IMPROVING IDENTIFICATION OF DIJET RESONANCES AT THE LHC

Brian Shuve

Perimeter Institute for Theoretical Physics

In collaboration with Eder Izaguirre, Itay Yavin

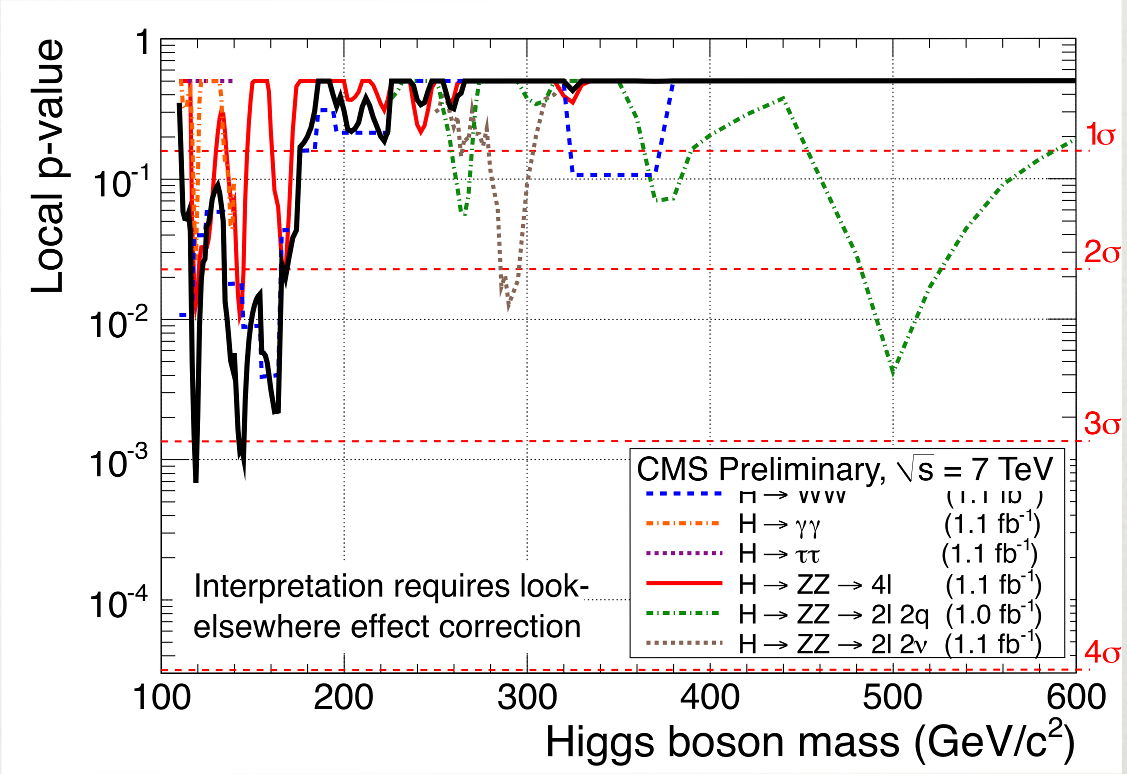
arXiv:1407.7037 & work in progress

University of Toronto seminar

17 November 2014

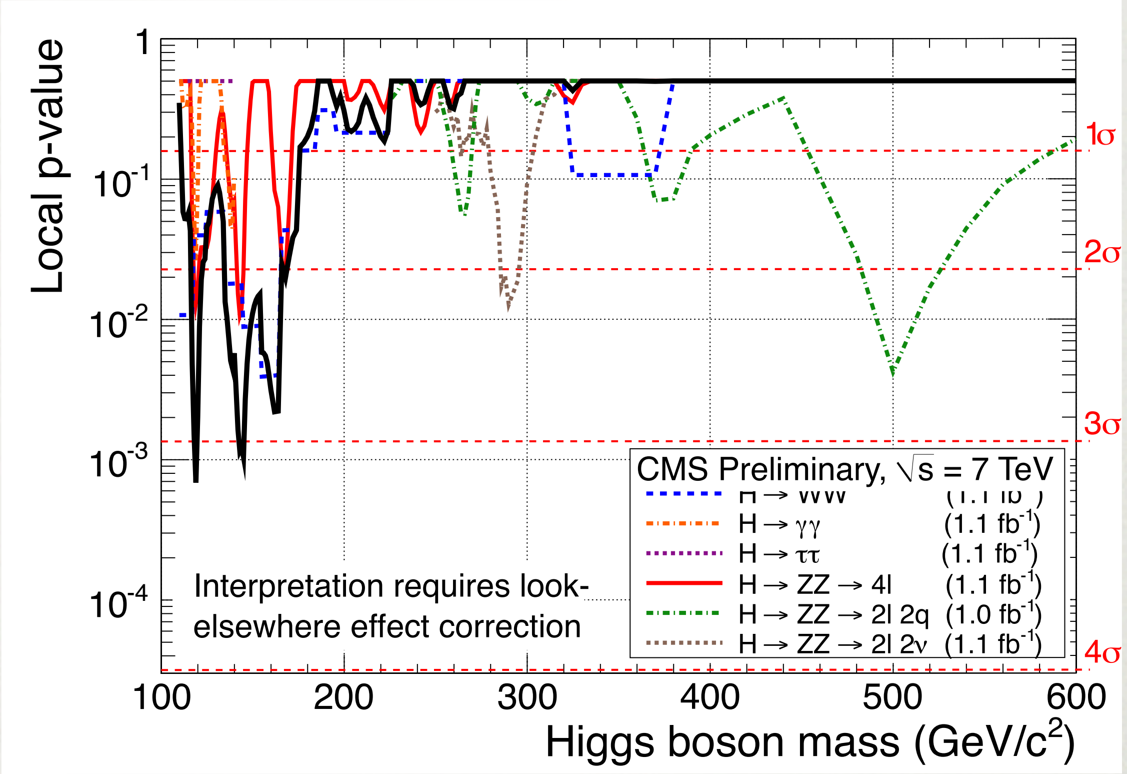
Summary of LHC Run I

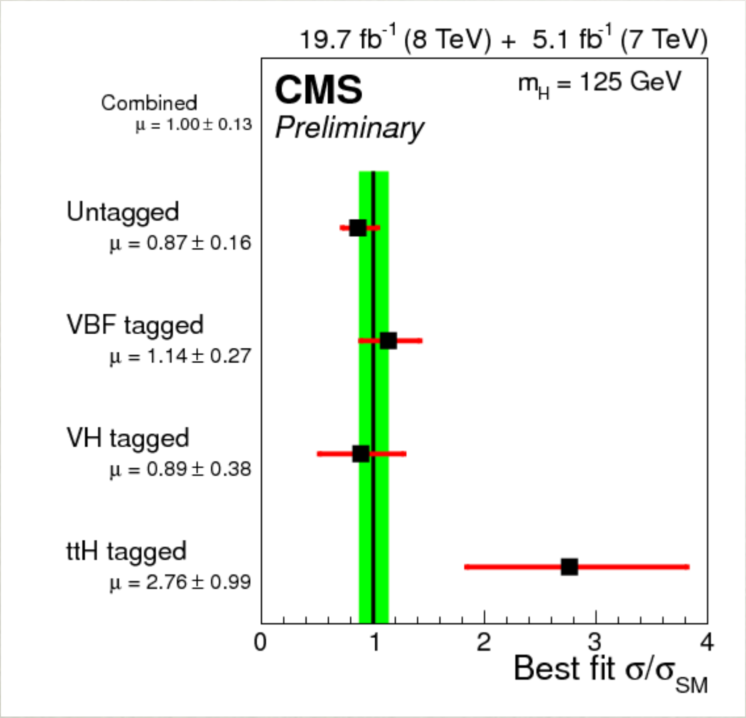
Then...



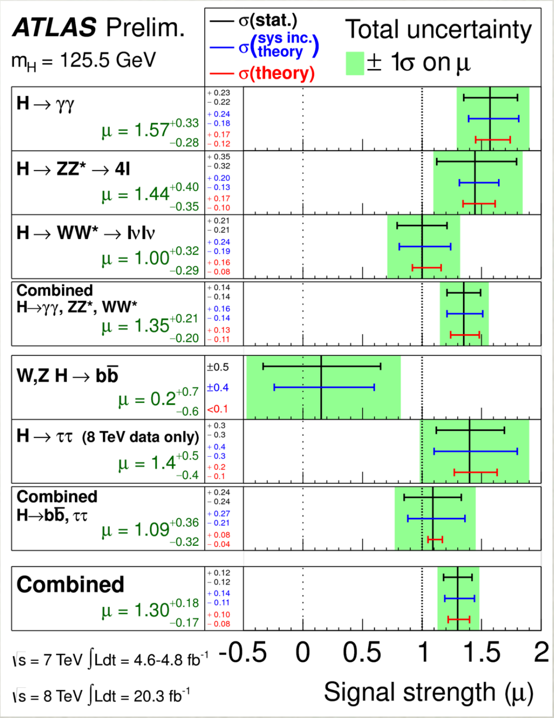
Summary of LHC Run I

Then...

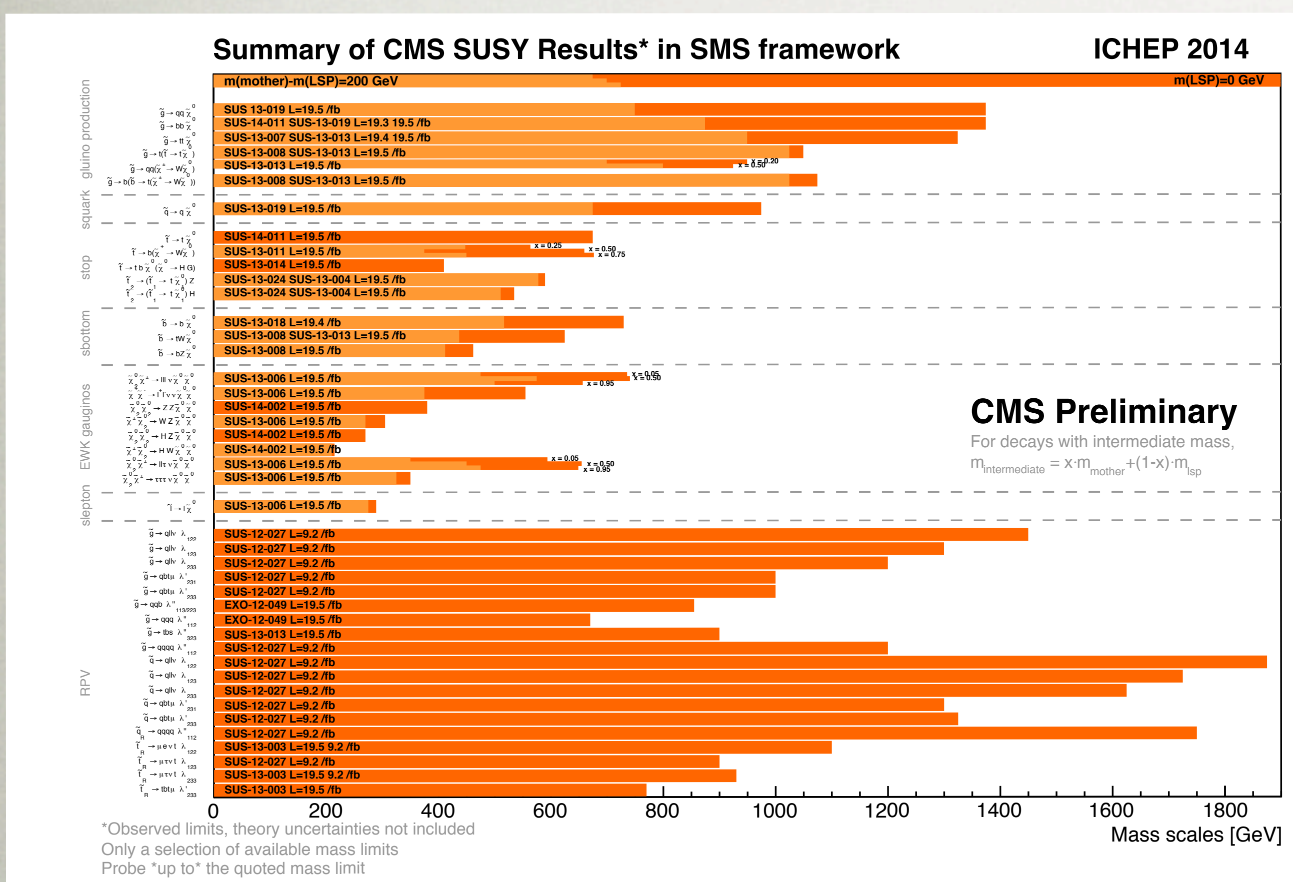


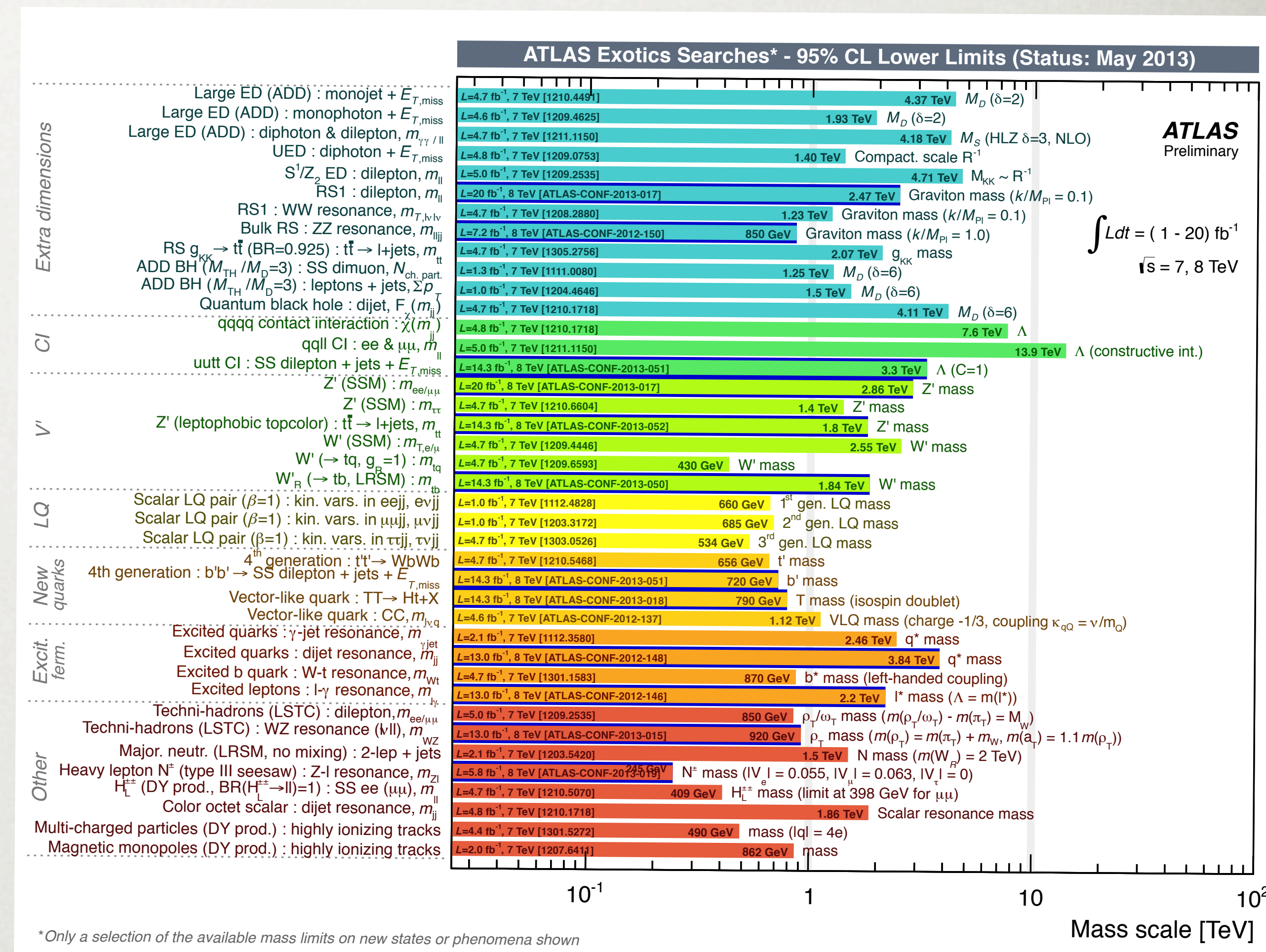


...and now



Summary of LHC Run I

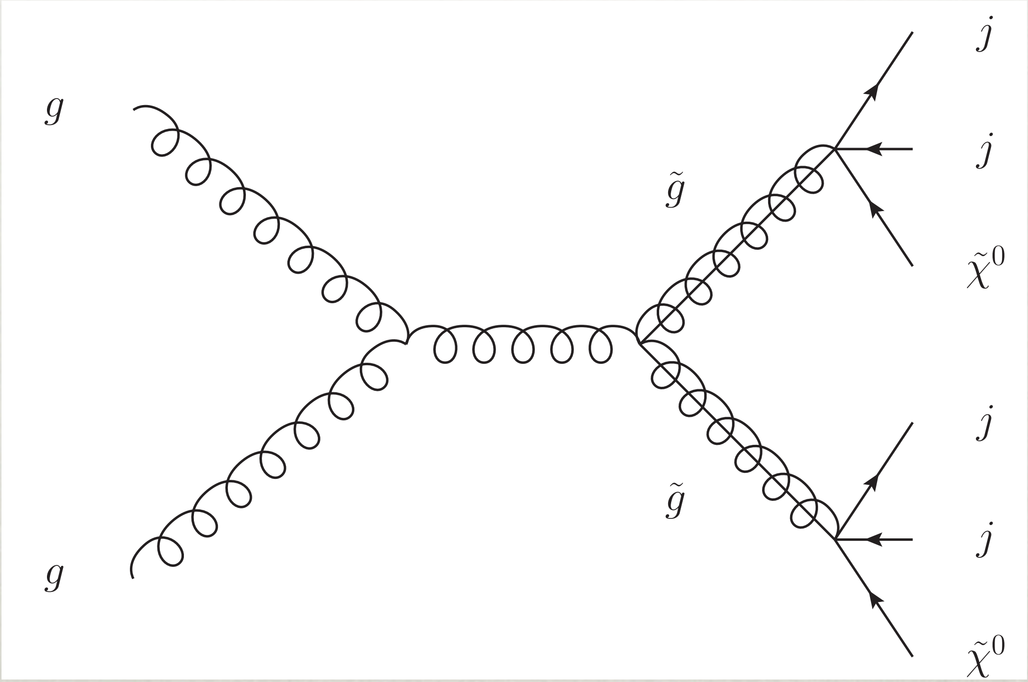




Looking forward to Runs II+

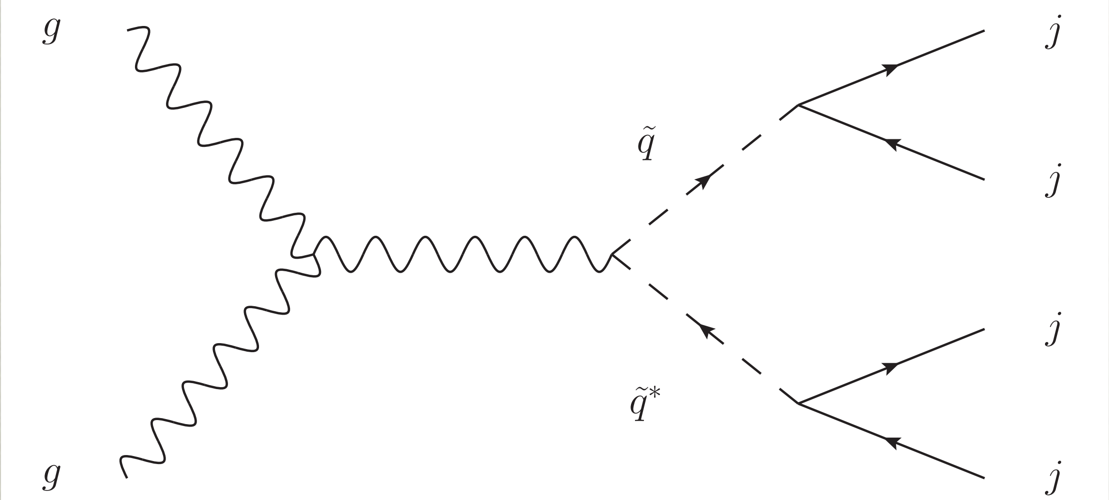
- Given that we haven't seen any new physics at Run I, what are the prospects moving forward?

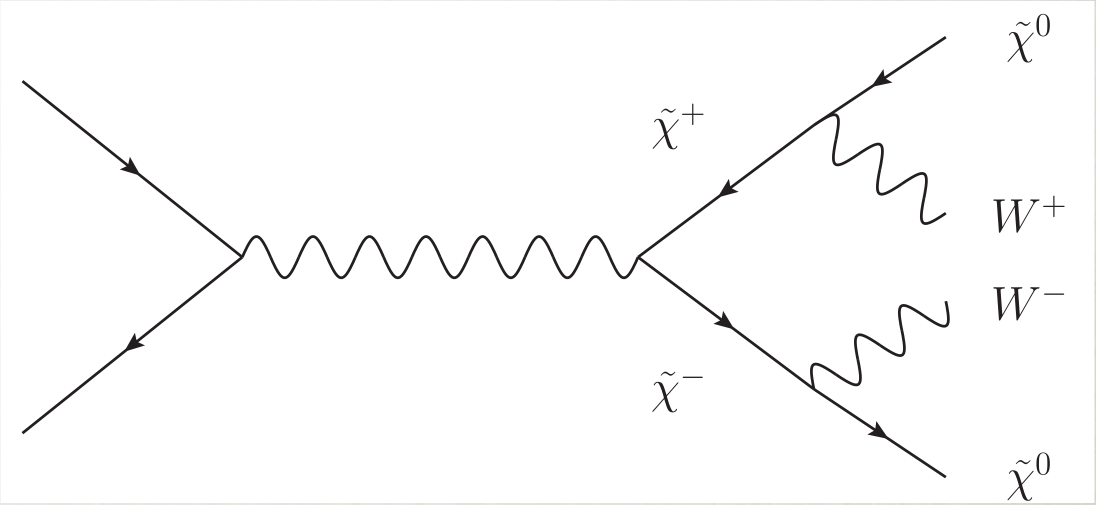
- **Scenario #1:** New states at > 1 TeV
    - Prospects are very good
    - Not much to say about this: scale up cuts and look for spectacular signatures!



Looking forward to Runs II+

- **Scenario #2:** New states at the electroweak scale
  - We haven't seen the new physics because it looks a lot like the SM...
  - Typically large backgrounds from QCD, V+jets, VV, tops, etc.





- Signal rates may be **large** but final states are much softer even at 13 TeV
  - Suffer from higher trigger thresholds
  - Suffer from higher pile-up

Looking forward to Runs II+

- Cutting out the SM background cuts out most of the signal, too
    - Want to exploit any differences between signal and background kinematics
    - Study BSM physics via precision SM physics

Looking forward to Runs II+

- Cutting out the SM background cuts out most of the signal, too
    - Want to exploit any differences between signal and background kinematics
    - Study BSM physics via precision SM physics

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

Looking forward to Runs II+

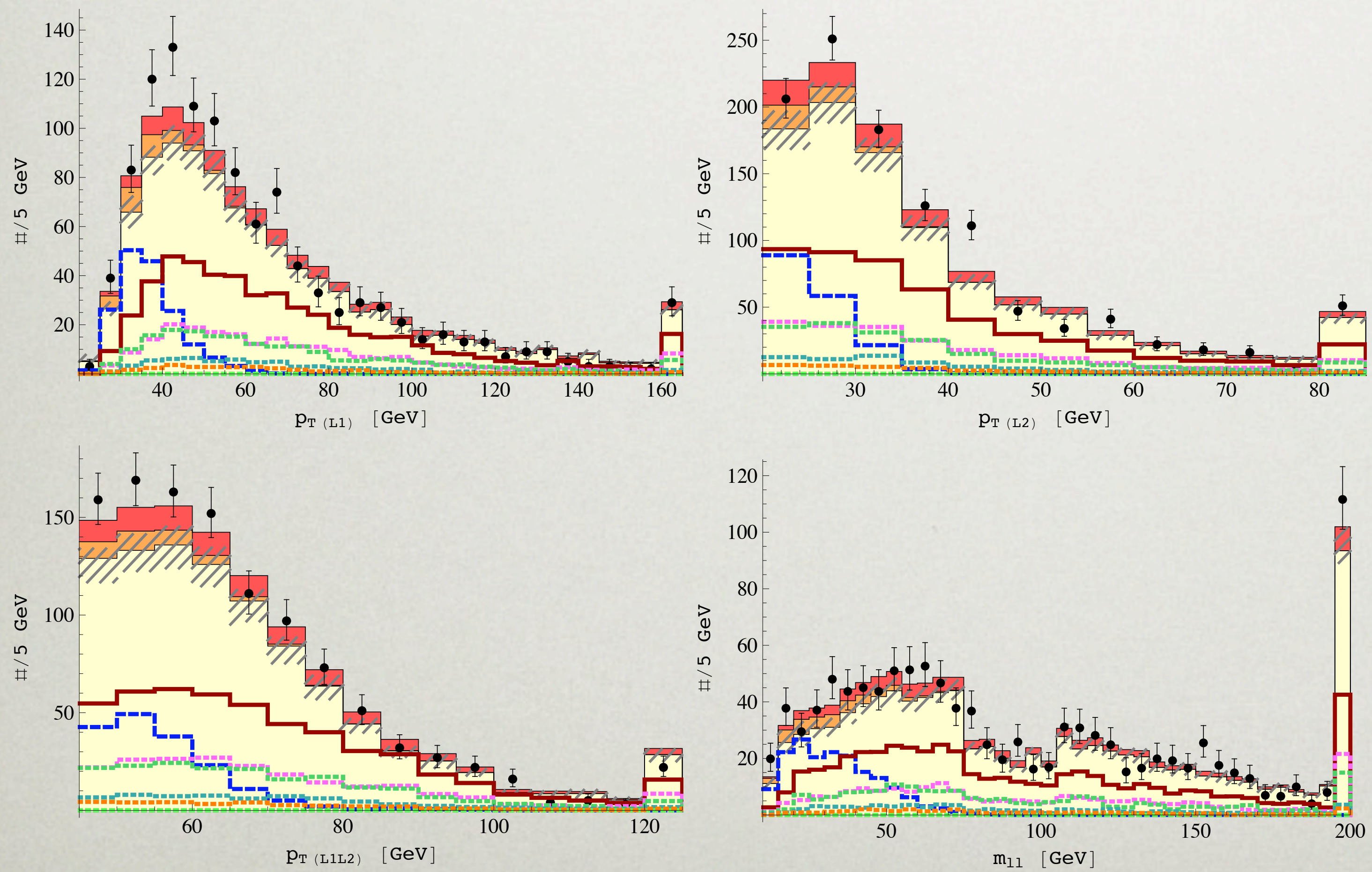
- Cutting out the SM background cuts out most of the signal, too
    - Want to exploit any differences between signal and background kinematics
    - Study BSM physics via precision SM physics

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

- I'll focus on **hadronic resonances**
    - Most challenging final states due to enormous QCD backgrounds
    - Jet substructure studies have shown that large improvements in signal identification are possible (at least in one kinematic regime)

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

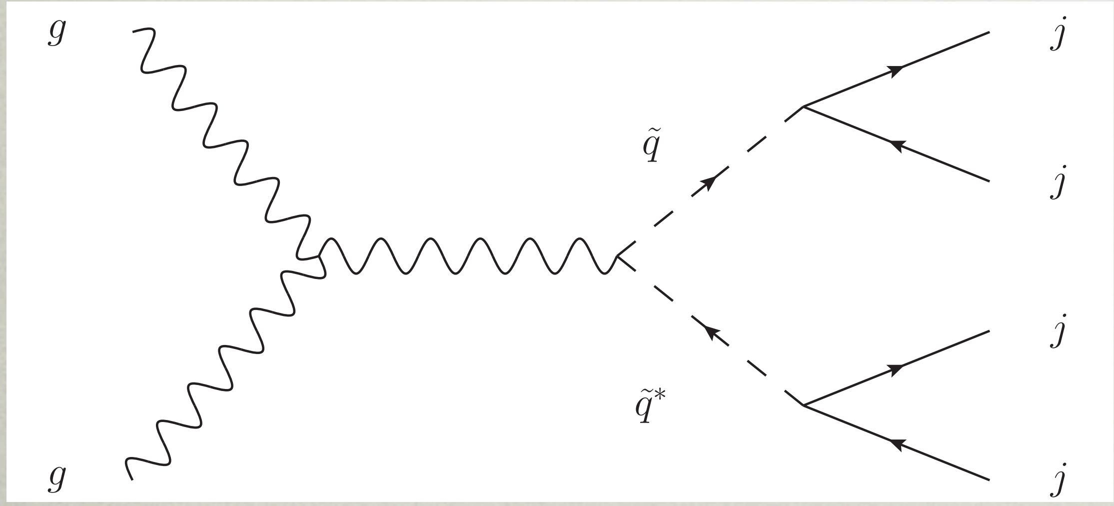
Hadronic resonances

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

Hadronic resonances

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

- Different signal kinematics depending on production mode:

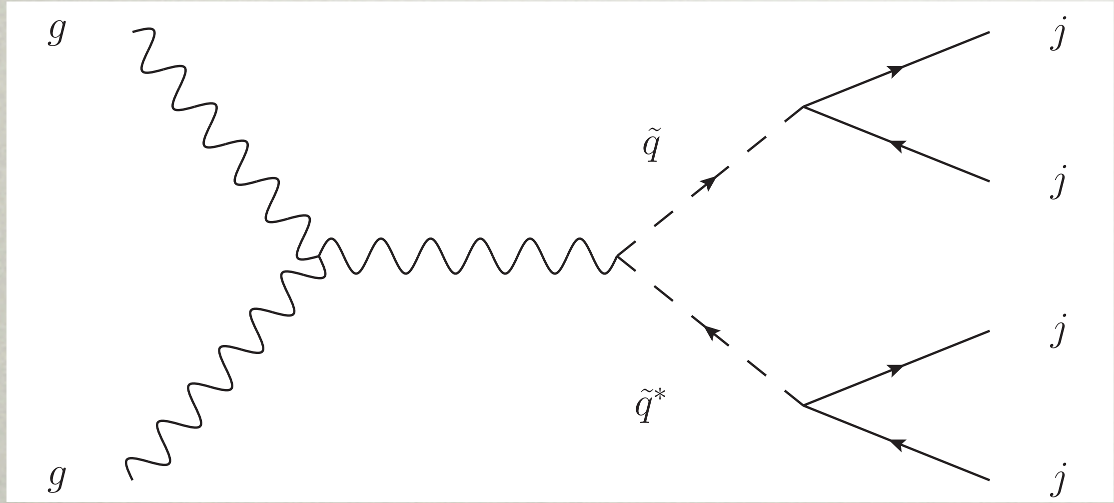


(threshold)

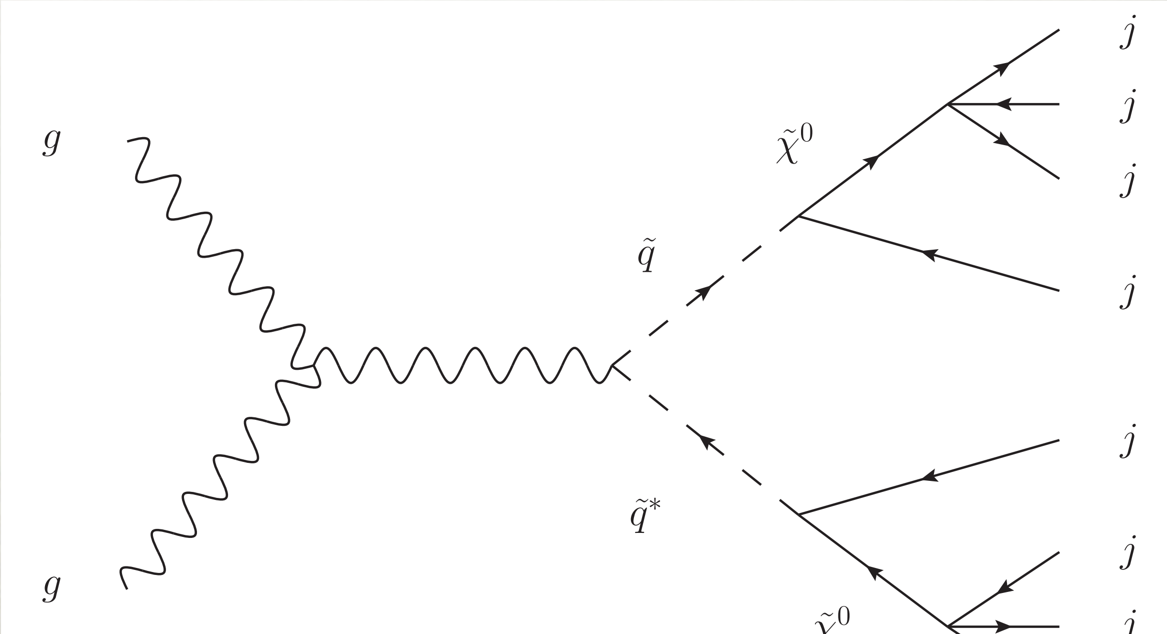
Hadronic resonances

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

- Different signal kinematics depending on production mode:



(threshold)

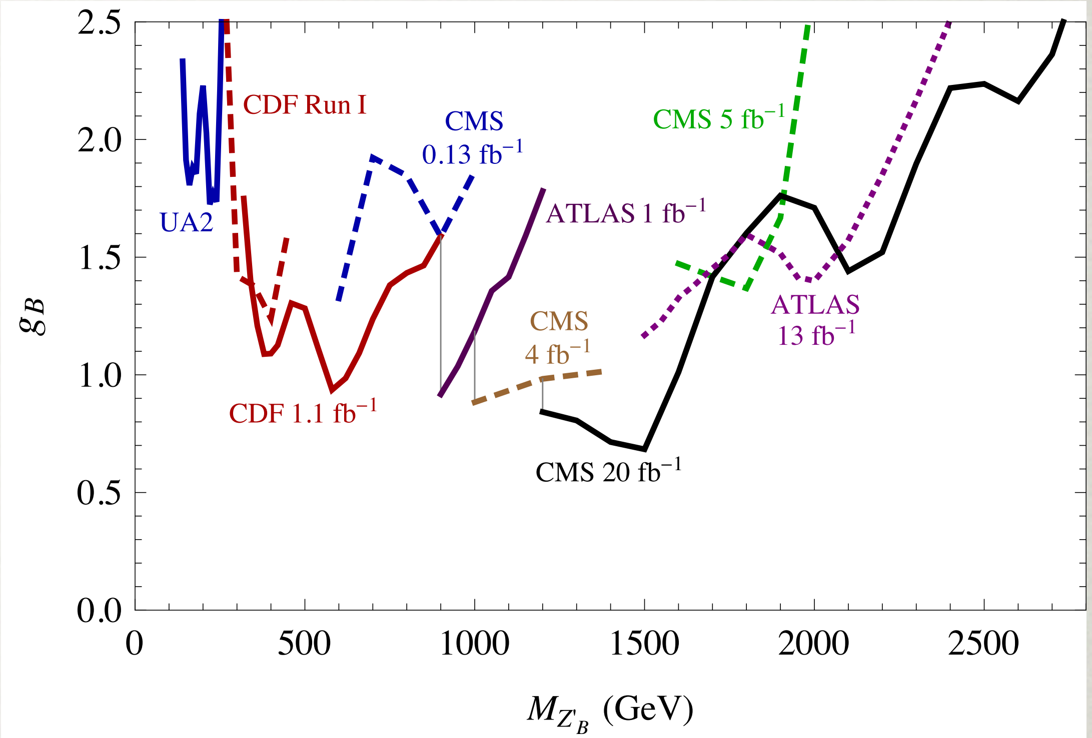


(boosted)

Hadronic resonances

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

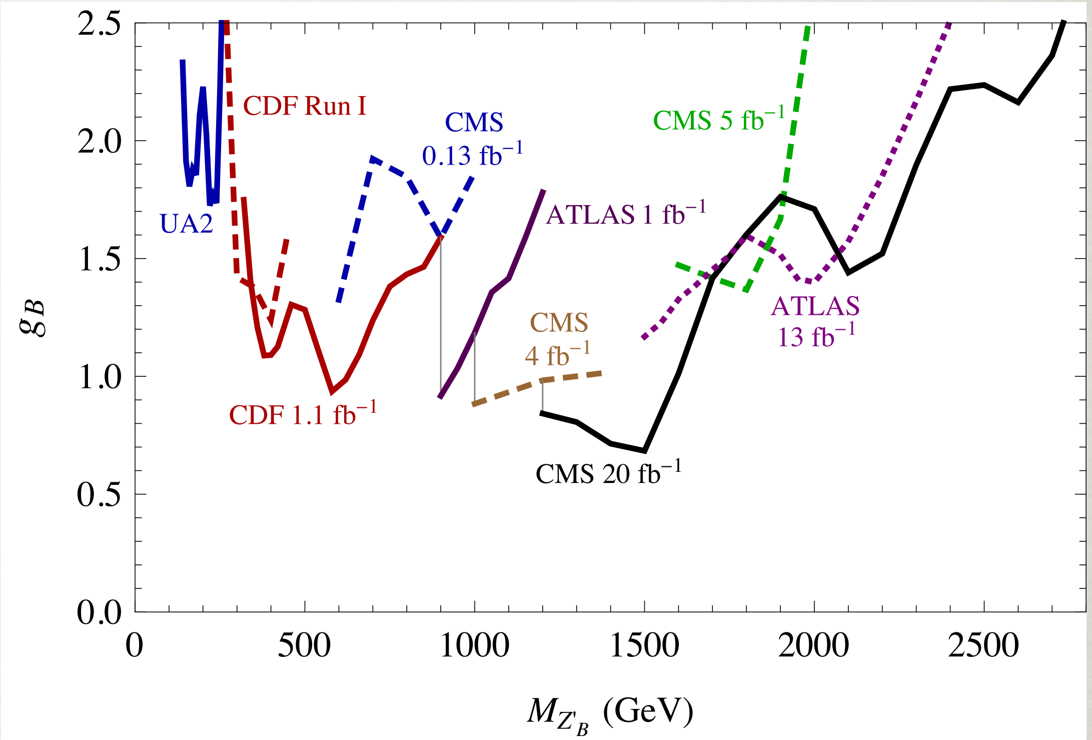
(taken from Dobrescu, Yu arXiv:1306.2629)



Hadronic resonances

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

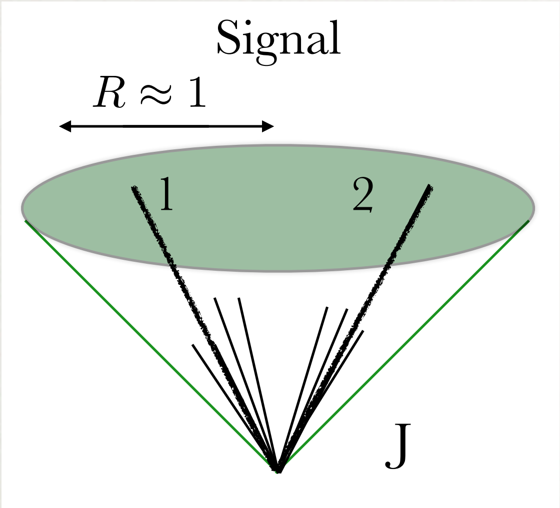
(taken from Dobrescu, Yu arXiv:1306.2629)

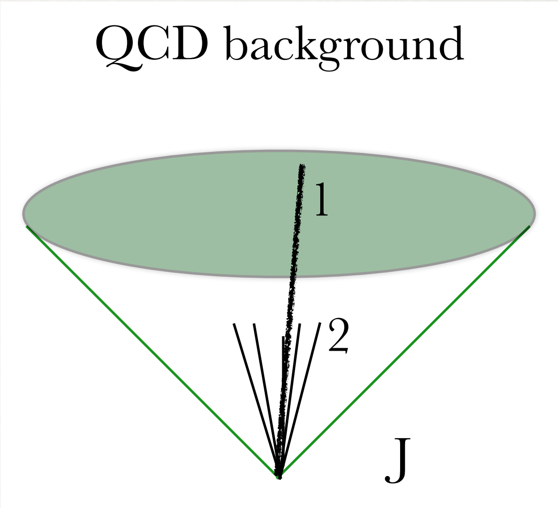


- Current approaches:
  - Some searches highly optimized, using sophisticated multivariable techniques (H to bb searches)
  - Others place simple cuts on jet kinematics and do a bump hunt (Z′→WW semileptonic, SM WW+WZ semileptonic,...)
  - Can we do better?

Hadronic resonances

- Take a lesson from jet substructure studies of boosted hadronic objects

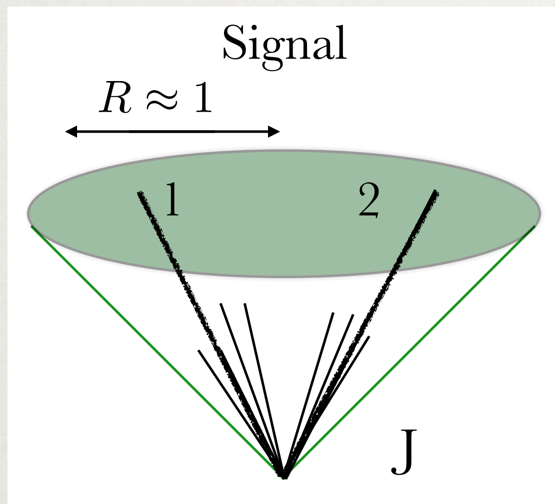


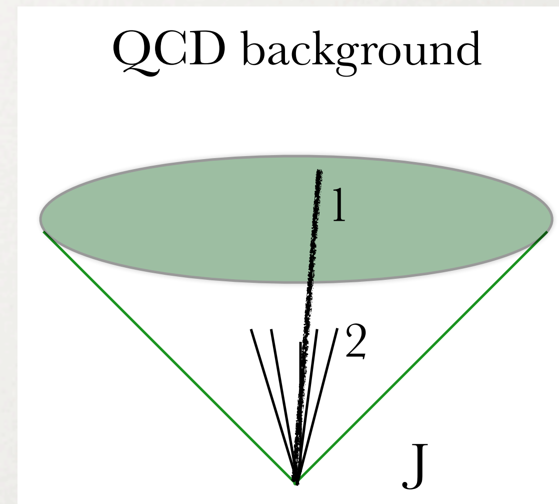


Seymour, 1994; Butterworth, Cox, Forshaw, 2002; Butterworth, Davison, Rubin, Salam, 2008

Hadronic resonances

- Take a lesson from jet substructure studies of boosted hadronic objects





Seymour, 1994; Butterworth, Cox, Forshaw, 2002; Butterworth, Davison, Rubin, Salam, 2008

- Generalize the differences between signal/QCD kinematics & radiation outside of the highly boosted regime
    - Useful for states typically produced near threshold
    - We define a new observable that generalizes the **mass drop criterion** of BDRS tagger
    - Gives factor of 2-6 gain in *S*/*B*, involves only resolved small-*R* jets
    - Outperforms other possible cuts we investigated

Outline

1. Jet substructure and the highly boosted regime

2. Resonance tagging in the mildly boosted regime

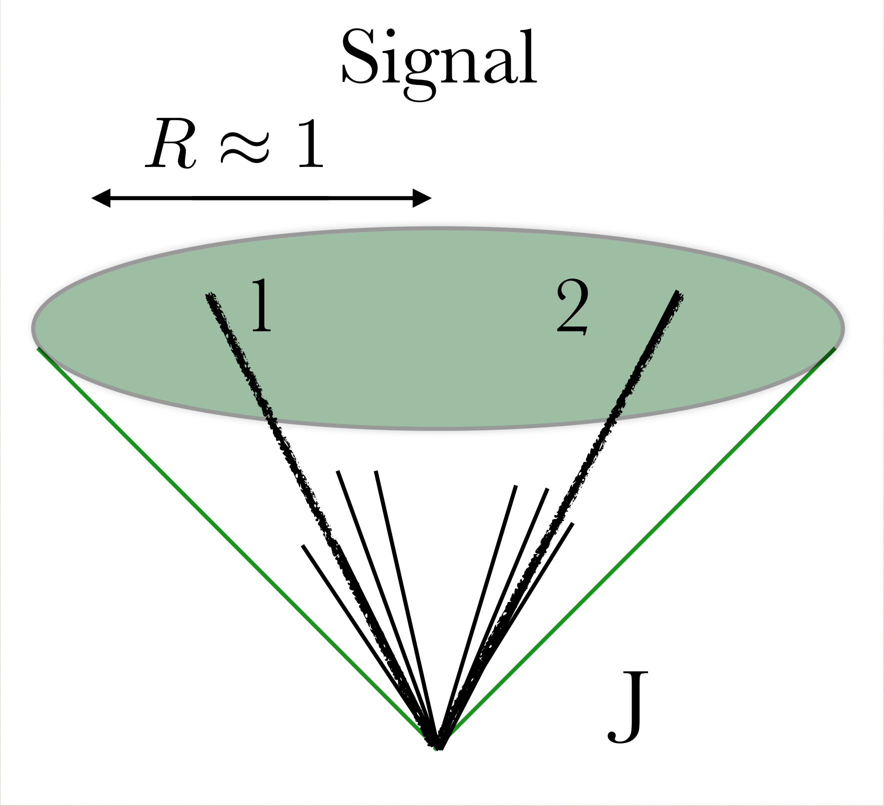
3. Examples
    - SM: WW+WZ
    - SM: $V(H \to bb)$
    - BSM: $Z' \to WW$

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

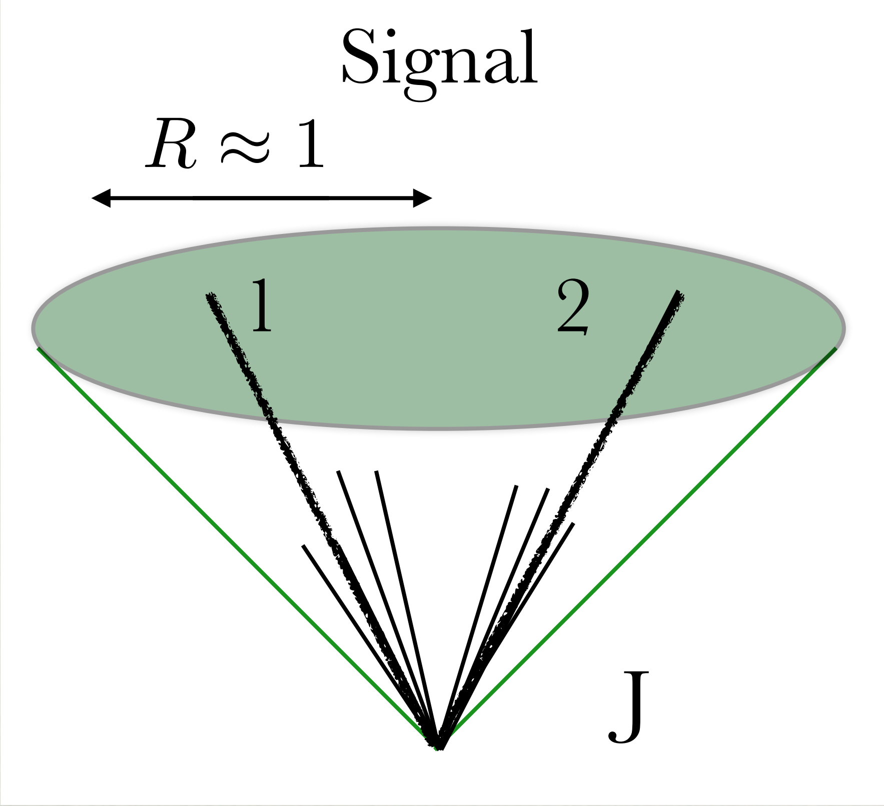
$$p_{\mathrm{T}} \gtrsim (\text{few}) \times m_{\text{resonance}}$$

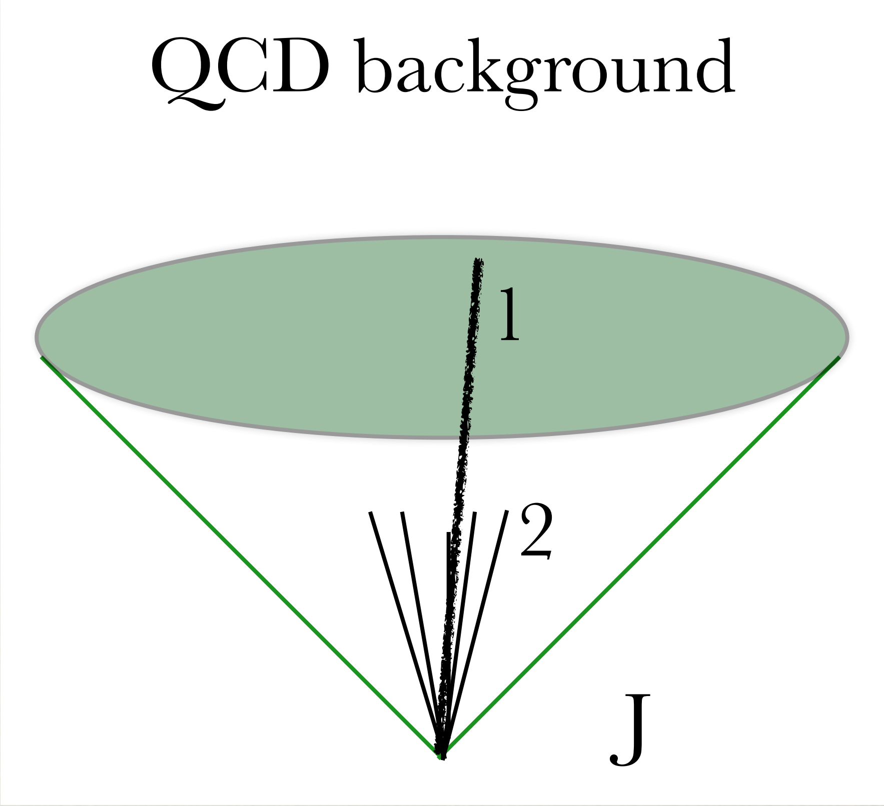


Jet substructure at high boost

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

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

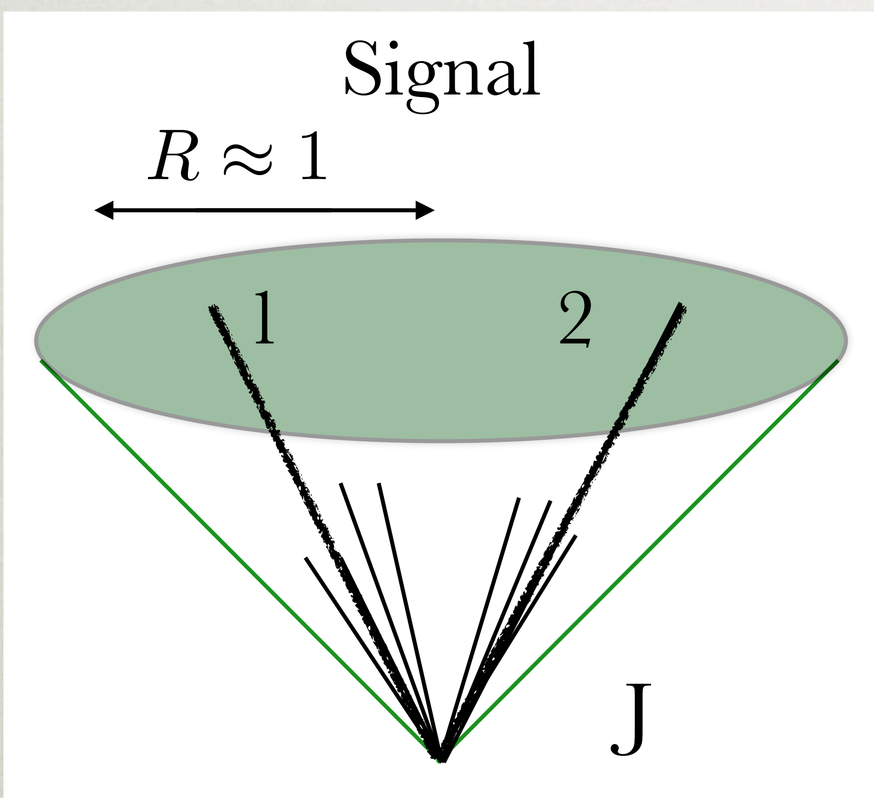


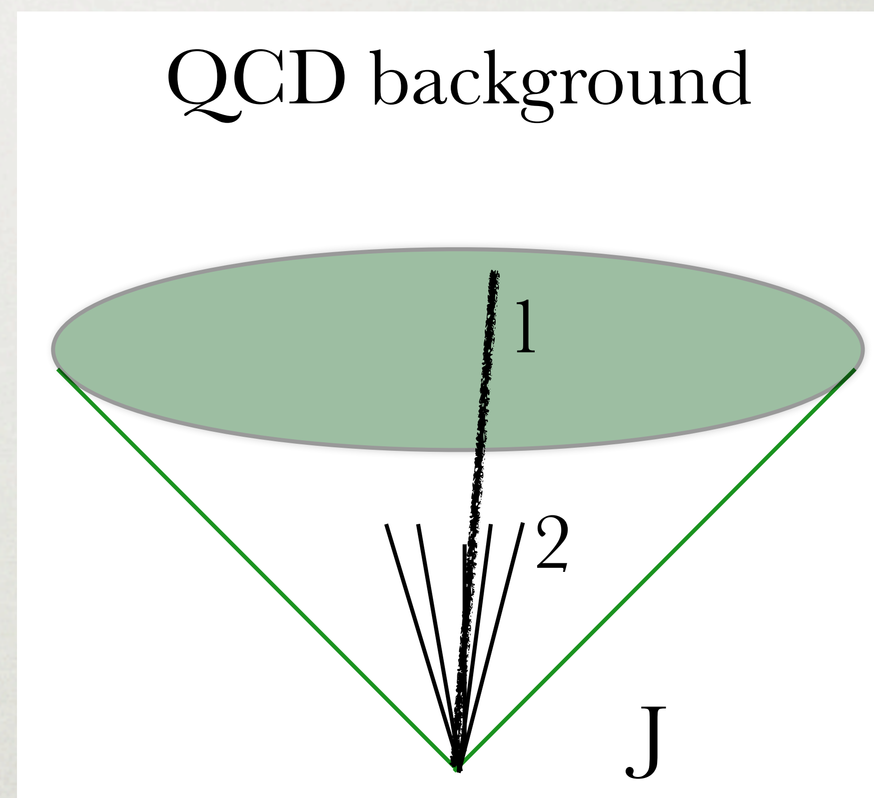


- Dominant background originates from a single QCD parton

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
  - We focus on decomposition approach as it is more readily generalized to resolved jet analyses





Mass drop tagger

- Canonical example: BDRS mass-drop tagger (arXiv:0802.2470)

- Exploits the structure of parton splitting in QCD

$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \, \frac{\alpha_{\mathrm{s}}}{2\pi} \mathcal{P}(z)_{a\to bc} \qquad z = \frac{E_b}{E_a}$$

Mass drop tagger

- Canonical example: BDRS mass-drop tagger (arXiv:0802.2470)

- Exploits the structure of parton splitting in QCD

$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \, \frac{\alpha_s}{2\pi} \mathcal{P}(z)_{a\to bc} \qquad\qquad z = \frac{E_b}{E_a}$$

1. **Asymmetric splittings**
    - Both q → q g and g → q q splittings tend to give asymmetric configurations
    - i.e. P(z) peaked towards z = 0 and z = 1
    - By contrast, partons from a resonance decay tend to have momentum divided symmetrically among them

Mass drop tagger

$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \, \frac{\alpha_{\rm s}}{2\pi} \mathcal{P}(z)_{a\to bc}$$

$$z = \frac{E_b}{E_a}$$

Mass drop tagger

$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \, \frac{\alpha_s}{2\pi} \mathcal{P}(z)_{a\to bc}$$

$$z = \frac{E_b}{E_a}$$

2. Origin of jet mass

- There is a **Sudakov suppression** of evolution from a hard scale down to massless partons

$$\Delta(t) \approx \exp\left[-\int_{t_0}^{t_\mathrm{f}} \frac{dt'}{t'} \, dz \, \frac{\alpha_s}{2\pi} \, \mathcal{P}(z)\right]$$

- If a parton has virtuality $t = m^2$, the transition to massless partons happens gradually
- i.e. the **mass** of a jet initiated by a QCD parton comes from a large number of splittings
- By contrast, when a resonance decays, it comes from a heavy mass m to massless partons in a single step

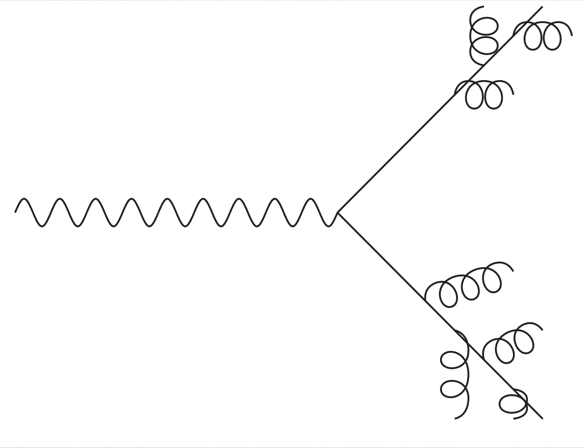
Mass drop tagger

$$d\sigma_{n+1} \approx d\sigma_n \, dz \, \frac{dt}{t} \, \frac{\alpha_s}{2\pi} \mathcal{P}(z)_{a\to bc} \qquad z = \frac{E_b}{E_a}$$

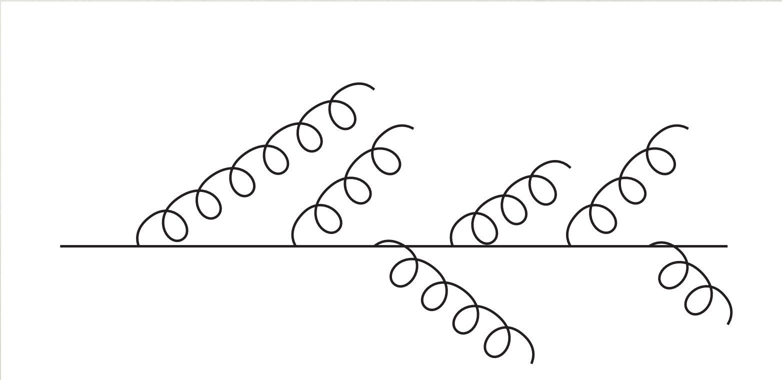
2. Origin of jet mass

- There is a **Sudakov suppression** of evolution from a hard scale down to massless partons $\Delta(t) \approx \exp\left[-\int_{t_0}^{t_f} \frac{dt'}{t'} \, dz \, \frac{\alpha_s}{2\pi} \, \mathcal{P}(z)\right]$
- If a parton has virtuality $t = m^2$, the transition to massless partons happens gradually
- i.e. the **mass** of a jet initiated by a QCD parton comes from a large number of splittings
- By contrast, when a resonance decays, it comes from a heavy mass *m* to massless partons in a single step

signal **QCD**



(equal mass)



Jet primer

- Use sequential jet recombination algorithms to get cluster sequence (jet radius R is input parameter)

  1. For all particles/calo cells, compute the distance d_{ij} in rapidity-azimuth space
  2. For the **shortest** distance, combine the 4-vectors for i and j
  3. Continue until the distance between the closest pair is $> R$

- This gives a collection of jets, and a cluster sequence for each jet

Mass drop tagger

- Basic idea of mass drop tagger: keep only jets that have **symmetric splittings** with a large **mass drop** at one step

- Mass drop procedure:

Mass drop tagger

- Basic idea of mass drop tagger: keep only jets that have **symmetric splittings** with a large **mass drop** at one step

- Mass drop procedure:

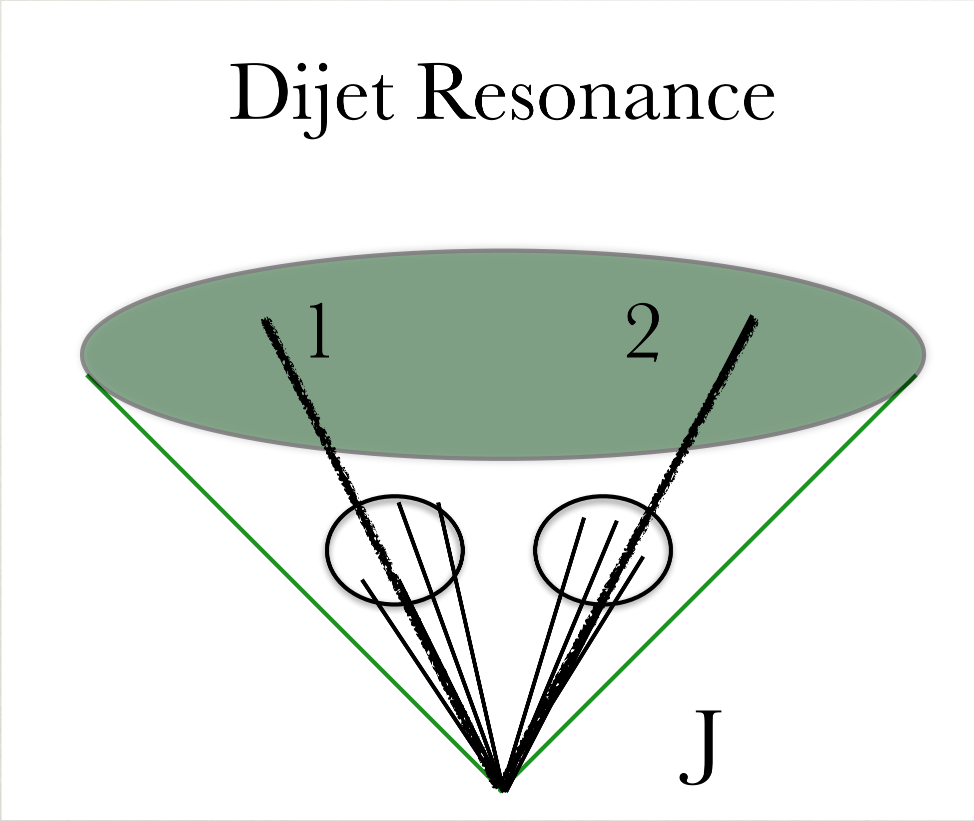
  1. Undo the last clustering step, splitting j into subjets j_1, j_2 with $m_{j1} > m_{j2}$
  2. Discard j_2, set $j = j_1$, and continue de-clustering until **both**:

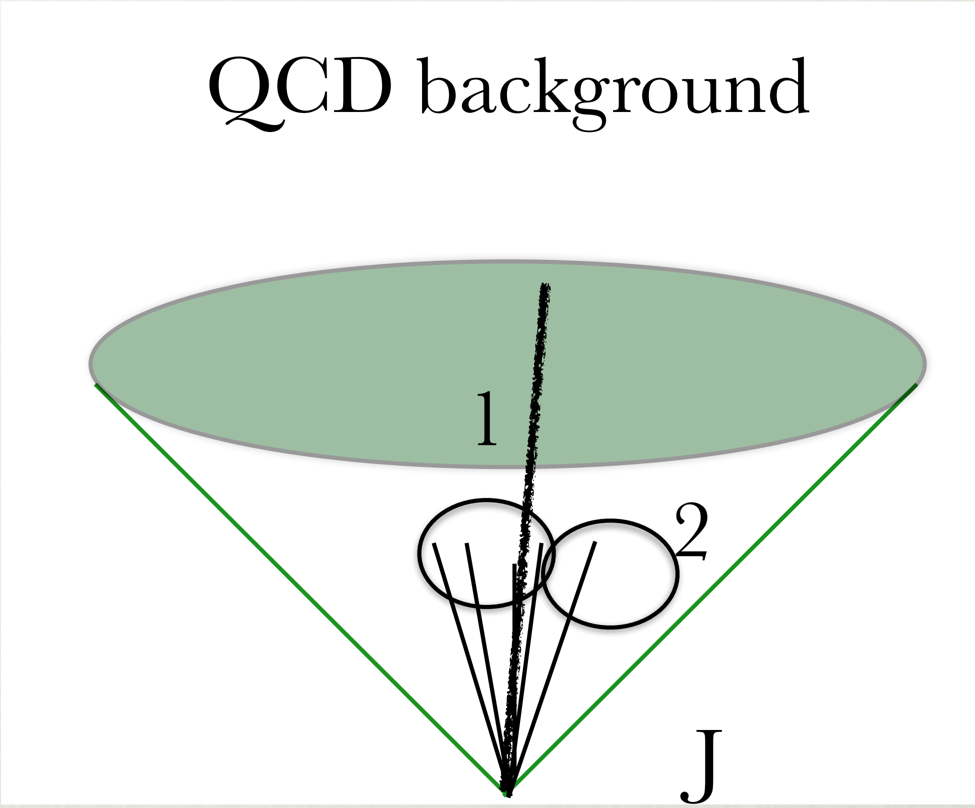
$$\frac{m_1}{m_j} < 0.67$$ (single-step mass drop)

$$\frac{\min(p_{\mathrm{T}1}^2, p_{\mathrm{T}2}^2)}{m_j^2} \Delta R_{12}^2 > 0.09$$ (symmetric splitting)

Mass Drop Tagger

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





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

Moderately boosted resonances

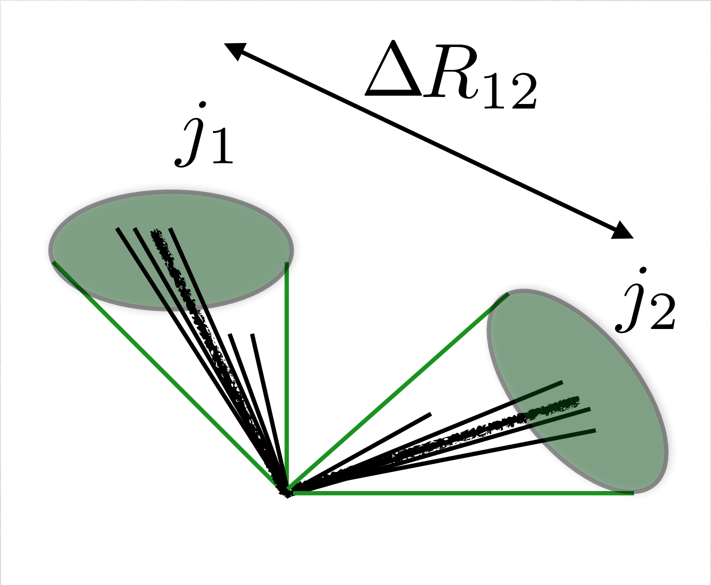
Tagging at moderate boosts

- Often, resonances are produced near threshold, paying a high penalty in signal acceptance for going to the boosted regime
    - Direct tt, diboson, ...

Tagging at moderate boosts

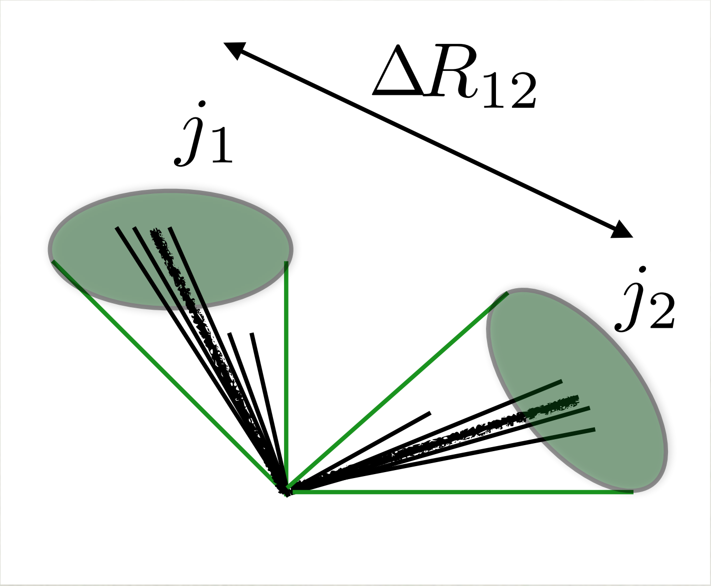
- Often, resonances are produced near threshold, paying a high penalty in signal acceptance for going to the boosted regime
    - Direct tt, diboson, ...

- In this scenario, the resonance decay products are reconstructed as **separately resolved jets**
    - Automatically eliminates soft, asymmetric QCD splittings
    - Can we expand on the mass-drop idea to include distinguishing signal from relatively **hard** splittings?



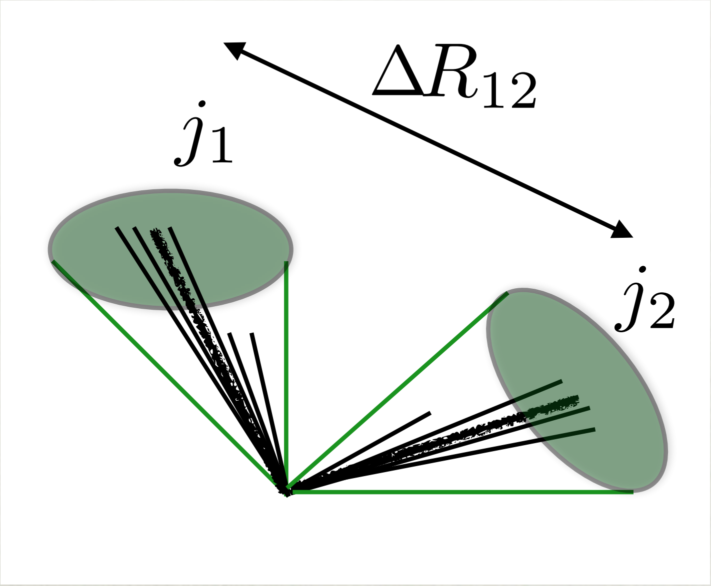
Tagging at moderate boosts

- 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**
    - Heuristic argument for background scaling:



Tagging at moderate boosts

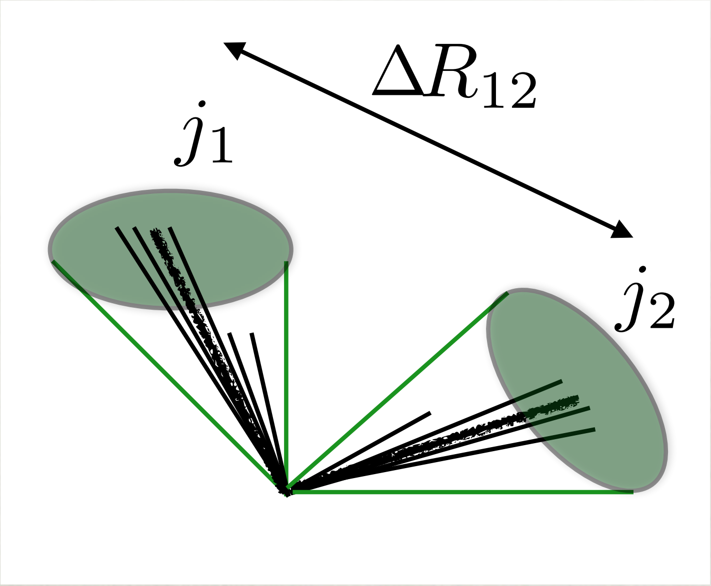
- Analogy of mass drop
    - The lax cut on mass drop from the boosted regime (<0.67) does not veto a hard QCD splitting
    - As jets become more widely separated, the mass drop becomes **smaller**
    - Heuristic argument for background scaling:



$$\langle m_1^2 \rangle \approx C \frac{\alpha_s}{\pi} R^2 p_{\mathrm{T}1}^2$$

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**
    - Heuristic argument for background scaling:

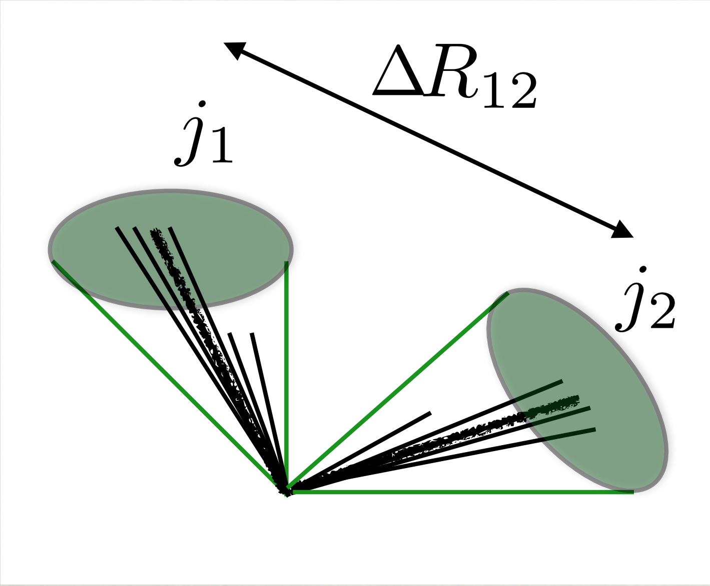


$$\langle m_1^2 \rangle \approx C \frac{\alpha_s}{\pi} R^2 p_{\mathrm{T}1}^2$$

$$m_{12}^2 \sim p_{\mathrm{T}1} p_{\mathrm{T}2} \, \Delta R_{12}^2$$

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**
  - Heuristic argument for background scaling:



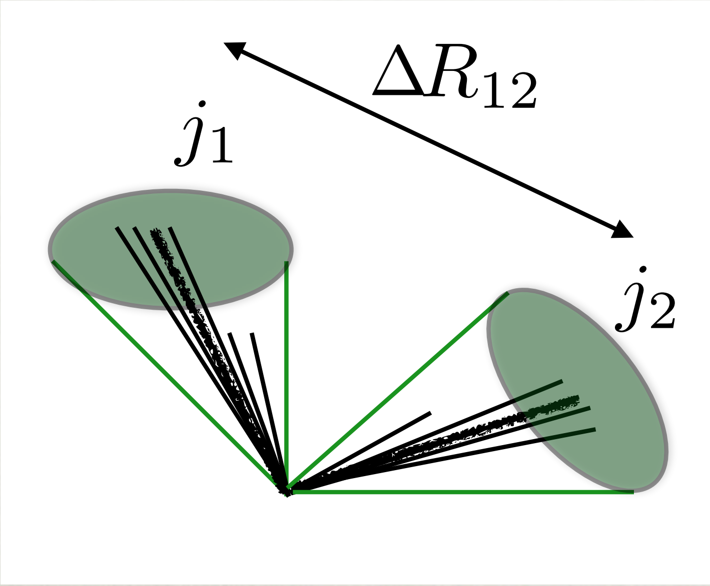
$$\langle m_1^2 \rangle \approx C \frac{\alpha_s}{\pi} R^2 p_{\mathrm{T}1}^2$$

$$m_{12}^2 \sim p_{\mathrm{T}1} p_{\mathrm{T}2} \, \Delta R_{12}^2$$

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

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**
    - Heuristic argument for background scaling:



$$\langle m_1^2 \rangle \approx C \frac{\alpha_s}{\pi} R^2 p_{\mathrm{T}1}^2$$

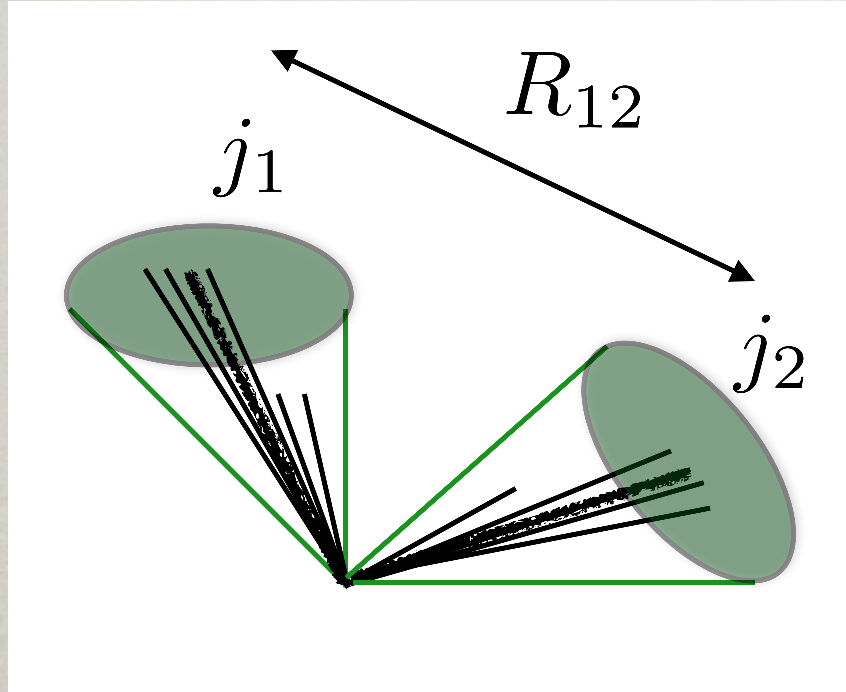
$$m_{12}^2 \sim p_{\mathrm{T}1} p_{\mathrm{T}2} \, \Delta R_{12}^2$$

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

- A **scaled mass drop cut** interpolates between boosted and unboosted regimes

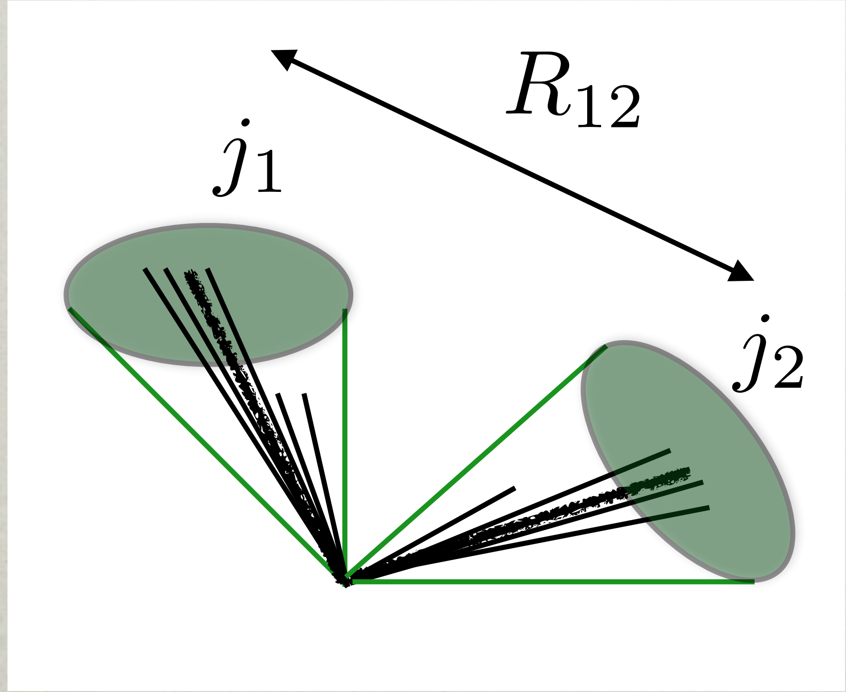
Tagging at moderate boosts

- Comparing mass drops (a heuristic argument):
  - Signal has a mass drop that is constant in rest frame of decaying resonance
  - QCD prefers asymmetric splittings/sheds virtuality more slowly, giving rise to **larger m_1**
  - For most QCD backgrounds, one of the radiated partons is a gluon ($C_A > C_F$), giving rise to **larger m_1** for more symmetric splittings (close to threshold)



Tagging at moderate boosts

- Comparing mass drops (a heuristic argument):
  - Signal has a mass drop that is constant in rest frame of decaying resonance
  - QCD prefers asymmetric splittings/sheds virtuality more slowly, giving rise to **larger m_1**
  - For most QCD backgrounds, one of the radiated partons is a gluon ($C_A > C_F$), giving rise to **larger m_1** for more symmetric splittings (close to threshold)



- All of these bias the mass drop **higher** for bkd
- This motivates a new cut:

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

Tagging at moderate boosts

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

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

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
    - Discrimination comes from relatively subtle effects, so usually no enhancement of statistical significance
    - Outperform other observables we studied
    - Uses simple, small-*R* jet properties

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
    - Discrimination comes from relatively subtle effects, so usually no enhancement of statistical significance
    - Outperform other observables we studied
    - Uses simple, small-*R* jet properties

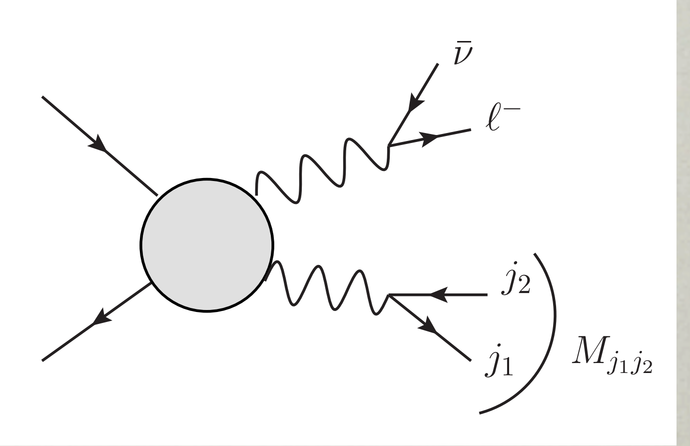
- Relatively robust under simple smearing, different shower MC, pile-up
    - Should validate in data (hadronic W from top?)
    - Work for more rigorous analytic result ongoing

Examples

- **SM: WW+WZ**
- SM: $V(H \rightarrow bb)$
- BSM: $Z' \rightarrow WW$

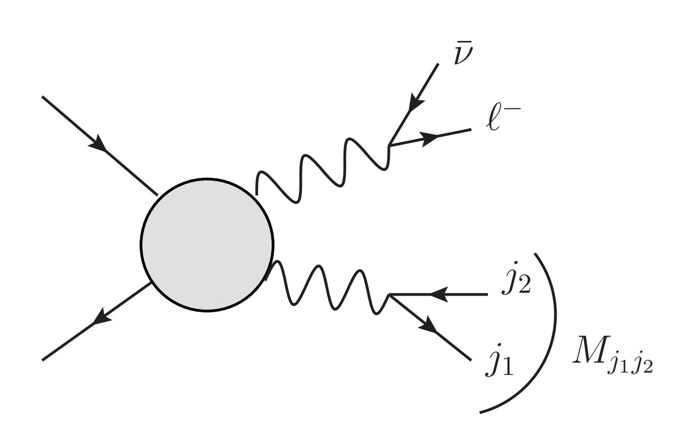
WW+WZ Analysis

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



WW+WZ Analysis

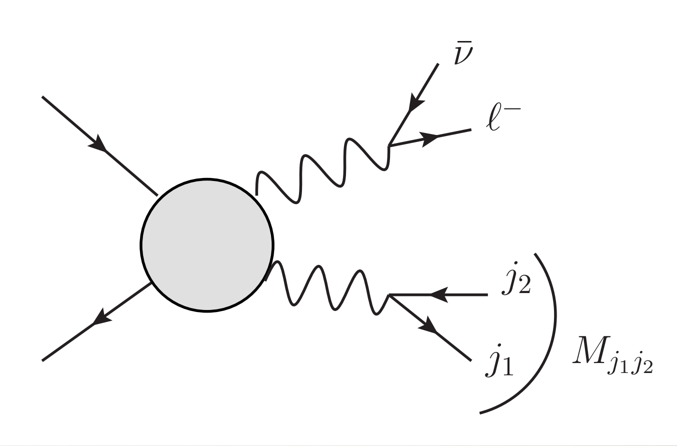
- Semileptonic channel is an independent check of the (possible) excess in the fully leptonic channel and an important SM measurement



- 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)

WW+WZ Analysis

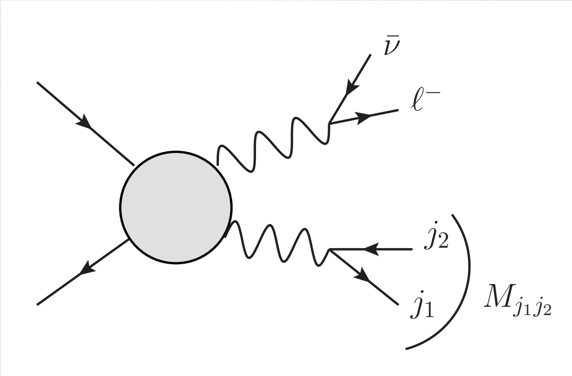
- Semileptonic channel is an independent check of the (possible) excess in the fully leptonic channel and an important SM measurement



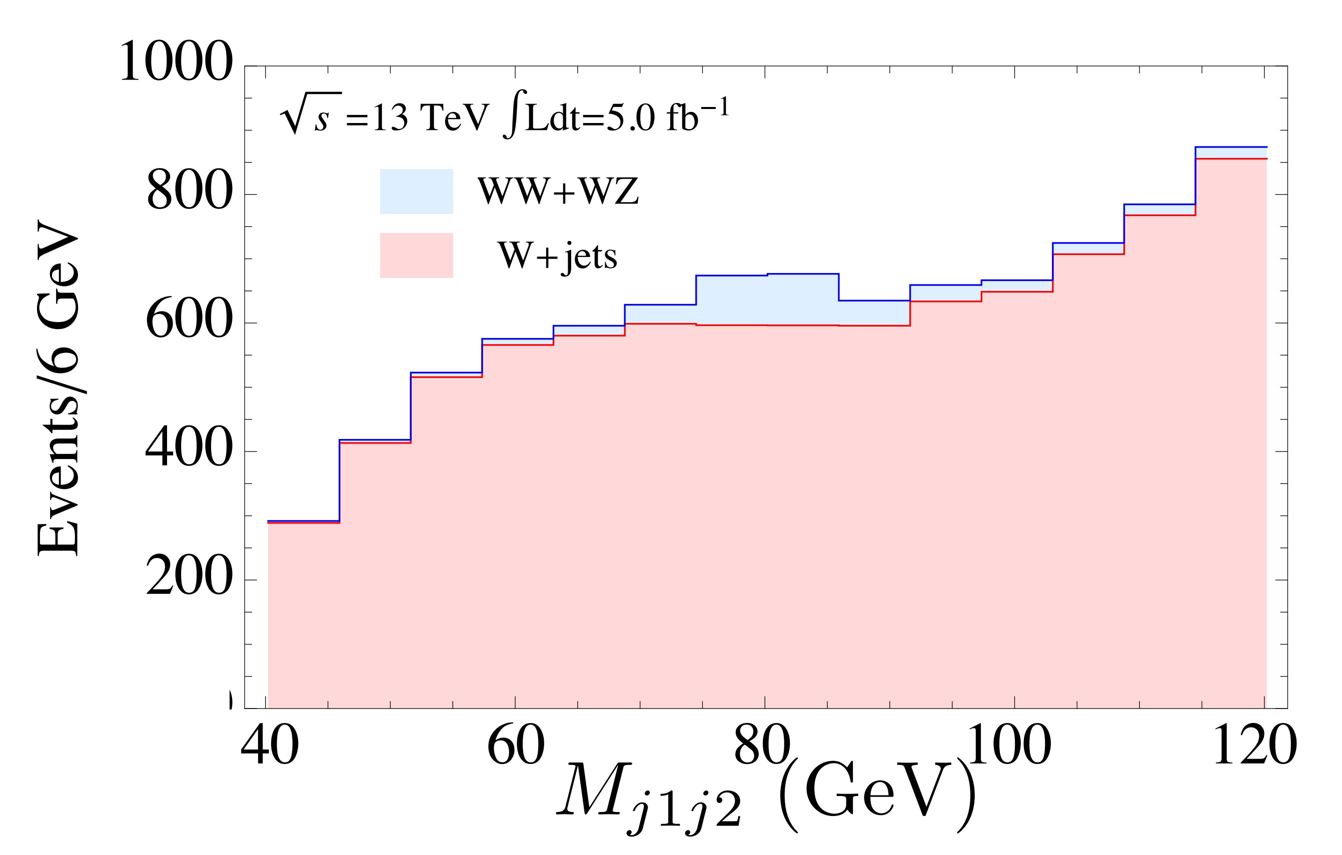
- Simulate WW+WZ, W+jets events with Madgraph 5
  - Match matrix element to Pythia 6 parton shower using shower-$k_\perp$ scheme
  - Cluster and analyze events with Fastjet 3
  - Validated MC with CMS analysis
  - Include UE but no pile-up (more on this later)

- 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

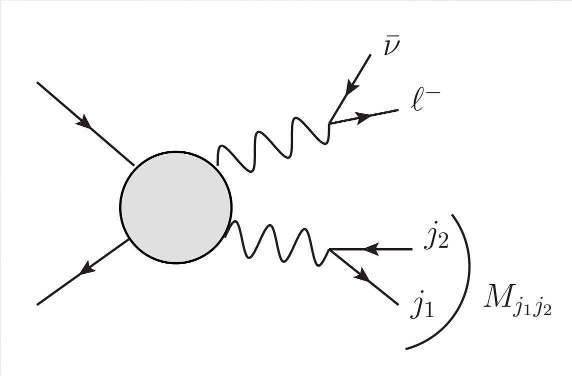
WW+WZ Analysis



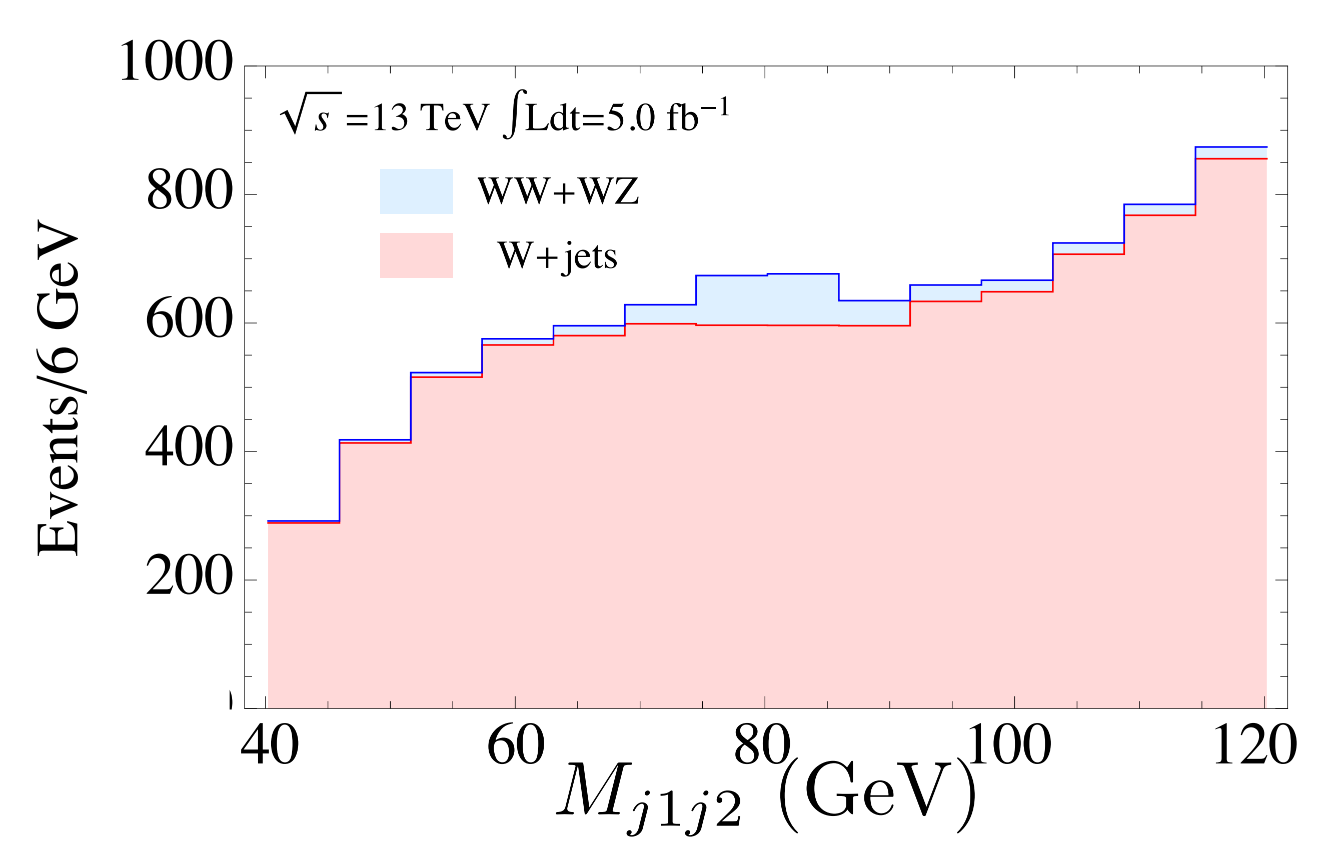
After CMS selection cuts:



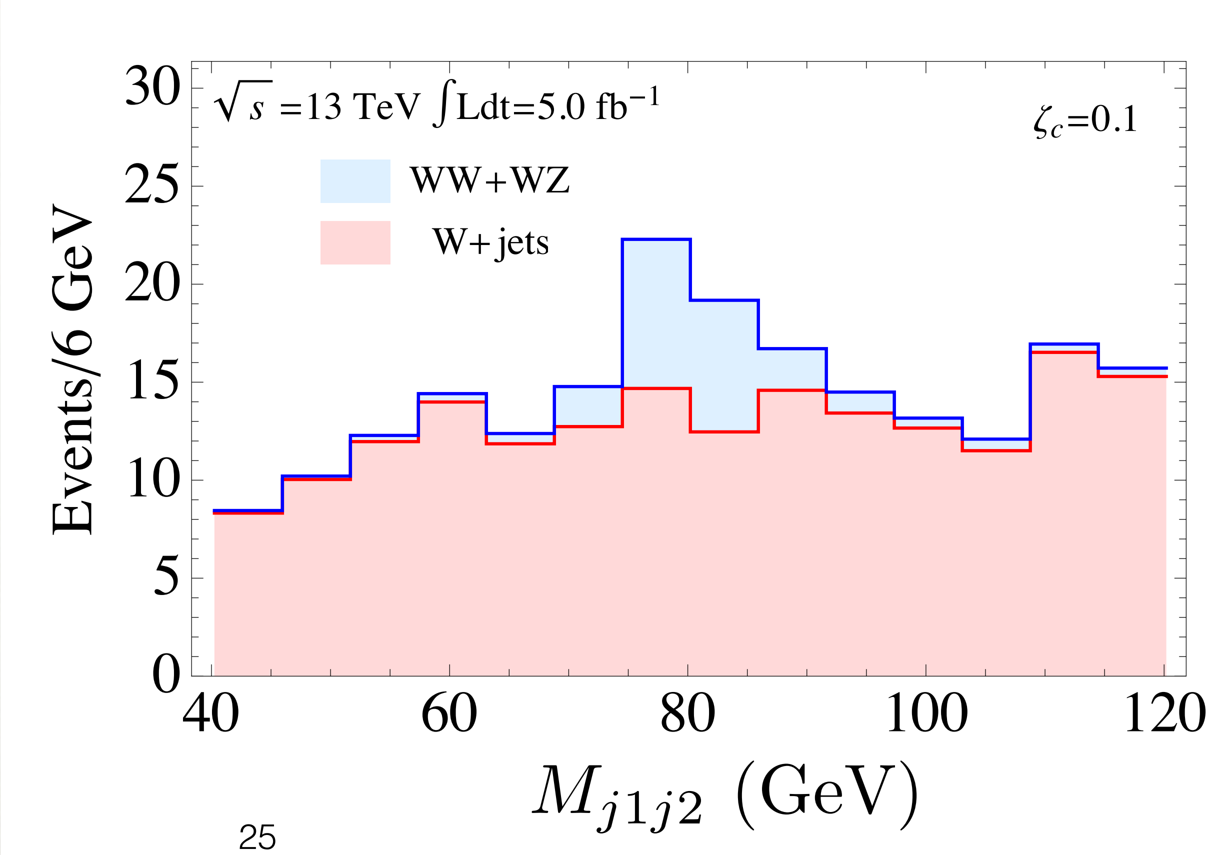
WW+WZ Analysis



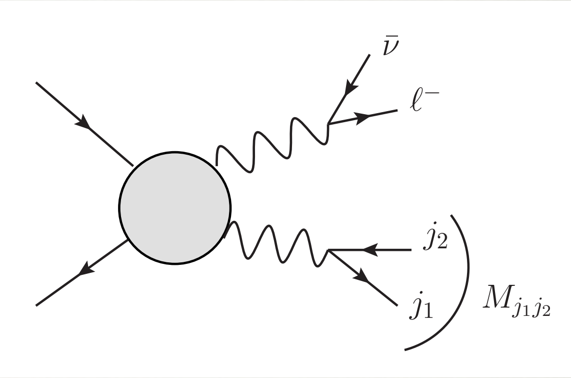
After CMS selection cuts:



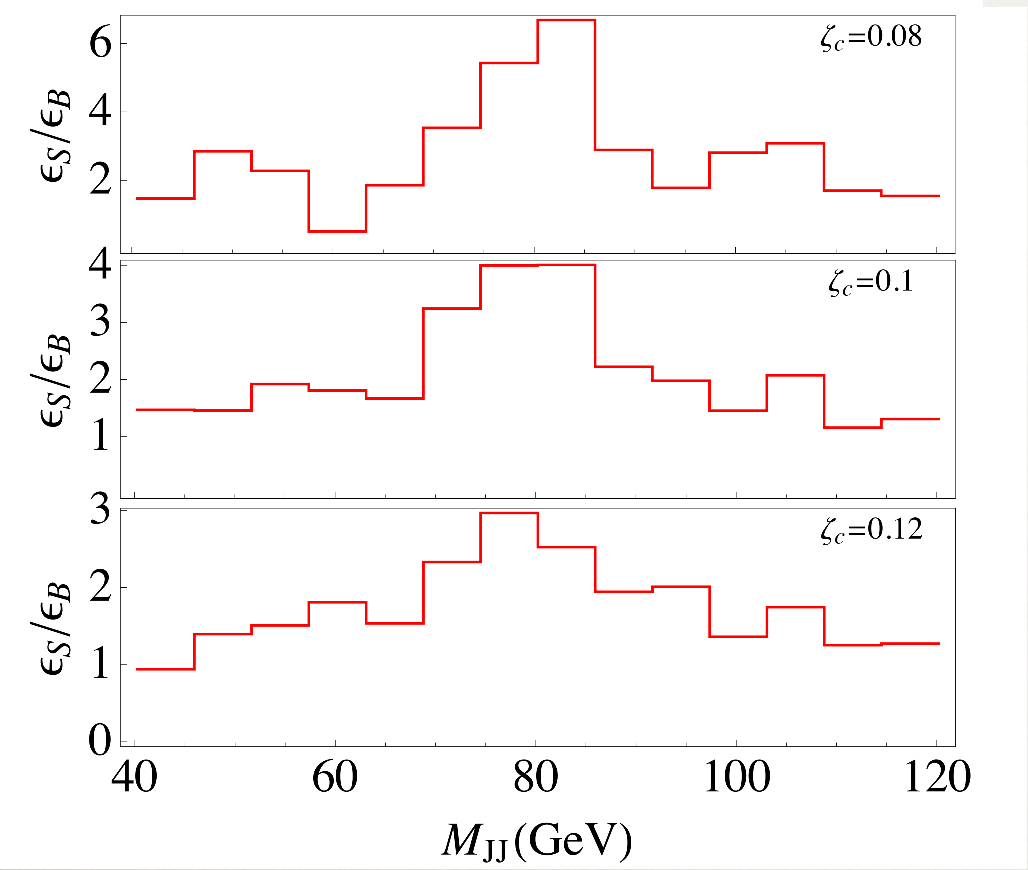
After CMS selection AND cut on $\zeta < \zeta_c$:



WW+WZ Analysis



- Gains for different choices of the cut

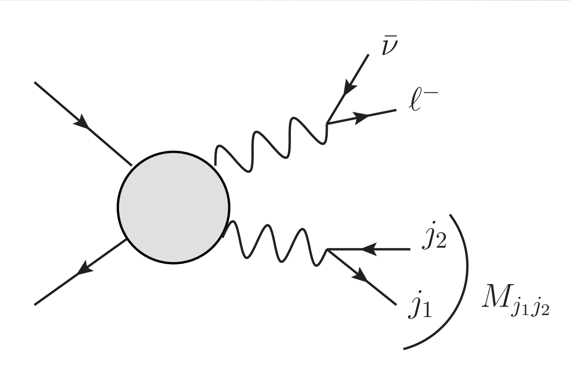


$$\epsilon_S(\zeta < \zeta_c) \approx 3\%$$

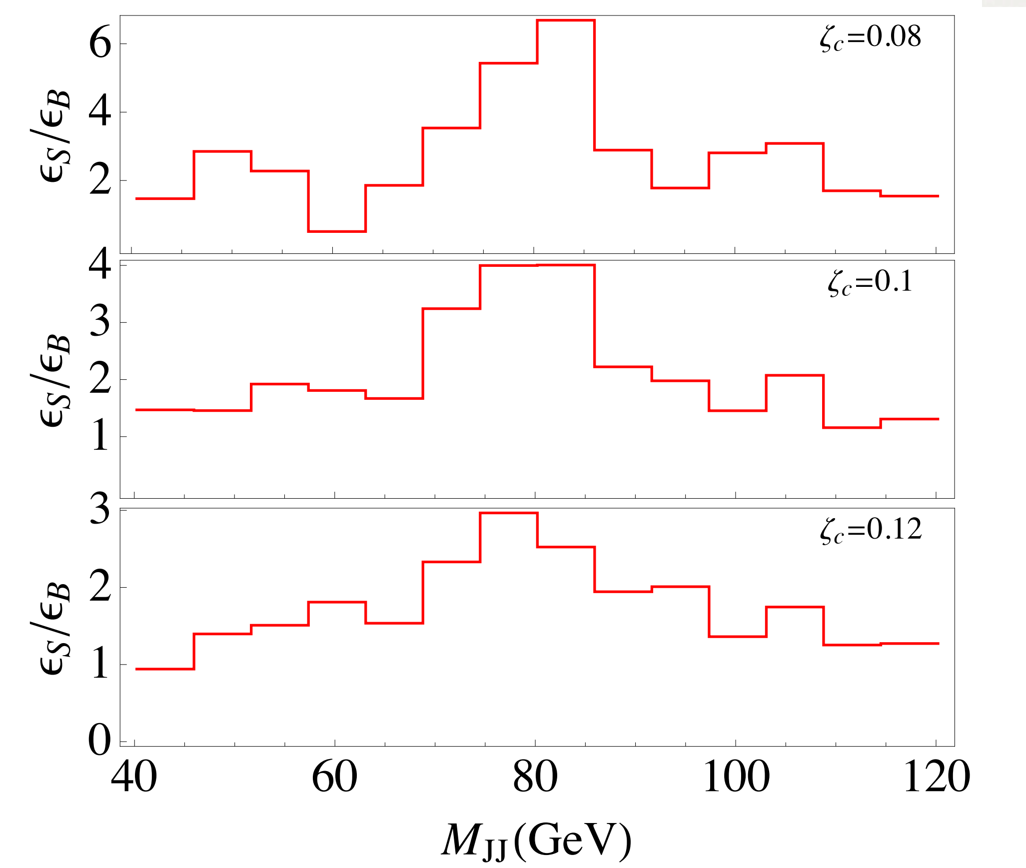
$$\epsilon_S(\zeta < \zeta_c) \approx 10\%$$

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

WW+WZ Analysis



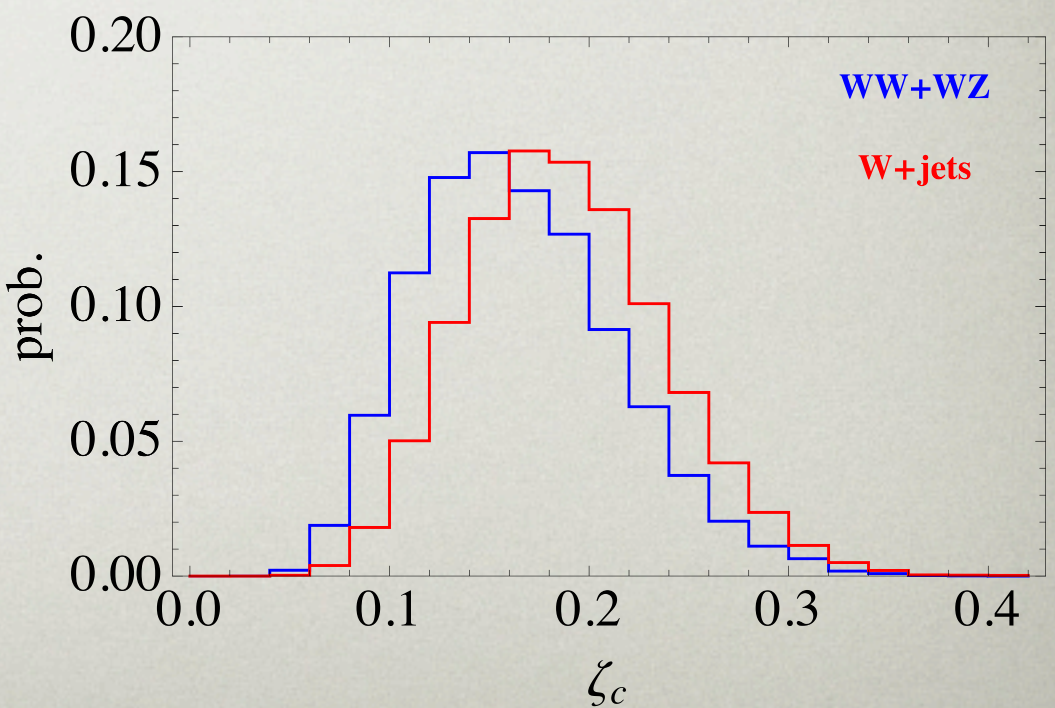
- Gains for different choices of the cut



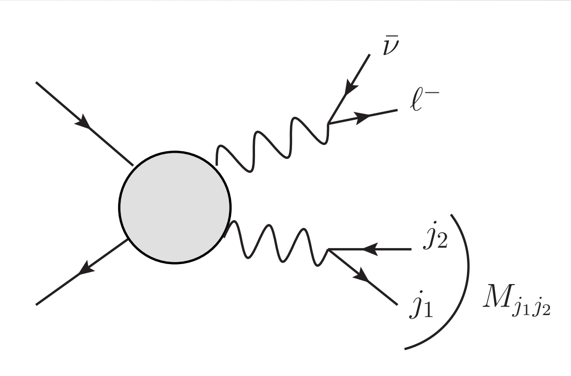
$\epsilon_S(\zeta < \zeta_c) \approx 3\%$

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

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

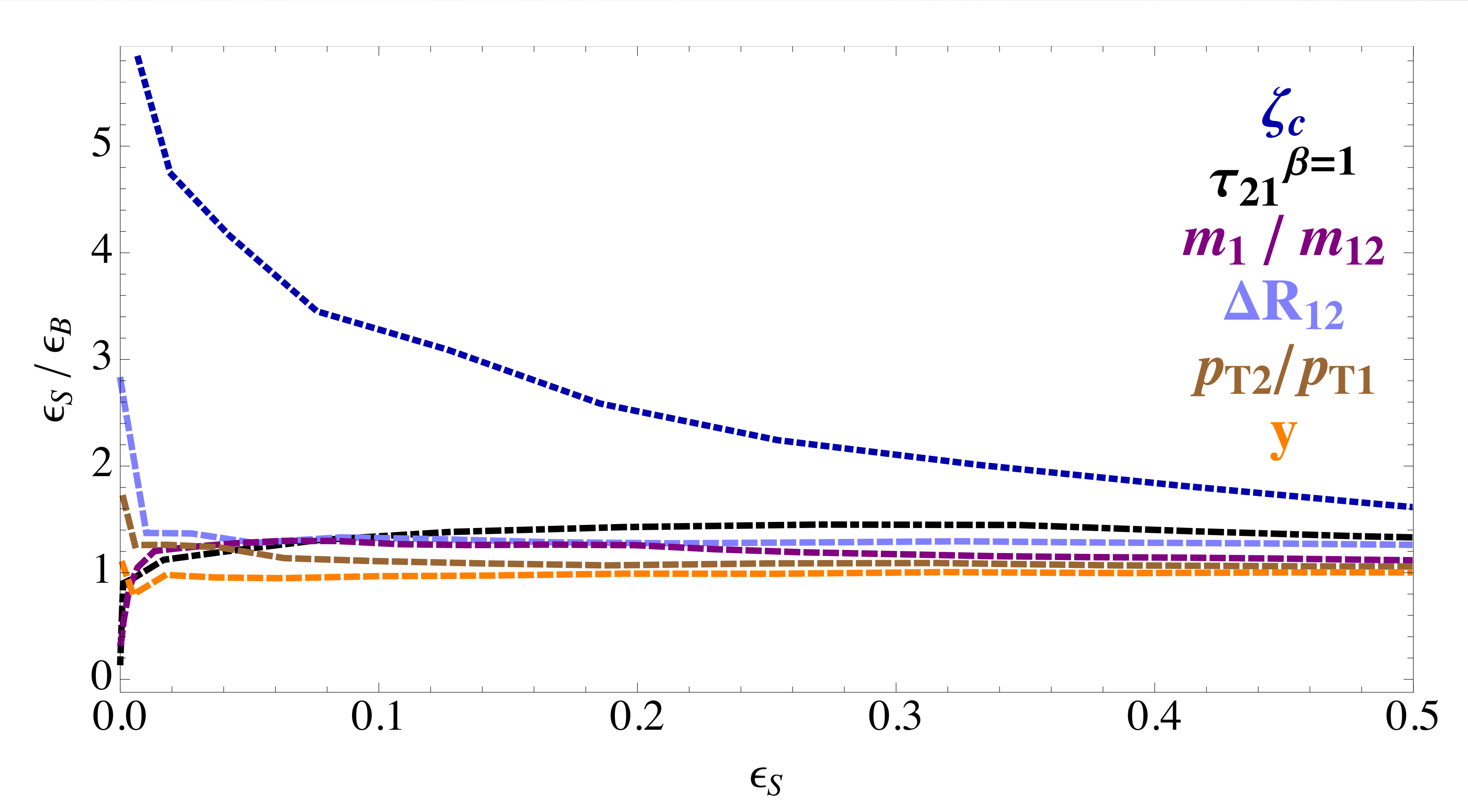


WW+WZ Analysis



- How does this compare to other possible cuts we could have used?
  - Look in M_{j1j2} window between 70-100 GeV
  - For jet substructure observables that require a single large-R jet, we take as constituents of the jet the union of the constituents of the two small-R jets

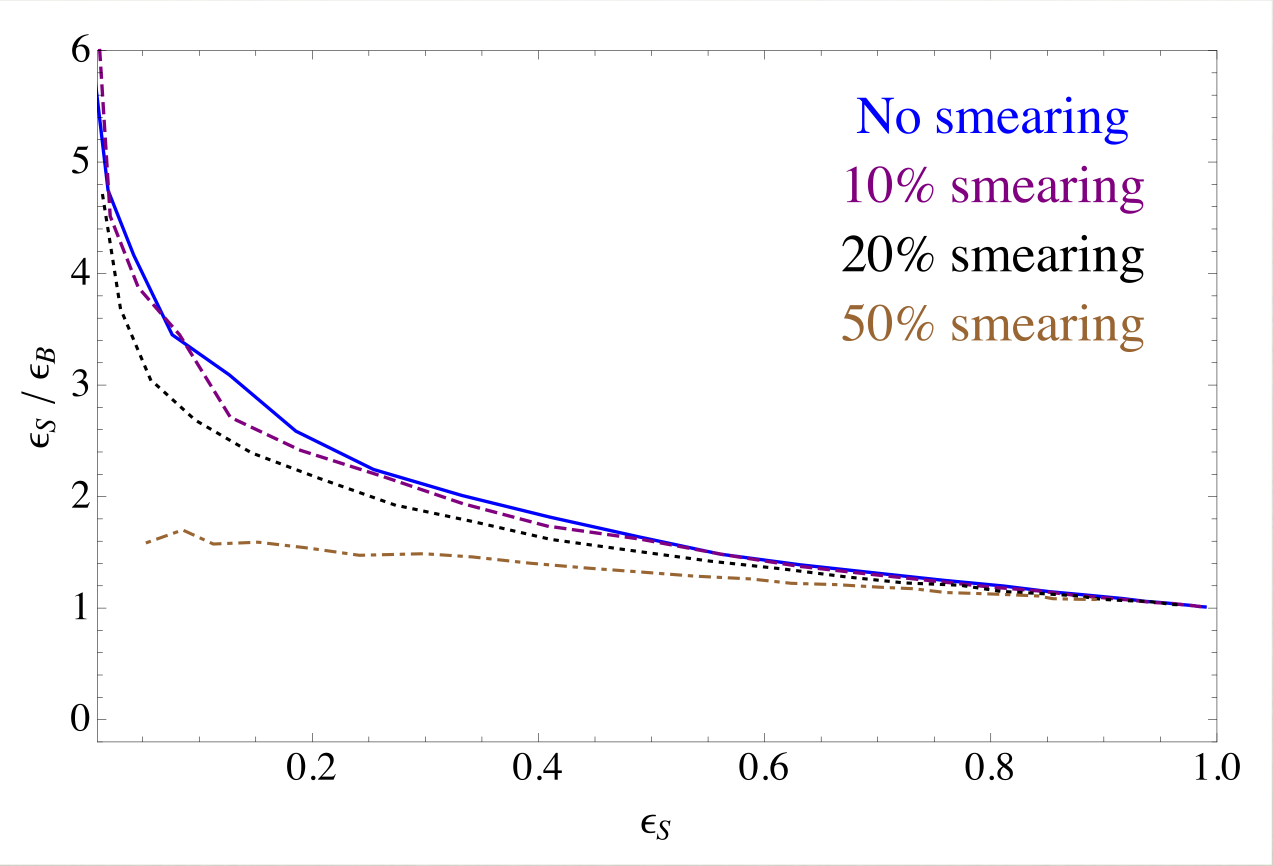
$$y = \frac{p_{T2}^2}{M_{12}^2} \Delta R_{12}^2$$



WW+WZ Analysis

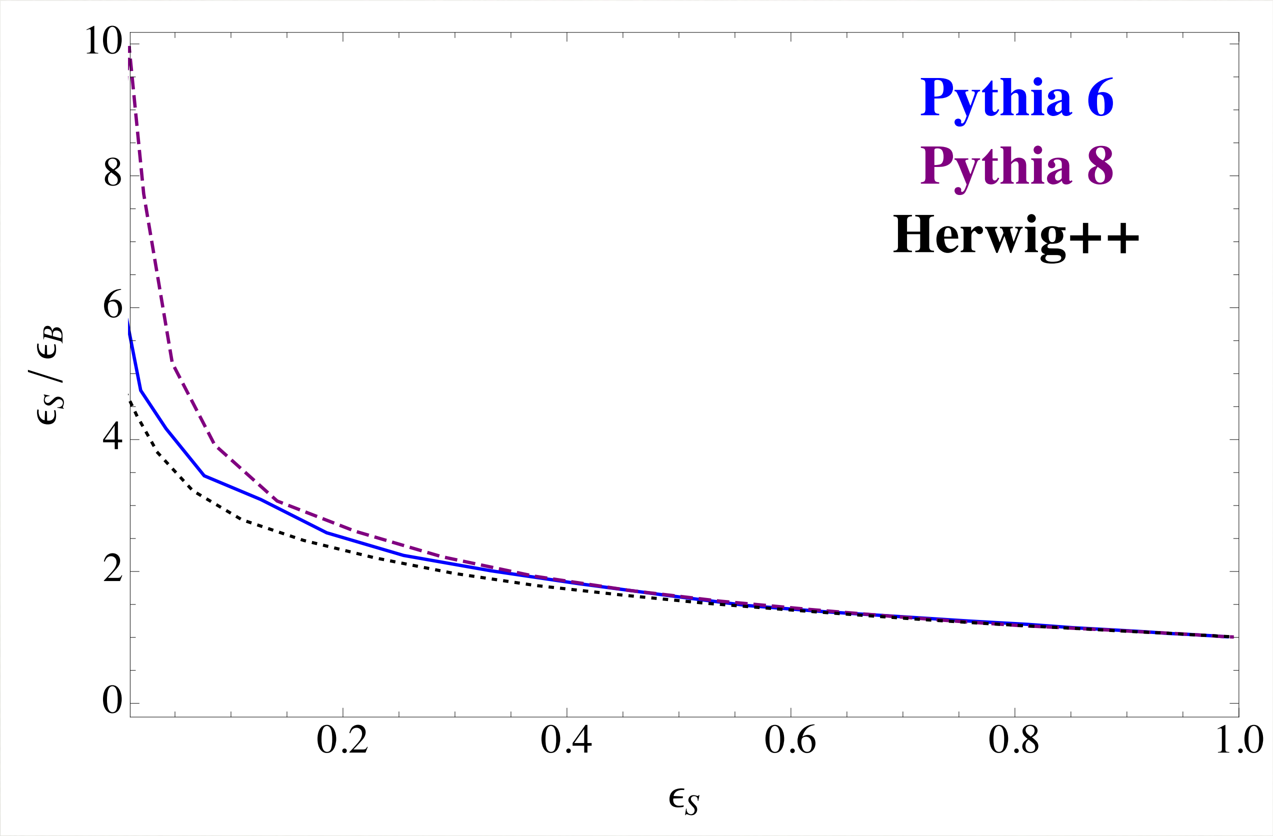
- Would this be included in a BDT analysis?
  - Not currently used for SM WW+WZ
  - Seems there is substantial gain that comes from using resolved jet *masses*, which are not included in most BDT analyses

- 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



- Zeta performs well and is robust against various uncertainties except at very small signal acceptance

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

Limitations and Caveats

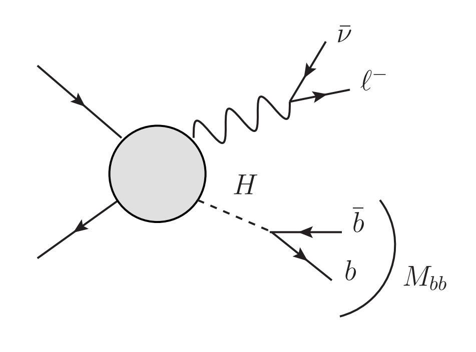
- Our observable gives a significant enhancement in S/B at the cost of a mild reduction in statistical significance
    - Most applicable to searches dominated by systematic uncertainties
    - Will become more relevant for later LHC running

- 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 grooming** 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

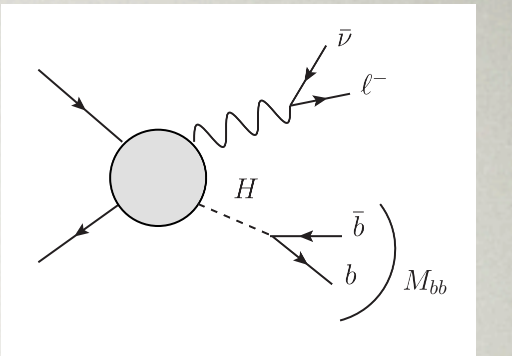
- SM: WW+WZ
- **SM: V(H→bb)**
- BSM: Z′ → WW

W(H→bb) Analysis



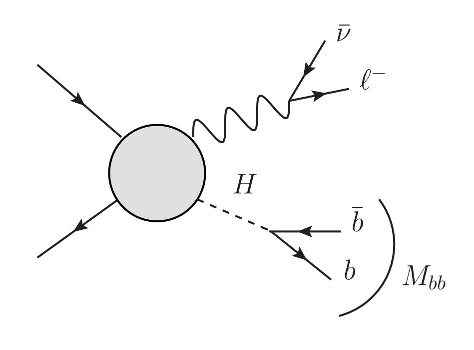
- ATLAS and CMS have both dijet-mass and multivariate analyses
  - We follow the ATLAS 7+8 TeV analysis (now arXiv:1409.6212)

W(H→bb) Analysis



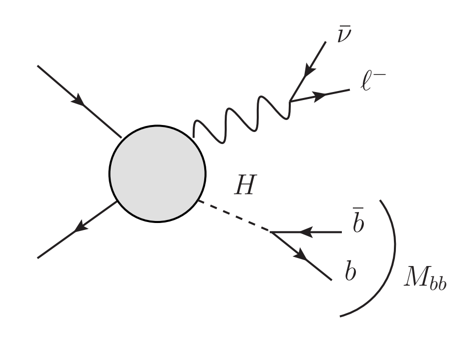
- ATLAS and CMS have both dijet-mass and multivariate analyses
    - We follow the ATLAS 7+8 TeV analysis (now arXiv:1409.6212)
- Focus on dijet search, associated leptonic W
    - Dominant backgrounds are W+b+jets, tt

W(H→bb) Analysis

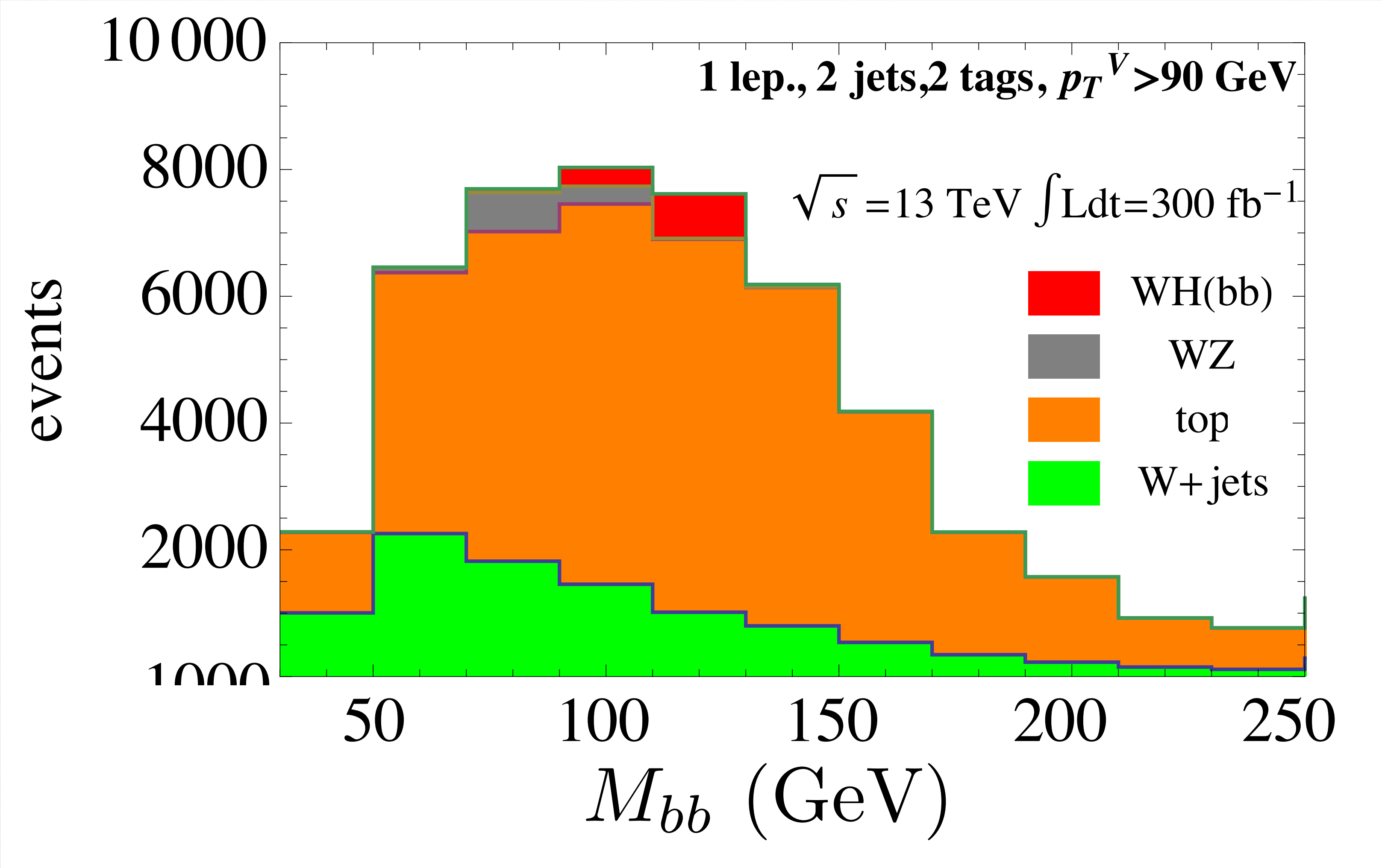


- ATLAS and CMS have both dijet-mass and multivariate analyses
    - We follow the ATLAS 7+8 TeV analysis (now arXiv:1409.6212)
- Focus on dijet search, associated leptonic W
    - Dominant backgrounds are W+b+jets, tt
- Use same selection cuts as ATLAS
    - One tight lepton, $p_T > 25$ GeV
    - Exactly 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

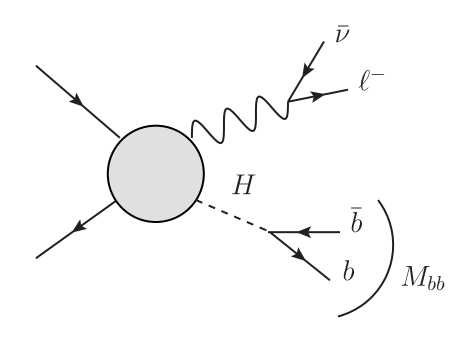
W(H→bb) Analysis



- After ATLAS selection cuts:

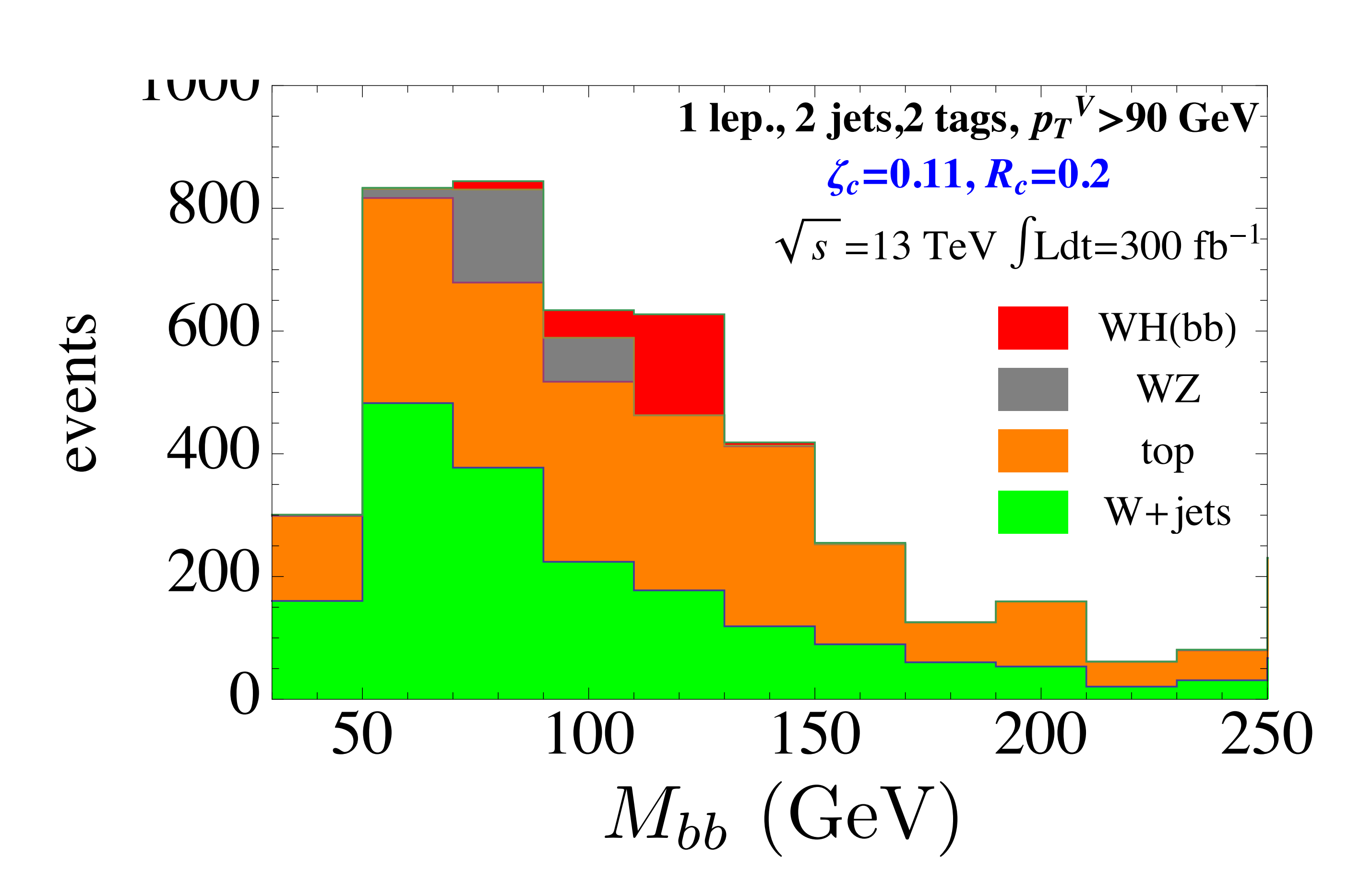


W(H→bb) Analysis



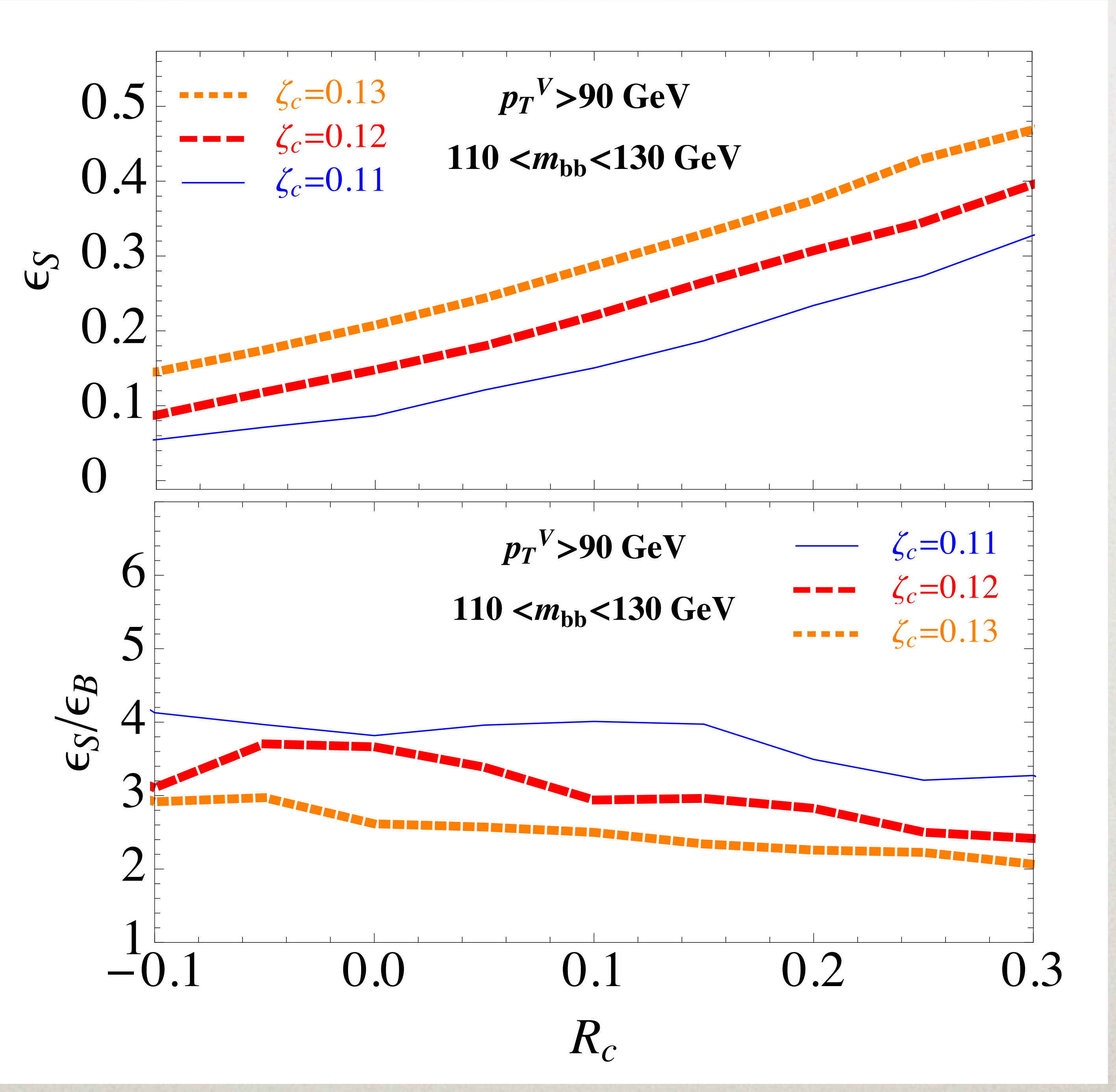
- After ATLAS selection and a cut on the shifted version of ζ:
  - Better at balancing preserving statistics and S/B gain

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



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

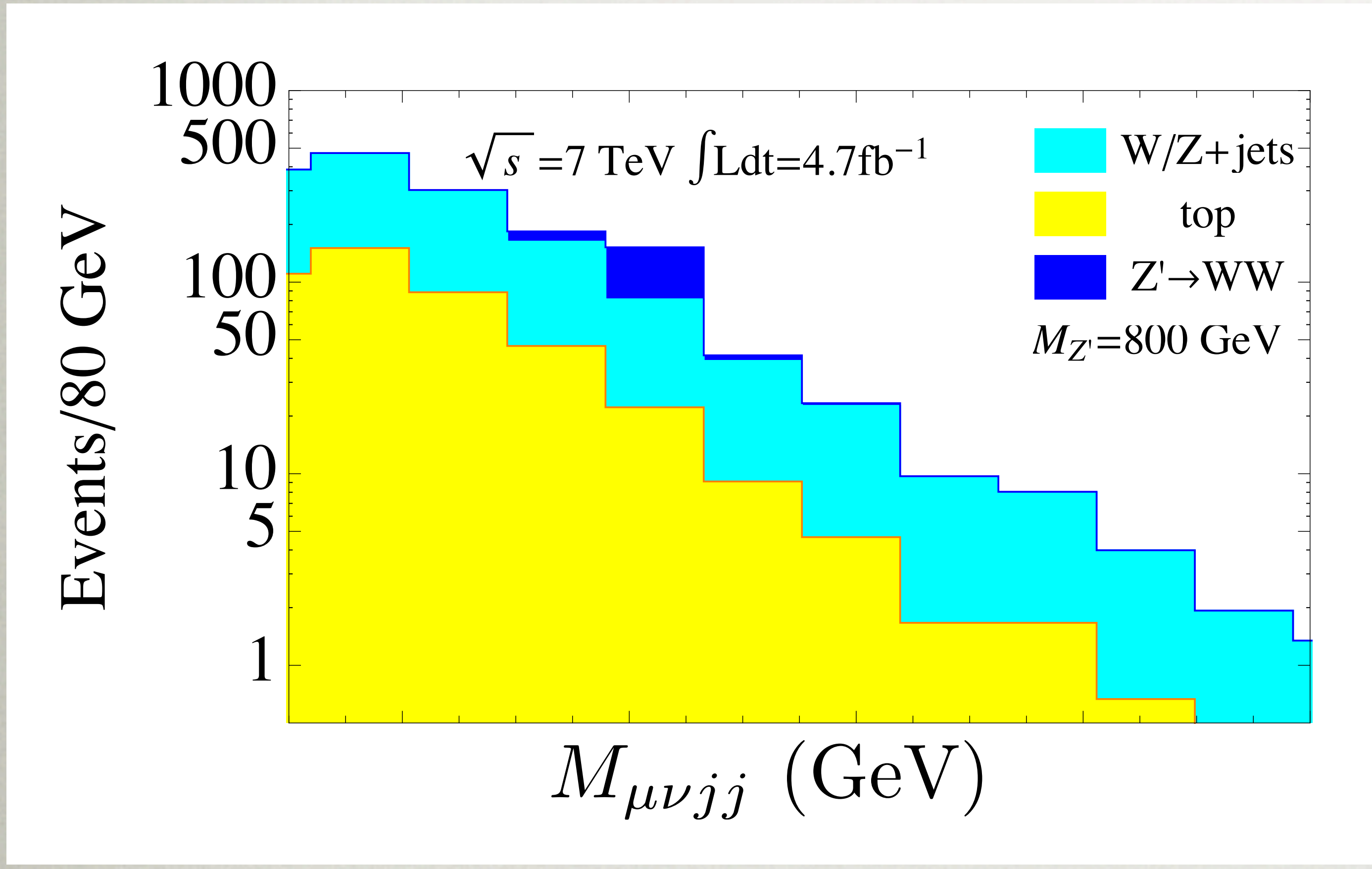
$Z' \to WW$ Analysis

- 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

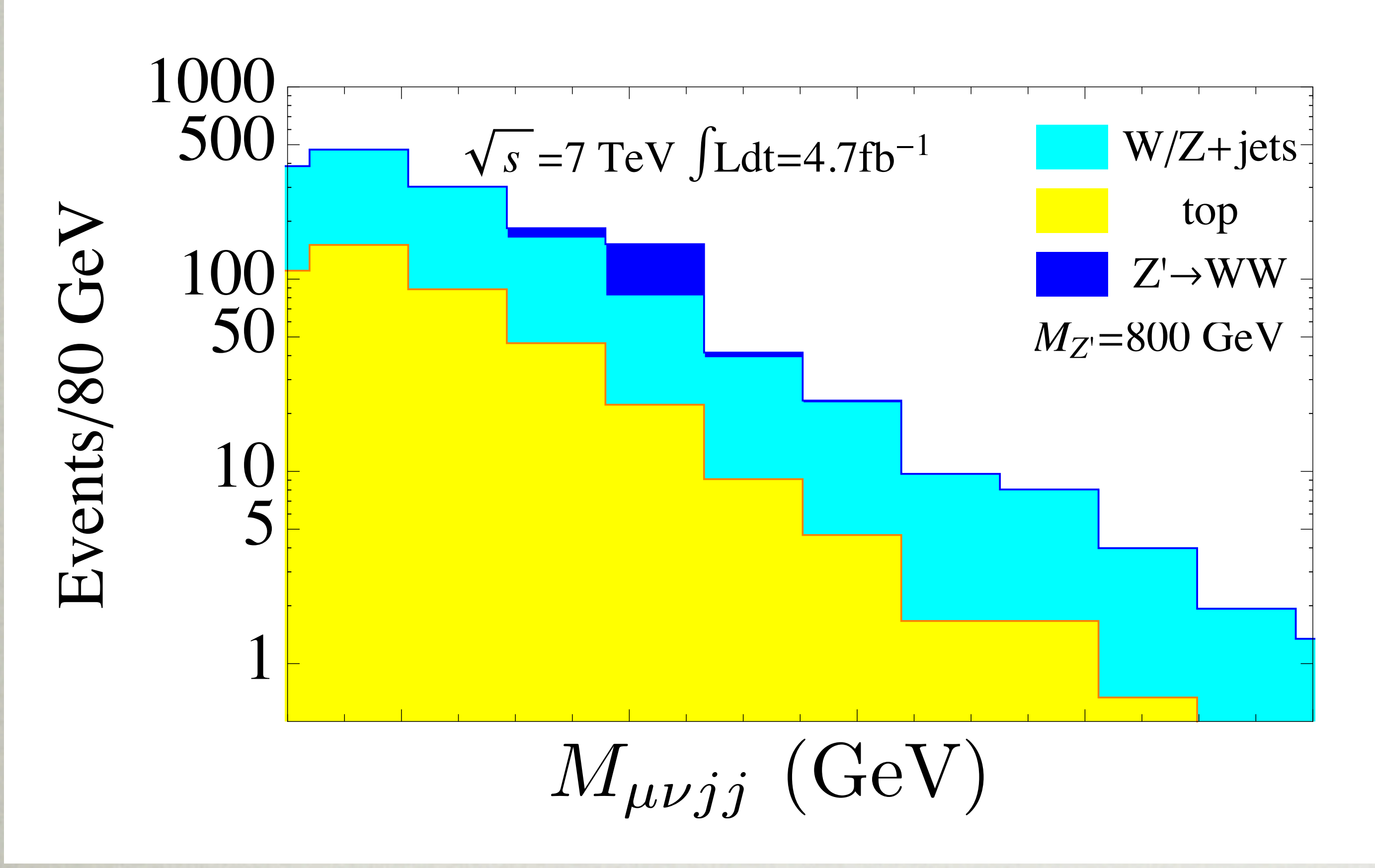
After ATLAS selection cuts:



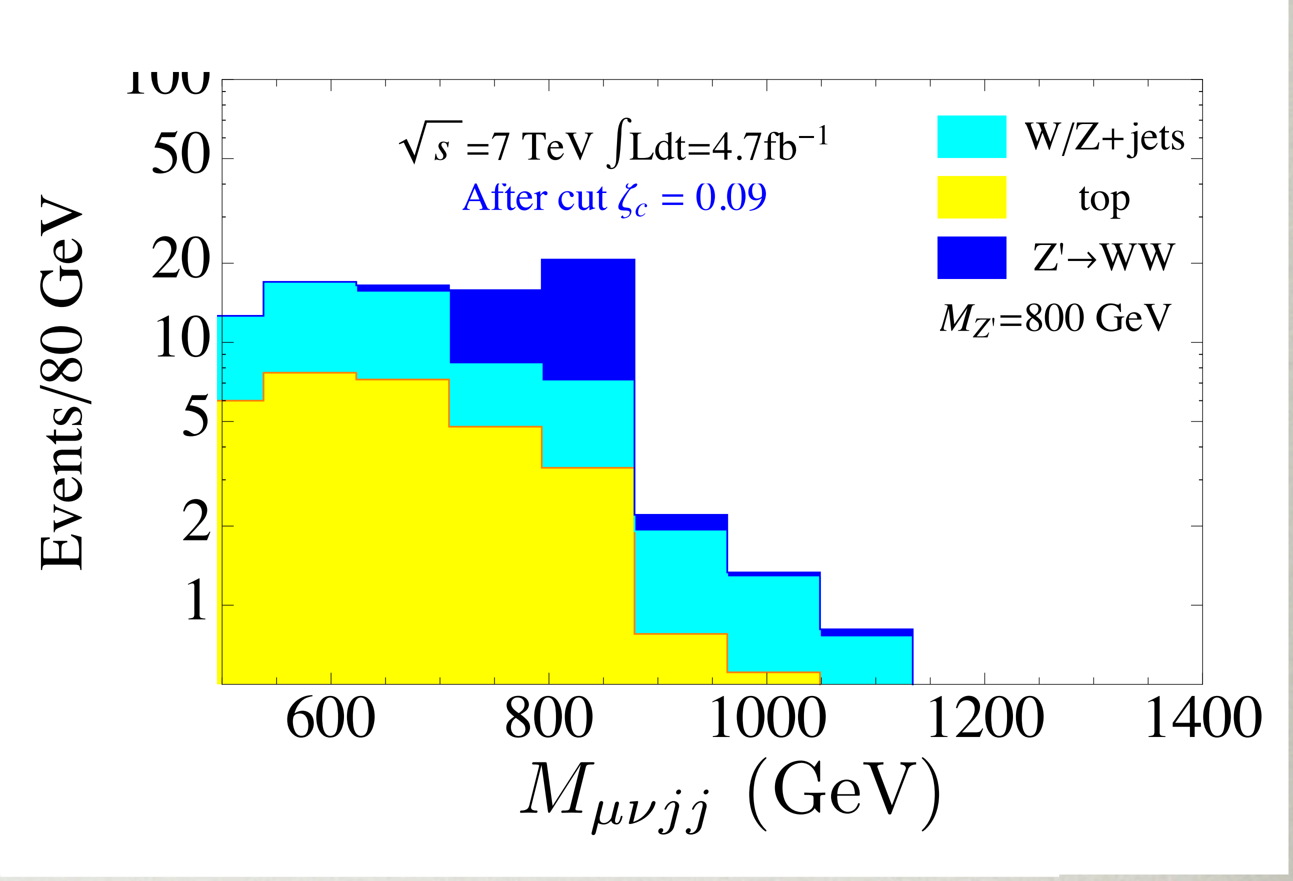
- Note: **large** systematic uncertainties (~30%)

Z'→WW Analysis

After ATLAS selection cuts:



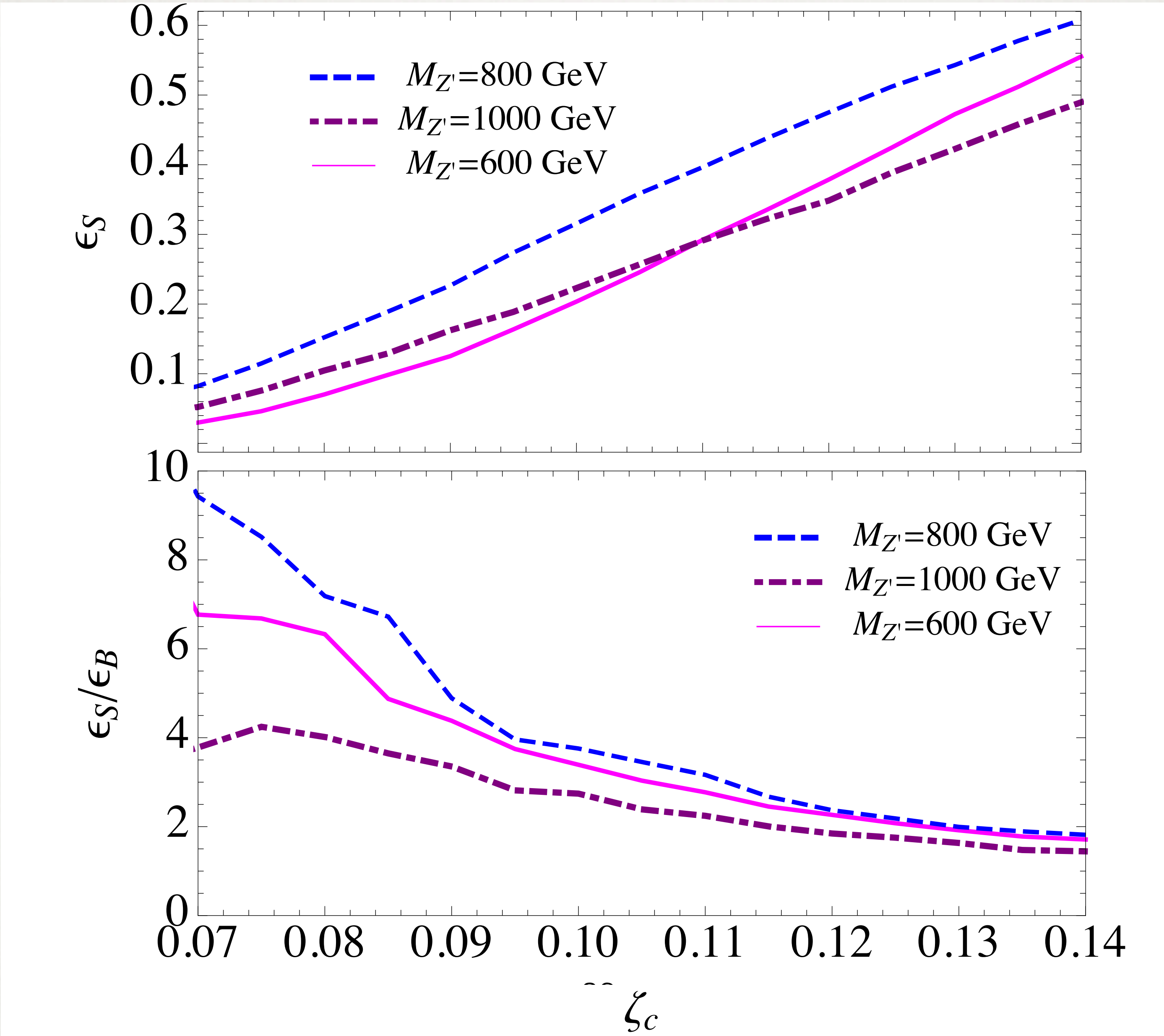
After ATLAS selection AND cut on $\zeta < \zeta_c$:



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

Z'→WW Analysis

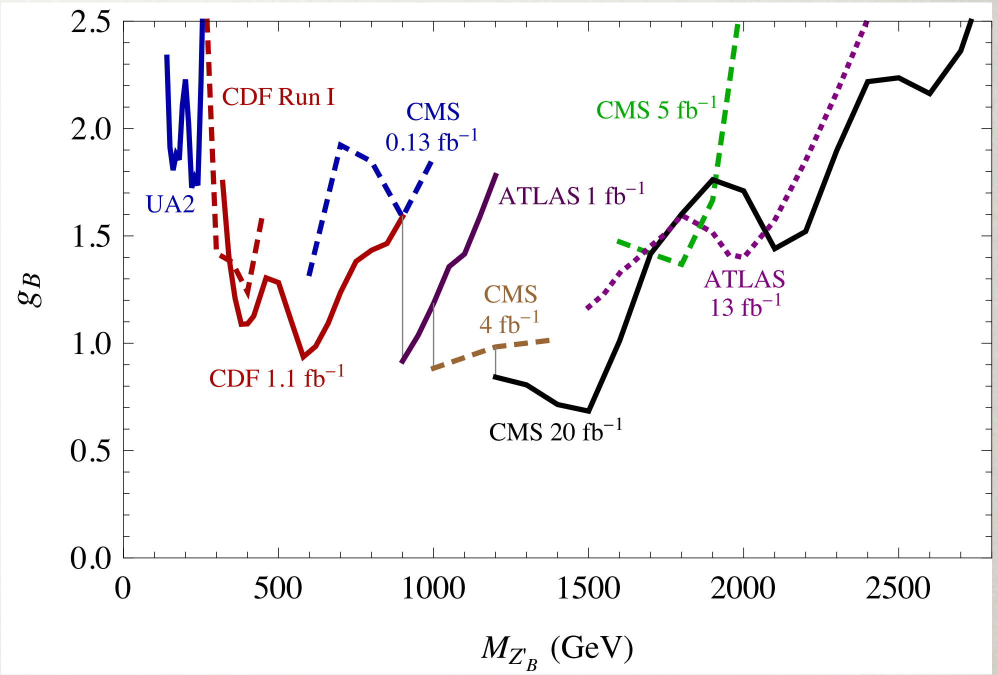
- *S*/*B* gains and efficiency change:



Future directions

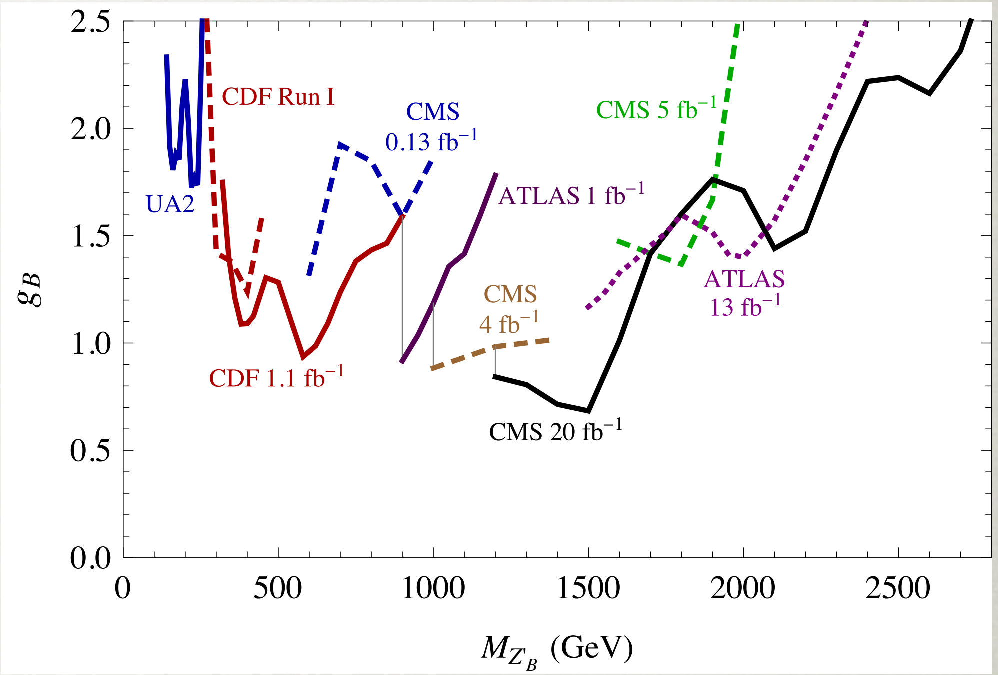
Direct resonance production

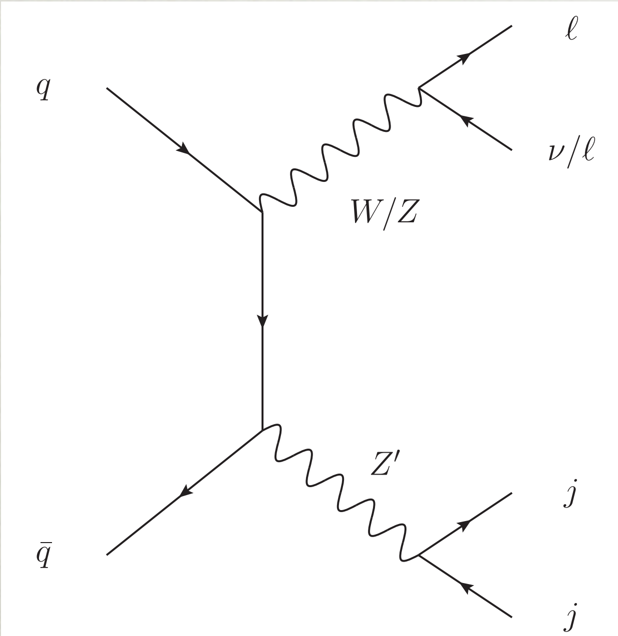
- Best bounds come from UA2/Tevatron
- At LHC, hard to pass triggers and discriminate from backgrounds



Direct resonance production

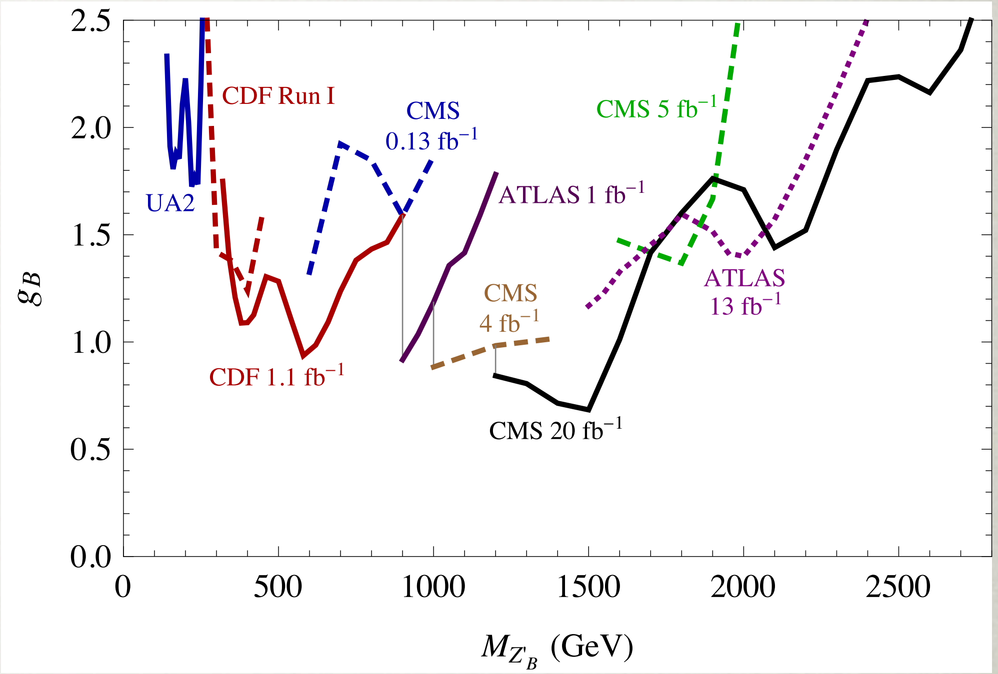
- Best bounds come from UA2/Tevatron
- At LHC, hard to pass triggers and discriminate from backgrounds
- Consider **associated production**
    - Provides handle for trigger
    - Gives resonance a (mild) boost



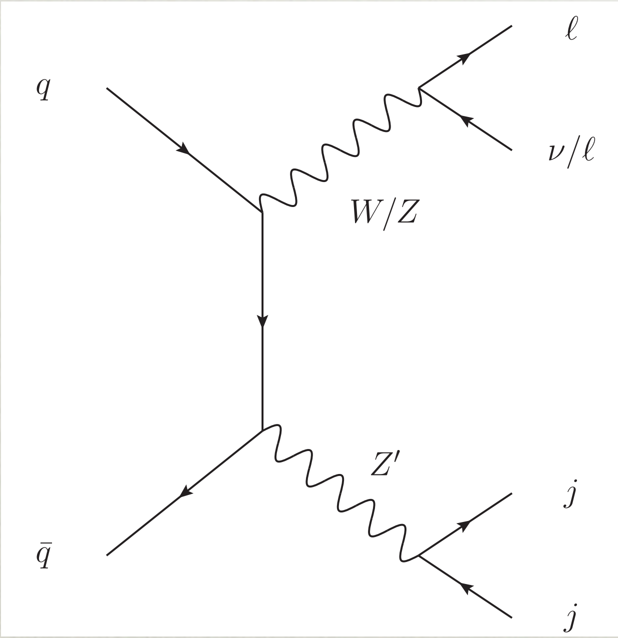


Direct resonance production

- Best bounds come from UA2/Tevatron
- At LHC, hard to pass triggers and discriminate from backgrounds



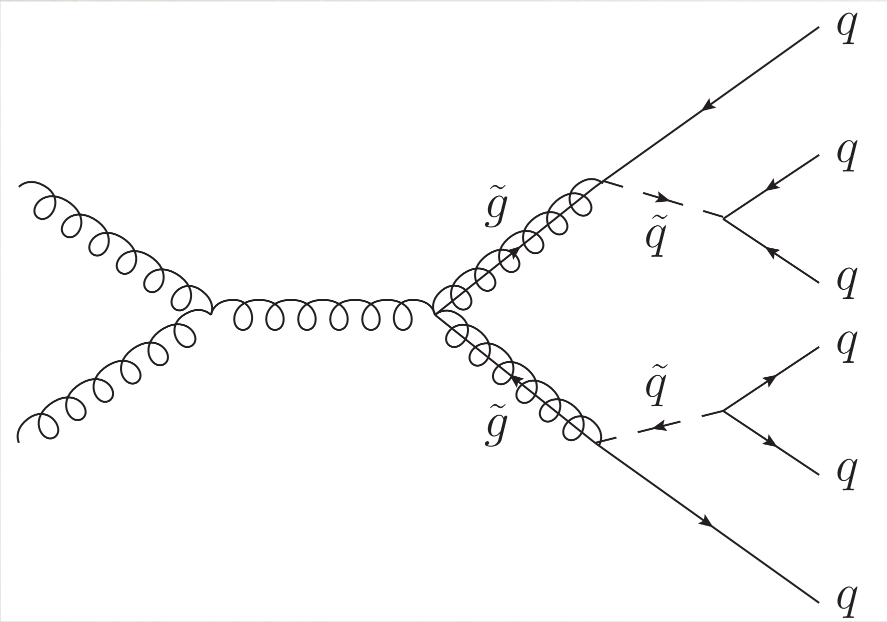
- Consider **associated production**
  - Provides handle for trigger
  - Gives resonance a (mild) boost



- 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?
- Decays to higher jet multiplicities?

Multijet resonances

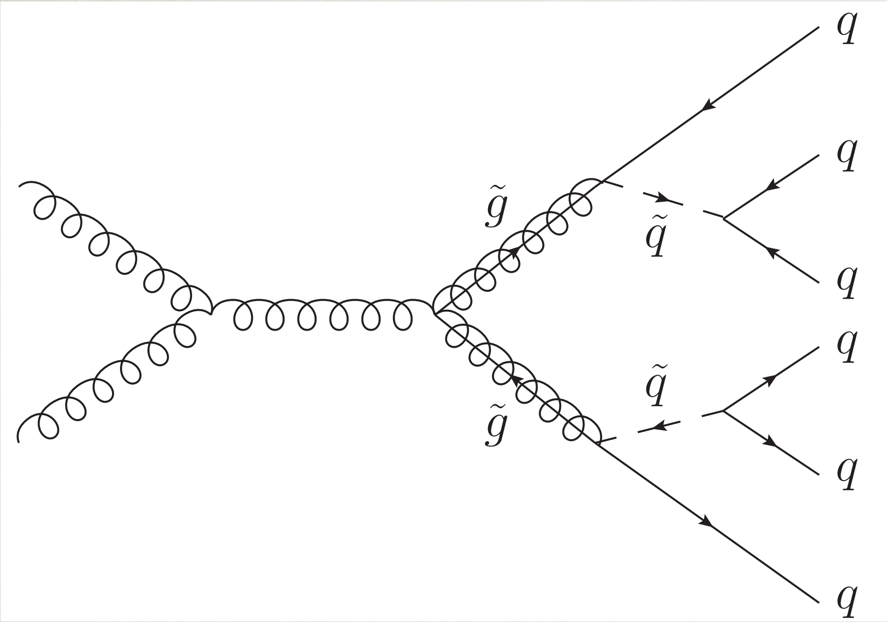
- Jet substructure can also be useful for three-jet resonances, but come at a cost of producing them well above threshold (ex. RPV gluinos in Curtin, Essig, BS arXiv:1210.5523)

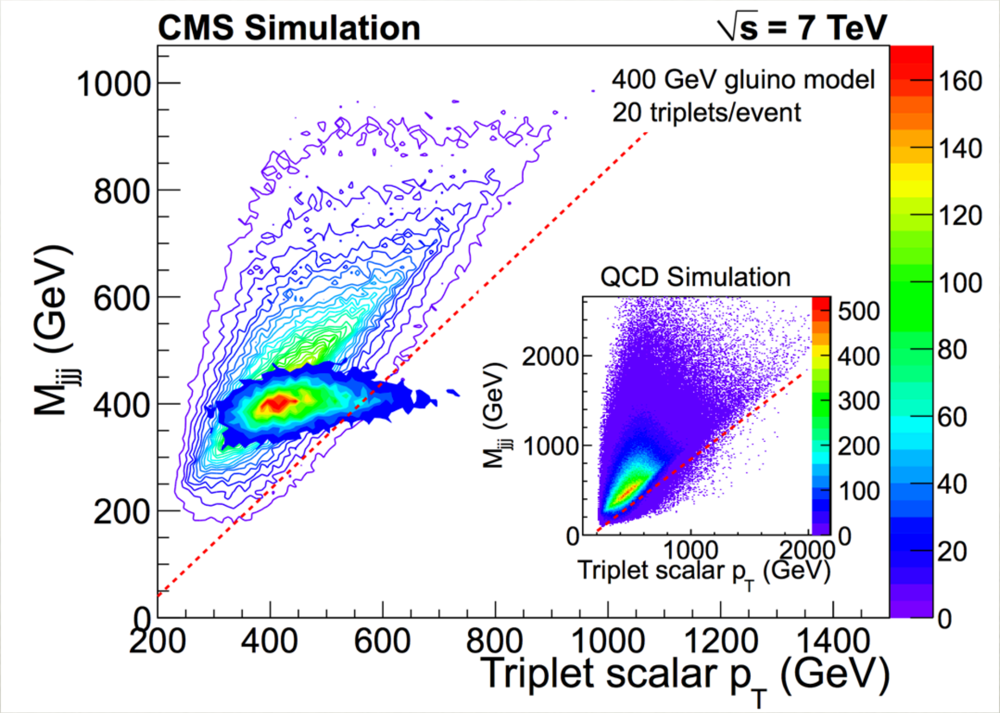


Multijet resonances

- 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!