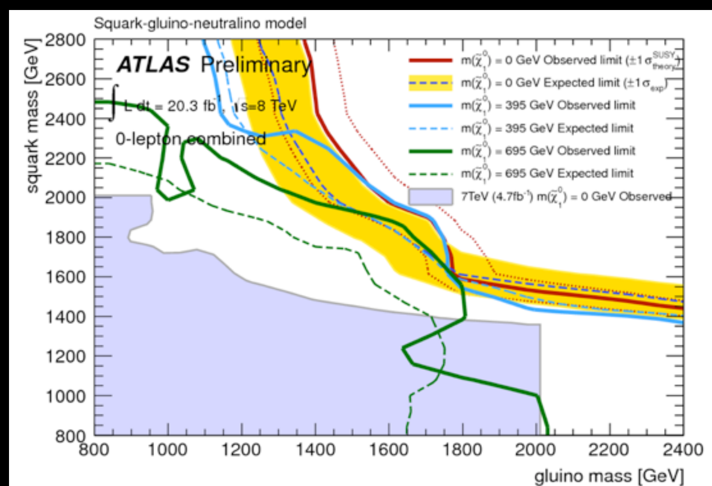
Pulling Out All the Stops

Brock Tweedie
PITT PACC, University of Pittsburgh
@ Rutgers
22 April 2014

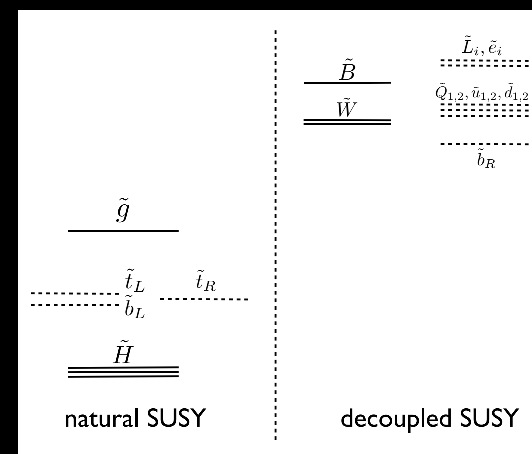
* Bai, Katz, Tweedie (1309.6631)
Han, Katz, Son, Tweedie (1211.4025)
Liu & Tweedie (1405.XXXX)

Motivation

+



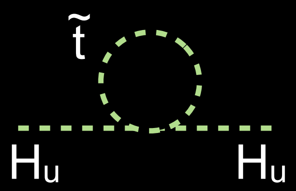
⇒



?

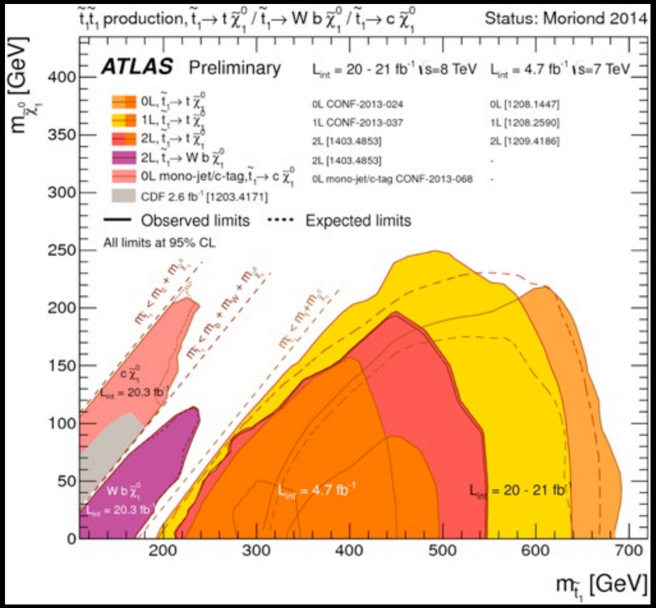
Dimopolous & Giudice (hep-ph/9507282)
Cohen, Kaplan, Nelson (hep-ph/9607394)
Kats, Meade, Reece, Shih (1110.6444)
Brust, Katz, Lawrence, Sundrum (1110.6670)
Papucci, Ruderman, Weiler (1110.6926)
.....

Motivation



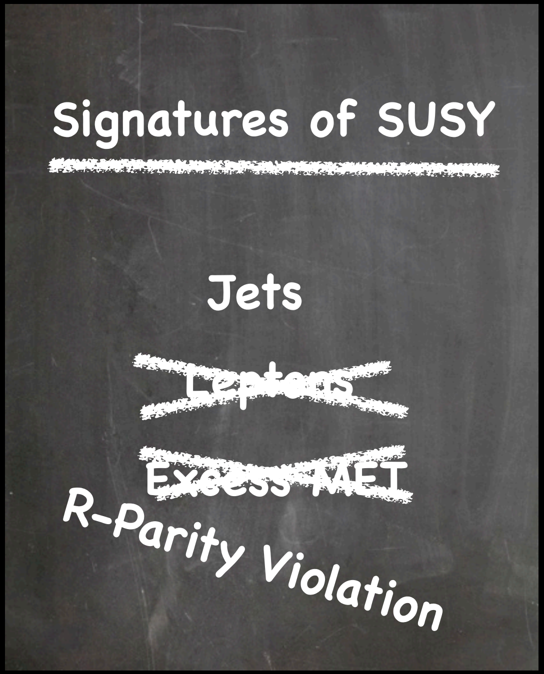
$\tilde{t}$
H_u
H_u

+



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$ / $\tilde{t}_1 \to W\,b\,\tilde{\chi}^0_1$ / $\tilde{t}_1 \to c\,\tilde{\chi}^0_1$
Status: Moriond 2014
ATLAS Preliminary
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$
1L, $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$
2L, $\tilde{t}_1 \to t\,\tilde{\chi}^0_1$
2L, $\tilde{t}_1 \to W\,b\,\tilde{\chi}^0_1$
0L mono-jet/c-tag, $\tilde{t}_1 \to c\,\tilde{\chi}^0_1$
CDF 2.6 fb^{-1} [1203.4171]
0L CONF-2013-024
1L CONF-2013-037
2L [1403.4853]
2L [1403.4853]
0L mono-jet/c-tag CONF-2013-068
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
Observed limits
Expected limits
All limits at 95% CL
$c\,\tilde{\chi}^0_1$
L_{int} = 20.3 fb^{-1}
$W\,b\,\tilde{\chi}^0_1$
L_{int} = 20.3 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 20 - 21 fb^{-1}
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

⇒



Signatures of SUSY
Jets
~~Leptons~~
~~Excess MET~~
R-Parity Violation

?

Implications of RPV

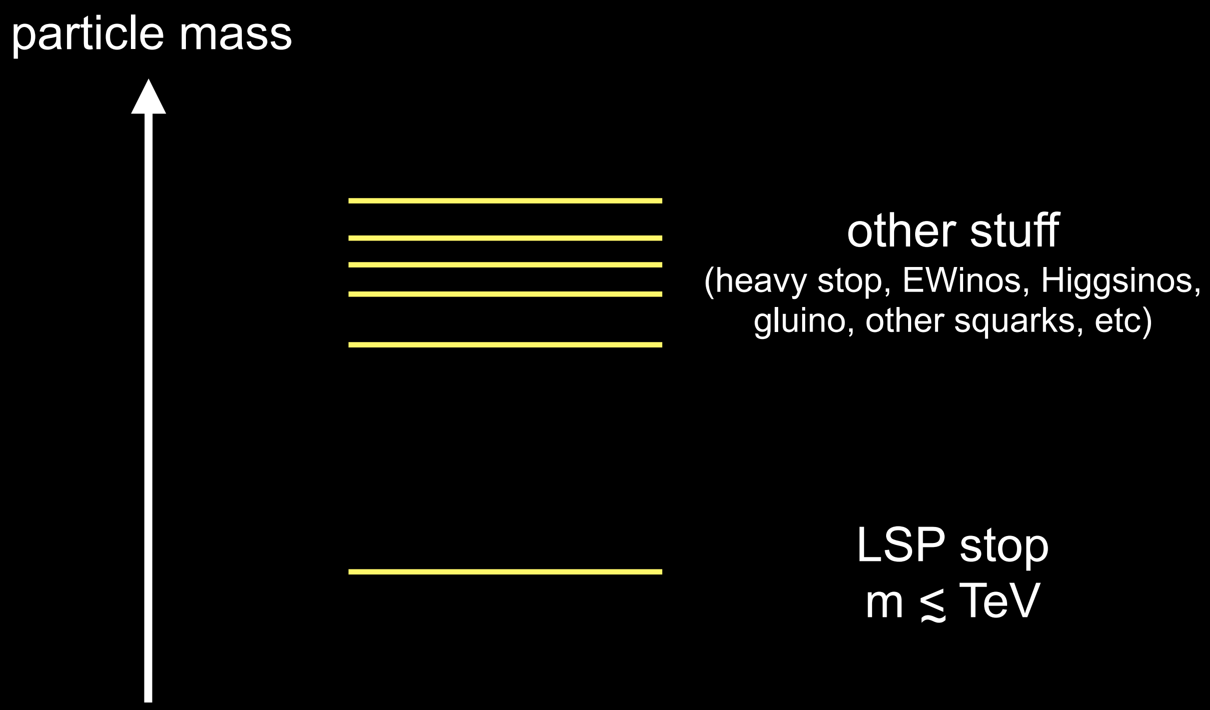
All decay chains end in jets

$$\begin{aligned} W_{\Delta \mathrm{L}=1} &= \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^{i} L_i H_u \\ W_{\Delta \mathrm{B}=1} &= \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k \end{aligned}$$

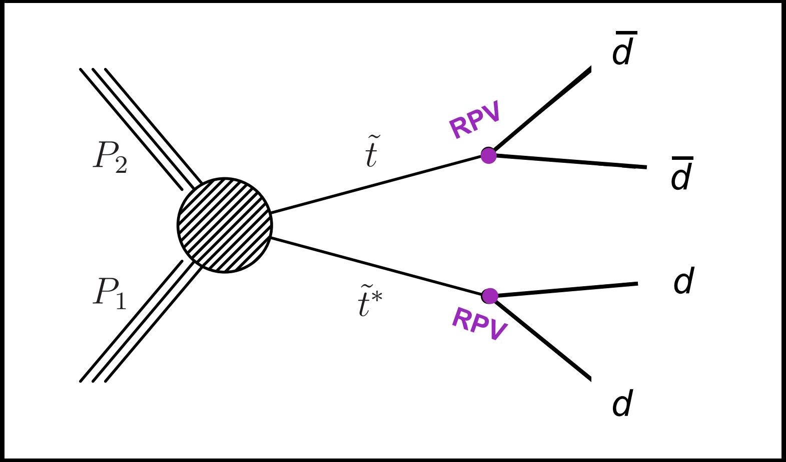
+ soft terms + Kähler terms

- ΔL or ΔB, not both simultaneously
- If active, LSP is unstable
  - anybody can be the LSP
  - lose dark matter
  - gain a "rich" set of new SUSY signals at colliders
- Contingent on limits from direct searches, rare processes
  - often depend sensitively on detailed spectrum/mixings
  - even tiny couplings can yield prompt decays

Stop on the Bottom

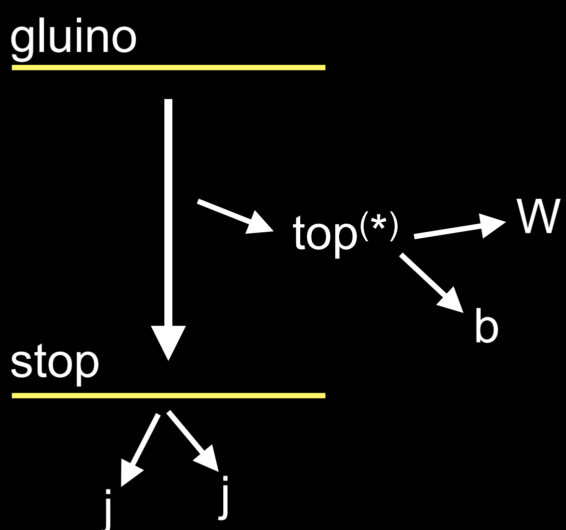


Baryon # Violating Stop Decay



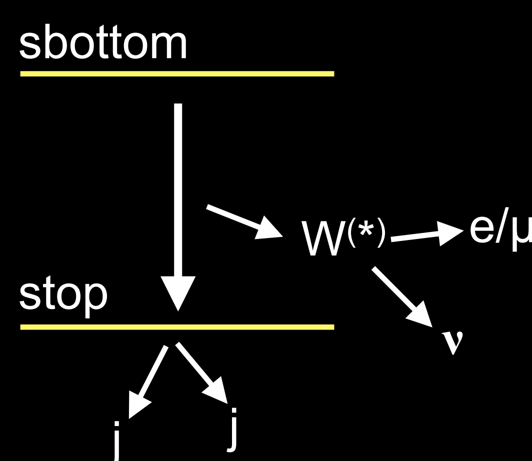
- 100% decays to 2 down-type quarks
  - prompt if λ'' > 10^{-7}
  - non-identical flavors: ds / db / sb
  - if MFV, 96% contain bottom

Stop Production in Cascades



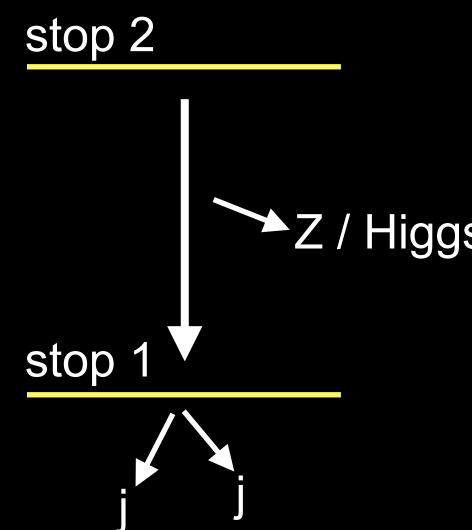
gluino pair to stops and tops

Lisanti, Schuster, Strassler, Toro (1107.5055)
Allanach & Gripaios (1202.6616)
Han, Katz, Son, Tweedie (1211.4025)
Berger, Perelstein, Saelim, Tanedo (1302.2146)
Evans, Kats, Shih, Strassler (1310.5758)
Bhattacherjee, Chakraborty (1311.5785)
ATLAS-CONF-2013-007
ATLAS (1308.1841)



sbottom pair to stops and leptonic $W^{(*)}$s

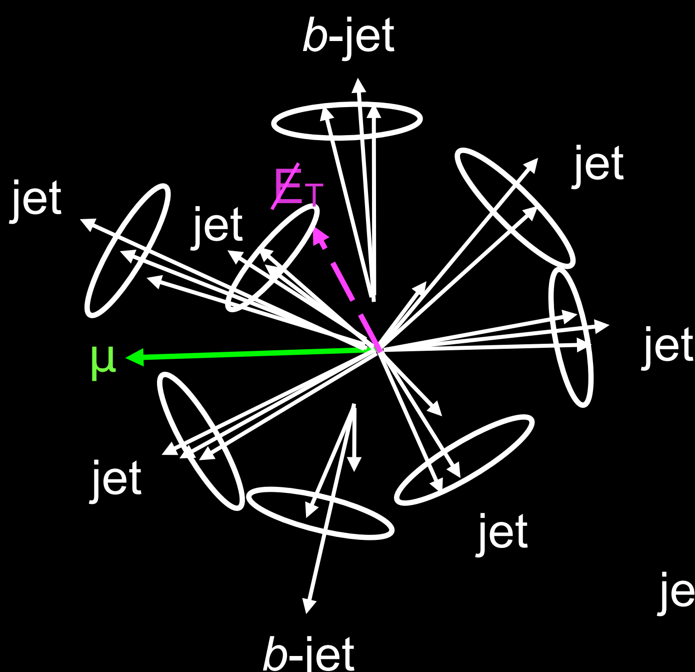
Brust, Katz, Sundrum (1206.2353)



heavy stop pair to stop+Higgs & stop+Z

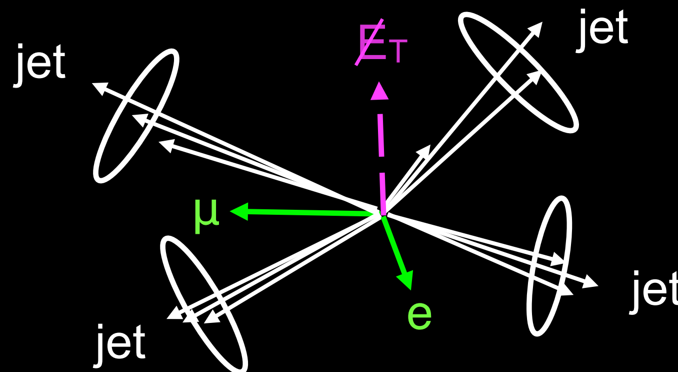
* Not studied in detail

Stop Production in Cascades



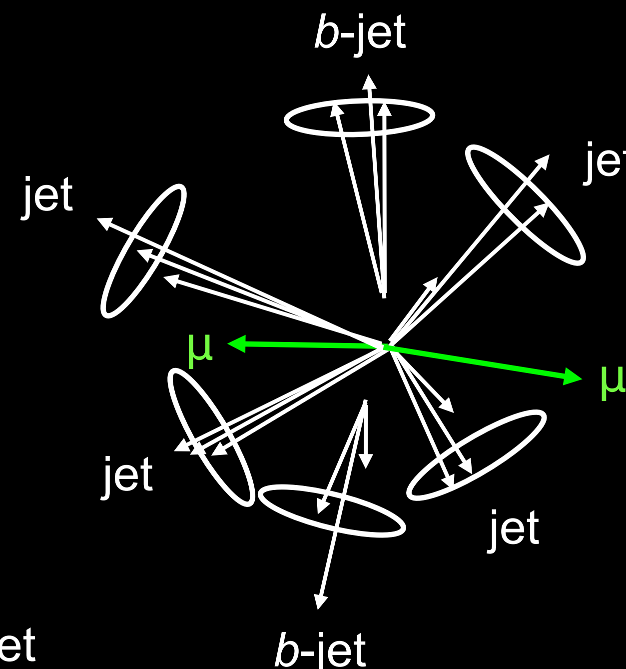
gluino pair to stops
and tops

Lisanti, Schuster, Strassler, Toro (1107.5055)
Allanach & Gripaios (1202.6616)
Han, Katz, Son, Tweedie (1211.4025)
Berger, Perelstein, Saelim, Tanedo (1302.2146)
Evans, Kats, Shih, Strassler (1310.5758)
Bhattacherjee, Chakraborty (1311.5785)
ATLAS-CONF-2013-007
ATLAS (1308.1841)



sbottom pair to stops
and leptonic $W^{(*)}$s

Brust, Katz, Sundrum (1206.2353)

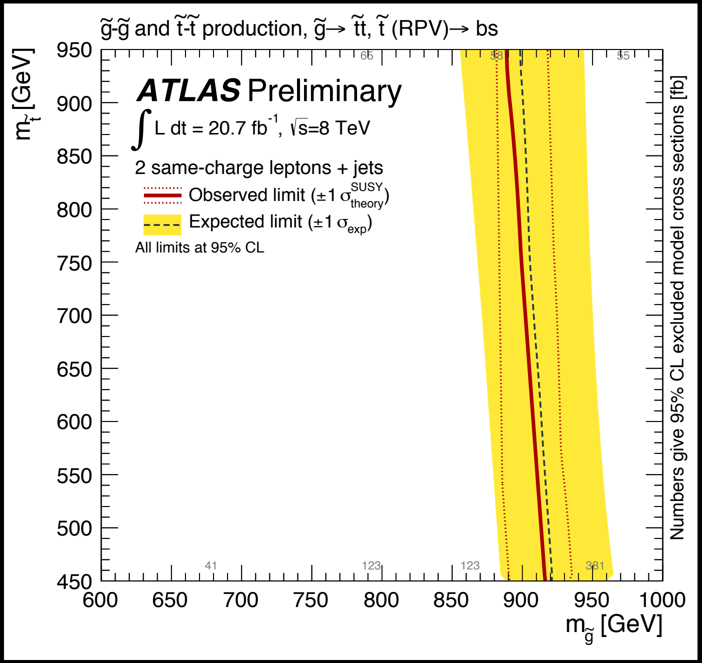


heavy stop pair to
stop+Higgs & stop+Z

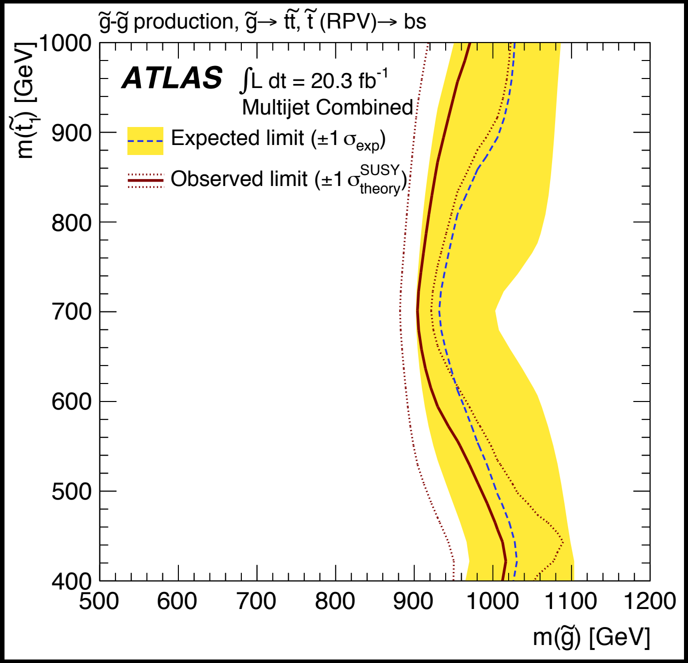
* Not studied in detail

ATLAS Exclusion via Gluinos

ATLAS CONF-2013-007
SS dilepton + (b-)jets



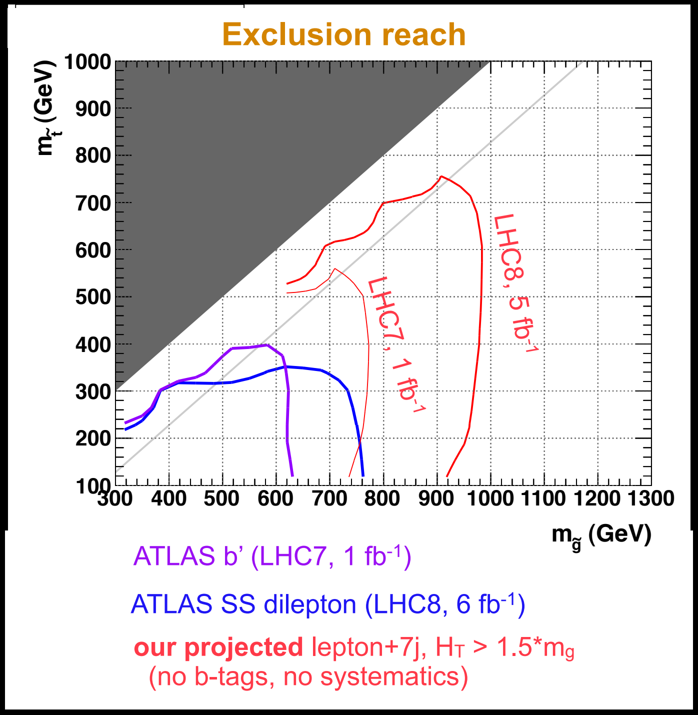
ATLAS (1308.1841)
multi-(b-)jets + MET



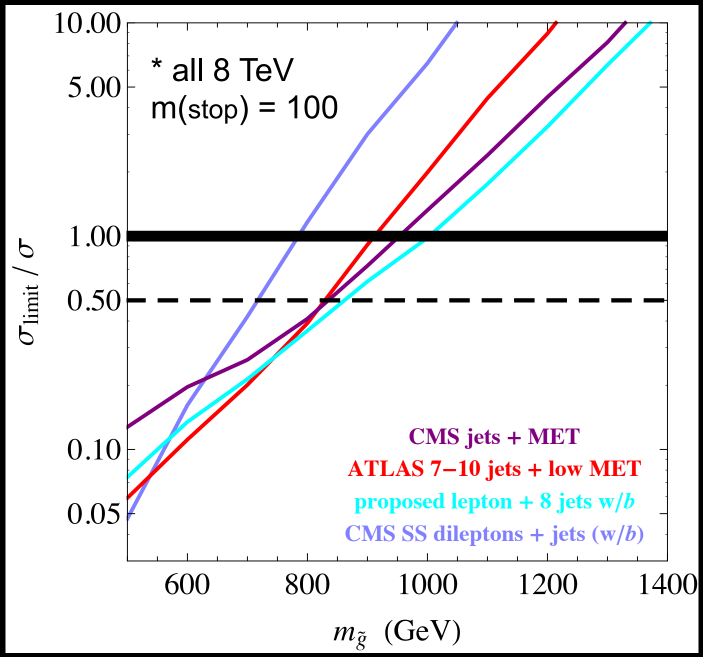
* Always decays to sb, λ'' ~ 1

Predicted / Recast Exclusions

Han, Katz, Son, Tweedie (1211.4025)



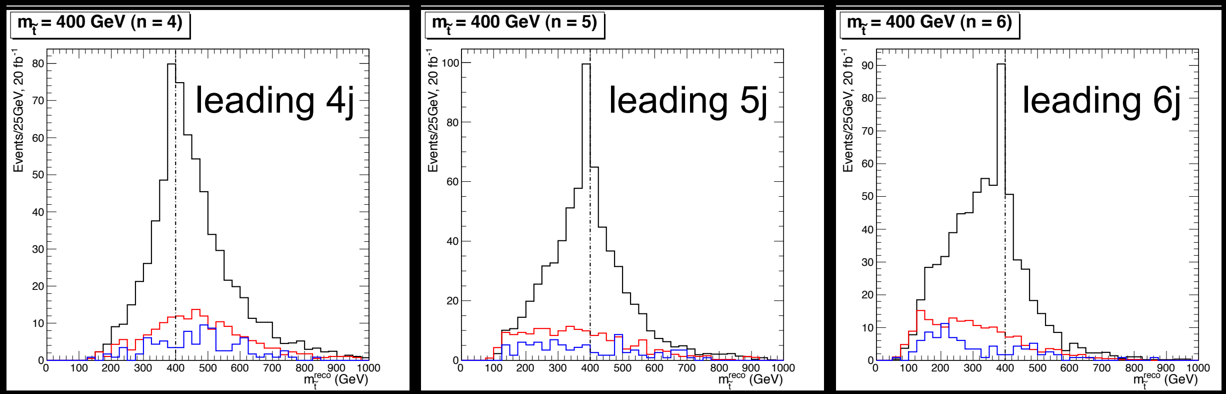
Evans, Kats, Shih, Strassler (1310.5758)



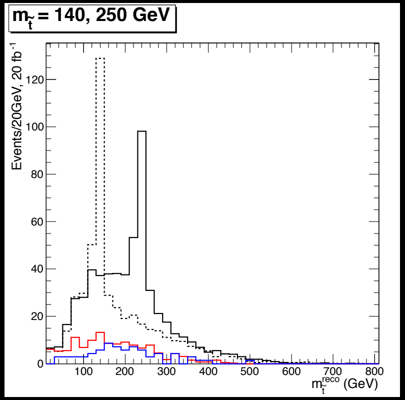
* No flavor assumptions, λ'' can be << 1

Going After the Stop Bump

m($\tilde{g}$) = 800
m($\tilde{t}$) = 400

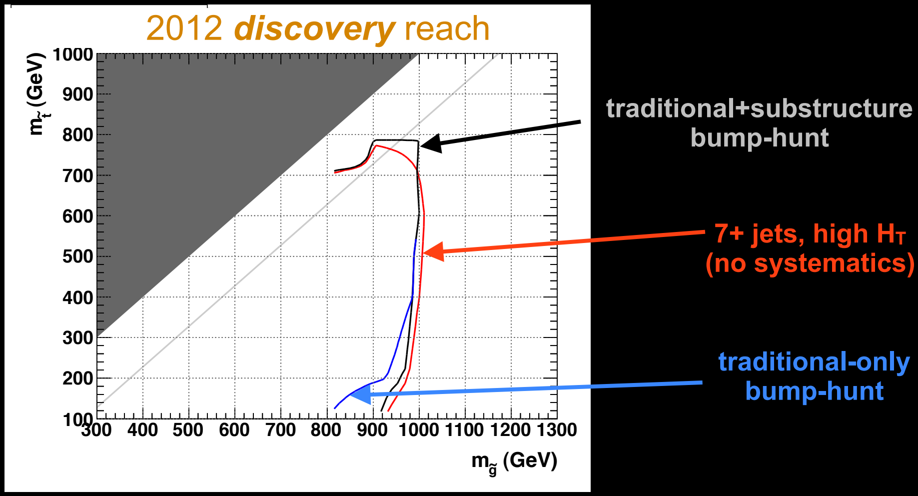


traditional jet reco: "best pair-of-pairs" amidst leading n jets (choose n carefully!)

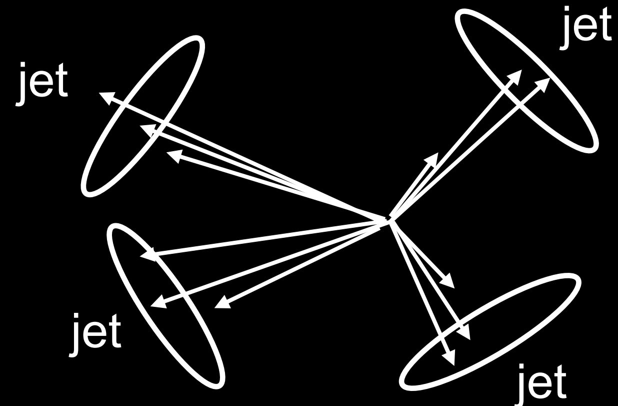


OR jet substructure reco:
highest-p_T fat-jet (after top-jet veto)

* Will be even more important at 13+ TeV



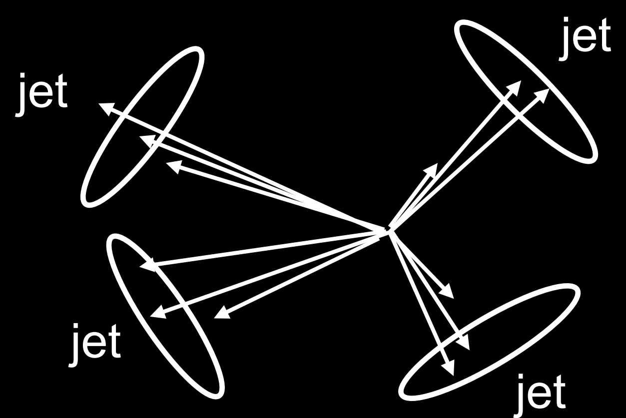
Direct Production



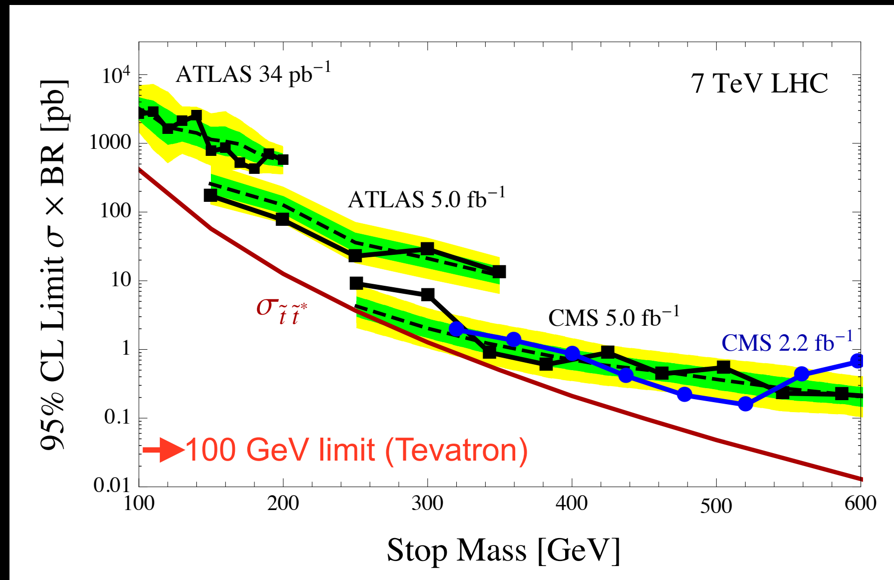
Franceschini & Torre (1212.3622)
Bai, Katz, Tweedie (1309.6631)

Pursuing Direct Production

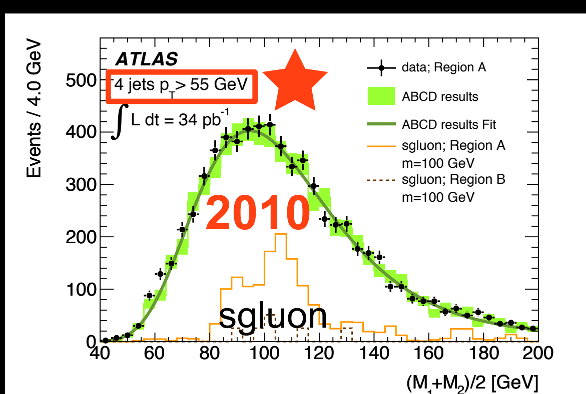
- Minimal model-dependence
  - rate/kinematics depend only on mass
  - inclusive analysis should ignore jet flavor (structure of λ'')
  - but still assuming prompt decays
- Benchmark for QCD pair-produced new physics searches
  - minimal color, spin, # decay products, flavor
  - not necessarily SUSY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

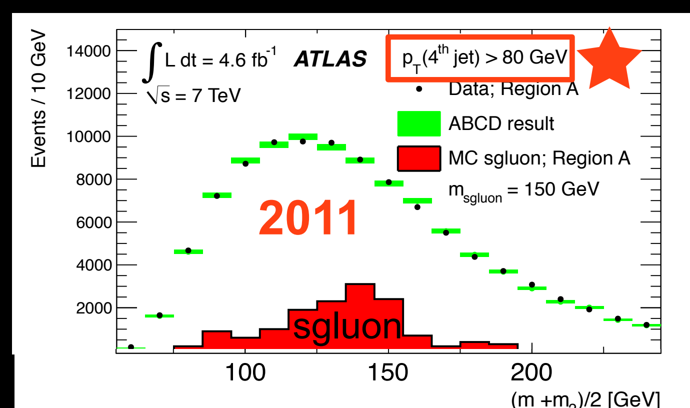


Trigger Creep at the LHC



* All searches to date are untagged
None use 8 TeV data

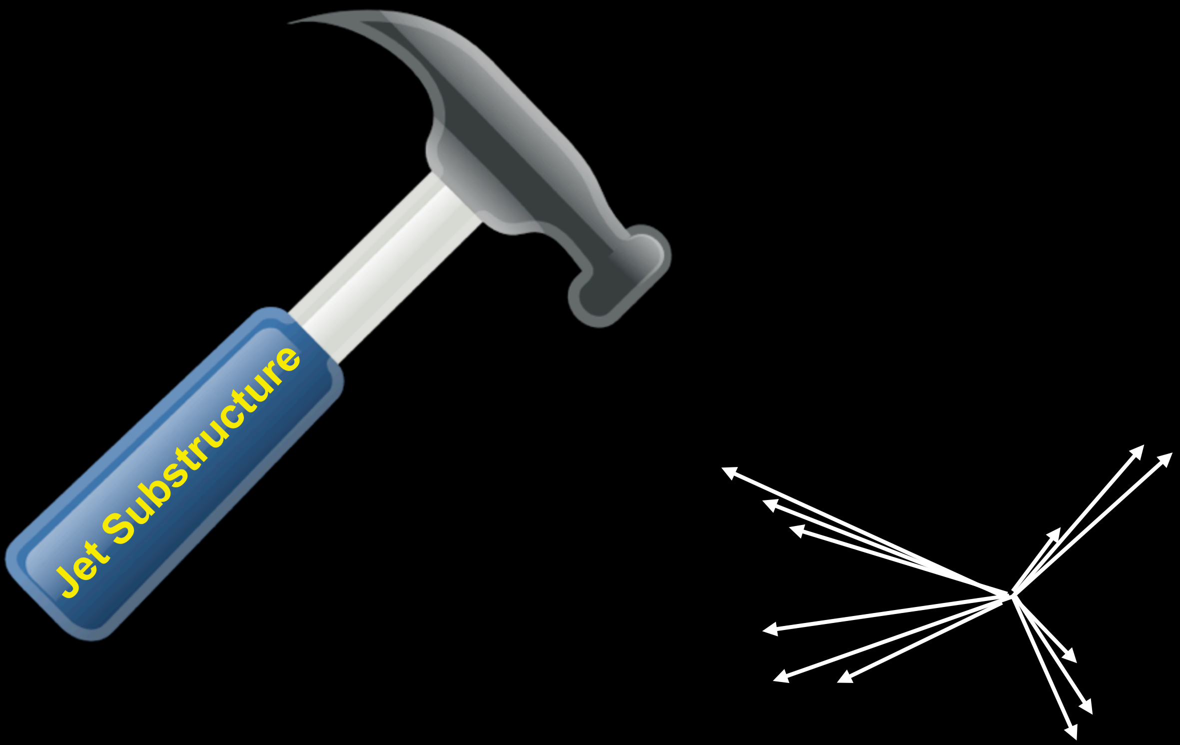




2012 ??

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

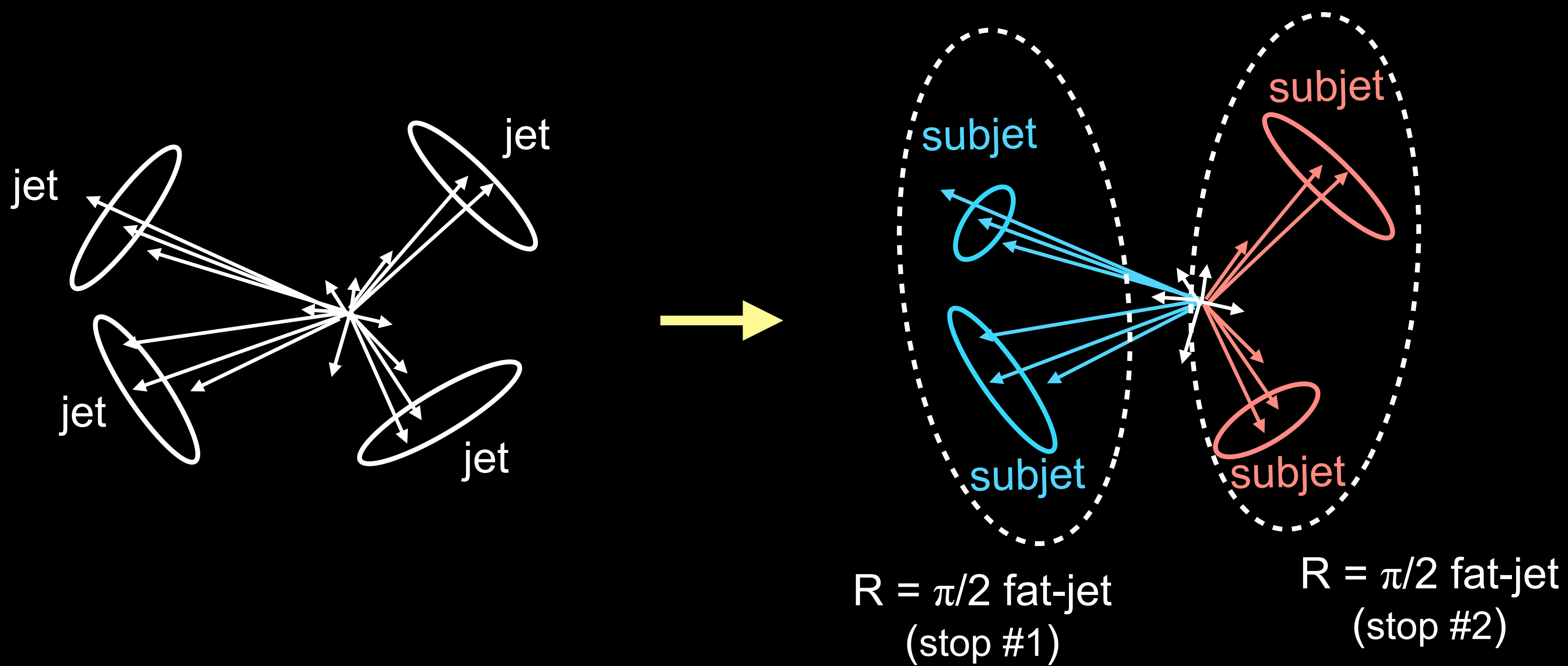
minimum possible mass ~ $p_T \times R$ ~ 26 GeV (2010), 40 GeV (2011), 50 GeV? (2012), ???? (2015)


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

Change of Perspective

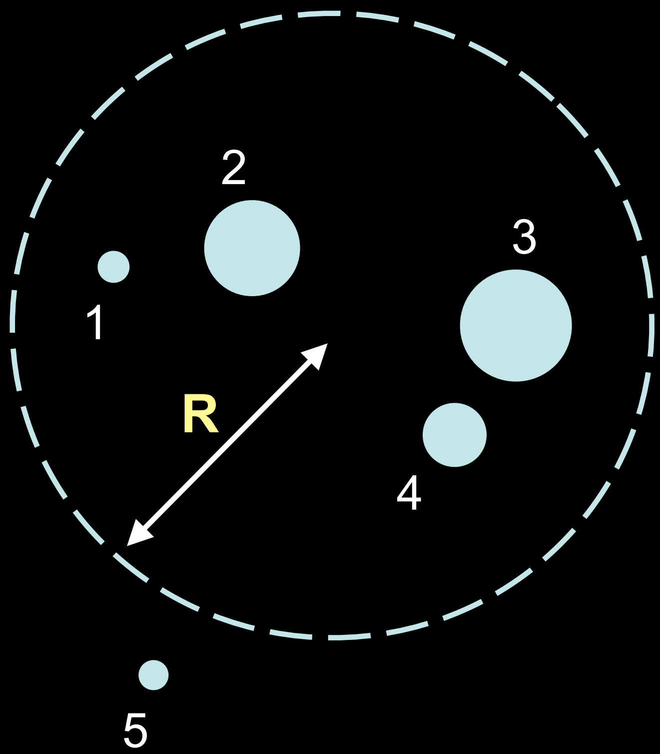


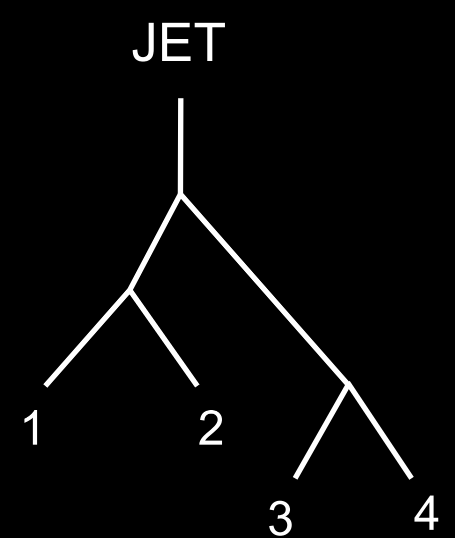
* Inspired by **Butterworth, Davison, Rubin, Salam (0802.2470)**

Basic Ingredients

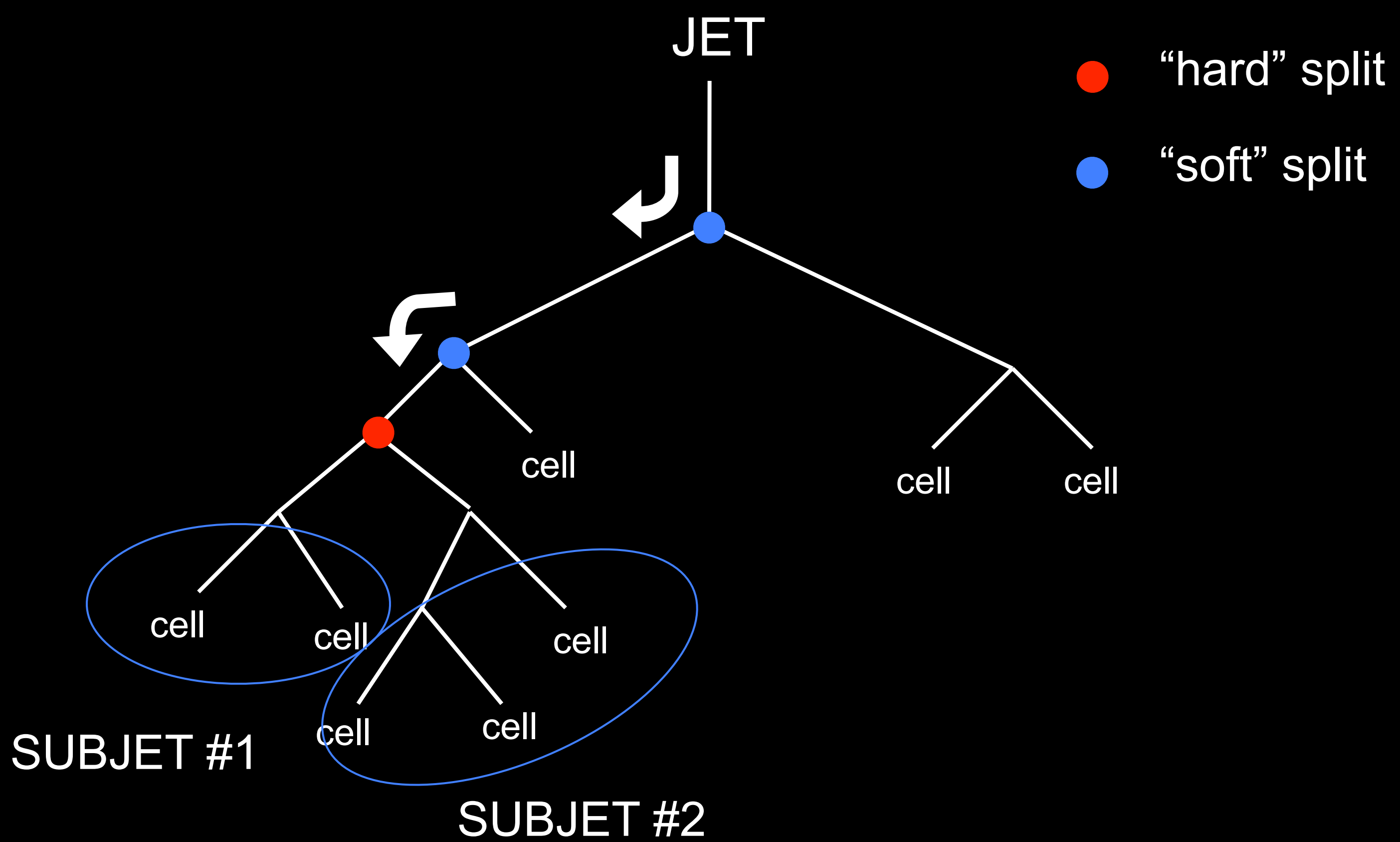
- Jet-H_T trigger: offline H_T > 900
- Pre-trim event to remove pileup
  - *Fixed* minijet p_T threshold, tuned to remove ‹N_{PV}› ~ 20
- Capture stop decays in R ~ $\pi/2$ fat-jets
  - maximize mass reach, minimize steepness of background
- Decluster into subjets using BDRS-like prescription
  - relative-p_T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

Jet Clustering History





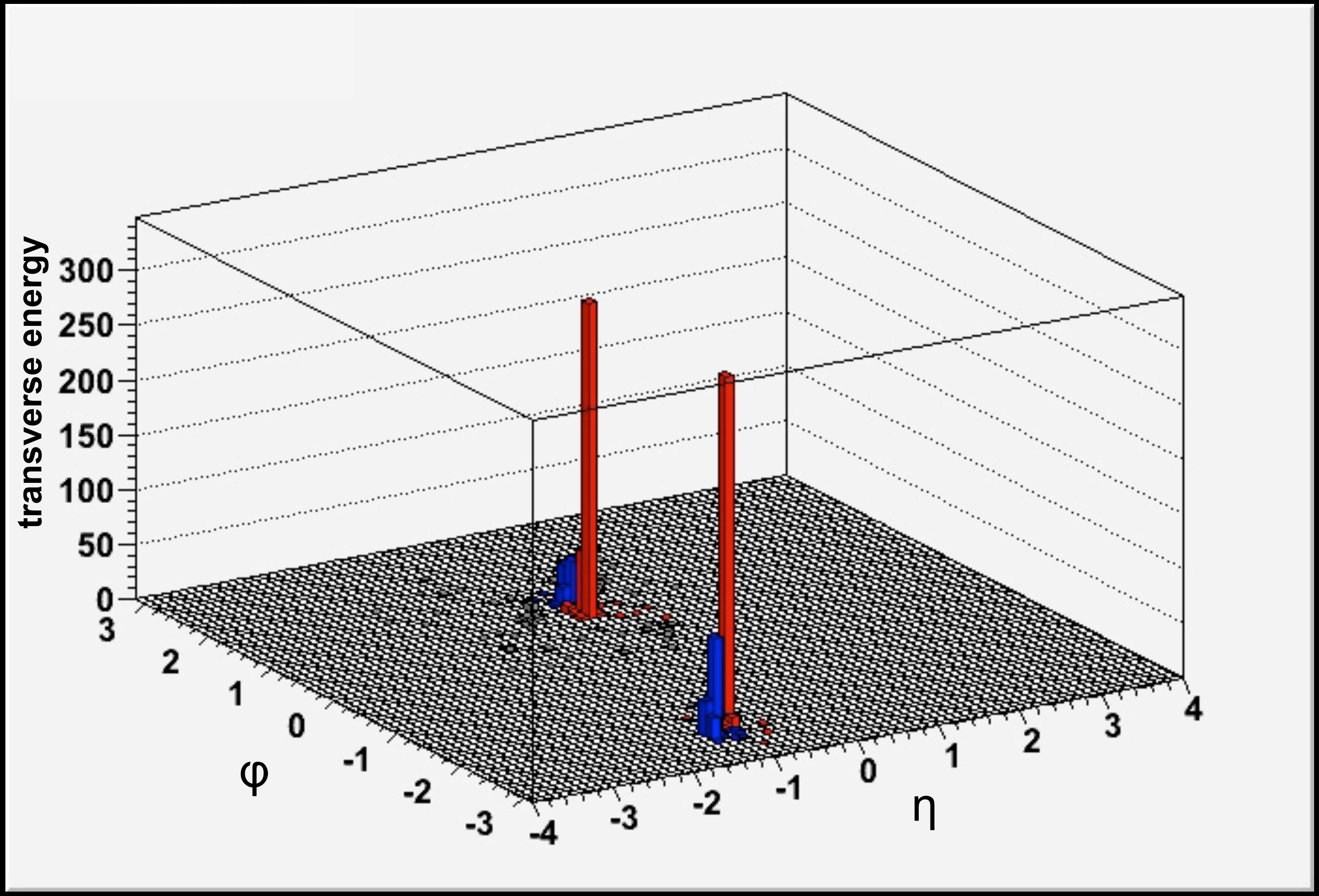
Jet Substructure via Declustering



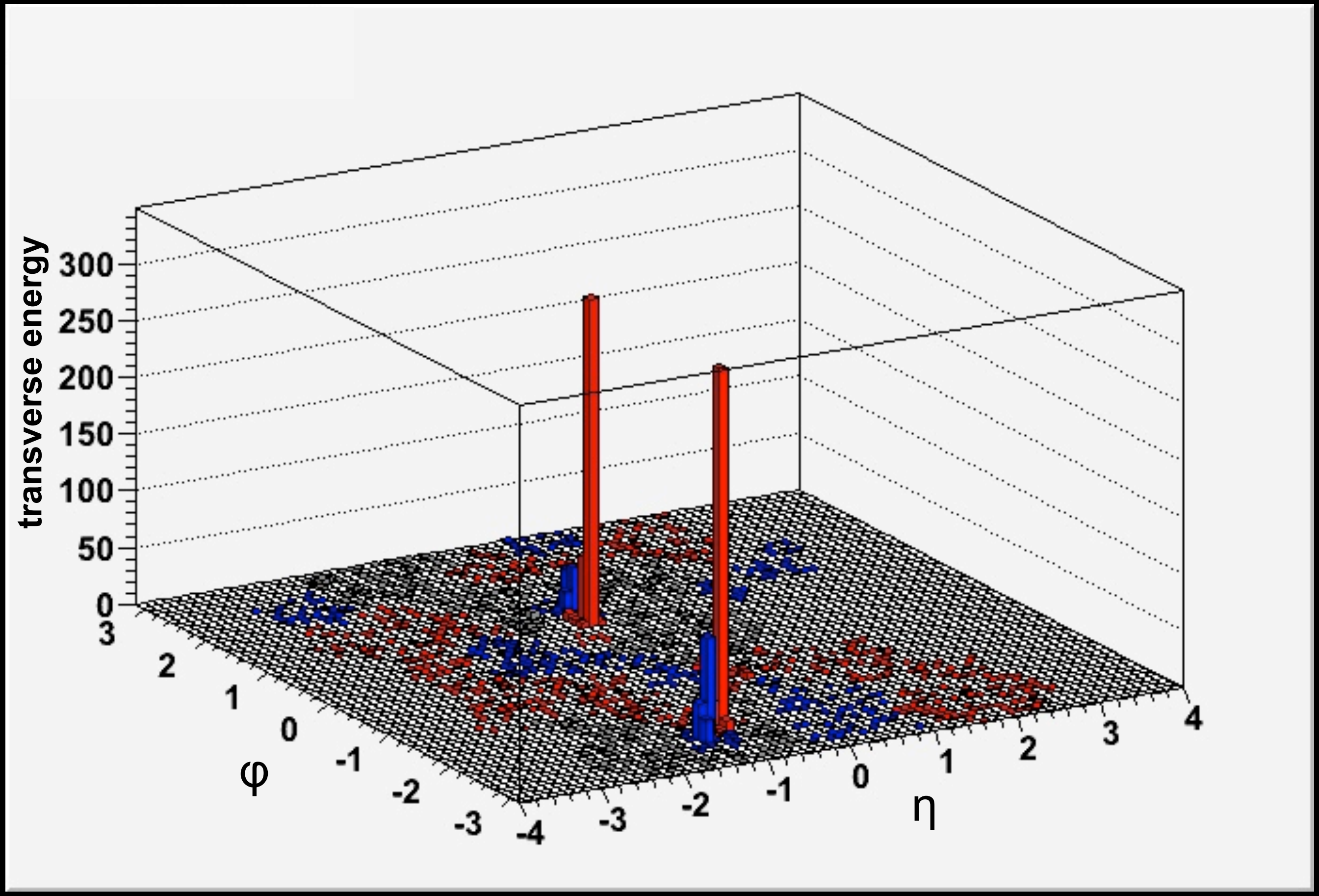
Monte Carlo Gory Details

- Signal matched up to 1 extra parton
  - MadGraph5 + PYTHIA6
  - k_T-MLM @ 30 GeV
  - (beware Pythia8 power shower)
- QCD background matched up to 4 partons
  - MadGraph5 + Pythia8
  - CKKW-L, Durham-k_T @ 50 GeV
- 0.1×0.1 calorimeter grid
- Smear subjet energies
  - e.g., p_T = 200 GeV smeared by 7%

Example Event, m(stop) = 100

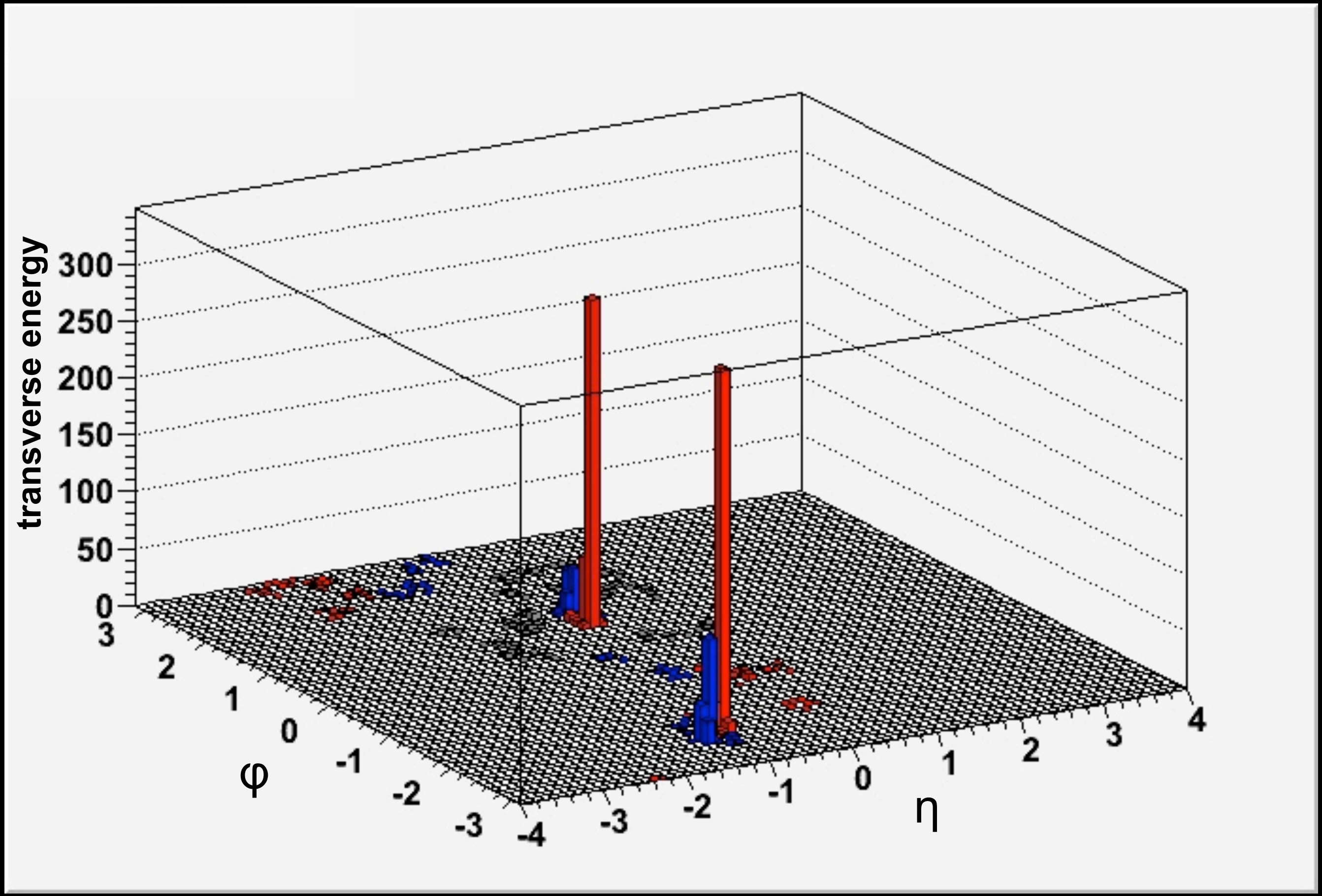


Example Event, m(stop) = 100



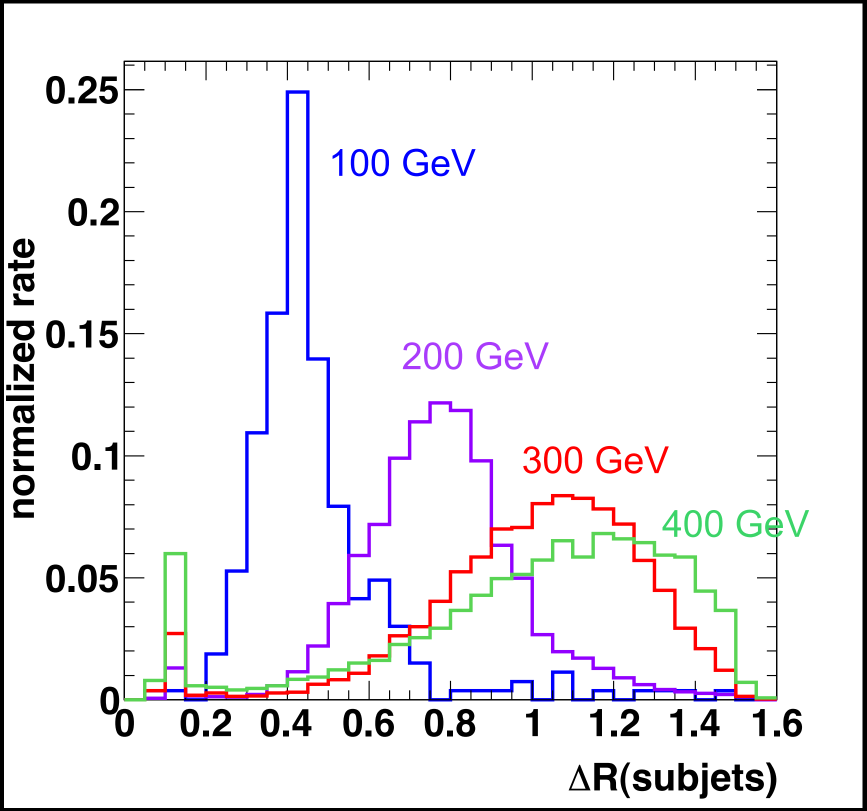
+ pileup

Example Event, m(stop) = 100



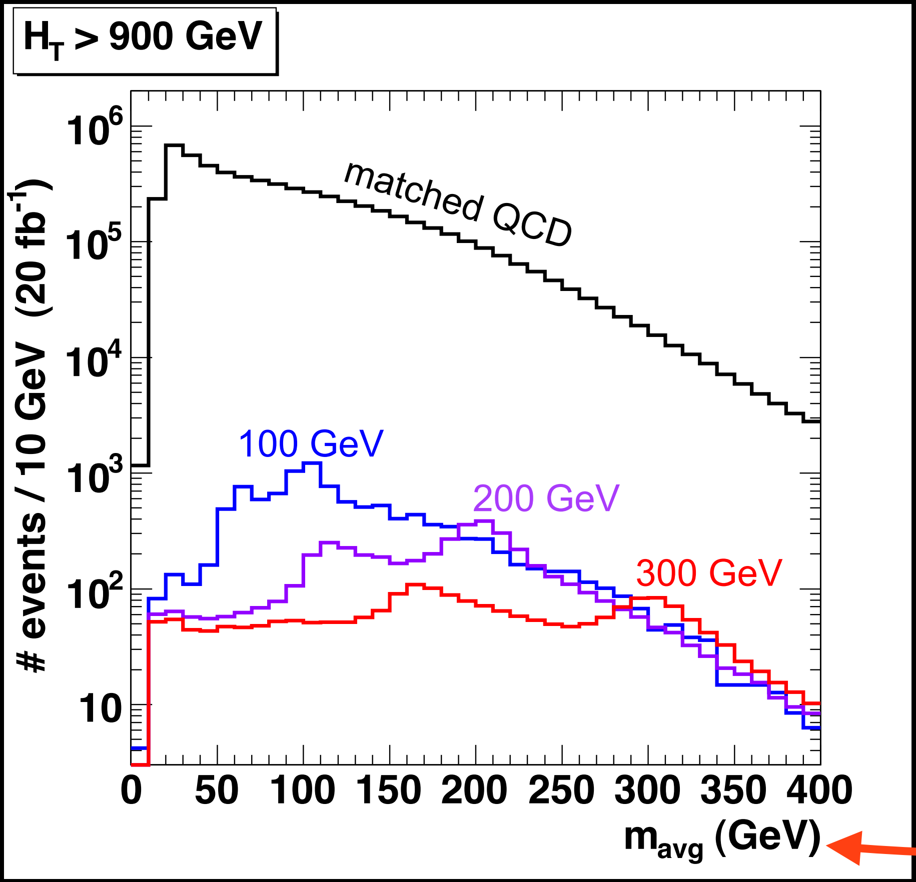
+ trimming

ΔR Distributions



*Passing all analysis cuts

Cut Flow

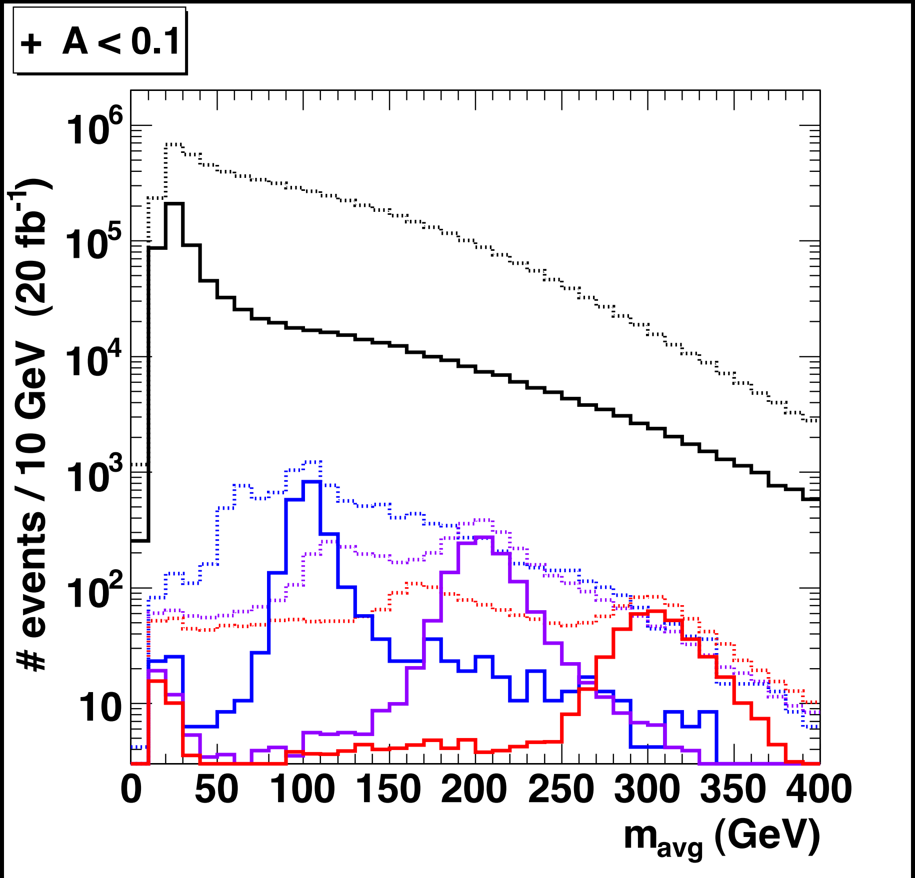


average mass of the two declustered fat-jets

Start with H_T-triggered sample (conventional jets), run substructure procedure to get subjets

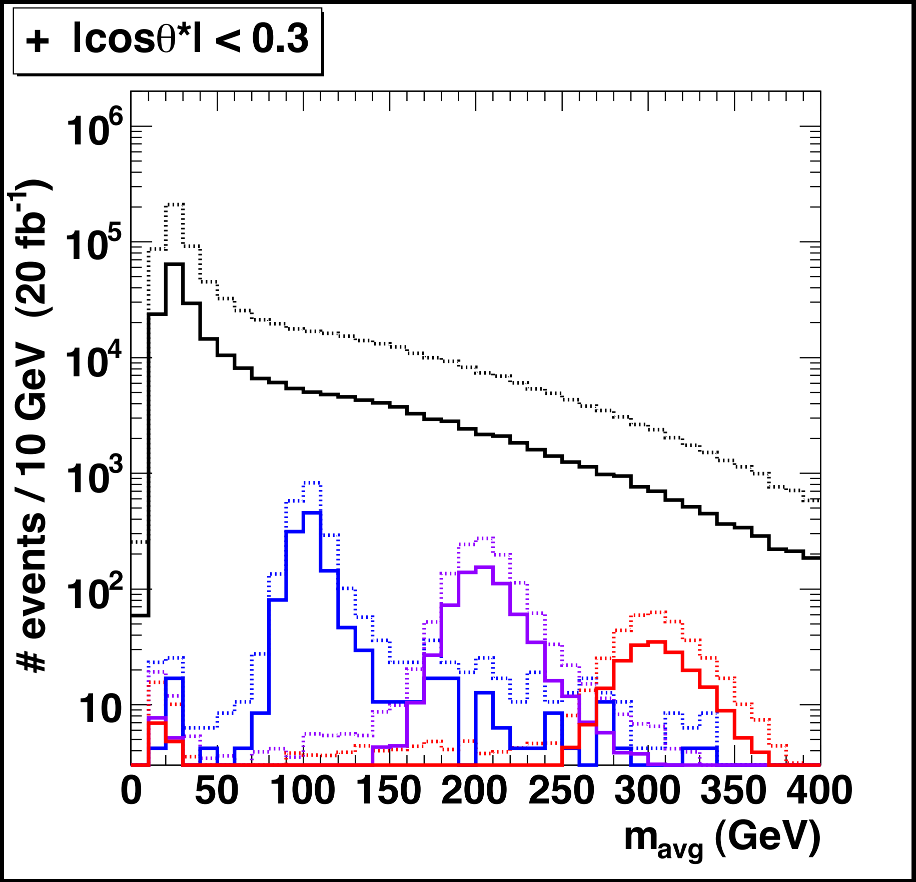
* LHC8, 20/fb

Cut Flow



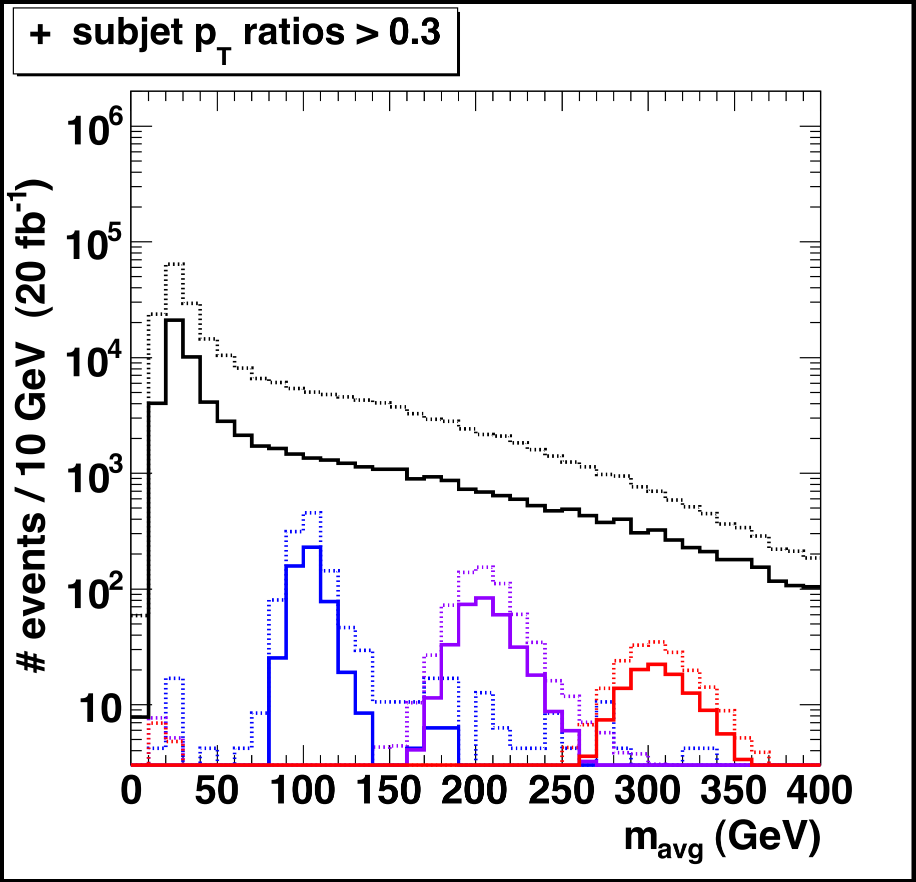
Small asymmetry between declustered fat-jet masses

Cut Flow



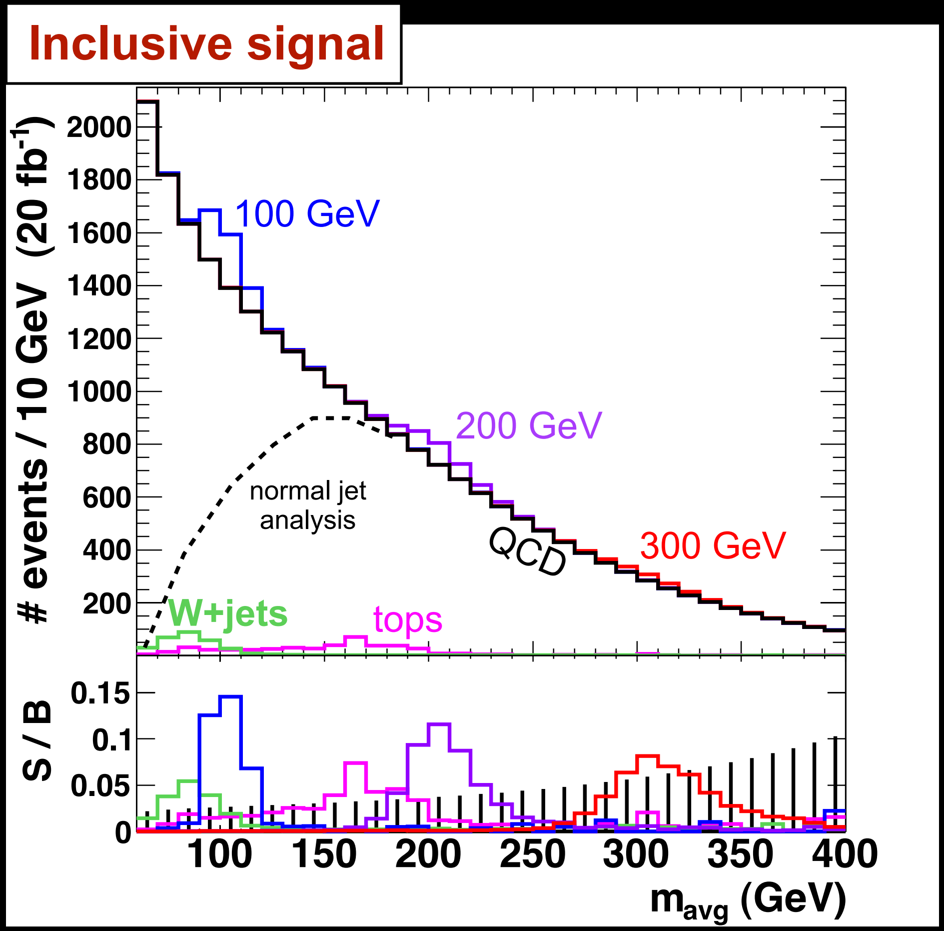
Centrally produced in CM frame

Cut Flow



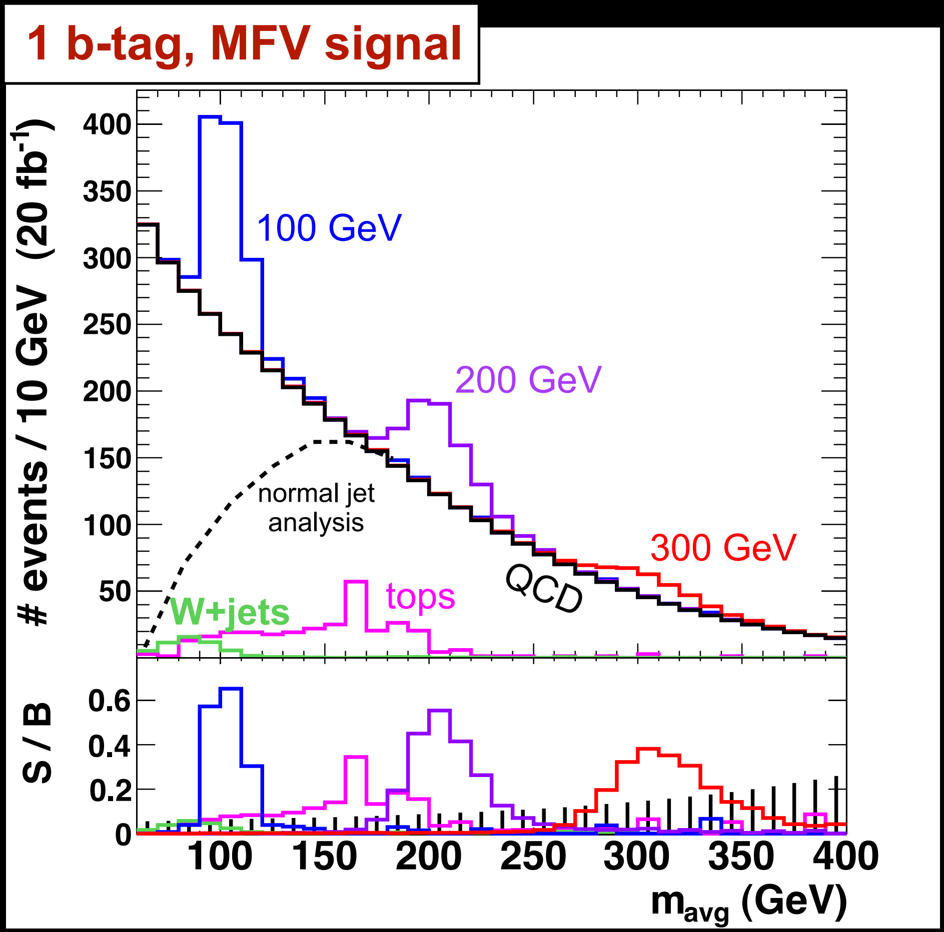
Subjets not hierarchical in energy

Average-Mass Spectrum



**Be careful of top background!

Average-Mass Spectrum



* Assuming ~100% BR to bd/bs

**Be careful of top background!

QCD Estimation 4-Ways

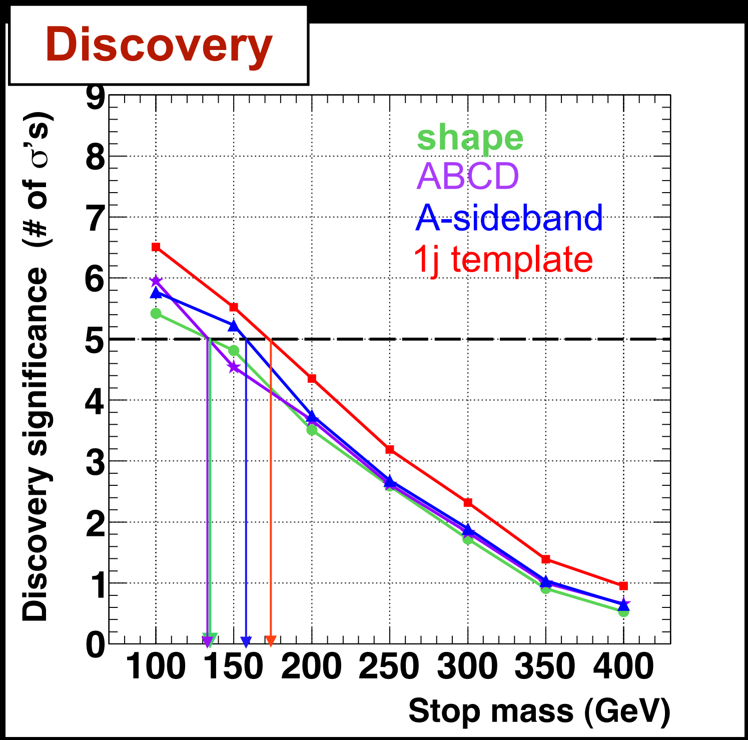
- Smooth function fit (CMS style)

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

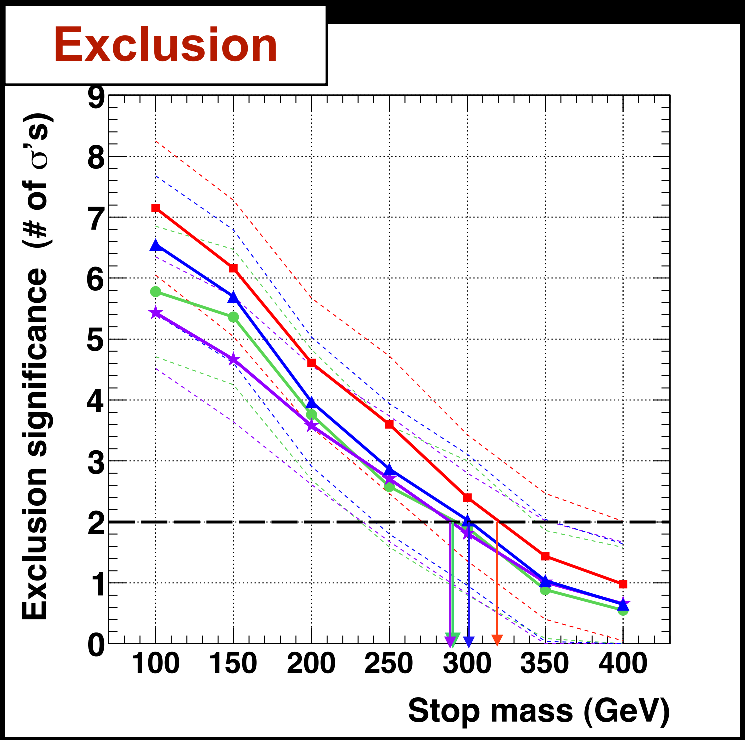
(+ signal bump)

- 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 ($\Leftrightarrow$ $m_1 m_2$-plane)
- Jet-mass template
  - derive m_{avg} spectrum from spectra of individual fat-jets
  - a control region with ~infinite statistics

2012 Sensitivities, Inclusive



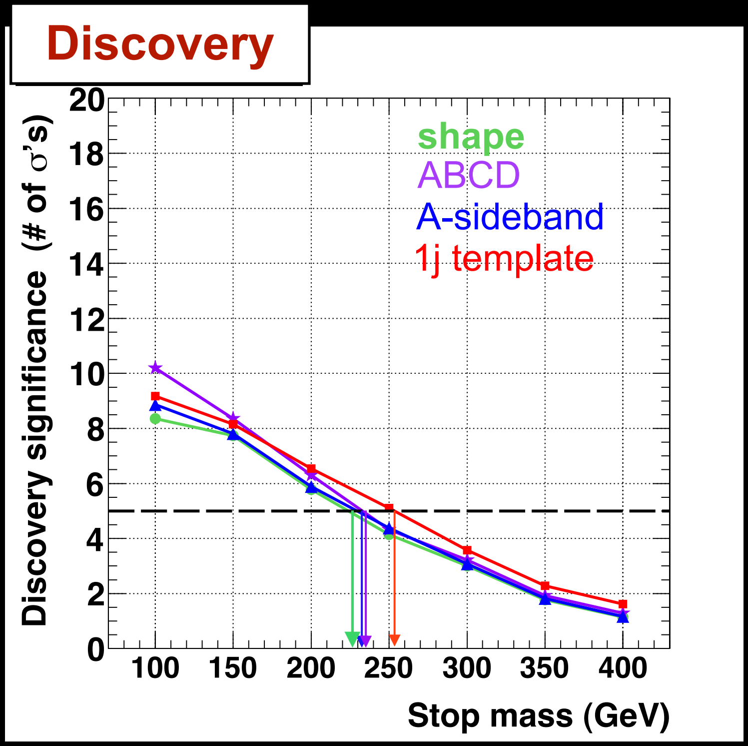
discover ~150 GeV

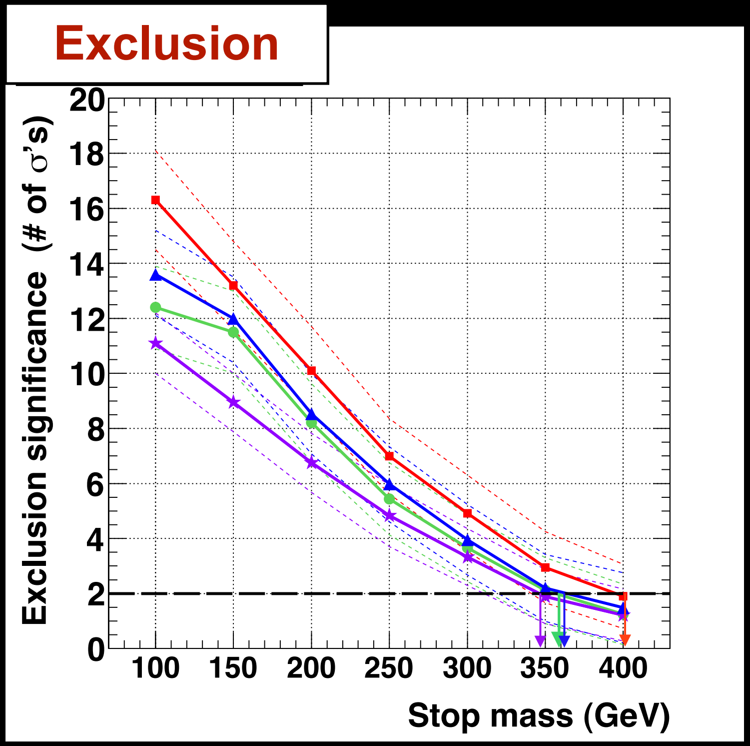


exclude ~300 GeV

*$\Delta\chi^2$ 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

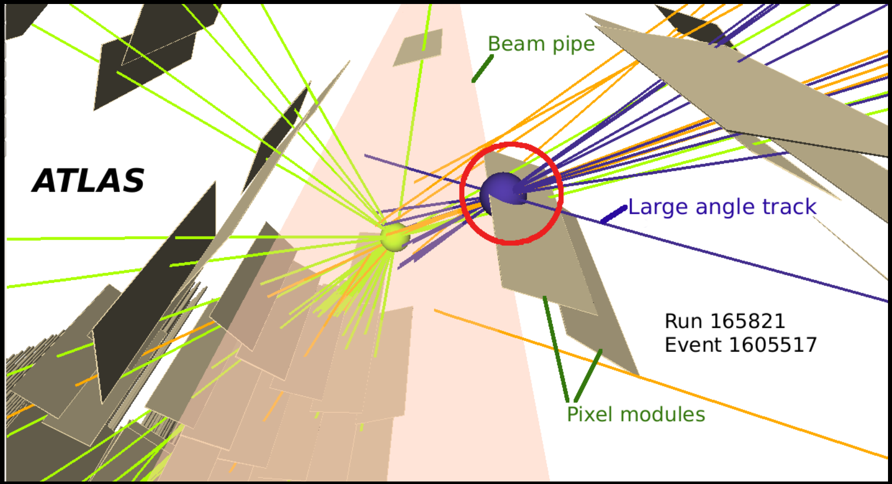
Looking Ahead to Future Runs

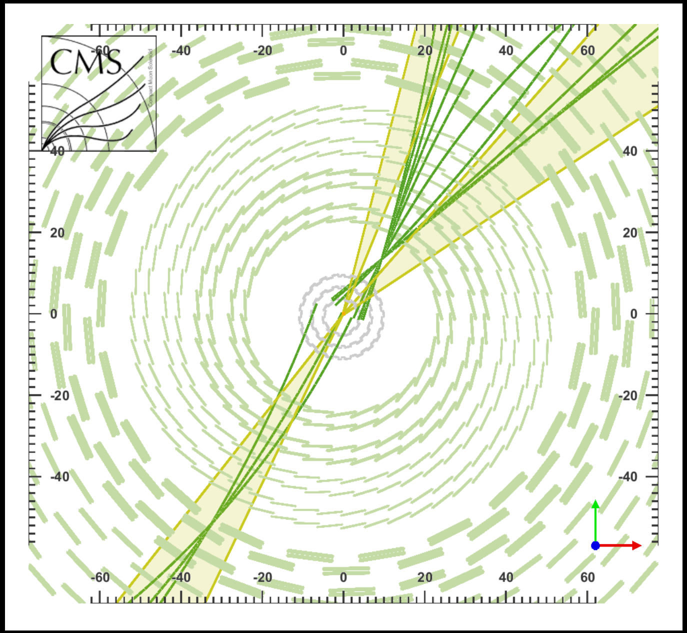
- 14 TeV, 300 fb^{-1}
  - H_T trigger assumed scaled up to 1600 GeV
- Inclusive analysis continues to improve
  - 100 GeV still visible with $>5\sigma$
  - $\sim 10\sigma$ for 200-300, discoverable up to 500
  - exclusion up to 650
- See also Snowmass projections **Duggan, et al (1308.3903)**
  - standard 4j style analysis
  - similar reach (though nothing below 300 GeV)

Pushing Further in Multijets?

- Direct Higgsino pairs to 6j (or more) via RPV
  - cross section ~15x smaller than stops, ~500x smaller than gluinos
  - but more structure & guaranteed flavor biases
- Generic colored X → n jets
  - BU axigluon for Tevatron top A_{FB} anomaly
  - complex all-hadronic light gluino cascades
  - (insert your favorite model here)
- Color-singlet pairs to 4j
  - light W'/Z' or analog...depends on couplings, spin
  - may be impossible without b/c flavor tags

Thinking Outside the Beampipe

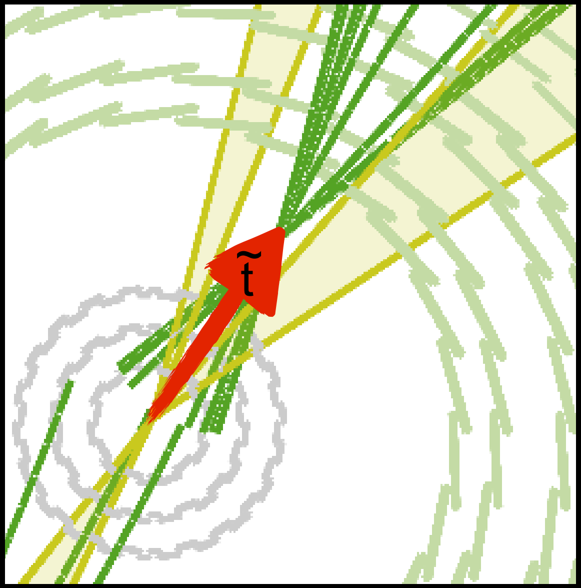




$$c\tau_{\mathrm{RPV}} \sim 0.1\mathrm{mm}\left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)\left(\frac{10^{-6}}{\lambda}\right)^2$$

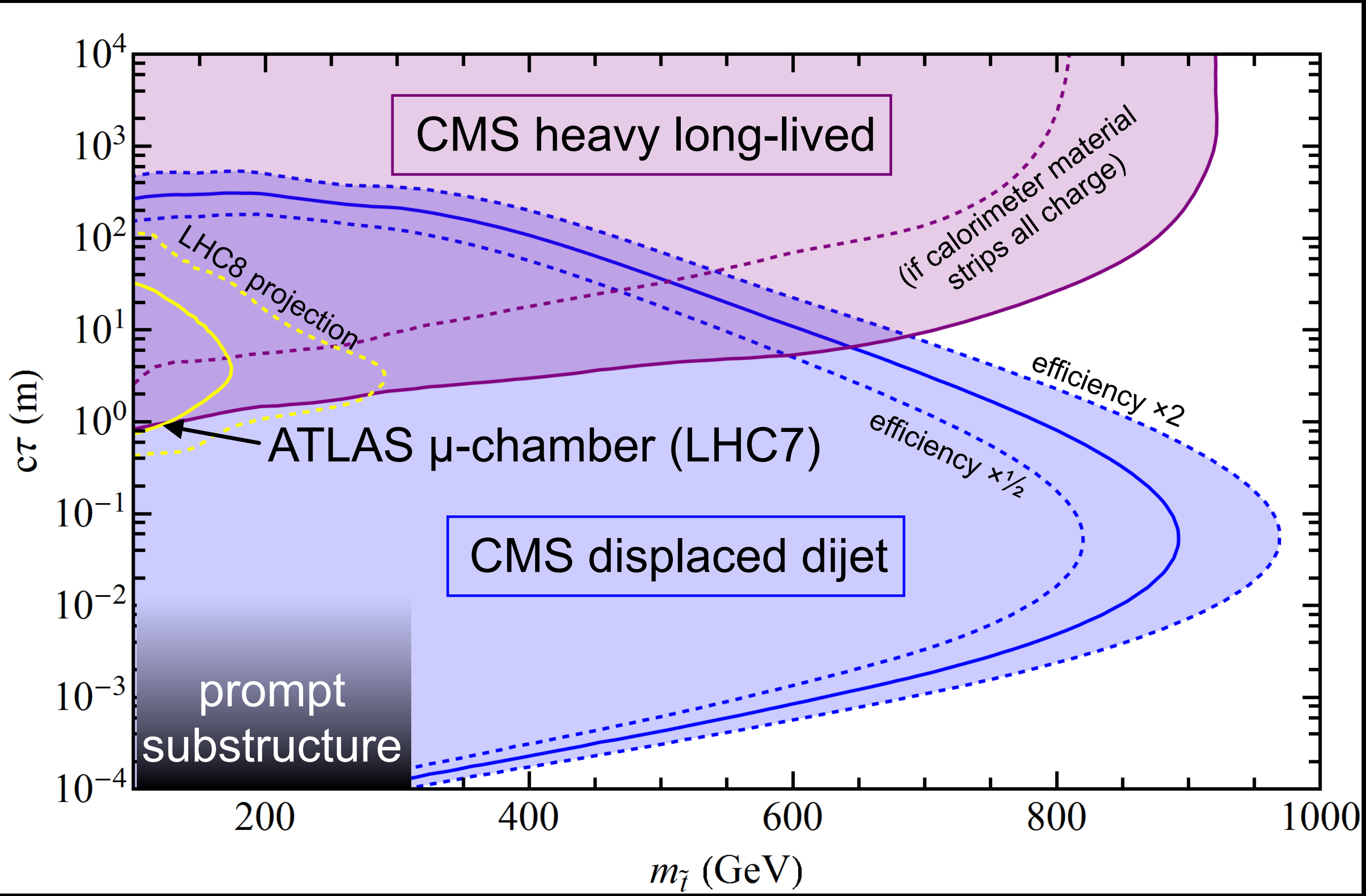
Displaced RPV Stop Back-of-the-Envelope

- $m(\tilde{t}) = 150$ & $\sqrt{\hat{s}} > 400 \Rightarrow \sigma \sim 30$ pb via direct QCD pair production
- ~50% chance to get neutral stop-hadron
- ~50% pass basic acceptance, ~5% reco efficiency for $c\tau \sim 40$ cm
- luminosity ~ 20,000 pb^{-1}
- TOTAL: 30 * 0.5 * 0.5 * 0.05 * 20,000 = 7,500 events
- O(1) background $\Rightarrow$ limit is ~4 events



CMS PAS EXO-12-038

Recast Limits

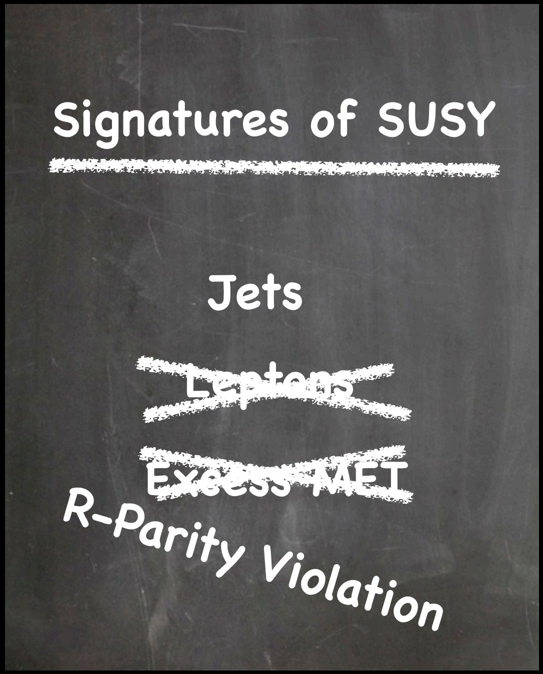


* Decays to light flavors

(b-quarks similar! Also covers dRPV decay to 2b via Kähler QQD†)

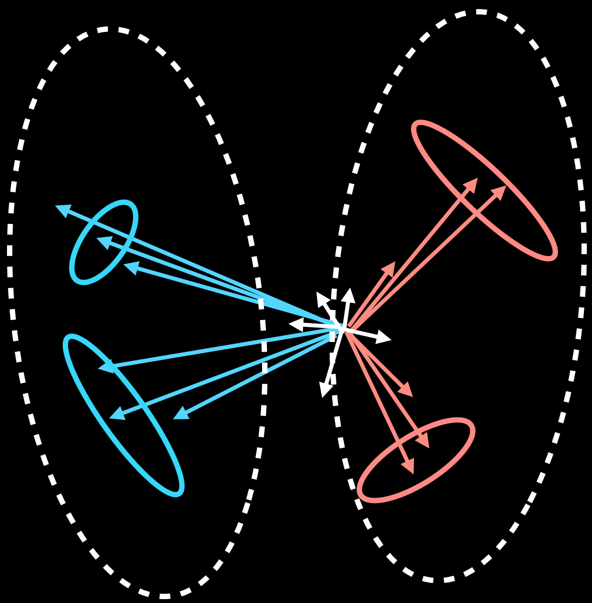
Liu & Tweedie (1405.XXXX)

Summary


Signatures of SUSY
Jets
~~Leptons~~
~~Excess MET~~
R-Parity Violation

Summary

- Stop LSP may be sitting in the data *now*, hidden in multijets
  - mass as low as 100 GeV still allowed
  - direct production might be our best shot if m(gluino) > 1 TeV
  - but traditional jet analyses throw much of the signal away due to triggers, sculpted continuum backgrounds
- Can be dug out using jet substructure approach
  - one dimensionful cut (H_T), otherwise scale-invariant
  - covers complete mass range
  - 2012 data probes up to 300 (400) GeV inclusively (b-tagged MFV)
  - 2015+ will uniformly improve by ~2×



Summary

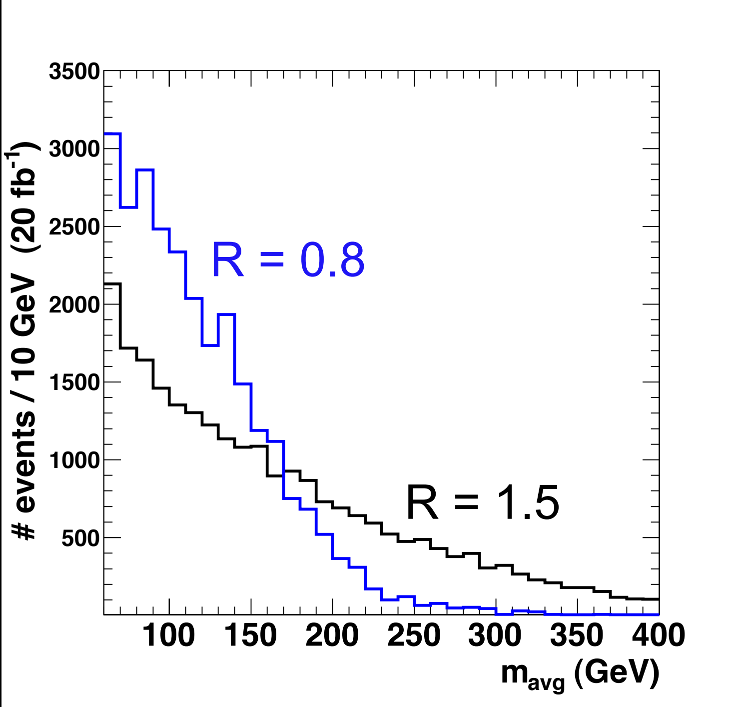
- Sets the stage for other ambitious fully jetty pair production searches
  - for strongly-produced particles, we can handle minimal color/spin/multiplicity/flavor....what else can we do?
- Displaced decays?
  - non-dedicated limits are already very strong
  - perhaps an observation of prompt RPV stops could have interesting implications for cosmology

Conclusion

- The number of places for SUSY to hide is shrinking, but....
- Exotic creatures may still be hiding in the data!

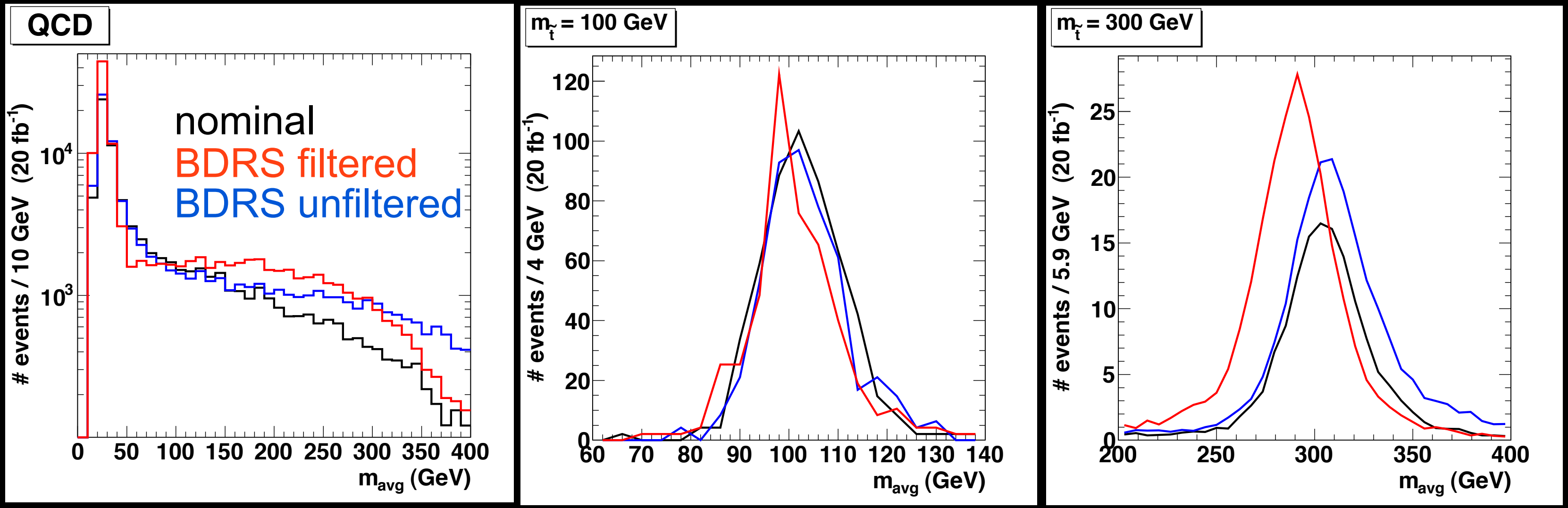
More…

Smaller Fat-Jets?



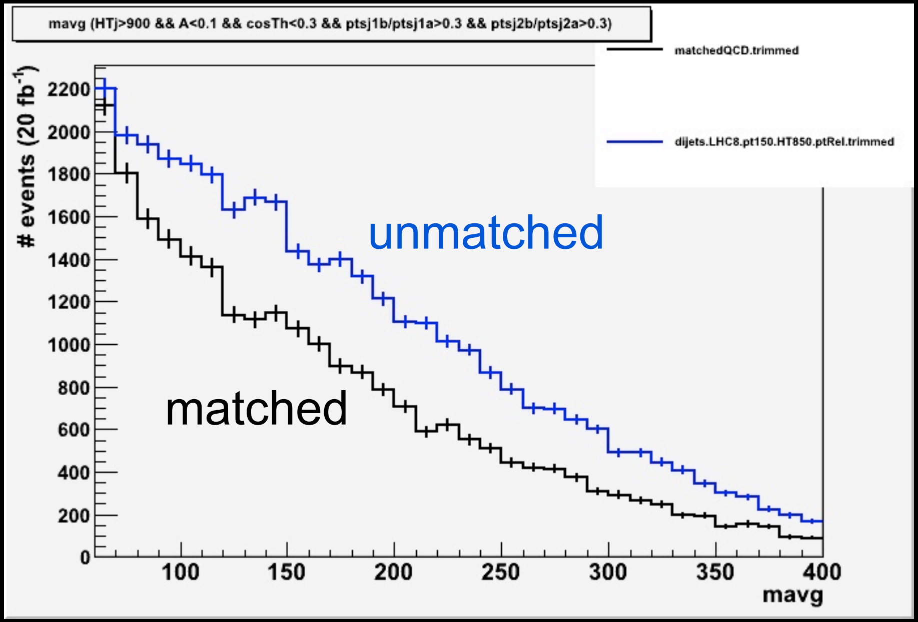
- ~2x steeper background
- 100 GeV signal acceptance up 30%, with slightly smaller S/B and slightly larger S/√B
- Higher-mass stop acceptances radically degrade (would need a separate "resolved" analysis)

Vs BDRS



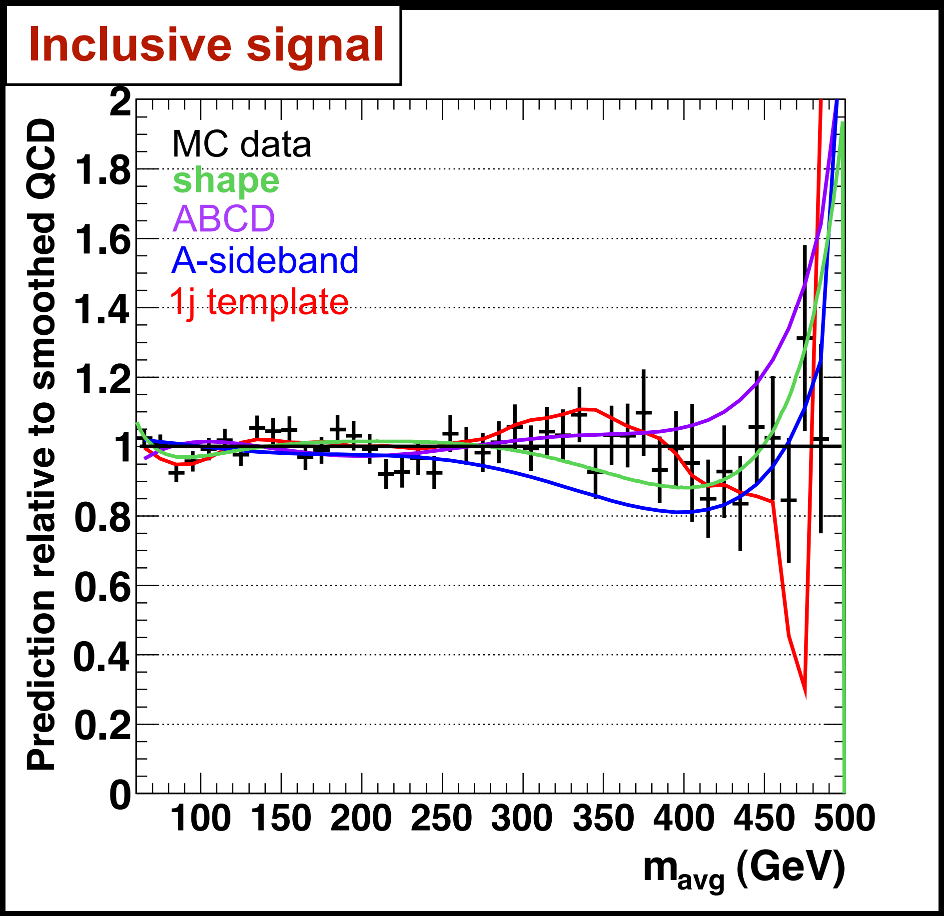
- Takeaway points
  - Traditional filtering is a bad idea (introduces mass scales via maximum R=0.3 for subjets)
  - Otherwise, the *major* difference w.r.t. BDRS is that our subjet m/p_T criterion gives more consistent slope and suppresses the tail
  - Unfiltered BDRS mass-asymmetry control region becomes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

Matched Vs Unmatched QCD



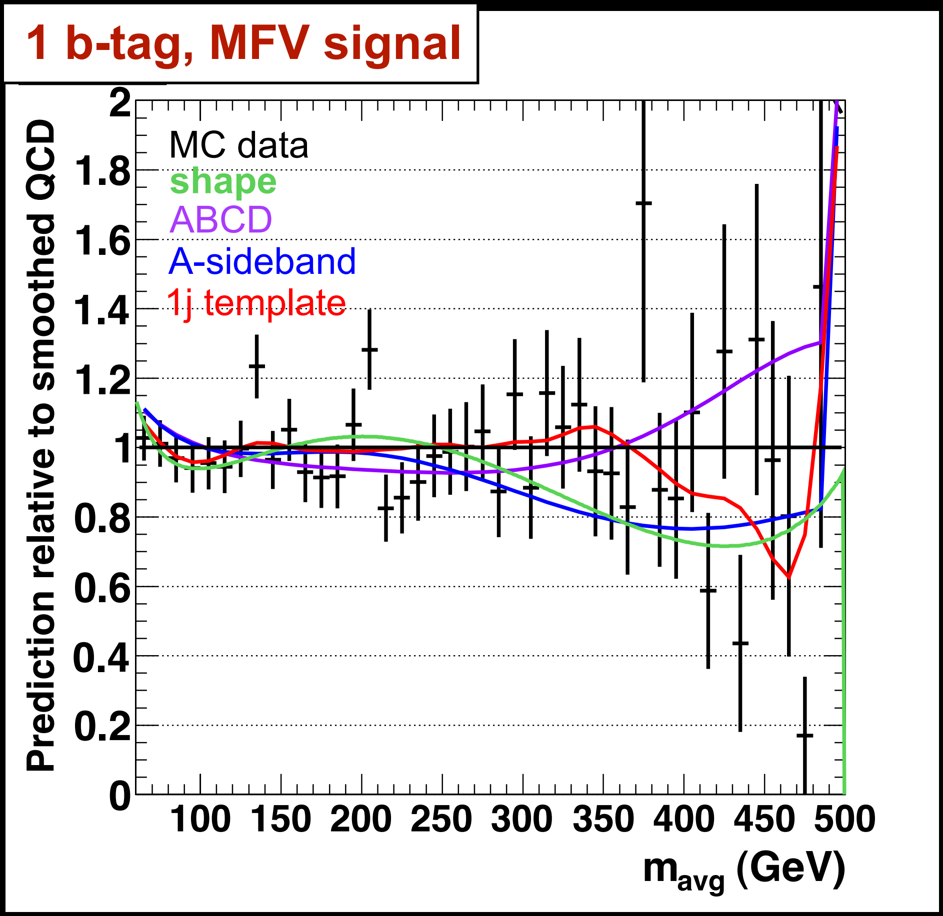
* Both approaches show good agreement with traditional 4j analysis

Performance of "Data-Driven" QCD Estimators



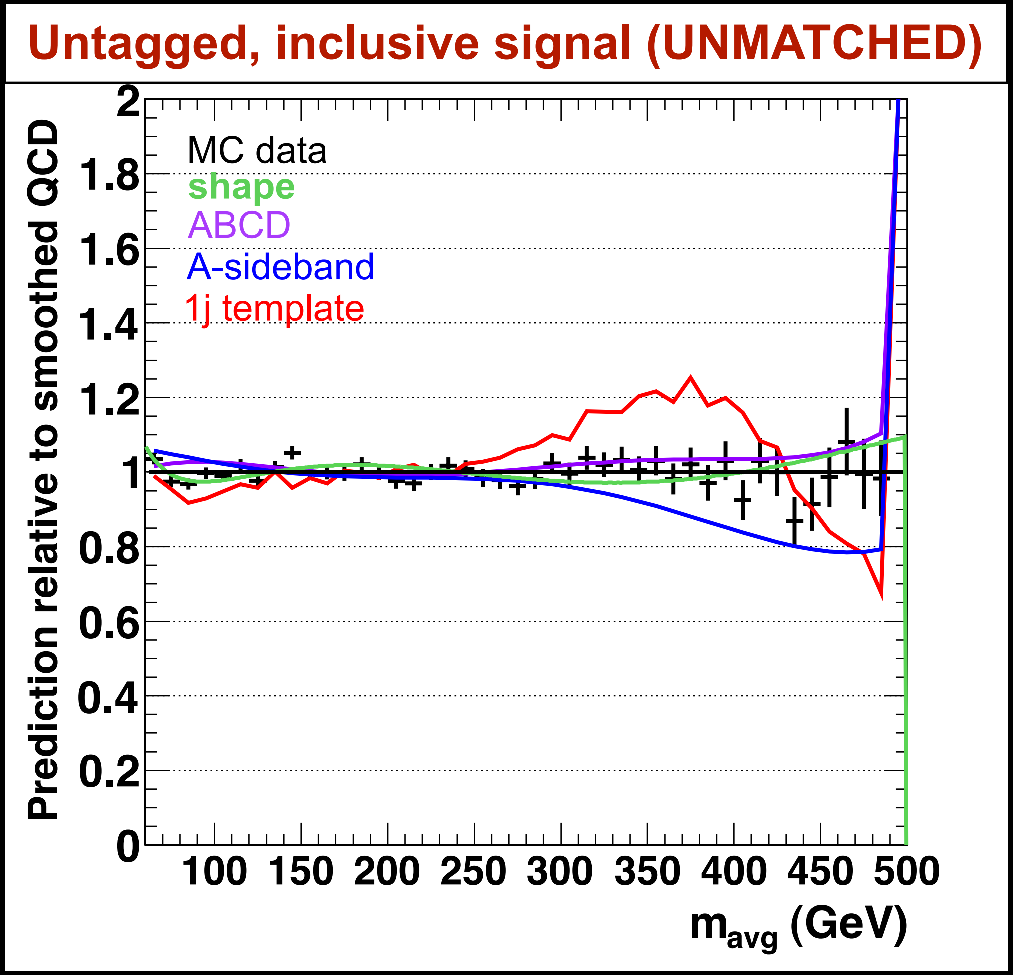
* Error bars are MC statistics (effective lumi ~ 20/fb)

Performance of "Data-Driven" QCD Estimators

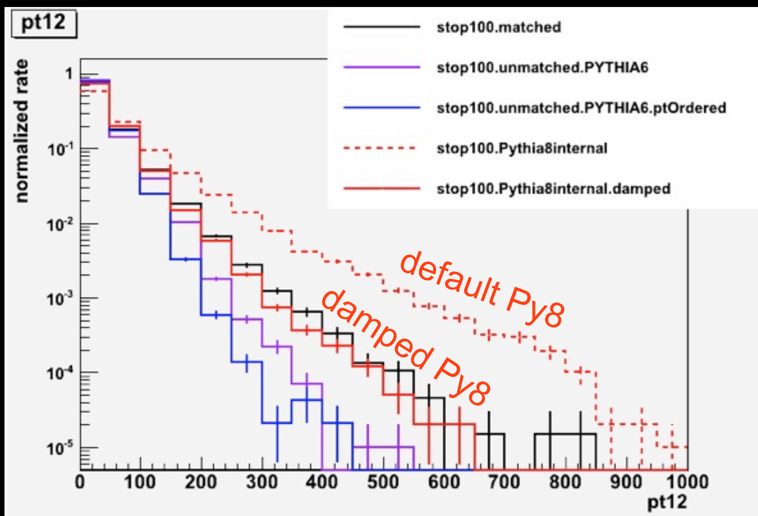


* Error bars are MC statistics (effective lumi ~ 20/fb)

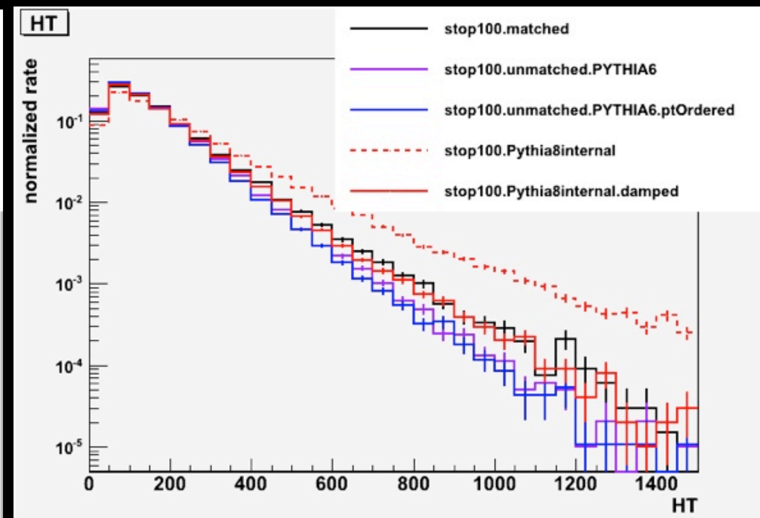
Performance of “Data-Driven” QCD Estimators (Unmatched)



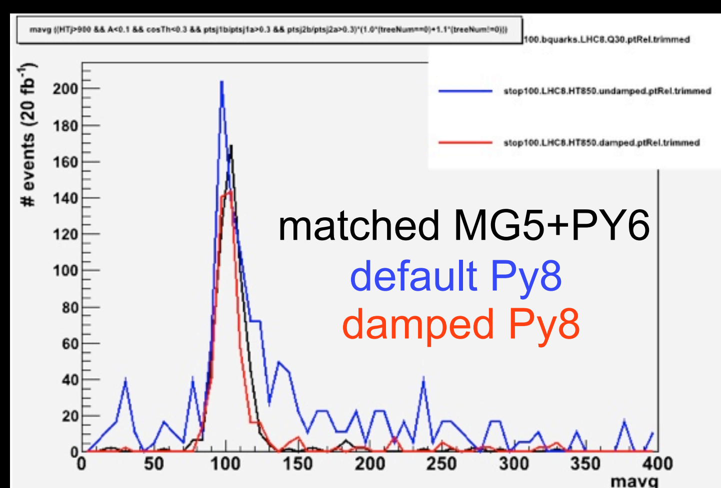
Lessons on Signal Showering



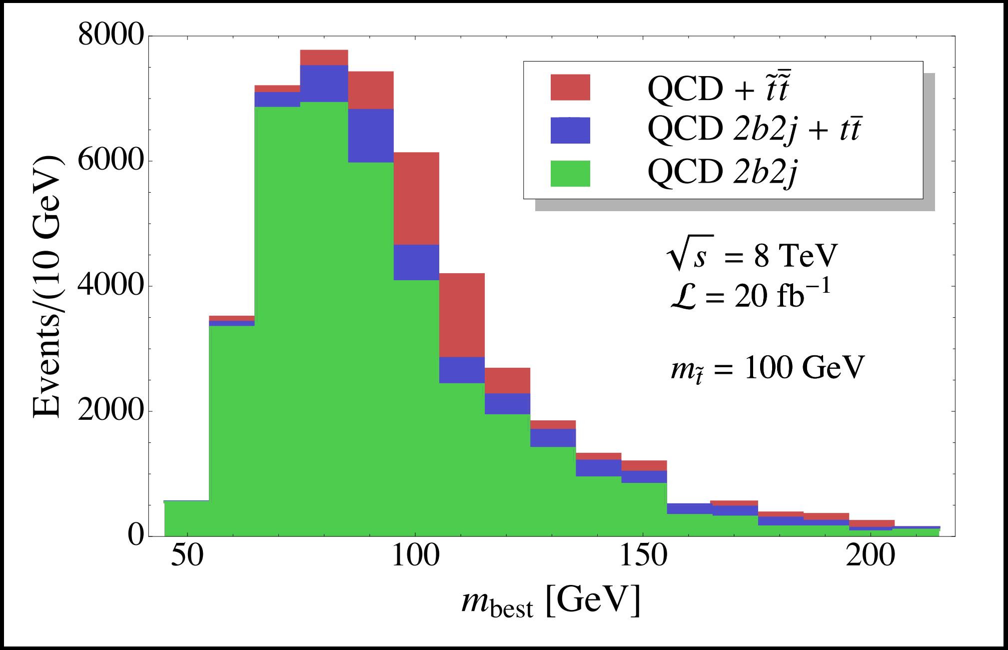
p_T(stop1+stop2)



p_T(stop1) + p_T(stop2) + Σp_T(j)



b-Triggered 4-Jet Analysis



~5σ for 100 & 200 GeV

Franceschini & Torre (1212.3622)