Some New Applications of Jet Substructure

Brock Tweedie
PITT PACC, University of Pittsburgh
@ ATLAS Searches Workshop
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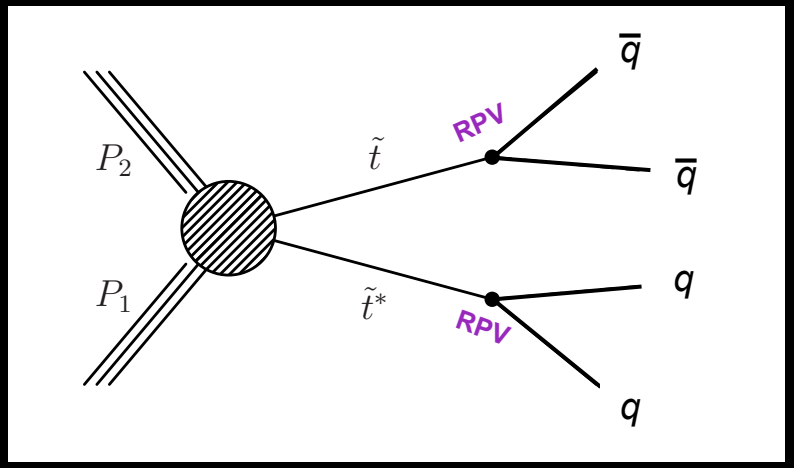
Y Bai, A Katz, BT, 1309.6631
BT, 1401.3021

Goals

- Show that direct RPV stop-pair → 4j search is viable
- Show tricks to measure boosted hadronic top spin

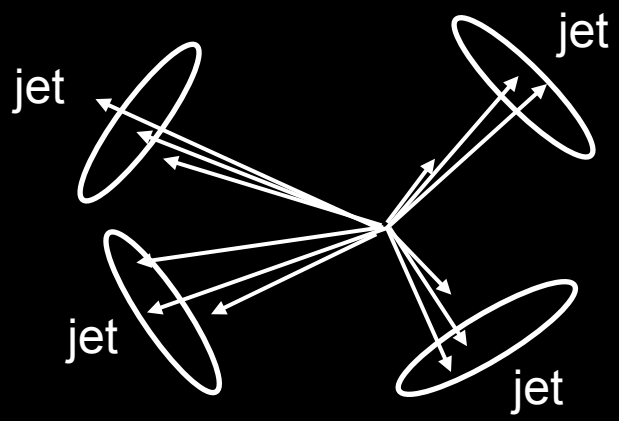
Baryon # Violating Stop LSP



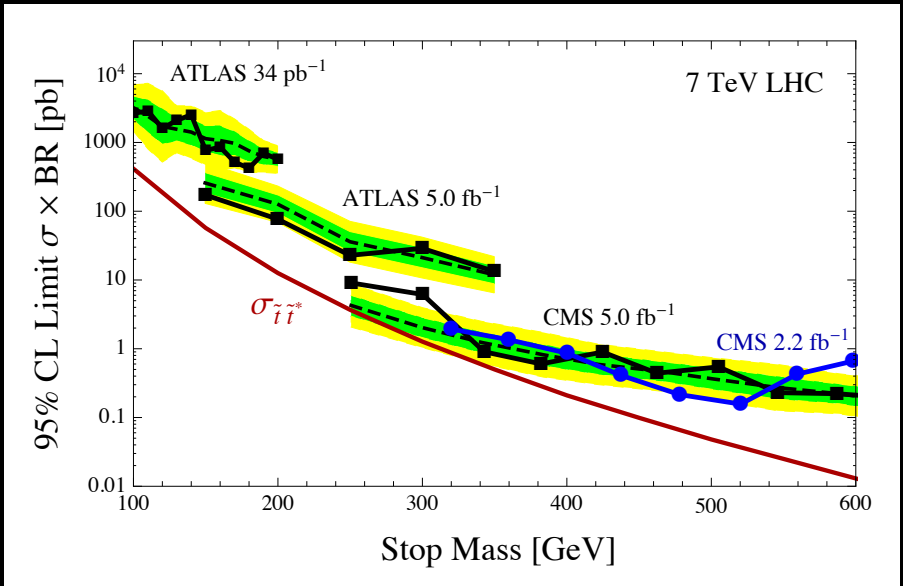
- Baryonic R-parity violation
  - $\lambda''_{3ij}\, \tilde{t}_R\, d_R^i\, d_R^j \quad (i \neq j)$
- 100% decays to 2 down-type quarks
  - prompt if $\lambda'' > 10^{-7}$
  - MFV: 96% bottom + down/strange
- Direct pair production ⇒ fully jetty final-state
  - no handles like leptons or MET

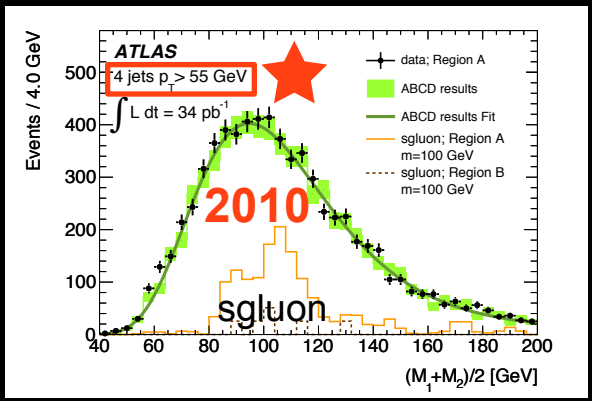
Pursuing Direct Production

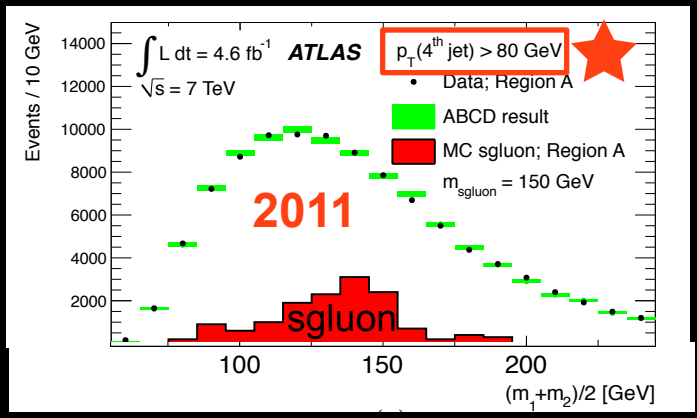
- Minimal model-dependence
  - rate/kinematics depend only on mass
  - inclusive analysis ignores jet flavor (structure of λ'')
  - not necessarily SUSY (generic triplet diquark)
  - but still assuming prompt decays
- Benchmark for QCD pair-produced NP searches
  - minimal color, spin, # decay products, flavor
- Current limits are weak (less than m_{top}!)
  - LEP: 90 GeV
  - Tevatron: 100 GeV
  - LHC: No limit!



Trigger Creep at the LHC





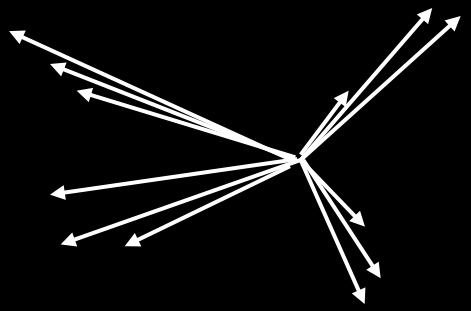


2012 ??

4j EF trigger:
$p_T(j_4)$ > 80
(~100 offline?)

minimum possible mass ~ $p_T \times R$ ~ 26 GeV (2010), 40 GeV (2011), 50 GeV? (2012), ???? (2015)


Jet Substructure



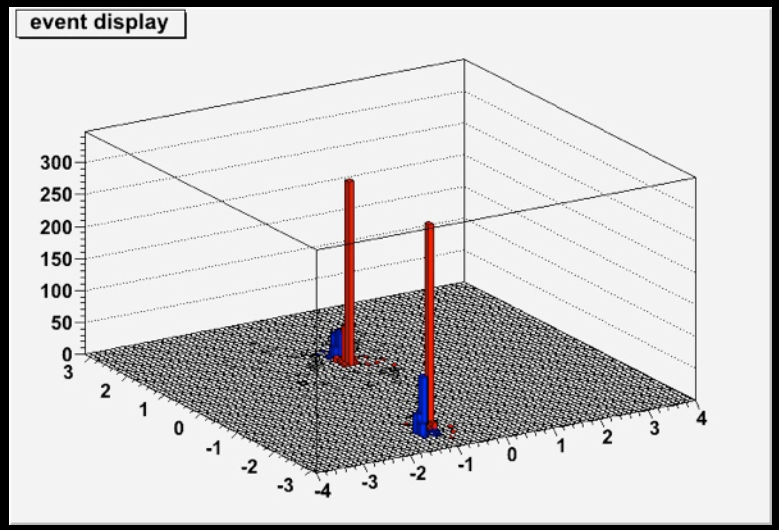
Why Jet Substructure?

- Focus on high-p_T “boosted” signal production
  - less combinatoric ambiguity
  - better S/B
- Flexible partition of decay radiation to individual “quarks”
  - better rejection of pileup, etc
  - better mass resolution
- Nearly scale-free procedure
  - bypass “4-jet” division of phase space, 4j trigger thresholds
  - background processed into “featureless” spectrum

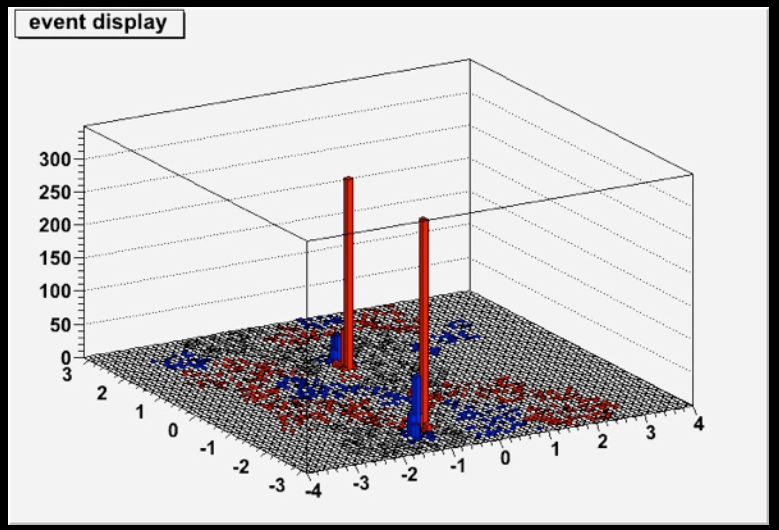
Basic Ingredients

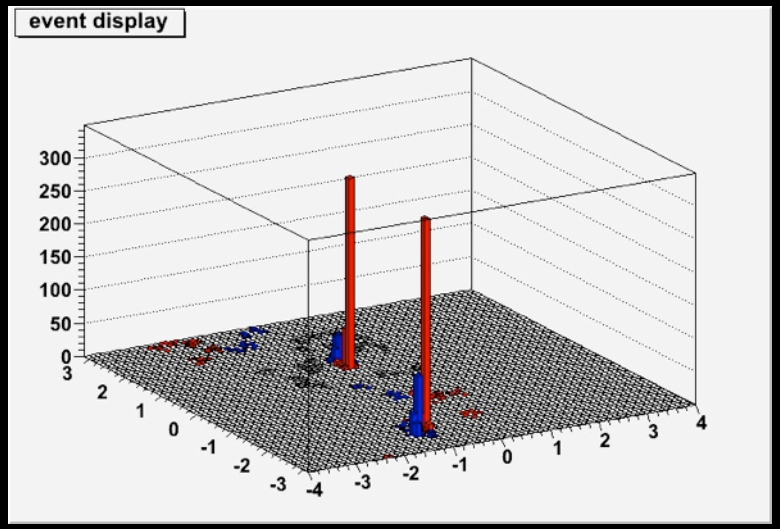
- Jet-H_T trigger: offline $H_T > 900$
- Pre-trim event to remove pileup
  - *Fixed* minijet p_T threshold, tuned to remove $\langle N_{PV} \rangle \sim 20$
- Capture stop decays in $R \sim \pi/2$ fat-jets
  - maximize mass reach, minimize steepness of BG
- Decluster into subjets using BDRS-like prescription
  - relative-p_T measure
  - extra demand on m/p_T of softer cluster
- Impose kinematic cuts, run a bump-hunt over $(m_1+m_2)/2$

Example Event, m(stop) = 100



+ pileup



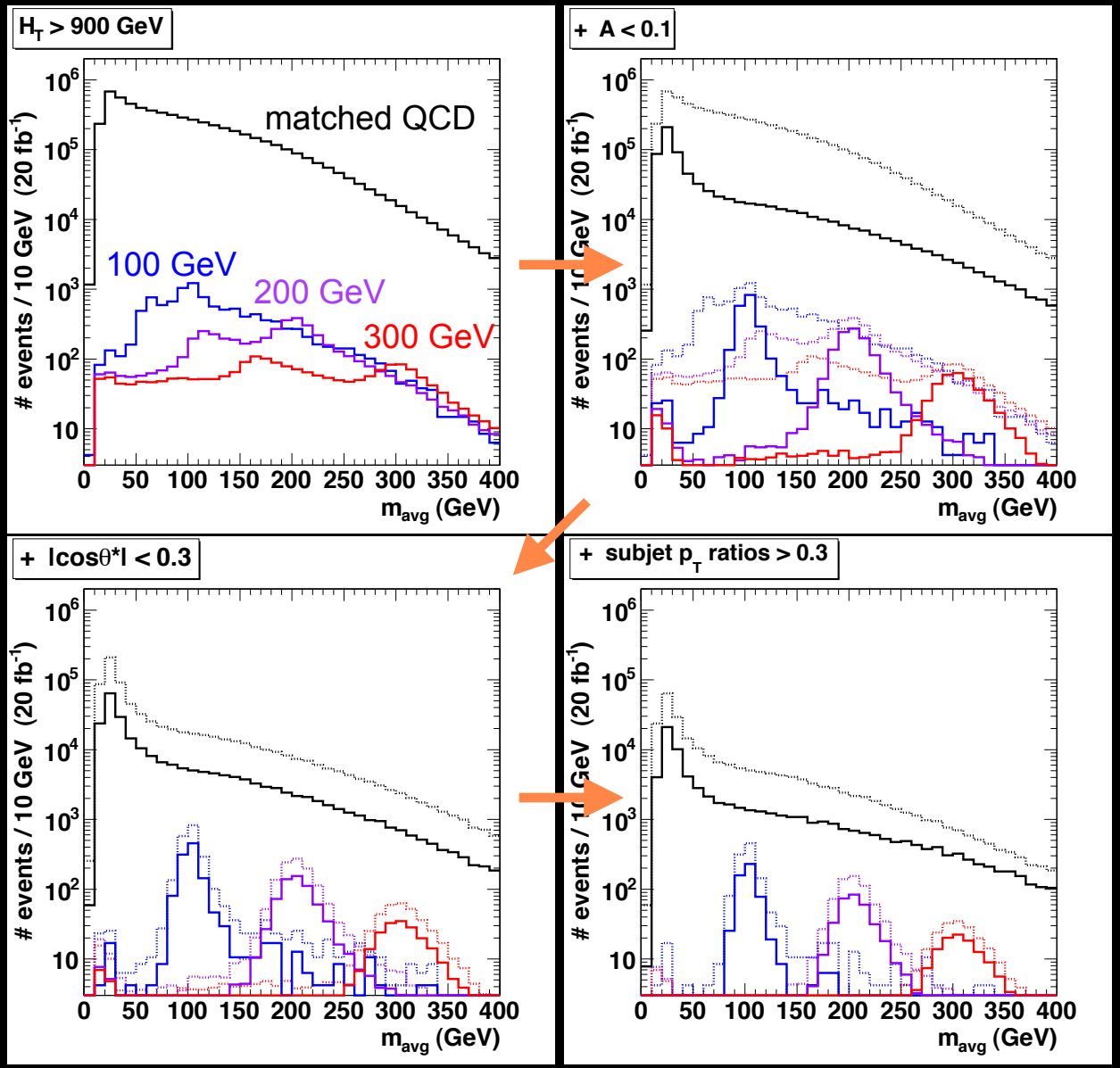


+ trimming

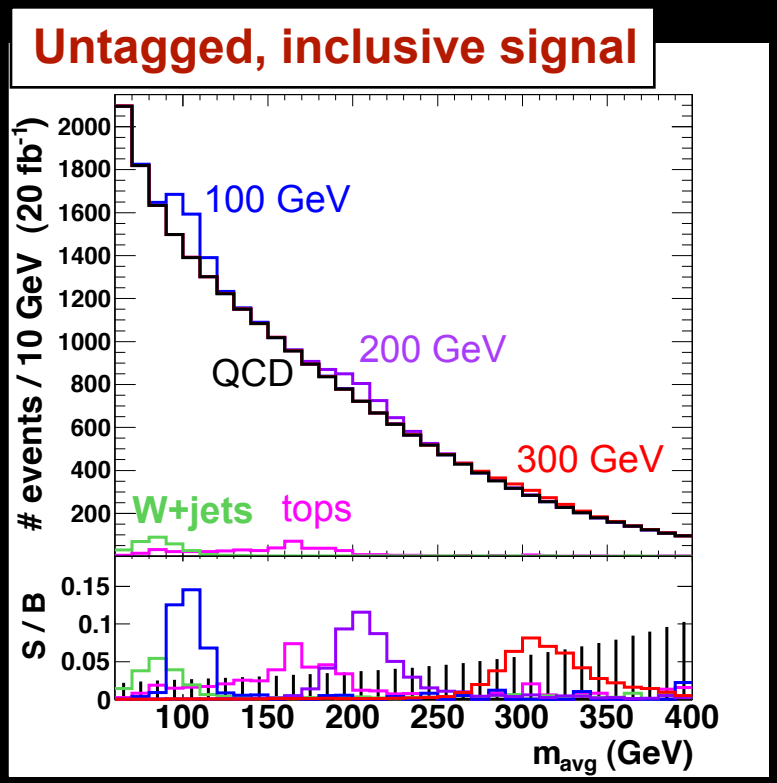
* 0.1 x 0.1 "calorimeter"

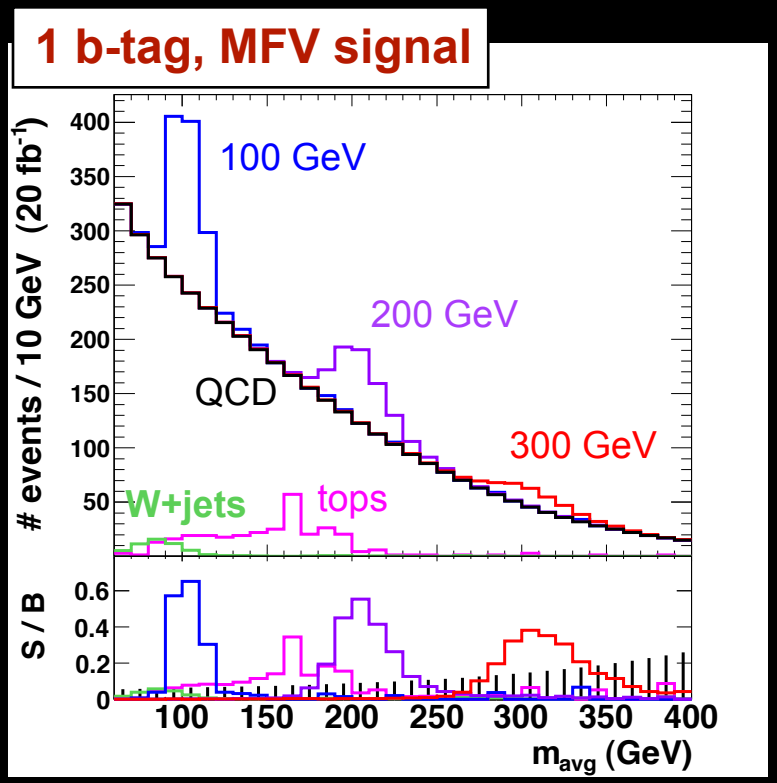
Cut Flow (Untagged)

* 8 TeV
20/fb



Average-Mass Spectra





**Be careful of top background!

QCD Estimation 4-Ways

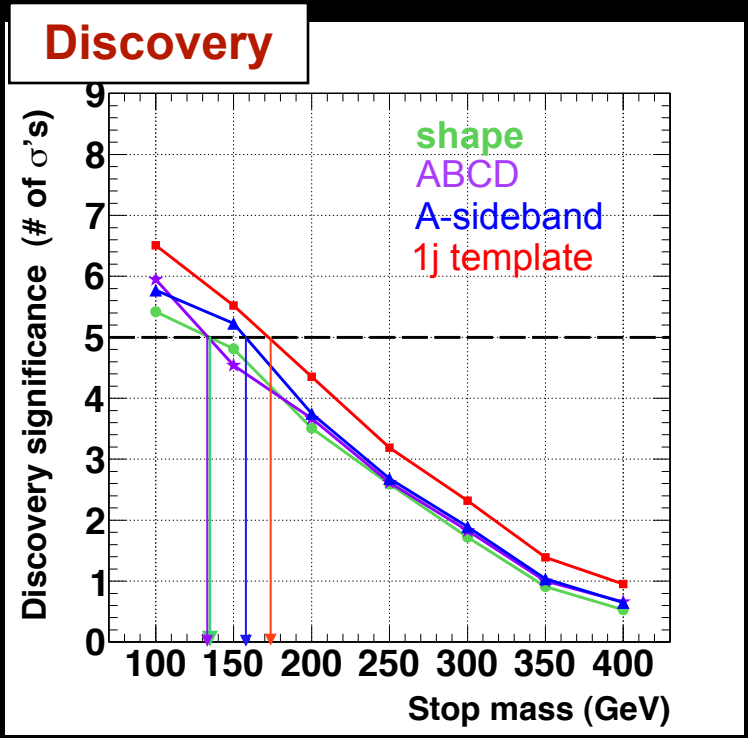
- Smooth function fit (CMS style)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{\mathrm{avg}}} = \frac{P_0(1 - m_{\mathrm{avg}}/\sqrt{s})^{P_1}}{(m_{\mathrm{avg}}/\sqrt{s})^{P_2 + P_3 \ln(m_{\mathrm{avg}}/\sqrt{s})}}$$

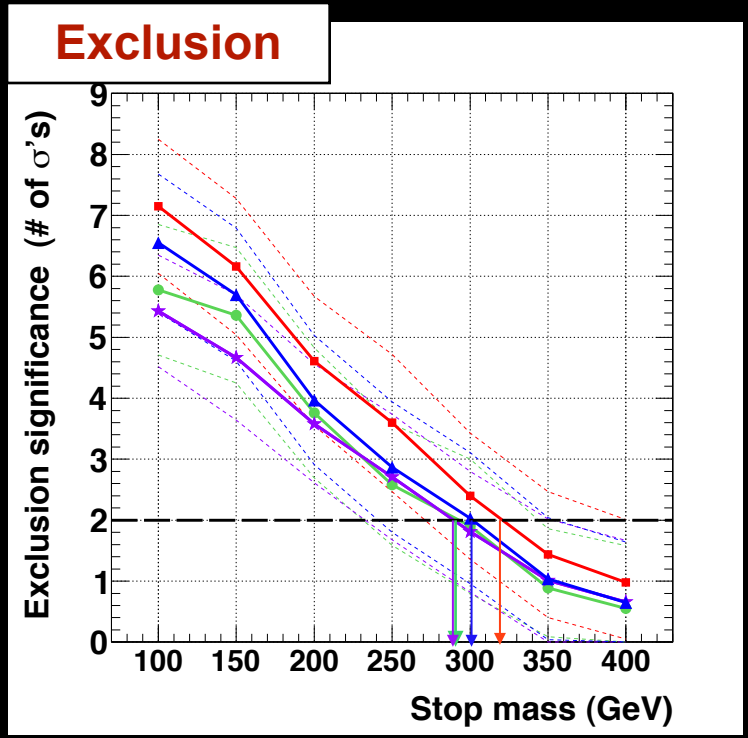
(+ signal bump)

- ABCD (ATLAS style)
  - control regions defined in asym and CM angle
  - signal-region spectrum derived bin-by-bin
- Asymmetry sideband
  - primitive 2D fit over m_{avg} and asym ($\Leftrightarrow$ m_1m_2-plane)
- Jet-mass template
  - derive m_{avg} spectrum from spectra of individual fat-jets
  - control region with ~infinite statistics

2012 Sensitivities, Inclusive



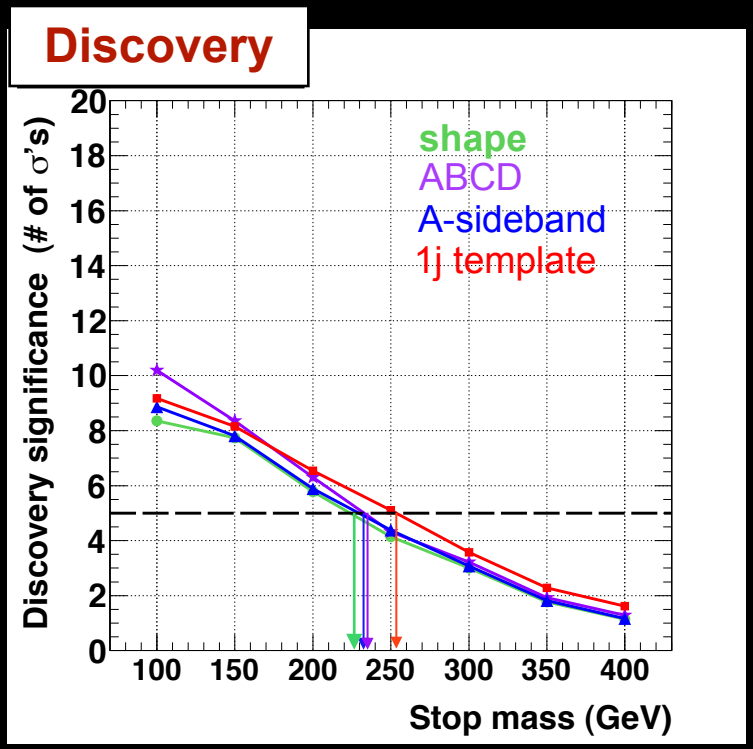
discover ~150 GeV



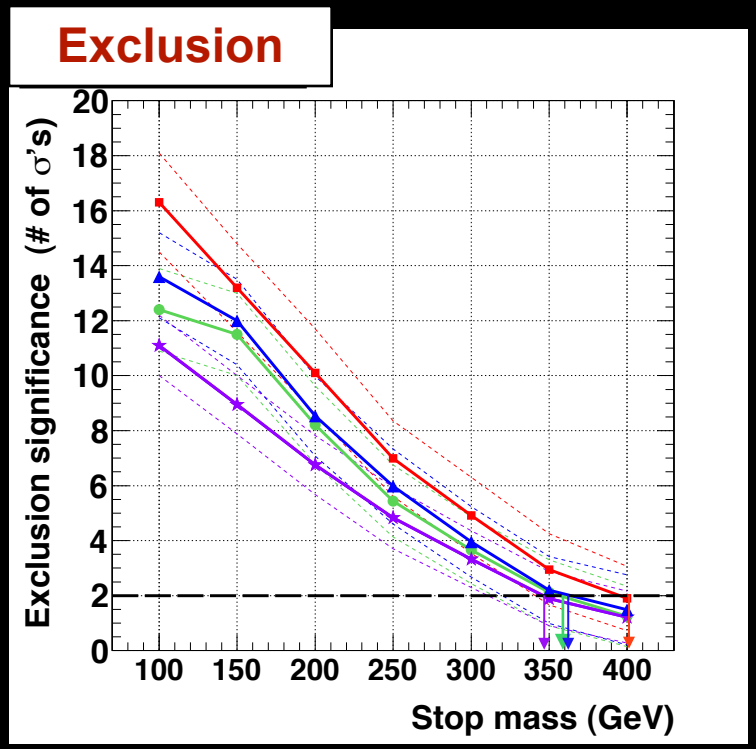
exclude ~300 GeV

*$\Delta\chi^2$ discriminator, Statistical errors ONLY

2012 Sensitivities, b-Tagged



discover ~250 GeV



exclude 350~400 GeV

* $\Delta\chi^2$ discriminator, Statistical errors ONLY (*Not* re-optimized for b-tag)

Summary (RPV Stops)

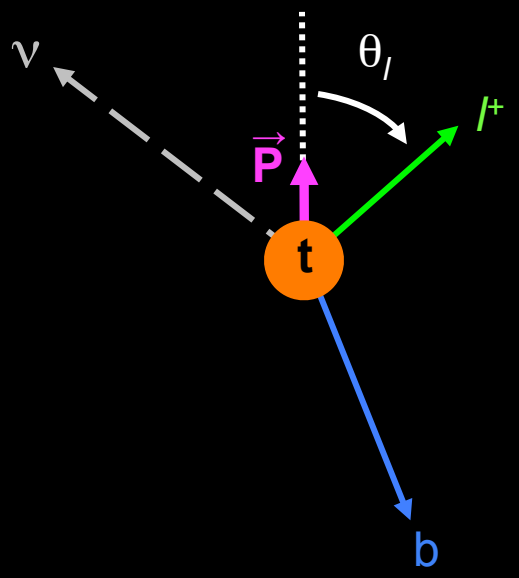
- LHC is sensitive to stop pair-production even when the stop is light and promptly decays to jets
  - trigger on H_T, substructure event reconstruction
  - inclusive m~100 GeV signal may be *discoverable* at 8 TeV
    - (similar conclusion at 7 TeV with looser triggers)
  - inclusive exclusion up to 300 GeV
  - b-tagged MFV exclusion (discovery) ~ 250 (400)
  - continues to work at LHC14 (H_T ~ 1500), mass reach roughly doubles

$$Q^{\alpha}[\mathrm{stop}] = [\mathrm{top}]^{\alpha}$$

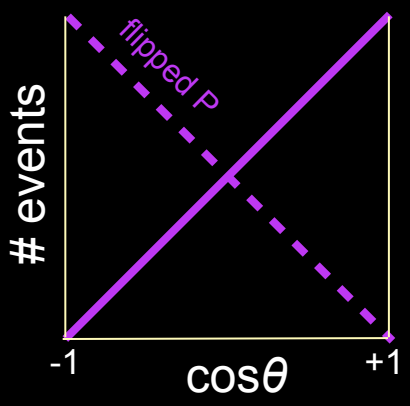
Why Measure Top Quark Spin?

- Characterize new particle production
  - stops (RPC) & other top-partners
  - top-antitop resonances
- Scan continuum for new interactions
  - broad resonances
  - higher-dimension operators (4-quark contact, color-dipoles)
- Test weak decay

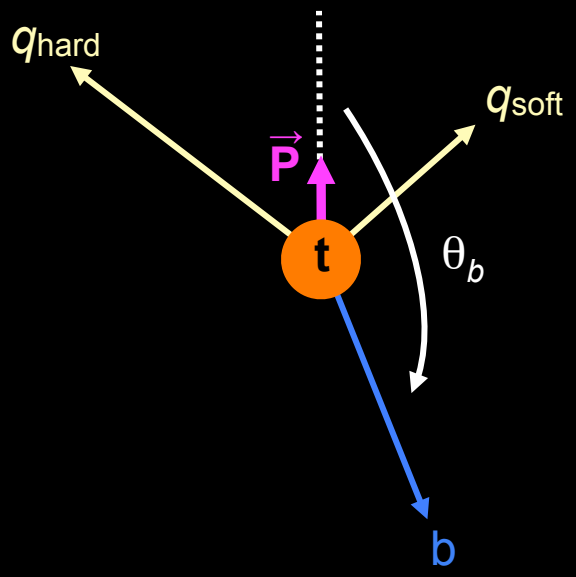
Analyzing the Spin...



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + \mathbf{1.0}\ \cos\theta\ )$$

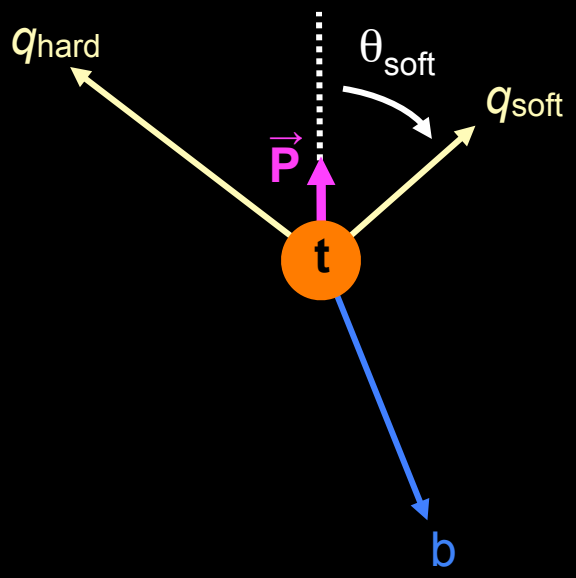


Analyzing the Spin...With Jets



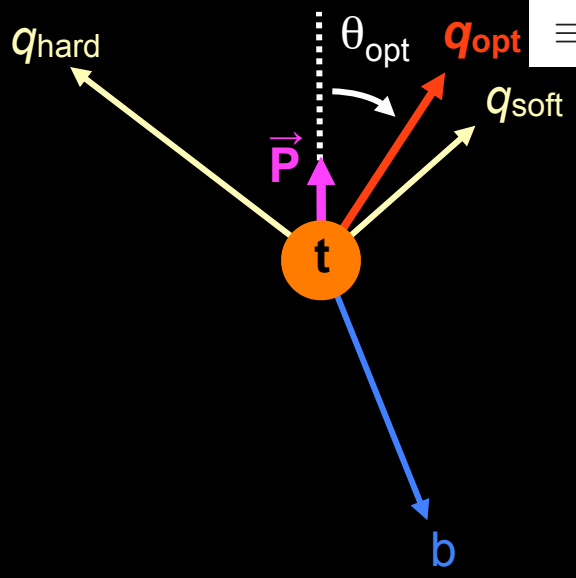
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + \textbf{-0.4}\cos\theta\ )$$

Analyzing the Spin...With Jets



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + \mathbf{0.5}\ \cos\theta\ )$$

The Optimal Hadronic Spin Analyzer



$$\equiv \; p(d \to q_{\text{soft}})\hat{q}_{\text{soft}} + p(d \to q_{\text{hard}})\hat{q}_{\text{hard}}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\left(1 + \mathbf{0.64}\,\cos\theta\;\right)$$

Case Study: Boosted Tops

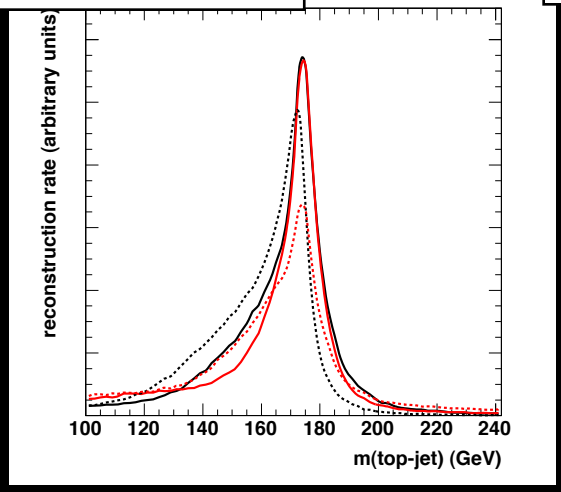
- 2.5 TeV spin-1 octet resonance
  - introduce different vector/axial mixtures
  - l+jets channel
- p_T(top) ~ 1 TeV
- R = 1.2 C/A fat-jets
- HEPTopTagger or JHU top-tagger
  - default and modified algorithms

* see also Bhattacherjee, Mandal, Nojiri, 1211.7261

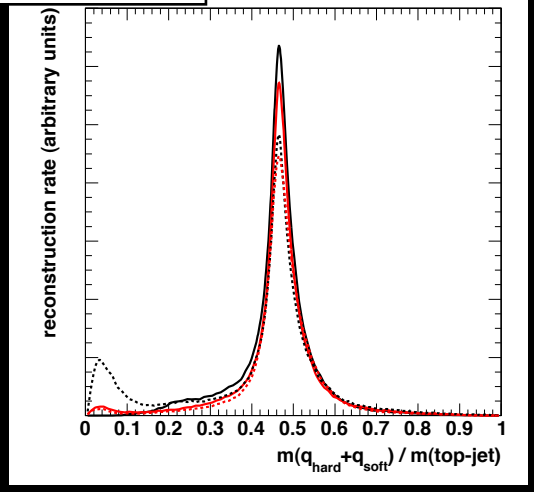
Default vs Modified (Loose Cuts)

JHU
HEP

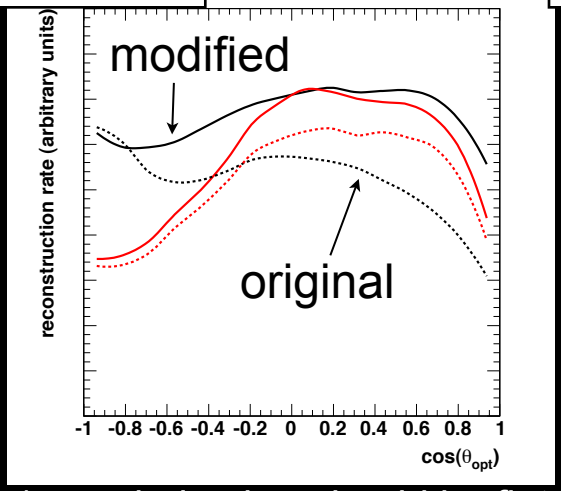
top-jet mass



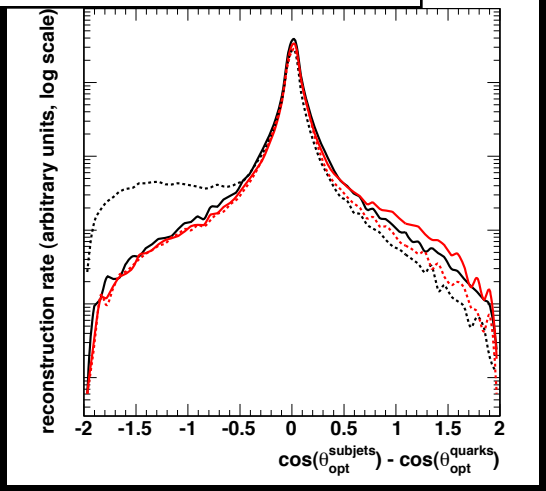
W mass



cosθ_{opt}



cosθ_{opt} accuracy



* unpolarized ⇒ should be flat

particle-level
perfect b-tag
no pileup

Suggested Modifications

HEP

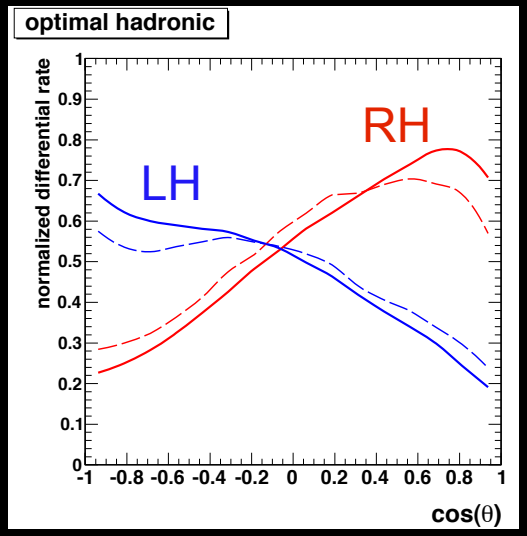
- eliminate mass-drop criterion
- consider only hardest 4 subjets
- do not filter, do not recluster

JHU

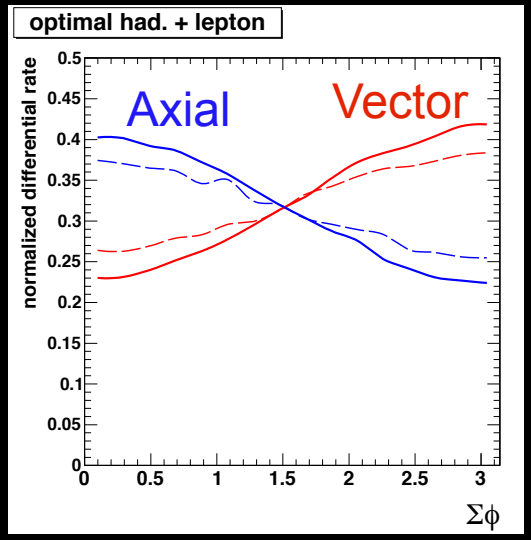
- eliminate δ_r parameter
- if 4 subjets, undo smaller-mass stage-two declustering
- also consider HEP-like “best top” combination of 3 subjets

Efficiencies and analyzing powers both *improve* 10~25%
With basic mass-windows, final efficiencies 70~80%

Performance (Modified HEP)



polar decay angle



azimuthal decay correlation

	(optimistic) Particle-Level			(pessimistic) Calorimeter-Level			
Spin Analyzer	b-tag	binary W	$\sum W$	b-tag	binary W	$\sum W$	parton-level
optimal hadronic	0.565	0.471	0.489	0.529	0.400	0.425	0.64
soft-quark	0.442	0.430	0.430	0.411	0.385	0.385	0.50
b-quark	0.400	0.272	0.345	0.390	0.217	0.319	0.40
lepton	0.870			0.834			1.00

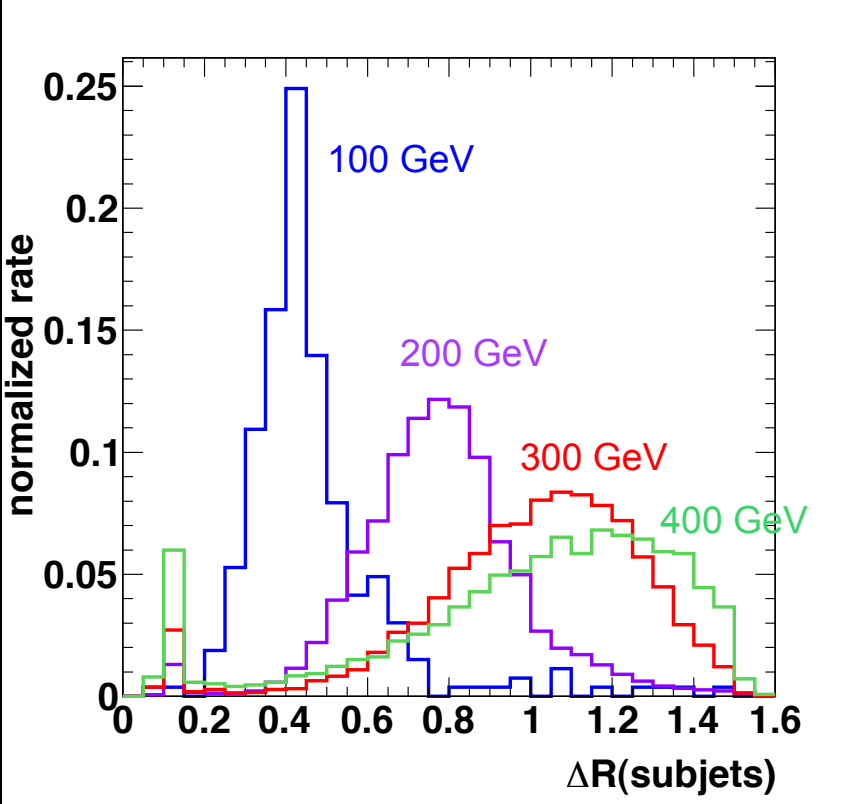
* Effective analyzing powers

Summary (Top Spin)

- An optimal hadronic spin analyzer exists...you should use it
  - power = 0.64 at parton-level (next-best option 0.5)
  - relative improvement can survive reconstruction
  - some kind of b-tag is very helpful
- Existing jet substructure methods aren't necessarily optimized to preserve spin information
  - small algorithm modifications, looser internal cuts improve total efficiency and reduce bias
  - keeping (relative) p_T cuts low would be ideal

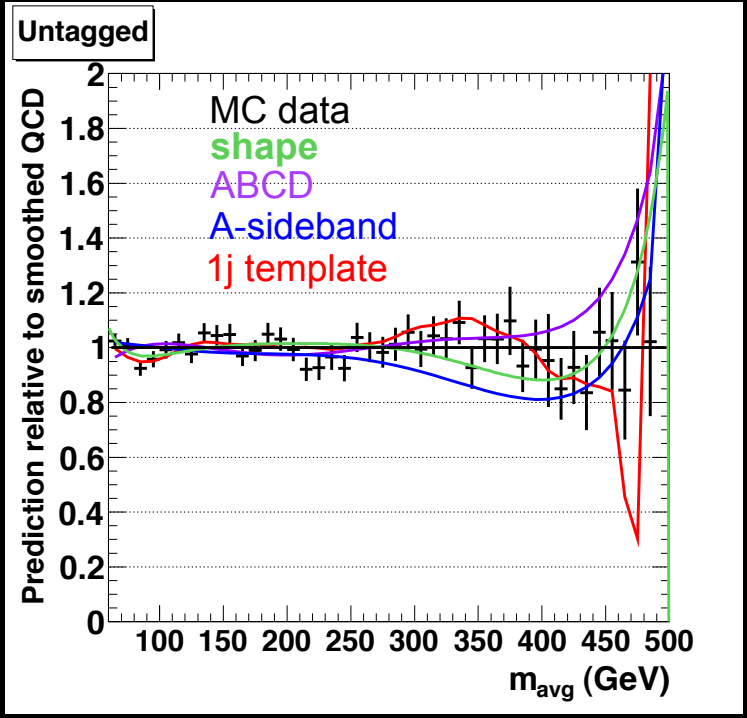
More…

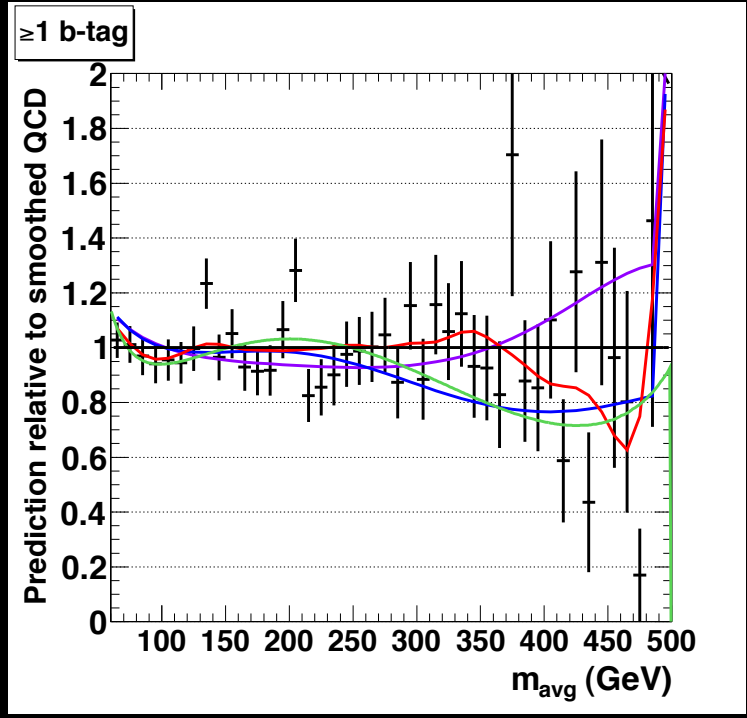
ΔR Distributions



*Passing all analysis cuts

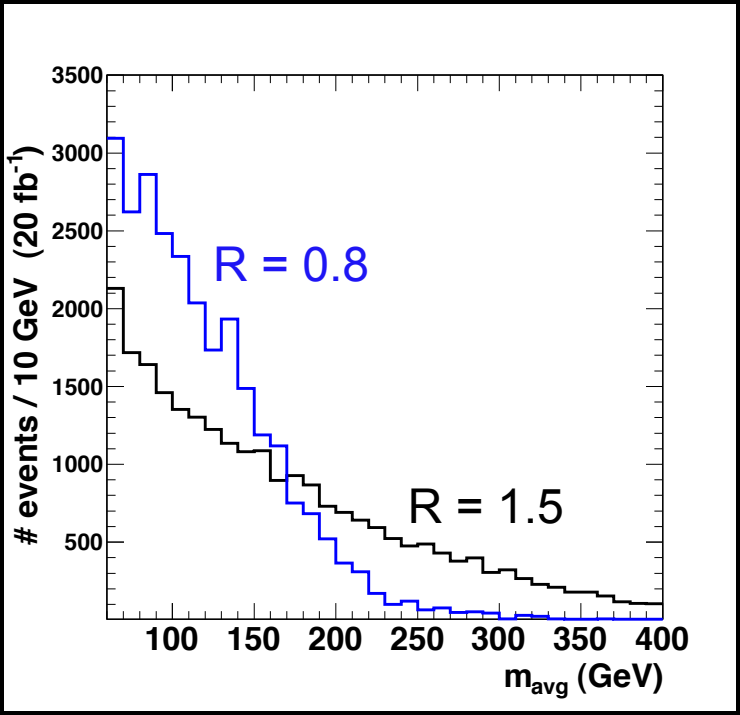
Performance of "Data-Driven" QCD Estimators





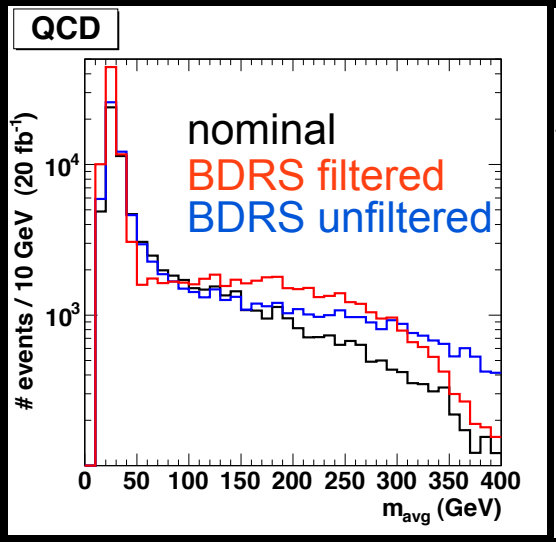
* Error bars are MC statistics (effective lumi ~ 20/fb)

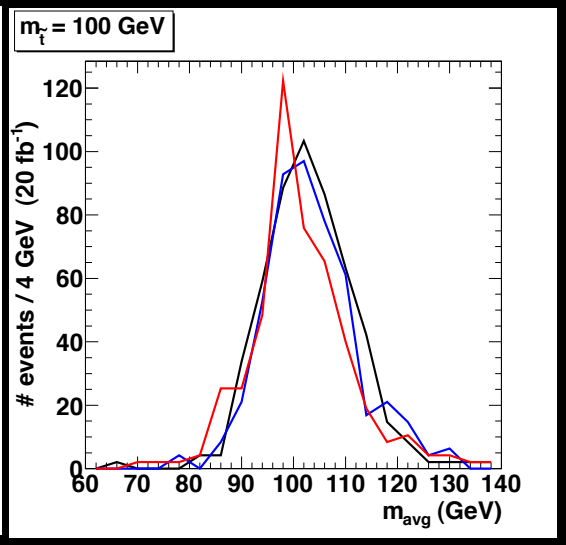
Smaller Fat-Jets?

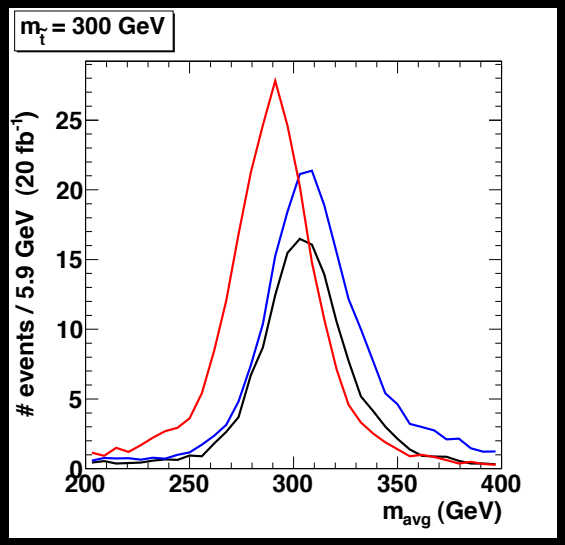


- ~2x steeper background
- 100 GeV signal acceptance up 30%, with slightly smaller S/B and slightly larger S/√B
- Higher-mass stop acceptances radically degrade

Vs BDRS

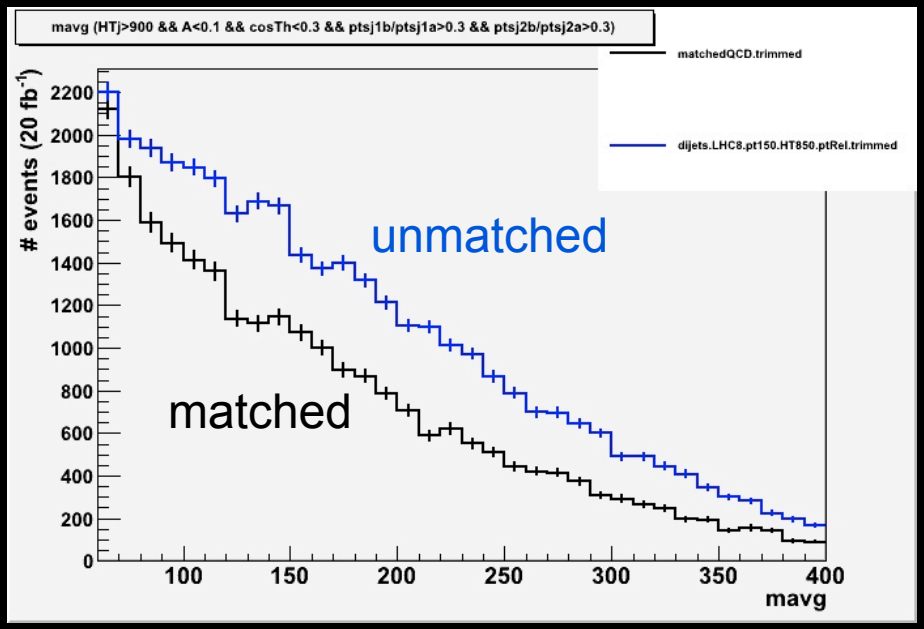






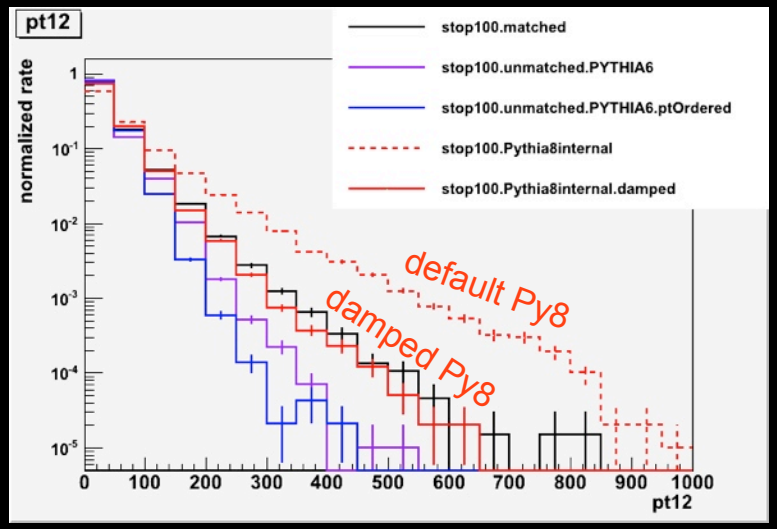
- Takeaway points
  - Traditional filtering is a bad idea (introduces mass scales via maximum R=0.3 for subjets)
  - Otherwise, the *major* difference w.r.t. BDRS is that our subjet m/p_T criterion gives more consistent slope and suppresses the tail
  - Unfiltered BDRS mass-asymmetry control region becomes less reliable; ABCD still looks okay; shape is trickier with default formula; 1j template, not sure...

Matched Vs Unmatched QCD

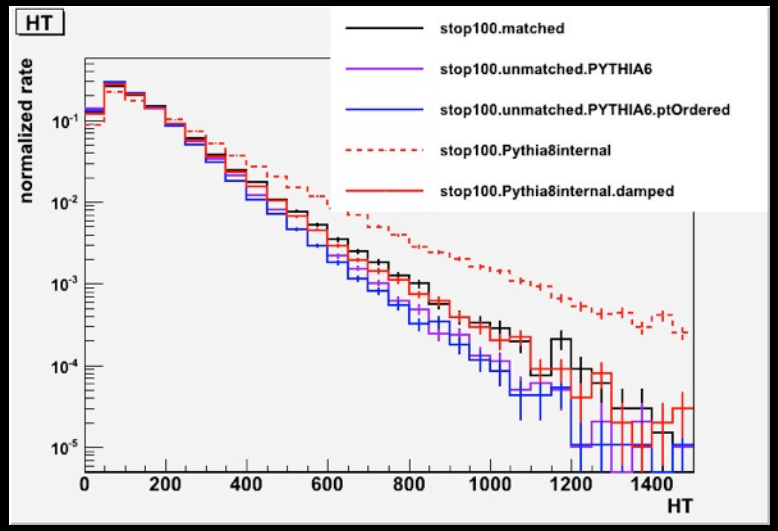


* Both approaches show good agreement with traditional 4j analysis

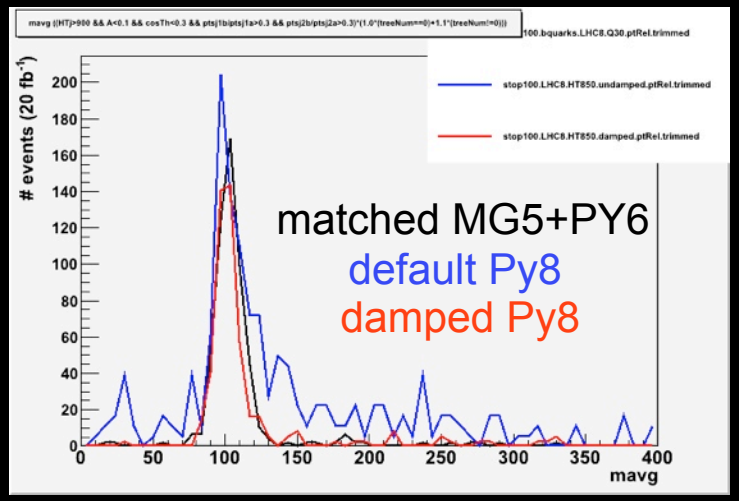
Lessons on Signal Showering



p_T(stop1+stop2)



p_T(stop1) + p_T(stop2) + Σp_T(j)



Optimal Analyzer Vs...