Identifying Dijet Resonances at the LHC

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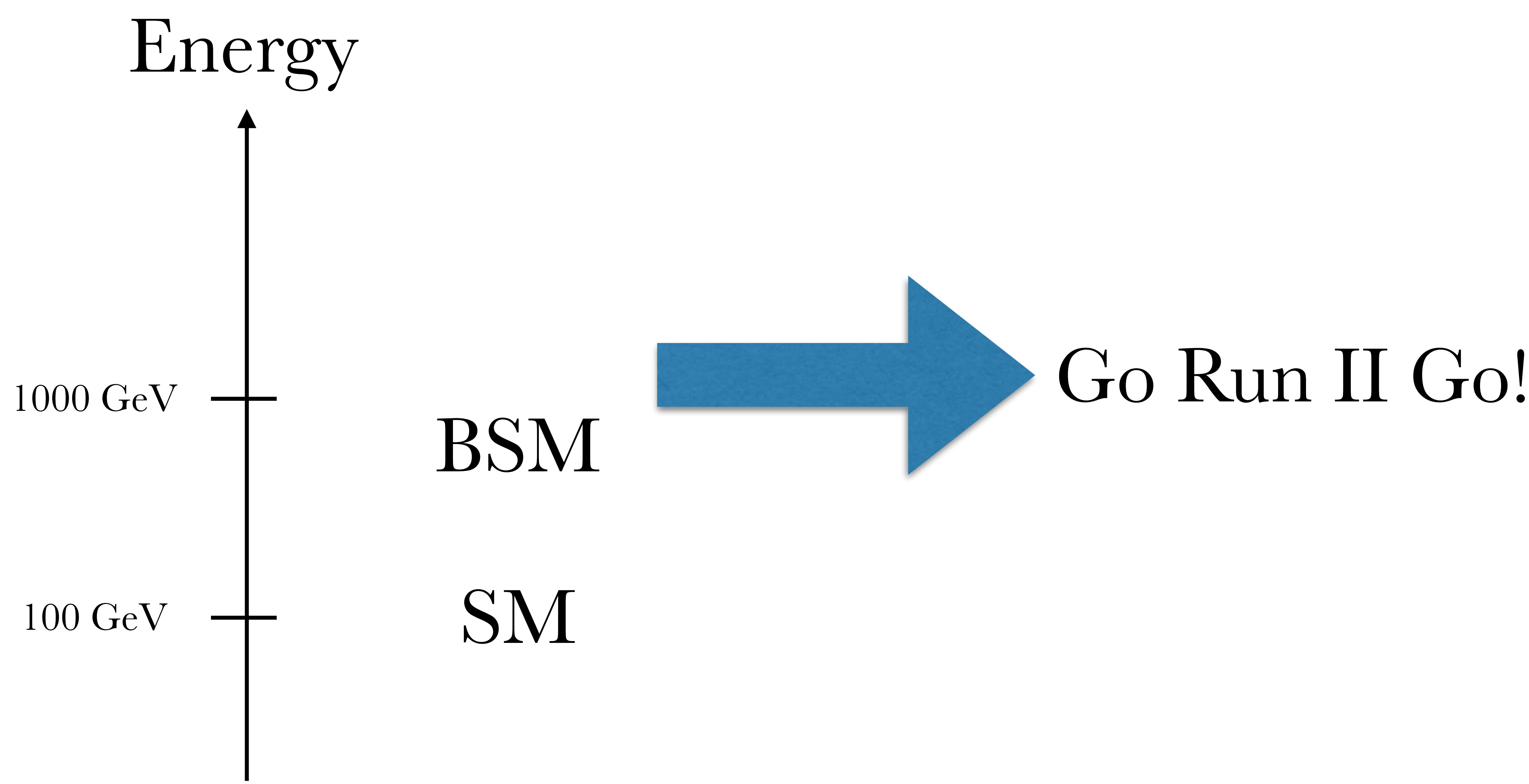
Beyond the SM

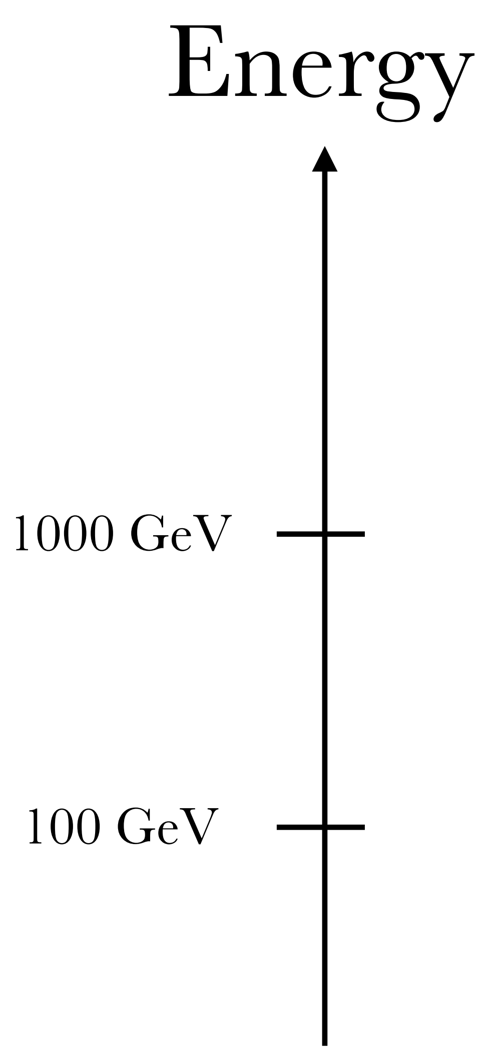
How do you find new physics?
Depends (and with caveats)

Case 1



Beyond the SM

Case 2



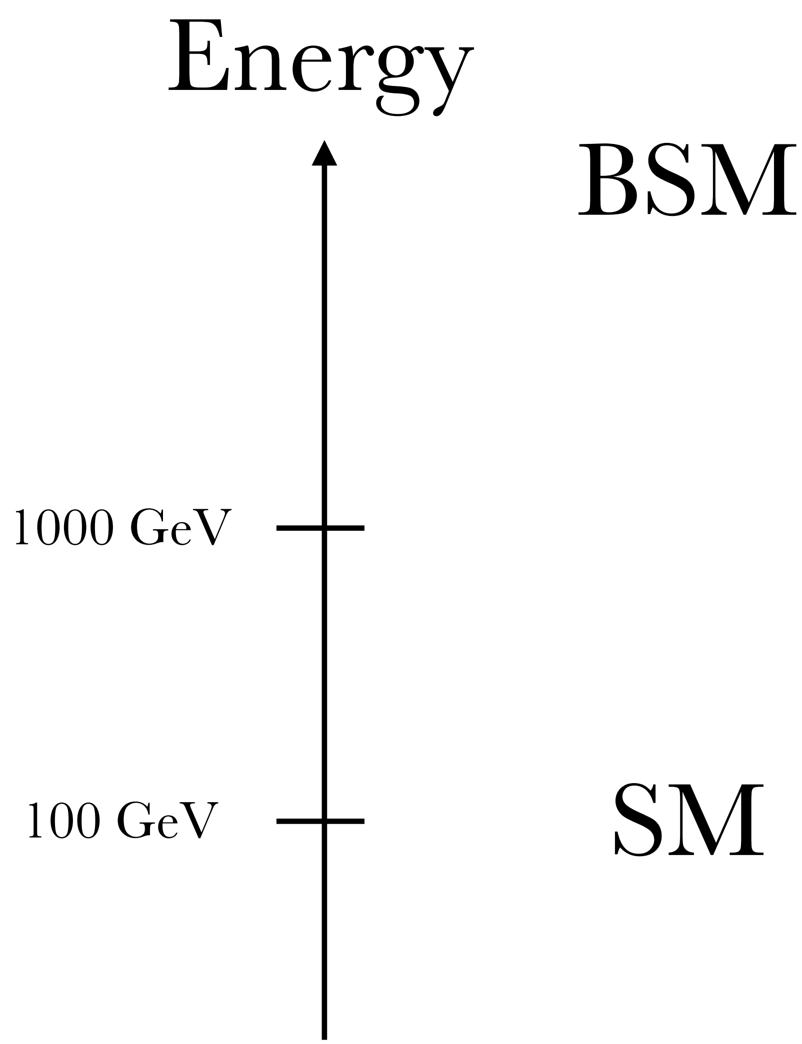
SM

BSM

LHC/Low E
High Intensity

Beyond the SM

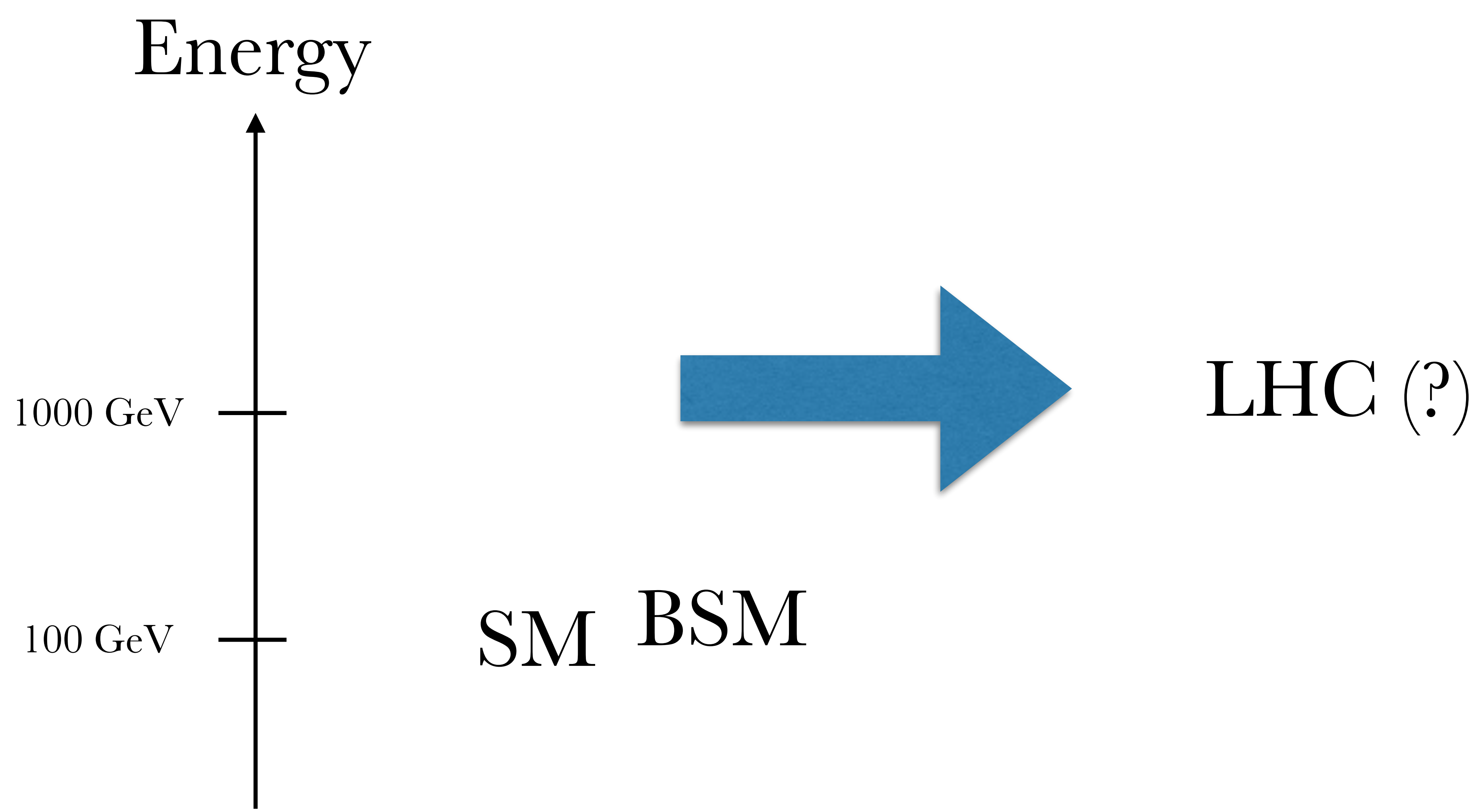
Case 3



Indirect tests
or
Higher energy
collider

Beyond the SM

Case 4



Beyond the SM

Case 4 can be trickier than it seems

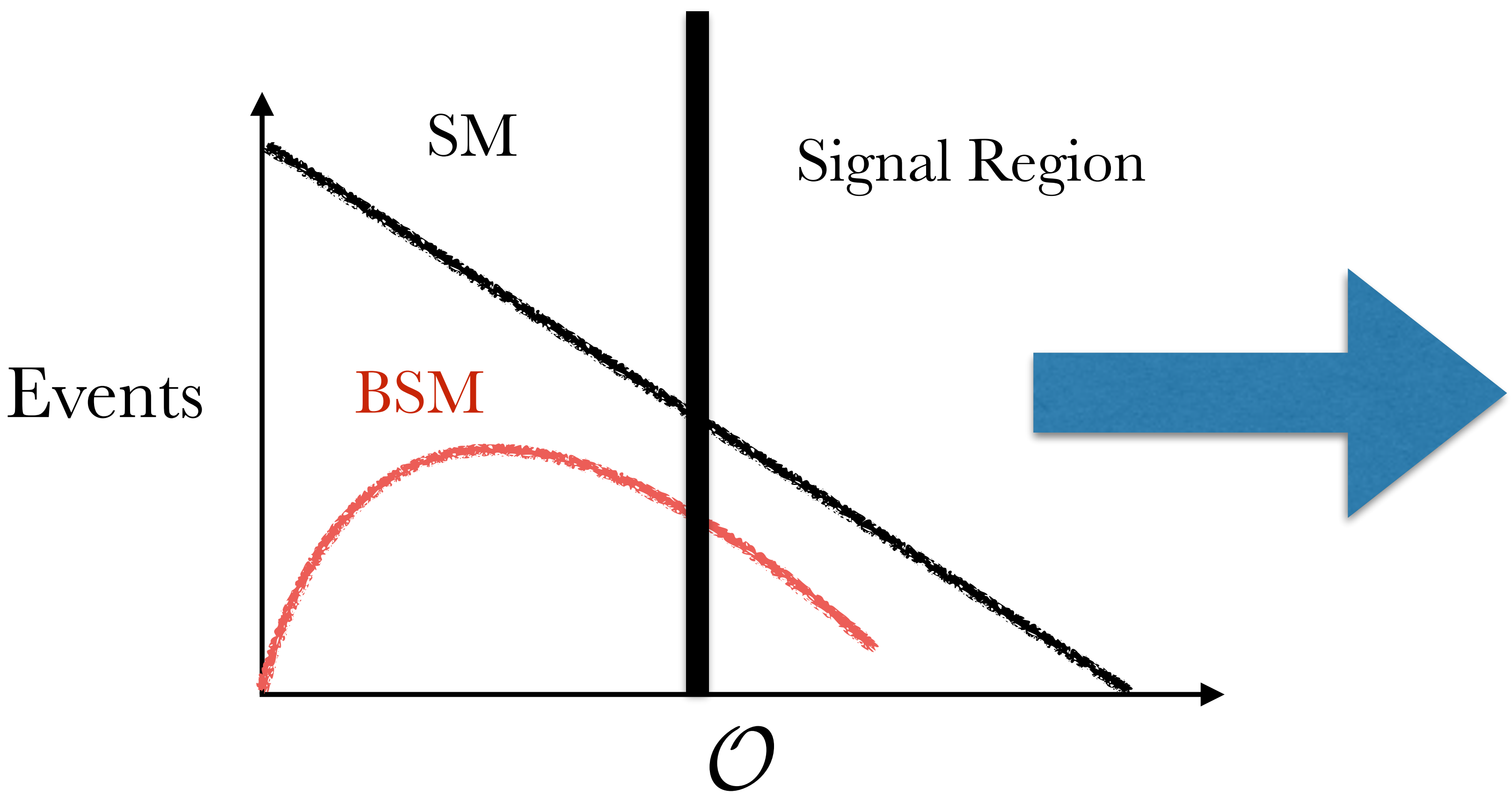
The new physics states could mimic the kinematics of SM processes

Cross sections not necessarily that small

How would one search for these “stealthy” new physics scenarios?

Two generic analyses to discover Case 4

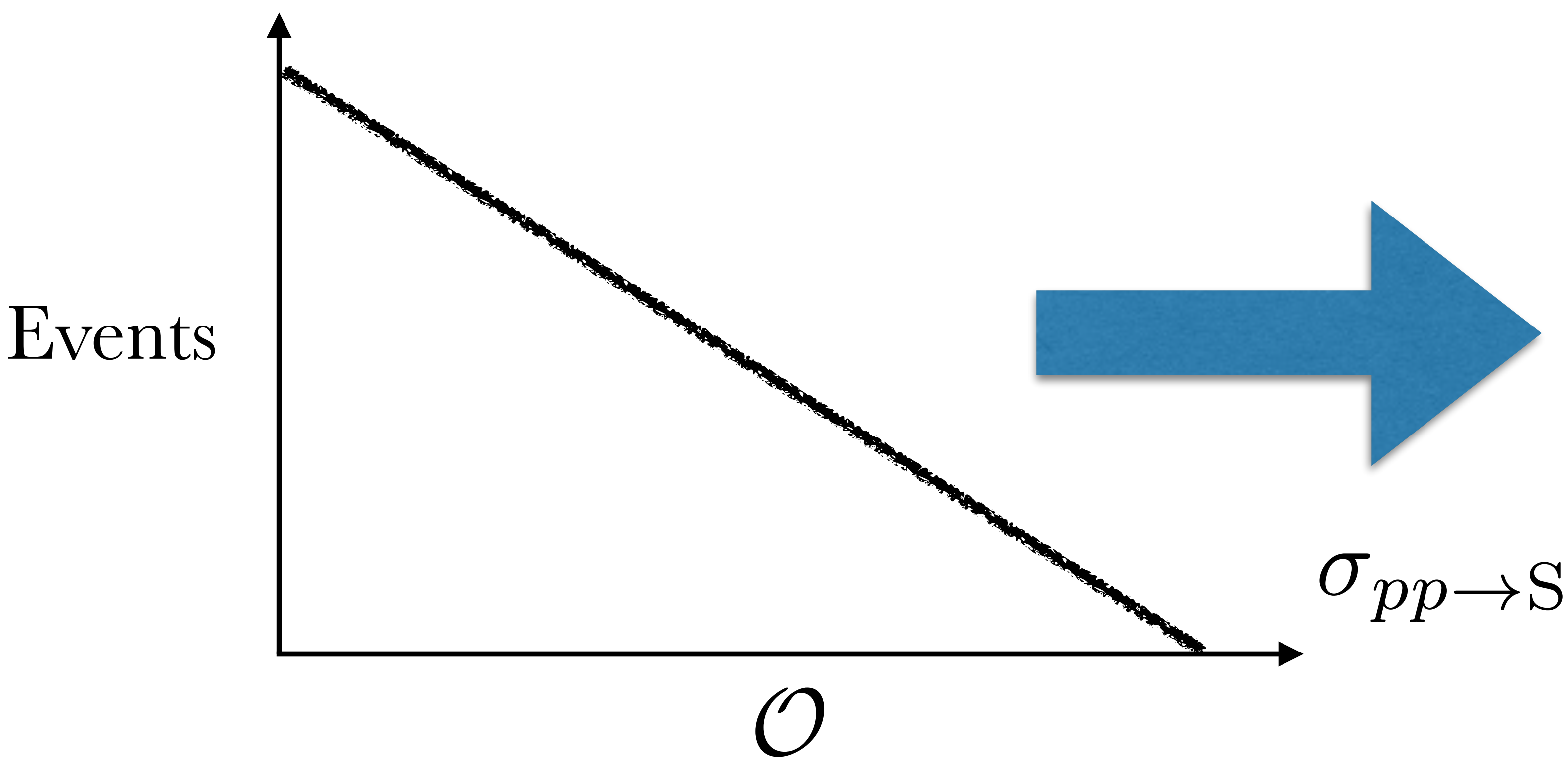
1. Beyond the SM Search: SM-poor signal region
   The problem: BSM-poor signal region



$\sigma_{pp\rightarrow \mathrm{BSM}+X} < \sigma_{\max}$

Two generic analyses to discover Case 4

2. SM Measurements: SM-rich signal region
Also BSM-rich signal region



$$\sigma_{pp\to \mathrm{SM}+X} \pm \Delta\sigma_{pp\to \mathrm{SM}+X}$$

We could try decreasing this

Precision SM as a probe of BSM

Examples where small deviations in SM rate could be indication of BSM

1. Higgs production x branching ratio measurements very sensitive to new thresholds

2. Top anti-top production cross section
Can set a bound on light stops (Case 4)
$m_{\tilde{t}} \approx m_t$

3. WW production cross section
Could be mimicked by light charginos, and/or squeezed stops/charginos (Case 4)

Outline

Why another dijet-tagging observable?

SM Application Part 1: WW + WZ cross section

SM Application Part 2: Higgs decays to b-quarks

BSM Application: Z\` > WW

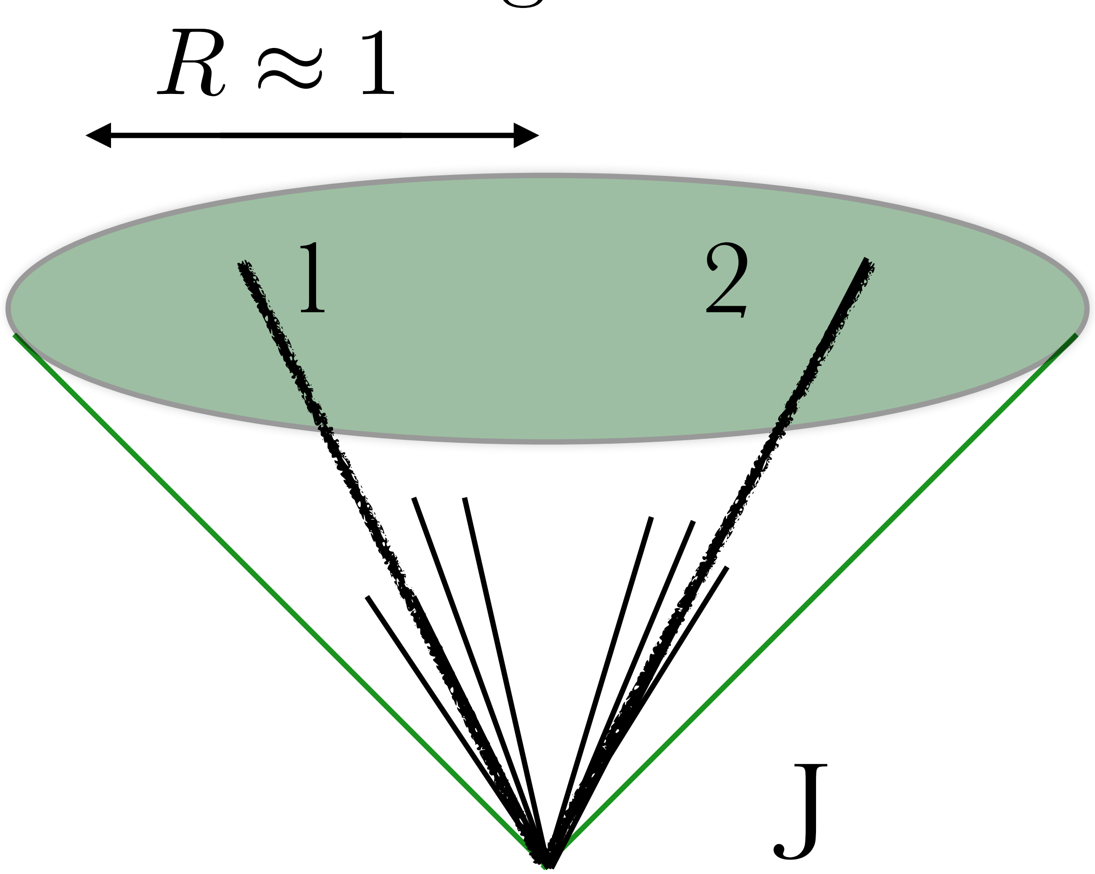
Example: Improving W/Z/H Identification

Predominantly decay to two quarks

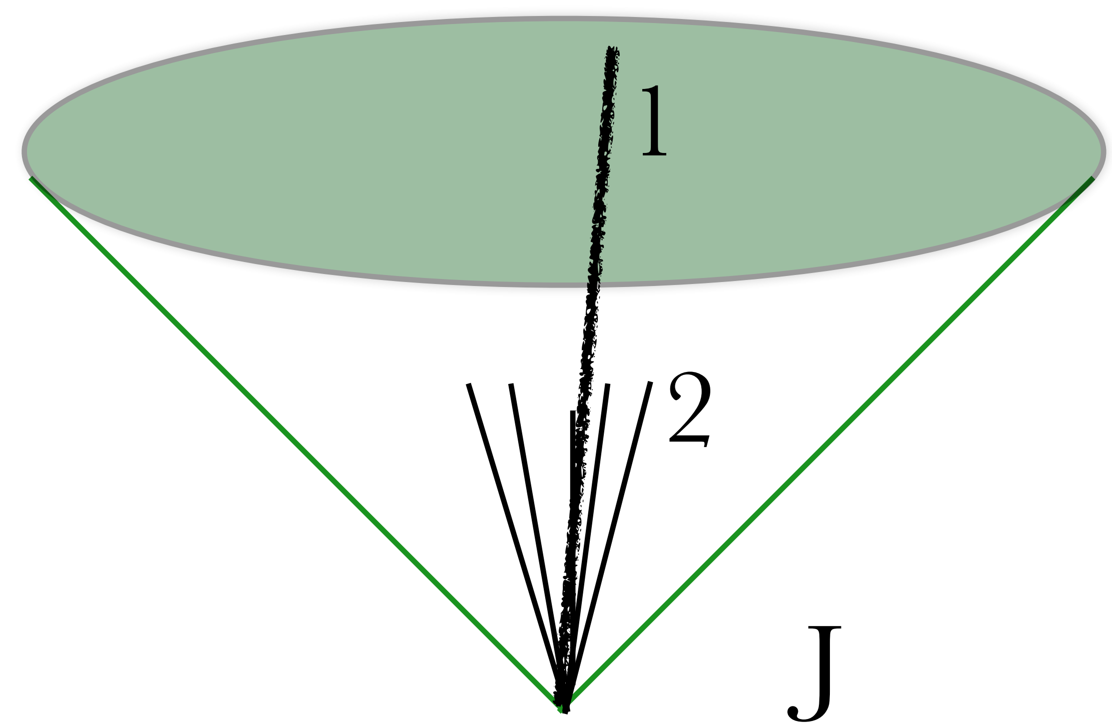
Substructure techniques proven successful in boosted regime

$$p_{T,R} > \text{few} \times m_R$$

Signal



QCD background



The Boosted Regime

Can distinguish a boosted resonance
with standard techniques: Groom-based or energy-flow based

e.g. BDRS mass-drop tagger (arXiv:0802.2470)

Undo the jet clustering until you find two subjets 1 and 2 such that:

$$\frac{min(p_{T,1}^2, p_{T,2}^2)\Delta R_{12}^2}{m_J^2} > y_{\mathrm{cut}}$$

Not too asymmetric

$$m_1/m_J < \mu$$

Mass drop

The Boosted Regime

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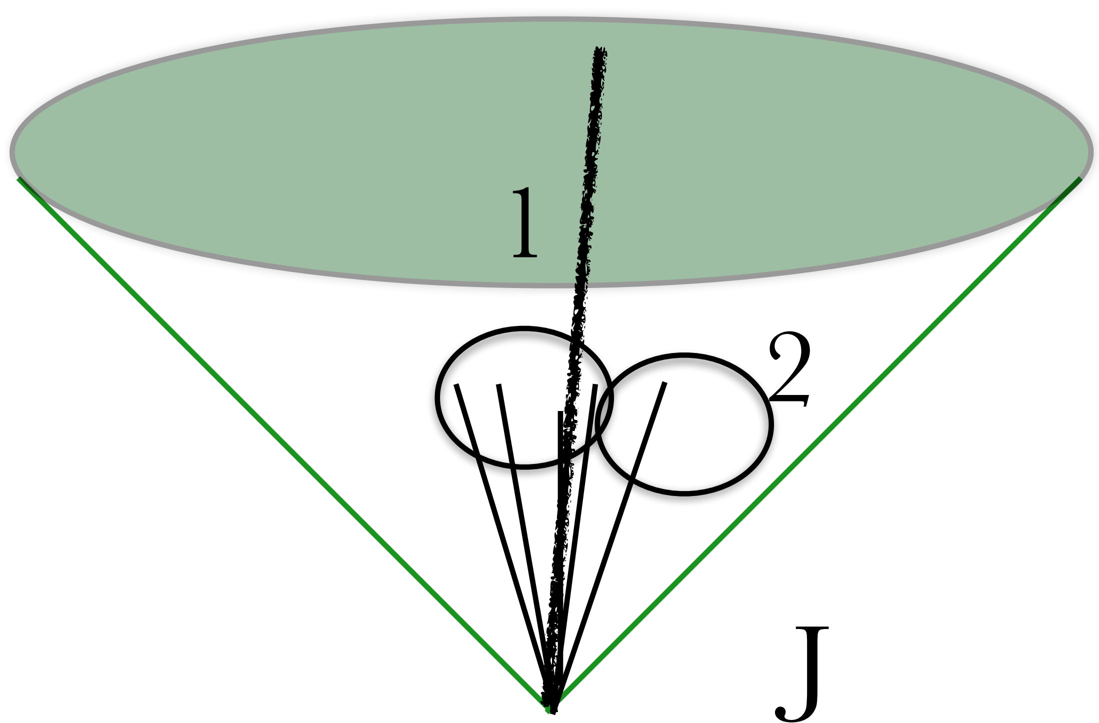
QCD background



$m_1/m_J \sim \mathcal{O}(1)$

The Boosted Regime

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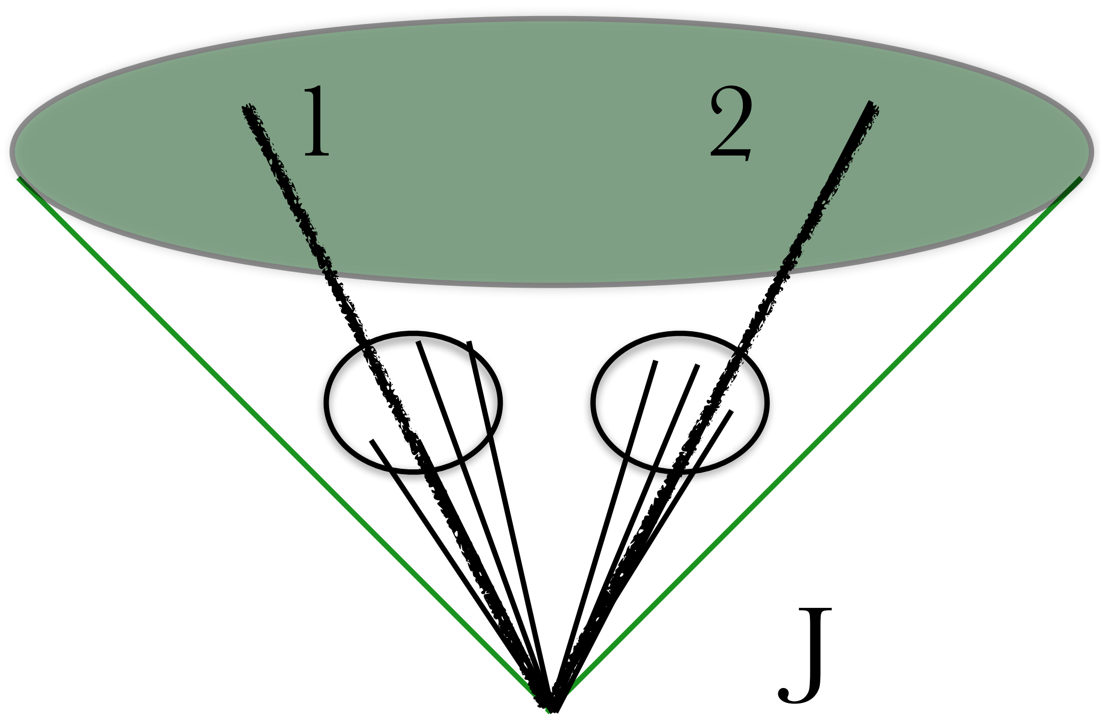
Dijet Resonance



$$m_1/m_J \lesssim \frac{1}{2}$$

An Alternative: Energy-based Observables

Track the energy flow in a jet to see how consistent with N subjets

e.g. N-subjettiness (arXiv:1011.2268)

$$\tau_2/\tau_1 < \text{small value}$$

i.e. How 2-subjetty the jet is w/r to it's 1-jettiness

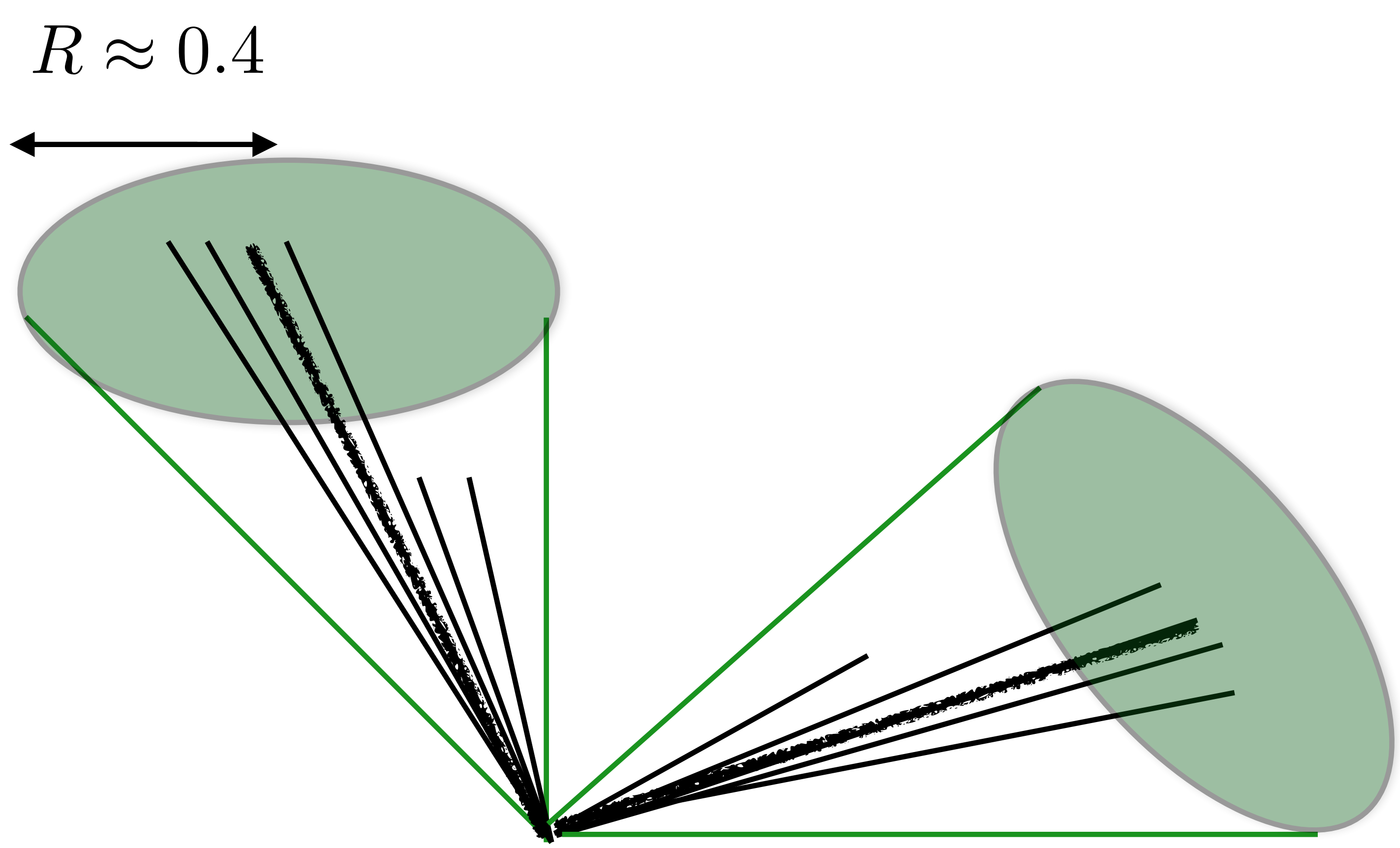
Dijet resonance exhibits smaller ratio than QCD jet

Mildly Boosted Regime

Can we still identify resonances when they're mildly boosted?

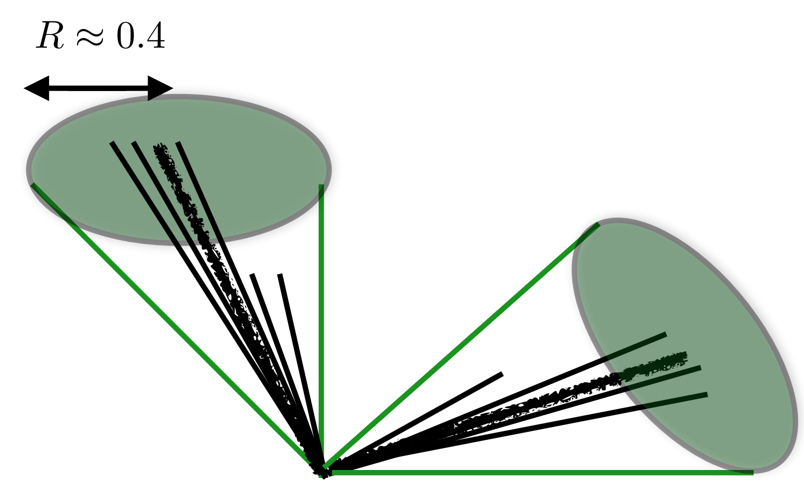
e.g. $p_{T,R} \approx m_R$

Decay products are separately resolved into "thin" jets



Mildly Boosted: Lessons from Mass-Drop

Physically, we still expect a gain
But signal looks more like QCD background



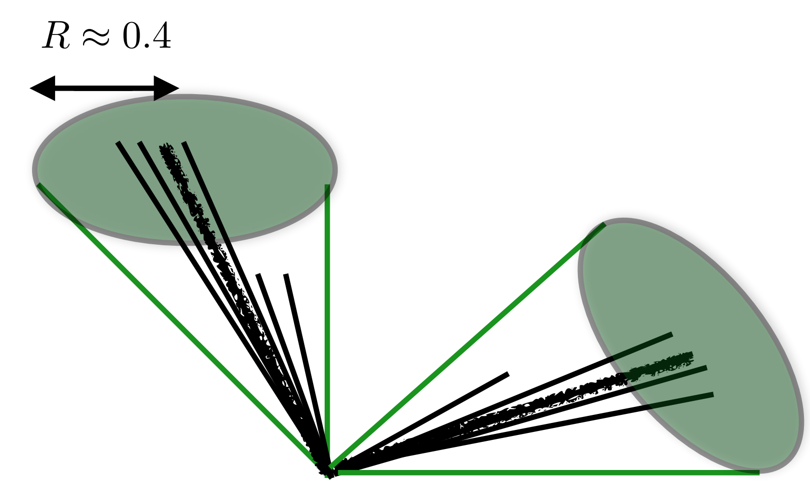
Mass-drop alone would lose its power

$$m_{j_1}/m_{j_1 j_2} = \text{small number}$$

We can still identify a resonance in this limit

Require 2 jets with combined invariant mass near resonance
Is that all we can do?

Mildly Boosted Regime



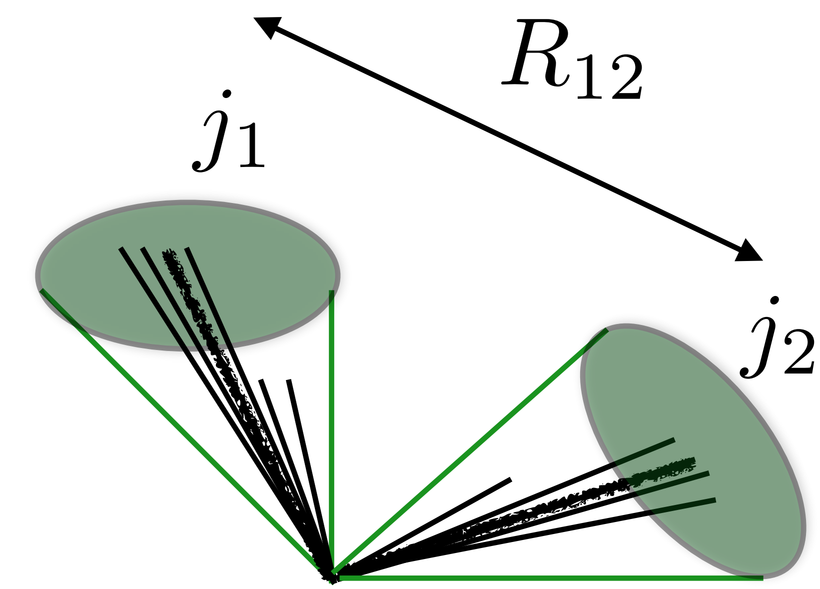
Can we generalize the mass-drop criterion for this regime?

Can we use the increasing separation to our advantage?

What happens to the background as we go from high boost to small boost?

i.e. from large boost (decay products inside one large R-jet) to moderate boost (decay products resolved separately)

A New Observable



As decay product separation increases (milder boost) QCD jets display a larger mass drop

How about having an increasingly tighter mass-drop cut with increasing separation between jets?

$$m_{j_1}/m_{j_1 j_2} < A \quad \longrightarrow \quad m_{j_1}/m_{j_1 j_2} < \frac{A}{R_{12}}$$

A Heuristic Argument for New Observable

The average jet mass is given by

$$\langle m_j^2 \rangle \approx C \frac{\alpha_s}{\pi} R^2 p_{T,j}^2$$

A significant fraction of background events arise from a hard splitting, so for these events

$$\langle m_{j_1 j_2}^2 \rangle \approx C \frac{\alpha_s}{\pi} R_{12}^2 p_{T,J}^2$$

Whereas for a resonance: $\langle m_{j_1 j_2}^2 \rangle = m_R^2$

Typical Scaling

Signal

$$m_{j1}/m_{j1j2} \propto \text{constant}$$

$$\text{constant} \approx 0.1$$

Background

$$m_{j1}/m_{j1j2} \propto \frac{1}{R_{j1j2}}$$

This motivates the observable: $\zeta \equiv \frac{m_{j_1}}{m_{j_1 j_2}} R_{12}$

and cutting: $\zeta < \zeta_c$

Outline

Why another dijet-tagging observable?

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SM Application Part 2: Higgs decays to b-quarks

BSM Application: Z` > WW

WW/WZ Cross Section Application

Ongoing discrepancy in the fully-leptonic channel (2l + MET)

Let's apply this observable idea to the semi-leptonic channel

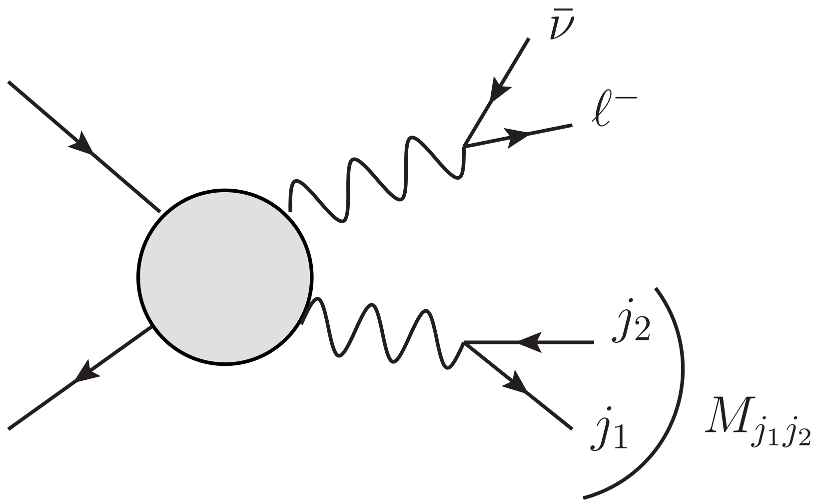
We use MG5+Pythia 6+Fastjet

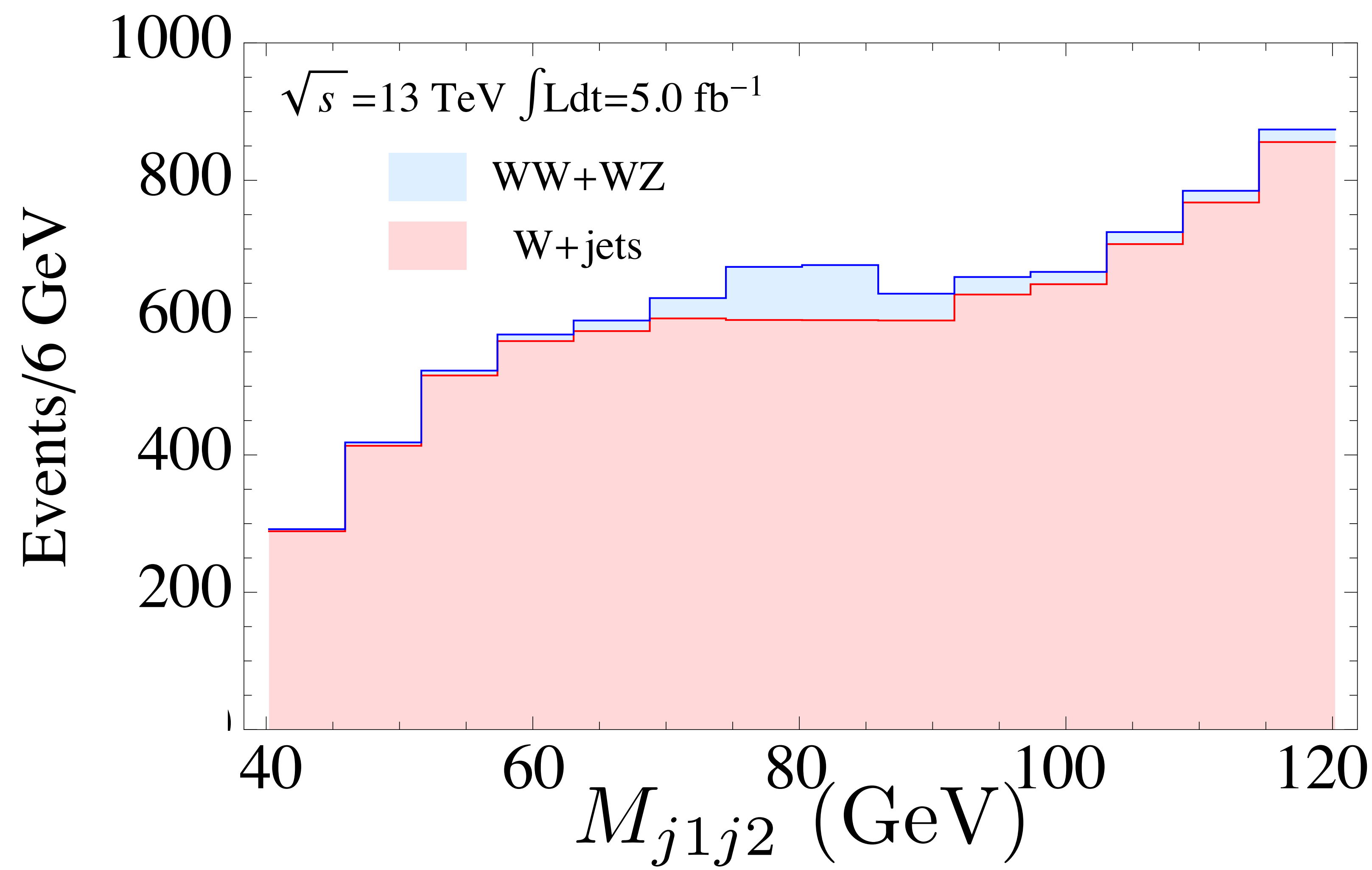
We mimic CMS' 7 TeV analysis, with re-scaled cuts to 13 TeV

		anti-kT (R=0.5)
$N_j = 2$	with	$p_T > 50$ GeV
$N_\ell = 1$	with	$p_T > 25$ GeV
$\not{E}_T > 50$ GeV	and	$M_T > 50$ GeV

WW/WZ Cross Section Application

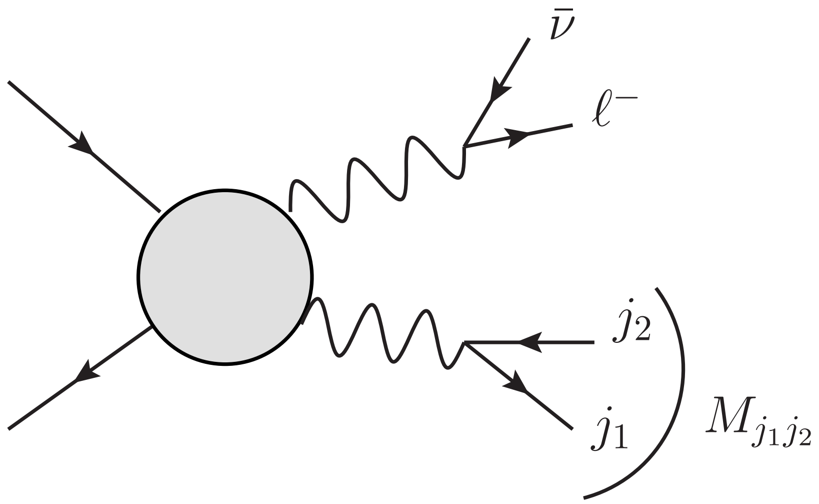
Before

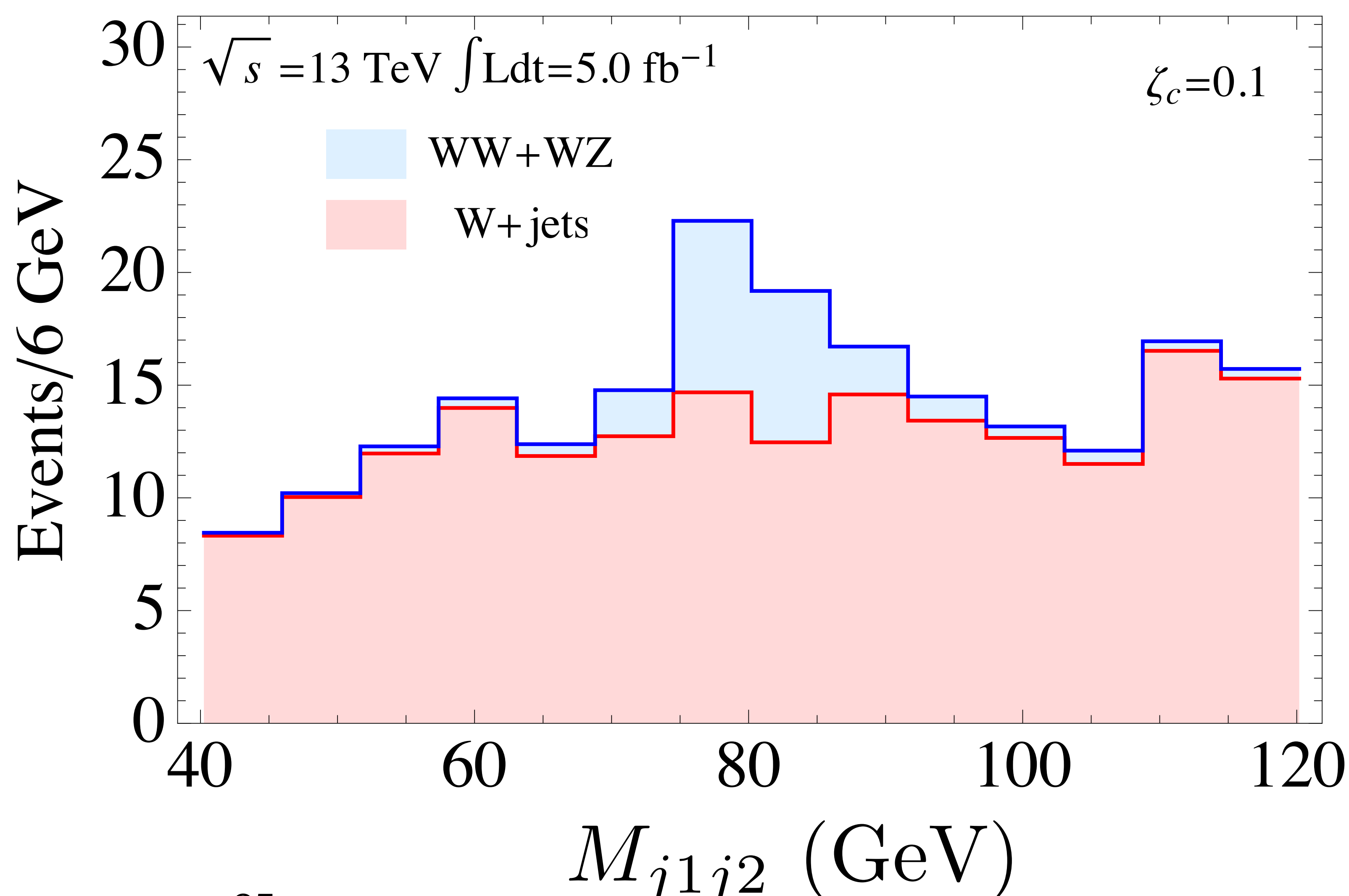




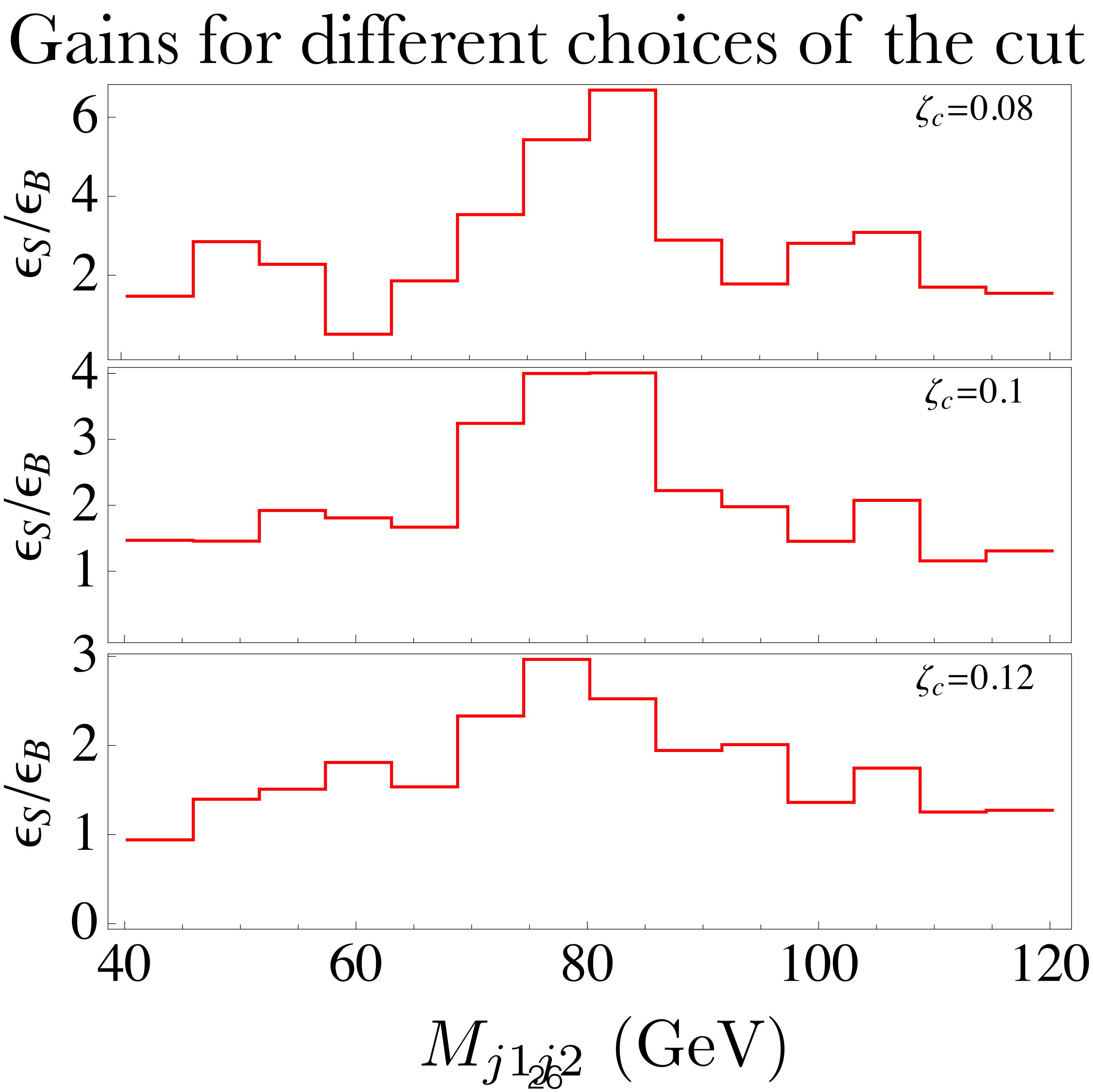
WW/WZ Cross Section Application

After





WW/WZ Cross Section Application

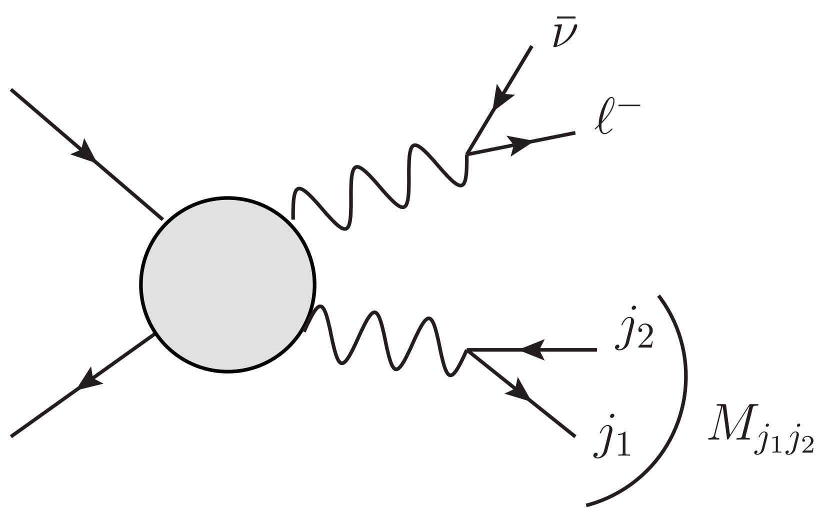


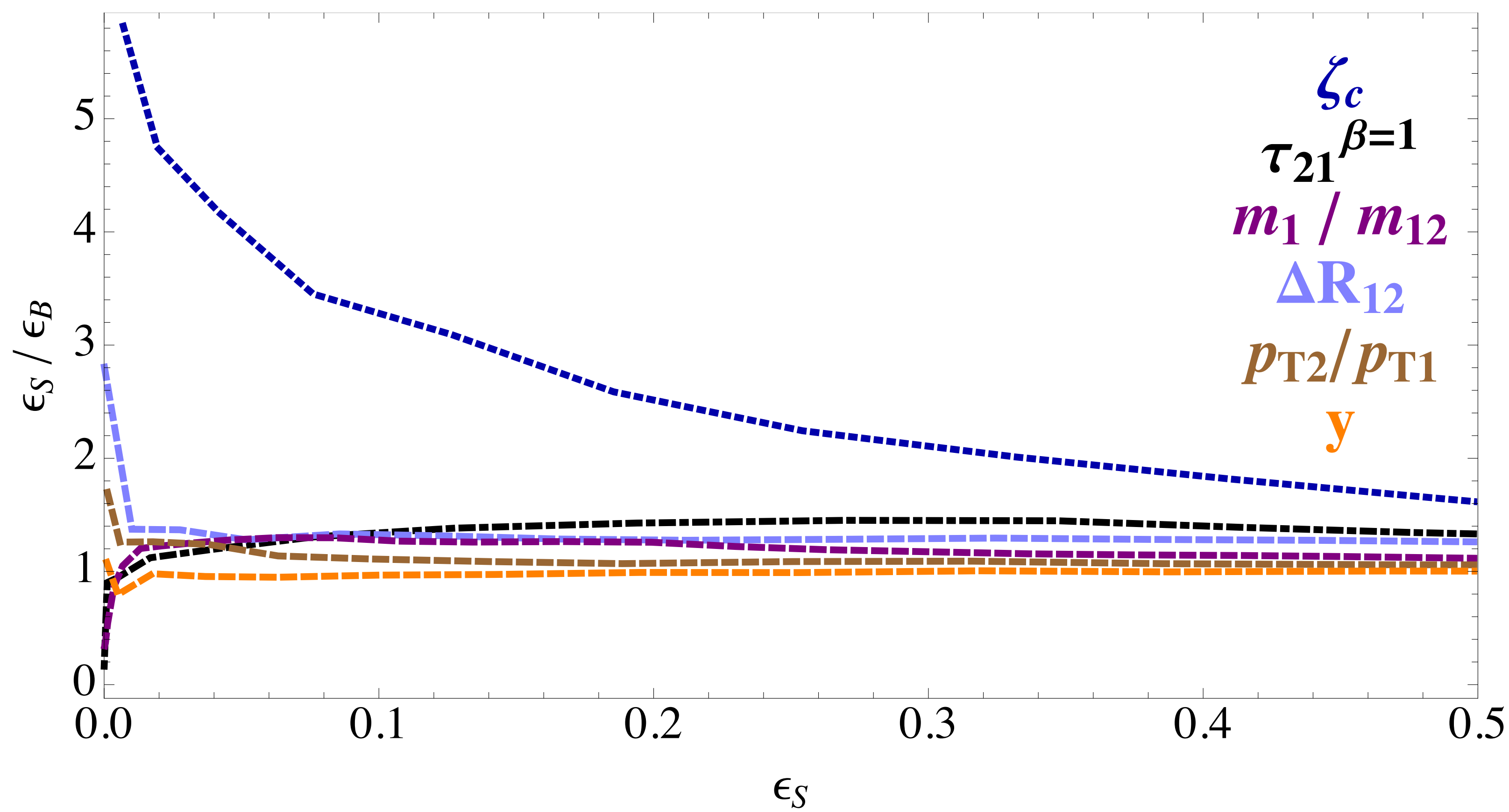
$\epsilon_s \sim 10\%$

Comparison with other cuts for WW case

For a given signal efficiency we compare the gain in S/B for different cuts.

$$70 \text{ GeV} < M_{j_1 j_2} < 100 \text{ GeV}$$





Outline

Why another dijet-tagging observable?

SM Application Part 1: WW + WZ cross section

SM Application Part 2: Higgs decays to b-quarks

BSM Application: Z` > WW

WH Example (With H > bb)

First, a phenomenological observation

We find similar S/B gains with a more general form of the cut on mass-drop

$$\frac{m_{j_1}}{m_{j_1 j_2}} < \frac{\zeta_c}{R_{12} - R_c}$$

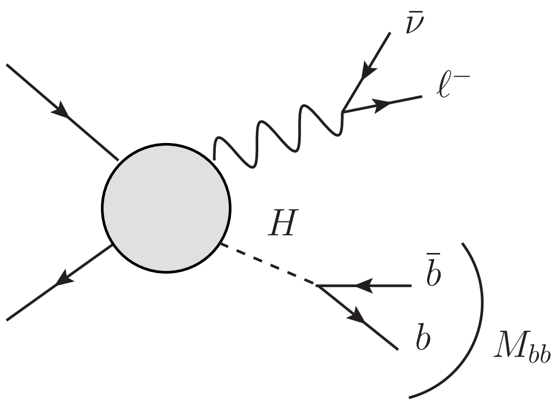
This form of the observable allows for higher signal efficiency

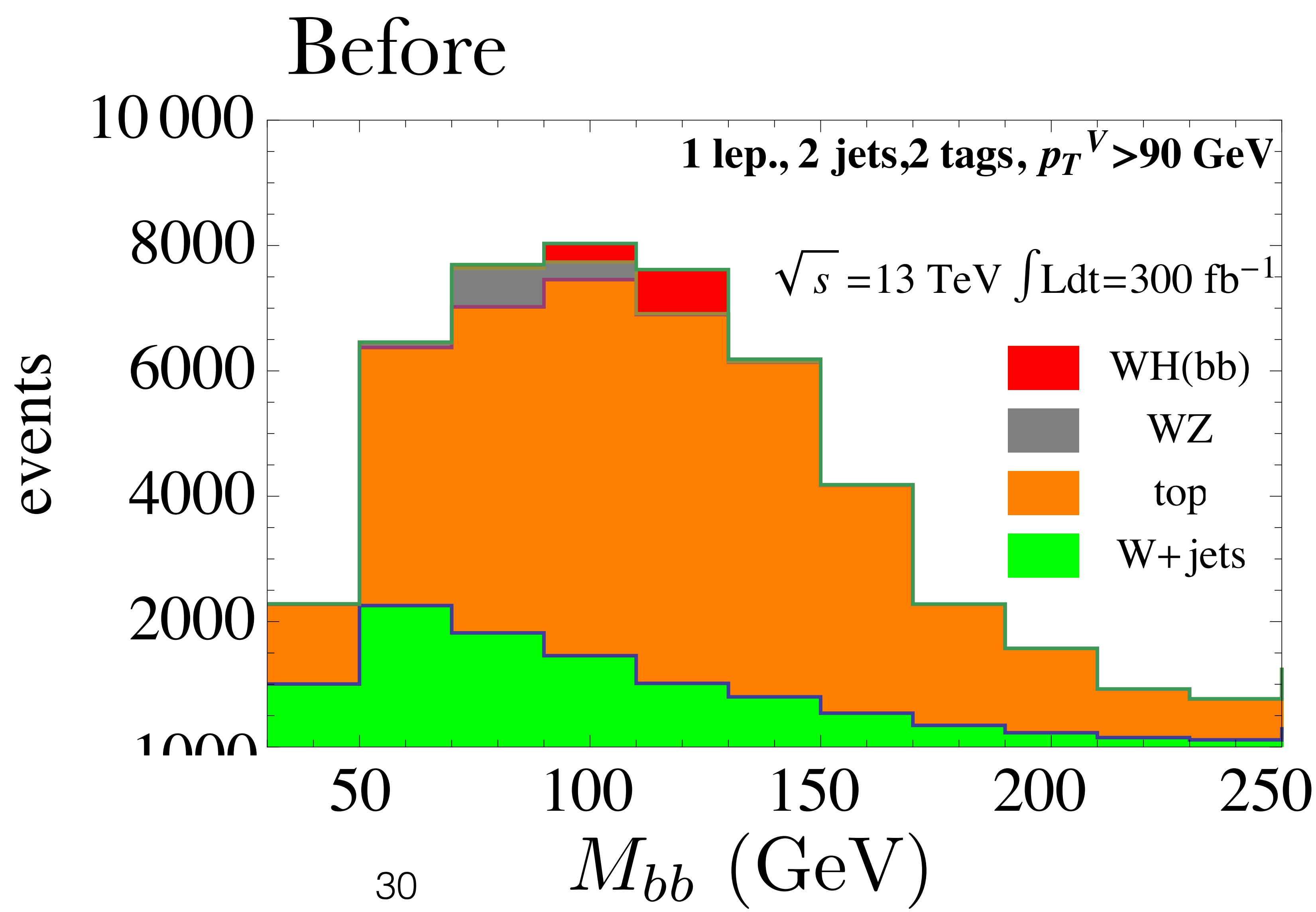
WH Example (With H > bb)

We replicate the ATLAS 7+8 TeV analysis at 13 TeV

ATLAS-CONF-2013-079

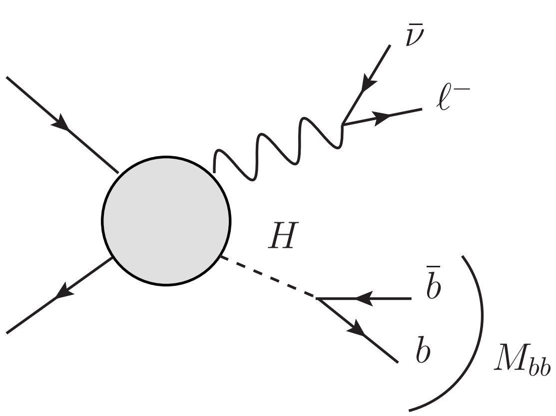
We look for 2 b-tags, one tight-lepton, and MET

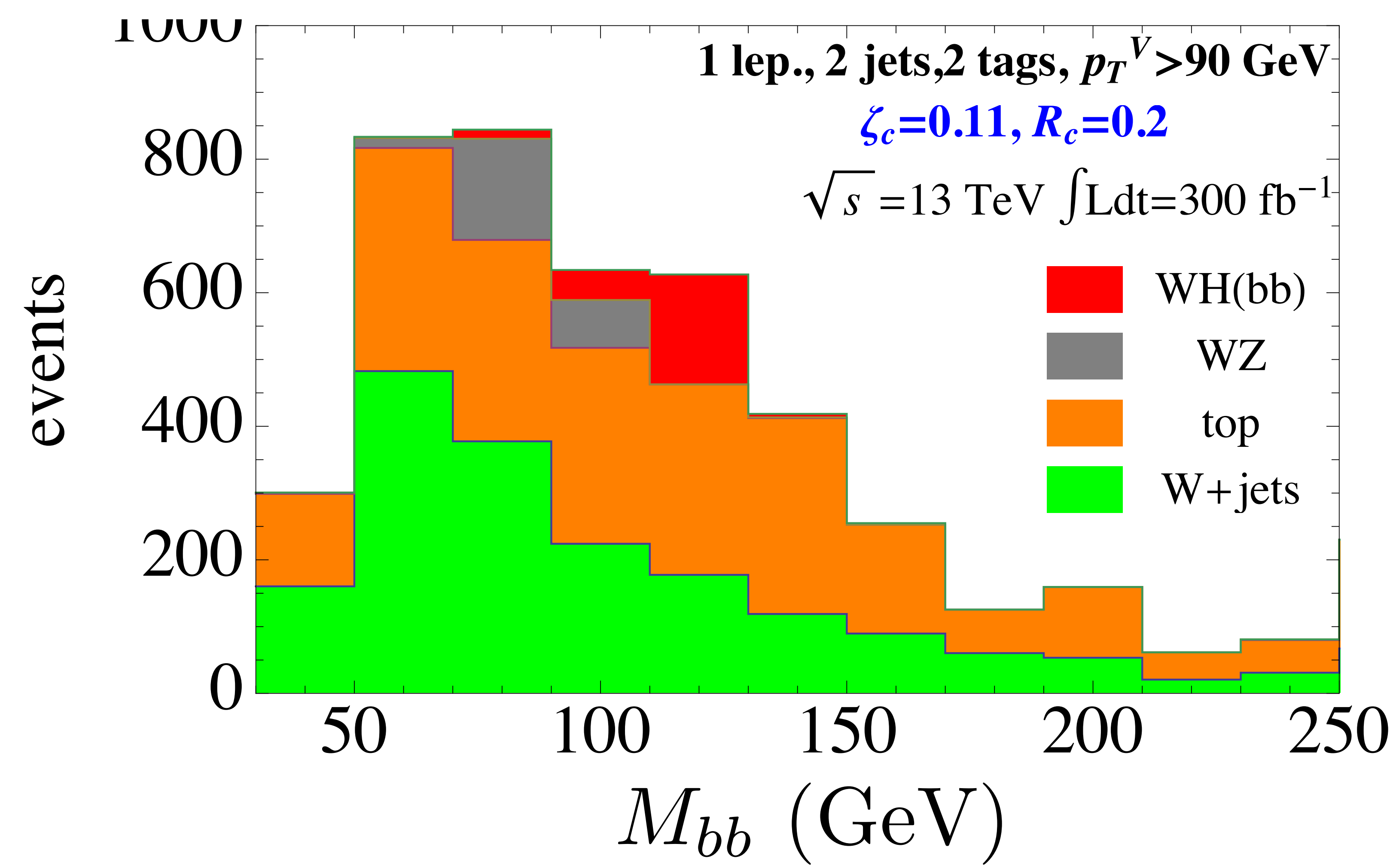




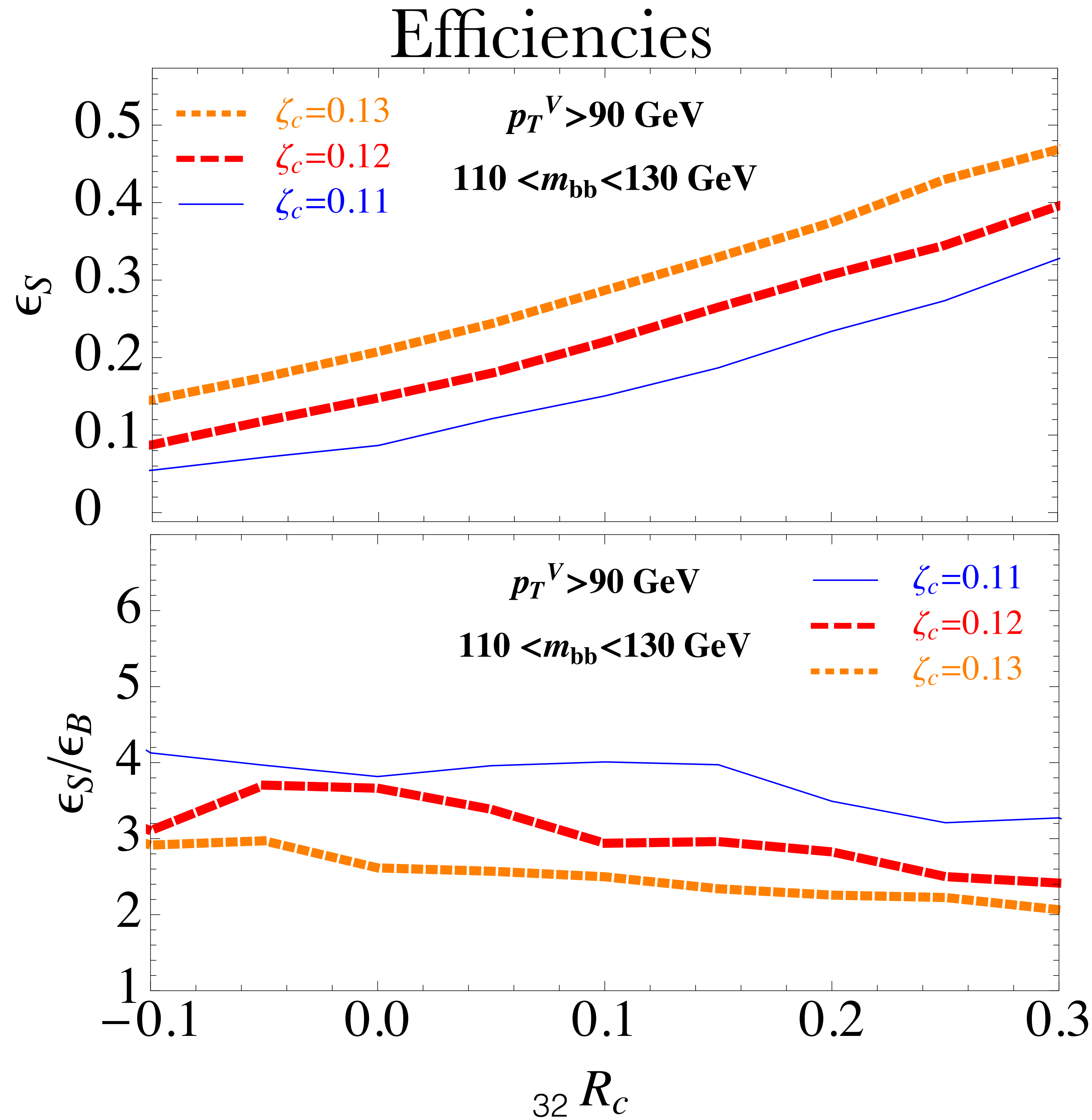
WH Example (With H > bb)

After





WH Example (With H > bb)



Comments

If we restrict ourselves to the moderate boost regime

$$90\ \text{GeV} < p_T^V < 200\ \text{GeV}$$

We still find a gain in S/B ~ 3

So our approach is effective in a boost range complementary to BDRS and other boosted substructure analysis

Outline

Why another dijet-tagging observable?

SM Application Part 1: WW + WZ cross section

SM Application Part 2: Higgs decays to b-quarks

BSM Application: Z` > WW

BSM Example: Z`

Our observable also effective at identifying BSM resonances

Example: Z` > WW

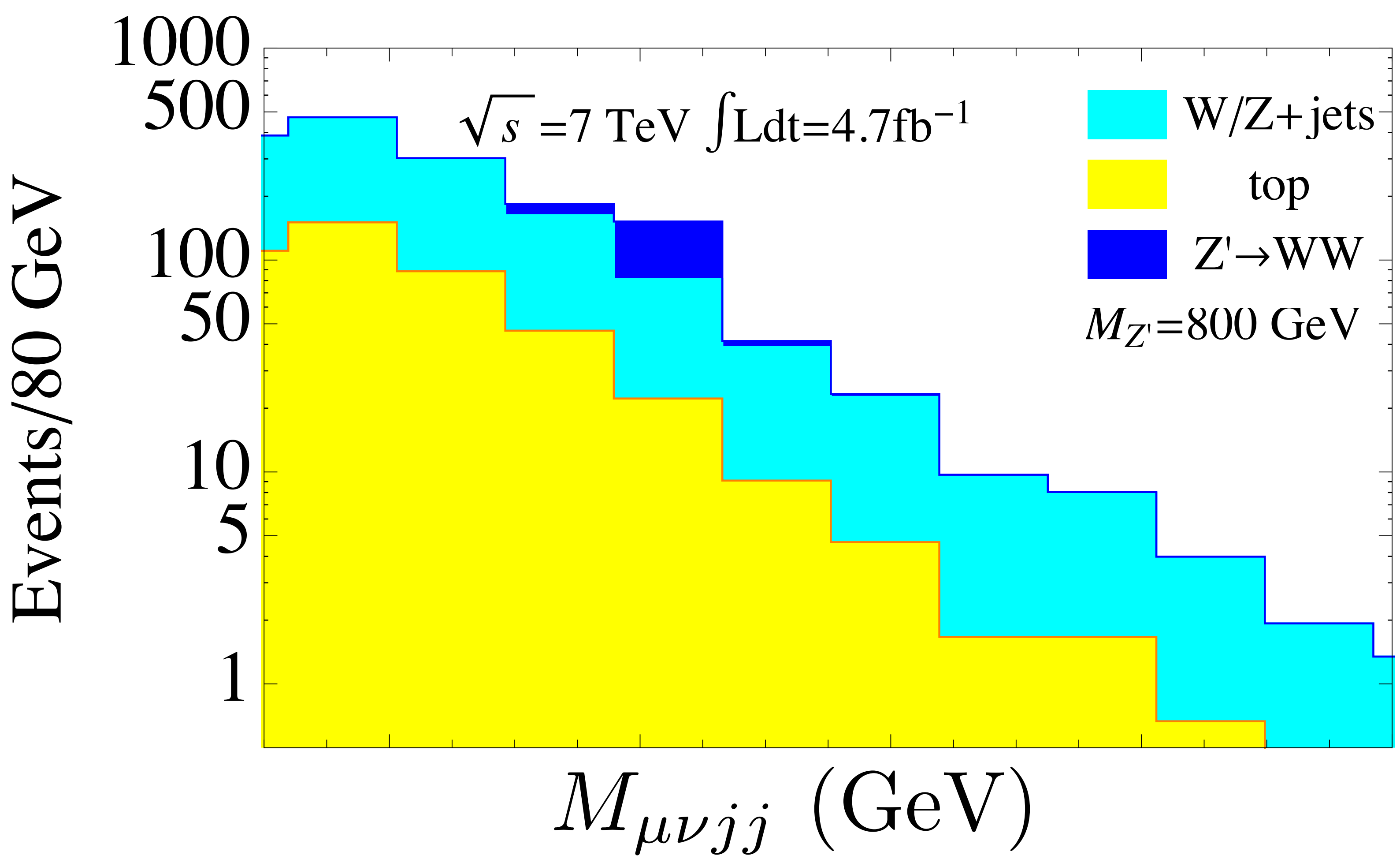
We apply the cuts of the ATLAS analysis
looking for lepton+MET+two-jets

arXiv:1305.0125

(See work by Dobrescu and Yu for lay of the land)

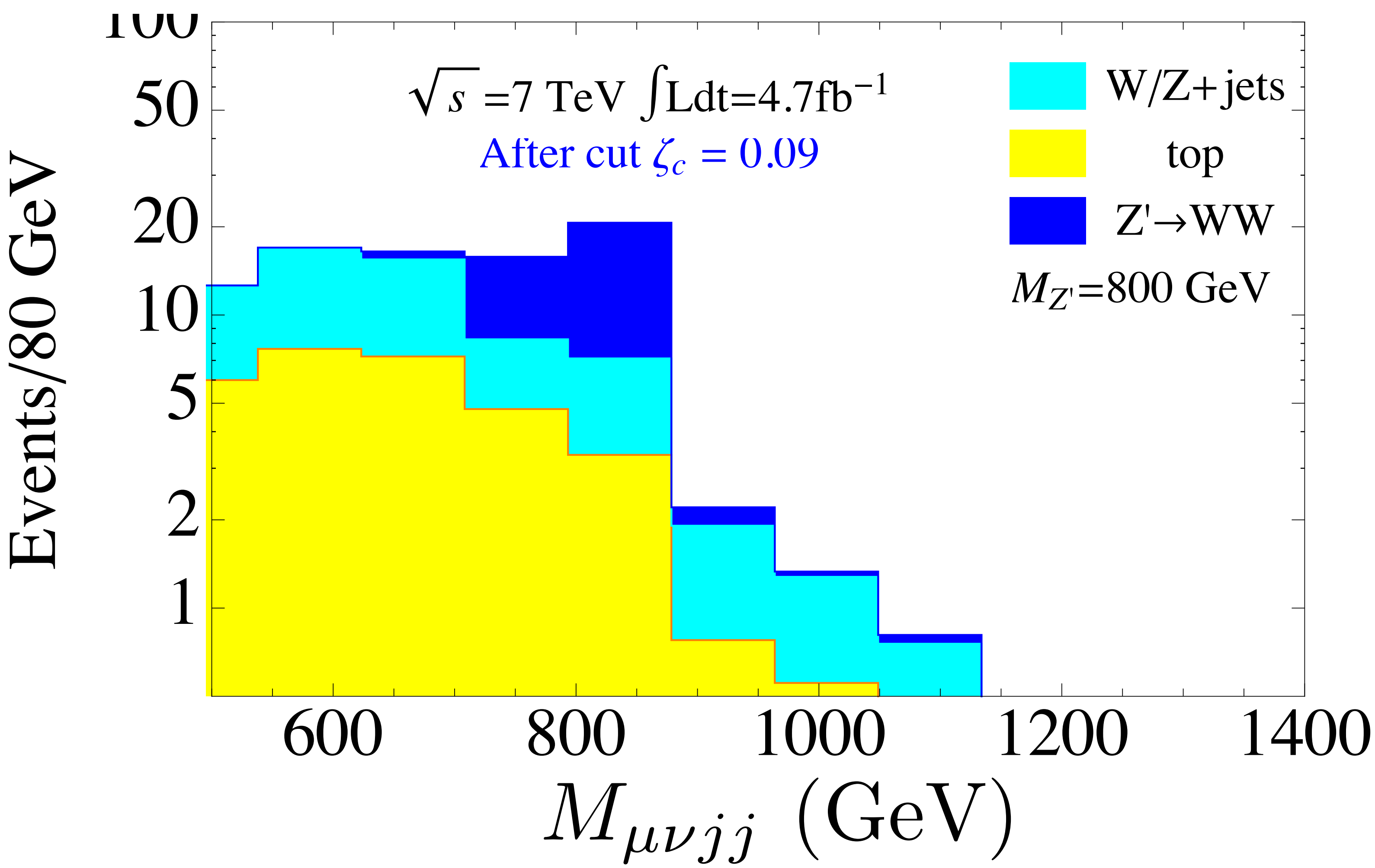
BSM Example: Z`

Before

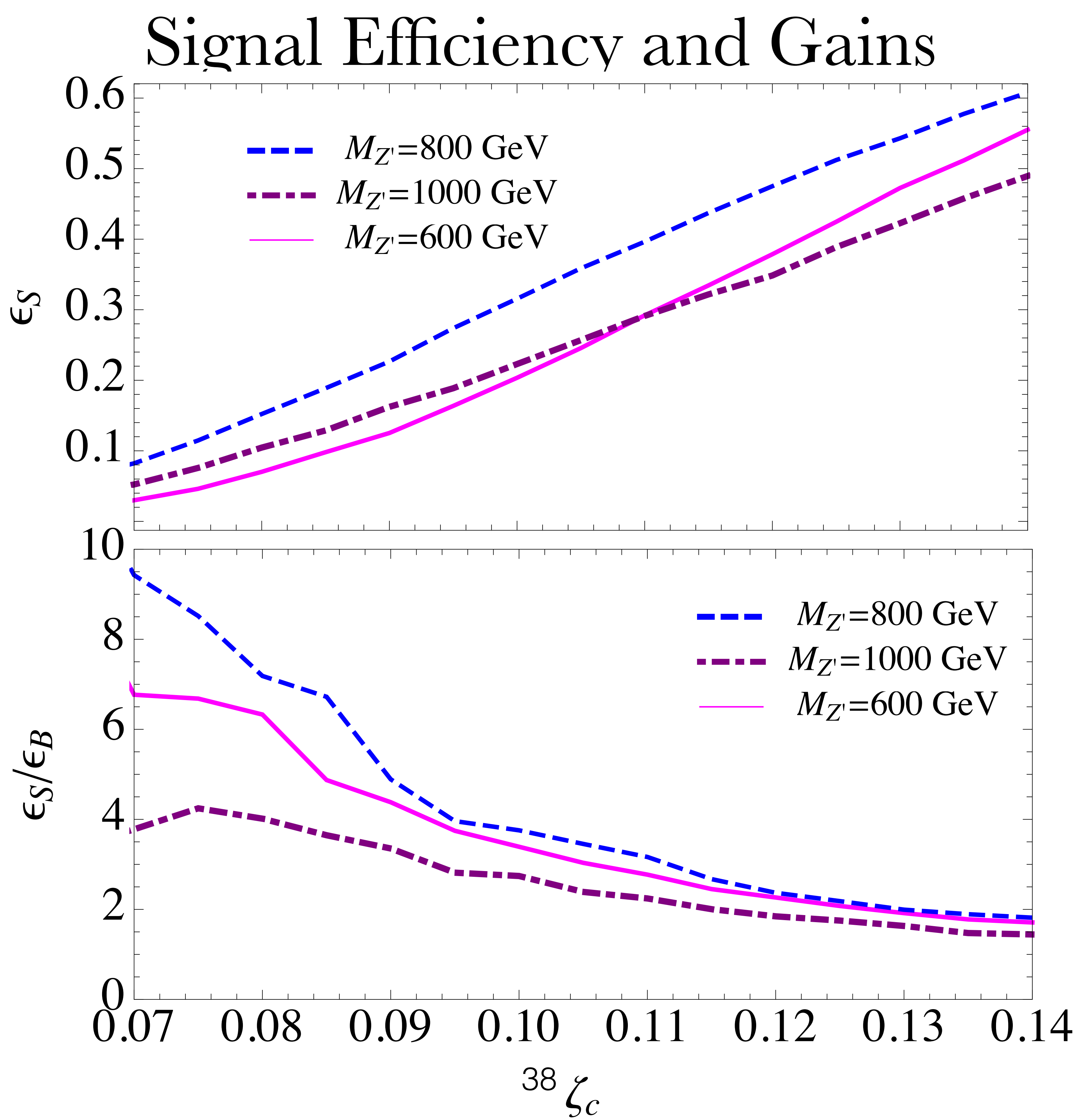


BSM Example: Z`

After



Dependence on Resonance Mass



Limitations

This isn't a cure-all approach

We find significant gains in S/B
Only a mild reduction in S/Sqrt(B)

But over the entire run of the LHC, the analyses that we focused on are limited by systematics, not statistics

Does pile-up ruin the party?
Not really. We checked that trimming recovers the same gains in S/B to within 10-20%

Conclusions

Presented a simple observable to identify dijet resonances
Effective even in the "resolved" limit (moderate boost)

We showed it works well for W/Z and H
Two extremely important examples in the SM

Also applicable to BSM searches
e.g. Z' > jj
(work to appear)

One advantage of using standard-radius jets:
Already being used by most analyses
Less sensitive to PU and UE effects (~ R^3 for jet mass)

Thank you