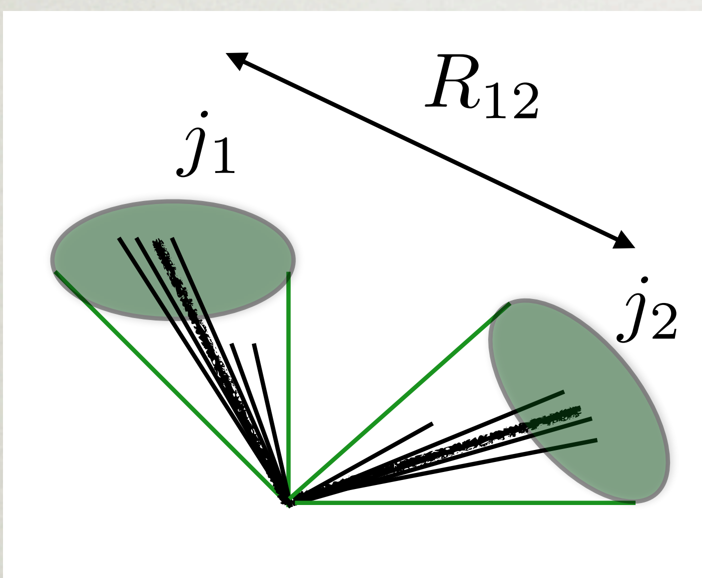
Moderately boosted resonances

Tagging at moderate boosts

- Often, resonances are produced near threshold, paying a high penalty in signal acceptance for going to the boosted regime
    - Direct tt, diboson, ...
- We can try to recover some of the signal discrimination in the **moderately** boosted regime
    - Still dominated by QCD splittings instead of uncorrelated emission
    - Requiring two separately resolved jets already eliminates most of the backgrounds from soft splittings
    - For further improvement, must now separate relatively hard QCD splittings from the signal
- Use decomposition approach because energy-flow observables are sensitive to all radiation between the jets
    - No longer need large-*R* jets

Tagging at moderate boosts

- Analogy of mass drop
    - The lax cut on mass drop from the boosted regime (<0.67) does not veto a hard QCD splitting
    - As jets become more widely separated, the mass drop becomes **smaller**
    - For background:



$$\langle m_1^2 \rangle \approx C \, \frac{\alpha_s}{\pi} R^2 p_{\mathrm{T1}}^2$$

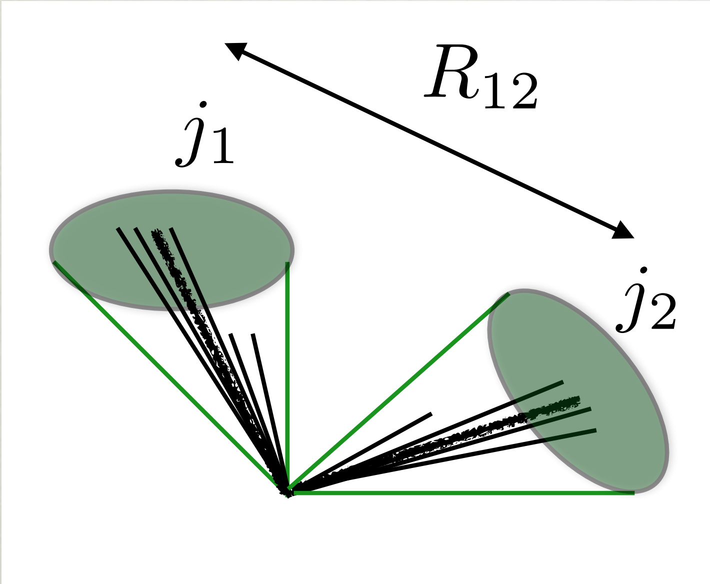
$$m_{12}^2 \sim p_{\mathrm{T1}} p_{\mathrm{T2}} \, \Delta R_{12}^2$$

$$\frac{m_1}{m_{12}} \propto \frac{1}{\Delta R_{12}}$$

- Interpolates between boosted and unboosted regimes

Tagging at moderate boosts

- This suggests that we **scale** the mass drop cut with ΔR
- Exploit differences between QCD splitting and resonance decay
    - Signal has a mass drop that is more constant in ΔR
    - QCD prefers asymmetric splittings, giving rise to **larger m_1**
    - In many examples with QCD backgrounds, one of the radiated partons is a gluon ($C_A > C_F$), giving rise to **larger m_1** (on average)



- This motivates a new observable:

$$\zeta \equiv \frac{m_1}{m_{12}} \Delta R_{12}$$

$$\zeta < \zeta_c$$

Tagging at moderate boosts

- Other functional forms could accomplish a similar scaling
    - For example:

$$\zeta(R_c) = \frac{m_1}{m_{12}}(\Delta R_{12} - R_c)$$

- These types of observables can be very effective at enhancing *S*/*B* when added on top of existing searches
    - Outperform other observables we studied
    - Robust performance under simple smearing and with different MC
    - Uses simple, small-*R* jet properties

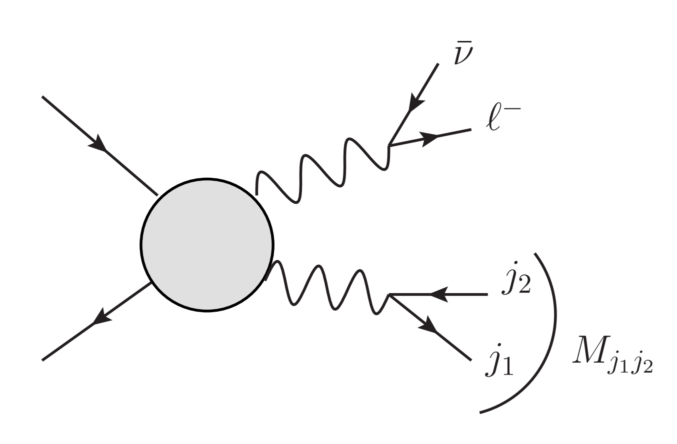
Examples

- **SM: WW+WZ**
- SM: V(H→bb)
- BSM: Z′ → WW

WW+WZ Analysis

- Semileptonic channel is an independent check of the (possible) excess in the fully leptonic channel and an important SM measurement

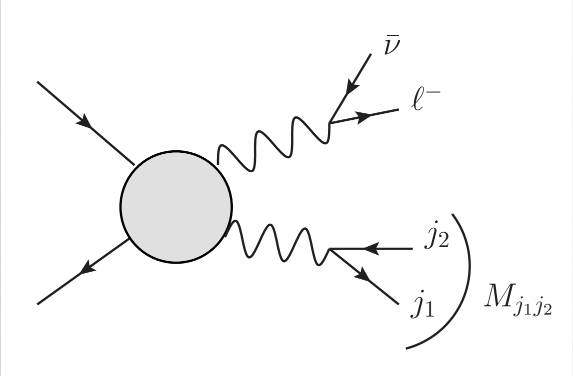
- Simulate WW+WZ, W+jets events with Madgraph 5
  - Match matrix element to Pythia 6 parton shower using shower-$k_\perp$ scheme
  - Cluster and analyze events with Fastjet 3
  - Validated MC with CMS analysis
  - Include UE but no pile-up (more on this later)

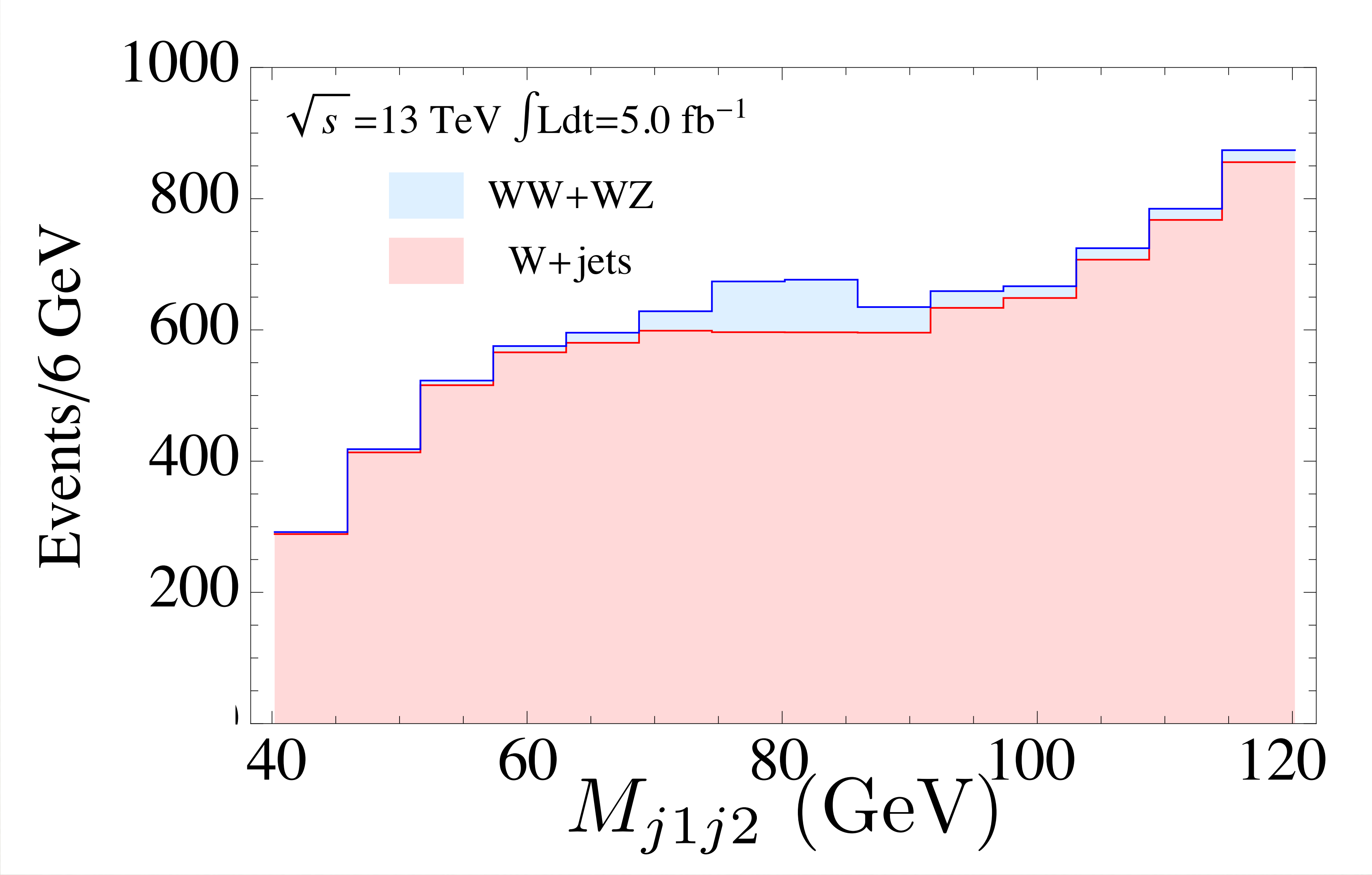


- Use similar cuts as CMS 7 TeV (arXiv: 1210.7544), re-scaled to 13 TeV
  - Two jets with $p_T > 50$ GeV
  - One lepton with $p_T > 25$ GeV
  - MET > 50 GeV
  - $M_T > 50$ GeV

WW+WZ Analysis

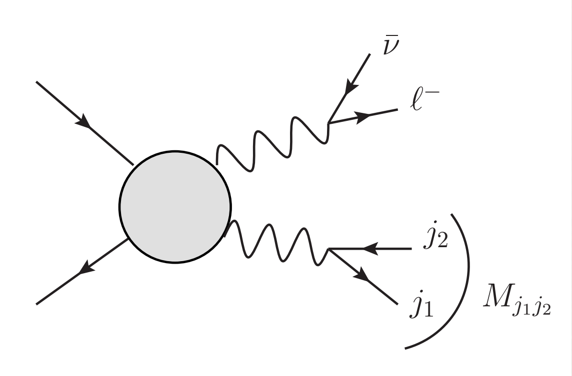
- After CMS selection cuts:

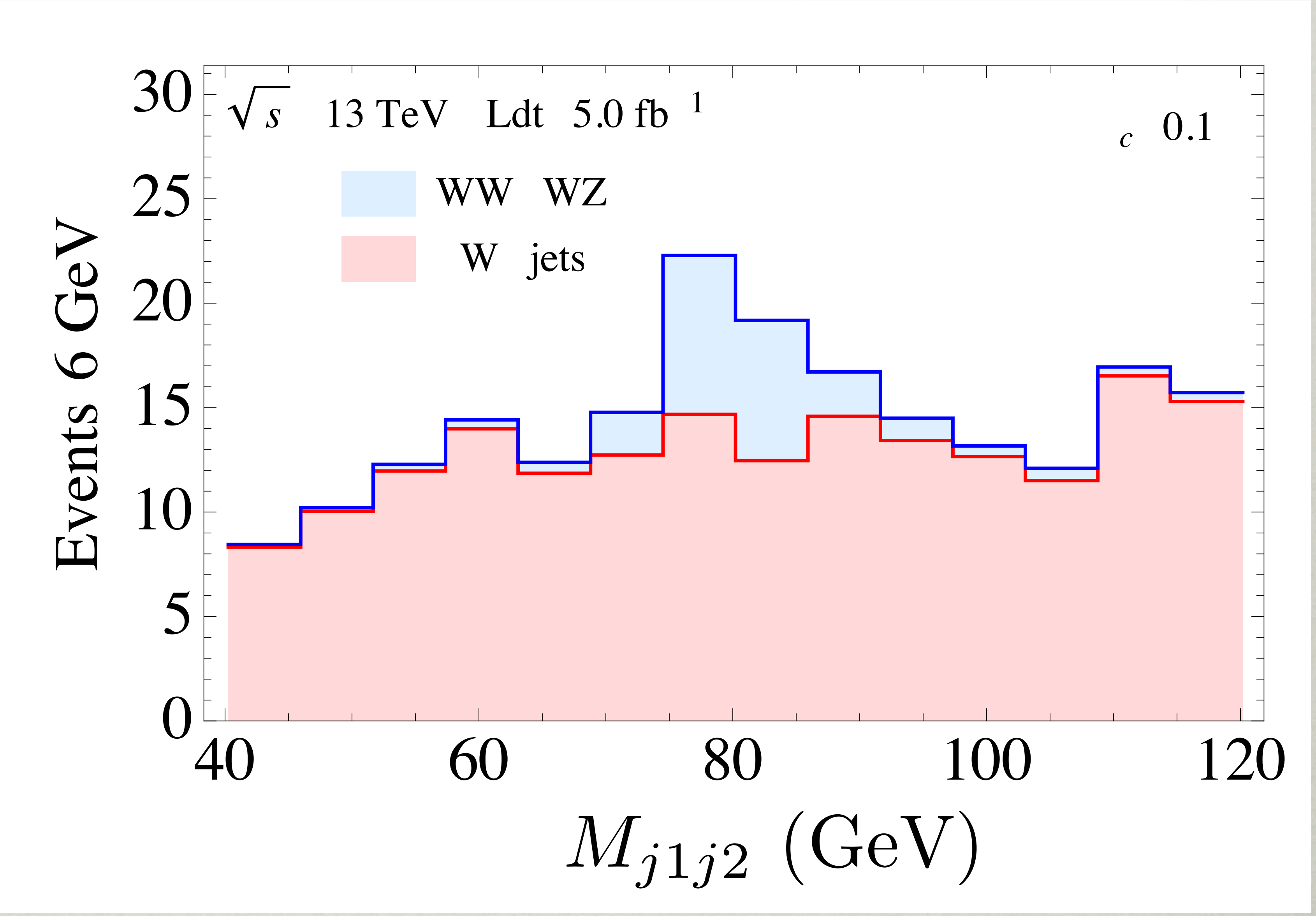




WW+WZ Analysis

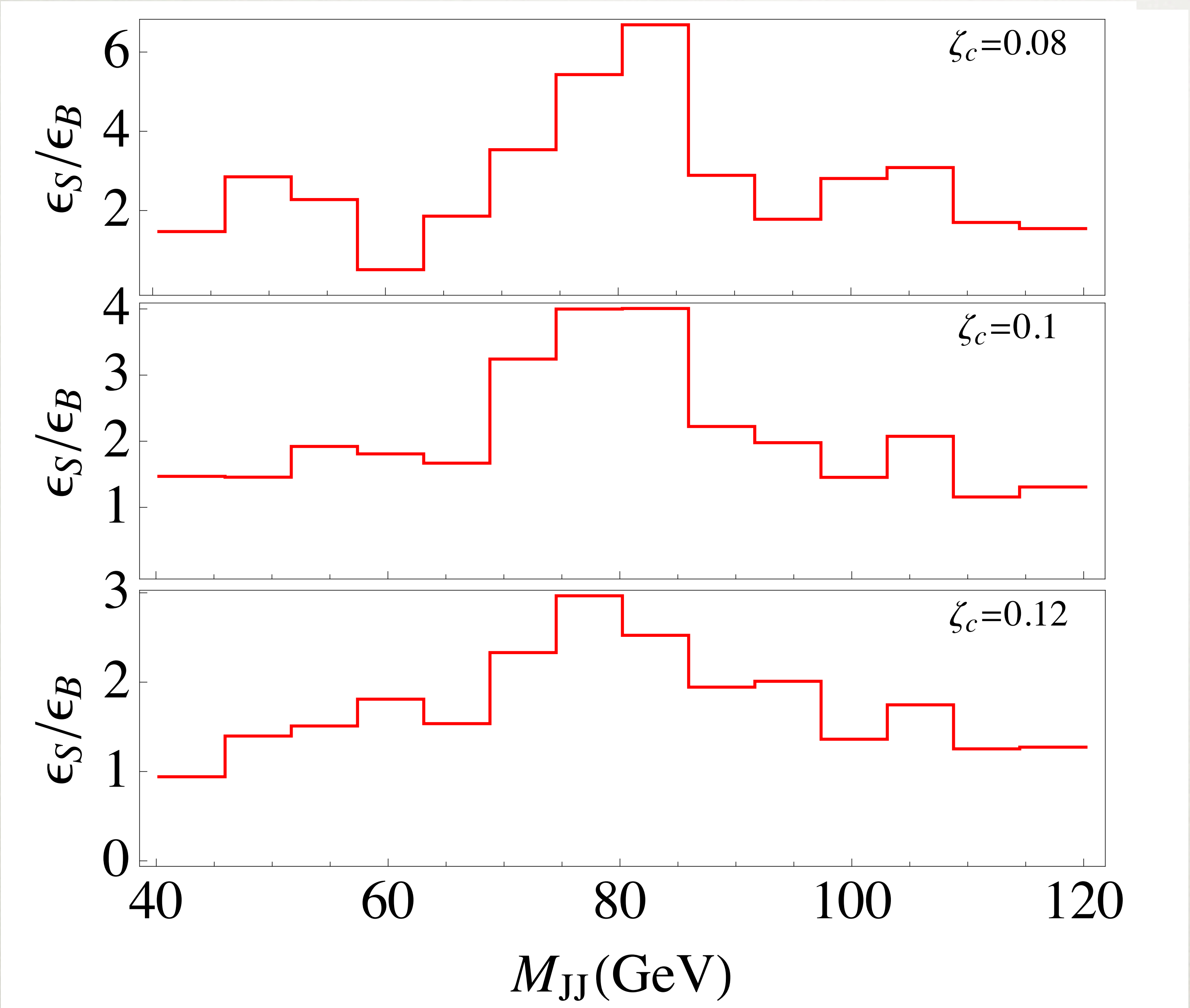
- After CMS selection AND cut on $\zeta < \zeta_c$





WW+WZ Analysis

- Gains for different choices of the cut



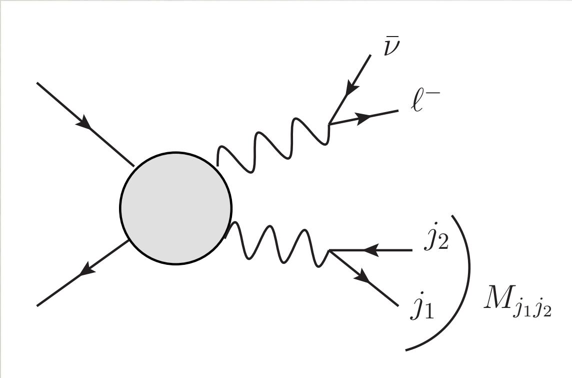
$\epsilon_S(\zeta < \zeta_c) \approx 3\%$

$\epsilon_S(\zeta < \zeta_c) \approx 10\%$

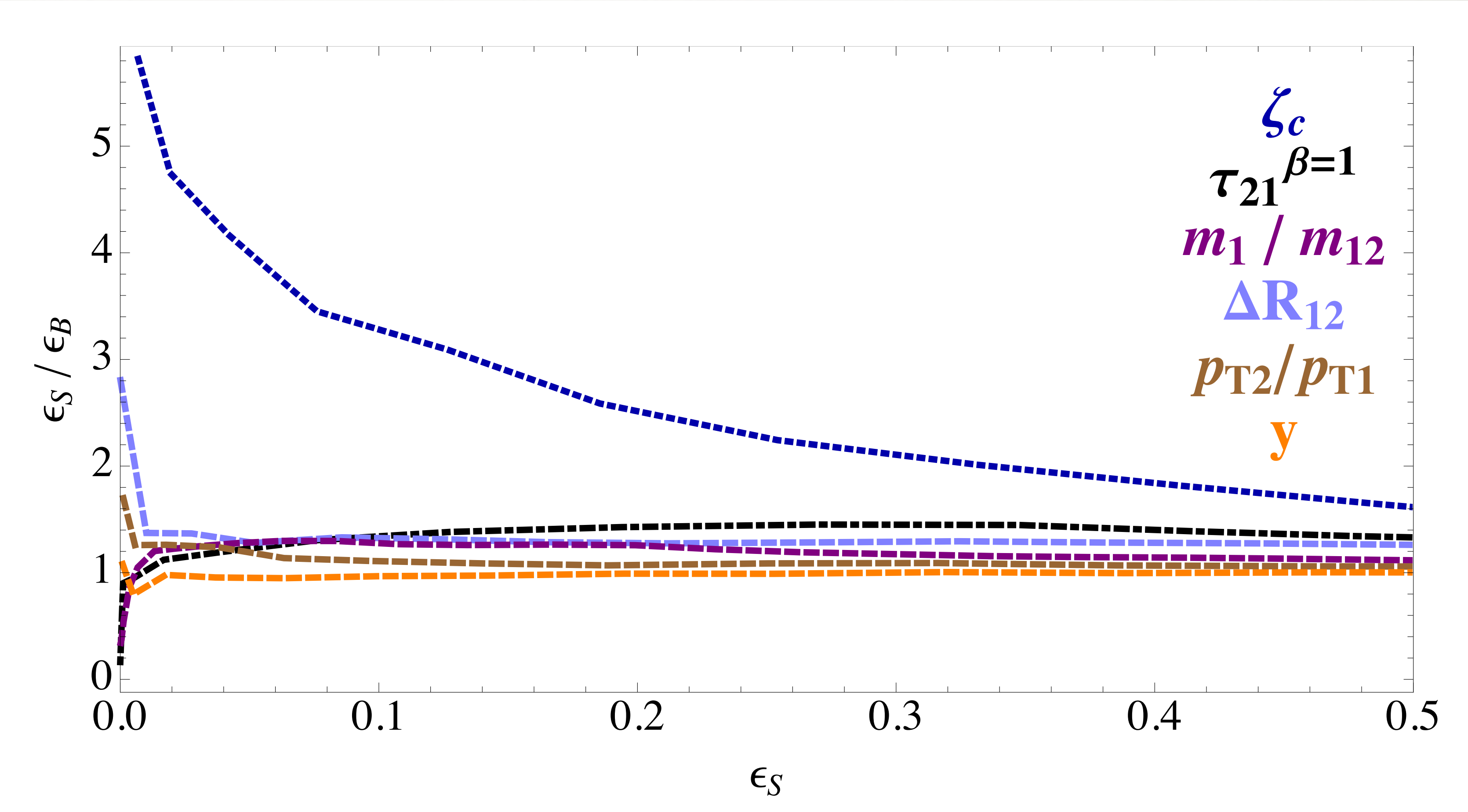
$\epsilon_S(\zeta < \zeta_c) \approx 25\%$

WW+WZ Analysis

- How does this compare to other possible cuts we could have used?
  - Look in M_{j1j2} window between 70-100 GeV
  - Use **filtered** version of shape/energy-flow observables



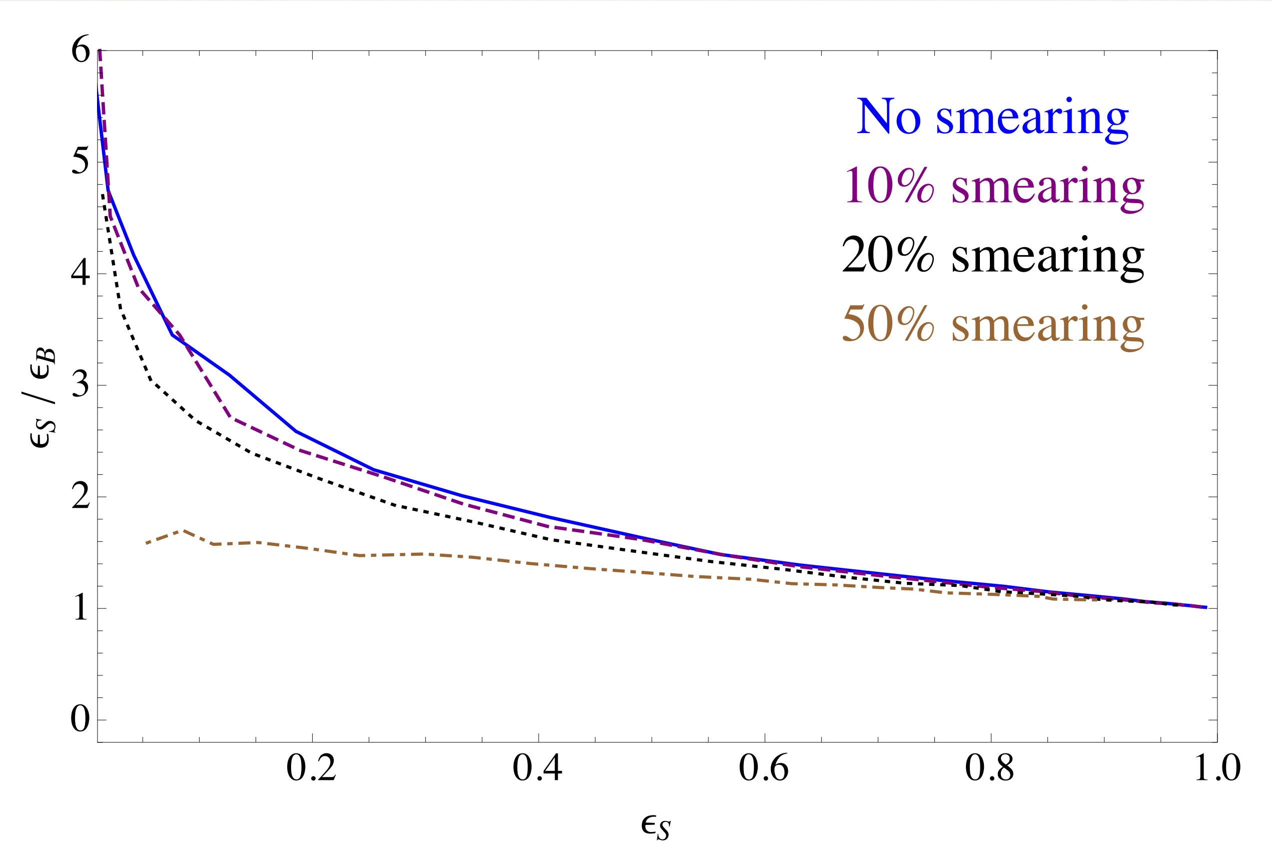
$$y = \frac{p_{T2}^2}{M_{12}^2} \Delta R_{12}^2$$



WW+WZ Analysis

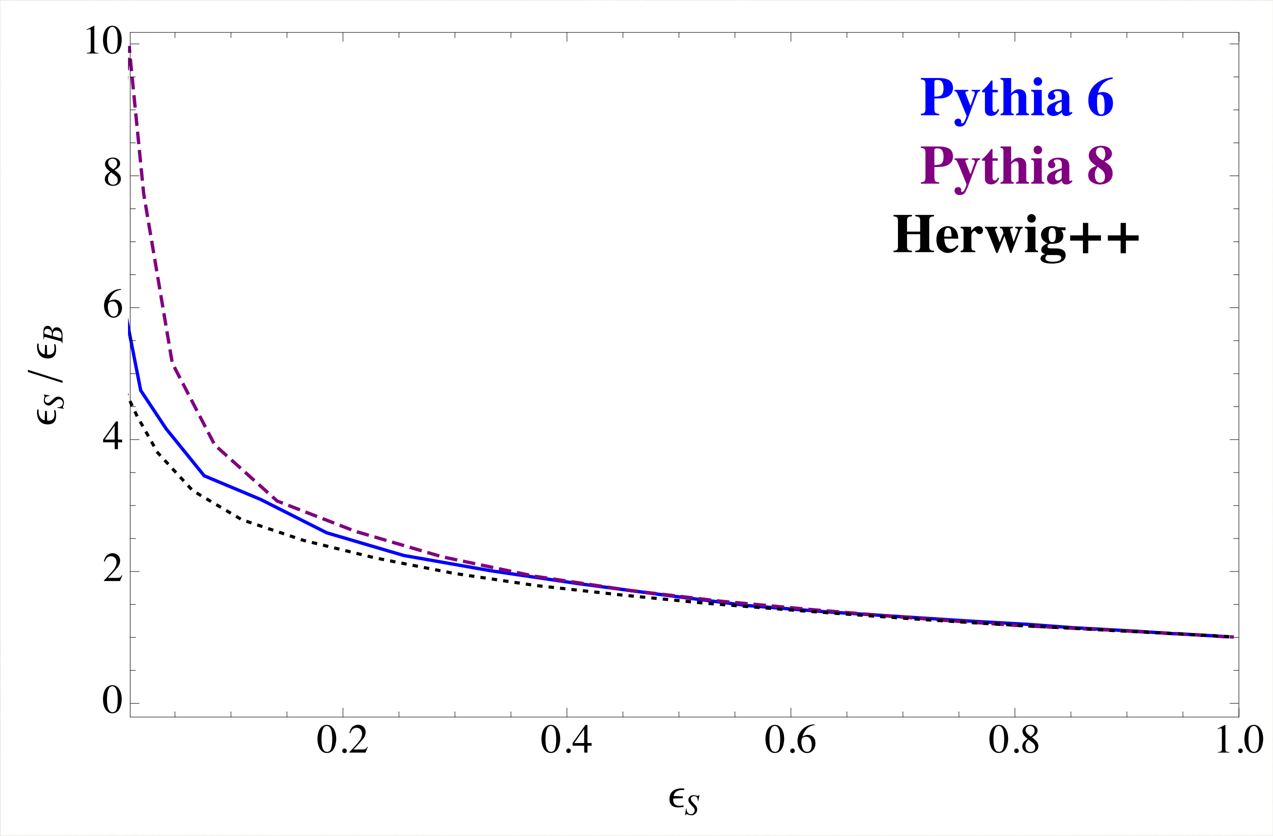
- Would this be included in a BDT analysis?
  - Not currently used for SM WW+WZ
  - Seems there is substantial gain that comes from using resolved jet *masses*, which are not included in most BDT analyses

- Possible worry: jet masses are subject to uncertainties in shower mechanism & reconstruction



WW+WZ Analysis

- Possible worry: jet masses are subject to uncertainties in shower mechanism & reconstruction
    - Show Pythia 6 vs. Pythia 8 vs. Herwig++



- Zeta performs well and is robust against various uncertainties

Limitations and Caveats

- Our observable gives a significant enhancement in S/B at the cost of a mild reduction in statistical significance
    - Most applicable to searches dominated by systematic uncertainties
    - Will become more relevant for later LHC running

- What about pile-up?
    - Serious challenge facing high-luminosity running
    - We simulated WW+WZ search with $\langle N_{PV} \rangle = 50$, found that a more aggressive form of **jet trimming** recovered S/B gains to within 10-20%
    - Ongoing work needed for pile-up mitigation of small-R jet masses
    - Our observable only involves small-R jets

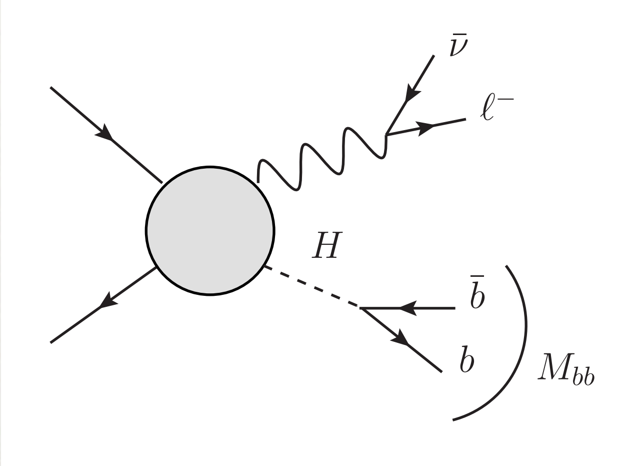
Examples

- SM: WW+WZ
- **SM: V(H→bb)**
- BSM: Z′ → WW

W(H→bb) Analysis

- ATLAS and CMS have both dijet-mass and multivariate analyses
  - We follow the ATLAS 7+8 TeV analysis (now arXiv:1409.6212)

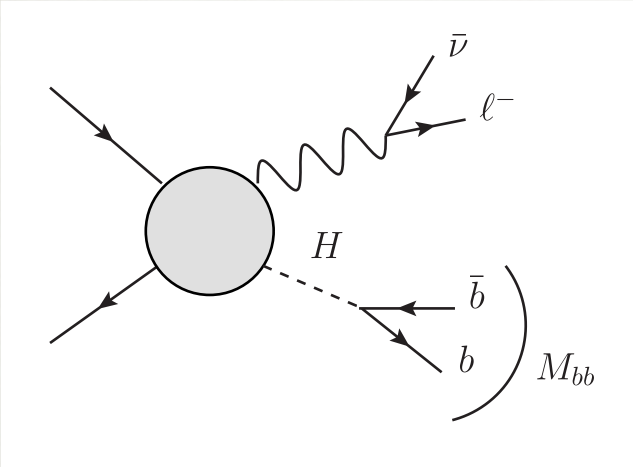
- Focus on dijet search, associated leptonic W
  - Dominant backgrounds are W+b+jets, tt

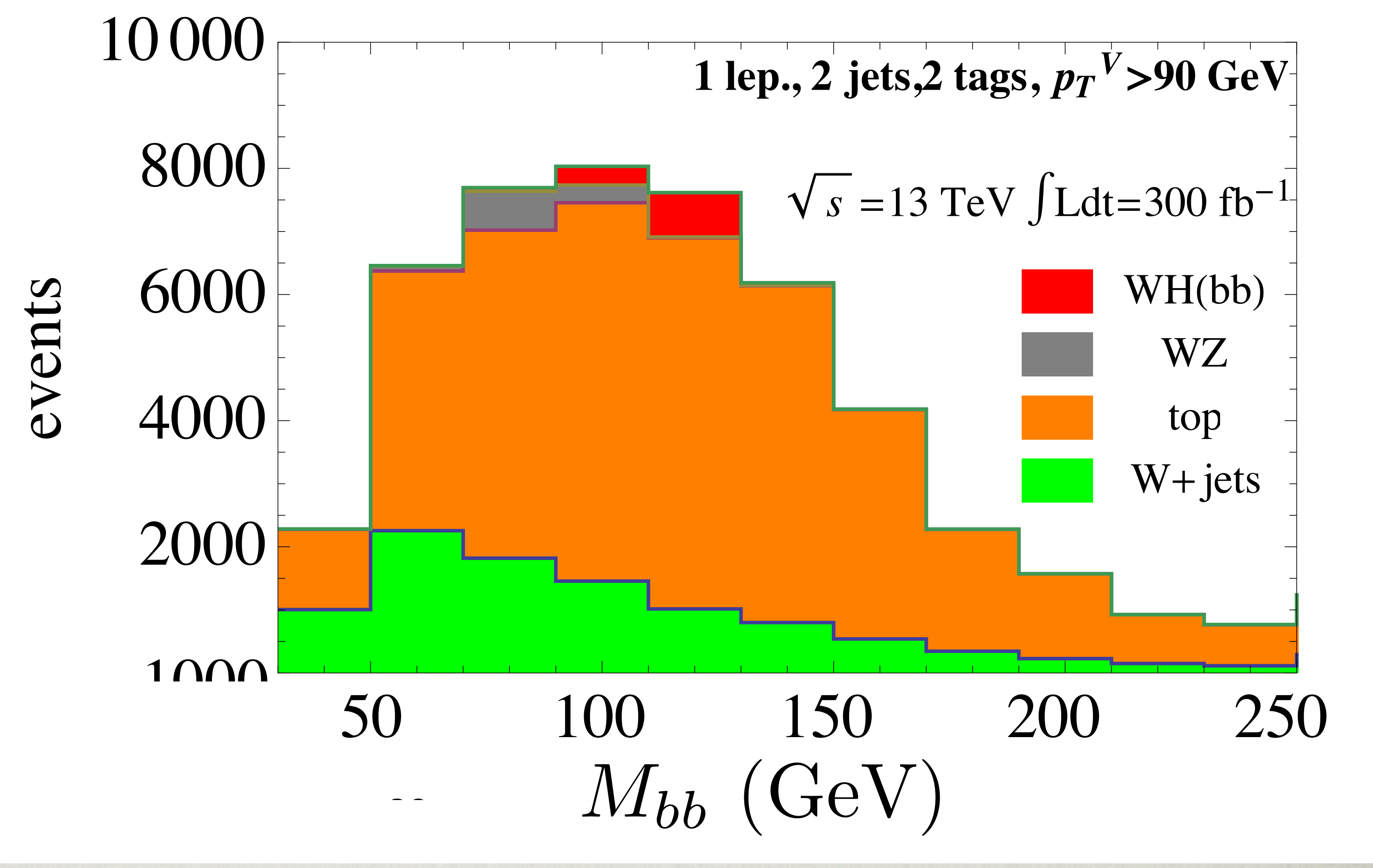


- Use same selection cuts as ATLAS
  - One tight lepton, $p_T > 25$ GeV
  - Exactly 2 b-tagged jets, $p_T > 20$ GeV (leading jet $p_T > 45$ GeV)
  - MET > 25 GeV
  - 120 GeV > M_T > 40 GeV
  - Loose selections on ΔR_{bb} as a function of p_T
  - Associate muons with adjacent b-jets to improve mass reconstruction

W(H→bb) Analysis

- After ATLAS selection cuts:

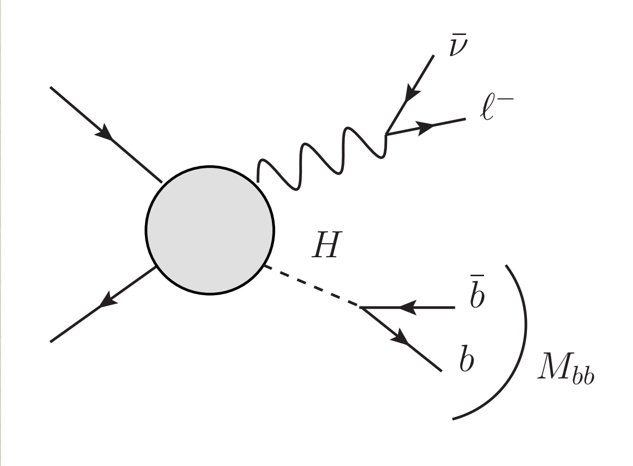


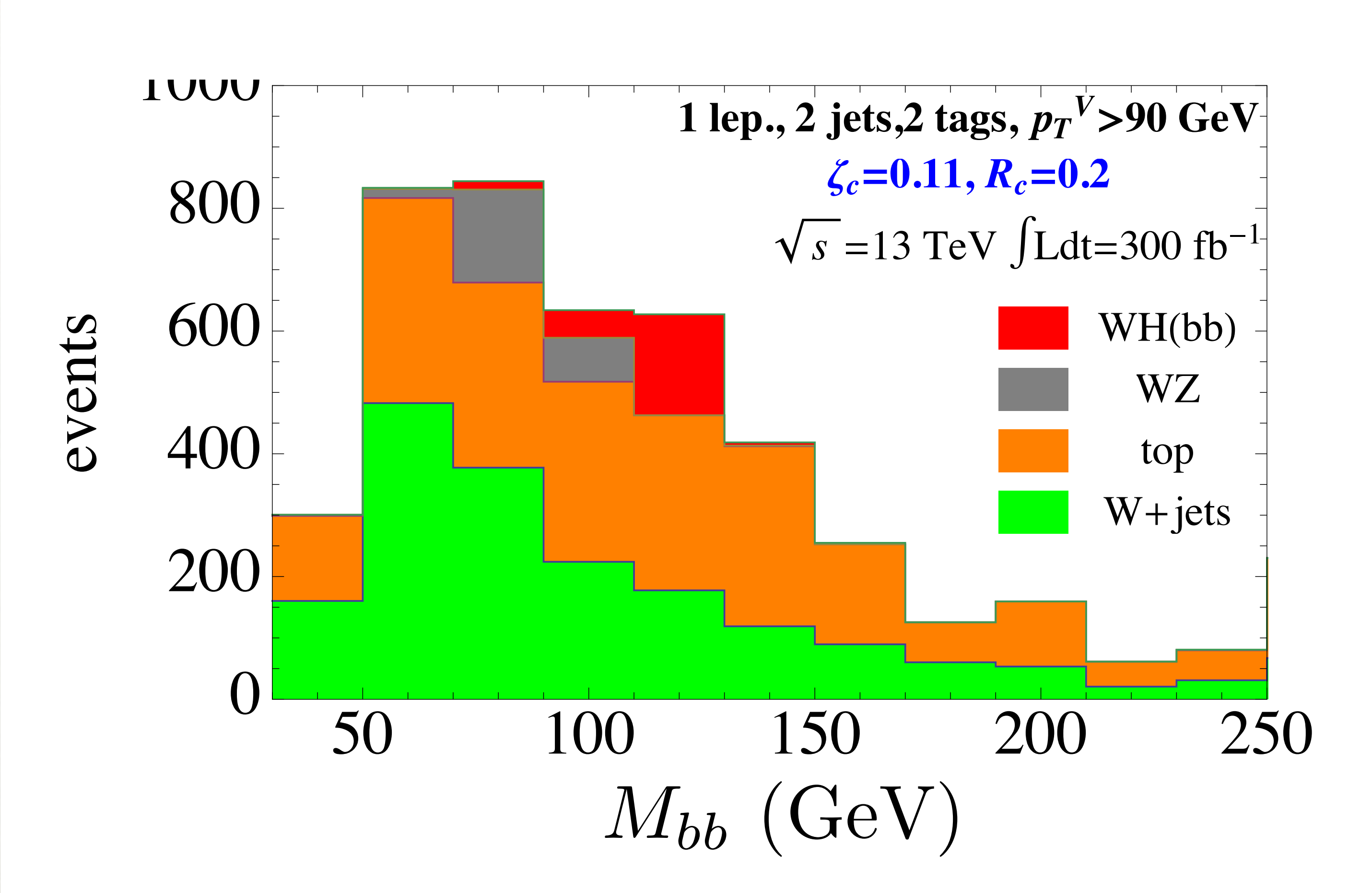


W(H→bb) Analysis

- After ATLAS selection and a cut on the shifted version of ζ:
  - Better at balancing preserving statistics and S/B gain

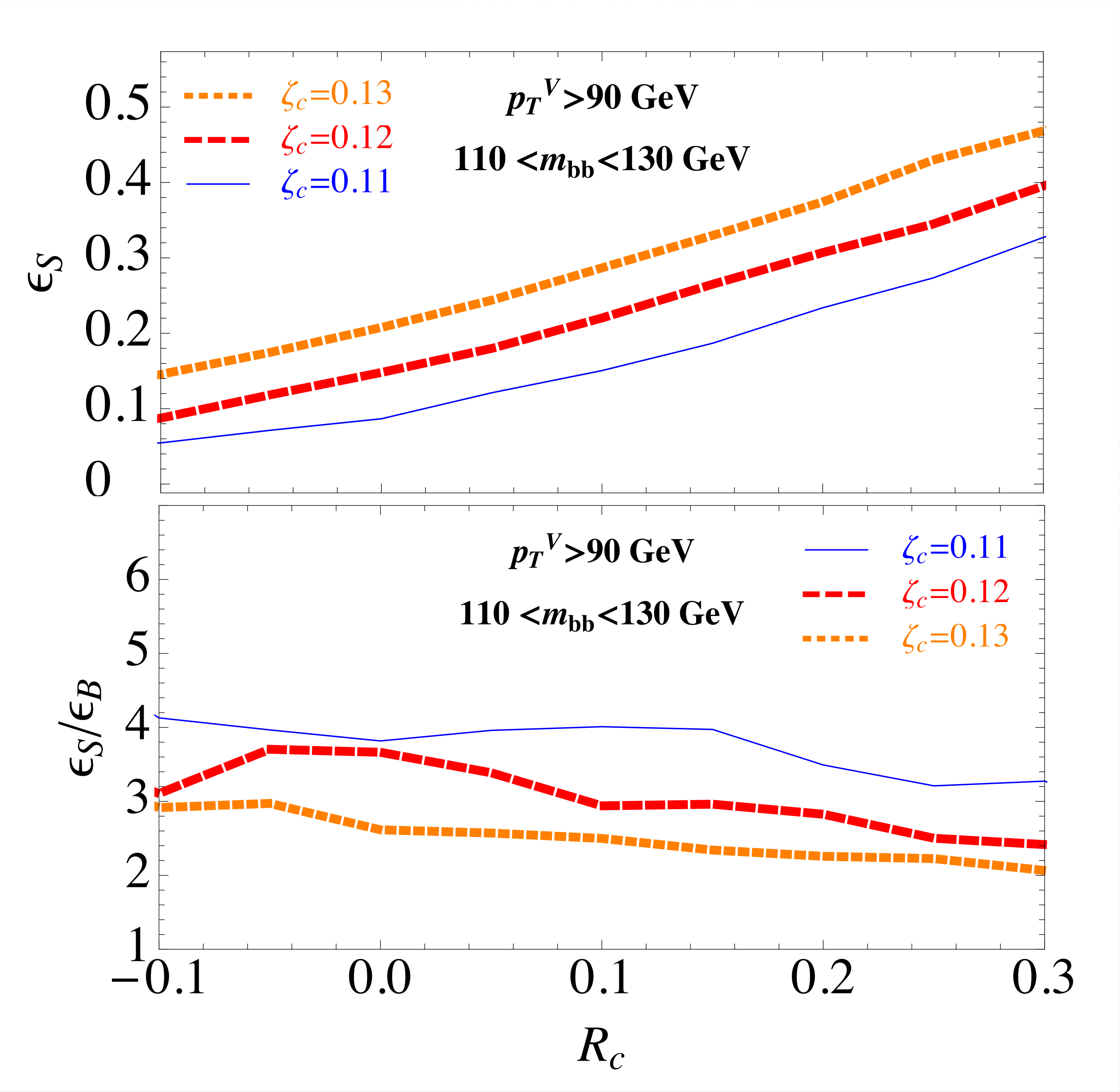
$$\zeta(R_c) = \frac{m_{j_1}}{m_{j_1 j_2}}(\Delta R_{12} - R_c) < \zeta_c$$





W(H→bb) Analysis

- Gains for different choices of the cut:



W(H→bb) Analysis

- Is our gain just coming from the highly boosted region?
  - BDRS requires $p_{TV} > 200$ GeV

- If we restrict ourselves to the **moderately boosted** regime,
  90 GeV $< p_{TV} <$ 200 GeV:
  - We still find an S/B gain of ~ 2-3 (reduction of ~25%)

- Our observable is effective in a boost range complementary to BDRS and other substructure methods

- Consider inclusion of jet masses in more sophisticated BDT as well

Examples

- SM: WW+WZ
- SM: V(H→bb)
- **BSM: Z′ → WW**

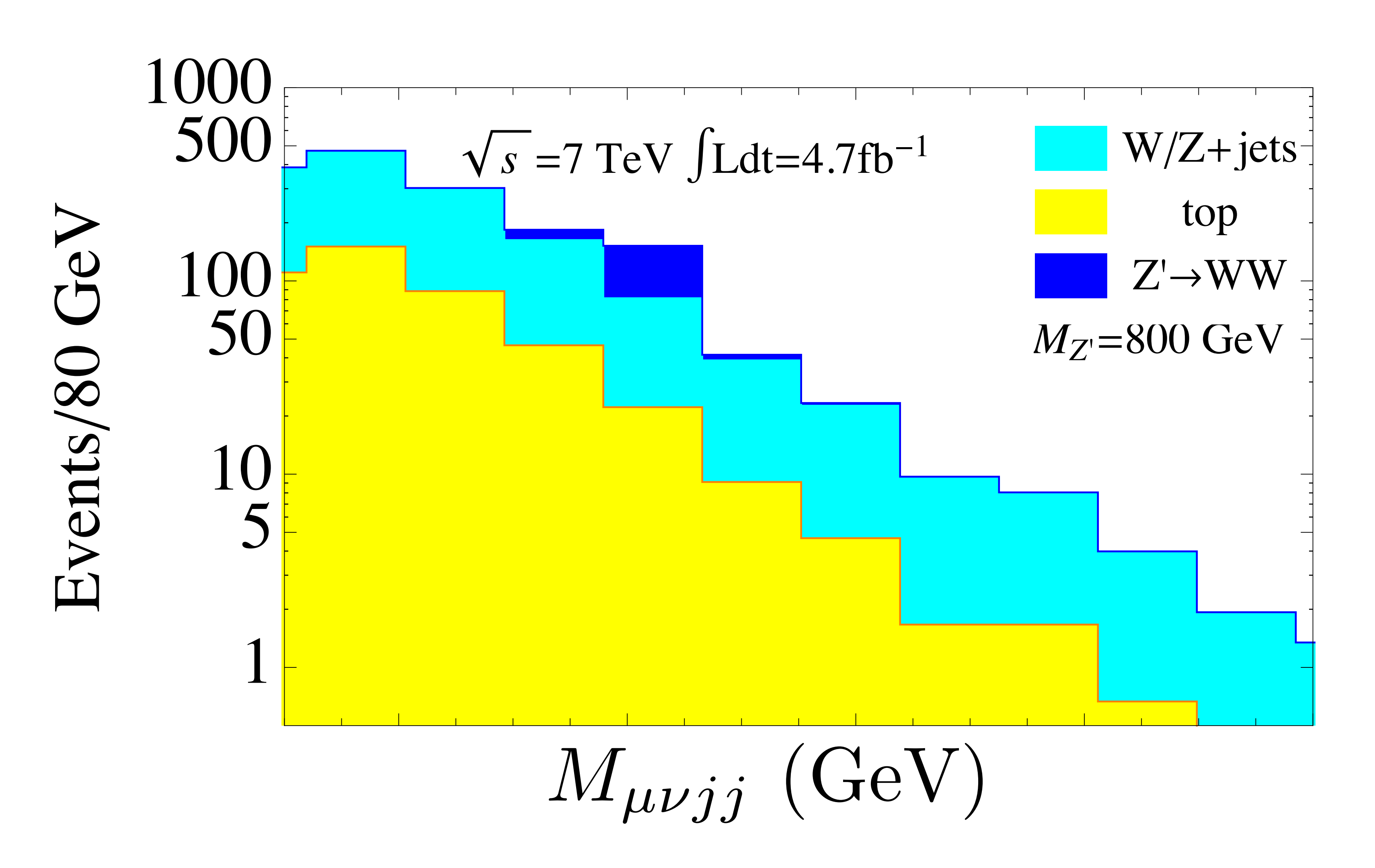
Z’→WW Analysis

- ATLAS has a search for resonant semileptonic WW/WZ production for masses up to 1 TeV (arXiv:1305.0125)
    - At higher masses, use jet substructure techniques
    - We consider a sequential SM Z′ decaying to WW
    - Dominant background is W+jets

- Use same selection cuts as ATLAS
    - Two jets, at least one with $p_T > 100$ GeV
    - One tight lepton, $p_T > 35$ GeV
    - MET > 40 GeV
    - $p_{TV} > 200$ GeV for each candidate gauge boson
    - 65 GeV $< m_{jj} <$ 115 GeV
    - Various cuts on $\Delta\phi_{\ell\nu}$

Z’→WW Analysis

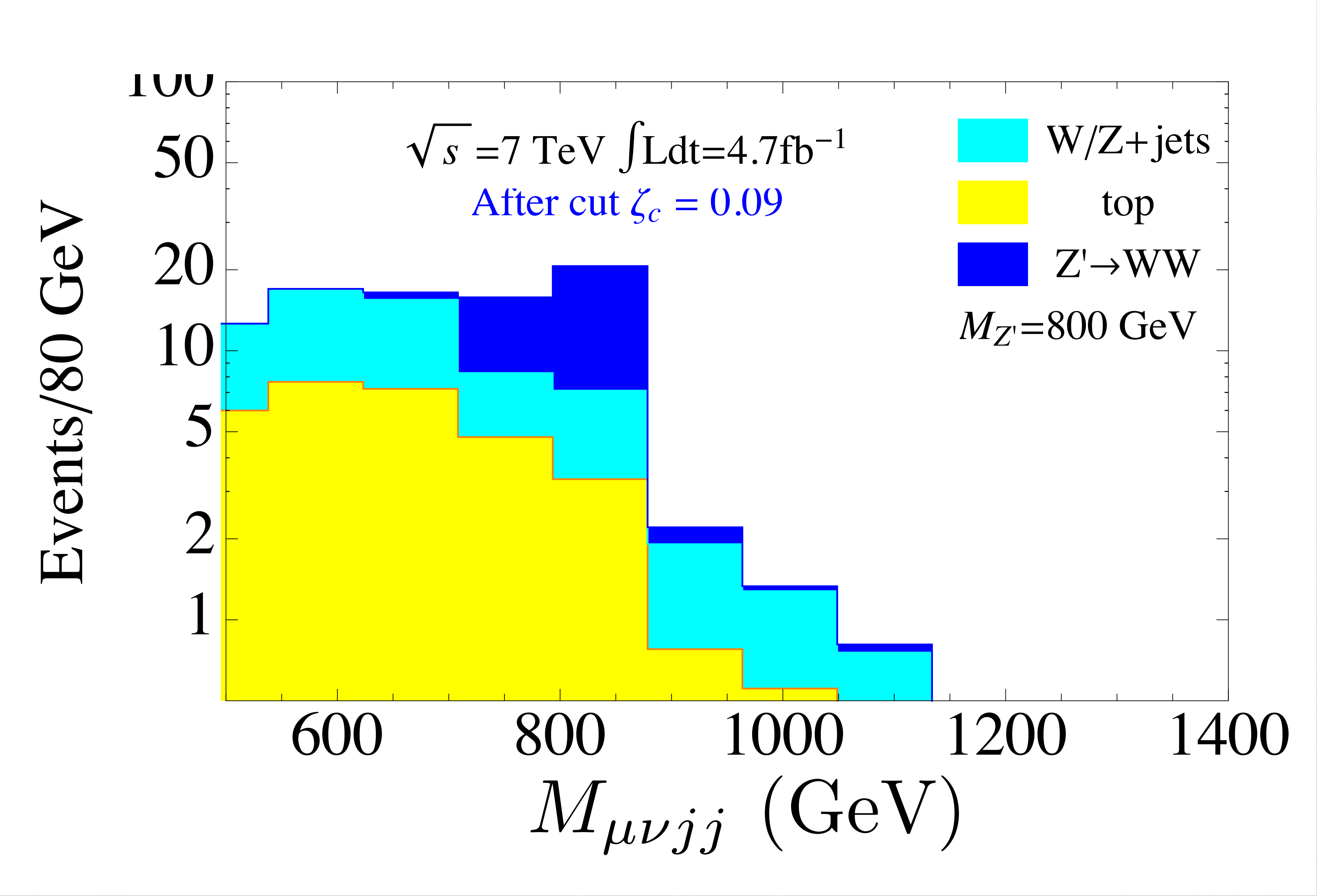
- After ATLAS selection cuts:



- Note: **large** systematic uncertainties (~30%)

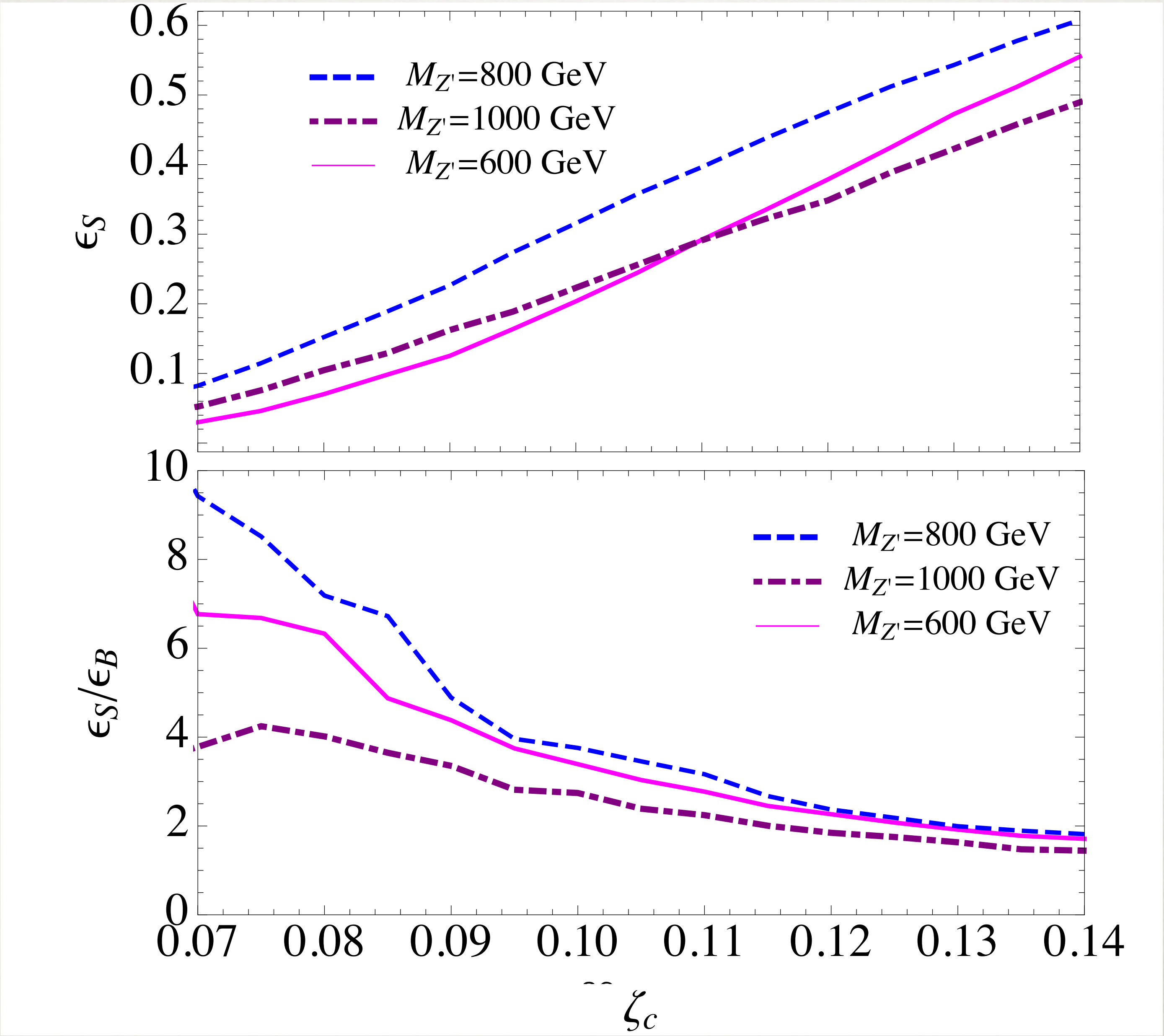
Z'→WW Analysis

- After ATLAS selection AND cut on $\zeta < \zeta_c$:



Z'→WW Analysis

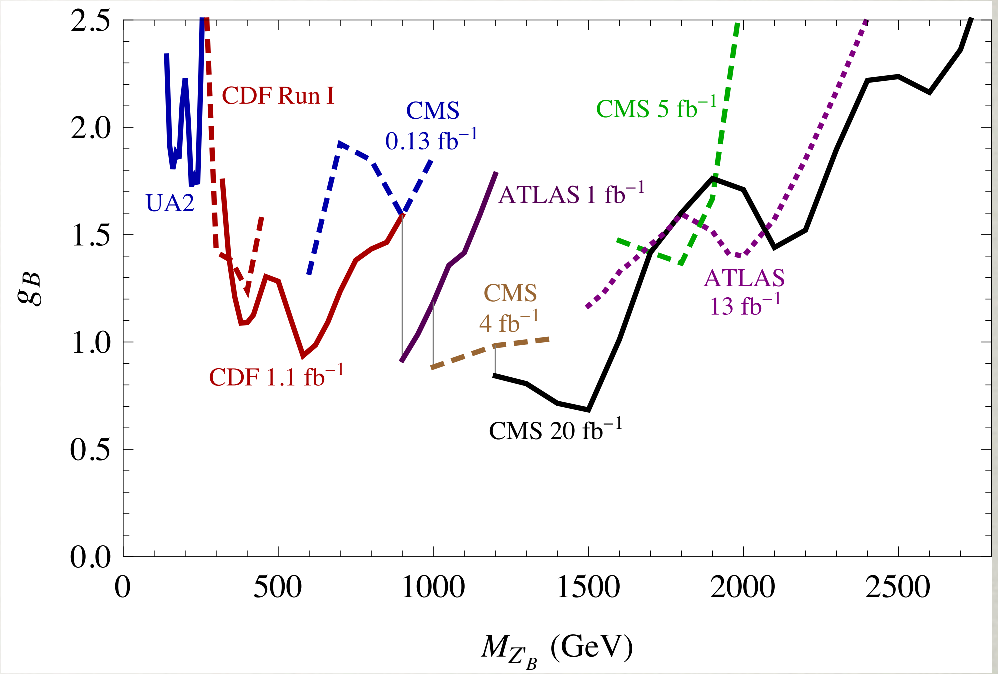
- *S*/*B* gains and efficiency change:

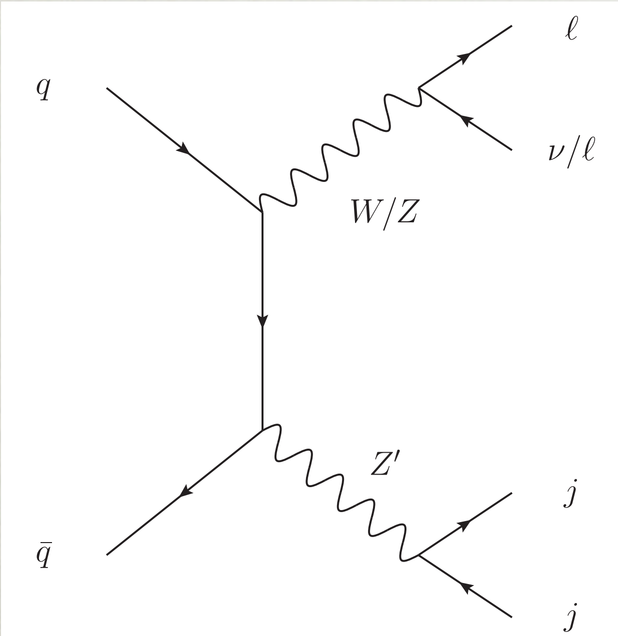


Future directions

Direct resonance production

- Best bounds come from UA2/Tevatron
- At LHC, hard to pass triggers and discriminate from backgrounds
- Consider **associated production**
    - Provides handle for trigger
    - Gives resonance a (mild) boost



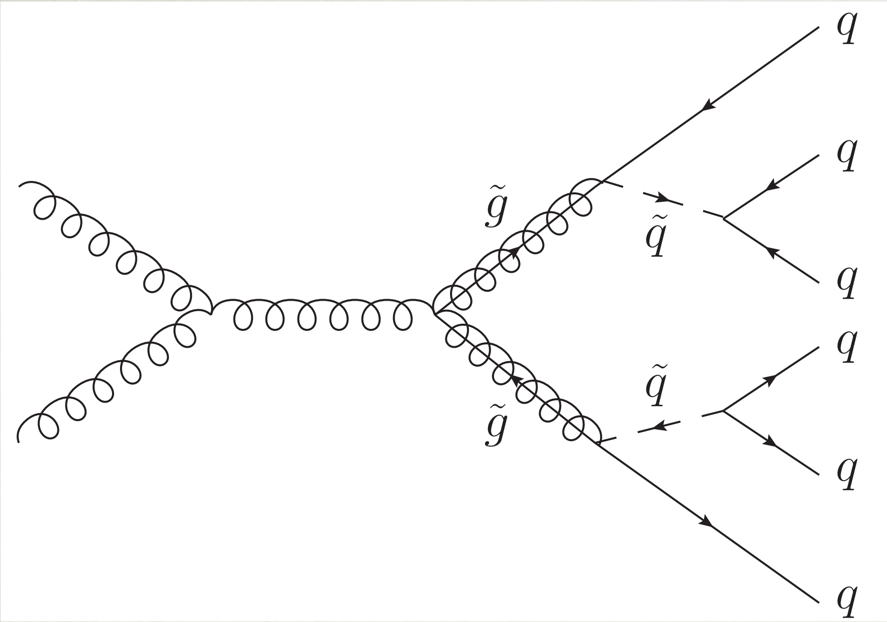


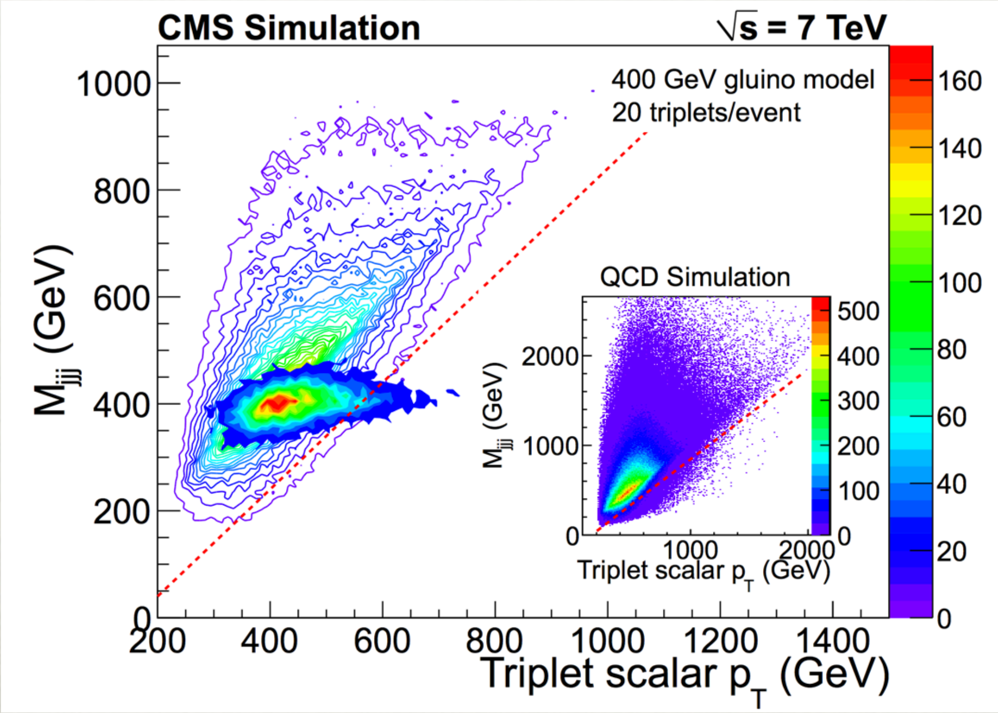
- Recast of ATLAS techni-rho W+dijet search can beat Tevatron by a factor of a few in cross section
- Can we do better with an optimized search?
- What about ζ/some similar observable?
- Work in progress

Multijet resonances

- Jet substructure can also be useful for three-jet resonances, but come at a cost of producing them well above threshold (ex. RPV gluinos in Curtin, Essig, BS arXiv:1210.5523)

- There are already good resolved 3-jet resonance searches (ex. Rutgers gp., CMS analysis arXiv:1311.1799)
    - Already in somewhat boosted regime





Conclusions

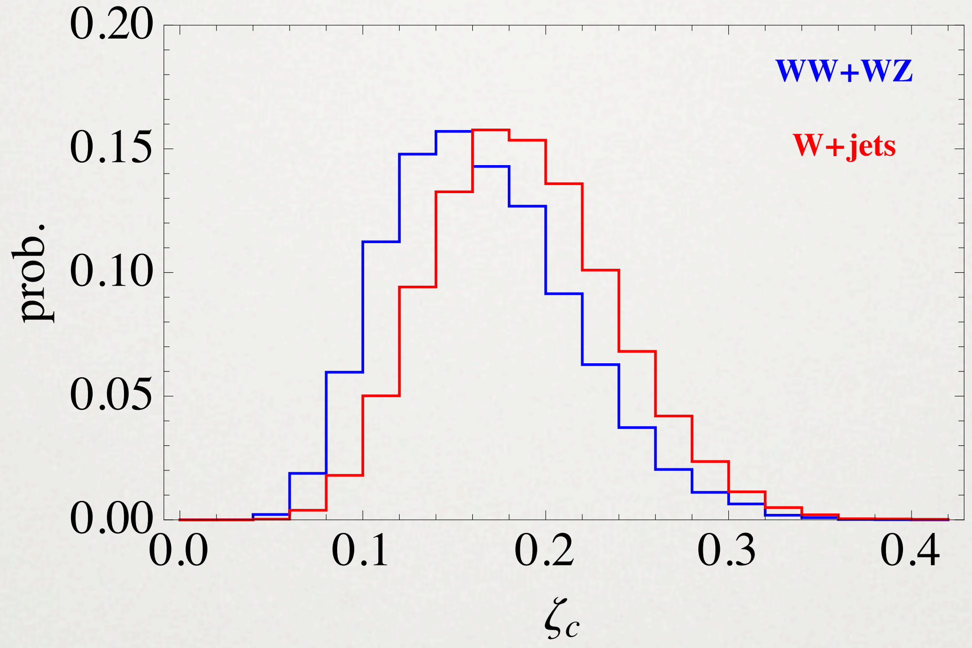
- Jet-substructure-inspired observables can improve identification of dijet resonances, even in the moderate boost regime/resolved limit
    - Interpolate between different kinematic regimes

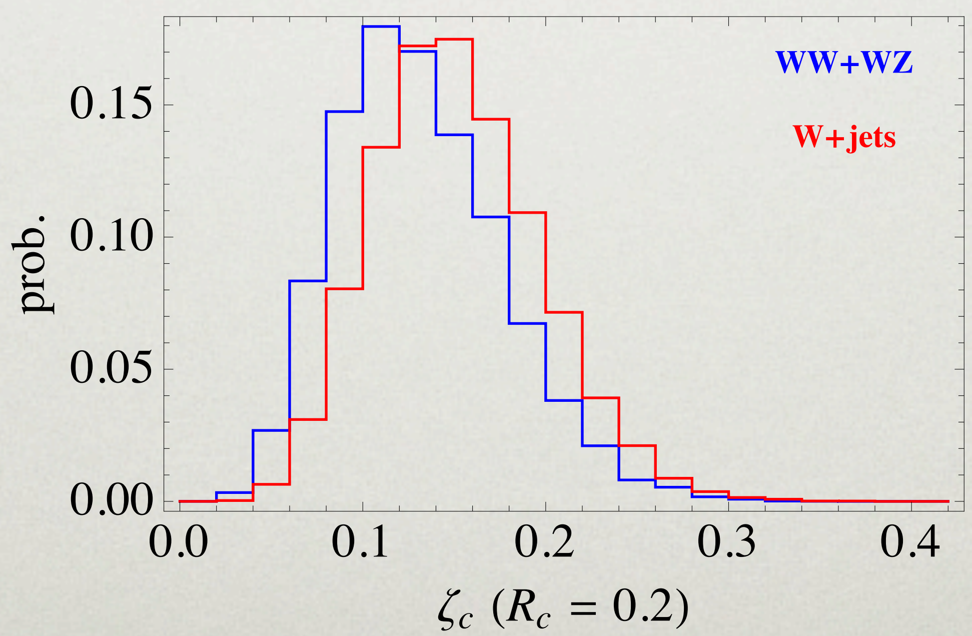
$$\zeta \equiv \frac{m_1}{m_{12}} \Delta R_{12} \quad \text{(and variations)}$$

- Works well for two important examples of SM hadronic resonances
    - WW+WZ
    - V + (H → bb)
- Also useful in beyond-SM physics searches
    - Z′ → WW
    - Z′ → jj
- Uses standard-radius jets, no optimization for different *R*
- Let’s find out what LHC13 has in store!

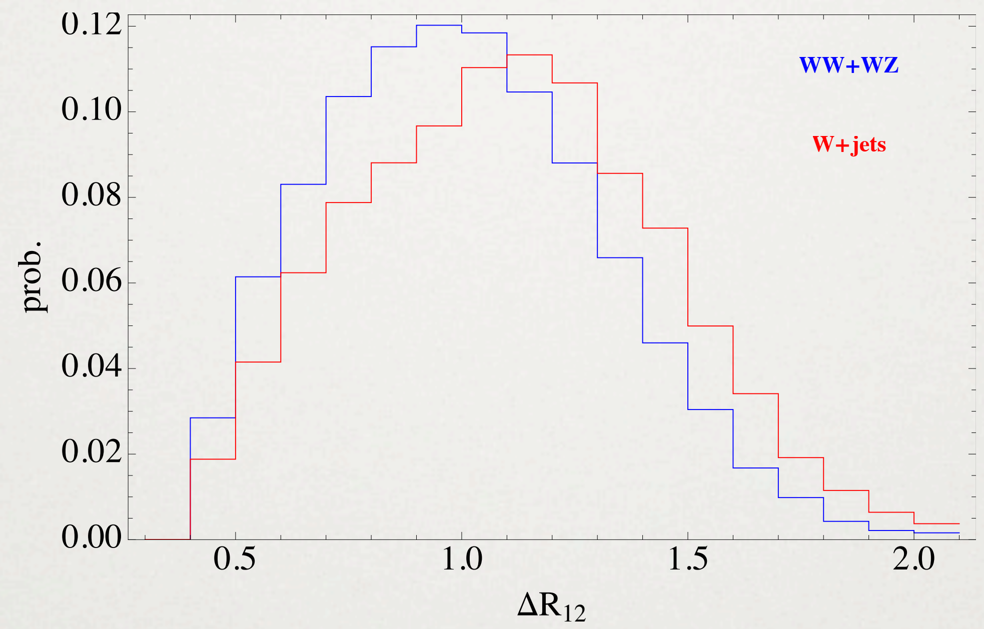
Back-up slides

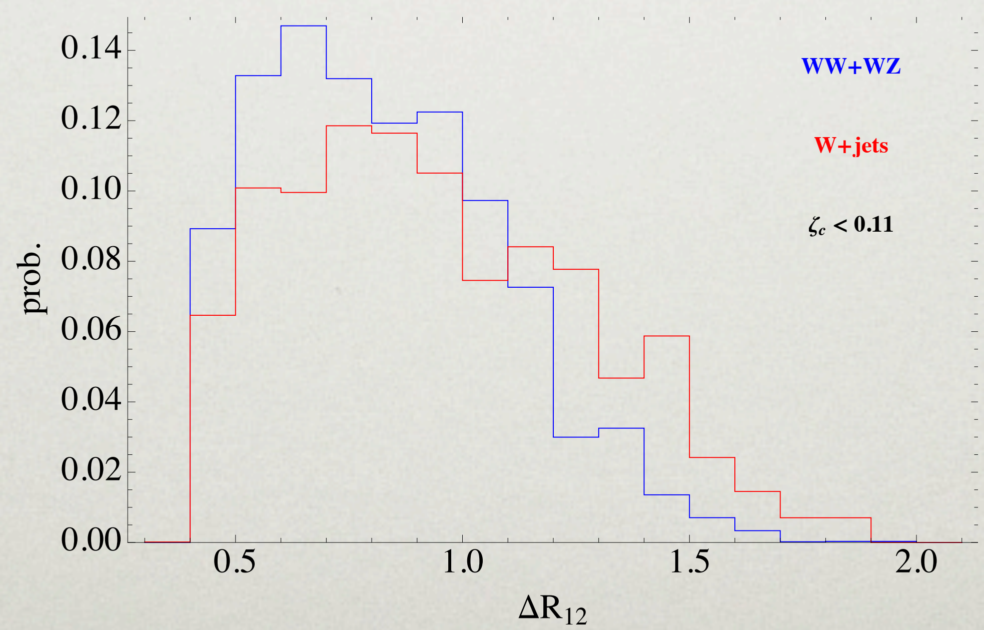
zeta distribution



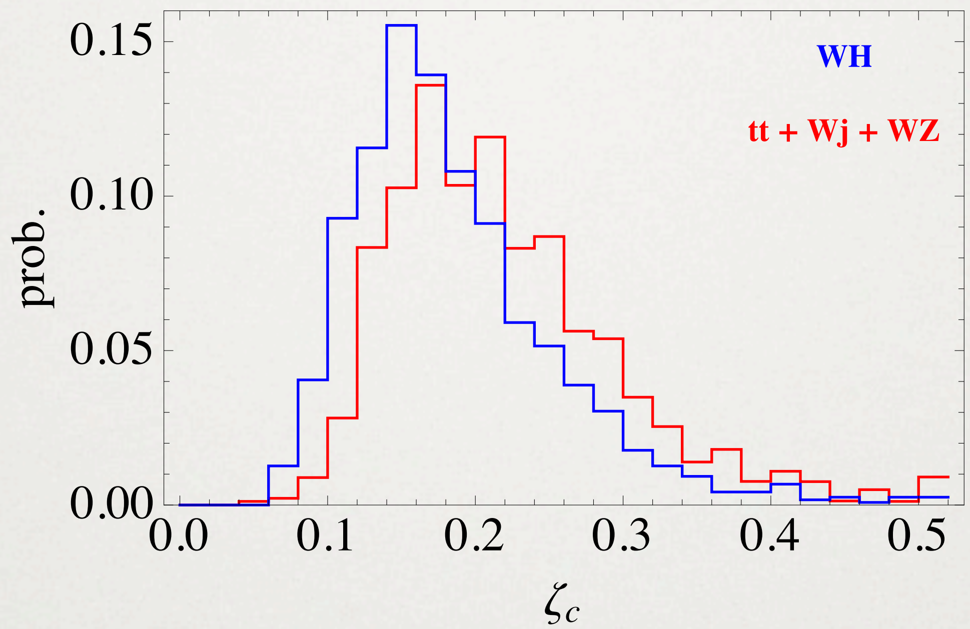


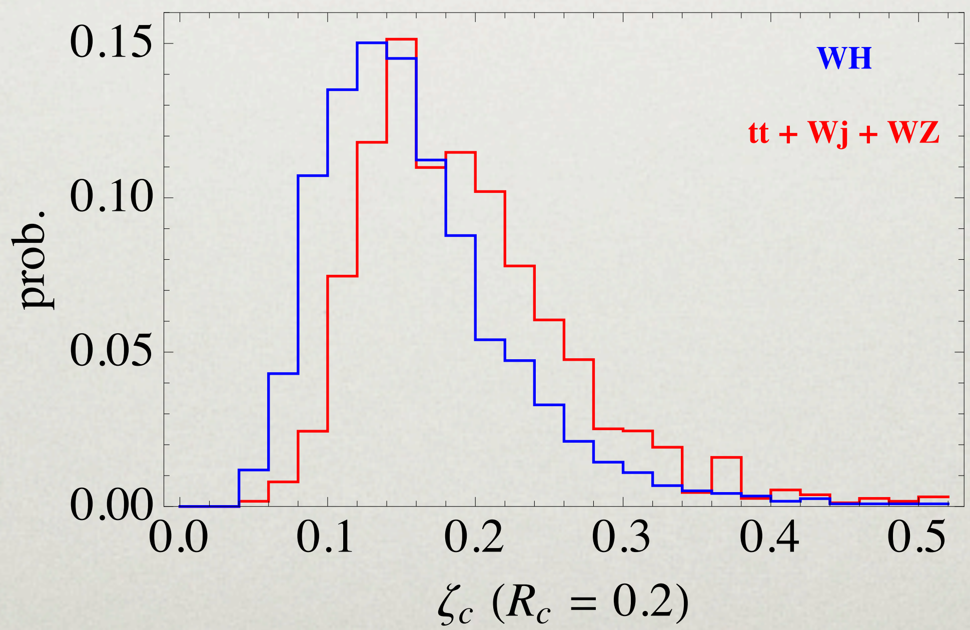
ΔR distribution



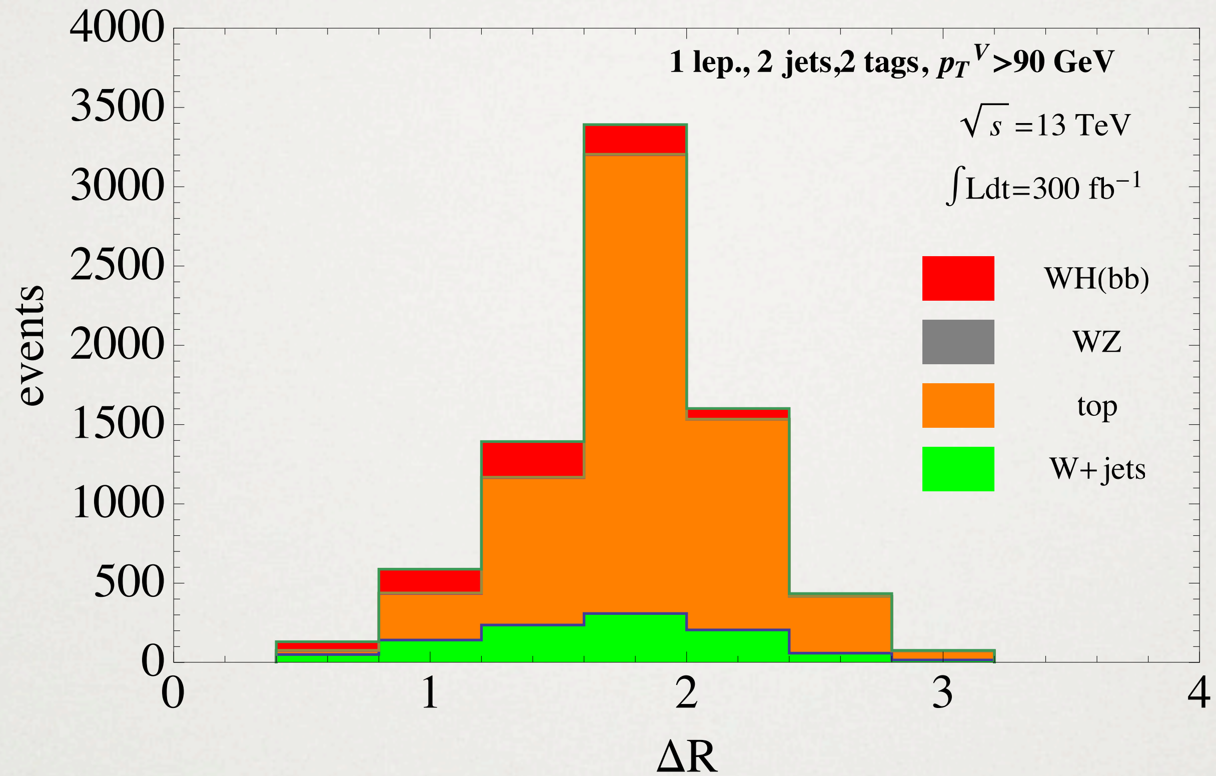


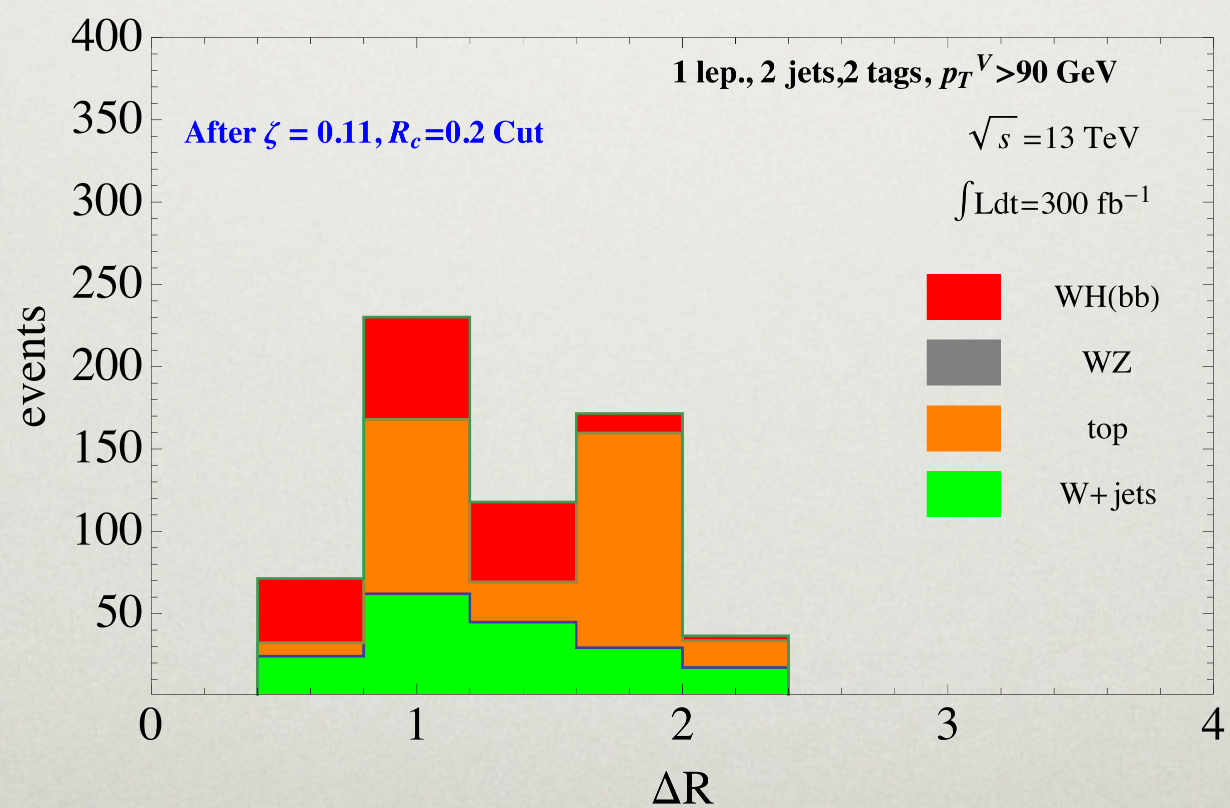
zeta distribution



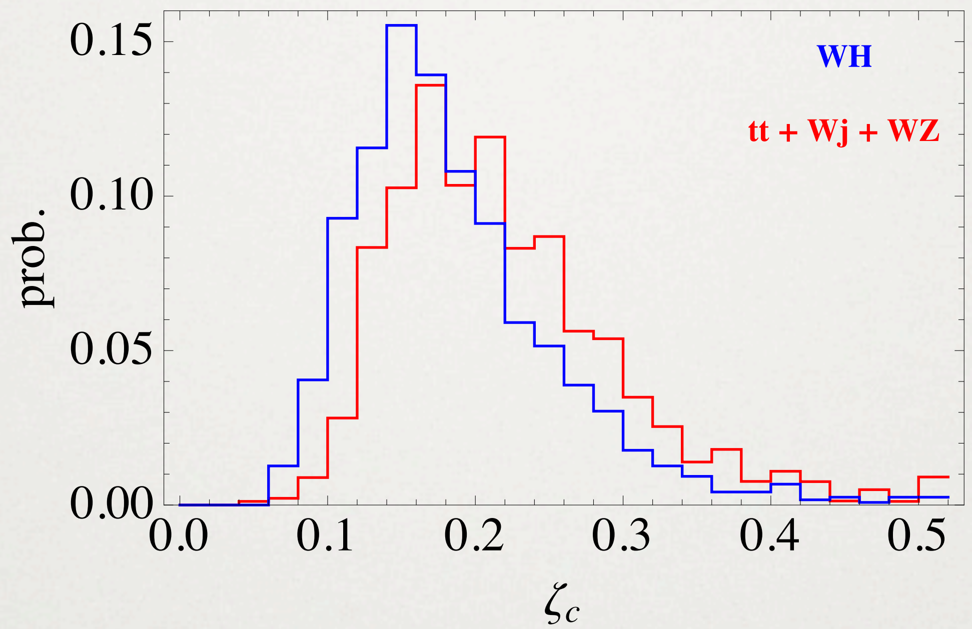


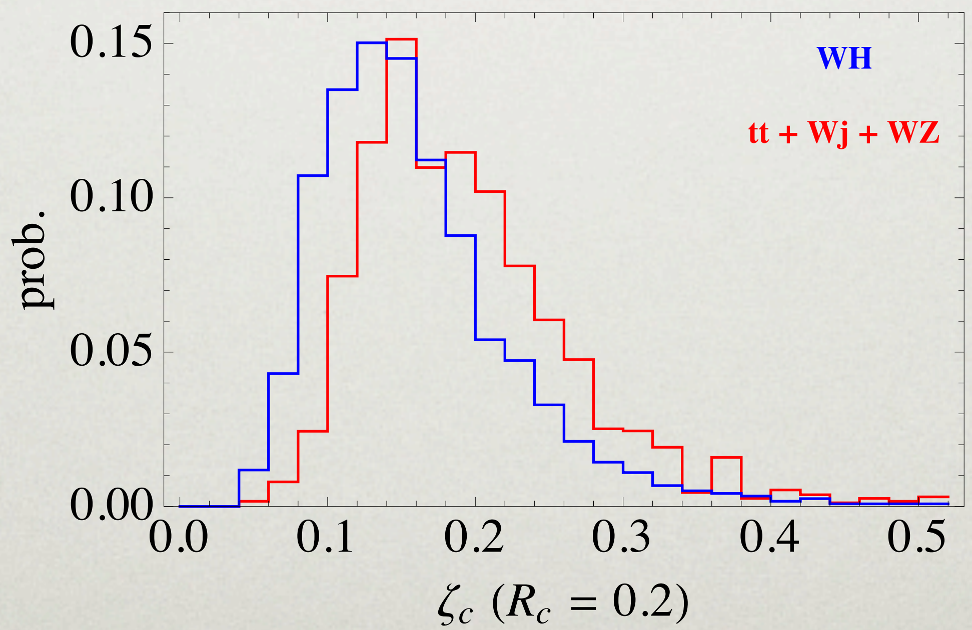
ΔR distribution



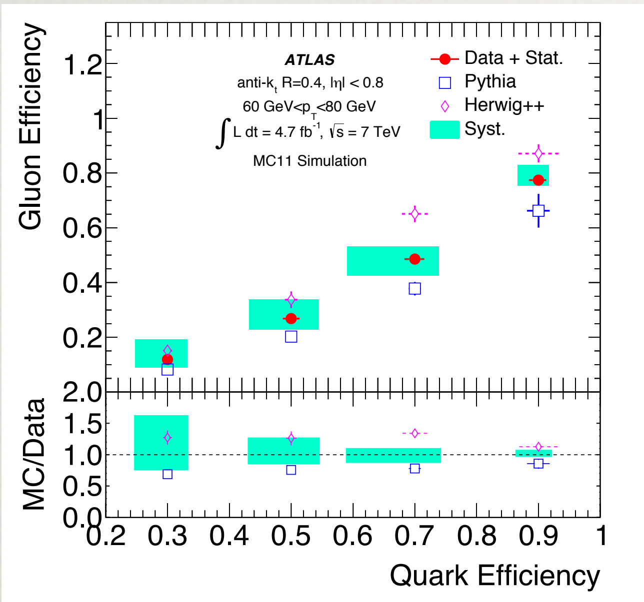


zeta distribution

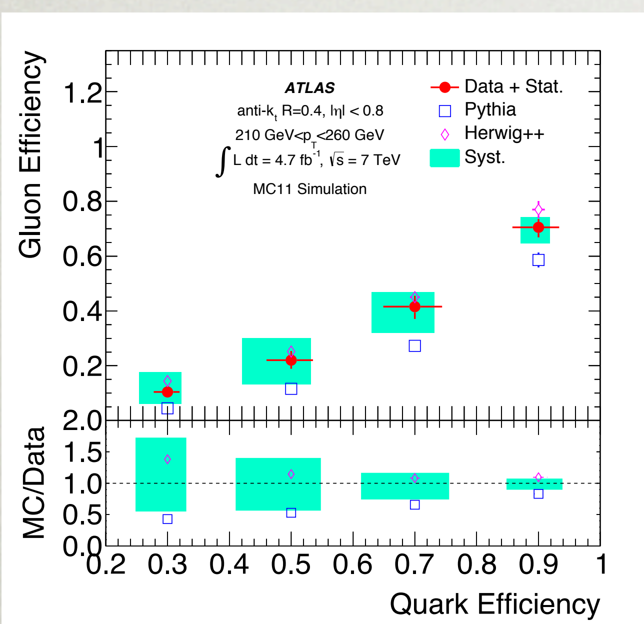




q/g tagging



(a)



Taken from ATLAS q/g tagging study
arXiv:1405.6583